This book is dedicated to
Intertec Superbrain II computer
Reverse Engineering for Beginners
(Understanding Assembly Language)

Dennis Yurichev
Reverse Engineering for Beginners

(Understanding Assembly Language)


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So do not hesitate to contact me: dennis@yurichev.com.
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\(^3\)Java Virtual Machine
\(^4\)Pseudorandom Number Generator
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What is with two titles?

The book was named “Reverse Engineering for Beginners” in 2014-2018, but I always suspected this makes readership too narrow.

Infosec people know about “reverse engineering”, but I’ve rarely hear the “assembler” word from them. Likewise, the “reverse engineering” term is somewhat cryptic to a general audience of programmers, but they know about “assembler”.

In July 2018, as an experiment, I’ve changed the title to “Assembly Language for Beginners” and posted the link to Hacker News website, and the book was received generally well.

So let it be, the book now has two titles.

However, I’ve changed the second title to “Understanding Assembly Language”, because someone already written “Assembly Language for Beginners” book. Also, people say “for Beginners” sounds a bit sarcastic for the book of ~1000 pages.

Two books differ only by title, filename (UAL-XX.pdf versus RE4B-XX.pdf), URL and couple of first pages.

About reverse engineering

There are several popular meanings of the term “reverse engineering”:
1) The reverse engineering of software; researching compiled programs
2) The scanning of 3D structures and the subsequent digital manipulation required in order to duplicate them
3) Recreating DBMS structure

This book is about the first meaning.

Prerequisites

Basic knowledge of the C PL. Recommended reading: 12.1.3 on page 1012.

Exercises and tasks

...can be found at: http://challenges.re.

About the author

Dennis Yurichev is an experienced reverse engineer and programmer. He can be contacted by email: dennis@yurichev.com.
Praise for this book

- “Now that Dennis Yurichev has made this book free (libre), it is a contribution to the world of free knowledge and free education.” Richard M. Stallman, GNU founder, software freedom activist.
- “It’s very well done .. and for free .. amazing.” Daniel Bilar, Siege Technologies, LLC.
- “… excellent and free” Pete Finnigan, Oracle RDBMS security guru.
- “… It is amazing and unbelievable.” Luis Rocha, CISSP / ISSAP, Technical Manager, Network & Information Security at Verizon Business.
- “Thanks for the great work and your book.” Joris van de Vis, SAP Netweaver & Security specialist.
- “… [a] reasonable intro to some of the techniques.” Mike Stay, teacher at the Federal Law Enforcement Training Center, Georgia, US.
- “I love this book! I have several students reading it at the moment, [and] plan to use it in graduate course.” Sergey Bratus, Research Assistant Professor at the Computer Science Department at Dartmouth College.
- “Dennis @Yurichev has published an impressive (and free!) book on reverse engineering” Tanel Poder, Oracle RDBMS performance tuning expert.
- “This book is a kind of Wikipedia to beginners…” Archer, Chinese Translator, IT Security Researcher.
- “[A] first-class reference for people wanting to learn reverse engineering. And it’s free for all.” Mikko Hyppönen, F-Secure.

Thanks

For patiently answering all my questions: Andrey “herm1t” Baranovich, Slava “Avid” Kazakov, SkullC0DEr.


For helping me in other ways: Andrew Zubinski, Arnaud Patard (rtp on #debian-arm IRC), noshadow on #gcc IRC, Aliaksandr Autayeu, Mohsen Mostafa Jokar.

For translating the book into Simplified Chinese: Antiy Labs (antiy.cn), Archer.

For translating the book into Korean: Byungho Min.

For translating the book into Dutch: Cedric Sambre (AKA Midas).

For translating the book into Spanish: Diego Boy, Luis Alberto Espinosa Calvo, Fernando Guida, Diogo Mussi, Patricio Galdames.

For translating the book into Portuguese: Thales Stevan de A. Gois, Diogo Mussi, Luiz Filipe.

For translating the book into Italian: Federico Ramondino, Paolo Stivanin, twyK.

10 twitter.com/daniel_bilar/status/436578617221742593
11 twitter.com/petefinnigan/status/400551705797869568
12 reddit
13 twitter.com/sergeybratus/status/505590326560833536
14 twitter.com/TanelPoder/status/524668104065159169
15 goto-vlad/github
16 https://github.com/pixjuan
17 https://github.com/73696e65
18 https://github.com/TheRenaissance
19 https://github.com/pinkrab
20 https://github.com/paolostivanin
**mini-FAQ**

Q: What are the prerequisites for reading this book?

A: A basic understanding of C/C++ is desirable.

Q: Should I really learn x86/x64/ARM and MIPS at once? Isn’t it too much?

A: Starters can read about just x86/x64, while skipping or skimming the ARM and MIPS parts.

Q: Can I buy a Russian or English hard copy/paper book?

A: Unfortunately, no. No publisher got interested in publishing a Russian or English version so far. Meanwhile, you can ask your favorite copy shop to print and bind it.

Q: Is there an epub or mobi version?

A: No. The book is highly dependent on TeX/LaTeX-specific hacks, so converting to HTML (epub/mobi are a set of HTMLs) would not be easy.

Q: Why should one learn assembly language these days?

21 [https://github.com/besnardf](https://github.com/besnardf)

22 [https://github.com/mremy](https://github.com/mremy)

23 [https://github.com/T30rix](https://github.com/T30rix)

24 [https://github.com/BlueSkeye](https://github.com/BlueSkeye)

25 [https://github.com/DSiekmeier](https://github.com/DSiekmeier)

26 [https://github.com/JAngres](https://github.com/JAngres)

27 [https://github.com/PolymathMonkey](https://github.com/PolymathMonkey)

28 [https://github.com/shmz](https://github.com/shmz)

29 [https://vasil.ludost.net/](https://vasil.ludost.net/)

30 [https://github.com/DennisYurichev/RE-for-beginners/graphs/contributors](https://github.com/DennisYurichev/RE-for-beginners/graphs/contributors)
A: Unless you are an **OS** developer, you probably don’t need to code in assembly—the latest compilers (2010s) are much better at performing optimizations than humans. Also, the latest **CPU**s are very complex devices, and assembly knowledge doesn’t really help towards understand their internals.

That being said, there are at least two areas where a good understanding of assembly can be helpful: First and foremost, for security/malware research. It is also a good way to gain a better understanding of your compiled code while debugging. This book is therefore intended for those who want to understand assembly language rather than to code in it, which is why there are many examples of compiler output contained within.

Q: I clicked on a hyperlink inside a PDF-document, how do I go back?
A: In Adobe Acrobat Reader click Alt+LeftArrow. In Evince click “<” button.

Q: May I print this book / use it for teaching?
A: Of course! That’s why the book is licensed under the Creative Commons license (CC BY-SA 4.0).

Q: Why is this book free? You’ve done great job. This is suspicious, as with many other free things.
A: In my own experience, authors of technical literature write mostly for self-advertisement purposes. It’s not possible to make any decent money from such work.

Q: How does one get a job in reverse engineering?
A: There are hiring threads that appear from time to time on reddit, devoted to RE[^34] (2016). Try looking there. A somewhat related hiring thread can be found in the “netsec” subreddit: 2016.

Q: How can I learn programming in general?

Q: I have a question...
A: Send it to me by email (dennis@yurichev.com).

### How to learn programming

Many people keep asking about it.

There is no “royal road”, but there are quite efficient ways.

From my own experience, this is just: solving exercises from:

- Harold Abelson, Gerald Jay Sussman, Julie Sussman – Structure and Interpretation of Computer Programs
- Donald E. Knuth, *The Art of Computer Programming*
- Niklaus Wirth’s books

... in pure C and LISP. You may never use these programming languages in future at all. Almost all commercial programmers don’t. But C and LISP coding experience will help enormously in long run.

Also, you can skip reading these books itselfs, just skim them whenever you feel you need to understand something you missing for the exercise you currently solve.

This may take years at best, or a lifetime, but still this is way faster than to rush between fads.

The success of these books probably related to the fact that their authors are teachers and all this material has been honed on students first.

[^31]: Operating System
[^32]: A very good text on this topic: [Agner Fog, *The microarchitecture of Intel, AMD and VIA CPUs*, (2016)](http://www.agner.org/micro/)
[^33]: Central Processing Unit
[^34]: [reddit.com/r.ReverseEngineering/](https://www.reddit.com/r/ReverseEngineering/)
[^35]: Structure and Interpretation of Computer Programs
As of LISP, I personally would recommend Racket (Scheme dialect). But this is matter of taste, anyway.

Some people say assembly language understanding is also very helpful, even if you will never use it. This is true. But this is a way for the most dedicated geeks, and it can be postponed at start.

Also, self-taught people (including author of these lines) often has the problem of trying too hard on hard problems, skipping easy ones. This is a great mistake. Compare to sport or music – no one starts at 100kg weights, or Paganini’s Caprices. I would say – you can try to tackle a problem if you can outline its solution in your mind.

---

I think the art of doing research consists largely of asking questions, and sometimes answering them. Learn how to repeatedly pose miniquestions that represent special cases of the big questions you are hoping to solve.

When you begin to explore some area, you take baby steps at first, building intuition about that territory. Play with many small examples, trying to get a complete understanding of particular parts of the general situation.

In that way you learn many properties that are true and many properties that are false. That gives guidance about directions that are fruitful versus directions to avoid.

Eventually your brain will have learned how to take larger and larger steps. And shazam, you’ll be ready to take some giant steps and solve the big problem.

But don’t stop there! At this point you’ll be one of very few people in the world who have ever understood your problem area so well. It will therefore be your responsibility to discover what else is true, in the neighborhood of that problem, using the same or similar methods to what your brain can now envision. Take your results to their “natural boundary” (in a sense analogous to the natural boundary where a function of a complex variable ceases to be analytic).

My little book Surreal Numbers provides an authentic example of research as it is happening. The characters in that story make false starts and useful discoveries in exactly the same order as I myself made those false starts and useful discoveries, when I first studied John Conway’s fascinating axioms about number systems — his amazingly simple axioms that go significantly beyond real-valued numbers.

(One of the characters in that book tends to succeed or fail by brute force and patience; the other is more introspective, and able to see a bigger picture. Both of them represent aspects of my own activities while doing research. With that book I hoped to teach research skills “by osmosis”, as readers observe a detailed case study.)

Surreal Numbers deals with a purely mathematical topic, not especially close to computer science; it features algebra and logic, not algorithms. When algorithms become part of the research, a beautiful new dimension also comes into play: Algorithms can be implemented on computers!

I strongly recommend that you look for every opportunity to write programs that carry out all or a part of whatever algorithms relate to your research. In my experience the very act of writing such a program never fails to deepen my understanding of the problem area.

---

(Donald E. Knuth – https://theorydish.blog/2018/02/01/donald-knuth-on-doing-research/)

Good luck!

---

About the Korean translation

In January 2015, the Acorn publishing company (www.acornpub.co.kr) in South Korea did a huge amount of work in translating and publishing this book (as it was in August 2014) into Korean.

It’s available now at their website.

The translator is Byungho Min (twitter/tais9). The cover art was done by the artistic Andy Nechaevsky, a friend of the author: facebook/andydinka. Acorn also holds the copyright to the Korean translation.

So, if you want to have a real book on your shelf in Korean and want to support this work, it is now available for purchase.
About the Persian/Farsi translation

In 2016 the book was translated by Mohsen Mostafa Jokar (who is also known to Iranian community for his translation of Radare manual\textsuperscript{36}). It is available on the publisher's website\textsuperscript{37} (Pendare Pars).

Here is a link to a 40-page excerpt: https://beginners.re/farsi.pdf.


About the Chinese translation

In April 2017, translation to Chinese was completed by Chinese PTPress. They are also the Chinese translation copyright holders.


The principal translator is Archer, to whom the author owes very much. He was extremely meticulous (in a good sense) and reported most of the known mistakes and bugs, which is very important in literature such as this book. The author would recommend his services to any other author!

The guys from Antiy Labs has also helped with translation. Here is preface written by them.

\textsuperscript{36}http://rada.re/get/radare2book-persian.pdf
\textsuperscript{37}http://goo.gl/2Tzx0H
Chapter 1

Code Patterns

1.1 The method

When the author of this book first started learning C and, later, C++, he used to write small pieces of code, compile them, and then look at the assembly language output. This made it very easy for him to understand what was going on in the code that he had written. He did this so many times that the relationship between the C/C++ code and what the compiler produced was imprinted deeply in his mind. It's now easy for him to imagine instantly a rough outline of a C code’s appearance and function. Perhaps this technique could be helpful for others.

By the way, there is a great website where you can do the same, with various compilers, instead of installing them on your box. You can use it as well: https://godbolt.org/.

Exercises

When the author of this book studied assembly language, he also often compiled small C functions and then rewrote them gradually to assembly, trying to make their code as short as possible. This probably is not worth doing in real-world scenarios today, because it’s hard to compete with the latest compilers in terms of efficiency. It is, however, a very good way to gain a better understanding of assembly. Feel free, therefore, to take any assembly code from this book and try to make it shorter. However, don’t forget to test what you have written.

Optimization levels and debug information

Source code can be compiled by different compilers with various optimization levels. A typical compiler has about three such levels, where level zero means that optimization is completely disabled. Optimization can also be targeted towards code size or code speed. A non-optimizing compiler is faster and produces more understandable (albeit verbose) code, whereas an optimizing compiler is slower and tries to produce code that runs faster (but is not necessarily more compact). In addition to optimization levels, a compiler can include some debug information in the resulting file, producing code that is easy to debug. One of the important features of the ‘debug’ code is that it might contain links between each line of the source code and its respective machine code address. Optimizing compilers, on the other hand, tend to produce output where entire lines of source code can be optimized away and thus not even be present in the resulting machine code. Reverse engineers can encounter either version, simply because some developers turn on the compiler’s optimization flags and others do not. Because of this, we’ll try to work on examples of both debug and release versions of the code featured in this book, wherever possible.

Sometimes some pretty ancient compilers are used in this book, in order to get the shortest (or simplest) possible code snippet.

1 In fact, he still does this when he can’t understand what a particular bit of code does.
1.2 Some basics

1.2.1 A short introduction to the CPU

The CPU is the device that executes the machine code a program consists of.

**A short glossary:**

**Instruction**: A primitive CPU command. The simplest examples include: moving data between registers, working with memory, primitive arithmetic operations. As a rule, each CPU has its own instruction set architecture (ISA).

**Machine code**: Code that the CPU directly processes. Each instruction is usually encoded by several bytes.

**Assembly language**: Mnemonic code and some extensions, like macros, that are intended to make a programmer’s life easier.

**CPU register**: Each CPU has a fixed set of general purpose registers (GPR), \( \approx 8 \) in x86, \( \approx 16 \) in x86-64, and also \( \approx 16 \) in ARM. The easiest way to understand a register is to think of it as an untyped temporary variable. Imagine if you were working with a high-level PL and could only use eight 32-bit (or 64-bit) variables. Yet a lot can be done using just these!

One might wonder why there needs to be a difference between machine code and a PL. The answer lies in the fact that humans and CPUs are not alike—it is much easier for humans to use a high-level PL like C/C++, Java, or Python, but it is easier for a CPU to use a much lower level of abstraction. Perhaps it would be possible to invent a CPU that can execute high-level PL code, but it would be many times more complex than the CPUs we know of today. In a similar fashion, it is very inconvenient for humans to write in assembly language, due to it being so low-level and difficult to write in without making a huge number of annoying mistakes. The program that converts the high-level PL code into assembly is called a compiler.

### A couple of words about different ISAs

The x86 ISA has always had variable-length instructions, so when the 64-bit era came, the x64 extensions did not impact the ISA very significantly. In fact, the x86 ISA still contains a lot of instructions that first appeared in 16-bit 8086 CPU, yet are still found in the CPUs of today. ARM is a RISC CPU designed with constant-length instructions in mind, which had some advantages in the past. In the very beginning, all ARM instructions were encoded in 4 bytes. This is now referred to as “ARM mode”. Then they realized it wasn’t as frugal as they first imagined. In fact, the most common CPU instructions in real world applications can be encoded using less information. They therefore added another ISA, called Thumb, in which each instruction was encoded in just 2 bytes. This is now referred to as “Thumb mode”. However, not all ARM instructions can be encoded in just 2 bytes, so the Thumb instruction set is somewhat limited. It is worth noting that code compiled for ARM mode and Thumb mode can coexist within one single program. The ARM creators thought Thumb could be extended, giving rise to Thumb-2, which appeared in ARMv7. Thumb-2 still uses 2-byte instructions, but has some new instructions which have the size of 4 bytes. There is a common misconception that Thumb-2 is a mix of ARM and Thumb. This is incorrect. Rather, Thumb-2 was extended to fully support all processor features so it could compete with ARM mode—a goal that was clearly achieved, as the majority of applications for iPod/iPhone/iPad are compiled for the Thumb-2 instruction set. (Though, admittedly, this is largely due to the fact that Xcode does this by default). Later the 64-bit ARM came out. This ISA has 4-byte instructions, and lacked the need of any additional Thumb mode. However, the 64-bit requirements affected the ISA, resulting in us now having three ARM instruction sets: ARM mode, Thumb mode (including Thumb-2) and ARM64. These ISAs intersect partially, but it can be said that they are different ISAs, rather than variations of the same one. Therefore, we will try to add fragments of code in all three ARM ISAs in this book. There are, by the way, many other RISC ISAs with fixed length 32-bit instructions, such as MIPS, PowerPC and Alpha AXP.

---

\(^2\) General Purpose Registers

\(^3\) Old-school Russian literature also uses the term “translator”.

\(^4\) Reduced Instruction Set Computing

\(^5\) Fixed-length instructions are handy because one can calculate the next (or previous) instruction address without effort. This feature will be discussed in the switch() operator (1.15.2 on page 173) section.

\(^6\) e.g. MOV/PUSH/CALL/Jcc
1.2. SOME BASICS

1.2.2 Numeral Systems

Humans have become accustomed to a decimal numeral system, probably because almost everyone has 10 fingers. Nevertheless, the number “10” has no significant meaning in science and mathematics. The natural numeral system in digital electronics is binary: 0 is for an absence of current in the wire, and 1 for presence. 10 in binary is 2 in decimal, 100 in binary is 4 in decimal, and so on.

If the numeral system has 10 digits, it has a *radix* (or *base*) of 10. The binary numeral system has a *radix* of 2.

Important things to recall:
1) A *number* is a number, while a *digit* is a term from writing systems, and is usually one character
2) The value of a number does not change when converted to another radix; only the writing notation for that value has changed (and therefore the way of representing it in RAM\(^7\)).

1.2.3 Converting From One Radix To Another

Positional notation is used almost every numerical system. This means that a digit has weight relative to where it is placed inside of the larger number. If 2 is placed at the rightmost place, it’s 2, but if it’s placed one digit before rightmost, it’s 20.

What does 1234 stand for?

\[
10^3 \cdot 1 + 10^2 \cdot 2 + 10^1 \cdot 3 + 1 \cdot 4 = 1234 \text{ or } 1000 \cdot 1 + 100 \cdot 2 + 10 \cdot 3 + 4 = 1234
\]

It’s the same story for binary numbers, but the base is 2 instead of 10. What does 0b101011 stand for?

\[
2^5 \cdot 1 + 2^4 \cdot 0 + 2^3 \cdot 1 + 2^2 \cdot 0 + 2^1 \cdot 1 + 2^0 \cdot 1 = 43 \text{ or } 32 \cdot 1 + 16 \cdot 0 + 8 \cdot 1 + 4 \cdot 0 + 2 \cdot 1 + 1 = 43
\]

There is such a thing as non-positional notation, such as the Roman numeral system. \(^8\). Perhaps, humankind switched to positional notation because it’s easier to do basic operations (addition, multiplication, etc.) on paper by hand.

Binary numbers can be added, subtracted and so on in the very same as taught in schools, but only 2 digits are available.

Binary numbers are bulky when represented in source code and dumps, so that is where the hexadecimal numeral system can be useful. A hexadecimal radix uses the digits 0..9, and also 6 Latin characters: A..F. Each hexadecimal digit takes 4 bits or 4 binary digits, so it’s very easy to convert from binary number to hexadecimal and back, even manually, in one’s mind.

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<tr>
<th>hexadecimal</th>
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<td>0101</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>0110</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>0111</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>1001</td>
<td>9</td>
</tr>
<tr>
<td>A</td>
<td>1010</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>1011</td>
<td>11</td>
</tr>
<tr>
<td>C</td>
<td>1100</td>
<td>12</td>
</tr>
<tr>
<td>D</td>
<td>1101</td>
<td>13</td>
</tr>
<tr>
<td>E</td>
<td>1110</td>
<td>14</td>
</tr>
<tr>
<td>F</td>
<td>1111</td>
<td>15</td>
</tr>
</tbody>
</table>

How can one tell which radix is being used in a specific instance?

Decimal numbers are usually written as is, i.e., 1234. Some assemblers allow an identifier on decimal

\(^7\)Random-Access Memory

1.2. SOME BASICS

radix numbers, in which the number would be written with a “d” suffix: 1234d.

Binary numbers are sometimes prepended with the “0b” prefix: 0b100110111 (GCC\(^9\) has a non-standard language extension for this\(^{10}\)). There is also another way: using a “b” suffix, for example: 100110111b. This book tries to use the “0b” prefix consistently throughout the book for binary numbers.

Hexadecimal numbers are prepended with “0x” prefix in C/C++ and other PLs: 0x1234ABCD. Alternatively, they are given a “h” suffix: 1234ABCDh. This is common way of representing them in assemblers and debuggers. In this convention, if the number is started with a Latin (A..F) digit, a 0 is added at the beginning: 0ABCDEFh. There was also convention that was popular in 8-bit home computers era, using $ prefix, like $ABCD. The book will try to stick to “0x” prefix throughout the book for hexadecimal numbers.

Should one learn to convert numbers mentally? A table of 1-digit hexadecimal numbers can easily be memorized. As for larger numbers, it’s probably not worth tormenting yourself.

Perhaps the most visible hexadecimal numbers are in URL\(^{11}\)s. This is the way that non-Latin characters are encoded. For example: \url{https://en.wiktionary.org/wiki/na%C3%AFvet%C3%A9} is the URL of Wiktionary article about “naïveté” word.

**Octal Radix**

Another numeral system heavily used in the past of computer programming is octal. In octal there are 8 digits (0..7), and each is mapped to 3 bits, so it’s easy to convert numbers back and forth. It has been superseded by the hexadecimal system almost everywhere, but, surprisingly, there is a *NIX utility, used often by many people, which takes octal numbers as argument: chmod.

As many *NIX users know, chmod argument can be a number of 3 digits. The first digit represents the rights of the owner of the file (read, write and/or execute), the second is the rights for the group to which the file belongs, and the third is for everyone else. Each digit that chmod takes can be represented in binary form:

<table>
<thead>
<tr>
<th>decimal</th>
<th>binary</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>111</td>
<td>rwx</td>
</tr>
<tr>
<td>6</td>
<td>110</td>
<td>rw-</td>
</tr>
<tr>
<td>5</td>
<td>101</td>
<td>r-x</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>r--</td>
</tr>
<tr>
<td>3</td>
<td>011</td>
<td>-wx</td>
</tr>
<tr>
<td>2</td>
<td>010</td>
<td>-w-</td>
</tr>
<tr>
<td>1</td>
<td>001</td>
<td>--x</td>
</tr>
<tr>
<td>0</td>
<td>000</td>
<td>---</td>
</tr>
</tbody>
</table>

So each bit is mapped to a flag: read/write/execute.

The importance of chmod here is that the whole number in argument can be represented as octal number. Let’s take, for example, 644. When you run chmod 644 file, you set read/write permissions for owner, read permissions for group and again, read permissions for everyone else. If we convert the octal number 644 to binary, it would be 110100100, or, in groups of 3 bits, 110 100 100.

Now we see that each triplet describe permissions for owner/group/others: first is rw-, second is r-- and third is r--.

The octal numeral system was also popular on old computers like PDP-8, because word there could be 12, 24 or 36 bits, and these numbers are all divisible by 3, so the octal system was natural in that environment. Nowadays, all popular computers employ word/address sizes of 16, 32 or 64 bits, and these numbers are all divisible by 4, so the hexadecimal system is more natural there.

The octal numeral system is supported by all standard C/C++ compilers. This is a source of confusion sometimes, because octal numbers are encoded with a zero prepended, for example, 0377 is 255. Sometimes, you might make a typo and write “09” instead of 9, and the compiler would report an error. GCC might report something like this:

error: invalid digit "9" in octal constant.

---

\(^9\)GNU Compiler Collection

\(^{10}\)https://gcc.gnu.org/onlinedocs/gcc/Binary-constants.html

\(^{11}\)Uniform Resource Locator
Also, the octal system is somewhat popular in Java. When the IDA shows Java strings with non-printable characters, they are encoded in the octal system instead of hexadecimal. The JAD Java decompiler behaves the same way.

### Divisibility

When you see a decimal number like 120, you can quickly deduce that it’s divisible by 10, because the last digit is zero. In the same way, 123400 is divisible by 100, because the two last digits are zeros.

Likewise, the hexadecimal number 0x1230 is divisible by 0x10 (or 16), 0x123000 is divisible by 0x1000 (or 4096), etc.

The binary number 0b1000101000 is divisible by 0b1000 (8), etc.

This property can often be used to quickly realize if an address or a size of some block in memory is padded to some boundary. For example, sections in PE files are almost always started at addresses ending with 3 hexadecimal zeros: 0x41000, 0x10001000, etc. The reason behind this is the fact that almost all PE sections are padded to a boundary of 0x1000 (4096) bytes.

### Multi-Precision Arithmetic and Radix

Multi-precision arithmetic can use huge numbers, and each one may be stored in several bytes. For example, RSA keys, both public and private, span up to 4096 bits, and maybe even more.

In [Donald E. Knuth, *The Art of Computer Programming*, Volume 2, 3rd ed., (1997), 265] we find the following idea: when you store a multi-precision number in several bytes, the whole number can be represented as having a radix of $2^8 = 256$, and each digit goes to the corresponding byte. Likewise, if you store a multi-precision number in several 32-bit integer values, each digit goes to each 32-bit slot, and you may think about this number as stored in radix of $2^{32}$.

### How to Pronounce Non-Decimal Numbers

Numbers in a non-decimal base are usually pronounced by digit by digit: “one-zero-zero-one-one-...”. Words like “ten” and “thousand” are usually not pronounced, to prevent confusion with the decimal base system.

### Floating point numbers

To distinguish floating point numbers from integers, they are usually written with “.0” at the end, like 0.0, 123.0, etc.

### 1.3 An Empty Function

The simplest possible function is arguably one that does nothing:

```
void f()
{
    return;
};
```

Let’s compile it!

---

12 Portable Executable
1.3. AN EMPTY FUNCTION

1.3.1 x86

Here’s what both the GCC and MSVC compilers produce on the x86 platform:

Listing 1.2: Optimizing GCC/MSVC (assembly output)

```assembly
f:
    ret
```

There is just one instruction: RET, which returns execution to the caller.

1.3.2 ARM

Listing 1.3: Optimizing Keil 6/2013 (ARM mode) assembly output

```assembly
f PROC
    BX lr
ENDP
```

The return address is not saved on the local stack in the ARM ISA, but rather in the link register, so the BX LR instruction causes execution to jump to that address—effectively returning execution to the caller.

1.3.3 MIPS

There are two naming conventions used in the world of MIPS when naming registers: by number (from $0 to $31) or by pseudo name ($V0, $A0, etc.).

The GCC assembly output below lists registers by number:

Listing 1.4: Optimizing GCC 4.4.5 (assembly output)

```assembly
j $31
nop
```

...while IDA\(^{13}\) does it by pseudo name:

Listing 1.5: Optimizing GCC 4.4.5 (IDA)

```assembly
j $ra
nop
```

The first instruction is the jump instruction (J or JR) which returns the execution flow to the caller, jumping to the address in the $31 (or $RA) register.

This is the register analogous to LR\(^{14}\) in ARM.

The second instruction is NOP\(^{15}\), which does nothing. We can ignore it for now.

A Note About MIPS Instructions and Register Names

Register and instruction names in the world of MIPS are traditionally written in lowercase. However, for the sake of consistency, this book will stick to using uppercase letters, as it is the convention followed by all the other ISAs featured in this book.

---

\(^{13}\) Interactive Disassembler and Debugger developed by Hex-Rays  
\(^{14}\) Link Register  
\(^{15}\) No Operation
1.4. RETURNING VALUES

1.3.4 Empty Functions in Practice

Despite the fact empty functions seem useless, they are quite frequent in low-level code. First of all, they are quite popular in debugging functions, like this one:

Listing 1.6: C/C++ Code

```c
void dbg_print (const char *fmt, ...) {
    #ifdef _DEBUG
        // open log file
        // write to log file
        // close log file
    #endif
}
void some_function() {
    ...
    dbg_print ("we did something\n");
    ...
};
```

In a non-debug build (as in a “release”), _DEBUG is not defined, so the dbg_print() function, despite still being called during execution, will be empty.

Similarly, a popular method of software protection is to make one build for legal customers, and another demo build. A demo build can lack some important functions, as with this example:

Listing 1.7: C/C++ Code

```c
void save_file () {
    #ifndef DEMO
        // actual saving code
    #endif
};
```

The save_file() function can be called when the user clicks File->Save on the menu. The demo version may be delivered with this menu item disabled, but even if a software cracker will enable it, only an empty function with no useful code will be called.

IDA marks such functions with names like nullsub_00, nullsub_01, etc.

1.4 Returning Values

Another simple function is the one that simply returns a constant value:

Listing 1.8: C/C++ Code

```c
int f() {
    return 123;
};
```

Let’s compile it.

1.4.1 x86

Here’s what both the GCC and MSVC compilers produce (with optimization) on the x86 platform:

Listing 1.9: Optimizing GCC/MSVC (assembly output)

```
f:                
    mov        eax, 123
    ret
```
1.5. HELLO, WORLD!

There are just two instructions: the first places the value 123 into the EAX register, which is used by convention for storing the return value, and the second one is RET, which returns execution to the caller. The caller will take the result from the EAX register.

1.4.2 ARM

There are a few differences on the ARM platform:

<table>
<thead>
<tr>
<th>Listing 1.10: Optimizing Keil 6/2013 (ARM mode) ASM Output</th>
</tr>
</thead>
</table>
| PROC
| MOV r0, #0x7b ; 123
| BX lr
| ENDP |

ARM uses the register R0 for returning the results of functions, so 123 is copied into R0. It is worth noting that MOV is a misleading name for the instruction in both the x86 and ARM ISAs. The data is not in fact moved, but copied.

1.4.3 MIPS

The GCC assembly output below lists registers by number:

<table>
<thead>
<tr>
<th>Listing 1.11: Optimizing GCC 4.4.5 (assembly output)</th>
</tr>
</thead>
</table>
| j $31
| li $2, 123 # 0x7b |

...while IDA does it by their pseudo names:

<table>
<thead>
<tr>
<th>Listing 1.12: Optimizing GCC 4.4.5 (IDA)</th>
</tr>
</thead>
</table>
| jr $ra
| li $v0, 0x7B |

The $2 (or $V0) register is used to store the function’s return value. LI stands for “Load Immediate” and is the MIPS equivalent to MOV.

The other instruction is the jump instruction (J or JR) which returns the execution flow to the caller.

You might be wondering why the positions of the load instruction (LI) and the jump instruction (J or JR) are swapped. This is due to a RISC feature called “branch delay slot”.

The reason this happens is a quirk in the architecture of some RISC ISAs and isn’t important for our purposes—we must simply keep in mind that in MIPS, the instruction following a jump or branch instruction is executed before the jump/branch instruction itself.

As a consequence, branch instructions always swap places with the instruction executed immediately beforehand.

In practice, functions which merely return 1 (true) or 0 (false) are very frequent.

The smallest ever of the standard UNIX utilities, /bin/true and /bin/false return 0 and 1 respectively, as an exit code. (Zero as an exit code usually means success, non-zero means error.)

1.5 Hello, world!

Let’s use the famous example from the book [Brian W. Kernighan, Dennis M. Ritchie, The C Programming Language, 2ed, (1988)]: 
1.5. **HELLO, WORLD!**

### Listing 1.13: C/C++ Code

```c
#include <stdio.h>

int main()
{
    printf("hello, world\n");
    return 0;
}
```

#### 1.5.1 x86

**MSVC**

Let’s compile it in MSVC 2010:

```bash
cl 1.cpp /Fa:1.asm
```

(The /Fa option instructs the compiler to generate an assembly listing file)

### Listing 1.14: MSVC 2010

```
CONST SEGMENT
$SG3830 DB 'hello, world', 0AH, 00H
CONST ENDS
PUBLIC _main
EXTRN _printf:PROC
; Function compile flags: /Odtp
_TEXT SEGMENT
_main PROC
    push ebp
    mov ebp, esp
    push OFFSET $SG3830
    call _printf
    add esp, 4
    xor eax, eax
    pop ebp
    ret 0
_main ENDP
_TEXT ENDS
```

MSVC produces assembly listings in Intel-syntax. The differences between Intel-syntax and AT&T-syntax will be discussed in 1.5.1 on page 11.

The compiler generated the file, 1.obj, which is to be linked into 1.exe. In our case, the file contains two segments: CONST (for data constants) and _TEXT (for code).

The string hello, world in C/C++ has type const char[] [Bjarne Stroustrup, *The C++ Programming Language, 4th Edition*, (2013)p176, 7.3.2], but it does not have its own name. The compiler needs to deal with the string somehow, so it defines the internal name $SG3830 for it.

That is why the example may be rewritten as follows:

```c
#include <stdio.h>

const char $SG3830[]="hello, world\n";

int main()
{
    printf($SG3830);
    return 0;
}
```

Let’s go back to the assembly listing. As we can see, the string is terminated by a zero byte, which is standard for C/C++ strings. More about C/C++ strings: 5.4.1 on page 704.

In the code segment, _TEXT, there is only one function so far: main(). The function main() starts with prologue code and ends with epilogue code (like almost any function) \(^{16}\).

\(^{16}\)You can read more about it in the section about function prologues and epilogues (1.6 on page 29).
1.5. HELLO, WORLD!

After the function prologue we see the call to the printf() function:

CALL _printf. Before the call, a string address (or a pointer to it) containing our greeting is placed on the stack with the help of the PUSH instruction.

When the printf() function returns the control to the main() function, the string address (or a pointer to it) is still on the stack. Since we do not need it anymore, the stack pointer (the ESP register) needs to be corrected.

ADD ESP, 4 means add 4 to the ESP register value.

Why 4? Since this is a 32-bit program, we need exactly 4 bytes for address passing through the stack. If it was x64 code we would need 8 bytes. ADD ESP, 4 is effectively equivalent to POP register but without using any register.17

For the same purpose, some compilers (like the Intel C++ Compiler) may emit POP ECX instead of ADD (e.g., such a pattern can be observed in the Oracle RDBMS code as it is compiled with the Intel C++ compiler). This instruction has almost the same effect but the ECX register contents will be overwritten. The Intel C++ compiler supposedly uses POP ECX since this instruction’s opcode is shorter than ADD ESP, x (1 byte for POP against 3 for ADD).

Here is an example of using POP instead of ADD from Oracle RDBMS:

Listing 1.15: Oracle RDBMS 10.2 Linux (app.o file)

```
.text:0800029A push ebx
.text:0800029B call qksfroChild
.text:080002A0 pop ecx
```

After calling printf(), the original C/C++ code contains the statement return 0 —return 0 as the result of the main() function.

In the generated code this is implemented by the instruction XOR EAX, EAX.

XOR is in fact just “eXclusive OR”18 but the compilers often use it instead of MOV EAX, 0—again because it is a slightly shorter opcode (2 bytes for XOR against 5 for MOV).

Some compilers emit SUB EAX, EAX, which means SUBtract the value in the EAX from the value in EAX. That in any case will result in zero.

The last instruction RET returns the control to the caller. Usually, this is C/C++ CRT19 code which in turn returns control to the OS.

GCC

Now let’s try to compile the same C/C++ code in the GCC 4.4.1 compiler in Linux: gcc 1.c -o 1. Next, with the assistance of the IDA disassembler, let’s see how the main() function was created. IDA, like MSVC, uses Intel-syntax20.

Listing 1.16: code in IDA

```
main proc near
var_10 = dword ptr -10h
push ebp
mov ebp, esp
and esp, 0FFFFFFF0h
sub esp, 10h
mov eax, offset aHelloWorld ; "hello, world\n"
mov [esp+10h+var_10], eax
call _printf
mov eax, 0
leave
retn
main endp
```

17CPU flags, however, are modified
18Wikipedia
19C Runtime library
20We could also have GCC produce assembly listings in Intel-syntax by applying the options -S -masm=intel.
1.5. **HELLO, WORLD!**

The result is almost the same. The address of the hello, world string (stored in the data segment) is loaded in the EAX register first, and then saved onto the stack.

In addition, the function prologue has AND ESP, 0FFFFFFFF0h — this instruction aligns the ESP register value on a 16-byte boundary. This results in all values in the stack being aligned the same way (The CPU performs better if the values it is dealing with are located in memory at addresses aligned on a 4-byte or 16-byte boundary)\(^\text{21}\).

SUB ESP, 10h allocates 16 bytes on the stack. Although, as we can see hereafter, only 4 are necessary here.

This is because the size of the allocated stack is also aligned on a 16-byte boundary.

The string address (or a pointer to the string) is then stored directly onto the stack without using the PUSH instruction. var_10 — is a local variable and is also an argument for printf(). Read about it below.

Then the printf() function is called.

Unlike MSVC, when GCC is compiling without optimization turned on, it emits MOV EAX, 0 instead of a shorter opcode.

The last instruction, LEAVE — is the equivalent of the MOV ESP, EBP and POP EBP instruction pair — in other words, this instruction sets the stack pointer (ESP) back and restores the EBP register to its initial state. This is necessary since we modified these register values (ESP and EBP) at the beginning of the function (by executing MOV EBP, ESP / AND ESP, …).

### GCC: AT&T syntax

Let’s see how this can be represented in assembly language AT&T syntax. This syntax is much more popular in the UNIX-world.

#### Listing 1.17: let’s compile in GCC 4.7.3

gcc -S 1_1.c

We get this:

#### Listing 1.18: GCC 4.7.3

```assembly
.file "1_1.c"
.section .rodata
.LC0:
.string "hello, world\n"
.text
.globl main
.type main, @function
main:
.LFB0:
.cfi_startproc
    pushl %ebp
    .cfi_def_cfa_offset 8
    movl %esp, %ebp
    .cfi_def_cfa_register 5
    andl $-16, %esp
    subl $16, %esp
    movl $.LC0, (%esp)
    call printf
    movl $0, %eax
    leave
    .cfi_restore 5
    .cfi_def_cfa 4, 4
    ret .cfi_endproc
.LFE0:
.size main, .-main
.ident "GCC: (Ubuntu/Linaro 4.7.3-1ubuntu1) 4.7.3"
```

\(^\text{21}\)Wikipedia: Data structure alignment
1.5. **HELLO, WORLD!**

The listing contains many macros (the parts that begin with a dot). These are not interesting for us at the moment.

For now, for the sake of simplicity, we can ignore them (except the `.string` macro which encodes a null-terminated character sequence just like a C-string). Then we’ll see this:\n
```
#include <stdio.h>

int main()
{
    printf("Hello, world\n");
    return 0;
}
```

Some of the major differences between Intel and AT&T syntax are:

- **Source and destination operands are written in opposite order.**
  - In Intel-syntax: `<instruction> <destination operand> <source operand>.
  - In AT&T syntax: `<instruction> <source operand> <destination operand>.

  Here is an easy way to memorize the difference: when you deal with Intel-syntax, you can imagine that there is an equality sign (=) between operands and when you deal with AT&T-syntax imagine there is a right arrow (→).\n
- **AT&T:** Before register names, a percent sign must be written (%) and before numbers a dollar sign ($). Parentheses are used instead of brackets.

- **AT&T:** A suffix is added to instructions to define the operand size:
  - q — quad (64 bits)
  - l — long (32 bits)
  - w — word (16 bits)
  - b — byte (8 bits)

To go back to the compiled result: it is almost identical to what was displayed by IDA. There is one subtle difference: `0xFFFFFF0h` is presented as `$-16`. It’s the same thing: 16 in the decimal system is `0x10` in hexadecimal. `-0x10` is equal to `0xFFFFFFF0` (for a 32-bit data type).

One more thing: the return value is set to 0 by using the usual `MOV`, not XOR. `MOV` just loads a value to a register. Its name is a misnomer (as the data is not moved but rather copied). In other architectures, this instruction is named “LOAD” or “STORE” or something similar.

### String patching (Win32)

We can easily find the “hello, world” string in the executable file using Hiew:

:\[22\]This GCC option can be used to eliminate “unnecessary” macros: `-fno-asynchronous-unwind-tables`\n
:\[23\]By the way, in some C standard functions (e.g., `memcpy()`, `strcpy()`) the arguments are listed in the same way as in Intel-syntax: first the pointer to the destination memory block, and then the pointer to the source memory block.
1.5. **HELLO, WORLD!**

And we can try to translate our message into Spanish:

The Spanish text is one byte shorter than English, so we also added the 0x0A byte at the end (\n) with a zero byte.

It works.

What if we want to insert a longer message? There are some zero bytes after original English text. It’s hard to say if they can be overwritten: they may be used somewhere in CRT code, or maybe not. Anyway, only overwrite them if you really know what you’re doing.

**String patching (Linux x64)**

Let’s try to patch a Linux x64 executable using rada.re:

```bash
Listing 1.20: rada.re session
dennis@bigbox ~/tmp % gcc hw.c
dennis@bigbox ~/tmp % radare2 a.out
-- SHALL WE PLAY A GAME?
[0x00400430]> / hello
Searching 5 bytes from 0x00400000 to 0x00601040: 68 65 6c 6c 6f
Searching 5 bytes in [0x400000-0x601040] hits: 1
0x004005c4 hit0_0 .HHhello, world;0.
[0x00400430]> s 0x004005c4
[0x004005c4]> px
- offset - 0 1 2 3 4 5 6 7 8 9 A B C D E F 0123456789ABCDEF
0x004005c4 656c 6c6f 2c20 77 6f72 6c64 0000 0000 hello, world....
0x004005d4 011b 033b 3000 0000 0000 0000 1cfe ffff ...:0........
0x004005e4 7c00 0000 5cfe ffff 4c00 0000 52ff ffff |...\...L...R...
0x004005f4 a400 0000 6cff ffff c400 0000 dcff ffff .....l........
```

![Figure 1.1: Hiew](image1)

![Figure 1.2: Hiew](image2)
1.5. HELLO, WORLD!

Here's what's going on: I searched for the “hello” string using the / command, then I set the cursor (seek, in rada.re terms) to that address. Then I want to be sure that this is really that place: px dumps bytes there. oo+ switches rada.re to read-write mode. w writes an ASCII string at the current seek. Note the \00 at the end—this is a zero byte. q quits.

**Software localization of MS-DOS era**

This method was a common way to translate MS-DOS software to Russian language back to 1980’s and 1990’s. Russian words and sentences are usually slightly longer than its English counterparts, so that is why localized software has a lot of weird acronyms and hardly readable abbreviations.

Perhaps this also happened to other languages during that era, in other countries.

1.5.2 x86-64

**MSVC: x86-64**

Let's also try 64-bit MSVC:

```assembly
Listing 1.21: MSVC 2012 x64

$SG2989 DB 'hello, world', 0AH, 00H
main PROC
sub rsp, 40
lea rcx, OFFSET FLAT:$SG2989
call printf
xor eax, eax
add rsp, 40
ret 0
main ENDP
```

In x86-64, all registers were extended to 64-bit, and now their names have an R- prefix. In order to use the stack less often (in other words, to access external memory/cache less often), there is a popular way to pass function arguments via registers (*fastcall*) 6.1.3 on page 735. I.e., a part of the function’s arguments are passed in registers, and the rest—via the stack. In Win64, 4 function arguments are passed in the RCX, RDX, R8, and R9 registers. That is what we see here: a pointer to the string for printf() is now passed not in the stack, but rather in the RCX register. The pointers are 64-bit now, so they are passed in the 64-bit registers (which have the R- prefix). However, for backward compatibility, it is still possible to access the 32-bit parts, using the E- prefix. This is how the RAX/EAX/AX/AL register looks like in x86-64:
The main() function returns an int-typed value, which in C/C++ is still 32-bit, for better backward compatibility and portability, so that is why the EAX register is cleared at the function end (i.e., the 32-bit part of the register) instead of with RAX. There are also 40 bytes allocated in the local stack. This is called the "shadow space", which we'll talk about later: 1.10.2 on page 100.

**GCC: x86-64**

Let's also try GCC in 64-bit Linux:

```
Listing 1.22: GCC 4.4.6 x64
.string "hello, world\n"
main:
  sub rsp, 8
  mov edi, OFFSET FLAT:.LC0 ; "hello, world\n"
  xor eax, eax ; number of vector registers passed
  call printf
  xor eax, eax
  add rsp, 8
  ret
```

Linux, *BSD and Mac OS X also use a method to pass function arguments in registers. [Michael Matz, Jan Hubicka, Andreas Jaeger, Mark Mitchell, System V Application Binary Interface. AMD64 Architecture Processor Supplement, (2013)]

The first 6 arguments are passed in the RDI, RSI, RDX, RCX, R8, and R9 registers, and the rest—via the stack.

So the pointer to the string is passed in EDI (the 32-bit part of the register). Why doesn’t it use the 64-bit part, RDI?

It is important to keep in mind that all MOV instructions in 64-bit mode that write something into the lower 32-bit register part also clear the higher 32-bits (as stated in Intel manuals: 12.1.4 on page 1013).

I.e., the MOV EAX, 011223344h writes a value into RAX correctly, since the higher bits will be cleared.

If we open the compiled object file (.o), we can also see all the instructions' opcodes:

```
Listing 1.23: GCC 4.4.6 x64
.text:00000000004004D0 main proc near
.text:00000000004004D0 48 83 EC 08 sub rsp, 8
.text:00000000004004D4 BF E8 05 40 00 mov edi, offset format ; "hello, world\n"
.text:00000000004004DA 31 C0 xor eax, eax ; number of vector registers passed
.text:00000000004004DB E8 D8 FE FF FF call _printf
.text:00000000004004EA 31 C0 xor eax, eax
.text:00000000004004EB 48 83 C4 08 add rsp, 8
.text:00000000004004EC C3 ret
.text:00000000004004ED main endp
```

As we can see, the instruction that writes into EDI at 0x4004D4 occupies 5 bytes. The same instruction writing a 64-bit value into RDI occupies 7 bytes. Apparently, GCC is trying to save some space. Besides, it can be sure that the data segment containing the string will not be allocated at the addresses higher than 4GiB.

We also see that the EAX register has been cleared before the printf() function call. This is done because according to ABI standard mentioned above, the number of used vector registers is to be passed in EAX in *NIX systems on x86-64.

24Also available as https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf
25This must be enabled in Options → Disassembly → Number of opcode bytes
26Application Binary Interface
1.5. HELLO, WORLD!

Address patching (Win64)

If our example was compiled in MSVC 2013 using /MD switch (meaning a smaller executable due to MSVCR*.DLL file linkage), the main() function comes first, and can be easily found:

As an experiment, we can increment address by 1:
1.5. **HELLO, WORLD!**

Hiew shows “ello, world”. And when we run the patched executable, this very string is printed.

### Pick another string from binary image (Linux x64)

The binary file I’ve got when I compile our example using GCC 5.4.0 on Linux x64 box has many other text strings. They are mostly imported function names and library names.

Run `objdump` to get the contents of all sections of the compiled file:

```
$ objdump -s a.out

a.out: file format elf64-x86-64

Contents of section .interp:
  400238 2f6c6962 36342f6c 642d6c642d6c696e75782d /lib64/ld-linux-x86-64.so.2.
  400248 783362d 6342e73 6f2e3200 ...............

Contents of section .note.ABI-tag:
  400254 04000000 10000000 01000000 474e5500 ............GNU.
  400264 00000000 02000000 06000000 20000000 ...............

Contents of section .note.gnu.build-id:
  400274 04000000 14000000 03000000 474e5500 ............GNU.
  400284 fe461178 5bbf10b4 bbf2aca8 e5c1ec10 .F.x[....]^...
  400294 cf3f7ae4 .?z.
```

It’s not a problem to pass address of the text string “/lib64/ld-linux-x86-64.so.2” to `printf()`:

```c
#include <stdio.h>

#include <stdio.h>
```
It’s hard to believe, but this code prints the aforementioned string.

If you would change the address to 0x400260, the “GNU” string would be printed. This address is true for my specific GCC version, GNU toolset, etc. On your system, the executable may be slightly different, and all addresses will also be different. Also, adding/removing code to/from this source code will probably shift all addresses back or forward.

### 1.5.3 GCC—one more thing

The fact that an *anonymous* C-string has *const* type (1.5.1 on page 9), and that C-strings allocated in constants segment are guaranteed to be immutable, has an interesting consequence: the compiler may use a specific part of the string.

Let’s try this example:

```c
#include <stdio.h>

int f1()
{
    printf("world\n");
}

int f2()
{
    printf("hello world\n");
}

int main()
{
    f1();
    f2();
}
```

Common C/C++-compilers (including MSVC) allocate two strings, but let’s see what GCC 4.8.1 does:

```asm
f1 proc near
s = dword ptr -1Ch
    sub esp, 1Ch
    mov [esp+1Ch+s], offset s ; "world\n"
    call _puts
    add esp, 1Ch
    retn
f1 endp

f2 proc near
s = dword ptr -1Ch
    sub esp, 1Ch
    mov [esp+1Ch+s], offset aHello ; "hello 
    call _puts
    add esp, 1Ch
    retn
f2 endp

aHello db 'hello '

s db 'world',0xa,0
```
1.5. Hello, World!

Indeed: when we print the “hello world” string these two words are positioned in memory adjacently and `puts()` called from `f2()` function is not aware that this string is divided. In fact, it’s not divided; it’s divided only “virtually”, in this listing.

When `puts()` is called from `f1()`, it uses the “world” string plus a zero byte. `puts()` is not aware that there is something before this string!

This clever trick is often used by at least GCC and can save some memory. This is close to string interning. Another related example is here: 3.2 on page 469.

1.5.4 ARM

For my experiments with ARM processors, several compilers were used:

- Apple Xcode 4.6.3 IDE with the LLVM-GCC 4.2 compiler.
- GCC 4.9 (Linaro) (for ARM64), available as win32-executables at http://go.yurichev.com/17325.

32-bit ARM code is used (including Thumb and Thumb-2 modes) in all cases in this book, if not mentioned otherwise. When we talk about 64-bit ARM here, we call it ARM64.

Non-optimizing Keil 6/2013 (ARM mode)

Let’s start by compiling our example in Keil:

```
armcc.exe --arm --c90 -O0 1.c
```

The `armcc` compiler produces assembly listings in Intel-syntax, but it has high-level ARM-processor related macros, but it is more important for us to see the instructions “as is” so let’s see the compiled result in IDA.

```
Listing 1.25: Non-optimizing Keil 6/2013 (ARM mode) IDA

.text:00000000 main
.text:00000000 10 40 2D E9 STMFD SP!, {R4,LR}
.text:00000004 1E 0E 8F E2 ADR R0, aHelloWorld ; "hello, world"
.text:00000008 15 19 00 EB BL __2printf
.text:0000000C 00 00 A0 E3 MOV R0, #0
.text:00000010 10 80 BD E8 LDMFD SP!, {R4,PC}
.text:0000001EC 68 65 6C 6C+aHelloWorld DCB "hello, world",0 ; DATA XREF: main+4
```

In the example, we can easily see each instruction has a size of 4 bytes. Indeed, we compiled our code for ARM mode, not for Thumb.

The very first instruction, `STMFD SP!, {R4,LR}`, works as an x86 PUSH instruction, writing the values of two registers (R4 and LR) into the stack.

Indeed, in the output listing from the `armcc` compiler, for the sake of simplification, actually shows the PUSH `{r4,lr}` instruction. But that is not quite precise. The PUSH instruction is only available in Thumb mode. So, to make things less confusing, we’re doing this in IDA.

This instruction first decrements the SP, so it points to the place in the stack that is free for new entries, then it saves the values of the R4 and LR registers at the address stored in the modified SP.

This instruction (like the PUSH instruction in Thumb mode) is able to save several register values at once which can be very useful. By the way, this has no equivalent in x86. It can also be noted that the STMFD instruction is a generalization of the PUSH instruction (extending its features), since it can work with any register, not just with SP. In other words, STMFD may be used for storing a set of registers at the specified memory address.

---

27It is indeed so: Apple Xcode 4.6.3 uses open-source GCC as front-end compiler and LLVM code generator
28e.g. ARM mode lacks PUSH/POP instructions
29STMFD
30stack pointer. SP/ESP/RSP in x86/x64. SP in ARM.
1.5. HELLO, WORLD!

The ADR R0, aHelloWorld instruction adds or subtracts the value in the PC\textsuperscript{32} register to the offset where the hello, world string is located. How is the PC register used here, one might ask? This is called “position-independent code”\textsuperscript{33}.

Such code can be executed at a non-fixed address in memory. In other words, this is PC-relative addressing. The ADR instruction takes into account the difference between the address of this instruction and the address where the string is located. This difference (offset) is always to be the same, no matter at what address our code is loaded by the OS. That’s why all we need is to add the address of the current instruction (from PC) in order to get the absolute memory address of our C-string.

BL __2printf\textsuperscript{34} instruction calls the printf() function. Here’s how this instruction works:

- store the address following the BL instruction (0xC) into the LR;
- then pass the control to printf() by writing its address into the PC register.

When printf() finishes its execution it must have information about where it needs to return the control to. That’s why each function passes control to the address stored in the LR register.

That is a difference between “pure” RISC-processors like ARM and CISC\textsuperscript{35}-processors like x86, where the return address is usually stored on the stack. Read more about this in next section (1.7 on page 30).

By the way, an absolute 32-bit address or offset cannot be encoded in the 32-bit BL instruction because it only has space for 24 bits. As we may recall, all ARM-mode instructions have a size of 4 bytes (32 bits). Hence, they can only be located on 4-byte boundary addresses. This implies that the last 2 bits of the instruction address (which are always zero bits) may be omitted. In summary, we have 26 bits for offset encoding. This is enough to encode current\_PC ± 32M.

Next, the MOV R0, #0\textsuperscript{36} instruction just writes 0 into the R0 register. That’s because our C-function returns 0 and the return value is to be placed in the R0 register.

The last instruction LDMFD SP!, R4, PC\textsuperscript{37}. It loads values from the stack (or any other memory place) in order to save them into R4 and PC, and increments the stack pointer SP. It works like POP here. N.B. The very first instruction STMFD saved the R4 and LR registers pair on the stack, but R4 and PC are restored during the LDMFD execution.

As we already know, the address of the place where each function must return control to is usually saved in the LR register. The very first instruction saves its value in the stack because the same register will be used by our main() function when calling printf(). In the function’s end, this value can be written directly to the PC register, thus passing control to where our function has been called.

Since main() is usually the primary function in C/C++, the control will be returned to the OS loader or to a point in a CRT, or something like that.

All that allows omitting the BX LR instruction at the end of the function.

DCB is an assembly language directive defining an array of bytes or ASCII strings, akin to the DB directive in the x86-assembly language.

Non-optimizing Keil 6/2013 (Thumb mode)

Let’s compile the same example using Keil in Thumb mode:

```bash
armcc.exe --thumb --c90 -O0 1.c
```

We are getting (in IDA):

<table>
<thead>
<tr>
<th>Listing 1.26: Non-optimizing Keil 6/2013 (Thumb mode) + IDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>.text:00000000 main</td>
</tr>
<tr>
<td>.text:00000000 10 B5 PUSH {R4,LR}</td>
</tr>
<tr>
<td>.text:00000002 C9 A0 ADR R0, aHelloWorld ; &quot;hello, world&quot;</td>
</tr>
<tr>
<td>.text:00000004 06 F0 2E F9 BL __2printf</td>
</tr>
<tr>
<td>.text:00000008 00 20 MOVS R0, #0</td>
</tr>
<tr>
<td>.text:0000000A 10 BD POP {R4,PC}</td>
</tr>
</tbody>
</table>

\textsuperscript{32}Program Counter. IP/EIP/RIP in x86/64. PC in ARM.
\textsuperscript{33}Read more about it in relevant section (6.4.1 on page 748)
\textsuperscript{34}Branch with Link
\textsuperscript{35}Complex Instruction Set Computing
\textsuperscript{36}Meaning MOVe
\textsuperscript{37}LDMFD\textsuperscript{38} is an inverse instruction of STMFD
We can easily spot the 2-byte (16-bit) opcodes. This is, as was already noted, Thumb. The BL instruction, however, consists of two 16-bit instructions. This is because it is impossible to load an offset for the printf() function while using the small space in one 16-bit opcode. Therefore, the first 16-bit instruction loads the higher 10 bits of the offset and the second instruction loads the lower 11 bits of the offset.

As was noted, all instructions in Thumb mode have a size of 2 bytes (or 16 bits). This implies it is impossible for a Thumb-instruction to be at an odd address whatsoever. Given the above, the last address bit may be omitted while encoding instructions.

In summary, the BL Thumb-instruction can encode an address in \( \text{current}_{PC} \pm 2M \).

As for the other instructions in the function: PUSH and POP work here just like the described STMFD/LDMFD only the SP register is not mentioned explicitly here. ADR works just like in the previous example. MOV writes 0 into the R0 register in order to return zero.

### Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Xcode 4.6.3 without optimization turned on produces a lot of redundant code so we’ll study optimized output, where the instruction count is as small as possible, setting the compiler switch -O3.

<table>
<thead>
<tr>
<th>_text:000028C4</th>
<th>__hello_world</th>
</tr>
</thead>
<tbody>
<tr>
<td>__text:000028C4</td>
<td>80  40  2D E9  STMFD</td>
</tr>
<tr>
<td>__text:000028C8</td>
<td>86  06  01 E3  MOV</td>
</tr>
<tr>
<td>__text:000028CC</td>
<td>0D  70 A0 E1  MOV</td>
</tr>
<tr>
<td>__text:000028D0</td>
<td>00  00  40 E3  MOVT</td>
</tr>
<tr>
<td>__text:000028D4</td>
<td>00  00  8F E0  ADD</td>
</tr>
<tr>
<td>__text:000028D8</td>
<td>C3  05  00 EB  BL _puts</td>
</tr>
<tr>
<td>__text:000028E0</td>
<td>80  80 BD E8  LDMFD</td>
</tr>
</tbody>
</table>

The instructions STMFD and LDMFD are already familiar to us.

The MOV instruction just writes the number 0x1686 into the R0 register. This is the offset pointing to the “Hello world!” string.

The R7 register (as it is standardized in [iOS ABI Function Call Guide, (2010)](http://go.yurichev.com/17276)) is a frame pointer. More on that below.

The MOVT R0, #0 (MOVe T op) instruction writes 0 into higher 16 bits of the register. The issue here is that the generic MOV instruction in ARM mode may write only the lower 16 bits of the register.

Keep in mind, all instruction opcodes in ARM mode are limited in size to 32 bits. Of course, this limitation is not related to moving data between registers. That’s why an additional instruction MOVT exists for writing into the higher bits (from 16 to 31 inclusive). Its usage here, however, is redundant because the MOV R0, #0 instruction above cleared the higher part of the register. This is supposedly a shortcoming of the compiler.

The ADD R0, PC, R0 instruction adds the value in the PC to the value in the R0, to calculate the absolute address of the “Hello world!” string. As we already know, it is “position-independent code” so this correction is essential here.

The BL instruction calls the puts() function instead of printf().

GCC replaced the first printf() call with puts(). Indeed: printf() with a sole argument is almost analogous to puts().

Almost, because the two functions are producing the same result only in case the string does not contain printf format identifiers starting with %. In case it does, the effect of these two functions would be different.

---

39 Also available as [http://go.yurichev.com/17276](http://go.yurichev.com/17276)

40 It has also to be noted the puts() does not require a ‘\n’ new line symbol at the end of a string, so we do not see it here.
1.5. HELLO, WORLD!

Why did the compiler replace the printf() with puts()? Presumably because puts() is faster.

Because it just passes characters to stdout without comparing every one of them with the % symbol.

Next, we see the familiar MOV R0, #0 instruction intended to set the R0 register to 0.

Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

By default Xcode 4.6.3 generates code for Thumb-2 in this manner:

Listing 1.28: Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```
__text:00002B6C _hello_world
__text:00002B6C 80 B5 PUSH {R7,LR}
__text:00002B6E 41 F2 D8 30 MOVW R0, #0x13D8
__text:00002B72 6F 46 MOV R7, SP
__text:00002B74 C0 F2 00 00 MOVT.W R0, #0
__text:00002B78 78 44 ADD R0, PC
__text:00002B7A 01 F0 38 EA BLX _puts
__text:00002B7E 00 20 MOVS R0, #0
__text:00002B80 80 BD POP {R7,PC}
...
__cstring:00003E70 48 65 6C 6C 6F 20+aHelloWorld DCB "Hello world!",0xA,0
```

The BL and BLX instructions in Thumb mode, as we recall, are encoded as a pair of 16-bit instructions. In Thumb-2 these surrogate opcodes are extended in such a way so that new instructions may be encoded here as 32-bit instructions.

That is obvious considering that the opcodes of the Thumb-2 instructions always begin with 0xFx or 0xEx.

But in the IDA listing the opcode bytes are swapped because for ARM processor the instructions are encoded as follows: last byte comes first and after that comes the first one (for Thumb and Thumb-2 modes) or for instructions in ARM mode the fourth byte comes first, then the third, then the second and finally the first (due to different endianness).

So that is how bytes are located in IDA listings:

- for ARM and ARM64 modes: 4-3-2-1;
- for Thumb mode: 2-1;
- for 16-bit instructions pair in Thumb-2 mode: 2-1-4-3.

So as we can see, the MOVW, MOVT.W and BLX instructions begin with 0xFx.

One of the Thumb-2 instructions is MOVW R0, #0x13D8—it stores a 16-bit value into the lower part of the R0 register, clearing the higher bits.

Also, MOVT.W R0, #0 works just like MOVT from the previous example only it works in Thumb-2.

Among the other differences, the BLX instruction is used in this case instead of the BL.

The difference is that, besides saving the RA in the LR register and passing control to the puts() function, the processor is also switching from Thumb/Thumb-2 mode to ARM mode (or back).

This instruction is placed here since the instruction to which control is passed looks like (it is encoded in ARM mode):

```
__symbolstub1:00003FEC _puts ; CODE XREF: _hello_world+E
__symbolstub1:00003FEC 44 F0 9F E5 LDR PC, =__imp__puts
```

This is essentially a jump to the place where the address of puts() is written in the imports’ section.

So, the observant reader may ask: why not call puts() right at the point in the code where it is needed?

Because it is not very space-efficient.

Almost any program uses external dynamic libraries (like DLL in Windows, .so in *NIX or .dylib in Mac OS X). The dynamic libraries contain frequently used library functions, including the standard C-function puts().

---

41ciselant.de/projects/gcc_printf/gcc_printf.html
42Return Address
In an executable binary file (Windows PE .exe, ELF or Mach-O) an import section is present. This is a list of symbols (functions or global variables) imported from external modules along with the names of the modules themselves.

The OS loader loads all modules it needs and, while enumerating import symbols in the primary module, determines the correct addresses of each symbol.

In our case, \texttt{\_imp\_puts} is a 32-bit variable used by the OS loader to store the correct address of the function in an external library. Then the LDR instruction just reads the 32-bit value from this variable and writes it into the PC register, passing control to it.

So, in order to reduce the time the OS loader needs for completing this procedure, it is good idea to write the address of each symbol only once, to a dedicated place.

Besides, as we have already figured out, it is impossible to load a 32-bit value into a register while using only one instruction without a memory access.

Therefore, the optimal solution is to allocate a separate function working in ARM mode with the sole goal of passing control to the dynamic library and then to jump to this short one-instruction function (the so-called thunk function) from the Thumb-code.

By the way, in the previous example (compiled for ARM mode) the control is passed by the BL to the same thunk function. The processor mode, however, is not being switched (hence the absence of an “X” in the instruction mnemonic).

\section*{More about thunk-functions}

Thunk-functions are hard to understand, apparently, because of a misnomer. The simplest way to understand it as adaptors or convertors of one type of jack to another. For example, an adaptor allowing the insertion of a British power plug into an American wall socket, or vice-versa. Thunk functions are also sometimes called wrappers.

Here are a couple more descriptions of these functions:

\begin{quote}
\begin{quote}
“A piece of coding which provides an address:”, according to P. Z. Ingerman, who invented thunks in 1961 as a way of binding actual parameters to their formal definitions in Algol-60 procedure calls. If a procedure is called with an expression in the place of a formal parameter, the compiler generates a thunk which computes the expression and leaves the address of the result in some standard location.

Microsoft and IBM have both defined, in their Intel-based systems, a “16-bit environment” (with bletcherous segment registers and 64K address limits) and a “32-bit environment” (with flat addressing and semi-real memory management). The two environments can both be running on the same computer and OS (thanks to what is called, in the Microsoft world, WOW which stands for Windows On Windows). MS and IBM have both decided that the process of getting from 16- to 32-bit and vice versa is called a “thunk”; for Windows 95, there is even a tool, THUNK.EXE, called a “thunk compiler”.
\end{quote}
\end{quote}

(\textbf{The Jargon File})

Another example we can find in LAPACK library—a “Linear Algebra PACKage” written in FORTRAN. C/C++ developers also want to use LAPACK, but it’s insane to rewrite it to C/C++ and then maintain several versions. So there are short C functions callable from C/C++ environment, which are, in turn, call FORTRAN functions, and do almost anything else:

\begin{verbatim}
double Blas_Dot_Prod(const LaVectorDouble &dx, const LaVectorDouble &dy)
{
  assert(dx.size()==dy.size());
  integer n = dx.size();
  integer incx = dx.inc(), incy = dy.inc();

  return F77NAME(ddot)(n, &dx(0), &incx, &dy(0), &incy);
}
\end{verbatim}

Also, functions like that are called “wrappers”.

23
1.5. HELLO, WORLD!

ARM64

GCC

Let's compile the example using GCC 4.8.1 in ARM64:

Listing 1.29: Non-optimizing GCC 4.8.1 + objdump

There are no Thumb and Thumb-2 modes in ARM64, only ARM, so there are 32-bit instructions only. The Register count is doubled: .2.4 on page 1041. 64-bit registers have X- prefixes, while its 32-bit parts—W-.

The STP instruction (Store Pair) saves two registers in the stack simultaneously: X29 and X30.

Of course, this instruction is able to save this pair at an arbitrary place in memory, but the SP register is specified here, so the pair is saved in the stack.

ARM64 registers are 64-bit ones, each has a size of 8 bytes, so one needs 16 bytes for saving two registers.

The exclamation mark (“!”) after the operand means that 16 is to be subtracted from SP first, and only then are values from register pair to be written into the stack. This is also called pre-index. About the difference between post-index and pre-index read here: 1.32.2 on page 439.

Hence, in terms of the more familiar x86, the first instruction is just an analogue to a pair of PUSH X29 and PUSH X30. X29 is used as FP in ARM64, and X30 as LR, so that's why they are saved in the function prologue and restored in the function epilogue.

The second instruction copies SP in X29 (or FP). This is made so to set up the function stack frame.

ADRP and ADD instructions are used to fill the address of the string “Hello!” into the X0 register, because the first function argument is passed in this register. There are no instructions, whatsoever, in ARM that can store a large number into a register (because the instruction length is limited to 4 bytes, read more about it here: 1.32.3 on page 440). So several instructions must be utilized. The first instruction (ADRP) writes the address of the 4KiB page, where the string is located, into X0, and the second one (ADD) just adds the remainder to the address. More about that in: 1.32.4 on page 442.

0x400000 + 0x648 = 0x400648, and we see our “Hello!” C-string in the .rodata data segment at this address.

puts() is called afterwards using the BL instruction. This was already discussed: 1.5.4 on page 21.

MOV writes 0 into W0. W0 is the lower 32 bits of the 64-bit X0 register:

<table>
<thead>
<tr>
<th>High 32-bit part</th>
<th>low 32-bit part</th>
</tr>
</thead>
<tbody>
<tr>
<td>X0</td>
<td>W0</td>
</tr>
</tbody>
</table>

The function result is returned via X0 and main() returns 0, so that's how the return result is prepared. But why use the 32-bit part?

Because the int data type in ARM64, just like in x86-64, is still 32-bit, for better compatibility.

So if a function returns a 32-bit int, only the lower 32 bits of X0 register have to be filled.

In order to verify this, let's change this example slightly and recompile it. Now main() returns a 64-bit value:

\(^{43}\text{Frame Pointer}\)

\[^{43}\text{Frame Pointer}\]
1.5. HELLO, WORLD!

Listing 1.30: main() returning a value of uint64_t type

```c
#include <stdio.h>
#include <stdint.h>

uint64_t main()
{
    printf("Hello!\n");
    return 0;
}
```

The result is the same, but that’s how MOV at that line looks like now:

Listing 1.31: Non-optimizing GCC 4.8.1 + objdump

```
4005a4: d2800000 mov x0, #0x0 // #0
```

LDP (Load Pair) then restores the X29 and X30 registers.

There is no exclamation mark after the instruction: this implies that the values are first loaded from the stack, and only then is SP increased by 16. This is called post-index.

A new instruction appeared in ARM64: RET. It works just as BX LR, only a special hint bit is added, informing the CPU that this is a return from a function, not just another jump instruction, so it can execute it more optimally.

Due to the simplicity of the function, optimizing GCC generates the very same code.

1.5.5 MIPS

A word about the “global pointer”

One important MIPS concept is the “global pointer”. As we may already know, each MIPS instruction has a size of 32 bits, so it’s impossible to embed a 32-bit address into one instruction: a pair has to be used for this (like GCC did in our example for the text string address loading). It’s possible, however, to load data from the address in the range of register−32768...register+32767 using one single instruction (because 16 bits of signed offset could be encoded in a single instruction). So we can allocate some register for this purpose and also allocate a 64KiB area of most used data. This allocated register is called a “global pointer” and it points to the middle of the 64KiB area. This area usually contains global variables and addresses of imported functions like printf(), because the GCC developers decided that getting the address of some function must be as fast as a single instruction execution instead of two. In an ELF file this 64KiB area is located partly in sections .sbsb (“small BSS”) for uninitialized data and .sdata (“small data”) for initialized data. This implies that the programmer may choose what data he/she wants to be accessed fast and place it into .sdata/.sbsb. Some old-school programmers may recall the MS-DOS memory model 11.6 on page 1003 or the MS-DOS memory managers like XMS/EMS where all memory was divided in 64KiB blocks.

This concept is not unique to MIPS. At least PowerPC uses this technique as well.

Optimizing GCC

Let’s consider the following example, which illustrates the “global pointer” concept.

Listing 1.32: Optimizing GCC 4.4.5 (assembly output)

```
$LC0:
; \000 is zero byte in octal base:
.ascii "Hello, world!\012\000"
main:
; function prologue.
; set the GP:
    lui $28,%hi(__gnu_local_gp)
    addiu $sp,$sp,-32
    addiu $28,$28,%lo(__gnu_local_gp)
; save the RA to the local stack:
    sw $31,28($sp)
```

44 Block Started by Symbol
1.5. HELLO, WORLD!

; load the address of the puts() function from the GP to $25:
lw $25,%call16(puts)($28)

; load the address of the text string to $4 ($a0):
lui $4,%hi($LC0)
addiu $4,$4,%lo($LC0) ; branch delay slot
jalr $25
addiu $4,$4,%lo($LC0) ; branch delay slot

; restore the RA:
lw $31,28($sp)

; copy 0 from $zero to $v0:
mv $2,$0

; return by jumping to the RA:
j $31

; function epilogue:
addiu $sp,$sp,32 ; branch delay slot + free local stack

As we see, the $GP register is set in the function prologue to point to the middle of this area. The RA
register is also saved in the local stack. puts() is also used here instead of printf(). The address of the
puts() function is loaded into $25 using LW (“Load Word”). Then the address of the text
string is loaded to $4 using LUI (“Load Upper Immediate”) and ADDIU (“Add Immediate Unsigned Word”) instruction pair. LUI sets the high 16 bits of the register (hence “upper” word in instruction name) and ADDIU adds the lower 16 bits of the address.

ADDIU follows JALR (haven’t you forgot branch delay slots yet?). The register $4 is also called $A0, which is
used for passing the first function argument.

JALR (“Jump and Link Register”) jumps to the address stored in the $25 register (address of puts()) while
saving the address of the next instruction (LW) in RA. This is very similar to ARM. Oh, and one important
thing is that the address saved in RA is not the address of the next instruction (because it’s in a delay slot
and is executed before the jump instruction), but the address of the instruction after the next one (after the
delay slot). Hence, PC+8 is written to RA during the execution of JALR, in our case, this is the address of
the LW instruction next to ADDIU.

LW (“Load Word”) at line 20 restores RA from the local stack (this instruction is actually part of the function
epilogue).

MOVE at line 22 copies the value from the $0 ($ZERO) register to $2 ($V0).

MIPS has a constant register, which always holds zero. Apparently, the MIPS developers came up with
the idea that zero is in fact the busiest constant in the computer programming, so let’s just use the $0
register every time zero is needed.

Another interesting fact is that MIPS lacks an instruction that transfers data between registers. In fact,
MOVE DST, SRC is ADD DST, SRC, $ZERO (DST = SRC + 0), which does the same. Apparently, the MIPS
developers wanted to have a compact opcode table. This does not mean an actual addition happens at
each MOVE instruction. Most likely, the CPU optimizes these pseudo instructions and the ALU is never
used.

J at line 24 jumps to the address in RA, which is effectively performing a return from the function. ADDIU
after J is in fact executed before J (remember branch delay slots?) and is part of the function epilogue.
Here is also a listing generated by IDA. Each register here has its own pseudo name:

```
Listing 1.33: Optimizing GCC 4.4.5 (IDA)

.text:00000000 main:
.text:00000000
.text:00000000 var_10 = -0x10
.text:00000000 var_4 = -4
.text:00000000
.text:00000000 ; function prologue.
.text:00000000 ; set the GP:
.text:00000000 lui $gp, ((__gnu_local_gp >> 16)
.text:00000000 addiu $sp, -0x20
.text:00000000 la $gp, ((__gnu_local_gp & 0xFFFF)
.text:00000000 ; save the RA to the local stack:
.text:00000000 sw $ra, 0x20+var_4($sp)
.text:00000000 ; save the GP to the local stack:
.text:00000000 ; for some reason, this instruction is missing in the GCC assembly output:
```

45The MIPS registers table is available in appendix 3.1 on page 1042
46Arithmetic Logic Unit
The instruction at line 15 saves the GP value into the local stack, and this instruction is missing mysteriously from the GCC output listing, maybe by a GCC error. The GP value has to be saved indeed, because each function can use its own 64KiB data window. The register containing the `puts()` address is called $T9, because registers prefixed with T- are called “temporaries” and their contents may not be preserved.

Non-optimizing GCC

Non-optimizing GCC is more verbose.

Listing 1.34: Non-optimizing GCC 4.4.5 (assembly output)

```
.LC0:
    .ascii "Hello, world!\012\000"
main:
    ; function prologue.
    ; save the RA ($31) and FP in the stack:
    addiu $sp,$sp,-32
    sw $31,28($sp)
    sw $fp,24($sp)
    ; set the FP (stack frame pointer):
    move $fp,$sp
    ; set the GP:
    lui $28,%hi(__gnu_local_gp)
    addiu $28,$28,%lo(__gnu_local_gp)
    ; load the address of the text string:
    lui $4,%hi($LC0)
    addiu $4,$2,%lo($LC0)
    ; load the address of puts() using the GP:
    lw $2,%call16(puts)($28)
    nop
    ; call puts():
    move $25,$2
    jalr $25
    nop ; branch delay slot
    ; restore the GP from the local stack:
    lw $28,16($fp)
    ; set register $2 ($V0) to zero:
    move $2,$0
    ; function epilogue.
    ; restore the SP:
    move $sp,$fp
    ; restore the RA:
    lw $31,28($sp)
    ; restore the FP:
    lw $fp,24($sp)
    addiu $sp,$sp,32
    ; jump to the RA:
    j $31
    nop ; branch delay slot
```

47Apparently, functions generating listings are not so critical to GCC users, so some unfixed errors may still exist.
1.5. HELLO, WORLD!

We see here that register FP is used as a pointer to the stack frame. We also see 3 NOPs. The second and third of which follow the branch instructions. Perhaps the GCC compiler always adds NOPs (because of branch delay slots) after branch instructions and then, if optimization is turned on, maybe eliminates them. So in this case they are left here.

Here is also IDA listing:

Listing 1.35: Non-optimizing GCC 4.4.5 (IDA)

```
.text:00000000 main:
.text:00000000
.text:00000000 var_10 = -0x10
.text:00000000 var_8 = -8
.text:00000000 var_4 = -4
.text:00000000

; function prologue.
; save the RA and FP in the stack:
.text:00000000 addiu $sp, -0x20
.text:00000004 sw $ra, 0x20+var_4($sp)
.text:00000008 sw $fp, 0x20+var_8($sp)

; set the FP (stack frame pointer):
.text:0000000C move $fp, $sp

; set the GP:
.text:00000010 la $gp, __gnu_local_gp
.text:00000018 sw $gp, 0x20+var_10($sp)

; load the address of the text string:
.text:0000001C lui $v0, (aHelloWorld >> 16) # "Hello, world!"
.text:00000020 addiu $a0, $v0, (aHelloWorld & 0xFFFF) # "Hello, world!"

; load the address of puts() using the GP:
.text:00000024 lw $v0, (puts & 0xFFFF)($gp)
.text:00000028 or $at, $zero ; NOP

; call puts():
.text:0000002C move $t9, $v0
.text:00000030 jalr $t9
.text:00000034 or $at, $zero ; NOP

; restore the GP from local stack:
.text:00000038 lw $gp, 0x20+var_10($fp)

; set register $2 ($V0) to zero:
.text:0000003C move $v0, $zero

; function epilogue.
; restore the SP:
.text:00000040 move $sp, $fp

; restore the RA:
.text:00000044 lw $ra, 0x20+var_4($sp)

; restore the FP:
.text:00000048 lw $fp, 0x20+var_8($sp)
.text:0000004C addiu $sp, 0x20

; jump to the RA:
.text:00000050 jr $ra
.text:00000054 or $at, $zero ; NOP
```

Interestingly, IDA recognized the LUI/ADDIU instructions pair and coalesced them into one LA (“Load Address”) pseudo instruction at line 15. We may also see that this pseudo instruction has a size of 8 bytes! This is a pseudo instruction (or macro) because it’s not a real MIPS instruction, but rather a handy name for an instruction pair.

Another thing is that IDA doesn’t recognize NOP instructions, so here they are at lines 22, 26 and 41. It is OR $AT, $ZERO. Essentially, this instruction applies the OR operation to the contents of the $AT register with zero, which is, of course, an idle instruction. MIPS, like many other ISAs, doesn’t have a separate NOP instruction.

Role of the stack frame in this example

The address of the text string is passed in the register. Why setup a local stack anyway? The reason for this lies in the fact that the values of registers RA and GP have to be saved somewhere (because printf() is called), and the local stack is used for this purpose. If this was a leaf function, it would have been possible to get rid of the function prologue and epilogue, for example: 1.4.3 on page 8.
1.6. FUNCTION PROLOGUE AND EPILOGUE

Optimizing GCC: load it into GDB

Listing 1.36: sample GDB session

```
root@debian-mips:~# gcc hw.c -O3 -o hw
root@debian-mips:~# gdb hw
GNU gdb (GDB) 7.0.1-debian
...
Reading symbols from /root/hw...(no debugging symbols found)...done.
(gdb) b main
Breakpoint 1 at 0x400654
(gdb) run
Starting program: /root/hw
Breakpoint 1, 0x00400654 in main ()
(gdb) set step-mode on
(gdb) disas
Dump of assembler code for function main:
0x00400640 <main+0>:  lui gp,0x42
0x00400644 <main+4>:  addiu sp,sp,-32
0x00400648 <main+8>:  addiu gp,gp,-30624
0x0040064c <main+12>: sw ra,28(sp)
0x00400650 <main+16>: sw gp,16(sp)
0x00400654 <main+20>: lw t9,-32716(gp)
0x00400658 <main+24>: lui a0,0x40
0x0040065c <main+28>: jalr t9
0x00400660 <main+32>: addiu a0,a0,2080
0x00400664 <main+36>: lw ra,28(sp)
0x00400668 <main+40>: move v0,zero
0x0040066c <main+44>: jr ra
0x00400670 <main+48>: addiu sp,sp,32
End of assembler dump.
(gdb) s
0x00400658 in main ()
(gdb) s
0x0040065c in main ()
(gdb) s
0x2ab2de60 in printf () from /lib/libc.so.6
(gdb) x/s $a0
0x400820:  "hello, world"
(gdb)
```

1.5.6 Conclusion

The main difference between x86/ARM and x64/ARM64 code is that the pointer to the string is now 64-bits in length. Indeed, modern CPUs are now 64-bit due to both the reduced cost of memory and the greater demand for it by modern applications. We can add much more memory to our computers than 32-bit pointers are able to address. As such, all pointers are now 64-bit.

1.5.7 Exercises

- [http://challenges.re/48](http://challenges.re/48)
- [http://challenges.re/49](http://challenges.re/49)

1.6 Function prologue and epilogue

A function prologue is a sequence of instructions at the start of a function. It often looks something like the following code fragment:

```
push   ebp
mov    ebp, esp
sub    esp, X
```
1.7. STACK

What these instruction do: save the value of the EBP register on the stack, set the value of the EBP register to the value of the ESP and then allocate space on the stack for local variables.

The value in the EBP stays the same over the period of the function execution and is to be used for local variables and arguments access. For the same purpose one can use ESP, but since it changes over time this approach is not too convenient.

The function epilogue frees the allocated space in the stack, returns the value in the EBP register back to its initial state and returns the control flow to the caller:

```c
mov esp, ebp
pop ebp
ret 0
```

Function prologues and epilogues are usually detected in disassemblers for function delimitation.

1.6.1 Recursion

Epilogues and prologues can negatively affect the recursion performance.

More about recursion in this book: 3.4.3 on page 481.

1.7 Stack

The stack is one of the most fundamental data structures in computer science. Technically, it is just a block of memory in process memory along with the ESP or RSP register in x86 or x64, or the SP register in ARM, as a pointer within that block.

The most frequently used stack access instructions are PUSH and POP (in both x86 and ARM Thumb-mode). PUSH subtracts from ESP/RSP/SP 4 in 32-bit mode (or 8 in 64-bit mode) and then writes the contents of its sole operand to the memory address pointed by ESP/RSP/SP.

POP is the reverse operation: retrieve the data from the memory location that SP points to, load it into the instruction operand (often a register) and then add 4 (or 8) to the stack pointer.

After stack allocation, the stack pointer points at the bottom of the stack. PUSH decreases the stack pointer and POP increases it. The bottom of the stack is actually at the beginning of the memory allocated for the stack block. It seems strange, but that’s the way it is.

ARM supports both descending and ascending stacks.

For example the STMFD/LDMFD, STMED/LDMED instructions are intended to deal with a descending stack (grows downwards, starting with a high address and progressing to a lower one). The STMFA/LDMFA, STMEA/LDMEA instructions are intended to deal with an ascending stack (grows upwards, starting from a low address and progressing to a higher one).

1.7.1 Why does the stack grow backwards?

Intuitively, we might think that the stack grows upwards, i.e. towards higher addresses, like any other data structure.

The reason that the stack grows backward is probably historical. When the computers were big and occupied a whole room, it was easy to divide memory into two parts, one for the heap and one for the stack. Of course, it was unknown how big the heap and the stack would be during program execution, so this solution was the simplest possible.

---

48 wikipedia.org/wiki/Call_stack
49 Also Known As
50 Last In First Out
51 Store Multiple Empty Descending (ARM instruction)
52 Load Multiple Empty Descending (ARM instruction)
53 Store Multiple Full Ascending (ARM instruction)
54 Load Multiple Full Ascending (ARM instruction)
55 Store Multiple Empty Ascending (ARM instruction)
56 Load Multiple Empty Ascending (ARM instruction)
In [D. M. Ritchie and K. Thompson, *The UNIX Time Sharing System*, (1974)](http://go.yurichev.com/17270) we can read:

> The user-core part of an image is divided into three logical segments. The program text segment begins at location 0 in the virtual address space. During execution, this segment is write-protected and a single copy of it is shared among all processes executing the same program. At the first 8K byte boundary above the program text segment in the virtual address space begins a nonshared, writable data segment, the size of which may be extended by a system call. Starting at the highest address in the virtual address space is a stack segment, which automatically grows downward as the hardware's stack pointer fluctuates.

This reminds us how some students write two lecture notes using only one notebook: notes for the first lecture are written as usual, and notes for the second one are written from the end of notebook, by flipping it. Notes may meet each other somewhere in between, in case of lack of free space.

### 1.7.2 What is the stack used for?

**Save the function's return address**

x86

When calling another function with a **CALL** instruction, the address of the point exactly after the **CALL** instruction is saved to the stack and then an unconditional jump to the address in the **CALL** operand is executed.

The **CALL** instruction is equivalent to a **PUSH** address after call / **JMP** operand instruction pair.

**RET** fetches a value from the stack and jumps to it — that is equivalent to a **POP** tmp / **JMP** tmp instruction pair.

Overflowing the stack is straightforward. Just run eternal recursion:

```c
void f()
{
    f();
}
```

MSVC 2008 reports the problem:

```c
MSVC 2008 reports the problem:
c:\tmp6>cl ss.cpp /Fass.asm
Microsoft (R) 32-bit C/C++ Optimizing Compiler Version 15.00.21022.08 for 80x86
Copyright (C) Microsoft Corporation. All rights reserved.
ss.cpp
c:\tmp6\ss.cpp(4) : warning C4717: 'f' : recursive on all control paths, function will cause runtime stack overflow
```

...but generates the right code anyway:

```c
?f@YAXXZ PROC ; f
; File c:\tmp6\ss.cpp
; Line 2
    push ebp
    mov ebp, esp
; Line 3
    call ?f@YAXXZ ; f
```

[^57]: Also available as [http://go.yurichev.com/17270](http://go.yurichev.com/17270)
...Also if we turn on the compiler optimization (/Ox option) the optimized code will not overflow the stack and will work correctly instead:

GCC 4.4.1 generates similar code in both cases without, however, issuing any warning about the problem.

ARM

ARM programs also use the stack for saving return addresses, but differently. As mentioned in “Hello, world!” (1.5.4 on page 19), the RA is saved to the LR (link register). If one needs, however, to call another function and use the LR register one more time, its value has to be saved. Usually it is saved in the function prologue.

Often, we see instructions like PUSH R4-R7,LR along with this instruction in epilogue POP R4-R7,PC—thus register values to be used in the function are saved in the stack, including LR.

Nevertheless, if a function never calls any other function, in RISC terminology it is called a leaf function59. As a consequence, leaf functions do not save the LR register (because they don’t modify it). If such function is small and uses a small number of registers, it may not use the stack at all. Thus, it is possible to call leaf functions without using the stack, which can be faster than on older x86 machines because external RAM is not used for the stack60. This can be also useful for situations when memory for the stack is not yet allocated or not available.

Some examples of leaf functions: 1.10.3 on page 103, 1.10.3 on page 103, 1.278 on page 315, 1.294 on page 333, 1.22.5 on page 333, 1.186 on page 210, 1.184 on page 208, 1.203 on page 226.

Passing function arguments

The most popular way to pass parameters in x86 is called “cdecl”:

Callee functions get their arguments via the stack pointer.

Therefore, this is how the argument values are located in the stack before the execution of the f() function’s very first instruction:

<table>
<thead>
<tr>
<th>ESP</th>
<th>return address</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESP+4</td>
<td>argument#1, marked in IDA as arg_0</td>
</tr>
<tr>
<td>ESP+8</td>
<td>argument#2, marked in IDA as arg_4</td>
</tr>
<tr>
<td>ESP+0xC</td>
<td>argument#3, marked in IDA as arg_8</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

58irony here
60Some time ago, on PDP-11 and VAX, the CALL instruction (calling other functions) was expensive; up to 50% of execution time might be spent on it, so it was considered that having a big number of small functions is an anti-pattern [Eric S. Raymond, *The Art of UNIX Programming*, (2003)Chapter 4, Part II].
1.7. STACK

For more information on other calling conventions see also section (6.1 on page 734).

By the way, the callee function does not have any information about how many arguments were passed. C functions with a variable number of arguments (like printf()) determine their number using format string specifiers (which begin with the % symbol).

If we write something like:

```c
printf("%d %d %d", 1234);
```

printf() will print 1234, and then two random numbers\(^{61}\), which were lying next to it in the stack.

That's why it is not very important how we declare the main() function: as main(),
main(int argc, char *argv[]) or main(int argc, char *argv[], char *envp[]).

In fact, the CRT-code is calling main() roughly as:

```c
push envp
push argv
push argc
call main
...
```

If you declare main() as main() without arguments, they are, nevertheless, still present in the stack, but are not used. If you declare main() as main(int argc, char *argv[]), you will be able to use first two arguments, and the third will remain "invisible" for your function. Even more, it is possible to declare main(int argc), and it will work.

**Alternative ways of passing arguments**

It is worth noting that nothing obliges programmers to pass arguments through the stack. It is not a requirement. One could implement any other method without using the stack at all.

A somewhat popular way among assembly language newbies is to pass arguments via global variables, like:

```assembly
Listing 1.37: Assembly code

...  
mov   X, 123  
mov   Y, 456  
call  do_something
...

X dd   ?  
Y dd   ?  

do_something proc near
    ; take X
    ; take Y
    ; do something
retn
do_something endp
```

But this method has obvious drawback: do_something() function cannot call itself recursively (or via another function), because it has to zap its own arguments. The same story with local variables: if you hold them in global variables, the function couldn't call itself. And this is also not thread-safe\(^ {62}\). A method to store such information in stack makes this easier—it can hold as many function arguments and/or values, as much space it has.


MS-DOS had a way of passing all function arguments via registers, for example, this is piece of code for ancient 16-bit MS-DOS prints “Hello, world!”:

\(^{61}\)Not random in strict sense, but rather unpredictable: [1.7.4 on page 37]

\(^{62}\)Correctly implemented, each thread would have its own stack with its own arguments/variables.
1.7. STACK

```
mov dx, msg     ; address of message
mov ah, 9      ; 9 means "print string" function
int 21h        ; DOS "syscall"

mov ah, 4ch    ; "terminate program" function
int 21h        ; DOS "syscall"

msg db 'Hello, World!$'
```

This is quite similar to 6.1.3 on page 735 method. And also it’s very similar to calling syscalls in Linux (6.3.1 on page 747) and Windows.

If a MS-DOS function is going to return a boolean value (i.e., single bit, usually indicating error state), CF flag was often used.

For example:

```
mov ah, 3ch     ; create file
lea dx, filename
mov cl, 1
int 21h
jc error
mov file_handle, ax
...
error:
...
```

In case of error, CF flag is raised. Otherwise, handle of newly created file is returned via AX.

This method is still used by assembly language programmers. In Windows Research Kernel source code (which is quite similar to Windows 2003) we can find something like this (file base/ntos/ke/i386/cpu.asm):

```
public Get386Stepping
Get386Stepping proc
    call MultiplyTest         ; Perform multiplication test
    jnc short G3s00           ; if nc, muttest is ok
    mov ax, 0
    ret

G3s00:
    call Check386B0          ; Check for B0 stepping
    jnc short G3s05          ; if nc, it's B1/ later
    mov ax, 100h             ; It is B0/earlier stepping
    ret

G3s05:
    call Check386D1          ; Check for D1 stepping
    jc short G3s10           ; if c, it is NOT D1
    mov ax, 301h             ; It is D1/later stepping
    ret

G3s10:
    mov ax, 101h             ; assume it is B1 stepping
    ret

MultiplyTest proc
    xor cx,cx                ; 64K times is a nice round number
mlt00: push cx
    call Multiply           ; does this chip's multiply work?
    pop cx
    jc short mltx           ; if c, No, exit
    loop mlt00              ; if nc, YEs, loop to try again
    clc
mltx:
    ret
MultiplyTest endp
```
1.7. STACK

Local variable storage

A function could allocate space in the stack for its local variables just by decreasing the stack pointer towards the stack bottom.

Hence, it’s very fast, no matter how many local variables are defined. It is also not a requirement to store local variables in the stack. You could store local variables wherever you like, but traditionally this is how it’s done.

x86: alloca() function

It is worth noting the alloca() function. This function works like malloc(), but allocates memory directly on the stack. The allocated memory chunk does not have to be freed via a free() function call, since the function epilogue (1.6 on page 29) returns ESP back to its initial state and the allocated memory is just dropped. It is worth noting how alloca() is implemented. In simple terms, this function just shifts ESP downwards toward the stack bottom by the number of bytes you need and sets ESP as a pointer to the allocated block.

Let’s try:

```c
#ifdef __GNUC__
#include <alloca.h> // GCC
#else
#include <malloc.h> // MSVC
#endif
#include <stdio.h>

void f()
{
    char *buf=(char*)alloca (600);
    #ifdef __GNUC__
    snprintf (buf, 600, "hi! %d, %d, %d\n", 1, 2, 3); // GCC
    #else
    _snprintf (buf, 600, "hi! %d, %d, %d\n", 1, 2, 3); // MSVC
    #endif
    puts (buf);
}
```

_snprintf() function works just like printf(), but instead of dumping the result into stdout (e.g., to terminal or console), it writes it to the buf buffer. Function puts() copies the contents of buf to stdout. Of course, these two function calls might be replaced by one printf() call, but we have to illustrate small buffer usage.

MSVC

Let’s compile (MSVC 2010):

```assembly
Listing 1.38: MSVC 2010

... 
    mov    eax, 600  ; 00000258H
    call   __alloca_probe_16
    mov    esi, esp
    push   3
    push   2
    push   1
    push   OFFSET $SG2672
    push   600  ; 00000258H
    push   esi
    call   __snprintf
```

63 In MSVC, the function implementation can be found in alloca16.asm and chkstk.asm in C:\Program Files (x86)\Microsoft Visual Studio 10.0\VC\crt\src\intel
The sole alloca() argument is passed via EAX (instead of pushing it into the stack)\(^{64}\).

**GCC + Intel syntax**

GCC 4.4.1 does the same without calling external functions:

**Listing 1.39: GCC 4.7.3**

```
.LC0:
.string "hi! %d, %d, %d\n"
f:
push ebp
mov ebp, esp
push ebx
sub esp, 660
lea ebx, [esp+39]
and ebx, -16 ; align pointer by 16-bit border
mov DWORD PTR [esp], ebx ; s
mov DWORD PTR [esp+20], 3
mov DWORD PTR [esp+16], 2
mov DWORD PTR [esp+12], 1
mov DWORD PTR [esp+8], OFFSET FLAT:.LC0 ; "hi! %d, %d, %d\n"
mov DWORD PTR [esp+4], 600 ; maxlen
call _snprintf
mov DWORD PTR [esp], ebx ; s
call puts
mov ebx, DWORD PTR [ebp-4]
leave
ret
```

**GCC + AT&T syntax**

Let's see the same code, but in AT&T syntax:

**Listing 1.40: GCC 4.7.3**

```
.LC0:
.string "hi! %d, %d, %d\n"
f:
pushl %ebp
movl %esp, %ebp
pushl %ebx
subl $660, %esp
leal 39(%esp), %ebx
andl $-16, %ebx
movl %ebx, (%esp)
movl $3, 20(%esp)
movl $2, 16(%esp)
movl $1, 12(%esp)
movl $.LC0, 8(%esp)
movl $600, 4(%esp)
call _snprintf
movl %ebx, (%esp)
call puts
movl -4(%ebp), %ebx
leave
```

\(^{64}\)It is because alloca() is rather a compiler intrinsic (\[11.3\] on page 999) than a normal function. One of the reasons we need a separate function instead of just a couple of instructions in the code, is because the MSVC\(^{65}\) alloca() implementation also has code which reads from the memory just allocated, in order to let the OS map physical memory to this VM\(^{66}\) region. After the alloca() call, ESP points to the block of 600 bytes and we can use it as memory for the buf array.
1.7. STACK

The code is the same as in the previous listing.

By the way, `movl $3, 20(%esp)` corresponds to `mov DWORD PTR [esp+20], 3` in Intel-syntax. In the AT&T syntax, the register+offset format of addressing memory looks like `offset(%register)`.

(Windows) SEH

SEH\(^{67}\) records are also stored on the stack (if they are present). Read more about it: (6.5.3 on page 764).

Buffer overflow protection

More about it here (1.20.2 on page 275).

Automatic deallocation of data in stack

Perhaps the reason for storing local variables and SEH records in the stack is that they are freed automatically upon function exit, using just one instruction to correct the stack pointer (it is often `ADD`). Function arguments, as we could say, are also deallocated automatically at the end of function. In contrast, everything stored in the heap must be deallocated explicitly.

1.7.3 A typical stack layout

A typical stack layout in a 32-bit environment at the start of a function, before the first instruction execution looks like this:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ESP-0xC</td>
<td>local variable#2, marked in IDA as var_8</td>
</tr>
<tr>
<td>ESP-8</td>
<td>local variable#1, marked in IDA as var_4</td>
</tr>
<tr>
<td>ESP-4</td>
<td>saved value ofEBP</td>
</tr>
<tr>
<td>ESP</td>
<td>Return Address</td>
</tr>
<tr>
<td>ESP+4</td>
<td>argument#1, marked in IDA as arg_0</td>
</tr>
<tr>
<td>ESP+8</td>
<td>argument#2, marked in IDA as arg_4</td>
</tr>
<tr>
<td>ESP+0xC</td>
<td>argument#3, marked in IDA as arg_8</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>

1.7.4 Noise in stack

When one says that something seems random, what one usually means in practice is that one cannot see any regularities in it.

Stephen Wolfram, A New Kind of Science.

Often in this book “noise” or “garbage” values in the stack or memory are mentioned. Where do they come from? These are what has been left there after other functions’ executions. Short example:

```c
#include <stdio.h>

void f1()
{
  int a=1, b=2, c=3;
};

void f2()
{
  int a, b, c;
  printf ("%d, %d, %d\n", a, b, c);
}
```

\(^{67}\)Structured Exception Handling
1.7. STACK

```c
int main()
{
    f1();
    f2();
}
```

Listing 1.41: Non-optimizing MSVC 2010

```
$SG2752 DB '%d, %d, %d', 0aH, 00H
_c$ = -12 ; size = 4
_b$ = -8 ; size = 4
_a$ = -4 ; size = 4
_f1 PROC
    push ebp
    mov ebp, esp
    sub esp, 12
    mov DWORD PTR _a$[ebp], 1
    mov DWORD PTR _b$[ebp], 2
    mov DWORD PTR _c$[ebp], 3
    mov esp, ebp
    pop ebp
    ret 0
_f1 ENDP

_c$ = -12 ; size = 4
_b$ = -8 ; size = 4
_a$ = -4 ; size = 4
_f2 PROC
    push ebp
    mov ebp, esp
    sub esp, 12
    mov eax, DWORD PTR _c$[ebp]
    push eax
    mov ecx, DWORD PTR _b$[ebp]
    push ecx
    mov edx, DWORD PTR _a$[ebp]
    push edx
    push OFFSET $SG2752 ; '%d, %d, %d'
    call DWORD PTR __imp__printf
    add esp, 16
    mov esp, ebp
    pop ebp
    ret 0
_f2 ENDP

_main PROC
    push ebp
    mov ebp, esp
    call _f1
    call _f2
    xor eax, eax
    pop ebp
    ret 0
_main ENDP
```

The compiler will grumble a little bit...

```
c:\Polygon\c\cl st.c /Fast.asm /MD
Microsoft (R) 32-bit C/C++ Optimizing Compiler Version 16.00.40219.01 for 80x86
Copyright (C) Microsoft Corporation. All rights reserved.

st.c
c:\polygon\c\st.c(11) : warning C4700: uninitialized local variable 'c' used
c:\polygon\c\st.c(11) : warning C4700: uninitialized local variable 'b' used
c:\polygon\c\st.c(11) : warning C4700: uninitialized local variable 'a' used
```
But when we run the compiled program ...

c:\Polygon\c>st
1, 2, 3

Oh, what a weird thing! We did not set any variables in f2(). These are “ghosts” values, which are still in the stack.
1.7. STACK

Let’s load the example into OllyDbg:

![OllyDbg screenshot](image)

Figure 1.5: OllyDbg: f1()

When f1() assigns the variables \( a, b \) and \( c \), their values are stored at the address 0x1FF860 and so on.
1.7. STACK

And when \texttt{f2()} executes:

\begin{verbatim}
Figure 1.6: OllyDbg: f2()

... a, b and c of \texttt{f2()} are located at the same addresses! No one has overwritten the values yet, so at that point they are still untouched. So, for this weird situation to occur, several functions have to be called one after another and \texttt{SP} has to be the same at each function entry (i.e., they have the same number of arguments). Then the local variables will be located at the same positions in the stack. Summarizing, all values in the stack (and memory cells in general) have values left there from previous function executions. They are not random in the strict sense, but rather have unpredictable values. Is there another option? It would probably be possible to clear portions of the stack before each function execution, but that's too much extra (and unnecessary) work.

MSVC 2013

The example was compiled by MSVC 2010. But the reader of this book made attempt to compile this example in MSVC 2013, ran it, and got all 3 numbers reversed:

c:\Polygon\c>st
3, 2, 1

Why? I also compiled this example in MSVC 2013 and saw this:

Listing 1.42: MSVC 2013

\begin{verbatim}
a$ = -12 ; size = 4
b$ = -8 ; size = 4
c$ = -4 ; size = 4
f2 PROC
...
f2 ENDP

c$ = -12 ; size = 4
b$ = -8 ; size = 4
a$ = -4 ; size = 4
f1 PROC
\end{verbatim}
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Unlike MSVC 2010, MSVC 2013 allocated a/b/c variables in function f2() in reverse order. And this is completely correct, because C/C++ standards has no rule, in which order local variables must be allocated in the local stack, if at all. The reason of difference is because MSVC 2010 has one way to do it, and MSVC 2013 has supposedly something changed inside of compiler guts, so it behaves slightly different.

1.7.5 Exercises

- [http://challenges.re/51](http://challenges.re/51)
- [http://challenges.re/52](http://challenges.re/52)

1.8 printf() with several arguments

Now let’s extend the *Hello, world!* ([1.5 on page 8](#)) example, replacing printf() in the main() function body with this:

```c
#include <stdio.h>

int main()
{
    printf("a=%d; b=%d; c=%d", 1, 2, 3);
    return 0;
}
```

1.8.1 x86

**x86: 3 arguments**

**MSVC**

When we compile it with MSVC 2010 Express we get:

```
$SG3830 DB 'a=%d; b=%d; c=%d', 00H
...

    push 3
    push 2
    push 1
    push OFFSET $SG3830
    call __printf
    add esp, 16  ; 00000010H
```

Almost the same, but now we can see the printf() arguments are pushed onto the stack in reverse order. The first argument is pushed last.

By the way, variables of int type in 32-bit environment have 32-bit width, that is 4 bytes.

So, we have 4 arguments here. $4 \times 4 = 16$ —they occupy exactly 16 bytes in the stack: a 32-bit pointer to a string and 3 numbers of type int.

When the stack pointer (ESP register) has changed back by the ADD ESP, X instruction after a function call, often, the number of function arguments could be deduced by simply dividing X by 4.

Of course, this is specific to the cdecl calling convention, and only for 32-bit environment.

See also the calling conventions section ([6.1 on page 734](#)).
In certain cases where several functions return right after one another, the compiler could merge multiple "ADD ESP, X" instructions into one, after the last call:

```assembly
push a1
push a2
call ...
...
push a1
call ...
...
push a1
push a2
push a3
call ...
add esp, 24
```

Here is a real-world example:

```assembly
Listing 1.43: x86
.text:100113E7 push 3
.text:100113E9 call sub_100018B0 ; takes one argument (3)
.text:100113EE call sub_100019D0 ; takes no arguments at all
.text:100113F3 call sub_10006A90 ; takes no arguments at all
.text:100113F8 push 1
.text:100113FA call sub_100018B0 ; takes one argument (1)
.text:100113FF add esp, 8 ; drops two arguments from stack at once
```
Now let's try to load this example in OllyDbg. It is one of the most popular user-land win32 debuggers. We can compile our example in MSVC 2012 with /MD option, which means to link with MSVCR*.DLL, so we can see the imported functions clearly in the debugger.

Then load the executable in OllyDbg. The very first breakpoint is in ntdll.dll, press F9 (run). The second breakpoint is in CRT-code. Now we have to find the main() function.

Find this code by scrolling the code to the very top (MSVC allocates the main() function at the very beginning of the code section):

Figure 1.7: OllyDbg: the very start of the main() function

Click on the PUSH EBP instruction, press F2 (set breakpoint) and press F9 (run). We have to perform these actions in order to skip CRT-code, because we aren't really interested in it yet.
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Press F8 (step over) 6 times, i.e. skip 6 instructions:

![CPU - main thread, module 1](image1)

Figure 1.8: OllyDbg: before printf() execution

Now the PC points to the CALL printf instruction. OllyDbg, like other debuggers, highlights the value of the registers which were changed. So each time you press F8, EIP changes and its value is displayed in red. ESP changes as well, because the arguments values are pushed into the stack.

Where are the values in the stack? Take a look at the right bottom debugger window:

![Debug window showing stack values](image2)

Figure 1.9: OllyDbg: stack after the argument values have been pushed (The red rectangular border was added by the author in a graphics editor)

We can see 3 columns there: address in the stack, value in the stack and some additional OllyDbg comments. OllyDbg understands printf()-like strings, so it reports the string here and the 3 values attached to it.

It is possible to right-click on the format string, click on “Follow in dump”, and the format string will appear in the debugger left-bottom window, which always displays some part of the memory. These memory values can be edited. It is possible to change the format string, in which case the result of our example would be different. It is not very useful in this particular case, but it could be good as an exercise so you start building a feel of how everything works here.
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Press F8 (step over).

We see the following output in the console:

```
a=1; b=2; c=3
```

Let’s see how the registers and stack state have changed:

![Figure 1.10: OllyDbg after printf() execution](image)

Register EAX now contains 0xD (13). That is correct, since printf() returns the number of characters printed. The value of EIP has changed: indeed, now it contains the address of the instruction coming after CALL printf. ECX and EDX values have changed as well. Apparently, the printf() function’s hidden machinery used them for its own needs.

A very important fact is that neither the ESP value, nor the stack state have been changed! We clearly see that the format string and corresponding 3 values are still there. This is indeed the cdecl calling convention behavior: callee does not return ESP back to its previous value. The caller is responsible to do so.
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Press F8 again to execute ADD ESP, 10 instruction:

![CPU - main thread, module 1](image)

Figure 1.11: OllyDbg: after ADD ESP, 10 instruction execution

ESP has changed, but the values are still in the stack! Yes, of course; no one needs to set these values to zeros or something like that. Everything above the stack pointer (SP) is noise or garbage and has no meaning at all. It would be time consuming to clear the unused stack entries anyway, and no one really needs to.

**GCC**

Now let’s compile the same program in Linux using GCC 4.4.1 and take a look at what we have got in IDA:

```assembly
main proc near

var_10 = dword ptr -10h
var_C = dword ptr -0Ch
var_8 = dword ptr -8
var_4 = dword ptr -4

push ebp
mov ebp, esp
and esp, 0FFFFFFF0h
sub esp, 10h
mov eax, offset aADBDCD ; "a=%d; b=%d; c=%d"
mov [esp+10h+var_4], 3
mov [esp+10h+var_8], 2
mov [esp+10h+var_C], 1
mov [esp+10h+var_10], eax
call _printf
mov eax, 0
leave
ret

main endp
```

Its noticeable that the difference between the MSVC code and the GCC code is only in the way the arguments are stored on the stack. Here the GCC is working directly with the stack without the use of PUSH/POP.

**GCC and GDB**
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Let’s try this example also in GDB in Linux.

-g option instructs the compiler to include debug information in the executable file.

```
$ gcc 1.c -g -o 1
```

```
$ gdb 1
GNU gdb (GDB) 7.6.1-ubuntu
... Reading symbols from /home/dennis/polygon/1...done.
```

**Listing 1.44: let’s set breakpoint on printf()**

```
(gdb) b printf
Breakpoint 1 at 0x80482f0
```

Run. We don’t have the printf() function source code here, so GDB can’t show it, but may do so.

```
(gdb) run
Starting program: /home/dennis/polygon/1
Breakpoint 1,  __printf (format=0x80484f0 "a=%d; b=%d; c=%d") at printf.c:29
29 printf.c: No such file or directory.
```

Print 10 stack elements. The most left column contains addresses on the stack.

```
(gdb) x/10w $esp
0xbffff11c: 0x0804844a 0x080484f0 0x00000001 0x00000002
0xbffff12c: 0x00000003 0x08048460 0x00000000 0x00000000
0xbffff13c: 0xb7e29905
```

The very first element is the RA (0x0804844a). We can verify this by disassembling the memory at this address:

```
(gdb) x/5i 0x0804844a
0x804844a <main+45>: mov $0x0,%eax
0x804844f <main+50>: leave
0x8048450 <main+51>: ret
0x8048451: xchg %ax,%ax
0x8048453: xchg %ax,%ax
```

The two XCHG instructions are idle instructions, analogous to NOPs.

The second element (0x080484f0) is the format string address:

```
(gdb) x/s 0x80484f0
0x80484f0: "a=%d; b=%d; c=%d"
```

Next 3 elements (1, 2, 3) are the printf() arguments. The rest of the elements could be just “garbage” on the stack, but could also be values from other functions, their local variables, etc. We can ignore them for now.

Run “finish”. The command instructs GDB to “execute all instructions until the end of the function”. In this case: execute till the end of printf().

```
(gdb) finish
Run till exit from #0  __printf (format=0x80484f0 "a=%d; b=%d; c=%d") at printf.c:29
main () at 1.c:6
6 return 0;
Value returned is $2 = 13
```

GDB shows what printf() returned in EAX (13). This is the number of characters printed out, just like in the OllyDbg example.

We also see “return 0;” and the information that this expression is in the 1.c file at the line 6. Indeed, the 1.c file is located in the current directory, and GDB finds the string there. How does GDB know which C-code line is being currently executed? This is due to the fact that the compiler, while generating

---

<sup>68 GNU Debugger</sup>
1.8. *PRINTF() WITH SEVERAL ARGUMENTS*

depending information, also saves a table of relations between source code line numbers and instruction addresses. GDB is a source-level debugger, after all.

Let's examine the registers. 13 in EAX:

```plaintext
(gdb) info registers
eax 0xd 13
ecx 0x0 0
edx 0x0 0
ebx 0xb7fc0000 -1208221696
esp 0xbffff120 0xbffff120
ebp 0xbffff138 0xbffff138
esi 0x0 0
edi 0x0 0
eip 0x804844a 0x804844a <main+45>
```

Let's disassemble the current instructions. The arrow points to the instruction to be executed next.

```plaintext
(gdb) disas
Dump of assembler code for function main:
0x0804841d <+0>: push %ebp
0x0804841e <+1>: mov %esp,%ebp
0x08048420 <+3>: and $0xfffffffff0,%esp
0x08048423 <+6>: sub $0x10,%esp
0x08048426 <+9>: movl $0x3,0xc(%esp)
0x0804842e <+17>: movl $0x2,0x8(%esp)
0x08048436 <+25>: movl $0x1,0x4(%esp)
0x0804843e <+33>: movl $0x80484f0,(%esp)
0x08048445 <+40>: call 0x80482f0 <printf@plt>
=> 0x0804844a <+45>: mov $0x0,%eax
0x0804844f <+50>: leave
0x08048450 <+51>: ret
End of assembler dump.
```

GDB uses AT&T syntax by default. But it is possible to switch to Intel syntax:

```plaintext
(gdb) set disassembly-flavor intel
(gdb) disas
Dump of assembler code for function main:
0x0804841d <+0>: push ebp
0x0804841e <+1>: mov ebp,esp
0x08048420 <+3>: and esp,0xfffffffff0
0x08048423 <+6>: sub esp,0x10
0x08048426 <+9>: mov DWORD PTR [esp+0xc],0x3
0x0804842e <+17>: mov DWORD PTR [esp+0x8],0x2
0x08048436 <+25>: mov DWORD PTR [esp+0x4],0x1
0x0804843e <+33>: mov DWORD PTR [esp],0x80484f0
0x08048445 <+40>: call 0x80482f0 <printf@plt>
=> 0x0804844a <+45>: mov eax,0x0
0x0804844f <+50>: leave
0x08048450 <+51>: ret
End of assembler dump.
```

Execute next instruction. GDB shows ending bracket, meaning, it ends the block.

```plaintext
(gdb) step
7 );
```

Let’s examine the registers after the MOV EAX, 0 instruction execution. Indeed EAX is zero at that point.

```plaintext
(gdb) info registers
eax 0x0 0
ecx 0x0 0
edx 0x0 0
ebx 0xb7fc0000 -1208221696
esp 0xbffff120 0xbffff120
ebp 0xbffff138 0xbffff138
esi 0x0 0
edi 0x0 0
```
1.8. PRINTF() WITH SEVERAL ARGUMENTS

x64: 8 arguments

To see how other arguments are passed via the stack, let’s change our example again by increasing the number of arguments to 9 (printf() format string + 8 int variables):

```c
#include <stdio.h>

int main()
{
    printf("a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n", 1, 2, 3, 4, 5, 6, 7, 8);
    return 0;
}
```

**MSVC**

As it was mentioned earlier, the first 4 arguments has to be passed through the RCX, RDX, R8, R9 registers in Win64, while all the rest—via the stack. That is exactly what we see here. However, the MOV instruction, instead of PUSH, is used for preparing the stack, so the values are stored to the stack in a straightforward manner.

Listing 1.45: MSVC 2012 x64

```assembly
$SG2923 DB 'a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d', 0aH, 00H
main PROC
    sub    rsi, 88
    mov    DWORD PTR [rsi+64], 8
    mov    DWORD PTR [rsi+56], 7
    mov    DWORD PTR [rsi+48], 6
    mov    DWORD PTR [rsi+40], 5
    mov    DWORD PTR [rsi+32], 4
    mov    r9d, 3
    mov    r8d, 2
    mov     edx, 1
    lea    rcx, OFFSET FLAT:$SG2923
    call   printf
    ; return 0
    xor    eax, eax
    add    rsi, 88
    ret    0
main ENDP
_TEXT ENDS
END
```

The observant reader may ask why are 8 bytes allocated for int values, when 4 is enough? Yes, one has to recall: 8 bytes are allocated for any data type shorter than 64 bits. This is established for the convenience’s sake: it makes it easy to calculate the address of arbitrary argument. Besides, they are all located at aligned memory addresses. It is the same in the 32-bit environments: 4 bytes are reserved for all data types.

**GCC**

The picture is similar for x86-64 *NIX OS-es, except that the first 6 arguments are passed through the RDI, RSI, RDX, RCX, R8, R9 registers. All the rest—via the stack. GCC generates the code storing the string pointer into EDI instead of RDI—we noted that previously: 1.5.2 on page 15.

We also noted earlier that the EAX register has been cleared before a printf() call: 1.5.2 on page 15.
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Listing 1.46: Optimizing GCC 4.4.6 x64

.LC0:
    .string "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n"

main:
    sub    rsp, 40
    mov    r9d, 5
    mov    r8d, 4
    mov    ecx, 3
    mov    edx, 2
    mov    esi, 1
    mov    edi, OFFSET FLAT:.LC0
    xor    eax, eax ; number of vector registers passed
    mov    DWORD PTR [rsp+16], 8
    mov    DWORD PTR [rsp+8], 7
    mov    DWORD PTR [rsp], 6
    call   printf
          ; return 0
    xor    eax, eax
    add    rsp, 40
    ret

GCC + GDB

Let’s try this example in GDB.

$ gcc -g 2.c -o 2

$ gdb 2
GNU gdb (GDB) 7.6.1-ubuntu
... Reading symbols from /home/dennis/polygon/2...done.

Listing 1.47: let’s set the breakpoint to printf(), and run

(gdb) b printf
Breakpoint 1 at 0x400410
(gdb) run
Starting program: /home/dennis/polygon/2
Breakpoint 1, __printf (format=0x400628 "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n") at printf.c:29
29    printf.c: No such file or directory.

Registers RSI/RDX/RCX/R8/R9 have the expected values. RIP has the address of the very first instruction of the printf() function.

(gdb) info registers
rax  0x0  0
rbx  0x0  0
rcx  0x3  3
rdx  0x2  2
rsi  0x1  1
rdi  0x400628 4195880
rbp  0x7ffffffdf60 0x7ffffffdf60
rsp  0x7ffffffdf38 0x7ffffffdf38
r8   0x4  4
r9   0x5  5
r10  0x7fffffffde0 140737488346336
r11  0x7fffffff7a65f60 140737348263776
r12  0x400440 4195392
r13  0x7fffffffbe040 140737488347200
r14  0x0   0
r15  0x0   0
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Listing 1.48: let’s inspect the format string

(gdb) x/s $rdi
0x400628: "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n"

Let’s dump the stack with the x/g command this time—g stands for giant words, i.e., 64-bit words.

(gdb) x/10g $rsp
0x7fffffffdf38: 0x0000000000400576 0x0000000000000006
0x7fffffffdf48: 0x0000000000000007 0x00007fff00000008
0x7fffffffdf58: 0x0000000000000000 0x0000000000000000
0x7fffffffdf68: 0x00007ffff7a33de5 0x0000000000000000
0x7fffffffdf78: 0x00007fffffffef048 0x0000000000000000

The very first stack element, just like in the previous case, is the RA. 3 values are also passed through the stack: 6, 7, 8. We also see that 8 is passed with the high 32-bits not cleared: 0x00007fff00000008. That’s OK, because the values are of int type, which is 32-bit. So, the high register or stack element part may contain “random garbage”.

If you take a look at where the control will return after the printf() execution, GDB will show the entire main() function:

(gdb) set disassembly-flavor intel
(gdb) disas 0x0000000000400576
Dump of assembler code for function main:
 0x000000000040052d <+0>: push rbp
 0x000000000040052e <+1>: mov rbp,rsp
 0x0000000000400531 <+4>: sub rsp,0x20
 0x0000000000400535 <+8>: mov DWORD PTR [rsp+0x10],0x8
 0x000000000040053d <+16>: mov DWORD PTR [rsp+0x8],0x7
 0x0000000000400545 <+24>: mov DWORD PTR [rsp],0x6
 0x000000000040054c <+31>: mov r9d,0x5
 0x0000000000400552 <+37>: mov r8d,0x4
 0x0000000000400558 <+43>: mov ecx,0x3
 0x000000000040055d <+48>: mov edx,0x2
 0x0000000000400562 <+53>: mov esi,0x1
 0x0000000000400567 <+58>: mov edi,0x400628
 0x000000000040056c <+63>: mov eax,0x0
 0x0000000000400571 <+68>: call 0x400410 <printf@plt>
 0x0000000000400576 <+73>: mov eax,0x0
 0x000000000040057b <+78>: leave
 0x000000000040057c <+79>: ret
End of assembler dump.

Let’s finish executing printf(), execute the instruction zeroing EAX, and note that the EAX register has a value of exactly zero. RIP now points to the LEAVE instruction, i.e., the penultimate one in the main() function.

(gdb) finish
Run till exit from #0 printf (format=0x400628 "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n") at printf.c:29
a=1; b=2; c=3; d=4; e=5; f=6; g=7; h=8
main () at 2.c:6
6       return 0;
Value returned is $1 = 39
(gdb) next
7     }
(gdb) info registers
rax 0x0 0
rbx 0x0 0
rcx 0x26 38
rdx 0x7fffffffdf59f0 140737351866864
rsi 0x7fffffff9 2147483609
rdi 0x0 0
rbp 0x7fffffffdf6f0 0x7fffffffdf6f0
rsp 0x7fffffffdf40 0x7fffffffdf40
r8 0x7fffffffdf6a0 0x7fffffffdf6a0
1.8. PRINTF() WITH SEVERAL ARGUMENTS

r9 0x7fffffff7a60134 140737348239668
r10 0x7fffffff7a95900 140737348458752
r12 0x400440 4195392
r13 0x7fffffffe040 140737488347200
r14 0x0 0
r15 0x0 0
rip 0x40057b 0x40057b <main+78>

1.8.2 ARM

ARM: 3 arguments

ARM’s traditional scheme for passing arguments (calling convention) behaves as follows: the first 4 arguments are passed through the R0-R3 registers; the remaining arguments via the stack. This resembles the arguments passing scheme infastcall (6.1.3 on page 735) or win64 (6.1.5 on page 737).

32-bit ARM

Non-optimizing Keil 6/2013 (ARM mode)

Listing 1.49: Non-optimizing Keil 6/2013 (ARM mode)

```
.text:00000000 main
.text:00000000 10 40 2D E9 STMFD SP!, {R4,LR}
.text:00000004 03 30 A0 E3 MOV R3, #3
.text:00000008 02 20 A0 E3 MOV R2, #2
.text:0000000C 01 10 A0 E3 MOV R1, #1
.text:00000010 08 00 8F E2 ADR R0, aADBDCD ; "a=%d; b=%d; c=%d"
.text:00000014 06 00 00 EB BL __2printf
.text:00000018 00 00 A0 E3 MOV R0, #0 ; return 0
.text:0000001C 10 80 BD E8 LDMFD SP!, {R4,PC}
```

So, the first 4 arguments are passed via the R0-R3 registers in this order: a pointer to the printf() format string in R0, then 1 in R1, 2 in R2 and 3 in R3. The instruction at 0x18 writes 0 to R0—this is return 0 C-statement. There is nothing unusual so far.

Optimizing Keil 6/2013 generates the same code.

Optimizing Keil 6/2013 (Thumb mode)

Listing 1.50: Optimizing Keil 6/2013 (Thumb mode)

```
.text:00000000 main
.text:00000000 10 B5 PUSH {R4,LR}
.text:00000002 03 23 MOVS R3, #3
.text:00000004 02 22 MOVS R2, #2
.text:00000006 01 21 MOVS R1, #1
.text:00000008 02 A0 ADR R0, aADBDCD ; "a=%d; b=%d; c=%d"
.text:0000000A 00 F0 0D F8 BL __2printf
.text:0000000E 00 20 MOVS R0, #0
.text:00000010 10 BD POP {R4,PC}
```

There is no significant difference from the non-optimized code for ARM mode.
Let’s rework example slightly by removing `return 0`:

```c
#include <stdio.h>
void main()
{
    printf("a=%d; b=%d; c=%d", 1, 2, 3);
}
```

The result is somewhat unusual:

Listing 1.51: Optimizing Keil 6/2013 (ARM mode)

```
.text:00000014 main
.text:00000014 03 30 A0 E3 MOV R3, #3
.text:00000018 02 20 A0 E3 MOV R2, #2
.text:0000001C 01 10 A0 E3 MOV R1, #1
.text:00000020 1E 0E 8F E2 ADR R0, aADBDCD ; "a=%d; b=%d; c=%d\n"
.text:00000024 CB 18 00 EA B __2printf
```

This is the optimized (-O3) version for ARM mode and this time we see B as the last instruction instead of the familiar BL. Another difference between this optimized version and the previous one (compiled without optimization) is the lack of function prologue and epilogue (instructions preserving the R0 and LR registers values). The B instruction just jumps to another address, without any manipulation of the LR register, similar to JMP in x86. Why does it work? Because this code is, in fact, effectively equivalent to the previous. There are two main reasons: 1) neither the stack nor SP (the stack pointer) is modified; 2) the call to printf() is the last instruction, so there is nothing going on afterwards. On completion, the printf() function simply returns the control to the address stored in LR. Since the LR currently stores the address of the point from where our function has been called then the control from printf() will be returned to that point. Therefore we do not have to save LR because we do not have necessity to modify LR. And we do not have necessity to modify LR because there are no other function calls except printf(). Furthermore, after this call we do not to do anything else! That is the reason such optimization is possible.

This optimization is often used in functions where the last statement is a call to another function. A similar example is presented here: 1.15.1 on page 154.

**ARM64**

**Non-optimizing GCC (Linaro) 4.9**

Listing 1.52: Non-optimizing GCC (Linaro) 4.9

```
.LC1:
    .string "a=%d; b=%d; c=%d"
f2:
; save FP and LR in stack frame:
    stp    x29, x30, [sp, -16]!
; set stack frame (FP=SP):
    add    x29, sp, 0
    adrp   x0, .LC1
    add    x0, x0, :lo12:.LC1
    mov    w1, 1
    mov    w2, 2
    mov    w3, 3
    bl     printf
    mov    w0, 0
; restore FP and LR
    ldp    x29, x30, [sp], 16
    ret
```

The first instruction STP (Store Pair) saves FP (X29) and LR (X30) in the stack. The second ADD X29, SP, 0 instruction forms the stack frame. It is just writing the value of SP into X29.
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Next, we see the familiar ADRP/ADD instruction pair, which forms a pointer to the string. lo12 meaning low 12 bits, i.e., linker will write low 12 bits of LC1 address into the opcode of ADD instruction. %d in printf() string format is a 32-bit int, so the 1, 2 and 3 are loaded into 32-bit register parts.

Optimizing GCC (Linaro) 4.9 generates the same code.

ARM: 8 arguments

Let's use again the example with 9 arguments from the previous section: 1.8.1 on page 50.

```
#include <stdio.h>

int main()
{
    printf("a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d\n", 1, 2, 3, 4, 5, 6, 7, 8);
    return 0;
}
```

Optimizing Keil 6/2013: ARM mode

This code can be divided into several parts:

- Function prologue:
  The very first STR LR, [SP,#var_4]! instruction saves LR on the stack, because we are going to use this register for the printf() call. Exclamation mark at the end indicates pre-index. This implies that SP is to be decreased by 4 first, and then LR will be saved at the address stored in SP. This is similar to PUSH in x86. Read more about it at: 1.32.2 on page 439.

  The second SUB SP, #0x18 instruction decreases SP (the stack pointer) in order to allocate 0x14 (20) bytes on the stack. Indeed, we have to pass 5 32-bit values via the stack to the printf() function, and each one occupies 4 bytes, which is exactly 5 * 4 = 20. The other 4 32-bit values are to be passed through registers.

- Passing 5, 6, 7 and 8 via the stack: they are stored in the R0, R1, R2 and R3 registers respectively. Then, the ADD R12, SP, #0x18+var_14 instruction writes the stack address where these 4 variables are to be stored, into the R12 register. var_14 is an assembly macro, equal to -0x14, created by IDA to conveniently display the code accessing the stack. The var_? macros generated by IDA reflect local variables in the stack.
1.8. PRINTF() WITH SEVERAL ARGUMENTS

So, SP+4 is to be stored into the R12 register. The next STMIA R12, R0-R3 instruction writes registers R0-R3 contents to the memory pointed by R12. STMIA abbreviates Store Multiple Increment After. “Increment After” implies that R12 is to be increased by 4 after each register value is written.

- Passing 4 via the stack: 4 is stored in R0 and then this value, with the help of the STR R0, [SP,#0x18+var_18] instruction is saved on the stack. var_18 is -0x18, so the offset is to be 0, thus the value from the R0 register (4) is to be written to the address written in SP.

- Passing 1, 2 and 3 via registers: The values of the first 3 numbers (a, b, c) (1, 2, 3 respectively) are passed through the R1, R2 and R3 registers right before the printf() call, and the other 5 values are passed via the stack:
- printf() call.
- Function epilogue:
The ADD SP, SP, #0x14 instruction restores the SP pointer back to its former value, thus annulling everything what has been stored on the stack. Of course, what has been stored on the stack will stay there, but it will all be rewritten during the execution of subsequent functions.

The LDR PC, [SP+4+var_4],#4 instruction loads the saved LR value from the stack into the PC register, thus causing the function to exit. There is no exclamation mark—indeed, PC is loaded first from the address stored in SP (4+var_4 = 4+(-4) = 0, so this instruction is analogous to LDR PC, [SP],#4), and then SP is increased by 4. This is referred as post-index. Why does IDA display the instruction like that? Because it wants to illustrate the stack layout and the fact that var_4 is allocated for saving the LR value in the local stack. This instruction is somewhat similar to POP PC in x86.

Optimizing Keil 6/2013: Thumb mode

```
.printf_main2

var_18 = -0x18
var_14 = -0x14
var_8  = -8

00 B5 PUSH {LR}
08 23 MOVS R3, #8
85 B0 SUB SP, SP, #0x14
04 93 STR R3, [SP,#0x18+var_8]
07 C3 STMIA R3!, {R0-R2}
00 90 STR R0, [SP,#0x18+var_14]
07 C3 STMIA R3!, {R0-R2}
01 21 MOVS R1, #1
```

The output is almost like in the previous example. However, this is Thumb code and the values are packed into stack differently: 8 goes first, then 5, 6, 7, and 4 goes third.

Optimizing Xcode 4.6.3 (LLVM): ARM mode

69Read more about it: 1.32.2 on page 439.
70It is impossible to set IP/EIP/RIP value using POP in x86, but anyway, you got the analogy right.
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Almost the same as what we have already seen, with the exception of STMFA (Store Multiple Full Ascending) instruction, which is a synonym of STMIB (Store Multiple Increment Before) instruction. This instruction increases the value in the SP register and only then writes the next register value into the memory, rather than performing those two actions in the opposite order.

Another thing that catches the eye is that the instructions are arranged seemingly random. For example, the value in the R0 register is manipulated in three places, at addresses 0x2918, 0x2920 and 0x2928, when it would be possible to do it in one point.

However, the optimizing compiler may have its own reasons on how to order the instructions so to achieve higher efficiency during the execution.

Usually, the processor attempts to simultaneously execute instructions located side-by-side. For example, instructions like MOVT R0, #0 and ADD R0, PC, R0 cannot be executed simultaneously since they both modify the R0 register. On the other hand, MOVT R0, #0 and MOV R2, #4 instructions can be executed simultaneously since the effects of their execution are not conflicting with each other. Presumably, the compiler tries to generate code in such a manner (wherever it is possible).

Optimizing Xcode 4.6.3 (LLVM): Thumb-2 mode
1.8. PRINTF() WITH SEVERAL ARGUMENTS

The output is almost the same as in the previous example, with the exception that Thumb-instructions are used instead.

ARM64

Non-optimizing GCC (Linaro) 4.9

Listing 1.53: Non-optimizing GCC (Linaro) 4.9

The first 8 arguments are passed in X- or W-registers: [Procedure Call Standard for the ARM 64-bit Architecture (AArch64), (2013)]\(^{71}\). A string pointer requires a 64-bit register, so it’s passed in X0. All other values have an int 32-bit type, so they are stored in the 32-bit part of the registers (W-). The 9th argument (8) is passed via the stack. Indeed: it’s not possible to pass large number of arguments through registers, because the number of registers is limited.

Optimizing GCC (Linaro) 4.9 generates the same code.

1.8.3 MIPS

3 arguments

Optimizing GCC 4.4.5

The main difference with the “Hello, world!” example is that in this case printf() is called instead of puts() and 3 more arguments are passed through the registers $5…$7 (or $A0…$A2). That is why these registers are prefixed with A-, which implies they are used for function arguments passing.

\(^{71}\)Also available as http://go.yurichev.com/17287
Listing 1.54: Optimizing GCC 4.4.5 (assembly output)

```assembly
$LC0:  .ascii "a=%d; b=%d; c=%d\000"
main:
    ; function prologue:
    lui $28,%hi(__gnu_local_gp)
    addiu $sp,$sp,-32
    addiu $28,$28,%lo(__gnu_local_gp)
    sw $31,28($sp)
    ; load address of printf():
    lw $25,%call16(printf)($28)
    ; load address of the text string and set 1st argument of printf():
    lui $4,%hi($LC0)
    addiu $4,$4,%lo($LC0)
    ; set 2nd argument of printf():
    li $5,1 # 0x1
    ; set 3rd argument of printf():
    li $6,2 # 0x2
    ; call printf():
    jalr $25
    ; set 4th argument of printf() (branch delay slot):
    li $7,3 # 0x3
    ; function epilogue:
    lw $31,28($sp)
    ; set return value to 0:
    move $2,$0
    ; return
    j $31
    addiu $sp,$sp,32 ; branch delay slot
```

Listing 1.55: Optimizing GCC 4.4.5 (IDA)

```assembly
.main:
    .var 10 = -0x10
    .var 4 = -4

    ; function prologue:
    lui $gp, (__gnu_local_gp >> 16)
    addiu $sp, -0x20
    la $gp, (__gnu_local_gp & 0xFFFF)
    sw $ra, 0x20+var_4($sp)
    sw $gp, 0x20+var_10($sp)
    ; load address of printf():
    lw $t9, (printf & 0xFFFF)($gp)
    ; load address of the text string and set 1st argument of printf():
    la $a0, $LC0 # "a=%d; b=%d; c=%d"
    ; set 2nd argument of printf():
    li $a1, 1
    ; set 3rd argument of printf():
    li $a2, 2
    ; call printf():
    jalr $t9
    ; set 4th argument of printf() (branch delay slot):
    li $a3, 3
    ; function epilogue:
    lw $ra, 0x20+var_4($sp)
    ; set return value to 0:
    move $v0, $zero
    ; return
    jr $ra
    addiu $sp, 0x20 ; branch delay slot
```

IDA has coalesced pair of LUI and ADDIU instructions into one LA pseudo instruction. That's why there are no instruction at address 0x1C: because LA occupies 8 bytes.
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Non-optimizing GCC 4.4.5

Non-optimizing GCC is more verbose:

Listing 1.56: Non-optimizing GCC 4.4.5 (assembly output)

```
$LCO:
  .ascii "a=%d; b=%d; c=%d\000"
main:
  ; function prologue:
  addiu $sp,$sp,-32
  sw $31,28($sp)
  sw $fp,24($sp)
  move $fp,$sp
  lui $28,%hi(__gnu_local_gp)
  addiu $28,$28,%lo(__gnu_local_gp)
  ; load address of the text string:
  lui $2,%hi($LCO)
  addiu $2,$2,%lo($LCO)
  ; set 1st argument of printf():
  move $4,$2
  ; set 2nd argument of printf():
  li $5,1 # 0x1
  ; set 3rd argument of printf():
  li $6,2 # 0x2
  ; set 4th argument of printf():
  li $7,3 # 0x3
  ; get address of printf():
  lw $2,%call16(printf)($28)
  nop
  ; call printf():
  move $25,$2
  jalr $25
  nop

  ; function epilogue:
  lw $28,16($fp)
  ; set return value to 0:
  move $2,$0
  move $sp,$fp
  lw $31,28($sp)
  lw $fp,24($sp)
  addiu $sp,$sp,32
  ; return
  j $31
  nop
```

Listing 1.57: Non-optimizing GCC 4.4.5 (IDA)

```
.text:00000000 main:
.text:00000000
.text:00000000 var_10 = -0x10
.text:00000000 var_8 = -8
.text:00000000 var_4 = -4
.text:00000000
  ; function prologue:
  .text:00000000  addiu $sp, -0x20
  .text:00000004  sw $ra, 0x20+var_4($sp)
  .text:00000008  sw $fp, 0x20+var_8($sp)
  .text:0000000C  move $fp, $sp
  .text:00000010  la $gp, __gnu_local_gp
  .text:00000018  sw $gp, 0x20+var_10($sp)
  ; load address of the text string:
  .text:0000001C  la $v0, aADBDCD     # "a=%d; b=%d; c=%d"
  ; set 1st argument of printf():
  .text:00000024  move $a0, $v0
  ; set 2nd argument of printf():
  .text:00000028  li $a1, 1
  ; set 3rd argument of printf():
  .text:0000002C  li $a2, 2
```
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Let's use again the example with 9 arguments from the previous section: 1.8.1 on page 50.

```
#include <stdio.h>

int main()
{
    printf("a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n", 1, 2, 3, 4, 5, 6, 7, 8);
    return 0;
}
```

Optimizing GCC 4.4.5

Only the first 4 arguments are passed in the $A0 ...$A3 registers, the rest are passed via the stack.

This is the O32 calling convention (which is the most common one in the MIPS world). Other calling conventions (like N32) may use the registers for different purposes.

SW abbreviates “Store Word” (from register to memory). MIPS lacks instructions for storing a value into memory, so an instruction pair has to be used instead (LI/SW).

Listing 1.58: Optimizing GCC 4.4.5 (assembly output)

```
$LC0:
    .ascii "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n", 1, 2, 3, 4, 5, 6, 7, 8"
main:
    ; function prologue:
    lui     $28,%hi(__gnu_local_gp)
    addiu   $sp,$sp,-56
    addiu   $28,$28,%lo(__gnu_local_gp)
    sw      $31,52($sp)
    ; pass 5th argument in stack:
    li      $2,4       # 0x4
    sw      $2,16($sp)
    ; pass 6th argument in stack:
    li      $2,5       # 0x5
    sw      $2,20($sp)
    ; pass 7th argument in stack:
    li      $2,6       # 0x6
    sw      $2,24($sp)
    ; pass 8th argument in stack:
    li      $2,7       # 0x7
    lw      $25,%call16(printf)($28)
    sw      $2,28($sp)
```

8 arguments

Let's use again the example with 9 arguments from the previous section: 1.8.1 on page 50.
### 1.8. `PRINTF() WITH SEVERAL ARGUMENTS`

```c
; pass 1st argument in $a0:
lui $4, %hi($LC0)
; pass 9th argument in stack:
  li $2, 8 # 0x8
  sw $2, 32($sp)
  addiu $4, $4, %lo($LC0)
; pass 2nd argument in $a1:
  li $5, 1 # 0x1
; pass 3rd argument in $a2:
  li $6, 2 # 0x2
; call printf():
  jalr $25
; pass 4th argument in $a3 (branch delay slot):
  li $7, 3 # 0x3
; function epilogue:
  lw $31, 52($sp)
; set return value to 0:
  move $2, $0
; return
  j $31
  addiu $sp, $sp, 56 ; branch delay slot
```

Listing 1.59: Optimizing GCC 4.4.5 (IDA)
1.8. PRINTF() WITH SEVERAL ARGUMENTS

Non-optimizing GCC 4.4.5

Non-optimizing GCC is more verbose:

Listing 1.60: Non-optimizing GCC 4.4.5 (assembly output)

$LC0: .ascii "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\012\000"

main:
    ; function prologue:
    addiu $sp,$sp,-56
    sw $31,52($sp)
    sw $fp,48($sp)
    move $fp,$sp
    lui $28,%hi(__gnu_local_gp)
    addiu $28,$28,%lo(__gnu_local_gp)
    lui $2,%hi($LC0)
    addiu $2,$2,%lo($LC0)
    ; pass 5th argument in stack:
    li $3,4 # 0x4
    sw $3,16($sp)
    ; pass 6th argument in stack:
    li $3,5 # 0x5
    sw $3,20($sp)
    ; pass 7th argument in stack:
    li $3,6 # 0x6
    sw $3,24($sp)
    ; pass 8th argument in stack:
    li $3,7 # 0x7
    sw $3,28($sp)
    ; pass 9th argument in stack:
    li $3,8 # 0x8
    sw $3,32($sp)
    ; pass 1st argument in $a0:
    move $4,$2
    ; pass 2nd argument in $a1:
    li $5,1 # 0x1
    ; pass 3rd argument in $a2:
    li $6,2 # 0x2
    ; pass 4th argument in $a3:
    li $7,3 # 0x3
    ; call printf():
    lw $2,%call16(printf)($28)
    nop
    move $25,$2
    jalr $25
    nop
    ; function epilogue:
    lw $28,40($fp)
    ; set return value to 0:
    move $2,$s0
    move $sp,$fp
    lw $31,52($sp)
    lw $fp,48($sp)
    addiu $sp,$sp,56
    ; return
    j $31
    nop
1.8. PRINTF() WITH SEVERAL ARGUMENTS

1.8.4 Conclusion

Here is a rough skeleton of the function call:

Listing 1.62: x86

```
.text:00000000 main:
.text:00000000 var_28 = -0x28
.text:00000000 var_24 = -0x24
.text:00000000 var_20 = -0x20
.text:00000000 var_1C = -0x1C
.text:00000000 var_18 = -0x18
.text:00000000 var_10 = -0x10
.text:00000000 var_8 = -8
.text:00000000 var_4 = -4
.text:00000000 ; function prologue:
.text:00000000 addiu $sp, -0x38
.text:00000004 sw $ra, 0x38+var_4($sp)
.text:00000008 sw $fp, 0x38+var_8($sp)
.text:0000000C move $fp, $sp
.text:00000010 la $gp, __gnu_local_gp
.text:00000018 sw $gp, 0x38+var_10($sp)
.text:0000001C la $v0, aADBDCDDDEDFDGD # "a=%d; b=%d; c=%d; d=%d; e=%d; f/
⤦
⤦/rcurvearrowse
.text:00000024 li $v1, 4
.text:00000028 sw $v1, 0x38+var_28($sp)
.text:0000002C li $v1, 5
.text:00000030 sw $v1, 0x38+var_24($sp)
.text:00000034 li $v1, 6
.text:00000038 sw $v1, 0x38+var_20($sp)
.text:0000003C li $v1, 7
.text:00000040 sw $v1, 0x38+var_1C($sp)
.text:00000044 li $v1, 8
.text:00000048 sw $v1, 0x38+var_18($sp)
; pass 1st argument in $a0:
.text:0000004C move $a0, $v0
; pass 2nd argument in $a1:
.text:00000050 li $a1, 1
; pass 3rd argument in $a2:
.text:00000054 li $a2, 2
; pass 4th argument in $a3:
.text:00000058 li $a3, 3
; call printf():
.text:0000005C lw $v0, (printf & 0xFFFF)($gp)
.text:00000060 or $at, $zero
.text:00000064 move $t9, $v0
.text:00000068 jalr $t9
.text:0000006C or $at, $zero ; NOP
; function epilogue:
.text:00000070 lw $gp, 0x38+var_10($fp)
; set return value to 0:
.text:00000074 move $v0, $zero
.text:00000078 move $sp, $fp
.text:0000007C lw $ra, 0x38+var_4($sp)
.text:00000080 lw $fp, 0x38+var_8($sp)
.text:00000084 addiu $sp, 0x38
; return
.text:00000088 jr $ra
.text:0000008C or $at, $zero ; NOP
```
1.8. PRINTF() WITH SEVERAL ARGUMENTS

...  
PUSH 3rd argument  
PUSH 2nd argument  
PUSH 1st argument  
CALL function  
; modify stack pointer (if needed)

Listing 1.63: x64 (MSVC)

MOV RCX, 1st argument  
MOV RDX, 2nd argument  
MOV R8, 3rd argument  
MOV R9, 4th argument  
...

PUSH 5th, 6th argument, etc. (if needed)  
CALL function  
; modify stack pointer (if needed)

Listing 1.64: x64 (GCC)

MOV RDI, 1st argument  
MOV RSI, 2nd argument  
MOV RDX, 3rd argument  
MOV RCX, 4th argument  
MOV R8, 5th argument  
MOV R9, 6th argument  
...

PUSH 7th, 8th argument, etc. (if needed)  
CALL function  
; modify stack pointer (if needed)

Listing 1.65: ARM

MOV R0, 1st argument  
MOV R1, 2nd argument  
MOV R2, 3rd argument  
MOV R3, 4th argument  

; pass 5th, 6th argument, etc., in stack (if needed)  
BL function  
; modify stack pointer (if needed)

Listing 1.66: ARM64

MOV X0, 1st argument  
MOV X1, 2nd argument  
MOV X2, 3rd argument  
MOV X3, 4th argument  
MOV X4, 5th argument  
MOV X5, 6th argument  
MOV X6, 7th argument  
MOV X7, 8th argument  

; pass 9th, 10th argument, etc., in stack (if needed)  
BL function  
; modify stack pointer (if needed)

Listing 1.67: MIPS (O32 calling convention)

LI $4, 1st argument ; AKA $A0  
LI $5, 2nd argument ; AKA $A1  
LI $6, 3rd argument ; AKA $A2  
LI $7, 4th argument ; AKA $A3  

; pass 5th, 6th argument, etc., in stack (if needed)  
LW temp_reg, address of function  
JALR temp_reg

1.8.5 By the way

By the way, this difference between the arguments passing in x86, x64, fastcall, ARM and MIPS is a good illustration of the fact that the CPU is oblivious to how the arguments are passed to functions. It is also
1.9. **SCANF()**

It is possible to create a hypothetical compiler able to pass arguments via a special structure without using stack at all.

MIPS $A0 ...$A3 registers are labeled this way only for convenience (that is in the O32 calling convention). Programmers may use any other register (well, maybe except $ZERO) to pass data or use any other calling convention.

The CPU is not aware of calling conventions whatsoever.

We may also recall how new coming assembly language programmers passing arguments into other functions: usually via registers, without any explicit order, or even via global variables. Of course, it works fine.

### 1.9 scanf()

Now let’s use scanf().

#### 1.9.1 Simple example

```c
#include <stdio.h>

int main()
{
    int x;
    printf (“Enter X:\n”);
    scanf (”%d”, &x);
    printf (“You entered %d...\n”, x);
    return 0;
}
```

It’s not clever to use scanf() for user interactions nowadays. But we can, however, illustrate passing a pointer to a variable of type `int`.

### About pointers

Pointers are one of the fundamental concepts in computer science. Often, passing a large array, structure or object as an argument to another function is too expensive, while passing their address is much cheaper. For example, if you going to print a text string to console, it’s much easier to pass its address into OS kernel.

In addition if the callee function needs to modify something in the large array or structure received as a parameter and return back the entire structure then the situation is close to absurd. So the simplest thing to do is to pass the address of the array or structure to the callee function, and let it change what needs to be changed.

A pointer in C/C++—is simply an address of some memory location.

In x86, the address is represented as a 32-bit number (i.e., it occupies 4 bytes), while in x86-64 it is a 64-bit number (occupying 8 bytes). By the way, that is the reason behind some people’s indignation related to switching to x86-64—all pointers in the x64-architecture require twice as much space, including cache memory, which is “expensive” memory.

It is possible to work with untyped pointers only, given some effort; e.g. the standard C function `memcpy()` , that copies a block from one memory location to another, takes 2 pointers of type `void*` as arguments, since it is impossible to predict the type of the data you would like to copy. Data types are not important, only the block size matters.

Pointers are also widely used when a function needs to return more than one value (we are going to get back to this later (3.21 on page 611)).

**scanf()** function—is such a case.
1.9. **SCANF()**

Besides the fact that the function needs to indicate how many values were successfully read, it also needs to return all these values.

In C/C++ the pointer type is only needed for compile-time type checking.

Internally, in the compiled code there is no information about pointer types at all.

### **x86**

### **MSVC**

Here is what we get after compiling with MSVC 2010:

```assembly
CONST SEGMENT
$SG3831 DB 'Enter X:', 0aH, 00H
$SG3832 DB '%d', 00H
$SG3833 DB 'You entered %d...', 0aH, 00H
CONST ENDS
PUBLIC _main
EXTRN _scanf:PROC
EXTRN _printf:PROC

; Function compile flags: /Odtp
_TEXT SEGMENT
_x$ = -4 ; size = 4
_main PROC
    push ebp
    mov ebp, esp
    push ecx
    push OFFSET $SG3831 ; 'Enter X:'
    call _printf
    add esp, 4
    lea eax, DWORD PTR _x$[ebp]
    push eax
    push OFFSET $SG3832 ; '%d'
    call _scanf
    add esp, 8
    mov ecx, DWORD PTR _x$[ebp]
    push ecx
    push OFFSET $SG3833 ; 'You entered %d...
    call _printf
    add esp, 8
    ; return 0
    xor eax, eax
    mov esp, ebp
    pop ebp
    ret 0
_main ENDP
_TEXT ENDS
```

x is a local variable.

According to the C/C++ standard it must be visible only in this function and not from any other external scope. Traditionally, local variables are stored on the stack. There are probably other ways to allocate them, but in x86 that is the way it is.

The goal of the instruction following the function prologue, `PUSH ECX`, is not to save the ECX state (notice the absence of corresponding `POP ECX` at the function’s end).

In fact it allocates 4 bytes on the stack for storing the x variable.

x is to be accessed with the assistance of the _x$ macro (it equals to -4) and the EBP register pointing to the current frame.

Over the span of the function’s execution, EBP is pointing to the current stack frame making it possible to access local variables and function arguments via EBP+offset.

It is also possible to use ESP for the same purpose, although that is not very convenient since it changes frequently. The value of the EBP could be perceived as a frozen state of the value in ESP at the start of the function’s execution.
1.9. **SCANF()**

Here is a typical stack frame layout in 32-bit environment:

```
...  ...
EBP-8  local variable #2, marked in IDA as var_8
EBP-4  local variable #1, marked in IDA as var_4
EBP    saved value of EBP
EBP+4  return address
EBP+8  argument#1, marked in IDA as arg_0
EBP+0xC argument#2, marked in IDA as arg_4
EBP+0x10 argument#3, marked in IDA as arg_8
...  ...
```

The `scanf()` function in our example has two arguments.

The first one is a pointer to the string containing `%d` and the second is the address of the `x` variable.

First, the `x` variable’s address is loaded into the EAX register by the `lea eax, DWORD PTR _x$[ebp]` instruction.

LEA stands for *load effective address*, and is often used for forming an address (.1.6 on page 1028).

We could say that in this case LEA simply stores the sum of the EBP register value and the _x$ macro in the EAX register.

This is the same as `lea eax, [ebp-4].`

So, 4 is being subtracted from the EBP register value and the result is loaded in the EAX register. Next the EAX register value is pushed into the stack and `scanf()` is being called.

`printf()` is being called after that with its first argument — a pointer to the string: *You entered %d...\n*.

The second argument is prepared with: `mov ecx, [ebp-4]`. The instruction stores the `x` variable value and not its address, in the ECX register.

Next the value in the ECX is stored on the stack and the last `printf()` is being called.
1.9. **SCANF()**

**MSVC + OllyDbg**

Let's try this example in OllyDbg. Let's load it and keep pressing F8 (step over) until we reach our executable file instead of ntdll.dll. Scroll up until `main()` appears.

Click on the first instruction (PUSH EBP), press F2 (set a breakpoint), then F9 (Run). The breakpoint will be triggered when `main()` begins.

Let's trace to the point where the address of the variable `x` is calculated:

![Image of OllyDbg interface showing the address of the local variable being calculated]

**Figure 1.12: OllyDbg: The address of the local variable is calculated**

Right-click the EAX in the registers window and then select “Follow in stack”.

This address will appear in the stack window. The red arrow has been added, pointing to the variable in the local stack. At that moment this location contains some garbage (0x6E494714). Now with the help of PUSH instruction the address of this stack element is going to be stored to the same stack on the next position. Let's trace with F8 until the `scanf()` execution completes. During the `scanf()` execution, we input, for example, 123, in the console window:

```
Enter X: 123
```
1.9. SCANF()

scanf() completed its execution already:

![OllyDbg: scanf() executed](image)

Figure 1.13: OllyDbg: scanf() executed

scanf() returns 1 in EAX, which implies that it has read successfully one value. If we look again at the stack element corresponding to the local variable it now contains 0x7B (123).
Later this value is copied from the stack to the ECX register and passed to printf().

GCC

Let’s try to compile this code in GCC 4.4.1 under Linux:

```
main proc near
var_20 = dword ptr -20h
var_1C = dword ptr -1Ch
var_4 = dword ptr -4
push ebp
mov ebp, esp
and esp, 0FFFFFFF0h
sub esp, 20h
mov [esp+20h+var_20], offset aEnterX ; "Enter X:"
call _puts
mov eax, offset aD ; "%d"
lea edx, [esp+20h+var_4]
mov [esp+20h+var_1C], edx
mov [esp+20h+var_20], eax
call ___isoc99_scanf
mov edx, [esp+20h+var_4]
mov eax, offset aYouEnteredD___ ; "You entered %d...
"
call _printf
mov eax, 0
leave
retn

main endp
```

GCC replaced the printf() call with call to puts(). The reason for this was explained in (1.5.4 on page 21).

As in the MSVC example—the arguments are placed on the stack using the MOV instruction.

By the way
1.9. **SCANF()**

This simple example is a demonstration of the fact that compiler translates list of expressions in C/C++-block into sequential list of instructions. There are nothing between expressions in C/C++, and so in resulting machine code, there are nothing between, control flow slips from one expression to the next one.

**x64**

The picture here is similar with the difference that the registers, rather than the stack, are used for arguments passing.

**MSVC**

Listing 1.68: MSVC 2012 x64

```assembly
_DATA SEGMENT
$SG1289 DB 'Enter X:', 0aH, 00H
$SG1291 DB '%d', 00H
$SG1292 DB 'You entered %d...', 0aH, 00H
_DATA ENDS

_TEXT SEGMENT
x$ = 32
main PROC
  $LN3:
  sub    rsp, 56
  lea    rcx, OFFSET FLAT:$SG1289 ; 'Enter X:'
  call   printf
  lea    rdx, QWORD PTR x$[rsp]
  lea    rcx, OFFSET FLAT:$SG1291 ; '%d'
  call   scanf
  mov    edx, DWORD PTR x$[rsp]
  lea    rcx, OFFSET FLAT:$SG1292 ; 'You entered %d...' 
  call   printf
  ; return 0
  xor    eax, eax
  add    rsp, 56
  ret    0
main ENDP
_TEXT ENDS
```

**GCC**

Listing 1.69: Optimizing GCC 4.4.6 x64

```assembly
.LC0: 
.string "Enter X:"
.LC1: 
.string "%d"
.LC2: 
.string "You entered %d...
"
main:
  sub    rsp, 24
  mov    edi, OFFSET FLAT:.LC0 ; "Enter X:"
  call   puts
  lea    rsi, [rsp+12]
  mov    edi, OFFSET FLAT:.LC1 ; "%d"
  xor    eax, eax
  call   __isoc99_scanf
  mov    esi, DWORD PTR [rsp+12]
  mov    edi, OFFSET FLAT:.LC2 ; "You entered %d...
"
  xor    eax, eax
  call   printf
```
In order for `scanf()` to be able to read item it needs a parameter—pointer to an `int`. `int` is 32-bit, so we need 4 bytes to store it somewhere in memory, and it fits exactly in a 32-bit register. A place for the local variable `x` is allocated in the stack and **IDA** has named it `var_8`. It is not necessary, however, to allocate a such since `SP` (stack pointer) is already pointing to that space and it can be used directly.

So, `SP`'s value is copied to the `R1` register and, together with the format-string, passed to `scanf()`. Later, with the help of the `LDR` instruction, this value is moved from the stack to the `R1` register in order to be passed to `printf()`.

**ARM64**

Listing 1.70: Non-optimizing GCC 4.9.1 ARM64

```assembly
.LC0: .string "Enter X:"
.LC1: .string "%d"
.LC2: .string "You entered %d...\n"
scanf_main:
    ; subtract 32 from SP, then save FP and LR in stack frame:
    stp x29, x30, [sp, -32]!
    ; set stack frame (FP=SP)
    add x29, sp, 0
    ; load pointer to the "Enter X:" string:
    adrp x0, .LC0
    ; add x0, x0, :lo12:.LC0
    ; X0=pointer to the "Enter X:" string
    ; print it:
    bl puts
    ; load pointer to the "%d" string:
    adrp x0, .LC1
    ; add x0, x0, :lo12:.LC1
    ; find a space in stack frame for "x" variable (X1=FP+28):
    add x1, x29, 28
    ; X1=address of "x" variable
    ; pass the address to scanf() and call it:
    bl __isoc99_scanf
    ; load 32-bit value from the variable in stack frame:
```

1.9. `SCANF()`

```assembly
; return 0
xor eax, eax
add rsp, 24
ret
```
1.9. **SCANF**

```assembly
    ldr   w1, [x29,28]  ; load pointer to the "You entered %d...\n" string
    ; printf() will take text string from X0 and "x" variable from X1 (or W1)
    adrp  x0, .LC2
    add   x0, x0, :lo12:.LC2
    bl    printf
    ; return 0
    mov   w0, 0
    ; restore FP and LR, then add 32 to SP:
    ldp   x29, x30, [sp], 32
    ret
```

There is 32 bytes are allocated for stack frame, which is bigger than it needed. Perhaps some memory aligning issue? The most interesting part is finding space for the \textit{x} variable in the stack frame (line 22). Why 28? Somehow, compiler decided to place this variable at the end of stack frame instead of beginning. The address is passed to scanf(), which just stores the user input value in the memory at that address. This is 32-bit value of type \textit{int}. The value is fetched at line 27 and then passed to printf().

**MIPS**

A place in the local stack is allocated for the \textit{x} variable, and it is to be referred as $sp + 24$. Its address is passed to scanf(), and the user input values is loaded using the \textit{LW} ("Load Word") instruction and then passed to printf().

```assembly
$LCO$: .ascii "Enter X:\000"
$LCl$: .ascii "%d\000"
$LC2$: .ascii "You entered %d...\012\000"
main:  ; function prologue:
    lui   $28,%hi(__gnu_local_gp)
    addiu $sp,$sp,-40
    addiu $28,$28,%lo(__gnu_local_gp)
    sw    $31,36($sp)
    ; call puts():
    lw    $25,%call16(puts)($28)
    lui   $4,%hi($LCO)
    jalr  $25
    addiu $4,$4,%lo($LC0) ; branch delay slot
    ; call scanf():
    lw    $28,16($sp)
    lui   $4,%hi($LC1)
    lw    $25,%call16(__isoc99_scanf)($28)
    ; set 2nd argument of scanf(), $a1=$sp+24:
    addiu $5,$sp,24
    jalr  $25
    addiu $4,$4,%lo($LC1) ; branch delay slot
    ; call printf():
    lw    $28,16($sp)
    ; set 2nd argument of printf(),
    ; load word at address $sp+24:
    lw    $5,24($sp)
    lw    $25,%call16(printf)($28)
    lui   $4,%hi($LC2)
    jalr  $25
    addiu $4,$4,%lo($LC2) ; branch delay slot
    ; function epilogue:
    lw    $31,36($sp)
    ; set return value to 0:
    move  $2,$0
    ; return:
```
1.9. SCANF()

The assembly code for the function `scanf()` is shown below:

```assembly
j $31
addiu $sp,$sp,40 ; branch delay slot
```

IDA displays the stack layout as follows:

**Listing 1.72: Optimizing GCC 4.4.5 (IDA)**

```assembly
.text:00000000 main:
.text:00000000 .text:00000000 var_18 = -0x18
.text:00000000 var_10 = -0x10
.text:00000000 var_4 = -4
.text:00000000 ; function prologue:
.text:00000000 lui $gp, (__gnu_local_gp >> 16)
.text:00000004 addiu $sp, -0x28
.text:00000008 la $gp, (__gnu_local_gp & 0xFFFF)
.text:00000010 sw $ra, 0x28+var_4($sp)
.text:00000010 sw $gp, 0x28+var_18($sp)
; call puts():
.text:00000014 lw $t9, (puts & 0xFFFF)($gp)
.text:00000018 lui $a0, ($LC0 >> 16) # "Enter X:"
.text:0000001C jalr $t9
.text:00000020 la $a0, ($LC0 & 0xFFFF) # "Enter X:"
; call scanf():
.text:00000024 lw $gp, 0x28+var_18($sp)
.text:00000028 lui $a0, ($LC1 >> 16) # "%d"
.text:0000002C lw $t9, (__isoc99_scanf & 0xFFFF)($gp)
; set 2nd argument of scanf(), $a1=$sp+24:
.text:00000030 addiu $a1, $sp, 0x28+var_10
.text:00000034 jalr $t9 ; branch delay slot
.text:00000038 la $a0, ($LC1 & 0xFFFF) # "%d"
; call printf():
.text:0000003C lw $gp, 0x28+var_18($sp)
; set 2nd argument of printf(),
; load word at address $sp+24:
.text:00000040 lw $a1, 0x28+var_10($sp)
.text:00000044 lw $t9, (printf & 0xFFFF)($gp)
.text:00000048 lui $a0, ($LC2 >> 16) # "You entered %d...
\n"
.text:0000004C jalr $t9
.text:00000050 la $a0, ($LC2 & 0xFFFF) # "You entered %d...
\n" ; branch delay
\.
; function epilogue:
.text:00000054 lw $ra, 0x28+var_4($sp)
; set return value to 0:
.text:00000058 move $v0, $zero
; return:
.text:0000005C jr $ra
.text:00000060 addiu $sp, 0x28 ; branch delay slot
```

1.9.2 Popular mistake

It’s a very popular mistake (and/or typo) to pass value of `x` instead of pointer to `x`:

```c
#include <stdio.h>

int main()
{
    int x;
    printf ("Enter X:\n");
    scanf ("%d", x); // BUG
    printf ("You entered %d...\n", x);
    return 0;
}
```
1.9. SCANF()

So what happens here? \( x \) is not uninitialized and contains some random noise from local stack. When \( \text{scanf}() \) called, it takes string from user, parses it into number and tries to write it into \( x \), treating it as an address in memory. But there is a random noise, so \( \text{scanf}() \) will try to write at random address. Most likely, the process will crash.

Interestingly enough, some CRT libraries in debug build, put visually distinctive patterns into memory just allocated, like \( 0xCCCCCCCCC \) or \( 0x0BADF00D \) and so on. In this case, \( x \) may contain \( 0xCCCCCCCCC \), and \( \text{scanf}() \) would try to write at address \( 0xCCCCCCCCC \). And if you’ll notice that something in your process tries to write at address \( 0xCCCCCCCCC \), you’ll know that uninitialized variable (or pointer) gets used without prior initialization. This is better than as if newly allocated memory is just cleared.

1.9.3 Global variables

What if the \( x \) variable from the previous example isn’t local but a global one? Then it would have been accessible from any point, not only from the function body. Global variables are considered anti-pattern, but for the sake of the experiment, we could do this.

```c
#include <stdio.h>

// now x is global variable
int x;

int main()
{
    printf ("Enter X:\n");
    scanf ("%d", &x);
    printf ("You entered %d..., x);
    return 0;
}
```

### MSVC: x86

```assembly
_DATA SEGMENT
_COMM x:DWORD
 <![CDATA[ $SG2456 DB 'Enter X:', 0aH, 00H
 $SG2457 DB '%d', 00H
 $SG2458 DB 'You entered %d...', 0aH, 00H
]]>
_DATA ENDS
PUBLIC _main
EXTERN _scanf:PROC
EXTERN _printf:PROC
; Function compile flags: /Odtp
_TEXT SEGMENT
_main PROC
    push ebp
    mov ebp, esp
    push OFFSET $SG2456
    call _printf
    add esp, 4
    push OFFSET _x
    push OFFSET $SG2457
    call _scanf
    add esp, 8
    mov eax, DWORD PTR _x
    push eax
    push OFFSET $SG2458
    call _printf
    add esp, 8
    xor eax, eax
    pop ebp
    ret 0
_main ENDP
_TEXT ENDS
```
1.9. **SCANF()**

In this case the x variable is defined in the _DATA segment and no memory is allocated in the local stack. It is accessed directly, not through the stack. Uninitialized global variables take no space in the executable file (indeed, why one needs to allocate space for variables initially set to zero?), but when someone accesses their address, the OS will allocate a block of zeros there\(^2\).

Now let's explicitly assign a value to the variable:

```c
int x=10; // default value
```

We got:

```
_DATA SEGMENT
_x DD 0aH
...
```

Here we see a value 0xA of DWORD type (DD stands for DWORD = 32 bit) for this variable.

If you open the compiled .exe in IDA, you can see the x variable placed at the beginning of the _DATA segment, and after it you can see text strings.

If you open the compiled .exe from the previous example in IDA, where the value of x hasn't been set, you would see something like this:

```
Listing 1.73: IDA
.data:0040FA80 _x    dd ? ; DATA XREF: _main+10
.data:0040FA80              ; _main+22
.data:0040FA84 dword_40FA84 dd ? ; DATA XREF: _memset+1E
.data:0040FA84              ; unknown_libname_1+28
.data:0040FA88 dword_40FA88 dd ? ; DATA XREF: ___sbh_find_block+5
.data:0040FA88              ; ___sbh_free_block+2BC
.data:0040FACB ; LPVOID lpMem
.data:0040FACB lpMem dd ? ; DATA XREF: ___sbh_find_block+B
.data:0040FACB              ; ___sbh_free_block+2CA
.data:0040FA90 dword_40FA90 dd ? ; DATA XREF: _V6_HeapAlloc+13
.data:0040FA90              ; __calloc_impl+72
.data:0040FA94 dword_40FA94 dd ? ; DATA XREF: ___sbh_free_block+2FE
```

\(x\) is marked with ? with the rest of the variables that do not need to be initialized. This implies that after loading the .exe to the memory, a space for all these variables is to be allocated and filled with zeros [ISO/IEC 9899:TC3 (C C99 standard), (2007)6.7.8p10]. But in the .exe file these uninitialized variables do not occupy anything. This is convenient for large arrays, for example.

\(^2\)That is how a VM behaves
1.9. SCANF()

MSVC: x86 + OllyDbg

Things are even simpler here:

![Figure 1.15: OllyDbg: after scanf() execution](image)

The variable is located in the data segment. After the PUSH instruction (pushing the address of \( x \)) gets executed, the address appears in the stack window. Right-click on that row and select “Follow in dump”. The variable will appear in the memory window on the left. After we have entered 123 in the console, 0x7B appears in the memory window (see the highlighted screenshot regions).

But why is the first byte 7B? Thinking logically, 00 00 00 7B must be there. The cause for this is referred as **endianness**, and x86 uses **little-endian**. This implies that the lowest byte is written first, and the highest written last. Read more about it at: 2.8 on page 464. Back to the example, the 32-bit value is loaded from this memory address into EAX and passed to printf().

The memory address of \( x \) is 0x00C53394.
1.9. SCANF()

In OllyDbg we can review the process memory map (Alt-M) and we can see that this address is inside the .data PE-segment of our program:

![OllyDbg process memory map](image)

Figure 1.16: OllyDbg: process memory map

GCC: x86

The picture in Linux is near the same, with the difference that the uninitialized variables are located in the _bss segment. In ELF file this segment has the following attributes:

<table>
<thead>
<tr>
<th>Segment type: Uninitialized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment permissions: Read/Write</td>
</tr>
</tbody>
</table>

If you, however, initialize the variable with some value e.g. 10, it is to be placed in the _data segment, which has the following attributes:

<table>
<thead>
<tr>
<th>Segment type: Pure data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment permissions: Read/Write</td>
</tr>
</tbody>
</table>

MSVC: x64

Listing 1.74: MSVC 2012 x64

```assembly
_DATA SEGMENT
COMM x:DWORD
SSG2924 DB 'Enter X: ', 0AH, 00H
SSG2925 DB '%d', 00H
SSG2926 DB 'You entered %d... ', 0AH, 00H
_DATA ENDS
```

73 Executable File format widely used in *NIX systems including Linux
The code is almost the same as in x86. Please note that the address of the \textit{x} variable is passed to \texttt{scanf()} using a \texttt{LEA} instruction, while the variable's value is passed to the second \texttt{printf()} using a \texttt{MOV} instruction. \texttt{DWORD PTR}—is a part of the assembly language (no relation to the machine code), indicating that the variable data size is 32-bit and the \texttt{MOV} instruction has to be encoded accordingly.

\textbf{ARM: Optimizing Keil 6/2013 (Thumb mode)}

Listing 1.75: IDA
1.9. **SCANF()**

So, the \texttt{x} variable is now global and for this reason located in another segment, namely the data segment (.data). One could ask, why are the text strings located in the code segment (.text) and \texttt{x} is located right here? Because it is a variable and by definition its value could change. Moreover it could possibly change often. While text strings has constant type, they will not be changed, so they are located in the .text segment.

The code segment might sometimes be located in a \texttt{ROM}\textsuperscript{74} chip (keep in mind, we now deal with embedded microelectronics, and memory scarcity is common here), and changeable variables —in \texttt{RAM}.

It is not very economical to store constant variables in \texttt{RAM} when you have \texttt{ROM}.

Furthermore, constant variables in \texttt{RAM} must be initialized, because after powering on, the \texttt{RAM}, obviously, contains random information.

Moving forward, we see a pointer to the \texttt{x} (off_2C) variable in the code segment, and that all operations with the variable occur via this pointer.

That is because the \texttt{x} variable could be located somewhere far from this particular code fragment, so its address must be stored somewhere in close proximity to the code.

The \texttt{LDR} instruction in Thumb mode can only address variables in a range of 1020 bytes from its location, and in ARM-mode —variables in range of $\pm 4095$ bytes.

And so the address of the \texttt{x} variable must be located somewhere in close proximity, because there is no guarantee that the linker would be able to accommodate the variable somewhere nearby the code, it may well be even in an external memory chip!

One more thing: if a variable is declared as \texttt{const}, the Keil compiler allocates it in the .constdata segment. Perhaps thereafter, the linker could place this segment in \texttt{ROM} too, along with the code segment.

\textbf{ARM64}

Listing 1.76: Non-optimizing GCC 4.9.1 ARM64

```assembly
.comm x,4,4
.LC0:  .string "Enter X:"
.LC1:  .string "%d"
.LC2:  .string "You entered %d\n"
f5:
; save FP and LR in stack frame:
stp x29, x30, [sp, -16]!
; set stack frame (FP=SP)
add x29, sp, 0
; load pointer to the "Enter X:" string:
adrp x0, .LC0
add x0, x0, :lo12:.LC0
bl puts
; load pointer to the "%d" string:
adrp x0, .LC1
add x0, x0, :lo12:.LC1
; form address of \texttt{x} global variable:
adrp x1, x
add x1, x1, :lo12:x
bl _isoc99_scanf
; form address of \texttt{x} global variable again:
adrp x0, x
add x0, x0, :lo12:x
; load value from memory at this address:
ldr w1, [x0]
; load pointer to the "You entered %d\n" string:
adrp x0, .LC2
add x0, x0, :lo12:.LC2
bl printf
; return 0
mov w0, 0
```

\textsuperscript{74}\textit{Read-Only Memory}
In this case the \( x \) variable is declared as global and its address is calculated using the ADRP/ADD instruction pair (lines 21 and 25).

**MIPS**

**Uninitialized global variable**

So now the \( x \) variable is global. Let's compile to executable file rather than object file and load it into IDA. IDA displays the \( x \) variable in the .sbss ELF section (remember the “Global Pointer”? 1.5.5 on page 25), since the variable is not initialized at the start.

Listing 1.77: Optimizing GCC 4.4.5 (IDA)

```plaintext
.text:004006C0 main:
.text:004006C0 .text:004006C0 var_10 = -0x10
.text:004006C0 var_4 = -4
.text:004006C0 ; function prologue:
.text:004006C0 .text:004006C0 lui $gp, 0x42
.text:004006C0 .text:004006C0 addiu $sp, -0x20
.text:004006C0 .text:004006C0 li $gp, 0x418940
.text:004006CC .text:004006CC sw $ra, 0x20+var_4($sp)
.text:004006D0 .text:004006D0 sw $gp, 0x20+var_10($sp)
; call puts():
.text:004006D4 .text:004006D4 la $t9, puts
.text:004006D8 .text:004006D8 lui $a0, 0x40
.text:004006DC .text:004006DC jalr $t9 ; puts
.text:004006E0 .text:004006E0 la $a0, aEnterX # "Enter X:" ; branch delay slot
; call scanf():
.text:004006E4 .text:004006E4 lw $gp, 0x20+var_10($sp)
.text:004006E8 .text:004006E8 lui $a0, 0x40
.text:004006EC .text:004006EC la $t9, __isoc99_scanf
; prepare address of x:
.text:004006F0 .text:004006F0 la $a1, x
.text:004006F4 .text:004006F4 jalr $t9 ; __isoc99_scanf
.text:004006F8 .text:004006F8 la $a0, aD # "%d" ; branch delay slot
; call printf():
.text:004006FC .text:004006FC lw $gp, 0x20+var_10($sp)
.text:00400700 .text:00400700 lui $a0, 0x40
; get address of x:
.text:00400704 .text:00400704 la $v0, x
.text:00400708 .text:00400708 la $t9, printf
; load value from "x" variable and pass it to printf() in $a1:
.text:0040070C .text:0040070C lw $a1, (x - 0x41099C)($v0)
.text:00400710 .text:00400710 jalr $t9 ; printf
.text:00400714 .text:00400714 la $a0, aYouEnteredD___ # "You entered %d...\n" ; branch \(~\)
\(~\) delay slot
; function epilogue:
.text:00400718 .text:00400718 lw $ra, 0x20+var_4($sp)
.text:0040071C .text:0040071C move $v0, $zero
.text:00400720 .text:00400720 jr $ra
.text:00400724 .text:00400724 addiu $sp, 0x20 ; branch delay slot
... 

.sbss:0041099C # Segment type: Uninitialized
.sbss:0041099C .sbss
.sbss:0041099C .globl x
.sbss:0041099C x: .space 4
.sbss:0041099C
```

IDA reduces the amount of information, so we'll also do a listing using objdump and comment it:
1.9. SCANF()  

Listing 1.78: Optimizing GCC 4.4.5 (objdump)

```
004006c0 <main>:

; function prologue:
4006c0: 3c1c0042 lui gp,0x42
4006c4: 27bdffe0 addiu sp,sp,-32
4006c8: 279c8940 addiu gp,gp,-30400
4006cc: afbf001c sw ra,28(sp)
4006d0: afbc0010 sw gp,16(sp)

; call puts():
9 4006d4: 8f998034 lw t9,-32716(gp)
10 4006d8: 3c040040 lui a0,0x40
11 4006dc: 0320f809 jalr t9
12 4006e0: 248408f0 addiu a0,a0,2288 ; branch delay slot

; call scanf():
14 4006e4: 8fbc0010 lw gp,16(sp)
15 4006e8: 3c040040 lui a0,0x40
16 4006ec: 8f998038 lw t9,-32712(gp)

; prepare address of x:
18 4006f0: 8f858044 lw a1,-32700(gp)
19 4006f4: 0320f809 jalr t9
20 4006f8: 248408fc addiu a0,a0,2300 ; branch delay slot

; call printf():
22 4006fc: 8fbc0010 lw gp,16(sp)
23 400700: 3c040040 lui a0,0x40

; get address of x:
25 400704: 8f828044 lw v0,-32700(gp)
26 400708: 8f99803c lw t9,-32708(gp)

; load value from "x" variable and pass it to printf() in $a1:
27 40070c: 8c450000 lw a1,0(v0)
28 40070e: 24840900 addiu a0,a0,2304 ; branch delay slot

; function epilogue:
31 400718: 8fbf001c lw ra,28(sp)
32 40071c: 00001021 move v0,zero
34 400720: 03e00008 jr ra
35 400724: 27bd0020 addiu sp,sp,32 ; branch delay slot
36 ; pack of NOPs used for aligning next function start on 16-byte boundary:
37 400728: 00200825 move at,at
38 40072c: 00200825 move at,at
```

Now we see the $x$ variable address is read from a 64KiB data buffer using GP and adding negative offset to it (line 18). More than that, the addresses of the three external functions which are used in our example (puts(), scanf(), printf()), are also read from the 64KiB global data buffer using GP (lines 9, 16 and 26). GP points to the middle of the buffer, and such offset suggests that all three function’s addresses, and also the address of the $x$ variable, are all stored somewhere at the beginning of that buffer. That make sense, because our example is tiny.

Another thing worth mentioning is that the function ends with two NOPs (MOVE $AT,$AT — an idle instruction), in order to align next function’s start on 16-byte boundary.

**Initialized global variable**

Let’s alter our example by giving the $x$ variable a default value:

```
int x=10; // default value
```

Now IDA shows that the $x$ variable is residing in the .data section:

Listing 1.79: Optimizing GCC 4.4.5 (IDA)

```
.text:004006A0 main:
.text:004006A0 var_10 = -0x10
.text:004006A0 var_8 = -8
.text:004006A0 var_4 = -4
.text:004006A0 lui $gp, 0x42
.text:004006A0 addiu $sp, -0x20
```

83
1.9. SCANF()

Why not .sdata? Perhaps that this depends on some GCC option?

Nevertheless, now \textit{x} is in .data, which is a general memory area, and we can take a look how to work with variables there.

The variable’s address must be formed using a pair of instructions. In our case those are \texttt{LUI} (“Load Upper Immediate”) and \texttt{ADDIU} (“Add Immediate Unsigned Word”).

Here is also the objdump listing for close inspection:

Listing 1.80: Optimizing GCC 4.4.5 (objdump)

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Operand(s)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>004006a0</td>
<td>3c1c0042 lui gp,0x42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006a4</td>
<td>27bdffe0 addiu sp,sp,-32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006a8</td>
<td>279c8930 addiu gp,gp,-30416</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006ac</td>
<td>afb8001c sw ra,28(sp)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006b0</td>
<td>afb00018 sw s0,24(sp)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006b4</td>
<td>afbc0010 sw gp,16(sp)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006b8</td>
<td>8f998034 lw t9,-32716(gp)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006bc</td>
<td>3c040040 lui a0,0x40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006c0</td>
<td>0320f809 jalr t9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006c4</td>
<td>248408d0 addiu a0,a0,2256</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006c8</td>
<td>8fbc0010 lw gp,16(sp)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006dc</td>
<td>3c100041 lui s0,0x41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006d0</td>
<td>8f998038 lw t9,-32716(gp)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006d4</td>
<td>3c040040 lui a0,0x40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006d8</td>
<td>26050920 addiu a1,s0,2336</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006dc</td>
<td>0320f809 jalr t9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006e0</td>
<td>248408d0 addiu a0,a0,2268</td>
<td></td>
<td></td>
</tr>
<tr>
<td>004006e4</td>
<td>8fbc0010 lw gp,16(sp)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

...
1.9. SCANF()

We see that the address is formed using LUI and ADDIU, but the high part of address is still in the $S0 register, and it is possible to encode the offset in a LW (“Load Word”) instruction, so one single LW is enough to load a value from the variable and pass it to printf().

Registers holding temporary data are prefixed with T-, but here we also see some prefixed with S-, the contents of which must be preserved before use in other functions (i.e., saved somewhere).

That is why the value of $S0 has been set at address 0x4006cc and has been used again at address 0x4006e8, after the scanf() call. The scanf() function does not change its value.

1.9.4 scanf()

As was noted before, it is slightly old-fashioned to use scanf() today. But if we have to, we have to check if scanf() finishes correctly without an error.

```
#include <stdio.h>

int main()
{
    int x;
    printf ("Enter X:\n");
    if (scanf ("%d", &x)==1)
        printf ("You entered %d...\n", x);
    else
        printf ("What you entered? Huh?\n");

    return 0;
};
```

By standard, the scanf()\(^\ddagger\) function returns the number of fields it has successfully read.

In our case, if everything goes fine and the user enters a number scanf() returns 1, or in case of error (or EOF\(^\ddagger\ddagger\)) — 0.

Let's add some C code to check the scanf() return value and print error message in case of an error.

This works as expected:

```
C:...>ex3.exe
Enter X:
123
You entered 123...
```

```
C:...>ex3.exe
Enter X:
ouch
What you entered? Huh?
```

\(^\ddagger\)scanf, wscanf: MSDN
\(^\ddagger\ddagger\)End of File
1.9. **SCANF()**

**MSVC: x86**

Here is what we get in the assembly output (MSVC 2010):

```
lea   eax, DWORD PTR _x$[ebp]
push  eax
push  OFFSET $SG3833 ; '%d', 00H
call _scanf
add   esp, 8
cmp   eax, 1
jne   SHORT $LN2@main
mov   ecx, DWORD PTR _x$[ebp]
push  ecx
push  OFFSET $SG3834 ; 'You entered %d...', 0aH, 00H
call _printf
add   esp, 8
jmp   SHORT $LN1@main
$LN2@main:
push  OFFSET $SG3836 ; 'What you entered? Huh?', 0aH, 00H
call _printf
add   esp, 4
$LN1@main:
xor   eax, eax
```

The **caller** function (main()) needs the **callee** function (scanf()) result, so the **callee** returns it in the EAX register.

We check it with the help of the instruction CMP EAX, 1 (CoMPare). In other words, we compare the value in the EAX register with 1.

A JNE conditional jump follows the CMP instruction. JNE stands for *Jump if Not Equal*.

So, if the value in the EAX register is not equal to 1, the CPU will pass the execution to the address mentioned in the JNE operand, in our case $LN2@main. Passing the control to this address results in the CPU executing printf() with the argument *What you entered? Huh?*. But if everything is fine, the conditional jump is not be taken, and another printf() call is to be executed, with two arguments: 'You entered %d...' and the value of x.

Since in this case the second printf() has not to be executed, there is a JMP preceding it (unconditional jump). It passes the control to the point after the second printf() and just before the XOR EAX, EAX instruction, which implements return 0.

So, it could be said that comparing a value with another is *usually* implemented by CMP/Jcc instruction pair, where *cc* is *condition code*. CMP compares two values and sets processor flags 77. Jcc checks those flags and decides to either pass the control to the specified address or not.

This could sound paradoxical, but the CMP instruction is in fact SUB (subtract). All arithmetic instructions set processor flags, not just CMP. If we compare 1 and 1, 1−1 is 0 so the ZF flag would be set (meaning that the last result is 0). In no other circumstances ZF can be set, except when the operands are equal. JNE checks only the ZF flag and jumps only if it is not set. JNE is in fact a synonym for JNZ (*Jump if Not Zero*). Assembler translates both JNE and JNZ instructions into the same opcode. So, the CMP instruction can be replaced with a SUB instruction and almost everything will be fine, with the difference that SUB alters the value of the first operand. CMP is *SUB without saving the result, but affecting flags*.

**MSVC: x86: IDA**

It is time to run **IDA** and try to do something in it. By the way, for beginners it is good idea to use /MD option in MSVC, which means that all these standard functions are not be linked with the executable file, but are to be imported from the MSVCR*.DLL file instead. Thus it will be easier to see which standard function are used and where.

While analyzing code in **IDA**, it is very helpful to leave notes for oneself (and others). In instance, analyzing this example, we see that JNZ is to be triggered in case of an error. So it is possible to move the cursor to the label, press “n” and rename it to “error”. Create another label—into “exit”. Here is my result:

```
.text:00401000 _main proc near
.text:00401000
```

77x86 flags, see also: wikipedia.
1.9. `SCANF()`

Now it is slightly easier to understand the code. However, it is not a good idea to comment on every instruction.

You could also hide(collapse) parts of a function in IDA. To do that mark the block, then press “–” on the numerical pad and enter the text to be displayed instead.

Let’s hide two blocks and give them names:

To expand previously collapsed parts of the code, use “+” on the numerical pad.
1.9. SCANF()

By pressing “space”, we can see how IDA represents a function as a graph:

```assembly
; int cdecl main()
_main proc near

var_4= dword ptr -4
argc= dword ptr 8
argv= dword ptr 0Ch
envp= dword ptr 10h

push ebp
mov ebp, esp
push ecx
push offset Format ; "Enter X:\n"
call ds:printf
add esp, 4
lea eax, [ebp+var_4]
push eax
push offset aD ; "%d"
call ds:scanf
add esp, 8
cmp eax, 1
jnz short error

mov ecx, [ebp+var_4]
push ecx
push offset aYou ; "You entered %d...\n"
call ds:printf
add esp, 8
jmp short exit

exit:
exor eax, eax
mov esp, ebp
pop ebp
ret

_main endp
```

Figure 1.17: Graph mode in IDA

There are two arrows after each conditional jump: green and red. The green arrow points to the block which executes if the jump is triggered, and red if otherwise.
1.9. `SCANF()`

It is possible to fold nodes in this mode and give them names as well ("group nodes"). Let's do it for 3 blocks:

```assembly
; int __cdecl main()
_main proc near

var_4= dword ptr -4
argc= dword ptr 8
argv= dword ptr 0Ch
envp= dword ptr 10h

push ebp
mov ebp, esp
push ecx
push offset Format ; "Enter X:\n"
call ds:printf
add esp, 4
lea eax, [ebp+var_4]
push eax
push offset aD ; "%d"
call ds:scanf
add esp, 8
cmp eax, 1
jnz short error
```

That is very useful. It could be said that a very important part of the reverse engineers’ job (and any other researcher as well) is to reduce the amount of information they deal with.
Let's try to hack our program in OllyDbg, forcing it to think scanf() always works without error. When an address of a local variable is passed into scanf(), the variable initially contains some random garbage, in this case 0x6E494714:

![Image of OllyDbg interface](image.png)

Figure 1.19: OllyDbg: passing variable address into scanf()
1.9. `SCANF()`

While `scanf()` executes, in the console we enter something that is definitely not a number, like “asdasd”. `scanf()` finishes with 0 in `EAX`, which indicates that an error has occurred:

![OllyDbg: scanf() returning error](image)

We can also check the local variable in the stack and note that it has not changed. Indeed, what would `scanf()` write there? It simply did nothing except returning zero.

Let’s try to “hack” our program. Right-click on `EAX`, Among the options there is “Set to 1”. This is what we need.

We now have 1 in `EAX`, so the following check is to be executed as intended, and `printf()` will print the value of the variable in the stack.

When we run the program (F9) we can see the following in the console window:

```
Listing 1.81: console window

Enter X:
asdasd
You entered 1850296084...
```

Indeed, 1850296084 is a decimal representation of the number in the stack (0x6E494714)!
1.9. SCANF()

This can also be used as a simple example of executable file patching. We may try to patch the executable so the program would always print the input, no matter what we enter.

Assuming that the executable is compiled against external MSVCR*.DLL (i.e., with /MD option) \(^{78}\), we see the `main()` function at the beginning of the `.text` section. Let’s open the executable in Hiew and find the beginning of the `.text` section (Enter, F8, F6, Enter, Enter).

We can see this:

![Figure 1.21: Hiew: main() function](image)

Hiew finds ASCII\(^{79}\) strings and displays them, as it does with the imported functions’ names.

\(^{78}\)that’s what also called “dynamic linking”

\(^{79}\)ASCII Zero (null-terminated ASCII string)
1.9. `SCANT()`

Move the cursor to address .00401027 (where the JNZ instruction, we have to bypass, is located), press F3, and then type “9090” (meaning two NOPs):

![Hiew: replacing JNZ with two NOPs](image)

Then press F9 (update). Now the executable is saved to the disk. It will behave as we wanted.

Two NOPs are probably not the most aesthetic approach. Another way to patch this instruction is to write just 0 to the second opcode byte (jump offset), so that JNZ will always jump to the next instruction.

We could also do the opposite: replace first byte with EB while not touching the second byte (jump offset). We would get an unconditional jump that is always triggered. In this case the error message would be printed every time, no matter the input.

**MSVC: x64**

Since we work here with int-typed variables, which are still 32-bit in x86-64, we see how the 32-bit part of the registers (prefixed with E-) are used here as well. While working with pointers, however, 64-bit register parts are used, prefixed with R-.
1.9. **SCANF()**

**Listing 1.82: MSVC 2012 x64**

```
_DATA SEGMENT
$SG2924 DB 'Enter X:', 0aH, 00H
$SG2926 DB '%d', 00H
$SG2927 DB 'You entered %d...', 0aH, 00H
$SG2929 DB 'What you entered? Huh?', 0aH, 00H
_DATA ENDS

_TEXT SEGMENT
x$ = 32
main PROC
$LN5:
  sub   rsp, 56
  lea   rcx, OFFSET FLAT:$SG2924 ; 'Enter X:'
  call  printf
  lea   rdx, QWORD PTR x$[rsp]
  lea   rcx, OFFSET FLAT:$SG2926 ; '%d'
  call  scanf
  cmp   eax, 1
  jne   SHORT $LN2@main
  mov   edx, DWORD PTR x$[rsp]
  lea   rcx, OFFSET FLAT:$SG2927 ; 'You entered %d...' 
  call  printf
  jmp   SHORT $LN1@main
$LN2@main:
  lea   rcx, OFFSET FLAT:$SG2929 ; 'What you entered? Huh?'
  call  printf
$LN1@main:
  ; return 0
  xor   eax, eax
  pop   {r3, pc}
main ENDP
_TEXT ENDS
END
```

**ARM**

**ARM: Optimizing Keil 6/2013 (Thumb mode)**

**Listing 1.83: Optimizing Keil 6/2013 (Thumb mode)**

```
var_8  = -8
PUSH   {r3, lr}
ADR    R0, aEnterX ; "Enter X:\n"
BL     __2printf
MOV    R1, SP
ADR    R0, aD ; "%d"
BL     0scanf
CMP    R0, #1
BEQ    loc_1E
ADR    R0, aWhatYouEntered ; "What you entered? Huh?\n"
BL     __2printf

loc_1A ; CODE XREF: main+26
MOVS   R0, #0
POP    {r3, pc}

loc_1E ; CODE XREF: main+12
LDR    R1, [SP,#8+var_8]
ADR    R0, aYouEnteredD__ ; "You entered %d...\n"
BL     __2printf
B      loc_1A
```
1.9. SCANF()

The new instructions here are CMP and BEQ\(^8\).

CMP is analogous to the x86 instruction with the same name, it subtracts one of the arguments from the other and updates the conditional flags if needed.

BEQ jumps to another address if the operands were equal to each other, or, if the result of the last computation has been 0, or if the Z flag is 1. It behaves as JZ in x86.

Everything else is simple: the execution flow forks in two branches, then the branches converge at the point where 0 is written into the R0 as a function return value, and then the function ends.

ARM64

Listing 1.84: Non-optimizing GCC 4.9.1 ARM64

```
.LC0:
.string "Enter X:"
.LC1:
.string "%d"
.LC2:
.string "You entered %d...\n"
.LC3:
.string "What you entered? Huh?"
f6:
    ; save FP and LR in stack frame:
    stp  x29, x30, [sp, -32]!
    ; set stack frame (FP=SP)
    add  x29, sp, 0
    ; load pointer to the "Enter X:" string:
    adrp  x0, .LC0
    add  x0, x0, :lo12:.LC0
    bl   puts
    ; load pointer to the "%d" string:
    adrp  x0, .LC1
    add  x0, x0, :lo12:.LC1
    ; calculate address of x variable in the local stack
    add  x1, x29, 28
    bl   __isoc99_scanf
    ; scanf() returned result in W0.
    ; check it:
    cmp  w0, 1
    ; BNE is Branch if Not Equal
    bne  .L2
    ; at this moment W0=1, meaning no error
    ; load x value from the local stack
    ldr  w1, [x29,28]
    ; load pointer to the "You entered %d...\n" string:
    adrp  x0, .LC2
    add  x0, x0, :lo12:.LC2
    bl   printf
    ; skip the code, which print the "What you entered? Huh?" string:
    b    .L3
    ; load pointer to the "What you entered? Huh?" string:
    adrp  x0, .LC3
    add  x0, x0, :lo12:.LC3
    bl   puts
    ; return 0
    mov  w0, 0
    ; restore FP and LR:
    ldp  x29, x30, [sp], 32
    ret
```

Code flow in this case forks with the use of CMP/BNE (Branch if Not Equal) instructions pair.

\(^8\)(PowerPC, ARM) Branch if Equal
1.9. SCANF()

Listing 1.85: Optimizing GCC 4.4.5 (IDA)

```
.text:004006A0 main:
.text:004006A0 .text:004006A0 var_18 = -0x18
.text:004006A4 .text:004006A0 var_10 = -0x10
.text:004006A8 .text:004006A0 var_4 = -4
.text:004006A0 lui $gp, 0x42
.text:004006A4 addiu $sp, -0x28
.text:004006A8 li $gp, 0x41960
.text:004006B0 sw $ra, 0x28+var_4($sp)
.text:004006B4 sw $gp, 0x28+var_18($sp)
.text:004006BC jalr $t9 ; puts
.text:004006C0 la $a0, aEnterX # "Enter X:"
.text:004006C4 lw $gp, 0x28+var_18($sp)
.text:004006C8 lui $a0, 0x40
.text:004006CC la $t9, __isoc99_scanf
.text:004006D0 la $a0, aD # "%d"
.text:004006D4 jalr $t9 ; __isoc99_scanf
.text:004006D8 addiu $a1, $sp, 0x28+var_10 # branch delay slot
.text:004006DC li $v1, 1
.text:004006E0 lw $gp, 0x28+var_18($sp)
.text:004006E4 beq $v0, $v1, loc_40070C
.text:004006E8 or $at, $zero # branch delay slot, NOP
.text:004006EC la $t9, puts
.text:004006F0 lui $a0, 0x40
.text:004006F4 jalr $t9 ; puts
.text:004006F8 la $a0, aWhatYouEntered # "What you entered? Huh?"
.text:004006FC lw $ra, 0x28+var_4($sp)
.text:00400700 move $v0, $zero
.text:00400704 jr $ra
.text:00400708 addiu $sp, 0x28
.text:0040070C loc_40070C:
.text:0040070C la $t9, printf
.text:00400710 lw $a1, 0x28+var_10($sp)
.text:00400714 lui $a0, 0x40
.text:00400718 jalr $t9 ; printf
.text:0040071C la $a0, aYouEnteredD___ # "You entered %d...
.text:00400720 lw $ra, 0x28+var_4($sp)
.text:00400724 move $v0, $zero
.text:00400728 jr $ra
.text:0040072C addiu $sp, 0x28
```

scanf() returns the result of its work in register $V0. It is checked at address 0x004006E4 by comparing the values in $V0 with $V1 (1 has been stored in $V1 earlier, at 0x004006DC). BEQ stands for “Branch Equal”. If the two values are equal (i.e., success), the execution jumps to address 0x0040070C.

**Exercise**

As we can see, the JNE/JNZ instruction can be easily replaced by the JE/JZ and vice versa (or BNE by BEQ and vice versa). But then the basic blocks must also be swapped. Try to do this in some of the examples.

1.9.5 Exercise

- [http://challenges.re/53](http://challenges.re/53)
1.10. ACCESSING PASSED ARGUMENTS

1.10 Accessing passed arguments

Now we figured out that the caller function is passing arguments to the callee via the stack. But how does the callee access them?

Listing 1.86: simple example

```c
#include <stdio.h>

int f (int a, int b, int c)
{
    return a*b+c;
};

int main()
{
    printf ("%d\n", f(1, 2, 3));
    return 0;
};
```

1.10.1 x86

MSVC

Here is what we get after compilation (MSVC 2010 Express):

Listing 1.87: MSVC 2010 Express

```asm
_TEXT SEGMENT
_a$ = 8 ; size = 4
_b$ = 12 ; size = 4
_c$ = 16 ; size = 4
_f PROC
    push ebp
    mov ebp, esp
    mov eax, DWORD PTR _a$[ebp]
    imul eax, DWORD PTR _b$[ebp]
    add eax, DWORD PTR _c$[ebp]
    pop ebp
    ret 0
_f ENDP

_main PROC
    push ebp
    mov ebp, esp
    push 3 ; 3rd argument
    push 2 ; 2nd argument
    push 1 ; 1st argument
    call _f
    add esp, 12
    push eax
    push OFFSET $SG2463 ; '%d', 0AH, 00H
    call _printf
    add esp, 8
    xor eax, eax
    pop ebp
    ret 0

_main ENDP
```

What we see is that the main() function pushes 3 numbers onto the stack and calls f(int,int,int).

Argument access inside f() is organized with the help of macros like: _a$ = 8, in the same way as local variables, but with positive offsets (addressed with plus). So, we are addressing the outer side of the stack frame by adding the _a$ macro to the value in the EBP register.

Then the value of a is stored into EAX. After IMUL instruction execution, the value in EAX is a product of the value in EAX and the content of _b.
1.10. ACCESSING PASSED ARGUMENTS

After that, ADD adds the value in _c to EAX.

The value in EAX does not need to be moved: it is already where it must be. On returning to caller, it takes the EAX value and uses it as an argument to printf().

MSVC + OllyDbg

Let's illustrate this in OllyDbg. When we trace to the first instruction in f() that uses one of the arguments (first one), we see that EBP is pointing to the stack frame, which is marked with a red rectangle.

The first element of the stack frame is the saved value of EBP, the second one is RA, the third is the first function argument, then the second and third ones.

To access the first function argument, one needs to add exactly 8 (2 32-bit words) to EBP.

OllyDbg is aware about this, so it has added comments to the stack elements like “RETURN from” and “Arg1 = …”, etc.

N.B.: Function arguments are not members of the function’s stack frame, they are rather members of the stack frame of the caller function.

Hence, OllyDbg marked “Arg” elements as members of another stack frame.

Figure 1.23: OllyDbg: inside of f() function

GCC

Let's compile the same in GCC 4.4.1 and see the results in IDA:

Listing 1.88: GCC 4.4.1

```
public f
proc near

arg_0 = dword ptr 8
arg_4 = dword ptr 0Ch
arg_8 = dword ptr 10h

push ebp
mov ebp, esp
mov eax, [ebp+arg_0] ; 1st argument
imul eax, [ebp+arg_4] ; 2nd argument
add eax, [ebp+arg_8] ; 3rd argument
pop ebp
```
1.10. ACCESSING PASSED ARGUMENTS

```
ret
f  endp

public main
main  proc near

var_10 = dword ptr -10h
var_C = dword ptr -0Ch
var_8 = dword ptr -8

push  ebp
mov   ebp, esp
and   esp, 0FFFFFFF0h
sub   esp, 10h
mov   [esp+10h+var_8], 3 ; 3rd argument
mov   [esp+10h+var_C], 2 ; 2nd argument
mov   [esp+10h+var_10], 1 ; 1st argument
call  f
mov   edx, offset aD ; "%d\n"
mov   [esp+10h+var_C], eax
mov   [esp+10h+var_10], edx
call  _printf
mov   eax, 0
leave
retn
main  endp
```

The result is almost the same with some minor differences discussed earlier.

The stack pointer is not set back after the two function calls (f and printf), because the penultimate LEAVE (.1.6 on page 1028) instruction takes care of this at the end.

1.10.2 x64

The story is a bit different in x86-64. Function arguments (first 4 or first 6 of them) are passed in registers i.e. the callee reads them from registers instead of reading them from the stack.

**MSVC**

Optimizing MSVC:

```
Listing 1.89: Optimizing MSVC 2012 x64

$SG2997 DB '%d', 0aH, 00H
main PROC
sub   rsp, 40
mov   edx, 2
lea   r8d, QWORD PTR [rdx+1] ; R8D=3
lea   ecx, QWORD PTR [rdx-1] ; ECX=1
call  f
lea   rcx, OFFSET FLAT:$SG2997 ; '%d'
mov   edx, eax
call  printf
xor   eax, eax
add   rsp, 40
ret   0
main  ENDP

f PROC
; ECX - 1st argument
; EDX - 2nd argument
; R8D - 3rd argument
imul  ecx, edx
lea   eax, DWORD PTR [r8+rcx]
ret   0
f  ENDP
```
As we can see, the compact function \( f() \) takes all its arguments from the registers.

The LEA instruction here is used for addition, apparently the compiler considered it faster than ADD.

LEA is also used in the main() function to prepare the first and third \( f() \) arguments. The compiler must have decided that this would work faster than the usual way of loading values into a register using MOV instruction.

Let's take a look at the non-optimizing MSVC output:

```
Listing 1.90: MSVC 2012 x64

f proc near
; shadow space:
arg_0 = dword ptr 8
arg_8 = dword ptr 10h
arg_10 = dword ptr 18h

; ECX - 1st argument
; EDX - 2nd argument
; R8D - 3rd argument
mov [rsp+arg_10], r8d
mov [rsp+arg_8], edx
mov [rsp+arg_0], ecx
imul eax, [rsp+arg_0]
imul eax, [rsp+arg_8]
add eax, [rsp+arg_10]
retn
f endp

main proc near
sub rsp, 28h
mov r8d, 3 ; 3rd argument
mov edx, 2 ; 2nd argument
mov ecx, 1 ; 1st argument
call f
lea rcx, $SG2931 ; "%d\n"
call printf
; return 0
xor eax, eax
add rsp, 28h
retn
main endp
```

It looks somewhat puzzling because all 3 arguments from the registers are saved to the stack for some reason. This is called “shadow space” \(^{81}\): every Win64 may (but is not required to) save all 4 register values there. This is done for two reasons: 1) it is too lavish to allocate a whole register (or even 4 registers) for an input argument, so it will be accessed via stack; 2) the debugger is always aware where to find the function arguments at a break \(^{82}\).

So, some large functions can save their input arguments in the “shadows space” if they want to use them during execution, but some small functions (like ours) may not do this.

It is a caller responsibility to allocate “shadow space” in the stack.

**GCC**

Optimizing GCC generates more or less understandable code:

```
Listing 1.91: Optimizing GCC 4.4.6 x64

f:

; EDI - 1st argument
; ESI - 2nd argument
; EDX - 3rd argument
```

---

\(^{81}\) [MSDN]

\(^{82}\) [MSDN]
1.10. ACCESSING PASSED ARGUMENTS

```assembly
imul esi, edi
lea eax, [rdx+rsi]
ret

main:
sub rsp, 8
mov edx, 3
mov esi, 2
mov edi, 1
call f
mov edi, OFFSET FLAT:.LC0 ; "%d\n"
mov esi, eax
xor eax, eax ; number of vector registers passed
call printf
xor eax, eax
add rsp, 8
ret
```

Non-optimizing GCC:

```assembly
Listing 1.92: GCC 4.4.6 x64

f:
    ; EDI - 1st argument
    ; ESI - 2nd argument
    ; EDX - 3rd argument
push rbp
mov rbp, rsp
mov DWORD PTR [rbp-4], edi
mov DWORD PTR [rbp-8], esi
mov DWORD PTR [rbp-12], edx
mov eax, DWORD PTR [rbp-4]
imul eax, DWORD PTR [rbp-8]
add eax, DWORD PTR [rbp-12]
leave
ret
main:
push rbp
mov rbp, rsp
mov edx, 3
mov esi, 2
mov edi, 1
call f
mov edx, eax
mov edi, 0 ; number of vector registers passed
call printf
mov eax, 0
leave
ret
```

There are no “shadow space” requirements in System V *NIX ([Michael Matz, Jan Hubicka, Andreas Jaeger, Mark Mitchell, System V Application Binary Interface. AMD64 Architecture Processor Supplement, (2013)]

83), but the callee may want to save its arguments somewhere in case of registers shortage.

**GCC: uint64_t instead of int**

Our example works with 32-bit int, that is why 32-bit register parts are used (prefixed by E-).

It can be altered slightly in order to use 64-bit values:

```c
#include <stdio.h>
#include <stdint.h>

uint64_t f (uint64_t a, uint64_t b, uint64_t c)
```

83Also available as https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf
1.10. ACCESSING PASSED ARGUMENTS

```c
{    return a*b+c;
};

int main()
{
    printf("%lld\n", f(0x1122334455667788,
                    0x1111111122222222,
                    0x3333333344444444));
    return 0;
};
```

Listing 1.93: Optimizing GCC 4.4.6 x64

```assembly
f proc near
    imul    rsi, rdi
    lea     rax, [rdx+rsi]
    retn
f endp

main proc near
    sub     rsp, 8
    mov     rdx, 3333333344444444h ; 3rd argument
    mov     rsi, 1111111122222222h ; 2nd argument
    mov     rdi, 1122334455667788h ; 1st argument
    call    f
    mov     edi, offset format ; "%lld\n"
    mov     rsi, rax
    xor eax, eax ; number of vector registers passed
    call    _printf
    xor eax, eax
    add     rsp, 8
    retn
main endp
```

The code is the same, but this time the full size registers (prefixed by R-) are used.

1.10.3 ARM

**Non-optimizing Keil 6/2013 (ARM mode)**

```
.text:000000A4 00 30 A0 E1 MOV R3, R0
.text:000000A8 93 21 20 E0 MLA R0, R3, R1, R2
.text:000000AC 1E FF 2F E1 BX LR
... .text:000000B0 main
.text:000000B0 10 40 2D E9 STMFD SP!, {R4,LR}
.text:000000B4 03 20 A0 E3 MOV R2, #3
.text:000000B8 02 10 A0 E3 MOV R1, #2
.text:000000BC 01 00 A0 E3 MOV R0, #1
.text:000000C0 F7 FF FF EB BL f
.text:000000C4 00 40 A0 E1 MOV R4, R0
.text:000000C8 04 10 A0 E1 MOV R1, R4
.text:000000CC 5A 0F 8F E2 ADR R0, aD_0 ; "%d\n"
.text:000000D0 E3 18 00 EB BL __2printf
.text:000000D4 00 00 A0 E3 MOV R0, #0
.text:000000D8 10 80 BD E8 LDMFD SP!, {R4,PC}
```

The `main()` function simply calls two other functions, with three values passed to the first one — `f()`.

As was noted before, in ARM the first 4 values are usually passed in the first 4 registers (R0-R3).

The `f()` function, as it seems, uses the first 3 registers (R0-R2) as arguments.

The MLA (*Multiply Accumulate*) instruction multiplies its first two operands (R3 and R1), adds the third operand (R2) to the product and stores the result into the zeroth register (R0), via which, by standard, functions return values.
1.10. ACCESSING PASSED ARGUMENTS

Multiplication and addition at once (Fused multiply–add) is a very useful operation. By the way, there was no such instruction in x86 before FMA-instructions appeared in SIMD 84.

The very first MOV R3, R0, instruction is, apparently, redundant (a single MLA instruction could be used here instead). The compiler has not optimized it, since this is non-optimizing compilation.

The BX instruction returns the control to the address stored in the LR register and, if necessary, switches the processor mode from Thumb to ARM or vice versa. This can be necessary since, as we can see, function f() is not aware from what kind of code it may be called, ARM or Thumb. Thus, if it gets called from Thumb code, BX is not only returns control to the calling function, but also switches the processor mode to Thumb. Or not switch, if the function has been called from ARM code [ARM(R) Architecture Reference Manual, ARMv7-A and ARMv7-R edition, (2012)A2.3.2].

Optimizing Keil 6/2013 (ARM mode)

```
.text:00000098  f
.text:00000098  91 20 20 E0  MLA  R0, R1, R0, R2
.text:0000009C  1F FF 2F E1  BX  LR
```

And here is the f() function compiled by the Keil compiler in full optimization mode (-O3).

The MOV instruction was optimized out (or reduced) and now MLA uses all input registers and also places the result right into R0, exactly where the calling function will read and use it.

Optimizing Keil 6/2013 (Thumb mode)

```
.text:0000005E  48 43  MULS  R0, R1
.text:00000060  80 18  ADDS  R0, R0, R2
.text:00000062  70 47  BX  LR
```

The MLA instruction is not available in Thumb mode, so the compiler generates the code doing these two operations (multiplication and addition) separately.

First the MULS instruction multiplies R0 by R1, leaving the result in register R0. The second instruction (ADDS) adds the result and R2 leaving the result in register R0.

ARM64

Optimizing GCC (Linaro) 4.9

Everything here is simple. MADD is just an instruction doing fused multiply/add (similar to the MLA we already saw). All 3 arguments are passed in the 32-bit parts of X-registers. Indeed, the argument types are 32-bit int's. The result is returned in W0.

<table>
<thead>
<tr>
<th>Listing 1.94: Optimizing GCC (Linaro) 4.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>f:</td>
</tr>
<tr>
<td>madd  w0, w0, w1, w2</td>
</tr>
<tr>
<td>ret</td>
</tr>
<tr>
<td>main:</td>
</tr>
<tr>
<td>; save FP and LR to stack frame:</td>
</tr>
<tr>
<td>stp  x29, x30, [sp, -16]!</td>
</tr>
<tr>
<td>mov  w2, 3</td>
</tr>
<tr>
<td>mov  w1, 2</td>
</tr>
<tr>
<td>add  x29, sp, 0</td>
</tr>
<tr>
<td>mov  w0, 1</td>
</tr>
<tr>
<td>bl  f</td>
</tr>
<tr>
<td>mov  w1, w0</td>
</tr>
<tr>
<td>adrp  x0, .LC7</td>
</tr>
<tr>
<td>add  x0, x0, :lo12:.LC7</td>
</tr>
<tr>
<td>bl  printf</td>
</tr>
<tr>
<td>; return 0</td>
</tr>
</tbody>
</table>

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1.10. ACCESSING PASSED ARGUMENTS

```asm
mov w0, 0
; restore FP and LR
ldp x29, x30, [sp], 16
ret

.LC7:
.string "\%d\n"
```

Let's also extend all data types to 64-bit uint64_t and test:

```c
#include <stdio.h>
#include <stdint.h>

uint64_t f (uint64_t a, uint64_t b, uint64_t c)
{
    return a*b+c;
};

int main()
{
    printf ("%lld\n", f(0x1122334455667788,
                     0x1111111122222222,
                     0x3333333344444444));
    return 0;
};
```

```asm
f:
madd x0, x0, x1, x2
ret

main:
mov x1, 13396
adrp x0, .LC8
stp x29, x30, [sp, -16]!
movk x1, 0x27d0, lsl 16
add x0, x0, :lo12:.LC8
movk x1, 0x122, lsl 32
add x29, sp, 0
movk x1, 0x58be, lsl 48
bl printf
mov w0, 0
ldp x29, x30, [sp], 16
ret

.LC8:
.string "%lld\n"
```

The f() function is the same, only the whole 64-bit X-registers are now used. Long 64-bit values are loaded into the registers by parts, this is also described here: 1.32.3 on page 440.

**Non-optimizing GCC (Linaro) 4.9**

The non-optimizing compiler is more redundant:

```asm
f:
sub sp, sp, #16
str w0, [sp,12]
str w1, [sp,8]
str w2, [sp,4]
ldr w1, [sp,12]
ldr w0, [sp,8]
mul w1, w1, w0
ldr w0, [sp,4]
add w0, w1, w0
add sp, sp, 16
ret
```
The code saves its input arguments in the local stack, in case someone (or something) in this function needs using the W0...W2 registers. This prevents overwriting the original function arguments, which may be needed again in the future.

This is called Register Save Area. ([Procedure Call Standard for the ARM 64-bit Architecture (AArch64), (2013)](http://www.arm.com/assets/ARM files/ Architecture/ARM64-ArchSpecUni.pdf)). The callee, however, is not obliged to save them. This is somewhat similar to “Shadow Space”: 1.10.2 on page 100.

Why did the optimizing GCC 4.9 drop this argument saving code? Because it did some additional optimizing work and concluded that the function arguments will not be needed in the future and also that the registers W0...W2 will not be used.

We also see a MUL/ADD instruction pair instead of single a MADD.

### 1.10.4 MIPS

Listing 1.95: Optimizing GCC 4.4.5

```assembly
.text:00000000 f:
    ; $a0=a
    ; $a1=b
    ; $a2=c
.text:00000000 mult $a1, $a0
.text:00000004 mflo $v0
.text:00000008 jr $ra
; result is in $v0 upon return
.text:00000010 main:
.text:00000010 .text:00000010 var_10 = -0x10
.text:00000010 var_4 = -4
.text:00000010 .text:00000010 lui $gp, (__gnu_local_gp >> 16)
.text:00000014 addiu $sp, -0x20
.text:00000018 la $gp, (__gnu_local_gp & 0xFFFF)
.text:0000001C sw $ra, 0x20+var_4($sp)
.text:00000020 sw $gp, 0x20+var_10($sp)
    ; set c:
.text:00000024 li $a2, 3
.text:00000028 li $a0, 1
.text:0000002C jal f
    ; set b:
.text:00000030 li $a1, 2
    ; result in $v0 now
.text:00000034 lw $gp, 0x20+var_10($sp)
.text:00000038 lui $a0, ($LC0 >> 16)
.text:0000003C lw $t9, (printf & 0xFFFF)( $gp)
.text:00000040 la $a0, ($LC0 & 0xFFFF)
.text:00000044 jalr $t9
; take result of f() function and pass it as a second argument to printf():
.text:00000048 move $a1, $v0
.text:0000004C lw $ra, 0x20+var_4($sp)
.text:00000050 move $v0, $zero
.text:00000054 jr $ra
.text:00000058 addiu $sp, 0x20
```

The first four function arguments are passed in four registers prefixed by A-.

There are two special registers in MIPS: HI and LO which are filled with the 64-bit result of the multiplication during the execution of the MULT instruction.

These registers are accessible only by using the MFL0 and MFHI instructions. MFL0 here takes the low-part of the multiplication result and stores it into $V0. So the high 32-bit part of the multiplication result is dropped (the HI register content is not used). Indeed: we work with 32-bit int data types here.

Finally, ADDU (“Add Unsigned”) adds the value of the third argument to the result.

---

85 Also available as [http://go.yurichev.com/17287](http://go.yurichev.com/17287)
1.11. MORE ABOUT RESULTS RETURNING

There are two different addition instructions in MIPS: ADD and ADDU. The difference between them is not related to signedness, but to exceptions. ADD can raise an exception on overflow, which is sometimes useful and supported in Ada PL, for instance. ADDU does not raise exceptions on overflow.

Since C/C++ does not support this, in our example we see ADDU instead of ADD.

The 32-bit result is left in $V0.

There is a new instruction for us in main(): JAL ("Jump and Link").

The difference between JAL and JALR is that a relative offset is encoded in the first instruction, while JALR jumps to the absolute address stored in a register ("Jump and Link Register").

Both f() and main() functions are located in the same object file, so the relative address of f() is known and fixed.

1.11 More about results returning

In x86, the result of function execution is usually returned in the EAX register. If it is byte type or a character (char), then the lowest part of register EAX (AL) is used. If a function returns a float number, the FPU register ST(0) is used instead. In ARM, the result is usually returned in the R0 register.

1.11.1 Attempt to use the result of a function returning void

So, what if the main() function return value was declared of type void and not int? The so-called startup-code is calling main() roughly as follows:

```
push envp
push argv
push argc
call main
push eax
call exit
```

In other words:

```
exit(main(argc,argv,envp));
```

If you declare main() as void, nothing is to be returned explicitly (using the return statement), then something random, that has been stored in the EAX register at the end of main() becomes the sole argument of the exit() function. Most likely, there will be a random value, left from your function execution, so the exit code of program is pseudorandom.

We can illustrate this fact. Please note that here the main() function has a void return type:

```
#include <stdio.h>

void main()
{
    printf ("Hello, world!\n");
};
```

Let's compile it in Linux.

GCC 4.8.1 replaced printf() with puts() (we have seen this before: 1.5.4 on page 21), but that's OK, since puts() returns the number of characters printed out, just like printf(). Please notice that EAX is not zeroed before main()'s end.

This implies that the value of EAX at the end of main() contains what puts() has left there.

Listing 1.96: GCC 4.8.1

```
.LC0:
    .string "Hello, world!"
main:
```

---

86 http://go.yurichev.com/17326
87 See also: MSDN: Return Values (C++): MSDN
1.11. MORE ABOUT RESULTS RETURNING

Let’s write a bash script that shows the exit status:

Listing 1.97: tst.sh

```bash
#!/bin/sh
./hello_world
echo $?
```

And run it:

```
$ tst.sh
Hello, world!
14
```

14 is the number of characters printed. The number of characters printed is slips from printf() through EAX/RAX into “exit code”.

By the way, when we decompile C++ in Hex-Rays, we can often encounter a function which terminated with destructor of some class:

```c
... 
call ??1CString@@QAE@XZ ; CString::~CString(void) 
mov ecx, [esp+30h+var_C] 
op edi 
op ebx 
mov large fs:0, ecx 
add esp, 28h 
retn
```

By C++ standard, destructor doesn’t return anything, but when Hex-Rays don’t know about it, and thinks that both destructor and this function returns int, we can see something like that in output:

```c
... 
    return CString::~CString(&Str);
}
```

1.11.2 What if we do not use the function result?

printf() returns the count of characters successfully output, but the result of this function is rarely used in practice.

It is also possible to call a function whose essence is in returning a value, and not use it:

```c
int f()
{
    // skip first 3 random values:
    rand();
    rand();
    rand();
    // and use 4th:
    return rand();
};
```

The result of the rand() function is left in EAX, in all four cases.

But in the first 3 cases, the value in EAX is just not used.
1.11.3 Returning a structure

Let’s go back to the fact that the return value is left in the EAX register.

That is why old C compilers cannot create functions capable of returning something that does not fit in one register (usually `int`), but if one needs it, one have to return information via pointers passed as function’s arguments.

So, usually, if a function needs to return several values, it returns only one, and all the rest—via pointers.

Now it has become possible to return, let’s say, an entire structure, but that is still not very popular. If a function has to return a large structure, the caller must allocate it and pass a pointer to it via the first argument, transparently for the programmer. That is almost the same as to pass a pointer in the first argument manually, but the compiler hides it.

Small example:

```c
struct s
{
    int a;
    int b;
    int c;
};
struct s get_some_values (int a)
{
    struct s rt;
    rt.a=a+1;
    rt.b=a+2;
    rt.c=a+3;
    return rt;
};
```

...what we got (MSVC 2010 /Ox):

```assembly
$T3853 = 8 ; size = 4
_a$ = 12 ; size = 4
$get_some_values@@YA?AUs@@H@Z PROC ; get_some_values
     mov ecx, DWORD PTR _a$[esp-4]
     mov eax, DWORD PTR $T3853[esp-4]
     lea edx, DWORD PTR [ecx+1]
     mov DWORD PTR [eax], edx
     lea edx, DWORD PTR [ecx+2]
     add ecx, 3
     mov DWORD PTR [eax+4], edx
     mov DWORD PTR [eax+8], ecx
     ret 0
$get_some_values@@YA?AUs@@H@Z ENDP ; get_some_values
```

The macro name for internal passing of pointer to a structure here is `$T3853`.

This example can be rewritten using the C99 language extensions:

```c
struct s
{
    int a;
    int b;
    int c;
};
struct s get_some_values (int a)
{
    return (struct s){.a=a+1,.b=a+2,.c=a+3};
};
```

Listing 1.98: GCC 4.8.1
1.12. POINTERS

ptr_to_struct = dword ptr 4
a = dword ptr 8

mov edx, [esp+a]
mov eax, [esp+ptr_to_struct]
lea ecx, [edx+1]
mov [eax], ecx
lea ecx, [edx+2]
add edx, 3
mov [eax+4], ecx
mov [eax+8], edx
retn

_get_some_values endp

As we see, the function is just filling the structure’s fields allocated by the caller function, as if a pointer to the structure has been passed. So there are no performance drawbacks.

1.12 Pointers

1.12.1 Swap input values

This will do the job:

```c
#include <memory.h>
#include <stdio.h>

void swap_bytes (unsigned char* first, unsigned char* second)
{
    unsigned char tmp1;
    unsigned char tmp2;

    tmp1=*first;
    tmp2=*second;

    *first=tmp2;
    *second=tmp1;
}

int main()
{
    // copy string into heap, so we will be able to modify it
    char *s=strdup("string");

    // swap 2nd and 3rd characters
    swap_bytes (s+1, s+2);

    printf ("%s\n", s);
}
```

As we can see, bytes are loaded into lower 8-bit parts of ECX and EBX using MOVZX (so higher parts of these registers will be cleared) and then bytes are written back swapped.

Listing 1.99: Optimizing GCC 5.4

```assembly
    push ebx
    mov edx, DWORD PTR [esp+8]
mov eax, DWORD PTR [esp+12]
movzx ecx, BYTE PTR [edx]
movzx ebx, BYTE PTR [eax]
mov BYTE PTR [edx], bl
mov BYTE PTR [eax], cl
pop ebx
ret
```

Addresses of both bytes are taken from arguments and through execution of the function are located in EDX and EAX.
1.12. POINTERS

So we use pointers: probably, there is no better way to solve this task without them.

1.12.2 Returning values

Pointers are often used to return values from functions (recall `scanf()` case (1.9 on page 66)). For example, when a function needs to return two values.

Global variables example

```c
#include <stdio.h>

void f1 (int x, int y, int *sum, int *product)
{
    *sum=x+y;
    *product=x*y;
}

int sum, product;
void main()
{
    f1(123, 456, &sum, &product);
    printf ("sum=%d, product=%d\n", sum, product);
}
```

This compiles to:

```assembly
Listing 1.100: Optimizing MSVC 2010 (/Ob0)
```

```assembly
COMM _product:DWORD
COMM _sum:DWORD
$SG2803 DB 'sum=%d, product=%d', 0aH, 00H
_x$ = 8 ; size = 4
_y$ = 12 ; size = 4
_sum$ = 16 ; size = 4
_product$ = 20 ; size = 4
_f1 PROC
    mov ecx, DWORD PTR _y$[esp-4]
    mov eax, DWORD PTR _x$[esp-4]
    lea edx, DWORD PTR [eax+ecx]
    imul eax, ecx
    mov ecx, DWORD PTR _product$[esp-4]
    push esi
    mov esi, DWORD PTR _sum$[esp]
    mov DWORD PTR [esi], edx
    mov DWORD PTR [ecx], eax
    pop esi
    ret 0
_f1 ENDP

_main PROC
    push OFFSET _product
    push OFFSET _sum
    push 456 ; 000001c8H
    push 123 ; 0000007bH
    call _f1
    mov eax, DWORD PTR _product
    mov ecx, DWORD PTR _sum
    push eax
    push ecx
    push OFFSET $SG2803
    call DWORD PTR __imp__printf
    add esp, 28
    xor eax, eax
    ret 0
```

```
1.12. POINTERS

_main ENDP
1.12. POINTERS

Let’s see this in OllyDbg:

![CPU - main thread, module global]

First, global variables’ addresses are passed to f1(). We can click “Follow in dump” on the stack element, and we can see the place in the data segment allocated for the two variables.
1.12. POINTERS

These variables are zeroed, because non-initialized data (from BSS) is cleared before the execution begins, [see ISO/IEC 9899:TC3 (C C99 standard), (2007) 6.7.8p10].

They reside in the data segment, we can verify this by pressing Alt-M and reviewing the memory map:

![Memory Map](image)

Figure 1.25: OllyDbg: memory map
Let's trace (F7) to the start of f1():

Figure 1.26: OllyDbg: f1() starts

Two values are visible in the stack: 456 (0x1C8) and 123 (0x7B), and also the addresses of the two global variables.
Let's trace until the end of f1(). In the left bottom window we see how the results of the calculation appear in the global variables:

Figure 1.27: OllyDbg: f1() execution completed
1.12. POINTERS

Now the global variables’ values are loaded into registers ready for passing to printf() (via the stack):

![Image of OllyDbg: global variables' values are passed into printf()](image)

**Local variables example**

Let’s rework our example slightly:

```c
void main()
{
    int sum, product; // now variables are local in this function
    f1(123, 456, &sum, &product);
    printf ("sum=%d, product=%d\n", sum, product);
}
```

f1() code will not change. Only the code of main() will do:

```assembly
; Line 10
sub esp, 8
; Line 13
lea eax, DWORD PTR _product$[esp+8]
push eax
lea ecx, DWORD PTR _sum$[esp+12]
push ecx
push 456 ; 000001c8H
push 123 ; 0000007bH
call _f1
; Line 14
mov edx, DWORD PTR _product$[esp+24]
push edx
mov eax, DWORD PTR _sum$[esp+24]
push eax
push OFFSET $SG2803
call DWORD PTR __imp__printf
; Line 15
xor eax, eax
add esp, 36
```

![Image of CPU - main thread, module global](image)
1.12. POINTERS

<table>
<thead>
<tr>
<th>ret</th>
<th>0</th>
</tr>
</thead>
</table>

Let’s look again with OllyDbg. The addresses of the local variables in the stack are 0x2EF854 and 0x2EF858. We see how these are pushed into the stack:

![OllyDbg: local variables’ addresses are pushed into the stack](image)

Figure 1.29: OllyDbg: local variables’ addresses are pushed into the stack
1.12. POINTERS

f1() starts. So far there is only random garbage in the stack at 0x2EF854 and 0x2EF858:

**Figure 1.30: OllyDbg: f1() starting**
1.13. GOTO OPERATOR

f1() completes:

![OllyDbg screenshot](image)

Figure 1.31: OllyDbg: f1() completes execution

We now find 0xDB18 and 0x243 at addresses 0x2EF854 and 0x2EF858. These values are the f1() results.

Conclusion

f1() could return pointers to any place in memory, located anywhere.

This is in essence the usefulness of the pointers.

By the way, C++ references work exactly the same way. Read more about them: (3.18.3 on page 558).

1.13 GOTO operator

The GOTO operator is generally considered as anti-pattern, see [Edgar Dijkstra, Go To Statement Considered Harmful (1968)](http://yurichev.com/mirrors/Dijkstra68.pdf). Nevertheless, it can be used reasonably, see [Donald E. Knuth, Structured Programming with go to Statements (1974)](http://yurichev.com/mirrors/KnuthStructuredProgrammingGoTo.pdf).

Here is a very simple example:

```c
#include <stdio.h>

int main()
{
    printf("begin\n");
    goto exit;
    printf("skip me!\n");
exit:
    printf("end\n");
}
```

Here is what we have got in MSVC 2012:

```
Listing 1.103: MSVC 2012
```

88 http://yurichev.com/mirrors/Dijkstra68.pdf
89 http://yurichev.com/mirrors/KnuthStructuredProgrammingGoTo.pdf
90 [Dennis Yurichev, C/C++ programming language notes] also has some examples.
The goto statement has been simply replaced by a JMP instruction, which has the same effect: unconditional jump to another place. The second printf() could be executed only with human intervention, by using a debugger or by patching the code.
1.13. GOTO OPERATOR

This could also be useful as a simple patching exercise. Let’s open the resulting executable in Hiew:

Figure 1.32: Hiew
1.13. **GOTO OPERATOR**

Place the cursor to address JMP (0x410), press F3 (edit), press zero twice, so the opcode becomes EB 00:

![Image of Hiew showing the edited opcode]

The second byte of the JMP opcode denotes the relative offset for the jump, 0 means the point right after the current instruction.

So now JMP not skipping the second `printf()` call.

Press F9 (save) and exit. Now if we run the executable we will see this:

```
C:\...>goto.exe
begin
skip me!
end
```

The same result could be achieved by replacing the JMP instruction with 2 NOP instructions.

NOP has an opcode of 0x90 and length of 1 byte, so we need 2 instructions as JMP replacement (which is 2 bytes in size).

### 1.13.1 Dead code

The second `printf()` call is also called “dead code” in compiler terms.

This means that the code will never be executed. So when you compile this example with optimizations, the compiler removes “dead code”, leaving no trace of it:

```
$SG2981 DB 'begin', 0aH, 00H
$SG2983 DB 'skip me!', 0aH, 00H
$SG2984 DB 'end', 0aH, 00H

_main PROC
    push OFFSET $SG2981 ; 'begin'
    call _printf
    push OFFSET $SG2984 ; 'end'
$exit$4:
    call _printf
    add esp, 8
```

![Image of Assembly code after optimization]
1.14. CONDITIONAL JUMPS

```
xor    eax, eax
ret    0
```

However, the compiler forgot to remove the “skip me!” string.

1.13.2 Exercise

Try to achieve the same result using your favorite compiler and debugger.

1.14 Conditional jumps

1.14.1 Simple example

```c
#include <stdio.h>

void f_signed (int a, int b)
{
    if (a>b)
        printf ("a>b\n");
    if (a==b)
        printf ("a==b\n");
    if (a<b)
        printf ("a<b\n");
};

void f_unsigned (unsigned int a, unsigned int b)
{
    if (a>b)
        printf ("a>b\n");
    if (a==b)
        printf ("a==b\n");
    if (a<b)
        printf ("a<b\n");
};

int main()
{
    f_signed(1, 2);
    f_unsigned(1, 2);
    return 0;
};
```

**x86**

**x86 + MSVC**

Here is how the `f_signed()` function looks like:

```
Listing 1.106: Non-optimizing MSVC 2010

    a$ = 8
    b$ = 12
    f_signed PROC
        push ebp
        mov ebp, esp
        mov eax, DWORD PTR _a$[ebp]
        cmp eax, DWORD PTR _b$[ebp]
        jle SHORT $LN3@f_signed
        push OFFSET $SG737 ; 'a>b'
        call _printf
        add esp, 4
```

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The first instruction, JLE, stands for *Jump if Less or Equal*. In other words, if the second operand is larger or equal to the first one, the control flow will be passed to the address or label specified in the instruction. If this condition does not trigger because the second operand is smaller than the first one, the control flow would not be altered and the first *printf()* would be executed. The second check is JNE: *Jump if Not Equal*. The control flow will not change if the operands are equal.

The third check is JGE: *Jump if Greater or Equal*—jump if the first operand is larger than the second or if they are equal. So, if all three conditional jumps are triggered, none of the *printf()* calls would be executed whatsoever. This is impossible without special intervention. Now let's take a look at the *f_unsigned()* function. The *f_unsigned()* function is the same as *f_signed()* function, with the exception that the JBE and JAE instructions are used instead of JLE and JGE, as follows:

Listing 1.107: GCC

As already mentioned, the branch instructions are different: JBE—*Jump if Below or Equal* and JAE—*Jump if Above or Equal*. These instructions (JA/JAE/JB/JBE) differ from JG/JGE/JL/JLE in the fact that they work with unsigned numbers.

See also the section about signed number representations (2.2 on page 452). That is why if we see JG/JL in use instead of JA/JB or vice-versa, we can be almost sure that the variables are signed or unsigned, respectively. Here is also the main() function, where there is nothing much new to us:
1.14. CONDITIONAL JUMPS

Listing 1.108: main()

```
_main PROC
    push ebp
    mov ebp, esp
    push 2
    push 1
    call _f_signed
    add esp, 8
    push 2
    push 1
    call _f_unsigned
    add esp, 8
    xor eax, eax
    pop ebp
    ret 0

_main ENDP
```
We can see how flags are set by running this example in OllyDbg. Let's begin with `f_unsigned()`, which works with unsigned numbers.

**Figure 1.34: OllyDbg: f_unsigned(): first conditional jump**

So, the flags are: C=1, P=1, A=1, Z=0, S=1, T=0, D=0, O=0.

They are named with one character for brevity in OllyDbg.

OllyDbg gives a hint that the (JBE) jump is to be triggered now. Indeed, if we take a look into Intel manuals (12.1.4 on page 1013), we can read there that JBE is triggering if CF=1 or ZF=1. The condition is true here, so the jump is triggered.
1.14. CONDITIONAL JUMPS

The next conditional jump:

![Image of OllyDbg showing the CPU and registers](image)

Figure 1.35: OllyDbg: `f_unsigned()`: second conditional jump

OllyDbg gives a hint that `JNZ` is to be triggered now. Indeed, `JNZ` triggering if ZF=0 (zero flag).
1.14. CONDITIONAL JUMPS

The third conditional jump, JNB:

In Intel manuals (12.1.4 on page 1013) we can see that JNB triggers if CF=0 (carry flag). That is not true in our case, so the third printf() will execute.
1.14. CONDITIONAL JUMPS

Now let’s review the $f_{\text{signed}}()$ function, which works with signed values, in OllyDbg. Flags are set in the same way: $C=1$, $P=1$, $A=1$, $Z=0$, $S=1$, $T=0$, $D=0$, $O=0$. The first conditional jump $JLE$ is to be triggered:

In Intel manuals ([12.1.4 on page 1013](#)) we find that this instruction is triggered if $ZF=1$ or $SF \neq OF$. $SF \neq OF$ in our case, so the jump triggers.

Figure 1.37: OllyDbg: $f_{\text{signed}}()$: first conditional jump
1.14. **CONDITIONAL JUMPS**

The second JNZ conditional jump triggering: if ZF=0 (zero flag):

![OllyDbg: f_signed() second conditional jump](image)

Figure 1.38: OllyDbg: f_signed(): second conditional jump
1.14. CONDITIONAL JUMPS

The third conditional jump JGE will not trigger because it would only do so if SF=OF, and that is not true in our case:

![Figure 1.39: OllyDbg: f_signed(): third conditional jump](image-url)

---

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We can try to patch the executable file in a way that the `f_unsigned()` function would always print “a==b”, no matter the input values. Here is how it looks in Hiew:

![Hiew code snippet](image)

Figure 1.40: Hiew: `f_unsigned()` function

Essentially, we have to accomplish three tasks:

- force the first jump to always trigger;
- force the second jump to never trigger;
- force the third jump to always trigger.

Thus we can direct the code flow to always pass through the second printf(), and output “a==b”.

Three instructions (or bytes) has to be patched:

- The first jump becomes JMP, but the jump offset would remain the same.
- The second jump might be triggered sometimes, but in any case it will jump to the next instruction, because, we set the jump offset to 0.
  
  In these instructions the jump offset is added to the address for the next instruction. So if the offset is 0, the jump will transfer the control to the next instruction.
- The third jump we replace with JMP just as we do with the first one, so it will always trigger.
1.14. CONDITIONAL JUMPS

Here is the modified code:

```
Figure 1.41: Hiew: let’s modify the f_unsigned() function

If we miss to change any of these jumps, then several printf() calls may execute, while we want to execute only one.

Non-optimizing GCC

Non-optimizing GCC 4.4.1 produces almost the same code, but with puts() (1.5.4 on page 21) instead of printf().

Optimizing GCC

An observant reader may ask, why execute CMP several times, if the flags has the same values after each execution?

Perhaps optimizing MSVC cannot do this, but optimizing GCC 4.8.1 can go deeper:

```
Listing 1.109: GCC 4.8.1 f_signed()

<table>
<thead>
<tr>
<th>Line</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>.L6:</td>
<td>mov DWORD PTR [esp+4], OFFSET FLAT:.LC2 ; &quot;a&lt;b&quot;</td>
</tr>
<tr>
<td>.L7:</td>
<td>jmp puts</td>
</tr>
<tr>
<td>.L8:</td>
<td>mov DWORD PTR [esp+4], OFFSET FLAT:.LC0 ; &quot;a&gt;b&quot;</td>
</tr>
</tbody>
</table>
```
### 1.14. CONDITIONAL JUMPS

```plaintext
jmp puts
.L1:
    rep ret
.L7:
    mov DWORD PTR [esp+4], OFFSET FLAT:.LC1 ; "a==b"
    jmp puts
```

We also see JMP puts here instead of CALL puts / RETN. This kind of trick will have explained later: [1.15.1 on page 154](#).

This type of x86 code is somewhat rare. MSVC 2012 as it seems, can’t generate such code. On the other hand, assembly language programmers are fully aware of the fact that Jcc instructions can be stacked. So if you see such stacking somewhere, it is highly probable that the code was hand-written.

The `f_unsigned()` function is not that æsthetically short:

Listing 1.110: GCC 4.8.1 `f_unsigned()`

```c
f_unsigned:
    push esi
    push ebx
    sub esp, 20
    mov esi, DWORD PTR [esp+32]
    mov ebx, DWORD PTR [esp+36]
    cmp esi, ebx
    ja .L13
    cmp esi, ebx ; this instruction could be removed
    je .L14
    .L10:
    jb .L15
    add esp, 20
    pop ebx
    pop esi
    ret
    .L15:
    mov DWORD PTR [esp+32], OFFSET FLAT:.LC2 ; "a<b"
    add esp, 20
    pop ebx
    pop esi
    jmp puts
    .L13:
    mov DWORD PTR [esp], OFFSET FLAT:.LC0 ; "a>b"
    call puts
    cmp esi, ebx
    jne .L10
    .L14:
    mov DWORD PTR [esp+32], OFFSET FLAT:.LC1 ; "a==b"
    add esp, 20
    pop ebx
    pop esi
    jmp puts
```

Nevertheless, there are two CMP instructions instead of three. So optimization algorithms of GCC 4.8.1 are probably not perfect yet.

### ARM

### 32-bit ARM

**Optimizing Keil 6/2013 (ARM mode)**

Listing 1.111: Optimizing Keil 6/2013 (ARM mode)
1.14. CONDITIONAL JUMPS

Many instructions in ARM mode could be executed only when specific flags are set. E.g. this is often used when comparing numbers.

For instance, the ADD instruction is in fact named ADDAL internally, where AL stands for Always, i.e., execute always. The predicates are encoded in 4 high bits of the 32-bit ARM instructions (condition field). The B instruction for unconditional jumping is in fact conditional and encoded just like any other conditional jump, but has AL in the condition field, and it implies execute Always, ignoring flags.

The ADRGT instruction works just like ADR but executes only in case the previous CMP instruction founds one of the numbers greater than the another, while comparing the two (Greater Than).

The next BLGT instruction behaves exactly as BL and is triggered only if the result of the comparison has been (Greater Than). ADRGT writes a pointer to the string a>b\n into R0 and BLGT calls printf(). Therefore, instructions suffixed with -GT are to execute only in case the value in R0 (which is a) is bigger than the value in R4 (which is b).

Moving forward we see the ADREQ and BLEQ instructions. They behave just like ADR and BL, but are to be executed only if operands were equal to each other during the last comparison. Another CMP is located before them (because the printf() execution may have tampered the flags).

Then we see LDMGEFD, this instruction works just like LDMFD\textsuperscript{91}, but is triggered only when one of the values is greater or equal than the other (Greater or Equal). The LDMGEFD SP!, {R4-R6,PC} instruction acts like a function epilogue, but it will be triggered only if a >= b, and only then the function execution will finish.

But if that condition is not satisfied, i.e., a < b, then the control flow will continue to the next “LDMFD SP!, {R4-R6,LR}” instruction, which is one more function epilogue. This instruction restores not only the R4-R6 registers state, but also LR instead of PC, thus, it does not return from the function. The last two instructions call printf() with the string «a<b\n» as a sole argument. We already examined an unconditional jump to the printf() function instead of function return in «printf() with several arguments» section (1.8.2 on page 54).

f_unsigned is similar, only the ADRHI, BLHI, and LDMCSFD instructions are used there, these predicates (HI = Unsigned higher, CS = Carry Set (greater than or equal)) are analogous to those examined before, but for unsigned values.

There is not much new in the main() function for us:

\text{Listing 1.112: main()}
\begin{verbatim}
.text:00000128 EXPORT main
.text:00000128 main
.text:00000128 10 40 2D E9 STMFD SP!, {R4-LR}
.text:0000012C 02 10 A0 E3 MOV R1, #2
.text:00000130 01 00 A0 E3 MOV R0, #1
.text:00000134 DF FF FF EB BL f_signed
.text:00000138 02 10 A0 E3 MOV R1, #2
.text:0000013C 01 00 A0 E3 MOV R0, #1
.text:00000140 EA FF FF EB BL f_unsigned
.text:00000144 00 00 A0 E3 MOV R0, #0
.text:00000148 10 80 BD E8 LDMFD SP!, {R4,PC}
.text:0000014C ; End of function main
\end{verbatim}

\textsuperscript{91}LDMFD
1.14. CONDITIONAL JUMPS

That is how you can get rid of conditional jumps in ARM mode.

Why is this so good? Read here: 2.10.1 on page 466.

There is no such feature in x86, except the CMOVcc instruction, it is the same as MOV, but triggered only when specific flags are set, usually set by CMP.

Optimizing Keil 6/2013 (Thumb mode)

Listing 1.113: Optimizing Keil 6/2013 (Thumb mode)

<table>
<thead>
<tr>
<th>Text</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>.text:00000072</td>
<td>f_signed ; CODE XREF: main+6</td>
</tr>
<tr>
<td>.text:00000072 70 B5</td>
<td>PUSH {R4-R6,LR}</td>
</tr>
<tr>
<td>.text:00000074 0C 00</td>
<td>MOVs R4, R1</td>
</tr>
<tr>
<td>.text:00000076 05 00</td>
<td>MOVs R5, R0</td>
</tr>
<tr>
<td>.text:00000078 A0 42</td>
<td>CMP R0, R4</td>
</tr>
<tr>
<td>.text:0000007A 02 DD</td>
<td>BLE loc_82</td>
</tr>
</tbody>
</table>
| .text:0000007E A4 A0 ADR R0, aAB ; "a>b"
| .text:00000082 06 F0 B7 F8 | BL _2printf |
| .text:00000082 | loc_82 ; CODE XREF: f_signed+8 |
| .text:00000082 A5 42 | CMP R5, R4 |
| .text:00000084 02 D1 | BNE loc_8C |
| .text:00000086 A4 A0 | ADR R0, aAB_0 ; "a==b"
| .text:00000088 06 F0 B2 F8 | BL _2printf |
| .text:00000088 | loc_8C ; CODE XREF: f_signed+12 |
| .text:00000088 A5 42 | CMP R5, R4 |
| .text:0000008E 02 DA | BGE locret_96 |
| .text:00000090 A3 A0 | ADR R0, aAB_1 ; "a<b"
| .text:00000092 06 F0 AD F8 | BL _2printf |
| .text:00000092 | locret_96 ; CODE XREF: f_signed+1C |
| .text:00000096 70 BD | POP {R4-R6,PC} |
| .text:00000096 | ; End of function f_signed |

Only B instructions in Thumb mode may be supplemented by condition codes, so the Thumb code looks more ordinary.

BLE is a normal conditional jump Less than or Equal, BNE—Not Equal, BGE—Greater than or Equal.

f_unsigned is similar, only other instructions are used while dealing with unsigned values: BLs (Unsigned lower or same) and BCS (Carry Set (Greater than or equal)).

ARM64: Optimizing GCC (Linaro) 4.9

Listing 1.114: f_signed()

<table>
<thead>
<tr>
<th>Text</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_signed:</td>
<td>; W0=a, W1=b</td>
</tr>
<tr>
<td>cmp</td>
<td>w0, w1</td>
</tr>
<tr>
<td>bgt .L19 ; Branch if Greater Than (a&gt;b)</td>
<td></td>
</tr>
<tr>
<td>beq .L20 ; Branch if Equal (a==b)</td>
<td></td>
</tr>
<tr>
<td>bge .L15 ; Branch if Greater than or Equal (a&gt;=b) (impossible here)</td>
<td></td>
</tr>
<tr>
<td>; a&lt;b</td>
<td></td>
</tr>
<tr>
<td>adrp x0, .LC11 ; &quot;a&lt;b&quot;</td>
<td></td>
</tr>
<tr>
<td>add x0, x0, :lo12:.LC11</td>
<td></td>
</tr>
<tr>
<td>b puts .L19:</td>
<td></td>
</tr>
<tr>
<td>adrp x0, .LC9 ; &quot;a&gt;b&quot;</td>
<td></td>
</tr>
<tr>
<td>add x0, x0, :lo12:.LC9</td>
<td></td>
</tr>
<tr>
<td>b puts .L15: ; impossible to get here</td>
<td></td>
</tr>
<tr>
<td>ret .L20:</td>
<td></td>
</tr>
<tr>
<td>adrp x0, .LC10 ; &quot;a==b&quot;</td>
<td></td>
</tr>
<tr>
<td>add x0, x0, :lo12:.LC10</td>
<td></td>
</tr>
<tr>
<td>b puts</td>
<td></td>
</tr>
</tbody>
</table>
1.14. CONDITIONAL JUMPS

Listing 1.115: f_unsigned()

```
.f_unsigned:
  stp  x29, x30, [sp, -48]!
  ; W0=a, W1=b
  cmp  w0, w1
  add  x29, sp, 0
  str  x19, [sp,16]
  mov  w19, w0
  bhi  .L25 ; Branch if HIgher (a>b)
  cmp  w19, w1
  beq  .L26 ; Branch if Equal (a==b)
.L23:
  bcc  .L27 ; Branch if Carry Clear (if less than) (a<b)
  ; function epilogue, impossible to be here
  ldr  x19, [sp,16]
  ldp  x29, x30, [sp], 48
  ret
.L27:
  ldr  x19, [sp,16]
  adrp  x0, .LC11 ; "a<b"
  ldp  x29, x30, [sp], 48
  add  x0, x0, :lo12:.LC11
  b    puts
.L25:
  adrp  x0, .LC9 ; "a>b"
  str  x1, [x29,40]
  add  x0, x0, :lo12:.LC9
  b1   puts
  ldr  x1, [x29,40]
  cmp  w19, w1
  bne  .L23 ; Branch if Not Equal
.L26:
  ldr  x19, [sp,16]
  adrp  x0, .LC10 ; "a==b"
  ldp  x29, x30, [sp], 48
  add  x0, x0, :lo12:.LC10
  b    puts
```

The comments were added by the author of this book. What is striking is that the compiler is not aware that some conditions are not possible at all, so there is dead code at some places, which can never be executed.

Exercise

Try to optimize these functions manually for size, removing redundant instructions, without adding new ones.

MIPS

One distinctive MIPS feature is the absence of flags. Apparently, it was done to simplify the analysis of data dependencies.

There are instructions similar to SETcc in x86: SLT (“Set on Less Than”: signed version) and SLTU (unsigned version). These instructions sets destination register value to 1 if the condition is true or to 0 if otherwise. The destination register is then checked using BEQ (“Branch on Equal”) or BNE (“Branch on Not Equal”) and a jump may occur. So, this instruction pair has to be used in MIPS for comparison and branch. Let’s first start with the signed version of our function:

Listing 1.116: Non-optimizing GCC 4.4.5 (IDA)

```
.text:00000000 f_signed:
  ; CODE XREF: main+18
  .text:00000000 var_10 = -0x10
  .text:00000000 var_8 = -8
  .text:00000000 var_4 = -4
```
1.14. CONDITIONAL JUMPS

```assembly
.text:00000000 arg_0 = 0
.text:00000000 arg_4 = 4
.text:00000000 addiu $sp, -0x20
.text:00000004 sw $ra, 0x20+var_4($sp)
.text:00000008 sw $fp, 0x20+var_8($sp)
.text:0000000C move $fp, $sp
.text:00000010 la $gp, __gnu_local_gp
.text:00000018 sw $gp, 0x20+var_10($sp)

; store input values into local stack:
.text:0000001C sw $a0, 0x20+arg_0($fp)
.text:00000020 sw $a1, 0x20+arg_4($fp)

; $v0=b
; $v1=a
.text:0000002C or $at, $zero ; NOP
; this is pseudoinstruction. in fact, "slt $v0,$v0,$v1" is there.
; so $v0 will be set to 1 if $v0<$v1 (b<a) or to 0 if otherwise:
.text:00000030 slt $v0, $v1
; jump to loc_5C, if condition is not true.
; this is pseudoinstruction. in fact, "beq $v0,$zero,loc_5C" is there:
.text:00000034 beqz $v0, loc_5C

; print "a>b" and finish
.text:00000038 or $at, $zero ; branch delay slot, NOP
.text:0000003C lui $v0, (unk_230 >> 16) # "a>b"
.text:00000040 addiu $a0, $v0, (unk_230 & 0xFFFF) # "a>b"
.text:00000044 lw $v0, (puts & 0xFFFF)($gp)
.text:00000048 or $at, $zero ; NOP
.text:0000004C move $t9, $v0
.text:00000050 jalr $t9
.text:00000054 or $at, $zero ; branch delay slot, NOP
.text:00000058 lw $gp, 0x20+var_10($fp)

.loc_5C:

; check if a==b, jump to loc_90 if its not true:
.text:00000068 bne $v1, $v0, loc_90
.text:0000006C or $at, $zero ; branch delay slot, NOP
; condition is true, so print "a==b" and finish:
.text:00000070 lui $v0, (aAB >> 16) # "a==b"
.text:00000074 addiu $a0, $v0, (aAB & 0xFFFF) # "a==b"
.text:00000078 lw $v0, (puts & 0xFFFF)($gp)
.text:0000007C or $at, $zero ; NOP
.text:00000080 move $t9, $v0
.text:00000084 jalr $t9
.text:00000088 or $at, $zero ; branch delay slot, NOP
.text:0000008C lw $gp, 0x20+var_10($fp)

.loc_90:

; check if $v1<$v0 (a<b), set $v0 to 1 if condition is true:
.text:00000090 slt $v0, $v1, $v0
; if condition is not true (i.e., $v0==0), jump to loc_c8:
.text:0000009C beqz $v0, loc_c8
.text:000000A0 or $at, $zero ; branch delay slot, NOP
; condition is true, print "a<b" and finish
.text:000000A8 lui $v0, (aAB_0 >> 16) # "a<b"
.text:000000AC addiu $a0, $v0, (aAB_0 & 0xFFFF) # "a<b"
.text:000000B0 lw $v0, (puts & 0xFFFF)($gp)
.text:000000B4 or $at, $zero ; NOP
.text:000000B8 move $t9, $v0
.text:000000BC jalr $t9
.text:000000C0 or $at, $zero ; branch delay slot, NOP
.text:000000C4 lw $gp, 0x20+var_10($fp)
```
1.14. CONDITIONAL JUMPS

SLT REG0, REG0, REG1 is reduced by IDA to its shorter form: SLT REG0, REG1.

We also see there BEQZ pseudo instruction (“Branch if Equal to Zero”), which are in fact BEQ REG, $ZERO, LABEL.

The unsigned version is just the same, but SLTU (unsigned version, hence “U” in name) is used instead of SLT:

Listing 1.117: Non-optimizing GCC 4.4.5 (IDA)
1.14. CONDITIONAL JUMPS

```
.text:000000178 or $at, $zero
.text:00000017C sltu $v0, $v1, $v0
.text:000000180 beqz $v0, loc_1A8
.text:000000184 or $at, $zero
.text:000000188 lui $v0, (aAB_0 >> 16) # "a<b"
.text:00000018C addiu $a0, $v0, (aAB_0 & 0xFFFF) # "a<b"
.text:000000190 lw $v0, (puts & 0xFFFF)($gp)
.text:000000194 or $at, $zero
.text:000000198 move $t9, $v0
.text:00000019C jalr $t9
.text:0000001A0 or $at, $zero
.text:0000001A4 lw $v0, (puts & 0xFFFF)($gp)
.text:0000001A8 loc_1A8: # CODE XREF: f_unsigned+A0
.text:0000001A8 move $sp, $fp
.text:0000001AC lw $ra, 0x20+var_10($sp)
.text:0000001B0 lw $fp, 0x20+var_4($sp)
.text:0000001B4 addiu $sp, 0x20
.text:0000001B8 jr $ra
.text:0000001BC or $at, $zero
.text:0000001BC # End of function f_unsigned
```

1.14.2 Calculating absolute value

A simple function:

```c
int my_abs (int i)
{
    if (i<0)
        return -i;
    else
        return i;
}
```

Optimizing MSVC

This is how the code is usually generated:

Listing 1.118: Optimizing MSVC 2012 x64

```
i$ = 8
my_abs PROC
; ECX = input
    test ecx, ecx
; check for sign of input value
; skip NEG instruction if sign is positive
    jns SHORT $LN2@my_abs
; negate value
    neg ecx
$LN2@my_abs:
; prepare result in EAX:
    mov eax, ecx
    ret 0
my_abs ENDP
```

GCC 4.9 does mostly the same.

Optimizing Keil 6/2013: Thumb mode

Listing 1.119: Optimizing Keil 6/2013: Thumb mode

```
my_abs PROC
    CMP r0,#0
; is input value equal to zero or greater than zero?
```
### 1.14. CONDITIONAL JUMPS

```assembly
; skip RSBS instruction then
BGE \[L0.6]\n; subtract input value from 0:
RSBS r0,r0,#0
\[L0.6]\nBX lr
ENDP
```

ARM lacks a negate instruction, so the Keil compiler uses the “Reverse Subtract” instruction, which just subtracts with reversed operands.

#### Optimizing Keil 6/2013: ARM mode

It is possible to add condition codes to some instructions in ARM mode, so that is what the Keil compiler does:

```assembly
my_abs PROC
    CMP r0,#0
    ; execute "Reverse Subtract" instruction only if input value is less than 0:
    RSBLT r0,r0,#0
    BX lr
ENDP
```

Now there are no conditional jumps and this is good: 2.10.1 on page 466.

#### Non-optimizing GCC 4.9 (ARM64)

ARM64 has instruction NEG for negating:

```assembly
my_abs:
    sub sp, sp, #16
    str w0, [sp,12]
    ldr w0, [sp,12]
    ; compare input value with contents of WZR register
    ; (which always holds zero)
    cmp w0, wzr
    bge .L2
    neg w0, w0
    b .L3
.L2:
    ldr w0, [sp,12]
.L3:
    add sp, sp, 16
    ret
```

#### MIPS

```assembly
my_abs:
    ; jump if $a0<0:
    bltz $a0, locret_10
    ; just return input value ($a0) in $v0:
    move $v0, $a0
    jr $ra
    or $at, $zero ; branch delay slot, NOP
locret_10:
    ; negate input value and store it in $v0:
    jr $ra
    ; this is pseudoinstruction. in fact, this is "subu $v0,$zero,$a0" ($v0=0-$a0)
    negu $v0, $a0
```

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1.14. CONDITIONAL JUMPS

Here we see a new instruction: **BLTZ** (“Branch if Less Than Zero”).

There is also the **NEGU** pseudo instruction, which just does subtraction from zero. The “U” suffix in both **SUBU** and **NEGU** implies that no exception to be raised in case of integer overflow.

**Branchless version?**

You could have also a branchless version of this code. This we will review later: 3.13 on page 518.

1.14.3 Ternary conditional operator

The ternary conditional operator in C/C++ has the following syntax:

\[
\text{expression} \ ? \ \text{expression} \ : \ \text{expression}
\]

Here is an example:

```c
const char* f (int a)
{
    return a==10 ? "it is ten" : "it is not ten";
}
```

**x86**

Old and non-optimizing compilers generate assembly code just as if an *if/else* statement was used:

```
Listing 1.123: Non-optimizing MSVC 2008

SG746 DB 'it is ten', 00H
SG747 DB 'it is not ten', 00H
tv65 = -4 ; this will be used as a temporary variable
_a$ = 8
_f PROC
    push ebp
    mov ebp, esp
    push ecx
    ; compare input value with 10
    cmp DWORD PTR _a$[ebp], 10
    ; jump to $LN3@f if not equal
    jne SHORT $LN3@f
    ; store pointer to the string into temporary variable:
    mov DWORD PTR tv65[ebp], OFFSET SG746 ; 'it is ten'
    ; jump to exit
    jmp SHORT $LN4@f
$LN3@f:
    ; store pointer to the string into temporary variable:
    mov DWORD PTR tv65[ebp], OFFSET SG747 ; 'it is not ten'
$LN4@f:
    ; this is exit. copy pointer to the string from temporary variable to EAX.
    mov eax, DWORD PTR tv65[ebp]
    mov esp, ebp
    pop ebp
    ret 0
_f ENDP
```

```
Listing 1.124: Optimizing MSVC 2008

SG792 DB 'it is ten', 00H
SG793 DB 'it is not ten', 00H
_a$ = 8 ; size = 4
_f PROC
    ; compare input value with 10
    cmp DWORD PTR _a$[esp-4], 10
    ; jump to $LN3@f if not equal
    jne SHORT $LN3@f
    ; store pointer to the string into temporary variable:
    mov DWORD PTR tv65[ebp], OFFSET SG746 ; 'it is ten'
    ; jump to exit
    jmp SHORT $LN4@f
$LN3@f:
    ; store pointer to the string into temporary variable:
    mov DWORD PTR tv65[ebp], OFFSET SG747 ; 'it is not ten'
$LN4@f:
    ; this is exit. copy pointer to the string from temporary variable to EAX.
    mov eax, DWORD PTR tv65[ebp]
    mov esp, ebp
    pop ebp
    ret 0
_f ENDP
```
1.14. CONDITIONAL JUMPS

```assembly
mov eax, OFFSET $SG792 ; 'it is ten'
; jump to $LN4@f if equal
je SHORT $LN4@f
mov eax, OFFSET $SG793 ; 'it is not ten'
$LN4@f:
    ret 0
_f ENDP
```

Newer compilers are more concise:

```
Listing 1.125: Optimizing MSVC 2012 x64

$SG1355 DB 'it is ten', 00H
$SG1356 DB 'it is not ten', 00H
a$ = 8
f PROC
; load pointers to the both strings
    lea rdx, OFFSET FLAT:$SG1355 ; 'it is ten'
    lea rax, OFFSET FLAT:$SG1356 ; 'it is not ten'
; compare input value with 10
    cmp ecx, 10
; if equal, copy value from RDX ("it is ten")
; if not, do nothing. pointer to the string "it is not ten" is still in RAX as for now.
    cmove rax, rdx
    ret 0
f ENDP
```

Optimizing GCC 4.8 for x86 also uses the CMOVcc instruction, while the non-optimizing GCC 4.8 uses conditional jumps.

ARM

Optimizing Keil for ARM mode also uses the conditional instructions ADRcc:

```
Listing 1.126: Optimizing Keil 6/2013 (ARM mode)

f PROC
; compare input value with 10
    CMP r0,#0xa
; if comparison result is EQual, copy pointer to the "it is ten" string into R0
    ADREQ r0,|L0.16| ; "it is ten"
; if comparison result is Not Equal, copy pointer to the "it is not ten" string into R0
    ADRNE r0,|L0.28| ; "it is not ten"
    BX lr
ENDP
```

Without manual intervention, the two instructions ADREQ and ADRNE cannot be executed in the same run.

Optimizing Keil for Thumb mode needs to use conditional jump instructions, since there are no load instructions that support conditional flags:

```
Listing 1.127: Optimizing Keil 6/2013 (Thumb mode)

f PROC
; compare input value with 10
    CMP r0,#0xa
; jump to |L0.8| if EQual
    BEQ |L0.8|
    ADR r0,|L0.12| ; "it is not ten"
    BX lr
    |L0.8|
    ADR r0,|L0.28| ; "it is ten"
    BX lr
ENDP
```
1.14. CONDITIONAL JUMPS

|L0.12| DCB  "it is not ten",0  
|L0.28| DCB  "it is ten",0

ARM64

Optimizing GCC (Linaro) 4.9 for ARM64 also uses conditional jumps:

Listing 1.128: Optimizing GCC (Linaro) 4.9

```assembly
f:
  cmp  x0, 10
  beq  .L3 ; branch if equal
  adrp x0, .LC1 ; "it is ten"
  add  x0, x0, :lo12:.LC1
  ret
.L3: 
  adrp x0, .LC0 ; "it is not ten"
  add  x0, x0, :lo12:.LC0
  ret
.LC0: 
  .string "it is ten"
.LC1: 
  .string "it is not ten"
```

That is because ARM64 does not have a simple load instruction with conditional flags, like ADRcc in 32-bit ARM mode or CMOVcc in x86.

It has, however, “Conditional SELect” instruction (CSEL)[ARM Architecture Reference Manual, ARMv8, for ARMv8-A architecture profile, (2013)p390, C5.5], but GCC 4.9 does not seem to be smart enough to use it in such piece of code.

MIPS

Unfortunately, GCC 4.4.5 for MIPS is not very smart, either:

Listing 1.129: Optimizing GCC 4.4.5 (assembly output)

```assembly
$L0: 
  .ascii "it is not ten\000"
$L1: 
  .ascii "it is ten\000"
$f: 
  li  $2,10 # 0xa
  ; compare $a0 and 10, jump if equal:
  beq  $4,$2,$L2
  nop ; branch delay slot
  ; leave address of "it is not ten" string in $v0 and return:
  lui  $2,%hi($L0)
  j   $31
  addiu $2,$2,%lo($L0)
$L2: 
  ; leave address of "it is ten" string in $v0 and return:
  lui  $2,%hi($L1)
  j   $31
  addiu $2,$2,%lo($L1)
```

Let's rewrite it in an if/else way
1.14. CONDITIONAL JUMPS

```c
const char* f (int a)
{
    if (a==10)
        return "it is ten";
    else
        return "it is not ten";
};
```

Interestingly, optimizing GCC 4.8 for x86 was also able to use CMOVcc in this case:

Listing 1.130: Optimizing GCC 4.8

```assembly
.LC0:
    .string "it is ten"
.LC1:
    .string "it is not ten"
f:
.LFB0:
; compare input value with 10
    cmp DWORD PTR [esp+4], 10
    mov edx, OFFSET FLAT:.LC1 ; "it is not ten"
    mov eax, OFFSET FLAT:.LC0 ; "it is ten"
; if comparison result is Not Equal, copy EDX value to EAX
; if not, do nothing
    cmovne eax, edx
    ret
```

Optimizing Keil in ARM mode generates code identical to listing 1.126.

But the optimizing MSVC 2012 is not that good (yet).

**Conclusion**

Why optimizing compilers try to get rid of conditional jumps? Read here about it: 2.10.1 on page 466.

1.14.4 Getting minimal and maximal values

32-bit

```c
int my_max(int a, int b)
{
    if (a>b)
        return a;
    else
        return b;
};

int my_min(int a, int b)
{
    if (a<b)
        return a;
    else
        return b;
};
```

Listing 1.131: Non-optimizing MSVC 2013

```
a$ = 8
_b$ = 12
_my_min PROC
    push ebp
    mov ebp, esp
    mov eax, DWORD PTR _a$[ebp]
    cmp eax, DWORD PTR _b$[ebp]
    ; jump, if A is greater or equal to B:
```
These two functions differ only in the conditional jump instruction: JGE ("Jump if Greater or Equal") is used in the first one and JLE ("Jump if Less or Equal") in the second.

There is one unneeded JMP instruction in each function, which MSVC presumably left by mistake.

**Branchless**

ARM for Thumb mode reminds us of x86 code:

```assembly
my_max PROC
    ; R0=A
    ; R1=B
    ; compare A and B:
    CMP    r0, r1
    ; branch if A is greater than B:
    BGT    [L0.6]
    ; otherwise (A<=B) return R1 (B):
    MOVS   r0, r1
    [L0.6]
    ; return
    BX     lr
ENDP

my_min PROC
    ; R0=A
    ; R1=B
    ; compare A and B:
    CMP    r0, r1
    ; branch if A is less than B:
    BLT    [L0.14]
    ; otherwise (A>=B) return R1 (B):
    MOVS   r0, r1
    [L0.14]
ENDP
```
The functions differ in the branching instruction: BGT and BLT. It’s possible to use conditional suffixes in ARM mode, so the code is shorter.

MOVcc is to be executed only if the condition is met:

Listing 1.133: Optimizing Keil 6/2013 (ARM mode)

```asm
my_max PROC
; R0=A
; R1=B
; compare A and B:
  CMP r0,r1
; return B instead of A by placing B in R0
; this instruction will trigger only if A<=B (hence, LE - Less or Equal)
; if instruction is not triggered (in case of A>B), A is still in R0 register
  MOVLE r0,r1
  BX lr
ENDP

my_min PROC
; R0=A
; R1=B
; compare A and B:
  CMP r0,r1
; return B instead of A by placing B in R0
; this instruction will trigger only if A>=B (hence, GE - Greater or Equal)
; if instruction is not triggered (in case of A<B), A value is still in R0 register
  MOVGE r0,r1
  BX lr
ENDP
```

Optimizing GCC 4.8.1 and optimizing MSVC 2013 can use CMOVcc instruction, which is analogous to MOVcc in ARM:

Listing 1.134: Optimizing MSVC 2013

```asm
my_max:
  mov edx, DWORD PTR [esp+4]
  mov eax, DWORD PTR [esp+8]
; EDX=A
; EAX=B
; compare A and B:
  cmp edx, eax
; if A>=B, load A value into EAX
; the instruction idle if otherwise (if A<B)
  cmovge eax, edx
  ret

my_min:
  mov edx, DWORD PTR [esp+4]
  mov eax, DWORD PTR [esp+8]
; EDX=A
; EAX=B
; compare A and B:
  cmp edx, eax
; if A<=B, load A value into EAX
; the instruction idle if otherwise (if A>B)
  cmovle eax, edx
  ret
```

64-bit

```c
#include <stdint.h>
```
1.14. CONDITIONAL JUMPS

int64_t my_max(int64_t a, int64_t b)
{
    if (a>b)
        return a;
    else
        return b;
};

int64_t my_min(int64_t a, int64_t b)
{
    if (a<b)
        return a;
    else
        return b;
};

There is some unneeded value shuffling, but the code is comprehensible:

Listing 1.135: Non-optimizing GCC 4.9.1 ARM64

my_max:
    sub sp, sp, #16
    str x0, [sp,8]
    str x1, [sp]
    ldr x1, [sp,8]
    ldr x0, [sp]
    cmp x1, x0
    ble .L2
    ldr x0, [sp,8]
    b .L3
.L2:
    ldr x0, [sp]
.L3:
    add sp, sp, 16
    ret

my_min:
    sub sp, sp, #16
    str x0, [sp,8]
    str x1, [sp]
    ldr x1, [sp,8]
    ldr x0, [sp]
    cmp x1, x0
    bge .L5
    ldr x0, [sp,8]
    b .L6
.L5:
    ldr x0, [sp]
.L6:
    add sp, sp, 16
    ret

Branchless

No need to load function arguments from the stack, as they are already in the registers:

Listing 1.136: Optimizing GCC 4.9.1 x64

my_max:
    ; RDI=A
    ; RSI=B
    ; compare A and B:
    cmp rdi, rsi
    ; prepare B in RAX for return:
    mov rax, rsi
    ; if A>B, put A (RDI) in RAX for return.
    ; this instruction is idle if otherwise (if A<B)
1.14. CONDITIONAL JUMPS

```assembly
my_min:
; RDI=A
; RSI=B
; compare A and B:
  cmp   rdi, rsi
; prepare B in RAX for return:
  mov   rax, rsi
; if A<=B, put A (RDI) in RAX for return.
; this instruction is idle if otherwise (if A>B)
  cmovle rax, rdi
ret
```

MSVC 2013 does almost the same.

ARM64 has the CSEL instruction, which works just as MOVcc in ARM or CMOVcc in x86, just the name is different: “Conditional SELECT”.

Listing 1.137: Optimizing GCC 4.9.1 ARM64

```assembly
my_max:
; X0=A
; X1=B
; compare A and B:
  cmp   x0, x1
; select X0 (A) to X0 if X0>=X1 or A>=B (Greater or Equal)
; select X1 (B) to X0 if A<B
  csel  x0, x0, x1, ge
ret
```

```assembly
my_min:
; X0=A
; X1=B
; compare A and B:
  cmp   x0, x1
; select X0 (A) to X0 if X0<=X1 or A<=B (Less or Equal)
; select X1 (B) to X0 if A>B
  csel  x0, x0, x1, le
ret
```

MIPS

Unfortunately, GCC 4.4.5 for MIPS is not that good:

Listing 1.138: Optimizing GCC 4.4.5 (IDA)

```assembly
my_max:
; set $v1 to 1 if $a1<$a0, or clear otherwise (if $a1>$a0):
  slt   $v1, $a1, $a0
; jump, if $v1 is 0 (or $a1>$a0):
  beqz  $v1, locret_10
; this is branch delay slot
; prepare $a1 in $v0 in case of branch triggered:
  move  $v0, $a1
; no branch triggered, prepare $a0 in $v0:
  move  $v0, $a0
locret_10:
  jr    $ra
or    $at, $zero ; branch delay slot, NOP

; the min() function is same, but input operands in SLT instruction are swapped:
my_min:
  slt   $v1, $a0, $a1
  beqz  $v1, locret_28
  move  $v0, $a1
  move  $v0, $a0
```

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1.14. CONDITIONAL JUMPS

locret_28:

jr $ra
or $at, $zero ; branch delay slot, NOP

Do not forget about the branch delay slots: the first MOVE is executed before BEQZ, the second MOVE is executed only if the branch hasn’t been taken.

1.14.5 Conclusion

x86

Here’s the rough skeleton of a conditional jump:

Listing 1.139: x86

```
CMP register, register/value
Jcc true ; cc=condition code
false:
... some code to be executed if comparison result is false ...
JMP exit
true:
... some code to be executed if comparison result is true ...
exit:
```

ARM

Listing 1.140: ARM

```
CMP register, register/value
Bcc true ; cc=condition code
false:
... some code to be executed if comparison result is false ...
JMP exit
true:
... some code to be executed if comparison result is true ...
exit:
```

MIPS

Listing 1.141: Check for zero

```
BEQZ REG, label
...
```

Listing 1.142: Check for less than zero using pseudoinstruction

```
BLTZ REG, label
...
```

Listing 1.143: Check for equal values

```
BEQ REG1, REG2, label
...
```

Listing 1.144: Check for non-equal values

```
BNE REG1, REG2, label
...
```

Listing 1.145: Check for less than (signed)

```
SLT REG1, REG2, REG3
BEQ REG1, label
...
```
1.15. SWITCH()/CASE/DEFAULT

Listing 1.146: Check for less than (unsigned)

```
SLTU REG1, REG2, REG3
BEQ REG1, label
...
```

Branchless

If the body of a condition statement is very short, the conditional move instruction can be used: MOVcc in ARM (in ARM mode), CSEL in ARM64, CMOVcc in x86.

ARM

It’s possible to use conditional suffixes in ARM mode for some instructions:

**Listing 1.147: ARM (ARM mode)**

```
CMP register, register/value
instr1 cc ; some instruction will be executed if condition code is true
instr2 cc ; some other instruction will be executed if other condition code is true
... etc...
```

Of course, there is no limit for the number of instructions with conditional code suffixes, as long as the CPU flags are not modified by any of them.

Thumb mode has the IT instruction, allowing to add conditional suffixes to the next four instructions. Read more about it: [1.19.7 on page 263](#).

**Listing 1.148: ARM (Thumb mode)**

```
CMP register, register/value
ITEEE EQ ; set these suffixes: if-then-else-else-else
instr1 ; instruction will be executed if condition is true
instr2 ; instruction will be executed if condition is false
instr3 ; instruction will be executed if condition is false
instr4 ; instruction will be executed if condition is false
```

1.14.6 Exercise

(ARM64) Try rewriting the code in listing [1.128](#) by removing all conditional jump instructions and using the CSEL instruction.

1.15 switch()/case/default

1.15.1 Small number of cases

```c
#include <stdio.h>

void f (int a)
{
    switch (a)
    {
        case 0: printf ("zero\n"); break;
        case 1: printf ("one\n"); break;
        case 2: printf ("two\n"); break;
        default: printf ("something unknown\n"); break;
    };

int main()
{
```
1.15. \textit{SWITCH()}/CASE/DEFAULT

\begin{verbatim}
f (2); // test
\end{verbatim}

\section*{x86}

\textbf{Non-optimizing MSVC}

Result (MSVC 2010):

\begin{verbatim}
Listing 1.149: MSVC 2010

tv64 = -4 ; size = 4
_a$ = 8 ; size = 4

_f PROC
    push ebp
    mov ebp, esp
    push ecx
    mov eax, DWORD PTR _a$[ebp]
    mov DWORD PTR tv64[ebp], eax
    cmp DWORD PTR tv64[ebp], 0
    je SHORT $LN4@f
    cmp DWORD PTR tv64[ebp], 1
    je SHORT $LN3@f
    cmp DWORD PTR tv64[ebp], 2
    je SHORT $LN2@f
    jmp SHORT $LN1@f
$LN4@f:
    push OFFSET $SG739 ; 'zero', 0aH, 00H
    call _printf
    add esp, 4
    jmp SHORT $LN7@f
$LN3@f:
    push OFFSET $SG741 ; 'one', 0aH, 00H
    call _printf
    add esp, 4
    jmp SHORT $LN7@f
$LN2@f:
    push OFFSET $SG743 ; 'two', 0aH, 00H
    call _printf
    add esp, 4
    jmp SHORT $LN7@f
$LN1@f:
    push OFFSET $SG745 ; 'something unknown', 0aH, 00H
    call _printf
    add esp, 4
$LN7@f:
    mov esp, ebp
    pop ebp
    ret 0

_f ENDP
\end{verbatim}

Our function with a few cases in switch() is in fact analogous to this construction:

\begin{verbatim}
void f (int a)
{
    if (a==0)
        printf("zero\n");
    else if (a==1)
        printf("one\n");
    else if (a==2)
        printf("two\n");
    else
        printf("something unknown\n");
}
\end{verbatim}

If we work with switch() with a few cases it is impossible to be sure if it was a real switch() in the source code, or just a pack of if() statements.

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1.15. **SWITCH()*/CASE/DEFAULT**

This implies that switch() is like syntactic sugar for a large number of nested if(). There is nothing especially new to us in the generated code, with the exception of the compiler moving input variable \( a \) to a temporary local variable tv64.

If we compile this in GCC 4.4.1, we’ll get almost the same result, even with maximal optimization turned on (-O3 option).

**Optimizing MSVC**

Now let’s turn on optimization in MSVC (/Ox): cl 1.c /Fa1.asm /Ox

```assembly
Listing 1.150: MSVC

a$ = 8 ; size = 4
_f PROC
    mov eax, DWORD PTR _a$[esp-4]
    sub eax, 0
    je SHORT $LN4@f
    sub eax, 1
    je SHORT $LN3@f
    sub eax, 1
    je SHORT $LN2@f
    mov DWORD PTR _a$[esp-4], OFFSET $SG791 ; 'something unknown', 0aH, 00H
    jmp _printf
$LN2@f:
    mov DWORD PTR _a$[esp-4], OFFSET $SG799 ; 'two', 0aH, 00H
    jmp _printf
$LN3@f:
    mov DWORD PTR _a$[esp-4], OFFSET $SG787 ; 'one', 0aH, 00H
    jmp _printf
$LN4@f:
    mov DWORD PTR _a$[esp-4], OFFSET $SG785 ; 'zero', 0aH, 00H
    jmp _printf
_f ENDP
```

Here we can see some dirty hacks.

First: the value of \( a \) is placed in EAX and 0 is subtracted from it. Sounds absurd, but it is done to check if the value in EAX is 0. If yes, the ZF flag is to be set (e.g. subtracting from 0 is 0) and the first conditional jump JE (Jump if Equal or synonym JZ — Jump if Zero) is to be triggered and control flow is to be passed to the $LN4@f label, where the 'zero' message is being printed. If the first jump doesn’t get triggered, 1 is subtracted from the input value and if at some stage the result is 0, the corresponding jump is to be triggered.

And if no jump gets triggered at all, the control flow passes to printf() with string argument 'something unknown'.

Second: we see something unusual for us: a string pointer is placed into the \( a \) variable, and then printf() is called not via CALL, but via JMP. There is a simple explanation for that: the caller pushes a value to the stack and calls our function via CALL. CALL itself pushes the return address (RA) to the stack and does an unconditional jump to our function address. Our function at any point of execution (since it do not contain any instruction that moves the stack pointer) has the following stack layout:

- ESP—points to RA
- ESP+4—points to the \( a \) variable

On the other side, when we have to call printf() here we need exactly the same stack layout, except for the first printf() argument, which needs to point to the string. And that is what our code does.

It replaces the function's first argument with the address of the string and jumps to printf(), as if we didn’t call our function f(), but directly printf(). printf() prints a string to stdout and then executes the RET instruction, which POPs RA from the stack and control flow is returned not to f() but rather to f()'s caller, bypassing the end of the f() function.

All this is possible because printf() is called right at the end of the f() function in all cases. In some way, it is similar to the longjmp() function. And of course, it is all done for the sake of speed.

---

92 Local variables in stack are prefixed with tv—that’s how MSVC names internal variables for its needs
93 Wikipedia
1.15. **SWITCH()/CASE/DEFAULT**

A similar case with the ARM compiler is described in “printf() with several arguments” section, here (1.8.2 on page 54).
Since this example is tricky, let's trace it in OllyDbg.

OllyDbg can detect such switch() constructs, and it can add some useful comments. EAX is 2 at the beginning, that's the function's input value:

![OllyDbg screenshot showing the switch construct and its tracing]

Figure 1.42: OllyDbg: EAX now contain the first (and only) function argument
1.15. **SWITCH() / CASE / DEFAULT**

0 is subtracted from 2 in EAX. Of course, EAX still contains 2. But the ZF flag is now 0, indicating that the resulting value is non-zero:

![CPU - main thread, module few](image)

<table>
<thead>
<tr>
<th>Address</th>
<th>Name</th>
<th>Value</th>
<th>ASCII</th>
<th>GCI - C0</th>
</tr>
</thead>
<tbody>
<tr>
<td>00496714</td>
<td>EC0</td>
<td>E844714 ASCII &quot;Hi&quot;</td>
<td>61090000</td>
<td>00000000</td>
</tr>
<tr>
<td>00004967</td>
<td>EB0</td>
<td>00000000</td>
<td>00000000</td>
<td>00000000</td>
</tr>
<tr>
<td>00000013</td>
<td>BP</td>
<td>00000000</td>
<td>00000000</td>
<td>00000000</td>
</tr>
<tr>
<td>00000002</td>
<td>SI</td>
<td>00000000</td>
<td>00000000</td>
<td>00000000</td>
</tr>
<tr>
<td>00000000</td>
<td>DI</td>
<td>00000000</td>
<td>00000000</td>
<td>00000000</td>
</tr>
</tbody>
</table>

![Figure 1.43: OllyDbg: SUB executed](image)

Figure 1.43: OllyDbg: SUB executed
DEC is executed and EAX now contains 1. But 1 is non-zero, so the ZF flag is still 0.

Figure 1.44: OllyDbg: first DEC executed
1.15. \texttt{SWITCH()/CASE/DEFAULT}

Next \texttt{DEC} is executed. \textsc{EAX} is finally 0 and the ZF flag gets set, because the result is zero:

![Figure 1.45: OllyDbg: second DEC executed](image)

OllyDbg shows that this jump is to be taken now.
1.15. **SWITCH()/CASE/DEFAULT**

A pointer to the string “two” is to be written into the stack now:

![Image](image-url)

Figure 1.46: OllyDbg: pointer to the string is to be written at the place of the first argument

Please note: the current argument of the function is 2 and 2 is now in the stack at the address 0x001EF850.
MOV writes the pointer to the string at address 0x001EF850 (see the stack window). Then, jump happens.
This is the first instruction of the printf() function in MSVCR100.DLL (This example was compiled with /MD switch):

Now printf() treats the string at 0x00FF3010 as its only argument and prints the string.
1.15. **SWITCH()*/CASE*/DEFAULT**

This is the last instruction of `printf()`:

![Code Snippet]

The string “two” has just been printed to the console window.
Now let’s press F7 or F8 (step over) and return…not to \texttt{f()}, but rather to \texttt{main}():

Yes, the jump has been direct, from the guts of \texttt{printf()} to \texttt{main}(). Because \texttt{RA} in the stack points not to some place in \texttt{f()}, but rather to \texttt{main}(). And \texttt{CALL 0x00FF1000} has been the actual instruction which called \texttt{f()}.

\textbf{ARM: Optimizing Keil 6/2013 (ARM mode)}

```assembly
.text:0000014C f1:
.text:0000014C 00 00 50 E3 CMP R0, #0
.text:00000150 13 0E 8F 02 ADREQ R0, aZero ; "zero\n"
.text:00000154 05 00 00 0A BEQ loc_170
.text:00000158 01 00 50 E3 CMP R0, #1
.text:0000015C 4B 0F 8F 12 ADRNE R0, aSomethingUnknown ; "something unknown"
.text:00000160 4E 0F 8F 02 ADREQ R0, aTwo ; "two\n"
.text:00000164 02 00 50 E3 CMP R0, #2
.text:00000168 4A 0F 8F 12 ADRNE R0, aSomethingUnknw ; "something unknown"
.text:0000016C 4E 0F 8F 02 ADREQ R0, aTwo ; "two\n"
.text:00000170
.text:00000170 loc_170: ; CODE XREF: f1+8
.text:00000174 f1+8
.text:00000170 ; f1+14
.text:00000170 78 18 00 EA B __2printf
```

Again, by investigating this code we cannot say if it was a switch() in the original source code, or just a pack of if() statements.

Anyway, we see here predicated instructions again (like ADREQ (\textit{Equal})) which is triggered only in case $R0 = 0$, and then loads the address of the string «zero\n» into R0. The next instruction BEQ redirects control flow to \texttt{loc_170}, if $R0 = 0$.

An astute reader may ask, will BEQ trigger correctly since ADREQ it has already filled the R0 register before with another value?

Yes, it will since BEQ checks the flags set by the CMP instruction, and ADREQ does not modify any flags at all.

The rest of the instructions are already familiar to us. There is only one call to printf(), at the end, and we have already examined this trick here (1.8.2 on page 54). At the end, there are three paths to printf().
1.15. `SWITCH()//CASE//DEFAULT`

The last instruction, `CMP R0, #2`, is needed to check if $a = 2$.

If it is not true, then `ADRNE` loads a pointer to the string «something unknown \n» into R0, since $a$ has already been checked to be equal to 0 or 1, and we can sure that the $a$ variable is not equal to these numbers at this point. And if $R0 = 2$, a pointer to the string «two\n» will be loaded by `ADREQ` into R0.

**ARM: Optimizing Keil 6/2013 (Thumb mode)**

```
.text:000000d4 f1:
   .text:000000d4 10 b5 push {r4,lr}
   .text:000000d6 00 28 cmp r0, #0
   .text:000000d8 05 d0 beq zero_case
   .text:000000da 01 28 cmp r0, #1
   .text:000000dc 05 d0 beq one_case
   .text:000000de 02 28 cmp r0, #2
   .text:000000e0 05 d0 beq two_case
   .text:000000e2 91 a0 adrr r0, aSomethingUnknown ; "something unknown\n"
   .text:000000e4 04 e0 b default_case
   .text:000000e6 zero_case: ; code xref: f1+4
   .text:000000e6 95 a0 adrr r0, aZero ; "zero\n"
   .text:000000e8 00 e0 b default_case
   .text:000000ea one_case: ; code xref: f1+8
   .text:000000ea 96 a0 adrr r0, aOne ; "one\n"
   .text:000000ec 00 e0 b default_case
   .text:000000ee two_case: ; code xref: f1+c
   .text:000000ee 97 a0 adrr r0, aTwo ; "two\n"
   .text:000000ef default_case ; code xref: f1+10
   .text:000000ef 06 f0 7e f8 bl __2printf
   .text:000000f4 10 bd pop {r4,pc}
```

As was already mentioned, it is not possible to add conditional predicates to most instructions in Thumb mode, so the Thumb-code here is somewhat similar to the easily understandable x86 CISC-style code.

**ARM64: Non-optimizing GCC (Linaro) 4.9**

```
.LC12:
 .string "zero"
.LC13:
 .string "one"
.LC14:
 .string "two"
.LC15:
 .string "something unknown"

f12:
   stp x29, x30, [sp, -32]!
   add x29, sp, 0
   str w0, [x29,28]
   ldr w0, [x29,28]
   cmp w0, 1
   beq .L34
   cmp w0, 2
   beq .L35
   cmp w0, wzr
   bne .L38 ; jump to default label
   adrp x0, .LC12 ; "zero"
   add x0, x0, :lo12:.LC12
   bl puts
   b .L32
.L34:
   adrp x0, .LC13 ; "one"
   add x0, x0, :lo12:.LC13
   bl puts
```

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1.15. SWITCH()/CASE/DEFAULT

```assembly
.L32:
    ld  x29, x30, [sp], 32
    ret
```

The type of the input value is `int`, hence register W0 is used to hold it instead of the whole X0 register.

The string pointers are passed to puts() using an ADRP/ADD instructions pair just like it was demonstrated in the “Hello, world!” example: 1.5.4 on page 24.

**ARM64: Optimizing GCC (Linaro) 4.9**

```assembly
f12:
    cmp w0, 1
    beq .L31
    cmp w0, 2
    beq .L32
    cbz w0, .L35
    ; default case
    adrp x0, .LC15 ; "something unknown"
    add x0, x0, :lo12:.LC15
    b   puts

.L35:
    adrp x0, .LC12 ; "zero"
    add x0, x0, :lo12:.LC12
    b   puts

.L32:
    adrp x0, .LC14 ; "two"
    add x0, x0, :lo12:.LC14
    b   puts

.L31:
    adrp x0, .LC13 ; "one"
    add x0, x0, :lo12:.LC13
    b   puts
```

Better optimized piece of code. CBZ (Compare and Branch on Zero) instruction does jump if W0 is zero. There is also a direct jump to puts() instead of calling it, like it was explained before: 1.15.1 on page 154.

**MIPS**

```assembly
Listing 1.151: Optimizing GCC 4.4.5 (IDA)

f:
    lui $gp, (__gnu_local_gp >> 16)
    ; is it 1?
    li  $v0, 1
    beq $a0, $v0, loc_60
    la  $gp, (__gnu_local_gp & 0xFFFF) ; branch delay slot

    ; is it 2?
    li  $v0, 2
    beq $a0, $v0, loc_4C
    or  $at, $zero ; branch delay slot, NOP

    ; jump, if not equal to 0:
    bnez $a0, loc_38
    or  $at, $zero ; branch delay slot, NOP

    ; zero case:
```

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1.15. SWITCH()/CASE/DEFAULT

```
1.15. SWITCH()/CASE/DEFAULT

lui $a0, ($LC0 >> 16)  # "zero"
lw $t9, (puts & 0xFFFF)($gp)
or $at, $zero ; load delay slot, NOP
jr $t9 ; branch delay slot, NOP
la $a0, ($LC0 & 0xFFFF) # "zero" ; branch delay slot

loc_38: # CODE XREF: f+1C
lui $a0, ($LC3 >> 16) # "something unknown"
lw $t9, (puts & 0xFFFF)($gp)
or $at, $zero ; load delay slot, NOP
jr $t9
la $a0, ($LC3 & 0xFFFF) # "something unknown" ; branch delay slot

loc_4C: # CODE XREF: f+14
lui $a0, ($LC2 >> 16) # "two"
lw $t9, (puts & 0xFFFF)($gp)
or $at, $zero ; load delay slot, NOP
jr $t9
la $a0, ($LC2 & 0xFFFF) # "two" ; branch delay slot

loc_60: # CODE XREF: f+8
lui $a0, ($LC1 >> 16) # "one"
lw $t9, (puts & 0xFFFF)($gp)
or $at, $zero ; load delay slot, NOP
jr $t9
la $a0, ($LC1 & 0xFFFF) # "one" ; branch delay slot
```

The function always ends with calling `puts()`, so here we see a jump to `puts()` (JR: “Jump Register”) instead of “jump and link”. We talked about this earlier: 1.15.1 on page 154.

We also often see NOP instructions after LW ones. This is “load delay slot”: another delay slot in MIPS.

An instruction next to LW may execute at the moment while LW loads value from memory. However, the next instruction must not use the result of LW.

Modern MIPS CPUs have a feature to wait if the next instruction uses result of LW, so this is somewhat outdated, but GCC still adds NOPs for older MIPS CPUs. In general, it can be ignored.

**Conclusion**

A switch() with few cases is indistinguishable from an if/else construction, for example: listing.1.15.1.

1.15.2 A lot of cases

If a switch() statement contains a lot of cases, it is not very convenient for the compiler to emit too large code with a lot JE/JNE instructions.

```
#include <stdio.h>

void f (int a)
{
    switch (a)
    {
    case 0: printf ("zero\n"); break;
    case 1: printf ("one\n"); break;
    case 2: printf ("two\n"); break;
    case 3: printf ("three\n"); break;
    case 4: printf ("four\n"); break;
    default: printf ("something unknown\n"); break;
    }
};

int main()
{
    f (2); // test
};
```
1.15. **SWITCH()/CASE/DEFAULT**

**x86 Non-optimizing MSVC**

We get (MSVC 2010):

Listing 1.152: MSVC 2010

```assembly
f PROC
    push ebp
    mov ebp, esp
    push ecx
    mov eax, DWORD PTR _a$[ebp]
    mov DWORD PTR tv64[ebp], eax
    cmp DWORD PTR tv64[ebp], 4
    ja SHORT $LN1@f
    mov ecx, DWORD PTR tv64[ebp]
    jmp DWORD PTR $LN11@f[ecx*4]
$LN6@f:
    push OFFSET $SG739 ; 'zero', 0aH, 00H
    call _printf
    add esp, 4
    jmp SHORT $LN9@f
$LN5@f:
    push OFFSET $SG741 ; 'one', 0aH, 00H
    call _printf
    add esp, 4
    jmp SHORT $LN9@f
$LN4@f:
    push OFFSET $SG743 ; 'two', 0aH, 00H
    call _printf
    add esp, 4
    jmp SHORT $LN9@f
$LN3@f:
    push OFFSET $SG745 ; 'three', 0aH, 00H
    call _printf
    add esp, 4
    jmp SHORT $LN9@f
$LN2@f:
    push OFFSET $SG747 ; 'four', 0aH, 00H
    call _printf
    add esp, 4
    jmp SHORT $LN9@f
$LN1@f:
    push OFFSET $SG749 ; 'something unknown', 0aH, 00H
    call _printf
    add esp, 4
$LN9@f:
    mov esp, ebp
    pop ebp
    ret 0
    npad 2 ; align next label
$LN11@f:
    DD $LN6@f ; 0
    DD $LN5@f ; 1
    DD $LN4@f ; 2
    DD $LN3@f ; 3
    DD $LN2@f ; 4
f ENDP
```

What we see here is a set of `printf()` calls with various arguments. All they have not only addresses in the memory of the process, but also internal symbolic labels assigned by the compiler. All these labels are also mentioned in the $LN11@f internal table.

At the function start, if `a` is greater than 4, control flow is passed to label $LN1@f, where `printf()` with argument 'something unknown' is called.
1.15. **SWITCH()/CASE/DEFAULT**

But if the value of $a$ is less or equals to 4, then it gets multiplied by 4 and added with the $\$LN11@f$ table address. That is how an address inside the table is constructed, pointing exactly to the element we need. For example, let’s say $a$ is equal to 2. $2 \times 4 = 8$ (all table elements are addresses in a 32-bit process and that is why all elements are 4 bytes wide). The address of the $\$LN11@f$ table + 8 is the table element where the $\$LN4@f$ label is stored. JMP fetches the $\$LN4@f$ address from the table and jumps to it.

This table is sometimes called *jumptable* or *branch table*[^1].

Then the corresponding printf() is called with argument ‘two’.

Literally, the jmp DWORD PTR $\$LN11@f[ecx*4]$ instruction implies *jump to the DWORD that is stored at address $\$LN11@f + ecx \times 4$.*

npad (.1.7 on page 1038) is an assembly language macro that align the next label so that it will be stored at an address aligned on a 4 bytes (or 16 bytes) boundary. This is very suitable for the processor since it is able to fetch 32-bit values from memory through the memory bus, cache memory, etc., in a more effective way if it is aligned.

[^1]: The whole method was once called *computed GOTO* in early versions of Fortran: wikipedia. Not quite relevant these days, but what a term!
Let’s try this example in OllyDbg. The input value of the function (2) is loaded into EAX:

![Figure 1.50: OllyDbg: function’s input value is loaded in EAX](image)
The input value is checked, is it bigger than 4? If not, the “default” jump is not taken:

**Figure 1.51:** OllyDbg: 2 is no bigger than 4: no jump is taken
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Here we see a jumptable:

Figure 1.52: OllyDbg: calculating destination address using jumptable

Here we’ve clicked “Follow in Dump” → “Address constant”, so now we see the jumptable in the data window. These are 5 32-bit values\(^{95}\). ECX is now 2, so the third element (can be indexed as 2\(^{96}\)) of the table is to be used. It’s also possible to click “Follow in Dump” → “Memory address” and OllyDbg will show the element addressed by the JMP instruction. That’s 0x010B103A.

\(^{95}\) They are underlined by OllyDbg because these are also FIXUPS: 6.5.2 on page 759, we are going to come back to them later.

\(^{96}\) About indexing, see also: 3.19.3
1.15. **SWITCH()*/CASEDEFAULT*/

After the jump we are at 0x010B103A: the code printing “two” will now be executed:

**Figure 1.53: OllyDbg: now we at the case: label**

**Non-optimizing GCC**

Let’s see what GCC 4.4.1 generates:

**Listing 1.153: GCC 4.4.1**

```c
public f
f proc near ; CODE XREF: main+10
var_18 = dword ptr -18h
arg_0 = dword ptr 8

push ebp
mov ebp, esp
sub esp, 18h
cmp [ebp+arg_0], 4
ja short loc_8048444
mov eax, [ebp+arg_0]
shl eax, 2
mov eax, ds:off_804855C[eax]
jmp eax

loc_80483FE: ; DATA XREF: .rodata:off 804855C
mov [esp+18h+var_18], offset aZero ; "zero"
call _puts
jmp short locret_8048450

loc_804840C: ; DATA XREF: .rodata:08048560
mov [esp+18h+var_18], offset aOne ; "one"
call _puts
jmp short locret_8048450

loc_804841A: ; DATA XREF: .rodata:08048564
mov [esp+18h+var_18], offset aTwo ; "two"
call _puts
jmp short locret_8048450

loc_8048428: ; DATA XREF: .rodata:08048568
```

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1.15. SWITCH()/CASE/DEFAULT

```assembly
mov [esp+18h+var_18], offset aThree ; "three"
call _puts
jmp short locret_8048450

loc_8048436: ; DATA XREF: .rodata:0804856C
mov [esp+18h+var_18], offset aFour ; "four"
call _puts
jmp short locret_8048450

loc_8048444: ; CODE XREF: f+A
mov [esp+18h+var_18], offset aSomethingUnkno ; "something unknown"
call _puts

locret_8048450: ; CODE XREF: f+26
leave
retn
f endp
```

It is almost the same, with a little nuance: argument arg_0 is multiplied by 4 by shifting it to left by 2 bits (it is almost the same as multiplication by 4) (1.18.2 on page 217). Then the address of the label is taken from the off_804855C array, stored in EAX, and then JMP EAX does the actual jump.

ARM: Optimizing Keil 6/2013 (ARM mode)

```
Listing 1.154: Optimizing Keil 6/2013 (ARM mode)

00000174 f2
00000178 f1 8f 30 ADDCC PC, PC, R0,LSL#2 ; switch jump
0000017c 0e 00 00 ea B default_case ; jumptable 00000178 default case
00000180 03 00 00 ea B zero_case ; jumptable 00000178 case 0
00000184 04 00 00 ea B one_case ; jumptable 00000178 case 1
00000188 05 00 00 ea B two_case ; jumptable 00000178 case 2
0000018c 06 00 00 ea B three_case ; jumptable 00000178 case 3
00000190 07 00 00 ea B four_case ; jumptable 00000178 case 4
00000194 zero_case ; CODE XREF: f2+4
00000196 ; f2:loc_180
00000198 ec 00 8f e2 ADR R0, aZero ; jumptable 00000178 case 0
0000019c 0d 00 00 ea B loc_188
0000019c one_case ; CODE XREF: f2+4
0000019c ; f2:loc_184
0000019e ec 00 8f e2 ADR R0, aOne ; jumptable 00000178 case 1
```
This code makes use of the ARM mode feature in which all instructions have a fixed size of 4 bytes.

Let’s keep in mind that the maximum value for $a$ is 4 and any greater value will cause “something unknown” string to be printed.

The first CMP R0, #5 instruction compares the input value of $a$ with 5.

The next ADDCC PC, PC, R0, LSL#2 instruction is being executed only if $R0 < 5$ ($CC=Carry clear / Less than$). Consequently, if ADDCC does not trigger (it is a $R0 \geq 5$ case), a jump to default_case label will occur.

But if $R0 < 5$ and ADDCC triggers, the following is to be happen:

The value in R0 is multiplied by 4. In fact, LSL#2 at the instruction’s suffix stands for “shift left by 2 bits”. But as we will see later (1.18.2 on page 217) in section “Shifts”, shift left by 2 bits is equivalent to multiplying by 4.

Then we add $R0 \times 4$ to the current value in PC, thus jumping to one of the B (Branch) instructions located below.

At the moment of the execution of ADDCC, the value in PC is 8 bytes ahead (0x180) than the address at which the ADDCC instruction is located (0x178), or, in other words, 2 instructions ahead.

This is how the pipeline in ARM processors works: when ADDCC is executed, the processor at the moment is beginning to process the instruction after the next one, so that is why PC points there. This has to be memorized.

If $a = 0$, then is to be added to the value in PC, and the actual value of the PC will be written into PC (which is 8 bytes ahead) and a jump to the label loc_180 will happen, which is 8 bytes ahead of the point where the ADDCC instruction is.

If $a = 1$, then $PC + 8 + a \times 4 = PC + 8 + 1 \times 4 = PC + 12 = 0x184$ will be written to PC, which is the address of the loc_184 label.

With every 1 added to $a$, the resulting PC is increased by 4.

4 is the instruction length in ARM mode and also, the length of each B instruction, of which there are 5 in row.

Each of these five B instructions passes control further, to what was programmed in the switch().

Pointer loading of the corresponding string occurs there, etc.

97ADD—addition
One cannot be sure that all instructions in Thumb and Thumb-2 modes have the same size. It can even be said that in these modes the instructions have variable lengths, just like in x86.

So there is a special table added that contains information about how much cases are there (not including default-case), and an offset for each with a label to which control must be passed in the corresponding
A special function is present here in order to deal with the table and pass control, named \texttt{__ARM_common_switch8_thumb}. It starts with \texttt{BX PC}, whose function is to switch the processor to ARM-mode. Then you see the function for table processing.

It is too advanced to describe it here now, so let’s omit it.

It is interesting to note that the function uses the LR register as a pointer to the table.

Indeed, after calling of this function, LR contains the address after \texttt{BL __ARM_common_switch8_thumb} instruction, where the table starts.

It is also worth noting that the code is generated as a separate function in order to reuse it, so the compiler doesn’t generate the same code for every switch() statement.

IDA successfully perceived it as a service function and a table, and added comments to the labels like jumptable 000000FA case 0.

### MIPS

#### Listing 1.156: Optimizing GCC 4.4.5 (IDA)

```mips
f:
    lui   $gp, (__gnu_local_gp >> 16)
; jump to loc_24 if input value is lesser than 5:
    sltiu $v0, $a0, 5
    bnez  $v0, loc_24
    la    $gp, (__gnu_local_gp & 0xFFFF) ; branch delay slot
; input value is greater or equal to 5.
; print "something unknown" and finish:
    lui   $a0, ($LC5 >> 16) # "something unknown"
    lw    $t9, (puts & 0xFFFF)($gp)
    or    $at, $zero ; NOP
    jr    $t9
    la    $a0, ($LC5 & 0xFFFF) # "something unknown" ; branch delay slot

loc_24: # CODE XREF: f+8
; load address of jumptable
; LA is pseudoinstruction, LUI and ADDIU pair are there in fact:
    la    $v0, off_120
; multiply input value by 4:
    sll   $a0, 2
; sum up multiplied value and jumptable address:
    addu  $a0, $v0, $a0
; load element from jumptable:
    lw    $v0, 0($a0)
    or    $at, $zero ; NOP
    jr    $v0
    or    $at, $zero ; branch delay slot, NOP

sub_44: # DATA XREF: .rodata:0000012C
; print "three" and finish
    lui   $a0, ($LC3 >> 16) # "three"
    lw    $t9, (puts & 0xFFFF)($gp)
    or    $at, $zero ; NOP
    jr    $t9
    la    $a0, ($LC3 & 0xFFFF) # "three" ; branch delay slot

sub_58: # DATA XREF: .rodata:00000130
; print "four" and finish
    lui   $a0, ($LC4 >> 16) # "four"
    lw    $t9, (puts & 0xFFFF)($gp)
    or    $at, $zero ; NOP
    jr    $t9
    la    $a0, ($LC4 & 0xFFFF) # "four" ; branch delay slot

sub_6C: # DATA XREF: .rodata:off_120
; print "zero" and finish
```

The new instruction for us is SLTIU (“Set on Less Than Immediate Unsigned”).

This is the same as SLTU (“Set on Less Than Unsigned”), but “I” stands for “immediate”, i.e., a number has to be specified in the instruction itself.

BNEZ is “Branch if Not Equal to Zero”.

Code is very close to the other ISAs. SLL (“Shift Word Left Logical”) does multiplication by 4.

MIPS is a 32-bit CPU after all, so all addresses in the jumptable are 32-bit ones.

**Conclusion**

Rough skeleton of switch():

```Assembly
MOV REG, input
CMP REG, 4 ; maximal number of cases
JA default
SRL REG, 2 ; find element in table. shift for 3 bits in x64.
MOV REG, jump_table[REG]
JMP REG

casel:
    ; do something
    JMP exit
case2:
    ; do something
    JMP exit
case3:
    ; do something
    JMP exit
case4:
    ; do something
    JMP exit
case5:
    ; do something
    JMP exit
default:
```
### 1.15. SWITCH()/CASE/DEFAULT

... exit: ....

```
jump_table dd case1
dd case2
dd case3
dd case4
dd case5
```

The jump to the address in the jump table may also be implemented using this instruction: JMP jump_table[REG*4]. Or JMP jump_table[REG*8] in x64.

A jmptable is just array of pointers, like the one described later: 1.20.5 on page 287.

#### 1.15.3 When there are several case statements in one block

Here is a very widespread construction: several case statements for a single block:

```c
#include <stdio.h>

void f(int a)
{
    switch (a) {
    case 1:
    case 2:
    case 7:
    case 10:
        printf ("1, 2, 7, 10\n");
        break;
    case 3:
    case 4:
    case 5:
    case 6:
        printf ("3, 4, 5\n");
        break;
    case 8:
    case 9:
    case 20:
    case 21:
        printf ("8, 9, 21\n");
        break;
    case 22:
        printf ("22\n");
        break;
    default:
        printf ("default\n");
        break;
    }
};

int main()
{
    f(4);
};
```

It's too wasteful to generate a block for each possible case, so what is usually done is to generate each block plus some kind of dispatcher.

**MSVC**
We see two tables here: the first table ($LN10@f$) is an index table, and the second one ($LN11@f$) is an array of pointers to blocks.

First, the input value is used as an index in the index table (line 13).

Here is a short legend for the values in the table: 0 is the first case block (for values 1, 2, 7, 10), 1 is the second one (for values 3, 4, 5), 2 is the third one (for values 8, 9, 21), 3 is the fourth one (for value 22), 4 is for the default block.

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There we get an index for the second table of code pointers and we jump to it (line 14).

What is also worth noting is that there is no case for input value 0.

That's why we see the DEC instruction at line 10, and the table starts at \(a = 1\), because there is no need to allocate a table element for \(a = 0\).

This is a very widespread pattern.

So why is this economical? Why isn't it possible to make it as before (1.15.2 on page 172), just with one table consisting of block pointers? The reason is that the elements in index table are 8-bit, hence it's all more compact.

GCC

GCC does the job in the way we already discussed (1.15.2 on page 172), using just one table of pointers.

ARM64: Optimizing GCC 4.9.1

There is no code to be triggered if the input value is 0, so GCC tries to make the jump table more compact and so it starts at 1 as an input value.

GCC 4.9.1 for ARM64 uses an even cleverer trick. It's able to encode all offsets as 8-bit bytes.

Let's recall that all ARM64 instructions have a size of 4 bytes.

GCC is uses the fact that all offsets in my tiny example are in close proximity to each other. So the jump table consisting of single bytes.

Listing 1.159: Optimizing GCC 4.9.1 ARM64

```assembly
f14:
; input value in W0
  sub   w0, w0, #1
  cmp   w0, 21
; branch if less or equal (unsigned):
  bls  .L9
.L2:
; print "default":
  adrp  x0, .LC4
  add  x0, x0, :lo12:.LC4
  b  puts
.L9:
; load jumptable address to X1:
  adrp  x1, .L4
  add  x1, x1, :lo12:.L4
; W0=input value-1
; load byte from the table:
  ldrb  w0, [x1,w0,uxtw]
; load address of the Lrtx label:
  adrx  x1, .Lrtx4
; multiply table element by 4 (by shifting 2 bits left) and add (or subtract) to the address of
`; Lrtx:
  add  x0, x1, w0, sxtb #2
; jump to the calculated address:
  br  x0
; this label is pointing in code (text) segment:
.Lrtx4:
; .section .rodata
; everything after ".section" statement is allocated in the read-only data (rodata) segment:
.L4:
  .byte  (.L3 - .Lrtx4) / 4 ; case 1
  .byte  (.L3 - .Lrtx4) / 4 ; case 2
  .byte  (.L5 - .Lrtx4) / 4 ; case 3
  .byte  (.L5 - .Lrtx4) / 4 ; case 4
  .byte  (.L5 - .Lrtx4) / 4 ; case 5
  .byte  (.L5 - .Lrtx4) / 4 ; case 6
  .byte  (.L3 - .Lrtx4) / 4 ; case 7
  .byte  (.L6 - .Lrtx4) / 4 ; case 8
  .byte  (.L6 - .Lrtx4) / 4 ; case 9
```

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\texttt{.byte (.L3 - \_rtx4) / 4 ; case 10}
\texttt{.byte (.L2 - \_rtx4) / 4 ; case 11}
\texttt{.byte (.L2 - \_rtx4) / 4 ; case 12}
\texttt{.byte (.L2 - \_rtx4) / 4 ; case 13}
\texttt{.byte (.L2 - \_rtx4) / 4 ; case 14}
\texttt{.byte (.L2 - \_rtx4) / 4 ; case 15}
\texttt{.byte (.L2 - \_rtx4) / 4 ; case 16}
\texttt{.byte (.L2 - \_rtx4) / 4 ; case 17}
\texttt{.byte (.L2 - \_rtx4) / 4 ; case 18}
\texttt{.byte (.L2 - \_rtx4) / 4 ; case 19}
\texttt{.byte (.L6 - \_rtx4) / 4 ; case 20}
\texttt{.byte (.L6 - \_rtx4) / 4 ; case 21}
\texttt{.byte (.L7 - \_rtx4) / 4 ; case 22}
\texttt{.text}

; everything after ".text" statement is allocated in the code (text) segment:
\texttt{.L7:}
; print "22"
\texttt{adrp x0, .LC3}
\texttt{add x0, x0, :lo12:.LC3}
\texttt{b puts}
\texttt{.L6:}
; print "8, 9, 21"
\texttt{adrp x0, .LC2}
\texttt{add x0, x0, :lo12:.LC2}
\texttt{b puts}
\texttt{.L5:}
; print "3, 4, 5"
\texttt{adrp x0, .LC1}
\texttt{add x0, x0, :lo12:.LC1}
\texttt{b puts}
\texttt{.L3:}
; print "1, 2, 7, 10"
\texttt{adrp x0, .LC0}
\texttt{add x0, x0, :lo12:.LC0}
\texttt{b puts}
\texttt{.LC0:}
\texttt{.string "1, 2, 7, 10"}
\texttt{.LC1:}
\texttt{.string "3, 4, 5"}
\texttt{.LC2:}
\texttt{.string "8, 9, 21"}
\texttt{.LC3:}
\texttt{.string "22"}
\texttt{.LC4:}
\texttt{.string "default"}

Let's compile this example to object file and open it in \texttt{IDA}. Here is the jump table:

\hspace*{1cm}\texttt{Listing 1.160: jumptable in IDA

\hspace*{1cm}.rodata:0000000000000064 AREA .rodata, DATA, READONLY
\hspace*{1cm}.rodata:0000000000000064 ; ORG 0x64
\hspace*{1cm}.rodata:0000000000000064 $d DCB 9 ; case 1
\hspace*{1cm}.rodata:0000000000000064 DCB 9 ; case 2
\hspace*{1cm}.rodata:0000000000000065 DCB 6 ; case 3
\hspace*{1cm}.rodata:0000000000000066 DCB 6 ; case 4
\hspace*{1cm}.rodata:0000000000000067 DCB 6 ; case 5
\hspace*{1cm}.rodata:0000000000000068 DCB 6 ; case 6
\hspace*{1cm}.rodata:0000000000000069 DCB 6 ; case 7
\hspace*{1cm}.rodata:000000000000006A DCB 3 ; case 8
\hspace*{1cm}.rodata:000000000000006B DCB 3 ; case 9
\hspace*{1cm}.rodata:000000000000006C DCB 9 ; case 10
\hspace*{1cm}.rodata:000000000000006D DCB 0xF7 ; case 11
\hspace*{1cm}.rodata:000000000000006E DCB 0xF7 ; case 12
\hspace*{1cm}.rodata:000000000000006F DCB 0xF7 ; case 13
\hspace*{1cm}.rodata:0000000000000070 DCB 0xF7 ; case 14
\hspace*{1cm}.rodata:0000000000000071 DCB 0xF7 ; case 15
\hspace*{1cm}.rodata:0000000000000072 DCB 0xF7 ; case 16
\hspace*{1cm}.rodata:0000000000000073 DCB 0xF7 ; case 17
\hspace*{1cm}.rodata:0000000000000074 DCB 0xF7 ; case 18
\hspace*{1cm}.rodata:0000000000000075 DCB 0xF7 ; case 19
\hspace*{1cm}.rodata:0000000000000076 DCB 0xF7 ; case 20
1.15. **SWITCH()//CASE/DEFAULT**

```
.rodata:0000000000000077 DCB 3 ; case 20
.rodata:0000000000000078 DCB 3 ; case 21
.rodata:0000000000000079 DCB 0 ; case 22
.rodata:000000000000007B ; .rodata ends
```

So in case of 1, 9 is to be multiplied by 4 and added to the address of Lrtx4 label.

In case of 22, 0 is to be multiplied by 4, resulting in 0.

Right after the Lrtx4 label is the L7 label, where you can find the code that prints “22”.

There is no jump table in the code segment, it’s allocated in a separate .rodata section (there is no special necessity to place it in the code section).

There are also negative bytes (0xF7), they are used for jumping back to the code that prints the “default” string (at .L2).

### 1.15.4 Fall-through

Another popular usage of `switch()` operator is so-called “fallthrough”. Here is simple example⁹⁸:

```c
bool is_whitespace(char c) {
    switch (c) {
        case ' ': // fallthrough
        case '	': // fallthrough
        case '': // fallthrough
        case '
':
            return true;
        default: // not whitespace
            return false;
    }
}
```

Slightly harder, from Linux kernel⁹⁹:

```c
char nco1, nco2;

void f(int if_freq_khz) {
    switch (if_freq_khz) {
        default:
            printf("IF=%d KHz is not supportted, 3250 assumed\n", if_freq_khz);
            /* fallthrough */
        case 3250: /* 3.25Mhz */
            nco1 = 0x34;
            nco2 = 0x00;
            break;
        case 3500: /* 3.50Mhz */
            nco1 = 0x38;
            nco2 = 0x00;
            break;
        case 4000: /* 4.00Mhz */
            nco1 = 0x40;
            nco2 = 0x00;
            break;
        case 5000: /* 5.00Mhz */
            nco1 = 0x50;
            nco2 = 0x00;
            break;
        case 5380: /* 5.38Mhz */
            nco1 = 0x56;
            nco2 = 0x14;
            break;
    }
}
```

⁹⁸Copypasted from https://github.com/azonalon/prgraas/blob/master/progllib/lecture_examples/is_whitespace.c
⁹⁹Copypasted from https://github.com/torvalds/linux/blob/master/drivers/media/dvb-frontends/lgdt3306a.c
We can get to .L5 label if there is number 3250 at function’s input. But we can get to this label from the other side: we see that there are no jumps between printf() call and .L5 label.

Now we can understand why switch() statement is sometimes a source of bugs: one forgotten break will transform your switch() statement into fallthrough one, and several blocks will be executed instead of single one.

### 1.15.5 Exercises

**Exercise #1**

It’s possible to rework the C example in 1.15.2 on page 166 in such way that the compiler can produce even smaller code, but will work just the same. Try to achieve it.
1.16. **Loops**

### 1.16.1 Simple example

**x86**

There is a special LOOP instruction in x86 instruction set for checking the value in register ECX and if it is not 0, to decrement ECX and pass control flow to the label in the LOOP operand. Probably this instruction is not very convenient, and there are no any modern compilers which emit it automatically. So, if you see this instruction somewhere in code, it is most likely that this is a manually written piece of assembly code.

In C/C++ loops are usually constructed using for(), while() or do/while() statements. Let's start with for().

This statement defines loop initialization (set loop counter to initial value), loop condition (is the counter bigger than a limit?), what is performed at each iteration (increment/decrement) and of course loop body.

```c
for (initialization; condition; at each iteration)
{
    loop_body;
}
```

The generated code is consisting of four parts as well. Let's start with a simple example:

```c
#include <stdio.h>

void printing_function(int i)
{
    printf ("f(%d)\n", i);
};

int main()
{
    int i;
    for (i=2; i<10; i++)
        printing_function(i);
    return 0;
};
```

Result (MSVC 2010):

```
Listing 1.162: MSVC 2010

_i$ = -4
_main PROC
    push ebp
    mov ebp, esp
    push ecx
    mov DWORD PTR _i$[ebp], 2 ; loop initialization
    jmp SHORT $LN3@main
$LN2@main:
    mov eax, DWORD PTR _i$[ebp] ; here is what we do after each iteration:
    add eax, 1 ; add 1 to (i) value
    mov DWORD PTR _i$[ebp], eax
$LN3@main:
    cmp DWORD PTR _i$[ebp], 10 ; this condition is checked before each iteration
    jge SHORT $LN1@main ; if (i) is biggest or equals to 10, lets finish loop
    mov ecx, DWORD PTR _i$[ebp] ; loop body: call printing_function(i)
    push ecx
    call _printing_function
    add esp, 4
    jmp SHORT $LN2@main ; jump to loop begin
$LN1@main:
    xor eax, eax ; loop end
    mov esp, ebp
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```
As we see, nothing special.

GCC 4.4.1 emits almost the same code, with one subtle difference:

Listing 1.163: GCC 4.4.1

```assembly
 main proc near
 var_20 = dword ptr -20h
 var_4 = dword ptr -4
 push ebp
 mov ebp, esp
 and esp, 0FFFFFFF0h
 sub esp, 20h
 mov [esp+20h+var_4], 2 ; (i) initializing
 jmp short loc_8048476

loc_8048465:
 mov eax, [esp+20h+var_4]
 mov [esp+20h+var_20], eax
 call printing_function
 add [esp+20h+var_4], 1 ; (i) increment

loc_8048476:
 cmp [esp+20h+var_4], 9
 jle short loc_8048465 ; if i<=9, continue loop
 mov eax, 0
 leave
 retn
 main endp
```

Now let's see what we get with optimization turned on (/Ox):

Listing 1.164: Optimizing MSVC

```assembly
 _main PROC
 push esi
 mov esi, 2
 $LL3@main:
 push esi
 call _printing_function
 inc esi
 add esp, 4
 cmp esi, 10 ; 0000000ah
 jl short $LL3@main
 xor eax, eax
 pop esi
 ret 0
 _main ENDP
```

What happens here is that space for the i variable is not allocated in the local stack anymore, but uses an individual register for it, ESI. This is possible in such small functions where there aren't many local variables.

One very important thing is that the f() function must not change the value in ESI. Our compiler is sure here. And if the compiler decides to use the ESI register in f() too, its value would have to be saved at the function’s prologue and restored at the function’s epilogue, almost like in our listing: please note PUSH ESI/POP ESI at the function start and end.

Let's try GCC 4.4.1 with maximal optimization turned on (-O3 option):

Listing 1.165: Optimizing GCC 4.4.1

```assembly
 main proc near
 var_10 = dword ptr -10h
```
1.16. LOOPS

push ebp
mov ebp, esp
and esp, 0FFFFFFF0h
sub esp, 10h
mov [esp+10h+var_10], 2
call printing_function
mov [esp+10h+var_10], 3
call printing_function
mov [esp+10h+var_10], 4
call printing_function
mov [esp+10h+var_10], 5
call printing_function
mov [esp+10h+var_10], 6
call printing_function
mov [esp+10h+var_10], 7
call printing_function
mov [esp+10h+var_10], 8
call printing_function
mov [esp+10h+var_10], 9
call printing_function
xor eax, eax
leave
retn

main endp

Huh, GCC just unwound our loop.

Loop unwinding has an advantage in the cases when there aren’t much iterations and we could cut some execution time by removing all loop support instructions. On the other side, the resulting code is obviously larger.

Big unrolled loops are not recommended in modern times, because bigger functions may require bigger cache footprint.

OK, let’s increase the maximum value of the \( i \) variable to 100 and try again. GCC does:

Listing 1.166: GCC

```assembly
public main
main proc near
var_20 = dword ptr -20h
push ebp
mov ebp, esp
and esp, 0FFFFFFF0h
push ebx
mov ebx, 2 ; i=2
sub esp, 1Ch ; aligning label loc_80484D0 (loop body begin) by 16-byte border:
nop
loc_80484D0:
; pass (i) as first argument to printing_function():
    mov [esp+20h+var_20], ebx
    add ebx, 1 ; i++
call printing_function
    cmp ebx, 64h ; i==100?
jnz short loc_80484D0 ; if not, continue
    add esp, 1Ch
    xor eax, eax ; return 0
    pop ebx
mov esp, ebp
pop ebp
retn
main endp
```

1.16. **LOOPS**

It is quite similar to what MSVC 2010 with optimization (/Ox) produce, with the exception that the EBX register is allocated for the \( i \) variable.

GCC is sure this register will not be modified inside of the \( f() \) function, and if it will, it will be saved at the function prologue and restored at epilogue, just like here in the \( \text{main()} \) function.
Let’s compile our example in MSVC 2010 with /Ox and /Ob0 options and load it into OllyDbg.

It seems that OllyDbg is able to detect simple loops and show them in square brackets, for convenience:

![Figure 1.54: OllyDbg: main() begin](image)

By tracing (F8 — step over) we see ESI incrementing. Here, for instance, $ESI = i = 6$:

![Figure 1.55: OllyDbg: loop body just executed with $i = 6$](image)

9 is the last loop value. That’s why JL is not triggering after the increment, and the function will finish:
1.16. LOOPS

Figure 1.56: OllyDbg: $ESI = 10$, loop end

**x86: tracer**

As we might see, it is not very convenient to trace manually in the debugger. That’s a reason we will try tracer.

We open compiled example in IDA, find the address of the instruction `PUSH ESI` (passing the sole argument to `f()`), which is 0x401026 for this case and we run the tracer:

```
tracer.exe -l:loops_2.exe bpx=loops_2.exe!0x00401026
```

BPX just sets a breakpoint at the address and tracer will then print the state of the registers.

In the tracer.log, this is what we see:

```diff
PID=12884|New process loops_2.exe
(0) loops_2.exe!0x401026
EAX=0x00a328c8 EBX=0x00000000 ECX=0x6f0f4714 EDX=0x00000000
ESI=0x00000002 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=PF ZF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000003 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF PF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000004 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF PF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000005 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF PF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000006 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF PF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000007 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF PF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000008 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
```

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We see how the value of ESI register changes from 2 to 9.

Even more than that, the tracer can collect register values for all addresses within the function. This is called trace there. Every instruction gets traced, all interesting register values are recorded.

Then, an IDA.idc-script is generated, that adds comments. So, in the IDA we’ve learned that the main() function address is 0x00401020 and we run:

```
tracer.exe -l:loops_2.exe bpf=loops_2.exe!0x00401020,trace:cc
```

BPF stands for set breakpoint on function.

As a result, we get the loops_2.exe.idc and loops_2.exe_clear.idc scripts.
1.16. LOOPS

We load loops_2.exe.idc into IDA and see:

![Figure 1.57: IDA with .idc-script loaded](image)

We see that ESI can be from 2 to 9 at the start of the loop body, but from 3 to 0xA (10) after the increment. We can also see that main() is finishing with 0 in EAX.

tracer also generates loops_2.exe.txt, that contains information about how many times each instruction has been executed and register values:

```plaintext
Listing 1.167: loops_2.exe.txt

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Count</th>
<th>Register Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x401020</td>
<td>.text+0x20</td>
<td>e=1</td>
<td>[PUSH ESI] ESI=1</td>
</tr>
<tr>
<td>0x401021</td>
<td>.text+0x21</td>
<td>e=1</td>
<td>[MOV ESI, 2]</td>
</tr>
<tr>
<td>0x401026</td>
<td>.text+0x26</td>
<td>e=8</td>
<td>[PUSH ESI] ESI=2..9</td>
</tr>
<tr>
<td>0x401027</td>
<td>.text+0x27</td>
<td>e=8</td>
<td>[CALL 8D1000h] tracing nested maximum level (1) reached, ⤵  skipping this CALL 8D1000h=0x8d1000</td>
</tr>
<tr>
<td>0x40102c</td>
<td>.text+0x2c</td>
<td>e=8</td>
<td>[INC ESI] ESI=2..9</td>
</tr>
<tr>
<td>0x40102d</td>
<td>.text+0x2d</td>
<td>e=8</td>
<td>[ADD ESP, 4] ESP=0x38fcbc</td>
</tr>
<tr>
<td>0x401030</td>
<td>.text+0x30</td>
<td>e=8</td>
<td>[CMP ESI, 0Ah] ESI=3..0xa</td>
</tr>
<tr>
<td>0x401033</td>
<td>.text+0x33</td>
<td>e=8</td>
<td>[JL short loc_401026] SF=false, true OF=false</td>
</tr>
<tr>
<td>0x401035</td>
<td>.text+0x35</td>
<td>e=8</td>
<td>[XOR EAX, EAX]</td>
</tr>
<tr>
<td>0x401037</td>
<td>.text+0x37</td>
<td>e=8</td>
<td>[POP ESI]</td>
</tr>
<tr>
<td>0x401038</td>
<td>.text+0x38</td>
<td>e=8</td>
<td>[RETN] EAX=0</td>
</tr>
</tbody>
</table>
```

We can use grep here.

**ARM**

Non-optimizing Keil 6/2013 (ARM mode)

```
main
  STMFD SP!, {R4,LR}
  MOV R4, #2
  B loc_368
loc_35c ; CODE XREF: main+1C
  MOV R0, R4
  BL printing_function
  ADD R4, R4, #1
loc_368 ; CODE XREF: main+8
```
1.16. LOOPS

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMP R4, #0xA</td>
<td>Compare R4 with 0xA</td>
</tr>
<tr>
<td>BLT loc_35C</td>
<td>Branch if less than</td>
</tr>
<tr>
<td>MOV R0, #0</td>
<td>Move value to R0</td>
</tr>
<tr>
<td>LDMFD SP!, {R4,PC}</td>
<td>Load memory to registers</td>
</tr>
</tbody>
</table>

Iteration counter $i$ is to be stored in the R4 register. The MOV R4, #2 instruction just initializes $i$. The MOV R0, R4 and BL printing_function instructions compose the body of the loop, the first instruction preparing the argument for $f()$ function and the second calling the function. The ADD R4, R4, #1 instruction just adds 1 to the $i$ variable at each iteration. CMP R4, #0xA compares $i$ with 0xA (10). The next instruction BLT (Branch Less Than) jumps if $i$ is less than 10. Otherwise, 0 is to be written into R0 (since our function returns 0) and function execution finishes.

**Optimizing Keil 6/2013 (Thumb mode)**

```assembly
_loc_132
MOVS R0, R4
BL printing_function
ADDS R4, R4, #1
CMP R4, #0xA
BLT loc_132
MOVS R0, #0
POP {R4,PC}
```

Practically the same.

**Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)**

```assembly
_main
PUSH {R4,R7,LR}
MOVW R4, #0x1124 ; "%d\n"
MOV R1, #2
MOV T.W R4, #0
ADD R7, SP, #4
ADD R4, PC
MOV R0, R4
BLX _printf
MOV R0, R4
MOVS R1, #3
BLX _printf
MOV R0, R4
MOVS R1, #4
BLX _printf
MOV R0, R4
MOVS R1, #5
BLX _printf
MOV R0, R4
MOVS R1, #6
BLX _printf
MOV R0, R4
MOVS R1, #7
BLX _printf
MOV R0, R4
MOVS R1, #8
BLX _printf
MOV R0, R4
MOVS R1, #9
BLX _printf
MOV R0, #0
POP {R4,R7,PC}
```

In fact, this was in my $f()$ function:
void printing_function(int i)
{
    printf("%d\n", i);
};

So, LLVM not just *unrolled* the loop, but also *inlined* my very simple function f(), and inserted its body 8 times instead of calling it.

This is possible when the function is so simple (like mine) and when it is not called too much (like here).

**ARM64: Optimizing GCC 4.9.1**

```
Listing 1.168: Optimizing GCC 4.9.1

printing_function:
; prepare second argument of printf():
    mov     w1, w0
; load address of the "f(%d)\n" string
    adrp    x0, .LC0
    add     x0, x0, :lo12:.LC0
; just branch here instead of branch with link and return:
    b printf

main:
; save FP and LR in the local stack:
    stp     x29, x30, [sp, -32]!
; set up stack frame:
    add     x29, sp, 0
; save contents of X19 register in the local stack:
    str     x19, [sp,16]
; we will use W19 register as counter.
; set initial value of 2 to it:
    mov     w19, 2
.L3:
; prepare first argument of printing_function():
    mov     w0, w19
; increment counter register.
    add     w19, w19, 1
; W0 here still holds value of counter value before increment.
    bl      printing_function
; is it end?
    cmp     w19, 10
; no, jump to the loop body begin:
    bne     .L3
; return 0
    mov     w0, 0
; restore contents of X19 register:
    ldr     x19, [sp,16]
; restore FP and LR values:
    ldp     x29, x30, [sp], 32
    ret

.LC0:
    .string "f(%d)\n"
```

**ARM64: Non-optimizing GCC 4.9.1**

```
Listing 1.169: Non-optimizing GCC 4.9.1 -fno-inline

printing_function:
; prepare second argument of printf():
    mov     w1, w0
; load address of the "f(%d)\n" string
    adrp    x0, .LC0
    add     x0, x0, :lo12:.LC0
; just branch here instead of branch with link and return:
    b      printf
```
1.16. LOOPS

```assembly
main:
; save FP and LR in the local stack:
    stp    x29, x30, [sp, -32]!
; set up stack frame:
    add    x29, sp, 0
; save contents of X19 register in the local stack:
    str    x19, [sp,16]
; we will use W19 register as counter.
; set initial value of 2 to it:
    mov    w19, 2
.L3:
; prepare first argument of printing_function():
    mov    w0, w19
; increment counter register.
    add    w19, w19, 1
; W0 here still holds value of counter value before increment.
    bl     printing_function
; is it end?
    cmp    w19, 10
; no, jump to the loop body begin:
    bne    .L3
; return 0
    mov    w0, 0
; restore contents of X19 register:
    ldr    x19, [sp,16]
; restore FP and LR values:
    ldp    x29, x30, [sp], 32
ret
.LC0:
.string "f(%d)\n"
```

MIPS

```assembly
Listing 1.170: Non-optimizing GCC 4.4.5 (IDA)
main:
; IDA is not aware of variable names in local stack
; We gave them names manually:
i       = -0x10
saved_FP = -8
saved_RA = -4

; function prologue:
    addiu $sp, -0x28
    sw $ra, 0x28+saved_RA($sp)
    sw $fp, 0x28+saved_FP($sp)
    move $fp, $sp

; initialize counter at 2 and store this value in local stack
    li $v0, 2
    sw $v0, 0x28+i($fp)

; pseudoinstruction. "BEQ $ZERO, $ZERO, loc_9C" there in fact:
    b loc_9C
or $at, $zero ; branch delay slot, NOP
loc_80: # CODE XREF: main+48
; load counter value from local stack and call printing_function():
    lw $a0, 0x28+i($fp)
    jal printing_function
or $at, $zero ; branch delay slot, NOP
; load counter, increment it, store it back:
    lw $v0, 0x28+i($fp)
    or $at, $zero ; NOP
    addiu $v0, 1
    sw $v0, 0x28+i($fp)
loc_9C: # CODE XREF: main+18
; check counter, is it 10?
```

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1.16. LOOPS

```
lw     $v0, 0x28+i($fp)
or     $at, $zero ; NOP
slti    $v0, 0xA
; if it is less than 10, jump to loc_80 (loop body begin):
  bnez   $v0, loc_80
or     $at, $zero ; branch delay slot, NOP
; finishing, return 0:
  move   $v0, $zero
 ; function epilogue:
  move   $sp, $fp
  lw     $ra, 0x28+saved_RA($sp)
  lw     $fp, 0x28+saved_FP($sp)
  addiu  $sp, 0x28
  jr      $ra
or     $at, $zero ; branch delay slot, NOP
```

The instruction that’s new to us is B. It is actually the pseudo instruction (BEQ).

**One more thing**

In the generated code we can see: after initializing i, the body of the loop is not to be executed, as the condition for i is checked first, and only after that loop body can be executed. And that is correct. Because, if the loop condition is not met at the beginning, the body of the loop must not be executed. This is possible in the following case:

```
for (i=0; i<total_entries_to_process; i++)
  loop_body;
```

If total_entries_to_process is 0, the body of the loop must not be executed at all. This is why the condition checked before the execution.

However, an optimizing compiler may swap the condition check and loop body, if it sure that the situation described here is not possible (like in the case of our very simple example and using compilers like Keil, Xcode (LLVM), MSVC in optimization mode).

1.16.2 Memory blocks copying routine

Real-world memory copy routines may copy 4 or 8 bytes at each iteration, use SIMD, vectorization, etc. But for the sake of simplicity, this example is the simplest possible.

```
#include <stdio.h>

void my_memcpy (unsigned char* dst, unsigned char* src, size_t cnt)
{
  size_t i;
  for (i=0; i<cnt; i++)
    dst[i]=src[i];
}
```

**Straight-forward implementation**

Listing 1.171: GCC 4.9 x64 optimized for size (-Os)

```
my_memcpy:
; RDI = destination address
; RSI = source address
; RDX = size of block
; initialize counter (i) at 0
  xor     eax, eax
.L2:
```

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1.16. LOOPS

; all bytes copied? exit then:
    cmp rax, rdx
    je .L5
; load byte at RSI+i:
    mov cl, BYTE PTR [rsi+rax]
; store byte at RDI+i:
    mov BYTE PTR [rdi+rax], cl
    inc rax ; i++
    jmp .L2
.L5:
    ret

Listing 1.172: GCC 4.9 ARM64 optimized for size (-Os)

my_memcpy:
; X0 = destination address
; X1 = source address
; X2 = size of block

; initialize counter (i) at 0
    mov x3, 0
.L2:
; all bytes copied? exit then:
    cmp x3, x2
    beq .L5
; load byte at X1+i:
    ldrb w4, [x1,x3]
; store byte at X0+i:
    strb w4, [x0,x3]
    add x3, x3, 1 ; i++
    b .L2
.L5:
    ret

Listing 1.173: Optimizing Keil 6/2013 (Thumb mode)

my_memcpy PROC
; R0 = destination address
; R1 = source address
; R2 = size of block

    PUSH {r4,lr}
; initialize counter (i) at 0
    MOV r3,#0
; condition checked at the end of function, so jump there:
    B |L0.12|
|L0.6| ; load byte at R1+i:
    LDRB r4,[r1,r3]
; store byte at R0+i:
    STRB r4,[r0,r3]
; i++
    ADDS r3,r3,#1
|L0.12| ; i<size?
    CMP r3,r2
; jump to the loop begin if its so:
    BCC |L0.6|
    POP {r4,pc}
ENDP

ARM in ARM mode

Keil in ARM mode takes full advantage of conditional suffixes:

Listing 1.174: Optimizing Keil 6/2013 (ARM mode)

my_memcpy PROC
1.16. LOOPS

; R0 = destination address
; R1 = source address
; R2 = size of block

; initialize counter (i) at 0
MOV    r3,#0
|L0.4|
; all bytes copied?
CMP    r3,r2
; the following block is executed only if less than condition,
; i.e., if R2<R3 or i<size.
; load byte at R1+i:
LDRBCC r12,[r1,r3]
; store byte at R0+i:
STRBCC r12,[r0,r3]
; i++
ADDCC  r3,r3,#1
; the last instruction of the conditional block.
; jump to loop begin if i<size
; do nothing otherwise (i.e., if i>=size)
BCC    |L0.4|
; return
BX     lr
ENDP

That’s why there is only one branch instruction instead of 2.

MIPS

Listing 1.175: GCC 4.4.5 optimized for size (-Os) (IDA)

my_memcpy:
; jump to loop check part:
    b loc_14
; initialize counter (i) at 0
; it will always reside in $v0:
    move $v0, $zero ; branch delay slot
loc_8:  # CODE XREF: my_memcpy+1C
; load byte as unsigned at address in $t0 to $v1:
    lbu $v1, 0($t0)
; increment counter (i):
    addiu $v0, 1
; store byte at $a3
    sb $v1, 0($a3)
loc_14: # CODE XREF: my_memcpy
; check if counter (i) in $v0 is still less then 3rd function argument ("cnt" in $a2):
    sltu $v1, $v0, $a2
; form address of byte in source block:
    addu $t0, $a1, $v0
; $t0 = $a1+$v0 = src+i
; jump to loop body if counter sill less then "cnt":
    bnez $v1, loc_8
; form address of byte in destination block ($a3 = $a0+$v0 = dst+i):
    addu $a3, $a0, $v0 ; branch delay slot
; finish if BNEZ wasnt triggered:
    jr $ra
    or $at, $zero ; branch delay slot, NOP

Here we have two new instructions: LBU (“Load Byte Unsigned”) and SB (“Store Byte”).
Just like in ARM, all MIPS registers are 32-bit wide, there are no byte-wide parts like in x86.
So when dealing with single bytes, we have to allocate whole 32-bit registers for them.
LBU loads a byte and clears all other bits (“Unsigned”).
On the other hand, LB (“Load Byte”) instruction sign-extends the loaded byte to a 32-bit value.
1.16. LOOPS

SB just writes a byte from lowest 8 bits of register to memory.

Vectorization

Optimizing GCC can do much more on this example: 1.29.1 on page 412.

1.16.3 Condition check

It’s important to keep in mind that in for() construct, condition is checked not at the end, but at the beginning, before execution of loop body. But often, it’s more convenient for compiler to check it at the end, after body. Sometimes, additional check can be appended at the beginning.

For example:

```c
#include <stdio.h>

void f(int start, int finish)
{
  for (; start<finish; start++)
    printf ("%d\n", start);
}
```

Optimizing GCC 5.4.0 x64:

```c
f:
  ; check condition (1):
  cmp     edi, esi
  jge    .L9
  push    rbp
  push    rbx
  mov     ebp, esi
  mov     ebx, edi
  sub     rsp, 8
  .L5:
    mov     edx, ebx
    xor     eax, eax
    mov     esi, OFFSET FLAT:.LC0 ; '%d\n"
    mov     edi, 1
    add     ebx, 1
    call    __printf_chk
  ; check condition (2):
  cmp     ebp, ebx
  jne    .L5
  add     rsp, 8
  pop     rbx
  pop     rbp
  .L9:
    rep ret
```

We see two checks.

Hex-Rays (at least version 2.2.0) decompiles this as:

```c
void __cdecl f(unsigned int start, unsigned int finish)
{
  unsigned int v2; // ebx@2
  __int64 v3; // rdx@3
  if ( (signed int)start < (signed int)finish )
  {
    v2 = start;
    do
    {
      v3 = v2++;
      _printf_chk(1LL, "%d\n", v3);
    }
    while ( finish != v2 );
  }
```

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1.16. LOOPS

In this case, `do/while()` can be replaced by `for()` without any doubt, and the first check can be removed.

1.16.4 Conclusion

Rough skeleton of loop from 2 to 9 inclusive:

Listing 1.176: x86

```
mov [counter], 2 ; initialization
jmp check
body:
    ; loop body
    ; do something here
    ; use counter variable in local stack
    add [counter], 1 ; increment
check:
    cmp [counter], 9
    jle body
```

The increment operation may be represented as 3 instructions in non-optimized code:

Listing 1.177: x86

```
MOV [counter], 2 ; initialization
JMP check
body:
    ; loop body
    ; do something here
    ; use counter variable in local stack
    MOV REG, [counter] ; increment
    INC REG
    MOV [counter], REG
check:
    CMP [counter], 9
    JLE body
```

If the body of the loop is short, a whole register can be dedicated to the counter variable:

Listing 1.178: x86

```
MOV EBX, 2 ; initialization
JMP check
body:
    ; loop body
    ; do something here
    ; use counter in EBX, but do not modify it!
    INC EBX ; increment
check:
    CMP EBX, 9
    JLE body
```

Some parts of the loop may be generated by compiler in different order:

Listing 1.179: x86

```
MOV [counter], 2 ; initialization
JMP label_check
label_increment:
    ADD [counter], 1 ; increment
label_check:
    CMP [counter], 10
    JGE exit
    ; loop body
    ; do something here
    ; use counter variable in local stack
    JMP label_increment
exit:
```
1.17. MORE ABOUT STRINGS

Usually the condition is checked \textit{before} loop body, but the compiler may rearrange it in a way that the condition is checked \textit{after} loop body.

This is done when the compiler is sure that the condition is always \textit{true} on the first iteration, so the body of the loop is to be executed at least once:

Listing 1.180: x86

\begin{verbatim}
MOV REG, 2 ; initialization
body:
; loop body
; do something here
; use counter in REG, but do not modify it!
INC REG ; increment
CMP REG, 10
JL body
\end{verbatim}

Using the \texttt{LOOP} instruction. This is rare, compilers are not using it. When you see it, it’s a sign that this piece of code is hand-written:

Listing 1.181: x86

\begin{verbatim}
; count from 10 to 1
MOV ECX, 10
body:
; loop body
; do something here
; use counter in ECX, but do not modify it!
LOOP body
\end{verbatim}

ARM.

The R4 register is dedicated to counter variable in this example:

Listing 1.182: ARM

\begin{verbatim}
MOV R4, 2 ; initialization
B check
body:
; loop body
; do something here
; use counter in R4, but do not modify it!
ADD R4,R4, #1 ; increment
check:
CMP R4, #10
BLT body
\end{verbatim}

1.16.5 Exercises

- \url{http://challenges.re/54}
- \url{http://challenges.re/55}
- \url{http://challenges.re/56}
- \url{http://challenges.re/57}

1.17 More about strings

1.17.1 strlen()

Let’s talk about loops one more time. Often, the \texttt{strlen()} function \footnote{counting the characters in a string in the C language} is implemented using a \texttt{while()} statement. Here is how it is done in the MSVC standard libraries:
1.17. MORE ABOUT STRINGS

```c
int my_strlen (const char * str)
{
    const char *eos = str;
    while( *eos++ )
        return( eos - str - 1 );
}

int main()
{
    // test
    return my_strlen("hello!");
};
```

x86

Non-optimizing MSVC

Let's compile:

```assembly
_eos$ = -.4 ; size = 4
_str$ = 8 ; size = 4
_strlen PROC
    push ebp
    mov ebp, esp
    push ecx
    mov eax, DWORD PTR _str$[ebp] ; place pointer to string from "str"
    mov DWORD PTR _eos$[ebp], eax ; place it to local variable "eos"
$LN2@strlen_:
    mov ecx, DWORD PTR _eos$[ebp] ; ECX=eos
    // take 8-bit byte from address in ECX and place it as 32-bit value to EDX with sign \ extension
    movsx edx, BYTE PTR [ecx]
    mov eax, DWORD PTR _eos$[ebp] ; EAX=eos
    add eax, 1 ; increment EAX
    mov DWORD PTR _eos$[ebp], eax ; place EAX back to "eos"
    test edx, edx ; EDX is zero?
    je SHORT $LN1@strlen_ ; yes, then finish loop
    jmp SHORT $LN2@strlen_ ; continue loop
$LN1@strlen_:
    ; here we calculate the difference between two pointers
    mov eax, DWORD PTR _eos$[ebp]
    sub eax, DWORD PTR _str$[ebp]
    sub eax, 1 ; subtract 1 and return result
    mov esp, ebp
    pop ebp
    ret 0
_strlen_ ENDP
```

We get two new instructions here: MOVsx and TEST.

The first one—MOVsx—takes a byte from an address in memory and stores the value in a 32-bit register. MOVsx stands for MOV with Sign-Extend. MOVsx sets the rest of the bits, from the 8th to the 31th, to 1 if the source byte is negative or to 0 if is positive.

And here is why.

By default, the char type is signed in MSVC and GCC. If we have two values of which one is char and the other is int, (int is signed too), and if the first value contain -2 (coded as 0xFE) and we just copy this byte into the int container, it makes 0x000000FE, and this from the point of signed int view is 254, but not -2. In signed int, -2 is coded as 0xFFFFFFFF. So if we have to transfer 0xFE from a variable of char type to int, we have to identify its sign and extend it. That is what MOVsx does.
1.17. MORE ABOUT STRINGS

You can also read about it in “Signed number representations” section (2.2 on page 452).

It’s hard to say if the compiler needs to store a char variable in EDX, it could just take a 8-bit register part (for example DL). Apparently, the compiler’s register allocator works like that.

Then we see TEST EDX, EDX. You can read more about the TEST instruction in the section about bit fields (1.22 on page 304). Here this instruction just checks if the value in EDX equals to 0.

Non-optimizing GCC

Let’s try GCC 4.4.1:

```
  public strlen
  strlen proc near
  eos = dword ptr -4
  arg_0 = dword ptr 8
 pushes ebp
  mov ebp, esp
  sub esp, 10h
  mov eax, [ebp+arg_0]
  mov [ebp+eos], eax
loc_80483F0:
  mov eax, [ebp+eos]
  movzx eax, byte ptr [eax]
  test al, al
  setnz al
  add [ebp+eos], 1
  test al, al
  jnz short loc_80483F0
  mov edx, [ebp+eos]
  mov [ebp+arg_0], ecx
  sub ecx, eax
  mov eax, ecx
  sub eax, 1
  leave
  ret
  strlen endp
```

The result is almost the same as in MSVC, but here we see MOVZX instead of MOVSX. MOVZX stands for MOV with Zero-Extend. This instruction copies a 8-bit or 16-bit value into a 32-bit register and sets the rest of the bits to 0. In fact, this instruction is convenient only because it enable us to replace this instruction pair:

```
xor eax, eax / mov al, [...].
```

On the other hand, it is obvious that the compiler could produce this code:

```
mov al, byte ptr [eax] / test al, al—it is almost the same, however, the highest bits of the EAX register will contain random noise. But let’s think it is compiler’s drawback—it cannot produce more understandable code. Strictly speaking, the compiler is not obliged to emit understandable (to humans) code at all.
```

The next new instruction for us is SETNZ. Here, if AL doesn’t contain zero, test al, al sets the ZF flag to 0, but SETNZ, if ZF==0 (NZ stands for not zero) sets AL to 1. Speaking in natural language, if AL is not zero, let’s jump to loc_80483F0. The compiler emits some redundant code, but let’s not forget that the optimizations are turned off.

Optimizing MSVC

Now let’s compile all this in MSVC 2012, with optimizations turned on (/Ox):

```
  _str$ = 8 ; size = 4
  _strlen PROC
Listing 1.183: Optimizing MSVC 2012 /Ob0
```
1.17. MORE ABOUT STRINGS

```assembly
mov edx, DWORD PTR _str$[esp-4]; EDX -> pointer to the string
mov eax, edx; move to EAX

$LL2@strlen:
   mov cl, BYTE PTR [eax]; CL = *EAX
   inc eax; EAX++
   test cl, cl; CL==0?
   jne SHORT $LL2@strlen; no, continue loop
   sub eax, edx; calculate pointers difference
   dec eax; decrement EAX
   ret 0

_strlen ENDP
```

Now it is all simpler. Needless to say, the compiler could use registers with such efficiency only in small functions with a few local variables.

INC/DEC—are increment/decrement instructions, in other words: add or subtract 1 to/from a variable.
We can try this (optimized) example in OllyDbg. Here is the first iteration:

![OllyDbg: first iteration start](image-url)

We see that OllyDbg found a loop and, for convenience, wrapped its instructions in brackets. By clicking the right button on EAX, we can choose “Follow in Dump” and the memory window scrolls to the right place. Here we can see the string “hello!” in memory. There is at least one zero byte after it and then random garbage.

If OllyDbg sees a register with a valid address in it, that points to some string, it is shown as a string.

Figure 1.58: OllyDbg: first iteration start
1.17. MORE ABOUT STRINGS

Let’s press F8 (step over) a few times, to get to the start of the body of the loop:

![CPU - main thread, module ex1](image)

Figure 1.59: OllyDbg: second iteration start

We see that EAX contains the address of the second character in the string.
1.17. **MORE ABOUT STRINGS**

We have to press F8 enough number of times in order to escape from the loop:

![CPU - main thread, module ex1](image)

We see that `EAX` now contains the address of zero byte that’s right after the string. Meanwhile, `EDX` hasn’t changed, so it still pointing to the start of the string.

The difference between these two addresses is being calculated now.

![OllyDbg: pointers difference to be calculated now](image)
The SUB instruction just got executed:

The difference of pointers is in the EAX register now—7. Indeed, the length of the “hello!” string is 6, but with the zero byte included—7. But `strlen()` must return the number of non-zero characters in the string. So the decrement executes and then the function returns.

Optimizing GCC

Let’s check GCC 4.4.1 with optimizations turned on (-O3 key):

```
public strlen
proc near

arg_0  = dword ptr 8

push  ebp
mov   ebp, esp
mov   ecx, [ebp+arg_0]
mov   eax, ecx

loc_8048418:
movzx  edx, byte ptr [eax]
add   eax, 1
test  dl, dl
jnz   short loc_8048418
not   ecx
add   eax, ecx
pop    ebp
retn

strlen
endp
```

Here GCC is almost the same as MSVC, except for the presence of `MOVZX`. However, here `MOVZX` could be replaced with `mov dl, byte ptr [eax].

Figure 1.61: OllyDbg: EAX to be decremented now
1.17. MORE ABOUT STRINGS

Perhaps it is simpler for GCC's code generator to remember the whole 32-bit EDX register is allocated for a char variable and it then can be sure that the highest bits has no any noise at any point.

After that we also see a new instruction—NOT. This instruction inverts all bits in the operand. You can say that it is a synonym to the XOR ECX, 0xffffffff instruction. NOT and the following ADD calculate the pointer difference and subtract 1, just in a different way. At the start ECX, where the pointer to str is stored, gets inverted and 1 is subtracted from it.

See also: “Signed number representations” (2.2 on page 452).

In other words, at the end of the function just after loop body, these operations are executed:

```assembly
ecx=str;
eax=eos;
ecx=(-ecx)-1;
eax=eax+ecx
return eax
```

... and this is effectively equivalent to:

```assembly
cedx=str;
eax=eos;
eax=eax-eax
return eax
```

Why did GCC decide it would be better? Hard to guess. But perhaps the both variants are equivalent in efficiency.

ARM

32-bit ARM

Non-optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 1.184: Non-optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
._strlen

eos = -8
str = -4

    SUB    SP, SP, #8 ; allocate 8 bytes for local variables
    STR    R0, [SP,#8+str]
    LDR    R0, [SP,#8+eos]
    STR    R0, [SP,#8+eos]

loc_2CB8 ; CODE XREF: _strlen+28
    LDR    R0, [SP,#8+eos]
    ADD    R1, R0, #1
    STR    R1, [SP,#8+eos]
    LDRSB  R0, [R0]
    CMP    R0, #0
    BEQ    loc_2CD4
    B      loc_2CB8

loc_2CD4 ; CODE XREF: _strlen+24
    LDR    R0, [SP,#8+eos]
    LDR    R1, [SP,#8+str]
    SUB    R0, R0, R1 ; R0=eos-str
    SUB    R0, R0, #1 ; R0=R0-1
    ADD    SP, SP, #8 ; free allocated 8 bytes
    BX     LR
```

Non-optimizing LLVM generates too much code, however, here we can see how the function works with local variables in the stack. There are only two local variables in our function: eos and str. In this listing, generated by IDA, we have manually renamed var_8 and var_4 to eos and str.
1.17. **MORE ABOUT STRINGS**

The first instructions just saves the input values into both `str` and `eos`.

The body of the loop starts at label `loc_2CB8`.

The first three instructions in the loop body (LDR, ADD, STR) load the value of `eos` into R0. Then the value is incremented and saved back into `eos`, which is located in the stack.

The next instruction, LDRSB R0, [R0] ("Load Register Signed Byte"), loads a byte from memory at the address stored in R0 and sign-extends it to 32-bit. This is similar to the MOVSSX instruction in x86.

The compiler treats this byte as signed since the `char` type is signed according to the C standard. It was already written about it (1.17.1 on page 201) in this section, in relation to x86.

It has to be noted that it is impossible to use 8- or 16-bit part of a 32-bit register in ARM separately of the whole register, as it is in x86.

Apparently, it is because x86 has a huge history of backwards compatibility with its ancestors up to the 16-bit 8086 and even 8-bit 8080, but ARM was developed from scratch as a 32-bit RISC-processor.

Consequently, in order to process separate bytes in ARM, one has to use 32-bit registers anyway.

So, LDRSB loads bytes from the string into R0, one by one. The following CMP and BNE instructions check if the loaded byte is 0. If it’s not 0, control passes to the start of the body of the loop. And if it’s 0, the loop ends.

At the end of the function, the difference between `eos` and `str` is calculated, 1 is subtracted from it, and resulting value is returned via R0.

N.B. Registers were not saved in this function.

That’s because in the ARM calling convention registers R0-R3 are "scratch registers", intended for arguments passing, and we’re not required to restore their value when the function exits, since the calling function will not use them anymore. Consequently, they may be used for anything we want.

No other registers are used here, so that is why we have nothing to save on the stack.

Thus, control may be returned back to calling function by a simple jump (BX), to the address in the LR register.

### Optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

Listing 1.185: Optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

```assembly
_strlen
    MOV R1, R0
loc_2DF6
    LDRB.W R2, [R1], #1
    CMP R2, #0
    BNE loc_2DF6
    MVNS R0, R0
    ADD R0, R1
    BX LR
```

As optimizing LLVM concludes, `eos` and `str` do not need space on the stack, and can always be stored in registers.

Before the start of the loop body, `str` is always in R0, and `eos`—in R1.

The `LDRB.W R2, [R1], #1` instruction loads a byte from the memory at the address stored in R1, to R2, sign-extending it to a 32-bit value, but not just that. #1 at the instruction’s end implies “Post-indexed addressing”, which means that 1 is to be added to R1 after the byte is loaded. Read more about it: 1.32.2 on page 439.

Then you can see CMP and BNE in the body of the loop, these instructions continue looping until 0 is found in the string.

---

104 The Keil compiler treats the `char` type as signed, just like MSVC and GCC.

105 (PowerPC, ARM) Branch if Not Equal
More About Strings

MVNS\textsuperscript{106} (inverts all bits, like NOT in x86) and ADD instructions compute \( \cos - \text{str} - 1 \). In fact, these two instructions compute \( R0 = \text{str} + \cos \), which is effectively equivalent to what was in the source code, and why it is so, was already explained here (1.17.1 on page 208).

Apparently, LLVM, just like GCC, concludes that this code can be shorter (or faster).

Optimizing Keil 6/2013 (ARM mode)

Listing 1.186: Optimizing Keil 6/2013 (ARM mode)

\begin{verbatim}
_strlen
  MOV      R1, R0
loc_2C8
  LDRB     R2, [R1],#1
  CMP      R2, #0
  SUBEQ    R0, R1, R0
  SUBEQ    R0, R0, #1
  BNE      loc_2C8
  BX       LR
\end{verbatim}

Almost the same as what we saw before, with the exception that the \( \text{str} - \cos - 1 \) expression can be computed not at the function’s end, but right in the body of the loop. The -EQ suffix, as we may recall, implies that the instruction executes only if the operands in the CMP that has been executed before were equal to each other. Thus, if \( R0 \) contains 0, both \text{SUBEQ} instructions executes and result is left in the \( R0 \) register.

ARM64

Optimizing GCC (Linaro) 4.9

\begin{verbatim}
my_strlen:
  mov     x1, x0
  ; X1 is now temporary pointer (eos), acting like cursor
.L58:
  ; load byte from X1 to W2, increment X1 (post-index)
  ldrb    w2, [x1],1
  ; Compare and Branch if NonZero: compare W2 with 0, jump to .L58 if it is not
  cbnz    w2, .L58
  ; calculate difference between initial pointer in X0 and current address in X1
  sub     x0, x1, x0
  ; decrement lowest 32-bit of result
  sub     w0, w0, #1
  ret
\end{verbatim}

The algorithm is the same as in 1.17.1 on page 202: find a zero byte, calculate the difference between the pointers and decrement the result by 1. Some comments were added by the author of this book.

The only thing worth noting is that our example is somewhat wrong: \text{my\_strlen()} returns 32-bit \text{int}, while it has to return \text{size\_t} or another 64-bit type.

The reason is that, theoretically, \text{strlen()} can be called for a huge blocks in memory that exceeds 4GB, so it must able to return a 64-bit value on 64-bit platforms.

Because of my mistake, the last \text{SUB} instruction operates on a 32-bit part of register, while the penultimate \text{SUB} instruction works on full the 64-bit register (it calculates the difference between the pointers).

It’s my mistake, it is better to leave it as is, as an example of how the code could look like in such case.

\textsuperscript{106}MoVe Not
1.17. MORE ABOUT STRINGS

Non-optimizing GCC (Linaro) 4.9

my_strlen:
    ; function prologue
    sub sp, sp, #32
    ; first argument (str) will be stored in [sp,8]
    str x0, [sp,8]
    ldr x0, [sp,8]
    ; copy "str" to "eos" variable
    str x0, [sp,24]
    nop
.L62:
    ; eos++
    ldr x0, [sp,24] ; load "eos" to x0
    add x1, x0, 1 ; increment x0
    str x1, [sp,24] ; save x0 to "eos"
    ; load byte from memory at address in x0 to w0
    ldrb w0, [x0]
    ; is it zero? (WZR is the 32-bit register always contain zero)
    cmp w0, wzr
    ; jump if not zero (Branch Not Equal)
    bne .L62
    ; zero byte found. now calculate difference.
    ; load "eos" to x1
    ldr x1, [sp,24]
    ; load "str" to x0
    ldr x0, [sp,8]
    ; calculate difference
    sub x0, x1, x0
    ; decrement result
    sub w0, w0, #1
    ; function epilogue
    add sp, sp, 32
    ret

It’s more verbose. The variables are often tossed here to and from memory (local stack). The same mistake here: the decrement operation happens on a 32-bit register part.

MIPS

Listing 1.187: Optimizing GCC 4.4.5 (IDA)

my_strlen:
    ; "eos" variable will always reside in $v1:
    move $v1, $a0
loc_4:
    ; load byte at address in "eos" into $a1:
    lb $a1, 0($v1)
    or $at, $zero ; load delay slot, NOP
    ; if loaded byte is not zero, jump to loc_4:
    bnez $a1, loc_4
    ; increment "eos" anyway:
    addiu $v1, 1 ; branch delay slot
    ; loop finished. invert "str" variable:
    nor $v0, $zero, $a0
    ; $v0=-str-1
    jr $ra
; return value = $v1 + $v0 = eos + ( -str-1 ) = eos - str - 1
    addu $v0, $v1, $v0 ; branch delay slot

MIPS lacks a NOT instruction, but has NOR which is OR + NOT operation.

This operation is widely used in digital electronics\textsuperscript{107}. For example, the Apollo Guidance Computer used in the Apollo program, was built by only using 5600 NOR gates: [Jens Eickhoff, \textit{Onboard Computers},

\textsuperscript{107}\textit{NOR is called "universal gate"}

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1.18. REPLACING ARITHMETIC INSTRUCTIONS TO OTHER ONES


So, the NOT operation is implemented here as NOR DST, $ZERO$, SRC.

From fundamentals 2.2 on page 452 we know that bitwise inverting a signed number is the same as changing its sign and subtracting 1 from the result.

So what NOT does here is to take the value of $str$ and transform it into $-str - 1$. The addition operation that follows prepares result.

1.17.2 Boundaries of strings

It’s interesting to note, how parameters are passed into win32 GetOpenFileName() function. In order to call it, one must set list of allowed file extensions:

```c
OPENFILENAME *LPOPENFILENAME;
...
char * filter = "Text files (*.txt)\0*.txt\0MS Word files (*.doc)\0*.doc\0\0";
...
LPOPENFILENAME = (OPENFILENAME *)malloc(sizeof(OPENFILENAME));
...
LPOPENFILENAME->lpstrFilter = filter;
...
if(GetOpenFileName(LPOPENFILENAME))
{
...
```

What happens here is that list of strings are passed into GetOpenFileName(). It is not a problem to parse it: whenever you encounter single zero byte, this is an item. Whenever you encounter two zero bytes, this is end of the list. If you will pass this string into printf(), it will treat first item as a single string.

So this is string, or...? It’s better say this is buffer containing several zero-terminated C-strings, which can be stored and processed as a whole.

Another example is strtok() function. It takes a string and write zero bytes in the middle of it. It thus transforms input string into some kind of buffer, which has several zero-terminated C-strings.

1.18 Replacing arithmetic instructions to other ones

In the pursuit of optimization, one instruction may be replaced by another, or even with a group of instructions. For example, ADD and SUB can replace each other: line 18 in listing.3.119.

For example, the LEA instruction is often used for simple arithmetic calculations: .1.6 on page 1028.

1.18.1 Multiplication

Multiplication using addition

Here is a simple example:

```c
unsigned int f(unsigned int a)
{
    return a*8;
};
```

Multiplication by 8 is replaced by 3 addition instructions, which do the same. Apparently, MSVC’s optimizer decided that this code can be faster.

Listing 1.188: Optimizing MSVC 2010

```c
_TEXT SEGMENT
_a$ = 8 ; size = 4
_f PROC
```
1.18. REPLACING ARITHMETIC INSTRUCTIONS TO OTHER ONES

; File c:\polygon\c\2.c
mov eax, DWORD PTR _a$[esp-4]
add eax, eax
add eax, eax
add eax, eax
ret 0
f ENDP
TEXT ENDS
END

Multiplication using shifting

Multiplication and division instructions by a numbers that’s a power of 2 are often replaced by shift instructions.

unsigned int f(unsigned int a)
{
    return a*4;
};

Listing 1.189: Non-optimizing MSVC 2010

_a$ = 8 ; size = 4
_f PROC
push ebp
mov ebp, esp
mov eax, DWORD PTR _a$[ebp]
shl eax, 2
pop ebp
ret 0
_f ENDP

Multiplication by 4 is just shifting the number to the left by 2 bits and inserting 2 zero bits at the right (as the last two bits). It is just like multiplying 3 by 100 —we just have to add two zeros at the right. That’s how the shift left instruction works:

![Shift left diagram]

The added bits at right are always zeros.

Multiplication by 4 in ARM:

Listing 1.190: Non-optimizing Keil 6/2013 (ARM mode)

f PROC
    LSL r0,r0,#2
    BX lr
ENDP

Multiplication by 4 in MIPS:

Listing 1.191: Optimizing GCC 4.4.5 (IDA)

jr $ra
sll $v0, $a0, 2 ; branch delay slot

SLL is “Shift Left Logical”.

Multiplication using shifting, subtracting, and adding

It’s still possible to get rid of the multiplication operation when you multiply by numbers like 7 or 17 again by using shifting. The mathematics used here is relatively easy.
```c
#include <stdint.h>

int f1(int a)
{
    return a*7;
};

int f2(int a)
{
    return a*28;
};

int f3(int a)
{
    return a*17;
};
```

### x86

Listing 1.192: Optimizing MSVC 2012

```assembly
; a*7
.a$ = 8
_f1 PROC
    mov ecx, DWORD PTR _a$[esp-4]
    ; ECX=a
    lea eax, DWORD PTR [ecx*8]
    ; EAX=ECX*8
    sub eax, ecx
    ; EAX=EAX-ECX=ECX*8-ECX=ECX*7=a*7
    ret 0
_f1 ENDP

; a*28
.a$ = 8
_f2 PROC
    mov ecx, DWORD PTR _a$[esp-4]
    ; ECX=a
    lea eax, DWORD PTR [ecx*8]
    ; EAX=ECX*8
    sub eax, ecx
    ; EAX=EAX-ECX=ECX*8-ECX=ECX*7=a*7
    shl eax, 2
    ; EAX=EAX<<2=(a*7)*4=a*28
    ret 0
_f2 ENDP

; a*17
.a$ = 8
_f3 PROC
    mov eax, DWORD PTR _a$[esp-4]
    ; EAX=a
    shl eax, 4
    ; EAX=EAX<<4=EAX*16=a*16
    add eax, DWORD PTR _a$[esp-4]
    ; EAX=EAX+a=a*16+a=a*17
    ret 0
_f3 ENDP
```

### ARM

Keil for ARM mode takes advantage of the second operand’s shift modifiers:
1.18. REPLACING ARITHMETIC INSTRUCTIONS TO OTHER ONES

Listing 1.193: Optimizing Keil 6/2013 (ARM mode)

; a*7
||f1|| PROC
RSB r0,r0,r0,LSL #3
; R0=R0<<3-R0=R0*8-R0=a*8-a=a*7
BX lr
ENDP

; a*28
||f2|| PROC
RSB r0,r0,r0,LSL #3
; R0=R0<<3-R0=R0*8-R0=a*8-a=a*7
LSL r0,r0,#2
; R0=R0<<2=R0*4=a*7*4=a*28
BX lr
ENDP

; a*17
||f3|| PROC
ADD r0,r0,r0,LSL #4
; R0=R0+R0<<4=R0+R0*16=R0*17=a*17
BX lr
ENDP

But there are no such modifiers in Thumb mode. It also can’t optimize f2():

Listing 1.194: Optimizing Keil 6/2013 (Thumb mode)

; a*7
||f1|| PROC
LSLS r1,r0,#3
; R1=R0<<3=a<<3=a*8
SUBS r0,r1,r0
; R0=R1-R0=a*8-a=a*7
BX lr
ENDP

; a*28
||f2|| PROC
MOVS r1,#0x1c ; 28
MULS r0,r1,r0
; R0=R1*R0=28*a
BX lr
ENDP

; a*17
||f3|| PROC
LSLS r1,r0,#4
; R1=R0<<4=R0*16=a*16
ADDS r0,r0,r1
; R0=R0+R1=a+a*16=a*17
BX lr
ENDP

MIPS

Listing 1.195: Optimizing GCC 4.4.5 (IDA)

_f1:
    sll $v0, $a0, 3
; $v0 = $a0<<3 = $a0*8
    jr $ra
    subu $v0, $a0 ; branch delay slot
; $v0 = $v0-$a0 = $a0*8-$a0 = $a0*7

_f2:
    sll $v0, $a0, 5
1.18. REPLACING ARITHMETIC INSTRUCTIONS TO OTHER ONES

; $v0 = $a0<<5 = $a0*32
  sll $a0, 2
; $a0 = $a0<<2 = $a0*4
  jr $ra
  subu $v0, $a0 ; branch delay slot
; $v0 = $a0*32-$a0*4 = $a0*28

_f3:
  sll $v0, $a0, 4
; $v0 = $a0<<4 = $a0*16
  jr $ra
  addu $v0, $a0 ; branch delay slot
; $v0 = $a0*16+$a0 = $a0*17

64-bit

#include <stdint.h>

int64_t f1(int64_t a)
{
    return a*7;
};

int64_t f2(int64_t a)
{
    return a*28;
};

int64_t f3(int64_t a)
{
    return a*17;
};

x64

Listing 1.196: Optimizing MSVC 2012

; a*7
f1:
  lea rax, [0+rdi*8]
; RAX=RDI*8=a*8
  sub rax, rdi
; RAX=RAX-RDI=a*8-a=a*7
  ret

; a*28
f2:
  lea rax, [0+rdi*4]
; RAX=RDI*4=a*4
  sal rdi, 5
; RDI=RDI<<5=RDI*32=a*32
  sub rdi, rax
; RDI=RDI-RAX=a*32-a*4=a*28
  mov rax, rdi
  ret

; a*17
f3:
  mov rax, rdi
  sal rax, 4
; RAX=RAX<<4=a*16
  add rax, rdi
; RAX=a*16+a=a*17
  ret
1.18. REPLACING ARITHMETIC INSTRUCTIONS TO OTHER ONES

ARM64

GCC 4.9 for ARM64 is also terse, thanks to the shift modifiers:

Listing 1.197: Optimizing GCC (Linaro) 4.9 ARM64

```assembly
; a*7
f1:
    lsl x1, x0, 3
    ; X1=X0<<3=X0*8=a*8
    sub x0, x1, x0
    ; X0=X1-X0=a*8-a=a*7
    ret

; a*28
f2:
    lsl x1, x0, 5
    ; X1=X0<<5=a*32
    sub x0, x1, x0, lsl 2
    ; X0=X1-X0<<2=a*32-a<<2=a*32-a*4=a*28
    ret

; a*17
f3:
    add x0, x0, x0, lsl 4
    ; X0=X0+X0<<4=a+a*16=a*17
    ret
```

Booth’s multiplication algorithm

There was a time when computers were big and that expensive, that some of them lacked hardware support of multiplication operation in CPU, like Data General Nova. And when one need multiplication operation, it can be provided at software level, for example, using Booth’s multiplication algorithm. This is a multiplication algorithm which uses only addition operation and shifts.

What modern optimizing compilers do, isn’t the same, but the goal (multiplication) and resources (faster operations) are the same.

1.18.2 Division

Division using shifts

Example of division by 4:

```c
unsigned int f(unsigned int a)
{
    return a/4;
}
```

We get (MSVC 2010):

Listing 1.198: MSVC 2010

```assembly
_a$ = 8 ; size = 4
_f PROC
    mov eax, DWORD PTR _a$[esp-4]
    shr eax, 2
    ret 0
_f ENDP
```

The SHR (Shift Right) instruction in this example is shifting a number by 2 bits to the right. The two freed bits at left (e.g., two most significant bits) are set to zero. The two least significant bits are dropped. In fact, these two dropped bits are the division operation remainder.

The SHR instruction works just like SHL, but in the other direction.
It is easy to understand if you imagine the number 23 in the decimal numeral system. 23 can be easily divided by 10 just by dropping last digit (3—division remainder). 2 is left after the operation as a quotient. So the remainder is dropped, but that’s OK, we work on integer values anyway, these are not a real numbers!

Division by 4 in ARM:

```
f PROC
    LSR r0,r0,#2
    BX lr
ENDP
```

Division by 4 in MIPS:

```
jr $ra
srl $v0, $a0, 2 ; branch delay slot
```

The SRL instruction is “Shift Right Logical”.

### 1.18.3 Exercise

- [http://challenges.re/59](http://challenges.re/59)

### 1.19 Floating-point unit

The FPU is a device within the main CPU, specially designed to deal with floating point numbers. It was called “coprocessor” in the past and it stays somewhat aside of the main CPU.

#### 1.19.1 IEEE 754

A number in the IEEE 754 format consists of a sign, a significand (also called fraction) and an exponent.

#### 1.19.2 x86

It is worth looking into stack machines or learning the basics of the Forth language, before studying the FPU in x86.

It is interesting to know that in the past (before the 80486 CPU) the coprocessor was a separate chip and it was not always pre-installed on the motherboard. It was possible to buy it separately and install it.

Starting with the 80486 DX CPU, the FPU is integrated in the CPU.

The FWAIT instruction reminds us of that fact—it switches the CPU to a waiting state, so it can wait until the FPU has finished with its work.

Another rudiment is the fact that the FPU instruction opcodes start with the so called “escape”-opcodes (D8..DF), i.e., opcodes passed to a separate coprocessor.

---

109 <https://wikipedia.org/wiki/Forth_(programming_language)>
110 For example, John Carmack used fixed-point arithmetic (<https://wikipedia.org/wiki/Fixed-point_arithmetic>) values in his Doom video game, stored in 32-bit GPR registers (16 bit for integral part and another 16 bit for fractional part), so Doom could work on 32-bit computers without FPU, i.e., 80386 and 80486 SX.
1.19. **FLOATING-POINT UNIT**

The FPU has a stack capable to holding 8 80-bit registers, and each register can hold a number in the IEEE 754\footnote{wikipedia.org/wiki/IEEE_floating_point} format.

They are ST(0)..ST(7). For brevity, IDA and OllyDbg show ST(0) as ST, which is represented in some textbooks and manuals as “Stack Top”.

1.19.3 **ARM, MIPS, x86/x64 SIMD**

In ARM and MIPS the FPU is not a stack, but a set of registers, which can be accessed randomly, like GPR. The same ideology is used in the SIMD extensions of x86/x64 CPUs.

1.19.4 **C/C++**

The standard C/C++ languages offer at least two floating number types, float (single-precision\footnote{wikipedia.org/wiki/Single-precision_floating-point_format}, 32 bits) \footnote{the single precision floating point number format is also addressed in the Handling float data type as a structure ( 1.24.6 on page 373) section} and double (double-precision\footnote{wikipedia.org/wiki/Double-precision_floating-point_format}, 64 bits).

In [Donald E. Knuth, *The Art of Computer Programming*, Volume 2, 3rd ed., (1997)246] we can find the single-precision means that the floating point value can be placed into a single [32-bit] machine word, double-precision means it can be stored in two words (64 bits).

GCC also supports the long double type (extended precision\footnote{wikipedia.org/wiki/Extended_precision}, 80 bit), which MSVC doesn’t.

The float type requires the same number of bits as the int type in 32-bit environments, but the number representation is completely different.

1.19.5 **Simple example**

Let’s consider this simple example:

```c
#include <stdio.h>

double f (double a, double b)
{
    return a/3.14 + b*4.1;
};

int main()
{
    printf ("%f\n", f(1.2, 3.4));
};
```

**x86**

**MSVC**

Compile it in MSVC 2010:

```
Listing 1.201: MSVC 2010: f()

CONST SEGMENT
    _real@4010666666666666 DQ 0401066666666666r ; 4.1
CONST ENDS
CONST SEGMENT
    _real@40091eb851eb851f DQ 040091eb851eb851fr ; 3.14
CONST ENDS
_TEXT SEGMENT
```

\footnote{wikipedia.org/wiki/IEEE_floating_point}
\footnote{wikipedia.org/wiki/Single-precision_floating-point_format}
\footnote{the single precision floating point number format is also addressed in the Handling float data type as a structure ( 1.24.6 on page 373) section}
\footnote{wikipedia.org/wiki/Double-precision_floating-point_format}
\footnote{wikipedia.org/wiki/Extended_precision}
1.19. FLOATING-POINT UNIT

```assembly
a$ = 8 ; size = 8
b$ = 16 ; size = 8
f PROC
  push ebp
  mov ebp, esp
  fld QWORD PTR _a$[ebp]
  ; current stack state: ST(0) = _a
  fdiv QWORD PTR __real@40091eb851eb851f
  ; current stack state: ST(0) = result of _a divided by 3.14
  fld QWORD PTR _b$[ebp]
  ; current stack state: ST(0) = _b;
  ; ST(1) = result of _a divided by 3.14
  fmul QWORD PTR __real@4010666666666666
  ; current stack state:
  ; ST(0) = result of _b * 4.1;
  ; ST(1) = result of _a divided by 3.14
  faddp ST(1), ST(0)
  ; current stack state: ST(0) = result of addition
  pop ebp
  ret 0
f ENDP
```

FLD takes 8 bytes from stack and loads the number into the ST(0) register, automatically converting it into the internal 80-bit format (extended precision).

FDIV divides the value in ST(0) by the number stored at address __real@40091eb851eb851f — the value 3.14 is encoded there. The assembly syntax doesn’t support floating point numbers, so what we see here is the hexadecimal representation of 3.14 in 64-bit IEEE 754 format.

After the execution of FDIV ST(0) holds the quotient.

By the way, there is also the FDIVP instruction, which divides ST(1) by ST(0), popping both these values from stack and then pushing the result. If you know the Forth language, you can quickly understand that this is a stack machine.

The subsequent FLD instruction pushes the value of b into the stack.

After that, the quotient is placed in ST(1), and ST(0) has the value of b.

The next FMUL instruction does multiplication: b from ST(0) is multiplied by value at __real@4010666666666666 (the number 4.1 is there) and leaves the result in the ST(0) register.

The last FADDP instruction adds the two values at top of stack, storing the result in ST(1) and then popping the value of ST(0), thereby leaving the result at the top of the stack, in ST(0).

The function must return its result in the ST(0) register, so there are no any other instructions except the function epilogue after FADDP.

---

116 wikipedia.org/wiki/Forth_(programming_language)
117 wikipedia.org/wiki/Stack_machine
2 pairs of 32-bit words are marked by red in the stack. Each pair is a double-number in IEEE 754 format and is passed from `main()`.

We see how the first FLD loads a value (1.2) from the stack and puts it into ST(0):

Figure 1.62: OllyDbg: the first FLD has been executed

Because of unavoidable conversion errors from 64-bit IEEE 754 floating point to 80-bit (used internally in the FPU), here we see 1.1999..., which is close to 1.2.

EIP now points to the next instruction (FDIV), which loads a double-number (a constant) from memory. For convenience, OllyDbg shows its value: 3.14
1.19. FLOATING-POINT UNIT

Let's trace further. FDIV has been executed, now ST(0) contains 0.382... (quotient):

![OllyDbg screenshot](image)

Figure 1.63: OllyDbg: FDIV has been executed
1.19. FLOATING-POINT UNIT

Third step: the next FLD has been executed, loading 3.4 into ST(0) (here we see the approximate value 3.39999...):

At the same time, quotient is pushed into ST(1). Right now, EIP points to the next instruction: FMUL. It loads the constant 4.1 from memory, which OllyDbg shows.
1.19. FLOATING-POINT UNIT

Next: FMUL has been executed, so now the product is in ST(0):

Figure 1.65: OllyDbg: the FMUL has been executed
1.19. FLOATING-POINT UNIT

Next: the FADDP has been executed, now the result of the addition is in ST(0), and ST(1) is cleared:

The result is left in ST(0), because the function returns its value in ST(0).

main() takes this value from the register later.

We also see something unusual: the 13.93...value is now located in ST(7). Why?

As we have read some time before in this book, the FPU registers are a stack: 1.19.2 on page 218. But this is a simplification.

Imagine if it was implemented in hardware as it’s described, then all 7 register's contents must be moved (or copied) to adjacent registers during pushing and popping, and that’s a lot of work.

In reality, the FPU has just 8 registers and a pointer (called TOP) which contains a register number, which is the current “top of stack”.

When a value is pushed to the stack, TOP is pointed to the next available register, and then a value is written to that register.

The procedure is reversed if a value is popped, however, the register which has been freed is not cleared (it could possibly be cleared, but this is more work which can degrade performance). So that’s what we see here.

It can be said that FADDP saved the sum in the stack, and then popped one element.

But in fact, this instruction saved the sum and then shifted TOP.

More precisely, the registers of the FPU are a circular buffer.

GCC
1.19. **FLOATING-POINT UNIT**

GCC 4.4.1 (with -O3 option) emits the same code, just slightly different:

![Listing 1.202: Optimizing GCC 4.4.1](image)

The difference is that, first of all, 3.14 is pushed to the stack (into ST(0)), and then the value in arg_0 is divided by the value in ST(0).

FDIVR stands for *Reverse Divide* — to divide with divisor and dividend swapped with each other. There is no likewise instruction for multiplication since it is a commutative operation, so we just have FMUL without its -R counterpart.

FADDP adds the two values but also pops one value from the stack. After that operation, ST(0) holds the sum.

### ARM: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Until ARM got standardized floating point support, several processor manufacturers added their own instructions extensions. Then, VFP (*Vector Floating Point*) was standardized.

One important difference from x86 is that in ARM, there is no stack, you work just with registers.

![Listing 1.203: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)](image)
1.19. FLOATING-POINT UNIT

So, we see here new some registers used, with D prefix.

These are 64-bit registers, there are 32 of them, and they can be used both for floating-point numbers (double) but also for SIMD (it is called NEON here in ARM).

There are also 32 32-bit S-registers, intended to be used for single precision floating pointer numbers (float).

It is easy to memorize: D-registers are for double precision numbers, while S-registers—for single precision numbers. More about it: .2.3 on page 1040.

Both constants (3.14 and 4.1) are stored in memory in IEEE 754 format.

VLDR and VMOV, as it can be easily deduced, are analogous to the LDR and MOV instructions, but they work with D-registers.

It has to be noted that these instructions, just like the D-registers, are intended not only for floating point numbers, but can be also used for SIMD (NEON) operations and this will also be shown soon.

The arguments are passed to the function in a common way, via the R-registers, however each number that has double precision has a size of 64 bits, so two R-registers are needed to pass each one.

VMOV D17, R0, R1 at the start, composes two 32-bit values from R0 and R1 into one 64-bit value and saves it to D17.

VMOV R0, R1, D16 is the inverse operation: what has been in D16 is split in two registers, R0 and R1, because a double-precision number that needs 64 bits for storage, is returned in R0 and R1.

VDIV, VMUL and VADD, are instruction for processing floating point numbers that compute quotient, product and sum, respectively.

The code for Thumb-2 is same.

ARM: Optimizing Keil 6/2013 (Thumb mode)

```assembly
f
    PUSH {R3-R7,LR}
    MOVS R7, R2
    MOVS R4, R3
    MOVS R5, R0
    MOVS R6, R1
    LDR R2, =0x66666666 ; 4.1
    LDR R3, =0x40106666
    MOVS R0, R7
    MOVS R1, R4
    BL __aeabi_dmul
    MOVS R7, R0
    MOVS R4, R1
    LDR R2, =0x51EB851F ; 3.14
    LDR R3, =0x40091EB8
    MOVS R0, R5
    MOVS R1, R6
    BL __aeabi_ddiv
    MOVS R2, R7
    MOVS R3, R4
    BL __aeabi_dadd
    POP {R3-R7,PC}

; 4.1 in IEEE 754 form:
dword_364 DCD 0x66666666 ; DATA XREF: f+A
dword_368 DCD 0x40106666 ; DATA XREF: f+C
; 3.14 in IEEE 754 form:
dword_36C DCD 0x51EB851F ; DATA XREF: f+1A
dword_370 DCD 0x40091EB8 ; DATA XREF: f+1C
```

Keil generated code for a processor without FPU or NEON support.

The double-precision floating-point numbers are passed via generic R-registers, and instead of FPU-instructions, service library functions are called (like __aeabi_dmul, __aeabi_ddiv, __aeabi_dadd) which emulate multiplication, division and addition for floating-point numbers.
1.19. FLOATING-POINT UNIT

Of course, that is slower than FPU-coprocessor, but it’s still better than nothing.

By the way, similar FPU-emulating libraries were very popular in the x86 world when coprocessors were rare and expensive, and were installed only on expensive computers.

The FPU-coprocessor emulation is called soft float or armel (emulation) in the ARM world, while using the coprocessor’s FPU-instructions is called hard float or armhf.

ARM64: Optimizing GCC (Linaro) 4.9

Very compact code:

```
Listing 1.204: Optimizing GCC (Linaro) 4.9

f:
; D0 = a, D1 = b
    ldr  d2, .LC25 ; 3.14
; D2 = 3.14
    fdiv  d0, d0, d2
; D0 = D0/D2 = a/3.14
    ldr  d2, .LC26 ; 4.1
; D2 = 4.1
    fmadd d0, d1, d2, d0
; D0 = D1*D2+D0 = b*4.1+a/3.14
ret

; constants in IEEE 754 format:
.LC25:
    .word 1374389535 ; 3.14
    .word 1074339512
.LC26:
    .word 1717986918 ; 4.1
    .word 1074816614
```

ARM64: Non-optimizing GCC (Linaro) 4.9

```
Listing 1.205: Non-optimizing GCC (Linaro) 4.9

f:
    sub  sp, sp, #16
    str  d0, [sp,8] ; save "a" in Register Save Area
    str  d1, [sp] ; save "b" in Register Save Area
    ldr  x1, [sp,8]
; X1 = a
    ldr  x0, .LC25
; X0 = 3.14
    fmov  d0, x1
    fmov  d1, x0
; D0 = a, D1 = 3.14
    fdiv  d0, d0, d1
; D0 = D0/D1 = a/3.14
    fmov  x1, d0
; X1 = a/3.14
    ldr  x2, [sp]
; X2 = b
    ldr  x0, .LC26
; X0 = 4.1
    fmov  d0, x2
; D0 = b
    fmov  d1, x0
; D1 = 4.1
    fmul  d0, d0, d1
; D0 = D0*D1 = b*4.1
    fmov  x0, d0
; X0 = D0 = b*4.1
    fmov  d0, x1
```
1.19. FLOATING-POINT UNIT

\[
\begin{align*}
D_0 &= \frac{a}{3.14} \\
D_1 &= X_0 = b \times 4.1 \\
D_0 + D_1 &= \frac{a}{3.14} + b \times 4.1
\end{align*}
\]

Non-optimizing GCC is more verbose.

There is a lot of unnecessary value shuffling, including some clearly redundant code (the last two FMOV instructions). Probably, GCC 4.9 is not yet good in generating ARM64 code.

What is worth noting is that ARM64 has 64-bit registers, and the D-registers are 64-bit ones as well. So the compiler is free to save values of type \textit{double} in GPRs instead of the local stack. This isn’t possible on 32-bit CPUs.

And again, as an exercise, you can try to optimize this function manually, without introducing new instructions like FMADD.

MIPS

MIPS can support several coprocessors (up to 4), the zeroth of which\footnote{Starting at 0.} is a special control coprocessor, and first coprocessor is the FPU.

As in ARM, the MIPS coprocessor is not a stack machine, it has 32 32-bit registers ($F0$-$F31$): .3.1 on page 1042.

When one needs to work with 64-bit \textit{double} values, a pair of 32-bit F-registers is used.

\begin{verbatim}
Listing 1.206: Optimizing GCC 4.4.5 (IDA)

f:
; $f12$-$f13$=A
; $f14$-$f15$=B
    lui $v0, (dword C4 >> 16) ; ?
    ; load low 32-bit part of 3.14 constant to $f0$:
    lwcl $f0$, dword BC
    or $at$, $zero ; load delay slot, NOP
    ; load high 32-bit part of 3.14 constant to $f1$:
    lwcl $f1$, $LC0$
    lui $v0$, (dword C4 >> 16) ; ?
    ; A in $f12$-$f13$, 3.14 constant in $f0$-$f1$, do division:
    div.d $f0$, $f12$, $f0$
    ; $f0$-$f1$=A/3.14
    ; load low 32-bit part of 4.1 to $f2$
    lwcl $f2$, dword C4
    or $at$, $zero ; load delay slot, NOP
    ; load high 32-bit part of 4.1 to $f3$
    lwcl $f3$, $LC1$
    or $at$, $zero ; load delay slot, NOP
    ; B in $f14$-$f15$, 4.1 constant in $f2$-$f3$, do multiplication:
    mul.d $f2$, $f14$, $f2$
    ; $f2$-$f3$=B*4.1
    jr $ra$
    ; sum 64-bit parts and leave result in $f0$-$f1$:
    add.d $f0$, $f2 ; branch delay slot, NOP
\end{verbatim}

118Starting at 0.
1.19. FLOATING-POINT UNIT

The new instructions here are:

- **LWC1** loads a 32-bit word into a register of the first coprocessor (hence “1” in instruction name).
  A pair of LWC1 instructions may be combined into a L.D pseudo instruction.
- **DIV.D, MUL.D, ADD.D** do division, multiplication, and addition respectively (“.D” in the suffix stands for double precision, “.S” stands for single precision)

There is also a weird compiler anomaly: the LUI instructions that we’ve marked with a question mark. It’s hard for me to understand why load a part of a 64-bit constant of **double** type into the $V0 register. These instructions has no effect. If someone knows more about it, please drop an email to author119.

1.19.6 Passing floating point numbers via arguments

```c
#include <math.h>
#include <stdio.h>

int main ()
{
    printf ("32.01 ^ 1.54 = %lf\n", pow (32.01,1.54));
    return 0;
}
```

**x86**

Let’s see what we get in (MSVC 2010):

```c
CONST SEGMENT
__real@40400147ae147ae1 DQ 040400147ae147ae1r ; 32.01
__real@3ff8a3d70a3d70a4 DQ 03ff8a3d70a3d70a4r ; 1.54
CONST ENDS

_main PROC
    push ebp
    mov ebp, esp
    sub esp, 8 ; allocate space for the first variable
    fld QWORD PTR __real@3ff8a3d70a3d70a4
    fstp QWORD PTR [esp]
    sub esp, 8 ; allocate space for the second variable
    fld QWORD PTR __real@40400147ae147ae1
    fstp QWORD PTR [esp]
    call _pow
    add esp, 8 ; return back place of one variable.
    ; in local stack here 8 bytes still reserved for us.
    ; result now in ST(0)
    fstp QWORD PTR [esp] ; move result from ST(0) to local stack for printf()
    push OFFSET $SG2651
    call _printf
    add esp, 12
    xor eax, eax
    pop ebp
    ret 0

_main ENDP
```

119dennis@yurichev.com
**1.19. FLOATING-POINT UNIT**

FLD and FSTP move variables between the data segment and the FPU stack. `pow()`\(^{120}\) takes both values from the stack and returns its result in the ST(0) register. `printf()` takes 8 bytes from the local stack and interprets them as `double` type variable.

By the way, a pair of MOV instructions could be used here for moving values from the memory into the stack, because the values in memory are stored in IEEE 754 format, and `pow()` also takes them in this format, so no conversion is necessary. That’s how it’s done in the next example, for ARM: **1.19.6**.

**ARM + Non-optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)**

```
var_C = -0xC

_main

PUSH {R7,LR}
MOV R7, SP
SUB SP, SP, #4
VLDR D16, =32.01
VMOV R0, R1, D16
VLDR D16, =1.54
VMOV R2, R3, D16
BLX _pow
VMOV D16, R0, R1
MOV R0, 0xFC1 ; "32.01 ^ 1.54 = %lf\n"
ADD R0, PC
VMOV R1, R2, D16
BLX _printf
MOVS R1, 0
STR R0, [SP,#0xC+var_C]
MOV R0, R1
ADD SP, SP, #4
POP {R7,PC}
```

As it was mentioned before, 64-bit floating pointer numbers are passed in R-registers pairs.

This code is a bit redundant (certainly because optimization is turned off), since it is possible to load values into the R-registers directly without touching the D-registers.

So, as we see, the `_pow` function receives its first argument in R0 and R1, and its second one in R2 and R3. The function leaves its result in R0 and R1. The result of `_pow` is moved into D16, then in the R1 and R2 pair, from where `printf()` takes the resulting number.

**ARM + Non-optimizing Keil 6/2013 (ARM mode)**

```
_main

STMFD SP!, {R4-R6,LR}
LDR R2, =0xA3D70A4 ; y
LDR R3, =0x3FF8A3D7
LDR R0, =0xAE147AE1 ; x
LDR R1, =0x40400147
BL pow
MOV R4, R0
MOV R2, R4
MOV R3, R1
ADR R0, a32_011_54Lf ; "32.01 ^ 1.54 = %lf\n"
BL __2printf
MOV R0, #0
LDMFD SP!, {R4-R6,PC}
```

\(^{120}\)A standard C function, raises a number to the given power (exponentiation)
D-registers are not used here, just R-register pairs.

**ARM64 + Optimizing GCC (Linaro) 4.9**

Listing 1.208: Optimizing GCC (Linaro) 4.9

```assembly
f:
    stp   x29, x30, [sp, -16]!
    add   x29, sp, 0
    ldr   d1, .LC1 ; load 1.54 into D1
    ldr   d0, .LC0 ; load 32.01 into D0
    bl    pow ; result of pow() in D0
    adrp  x0, .LC2
    add   x0, x0, :lo12:.LC2
    bl    printf
    mov   w0, 0
    ldp   x29, x30, [sp], 16
    ret

.LC0: ; 32.01 in IEEE 754 format
    .word  -1374389535
    .word   1077936455

.LC1: ; 1.54 in IEEE 754 format
    .word    171798692
    .word   1073259479

.LC2: .string "32.01 ^ 1.54 = %lf

The constants are loaded into D0 and D1: pow() takes them from there. The result will be in D0 after the execution of pow(). It is to be passed to printf() without any modification and moving, because printf() takes arguments of integral types and pointers from X-registers, and floating point arguments from D-registers.

**MIPS**

Listing 1.209: Optimizing GCC 4.4.5 (IDA)

```assembly
main:
    var_10   = -0x10
    var_4    = -4

; function prologue:
    lui    $gp, (dword_9C >> 16)
    addiu  $sp, -0x20
    la     $gp, (__gnu_local_gp & 0xFFFF)
    sw     $ra, 0x20+var_4($sp)
    sw     $gp, 0x20+var_10($sp)
    lui    $v0, (dword_A4 >> 16) ; ?

; load low 32-bit part of 32.01:
    lwcl   $f12, dword_9C
; load address of pow() function:
    lw     $t9, (pow & 0xFFFF($gp))
; load high 32-bit part of 32.01:
    lwcl   $f13, $LC0
    lui    $v0, ($LC1 >> 16) ; ?

; load low 32-bit part of 1.54:
    lwcl   $f14, dword_A4
    or     $at, $zero ; load delay slot, NOP
; load high 32-bit part of 1.54:
```
1.19. FLOATING-POINT UNIT

```assembly
lwcl $f15, $LC1
; call pow:
    jalr $t9
or $at, $zero ; branch delay slot, NOP
lw $gp, 0x20+var_10($sp)
; copy result from $f0 and $f1 to $a3 and $a2:
    mfc1 $a3, $f0
    lw $t9, (printf & 0xFFFF)($gp)
    mfc1 $a2, $f1
; call printf:
    lui $a0, ($LC2 >> 16) # "32.01 ^ 1.54 = %lf\n"
    jalr $t9
la $a0, ($LC2 & 0xFFFF) # "32.01 ^ 1.54 = %lf\n"
; function epilogue:
    lw $ra, 0x20+var_4($sp)
; return 0:
    move $v0, $zero
    jr $ra
addiu $sp, 0x20
.rodata.str1.4:00000084 $LC2: .ascii "32.01 ^ 1.54 = %lf\n"
; 32.01:
.rodata.cst8:00000098 $LC0: .word 0x40400147 # DATA XREF: main+20
.rodata.cst8:0000009C dword_9C: .word 0xAE147AE1 # DATA XREF: main
.rodata.cst8:0000009C # main+18
; 1.54:
.rodata.cst8:000000A0 $LC1: .word 0x3FF8A3D7 # DATA XREF: main+24
.rodata.cst8:000000A0 # main+30
.rodata.cst8:000000A4 dword_A4: .word 0xA3D70A4 # DATA XREF: main+14
```

And again, we see here LUI loading a 32-bit part of a double number into $V0. And again, it's hard to comprehend why.

The new instruction for us here is MFC1 (“Move From Coprocessor 1”). The FPU is coprocessor number 1, hence “1” in the instruction name. This instruction transfers values from the coprocessor’s registers to the registers of the CPU (GPR). So at the end the result of pow() is moved to registers $A3 and $A2, and printf() takes a 64-bit double value from this register pair.

### 1.19.7 Comparison example

Let’s try this:

```c
#include <stdio.h>

double d_max (double a, double b)
{
    if (a>b)
        return a;
    return b;
}

int main()
{
    printf("%f\n", d_max (1.2, 3.4));
    printf("%f\n", d_max (5.6, -4));
}
```

Despite the simplicity of the function, it will be harder to understand how it works.

**x86**

**Non-optimizing MSVC**

MSVC 2010 generates the following:
So, **FLD** loads _b into ST(0).**

**FCOMP** compares the value in ST(0) with what is in _a and sets C3/C2/C0 bits in FPU status word register, accordingly. This is a 16-bit register that reflects the current state of the FPU.

After the bits are set, the **FCOMP** instruction also pops one variable from the stack. This is what distinguishes it from **FCOM**, which is just compares values, leaving the stack in the same state.

Unfortunately, CPUs before Intel P6[^121] don’t have any conditional jumps instructions which check the C3/C2/C0 bits. Perhaps, it is a matter of history (recall: FPU was a separate chip in past). Modern CPU starting at Intel P6 have **FCOMI/FCOMIP/FUCOMI/FUCOMIP** instructions—which do the same, but modify the **ZF/PF/CF** CPU flags.

The **FNSTSW** instruction copies FPU the status word register to **AX**. C3/C2/C0 bits are placed at positions 14/10/8, they are at the same positions in the AX register and all they are placed in the high part of AX—**AH**.

- If _b > _a in our example, then C3/C2/C0 bits are to be set as following: 0, 0, 0.
- If _a > _b, then the bits are: 0, 0, 1.
- If _a = _b, then the bits are: 1, 0, 0.
- If the result is unordered (in case of error), then the set bits are: 1, 1, 1.

This is how C3/C2/C0 bits are located in the AX register:

```
  14 10 9 8
  C3 C2 C0
```

This is how C3/C2/C0 bits are located in the AH register:

```
  6 2 1 0
  C3 C2 C0
```

After the execution of **test ah, 5**[^122], only C0 and C2 bits (on 0 and 2 position) are considered, all other bits are just ignored.

[^121]: Intel P6 is Pentium Pro, Pentium II, etc.
[^122]: 5=101b
Now let’s talk about the parity flag, another notable historical rudiment. This flag is set to 1 if the number of ones in the result of the last calculation is even, and to 0 if it is odd.

Let’s look into Wikipedia:\(^{123}\):

One common reason to test the parity flag actually has nothing to do with parity. The FPU has four condition flags (C0 to C3), but they cannot be tested directly, and must instead be first copied to the flags register. When this happens, C0 is placed in the carry flag, C2 in the parity flag and C3 in the zero flag. The C2 flag is set when e.g. incomparable floating point values (NaN or unsupported format) are compared with the FUCOM instructions.

As noted in Wikipedia, the parity flag used sometimes in FPU code, let’s see how.

The PF flag is to be set to 1 if both C0 and C2 are set to 0 or both are 1, in which case the subsequent JP (jump if PF==1) is triggering. If we recall the values of C3/C2/C0 for various cases, we can see that the conditional jump JP is triggering in two cases: if \( b > a \) or \( a = b \) (C3 bit is not considered here, since it has been cleared by the test ah, 5 instruction).

It is all simple after that. If the conditional jump has been triggered, FLD loads the value of \( _b \) in ST(0), and if it hasn’t been triggered, the value of \( _a \) is loaded there.

And what about checking C2?

The C2 flag is set in case of error (NaN, etc.), but our code doesn’t check it.

If the programmer cares about FPU errors, he/she must add additional checks.

\(^{123}\)wikipedia.org/wiki/Parity_flag
1.19. FLOATING-POINT UNIT

First OllyDbg example: \(a=1.2\) and \(b=3.4\)

Let's load the example into OllyDbg:

Current arguments of the function: \(a = 1.2\) and \(b = 3.4\) (We can see them in the stack: two pairs of 32-bit values). \(b\) (3.4) is already loaded in ST(0). Now FCOMP is being executed. OllyDbg shows the second FCOMP argument, which is in stack right now.
1.19. FLOATING-POINT UNIT

FCOMP has been executed:

We see the state of the FPU's condition flags: all zeros. The popped value is reflected as ST(7), it was written earlier about reason for this: 1.19.5 on page 225.

Figure 1.68: OllyDbg: FCOMP has been executed

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1.19. FLOATING-POINT UNIT

FNSTSW has been executed:

![Image of OllyDbg window showing the execution of FNSTSW]

Figure 1.69: OllyDbg: FNSTSW has been executed

We see that the AX register contain zeros: indeed, all condition flags are zero. (OllyDbg disassembles the FNSTSW instruction as FSTSW—they are synonyms).

---

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1.19. FLOATING-POINT UNIT

TEST has been executed:

The PF flag is set to 1.

Indeed: the number of bits set in 0 is 0 and 0 is an even number. OllyDbg disassembles JP as JPE\textsuperscript{124}—they are synonyms. And it is about to trigger now.

\textsuperscript{124}Jump Parity Even (x86 instruction)
1.19. FLOATING-POINT UNIT

JPE triggered, FLD loads the value of $b(3.4)$ in ST(0):

The function finishes its work.
1.19. FLOATING-POINT UNIT

Second OllyDbg example: a=5.6 and b=-4

Let’s load example into OllyDbg:

Figure 1.72: OllyDbg: first FLD executed

Current function arguments: \( a = 5.6 \) and \( b = -4 \). \( b (-4) \) is already loaded in \( ST(0) \). FCOMP about to execute now. OllyDbg shows the second FCOMP argument, which is in stack right now.
We see the state of the FPU's condition flags: all zeros except C0.
We see that the AX register contains 0x100: the C0 flag is at the 8th bit.
The PF flag is cleared. Indeed: the count of bits set in 0x100 is 1 and 1 is an odd number. JPE is being skipped now.
1.19. FLOATING-POINT UNIT

JPE hasn’t been triggered, so FLD loads the value of a (5.6) in ST(0):

Figure 1.76: OllyDbg: second FLD executed

The function finishes its work.

Optimizing MSVC 2010

Listing 1.211: Optimizing MSVC 2010

```assembly
.a$ = 8 ; size = 8
.b$ = 16 ; size = 8
.d_max PROC
    fld QWORD PTR _b$[esp-4]
    fld QWORD PTR _a$[esp-4]

    ; current stack state: ST(0) = _a, ST(1) = _b
    fcom ST(1) ; compare _a and ST(1) = (_b)
    fnstsw ax
    test ah, 65 ; 00000001H
    jne SHORT $LN5@d_max

    ; copy ST(0) to ST(1) and pop register,
    ; leave (_a) on top
    fstp ST(1)

    ; current stack state: ST(0) = _a
    ret 0
$LN5@d_max:
    ; copy ST(0) to ST(0) and pop register,
```
FCOM differs from FCOMP in the sense that it just compares the values and doesn’t change the FPU stack. Unlike the previous example, here the operands are in reverse order, which is why the result of the comparison in C3/C2/C0 is different:

- If \( a > b \) in our example, then C3/C2/C0 bits are to be set as: 0, 0, 0.
- If \( b > a \), then the bits are: 0, 0, 1.
- If \( a = b \), then the bits are: 1, 0, 0.

The test ah, 65 instruction leaves just two bits —C3 and C0. Both will be zero if \( a > b \): in that case the JNE jump will not be triggered. Then FSTP ST(1) follows —this instruction copies the value from ST(0) to the operand and pops one value from the FPU stack. In other words, the instruction copies ST(0) (where the value of _a is now) into ST(1). After that, two copies of _a are at the top of the stack. Then, one value is popped. After that, ST(0) contains _a and the function is finishes.

The conditional jump JNE is triggering in two cases: if \( b > a \) or \( a = b \). ST(0) is copied into ST(0), it is just like an idle (NOP) operation, then one value is popped from the stack and the top of the stack (ST(0)) is contain what has been in ST(1) before (that is _b). Then the function finishes. The reason this instruction is used here probably is because the FPU has no other instruction to pop a value from the stack and discard it.
1.19. FLOATING-POINT UNIT

First OllyDbg example: \( a = 1.2 \) and \( b = 3.4 \)

Both FLD are executed:

![CPU main thread, module d_max](image)

Figure 1.77: OllyDbg: both FLD are executed

FCOM being executed: OllyDbg shows the contents of ST(0) and ST(1) for convenience.
1.19. FLOATING-POINT UNIT

FCOM has been executed:

C0 is set, all other condition flags are cleared.

Figure 1.78: OllyDbg: FCOM has been executed
1.19. FLOATING-POINT UNIT

FNSTSW has been executed, AX=0x3100:

Figure 1.79: OllyDbg: FNSTSW is executed
1.19. FLOATING-POINT UNIT

TEST is executed:

ZF=0, conditional jump is about to trigger now.
1.19. FLOATING-POINT UNIT

FSTP ST (or FSTP ST(0)) has been executed —1.2 has been popped from the stack, and 3.4 was left on top:

We see that the FSTP ST instruction works just like popping one value from the FPU stack.
Both FLD are executed:

FCOM is about to execute.

Figure 1.82: OllyDbg: both FLD are executed
1.19. FLOATING-POINT UNIT

FCOM has been executed:

Figure 1.83: OllyDbg: FCOM is finished

All conditional flags are cleared.
1.19. FLOATING-POINT UNIT

FNSTSW done, AX=0x3000:

Figure 1.84: OllyDbg: FNSTSW has been executed
1.19. FLOATING-POINT UNIT

TEST has been executed:

---

**Figure 1.85: OllyDbg: TEST has been executed**

\[ ZF=1, \text{jump will not happen now.} \]
1.19. FLOATING-POINT UNIT

FSTP ST(1) has been executed: a value of 5.6 is now at the top of the FPU stack.

We now see that the FSTP ST(1) instruction works as follows: it leaves what has been at the top of the stack, but clears ST(1).

GCC 4.4.1

Listing 1.212: GCC 4.4.1

```assembly
Listing 1.212: GCC 4.4.1

b = qword ptr -10h
a = qword ptr -8
a_first_half = dword ptr 8
a_second_half = dword ptr 0Ch
b_first_half = dword ptr 10h
b_second_half = dword ptr 14h

push ebp
mov ebp, esp
sub esp, 10h

; put a and b to local stack:
mov eax, [ebp+a_first_half]
mov DWORD PTR [ebp+a], eax
mov eax, [ebp+a_second_half]
mov DWORD PTR [ebp+a+4], eax
mov eax, [ebp+b_first_half]
mov DWORD PTR [ebp+b], eax
mov DWORD PTR [ebp+b+4], eax
```
FUCOMPP is almost like FCOM, but pops both values from the stack and handles “not-a-numbers” differently.

A bit about not-a-numbers.

The FPU is able to deal with special values which are not-a-numbers or NaNs\(^\text{125}\). These are infinity, result of division by 0, etc. Not-a-numbers can be “quiet” and “signaling”. It is possible to continue to work with “quiet” NaNs, but if one tries to do any operation with “signaling” NaNs, an exception is to be raised.

FCOM raising an exception if any operand is NaN. FUCOM raising an exception only if any operand is a signaling NaN (SNaN).

The next instruction is SAHF (Store AH into Flags) —this is a rare instruction in code not related to the FPU. 8 bits from AH are moved into the lower 8 bits of the CPU flags in the following order:

\[
\begin{array}{cccc}
\text{SF} & \text{ZF} & \text{AF} & \text{PF} & \text{CF} \\
7 & 6 & 4 & 2 & 0
\end{array}
\]

Let’s recall that FNSTSW moves the bits that interest us (C3/C2/C0) into AH and they are in positions 6, 2, 0 of the AH register:

\[
\begin{array}{cccc}
\text{C3} & \text{C2} & \text{C1} & \text{C0} \\
6 & 2 & 1 & 0
\end{array}
\]

In other words, the FNSTSW / SAHF instruction pair moves C3/C2/C0 into ZF, PF and CF.

Now let’s also recall the values of C3/C2/C0 in different conditions:

- If \(a\) is greater than \(b\) in our example, then C3/C2/C0 are to be set to: 0, 0, 0.
- If \(a\) is less than \(b\), then the bits are to be set to: 0, 0, 1.
- If \(a = b\), then: 1, 0, 0.

In other words, these states of the CPU flags are possible after three FUCOMPP/FNSTSW/SAHF instructions:

- If \(a > b\), the CPU flags are to be set as: ZF=0, PF=0, CF=0.
- If \(a < b\), then the flags are to be set as: ZF=0, PF=0, CF=1.

\(^{125}\)wikipedia.org/wiki/NaN
1.19. FLOATING-POINT UNIT

- And if \( a = b \), then: \( ZF=1, PF=0, CF=0 \).

Depending on the CPU flags and conditions, SETNBE stores 1 or 0 to AL. It is almost the counterpart of JNBE, with the exception that SETcc\(^{126} \) stores 1 or 0 in AL, but Jcc does actually jump or not. SETNBE stores 1 only if \( CF=0 \) and \( ZF=0 \). If it is not true, 0 is to be stored into AL.

Only in one case both \( CF \) and \( ZF \) are 0: if \( a > b \).

Then 1 is to be stored to AL, the subsequent JZ is not to be triggered and the function will return \_a. In all other cases, \_b is to be returned.

Optimizing GCC 4.4.1

Listing 1.213: Optimizing GCC 4.4.1

```asm
public d_max
d_max proc near
arg_0 = qword ptr 8
arg_8 = qword ptr 10h
push ebp
mov ebp, esp
fld [ebp+arg_0]; _a
fld [ebp+arg_8]; _b
; stack state now: ST(0) = _b, ST(1) = _a
fxch st(1)
; stack state now: ST(0) = _a, ST(1) = _b
fucom st(1); compare _a and _b
fnstsw ax
sahf
ja short loc_8048448
; store ST(0) to ST(0) (idle operation),
; pop value at top of stack,
; leave _b at top
fstp st
jmp short loc_804844A
loc_8048448:
; store _a to ST(1), pop value at top of stack, leave _a at top
fstp st(1)
loc_804844A:
pop ebp
retn
d_max endp
```

It is almost the same except that JA is used after SAHF. Actually, conditional jump instructions that check “larger”, “lesser” or “equal” for unsigned number comparison (these are JA, JAE, JB, JBE, JE/JZ, JNA, JNAE, JNB, JNBE, JNE/JNZ) check only flags CF and ZF.

Let’s recall where bits C3/C2/C0 are located in the AH register after the execution of FSTSW/FNSTSW:

```
       6 5 4 3 2 1 0
C3  C2  C1  C0
```

Let’s also recall, how the bits from AH are stored into the CPU flags after the execution of SAHF:

```
       6 5 4 3 2 1 0
SF  ZF  AF  PF  CF
```

After the comparison, the C3 and C0 bits are moved into ZF and CF, so the conditional jumps are able work after. JA is triggering if both CF are ZF zero.

\(^{126} \text{cc is condition code} \)
1.19. FLOATING-POINT UNIT

Thereby, the conditional jumps instructions listed here can be used after a FNSTSW/SAHF instruction pair.

Apparently, the FPU C3/C2/C0 status bits were placed there intentionally, to easily map them to base CPU flags without additional permutations?

GCC 4.8.1 with -O3 optimization turned on

Some new FPU instructions were added in the P6 Intel family\textsuperscript{127}. These are FUCOMI (compare operands and set flags of the main CPU) and FCMOVcc (works like CMOVcc, but on FPU registers).

Apparently, the maintainers of GCC decided to drop support of pre-P6 Intel CPUs (early Pentiums, 80486, etc.).

And also, the FPU is no longer separate unit in P6 Intel family, so now it is possible to modify/check flags of the main CPU from the FPU.

So what we get is:

Listing 1.214: Optimizing GCC 4.8.1

```
fld QWORD PTR [esp+4] ; load "a"
fld QWORD PTR [esp+12] ; load "b"
fxch st(1)
; ST0=a, ST1=b
; compare "a" and "b"
fucomi st, st(1)
; copy ST1 ("b" here) to ST0 if a<=b
; leave "a" in ST0 otherwise
fcmovbe st, st(1)
; discard value in ST1
fstp st(1)
ret
```

Hard to guess why FXCH (swap operands) is here.

It’s possible to get rid of it easily by swapping the first two FLD instructions or by replacing FCMOVBE (below or equal) by FCMOVA (above). Probably it’s a compiler inaccuracy.

So FUCOMI compares ST(0) \((a)\) and ST(1) \((b)\) and then sets some flags in the main CPU. FCMOVBE checks the flags and copies ST(1) \((b\) here at the moment) to ST(0) \((a\) here) if \(ST0(a) \leq ST1(b)\). Otherwise \((a > b)\), it leaves \(a\) in ST(0).

The last FSTP leaves ST(0) on top of the stack, discarding the contents of ST(1).

Let’s trace this function in GDB:

Listing 1.215: Optimizing GCC 4.8.1 and GDB

```
dennis@ubuntuvm:~/polygon$ gcc -O3 d_max.c -o d_max -fno-inline
dennis@ubuntuvm:~/polygon$ gdb d_max
GNU gdb (GDB) 7.6.1-ubuntu
... 
Reading symbols from /home/dennis/polygon/d_max...(no debugging symbols found)...done.
(gdb) b d_max
Breakpoint 1 at 0x80484a0
(gdb) run
Starting program: /home/dennis/polygon/d_max
(gdb) n
Breakpoint 1, 0x080484a0 in d_max ()
(gdb) n
0x080484a4 in d_max ()
(gdb) disas $eip
Dump of assembler code for function d_max:
0x080484a0 <+0>: fdl 0x4(%esp)
0x080484a4 <+4>: fdl 0xc(%esp)
0x080484a8 <+8>: fxch %st(1)
0x080484aa <+10>: fucomi %st(1),%st
0x080484ac <+12>: fcmovbe %st(1),%st
0x080484ae <+14>: fstp %st(1)
```

\textsuperscript{127}Starting at Pentium Pro, Pentium-II, etc.
1.19. FLOATING-POINT UNIT

0x080484b0 <+16>:    ret
End of assembler dump.
(gdb) ni
0x080484a8 in d_max ()
(gdb) info float
R7: Valid 0x3fff9999999999999800 +1.199999999999999956
==R6: Valid 0x4000d999999999999800 +3.399999999999999911
R5: Empty 0x00000000000000000000
R4: Empty 0x00000000000000000000
R3: Empty 0x00000000000000000000
R2: Empty 0x00000000000000000000
R1: Empty 0x00000000000000000000
R0: Empty 0x00000000000000000000

Status Word: 0x3000
TOP: 6
Control Word: 0x037f IM DM ZM OM UM PM
PC: Extended Precision (64-bits)
RC: Round to nearest
Tag Word: 0x0fff
Instruction Pointer: 0x73:0x080484a4
Operand Pointer: 0x7b:0xbffff118
Opcode: 0x0000

(gdb) ni
0x080484ac in d_max ()
(gdb) info float
R7: Valid 0x4000d999999999999800 +3.399999999999999911
==>R6: Valid 0x3fff9999999999999800 +1.199999999999999956
R5: Empty 0x00000000000000000000
R4: Empty 0x00000000000000000000
R3: Empty 0x00000000000000000000
R2: Empty 0x00000000000000000000
R1: Empty 0x00000000000000000000
R0: Empty 0x00000000000000000000

Status Word: 0x3000
TOP: 6
Control Word: 0x037f IM DM ZM OM UM PM
PC: Extended Precision (64-bits)
RC: Round to nearest
Tag Word: 0x0fff
Instruction Pointer: 0x73:0x080484a8
Operand Pointer: 0x7b:0xbffff118
Opcode: 0x0000

(gdb) disas $eip
Dump of assembler code for function d_max:
0x080484a0 <+0>:fldl 0x4(%esp)
0x080484a4 <+4>:fldl 0xc(%esp)
0x080484a8 <+8>:fxch %st(1)
0x080484aa <+10>:fucomi %st(1),%st
0x080484ac <+12>:fcmovbe %st(1),%st
0x080484ae <+14>:fstp %st(1)
0x080484b0 <+16>:ret
End of assembler dump.
(gdb) ni
0x080484ac in d_max ()
(gdb) info registers
eax 0x1
ecx 0xbffff1c4 -1073745468
dx 0x8048340 134513472
ebx 0xb7fbf000 -1208225792
esp 0xbffff10c 0xbffff10c
esi 0x0 0
edi 0x0 0
epi 0x80484ac 0x80484ac <d_max+12>
eflags 0x203 [ CF IF ]
cs 0x73 115
ss 0x7b 123
ds 0x7b 123
Using “ni”, let’s execute the first two FLD instructions.

Let’s examine the FPU registers (line 33).

As it was mentioned before, the FPU registers set is a circular buffer rather than a stack (1.19.5 on page 225). And GDB doesn’t show STx registers, but internal the FPU registers (Rx). The arrow (at line 35) points to the current top of the stack.
1.19. FLOATING-POINT UNIT

You can also see the TOP register contents in Status Word (line 44)—it is 6 now, so the stack top is now pointing to internal register 6.

The values of \(a\) and \(b\) are swapped after FXCH is executed (line 54).

FUCOMI is executed (line 83). Let’s see the flags: CF is set (line 95).

FCMOVBE has copied the value of \(b\) (see line 104).

FSTP leaves one value at the top of stack (line 136). The value of TOP is now 7, so the FPU stack top is pointing to internal register 7.

ARM

Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Register 1</th>
<th>Register 2</th>
<th>Register 3</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMOV</td>
<td>D16, R2, R3</td>
<td>b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VMOV</td>
<td>D17, R0, R1</td>
<td>a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VCMPE.F64</td>
<td>D17, D16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VMRS</td>
<td>APSR_nzcv, FPSCR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VMOVGT.F64</td>
<td>D16, D17</td>
<td>copy &quot;a&quot; to D16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VMOV</td>
<td>R0, R1, D16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BX</td>
<td>LR</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A very simple case. The input values are placed into the D17 and D16 registers and then compared using the VCMPE instruction.

Just like in the x86 coprocessor, the ARM coprocessor has its own status and flags register (FPSCR\(^{128}\)), since there is a necessity to store coprocessor-specific flags. And just like in x86, there are no conditional jump instruction in ARM, that can check bits in the status register of the coprocessor. So there is VMRS, which copies 4 bits (N, Z, C, V) from the coprocessor status word into bits of the general status register (APSR\(^{129}\)).

VMOVGT is the analog of the MOVGT, instruction for D-registers, it executes if one operand is greater than the other while comparing (GT—Greater Than).

If it gets executed, the value of \(a\) is to be written into D16 (that is currently stored in D17). Otherwise the value of \(b\) stays in the D16 register.

The penultimate instruction VMOV prepares the value in the D16 register for returning it via the R0 and R1 register pair.

Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Register 1</th>
<th>Register 2</th>
<th>Register 3</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMOV</td>
<td>D16, R2, R3</td>
<td>b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VMOV</td>
<td>D17, R0, R1</td>
<td>a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VCMPE.F64</td>
<td>D17, D16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VMRS</td>
<td>APSR_nzcv, FPSCR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IT GT</td>
<td>D16, D17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VMOV</td>
<td>R0, R1, D16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BX</td>
<td>LR</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Almost the same as in the previous example, however slightly different. As we already know, many instructions in ARM mode can be supplemented by condition predicate. But there is no such thing in Thumb mode. There is no space in the 16-bit instructions for 4 more bits in which conditions can be encoded.

However, Thumb-2 was extended to make it possible to specify predicates to old Thumb instructions. Here, in the IDA-generated listing, we see the VMOVGT instruction, as in previous example.

\(^{128}\)(ARM) Floating-Point Status and Control Register

\(^{129}\)(ARM) Application Program Status Register
1.19. FLOATING-POINT UNIT

In fact, the usual VM0V is encoded there, but IDA adds the -GT suffix to it, since there is a IT GT instruction placed right before it.

The IT instruction defines a so-called if-then block.

After the instruction it is possible to place up to 4 instructions, each of them has a predicate suffix. In our example, IT GT implies that the next instruction is to be executed, if the GT (Greater Than) condition is true.

Here is a more complex code fragment, by the way, from Angry Birds (for iOS):

Listing 1.218: Angry Birds Classic

ITE NE
VMOVNE R2, R3, D16
VMOVEQ R2, R3, D17
BLX _objc_msgSend ; not suffixed
...

ITE stands for if-then-else
and it encodes suffixes for the next two instructions.

The first instruction executes if the condition encoded in ITE (NE, not equal) is true at, and the second—if the condition is not true. (The inverse condition of NE is EQ (equal)).

The instruction followed after the second VM0V (or VM0VEQ) is a normal one, not suffixed (BLX).

One more that’s slightly harder, which is also from Angry Birds:

Listing 1.219: Angry Birds Classic

ITTTT EQ
MOVEQ R0, R4
ADDEQ SP, SP, #0x20
POPEQ.W {R8,R10}
POPEQ {R4-R7,PC}
BLX ___stack_chk_fail ; not suffixed
...

Four “T” symbols in the instruction mnemonic mean that the four subsequent instructions are to be executed if the condition is true.

That’s why IDA adds the -EQ suffix to each one of them.

And if there was, for example, ITEEE EQ (if-then-else-else-else), then the suffixes would have been set as follows:

-EQ
-NE
-NE
-NE

Another fragment from Angry Birds:

Listing 1.220: Angry Birds Classic

CMP.W R0, #0xFFFFFFFF
ITTE LE
SUBLE.W R10, R0, #1
NEGLE R0, R0
MOVGT R10, R0
MOVHS R6, #0 ; not suffixed
CBZ R0, loc_1E7E32 ; not suffixed
...

ITTE (if-then-then-else)
implies that the 1st and 2nd instructions are to be executed if the LE (Less or Equal) condition is true, and the 3rd—if the inverse condition (GT—Greater Than) is true.
Compilers usually don’t generate all possible combinations.

For example, in the mentioned Angry Birds game (classic version for iOS) only these variants of the IT instruction are used: IT, ITI, ITT, ITTE, ITTTT. How to learn this? In IDA, it is possible to produce listing files, so it was created with an option to show 4 bytes for each opcode. Then, knowing the high part of the 16-bit opcode (IT is 0xBF), we do the following using `grep`:

```
cat AngryBirdsClassic.lst | grep " BF" | grep "IT" > results.lst
```

By the way, if you program in ARM assembly language manually for Thumb-2 mode, and you add conditional suffixes, the assembler will add the IT instructions automatically with the required flags where it is necessary.

### Non-optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 1.221: Non-optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
b = -0x20
a = -0x18
val_to_return = -0x10
saved_R7 = -4

STR R7, [SP,#saved_R7]!
MOV R7, SP
SUB SP, SP, #0x1C
BIC SP, SP, #7
VMOV D16, R2, R3
VMOV D17, R0, R1
VSTR D17, [SP,#0x20+a]
VSTR D16, [SP,#0x20+b]
VLDR D16, [SP,#0x20+a]
VLDR D17, [SP,#0x20+b]
VCMPE.F64 D16, D17
VMRS APSR_nzcv, FPSCR
BLE loc_2E08
VLDR D16, [SP,#0x20+a]
VSTR D16, [SP,#0x20+val_to_return]
B loc_2E10

loc_2E08
VLDR D16, [SP,#0x20+b]
VSTR D16, [SP,#0x20+val_to_return]

loc_2E10
VLDR D16, [SP,#0x20+val_to_return]
VMOV R0, R1, D16
MOV SP, R7
LDR R7, [SP+0x20+b],#4
BX LR
```

Almost the same as we already saw, but there is too much redundant code because the \(a\) and \(b\) variables are stored in the local stack, as well as the return value.

### Optimizing Keil 6/2013 (Thumb mode)

Listing 1.222: Optimizing Keil 6/2013 (Thumb mode)

```
PUSH {R3-R7,LR}
MOV S R4, R2
MOV S R5, R3
MOV S R6, R0
MOV S R7, R1
BL aeabi_cdrcmple
BCS loc_1C0
MOV S R0, R6
MOV S R1, R7
```
Keil doesn’t generate FPU-instructions since it cannot rely on them being supported on the target CPU, and it cannot be done by straightforward bitwise comparing. So it calls an external library function to do the comparison: __aeabi_cdrcmple.

N.B. The result of the comparison is to be left in the flags by this function, so the following BCS (Carry set—Greater than or equal) instruction can work without any additional code.

**ARM64**

**Optimizing GCC (Linaro) 4.9**

The ARM64 ISA has FPU-instructions which set APSR the CPU flags instead of FPSCR for convenience. The FPU is not a separate device here anymore (at least, logically). Here we see FCMPE. It compares the two values passed in D0 and D1 (which are the first and second arguments of the function) and sets APSR flags (N, Z, C, V).

FCSEL (Floating Conditional Select) copies the value of D0 or D1 into D0 depending on the condition (GT—Greater Than), and again, it uses flags in APSR register instead of FPSCR.

This is much more convenient, compared to the instruction set in older CPUs.

If the condition is true (GT), then the value of D0 is copied into D0 (i.e., nothing happens). If the condition is not true, the value of D1 is copied into D0.

**Non-optimizing GCC (Linaro) 4.9**

Non-optimizing GCC (Linaro) 4.9
1.19. FLOATING-POINT UNIT

Non-optimizing GCC is more verbose.

First, the function saves its input argument values in the local stack (Register Save Area). Then the code reloads these values into registers X0/X1 and finally copies them to D0/D1 to be compared using FCMPE. A lot of redundant code, but that is how non-optimizing compilers work. FCMPE compares the values and sets the APSR flags. At this moment, the compiler is not thinking yet about the more convenient FCSEL instruction, so it proceed using old methods: using the BLE instruction (Branch if Less than or Equal). In the first case \((a > b)\), the value of \(a\) gets loaded into X0. In the other case \((a <= b)\), the value of \(b\) gets loaded into X0. Finally, the value from X0 gets copied into D0, because the return value needs to be in this register.

Exercise

As an exercise, you can try optimizing this piece of code manually by removing redundant instructions and not introducing new ones (including FCSEL).

Optimizing GCC (Linaro) 4.9—float

Let’s also rewrite this example to use float instead of double.

```c
float f_max (float a, float b)
{
    if (a>b)
        return a;
    return b;
}
```

It is the same code, but the S-registers are used instead of D- ones. It’s because numbers of type float are passed in 32-bit S-registers (which are in fact the lower parts of the 64-bit D-registers).

MIPS

The co-processor of the MIPS processor has a condition bit which can be set in the FPU and checked in the CPU.

Earlier MIPS-es have only one condition bit (called FCC0), later ones have 8 (called FCC7-FCC0). This bit (or bits) are located in the register called FCCR.

```c
Listing 1.223: Optimizing GCC 4.4.5 (IDA)
```

```assembly
d_max:
; set FPU condition bit if $f14<$f12 (b<a):
    c.lt.d   $f14, $f12
    or      $at, $zero ; NOP
; jump to locret_14 if condition bit is set
    bclt    locret_14
; this instruction is always executed (set return value to "a"):
    mov.d   $f0, $f12 ; branch delay slot
; this instruction is executed only if branch was not taken (i.e., if b>=a)
; set return value to "b":
    mov.d   $f0, $f14
locret_14:
    jr      $ra
    or      $at, $zero ; branch delay slot, NOP
```
1.20. ARRAYS

C.LT.D compares two values. LT is the condition “Less Than”. D implies values of type double. Depending on the result of the comparison, the FCC0 condition bit is either set or cleared.

BC1T checks the FCC0 bit and jumps if the bit is set. T means that the jump is to be taken if the bit is set (“True”). There is also the instruction BC1F which jumps if the bit is cleared (“False”). Depending on the jump, one of function arguments is placed into $F0.

1.19.8 Some constants

It’s easy to find representations of some constants in Wikipedia for IEEE 754 encoded numbers. It’s interesting to know that 0.0 in IEEE 754 is represented as 32 zero bits (for single precision) or 64 zero bits (for double). So in order to set a floating point variable to 0.0 in register or memory, one can use MOV or XOR reg, reg instruction. This is suitable for structures where many variables present of various data types. With usual memset() function one can set all integer variables to 0, all boolean variables to false, all pointers to NULL, and all floating point variables (of any precision) to 0.0.

1.19.9 Copying

One may think inertially that FLD/FST instructions must be used to load and store (and hence, copy) IEEE 754 values. Nevertheless, same can be achieved easier by usual MOV instruction, which, of course, copies values bitwisely.

1.19.10 Stack, calculators and reverse Polish notation

Now we understand why some old calculators use reverse Polish notation[^130]. For example, for addition of 12 and 34 one has to enter 12, then 34, then press “plus” sign. It’s because old calculators were just stack machine implementations, and this was much simpler than to handle complex parenthesized expressions.

1.19.11 80 bits?

Internal numbers representation in FPU — 80-bit. Strange number, because the number not in $2^n$ form. There is a hypothesis that this is probably due to historical reasons—the standard IBM punched card can encode 12 rows of 80 bits. 80·25 text mode resolution was also popular in past.


If you know better, please a drop email to the author: dennis@yurichev.com.

1.19.12 x64

On how floating point numbers are processed in x86-64, read more here: [1.31 on page 427](#).

1.19.13 Exercises

- [http://challenges.re/60](http://challenges.re/60)
- [http://challenges.re/61](http://challenges.re/61)

1.20 Arrays

An array is just a set of variables in memory that lie next to each other and that have the same type[^131].

[^131]: AKA “homogeneous container”
#include <stdio.h>

int main()
{
    int a[20];
    int i;

    for (i=0; i<20; i++)
        a[i]=i*2;

    for (i=0; i<20; i++)
        printf ("a[%d]=%d\n", i, a[i]);

    return 0;
}

x86

MSVC

Let's compile:

Listing 1.224: MSVC 2008

<table>
<thead>
<tr>
<th>TEXT SEGMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>_i$ = -84</td>
</tr>
<tr>
<td>_a$ = -80</td>
</tr>
</tbody>
</table>

```asm
_main PROC
    push ebp
    mov ebp, esp
    sub esp, 84 ; 00000054H
    mov DWORD PTR _i$[ebp], 0
    jmp SHORT $LN6@main
$LN5@main:
    mov eax, DWORD PTR _i$[ebp]
    add eax, 1
    mov DWORD PTR _i$[ebp], eax
$LN6@main:
    cmp DWORD PTR _i$[ebp], 20 ; 00000014H
    jge SHORT $LN4@main
    mov ecx, DWORD PTR _i$[ebp]
    shl ecx, 1
    mov edx, DWORD PTR _a$[ebp+ecx*4]
    jmp SHORT $LN5@main
$LN4@main:
    mov DWORD PTR _i$[ebp], 0
    jmp SHORT $LN3@main
$LN2@main:
    mov eax, DWORD PTR _i$[ebp]
    add eax, 1
    mov DWORD PTR _i$[ebp], eax
$LN3@main:
    cmp DWORD PTR _i$[ebp], 20 ; 00000014H
    jge SHORT $LN1@main
    mov ecx, DWORD PTR _i$[ebp]
    mov edx, DWORD PTR _a$[ebp+ecx*4]
    push edx
    mov eax, DWORD PTR _i$[ebp]
    push eax
    push OFFSET $SG2463
    call _printf
    add esp, 12 ; 0000000cH
    jmp SHORT $LN2@main
$LN1@main:  
```
Nothing very special, just two loops: the first is a filling loop and second is a printing loop. The `shl ecx, 1` instruction is used for value multiplication by 2 in ECX, more about below 1.18.2 on page 217.

80 bytes are allocated on the stack for the array, 20 elements of 4 bytes.
Let's try this example in OllyDbg.

We see how the array gets filled:

each element is 32-bit word of int type and its value is the index multiplied by 2:

Since this array is located in the stack, we can see all its 20 elements there.

GCC

Here is what GCC 4.4.1 does:
1.20. ARRAYS

```assembly
and esp, 0FFFFFFF0h
sub esp, 70h
mov [esp+70h+i], 0 ; i=0
jmp short loc_804840A

loc_80483F7:
mov eax, [esp+70h+i]
mov edx, [esp+70h+i]
add edx, edx ; edx=i*2
mov [esp+eax*4+70h+i*2], edx
add [esp+70h+i], 1 ; i++

loc_804840A:
cmp [esp+70h+i], 13h
jle short loc_80483F7
mov [esp+70h+i], 0
jmp short loc_8048441

loc_804841B:
mov eax, [esp+70h+i]
mov edx, [esp+eax*4+70h+i*2]
mov eax, offset aADD ; "a[%d]=%d\n"
mov [esp+70h+var_68], edx
mov edx, [esp+70h+i]
mov [esp+70h+var_6C], edx
mov [esp+70h+var_70], eax
call printf
add [esp+70h+i], 1

loc_8048441:
cmp [esp+70h+i], 13h
jle short loc_804841B
leave
jmp main

main endp
```

By the way, variable `a` is of type `int*` (the pointer to `int`)—you can pass a pointer to an array to another function, but it’s more correct to say that a pointer to the first element of the array is passed (the addresses of rest of the elements are calculated in an obvious way).

If you index this pointer as `a[idx]`, `idx` is just to be added to the pointer and the element placed there (to which calculated pointer is pointing) is to be returned.

An interesting example: a string of characters like “`string`” is an array of characters and it has a type of `const char[]`.

An index can also be applied to this pointer.

And that is why it is possible to write things like “`string`[i]”—this is a correct C/C++ expression!

ARM

Non-optimizing Keil 6/2013 (ARM mode)

```
EXPORT _main

_main

STMFD SP!, {R4,LR}
SUB SP, SP, #0x50 ; allocate place for 20 int variables

; first loop

MOV R4, #0 ; i
B loc_4A0

loc_494

MOV R0, R4,LSL#1 ; R0=R4*2
STR R0, [SP,R4,LSL#2] ; store R0 to SP+R4<<2 (same as SP+R4*4)
ADD R4, R4, #1 ; i=i+1
```
int type requires 32 bits for storage (or 4 bytes),
so to store 20 int variables 80 (0x50) bytes are needed. So that is why the SUB SP, SP, #0x50 instruction in the function’s prologue allocates exactly this amount of space in the stack.

In both the first and second loops, the loop iterator \( i \) is placed in the \( R4 \) register.

The number that is to be written into the array is calculated as \( i \times 2 \), which is effectively equivalent to shifting it left by one bit, so MOV R0, R4,LSL#1 instruction does this.

STR R0, [SP,R4,LSL#1] writes the contents of R0 into the array.

Here is how a pointer to array element is calculated: SP points to the start of the array, R4 is \( i \).

So shifting \( i \) left by 2 bits is effectively equivalent to multiplication by 4 (since each array element has a size of 4 bytes) and then it’s added to the address of the start of the array.

The second loop has an inverse LDR R2, [SP,R4,LSL#1] instruction. It loads the value we need from the array, and the pointer to it is calculated likewise.

**Optimizing Keil 6/2013 (Thumb mode)**

```assembly
main
PUSH {R4,R5,LR} ; allocate place for 20 int variables + one more variable
SUB SP, SP, #0x54 ; first loop

MOV S R0, #0 ; i
MOV R5, SP ; pointer to first array element

loc_1CE
LSLS R1, R0, #1 ; R1=i<<1 (same as i*2)
LSLS R2, R0, #2 ; R2=i<<2 (same as i*4)
ADDS R0, R0, #1 ; i=i+1
CMP R0, #20 ; i<20?
STR R1, [R5,R2] ; store R1 to *(R5+R2) (same R5+i*4)
BLT loc_1CE ; yes, i<20, run loop body again

; second loop
MOV S R4, #0 ; i=0
loc_1DC
```

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<table>
<thead>
<tr>
<th>Thumb code is very similar.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thumb mode has special instructions for bit shifting (like LLSL), which calculates the value to be written into the array and the address of each element in the array as well.</td>
</tr>
<tr>
<td>The compiler allocates slightly more space in the local stack, however, the last 4 bytes are not used.</td>
</tr>
</tbody>
</table>

Non-optimizing GCC 4.9.1 (ARM64)

Listing 1.226: Non-optimizing GCC 4.9.1 (ARM64)

```
.LC0: .string "a[%d]=%d\n"
main:
; save FP and LR in stack frame:
stp x29, x30, [sp, -112]!
; set stack frame (FP=SP)
add x29, sp, 0
; setting initial counter variable at 0 (WZR is the register always holding zero):
str wzr, [x29,108]
; jump to loop condition checking code:
b .L2
.L3:
; load value of "i" variable:
  ldr w0, [x29,108]
; multiplicate it by 2:
  lsl w2, w0, 1
; find a place of an array in local stack:
  add x0, x29, 24
; load 32-bit integer from local stack and sign extend it to 64-bit one:
  ldrsw x1, [x29,108]
; calculate address of element (X0+X1<<2=array address+i*4) and store W2 (i*2) there:
  str w2, [x0,x1,lsl 2]
; increment counter (i):
  ldr w0, [x29,108]
  add w0, w0, 1
  str w0, [x29,108]
.L2:
; check if we finished:
  ldr w0, [x29,108]
  cmp w0, 19
  bale .L3
; second part of the function begins here.
; setting initial counter variable at 0.
; by the way, the same place in the local stack was used for counter,
; because the same local variable (i) is being used as counter.
  str wzr, [x29,108]
b .L4
.L5:
; calculate array address:
  add x0, x29, 24
; load "i" value:
  ldrsw x1, [x29,108]
; load value from the array at the address (X0+X1<<2 = address of array + i*4)
  ldr w2, [x0,x1,lsl 2]
```

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1.20. ARRAYS

; load address of the "a[%d]=%d\n" string:
    adrp x0, .LC0
    add x0, x0, :lo12:.LC0

; load "i" variable to W1 and pass it to printf() as second argument:
    ldr w1, [x29,108]

; W2 still contains the value of array element which was just loaded.
; call printf():
    bl printf

; increment "i" variable:
    ldr w0, [x29,108]
    add w0, w0, 1
    str w0, [x29,108]

.L4:
; are we finished?
    ldr w0, [x29,108]
    cmp w0, 19
    ble .L5
; return 0
    mov w0, 0
; restore FP and LR:
    ldp x29, x30, [sp], 112
    ret

MIPS

The function uses a lot of S- registers which must be preserved, so that’s why its values are saved in the
function prologue and restored in the epilogue.

Listing 1.227: Optimizing GCC 4.4.5 (IDA)

main:

var_70 = -0x70
var_68 = -0x68
var_14 = -0x14
var_10 = -0x10
var_C = -0xC
var_8 = -8
var_4 = -4

; function prologue:
lui $gp, (__gnu_local_gp >> 16)
addiu $sp, -0x80
la $gp, (__gnu_local_gp & 0xFFFF)
sw $ra, 0x80+var_4($sp)
sw $s3, 0x80+var_8($sp)
sw $s2, 0x80+var_C($sp)
sw $s1, 0x80+var_10($sp)
sw $s0, 0x80+var_14($sp)
sw $gp, 0x80+var_70($sp)
addiu $s1, $sp, 0x80+var_68
move $v1, $s1
move $v0, $zero

; that value will be used as a loop terminator.
; it was precalculated by GCC compiler at compile stage:
    li $a0, 0x28 # '('
loc_34: # CODE XREF: main+3C

; store value into memory:
    sw $v0, 0($v1)

; increase value to be stored by 2 at each iteration:
    addiu $v0, 2

; loop terminator reached?
    bne $v0, $a0, loc_34

; add 4 to address anyway:
    addiu $v1, 4

; array filling loop is ended
; second loop begin

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1.20. ARRAYS

```
la  $s3, $LC0  # "a[%d]=%d\n"

; "i" variable will reside in $s0:
move  $s0, $zero
li  $s2, 0x14

loc_54:  # CODE XREF: main+70
; call printf():
lw  $t9, (printf & 0xFFFF)($gp)
lw  $a2, 0($s1)
move  $a1, $s0
move  $a0, $s3
jalr  $t9;

; increment "i":
addiu  $s0, 1
lw  $gp, 0x80+var_70($sp)

; jump to loop body if end is not reached:
bne  $s0, $s2, loc_54

; move memory pointer to the next 32-bit word:
addiu  $s1, 4

; function epilogue
lw  $ra, 0x80+var_4($sp)
move  $v0, $zero
lw  $s3, 0x80+var_8($sp)
lw  $s2, 0x80+var_C($sp)
lw  $s1, 0x80+var_10($sp)
lw  $s0, 0x80+var_14($sp)
jr  $ra

addiu  $sp, 0x80

$LC0:  .ascii "a[%d]=%d\n"<0>  # DATA XREF: main+44
```

Something interesting: there are two loops and the first one doesn’t need \textit{i}, it needs only \textit{i} \times 2 (increased by 2 at each iteration) and also the address in memory (increased by 4 at each iteration).

So here we see two variables, one (in $V0) increasing by 2 each time, and another (in $V1) — by 4.

The second loop is where \texttt{printf()} is called and it reports the value of \textit{i} to the user, so there is a variable which is increased by 1 each time (in $S0) and also a memory address (in $S1) increased by 4 each time.

That reminds us of loop optimizations we considered earlier: \textit{3.7 on page 490}.

Their goal is to get rid of multiplications.

### 1.20.2 Buffer overflow

#### Reading outside array bounds

So, array indexing is just \texttt{array[index]}. If you study the generated code closely, you’ll probably note the missing index bounds checking, which could check \textit{if it is less than 20}. What if the index is 20 or greater? That’s the one C/C++ feature it is often blamed for.

Here is a code that successfully compiles and works:

```c
#include <stdio.h>

int main()
{
    int a[20];
    int i;

    for (i=0; i<20; i++)
        a[i]=i*2;

    printf("a[20]=%d\n", a[20]);

    return 0;
}
```

Compilation results (MSVC 2008):

```
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```
The code produced this result:

```
Listing 1.229: OllyDbg: console output

a[20]=1638280
```

It is just something that has been lying in the stack near to the array, 80 bytes away from its first element.
1.20. ARRAYS

Let's try to find out where did this value come from, using OllyDbg.

Let's load and find the value located right after the last array element:

![Figure 1.88: OllyDbg: reading of the 20th element and execution of printf()](image)

What is this? Judging by the stack layout, this is the saved value of the EBP register.
1.20. ARRAYS

Let's trace further and see how it gets restored:

Figure 1.89: OllyDbg: restoring value of EBP

Indeed, how it could be different? The compiler may generate some additional code to check the index value to be always in the array's bounds (like in higher-level programming languages\(^{132}\)) but this makes the code slower.

Writing beyond array bounds

OK, we read some values from the stack \textit{illegally}, but what if we could write something to it?

Here is what we have got:

```c
#include <stdio.h>

int main()
{
    int a[20];
    int i;
    for (i=0; i<30; i++)
        a[i]=i;
    return 0;
}
```

\(^{132}\)Java, Python, etc.
1.20. ARRAYS

And what we get:

Listing 1.230: Non-optimizing MSVC 2008

```assembly
_TEXT SEGMENT
_i$ = -84 ; size = 4
_a$ = -80 ; size = 80
_main PROC
    push ebp
    mov ebp, esp
    sub esp, 84
    mov DWORD PTR _i$[ebp], 0
    jmp SHORT $LN3@main
$LN2@main:
    mov eax, DWORD PTR _i$[ebp]
    add eax, 1
    mov DWORD PTR _i$[ebp], eax
$LN3@main:
    cmp DWORD PTR _i$[ebp], 30 ; 0000001eH
    jge SHORT $LN1@main
    mov ecx, DWORD PTR _i$[ebp]
    mov edx, DWORD PTR _i$[ebp] ; that instruction is obviously redundant
    mov DWORD PTR _a$[ebp+ecx*4], edx ; ECX could be used as second operand here instead
    jmp SHORT $LN2@main
$LN1@main:
    xor eax, eax
    mov esp, ebp
    pop ebp
    ret 0
_main ENDP
```

The compiled program crashes after running. No wonder. Let’s see where exactly does it crash.
1.20. ARRAYS

Let’s load it into OllyDbg, and trace until all 30 elements are written:

![OllyDbg screenshot showing the debugging process](image_url)

Figure 1.90: OllyDbg: after restoring the value of EBP
1.20. ARRAYS

Trace until the function end:

Figure 1.91: OllyDbg: EIP has been restored, but OllyDbg can’t disassemble at 0x15

Now please keep your eyes on the registers.

EIP is 0x15 now. It is not a legal address for code—at least for win32 code! We got there somehow against our will. It is also interesting that the EBP register contain 0x14, ECX and EDX contain 0x1D.

Let’s study stack layout a bit more.

After the control flow has been passed to main(), the value in the EBP register was saved on the stack. Then, 84 bytes were allocated for the array and the i variable. That’s (20+1)*sizeof(int). ESP now points to the i variable in the local stack and after the execution of the next PUSH something, something is appearing next to i.

That’s the stack layout while the control is in main():

| ESP | 4 bytes allocated for i variable |
| ESP+4 | 80 bytes allocated for a[20] array |
| ESP+84 | saved EBP value |
| ESP+88 | return address |

a[19]=something statement writes the last int in the bounds of the array (in bounds so far!).

a[20]=something statement writes something to the place where the value of EBP is saved.

Please take a look at the register state at the moment of the crash. In our case, 20 has been written in the 20th element. At the function end, the function epilogue restores the original EBP value. (20 in decimal 281)
1.20. ARRAYS

is 0x14 in hexadecimal). Then RET gets executed, which is effectively equivalent to POP EIP instruction.

The RET instruction takes the return address from the stack (that is the address in CRT, which has called main()), and 21 is stored there (0x15 in hexadecimal). The CPU traps at address 0x15, but there is no executable code there, so exception gets raised.

Welcome! It is called a buffer overflow\textsuperscript{133}.

Replace the int array with a string (char array), create a long string deliberately and pass it to the program, to the function, which doesn't check the length of the string and copies it in a short buffer, and you'll able to point the program to an address to which it must jump. It's not that simple in reality, but that is how it emerged. Classic article about it: [Aleph One, Smashing The Stack For Fun And Profit, (1996)]\textsuperscript{134}.

GCC

Let's try the same code in GCC 4.4.1. We get:

```
public main
main proc near
a = dword ptr -54h
i = dword ptr -4
push ebp
mov ebp, esp
sub esp, 60h ; 96
mov [ebp+i], 0
jmp short loc_80483D1
loc_80483C3:
    mov eax, [ebp+i]
    mov edx, [ebp+i]
    mov [ebp+eax*4+a], edx
    add [ebp+i], 1
loc_80483D1:
    cmp [ebp+i], 1Dh
    jle short loc_80483C3
    mov eax, 0
    leave
    ret
main endp
```

Running this in Linux will produce: Segmentation fault.

If we run this in the GDB debugger, we get this:

```
(gdb) r
Starting program: /home/dennis/RE/1
Program received signal SIGSEGV, Segmentation fault.
0x000000016 in ?? ()
(gdb) info registers
eax 0x0 0
ecx 0xd2f96388 -755407992
edx 0x1d 29
ebx 0x26eff4 2551796
esp 0xbffff4b0 0xbffff4b0
ebp 0x15 0x15
esi 0x0 0
edi 0x0 0
eip 0x16 0x16
eflags 0x10202 [ IF RF ]
cs 0x73 115
ss 0x7b 123
ds 0x7b 123
es 0x7b 123
fs 0x0 0
gs 0x33 51
```

\textsuperscript{133}wikipedia
\textsuperscript{134}Also available as http://go.yurichev.com/17266
1.20. ARRAYS

The register values are slightly different than in win32 example, since the stack layout is slightly different too.

1.20.3 Buffer overflow protection methods

There are several methods to protect against this scourge, regardless of the C/C++ programmers’ negligence. MSVC has options like:

/RTCs Stack Frame runtime checking
/GZ Enable stack checks (/RTCs)

One of the methods is to write a random value between the local variables in stack at function prologue and to check it in function epilogue before the function exits. If value is not the same, do not execute the last instruction RET, but stop (or hang). The process will halt, but that is much better than a remote attack to your host.

This random value is called a “canary” sometimes, it is related to the miners’ canary, they were used by miners in the past days in order to detect poisonous gases quickly.

Canaries are very sensitive to mine gases, they become very agitated in case of danger, or even die.

If we compile our very simple array example (1.20.1 on page 268) in MSVC with RTC1 and RTCs option, you can see a call to `_RTC_CheckStackVars@8` a function at the end of the function that checks if the “canary” is correct.

Let’s see how GCC handles this. Let’s take an `alloca()` (1.7.2 on page 35) example:

```c
#ifdef __GNUC__
#include <alloca.h> // GCC
#else
#include <malloc.h> // MSVC
#endif
#include <stdio.h>

void f()
{
    char *buf=(char*)alloca (600);
    #ifdef __GNUC__
    sprintf (buf, 600, "hi! %d, %d, %d\n", 1, 2, 3); // GCC
    #else
    _snprintf (buf, 600, "hi! %d, %d, %d\n", 1, 2, 3); // MSVC
    #endif
    puts (buf);
}
```

By default, without any additional options, GCC 4.7.3 inserts a “canary” check into the code:

Listing 1.231: GCC 4.7.3

```
.LC0:
    .string "hi! %d, %d, %d\n"
.f:
    push   ebp
    mov    ebp, esp
    push   ebx
    sub    esp, 676
    lea    ebx, [esp+39]
    and    ebx, -16
    mov    DWORD PTR [esp+20], 3
    mov    DWORD PTR [esp+16], 2
    mov    DWORD PTR [esp+12], 1
    mov    DWORD PTR [esp+8], OFFSET FLAT:.LC0 ; "hi! %d, %d, %d\n"
    mov    DWORD PTR [esp+4], 600
```

Footnotes:

135 [compiler-side buffer overflow protection methods](wikipedia.org/wiki/Buffer_overflow_protection)
136 [wikipedia.org/wiki/Domestic_canary#Miner.27s_canary](wikipedia.org/wiki/Domestic_canary#Miner.27s_canary)
1.20. ARRAYS

```
mov DWORD PTR [esp], ebx
mov eax, DWORD PTR gs:20 ; canary
mov DWORD PTR [ebp-12], eax
xor eax, eax
call _snprintf
mov DWORD PTR [esp], ebx
call puts
mov eax, DWORD PTR [ebp-12]
xor eax, DWORD PTR gs:20 ; check canary
jne .L5
mov ebx, DWORD PTR [ebp-4]
leave
ret
.L5:
call __stack_chk_fail
```

The random value is located in gs:20. It gets written on the stack and then at the end of the function the value in the stack is compared with the correct “canary” in gs:20. If the values are not equal, the __stack_chk_fail function is called and we can see in the console something like that (Ubuntu 13.04 x86):

```
 *** buffer overflow detected ***: ./2_1 terminated
 Backtrace: ========
/lib/i386-linux-gnu/libc.so.6(__fortify_fail+0x63)[0xb7699bc3]
/lib/i386-linux-gnu/libc.so.6(+0x10593a)[0xb769893a]
/lib/i386-linux-gnu/libc.so.6(+0x105008)[0xb7698008]
/lib/i386-linux-gnu/libc.so.6(_IO_default_xsputn+0x8c)[0xb7606a8c]
/lib/i386-linux-gnu/libc.so.6(_IO_vfprintf+0x165)[0xb75d7a45]
/lib/i386-linux-gnu/libc.so.6(__vsprintf_chk+0xc9)[0xb76980d9]
/lib/i386-linux-gnu/libc.so.6(__sprintf_chk+0x2f)[0xb7697fef]
./2_1[0x8048404]
/lib/i386-linux-gnu/libc.so.6(__libc_start_main+0xf5)[0xb75ac935]
```

The random value is located in gs:20. It gets written on the stack and then at the end of the function the value in the stack is compared with the correct “canary” in gs:20. If the values are not equal, the __stack_chk_fail function is called and we can see in the console something like that (Ubuntu 13.04 x86):

```
 *** buffer overflow detected ***: ./2_1 terminated
 Backtrace: ========
/lib/i386-linux-gnu/libc.so.6(__fortify_fail+0x63)[0xb7699bc3]
/lib/i386-linux-gnu/libc.so.6(+0x10593a)[0xb769893a]
/lib/i386-linux-gnu/libc.so.6(+0x105008)[0xb7698008]
/lib/i386-linux-gnu/libc.so.6(_IO_default_xsputn+0x8c)[0xb7606a8c]
/lib/i386-linux-gnu/libc.so.6(_IO_vfprintf+0x165)[0xb75d7a45]
/lib/i386-linux-gnu/libc.so.6(__vsprintf_chk+0xc9)[0xb76980d9]
/lib/i386-linux-gnu/libc.so.6(__sprintf_chk+0x2f)[0xb7697fef]
./2_1[0x8048404]
/lib/i386-linux-gnu/libc.so.6(__libc_start_main+0xf5)[0xb75ac935]
```

gs is the so-called segment register. These registers were used widely in MS-DOS and DOS-extenders times. Today, its function is different.

To say it briefly, the gs register in Linux always points to the **TLS**137 (6.2 on page 742)—some information specific to thread is stored there. By the way, in win32 the fs register plays the same role, pointing to **TIB**138 139.

More information can be found in the Linux kernel source code (at least in 3.11 version), in arch/x86/include/asm/stackprotector.h this variable is described in the comments.

---

137 Thread Local Storage
138 Thread Information Block
139 wikipedia.org/wiki/Win32_Thread_Information_Block
Let's get back to our simple array example (1.20.1 on page 268), again, now we can see how LLVM checks the correctness of the “canary”:

```assembly
main

var_64 = -0x64
var_60 = -0x60
var_5C = -0x5C
var_58 = -0x58
var_54 = -0x54
var_50 = -0x50
var_4C = -0x4C
var_48 = -0x48
var_44 = -0x44
var_40 = -0x40
var_3C = -0x3C
var_38 = -0x38
var_34 = -0x34
var_30 = -0x30
var_2C = -0x2C
var_28 = -0x28
var_24 = -0x24
var_20 = -0x20
var_1C = -0x1C
var_18 = -0x18
canary = -0x14
var_10 = -0x10

PUSH {R4-R7,LR}
ADD R7, SP, #0xC
STR.W R8, [SP,#0xC+var_10]!
SUB SP, SP, #0x54
MOVT.W R0, #0
MOVS R2, #aObjc_methtype ; "objc_methtype"
MOVW R0, #0
MOV R5, #0
ADD R0, PC
LDR.W R8, [R0]
LDR.W R0, [R8]
STR R0, [SP,#0x64+canary]
MOVS R0, #2
STR R2, [SP,#0x64+var_64]
STR R0, [SP,#0x64+var_60]
MOVS R0, #4
STR R0, [SP,#0x64+var_5C]
MOVS R0, #6
STR R0, [SP,#0x64+var_58]
MOVS R0, #8
STR R0, [SP,#0x64+var_54]
MOVS R0, #0xA
STR R0, [SP,#0x64+var_50]
MOVS R0, #0xC
STR R0, [SP,#0x64+var_4C]
MOVS R0, #0xE
STR R0, [SP,#0x64+var_48]
MOVS R0, #0x10
STR R0, [SP,#0x64+var_44]
MOVS R0, #0x12
STR R0, [SP,#0x64+var_40]
MOVS R0, #0x14
STR R0, [SP,#0x64+var_3C]
MOVS R0, #0x16
STR R0, [SP,#0x64+var_38]
MOVS R0, #0x18
STR R0, [SP,#0x64+var_34]
MOVS R0, #0x1A
STR R0, [SP,#0x64+var_30]
```
First of all, as we see, LLVM “unrolled” the loop and all values were written into an array one-by-one, pre-calculated, as LLVM concluded it can work faster. By the way, instructions in ARM mode may help to do this even faster, and finding this could be your homework.

At the function end we see the comparison of the “canaries”—the one in the local stack and the correct one, to which \texttt{R8} points.

If they are equal to each other, a 4-instruction block is triggered by \texttt{ITTTT EQ}, which contains writing 0 in \texttt{R0}, the function epilogue and exit. If the “canaries” are not equal, the block being skipped, and the jump to \texttt{___stack_chk_fail} function will occur, which, perhaps will halt execution.

### 1.20.4 One more word about arrays

Now we understand why it is impossible to write something like this in C/C++ code:

```c
void f(int size)
{
    int a[size];
    ...
}
```

That’s just because the compiler must know the exact array size to allocate space for it in the local stack layout on at the compiling stage.

If you need an array of arbitrary size, allocate it by using \texttt{malloc()}, then access the allocated memory block as an array of variables of the type you need.
1.20. ARRAYS

Or use the C99 standard feature [ISO/IEC 9899:TC3 (C C99 standard), (2007)6.7.5/2], and it works like `alloca()` (1.7.2 on page 35) internally.

It's also possible to use garbage collecting libraries for C.

And there are also libraries supporting smart pointers for C++.

### 1.20.5 Array of pointers to strings

Here is an example for an array of pointers.

```c
#include <stdio.h>

const char* month1[] =
{
    "January", "February", "March", "April",
    "May", "June", "July", "August",
    "September", "October", "November", "December"
};

// in 0..11 range
const char* get_month1 (int month)
{
    return month1[month];
}
```

---

**Listing 1.233: Optimizing MSVC 2013 x64**

```
_DATA SEGMENT
month1 DQ FLAT:$SG3122
    DQ FLAT:$SG3123
    DQ FLAT:$SG3124
    DQ FLAT:$SG3125
    DQ FLAT:$SG3126
    DQ FLAT:$SG3127
    DQ FLAT:$SG3128
    DQ FLAT:$SG3129
    DQ FLAT:$SG3130
    DQ FLAT:$SG3131
    DQ FLAT:$SG3132
    DQ FLAT:$SG3133

$SG3122 DB 'January', 00H
$SG3123 DB 'February', 00H
$SG3124 DB 'March', 00H
$SG3125 DB 'April', 00H
$SG3126 DB 'May', 00H
$SG3127 DB 'June', 00H
$SG3128 DB 'July', 00H
$SG3129 DB 'August', 00H
$SG3130 DB 'September', 00H
$SG3131 DB 'October', 00H
$SG3132 DB 'November', 00H
$SG3133 DB 'December', 00H
_DATA ENDS

month$ = 8
get_month1 PROC
    movsxd rax, ecx
    lea rcx, OFFSET FLAT:month1
    mov rax, QWORD PTR [rcx+rax*8]
    ret 0
get_month1 ENDP
```
1.20. ARRAYS

The code is very simple:

• The first MOVSD instruction copies a 32-bit value from ECX (where month argument is passed) to RAX with sign-extension (because the month argument is of type int).

The reason for the sign extension is that this 32-bit value is to be used in calculations with other 64-bit values.

Hence, it has to be promoted to 64-bit:\textsuperscript{140}

• Then the address of the pointer table is loaded into RCX.

• Finally, the input value (month) is multiplied by 8 and added to the address. Indeed: we are in a 64-bit environment and all address (or pointers) require exactly 64 bits (or 8 bytes) for storage. Hence, each table element is 8 bytes wide. And that’s why to pick a specific element, month \times 8 bytes has to be skipped from the start. That’s what MOV does. In addition, this instruction also loads the element at this address. For 1, an element would be a pointer to a string that contains “February”, etc.

Optimizing GCC 4.9 can do the job even better:\textsuperscript{141}

\begin{verbatim}
movsx rdi, edi
mov rax, QWORD PTR month1[0+rdi*8]
ret
\end{verbatim}

\textbf{32-bit MSVC}

Let’s also compile it in the 32-bit MSVC compiler:

\begin{verbatim}
_month$ = 8
_get_month1 PROC
    mov eax, DWORD PTR _month$[esp-4]
    mov eax, DWORD PTR _month1[eax*4]
    ret 0
_get_month1 ENDP
\end{verbatim}

The input value does not need to be extended to 64-bit value, so it is used as is.

And it’s multiplied by 4, because the table elements are 32-bit (or 4 bytes) wide.

\textbf{32-bit ARM}

\textit{ARM in ARM mode}

\begin{verbatim}
get_month1 PROC
    LDR r1, |L0.100|
    LDR r0, [r1, r0, LSL #2]
    BX lr
ENDP
|L0.100|
DCD ||.data||
DCB "January", 0
DCB "February", 0
DCB "March", 0
DCB "April", 0
DCB "May", 0
\end{verbatim}

\textsuperscript{140}It is somewhat weird, but negative array index could be passed here as month (negative array indices will have been explained later: 3.19 on page 593). And if this happens, the negative input value of int type is sign-extended correctly and the corresponding element before table is picked. It is not going to work correctly without sign-extension.

\textsuperscript{141}"0+" was left in the listing because GCC assembler output is not tidy enough to eliminate it. It’s displacement, and it’s zero here.
The address of the table is loaded in R1.

All the rest is done using just one LDR instruction.

Then input value \textit{month} is shifted left by 2 (which is the same as multiplying by 4), then added to R1 (where the address of the table is) and then a table element is loaded from this address.

The 32-bit table element is loaded into R0 from the table.

\textbf{ARM in Thumb mode}

The code is mostly the same, but less dense, because the LSL suffix cannot be specified in the LDR instruction here:

\begin{verbatim}
get_month1 PROC
  LSLS  r0,r0,#2
  LDR   r1,[L0.64]
  LDR   r0,[r1,r0]
  BX    lr
ENDP
\end{verbatim}

\textbf{ARM64}

Listing 1.237: Optimizing GCC 4.9 ARM64

\begin{verbatim}
get_month1:         
  adrp  x1, .LANCHOR0
  add   x1, x1, :lo12:.LANCHOR0
  ldr   x0, [x1,w0,sxtw 3]
  ret

.LANCHOR0 = . + 0
.type  month1, %object
.size  month1, 96

month1:             
  .xword  .LC2
  .xword  .LC3
  .xword  .LC4
  .xword  .LC5
  .xword  .LC6
  .xword  .LC7
  .xword  .LC8
  .xword  .LC9
  .xword  .LC10
\end{verbatim}
The address of the table is loaded in X1 using ADRP/ADD pair.
Then corresponding element is picked using just one LDR, which takes W0 (the register where input argument \textit{month} is), shifts it 3 bits to the left (which is the same as multiplying by 8), sign-extends it (this is what “sxtw” suffix implies) and adds to X0. Then the 64-bit value is loaded from the table into X0.

MIPS Listing 1.238: Optimizing GCC 4.4.5 (IDA)

get\_month1:
; load address of table into $v0:
   la $v0, month1
; take input value and multiply it by 4:
   sll $a0, 2
; sum up address of table and multiplied value:
   addu $a0, $v0
; load table element at this address into $v0:
   lw $v0, 0($a0)
; return
   jr $ra
or $at, $zero ; branch delay slot, NOP

.data # .data.rel.local
.globl month1
month1: .word aJanuary  # "January"
   .word aFebruary  # "February"
   .word aMarch     # "March"
   .word aApril     # "April"
   .word aMay       # "May"
   .word aJune      # "June"
   .word aJuly      # "July"
   .word aAugust    # "August"
   .word aSeptember # "September"
   .word aOctober   # "October"
   .word aNovember  # "November"
   .word aDecember  # "December"

.a data # .rodata.str1.4
aJanuary: .asci "January"<0>
aFebruary: .asci "February"<0>
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```
aMarch: ascii "March"<0>
aApril: ascii "April"<0>
aMay: ascii "May"<0>
aJune: ascii "June"<0>
aJuly: ascii "July"<0>
aAugust: ascii "August"<0>
aSeptember: ascii "September"<0>
aOctober: ascii "October"<0>
aNovember: ascii "November"<0>
aDecember: ascii "December"<0>
```

**Array overflow**

Our function accepts values in the range of 0..11, but what if 12 is passed? There is no element in table at this place.

So the function will load some value which happens to be there, and return it.

Soon after, some other function can try to get a text string from this address and may crash.

Let's compile the example in MSVC for win64 and open it in IDA to see what the linker has placed after the table:

```
Listing 1.239: Executable file in IDA

off_140011000 dq offset aJanuary_1 ; DATA XREF: .text:0000000140001003
    ; "January"
    dq offset aFebruary_1 ; "February"
    dq offset aMarch_1 ; "March"
    dq offset aApril_1 ; "April"
    dq offset aMay_1 ; "May"
    dq offset aJune_1 ; "June"
    dq offset aJuly_1 ; "July"
    dq offset aAugust_1 ; "August"
    dq offset aSeptember_1 ; "September"
    dq offset aOctober_1 ; "October"
    dq offset aNovember_1 ; "November"
    dq offset aDecember_1 ; "December"
aJanuary_1 db 'January',0 ; DATA XREF: sub_140001020+4
    ; .data:off_140011000
aFebruary_1 db 'February',0 ; DATA XREF: .data:0000000140011008
    align 4
aMarch_1 db 'March',0 ; DATA XREF: .data:0000000140011010
    align 4
aApril_1 db 'April',0 ; DATA XREF: .data:0000000140011018
```

Month names are came right after.

Our program is tiny, so there isn’t much data to pack in the data segment, so it just the month names. But it has to be noted that there might be really *anything* that linker has decided to put by chance.

So what if 12 is passed to the function? The 13th element will be returned.

Let’s see how the CPU treats the bytes there as a 64-bit value:

```
Listing 1.240: Executable file in IDA

off_140011000 dq offset qword_140011060 ; DATA XREF: .text:0000000140001003
    ; "February"
    dq offset aMarch_1 ; "March"
    dq offset aApril_1 ; "April"
    dq offset aMay_1 ; "May"
    dq offset aJune_1 ; "June"
    dq offset aJuly_1 ; "July"
    dq offset aAugust_1 ; "August"
    dq offset aSeptember_1 ; "September"
    dq offset aOctober_1 ; "October"
    dq offset aNovember_1 ; "November"
    dq offset aDecember_1 ; "December"
qword_140011060 dq 797261756E614Ah ; DATA XREF: sub_140001020+4
```

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And this is 0x797261756E614A.

Soon after, some other function (presumably, one that processes strings) may try to read bytes at this address, expecting a C-string there.

Most likely it is about to crash, because this value doesn’t look like a valid address.

Array overflow protection

If something can go wrong, it will

Murphy’s Law

It’s a bit naïve to expect that every programmer who use your function or library will never pass an argument larger than 11.

There exists the philosophy that says “fail early and fail loudly” or “fail-fast”, which teaches to report problems as early as possible and halt.

One such method in C/C++ is assertions.

We can modify our program to fail if an incorrect value is passed:

Listing 1.241: assert() added

```c
const char* get_month1_checked (int month)
{
    assert (month<12);
    return month1[month];
}
```

The assertion macro checks for valid values at every function start and fails if the expression is false.

Listing 1.242: Optimizing MSVC 2013 x64

```asm
get_month1_checked PROC
    push rbx
    sub rsp, 32
    movsxd rbx, ecx
    cmp ebx, 12
    jl SHORT $LN3@get_month1
    lea rdx, OFFSET FLAT:$SG3143
    lea rcx, OFFSET FLAT:$SG3144
    mov r8d, 29
    call _wassert

$LN3@get_month1:
    lea rcx, OFFSET FLAT:month1
    mov rax, QWORD PTR [rcx+rbx*8]
    add rsp, 32
    pop rbx
    ret 0
get_month1_checked ENDP
```

In fact, assert() is not a function, but macro. It checks for a condition, then passes also the line number and file name to another function which reports this information to the user.

Here we see that both file name and condition are encoded in UTF-16. The line number is also passed (it’s 29).

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This mechanism is probably the same in all compilers. Here is what GCC does:

Listing 1.243: Optimizing GCC 4.9 x64

```
.LC1:
  .string "month.c"
.LC2:
  .string "month<12"

get_month1_checked:
  cmp    edi, 11
  jg     .L6
  movsx  rdi, edi
  mov    rax, QWORD PTR month1[0+rdi*8]
  ret

.L6:
  push   rax
  mov    ecx, OFFSET FLAT:__PRETTY_FUNCTION__.2423
  mov    edx, 29
  mov    esi, OFFSET FLAT:.LC1
  mov    edi, OFFSET FLAT:.LC2
  call   __assert_fail

__PRETTY_FUNCTION__.2423:
  .string "get_month1_checked"
```

So the macro in GCC also passes the function name for convenience.

Nothing is really free, and this is true for the sanitizing checks as well. They make your program slower, especially if the assert() macros used in small time-critical functions. So MSVC, for example, leaves the checks in debug builds, but in release builds they all disappear.

Microsoft Windows NT kernels come in “checked” and “free” builds. The first has validation checks (hence, “checked”), the second one doesn’t (hence, “free” of checks). Of course, “checked” kernel works slower because of all these checks, so it is usually used only in debug sessions.

### Accessing specific character

An array of pointers to strings can be accessed like this:

```c
#include <stdio.h>

const char* month[] =
  { "January", "February", "March", "April",
    "May", "June", "July", "August",
    "September", "October", "November", "December"
  };

int main()
{   // 4th month, 5th character:
    printf ("%c\n", month[3][4]);
}
```

...since `month[3]` expression has a `const char*` type. And then, 5th character is taken from that expression by adding 4 bytes to its address.

By the way, arguments list passed to `main()` function has the same data type:

```c
#include <stdio.h>

int main(int argc, char *argv[])
{   printf ("3rd argument, 2nd character: %c\n", argv[3][1]);
```

---

It’s very important to understand, that, despite similar syntax, this is different from two-dimensional arrays, which we will consider later.

Another important thing to notice: strings to be addressed must be encoded in a system, where each character occupies single byte, like ASCII and extended ASCII. UTF-8 wouldn’t work here.

### 1.20.6 Multidimensional arrays

Internally, a multidimensional array is essentially the same thing as a linear array.

Since the computer memory is linear, it is an one-dimensional array. For convenience, this multi-dimensional array can be easily represented as one-dimensional.

For example, this is how the elements of the 3x4 array are placed in one-dimensional array of 12 cells:

<table>
<thead>
<tr>
<th>Offset in memory</th>
<th>array element</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>[0][0]</td>
</tr>
<tr>
<td>1</td>
<td>[0][1]</td>
</tr>
<tr>
<td>2</td>
<td>[0][2]</td>
</tr>
<tr>
<td>3</td>
<td>[0][3]</td>
</tr>
<tr>
<td>4</td>
<td>[1][0]</td>
</tr>
<tr>
<td>5</td>
<td>[1][1]</td>
</tr>
<tr>
<td>6</td>
<td>[1][2]</td>
</tr>
<tr>
<td>7</td>
<td>[1][3]</td>
</tr>
<tr>
<td>8</td>
<td>[2][0]</td>
</tr>
<tr>
<td>9</td>
<td>[2][1]</td>
</tr>
<tr>
<td>10</td>
<td>[2][2]</td>
</tr>
<tr>
<td>11</td>
<td>[2][3]</td>
</tr>
</tbody>
</table>

Table 1.3: Two-dimensional array represented in memory as one-dimensional

Here is how each cell of 3*4 array are placed in memory:

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>

Table 1.4: Memory addresses of each cell of two-dimensional array

So, in order to calculate the address of the element we need, we first multiply the first index by 4 (array width) and then add the second index. That’s called row-major order, and this method of array and matrix representation is used in at least C/C++ and Python. The term row-major order in plain English language means: “first, write the elements of the first row, then the second row ...and finally the elements of the last row”.

Another method for representation is called column-major order (the array indices are used in reverse order) and it is used at least in Fortran, MATLAB and R. column-major order term in plain English language means: “first, write the elements of the first column, then the second column ...and finally the elements of the last column”.

Which method is better?

In general, in terms of performance and cache memory, the best scheme for data organization is the one, in which the elements are accessed sequentially.

So if your function accesses data per row, row-major order is better, and vice versa.

### Two-dimensional array example

We are going to work with an array of type `char`, which implies that each element requires only one byte in memory.

\(^{143}\)American Standard Code for Information Interchange
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Row filling example

Let's fill the second row with these values 0..3:

Listing 1.244: Row filling example

```c
#include <stdio.h>
char a[3][4];
int main()
{
    int x, y;
    // clear array
    for (x=0; x<3; x++)
        for (y=0; y<4; y++)
            a[x][y]=0;
    // fill second row by 0..3:
    for (y=0; y<4; y++)
        a[1][y]=y;
}
```

All three rows are marked with red. We see that second row now has values 0, 1, 2 and 3:

![OllyDbg: array is filled](image)

Column filling example

Let's fill the third column with values: 0..2:

Listing 1.245: Column filling example

```c
#include <stdio.h>
char a[3][4];
int main()
{
    int x, y;
    // clear array
    for (x=0; x<3; x++)
        for (y=0; y<4; y++)
            a[x][y]=0;
    // fill third column by 0..2:
    for (x=0; x<3; x++)
        a[x][2]=x;
}
```

The three rows are also marked in red here.

We see that in each row, at third position these values are written: 0, 1 and 2.

![OllyDbg: array is filled](image)
Access two-dimensional array as one-dimensional

We can be easily assured that it's possible to access a two-dimensional array as one-dimensional array in at least two ways:

```c
#include <stdio.h>

char a[3][4];

char get_by_coordinates1 (char array[3][4], int a, int b)
{
    return array[a][b];
};

char get_by_coordinates2 (char *array, int a, int b)
{
    // treat input array as one-dimensional
    // 4 is array width here
    return array[a*4+b];
};

char get_by_coordinates3 (char *array, int a, int b)
{
    // treat input array as pointer,
    // calculate address, get value at it
    // 4 is array width here
    return *(array+a*4+b);
};

int main()
{
    a[2][3]=123;
    printf("%d\n", get_by_coordinates1(a, 2, 3));
    printf("%d\n", get_by_coordinates2(a, 2, 3));
    printf("%d\n", get_by_coordinates3(a, 2, 3));
};
```

Compile144 and run it: it shows correct values.

What MSVC 2013 did is fascinating, all three routines are just the same!

Listing 1.246: Optimizing MSVC 2013 x64

```assembly
array$ = 8
a$ = 16
b$ = 24
get_by_coordinates3 PROC
    ; RCX=address of array
    ; RDX=a
    ; R8=b
        movsxd    rax, r8d ; EAX=b
    movsxd    r9, edx ; R9=a
    add       rax, rcx ; RAX=b+address of array
        movzx     eax, BYTE PTR [rax+r9*4] ; AL=load byte at address RAX+R9*4=b+address of array+a*4=address of array+a*4+b
    ret 0
get_by_coordinates3 ENDP
array$ = 8
a$ = 16
b$ = 24
get_by_coordinates2 PROC
    movsxd    rax, r8d
    movsxd    r9, edx
    add       rax, rcx
        movzx     eax, BYTE PTR [rax+r9*4]
get_by_coordinates2 ENDP
```

144This program is to be compiled as C program, not C++, save it to a file with .c extension to compile it using MSVC

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### 1.20. ARRAYS

 GCC also generates equivalent routines, but slightly different:

#### Listing 1.247: Optimizing GCC 4.9 x64

```assembly
; RDI=address of array
; RSI=a
; RDX=b

get_by_coordinates1:
    ; sign-extend input 32-bit int values "a" and "b" to 64-bit ones
    movsx rsi, esi
    movsx rdx, edx
    lea rax, [rdi+rsi*4]  ; RAX=RDI+RSI*4=address of array+a*4
    movzx eax, BYTE PTR [rax+rdx]  ; AL=load byte at address RAX+RDX=address of array+a*4+b
    ret

get_by_coordinates2:
    lea eax, [rdx+rsi*4]  ; RAX=RDX+RSI*4=b+a*4
    cdqe
    movzx eax, BYTE PTR [rdi+rax]  ; AL=load byte at address RDI+RAX=address of array+b+a*4
    ret

get_by_coordinates3:
    sal esi, 2  ; ESI=a<<2=a*4
    ; sign-extend input 32-bit int values "a*4" and "b" to 64-bit ones
    movsx rdx, edx
    movsx rsi, esi
    add rdi, rsi  ; RDI=RDI+RSI=address of array+a*4
    movzx eax, BYTE PTR [rdi+rdx]  ; AL=load byte at address RDI+RDX=address of array+a*4+b
    ret
```

### Three-dimensional array example

It’s the same for multidimensional arrays.

Now we are going to work with an array of type `int`: each element requires 4 bytes in memory.

Let’s see:

#### Listing 1.248: simple example

```c
#include <stdio.h>

int a[10][20][30];

void insert(int x, int y, int z, int value) {
    a[x][y][z]=value;
};
```
We get (MSVC 2010):

```
Listing 1.249: MSVC 2010

DATA SEGMENT
COMM   a:DWORD:01770H
DATA ENDS
PUBLIC insert
_TEXT SEGMENT
_x$ = 8        ; size = 4
_y$ = 12       ; size = 4
_z$ = 16       ; size = 4
_value$ = 20   ; size = 4
_insert PROC
    push ebp
    mov ebp, esp
    mov eax, DWORD PTR _x$[ebp]  ; eax=600*4*x
    imul eax, 2400
    mov ecx, DWORD PTR _y$[ebp]  ; ecx=30*4*y
    imul ecx, 120
    lea edx, DWORD PTR _a[eax+ecx]  ; edx=a + 600*4*x + 30*4*y
    mov eax, DWORD PTR _z$[ebp]  ; eax=y
    mov ecx, DWORD PTR _value$[ebp]
    lea edx, DWORD PTR [eax+ecx*4], ecx  ; *(edx+z*4)=value
    pop ebp
    ret 0
_insert ENDP
_TEXT ENDS

Nothing special. For index calculation, three input arguments are used in the formula \( \text{address} = 600 \cdot 4 \cdot x + 30 \cdot 4 \cdot y + 4z \), to represent the array as multidimensional. Do not forget that the int type is 32-bit (4 bytes), so all coefficients must be multiplied by 4.

```

```
Listing 1.250: GCC 4.4.1

```public insert
insert proc near

x = dword ptr 8
y = dword ptr 0Ch
z = dword ptr 10h
value = dword ptr 14h

push ebp
mov ebp, esp
push ebx
mov ebx, [ebp+x]
mov eax, [ebp+y]
mov ecx, [ebp+z]
lea edx, [eax+eax]  ; edx=y*2
mov eax, edx  ; eax=y*2
shl eax, 4  ; eax=(y*2)<<4 = y*2*16 = y*32
sub eax, edx  ; eax=y*32 - y*2=y*30
imul edx, ebx, 600  ; edx=x*600
add eax, edx  ; eax=eax+edx=y*30 + x*600
lea edx, [eax+ecx]  ; edx=y*30 + x*600 + z
mov eax, [ebp+value]
mov dword ptr ds:a[edx*4], eax  ; *(a+edx*4)=value
pop ebx
pop ebp
retn
insert endp

The GCC compiler does it differently.

For one of the operations in the calculation \((30y)\), GCC produces code without multiplication instructions. This is how it done: \((y + y) \ll 4 - (y + y) = (2y) \ll 4 - 2y = 2 \cdot 16 \cdot y - 2y = 32y - 2y = 30y\). Thus, for the 30y calculation, only one addition operation, one bitwise shift operation and one subtraction operation are used. This works faster.
1.20. ARRAYS

ARM + Non-optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

Listing 1.251: Non-optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

```assembly
_insert
value = -0x10
z = -0xC
y = -8
x = -4

; allocate place in local stack for 4 values of int type
SUB SP, SP, #0x10
MOV R9, 0xFC2 ; a
ADD R9, PC
LDR.W R9, [R9] ; get pointer to array
STR R0, [SP,#0x10+x]
STR R1, [SP,#0x10+y]
STR R2, [SP,#0x10+z]
STR R3, [SP,#0x10+value]
LDR R0, [SP,#0x10+value]
LDR R1, [SP,#0x10+z]
LDR R2, [SP,#0x10+y]
LDR R3, [SP,#0x10+x]
MOV R12, 2400
MUL.W R3, R3, R12
ADD R3, R9
MOV R9, 120
MUL.W R2, R2, R9
ADD R2, R3
LSLS R1, R1, #2 ; R1=R1<<2
ADD R1, R2
STR R0, [R1] ; R1 - address of array element
; deallocate chunk in local stack, allocated for 4 values of int type
ADD SP, SP, #0x10
BX LR
```

Non-optimizing LLVM saves all variables in local stack, which is redundant.
The address of the array element is calculated by the formula we already saw.

ARM + Optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

Listing 1.252: Optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

```assembly
_insert
MOVW R9, #0x10FC
MOV.W R12, #2400
MOVT.W R9, #0
RSB.W R1, R1, R1,LSL#4 ; R1 - y. R1=y<<4 - y = y*16 - y = y*15
ADD R9, PC
LDR.W R9, [R9] ; R0 - pointer to a array
MLA.W R0, R0, R12, R9 ; R0 - x, R12 - 2400, R9 - pointer to a. R0=x*2400 + ptr to a
ADD.W R0, R0, R1,LSL#3 ; R0 = R0+R1<<3 = R0+R1*8 = x*2400 + ptr to a + y*15*8 =
; ptr to a + y*30*4 + x*600*4
STR.W R3, [R0,R2,LSL#2] ; R2 - z, R3 - value. address=R0+z*4 =
; ptr to a + y*30*4 + x*600*4 + z*4
BX LR
```

The tricks for replacing multiplication by shift, addition and subtraction which we already saw are also present here.

Here we also see a new instruction for us: RSB (Reverse Subtract).

It works just as SUB, but it swaps its operands with each other before execution. Why? SUB and RSB are instructions, to the second operand of which shift coefficient may be applied: (LSL#4).

But this coefficient can be applied only to second operand.
That’s fine for commutative operations like addition or multiplication (operands may be swapped there without changing the result).

But subtraction is a non-commutative operation, so RSB exist for these cases.

**MIPS**

My example is tiny, so the GCC compiler decided to put the \( a \) array into the 64KiB area addressable by the Global Pointer.

Listing 1.253: Optimizing GCC 4.4.5 (IDA)

```
insert:
    ; $a0=x
    ; $a1=y
    ; $a2=z
    ; $a3=value
    sll   $v0, $a0, 5
    ; $v0 = $a0<<5 = x*32
    sll   $a0, 3
    ; $a0 = $a0<<3 = x*8
    addu  $a0, $v0
    ; $a0 = $a0+$v0 = x*8+x*32 = x*40
    sll   $v1, $a1, 5
    ; $v1 = $a1<<5 = y*32
    sll   $v0, $a0, 4
    ; $v0 = $a0<<4 = x*40*16 = x*640
    sll   $a1, 1
    ; $a1 = $a1<<1 = y*2
    subu  $a1, $v1, $a1
    ; $a1 = $v1-$a1 = y*32-y*2 = y*30
    subu  $a0, $v0, $a0
    ; $a0 = $v0-$a0 = x*640-x*40 = x*600
    la     $gp, __gnu_local_gp
    addu  $a0, $a1, $a0
    ; $a0 = $a1+$a0 = y*30+x*600
    addu  $a0, $a2
    ; $a0 = $a0+$a2 = y*30+x*600+z
    ; load address of table:
    lw     $v0, (a & 0xFFFF)($gp)
    ; multiply index by 4 to seek array element:
    sll     $a0, 2
    ; sum up multiplied index and table address:
    addu  $a0, $v0, $a0
    ; store value into table and return:
    jr      $ra
    sw      $a3, 0($a0)

.comm a:0x1770
```

More examples

The computer screen is represented as a 2D array, but the video-buffer is a linear 1D array. We talk about it here: 8.13.2 on page 916.

Another example in this book is Minesweeper game: it’s field is also two-dimensional array: 8.3.

### 1.20.7 Pack of strings as a two-dimensional array

Let’s revisit the function that returns the name of a month: listing.1.232.

As you see, at least one memory load operation is needed to prepare a pointer to the string that’s the month’s name.

Is it possible to get rid of this memory load operation?
### 1.20. ARRAYS

In fact yes, if you represent the list of strings as a two-dimensional array:

```c
#include <stdio.h>
#include <assert.h>

const char month2[12][10] =
{
    { 'J','a','n','u','a','r','y', 0, 0, 0 },
    { 'F','e','b','r','u','a','r','y', 0, 0 },
    { 'M','a','r','c','h', 0, 0, 0, 0, 0 },
    { 'A','p','r','i','l', 0, 0, 0, 0, 0 },
    { 'M','a','y', 0, 0, 0, 0, 0, 0, 0 },
    { 'J','u','n','e', 0, 0, 0, 0, 0, 0 },
    { 'J','u','l','y', 0, 0, 0, 0, 0, 0 },
    { 'A','u','g','u','s','t', 0, 0, 0, 0 },
    { 'S','e','p','t','e','m','b','e','r', 0 },
    { 'O','c','t','o','b','e','r', 0, 0, 0 },
    { 'N','o','v','e','m','b','e','r', 0, 0 },
    { 'D','e','c','e','m','b','e','r', 0, 0 }
};

// in 0..11 range
const char* get_month2 (int month)
{
    return &month2[month][0];
}
```

Here is what we’ve get:

Listing 1.254: Optimizing MSVC 2013 x64

```
month2  DB  04aH
DB  061H
DB  06eH
DB  075H
DB  061H
DB  072H
DB  079H
DB  00H
DB  00H
... 

get_month2 PROC
    ; sign-extend input argument and promote to 64-bit value
    movsxd rax, ecx
    lea    rcx, QWORD PTR [rax+rax*4]
    ; RCX=month+month*4=month*5
    lea    rax, OFFSET FLAT:month2
    ; RAX=pointer to table
    lea    rax, QWORD PTR [rax+rcx*2]
    ; RAX=pointer to table + RCX*2:pointer to table + month*5*2=pointer to table + month*10
    ret 0
get_month2 ENDP
```

There are no memory accesses at all.

All this function does is to calculate a point at which the first character of the name of the month is:

```
pointer_to_the_table + month * 10.
```

There are also two LEA instructions, which effectively work as several MUL and MOV instructions.

The width of the array is 10 bytes.

Indeed, the longest string here—“September”—is 9 bytes, and plus the terminating zero is 10 bytes.

The rest of the month names are padded by zero bytes, so they all occupy the same space (10 bytes).

Thus, our function works even faster, because all string start at an address which can be calculated easily. Optimizing GCC 4.9 can do it even shorter:
1.20. ARRAYS

Listing 1.255: Optimizing GCC 4.9 x64

```
    movsx  rdi, edi
    lea   rax, [rdi+rdi*4]
    lea   rax, month2[rax+rax]
    ret
```

LEA is also used here for multiplication by 10.

Non-optimizing compilers do multiplication differently.

Listing 1.256: Non-optimizing GCC 4.9 x64

```
get_month2:
    push rbp
    mov rbp, rsp
    mov DWORD PTR [rbp-4], edi
    mov eax, DWORD PTR [rbp-4]
    movsx rdx, eax
    ; RDX = sign-extended input value
    mov rax, rdx
    ; RAX = month
    sal rax, 2
    ; RAX = month<<2 = month*4
    add rax, rdx
    ; RAX = RAX+RDX = month*4+month = month*5
    add rax, rax
    ; RAX = RAX*2 = month*5*2 = month*10
    add rax, OFFSET FLAT:month2
    ; RAX = month*10 + pointer to the table
    pop rbp
    ret
```

Non-optimizing MSVC just uses IMUL instruction:

Listing 1.257: Non-optimizing MSVC 2013 x64

```
month$ = 8
get_month2 PROC
    mov DWORD PTR [rsp+8], ecx
    movsx  rax, DWORD PTR month$[rsp]
    ; RAX = sign-extended input value into 64-bit one
    imul  rax, rax, 10
    ; RAX = RAX*10
    lea rcx, OFFSET FLAT:month2
    ; RCX = pointer to the table
    add rcx, rax
    ; RCX = RCX+RAX = pointer to the table+month*10
    mov rax, rcx
    ; RAX = pointer to the table+month*10
    mov ecx, 1
    ; RCX = 1
    imul rcx, rcx, 0
    ; RCX = 1*0 = 0
    add rax, rcx
    ; RAX = pointer to the table+month*10 + 0 = pointer to the table+month*10
    ret
get_month2 ENDP
```

But one thing is weird here: why add multiplication by zero and adding zero to the final result?

This looks like a compiler code generator quirk, which wasn’t caught by the compiler’s tests (the resulting code works correctly, after all). We intentionally consider such pieces of code so the reader would understand, that sometimes one shouldn’t puzzle over such compiler artifacts.

32-bit ARM

Optimizing Keil for Thumb mode uses the multiplication instruction MULS:
1.20. ARRAYS

Listing 1.258: Optimizing Keil 6/2013 (Thumb mode)

```
; R0 = month
 MOV r1,#0xa
; R1 = 10
 MULS r0,r1,r0
; R0 = R1*R0 = 10*month
 LDR r1,[L0.68]
; R1 = pointer to the table
 ADDS r0,r0,r1
; R0 = R0+R1 = 10*month + pointer to the table
 BX lr
```

Listing 1.259: Optimizing Keil 6/2013 (ARM mode)

```
; R0 = month
 LDR r1,[L0.104]
; R1 = pointer to the table
 ADD r0,r0,r0,LSL #2
; R0 = R0+R0<<2 = R0+R0*4 = month*5
 ADD r0,r1,r0,LSL #1
; R0 = R1+R0<<2 = pointer to the table + month*5*2 = pointer to the table + month*10
 BX lr
```

ARM64

Listing 1.260: Optimizing GCC 4.9 ARM64

```
; W0 = month
 sxtw x0, w0
; X0 = sign-extended input value
 adrp x1, .LANCHOR1
 add x1, x1, :lo12:.LANCHOR1
; X1 = pointer to the table
 add x0, x0, x0, lsl 2
; X0 = X0+X0<<2 = X0+X0*4 = X0*5
 add x0, x1, x0, lsl 1
; X0 = X1+X0<<1 = X1+X0*2 = pointer to the table + X0*10
ret
```

SXTW is used for sign-extension and promoting input 32-bit value into a 64-bit one and storing it in X0. ADRP/ADD pair is used for loading the address of the table.

The ADD instructions also has a LSL suffix, which helps with multiplications.

MIPS

Listing 1.261: Optimizing GCC 4.4.5 (IDA)

```
.globl get_month2
get_month2:
; $a0=month
   sll $v0, $a0, 3
; $v0 = $a0<<3 = month*8
   sll $a0, 1
; $a0 = $a0<<1 = month*2
   addu $a0, $v0
; $a0 = month*2+month*8 = month*10
; load address of the table:
   la $v0, month2
; sum up table address and index we calculated and return:
   jr $ra
   addu $v0, $v0, $a0
month2:    .ascii "January"<0>
```
1.21. **By the way**

An array is a pack of values in memory located adjacently.

It’s true for any element type, including structures.

Access to a specific array element is just a calculation of its address.

1.21.1 **Exercises**

- [http://challenges.re/62](http://challenges.re/62)
- [http://challenges.re/63](http://challenges.re/63)
- [http://challenges.re/64](http://challenges.re/64)
- [http://challenges.re/65](http://challenges.re/65)
- [http://challenges.re/66](http://challenges.re/66)

1.22 **Manipulating specific bit(s)**

A lot of functions define their input arguments as flags in bit fields.

Of course, they could be substituted by a set of `bool`-typed variables, but it is not frugally.
1.22. MANIPULATING SPECIFIC BIT(S)

1.22.1 Specific bit checking

x86

Win32 API example:

```c
HANDLE fh;
fh=CreateFile ("file", GENERIC_WRITE | GENERIC_READ, FILE_SHARE_READ, NULL, OPEN_ALWAYS, FILE_ATTRIBUTE_NORMAL, NULL);
```

We get (MSVC 2010):

```c
push 0
push 128 ; 00000080H
push 4
push 0
push 1
push -1073741824 ; c0000000H
push OFFSET $SG78813
call DWORD PTR __imp__CreateFileA@28
mov DWORD PTR _fh$[ebp], eax
```

Let's take a look in WinNT.h:

```c
#define GENERIC_READ (0x80000000L)
#define GENERIC_WRITE (0x40000000L)
#define GENERIC_EXECUTE (0x20000000L)
#define GENERIC_ALL (0x10000000L)
```

Everything is clear, GENERIC_READ | GENERIC_WRITE = 0x80000000 | 0x40000000 = 0xC0000000, and that value is used as the second argument for the CreateFile() function.

How would CreateFile() check these flags?

If we look in KERNEL32.DLL in Windows XP SP3 x86, we'll find this fragment of code in CreateFileW:

```c
.text:7C83D429 test byte ptr [ebp+dwDesiredAccess+3], 40h
.text:7C83D42D mov [ebp+var_8], 1
.text:7C83D434 jz short loc_7C83D417
.text:7C83D436 jmp loc_7C810817
```

Here we see the TEST instruction, however it doesn't take the whole second argument, but only the most significant byte (ebp+dwDesiredAccess+3) and checks it for flag 0x40 (which implies the GENERIC_WRITE flag here).

TEST is basically the same instruction as AND, but without saving the result (recall the fact CMP is merely the same as SUB, but without saving the result (1.9.4 on page 86)).

The logic of this code fragment is as follows:

```c
if ((dwDesiredAccess&0x40000000) == 0) goto loc_7C83D417
```

If AND instruction leaves this bit, the ZF flag is to be cleared and the JZ conditional jump is not to be triggered. The conditional jump is triggered only if the 0x40000000 bit is absent in dwDesiredAccess variable —then the result of AND is 0, ZF is to be set and the conditional jump is to be triggered.

Let's try GCC 4.4.1 and Linux:

```c
#include <stdio.h>
#include <fcntl.h>

void main()
{
```

---

1.22. MANIPULATING SPECIFIC BIT(S)

```c
int handle;
handle=open ("file", O_RDWR | O_CREAT);
```

We get:

Listing 1.265: GCC 4.4.1

```assembly
public main
main proc near
var_20 = dword ptr -20h
var_1C = dword ptr -1Ch
var_4 = dword ptr -4
push ebp
mov ebp, esp
and esp, 0FFFFFFF0h
sub esp, 20h
mov [esp+20h+var_1C], 42h
mov [esp+20h+var_20], offset aFile ; "file"
call _open
mov [esp+20h+var_4], eax
leave
retn
main endp
```

If we take a look in the open() function in the libc.so.6 library, it is only a syscall:

Listing 1.266: open() (libc.so.6)

```assembly
.text:000BE69B mov edx, [esp+4+mode] ; mode
.text:000BE69F mov ecx, [esp+4+flags] ; flags
.text:000BE6A3 mov ebx, [esp+4+filename] ; filename
.text:000BE6A7 mov eax, 5
.text:000BE6AC int 80h ; LINUX - sys_open
```

So, the bit fields for open() are apparently checked somewhere in the Linux kernel.

Of course, it is easy to download both Glibc and the Linux kernel source code, but we are interested in understanding the matter without it.

So, as of Linux 2.6, when the sys_open syscall is called, control eventually passes to do_sys_open, and from there—to the do_filp_open() function (it’s located in the kernel source tree in fs/namei.c).

N.B. Aside from passing arguments via the stack, there is also a method of passing some of them via registers. This is also calledfastcall (6.1.3 on page 735). This works faster since CPU does not need to access the stack in memory to read argument values. GCC has the option regparm\(^{146}\), through which it’s possible to set the number of arguments that can be passed via registers.

The Linux 2.6 kernel is compiled with -mregparm=3 option\(^{147}\)\(^{148}\).

What this means to us is that the first 3 arguments are to be passed via registers EAX, EDX and ECX, and the rest via the stack. Of course, if the number of arguments is less than 3, only part of registers set is to be used.

So, let’s download Linux Kernel 2.6.31, compile it in Ubuntu: make vmlinux, open it in IDA, and find the do_filp_open() function. At the beginning, we see (the comments are mine):

Listing 1.267: do_filp_open() (linux kernel 2.6.31)

```assembly
do_filp_open proc near
...
push ebp
mov ebp, esp
push edi
push esi
push ebx
```

\(^{146}\)ohse.de/uwe/articles/gcc-attributes.html#func-regparm

\(^{147}\)kernelnewbies.org/Linux_2_6_20#head-042c62f290834eb1fe0a1942bbf5bb9a4accbc8f

\(^{148}\)See also arch/x86/include/asm/calling.h file in kernel tree
GCC saves the values of the first 3 arguments in the local stack. If that wasn’t done, the compiler would not touch these registers, and that would be too tight environment for the compiler’s register allocator.

Let’s find this fragment of code:

Listing 1.268: do_filp_open() (linux kernel 2.6.31)

```c
loc_C01EF6B4: ; CODE XREF: do_filp_open+4F
    test bl, 40h ; O_CREAT
    jnz loc_C01EF810
    mov edi, ebx
    shr edi, 11h
    xor edi, 1
    and edi, 1
    test ebx, 10000h
    jz short loc_C01EF6D3
    or edi, 2
```

0x40—is what the 0_CREAT macro equals to. open_flag gets checked for the presence of the 0x40 bit, and if this bit is 1, the next JNZ instruction is triggered.

**ARM**

The 0_CREAT bit is checked differently in Linux kernel 3.8.0.

Listing 1.269: linux kernel 3.8.0

```c
struct file *do_filp_open(int dfd, struct filename *pathname,
    const struct open_flags *op)
{
    ... 
    filp = path_openat(dfd, pathname, &nd, op, flags | LOOKUP_RCU);
    ... 
}

static struct file *path_openat(int dfd, struct filename *pathname,
    struct nameidata *nd, const struct open_flags *op, int flags)
{
    ... 
    error = do_last(nd, &path, file, op, &opened, pathname);
    ... 
}

static int do_last(struct nameidata *nd, struct path *path,
    struct file *file, const struct open_flags *op,
    int *opened, struct filename *name)
{
    ... 
    if (!(open_flag & O_CREAT)) {
        ... 
        error = lookup_fast(nd, path, &inode);
        ... 
    } else {
        ... 
        error = complete_walk(nd);
        ... 
    }
}
Here is how the kernel compiled for ARM mode looks in IDA:

Listing 1.270: do_last() from vmlinux (IDA)

```
... .text:C0169EA8 MOV R9, R3 ; R3 - (4th argument) open_flag
... .text:C0169ED4 LDR R6, [R9] ; R6 - open_flag
... .text:C0169F68 TST R6, #0x40 ; jumptable C0169F00 default case
.text:C0169F6C BNE loc_C016A128
.text:C0169F70 LDR R2, [R4,#0x10]
.text:C0169F74 ADD R12, R4, #8
.text:C0169F78 LDR R3, [R4,#0xC]
.text:C0169F7C MOV R0, R4
.text:C0169F80 STR R12, [R11,#var_50]
.text:C0169F84 LDRB R3, [R2,R3]
.text:C0169F88 MOV R2, R8
.text:C0169F8C CMP R3, #0
.text:C0169F90 ORRNE R1, R1, #3
.text:C0169F94 STRNE R1, [R4,#0x24]
.text:C0169F98 ANDS R3, R6, #0x200000
.text:C0169F9C MOV R1, R12
.text:C0169FA0 LDRNE R3, [R4,#0x24]
.text:C0169FA4 ANDNE R3, R3, #1
.text:C0169FA8 EORNE R3, R3, #1
.text:C0169FAC STR R3, [R11,#var_54]
.text:C0169FB0 SUB R3, R11, #-var_38
.text:C0169FB4 BL lookup_fast
...
.text:C016A128 loc_C016A128 ; CODE XREF: do_last.isra.14+DC
.text:C016A128 MOV R0, R4
.text:C016A12C BL complete_walk
...
```

TST is analogous to the TEST instruction in x86. We can “spot” visually this code fragment by the fact the lookup_fast() is to be executed in one case and complete_walk() in the other. This corresponds to the source code of the do_last() function. The O_CREAT macro equals to 0x40 here too.

### 1.22.2 Setting and clearing specific bits

For example:

```c
#include <stdio.h>

#define IS_SET(flag, bit) ((flag) & (bit))
#define SET_BIT(var, bit) ((var) |= (bit))
#define REMOVE_BIT(var, bit) ((var) &= ~(bit))

int f(int a)
{
    int rt=a;

    SET_BIT (rt, 0x4000);
    REMOVE_BIT (rt, 0x200);

    return rt;
};

int main()
{
    f(0x12340678);
};
```
### Non-optimizing MSVC

We get (MSVC 2010):

```
Listing 1.271: MSVC 2010

_rts$ = -4 ; size = 4
_a$ = 8 ; size = 4
_f PROC
    push ebp
    mov ebp, esp
    push ecx
    mov eax, DWORD PTR _a$[ebp]
    mov DWORD PTR _rts$[ebp], eax
    mov ecx, DWORD PTR _rts$[ebp]
    or ecx, 16384 ; 00004000H
    mov DWORD PTR _rts$[ebp], ecx
    mov edx, DWORD PTR _rts$[ebp]
    and edx, -513 ; ffffdffH
    mov DWORD PTR _rts$[ebp], edx
    mov eax, DWORD PTR _rts$[ebp]
    mov esp, ebp
    pop ebp
_f ENDP
```

The OR instruction sets one bit into a register while ignoring other 1 bits.

AND resets one bit. It can be said that AND just copies all bits except one. Indeed, in the second AND operand only the bits that need to be saved are set, just the one do not want to copy is not (which is 0 in the bitmask). It is the easier way to memorize the logic.
Let's try this example in OllyDbg.

First, let's see the binary form of the constants we are going to use:
0x200 (0b00000000000000000000000000100000000) (i.e., the 10th bit (counting from 1st)).
Inverted 0x200 is 0xFFFFFDFF (0b1111111111111111111111111011111111).
0x4000 (0b00000000000000000000000000000000) (i.e., the 15th bit).
The input value is: 0x12340678 (0b10010001101000000011001111000). We see how it's loaded:

Figure 1.94: OllyDbg: value is loaded into ECX
1.22. MANIPULATING SPECIFIC BIT(S)

OR got executed:

Figure 1.95: OllyDbg: OR executed

15th bit is set: 0x12344678 (0b1001000110100010001100111000).
1.22. MANIPULATING SPECIFIC BIT(S)

The value is reloaded again (because the compiler is not in optimizing mode):

![Image showing CPU registers and memory dump]

Figure 1.96: OllyDbg: value has been reloaded into EDX
AND got executed:

The 10th bit has been cleared (or, in other words, all bits were left except the 10th) and the final value now is 0x1234478 (0b100100011010001000111100).

**Optimizing MSVC**

If we compile it in MSVC with optimization turned on (`/Ox`), the code is even shorter:

```assembly
Listing 1.272: Optimizing MSVC

```

**Non-optimizing GCC**

Let's try GCC 4.4.1 without optimization:

```assembly
Listing 1.273: Non-optimizing GCC

```

1.22. MANIPULATING SPECIFIC BIT(S)

| leave  
|       
| retn   
| f      
| endp   |

There is a redundant code present, however, it is shorter than the MSVC version without optimization. Now let's try GCC with optimization turned on `-O3`:

**Optimizing GCC**

```assembly
public f
f proc near
arg_0 = dword ptr 8
push  ebp
mov   ebp, esp
mov   eax, [ebp+arg_0]
op    ebp
or    ah, 40h
and   ah, 0FDh
retn  
f endp
```

That’s shorter. It is worth noting the compiler works with the EAX register part via the AH register—that is the EAX register part from the 8th to the 15th bits included.

<table>
<thead>
<tr>
<th>Byte number:</th>
</tr>
</thead>
<tbody>
<tr>
<td>7th</td>
</tr>
<tr>
<td>RAX&lt;sub&gt;x64&lt;/sub&gt;</td>
</tr>
<tr>
<td>EAX</td>
</tr>
<tr>
<td>AX</td>
</tr>
<tr>
<td>AH</td>
</tr>
</tbody>
</table>

N.B. The 16-bit CPU 8086 accumulator was named AX and consisted of two 8-bit halves—AL (lower byte) and AH (higher byte). In 80386 almost all registers were extended to 32-bit, the accumulator was named EAX, but for the sake of compatibility, its older parts may be still accessed as AX/AH/AL.

Since all x86 CPUs are successors of the 16-bit 8086 CPU, these older 16-bit opcodes are shorter than the newer 32-bit ones. That's why the `or ah, 40h` instruction occupies only 3 bytes. It would be more logical way to emit here `or eax, 04000h` but that is 5 bytes, or even 6 (in case the register in the first operand is not EAX).

**Optimizing GCC and regparm**

It would be even shorter if to turn on the `-O3` optimization flag and also set `regparm=3`.

```assembly
public f
f proc near
push  ebp
or    ah, 40h
mov   ebp, esp
and   ah, 0FDh
pop   ebp
retn  
f endp
```

Indeed, the first argument is already loaded in EAX, so it is possible to work with it in-place. It is worth noting that both the function prologue (`push ebp / mov ebp,esp`) and epilogue (`pop ebp`) can easily be omitted here, but GCC probably is not good enough to do such code size optimizations. However, such short functions are better to be *inlined functions* (3.11 on page 507).
1.22. MANIPULATING SPECIFIC BIT(S)

**ARM + Optimizing Keil 6/2013 (ARM mode)**

Listing 1.276: Optimizing Keil 6/2013 (ARM mode)

| 02 0C C0 E3 | BIC    | R0, R0, #0x200 |
| 01 09 80 E3 | ORR    | R0, R0, #0x4000 |
| 1E FF 2F E1 | BX     | LR             |

BIC (Bitwise bit Clear) is an instruction for clearing specific bits. This is just like the AND instruction, but with inverted operand. I.e., it’s analogous to a NOT + AND instruction pair.

ORR is “logical or”, analogous to OR in x86.

So far it’s easy.

**ARM + Optimizing Keil 6/2013 (Thumb mode)**

Listing 1.277: Optimizing Keil 6/2013 (Thumb mode)

| 01 21 89 03 | MOVS   | R1, 0x4000 |
| 08 43       | ORRS   | R0, R1    |
| 49 11       | ASRS   | R1, R1, #5 ; generate 0x200 and place to R1 |
| 88 43       | BICS   | R0, R1    |
| 70 47       | BX     | LR        |

Seems like Keil decided that the code in Thumb mode, making 0x200 from 0x4000, is more compact than the code for writing 0x200 to an arbitrary register.

So that is why, with the help of ASRS (arithmetic shift right), this value is calculated as 0x4000 \(\gg 5\).

**ARM + Optimizing Xcode 4.6.3 (LLVM) (ARM mode)**

Listing 1.278: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

| 42 0C C0 E3 | BIC    | R0, R0, #0x4200 |
| 01 09 80 E3 | ORR    | R0, R0, #0x4000 |
| 1E FF 2F E1 | BX     | LR             |

The code that was generated by LLVM, in source code form could be something like this:

```c
REMOVE_BIT (rt, 0x4200);
SET_BIT (rt, 0x4000);
```

And it does exactly what we need. But why 0x4200? Perhaps that an artifact from LLVM’s optimizer\(^\text{149}\). Probably a compiler’s optimizer error, but the generated code works correctly anyway.

You can read more about compiler anomalies here (11.4 on page 1000).

Optimizing Xcode 4.6.3 (LLVM) for Thumb mode generates the same code.

**ARM: more about the BIC instruction**

Let’s rework the example slightly:

```c
int f(int a)
{
    int rt=a;
    REMOVE_BIT (rt, 0x1234);
    return rt;
}
```

Then the optimizing Keil 5.03 in ARM mode does:

\(^{149}\)It was LLVM build 2410.2.00 bundled with Apple Xcode 4.6.3
There are two BIC instructions, i.e., bits 0x1234 are cleared in two passes. This is because it’s not possible to encode 0x1234 in a BIC instruction, but it’s possible to encode 0x1000 and 0x234.

**ARM64: Optimizing GCC (Linaro) 4.9**

Optimizing GCC compiling for ARM64 can use the AND instruction instead of BIC:

<table>
<thead>
<tr>
<th>Listing 1.279: Optimizing GCC (Linaro) 4.9</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>f:</code></td>
</tr>
<tr>
<td>and w0, w0, -513 ; 0xFFFFFFFFFFFFFDFF</td>
</tr>
<tr>
<td>orr w0, w0, 16384 ; 0x4000</td>
</tr>
<tr>
<td>ret</td>
</tr>
</tbody>
</table>

**ARM64: Non-optimizing GCC (Linaro) 4.9**

Non-optimizing GCC generates more redundant code, but works just like optimized:

<table>
<thead>
<tr>
<th>Listing 1.280: Non-optimizing GCC (Linaro) 4.9</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>f:</code></td>
</tr>
<tr>
<td>sub sp, sp, #32</td>
</tr>
<tr>
<td>str w0, [sp,12]</td>
</tr>
<tr>
<td>ldr w0, [sp,12]</td>
</tr>
<tr>
<td>str w0, [sp,28]</td>
</tr>
<tr>
<td>ldr w0, [sp,28]</td>
</tr>
<tr>
<td>orr w0, w0, 16384 ; 0x4000</td>
</tr>
<tr>
<td>str w0, [sp,28]</td>
</tr>
<tr>
<td>ldr w0, [sp,28]</td>
</tr>
<tr>
<td>and w0, w0, -513 ; 0xFFFFFFFFFFFFFDFF</td>
</tr>
<tr>
<td>str w0, [sp,28]</td>
</tr>
<tr>
<td>ldr w0, [sp,28]</td>
</tr>
<tr>
<td>add sp, sp, 32</td>
</tr>
<tr>
<td>ret</td>
</tr>
</tbody>
</table>

**MIPS**

<table>
<thead>
<tr>
<th>Listing 1.281: Optimizing GCC 4.4.5 (IDA)</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>f:</code></td>
</tr>
<tr>
<td>; $a0=a</td>
</tr>
<tr>
<td>ori $a0, 0x4000</td>
</tr>
<tr>
<td>; $a0=a</td>
</tr>
<tr>
<td>li $v0, 0xFFFFFFFFDFF</td>
</tr>
<tr>
<td>jr $ra</td>
</tr>
<tr>
<td>and $v0, $a0, $v0</td>
</tr>
</tbody>
</table>
| ; at finish: $v0 = $a0|$v0 = a|0x4000 & 0xFFFFFFFFDFF

ORI is, of course, the OR operation. “I” in the instruction name means that the value is embedded in the machine code.

But after that we have AND. There is no way to use ANDI because it’s not possible to embed the 0xFFFFFFFFDFF number in a single instruction, so the compiler has to load 0xFFFFFFFFDFF into register $V0 first and then generates AND which takes all its values from registers.
1.22. MANIPULATING SPECIFIC BIT(S)

1.22.3 Shifts

Bit shifts in C/C++ are implemented using « and » operators. The x86 ISA has the SHL (SHift Left) and SHR (SHift Right) instructions for this. Shift instructions are often used in division and multiplications by powers of two: $2^n$ (e.g., 1, 2, 4, 8, etc.): 1.18.1 on page 213, 1.18.2 on page 217.

Shifting operations are also so important because they are often used for specific bit isolation or for constructing a value of several scattered bits.

1.22.4 Setting and clearing specific bits: FPU example

Here is how bits are located in the float type in IEEE 754 form:

```
0222330 31
  S exponent mantissa or fraction
          (S—sign)
```

The sign of number is in the MSB\textsuperscript{150}. Will it be possible to change the sign of a floating point number without any FPU instructions?

```c
#include <stdio.h>

float my_abs (float i)
{
    unsigned int tmp=(*(unsigned int*)&i) & 0x7FFFFFFF;
    return *(float*)&tmp;
};

float set_sign (float i)
{
    unsigned int tmp=(*(unsigned int*)&i) | 0x80000000;
    return *(float*)&tmp;
};

float negate (float i)
{
    unsigned int tmp=(*(unsigned int*)&i) ^ 0x80000000;
    return *(float*)&tmp;
};

int main()
{
    printf ("my_abs():\n");
    printf ("%f\n", my_abs (123.456));
    printf ("%f\n", my_abs (-456.123));
    printf ("set_sign():\n");
    printf ("%f\n", set_sign (123.456));
    printf ("%f\n", set_sign (-456.123));
    printf ("negate():\n");
    printf ("%f\n", negate (123.456));
    printf ("%f\n", negate (-456.123));
};
```

We need this trickery in C/C++ to copy to/from float value without actual conversion. So there are three functions: my_abs() resets MSB; set_sign() sets MSB and negate() flips it.

XOR can be used to flip a bit: 2.6 on page 461.

\textbf{x86}

The code is pretty straightforward:

\textsuperscript{150}Most Significant Bit
An input value of type float is taken from the stack, but treated as an integer value.

AND and OR reset and set the desired bit. XOR flips it.

Finally, the modified value is loaded into ST0, because floating-point numbers are returned in this register.

Now let’s try optimizing MSVC 2012 for x64:

The input value is passed in XMM0, then it is copied into the local stack and then we see some instructions that are new to us: BTR, BTS, BTC.
1.22. MANIPULATING SPECIFIC BIT(S)

These instructions are used for resetting (BTR), setting (BTS) and inverting (or complementing: BTC) specific bits. The 31st bit is MSB, counting from 0.

Finally, the result is copied into XMM0, because floating point values are returned through XMM0 in Win64 environment.

MIPS

GCC 4.4.5 for MIPS does mostly the same:

Listing 1.284: Optimizing GCC 4.4.5 (IDA)

```assembly
my_abs:
; move from coprocessor 1:
  mfc1 $v1, $f12
  li $v0, 0x7FFFFFFF
; $v0=0x7FFFFFFF
; do AND:
  and $v0, $v1
; move to coprocessor 1:
  mtc1 $v0, $f0
; return
  jr $ra
  or $at, $zero ; branch delay slot

set_sign:
; move from coprocessor 1:
  mfc1 $v1, $f12
  lui $v1, 0x8000
; $v1=0x80000000
; do OR:
  or $v0, $v1, $v0
; move to coprocessor 1:
  mtc1 $v0, $f0
; return
  jr $ra
  or $at, $zero ; branch delay slot

negate:
; move from coprocessor 1:
  mfc1 $v1, $f12
  lui $v1, 0x8000
; $v1=0x80000000
; do XOR:
  xor $v0, $v1, $v0
; move to coprocessor 1:
  mtc1 $v0, $f0
; return
  jr $ra
  or $at, $zero ; branch delay slot
```

One single LUI instruction is used to load 0x80000000 into a register, because LUI is clearing the low 16 bits and these are zeros in the constant, so one LUI without subsequent ORI is enough.

ARM

Optimizing Keil 6/2013 (ARM mode)

Listing 1.285: Optimizing Keil 6/2013 (ARM mode)

```assembly
my_abs PROC
; clear bit:
  BIC r0, r0, #0x80000000
  BX lr
ENDP

set_sign PROC
```
1.22. MANIPULATING SPECIFIC BIT(S)

; do OR:
    ORR    r0,r0,#0x80000000
    BX     lr
    ENDP

negate PROC
; do XOR:
    EOR    r0,r0,#0x80000000
    BX     lr
    ENDP

So far so good.

ARM has the BIC instruction, which explicitly clears specific bit(s). EOR is the ARM instruction name for XOR ("Exclusive OR").

Optimizing Keil 6/2013 (Thumb mode)

my_abs PROC
    LSLS   r0,r0,#1
    ; r0=i<<1
    LSRS   r0,r0,#1
    ; r0=(i<<1)>>1
    BX     lr
    ENDP

set_sign PROC
    MOVS   r1,#1
    ; r1=1
    LSLS   r1,r1,#31
    ; r1=1<<31=0x80000000
    ORRS   r0,r0,r1
    ; r0=r0 | 0x80000000
    BX     lr
    ENDP

negate PROC
    MOVS   r1,#1
    ; r1=1
    LSLS   r1,r1,#31
    ; r1=1<<31=0x80000000
    EORS   r0,r0,r1
    ; r0=r0 ^ 0x80000000
    BX     lr
    ENDP

Thumb mode in ARM offers 16-bit instructions and not much data can be encoded in them, so here a MOVSLSLS instruction pair is used for forming the 0x80000000 constant. It works like this: \( 1 \ll 31 = 0x80000000 \).

The code of my_abs is weird and it effectively works like this expression: \((i \ll 1) \gg 1\). This statement looks meaningless. But nevertheless, when input \(i \ll 1\) is executed, the MSB (sign bit) is just dropped. When the subsequent result \(\gg 1\) statement is executed, all bits are now in their own places, but MSB is zero, because all “new” bits appearing from the shift operations are always zeros. That is how the LSLS/LSRS instruction pair clears MSB.

Optimizing GCC 4.6.3 (Raspberry Pi, ARM mode)

my_abs
; copy from S0 to R2:
    FMRS   R2, S0
; clear bit:
1.22. MANIPULATING SPECIFIC BIT(S)

```assembly
BIC    R3, R2, #0x80000000
; copy from R3 to S0:
FMSR   S0, R3
BX     LR

set_sign
; copy from S0 to R2:
FMSR   R2, S0
; do OR:
ORR    R3, R2, #0x80000000
; copy from R3 to S0:
FMSR   S0, R3
BX     LR

negate
; copy from S0 to R2:
FMSR   R2, S0
; do ADD:
ADD    R3, R2, #0x80000000
; copy from R3 to S0:
FMSR   S0, R3
BX     LR
```

Let’s run Raspberry Pi Linux in QEMU and it emulates an ARM FPU, so S-registers are used here for floating point numbers instead of R-registers.

The FMSR instruction copies data from GPR to the FPU and back.

`my_abs()` and `set_sign()` looks as expected, but `negate()`? Why is there `ADD` instead of `XOR`?

It’s hard to believe, but the instruction `ADD` register, 0x80000000 works just like `XOR` register, 0x80000000. First of all, what’s our goal? The goal is to flip the MSB, so let’s forget about the XOR operation. From school-level mathematics we may recall that adding values like 1000 to other values never affects the last 3 digits. For example: \(1234567 + 10000 = 1244567\) (last 4 digits are never affected).

But here we operate in binary base and 0x80000000 is 0b10000000000000000000000000000000, i.e., only the highest bit is set.

Adding 0x80000000 to any value never affects the lowest 31 bits, but affects only the MSB. Adding 1 to 0 is resulting in 1.

Adding 1 to 1 is resulting in 0b10 in binary form, but the 32th bit (counting from zero) gets dropped, because our registers are 32 bit wide, so the result is 0. That’s why XOR can be replaced by ADD here.

It’s hard to say why GCC decided to do this, but it works correctly.

### 1.22.5 Counting bits set to 1

Here is a simple example of a function that calculates the number of bits set in the input value. This operation is also called “population count”\(^{151}\).

```c
#include <stdio.h>
#define IS_SET(flag, bit)   ((flag) & (bit))

int f(unsigned int a)
{
  int i;
  int rt=0;
  for (i=0; i<32; i++)
    if (IS_SET (a, 1<<i))
      rt++;
  return rt;
}
```

\(^{151}\) modern x86 CPUs (supporting SSE4) even have a POPCNT instruction for it
1.22. MANIPULATING SPECIFIC BIT(S)

```c
int main()
{
    f(0x12345678); // test
};
```

In this loop, the iteration count value $i$ is counting from 0 to 31, so the $1 \ll i$ statement is counting from 1 to 0x80000000. Describing this operation in natural language, we would say shift 1 by n bits left. In other words, $1 \ll i$ statement consequently produces all possible bit positions in a 32-bit number. The freed bit at right is always cleared.

Here is a table of all possible $1 \ll i$ for $i = 0 \ldots 31$:

<table>
<thead>
<tr>
<th>C/C++ expression</th>
<th>Power of two</th>
<th>Decimal form</th>
<th>Hexadecimal form</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \ll 0$</td>
<td>$2^0$</td>
<td>1</td>
<td>0x00000001</td>
</tr>
<tr>
<td>$1 \ll 1$</td>
<td>$2^1$</td>
<td>2</td>
<td>0x00000002</td>
</tr>
<tr>
<td>$1 \ll 2$</td>
<td>$2^2$</td>
<td>4</td>
<td>0x00000004</td>
</tr>
<tr>
<td>$1 \ll 3$</td>
<td>$2^3$</td>
<td>8</td>
<td>0x00000008</td>
</tr>
<tr>
<td>$1 \ll 4$</td>
<td>$2^4$</td>
<td>16</td>
<td>0x00000010</td>
</tr>
<tr>
<td>$1 \ll 5$</td>
<td>$2^5$</td>
<td>32</td>
<td>0x00000020</td>
</tr>
<tr>
<td>$1 \ll 6$</td>
<td>$2^6$</td>
<td>64</td>
<td>0x00000040</td>
</tr>
<tr>
<td>$1 \ll 7$</td>
<td>$2^7$</td>
<td>128</td>
<td>0x00000100</td>
</tr>
<tr>
<td>$1 \ll 8$</td>
<td>$2^8$</td>
<td>256</td>
<td>0x00000200</td>
</tr>
<tr>
<td>$1 \ll 9$</td>
<td>$2^9$</td>
<td>512</td>
<td>0x00000400</td>
</tr>
<tr>
<td>$1 \ll 10$</td>
<td>$2^{10}$</td>
<td>1024</td>
<td>0x00000800</td>
</tr>
<tr>
<td>$1 \ll 11$</td>
<td>$2^{11}$</td>
<td>2048</td>
<td>0x00001000</td>
</tr>
<tr>
<td>$1 \ll 12$</td>
<td>$2^{12}$</td>
<td>4096</td>
<td>0x00002000</td>
</tr>
<tr>
<td>$1 \ll 13$</td>
<td>$2^{13}$</td>
<td>8192</td>
<td>0x00004000</td>
</tr>
<tr>
<td>$1 \ll 14$</td>
<td>$2^{14}$</td>
<td>16384</td>
<td>0x00008000</td>
</tr>
<tr>
<td>$1 \ll 15$</td>
<td>$2^{15}$</td>
<td>32768</td>
<td>0x00010000</td>
</tr>
<tr>
<td>$1 \ll 16$</td>
<td>$2^{16}$</td>
<td>65536</td>
<td>0x00020000</td>
</tr>
<tr>
<td>$1 \ll 17$</td>
<td>$2^{17}$</td>
<td>131072</td>
<td>0x00040000</td>
</tr>
<tr>
<td>$1 \ll 18$</td>
<td>$2^{18}$</td>
<td>262144</td>
<td>0x00080000</td>
</tr>
<tr>
<td>$1 \ll 19$</td>
<td>$2^{19}$</td>
<td>524288</td>
<td>0x00100000</td>
</tr>
<tr>
<td>$1 \ll 20$</td>
<td>$2^{20}$</td>
<td>1048576</td>
<td>0x00200000</td>
</tr>
<tr>
<td>$1 \ll 21$</td>
<td>$2^{21}$</td>
<td>2097152</td>
<td>0x00400000</td>
</tr>
<tr>
<td>$1 \ll 22$</td>
<td>$2^{22}$</td>
<td>4194304</td>
<td>0x00800000</td>
</tr>
<tr>
<td>$1 \ll 23$</td>
<td>$2^{23}$</td>
<td>8388608</td>
<td>0x01000000</td>
</tr>
<tr>
<td>$1 \ll 24$</td>
<td>$2^{24}$</td>
<td>16777216</td>
<td>0x02000000</td>
</tr>
<tr>
<td>$1 \ll 25$</td>
<td>$2^{25}$</td>
<td>33554432</td>
<td>0x04000000</td>
</tr>
<tr>
<td>$1 \ll 26$</td>
<td>$2^{26}$</td>
<td>67108864</td>
<td>0x08000000</td>
</tr>
<tr>
<td>$1 \ll 27$</td>
<td>$2^{27}$</td>
<td>134217728</td>
<td>0x10000000</td>
</tr>
<tr>
<td>$1 \ll 28$</td>
<td>$2^{28}$</td>
<td>268435456</td>
<td>0x20000000</td>
</tr>
<tr>
<td>$1 \ll 29$</td>
<td>$2^{29}$</td>
<td>536870912</td>
<td>0x40000000</td>
</tr>
<tr>
<td>$1 \ll 30$</td>
<td>$2^{30}$</td>
<td>1073741824</td>
<td>0x80000000</td>
</tr>
<tr>
<td>$1 \ll 31$</td>
<td>$2^{31}$</td>
<td>2147483648</td>
<td>0x100000000</td>
</tr>
</tbody>
</table>

These constant numbers (bit masks) very often appear in code and a practicing reverse engineer must be able to spot them quickly.

Decimal numbers below 63356 and hexadecimal ones are very easy to memorize. While decimal numbers above 65536 are, probably, not worth memorizing.

These constants are very often used for mapping flags to specific bits. For example, here is excerpt from ssl_private.h from Apache 2.4.6 source code:

```c
/**
 * Define the SSL options
 */
#define SSL_OPT_NONE   (0)
#define SSL_OPT_RELSET  (1<<0)
#define SSL_OPT_STDENVVARS (1<<1)
#define SSL_OPT_EXPORTCERTDATA (1<<3)
#define SSL_OPT_FAKEBASICAUTH (1<<4)
#define SSL_OPT_STRICTREQUIRE (1<<5)
#define SSL_OPT_OPTRENEGOTIATE (1<<6)
#define SSL_OPT_LEGACYDNFORMAT (1<<7)
```

Let’s get back to our example.

The IS_SET macro checks bit presence in a.
1.22. MANIPULATING SPECIFIC BIT(S)

The IS_SET macro is in fact the logical AND operation (AND) and it returns 0 if the specific bit is absent there, or the bit mask, if the bit is present. The if() operator in C/C++ triggers if the expression in it is not zero, it might be even 123456, that is why it always works correctly.

x86

MSVC

Let's compile (MSVC 2010):

Listing 1.288: MSVC 2010

```assembly
_rts$ = -8 ; size = 4
_is$ = -4 ; size = 4
_a$ = 8 ; size = 4
_f PROC
    push ebp
    mov ebp, esp
    sub esp, 8
    mov DWORD PTR _rts$[ebp], 0
    mov DWORD PTR _is$[ebp], 0
    jmp SHORT $LN4@f
$LN3@f:
    mov eax, DWORD PTR _is$[ebp] ; increment of i
    add eax, 1
    mov DWORD PTR _is$[ebp], eax
$LN4@f:
    cmp DWORD PTR _is$[ebp], 32 ; 00000020H
    jge SHORT $LN2@f ; loop finished?
    mov edx, 1
    mov ecx, DWORD PTR _is$[ebp]
    shl edx, cl ; EDX=EDX<<CL
    and edx, DWORD PTR _a$[ebp]
    je SHORT $LN1@f ; result of AND instruction was 0?
    ; then skip next instructions
    mov eax, DWORD PTR _rts$[ebp] ; no, not zero
    add eax, 1 ; increment rt
    mov DWORD PTR _rts$[ebp], eax
$LN1@f:
    jmp SHORT $LN3@f
$LN2@f:
    mov eax, DWORD PTR _rts$[ebp]
    mov esp, ebp
    pop ebp
    ret 0
_f ENDP
```

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1.22. MANIPULATING SPECIFIC BIT(S)

Let’s load this example into OllyDbg. Let the input value be 0x12345678.
For \( i = 1 \), we see how \( i \) is loaded into ECX:

Figure 1.98: OllyDbg: \( i = 1 \), \( i \) is loaded into ECX

EDX is 1. SHL is to be executed now.
1.22. MANIPULATING SPECIFIC BIT(S)

SHL has been executed:

Figure 1.99: OllyDbg: $i = 1$, EDX $= 1 \ll 1 = 2$

EDX contain $1 \ll 1$ (or 2). This is a bit mask.
1.22. **MANIPULATING SPECIFIC BIT(S)**

AND sets ZF to 1, which implies that the input value (0x12345678) ANDed with 2 results in 0:

So, there is no corresponding bit in the input value.

The piece of code, which increments the counter is not to be executed: the JZ instruction *bypassing* it.
1.22. MANIPULATING SPECIFIC BIT(S)

Let’s trace a bit further and \( i \) is now 4. \textit{SHL} is to be executed now:

Figure 1.101: OllyDbg: \( i = 4 \), \( i \) is loaded into ECX
1.22. MANIPULATING SPECIFIC BIT(S)

EDX = 1 << 4 (or 0x10 or 16):

Figure 1.102: OllyDbg: $i = 4$, EDX = 1 << 4 = 0x10

This is another bit mask.
1.22. MANIPULATING SPECIFIC BIT(S)

AND is executed:

Figure 1.103: OllyDbg: \( i = 4 \), is there that bit in the input value? Yes. (ZF = 0)

ZF is 0 because this bit is present in the input value. Indeed, \( 0x12345678 \& 0x10 = 0x10 \).

This bit counts: the jump is not triggering and the bit counter incrementing.

The function returns 13. This is total number of bits set in \( 0x12345678 \).

GCC

Let’s compile it in GCC 4.4.1:

```
Listing 1.289: GCC 4.4.1

public f
f proc near
rt = dword ptr -0Ch
i = dword ptr -8
arg_0 = dword ptr 8
push ebp
mov ebp, esp
push ebx
sub esp, 10h
mov [ebp+rt], 0
mov [ebp+i], 0
jmp short loc_80483EF
loc_80483D0:
    mov eax, [ebp+i]
    mov edx, 1
    mov ebx, edx
    mov ecx, eax
    shl ebx, cl
    mov eax, ebx
    and eax, [ebp+arg_0]
    test eax, eax
    jz short loc_80483EB
    add [ebp+rt], 1
loc_80483EB:
    add [ebp+i], 1
loc_80483EF:
```

1.22. MANIPULATING SPECIFIC BIT(S)

```assembly
    cmp [ebp+i], 1Fh
    jle short loc_80483D0
    mov eax, [ebp+rt]
    add esp, 10h
    pop ebx
    pop ebp
    retn
```

x64

Let's modify the example slightly to extend it to 64-bit:

```c
#include <stdio.h>
#include <stdint.h>

#define IS_SET(flag, bit) ((flag) & (bit))

int f(uint64_t a)
{
    uint64_t i;
    int rt=0;
    for (i=0; i<64; i++)
        if (IS_SET (a, 1ULL<<i))
            rt++;
    return rt;
}
```

Non-optimizing GCC 4.8.2

So far so easy.

```c
    push rbp
    mov rbp, rsp
    mov QWORD PTR [rbp-24], rdi ; a
    mov DWORD PTR [rbp-12], 0 ; rt=0
    mov QWORD PTR [rbp-8], 0 ; i=0
    jmp .L2
.L4:
    mov rax, QWORD PTR [rbp-8]
    mov rdx, QWORD PTR [rbp-24]
    ; RAX = i, RDX = a
    mov ecx, eax
    ; ECX = i
    shr rdx, cl
    ; RDX = RDX>>CL = a>>i
    mov rax, rdx
    ; RAX = RDX = a>>i
    and eax, 1
    ; EAX = EAX&1 = (a>>i)&1
    test rax, rax
    ; the last bit is zero?
    ; skip the next ADD instruction, if it was so.
    je .L3
    add DWORD PTR [rbp-12], 1 ; rt++
.L3:
    add QWORD PTR [rbp-8], 1 ; i++
.L2:
    cmp QWORD PTR [rbp-8], 63 ; i<63?
    jbe .L4 ; jump to the loop body begin, if so
    mov eax, DWORD PTR [rbp-12] ; return rt
```

Listing 1.290: Non-optimizing GCC 4.8.2
1.22. MANIPULATING SPECIFIC BIT(S)

Optimizing GCC 4.8.2

Listing 1.291: Optimizing GCC 4.8.2

1: f:
2: xor eax, eax  ; rt variable will be in EAX register
3: xor ecx, ecx  ; i variable will be in ECX register
4: .L3:
5: mov rsi, rdi  ; load input value
6: lea edx, [rax+1]  ; EDX=EAX+1
7: ; EDX here is a new version of rt,
8: ; which will be written into rt variable, if the last bit is 1
9: shr rsi, cl  ; RSI=RSI>>CL
10: and esi, 1  ; ESI=ESI&1
11: ; the last bit is 1? If so, write new version of rt into EAX
12: cmovne eax, edx
13: add rcx, 1  ; RCX++
14: cmp rcx, 64
15: jne .L3
16: rep ret  ; AKA fatret

This code is terser, but has a quirk.

In all examples that we see so far, we were incrementing the “rt” value after comparing a specific bit, but the code here increments “rt” before (line 6), writing the new value into register EDX. Thus, if the last bit is 1, the CMOVNE instruction (which is a synonym for CMOVNZ) commits the new value of “rt” by moving EDX (“proposed rt value”) into EAX (“current rt” to be returned at the end).

Hence, the incrementing is performed at each step of loop, i.e., 64 times, without any relation to the input value.

The advantage of this code is that it contain only one conditional jump (at the end of the loop) instead of two jumps (skipping the “rt” value increment and at the end of loop). And that might work faster on the modern CPUs with branch predictors:

2.10.1 on page 466.

The last instruction is REP RET (opcode F3 C3) which is also called FATRET by MSVC. This is somewhat optimized version of RET, which is recommended by AMD to be placed at the end of function, if RET goes right after conditional jump: [[Software Optimization Guide for AMD Family 16h Processors, (2013)]p.15]

Optimizing MSVC 2010

Listing 1.292: Optimizing MSVC 2010

a$ = 8
f PROC
; RCX = input value
xor eax, eax
mov edx, 1
lea r8d, QWORD PTR [rax+64]
; R8D=64
npad 5
$LL4@f:
test rdx, rcx
; there are no such bit in input value?
; skip the next INC instruction then.
je SHORT $LN3@f
inc eax  ; rt++
$LN3@f:
rol rdx, 1  ; RDX=RDX<<1

152 Conditional MOVe if Not Equal
153 Conditional MOVe if Not Zero
154 More information on it: [http://go.yurichev.com/17328](http://go.yurichev.com/17328)
Here the ROL instruction is used instead of SHL, which is in fact “rotate left” instead of “shift left”, but in this example it works just as SHL.

You can read more about the rotate instruction here: .1.6 on page 1034.

R8 here is counting from 64 to 0. It’s just like an inverted i.

Here is a table of some registers during the execution:

<table>
<thead>
<tr>
<th>RDX</th>
<th>R8</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x0000000000000001</td>
<td>64</td>
</tr>
<tr>
<td>0x0000000000000002</td>
<td>63</td>
</tr>
<tr>
<td>0x0000000000000004</td>
<td>62</td>
</tr>
<tr>
<td>0x0000000000000008</td>
<td>61</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>0x4000000000000000</td>
<td>2</td>
</tr>
<tr>
<td>0x8000000000000000</td>
<td>1</td>
</tr>
</tbody>
</table>

At the end we see the FATRET instruction, which was explained here: 1.22.5 on the preceding page.

Optimizing MSVC 2012

Optimizing MSVC 2012 does almost the same job as optimizing MSVC 2010, but somehow, it generates two identical loop bodies and the loop count is now 32 instead of 64.

To be honest, it’s not possible to say why. Some optimization trick? Maybe it’s better for the loop body to be slightly longer?

Anyway, such code is relevant here to show that sometimes the compiler output may be really weird and illogical, but perfectly working.
1.22. MANIPULATING SPECIFIC BIT(S)

ARM + Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 1.294: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

<table>
<thead>
<tr>
<th>Line</th>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOV</td>
<td>R1, R0</td>
<td></td>
</tr>
<tr>
<td>MOV</td>
<td>R0, #0</td>
<td></td>
</tr>
<tr>
<td>MOV</td>
<td>R2, #1</td>
<td></td>
</tr>
<tr>
<td>MOV</td>
<td>R3, R0</td>
<td></td>
</tr>
<tr>
<td>loc_E254</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TST</td>
<td>R1, R2,LSL R3</td>
<td>set flags according to R1 &amp; (R2&lt;&lt;R3)</td>
</tr>
<tr>
<td>ADD</td>
<td>R3, R3, #1</td>
<td>; R3++</td>
</tr>
<tr>
<td>ADDNE</td>
<td>R0, R0, #1</td>
<td>; if ZF flag is cleared by TST, then R0++</td>
</tr>
<tr>
<td>CMP</td>
<td>R3, #32</td>
<td></td>
</tr>
<tr>
<td>BNE</td>
<td>loc_E254</td>
<td></td>
</tr>
<tr>
<td>BX</td>
<td>LR</td>
<td></td>
</tr>
</tbody>
</table>

TST is the same thing as TEST in x86.

As was noted before (3.9.3 on page 499), there are no separate shifting instructions in ARM mode. However, there are modifiers LSL (Logical Shift Left), LSR (Logical Shift Right), ASR (Arithmetic Shift Right), ROR (Rotate Right) and RRX (Rotate Right with Extend), which may be added to such instructions as MOV, TST, CMP, ADD, SUB, RSB.\(^{155}\)

These modifiers define how to shift the second operand and by how many bits.

Thus the “TST R1, R2,LSL R3” instruction works here as \(R_1 \land (R_2 \ll R_3)\).

ARM + Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

Almost the same, but here are two LSL.W/TST instructions are used instead of a single TST, because in Thumb mode it is not possible to define LSL modifier directly in TST.

<table>
<thead>
<tr>
<th>Line</th>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOV</td>
<td>R1, R0</td>
<td></td>
</tr>
<tr>
<td>MOVS</td>
<td>R0, #0</td>
<td></td>
</tr>
<tr>
<td>MOV.W</td>
<td>R9, #1</td>
<td></td>
</tr>
<tr>
<td>MOVS</td>
<td>R3, #0</td>
<td></td>
</tr>
<tr>
<td>loc_F27A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSL.W</td>
<td>R2, R9, R3</td>
<td></td>
</tr>
<tr>
<td>TST</td>
<td>R2, R1</td>
<td></td>
</tr>
<tr>
<td>ADD.W</td>
<td>R3, R3, #1</td>
<td></td>
</tr>
<tr>
<td>IT</td>
<td>NE</td>
<td></td>
</tr>
<tr>
<td>ADDNE</td>
<td>R0, #1</td>
<td></td>
</tr>
<tr>
<td>CMP</td>
<td>R3, #32</td>
<td></td>
</tr>
<tr>
<td>BNE</td>
<td>loc_F27A</td>
<td></td>
</tr>
<tr>
<td>BX</td>
<td>LR</td>
<td></td>
</tr>
</tbody>
</table>

ARM64 + Optimizing GCC 4.9

Let’s take the 64-bit example which has been already used: 1.22.5 on page 330.

Listing 1.295: Optimizing GCC (Linaro) 4.8

f:

```assembly
mov  w2, 0 ; rt=0
mov  x5, 1
mov  w1, w2
.L2:
lsl x4, x5, x1 ; w4 = w5<<w1 = 1<<i
add w3, w2, 1 ; new rt=rt+1
tst x4, x0 ; (1<<i) & a
add w1, w1, 1 ; i++
; result of TST was non-zero?
; then w2=w3 or rt=new rt.
; otherwise: w2=w2 or rt=rt (idle operation)
csel w2, w3, w2, ne
cmp w1, 64 ; i<64?
```

\(^{155}\)These instructions are also called “data processing instructions”
### ARM64 + Non-optimizing GCC 4.9

And again, we’ll work on the 64-bit example which was already used: \text{1.22.5 on page 330}. The code is more verbose, as usual.

#### Listing 1.296: Non-optimizing GCC (Linaro) 4.8

```assembly
f:
    sub    sp, sp, #32
    str    x0, [sp,8] ; store "a" value to Register Save Area
    str    wzr, [sp,24] ; rt=0
    str    wzr, [sp,28] ; i=0
    b      .L2
.L4:
    ldr    w0, [sp,28]
    mov    x1, 1
    lsl    x0, x1, x0 ; X0 = X1<<X0 = 1<<i
    mov    x1, x0
    ; X1 = 1<<i
    ldr    x0, [sp,8] ; X0 = a
    and    x0, x1, x0 ; X0 contain zero? then jump to .L3, skipping "rt" increment
    cmp    x0, xzr
    beq    .L3
    ; rt++
    ldr    w0, [sp,24]
    add    w0, w0, 1
    str    w0, [sp,24]
.L3:
    ; i++
    ldr    w0, [sp,28]
    add    w0, w0, 1
    str    w0, [sp,28]
.L2:
    ; i<=63? then jump to .L4
    ldr    w0, [sp,28]
    cmp    w0, 63
    ble    .L4
    ; return rt
    ldr    w0, [sp,24]
    add    w0, [sp,24]
    ret
```

### MIPS

#### Non-optimizing GCC

#### Listing 1.297: Non-optimizing GCC 4.4.5 (IDA)

```assembly
f:
    ; IDA is not aware of variable names, we gave them manually:
    rt   = -0x10
    i    = -0xC
    var_4 = -4
    a    = 0
```

The result is very similar to what GCC generates for x64: \text{1.291 on page 331}.

The 	ext{CSEL} instruction is “Conditional SELect”. It just chooses one variable of two depending on the flags set by 	ext{TST} and copies the value into \text{W2}, which holds the “rt” variable.
1.22. MANIPULATING SPECIFIC BIT(S)

```assembly
addiu $sp, -0x18
sw $fp, 0x18+var_4($sp)
move $fp, $sp
sw $a0, 0x18+a($fp)

; initialize rt and i variables to zero:
sw $zero, 0x18+rt($fp)
sw $zero, 0x18+i($fp)

; jump to loop check instructions:
b loc_68
or $at, $zero ; branch delay slot, NOP

loc_20:
   li $v1, 1
   lw $v0, 0x18+i($fp)
or $at, $zero ; load delay slot, NOP
   sllv $v0, $v1, $v0
   ; $v0 = 1<<i
move $v1, $v0
   lw $v0, 0x18+a($fp)
or $at, $zero ; load delay slot, NOP
   and $v0, $v1, $v0
   ; $v0 = a&(1<<i)
   ; is a&(1<<i) equals to zero? jump to loc_58 then:
   beqz $v0, loc_58
   or $at, $zero
   ; no jump occurred, that means a&(1<<i)!=$0, so increment "rt" then:
   lw $v0, 0x18+rt($fp)
or $at, $zero ; load delay slot, NOP
   addiu $v0, 1
   sw $v0, 0x18+rt($fp)

loc_58:
   ; increment i:
   lw $v0, 0x18+i($fp)
or $at, $zero ; load delay slot, NOP
   addiu $v0, 1
   sw $v0, 0x18+i($fp)

loc_68:
   ; load i and compare it with 0x20 (32).
   ; jump to loc_20 if it is less then 0x20 (32):
   lw $v0, 0x18+i($fp)
or $at, $zero ; load delay slot, NOP
   slti $v0, 0x20 # ' '
   bnez $v0, loc_20
   or $at, $zero ; branch delay slot, NOP

; function epilogue. return rt:
   lw $v0, 0x18+rt($fp)
move $sp, $fp ; load delay slot
lw $fp, 0x18+var_4($sp)
addiu $sp, 0x18 ; load delay slot
jr $ra
or $at, $zero ; branch delay slot, NOP
```

That is verbose: all local variables are located in the local stack and reloaded each time they’re needed.
The SLLV instruction is “Shift Word Left Logical Variable”, it differs from SLL only in that the shift amount is encoded in the SLL instruction (and is fixed, as a consequence), but SLLV takes shift amount from a register.

**Optimizing GCC**

That is terser. There are two shift instructions instead of one. Why?

It’s possible to replace the first SLLV instruction with an unconditional branch instruction that jumps right to the second SLLV. But this is another branching instruction in the function, and it’s always favorable to get rid of them: 2.10.1 on page 466.
1.22. MANIPULATING SPECIFIC BIT(S)

Listing 1.298: Optimizing GCC 4.4.5 (IDA)

```assembly
f:
; $a0=a
; rt variable will reside in $v0:
    move $v0, $zero
; i variable will reside in $v1:
    move $v1, $zero
    li $t0, 1
    li $a3, 32
    sllv $a1, $t0, $v1
; $a1 = $t0<<$v1 = 1<<i
loc_14:
    and $a1, $a0
; $a1 = a&(1<<i)
; increment i:
    addiu $v1, 1
; jump to loc_28 if a&(1<<i)==0 and increment rt:
    beqz $a1, loc_28
    addiu $a2, $v0, 1
; if BEQZ was not triggered, save updated rt into $v0:
    move $v0, $a2
loc_28:
; if i!=32, jump to loc_14 and also prepare next shifted value:
    bne $v1, $a3, loc_14
    sllv $a1, $t0, $v1
; return
    jr $ra
or $at, $zero ; branch delay slot, NOP
```

1.22.6 Conclusion

Analogous to the C/C++ shifting operators ≪ and ≫, the shift instructions in x86 are SHR/SHL (for unsigned values) and SAR/SHL (for signed values).

The shift instructions in ARM are LSR/LSL (for unsigned values) and ASR/LSL (for signed values).

It’s also possible to add shift suffix to some instructions (which are called “data processing instructions”).

Check for specific bit (known at compile stage)

Test if the 0b1000000 bit (0x40) is present in the register’s value:

Listing 1.299: C/C++

```c
if (input&0x40)
...
```

Listing 1.300: x86

```assembly
TEST REG, 40h
JNZ is_set
; bit is not set
```

Listing 1.301: x86

```assembly
TEST REG, 40h
JZ is_cleared
; bit is set
```

Listing 1.302: ARM (ARM mode)

```assembly
TST REG, #0x40
BNE is_set
; bit is not set
```

Sometimes, AND is used instead of TEST, but the flags that are set are the same.
1.22. MANIPULATING SPECIFIC BIT(S)

Check for specific bit (specified at runtime)

This is usually done by this C/C++ code snippet (shift value by \( n \) bits right, then cut off lowest bit):

Listing 1.303: C/C++

\[
\text{if } ((\text{value} >> n) & 1)
\]

This is usually implemented in x86 code as:

Listing 1.304: x86

\[
; \text{REG=\text{input\_value}}
; \text{CL=\(n\)}
\text{SHR REG, CL}
\text{AND REG, 1}
\]

Or (shift 1 bit \( n \) times left, isolate this bit in input value and check if it’s not zero):

Listing 1.305: C/C++

\[
\text{if } (\text{value} \& (1 \ll n))
\]

This is usually implemented in x86 code as:

Listing 1.306: x86

\[
; \text{CL=\(n\)}
\text{MOV REG, 1}
\text{SHL REG, CL}
\text{AND input\_value, REG}
\]

Set specific bit (known at compile stage)

Listing 1.307: C/C++

\[
\text{value=value}|0x40;
\]

Listing 1.308: x86

\[
\text{OR REG, 40h}
\]

Listing 1.309: ARM (ARM mode) and ARM64

\[
\text{ORR R0, R0, #0x40}
\]

Set specific bit (specified at runtime)

Listing 1.310: C/C++

\[
\text{value=value}|(1\ll n);
\]

This is usually implemented in x86 code as:

Listing 1.311: x86

\[
; \text{CL=\(n\)}
\text{MOV REG, 1}
\text{SHL REG, CL}
\text{OR input\_value, REG}
\]
1.23. LINEAR CONGRUENTIAL GENERATOR

Clear specific bit (known at compile stage)

Just apply AND operation with the inverted value:

Listing 1.312: C/C++
```c
value=value&(~0x40);
```

Listing 1.313: x86
```
AND REG, 0FFFFFFBFh
```

Listing 1.314: x64
```
AND REG, 0FFFFFFFFFFFFFFBFh
```

This is actually leaving all bits set except one.

ARM in ARM mode has BIC instruction, which works like the NOT +AND instruction pair:

Listing 1.315: ARM (ARM mode)
```
BIC R0, R0, #0x40
```

Clear specific bit (specified at runtime)

Listing 1.316: C/C++
```c
value=value&(~(1<<n));
```

Listing 1.317: x86
```
; CL=n
MOV REG, 1
SHL REG, CL
NOT REG
AND input_value, REG
```

1.22.7 Exercises

- [http://challenges.re/67](http://challenges.re/67)
- [http://challenges.re/68](http://challenges.re/68)
- [http://challenges.re/69](http://challenges.re/69)
- [http://challenges.re/70](http://challenges.re/70)

1.23 Linear congruential generator as pseudorandom number generator

Perhaps, the linear congruential generator is the simplest possible way to generate random numbers. It’s not in favour nowadays\(^\text{156}\), but it’s so simple (just one multiplication, one addition and AND operation), that we can use it as an example.

```c
#include <stdint.h>

// constants from the Numerical Recipes book
#define RNG_a 1664525
#define RNG_c 1013904223

static uint32_t rand_state;
```

\(^{156}\)Mersenne twister is better
1.23. **LINEAR CONGRUENTIAL GENERATOR**

```c
void my_srand (uint32_t init)
{
    rand_state=init;
}

int my_rand ()
{
    rand_state=rand_state*RNG_a;
    rand_state=rand_state+RNG_c;
    return rand_state & 0x7fff;
}
```

There are two functions: the first one is used to initialize the internal state, and the second one is called to generate pseudorandom numbers.

We see that two constants are used in the algorithm. They are taken from [William H. Press and Saul A. Teukolsky and William T. Vetterling and Brian P. Flannery, *Numerical Recipes*, (2007)].

Let's define them using a `#define` C/C++ statement. It's a macro.

The difference between a C/C++ macro and a constant is that all macros are replaced with their value by C/C++ preprocessor, and they don't take any memory, unlike variables.

In contrast, a constant is a read-only variable.

It's possible to take a pointer (or address) of a constant variable, but impossible to do so with a macro.

The last AND operation is needed because by C-standard `my_rand()` has to return a value in the 0..32767 range.

If you want to get 32-bit pseudorandom values, just omit the last AND operation.

### 1.23.1 x86

Listing 1.318: Optimizing MSVC 2013

```asm
.BSS SEGMENT
_rand_state DD 01H DUP (?)
.BSS ENDS

_init$ = 8
_srand PROC
    mov eax, DWORD PTR _init$[esp-4]
    mov DWORD PTR _rand_state, eax
    ret 0
_srand ENDP

(TEXT SEGMENT
_rand PROC
    imul eax, DWORD PTR _rand_state, 1664525
    add eax, 1013904223 ; 3c6ef35fH
    mov DWORD PTR _rand_state, eax
    and eax, 32767 ; 00007fffH
    ret 0
_rand ENDP

(TEXT ENDS
```

Here we see it: both constants are embedded into the code. There is no memory allocated for them.

The `my_srand()` function just copies its input value into the internal `rand_state` variable.

`my_rand()` takes it, calculates the next `rand_state`, cuts it and leaves it in the EAX register.

The non-optimized version is more verbose:

Listing 1.319: Non-optimizing MSVC 2013

```asm
.BSS SEGMENT
_rand_state DD 01H DUP (?)
```
1.23. LINEAR CONGRUENTIAL GENERATOR

```
_BSS ENDS
_init$ = 8
_srand PROC
    push ebp
    mov ebp, esp
    mov eax, DWORD PTR _init$[ebp]
    mov DWORD PTR _rand_state, eax
    pop ebp
    ret 0
_srand ENDP

_TEXT SEGMENT
_rand PROC
    push ebp
    mov ebp, esp
    imul eax, DWORD PTR _rand_state, 1664525
    mov DWORD PTR _rand_state, eax
    mov ecx, DWORD PTR _rand_state
    add ecx, 1013904223 ; 3c6ef35fH
    mov DWORD PTR _rand_state, ecx
    mov eax, DWORD PTR _rand_state
    and eax, 32767 ; 00007fffH
    pop ebp
    ret 0
_rand ENDP

_TEXT ENDS
```

1.23.2 x64

The x64 version is mostly the same and uses 32-bit registers instead of 64-bit ones (because we are working with int values here).

But my_srand() takes its input argument from the ECX register rather than from stack:

```
_BSS SEGMENT
rand_state DD 01H DUP (?)
_BSS ENDS

_init$ = 8
my_srand PROC
    ; ECX = input argument
    mov DWORD PTR rand_state, ecx
    ret 0
my_srand ENDP

_TEXT SEGMENT
my_rand PROC
    imul eax, DWORD PTR rand_state, 1664525 ; 0019660dH
    add eax, 1013904223 ; 3c6ef35fH
    mov DWORD PTR rand_state, eax
    and eax, 32767 ; 00007fffH
    ret 0
my_rand ENDP

_TEXT ENDS
```

GCC compiler generates mostly the same code.

1.23.3 32-bit ARM

```
Listing 1.321: Optimizing Keil 6/2013 (ARM mode)
```

340
1.23. **LINEAR CONGRUENTIAL GENERATOR**

| L0.52 | DCD ||.data||
| L0.56 | DCD 0x0019660d
| L0.60 | DCD 0x3c6ef35f

**AREA ||.data||, DATA, ALIGN=2**

rand_state

DCD 0x00000000

It’s not possible to embed 32-bit constants into ARM instructions, so Keil has to place them externally and load them additionally. One interesting thing is that it’s not possible to embed the 0x7FFF constant as well. So what Keil does is shifting rand_state left by 17 bits and then shifting it right by 17 bits. This is analogous to the \((\text{rand} \_\text{state} \ll 17) \gg 17\) statement in C/C++. It seems to be useless operation, but what it does is clearing the high 17 bits, leaving the low 15 bits intact, and that’s our goal after all.

Optimizing Keil for Thumb mode generates mostly the same code.

### 1.23.4 **MIPS**

**Listing 1.322: Optimizing GCC 4.4.5 (IDA)**

```assembly
my_srand:
    ; store $a0 to rand_state:
    lui $v0, (rand_state >> 16)
    jr $ra
    sw $a0, rand_state

my_rand:
    ; load rand_state to $v0:
    lui $v1, (rand_state >> 16)
    lw $v0, rand_state
    or $at, $zero ; load delay slot
    ; multiplicate rand_state in $v0 by 1664525 (RNG_a):
    sll $a1, $v0, 2
    sll $a0, $v0, 4
    addu $a0, $a1, $a0
    sll $a1, $a0, 6
    subu $a0, $a1, $a0
    addu $a0, $v0
    sll $a1, $a0, 5
    addu $a0, $a1
    sll $a0, 3
    addu $v0, $a0, $v0
    sll $a0, $v0, 2
    addu $v0, $a0
    ; add 1013904223 (RNG_c)
```
1.23. LINEAR CONGRUENTIAL GENERATOR

; the LI instruction is coalesced by IDA from LUI and ORI
    li  $a0, 0x3C6EF35F
    addu $v0, $a0
; store to rand_state:
    sw  $v0, (rand_state & 0xFFFF)($v1)
    jr  $ra
    andi $v0, 0x7FFF ; branch delay slot

Wow, here we see only one constant (0x3C6EF35F or 1013904223). Where is the other one (1664525)?
It seems that multiplication by 1664525 is performed by just using shifts and additions! Let’s check this assumption:

#define RNG_a 1664525
int f (int a)
{
    return a* RNG_a;
}

Listing 1.323: Optimizing GCC 4.4.5 (IDA)

f:
    sll  $v1, $a0, 2
    sll  $v0, $a0, 4
    addu $v0, $v1, $v0
    sll  $v1, $v0, 6
    subu $v0, $v1, $v0
    addu $v0, $a0
    sll  $v1, $v0, 5
    addu $v0, $v1
    sll  $v0, 3
    addu $a0, $v0, $a0
    sll  $v0, $a0, 2
    jr  $ra
    addu $v0, $a0, $v0 ; branch delay slot

Indeed!

MIPS relocations

We will also focus on how such operations as load from memory and store to memory actually work.
The listings here are produced by IDA, which hides some details.
We’ll run objdump twice: to get a disassembled listing and also relocations list:

Listing 1.324: Optimizing GCC 4.4.5 (objdump)

# objdump -D rand_O3.o
...
00000000  <my_srand>:
0: 3c020000  lui  v0,0x0
4: 03e00008  jr  ra
8: ac440000  sw  a0,0(v0)
00000000c  <my_rand>:
  c: 3c030000  lui  v1,0x0
10: 8c620000  lw  v0,0(v1)
14: 00200825  move  at,at
18: 00022880  sll  a1,v0,0x2
1c: 000022100  sll  a0,v0,0x4
20: 00a42021  addu  a0,a1,a0
24: 00042980  sll  a1,a0,0x6
28: 00a42023  subu  a0,a1,a0
2c: 00822021  addu  a0,a0,v0
30: 00042940  sll  a1,a0,0x5
34: 00852021  addu  a0,a0,a1
1.24. STRUCTURES

Let's consider the two relocations for the my_srand() function. The first one, for address 0 has a type of R_MIPS_HI16 and the second one for address 8 has a type of R_MIPS_LO16. That implies that address of the beginning of the .bss segment is to be written into the instructions at address of 0 (high part of address) and 8 (low part of address).

The rand_state variable is at the very start of the .bss segment. So we see zeros in the operands of instructions LUI and SW, because nothing is there yet— the compiler don’t know what to write there.

The linker will fix this, and the high part of the address will be written into the operand of LUI and the low part of the address—to the operand of SW.

SW will sum up the low part of the address and what is in register $V0 (the high part is there). It’s the same story with the my_rand() function: R_MIPS_HI16 relocation instructs the linker to write the high part of the .bss segment address into instruction LUI.

So the high part of the rand_state variable address is residing in register $V1. The LW instruction at address 0x10 sums up the high and low parts and loads the value of the rand_state variable into $V0.

The SW instruction at address 0x54 do the summing again and then stores the new value to the rand_state global variable.

IDA processes relocations while loading, thus hiding these details, but we should keep them in mind.

1.23.5 Thread-safe version of the example

The thread-safe version of the example is to be demonstrated later: 6.2.1 on page 742.

1.24 Structures

A C/C++ structure, with some assumptions, is just a set of variables, always stored in memory together, not necessary of the same type.\textsuperscript{157}

\textsuperscript{157}AKA “heterogeneous container”
Let's take the SYSTEMTIME\textsuperscript{158} win32 structure that describes time.

This is how it's defined:

\begin{verbatim}
Listing 1.325: WinBase.h

typedef struct _SYSTEMTIME {
    WORD wYear;
    WORD wMonth;
    WORD wDayOfWeek;
    WORD wDay;
    WORD wHour;
    WORD wMinute;
    WORD wSecond;
    WORD wMilliseconds;
} SYSTEMTIME, *PSYSTEMTIME;
\end{verbatim}

Let's write a C function to get the current time:

\begin{verbatim}
# include <windows.h>
# include <stdio.h>

void main()
{
    SYSTEMTIME t;
    GetSystemTime (&t);

    printf("%04d-%02d-%02d %02d:%02d:%02d\n",
        t.wYear, t.wMonth, t.wDay,
        t.wHour, t.wMinute, t.wSecond);

    return;
}
\end{verbatim}

We get (MSVC 2010):

\begin{verbatim}
Listing 1.326: MSVC 2010 /GS-

t$ = -16 ; size = 16
\_main PROC
    push ebp
    mov ebp, esp
    sub esp, 16
    lea eax, DWORD PTR \_t$[ebp]
    push eax
    call DWORD PTR __imp__GetSystemTime@4
    movzx ecx, WORD PTR \_t$[ebp+12] ; wSecond
    push ecx
    movzx edx, WORD PTR \_t$[ebp+10] ; wMinute
    push edx
    movzx eax, WORD PTR \_t$[ebp+8] ; wHour
    push eax
    movzx ecx, WORD PTR \_t$[ebp+6] ; wDay
    push ecx
    movzx edx, WORD PTR \_t$[ebp+2] ; wMonth
    push edx
    movzx eax, WORD PTR \_t$[ebp] ; wYear
    push eax
    push OFFSET $SG78811 ; '%04d-%02d-%02d %02d:%02d:%02d', 0aH, 00H
    call _printf
    add esp, 28
    xor eax, eax
    mov esp, ebp
    pop ebp
    ret 0
\_main ENDP
\end{verbatim}

\textsuperscript{158}MSDN: \texttt{SYSTEMTIME} structure
1.24. STRUCTURES

16 bytes are allocated for this structure in the local stack — that is exactly `sizeof(WORD)*8` (there are 8 WORD variables in the structure).

Pay attention to the fact that the structure begins with the `wYear` field. It can be said that a pointer to the SYSTEMTIME structure is passed to the `GetSystemTime()` function, but it is also can be said that a pointer to the `wYear` field is passed, and that is the same! `GetSystemTime()` writes the current year to the WORD pointer pointing to, then shifts 2 bytes ahead, writes current month, etc., etc.

^{159} MSDN: SYSTEMTIME structure
Let's compile this example in MSVC 2010 with /GS- /MD keys and run it in OllyDbg.

Let's open windows for data and stack at the address which is passed as the first argument of the GetSystemTime() function, and let's wait until it's executed. We see this:

![OllyDbg screenshot](image)

Figure 1.104: OllyDbg: GetSystemTime() just executed

The system time of the function execution on my computer is 9 December 2014, 22:29:52:

```
Listing 1.327: printf() output
2014-12-09 22:29:52
```

So we see these 16 bytes in the data window:

```
DE 07 0C 00 02 00 09 00 16 00 01 00 34 00 0D 03
```

Each two bytes represent one field of the structure. Since the endianness is little endian, we see the low byte first and then the high one. Hence, these are the values currently stored in memory:

<table>
<thead>
<tr>
<th>Hexadecimal number</th>
<th>decimal number</th>
<th>field name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x07DE</td>
<td>2014</td>
<td>wYear</td>
</tr>
<tr>
<td>0x000C</td>
<td>12</td>
<td>wMonth</td>
</tr>
<tr>
<td>0x0002</td>
<td>2</td>
<td>wDayOfWeek</td>
</tr>
<tr>
<td>0x0009</td>
<td>9</td>
<td>wDay</td>
</tr>
<tr>
<td>0x0016</td>
<td>22</td>
<td>wHour</td>
</tr>
<tr>
<td>0x001D</td>
<td>29</td>
<td>wMinute</td>
</tr>
<tr>
<td>0x0034</td>
<td>52</td>
<td>wSecond</td>
</tr>
<tr>
<td>0x03D4</td>
<td>980</td>
<td>wMilliseconds</td>
</tr>
</tbody>
</table>

The same values are seen in the stack window, but they are grouped as 32-bit values. And then printf() just takes the values it needs and outputs them to the console.

Some values aren't output by printf() (wDayOfWeek and wMilliseconds), but they are in memory right now, available for use.

**Replacing the structure with array**

The fact that the structure fields are just variables located side-by-side, can be easily demonstrated by doing the following. Keeping in mind the SYSTEMTIME structure description, it's possible to rewrite this...
1.24. **STRUCTURES**

simple example like this:

```c
#include <windows.h>
#include <stdio.h>

void main()
{
    WORD array[8];
    GetSystemTime (array);

    printf ("%04d-%02d-%02d %02d:%02d:%02d",
            array[0] /* wYear */, array[1] /* wMonth */, array[3] /* wDay */,
    return;
}
```

The compiler grumbles a bit:

```
systemtime2.c(7) : warning C4133: 'function' : incompatible types - from 'WORD [8]' to 'LPSYSTEMTIME'
```

But nevertheless, it produces this code:

**Listing 1.328: Non-optimizing MSVC 2010**

```assembly
$SG78573 DB '%04d-%02d-%02d %02d:%02d:%02d', 0aH, 00H
_array$ = -16 ; size = 16
_main PROC
    push ebp
    mov ebp, esp
    sub esp, 16
    lea eax, DWORD PTR _array$[ebp]
    push eax
    call DWORD PTR __imp__GetSystemTime@4
    movzx ecx, WORD PTR _array$[ebp+12] ; wSecond
    push ecx
    movzx edx, WORD PTR _array$[ebp+10] ; wMinute
    push edx
    movzx eax, WORD PTR _array$[ebp+8] ; wHoure
    push eax
    movzx ecx, WORD PTR _array$[ebp+6] ; wDay
    push ecx
    movzx edx, WORD PTR _array$[ebp+2] ; wMonth
    push edx
    movzx eax, WORD PTR _array$[ebp] ; wYear
    push eax
    push OFFSET $SG78573
    call _printf
    add esp, 28
    xor eax, 28
    mov esp, ebp
    pop ebp
    ret 0
_main ENDP
```

And it works just as the same!

It is very interesting that the result in assembly form cannot be distinguished from the result of the previous compilation.

So by looking at this code, one cannot say for sure if there was a structure declared, or an array.

Nevertheless, no sane person would do it, as it is not convenient.

Also the structure fields may be changed by developers, swapped, etc.

We will not study this example in OllyDbg, because it will be just the same as in the case with the structure.
1.24. STRUCTURES

1.24.2 Let’s allocate space for a structure using malloc()

Sometimes it is simpler to place structures not in the local stack, but in the heap:

```
#include <windows.h>
#include <stdio.h>

void main()
{
    SYSTEMTIME *t;
    t=(SYSTEMTIME *)malloc(sizeof(SYSTEMTIME));
    GetSystemTime (t);
    printf ("%04d-%02d-%02d %02d:%02d:%02d\n",
            t->wYear, t->wMonth, t->wDay,
            t->wHour, t->wMinute, t->wSecond);
    free (t);
    return;
}
```

Let’s compile it now with optimization (\0x) so it would be easy to see what we need.

```
Listing 1.329: Optimizing MSVC

_main PROC
    push esi
    push 16
    call _malloc
    add esp, 4
    mov esi, eax
    push esi
    call DWORD PTR __imp__GetSystemTime@4
    movzx eax, WORD PTR [esi+12] ; wSecond
    movzx ecx, WORD PTR [esi+10] ; wMinute
    movzx edx, WORD PTR [esi+8] ; wHour
    push eax
    movzx eax, WORD PTR [esi+6] ; wDay
    push ecx
    movzx ecx, WORD PTR [esi+2] ; wMonth
    push edx
    movzx edx, WORD PTR [esi] ; wYear
    push eax
    push ecx
    push edx
    push OFFSET $SG78833
    call _printf
    push esi
    call _free
    add esp, 32
    xor eax, eax
    pop esi
    ret 0

_main ENDP
```

So, sizeof(SYSTEMTIME) = 16 and that is exact number of bytes to be allocated by malloc(). It returns a pointer to a freshly allocated memory block in the EAX register, which is then moved into the ESI register. GetSystemTime() win32 function takes care of saving value in ESI, and that is why it is not saved here and continues to be used after the GetSystemTime() call.

New instruction —MOVZX (Move with Zero eXtend). It may be used in most cases as MOVZX, but it sets the remaining bits to 0. That’s because printf() requires a 32-bit int, but we got a WORD in the structure — that is 16-bit unsigned type. That’s why by copying the value from a WORD into int, bits from 16 to 31 must be cleared, because a random noise may be there, which is left from the previous operations on the register(s).

In this example, it’s possible to represent the structure as an array of 8 WORDs:
#include <windows.h>
#include <stdio.h>

void main()
{
    WORD *t;
    t=(WORD *)malloc (16);
    GetSystemTime (t);
    printf("%04d-%02d-%02d %02d:%02d:%02d\n",
           t[0] /* wYear */, t[1] /* wMonth */, t[3] /* wDay */,
    free (t);
    return;
};

We get:

Listing 1.330: Optimizing MSVC

SG78594 DB '%04d-%02d-%02d %02d:%02d:%02d', 0aH, 0H
_main PROC
    push esi
    push 16
    call _malloc
    add esp, 4
    mov esi, eax
    push esi
    call DWORD PTR __imp__GetSystemTime@4
    movzx eax, WORD PTR [esi+12]
    movzx ecx, WORD PTR [esi+10]
    movzx edx, WORD PTR [esi+8]
    push eax
    movzx eax, WORD PTR [esi+6]
    push ecx
    movzx ecx, WORD PTR [esi+2]
    push edx
    movzx edx, WORD PTR [esi]
    push eax
    push ecx
    push edx
    push OFFSET $SG78594
    call _printf
    push esi
    call _free
    add esp, 32
    xor eax, eax
    pop esi
    ret 0
_main ENDP

Again, we got the code that cannot be distinguished from the previous one.
And again it has to be noted, you haven’t to do this in practice, unless you really know what you are doing.

1.24.3 UNIX: struct tm

Linux

Let’s take the tm structure from time.h in Linux for example:

#include <stdio.h>
#include <time.h>
1.24. STRUCTURES

```c
void main()
{
    struct tm t;
    time_t unix_time;

    unix_time=time(NULL);
    localtime_r (&unix_time, &t);

    printf ("Year: %d\n", t.tm_year+1900);
    printf ("Month: %d\n", t.tm_mon);
    printf ("Day: %d\n", t.tm_mday);
    printf ("Hour: %d\n", t.tm_hour);
    printf ("Minutes: %d\n", t.tm_min);
    printf ("Seconds: %d\n", t.tm_sec);
};
```

Let's compile it in GCC 4.4.1:

```
Listing 1.331: GCC 4.4.1

main proc near
    push ebp
    mov ebp, esp
    and esp, 0FFFFFFF0h
    sub esp, 40h
    mov dword ptr [esp], 0 ; first argument for time()
call time
    mov [esp+3Ch], eax
    lea eax, [esp+3Ch] ; take pointer to what time() returned
    lea edx, [esp+10h] ; at ESP+10h struct tm will begin
    mov [esp+4], edx ; pass pointer to the structure begin
    mov [esp], eax ; pass pointer to result of time()
call localtime_r
    mov eax, [esp+24h] ; tm_year
    lea edx, [eax+76Ch] ; edx=eax+1900
    mov eax, offset format ; "Year: %d\n"
mov [esp+4], edx
    mov [esp], eax
call printf
    mov edx, [esp+20h] ; tm_mon
    mov eax, offset aMonthD ; "Month: %d\n"
mov [esp+4], edx
    mov [esp], eax
call printf
    mov edx, [esp+1Ch] ; tm_mday
    mov eax, offset aDayD ; "Day: %d\n"
mov [esp+4], edx
    mov [esp], eax
call printf
    mov edx, [esp+18h] ; tm_hour
    mov eax, offset aHourD ; "Hour: %d\n"
mov [esp+4], edx
    mov [esp], eax
call printf
    mov edx, [esp+14h] ; tm_min
    mov eax, offset aMinutesD ; "Minutes: %d\n"
mov [esp+4], edx
    mov [esp], eax
call printf
    mov edx, [esp+10h]
mov eax, offset aSecondsD ; "Seconds: %d\n"
mov [esp+4], edx
    mov [esp], eax
call printf
leave
retn
```
```
1.24. STRUCTURES

Somehow, IDA did not write the local variables' names in the local stack. But since we already are experienced reverse engineers :-) we may do it without this information in this simple example.

Please also pay attention to the lea edx, [eax+76Ch] —this instruction just adds 0x76C (1900) to value in EAX, but doesn’t modify any flags. See also the relevant section about LEA (.1.6 on page 1028).

GDB

Let’s try to load the example into GDB 160:

Listing 1.332: GDB
dennis@ubuntuvm:~/polygon$ date
Mon Jun 2 18:10:37 EEST 2014
dennis@ubuntuvm:~/polygon$ gcc GCC_tm.c -o GCC_tm
dennis@ubuntuvm:~/polygon$ gdb GCC_tm
GNU gdb (GDB) 7.6.1-ubuntu
... Reading symbols from /home/dennis/polygon/GCC_tm...(no debugging symbols found)...done.
(gdb) b printf
Breakpoint 1 at 0x8048330
(gdb) run
Starting program: /home/dennis/polygon/GCC_tm
Breakpoint 1, __printf (format=0x80485c0 "Year: %d\n") at printf.c:29
29 printf.c: No such file or directory.
(gdb) x/20x $esp
0xbffff0dc: 0x080484c3 0x080485c0 0x000007de 0x00000000
0xbffff0ec: 0x08048301 0x538c93ed 0x00000025 0x0000000a
0xbffff0fc: 0x00000012 0x00000025 0x00000005 0x00000072
0xbffff10c: 0x00000000 0x00000000 0x00000000 0x00000000
0xbffff11c: 0x00000000 0x00000000 0x00000000 0x00000000
(gdb)

We can easily find our structure in the stack. First, let’s see how it’s defined in time.h:

Listing 1.333: time.h

    struct tm
    {
        int    tm_sec;
        int    tm_min;
        int    tm_hour;
        int    tm_mday;
        int    tm_mon;
        int    tm_year;
        int    tm_wday;
        int    tm_yday;
        int    tm_isdst;
    };

Pay attention that 32-bit int is used here instead of WORD in SYSTEMTIME. So, each field occupies 32-bit. Here are the fields of our structure in the stack:

    0xbffff0dc: 0x080484c3 0x080485c0 0x0000007de 0x00000000
    0xbffff0ec: 0x08048301 0x538c93ed 0x000000025 0x0000000a
    0xbffff0fc: 0x00000012 0x0000000025 0x00000005 0x00000072
    0xbffff10c: 0x00000000 0x00000000 0x00000000 0x00000000
    0xbffff11c: 0x00000000 0x00000000 0x00000000 0x00000000

Or as a table:

160The date result is slightly corrected for demonstration purposes. Of course, it’s not possible to run GDB that quickly, in the same second.
1.24. STRUCTURES

<table>
<thead>
<tr>
<th>Hexadecimal number</th>
<th>Decimal number</th>
<th>Field name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x0000000025</td>
<td>37</td>
<td>tm_sec</td>
</tr>
<tr>
<td>0x00000000a</td>
<td>10</td>
<td>tm_min</td>
</tr>
<tr>
<td>0x000000012</td>
<td>18</td>
<td>tm_hour</td>
</tr>
<tr>
<td>0x000000002</td>
<td>2</td>
<td>tm_mday</td>
</tr>
<tr>
<td>0x000000005</td>
<td>5</td>
<td>tm_mon</td>
</tr>
<tr>
<td>0x000000072</td>
<td>114</td>
<td>tm_year</td>
</tr>
<tr>
<td>0x000000001</td>
<td>1</td>
<td>tm_wday</td>
</tr>
<tr>
<td>0x000000098</td>
<td>152</td>
<td>tm_yday</td>
</tr>
<tr>
<td>0x000000001</td>
<td>1</td>
<td>tm_isdst</td>
</tr>
</tbody>
</table>

Just like SYSTEMTIME (1.24.1 on page 344), there are also other fields available that are not used, like tm_wday, tm_yday, tm_isdst.

ARM

Optimizing Keil 6/2013 (Thumb mode)

Same example:

```assembly
var_38 = -0x38
var_34 = -0x34
var_30 = -0x30
var_2C = -0x2C
var_28 = -0x28
var_24 = -0x24
timer = -0xC

PUSH {LR}
MOV  R0, #0 ; timer
SUB  SP, SP, #0x34
BL   time
STR  R0, [SP,#0x38+timer]
MOV  R1, SP ; tp
ADD  R0, SP, #0x38+timer ; timer
BL   localtime_r
LDR  R1, =0x76C
LDR  R0, [SP,#0x38+var_24]
ADDS R1, R0, R1
ADR  R0, aYearD ; "Year: %d\n"
BL   __2printf
LDR  R1, [SP,#0x38+var_28]
ADR  R0, aMonthD ; "Month: %d\n"
BL   __2printf
LDR  R1, [SP,#0x38+var_2C]
ADR  R0, aDayD  ; "Day: %d\n"
BL   __2printf
LDR  R1, [SP,#0x38+var_30]
ADR  R0, aHourD ; "Hour: %d\n"
BL   __2printf
LDR  R1, [SP,#0x38+var_34]
ADR  R0, aMinutesD ; "Minutes: %d\n"
BL   __2printf
LDR  R1, [SP,#0x38+var_38]
ADR  R0, aSecondsD ; "Seconds: %d\n"
BL   __2printf
ADD  SP, SP, #0x34
POP  {PC}
```

Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

IDA “knows” the tm structure (because IDA “knows” the types of the arguments of library functions like localtime_r()).
1.24. **STRUCTURES**

so it shows here structure elements accesses and their names.

Listing 1.335: Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```c
var_38 = -0x38
var_34 = -0x34

PUSH {R7,LR}
MOV R7, SP
SUB SP, SP, #0x30
MOVS R0, #0 ; time_t *
BLX _time
ADD R1, SP, #0x38+var_34 ; struct tm *
STR R0, [SP,#0x38+var_38]
MOV R0, SP ; time_t *
BLX _localtime_r
LDR R1, [SP,#0x38+var_34.tm_year]
ADD R0, PC ; char *
ADDW R1, R1, #0x76C
BLX _printf
LDR R1, [SP,#0x38+var_34.tm_mon]
ADD R0, PC ; char *
BLX _printf
LDR R1, [SP,#0x38+var_34.tm_hour]
ADD R0, PC ; char *
BLX _printf
LDR R1, [SP,#0x38+var_34]
ADD R0, PC ; char *
ADD SP, SP, #0x30
POP {R7,PC}
...
```

MIPS

Listing 1.336: Optimizing GCC 4.4.5 (IDA)

```c
main:

; IDA is not aware of structure field names, we named them manually:

var_40 = -0x40
```
1.24. STRUCTURES

<table>
<thead>
<tr>
<th>Line</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-8</td>
<td><code>var_38 = -0x38</code> <code>seconds = -0x34</code> <code>minutes = -0x30</code> <code>hour = -0x2C</code></td>
</tr>
<tr>
<td>9-11</td>
<td><code>day = -0x28</code> <code>month = -0x24</code> <code>year = -0x20</code> <code>var_4 = -4</code></td>
</tr>
<tr>
<td>15-56</td>
<td>Code for date and time formatting</td>
</tr>
<tr>
<td>66-75</td>
<td>ASCII strings for date and time display</td>
</tr>
</tbody>
</table>

---

```
lui $gp, (__gnu_local_gp >> 16)
addiu $sp, -0x50
la $gp, (__gnu_local_gp & 0xFFFF)
sw $ra, 0x50+var_4($sp)
sw $gp, 0x50+var_40($sp)
lw $t9, (time & 0xFFFF)($gp)
or $at, $zero ; load delay slot, NOP
jalr $t9
move $a0, $zero ; branch delay slot, NOP
lw $gp, 0x50+var_40($sp)
addiu $a0, $sp, 0x50+var_38
lw $t9, (localtime_r & 0xFFFF)($gp)
addiu $a1, $sp, 0x50+seconds
jalr $t9
sw $v0, 0x50+var_38($sp); branch delay slot
lw $gp, 0x50+var_40($sp)
lw $a1, 0x50+year($sp)
lw $t9, (printf & 0xFFFF)($gp)
la $a0, $LC0 # "Year: %d\n"
jalr $t9
addiu $a1, 1900 ; branch delay slot
lw $gp, 0x50+var_40($sp)
lw $a1, 0x50+month($sp)
lw $t9, (printf & 0xFFFF)($gp)
lui $a0, ($LC1 >> 16) # "Month: %d\n"
jalr $t9
la $a0, ($LC1 & 0xFFFF) # "Month: %d\n" ; branch delay slot
lw $gp, 0x50+var_40($sp)
lw $a1, 0x50+day($sp)
lw $t9, (printf & 0xFFFF)($gp)
lui $a0, ($LC2 >> 16) # "Day: %d\n"
jalr $t9
la $a0, ($LC2 & 0xFFFF) # "Day: %d\n" ; branch delay slot
lw $gp, 0x50+var_40($sp)
lw $a1, 0x50+hour($sp)
lw $t9, (printf & 0xFFFF)($gp)
lui $a0, ($LC3 >> 16) # "Hour: %d\n"
jalr $t9
la $a0, ($LC3 & 0xFFFF) # "Hour: %d\n" ; branch delay slot
lw $gp, 0x50+var_40($sp)
lw $a1, 0x50+minutes($sp)
lw $t9, (printf & 0xFFFF)($gp)
lui $a0, ($LC4 >> 16) # "Minutes: %d\n"
jalr $t9
la $a0, ($LC4 & 0xFFFF) # "Minutes: %d\n" ; branch delay slot
lw $gp, 0x50+var_40($sp)
lw $a1, 0x50+seconds($sp)
lw $t9, (printf & 0xFFFF)($gp)
lui $a0, ($LC5 >> 16) # "Seconds: %d\n"
jalr $t9
la $a0, ($LC5 & 0xFFFF) # "Seconds: %d\n" ; branch delay slot
lw $ra, 0x50+var_4($sp)
or $at, $zero ; load delay slot, NOP
jr $ra
addiu $sp, 0x50
```

---

```
$LC0: .ascii "Year: %d\n"<0>
$LC1: .ascii "Month: %d\n"<0>
$LC2: .ascii "Day: %d\n"<0>
$LC3: .ascii "Hour: %d\n"<0>
$LC4: .ascii "Minutes: %d\n"<0>
```
This is an example where the branch delay slots can confuse us.
For example, there is the instruction `addiu $a1, 1900` at line 35 which adds 1900 to the year number. It’s executed before the corresponding JALR at line 34, do not forget about it.

**Structure as a set of values**

In order to illustrate that the structure is just variables laying side-by-side in one place, let’s rework our example while looking at the `tm` structure definition again: listing 1.333.

```c
#include <stdio.h>
#include <time.h>

void main()
{
    int tm_sec, tm_min, tm_hour, tm_mday, tm_mon, tm_year, tm_wday, tm_yday, tm_isdst;
    time_t unix_time;
    unix_time=time(NULL);
    localtime_r (&unix_time, &tm_sec);

    printf ("Year: %d\n", tm_year+1900);
    printf ("Month: %d\n", tm_mon);
    printf ("Day: %d\n", tm_mday);
    printf ("Hour: %d\n", tm_hour);
    printf ("Minutes: %d\n", tm_min);
    printf ("Seconds: %d\n", tm_sec);
}
```

N.B. The pointer to the `tm_sec` field is passed into `localtime_r`, i.e., to the first element of the “structure”. The compiler warns us:

```
GCC_tm2.c: In function 'main':
GCC_tm2.c:11:5: warning: passing argument 2 of 'localtime_r' from incompatible pointer type [\(\swerf\) enabled by default]
In file included from GCC_tm2.c:2:0:
/usr/include/time.h:59:12: note: expected 'struct tm *' but argument is of type 'int *'
```

But nevertheless, it generates this:

```
main proc near
var_30 = dword ptr -30h
var_2C = dword ptr -2Ch
unix_time = dword ptr -1Ch
tm_sec = dword ptr -18h
tm_min = dword ptr -14h
tm_hour = dword ptr -10h
tm_mday = dword ptr -0Ch
tm_mon = dword ptr -8
 tm_year = dword ptr -4

push ebp
mov ebp, esp
and esp, 0FFFFFFF0h
sub esp, 30h
```

This code is identical to what we saw previously and it is not possible to say, was it a structure in original source code or just a pack of variables.

And this works. However, it is not recommended to do this in practice. Usually, non-optimizing compilers allocates variables in the local stack in the same order as they were declared in the function.

Nevertheless, there is no guarantee.

By the way, some other compiler may warn about the `tm_year`, `tm_mon`, `tm_mday`, `tm_hour`, `tm_min` variables, but not `tm_sec` are used without being initialized.

Indeed, the compiler is not aware that these are to be filled by `localtime_r()` function.

We chose this example, since all structure fields are of type `int`.

This would not work if structure fields are 16-bit (`WORD`), like in the case of the SYSTEMTIME structure—`GetSystemTime()` will fill them incorrectly (because the local variables are aligned on a 32-bit boundary). Read more about it in next section: "Fields packing in structure" (1.24.4 on page 359).

So, a structure is just a pack of variables laying in one place, side-by-side. We could say that the structure is the instruction to the compiler, directing it to hold variables in one place. By the way, in some very early C versions (before 1972), there were no structures at all [Dennis M. Ritchie, The development of the C language, (1993)].

There is no debugger example here: it is just the same as you already saw.

**Structure as an array of 32-bit words**

```c
#include <stdio.h>
#include <time.h>

void main()
{
```

[161] Also available as [http://go.yurichev.com/17264](http://go.yurichev.com/17264)
1.24. STRUCTURES

```c
struct tm t;
t time t unix_time;
int i;

unix_time=time(NULL);
localtime_r (&unix_time, &t);
for (i=0; i<9; i++)
{
    int tmp=((int*)&t)[i];
    printf("0x%08X (%d)\n", tmp, tmp);
}
```

We just cast a pointer to structure to an array of int’s. And that works! We run the example at 23:51:45 26-July-2014.

0x0000002D (45)
0x00000033 (51)
0x00000017 (23)
0x0000001A (26)
0x00000006 (6)
0x00000072 (114)
0x00000006 (6)
0x000000CE (206)
0x00000001 (1)

The variables here are in the same order as they are enumerated in the definition of the structure: 1.333 on page 351.

Here is how it gets compiled:

Listing 1.339: Optimizing GCC 4.8.1

```
main proc near
    push ebp
    mov ebp, esp
    push esi
    push ebx
    and esp, 0FFFFFFF0h
    sub esp, 40h
    mov dword ptr [esp], 0 ; timer
    lea ebx, [esp+14h]
    call _time
    lea esi, [esp+38h]
    mov [esp+4], ebx ; tp
    mov [esp+10h], eax
    lea eax, [esp+10h]
    mov [esp], eax ; timer
    call _localtime_r
    nop
    lea esi, [esi+0] ; NOP
loc_80483D8:
; EBX here is pointer to structure, ESI is the pointer to the end of it.
    mov eax, [ebx] ; get 32-bit word from array
    add ebx, 4 ; next field in structure
    mov dword ptr [esp+4], offset a0x08xD ; "0x%08X (%d)\n"
    mov dword ptr [esp], 1
    mov [esp+0Ch], eax ; pass value to printf()
    mov [esp+8], eax ; pass value to printf()
    call __printf_chk
    cmp ebx, esi ; meet structure end?
    jnz short loc_80483D8 ; no - load next value then
    lea esp, [ebp-8]
    pop ebp
    pop esi
    pop ebp
main endp
```
1.24. STRUCTURES

Indeed: the space in the local stack is first treated as a structure, and then it’s treated as an array. It’s even possible to modify the fields of the structure through this pointer. And again, it’s dubiously hackish way to do things, not recommended for use in production code.

Exercise

As an exercise, try to modify (increase by 1) the current month number, treating the structure as an array.

Structure as an array of bytes

We can go even further. Let’s cast the pointer to an array of bytes and dump it:

```c
#include <stdio.h>
#include <time.h>

void main()
{
    struct tm t;
    time_t unix_time;
    int i, j;

    unix_time = time(NULL);
    localtime_r (&unix_time, &t);
    for (i=0; i<9; i++)
    {
        for (j=0; j<4; j++)
            printf("0x%02X ", ((unsigned char*)&t)[i*4+j]);
        printf(\n"");
    }
};
```

0x2D 0x00 0x00 0x00
0x33 0x00 0x00 0x00
0x17 0x00 0x00 0x00
0x1A 0x00 0x00 0x00
0x06 0x00 0x00 0x00
0x72 0x00 0x00 0x00
0x06 0x00 0x00 0x00
0xCE 0x00 0x00 0x00
0x01 0x00 0x00 0x00

We also run this example at 23:51:45 26-July-2014. The values are just the same as in the previous dump (1.24.3 on the previous page), and of course, the lowest byte goes first, because this is a little-endian architecture (2.8 on page 464).

Listing 1.340: Optimizing GCC 4.8.1

```assembly
main proc near
    push ebp
    mov ebp, esp
    push edi
    push esi
    push ebx
    and esp, 0FFFFFFF0h
    sub esp, 40h
    mov DWORD PTR [esp], 0 ; timer
    lea esi, [esp+14h]
    call _time
    lea edi, [esp+38h] ; struct end
    mov [esp+4], esi ; tp
    mov [esp+10h], eax
```

162The time and date are the same for demonstration purposes. Byte values are fixed up.
1.24. STRUCTURES

```assembly
lea  eax, [esp+10h]
mov  [esp], eax ; timer
call _localtime_r
lea  esi, [esi+0] ; NOP

; ESI here is the pointer to structure in local stack. EDI is the pointer to structure end.
loc_8048408:
xor  ebx, ebx ; j=0

loc_804840A:
movzx eax, byte ptr [esi+ebx] ; load byte
add  ebx, 1 ; j=j+1
mov  dword ptr [esp+4], offset a0x02x ; "0x%02X
mov  dword ptr [esp], 1
mov  [esp+8], eax ; pass loaded byte to printf()
call ___printf_chk
cmp  ebx, 4
jnz  short loc_804840A

; print carriage return character (CR)
mov  dword ptr [esp], 0Ah ; c
add  esi, 4
call _putchar
cmp  esi, edi ; meet struct end?
jnz  short loc_804840A
lea  esp, [ebp-0Ch]
pop  ebx
pop  esi
pop  edi
pop  ebp
retn

main  endp
```

1.24.4 Fields packing in structure

One important thing is fields packing in structures\(^\text{163}\).

Let's take a simple example:

```c
#include <stdio.h>

struct s
{
    char a;
    int b;
    char c;
    int d;
};

void f(struct s s)
{
    printf ("a=%d; b=%d; c=%d; d=%d\n", s.a, s.b, s.c, s.d);
}

int main()
{
    struct s tmp;
    tmp.a=1;
    tmp.b=2;
    tmp.c=3;
    tmp.d=4;
    f(tmp);
}
```

As we see, we have two \textit{char} fields (each is exactly one byte) and two more — \textit{int} (each — 4 bytes).

\(^{163}\text{See also: Wikipedia: Data structure alignment}\)
This compiles to:

Listing 1.341: MSVC 2012 /GS- /Ob0

We pass the structure as a whole, but in fact, as we can see, the structure is being copied to a temporary one (a place in stack is allocated in line 10 for it, and then all 4 fields, one by one, are copied in lines 12 ... 19), and then its pointer (address) is to be passed.

The structure is copied because it's not known whether the f() function going to modify the structure or not. If it gets changed, then the structure in main() has to remain as it has been.

We could use C/C++ pointers, and the resulting code will be almost the same, but without the copying.

As we can see, each field's address is aligned on a 4-byte boundary. That's why each char occupies 4 bytes here (like int). Why? Because it is easier for the CPU to access memory at aligned addresses and to cache data from it.

However, it is not very economical.

Let's try to compile it with option (/Zp1) (/Zp[n] pack structures on n-byte boundary).

Listing 1.342: MSVC 2012 /GS- /Zp1
Now the structure takes only 10 bytes and each char value takes 1 byte. What does it give to us? Size economy. And as drawback —the CPU accessing these fields slower than it could.

The structure is also copied in main(). Not field-by-field, but directly 10 bytes, using three pairs of MOV. Why not 4?

The compiler decided that it’s better to copy 10 bytes using 3 MOV pairs than to copy two 32-bit words and two bytes using 4 MOV pairs.

By the way, such copy implementation using MOV instead of calling the memcpy() function is widely used, because it’s faster than a call to memcpy()—for short blocks, of course: 3.11.1 on page 511.

As it can be easily guessed, if the structure is used in many source and object files, all these must be compiled with the same convention about structures packing.

Aside from MSVC /Zp option which sets how to align each structure field, there is also the #pragma pack compiler option, which can be defined right in the source code. It is available in both MSVC164 and GCC165.

Let’s get back to the SYSTEMTIME structure that consists of 16-bit fields. How does our compiler know to pack them on 1-byte alignment boundary?

WinNT.h file has this:

```
#include "pshpack1.h"
```

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1.24. STRUCTURES

And this:

Listing 1.344: WinNT.h
#include "pshpack4.h" // 4 byte packing is the default

The file PshPack1.h looks like:

Listing 1.345: PshPack1.h
#if ! (defined(lint) || defined(RC_INVOKED))
#if ( _MSC_VER >= 800 && !defined(_M_I86)) || defined(_PUSHPOP_SUPPORTED)
#pragma warning(disable:4103)
#if !(defined( MIDL_PASS )) || defined( __midl )
#pragma pack(push,1)
#else
#pragma pack(1)
#else
#pragma pack(1)
#endif
#endif /* ! (defined(lint) || defined(RC_INVOKED)) */

This tell the compiler how to pack the structures defined after `#pragma pack`.
Let's try our example (where the fields are aligned by default (4 bytes)) in OllyDbg:

1.24. STRUCTURES

OllyDbg + fields are packed by default

Figure 1.105: OllyDbg: Before printf() execution

We see our 4 fields in the data window.

But where do the random bytes (0x30, 0x37, 0x01) come from, that are next to the first (a) and third (c) fields?

By looking at our listing 1.341 on page 360, we can see that the first and third fields are char, therefore only one byte is written, 1 and 3 respectively (lines 6 and 8).

The remaining 3 bytes of the 32-bit words are not being modified in memory! Hence, random garbage is left there.

This garbage doesn’t influence the printf() output in any way, because the values for it are prepared using the MOVVSX instruction, which takes bytes, not words: listing.1.341 (lines 34 and 38).

By the way, the MOVVSX (sign-extending) instruction is used here, because char is signed by default in MSVC and GCC. If the unsigned char data type or uint8_t was used here, MOVZX instruction would have been used instead.
OllyDbg + fields aligning on 1 byte boundary

Things are much clearer here: 4 fields occupy 10 bytes and the values are stored side-by-side.

ARM

Optimizing Keil 6/2013 (Thumb mode)

As we may recall, here a structure is passed instead of pointer to one, and since the first 4 function arguments in ARM are passed via registers, the structure’s fields are passed via R0-R3.

LDRB loads one byte from memory and extends it to 32-bit, taking its sign into account. This is similar to MOVSX in x86. Here it is used to load fields \( a \) and \( c \) from the structure.
One more thing we spot easily is that instead of function epilogue, there is jump to another function’s epilogue! Indeed, that was quite different function, not related in any way to ours, however, it has exactly the same epilogue (probably because, it hold 5 local variables too \((5 \times 4 = 0x14)\)).

Also it is located nearby (take a look at the addresses).

Indeed, it doesn’t matter which epilogue gets executed, if it works just as we need.

Apparently, Keil decides to reuse a part of another function to economize.

The epilogue takes 4 bytes while jump—only 2.

**ARM + Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)**

Listing 1.347: Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```assembly
var_C = -0xC

PUSH {R7,LR}
MOV R7, SP
SUB SP, SP, #4
MOV R1, R0 ; a
MOVW R0, #0xF10 ; "a=%d; b=%d; c=%d; d=%d\n"
SXTB R1, R1 ; prepare a
MOVT.W R0, #0
STR R3, [SP,#0xC+var_C] ; place d to stack for printf()
ADD R0, PC ; format-string
SXTB R3, R2 ; prepare c
MOV R2, R9 ; b
BLX _printf
ADD SP, SP, #4
POP {R7,PC}
```

SXTB (Signed Extend Byte) is analogous to MOVVSX in x86. All the rest—just the same.

**MIPS**

Listing 1.348: Optimizing GCC 4.4.5 (IDA)

```assembly
16
f:
17
var_18 = -0x18
18
var_10 = -0x10
19
var_4 = -4
20
arg_0 = 0
21
arg_4 = 4
22
arg_8 = 8
23
arg_C = 0xC
24

; $a0=s.a
25
; $a1=s.b
26
; $a2=s.c
27
; $a3=s.d
28
lui $gp, (__gnu_local_gp >> 16)
29
addiu $sp, -0x28
30
la $gp, (__gnu_local_gp & 0xFFFF)
31
sw $ra, 0x28+var_4($sp)
32
sw $gp, 0x28+var_10($sp)
33
; prepare byte from 32-bit big-endian integer:
34
sra $t0, $a0, 24
35
move $v1, $a1
36
; prepare byte from 32-bit big-endian integer:
37
sra $t9, (printf & 0xFFFF)($gp)
38
sw $a0, 0x28+arg_0($sp)
39
lui $a0, ($LC0 >> 16) # "a=%d; b=%d; c=%d; d=%d\n"
40
sw $a3, 0x28+var_18($sp)
```
1.24. **STRUCTURES**

Structure fields come in registers $A0..A3 and then get reshuffled into $A1..A3 for printf(), while 4th field (from $A3) is passed via local stack using SW.

But there are two SRA ("Shift Word Right Arithmetic") instructions, which prepare char fields. Why?

MIPS is a big-endian architecture by default 2.8 on page 464, and the Debian Linux we work in is big-endian as well.

So when byte variables are stored in 32-bit structure slots, they occupy the high 31..24 bits.

And when a char variable needs to be extended into a 32-bit value, it must be shifted right by 24 bits. char is a signed type, so an arithmetical shift is used here instead of logical.

**One more word**

Passing a structure as a function argument (instead of a passing pointer to structure) is the same as passing all structure fields one by one.

If the structure fields are packed by default, the f() function can be rewritten as:

```c
void f(char a, int b, char c, int d)
{
    printf ("a=%d; b=%d; c=%d; d=%d\n", a, b, c, d);
};
```

And that leads to the same code.

### 1.24.5 Nested structures

Now what about situations when one structure is defined inside of another?

```c
#include <stdio.h>

struct inner_struct
{
    int a;
    int b;
};

struct outer_struct
{
    char a;
    int b;
    struct inner_struct c;
    char d;
    int e;
};

void f(struct outer_struct s)
{
    printf ("a=%d; b=%d; c.a=%d; c.b=%d; d=%d; e=%d\n", 
            s.a, s.b, s.c.a, s.c.b, s.d, s.e);
}
```
1.24. STRUCTURES

```c
int main()
{
    struct outer_struct s;
    s.a=1;
    s.b=2;
    s.c.a=100;
    s.c.b=101;
    s.d=3;
    s.e=4;
    f(s);
}
```

...in this case, both inner_struct fields are to be placed between the a, b and d, e fields of the outer_struct.

Let's compile (MSVC 2010):

Listing 1.349: Optimizing MSVC 2010 /Ob0

```assembly
$sG2802 DB 'a=%d; b=%d; c.a=%d; c.b=%d; d=%d; e=%d', 0aH, 00H

_TEXT SEGMENT
   s$ = 8
   _f PROC
       mov eax, DWORD PTR _s$[esp+16]
       movsx ecx, BYTE PTR _s$[esp+12]
       mov edx, DWORD PTR _s$[esp+8]
       push eax
       mov eax, DWORD PTR _s$[esp+8]
       push ecx
       mov ecx, DWORD PTR _s$[esp+8]
       push edx
       movsx edx, BYTE PTR _s$[esp+8]
       push eax
       push ecx
       push edx
       push OFFSET $SG2802 ; 'a=%d; b=%d; c.a=%d; c.b=%d; d=%d; e=%d'
       call _printf
       add esp, 28
       ret 0
   _f ENDP

   _s$ = -24
   _main PROC
       sub esp, 24
       push ebx
       push esi
       push edi
       mov ecx, 2
       sub esp, 24
       mov eax, esp
       ; from this moment, EAX is synonymous to ESP:
       mov BYTE PTR _s$[esp+60], 1
       mov ebx, DWORD PTR _s$[esp+60]
       mov DWORD PTR [eax], ebx
       mov DWORD PTR [eax+4], ecx
       lea edx, DWORD PTR [ecx+98]
       lea esi, DWORD PTR [ecx+99]
       lea edi, DWORD PTR [ecx+2]
       mov DWORD PTR [eax+8], edx
       mov BYTE PTR _s$[esp+76], 3
       mov ecx, DWORD PTR _s$[esp+76]
       mov DWORD PTR [eax+12], esi
       mov DWORD PTR [eax+16], ecx
       mov DWORD PTR [eax+20], edi
       call _f
       add esp, 24
       pop edi
       pop esi
       xor eax, eax
   _main ENDP
```

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One curious thing here is that by looking onto this assembly code, we do not even see that another structure was used inside of it! Thus, we would say, nested structures are unfolded into linear or one-dimensional structure.

Of course, if we replace the struct inner_struct c; declaration with struct inner_struct *c; (thus making a pointer here) the situation will be quite different.
Let's load the example into OllyDbg and take a look at `outer_struct` in memory:

![OllyDbg: Before printf() execution](image)

That's how the values are located in memory:

- `(outer_struct.a)` (byte) 1 + 3 bytes of random garbage;
- `(outer_struct.b)` (32-bit word) 2;
- `(inner_struct.a)` (32-bit word) 0x64 (100);
- `(inner_struct.b)` (32-bit word) 0x65 (101);
- `(outer_struct.d)` (byte) 3 + 3 bytes of random garbage;
- `(outer_struct.e)` (32-bit word) 4.

### 1.24.6 Bit fields in a structure

#### CPUID example

The C/C++ language allows to define the exact number of bits for each structure field. It is very useful if one needs to save memory space. For example, one bit is enough for a `bool` variable. But of course, it is not rational if speed is important.

Let's consider the `CPUID` instruction example. This instruction returns information about the current CPU and its features.

If the `EAX` is set to 1 before the instruction's execution, `CPUID` returning this information packed into the `EAX` register:

<table>
<thead>
<tr>
<th>Bit Field</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:0</td>
<td>Stepping</td>
</tr>
<tr>
<td>7:4</td>
<td>Model</td>
</tr>
<tr>
<td>11:8</td>
<td>Family</td>
</tr>
<tr>
<td>13:12</td>
<td>Processor Type</td>
</tr>
<tr>
<td>19:16</td>
<td>Extended Model</td>
</tr>
<tr>
<td>27:20</td>
<td>Extended Family</td>
</tr>
</tbody>
</table>

MSVC 2010 has `CPUID` macro, but GCC 4.4.1 does not. So let's make this function by ourselves for GCC with the help of its built-in assembler\(^\text{167}\).


```c
#include <stdio.h>

#ifdef __GNUC__
static inline void cpuid(int code, int *a, int *b, int *c, int *d) {
    asm volatile("cpuid":"=a"(*a),"=b"(*b),"=c"(*c),"=d"(*d):"a"(code));
}
#endif

#ifdef _MSC_VER
#include <intrin.h>
#endif

struct CPUID_1_EAX
{
    unsigned int stepping:4;
    unsigned int model:4;
    unsigned int family_id:4;
    unsigned int processor_type:2;
    unsigned int reserved1:2;
    unsigned int extended_model_id:4;
    unsigned int extended_family_id:8;
    unsigned int reserved2:4;
};

int main()
{
    struct CPUID_1_EAX *tmp;
    int b[4];

    #ifdef _MSC_VER
    __cpuid(b,1);
    #endif

    #ifdef __GNUC__
    cpuid (1, &b[0], &b[1], &b[2], &b[3]);
    #endif

    tmp=(struct CPUID_1_EAX *)&b[0];
    printf ("stepping=%d\n", tmp->stepping);
    printf ("model=%d\n", tmp->model);
    printf ("family_id=%d\n", tmp->family_id);
    printf ("processor_type=%d\n", tmp->processor_type);
    printf ("extended_model_id=%d\n", tmp->extended_model_id);
    printf ("extended_family_id=%d\n", tmp->extended_family_id);
    return 0;
};
```

After CPUID fills EAX/EBX/ECX/EDX, these registers are to be written in the b[] array. Then, we have a pointer to the CPUID_1_EAX structure and we point it to the value in EAX from the b[] array.

In other words, we treat a 32-bit int value as a structure. Then we read specific bits from the structure.

**MSVC**

Let’s compile it in MSVC 2008 with /Ox option:

Listing 1.350: Optimizing MSVC 2008

```c
_b$ = -16 ; size = 16
_main PROC
    sub esp, 16
    push ebx
    xor ecx, ecx
    mov eax, 1
    cpuid
```
1.24. STRUCTURES

push esi
lea esi, DWORD PTR _b$[esp+24]
mov DWORD PTR [esi], eax
mov DWORD PTR [esi+4], ebx
mov DWORD PTR [esi+8], ecx
mov DWORD PTR [esi+12], edx

mov esi, DWORD PTR _b$[esp+24]
mov eax, esi
and eax, 15
push eax
push OFFSET $SG15435 ; 'stepping=%d', 0aH, 00H
call _printf

mov ecx, esi
shr ecx, 4
and ecx, 15
push ecx
push OFFSET $SG15436 ; 'model=%d', 0aH, 00H
call _printf

mov edx, esi
shr edx, 8
and edx, 15
push edx
push OFFSET $SG15437 ; 'family_id=%d', 0aH, 00H
call _printf

mov eax, esi
shr eax, 12
and eax, 3
push eax
push OFFSET $SG15438 ; 'processor_type=%d', 0aH, 00H
call _printf

mov ecx, esi
shr ecx, 16
and ecx, 15
push ecx
push OFFSET $SG15439 ; 'extended_model_id=%d', 0aH, 00H
call _printf

shr esi, 20
and esi, 255
push esi
push OFFSET $SG15440 ; 'extended_family_id=%d', 0aH, 00H
call _printf
add esp, 48
pop esi

xor eax, eax
pop ebx

add esp, 16
ret 0

_main ENDP

The SHR instruction shifting the value in EAX by the number of bits that must be skipped, e.g., we ignore some bits at the right side.

The AND instruction clears the unneeded bits on the left, or, in other words, leaves only those bits in the EAX register we need.
Let’s load our example into OllyDbg and see, what values are set in EAX/EBX/ECX/EDX after the execution of CPUID:

![OllyDbg: After CPUID execution](image)

EAX has 0x000206A7 (my CPU is Intel Xeon E3-1220).

This is 0b00000000000000100000011010100111 in binary form.

Here is how the bits are distributed by fields:

<table>
<thead>
<tr>
<th>Field</th>
<th>Binary Form</th>
<th>Decimal Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>reserved2</td>
<td>0000</td>
<td>0</td>
</tr>
<tr>
<td>extended_family_id</td>
<td>00000000</td>
<td>0</td>
</tr>
<tr>
<td>extended_model_id</td>
<td>0010</td>
<td>2</td>
</tr>
<tr>
<td>reserved1</td>
<td>00</td>
<td>0</td>
</tr>
<tr>
<td>processor_id</td>
<td>00</td>
<td>0</td>
</tr>
<tr>
<td>family_id</td>
<td>0110</td>
<td>6</td>
</tr>
<tr>
<td>model</td>
<td>1010</td>
<td>10</td>
</tr>
<tr>
<td>stepping</td>
<td>0111</td>
<td>7</td>
</tr>
</tbody>
</table>

**Listing 1.351: Console output**

```plaintext
stepping=7
model=10
family_id=6
processor_type=0
extended_model_id=2
extended_family_id=0
```

**GCC**

Let’s try GCC 4.4.1 with -O3 option.

**Listing 1.352: Optimizing GCC 4.4.1**

```assembly
main proc near ; DATA XREF: _start+17
    push ebp
    mov ebp, esp
    and esp, 0FFFFFFF0h
    push esi
```
Almost the same. The only thing worth noting is that GCC somehow combines the calculation of extended_model_id and extended_family_id into one block, instead of calculating them separately before each printf() call.

Handling float data type as a structure

As we already noted in the section about FPU (1.19 on page 218), both float and double types consist of a sign, a significant (or fraction) and an exponent. But will we be able to work with these fields directly? Let’s try this with float.

```
31 30 23 22 0

| exponent | mantissa or fraction |
```
The `float_as_struct` structure occupies the same amount of memory as `float`, i.e., 4 bytes or 32 bits.

Now we are setting the negative sign in the input value and also, by adding 2 to the exponent, we thereby multiply the whole number by $2^n$ (n here is 2).

Let’s compile in MSVC 2008 without optimization turned on:

```
Listing 1.353: Non-optimizing MSVC 2008
```
1.24. STRUCTURES

add eax, 2 ; add 2 to it
and eax, 255 ; 000000ffH
shl eax, 23 ; 00000017H - shift result to place of bits 30:23
mov ecx, DWORD PTR _t$[ebp]
and ecx, -2139095041 ; 807fffffH - drop exponent

; add original value without exponent with new calculated exponent:
or ecx, eax
mov DWORD PTR _t$[ebp], ecx
push 4
lea edx, DWORD PTR _t$[ebp]
push edx
lea eax, DWORD PTR _f$[ebp]
push eax
call _memcpy
add esp, 12
fld DWORD PTR _f$[ebp]
mov esp, ebp
pop ebp
ret 0
?f@@YAMM@Z ENDP ; f

A bit redundant. If it was compiled with /Ox flag there would be no memcpy() call, the f variable is used directly. But it is easier to understand by looking at the unoptimized version.

What would GCC 4.4.1 with -O3 do?

Listing 1.354: Optimizing GCC 4.4.1

; f(float)
public _Z1ff
_Z1ff proc near
var_4 = dword ptr -4
arg_0 = dword ptr 8

push ebp
mov ebp, esp
sub esp, 4
mov eax, [ebp+arg_0]
or eax, 80000000h ; set minus sign
mov edx, eax
and eax, 807FFFFFh ; leave only sign and significand in EAX
shr edx, 23 ; prepare exponent
add edx, 2 ; add 2
movzx edx, dl ; clear all bits except 7:0 in EAX
shl edx, 23 ; shift new calculated exponent to its place
or eax, edx ; join new exponent and original value without exponent
mov [ebp+var_4], eax
fld [ebp+var_4]
leave
ret
_Z1ff endp

public main
main proc near
push ebp
mov ebp, esp
and esp, 0FFFFFFF0h
sub esp, 10h
fld ds:dword_8048614 ; -4.936
fstp qword ptr [esp+8]
mov dword ptr [esp+4], offset asc_8048610 ; "%f\n"
mov dword ptr [esp], 1
call __printf_chk
xor eax, eax
leave
retn
1.25. **UNIONS**

The \( f() \) function is almost understandable. However, what is interesting is that GCC was able to calculate the result of \( f(1.234) \) during compilation despite all this hodge-podge with the structure fields and prepared this argument to printf() as precalculated at compile time!

### 1.24.7 Exercises

- [http://challenges.re/71](http://challenges.re/71)
- [http://challenges.re/72](http://challenges.re/72)

### 1.25 Unions

C/C++ union is mostly used for interpreting a variable (or memory block) of one data type as a variable of another data type.

#### 1.25.1 Pseudo-random number generator example

If we need float random numbers between 0 and 1, the simplest thing is to use a PRNG like the Mersenne twister. It produces random unsigned 32-bit values (in other words, it produces random 32 bits). Then we can transform this value to float and then divide it by \( RAND\_MAX \) (\( 0xFFFFFFFF \) in our case)—we getting a value in the 0..1 interval.

But as we know, division is slow. Also, we would like to issue as few FPU operations as possible. Can we get rid of the division?

Let's recall what a floating point number consists of: sign bit, significand bits and exponent bits. We just have to store random bits in all significand bits to get a random float number!

The exponent cannot be zero (the floating number is denormalized in this case), so we are storing 0b01111111 to exponent—this means that the exponent is 1. Then we filling the significand with random bits, set the sign bit to 0 (which means a positive number) and voilà. The generated numbers is to be between 1 and 2, so we must also subtract 1.

A very simple linear congruential random numbers generator is used in my example\(^{168}\), it produces 32-bit numbers. The PRNG is initialized with the current time in UNIX timestamp format.

Here we represent the float type as an union—it is the C/C++ construction that enables us to interpret a piece of memory as different types. In our case, we are able to create a variable of type union and then access to it as it is float or as it is uint32_t. It can be said, it is just a hack. A dirty one.

The integer PRNG code is the same as we already considered: **1.23 on page 338**. So this code in compiled form is omitted.

```c
#include <stdio.h>
#include <stdint.h>
#include <time.h>

// integer PRNG definitions, data and routines:

// constants from the Numerical Recipes book
const uint32_t RNG_a=1664525;
const uint32_t RNG_c=1013904223;
uint32_t RNG_state; // global variable

void my_srand(uint32_t i)
{
    RNG_state=i;
}

uint32_t my_rand()
{
    return RNG_a*Rua+RNG_c;
}
```

\(^{168}\)the idea was taken from: [http://go.yurichev.com/17308](http://go.yurichev.com/17308)
1.25. UNIONS

```c
RNG_state = RNG_state * RNG_a + RNG_c;
return RNG_state;
```

// FPU PRNG definitions and routines:

```c
union uint32_t_float
{
    uint32_t i;
    float f;
};
float float_rand()
{
    union uint32_t_float tmp;
    tmp.i = my_rand() & 0x007fffff | 0x3F800000;
    return tmp.f - 1;
}
```

// test

```c
int main()
{
    my_srand(time(NULL)); // PRNG initialization
    for (int i = 0; i < 100; i++)
        printf("%f\n", float_rand());
    return 0;
}
```

x86

Listing 1.355: Optimizing MSVC 2010

```assembly
$SG4238 DB '%f', 0AH, 00H
__real@3ff0000000000000 DQ 03ff0000000000000r ; 1
tv130 = -4
_tmp$ = -4
?float_rand@YAMXZ PROC
    push ecx
    call ?my_rand@YAI
    ; EAX = pseudorandom value
    and eax, 8388607 ; 007fffffH
    or eax, 1065353216 ; 3f800000H
    ; EAX = pseudorandom value & 0x007fffff | 0x3f800000
    ; store it into local stack:
    mov DWORD PTR _tmp$[esp+4], eax
    ; reload it as float point number:
    fld DWORD PTR _tmp$[esp+4]
    ; subtract 1.0:
    fsub QWORD PTR __real@3ff00000000000000r
    ; store value we got into local stack and reload it:
    fstp DWORD PTR tv130[esp+4]; ; these instructions are redundant
    fld DWORD PTR tv130[esp+4]; /
    pop ecx
    ret 0
?float_rand@YAMXZ ENDP
_main PROC
    push esi
    xor eax, eax
    call __time
    push eax
    call ?my_srand@YAXI@Z
    add esp, 4
```

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1.25. UNIONS

```assembly
mov esi, 100
$LL3@main:
call ?float_rand@@YAMXZ
sub esp, 8
fstp QWORD PTR [esp]
push OFFSET $SG4238
call _printf
add esp, 12
dec esi
jne SHORT $LL3@main
xor eax, eax
pop esi
ret 0
_main ENDP
```

Function names are so strange here because this example was compiled as C++ and this is name mangling in C++, we will talk about it later: 3.18.1 on page 542. If we compile this in MSVC 2012, it uses the SIMD instructions for the FPU, read more about it here: 1.31.5 on page 438.

MIPS

Listing 1.356: Optimizing GCC 4.4.5

```assembly
float_rand:
var_10  = -0x10
var_4   = -4

   lui   $gp, (__gnu_local_gp >> 16)
  addiu $sp, -0x20
    la   $gp, (__gnu_local_gp & 0xFFFF)
    sw   $ra, 0x20+var_4($sp)
    sw   $gp, 0x20+var_10($sp)

; call my_rand():
   jal   my_rand
    or  $at, $zero ; branch delay slot, NOP
$v0=32-bit pseudorandom value
   li    $v1, 0x7FFFFF
$v1=0x7FFFFF
   and  $v1, $v0, $v1
$v1=pseudorandom value & 0x7FFFFF
   lui   $a0, 0x3F80
$a0=0x3F800000
   or   $v1, $a0
$v1=pseudorandom value & 0x7FFFFF | 0x3F800000
; matter of the following instruction is still hard to get:
   lui   $v0, ($LC0 >> 16)
$LC0 = 1.0
; load 1.0 into $f0:
   lwc1  $f0, $LC0
; move value from $v1 to coprocessor 1 (into register $f2)
; it behaves like bitwise copy, no conversion done:
   mtc1  $v1, $f2
   lw    $ra, 0x20+var_4($sp)
; subtract 1.0. leave result in $f0:
   sub.s $f0, $f2, $f0
   jr     $ra
   addiu $sp, 0x20 ; branch delay slot
main:
var_18  = -0x18
var_10  = -0x10
var_C   = -0xC
var_8   = -8
var_4   = -4
   lui   $gp, (__gnu_local_gp >> 16)
  addiu $sp, -0x28
```

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There is also an useless LUI instruction added for some weird reason. We considered this artifact earlier: 1.19.5 on page 230.

ARM (ARM mode)
1.25. UNIONS

```assembly
MOV R0, #0
BL time
BL my_srand
MOV R4, #0x64 ; 'd'
```

```assembly
loc_78
BL float_rand
; S0=pseudorandom value
LDR R0, =aF ; "%f"
; convert float type value into double type value (printf() will need it):
FCVTDS D7, S0
; bitwise copy from D7 into R2/R3 pair of registers (for printf()):
FMRRD R2, R3, D7
BL printf
SUBS R4, R4, #1
BNE loc_78
MOV R0, R4
LDMFD SP!, {R4,PC}
```

We'll also make a dump in objdump and we'll see that the FPU instructions have different names than in IDA. Apparently, IDA and binutils developers used different manuals? Perhaps it would be good to know both instruction name variants.

Listing 1.358: Optimizing GCC 4.6.3 (objdump)

```assembly
00000038 <float_rand>:
    38: e92d4008 push {r3, lr}
    3c: ebfffffe bl 10 <my_rand>
    40: ed9f0a05 vldr s0, [pc, #20] ; 5c <float_rand+0x24>
    44: e3c034ff bic r3, r0, #-16777216 ; 0xff000000
    48: e3c33502 bic r3, r3, #8388608 ; 0x800000
    4c: e38335fe orr r3, r3, #1065353216 ; 0x3f800000
    50: ee073a90 vmov s15, r3
    54: ee370ac0 vsub.f32 s0, s15, s0
    58: e8bd8008 pop {r3, pc}
    5c: 3f800000 svccc 0x00800000
```

```assembly
00000000 <main>:
    0: e92d4010 push {r4, lr}
    4: e3a00000 mov r0, #0
    8: ebfffffe bl 0 <time>
    c: ebfffffe bl 0 <main>
    10: e3a04064 mov r4, #100 ; 0x64
    14: ebfffffe bl 38 <main+0x38>
    18: e59f0018 ldr r0, [pc, #24] ; 38 <main+0x38>
    1c: eeab77ac0 vcvt.f64.f32 d7, s0
    20: ec532b17 vmov r2, r3, d7
    24: ebfffffe bl 0 <printf>
    28: e2544001 subs r4, r4, #1
    2c: 1afffffe bne 14 <main+0x14>
    30: e1a00004 mov r0, r4
    34: e8bd8010 pop {r4, pc}
    38: 00000000 andeq r0, r0, r0
```

The instructions at 0x5c in `float_rand()` and at 0x38 in `main()` are (pseudo-)random noise.

### 1.25.2 Calculating machine epsilon

The machine epsilon is the smallest possible value the FPU can work with. The more bits allocated for floating point number, the smaller the machine epsilon. It is $2^{-23} = 1.19e-07$ for `float` and $2^{-52} = 2.22e-16$ for `double`. See also: [Wikipedia article](#).

It’s interesting, how easy it’s to calculate the machine epsilon:

```c
#include <stdio.h>
#include <stdint.h>
```

```c
```
What we do here is just treat the fraction part of the IEEE 754 number as integer and add 1 to it. The resulting floating number is equal to starting value + machine epsilon, so we just have to subtract the starting value (using floating point arithmetic) to measure, what difference one bit reflects in the single precision (float). The union serves here as a way to access IEEE 754 number as a regular integer. Adding 1 to it in fact adds 1 to the fraction part of the number, however, needless to say, overflow is possible, which will add another 1 to the exponent part.

### x86

```
Listing 1.359: Optimizing MSVC 2010

tv130 = 8
_v$ = 8
_start$ = 8
_calculate_machine_epsilon PROC
    fld DWORD PTR _start$[esp-4]
    fst DWORD PTR _v$[esp-4] ; this instruction is redundant
    inc DWORD PTR _v$[esp-4]
    fsbbr DWORD PTR _v$[esp-4]
    fstp DWORD PTR tv130[esp-4] ; \ this instruction pair is also redundant
    fld DWORD PTR tv130[esp-4] ; /
    ret 0
_calculate_machine_epsilon ENDP
```

The second FST instruction is redundant: there is no necessity to store the input value in the same place (the compiler decided to allocate the v variable at the same point in the local stack as the input argument). Then it is incremented with INC, as it is a normal integer variable. Then it is loaded into the FPU as a 32-bit IEEE 754 number, FSUBR does the rest of job and the resulting value is stored in ST0. The last FSTP/FLD instruction pair is redundant, but the compiler didn’t optimize it out.

### ARM64

Let’s extend our example to 64-bit:

```c
#include <stdio.h>
#include <stdint.h>

typedef union
{
    uint64_t i;
    double d;
} uint_double;

double calculate_machine_epsilon(double start)
{
    union uint_float v;
    v.f=start;
    v.i++;
    return v.f-start;
}
```
1.26. FSCALE REPLACEMENT

```c
v.d=start;
v.i++; return v.d-start;
}

void main()
{
 printf ("%g\n", calculate_machine_epsilon(1.0));
}
```

ARM64 has no instruction that can add a number to a FPU D-register, so the input value (that came in D0) is first copied into GPR, incremented, copied to FPU register D1, and then subtraction occurs.

```
calculate_machine_epsilon:
  fmov x0, d0 ; load input value of double type into X0
  add x0, x0, 1 ; X0++
  fmov d1, x0 ; move it to FPU register
  fsub d0, d1, d0 ; subtract
  ret
```

See also this example compiled for x64 with SIMD instructions: 1.31.4 on page 437.

**MIPS**

The new instruction here is MTC1 (“Move To Coprocessor 1”), it just transfers data from GPR to the FPU’s registers.

```
calculate_machine_epsilon:
  mfc1 $v0, $f12
  or $at, $zero ; NOP
  addiu $v1, $v0, 1
  mtc1 $v1, $f2
  jr $ra
  sub.s $f0, $f2, $f12 ; branch delay slot
```

**Conclusion**

It’s hard to say whether someone may need this trickery in real-world code, but as was mentioned many times in this book, this example serves well for explaining the IEEE 754 format and unions in C/C++.

### 1.26 FSCALE replacement

Agner Fog in his *Optimizing subroutines in assembly language / An optimization guide for x86 platforms* work 169 states that FSCALE FPU instruction (calculating $2^n$) may be slow on many CPUs, and he offers faster replacement.

Here is my translation of his assembly code to C/C++:

```c
#include <stdint.h>
#include <stdio.h>

union uint_float
{
  uint32_t i;
  float f;
};

float flt_2n(int N)
```

FScale replacement

{  
  union uint float tmp;
  tmp.i=(N<<23)+0x3f800000;
  return tmp.f;
};

struct float_as_struct
{
  unsigned int fraction : 23;
  unsigned int exponent : 8;
  unsigned int sign : 1;
};

float flt_2n_v2(int N)
{
  struct float_as_struct tmp;
  tmp.fraction=0;
  tmp.sign=0;
  tmp.exponent=N+0x7f;
  return *(float*)(&tmp);
};

union uint64_double
{
  uint64_t i;
  double d;
};

double dbl_2n(int N)
{
  union uint64_double tmp;
  tmp.i=((uint64_t)N<<52)+0x3ff0000000000000UL;
  return tmp.d;
};

struct double_as_struct
{
  uint64_t fraction : 52;
  int exponent : 11;
  int sign : 1;
};

double dbl_2n_v2(int N)
{
  struct double_as_struct tmp;
  tmp.fraction=0;
  tmp.sign=0;
  tmp.exponent=N+0x3ff;
  return *(double*)(&tmp);
};

int main()
{
  // 2^11=2048
  printf("%f\n", flt_2n(11));
  printf("%f\n", flt_2n_v2(11));
  printf("%lf\n", dbl_2n(11));
  printf("%lf\n", dbl_2n_v2(11));
};

FScale instruction may be faster in your environment, but still, it’s a good example of union's and the fact that exponent is stored in 2^n form, so an input n value is shifted to the exponent in IEEE 754 encoded number. Then exponent is then corrected with addition of 0x3f800000 or 0x3ff0000000000000.

The same can be done without shift using struct, but internally, shift operations still occurred.
1.27. **POINTERS TO FUNCTIONS**

### 1.26.1 Fast square root calculation

Another well-known algorithm where \( \textit{float} \) is interpreted as integer is fast calculation of square root.

Listing 1.362: The source code is taken from Wikipedia: [http://go.yurichev.com/17364](http://go.yurichev.com/17364)

```c
* and that int is 32 bits. */
float sqrt_approx(float z)
{
    int val_int = *(int*)&z; /* Same bits, but as an int */
    /*
    * To justify the following code, prove that
    * (((val_int / 2^m) - b) / 2) + b) * 2^m = ((val_int - 2^m) / 2) + ((b + 1) / 2) * 2^m
    * where
    * b = exponent bias
    * m = number of mantissa bits
    */
    val_int -= 1 << 23; /* Subtract 2^m. */
    val_int >>= 1; /* Divide by 2. */
    val_int += 1 << 29; /* Add ((b + 1) / 2) * 2^m. */
    return *(float*)&val_int; /* Interpret again as float */
}
```

As an exercise, you can try to compile this function and to understand, how it works.

There is also well-known algorithm of fast calculation of \( \frac{1}{\sqrt{x}} \). Algorithm became popular, supposedly, because it was used in Quake III Arena.

Algorithm description can be found in Wikipedia: [http://go.yurichev.com/17360](http://go.yurichev.com/17360).

### 1.27 Pointers to functions

A pointer to a function, as any other pointer, is just the address of the function’s start in its code segment. They are often used for calling callback functions\(^{170}\).

Well-known examples are:

- `qsort()`\(^{171}\), `atexit()`\(^{172}\) from the standard C library;
- *NIX OS signals\(^{173}\);
- thread starting: `CreateThread()` (win32), `pthread_create()` (POSIX);
- lots of win32 functions, like `EnumChildWindows()`\(^{174}\);
- lots of places in the Linux kernel, for example the filesystem driver functions are called via callbacks: [http://go.yurichev.com/17076](http://go.yurichev.com/17076)
- The GCC plugin functions are also called via callbacks: [http://go.yurichev.com/17077](http://go.yurichev.com/17077)
- Another example of function pointers is a table in the “dwm” Linux window manager that defines shortcuts. Each shortcut has a corresponding function to call if a specific key is pressed: GitHub. As we can see, such table is easier to handle than a large switch() statement.

So, the `qsort()` function is an implementation of quicksort in the C/C++ standard library. The function is able to sort anything, any type of data, as long as you have a function to compare these two elements and `qsort()` is able to call it.

---

\(^{170}\) wikipedia
\(^{171}\) wikipedia
\(^{172}\) wikipedia
\(^{173}\) http://go.yurichev.com/17073
\(^{174}\) wikipedia
\(^{175}\) MSDN
1.27. POINTERS TO FUNCTIONS

The comparison function can be defined as:

```
int (*compare)(const void *, const void *)
```

Let's use the following example:

```c
/* ex3 Sorting ints with qsort */
#include <stdio.h>
#include <stdlib.h>

int comp(const void * _a, const void * _b)
{
    const int *a=(const int *)_a;
    const int *b=(const int *)_b;

    if (*a==*b)
        return 0;
    else
        if (*a < *b)
            return -1;
        else
            return 1;
}

int main(int argc, char* argv[])
{
    int numbers[10]={1892,45,200,-98,4087,5,-12345,1087,88,-100000};
    int i;

    /* Sort the array */
    qsort(numbers,10,sizeof(int),comp) ;
    for (i=0;i<9;i++)
        printf("Number = %d\n",numbers[ i ]);
    return 0;
}
```

### 1.27.1 MSVC

Let's compile it in MSVC 2010 (some parts were omitted for the sake of brevity) with /Ox option:

```
Listing 1.363: Optimizing MSVC 2010: /GS- /MD

__a$ = 8 ; size = 4
__b$ = 12 ; size = 4

_comp PROC
    mov    eax, DWORD PTR __a$[esp-4]
    mov    ecx, DWORD PTR __b$[esp-4]
    mov    eax, DWORD PTR [eax]
    mov    ecx, DWORD PTR [ecx]
    cmp    eax, ecx
    jne    SHORT $LN4@comp
    xor    eax, eax
    ret    0
$LN4@comp:
    xor    edx, edx
    cmp    eax, ecx
    setge  dl
    lea    eax, DWORD PTR [edx+edx-1]
    ret    0
_comp ENDP

.numbers$ = -40 ; size = 40
_argc$ = 8 ; size = 4
_argv$ = 12 ; size = 4
_main PROC
    sub    esp, 40 ; 00000028H
```

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1.27. POINTERS TO FUNCTIONS

Nothing surprising so far. As a fourth argument, the address of label _comp is passed, which is just a place where comp() is located, or, in other words, the address of the very first instruction of that function.

How does qsort() call it?

Let’s take a look at this function, located in MSVCR80.DLL (a MSVC DLL module with C standard library functions):

Listing 1.364: MSVCR80.DLL

comp—is the fourth function argument. Here the control gets passed to the address in the comp argument. Before it, two arguments are prepared for comp(). Its result is checked after its execution.

That’s why it is dangerous to use pointers to functions. First of all, if you call qsort() with an incorrect function pointer, qsort() may pass control flow to an incorrect point, the process may crash and this bug will be hard to find.
1.27. POINTERS TO FUNCTIONS

The second reason is that the callback function types must comply strictly, calling the wrong function with wrong arguments of wrong types may lead to serious problems, however, the crashing of the process is not a problem here —the problem is how to determine the reason for the crash —because the compiler may be silent about the potential problems while compiling.
Let's load our example into OllyDbg and set a breakpoint on `comp()`. We can see how the values are compared at the first `comp()` call:

![Figure 1.109: OllyDbg: first call of `comp()`](image)

OllyDbg shows the compared values in the window under the code window, for convenience. We can also see that the SP points to RA, where the `qsort()` function is (located in MSVCR100.DLL).
By tracing (F8) until the RETN instruction and pressing F8 one more time, we return to the `qsort()` function:

![CPU - main thread, module MSVCRI100](image)

Figure 1.110: OllyDbg: the code in `qsort()` right after `comp()` call

That has been a call to the comparison function.
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Here is also a screenshot of the moment of the second call of `comp()`—now values that have to be compared are different:

![OllyDbg: second call of `comp()`](image)

**MSVC + tracer**

Let's also see which pairs are compared. These 10 numbers are being sorted: 1892, 45, 200, -98, 4087, 5, -12345, 1087, 88, -100000.

We got the address of the first `CMP` instruction in `comp()`, it is 0x0040100C and we've set a breakpoint on it:

```
tracer.exe -l:17_1.exe bpx=17_1.exe!0x0040100C
```

Now we get some information about the registers at the breakpoint:

```plaintext
PID=4336 | New process 17_1.exe
(0) 17_1.exe!0x40100c
EAX=0x00000005 EBX=0x0051f7c8 ECX=0x00000000 EDX=0x00000000 ESI=0x000517f8 EDI=0x00051f7b4 EBP=0x0051f794 ESP=0x0051f7c7 EIP=0x0028100c
FLAGS=IF
(0) 17_1.exe!0x40100c
EAX=0x00000005 EBX=0x0051f7c8 ECX=0xfffe7960 EDX=0x00000000 ESI=0x000517f8 EDI=0x00051f7b4 EBP=0x0051f794 ESP=0x0051f7c7 EIP=0x0028100c
FLAGS=PF ZF IF
(0) 17_1.exe!0x40100c
EAX=0x00000005 EBX=0x0051f7c8 ECX=0x00000000 EDX=0x00000000 ESI=0x000517f8 EDI=0x00051f7b4 EBP=0x0051f794 ESP=0x0051f7c7 EIP=0x0028100c
FLAGS=PF ZF IF
(0) 17_1.exe!0x40100c
EAX=0x00000005 EBX=0x0051f7c8 ECX=0x00000000 EDX=0x00000000 ESI=0x000517f8 EDI=0x00051f7b4 EBP=0x0051f794 ESP=0x0051f7c7 EIP=0x0028100c
FLAGS=PF ZF IF
...```

Let's filter out `EAX` and `ECX` and we got:

```
EAX=0x00000005 ECX=0x00000000
EAX=0x00000005 ECX=0xfffe7960
EAX=0x00000005 ECX=0x00000000
EAX=0x00000005 ECX=0x00000000
EAX=0x00000005 ECX=0x00000000
EAX=0x00000005 ECX=0x00000000
EAX=0x00000005 ECX=0x00000000
```

```
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```
That’s 34 pairs. Therefore, the quick sort algorithm needs 34 comparison operations to sort these 10 numbers.
We can also use the tracer’s feature to collect all possible register values and show them in IDA.

Let’s trace all instructions in `comp()`:

```
tracer.exe -l:17_1.exe bpf=17_1.exe!0x00401000,trace:cc
```

We get an .idc-script for loading into IDA and load it:

```
.int cdecl PtFuncCompare(const void *, const void *)
PtFuncCompare proc near ; DATA XREF: _main+50
arg_0 = dword ptr 4
arg_4 = dword ptr 8
mov eax, [esp+arg_0]; [ESP+4]=0x45F7ec..0x45F810(step=4), L"?\X04?
mov ecx, [esp+arg_4]; [ESP+8]=0x45F7ec..0x45F7f4(step=4), 0x45F7fc
mov eax, [ecx]; [EAX]=5, 0x2d, 0x58, 0xc8, 0x43f, 0x764, 0xfff
mov ecx, [eax]; [EAX]=5, 0x2d, 0x58, 0xc8, 0x43f, 0x764, 0xff7
cmp eax, ecx; EAX=5, 0x2d, 0x58, 0xc8, 0x43f, 0x764, 0xff7,
jnz short loc_401019 ; 2F=false
xor eax, eax
ret
loc_401013:
lea eax, [esp+40h+var_28]
lea eax, [esp+40h+var_34]
lea eax, offset comp
lea eax, [edx+edx-1]
PtFuncCompare endp
```

IDA gave the function a name (PtFuncCompare)—because IDA sees that the pointer to this function is passed to `qsort()`.

We see that the `a` and `b` pointers are pointing to various places in the array, but the step between them is 4, as 32-bit values are stored in the array.

We see that the instructions at 0x401010 and 0x401012 were never executed (so they left as white): indeed, `comp()` has never returned 0, because there no equal elements in the array.

### 1.27.2 GCC

Not a big difference:

```
lea eax, [esp+40h+var_28]
mov [esp+40h+var_40], eax
mov [esp+40h+var_28], 764h
mov [esp+40h+var_24], 20h
mov [esp+40h+var_20], 0C8h
mov [esp+40h+var_1C], 0FFFFFF9Eh
mov [esp+40h+var_18], 0FF7h
mov [esp+40h+var_14], 5
mov [esp+40h+var_10], 0FFFFFFC7h
mov [esp+40h+var_14], 43Fh
mov [esp+40h+var_8], 58h
mov [esp+40h+var_4], 0FFFFFFE760h
mov [esp+40h+var_34], offset comp
mov [esp+40h+var_38], 4
mov [esp+40h+var_3C], 0Ah
```

Figure 1.112: tracer and IDA. N.B.: some values are cut at right
1.27. POINTERS TO FUNCTIONS

comp() function:

```
public comp
comp proc near
arg_0 = dword ptr 8
arg_4 = dword ptr 0Ch

push ebp
mov ebp, esp
mov eax, [ebp+arg_4]
mov ecx, [ebp+arg_0]
mov edx, [eax]
xor eax, eax
cmp [ecx], edx
jnz short loc_8048458
pop ebp
retn

loc_8048458:
    setnl al
movzx eax, al
lea eax, [eax+eax-1]
pop ebp
retn

comp endp
```

The implementation of `qsort()` is located in libc.so.6 and it is in fact just a wrapper\(^{175}\) for `qsort_r()`. In turn, it is calling `quicksort()`, where our defined function is called via a passed pointer:

```
Listing 1.366: (file libc.so.6, glibc version—2.10.1)
... .text:0002DDF6    mov edx, [ebp+arg_10]
   .text:0002DDF9    mov [esp+4], esi
   .text:0002DDFD    mov [esp], edi
   .text:0002DE00    mov [esp+8], edx
   .text:0002DE04    call [ebp+arg_C]
...
```

GCC + GDB (with source code)

Obviously, we have the C-source code of our example (1.27 on page 385), so we can set a breakpoint (b) on line number 11—the line where the first comparison occurs. We also have to compile the example with debugging information included (-g), so the table with addresses and corresponding line numbers is present.

We can also print values using variable names (p): the debugging information also has tells us which register and/or local stack element contains which variable.

We can also see the stack (bt) and find out that there is some intermediate function `msort_with_tmp()` used in Glibc.

```
Listing 1.367: GDB session
... dennis@ubuntuvm:~/polygon$ gcc 17_1.c -g
dennis@ubuntuvm:~/polygon$ gdb ./a.out
GNU gdb (GDB) 7.6.1-ubuntu
Copyright (C) 2013 Free Software Foundation, Inc.
... Reading symbols from /home/dennis/polygon/a.out...done.
(gdb) b 17_1.c:11
Breakpoint 1 at 0x804845f: file 17_1.c, line 11.
(gdb) run
Starting program: /home/dennis/polygon/./a.out
Breakpoint 1, comp ( _a=0xbffff0f8, _b=_b@entry=0xbffff0fc) at 17_1.c:11
11 if (*a==*b)
```

\(^{175}\)A concept like thunk function
1.27. POINTERS TO FUNCTIONS

```c
(gdb) p *a
$1 = 1892
(gdb) p *b
$2 = 45
(gdb) c
Continuing.
Breakpoint 1, comp (_a=0xbffff104, _b=_b@entry=0xbffff108) at 17_1.c:11
11  if (*a==*b)
(gdb) p *a
$3 = -98
(gdb) p *b
$4 = 4087
(gdb) bt
#0 comp (_a=0xbffff0f8, _b=_b@entry=0xbffff0fc) at 17_1.c:11
#1 0xb7e42872 in msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=2)
at msort.c:65
#2 0xb7e4273e in msort_with_tmp (n=2, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#3 0xb7e42738 in msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=5)
at msort.c:53
#4 0xb7e4273e in msort_with_tmp (n=5, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#5 0xb7e42738 in msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=10)
at msort.c:53
#6 0xb7e42cef in msort with tmp (n=10, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#7 __GI_qsort_r (b=b@entry=0xbffff0f8, n=n@entry=10, s=s@entry=4, cmp=cmp@entry=0x804844d <comp>,
arg=arg@entry=0x0) at msort.c:297
#8 0xb7e42dcf in __GI_qsort (b=0xbffff0f8, n=10, s=4, cmp=0xbfffff1c4 <comp>) at msort.c:207
#9 0xb004850d in main (argc=1, argv=0xbffff1c4) at 17_1.c:26
```

**GCC + GDB (no source code)**

But often there is no source code at all, so we can disassemble the `comp()` function (`disas`), find the very first CMP instruction and set a breakpoint (`b`) at that address.

At each breakpoint, we are going to dump all register contents (`info registers`). The stack information is also available (`bt`), but partially: there is no line number information for `comp()`.

**Listing 1.368: GDB session**

dennis@ubuntuvm:~/polygon$ gcc 17_1.c
dennis@ubuntuvm:~/polygon$ gdb ./a.out
GNU gdb (GDB) 7.6.1-ubuntu
Copyright (C) 2013 Free Software Foundation, Inc.
...  
Reading symbols from /home/dennis/polygon/a.out...(no debugging symbols found)...done.
(gdb) set disassembly-flavor intel
(gdb) disas comp
Dump of assembler code for function comp:
 0x8048444 <+0>: push ebp
 0x8048446 <+1>: mov ebp,esp
 0x8048450 <+3>: sub esp,0x10
 0x8048453 <+6>: mov eax,DWORD PTR [ebp+0x8]
 0x8048456 <+9>: mov DWORD PTR [ebp-0x8],eax
 0x8048459 <+12>: mov eax,DWORD PTR [ebp+0xc]
 0x804845c <+15>: mov DWORD PTR [ebp-0x4],eax
 0x804845f <+18>: mov eax,DWORD PTR [ebp-0x8]
 0x8048462 <+21>: mov edx,DWORD PTR [eax]
 0x8048464 <+23>: mov eax,DWORD PTR [ebp-0x4]
 0x8048467 <+26>: mov edx,DWORD PTR [eax]
 0x8048469 <+28>: cmp edx,eax
 0x804846b <+30>: jne 0x8048474 <comp+39>
 0x804846d <+32>: mov eax,0x0
 0x8048472 <+37>: jmp 0x804848e <comp+65>
 0x8048474 <+39>: mov eax,DWORD PTR [ebp-0x8]
 0x8048477 <+42>: mov edx,DWORD PTR [eax]
 0x8048479 <+44>: mov eax,DWORD PTR [ebp-0x4]
 0x804847c <+47>: mov eax,DWORD PTR [eax]

```

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1.27. POINTERS TO FUNCTIONS

```
0x804847e <+49>:   cmp   edx,eax
0x8048480 <+51>:   jge  0x8048489 <comp+60>
0x8048482 <+53>:   mov   eax,0xffffffff
0x8048487 <+58>:   jmp  0x804848e <comp+65>
0x8048489 <+60>:   mov   eax,0x1
0x804848e <+65>:   leave
0x804848f <+66>:   ret

End of assembler dump.
```

(gdb) b *0x8048469
Breakpoint 1 at 0x8048469
(gdb) run
Starting program: /home/dennis/polygon/./a.out

Breakpoint 1, 0x8048469 in comp ()
(gdb) info registers
eax  0x2d    45
ecx  0xbffff0f8  -1073745672
edx  0x764    1892
ebx  0xb7fc0000 -1208221696
esp  0xbffffeeb8  0xbffffeeb8
ebp  0xbffffeeec8  0xbffffeeec8
esi  0xbffff0fc  -1073745668
edi  0xbfffff010  -1073745904
eip  0x8048469  0x8048469 <comp+28>
eflags 0x286 [ PF SF IF ]
cs  0x73    115
ss  0x7b    123
ds  0x7b    123
es  0x7b    123
fs  0x7b    123
gs  0x0      0
(gdb) c
Continuing.

Breakpoint 1, 0x8048469 in comp ()
(gdb) info registers
eax  0xff7   4087
ecx  0xbffff104  -1073745660
edx  0xbffff9e  -98
ebx  0xb7fc0000 -1208221696
esp  0xbffffee58  0xbffffee58
ebp  0xbffffee68  0xbffffee68
esi  0xbfffff0b0  -1073745656
edi  0xbfffff010  -1073745904
eip  0x8048469  0x8048469 <comp+28>
eflags 0x282 [ SF IF ]
cs  0x73    115
ss  0x7b    123
ds  0x7b    123
es  0x7b    123
fs  0x0      0
gs  0x0      0
(gdb) c
Continuing.

Breakpoint 1, 0x8048469 in comp ()
(gdb) info registers
eax  0xffffffff9e  -98
ecx  0xbfffff100  -1073745664
edx  0xc8      200
ebx  0xb7fc0000 -1208221696
esp  0xbffffeeb8  0xbffffeeb8
ebp  0xbffffeeec8  0xbffffeeec8
esi  0xbfffff0b0  -1073745656
edi  0xbfffff010  -1073745904
eip  0x8048469  0x8048469 <comp+28>
eflags 0x286 [ PF SF IF ]
cs  0x73    115
ss  0x7b    123
ds  0x7b    123
### 1.28. 64-BIT VALUES IN 32-BIT ENVIRONMENT

#### 1.28.1 Returning of 64-bit value

```c
#include <stdint.h>

uint64_t f ()
{
    return 0x1234567890ABCDEF;
}
```

**x86**

In a 32-bit environment, 64-bit values are returned from functions in the EDX:EAX register pair.

Listing 1.369: Optimizing MSVC 2010

```assembly
_f PROC
    mov    eax, -1867788817 ; 90abcdefH
    mov    edx, 305419896 ; 12345678H
    ret
_f ENDP
```

**ARM**

A 64-bit value is returned in the R0-R1 register pair (R1 is for the high part and R0 for the low part):

---

By the way, 32-bit values are passed as pairs in 16-bit environment in the same way: [3.29.4 on page 652](#)
1.28. 64-BIT VALUES IN 32-BIT ENVIRONMENT

Listing 1.370: Optimizing Keil 6/2013 (ARM mode)

|f| PROC
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LDR</td>
<td>r0,</td>
</tr>
<tr>
<td>LDR</td>
<td>r1,</td>
</tr>
<tr>
<td>BX</td>
<td>lr</td>
</tr>
<tr>
<td>ENDP</td>
<td></td>
</tr>
<tr>
<td>L0.12</td>
<td></td>
</tr>
<tr>
<td>DCD</td>
<td>0x90abcdef</td>
</tr>
<tr>
<td>L0.16</td>
<td></td>
</tr>
<tr>
<td>DCD</td>
<td>0x12345678</td>
</tr>
</tbody>
</table>

MIPS

A 64-bit value is returned in the V0-V1 ($2-$3) register pair (V0 ($2) is for the high part and V1 ($3) for the low part):

Listing 1.371: Optimizing GCC 4.4.5 (assembly listing)

| li  | $3,-1867841536  # 0xffffffff90ab0000 |
| li  | $2,305397760    # 0x12340000 |
| ori | $3,$3,0xcdef    |
| j   | $31             |
| ori | $2,$2,0x5678    |

Listing 1.372: Optimizing GCC 4.4.5 (IDA)

| lui  | $v1, 0x90AB |
| lui  | $v0, 0x1234 |
| li   | $v1, 0x90ABCD |
| jr   | $ra |
| li   | $v0, 0x12345678 |

1.28.2 Arguments passing, addition, subtraction

```c
#include <stdint.h>

uint64_t f_add (uint64_t a, uint64_t b) {
  return a+b;
};

void f_add_test () {
  #ifdef __GNUC__
  printf(“%lld\n”, f_add(12345678901234, 23456789012345));
  #else
  printf("%I64d\n", f_add(12345678901234, 23456789012345));
  #endif
};
```

```c
uint64_t f_sub (uint64_t a, uint64_t b) {
  return a-b;
};
```

x86

Listing 1.373: Optimizing MSVC 2012 /Ob1

```c
_a$ = 8 ; size = 8
_b$ = 16 ; size = 8
_f_add PROC
```
1.28. 64-BIT VALUES IN 32-BIT ENVIRONMENT

We can see in the \_f_add_test() function that each 64-bit value is passed using two 32-bit values, high part first, then low part.

Addition and subtraction occur in pairs as well.

In addition, the low 32-bit part are added first. If carry has been occurred while adding, the CF flag is set.

The following ADC instruction adds the high parts of the values, and also adds 1 if $CF = 1$.

Subtraction also occurs in pairs. The first SUB may also turn on the CF flag, which is to be checked in the subsequent SBB instruction: if the carry flag is on, then 1 is also to be subtracted from the result.

It is easy to see how the \_f_add() function result is then passed to printf().

Listing 1.374: GCC 4.8.1 -O1 -fno-inline

```
_f_add:
    mov    eax, DWORD PTR [esp+12]
    mov    edx, DWORD PTR [esp+16]
    add    eax, DWORD PTR [esp+4]
    adc    edx, DWORD PTR [esp+8]
    ret

_f_add_test:
    sub    esp, 28
    mov    DWORD PTR [esp+8], 1972608889 ; 75939f79H
    mov    DWORD PTR [esp+12], 5461 ; 00001555H
    mov    DWORD PTR [esp+14], 1942892530 ; 73ce2ff_subH
    mov    DWORD PTR [esp+4], 2874 ; 00000b3aH
    call   _f_add
    mov    eax, DWORD PTR [esp+4]
    mov    edx, DWORD PTR [esp+8]
    sub    eax, DWORD PTR [esp+12]
    sbb    edx, DWORD PTR [esp+16]
    ret

_f_sub:
    mov    eax, DWORD PTR [esp+4]
    mov    edx, DWORD PTR [esp+8]
    sub    eax, DWORD PTR [esp+12]
    sbb    edx, DWORD PTR [esp+16]
    ret
```
1.28. 64-BIT VALUES IN 32-BIT ENVIRONMENT

GCC code is the same.

ARM

Listing 1.375: Optimizing Keil 6/2013 (ARM mode)

f_add PROC
  ADDS r0,r0,r2
  ADC r1,r1,r3
  BX lr
ENDP

f_sub PROC
  SUBS r0,r0,r2
  SBC r1,r1,r3
  BX lr
ENDP

f_add_test PROC
  PUSH {r4,lr}
  LDR r2,|L0.68| ; 0x75939f79
  LDR r3,|L0.72| ; 0x00001555
  LDR r0,|L0.76| ; 0x73ce2ff2
  LDR r1,|L0.80| ; 0x00000b3a
  BL f_add
  POP {r4,lr}
  MOV r2,r0
  MOV r3,r1
  ADR r0,|L0.84| ; "%I64d\n"
  B __2printf
ENDP

|L0.68|
DCD 0x75939f79

|L0.72|
DCD 0x00001555

|L0.76|
DCD 0x73ce2ff2

|L0.80|
DCD 0x00000b3a

|L0.84|
DCB "%I64d\n",0

The first 64-bit value is passed in R0 and R1 register pair, the second in R2 and R3 register pair. ARM has the ADC instruction as well (which counts carry flag) and SBC ("subtract with carry"). Important thing: when the low parts are added/subtracted, ADDS and SUBS instructions with -S suffix are used. The -S suffix stands for "set flags", and flags (esp. carry flag) is what consequent ADC/SBC instructions definitely need. Otherwise, instructions without the -S suffix would do the job (ADD and SUB).

MIPS

Listing 1.376: Optimizing GCC 4.4.5 (IDA)

f_add:
  ; $a0 - high part of a
  ; $a1 - low part of a
  ; $a2 - high part of b
  ; $a3 - low part of b
  addu $v1, $a3, $a1 ; sum up low parts
  addu $a0, $a2, $a0 ; sum up high parts
  ; will carry generated while summing up low parts?
  ; if yes, set $v0 to 1
  sltu $v0, $v1, $a3
  jr $ra
  ; add 1 to high part of result if carry should be generated:
  addu $v0, $a0 ; branch delay slot
  ; $v0 - high part of result
### 1.28. 64-BIT VALUES IN 32-BIT ENVIRONMENT

; $v1 - low part of result
f_sub:
; $a0 - high part of a
; $a1 - low part of a
; $a2 - high part of b
; $a3 - low part of b
    subu $v1, $a1, $a3 ; subtract low parts
    subu $v0, $a0, $a2 ; subtract high parts
; will carry generated while subtracting low parts?
; if yes, set $a0 to 1
    sltu $a1, $v1
    jr $ra
; subtract 1 from high part of result if carry should be generated:
    subu $v0, $a1 ; branch delay slot
; $v0 - high part of result
; $v1 - low part of result
f_add_test:

var_10  = -0x10
var_4   = -4

lui $gp, (__gnu_local_gp >> 16)
addiu $sp, -0x20
la $gp, (__gnu_local_gp & 0xFFFF)
sw $ra, 0x20+var_4($sp)
sw $gp, 0x20+var_10($sp)
lui $a1, 0x73CE
lui $a3, 0x7593
li $a0, 0xB3A
li $a3, 0x75939F79
li $a2, 0x1555
jal f_add
li $a1, 0x73CE2FF2
lw $gp, 0x20+var_10($sp)
lui $a0, ($LC0 >> 16) # "%lld\n"
lw $t9, (printf & 0xFFFF)($gp)
lw $ra, 0x20+var_4($sp)
la $a0, ($LC0 & 0xFFFF) # "%lld\n"
move $a3, $v1
move $a2, $v0
jr $t9
addiu $sp, 0x20

$LC0: .ascii "%lld\n"

MIPS has no flags register, so there is no such information present after the execution of arithmetic operations. So there are no instructions like x86’s ADC and SBB. To know if the carry flag would be set, a comparison (using SLTU instruction) also occurs, which sets the destination register to 1 or 0. This 1 or 0 is then added or subtracted to/from the final result.

### 1.28.3 Multiplication, division

```c
#include <stdint.h>

uint64_t f_mul (uint64_t a, uint64_t b)
{
    return a*b;
};

uint64_t f_div (uint64_t a, uint64_t b)
{
    return a/b;
};

uint64_t f_rem (uint64_t a, uint64_t b)
{
```
1.28. 64-BIT VALUES IN 32-BIT ENVIRONMENT

```c
return a % b;
```

### x86

Listing 1.377: Optimizing MSVC 2013 /Ob1

```assembler
.a$ = 8 ; size = 8
.b$ = 16 ; size = 8
_f_mul PROC
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _b$[ebp+4]
    push   eax
    mov    ecx, DWORD PTR _b$[ebp]
    push   ecx
    mov    edx, DWORD PTR _a$[ebp+4]
    push   edx
    mov    eax, DWORD PTR _a$[ebp]
    push   eax
    call   __allmul ; long long multiplication
    pop    ebp
    ret    0
_f_mul ENDP

.a$ = 8 ; size = 8
.b$ = 16 ; size = 8
_f_div PROC
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _b$[ebp+4]
    push   eax
    mov    ecx, DWORD PTR _b$[ebp]
    push   ecx
    mov    edx, DWORD PTR _a$[ebp+4]
    push   edx
    mov    eax, DWORD PTR _a$[ebp]
    push   eax
    call   __aulldiv ; unsigned long long division
    pop    ebp
    ret    0
_f_div ENDP

.a$ = 8 ; size = 8
.b$ = 16 ; size = 8
_f_rem PROC
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _b$[ebp+4]
    push   eax
    mov    ecx, DWORD PTR _b$[ebp]
    push   ecx
    mov    edx, DWORD PTR _a$[ebp+4]
    push   edx
    mov    eax, DWORD PTR _a$[ebp]
    push   eax
    call   __aullrem ; unsigned long long remainder
    pop    ebp
    ret    0
_f_rem ENDP
```

Multiplication and division are more complex operations, so usually the compiler embeds calls to a library functions doing that.

These functions are described here: .5 on page 1043.

Listing 1.378: Optimizing GCC 4.8.1 -fno-inline

```c
_f_mul:
```
GCC does the expected, but the multiplication code is inlined right in the function, thinking it could be more efficient. GCC has different library function names: . on page 1043.

ARM

Keil for Thumb mode inserts library subroutine calls:

Listing 1.379: Optimizing Keil 6/2013 (Thumb mode)
1.28. 64-BIT VALUES IN 32-BIT ENVIRONMENT

Keil for ARM mode, on the other hand, is able to produce 64-bit multiplication code:

Listing 1.380: Optimizing Keil 6/2013 (ARM mode)

```
||f_mul|| PROC
  PUSH {r4,lr}
  UMULL r12,r4,r0,r2
  MLA r1,r2,r1,r4
  MLA r1,r0,r3,r1
  MOV r0,r12
  POP {r4,pc}
ENDP

||f_div|| PROC
  PUSH {r4,lr}
  BL __aeabi_uldivmod
  POP {r4,pc}
ENDP

||f_rem|| PROC
  PUSH {r4,lr}
  BL __aeabi_uldivmod
  MOV r0,r8
  MOV r1,r2
  POP {r4,pc}
ENDP
```

MIPS

Optimizing GCC for MIPS can generate 64-bit multiplication code, but has to call a library routine for 64-bit division:

Listing 1.381: Optimizing GCC 4.4.5 (IDA)

```
f_mul:
  mult $a2, $a1
  mflo $v0
  or $at, $zero ; NOP
  or $at, $zero ; NOP
  mult $a0, $a3
  mflo $a0
  addu $v0, $a0
  or $at, $zero ; NOP
  multu $a3, $a1
  mfhi $a2
  mflo $v1
  jr $ra
  addu $v0, $a2

f_div:
  var_10 = -0x10
  var_4 = -4
    lui $gp, (__gnu_local_gp >> 16)
    addiu $sp, -0x20
    la $gp, (__gnu_local_gp & 0xFFFF)
    sw $ra, 0x20+var_4($sp)
    sw $gp, 0x20+var_10($sp)
    lw $t9, (__udivdi3 & 0xFFFF)($gp)
    or $at, $zero
    jalr $t9
    or $at, $zero
    lw $ra, 0x20+var_4($sp)
    or $at, $zero
    jr $ra
    addiu $sp, 0x20

f_rem:
```

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There are a lot of **NOP**s, probably delay slots filled after the multiplication instruction (it's slower than other instructions, after all).

### 1.28.4 Shifting right

```c
#include <stdint.h>

uint64_t f (uint64_t a)
{
    return a>>7;
};
```

**x86**

**Listing 1.382: Optimizing MSVC 2012 /Ob1**

```
_a$ = 8 ; size = 8

_f PROC
    mov eax, DWORD PTR _a$[esp-4]
    mov edx, DWORD PTR _a$[esp]
    shrd eax, edx, 7
    shr edx, 7
    ret 0
_f ENDP
```

**Listing 1.383: Optimizing GCC 4.8.1 -fno-inline**

```
f:
    mov edx, DWORD PTR [esp+8]
    mov eax, DWORD PTR [esp+4]
    shrd eax, edx, 7
    shr edx, 7
    ret
```

Shifting also occurs in two passes: first the lower part is shifted, then the higher part. But the lower part is shifted with the help of the **SHRD** instruction, it shifts the value of **EAX** by 7 bits, but pulls new bits from **EDX**, i.e., from the higher part. In other words, 64-bit value from **EDX:EAX** register's pair, as a whole, is shifted by 7 bits and lowest 32 bits of result are placed into **EAX**. The higher part is shifted using the much more popular **SHR** instruction: indeed, the freed bits in the higher part must be filled with zeros.

**ARM**

ARM doesn’t have such instruction as **SHRD** in x86, so the Keil compiler ought to do this using simple shifts and **OR** operations:
### 1.28. 64-BIT VALUES IN 32-BIT ENVIRONMENT

#### Listing 1.384: Optimizing Keil 6/2013 (ARM mode)

```
||f|| PROC
  LSR r0,r0,#7
  ORR r0,r0,r1,LSL #25
  LSR r1,r1,#7
  BX lr
ENDP
```

#### Listing 1.385: Optimizing Keil 6/2013 (Thumb mode)

```
||f|| PROC
  LSLS r2,r1,#25
  LSRS r0,r0,#7
  ORRS r0,r0,r2
  LSRS r1,r1,#7
  BX lr
ENDP
```

#### MIPS

GCC for MIPS follows the same algorithm as Keil does for Thumb mode:

#### Listing 1.386: Optimizing GCC 4.4.5 (IDA)

```
f:
  sll $v0, $a0, 25
  srl $v1, $a1, 7
  or $v1, $v0, $v1
  jr $ra
  srl $v0, $a0, 7
```

### 1.28.5 Converting 32-bit value into 64-bit one

```c
#include <stdint.h>

int64_t f (int32_t a)
{
  return a;
};
```

#### x86

#### Listing 1.387: Optimizing MSVC 2012

```
_a$ = 8
_f PROC
  mov eax, DWORD PTR _a$[esp-4]
  cdq
  ret 0
_f ENDP
```

Here we also run into necessity to extend a 32-bit signed value into a 64-bit signed one. Unsigned values are converted straightforwardly: all bits in the higher part must be set to 0. But this is not appropriate for signed data types: the sign has to be copied into the higher part of the resulting number.

The CDQ instruction does that here, it takes its input value in EAX, extends it to 64-bit and leaves it in the EDX:EAX register pair. In other words, CDQ gets the number sign from EAX (by getting the most significant bit in EAX), and depending of it, sets all 32 bits in EDX to 0 or 1. Its operation is somewhat similar to the MOVSX instruction.
1.29. **SIMD**

**ARM**

Listing 1.388: Optimizing Keil 6/2013 (ARM mode)

```assembly
||f|| PROC
    ASR r1,r0,#31
    BX lr
ENDP
```

Keil for ARM is different: it just arithmetically shifts right the input value by 31 bits. As we know, the sign bit is **MSB**, and the arithmetical shift copies the sign bit into the “emerged” bits. So after “ASR r1,r0,#31”, R1 containing 0xFFFFFFFF if the input value has been negative and 0 otherwise. R1 contains the high part of the resulting 64-bit value. In other words, this code just copies the **MSB** (sign bit) from the input value in R0 to all bits of the high 32-bit part of the resulting 64-bit value.

**MIPS**

GCC for MIPS does the same as Keil did for ARM mode:

Listing 1.389: Optimizing GCC 4.4.5 (IDA)

```assembly
f:
sra $v0, $a0, 31
jr $ra
move $v1, $a0
```

### 1.29 SIMD

**SIMD** is an acronym: *Single Instruction, Multiple Data*.

As its name implies, it processes multiple data using only one instruction.

Like the **FPU**, that **CPU** subsystem looks like a separate processor inside x86.

SIMD began as MMX in x86. 8 new 64-bit registers appeared: MM0-MM7.

Each MMX register can hold 2 32-bit values, 4 16-bit values or 8 bytes. For example, it is possible to add 8 8-bit values (bytes) simultaneously by adding two values in MMX registers.

One simple example is a graphics editor that represents an image as a two dimensional array. When the user changes the brightness of the image, the editor must add or subtract a coefficient to/from each pixel value. For the sake of brevity if we say that the image is grayscale and each pixel is defined by one 8-bit byte, then it is possible to change the brightness of 8 pixels simultaneously.

By the way, this is the reason why the saturation instructions are present in SIMD.

When the user changes the brightness in the graphics editor, overflow and underflow are not desirable, so there are addition instructions in SIMD which are not adding anything if the maximum value is reached, etc.

When MMX appeared, these registers were actually located in the FPU’s registers. It was possible to use either FPU or MMX at the same time. One might think that Intel saved on transistors, but in fact the reason of such symbiosis was simpler —older OSes that are not aware of the additional CPU registers would not save them at the context switch, but saving the FPU registers. Thus, MMX-enabled CPU + old OS + process utilizing MMX features will still work.

SSE—is extension of the SIMD registers to 128 bits, now separate from the FPU.

AVX—another extension, to 256 bits.

Now about practical usage.

Of course, this is memory copy routines (memcpy), memory comparing (memcmp) and so on.

One more example: the DES encryption algorithm takes a 64-bit block and a 56-bit key, encrypt the block and produces a 64-bit result. The DES algorithm may be considered as a very large electronic circuit, with wires and AND/OR/NOT gates.
1.29. SIMD

Bitslice DES\(^{177}\) —is the idea of processing groups of blocks and keys simultaneously. Let’s say, variable of type \texttt{unsigned int} on x86 can hold up to 32 bits, so it is possible to store there intermediate results for 32 block-key pairs simultaneously, using 64+56 variables of type \texttt{unsigned int}.

There is an utility to brute-force Oracle RDBMS passwords/hashes (ones based on DES), using slightly modified bitslice DES algorithm for SSE2 and AVX—now it is possible to encrypt 128 or 256 block-keys pairs simultaneously.

http://go.yurichev.com/17313

### 1.29.1 Vectorization

Vectorization\(^{178}\) is when, for example, you have a loop taking couple of arrays for input and producing one array. The loop body takes values from the input arrays, does something and puts the result into the output array. Vectorization is to process several elements simultaneously.

Vectorization is not very fresh technology: the author of this textbook saw it at least on the Cray Y-MP supercomputer line from 1988 when he played with its “lite” version Cray Y-MP EL\(^{179}\).

For example:

```c
for (i = 0; i < 1024; i++)
{
    C[i] = A[i]*B[i];
}
```

This fragment of code takes elements from A and B, multiplies them and saves the result into C.

If each array element we have is 32-bit \texttt{int}, then it is possible to load 4 elements from A into a 128-bit XMM-register, from B to another XMM-registers, and by executing \texttt{PMULLD} (Multiply Packed Signed Dword Integers and Store Low Result) and \texttt{PMULHW} (Multiply Packed Signed Integers and Store High Result), it is possible to get 4 64-bit \texttt{products} at once.

Thus, loop body execution count is \(1024/4\) instead of 1024, that is 4 times less and, of course, faster.

#### Addition example

Some compilers can do vectorization automatically in simple cases, e.g., Intel C++\(^{180}\).

Here is tiny function:

```c
int f (int sz, int *ar1, int *ar2, int *ar3)
{
    for (int i=0; i<sz; i++)
        ar3[i]=ar1[i]+ar2[i];
    return 0;
}
```

#### Intel C++

Let’s compile it with Intel C++ 11.1.051 win32:

icl intel.cpp /QaxSSE2 /Faintel.asm /Ox

We got in IDA:

```plaintext
; int __cdecl f(int, int *, int *, int *)
public ?f@YAHHPAH00@Z
?f@YAHHPAH00@Z proc near
var_10 = dword ptr -10h
```

\(^{177}\)http://go.yurichev.com/17329

\(^{178}\)Wikipedia: vectorization

\(^{179}\)Remotely. It is installed in the museum of supercomputers: http://go.yurichev.com/17081

\(^{180}\)More about Intel C++ automatic vectorization: Excerpt: Effective Automatic Vectorization
1.29. SIMD

sz = dword ptr 4
ar1 = dword ptr 8
ar2 = dword ptr 0Ch
ar3 = dword ptr 10h

    push    edi
    push    esi
    push    ebx
    push    esi
    mov     edx, [esp+10h+sz]
    test    edx, edx
    jle     loc_15B
    mov     eax, [esp+10h+ar3]
    cmp     edx, 6
    jle     loc_143
    cmp     eax, [esp+10h+ar2]
    jbe     short loc_36
    mov     esi, [esp+10h+ar2]
    sub     esi, eax
    lea     ecx, ds:0[edx*4]
    neg     esi
    cmp     ecx, esi
    jbe     short loc_55

loc_36: ; CODE XREF: f(int,int *,int *,int *)+21
    cmp     eax, [esp+10h+ar2]
    jnb     loc_143
    mov     esi, [esp+10h+ar2]
    sub     esi, eax
    lea     ecx, ds:0[edx*4]
    cmp     esi, ecx
    jb      loc_143

loc_55: ; CODE XREF: f(int,int *,int *,int *)+34
    cmp     eax, [esp+10h+ar1]
    jbe     short loc_67
    mov     esi, [esp+10h+ar1]
    sub     esi, eax
    neg     esi
    cmp     ecx, esi
    jbe     short loc_7F

loc_67: ; CODE XREF: f(int,int *,int *,int *)+59
    cmp     eax, [esp+10h+ar1]
    jnb     loc_143
    mov     esi, [esp+10h+ar1]
    sub     esi, eax
    cmp     esi, ecx
    jb      loc_143

loc_7F: ; CODE XREF: f(int,int *,int *,int *)+65
    mov     edi, eax
        ; edi = ar3
    and     edi, 0Fh
        ; is ar3 16-byte aligned?
    jz      short loc_9A
        ; yes
    test    edi, 3
    jnz     loc_162
    neg     edi
    add     edi, 10h
    shr     edi, 2

loc_9A: ; CODE XREF: f(int,int *,int *,int *)+84
    lea     ecx, [edi+4]
    cmp     edx, ecx
    jl      loc_162
    mov     ecx, edx
    sub     ecx, edi
    and     ecx, 3
    neg     ecx
    add     ecx, edi
    test    edi, edi
1.29. SIMD

```
jbe short loc_D6
mov ebx, [esp+10h+ar2]
mov [esp+10h+var_10], ecx
mov ecx, [esp+10h+ar1]
xor esi, esi

loc_C1: ; CODE XREF: f(int,int *,int *,int *)+CD
  mov edx, [ecx+esi*4]
  add edx, [ebx+esi*4]
  mov [eax+esi*4], edx
  inc esi
  cmp esi, edi
  jb short loc_C1
  mov ecx, [esp+10h+var_10]
  mov edx, [esp+10h+sz]

loc_D6: ; CODE XREF: f(int,int *,int *,int *)+B2
  mov esi, [esp+10h+ar2]
  lea esi, [esi+edi*4] ; is ar2+i*4 16-byte aligned?
  test esi, 0Fh
  jz short loc_109 ; yes!
  mov ebx, [esp+10h+ar1]
  mov esi, [esp+10h+ar2]

loc_ED: ; CODE XREF: f(int,int *,int *,int *)+105
  movdqu xmm1, xmmword ptr [ebx+edi*4] ; ar1+i*4
  movdqu xmm0, xmmword ptr [esi+edi*4] ; ar2+i*4 is not 16-byte aligned, so load it to
  \[\]
  \XMM0
  paddd xmm1, xmm0
  movdqa xmmword ptr [eax+edi*4], xmm1 ; ar3+i*4
  add edi, 4
  cmp edi, ecx
  jb short loc_ED
  jmp short loc_127

loc_109: ; CODE XREF: f(int,int *,int *,int *)+E3
  mov ebx, [esp+10h+ar1]
  mov es1, [esp+10h+ar2]

loc_111: ; CODE XREF: f(int,int *,int *,int *)+125
  movdqu xmm0, xmmword ptr [ebx+edi*4] ; ar1+i*4
  paddd xmm0, xmmword ptr [esi+edi*4] ; ar2+i*4
  movdqa xmmword ptr [eax+edi*4], xmm0
  add edi, 4
  cmp edi, ecx
  jb short loc_111

loc_127: ; CODE XREF: f(int,int *,int *,int *)+107
  ; f(int,int *,int *,int *)+164
  cmp ecx, edx
  jnb short loc_15B
  mov esi, [esp+10h+ar1]
  mov edi, [esp+10h+ar2]

loc_133: ; CODE XREF: f(int,int *,int *,int *)+13F
  mov ebx, [esi+ecx*4]
  add ebx, [edi+ecx*4]
  mov [eax+ecx*4], ebx
  inc ecx
  cmp ecx, edx
  jb short loc_133
  jmp short loc_15B

loc_143: ; CODE XREF: f(int,int *,int *,int *)+17
  ; f(int,int *,int *,int *)+3A ...
  mov esi, [esp+10h+ar1]
  mov edi, [esp+10h+ar2]
  xor ecx, ecx

loc_14D: ; CODE XREF: f(int,int *,int *,int *)+159
```
The SSE2-related instructions are:

- **MOVDQU** (*Move Unaligned Double Quadword*)—just loads 16 bytes from memory into a XMM-register.
- **PADDD** (*Add Packed Integers*)—adds 4 pairs of 32-bit numbers and leaves the result in the first operand.
  
  By the way, no exception is raised in case of overflow and no flags are to be set, just the low 32 bits of the result are to be stored. If one of PADDD’s operands is the address of a value in memory, then the address must be aligned on a 16-byte boundary. If it is not aligned, an exception will be triggered.

- **MOVDQA** (*Move Aligned Double Quadword*) is the same as MOVDQU, but requires the address of the value in memory to be aligned on a 16-bit boundary. If it is not aligned, exception will be raised. MOVDQA works faster than MOVDQU, but requires aforesaid.

So, these SSE2-instructions are to be executed only in case there are more than 4 pairs to work on and the pointer ar3 is aligned on a 16-byte boundary.

Also, if ar2 is aligned on a 16-byte boundary as well, this fragment of code is to be executed:

```assembly
movdqu xmm0, xmmword ptr [ebx+edi*4] ; ar1+i*4
paddd xmm0, xmmword ptr [esi+edi*4] ; ar2+i*4
movdqa xmmword ptr [eax+edi*4], xmm0 ; ar3+i*4
```

Otherwise, the value from ar2 is to be loaded into XMM0 using MOVDQU, which does not require aligned pointer, but may work slower:

```assembly
movdqu xmm1, xmmword ptr [ebx+edi*4] ; ar1+i*4
movdqu xmm0, xmmword ptr [esi+edi*4] ; ar2+i*4 is not 16-byte aligned, so load it to XMM0
paddd xmm1, xmm0
movdqa xmmword ptr [eax+edi*4], xmm1 ; ar3+i*4
```

In all other cases, non-SSE2 code is to be executed.

**GCC**

GCC may also vectorize in simple cases, if the -O3 option is used and SSE2 support is turned on: -msse2.

What we get (GCC 4.4.1):

```assembly
; f(int, int *, int *, int *)
public _ZlfiPiS_S_
_ZlfiPiS_S_ proc near
var_18 = dword ptr -18h
var_14 = dword ptr -14h
```
var_10 = dword ptr -10h
arg_0 = dword ptr 8
arg_4 = dword ptr 0Ch
arg_8 = dword ptr 10h
arg_C = dword ptr 14h

push ebp
mov ebp, esp
push edi
push esi
push ebx
sub esp, 0Ch
mov ecx, [ebp+arg_0]
mov esi, [ebp+arg_4]
mov edi, [ebp+arg_8]
mov ebx, [ebp+arg_C]
test ecx, ecx
jle short loc_80484D8
cmp ecx, 6
lea eax, [ebx+10h]
ja short loc_80484E8

loc_80484C1: ; CODE XREF: f(int,int *,int *,int *)+4B
; f(int,int *,int *,int *)+61 ...
xor eax, eax
nop
lea esi, [esi+0]

loc_80484CB: ; CODE XREF: f(int,int *,int *,int *)+36
mov edx, [edi+eax*4]
add edx, [esi+eax*4]
mov [ebx+eax*4], edx
add eax, 1
cmp eax, ecx
jnz short loc_80484C8

loc_80484D8: ; CODE XREF: f(int,int *,int *,int *)+17
; f(int,int *,int *,int *)+A5
add esp, 0Ch
xor eax, eax
pop ebx
pop esi
pop edi
pop ebp
retn

align 8

loc_80484E8: ; CODE XREF: f(int,int *,int *,int *)+1F
test bl, 0Fh
jnz short loc_80484C1
lea edx, [esi+10h]
cmp ebx, edx
jbe short loc_8048578

loc_80484FB: ; CODE XREF: f(int,int *,int *,int *)+E0
lea edx, [edi+10h]
cmp ebx, edx
ja short loc_8048503
cmp edi, eax
jbe short loc_80484C1

loc_8048503: ; CODE XREF: f(int,int *,int *,int *)+5D
mov eax, ecx
shr eax, 2
mov [ebp+var_14], eax
shl eax, 2
test eax, eax
mov [ebp+var_10], eax
jz short loc_8048547

1.29. SIMD
Almost the same, however, not as meticulously as Intel C++.

**Memory copy example**

Let's revisit the simple memcpy() example (1.16.2 on page 195):

```c
#include <stdio.h>

void my_memcpy (unsigned char* dst, unsigned char* src, size_t cnt) {
    size_t i;
    for (i=0; i<cnt; i++)
        dst[i]=src[i];
}
```

And that's what optimizations GCC 4.9.1 did:
Listing 1.390: Optimizing GCC 4.9.1 x64

my_memcpy:
; RDI = destination address
; RSI = source address
; RDX = size of block
    test    rdx, rdx
    je      .L41
    lea     rax, [rdi+16]
    cmp     rsi, rax
    lea     rax, [rsi+16]
    setae   cl
    cmp     rdi, rax
    setae   al
    or      cl, al
    je      .L13
    cmp     rdx, 22
    jbe     .L13
    mov     rcx, rsi
    push    rbp
    push    rbx
    neg     rcx
    and     ecx, 15
    cmp     rcx, rdx
    cmova   rcx, rdx
    xor     eax, eax
    test    rcx, rcx
    je      .L4
    movzx   eax, BYTE PTR [rsi]
    cmp     rcx, 1
    mov     BYTE PTR [rdi], al
    je      .L15
    movzx   eax, BYTE PTR [rsi+1]
    cmp     rcx, 2
    mov     BYTE PTR [rdi+1], al
    je      .L16
    movzx   eax, BYTE PTR [rsi+2]
    cmp     rcx, 3
    mov     BYTE PTR [rdi+2], al
    je      .L17
    movzx   eax, BYTE PTR [rsi+3]
    cmp     rcx, 4
    mov     BYTE PTR [rdi+3], al
    je      .L18
    movzx   eax, BYTE PTR [rsi+4]
    cmp     rcx, 5
    mov     BYTE PTR [rdi+4], al
    je      .L19
    movzx   eax, BYTE PTR [rsi+5]
    cmp     rcx, 6
    mov     BYTE PTR [rdi+5], al
    je      .L20
    movzx   eax, BYTE PTR [rsi+6]
    cmp     rcx, 7
    mov     BYTE PTR [rdi+6], al
    je      .L21
    movzx   eax, BYTE PTR [rsi+7]
    cmp     rcx, 8
    mov     BYTE PTR [rdi+7], al
    je      .L22
    movzx   eax, BYTE PTR [rsi+8]
    cmp     rcx, 9
    mov     BYTE PTR [rdi+8], al
    je      .L23
    movzx   eax, BYTE PTR [rsi+9]
    cmp     rcx, 10
    mov     BYTE PTR [rdi+9], al
    je      .L24
    movzx   eax, BYTE PTR [rsi+10]
    cmp     rcx, 11
    mov     BYTE PTR [rdi+10], al
1.29. SIMD

```
.L25:
movzx eax, BYTE PTR [rsi+11]
cmp rcx, 12
mov BYTE PTR [rdi+11], al
je .L26
movzx eax, BYTE PTR [rsi+12]
cmp rcx, 13
mov BYTE PTR [rdi+12], al
je .L27
movzx eax, BYTE PTR [rsi+13]
cmp rcx, 15
mov BYTE PTR [rdi+13], al
jne .L28
movzx eax, BYTE PTR [rsi+14]
mov BYTE PTR [rdi+14], al
mov eax, 15
.L4:
mov r10, rdx
lea r9, [rdx-1]
sub r10, rcx
lea r8, [r10-16]
sub r9, rcx
shr r8, 4
add r8, 1
mov r11, r8
sal r11, 4
cmp r9, 14
jbe .L6
lea rbp, [rsi+rcx]
xor r9d, r9d
add rcx, rdi
xor ebx, ebx
.L7:
movdqa xmm0, XMMWORD PTR [rbp+0+r9]
add rbx, 1
movups XMMWORD PTR [rcx+r9], xmm0
add r9, 16
cmp rbx, r8
jb .L7
add rax, r11
cmp r10, r11
je .L1
.L6:
movzx ecx, BYTE PTR [rsi+rax]
mov BYTE PTR [rdi+rax], cl
lea rcx, [rax+1]
cmp rdx, rcx
jbe .L1
movzx ecx, BYTE PTR [rsi+1+rax]
mov BYTE PTR [rdi+1+rax], cl
lea rcx, [rax+2]
cmp rdx, rcx
jbe .L1
movzx ecx, BYTE PTR [rsi+2+rax]
mov BYTE PTR [rdi+2+rax], cl
lea rcx, [rax+3]
cmp rdx, rcx
jbe .L1
movzx ecx, BYTE PTR [rsi+3+rax]
mov BYTE PTR [rdi+3+rax], cl
lea rcx, [rax+4]
cmp rdx, rcx
jbe .L1
movzx ecx, BYTE PTR [rsi+4+rax]
mov BYTE PTR [rdi+4+rax], cl
lea rcx, [rax+5]
cmp rdx, rcx
jbe .L1
movzx ecx, BYTE PTR [rsi+5+rax]
mov BYTE PTR [rdi+5+rax], cl
```
1.29. SIMD

```
lea    rcx, [rax+6]
cmp    rdx, rcx
jbe    .L1
movzx  ecx, BYTE PTR [rsi+6+rax]
mov    BYTE PTR [rdi+6+rax], cl
lea    rcx, [rax+7]
cmp    rdx, rcx
jbe    .L1
movzx  ecx, BYTE PTR [rsi+7+rax]
mov    BYTE PTR [rdi+7+rax], cl
lea    rcx, [rax+8]
cmp    rdx, rcx
jbe    .L1
movzx  ecx, BYTE PTR [rsi+8+rax]
mov    BYTE PTR [rdi+8+rax], cl
lea    rcx, [rax+9]
cmp    rdx, rcx
jbe    .L1
movzx  ecx, BYTE PTR [rsi+9+rax]
mov    BYTE PTR [rdi+9+rax], cl
lea    rcx, [rax+10]
cmp    rdx, rcx
jbe    .L1
movzx  ecx, BYTE PTR [rsi+10+rax]
mov    BYTE PTR [rdi+10+rax], cl
lea    rcx, [rax+11]
cmp    rdx, rcx
jbe    .L1
movzx  ecx, BYTE PTR [rsi+11+rax]
mov    BYTE PTR [rdi+11+rax], cl
lea    rcx, [rax+12]
cmp    rdx, rcx
jbe    .L1
movzx  ecx, BYTE PTR [rsi+12+rax]
mov    BYTE PTR [rdi+12+rax], cl
lea    rcx, [rax+13]
cmp    rdx, rcx
jbe    .L1
movzx  ecx, BYTE PTR [rsi+13+rax]
mov    BYTE PTR [rdi+13+rax], cl
lea    rcx, [rax+14]
cmp    rdx, rcx
jbe    .L1
movzx  edx, BYTE PTR [rsi+14+rax]
lea    rcx, [rax+14+rax]
mov    BYTE PTR [rdi+14+rax], dl

.L1:    pop    rbx
        pop    rbp

.L41:   rep     ret

.L13:   xor    eax, eax

.L3:    movzx  ecx, BYTE PTR [rsi+rax]
        mov    BYTE PTR [rdi+rax], cl
        add    rax, 1
        cmp    rax, rdx
        jne    .L3
        rep     ret

.L28:   mov    eax, 14
        jmp    .L4

.L15:   mov    eax, 1
        jmp    .L4

.L16:   mov    eax, 2
        jmp    .L4

.L17:   mov    eax, 3
```
1.29. SIMD

It has to be noted that the SIMD instructions can be inserted in C/C++ code via special macros\textsuperscript{183}. For MSVC, some of them are located in the intrin.h file.

It is possible to implement the `strlen()` function\textsuperscript{184} using SIMD instructions that works 2-2.5 times faster than the common implementation. This function loads 16 characters into a XMM-register and check each against zero\textsuperscript{185}.

```c
size_t strlen_sse2(const char *str)
{
    register size_t len = 0;
    const char *s=str;
    bool str_is_aligned=((unsigned int)str)&0xFFFFFFF0) == (unsigned int)str;
    if (str_is_aligned==false)
        return strlen (str);
    __m128i xmm0 = _mm_setzero_si128();
    __m128i xmm1;
    int mask = 0;
    for (;;)
    {
        xmm1 = _mm_load_si128((__m128i *)s);
        xmm1 = _mm_cmpeq_epi8(xmm1, xmm0);
        if ((mask = _mm_movemask_epi8(xmm1)) != 0)
        {
            unsigned long pos;
            _BitScanForward(&pos, mask);
            len += (size_t)pos;
        }
    }
}
```

\textsuperscript{183}MSDN: MMX, SSE, and SSE2 Intrinsics
\textsuperscript{184}`strlen()` —standard C library function for calculating string length
\textsuperscript{185}The example is based on source code from: http://go.yurichev.com/17330.
Let's compile it in MSVC 2010 with /Ox option:

Listing 1.391: Optimizing MSVC 2010

```c
_pos$75552 = -4 ; size = 4
_str$ = 8 ; size = 4
?strlen_sse2@YAIPBD@Z PROC ; strlen_sse2

    push ebp
    mov ebp, esp
    and esp, -16 ; fffffff0H
    mov eax, DWORD PTR _str$[ebp]
    sub esp, 12 ; 0000000cH
    push esi
    mov esi, eax
    and esi, -16 ; fffffff0H
    xor edx, edx
    mov ecx, eax
    cmp esi, eax
    je SHORT $LN4@strlen_sse
    lea edx, DWORD PTR [eax+1]
    npad 3 ; align next label

$LL11@strlen_sse:
    mov cl, BYTE PTR [eax]
    inc eax
    test cl, cl
    jne SHORT $LL11@strlen_sse
    sub eax, edx
    pop esi
    mov esp, ebp
    pop ebp
    ret 0

$LN4@strlen_sse:
    movdqa xmm1, XMMWORD PTR [eax]
    pxor xmm0, xmm0
    pcmpeqb xmm1, xmm0
    pmovmskb eax, xmm1
    test eax, eax
    jne SHORT $LN9@strlen_sse

$LL3@strlen_sse:
    movdqa xmm1, XMMWORD PTR [ecx+16]
    add ecx, 16 ; 00000010H
    pcmpeqb xmm1, xmm0
    add edx, 16 ; 00000010H
    pmovmskb eax, xmm1
    test eax, eax
    je SHORT $LL3@strlen_sse

$LN9@strlen_sse:
    bsf eax, eax
    mov ecx, eax
    mov DWORD PTR _pos$75552[esp+16], eax
    lea eax, DWORD PTR [ecx+edx]
    pop esi
    mov esp, ebp
    pop ebp
    ret 0
?strlen_sse2@YAIPBD@Z ENDP ; strlen_sse2
```

How it works? First of all, we must understand goal of the function. It calculates C-string length, but we can use different terms: it’s task is searching for zero byte, and then calculating its position relatively to string start.
First, we check if the str pointer is aligned on a 16-byte boundary. If not, we call the generic strlen() implementation.

Then, we load the next 16 bytes into the XMM1 register using MOVDQA.

An observant reader might ask, why can’t MOVDQU be used here since it can load data from the memory regardless pointer alignment?

Yes, it might be done in this way: if the pointer is aligned, load data using MOVDQA, if not — use the slower MOVDQU.

But here we are may hit another caveat:

In the Windows NT line of OS (but not limited to it), memory is allocated by pages of 4 KiB (4096 bytes). Each win32-process has 4 GiB available, but in fact, only some parts of the address space are connected to real physical memory. If the process is accessing an absent memory block, an exception is to be raised. That’s how VM works.

So, a function loading 16 bytes at once may step over the border of an allocated memory block. Let’s say that the OS has allocated 8192 (0x2000) bytes at address 0x008c0000. Thus, the block is the bytes starting from address 0x008c0000 to 0x008c1fff inclusive.

After the block, that is, starting from address 0x008c2000 there is nothing at all, e.g. the OS not allocated any memory there. Any attempt to access memory starting from that address will raise an exception.

And let’s consider the example in which the program is holding a string that contains 5 characters almost at the end of a block, and that is not a crime.

So, in normal conditions the program calls strlen(), passing it a pointer to the string 'hello' placed in memory at address 0x008c1ff8. strlen() reads one byte at a time until 0x008c1ffd, where there’s a zero byte, and then it stops.

Now if we implement our own strlen() reading 16 bytes at once, starting at any address, aligned or not, MOVDQU may attempt to load 16 bytes at once at address 0x008c1ff8 up to 0x008c2008, and then an exception will be raised. That situation is to be avoided, of course.

So then we’ll work only with the addresses aligned on a 16 bytes boundary, which in combination with the knowledge that the OS page size is usually aligned on a 16-byte boundary gives us some warranty that our function will not read from unallocated memory.

Let’s get back to our function.

_mm_setzero_si128()— is a macro generating pxor xmm0, xmm0—it just clears the XMM0 register.

_mm_load_si128()—is a macro for MOVDQA, it just loads 16 bytes from the address into the XMM1 register.

_mm_cmpeq_epi8()— is a macro for PCMPEQB, an instruction that compares two XMM-registers bytewise.

And if some byte is equals to the one in the other register, there will be 0xff at this point in the result or 0 if otherwise.

For example:

XMM1: 0x11233445566778890000000000000000
XMM0: 0x11ab3444007877881111111111111111

After the execution of pcmpeqb xmm1, xmm0, the XMM1 register contains:

XMM1: 0xff0000ff0000ffff0000000000000000

In our case, this instruction compares each 16-byte block with a block of 16 zero-bytes, which has been set in the XMM0 register by pxor xmm0, xmm0.

The next macro is _mm_movemask_epi8()— that is the PMOVMSKB instruction.

It is very useful with PCMPEQB.

186 wikipedia
This instruction sets first EAX bit to 1 if the most significant bit of the first byte in XMM1 is 1. In other words, if the first byte of the XMM1 register is 0xff, then the first bit of EAX is to be 1, too.

If the second byte in the XMM1 register is 0xff, then the second bit in EAX is to be set to 1. In other words, the instruction is answering the question “which bytes in XMM1 has the most significant bit set, or greater than 0x7f”, and returns 16 bits in the EAX register. The other bits in the EAX register are to be cleared.

By the way, do not forget about this quirk of our algorithm. There might be 16 bytes in the input like:

<table>
<thead>
<tr>
<th>15</th>
<th>14</th>
<th>13</th>
<th>12</th>
<th>11</th>
<th>10</th>
<th>9</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘h’</td>
<td>‘e’</td>
<td>‘l’</td>
<td>‘l’</td>
<td>‘o’</td>
<td>0</td>
<td>garbage</td>
<td>0</td>
<td>garbage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It is the 'hello' string, terminating zero, and some random noise in memory.

If we load these 16 bytes into XMM1 and compare them with the zeroed XMM0, we are getting something like 187:

XMM1: 0x0000ff00000000000000ff0000000000

This means that the instruction found two zero bytes, and it is not surprising.

PMOVMSKB in our case will set EAX to 0b0010000000100000.

Obviously, our function must take only the first zero bit and ignore the rest.

The next instruction is BSF (Bit Scan Forward).

This instruction finds the first bit set to 1 and stores its position into the first operand.

EAX=0b0010000000100000

After the execution of bsf eax, eax, EAX contains 5, meaning 1 has been found at the 5th bit position (starting from zero).

MSVC has a macro for this instruction: _BitScanForward.

Now it is simple. If a zero byte has been found, its position is added to what we have already counted and now we have the return result.

Almost all.

By the way, it is also has to be noted that the MSVC compiler emitted two loop bodies side by side, for optimization.

By the way, SSE 4.2 (that appeared in Intel Core i7) offers more instructions where these string manipulations might be even easier: http://go.yurichev.com/17331

1.30 64 bits

1.30.1 x86-64

It is a 64-bit extension to the x86 architecture.

From the reverse engineer’s perspective, the most important changes are:

- Almost all registers (except FPU and SIMD) were extended to 64 bits and got a R- prefix. 8 additional registers were added. Now GPR’s are: RAX, RBX, RCX, RDX, RBP, RSP, RSI, RDI, R8, R9, R10, R11, R12, R13, R14, R15.

  It is still possible to access the older register parts as usual. For example, it is possible to access the lower 32-bit part of the RAX register using EAX:

<table>
<thead>
<tr>
<th>Byte number:</th>
</tr>
</thead>
<tbody>
<tr>
<td>7th</td>
</tr>
<tr>
<td>RAX&lt;sub&gt;64&lt;/sub&gt; EAX</td>
</tr>
<tr>
<td>AX</td>
</tr>
<tr>
<td>AH</td>
</tr>
</tbody>
</table>

<sup>187</sup>An order from MSB to LSB<sup>188</sup> is used here.
The new R8-R15 registers also have their lower parts: R8D-R15D (lower 32-bit parts), R8W-R15W (lower 16-bit parts), R8L-R15L (lower 8-bit parts).

<table>
<thead>
<tr>
<th>Byte number:</th>
<th>7th</th>
<th>6th</th>
<th>5th</th>
<th>4th</th>
<th>3rd</th>
<th>2nd</th>
<th>1st</th>
<th>0th</th>
</tr>
</thead>
<tbody>
<tr>
<td>R8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R8D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R8W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R8L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The number of SIMD registers was doubled from 8 to 16: XMM0-XMM15.

- In Win64, the function calling convention is slightly different, somewhat resemblingfastcall (6.1.3 on page 735). The first 4 arguments are stored in the RCX, RDX, R8, R9 registers, the rest—in the stack. The caller function must also allocate 32 bytes so the callee may save there 4 first arguments and use these registers for its own needs. Short functions may use arguments just from registers, but larger ones may save their values on the stack.

System V AMD64 ABI (Linux, *BSD, Mac OS X)[Michael Matz, Jan Hubicka, Andreas Jaeger, Mark Mitchell, System V Application Binary Interface. AMD64 Architecture Processor Supplement, (2013)] also somewhat resemblesfastcall, it uses 6 registers RDI, RSI, RDX, RCX, R8, R9 for the first 6 arguments. All the rest are passed via the stack.

See also the section on calling conventions (6.1 on page 734).

- The C/C++ int type is still 32-bit for compatibility.

- All pointers are 64-bit now.

Since now the number of registers is doubled, the compilers have more space for maneuvering called register allocation. For us this implies that the emitted code containing less number of local variables.

For example, the function that calculates the first S-box of the DES encryption algorithm processes 32/64/128/256 values at once (depending on DES_type type (uint32, uint64, SSE2 or AVX)) using the bitslice DES method (read more about this technique here (1.29 on page 406)):

```c
/*
 * Generated S-box files.
 * This software may be modified, redistributed, and used for any purpose,
 * so long as its origin is acknowledged.
 * Produced by Matthew Kwan - March 1998
 */

#ifdef _WIN64
#define DES_type unsigned __int64
#else
#define DES_type unsigned int
#endif

void s1 (DES_type a1, DES_type a2, DES_type a3, DES_type a4, DES_type a5, DES_type a6, DES_type *out1, DES_type *out2, DES_type *out3, DES_type *out4 ) {
    DES_type x1, x2, x3, x4, x5, x6, x7, x8;
    DES_type x9, x10, x11, x12, x13, x14, x15, x16;
    DES_type x17, x18, x19, x20, x21, x22, x23, x24;
    DES_type x25, x26, x27, x28, x29, x30, x31, x32;
    DES_type x33, x34, x35, x36, x37, x38, x39, x40;
    DES_type x41, x42, x43, x44, x45, x46, x47, x48;
```

Also available as https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf
There are a lot of local variables. Of course, not all those going into the local stack. Let’s compile it with MSVC 2008 with /Ox option:

Listing 1.392: Optimizing MSVC 2008
; Function compile flags: /Ogtpy

_TEXT SEGMENT
_x6$ = -20 ; size = 4
_x3$ = -16 ; size = 4
_x1$ = -12 ; size = 4
_x8$ = -8 ; size = 4
_x4$ = -4 ; size = 4
_a1$ = 8 ; size = 4
_a2$ = 12 ; size = 4
_a3$ = 16 ; size = 4
_x33$ = 20 ; size = 4
_x7$ = 20 ; size = 4
_a4$ = 20 ; size = 4
_a5$ = 24 ; size = 4
tv326 = 28 ; size = 4
_x36$ = 28 ; size = 4
_x28$ = 28 ; size = 4
_a6$ = 28 ; size = 4
_out1$ = 32 ; size = 4
_x24$ = 36 ; size = 4
_out2$ = 36 ; size = 4
_out3$ = 40 ; size = 4
_out4$ = 44 ; size = 4

_s1 PROC
  sub esp, 20 ; 00000014H
  mov edx, DWORD PTR _a5$[esp+16]
  push ebx
  mov ebx, DWORD PTR _a4$[esp+20]
  push ebp
  push esi
  mov esi, DWORD PTR _a3$[esp+28]
  push edi
  mov edi, ebx
  push ebp
  push esi
  mov esi, DWORD PTR _a5$[esp+32]
  push ecx
  mov ecx, edx
  not ecx
  and ecx, esi
to
  and eax, esi
to
  and ecx, ebx
  mov DWORD PTR _x1$[esp+36], eax
  xor eax, ebx
  mov esi, ebp
  or esi, edx
  mov DWORD PTR _x4$[esp+36], esi
  and esi, DWORD PTR _a6$[esp+32]
  mov DWORD PTR _x7$[esp+32], ecx
  mov edx, esi
  xor edx, eax
  mov DWORD PTR _x6$[esp+36], edx
  mov edx, DWORD PTR _a3$[esp+32]
  xor edx, ebx
  mov ebx, esi
  xor ebx, DWORD PTR _a5$[esp+32]
  mov DWORD PTR _x8$[esp+36], edx
  and ebx, edx
  mov ecx, edx
  mov edx, ebx
  xor edx, ebp
  or edx, DWORD PTR _a6$[esp+32]
  not ecx
  and ecx, DWORD PTR _a6$[esp+32]
  xor edx, edi
  mov edi, edx
  or edi, DWORD PTR _a2$[esp+32]
  mov DWORD PTR _x3$[esp+36], ebp
  mov ebp, DWORD PTR _a2$[esp+32]
  xor edi, ebx

422
and    edi, DWORD PTR _a1$[esp+32]
mov    ebx, ecx
xor    ebx, DWORD PTR _x7$[esp+32]
not    edi
or     ebx, ebp
xor    edi, ebx
mov    edi, DWORD PTR _out2$[esp+32]
oxr    ebx, DWORD PTR [edi]
not    eax
xor    ebx, DWORD PTR _x6$[esp+36]
and    eax, edx
mov    DWORD PTR [edi], ebx
mov    ebx, DWORD PTR _x7$[esp+32]
or     ebx, DWORD PTR _x6$[esp+36]
mov    edi, esi
or     edi, DWORD PTR _x1$[esp+36]
mov    DWORD PTR _x28$[esp+32], ebx
xor    edi, DWORD PTR _x7$[esp+36]
or     ebx, DWORD PTR _x6$[esp+36]
om    edi, DWORD PTR _out4$[esp+32], edx
xor    ebx, DWORD PTR _x24$[esp+32]
not    eax
mov    DWORD PTR _x33$[esp+32], ebx
and    ebx, DWORD PTR _a1$[esp+32]
and    eax, edx
mov    ebx, DWORD PTR _out4$[esp+32]
oxr    eax, DWORD PTR [edi]
not    eax
or     ebx, ebp
xor    ebx, eax
not    eax
and    eax, DWORD PTR _x24$[esp+32]
not    ebp
or     eax, DWORD PTR _x3$[esp+36]
ot    esi
and    edx, eax
or     eax, edx
mov    edx, DWORD PTR _x36$[esp+32]
oxr    edx, DWORD PTR _x4$[esp+36]
oxr    ebp, edi
mov    edi, DWORD PTR _out1$[esp+32]
not    eax
and    eax, DWORD PTR _a5$[esp+32]
not    ebp
and    eax, DWORD PTR _a1$[esp+32]
and    esi, edx
or     eax, edx
not    ebp
xor    ebp, DWORD PTR [edi]
not    ecx
xor    ebx, DWORD PTR _x33$[esp+32]
xor    ebx, ebp
not    eax
1.30. 64 BITS

```assembly
mov DWORD PTR [edi], ebp
xor eax, ecx
mov ecx, DWORD PTR _out3$[esp+32]
xor eax, DWORD PTR [ecx]
pop edi
pop esi
xor eax, ebx
pop ebp
mov DWORD PTR [ecx], eax
pop ebx
add esp, 20
ret 0
```

_s1 ENDP

5 variables were allocated in the local stack by the compiler.

Now let’s try the same thing in the 64-bit version of MSVC 2008:

### Listing 1.393: Optimizing MSVC 2008

```assembly
a1$ = 56
a2$ = 64
a3$ = 72
a4$ = 80
x36$1$ = 88
a5$ = 88
a6$ = 96
out1$ = 104
out2$ = 112
out3$ = 120
out4$ = 128

s1 PROC
$LN3:
    mov QWORD PTR [rsp+24], rbx
    mov QWORD PTR [rsp+32], rbp
    mov QWORD PTR [rsp+16], rdx
    mov QWORD PTR [rsp+8], rcx
    push rsi
    push rdi
    push r12
    push r13
    push r14
    push r15
    mov r15, QWORD PTR a5$[rsp]
    mov rcx, QWORD PTR a6$[rsp]
    mov rbp, r8
    mov r10, r9
    mov rax, r15
    mov rdx, rbp
    not rax
    xor rdx, r9
    not r10
    mov r11, rax
    and rax, r9
    mov rsi, r10
    mov QWORD PTR x36$1$[rsp], rax
    and r11, r8
    and rsi, r8
    and r10, r15
    mov r13, rdx
    mov rbx, r11
    xor rbx, r9
    mov r9, QWORD PTR a2$[rsp]
    mov r12, rsi
    or r12, r15
    not r13
    and r13, rcx
    mov r14, r12
    and r14, rcx
    mov rax, r14
    mov r8, r14
```
xor r8, rbx
xor rax, r15
not rbx,
and rax, rdx
mov rdi, rax
xor rdi, rsi
or rdi, rcx
xor rdi, r10
and rbx, rdi
mov rcx, rdi
or rcx, r9
xor rcx, rax
mov rax, r13
xor rax, QWORD PTR x36$1$[rsp]
and rcx, QWORD PTR a1$[rsp]
or rax, r9
not rcx
xor rcx, rax
mov rax, QWORD PTR out2$[rsp]
xor rcx, QWORD PTR [rax]
xor rcx, r8
mov QWORD PTR [rax], rcx
mov rax, QWORD PTR x36$1$[rsp]
mov rcx, r14
or rax, r8
or rcx, r11
mov r11, r9
xor rcx, rdx
mov QWORD PTR x36$1$[rsp], rax
mov r8, rsi
mov rdx, rcx
xor rdx, r13
not rdx
and rdx, rdi
mov r10, rdx
and r10, r9
xor r10, rax
xor r10, rbx
not rbx
and rbx, r9
mov rax, r10
and rax, QWORD PTR a1$[rsp]
xor rbx, rax
mov rax, QWORD PTR out4$[rsp]
xor rbx, QWORD PTR [rax]
xor rbx, rcx
mov QWORD PTR [rax], rbx
mov rbx, QWORD PTR x36$1$[rsp]
and rbx, rbp
mov r9, rbx
not r9
and r9, rdi
or r8, r11
mov rax, QWORD PTR out1$[rsp]
xor r8, r9
not r9
and r9, rcx
or rdx, rbp
mov rbp, QWORD PTR [rsp+80]
or r9, rsi
xor rbx, r12
mov rcx, r11
not rcx
not r14
not r13
and rcx, r9
or r9, rdi
and rbx, r14
xor r9, r15
xor rcx, rdx
1.30. 64 BITS

```
mov rdx, QWORD PTR a1$[rsp]
not r9
not rcx
and r13, r10
and r9, r11
and rcx, rdx
xor r9, rbx
mov rbx, QWORD PTR [rsp+72]
not rcx
xor rcx, QWORD PTR [rax]
or r9, rdx
not r9
xor rcx, r8
mov QWORD PTR [rax], rcx
mov rax, QWORD PTR out3$[rsp]
xor r9, r13
xor r9, QWORD PTR [rax]
xor r9, r8
mov QWORD PTR [rax], r9
pop r15
pop r14
pop r13
pop r12
pop rdi
pop rsi
ret 0
s1 ENDP
```

Nothing was allocated in the local stack by the compiler, x36 is synonym for a5.
By the way, there are CPUs with much more GPR’s, e.g. Itanium (128 registers).

1.30.2 ARM

64-bit instructions appeared in ARMv8.

1.30.3 Float point numbers

How floating point numbers are processed in x86-64 is explained here: 1.31 on the following page.

1.30.4 64-bit architecture criticism

Some people has irritation sometimes: now one needs twice as much memory for storing pointers, including cache memory, despite the fact that x64 CPUs can address only 48 bits of external RAM.

> Pointers have gone out of favor to the point now where I had to flame about it because on my 64-bit computer that I have here, if I really care about using the capability of my machine I find that I’d better not use pointers because I have a machine that has 64-bit registers but it only has 2 gigabytes of RAM. So a pointer never has more than 32 significant bits to it. But every time I use a pointer it’s costing me 64 bits and that doubles the size of my data structure. Worse, it goes into the cache and half of my cache is gone and that costs cash—cache is expensive.

> So if I’m really trying to push the envelope now, I have to use arrays instead of pointers. I make complicated macros so that it looks like I’m using pointers, but I’m not really.

( Donald Knuth in “Coders at Work: Reflections on the Craft of Programming ”. )

Some people make their own memory allocators. It’s interesting to know about CryptoMiniSat\textsuperscript{190} case. This program rarely uses more than 4GiB of RAM, but it uses pointers heavily. So it requires less memory on 32-bit architecture than on 64-bit one. To mitigate this problem, author made his own allocator (in

\textsuperscript{190}https://github.com/msoos/cryptominisat/}

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1.31. WORKING WITH FLOATING POINT NUMBERS USING SIMD

clauseallocator.(h|cpp) files), which allows to have access to allocated memory using 32-bit identifiers instead of 64-bit pointers.

1.31  Working with floating point numbers using SIMD

Of course, the FPU has remained in x86-compatible processors when the SIMD extensions were added. The SIMD extensions (SSE2) offer an easier way to work with floating-point numbers. The number format remains the same (IEEE 754).

So, modern compilers (including those generating for x86-64) usually use SIMD instructions instead of FPU ones.

It can be said that it's good news, because it's easier to work with them.

We are going to reuse the examples from the FPU section here: 1.19 on page 218.

1.31.1  Simple example

```c
#include <stdio.h>

double f (double a, double b)
{
    return a/3.14 + b*4.1;
};

int main()
{
    printf ("%f\n", f(1.2, 3.4));
};
```

x64

Listing 1.394: Optimizing MSVC 2012 x64

```assembly
__real@4010666666666666 DQ 04010666666666666r ; 4.1
__real@40091eb851eb851f DQ 040091eb851eb851fr ; 3.14
a$ = 8
b$ = 16
f PROC
    divsd xmm0, QWORD PTR __real@40091eb851eb851f
    mulsd xmm1, QWORD PTR __real@4010666666666666
    addsd xmm0, xmm1
    ret 0
f ENDP
```

The input floating point values are passed in the XMM0-XMM3 registers, all the rest—via the stack 191.

a is passed in XMM0, b—via XMM1.

The XMM-registers are 128-bit (as we know from the section about SIMD: 1.29 on page 406), but the double values are 64 bit, so only lower register half is used.

DIVSD is an SSE-instruction that stands for “Divide Scalar Double-Precision Floating-Point Values”, it just divides one value of type double by another, stored in the lower halves of operands.

The constants are encoded by compiler in IEEE 754 format.

MULSD and ADDSD work just as the same, but do multiplication and addition.

The result of the function’s execution in type double is left in the in XMM0 register.

That is how non-optimizing MSVC works:

---

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Listing 1.395: MSVC 2012 x64

```c
__real@4010666666666666 DQ 04010666666666666r ; 4.1
__real@40091eb851eb851f DQ 040091eb851eb851fr ; 3.14

a$ = 8
b$ = 16
f PROC
    movsdx QWORD PTR [rsp+16], xmm1
    movsdx QWORD PTR [rsp+8], xmm0
    movsdx xmm0, QWORD PTR a$[rsp]
    divsd xmm0, QWORD PTR __real@40091eb851eb851f
    movsdx xmm1, QWORD PTR b$[rsp]
    mulsd xmm1, QWORD PTR __real@4010666666666666
    addsd xmm0, xmm1
    ret 0
f ENDP
```

Slightly redundant. The input arguments are saved in the “shadow space” (1.10.2 on page 100), but only their lower register halves, i.e., only 64-bit values of type `double`. GCC produces the same code.

x86

Let’s also compile this example for x86. Despite the fact it’s generating for x86, MSVC 2012 uses SSE2 instructions:

Listing 1.396: Non-optimizing MSVC 2012 x86

```c
tv70 = -8 ; size = 8
_a$ = 8 ; size = 8
_b$ = 16 ; size = 8
_f PROC
    push ebp
    mov ebp, esp
    sub esp, 8
    movsd xmm0, QWORD PTR _a$[ebp]
    divsd xmm0, QWORD PTR __real@40091eb851eb851f
    movsd xmm1, QWORD PTR _b$[ebp]
    mulsd xmm1, QWORD PTR __real@4010666666666666
    addsd xmm0, xmm1
    movsd QWORD PTR tv70[ebp], xmm0
    fld QWORD PTR tv70[ebp]
    mov esp, ebp
    pop ebp
    ret 0
_f ENDP
```

Listing 1.397: Optimizing MSVC 2012 x86

```c
tv67 = 8 ; size = 8
_a$ = 8 ; size = 8
_b$ = 16 ; size = 8
_f PROC
    movsd xmm1, QWORD PTR _a$[esp-4]
    divsd xmm1, QWORD PTR __real@40091eb851eb851f
    movsd xmm0, QWORD PTR _b$[esp-4]
    mulsd xmm0, QWORD PTR __real@4010666666666666
    addsd xmm1, xmm0
    movsd QWORD PTR tv67[esp-4], xmm1
    fld QWORD PTR tv67[esp-4]
    ret 0
_f ENDP
```

It’s almost the same code, however, there are some differences related to calling conventions: 1) the arguments are passed not in XMM registers, but in the stack, like in the FPU examples (1.19 on page 218); 2) the result of the function is returned in ST(0) — in order to do so, it’s copied (through local variable `tv`) from one of the XMM registers to ST(0).
Let's try the optimized example in OllyDbg:

Figure 1.113: OllyDbg: MOVSD loads the value of $a$ into XMM1
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**Figure 1.114:** OllyDbg: DIVSD calculated \textit{quotient} and stored it in XMM1.
Figure 1.115: OllyDbg: MULSD calculated product and stored it in XMM0
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Figure 1.116: OllyDbg: ADDSD adds value in XMM0 to XMM1
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We see that OllyDbg shows the XMM registers as pairs of double numbers, but only the lower part is used. Apparently, OllyDbg shows them in that format because the SSE2 instructions (suffixed with -SD) are executed right now.

But of course, it’s possible to switch the register format and to see their contents as 4 float-numbers or just as 16 bytes.
1.31. WORKING WITH FLOATING POINT NUMBERS USING SIMD

1.31.2 Passing floating point number via arguments

```c
#include <math.h>
#include <stdio.h>

int main ()
{
    printf ("32.01 ^ 1.54 = %lf\n", pow (32.01,1.54));
    return 0;
}
```

They are passed in the lower halves of the XMM0-XMM3 registers.

Listing 1.398: Optimizing MSVC 2012 x64

```assembly
SG1354 DB '32.01 ^ 1.54 = %lf', 0aH, 00H
__real@40400147ae147ae1 DQ 040400147ae147ae1r ; 32.01
__real@3ff8a3d70a3d70a4 DQ 03ff8a3d70a3d70a4r ; 1.54
main PROC
    sub rsp, 40 ; 00000028H
    movsdx xmm1, QWORD PTR __real@3ff8a3d70a3d70a4
    movsdx xmm0, QWORD PTR __real@40400147ae147ae1
    call pow
    lea rcx, OFFSET FLAT:$SG1354
    movaps xmm1, xmm0
    movd rdx, xmm1
    call printf
    xor eax, eax
    add rsp, 40 ; 00000028H
ret 0
main ENDP
```

There is no MOVSDX instruction in Intel and AMD manuals (12.1.4 on page 1013), there it is called just MOVSD. So there are two instructions sharing the same name in x86 (about the other see: 1.6 on page 1029). Apparently, Microsoft developers wanted to get rid of the mess, so they renamed it to MOVSDX. It just loads a value into the lower half of a XMM register.

`pow()` takes arguments from XMM0 and XMM1, and returns result in XMM0. It is then moved to RDX for `printf()`. Why? Maybe because `printf()`—is a variable arguments function?

Listing 1.399: Optimizing GCC 4.4.6 x64

```
.LC2:
    .string "32.01 ^ 1.54 = %lf\n"
main:
    sub rsp, 8
    movsd xmm1, QWORD PTR .LC0[rip]
    movsd xmm0, QWORD PTR .LC1[rip]
    call pow
    ; result is now in XMM0
    mov edi, OFFSET FLAT:.LC2
    mov eax, 1 ; number of vector registers passed
    call printf
    xor eax, eax
    add rsp, 8
    ret .LC0:
    .long 171798692
    .long 1073259479
.LC1:
    .long 2920577761
    .long 1077936455
```

GCC generates clearer output. The value for `printf()` is passed in XMM0. By the way, here is a case when 1 is written into EAX for `printf()`—this implies that one argument will be passed in vector registers, just
1.31 WORKING WITH FLOATING POINT NUMBERS USING SIMD

as the standard requires [Michael Matz, Jan Hubicka, Andreas Jaeger, Mark Mitchell, System V Application Binary Interface. AMD64 Architecture Processor Supplement, (2013)]^{192}.

1.31.3 Comparison example

```c
#include <stdio.h>

double d_max (double a, double b) 
{ 
    if (a>b) 
        return a; 
    return b; 
};

int main() 
{ 
    printf ("%f
", d_max (1.2, 3.4)); 
    printf ("%f
", d_max (5.6, -4)); 
};
```

---

```
x64

Listing 1.400: Optimizing MSVC 2012 x64

a$ = 8
b$ = 16
d_max PROC
    comisd xmm0, xmm1
    ja SHORT $LN2@d_max
    movaps xmm0, xmm1
$LN2@d_max:
    fatret 0
d_max ENDP

Optimizing MSVC generates a code very easy to understand.

COMISD is “Compare Scalar Ordered Double-Precision Floating-Point Values and Set EFLAGS”. Essentially, that is what it does.

Non-optimizing MSVC generates more redundant code, but it is still not hard to understand:

Listing 1.401: MSVC 2012 x64

```
```
a$ = 8
b$ = 16
d_max PROC
    movsdx QWORD PTR [rsp+16], xmm1
    movsdx QWORD PTR [rsp+8], xmm0
    movsdx xmm0, QWORD PTR a$[rsp]
    comisd xmm0, QWORD PTR b$[rsp]
    jbe SHORT $LN1@d_max
    movsdx xmm0, QWORD PTR a$[rsp]
    jmp SHORT $LN2@d_max
$LN1@d_max:
    movsdx xmm0, QWORD PTR b$[rsp]
$LN2@d_max:
    fatret 0
d_max ENDP
```

However, GCC 4.4.6 did more optimizations and used the MAXSD (“Return Maximum Scalar Double-Precision Floating-Point Value”) instruction, which just choose the maximum value!

^{192} Also available as [https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf](https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf)
d_max:
  maxsd  xmm0, xmm1
ret
Let’s compile this example in MSVC 2012 with optimization turned on:

```assembly
Listing 1.403: Optimizing MSVC 2012 x86

.a$ = 8 ; size = 8
.b$ = 16 ; size = 8
_d_max PROC

    movsd xmm0, QWORD PTR _a$[esp-4]
    comisd xmm0, QWORD PTR _b$[esp-4]
    jbe SHORT $LN1@d_max
    fld QWORD PTR _a$[esp-4]
    ret 0

$LN1@d_max:

    fld QWORD PTR _b$[esp-4]
    ret 0

_d_max ENDP
```

Almost the same, but the values of \( a \) and \( b \) are taken from the stack and the function result is left in ST(0).

If we load this example in OllyDbg, we can see how the COMISD instruction compares values and sets/clears the CF and PF flags:

![OllyDbg: COMISD changed CF and PF flags](image)

### 1.31.4 Calculating machine epsilon: x64 and SIMD

Let’s revisit the “calculating machine epsilon” example for `double` listing.1.25.2.

Now we compile it for x64:
There is no way to add 1 to a value in 128-bit XMM register, so it must be placed into memory. There is, however, the ADDSD instruction (\textit{Add Scalar Double-Precision Floating-Point Values}) which can add a value to the lowest 64-bit half of a XMM register while ignoring the higher one, but MSVC 2012 probably is not that good yet $^{193}$. Nevertheless, the value is then reloaded to a XMM register and subtraction occurs. SUBSD is “Subtract Scalar Double-Precision Floating-Point Values”, i.e., it operates on the lower 64-bit part of 128-bit XMM register. The result is returned in the XMM0 register.

1.31.5 Pseudo-random number generator example revisited

Let’s revisit “pseudo-random number generator example” example listing 1.25.1. If we compile this in MSVC 2012, it will use the SIMD instructions for the FPU.

All instructions have the -SS suffix, which stands for “Scalar Single”. “Scalar” implies that only one value is stored in the register. “Single”$^{194}$ stands for \textit{float} data type.

1.31.6 Summary

Only the lower half of XMM registers is used in all examples here, to store number in IEEE 754 format.

$^{193}$As an exercise, you may try to rework this code to eliminate the usage of the local stack.
$^{194}$i.e., single precision.
1.32. ARM-SPECIFIC DETAILS

Essentially, all instructions prefixed by `-SD` ("Scalar Double-Precision")—are instructions working with floating point numbers in IEEE 754 format, stored in the lower 64-bit half of a XMM register.

And it is easier than in the FPU, probably because the SIMD extensions were evolved in a less chaotic way than the FPU ones in the past. The stack register model is not used.

If you would try to replace `double` with `float` in these examples, the same instructions will be used, but prefixed with `-SS` ("Scalar Single-Precision"), for example, `MOVSS, COMISS, ADDSS`, etc.

"Scalar" implies that the SIMD register containing only one value instead of several.

Instructions working with several values in a register simultaneously have “Packed” in their name.

Needless to say, the SSE2 instructions work with 64-bit IEEE 754 numbers (`double`), while the internal representation of the floating-point numbers in FPU is 80-bit numbers.

Hence, the FPU may produce less round-off errors and as a consequence, FPU may give more precise calculation results.

### 1.32 ARM-specific details

#### 1.32.1 Number sign (#) before number

The Keil compiler, IDA and objdump precede all numbers with the “#” number sign, for example: listing.1.16.1.

But when GCC 4.9 generates assembly language output, it doesn’t, for example: listing.3.15.

The ARM listings in this book are somewhat mixed.

It’s hard to say, which method is right. Supposedly, one has to obey the rules accepted in environment he/she works in.

#### 1.32.2 Addressing modes

This instruction is possible in ARM64:

```assembly
ldr    x0, [x29,24]
```

This means add 24 to the value in X29 and load the value from this address.

Please note that 24 is inside the brackets. The meaning is different if the number is outside the brackets:

```assembly
ldr    w4, [x1],28
```

This means load the value at the address in X1, then add 28 to X1.

ARM allows you to add or subtract a constant to/from the address used for loading.

And it’s possible to do that both before and after loading.

There is no such addressing mode in x86, but it is present in some other processors, even on PDP-11.

There is a legend that the pre-increment, post-increment, pre-decrement and post-decrement modes in PDP-11,

were “guilty” for the appearance of such C language (which developed on PDP-11) constructs as `*ptr++`, `*++ptr`, `*ptr--`, `*--ptr`.

By the way, this is one of the hard to memorize C features. This is how it is:
1.32. ARM-SPECIFIC DETAILS

<table>
<thead>
<tr>
<th>C term</th>
<th>ARM term</th>
<th>C statement</th>
<th>how it works</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-increment</td>
<td>post-indexed addressing</td>
<td>*ptr++</td>
<td>use *ptr value, then increment ptr pointer</td>
</tr>
<tr>
<td>Post-decrement</td>
<td>post-indexed addressing</td>
<td>*ptr--</td>
<td>use *ptr value, then decrement ptr pointer</td>
</tr>
<tr>
<td>Pre-increment</td>
<td>pre-indexed addressing</td>
<td>*++ptr</td>
<td>increment ptr pointer, then use *ptr value</td>
</tr>
<tr>
<td>Pre-decrement</td>
<td>pre-indexed addressing</td>
<td>*--ptr</td>
<td>decrement ptr pointer, then use *ptr value</td>
</tr>
</tbody>
</table>

Pre-indexing is marked with an exclamation mark in the ARM assembly language. For example, see line 2 in listing 1.29.

Dennis Ritchie (one of the creators of the C language) mentioned that it presumably was invented by Ken Thompson (another C creator) because this processor feature was present in PDP-7 [195], [Dennis M. Ritchie, The development of the C language, (1993)] [196].

Thus, C language compilers may use it, if it is present on the target processor.

That’s very convenient for array processing.

1.32.3 Loading a constant into a register

32-bit ARM

As we already know, all instructions have a length of 4 bytes in ARM mode and 2 bytes in Thumb mode. Then how can we load a 32-bit value into a register, if it’s not possible to encode it in one instruction?

Let’s try:

```c
unsigned int f()
{
    return 0x12345678;
};
```

Listing 1.406: GCC 4.6.3 -O3 ARM mode

```assembly
f:
   ldr  r0, .L2
   bx   lr
.L2:
   .word  305419896 ; 0x12345678
```

So, the 0x12345678 value is just stored aside in memory and loaded if needed.

But it’s possible to get rid of the additional memory access.

Listing 1.407: GCC 4.6.3 -O3 -march=armv7-a (ARM mode)

```assembly
movw r0, #22136 ; 0x5678
movt r0, #4660 ; 0x1234
bx   lr
```

We see that the value is loaded into the register by parts, the lower part first (using MOVW), then the higher (using MOVT).

This implies that 2 instructions are necessary in ARM mode for loading a 32-bit value into a register.

It’s not a real problem, because in fact there are not many constants in real code (except of 0 and 1).

Does it mean that the two-instruction version is slower than one-instruction version?

Doubtfully. Most likely, modern ARM processors are able to detect such sequences and execute them fast.

On the other hand, IDA is able to detect such patterns in the code and disassembles this function as:

[196] Also available as http://go.yurichev.com/17264
### ARM64

```c
uint64_t f()
{
    return 0x12345678ABCDEF01;
};
```

Listing 1.408: GCC 4.9.1 -O3

```assembly
mov x0, 61185 ; 0xef01
movk x0, 0xabcd, lsl 16
movk x0, 0x5678, lsl 32
movk x0, 0x1234, lsl 48
ret
```

MOVK stands for “MOV Keep”, i.e., it writes a 16-bit value into the register, not touching the rest of the bits. The LSL suffix shifts left the value by 16, 32 and 48 bits at each step. The shifting is done before loading. This implies that 4 instructions are necessary to load a 64-bit value into a register.

### Storing floating-point number into register

It’s possible to store a floating-point number into a D-register using only one instruction.

For example:

```c
double a()
{
    return 1.5;
};
```

Listing 1.409: GCC 4.9.1 -O3 + objdump

```
0: 1e6f1000 fmov d0, #1.500000000000000000e+000
4: d65f03c0 ret
```

The number 1.5 was indeed encoded in a 32-bit instruction. But how?

In ARM64, there are 8 bits in the FMOV instruction for encoding some floating-point numbers.

The algorithm is called VFPExpandImm() in [ARM Architecture Reference Manual, ARMv8, for ARMv8-A architecture profile, (2013)](http://yurichev.com/mirrors/ARMv8-A_Architecture_Reference_Manual_(Issue_A.a).pdf). This is also called minifloat

We can try different values: the compiler is able to encode 30.0 and 31.0, but it couldn’t encode 32.0, as 8 bytes have to be allocated for this number in the IEEE 754 format:

```c
double a()
{
    return 32;
};
```

Listing 1.410: GCC 4.9.1 -O3

```
a:
    ldr d0, .LC0
    ret
.LC0:
    .word 0
    .word 1077936128
```


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1.32. ARM-SPECIFIC DETAILS

1.32.4 Relocs in ARM64

As we know, there are 4-byte instructions in ARM64, so it is impossible to write a large number into a register using a single instruction.

Nevertheless, an executable image can be loaded at any random address in memory, so that’s why relocations exist. Read more about them (in relation to Win32 PE): 6.5.2 on page 759.

The address is formed using the ADRP and ADD instruction pair in ARM64.

The first loads a 4KiB-page address and the second one adds the remainder. Let’s compile the example from “Hello, world!” (listing 1.8) in GCC (Linaro) 4.9 under win32:

Listing 1.411: GCC (Linaro) 4.9 and objdump of object file

```bash
...>aarch64-linux-gnu-gcc.exe hw.c -c
...>aarch64-linux-gnu-objdump.exe -d hw.o
...
0000000000000000 <main>:
  0: a9bf7bfd stp x29, x30, [sp,#-16]!
  4: 910003fd mov x29, sp
  8: 90000000 adrp x0, 0 <main>
   c: 91000000 add x0, x0, #0x0
 10: 94000000 bl 0 <printf>
 14: 52800000 mov w0, #0x0 // #0
 18: a8c17bfd ldp x29, x30, [sp],#16
1c: d65f03c0 ret
...>aarch64-linux-gnu-objdump.exe -r hw.o
...
RELOCATION RECORDS FOR [.text]:
OFFSET TYPE VALUE
0000000000000008 R_AARCH64_ADR_PREL_PG_HI21 .rodata
000000000000000c R_AARCH64_ADD_ABS_LO12_NC .rodata
0000000000000010 R_AARCH64_CALL26 printf
```

So there are 3 relocations in this object file.

- The first one takes the page address, cuts the lowest 12 bits and writes the remaining high 21 bits to the ADRP instruction’s bit fields. This is because we don’t need to encode the low 12 bits, and the ADRP instruction has space only for 21 bits.
- The second one puts the 12 bits of the address relative to the page start into the ADD instruction’s bit fields.
- The last, 26-bit one, is applied to the instruction at address 0x10 where the jump to the printf() function is.

All ARM64 (and in ARM in ARM mode) instruction addresses have zeros in the two lowest bits (because all instructions have a size of 4 bytes), so one have to encode only the highest 26 bits of 28-bit address space (±128MB).

There are no such relocations in the executable file: because it’s known where the “Hello!” string is located, in which page, and the address of puts() is also known.

So there are values set already in the ADRP, ADD and BL instructions (the linker has written them while linking):

Listing 1.412: objdump of executable file

```bash
0000000000000000 <main>:
  0: a9bf7bfd stp x29, x30, [sp,#-16]!
  4: 910003fd mov x29, sp
  8: 90000000 adrp x0, 400000 <_init-0x3b8>
  c: 91192000 add x0, x0, #0x648
 10: 97ffffa0 bl 400420 <puts@plt>
 14: 52800000 mov w0, #0x0 // #0
 18: a8c17bfd ldp x29, x30, [sp],#16
```

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1.33  MIPS-specific details

### Loading a 32-bit constant into register

unsigned int f()
{
    return 0x12345678;
};

All instructions in MIPS, just like ARM, have a size of 32-bit, so it’s not possible to embed a 32-bit constant into one instruction.

So one have to use at least two instructions: the first loads the high part of the 32-bit number and the second one applies an OR operation, which effectively sets the low 16-bit part of the target register:

Listing 1.413: GCC 4.4.5 -O3 (assembly output)

```
    li $2,305397760 # 0x12340000
    j $31
    ori $2,$2,0x5678 ; branch delay slot
```

IDA is fully aware of such frequently encountered code patterns, so, for convenience it shows the last ORI instruction as the LI pseudo instruction, which allegedly loads a full 32-bit number into the $V0 register.

Listing 1.414: GCC 4.4.5 -O3 (IDA)

```
    lui $v0, 0x1234
    jr $ra
    li $v0, 0x12345678 ; branch delay slot
```

The GCC assembly output has the LI pseudo instruction, but in fact, LUI ("Load Upper Immediate") is there, which stores a 16-bit value into the high part of the register.

Let’s see in objdump output:

Listing 1.415: objdump

```
00000000 <f>:
  0: 3c021234 lui v0,0x1234
  4: 03e00008 jr ra
  8: 34425678 ori v0,v0,0x5678
```

199Also available as [http://go.yurichev.com/17288](http://go.yurichev.com/17288)
1.33. MIPS-SPECIFIC DETAILS

Loading a 32-bit global variable into register

```c
unsigned int global_var=0x12345678;
unsigned int f2()
{
    return global_var;
};
```

This is slightly different: LUI loads upper 16-bit from `global_var` into $2 (or $V0) and then LW loads lower 16-bits summing it with the contents of $2:

```
Listing 1.416: GCC 4.4.5 -O3 (assembly output)

f2:
lui $2,%hi(global_var)
lw $2,%lo(global_var)($2)
j $31 ; branch delay slot
...

global_var: .word 305419896
```

IDA is fully aware of often used LUI/LW instruction pair, so it coalesces both into a single LW instruction:

```
Listing 1.417: GCC 4.4.5 -O3 (IDA)

_f2:
lw $v0, global_var
jr $ra
or $at, $zero ; branch delay slot
...
.data
.globl global_var
global_var: .word 0x12345678 # DATA XREF: _f2
```

`objdump`'s output is the same as GCC's assembly output. Let's also dump rerels of the object file:

```
Listing 1.418: objdump

objdump -D filename.o
...
0000000c <f2>:
c: 3c020000 lui v0,0x0
10: 8c420000 lw v0,0(v0)
14: 03e00008 jr ra
18: 00200825 move at,at ; branch delay slot
1c: 00200825 move at,at
Disassembly of section .data:
00000000 <global_var>:
  0: 12345678 beq s1,s4,159e4 <f2+0x159d8>
...
objdump -r filename.o
...
RELOCATION RECORDS FOR [.text]:
OFFSET TYPE  VALUE
00000000c R_MIPS_HI16 global_var
00000010 R_MIPS_LO16 global_var
```

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We can see that address of `global_var` is to be written right into LUI and LW instructions during executable file loading: high 16-bit part of `global_var` goes into the first one (LUI), lower 16-bit part goes into the second one (LW).

### 1.33.2 Further reading about MIPS

Chapter 2

Important fundamentals
2.1 Integral datatypes

Integral datatype is a type for a value which can be converted to number. These are numbers, enumerations, booleans.

2.1.1 Bit

Obvious usage for bits are boolean values: 0 for false and 1 for true.

Set of booleans can be packed into word: there will be 32 booleans in 32-bit word, etc. This way is called bitmap or bitfield.

But it has obvious overhead: a bit jiggling, isolating, etc. While using word (or int type) for boolean variable is not economic, but highly efficient.

In C/C++ environment, 0 is for false and any non-zero value is for true. For example:

```c
if (1234)
    printf ("this will always be executed\n");
else
    printf ("this will never\n");
```

This is popular way of enumerating characters in a C-string:

```c
char *input=...;
while(*input) // execute body if *input character is non-zero
{
    // do something with *input
    input++;
}
```

2.1.2 Nibble AKA nybble

AKA half-byte, tetrade. Equals to 4 bits.

All these terms are still in use today.

Binary-coded decimal (BCD)

4-bit nibbles were used in 4-bit CPUs like legendary Intel 4004 (used in calculators).

It’s interesting to know that there was binary-coded decimal (BCD) way of representing decimal digit using 4 bits. Decimal 0 is represented as 0b0000, decimal 9 as 0b1001 and higher values are not used. Decimal 1234 is represented as 0x1234. Of course, this way is not economical.

Nevertheless, it has one advantage: decimal to BCD-packed number conversion and back is extremely easy. BCD-numbers can be added, subtracted, etc., but an additional correction is needed. x86 CPUs has rare instructions for that: AAA/DAA (adjust after addition), AAS/DAS (adjust after subtraction), AAM (after multiplication), AAD (after division).

The need for CPUs to support BCD numbers is a reason why half-carry flag (on 8080/Z80) and auxiliary flag (AF on x86) are exist: this is carry-flag generated after proceeding of lower 4 bits. The flag is then used for adjustment instructions.

The fact of easy conversion had led to popularity of [Peter Abel, IBM PC assembly language and programming (1987)] book. But aside of this book, the author of these notes never seen BCD numbers in practice, except for magic numbers (5.6.1 on page 712), like when someone’s birthday is encoded like 0x19791011—this is indeed packed BCD number.

BCD instructions in x86 were often used for other purposes, especially in undocumented ways, for example:

---

1 Binary-Coded Decimal
This obscure code converts number in 0..15 range into **ASCII** character ‘0’..‘9’, ‘A’..'F'.

**Z80**

Z80 was clone of 8-bit Intel 8080 CPU, and because of space constraints, it has 4-bit **ALU**, i.e., each operation over two 8-bit numbers had to be proceeded in two steps. One side-effect of this was easy and natural generation of **half-carry flag**.

### 2.1.3 Byte

Byte is primarily used for character storage. 8-bit bytes were not common as today. Punched tapes for teletypes had 5 and 6 possible holes, this is 5 or 6 bits for byte.

To emphasize the fact the byte has 8 bits, byte is sometimes called **octet**: at least **fetchmail** uses this terminology.

9-bit bytes used to exist in 36-bit architectures: 4 9-bit bytes would fit in a single **word**. Probably because of this fact, C/C++ standard tells that **char** has to have a room for at least 8 bits, but more bits are allowable.

For example, in the early C language manual[^2], we can find this:

<table>
<thead>
<tr>
<th>char</th>
<th>one byte character (PDP-11, IBM360: 8 bits; H6070: 9 bits)</th>
</tr>
</thead>
</table>

By H6070 they probably meant Honeywell 6070, with 36-bit words.

### Standard ASCII table

7-bit ASCII table is standard, which has only 128 possible characters. Early E-Mail transport software were operating only on 7-bit ASCII codes, so a **MIME**[^3] standard needed to encode messages in non-Latin writing systems. 7-bit ASCII code was augmented by parity bit, resulting in 8 bits.

**Data Encryption Standard** (**DES**[^4]) has a 56 bits key, this is 8 7-bit bytes, leaving a space to parity bit for each character.

There is no need to memorize whole **ASCII** table, but rather ranges. [0..0x1F] are control characters (non-printable), [0x20..0x7E] are printable ones. Codes starting at 0x80 are usually used for non-Latin writing systems and/or pseudographics.

Significant codes which will be easily memorized are: 0 (end of C-string, ‘\0’ in C/C++); 0xA or 10 (line feed, ‘\n’ in C/C++); 0xD or 13 (carriage return, ‘\r’ in C/C++).

0x20 (space) is also often memorized.

### 8-bit CPUs

x86 has capability to work with byte(s) on register level (because they are descendants of 8-bit 8080 CPU), RISC CPUs like ARM and MIPS—not.

[^3]: Multipurpose Internet Mail Extensions
[^4]: Data Encryption Standard
2.1. INTEGRAL DATATYPES

2.1.4 Wide char

This is an attempt to support multi-lingual environment by extending byte to 16-bit. Most well-known example is Windows NT kernel and win32 functions with W suffix. This is why each Latin character in plain English text string is interleaved with zero byte. This encoding is called UCS-2 or UTF-16. Usually, wchar_t is synonym to 16-bit short data type.

2.1.5 Signed integer vs unsigned

Some may argue, why unsigned data types exist at first place, since any unsigned number can be represented as signed. Yes, but absence of sign bit in a value extends its range twice. Hence, signed byte has range of -128..127, and unsigned one: 0..255. Another benefit of using unsigned data types is self-documenting: you define a variable which can’t be assigned to negative values.

Unsigned data types are absent in Java, for which it’s criticized. It’s hard to implement cryptographical algorithms using boolean operations over signed data types.

Values like 0xFFFFFFFF (-1) are used often, mostly as error codes.

2.1.6 Word

Word word is somewhat ambiguous term and usually denotes a data type fitting in GPR. Bytes are practical for characters, but impractical for other arithmetical calculations.

Hence, many CPUs have GPRs with width of 16, 32 or 64 bits. Even 8-bit CPUs like 8080 and Z80 offer to work with 8-bit register pairs, each pair forming a 16-bit pseudoregister (BC, DE, HL, etc.). Z80 has some capability to work with register pairs, and this is, in a sense, some kind of 16-bit CPU emulation.

In general, if a CPU marketed as “n-bit CPU”, this usually means it has n-bit GPRs.

There was a time when hard disks and RAM modules were marketed as having \( n \) kilo-words instead of \( b \) kilobytes/megabytes.

For example, Apollo Guidance Computer\(^5\) has 2048 words of RAM. This was a 16-bit computer, so there was 4096 bytes of RAM.

TX-0\(^6\) had 64K of 18-bit words of magnetic core memory, i.e., 64 kilo-words.

DECSYSTEM-2060\(^7\) could have up to 4096 kilowords of solid state memory (i.e., hard disks, tapes, etc). This was 36-bit computer, so this is 18432 kilobytes or 18 megabytes.

---

\( \text{int} \) in C/C++ is almost always mapped to \( \text{word} \). (Except of AMD64 architecture where \( \text{int} \) is still 32-bit one, perhaps, for the reason of better portability.)

\( \text{int} \) is 16-bit on PDP-11 and old MS-DOS compilers. \( \text{int} \) is 32-bit on VAX, on x86 starting at 80386, etc.

Even more than that, if type declaration for a variable is omitted in C/C++ program, \( \text{int} \) is used silently by default. Perhaps, this is inheritance of B programming language\(^8\).

---

GPR is usually fastest container for variable, faster than packed bit, and sometimes even faster than byte (because there is no need to isolate a single bit/byte from GPR). Even if you use it as a container for loop counter in 0..99 range.

---

\( \text{Word} \) in assembly language is still 16-bit for x86, because it was so for 16-bit 8086. Double word is 32-bit, quad word is 64-bit. That’s why 16-bit words are declared using DW in x86 assembly, 32-bit ones using DD and 64-bit ones using DQ. 

\( \text{Word} \) is 32-bit for ARM, MIPS, etc., 16-bit data types are called half-word there. Hence, double word on 32-bit RISC is 64-bit data type.

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\(^6\)https://en.wikipedia.org/wiki/TX-0

\(^7\)https://en.wikipedia.org/wiki/DECSYSTEM-20

\(^8\)http://yurichev.com/blog/typeless/
2.1. INTEGRAL DATATYPES

GDB has the following terminology: halfword for 16-bit, word for 32-bit and giant word for 64-bit.

16-bit C/C++ environment on PDP-11 and MS-DOS has long data type with width of 32 bits, perhaps, they meant long word or long int?

32-bit C/C++ environment has long long data type with width of 64 bits.

Now you see why the word word is ambiguous.

Should I use int?

Some people argue that int shouldn’t be used at all, because it ambiguity can lead to bugs. For example, well-known lzhuf library uses int at one point and everything works fine on 16-bit architecture. But if ported to architecture with 32-bit int, it can crash: http://yurichev.com/blog/lzhuf/.

Less ambiguous types are defined in stdint.h file: uint8_t, uint16_t, uint32_t, uint64_t, etc.

Some people like Donald E. Knuth proposed9 more sonorous words for these types: byte/wyde/tetabyte/octabyte. But these names are less popular than clear terms with inclusion of u (unsigned) character and number right into the type name.

Word-oriented computers

Despite the ambiguity of the word term, modern computers are still word-oriented: RAM and all levels of cache are still organized by words, not by bytes. However, size in bytes is used in marketing.

Access to RAM/cache by address aligned by word boundary is often cheaper than non-aligned.

During data structures development, which are supposed to be fast and efficient, one should always take into consideration length of the word on the CPU to be executed on. Sometimes the compiler will do this for programmer, sometimes not.

2.1.7 Address register

For those who fostered on 32-bit and/or 64-bit x86, and/or RISC of 90s like ARM, MIPS, PowerPC, it’s natural that address bus has the same width as GPR or word. Nevertheless, width of address bus can be different on other architectures.

8-bit Z80 can address $2^{16}$ bytes, using 8-bit registers pairs or dedicated registers (IX, IY). SP and PC registers are also 16-bit ones.

Cray-1 supercomputer has 64-bit GPRs, but 24-bit address registers, so it can address $2^{24}$ (16 megawords or 128 megabytes). RAM was very expensive in 1970s, and even in supercomputing environment it cannot be expected it could have more. So why to allocate 64-bit register for address or pointer?

8086/8088 CPUs had a really weird addressing scheme: values of two 16-bit registers were summed in a weird manner resulting in a 20-bit address. Perhaps, this was some kind of toy-level virtualization (11.6 on page 1003)? 8086 could run several programs (not simultaneously, though).

Early ARM1 has an interesting artifact:

Another interesting thing about the register file is the PC register is missing a few bits. Since the ARM1 uses 26-bit addresses, the top 6 bits are not used. Because all instructions are aligned on a 32-bit boundary, the bottom two address bits in the PC are always zero. These 8 bits are not only unused, they are omitted from the chip entirely.

(11.6 on page 1003) 8086 could run several programs (not simultaneously, though).

x86-64 architecture has virtual 64-bit pointers/addresses, but internally, width of address bus is 48 bits (seems enough to address 256TB of RAM).

9http://www-cs-faculty.stanford.edu/~uno/news98.html
2.1. INTEGRAL DATATYPES

2.1.8 Numbers

What are numbers used for?

When you see some number(s) altering in a CPU register, you may be interested in what this number means. It’s an important skill for a reverse engineer to determine possible data type from a set of changing numbers.

Boolean

If the number is switching from 0 to 1 and back, most chances that this value has boolean data type.

Loop counter, array index

Variable increasing from 0, like: 0, 1, 2, 3...—a good chance this is a loop counter and/or array index.

Signed numbers

If you see a variable which holds very low numbers and sometimes very high numbers, like 0, 1, 2, 3, and 0xFFFFFFFF, 0xFFFFFFFE, 0xFFFFFFFD, there’s a good chance it is a signed variable in two’s complement form (2.2 on the next page), and last 3 numbers are -1, -2, -3.

32-bit numbers

There are numbers so large\(^{10}\), that there is even a special notation which exists to represent them (Knuth’s up-arrow notation\(^{11}\)). These numbers are so large so these are not practical for engineering, science and mathematics.

Almost all engineers and scientists are happy with IEEE 754 double precision floating point, which has maximal value around \(1.8 \cdot 10^{308}\). (As a comparison, the number of atoms in the observable universe, is estimated to be between \(4 \cdot 10^{79}\) and \(4 \cdot 10^{81}\).)

In fact, upper bound in practical computing is much, much lower. If you get the source code of UNIX v6 for PDP-11\(^{12}\), 16-bit int is used everywhere while 32-bit long type is not used at all.

Same story was in MS-DOS era: 16-bit int was used almost for everything (array indices, loop counters), while 32-bit long was used rarely.

During advent of x86-64, it was decided for int to stay as 32 bit size integer, because, probably, usage of 64-bit int is even rarer.

I would say, 16-bit numbers in range 0..65535 are probably most used numbers in computing.

Given that, if you see unusually large 32-bit value like 0x87654321, this is a good chance this can be:

- this can still be a 16-bit number, but signed, between 0xFFFF8000 (-32768) and 0xFFFFFFFF (-1).
- address of memory cell (can be checked using memory map feature of debugger).
- packed bytes (can be checked visually).
- bit flags.
- something related to (amateur) cryptography.
- magic number (5.6.1 on page 712).
- IEEE 754 floating point number (can also be checked).

Almost same story for 64-bit values.

---

\(^{10}\)https://en.wikipedia.org/wiki/Large_numbers

\(^{11}\)https://en.wikipedia.org/wiki/Knuth%27s_up-arrow_notation

\(^{12}\)http://minnie.tuhs.org/Archive/PDP-11/Distributions/research/Dennis_v6/
2.2. Signed number representations

...so 16-bit int is enough for almost everything?

It’s interesting to note: in [Michael Abrash, *Graphics Programming Black Book*, 1997 chapter 13] we can find that there are plenty cases in which 16-bit variables are just enough. In a meantime, Michael Abrash has a pity that 80386 and 80486 CPUs has so little available registers, so he offers to put two 16-bit values into one 32-bit register and then to rotate it using ROR reg, 16 (on 80386 and later) (ROL reg, 16 will also work) or BSWAP (on 80486 and later) instruction.

That reminds us Z80 with alternate pack of registers (suffixed with apostrophe), to which CPU can switch (and then switch back) using EXX instruction.

Size of buffer

When a programmer needs to declare the size of some buffer, values in form of $2^n$ are usually used (512 bytes, 1024, etc.). Values in $2^n$ form are easily recognizable (1.22.5 on page 322) in decimal, hexadecimal and binary base.

But needless to say, programmers are still humans with their decimal culture. And somehow, in DBMS area, size of textual database fields is often chosen as $10^n$ number, like 100, 200. They just think “Okay, 100 is enough, wait, 200 will be better”. And they are right, of course.

Maximum width of VARCHAR2 data type in Oracle RDBMS is 4000 characters, not 4096.

There is nothing wrong with this, this is just a place where numbers like $10^n$ can be encountered.

Address

It’s always a good idea to keep in mind an approximate memory map of the process you currently debug. For example, many win32 executables started at 0x00401000, so an address like 0x00451230 is probably located inside executable section. You’ll see addresses like these in the EIP register.

Stack is usually located somewhere below.

Many debuggers are able to show the memory map of the debuggee, for example: 1.9.3 on page 79.

If a value is increasing by step 4 on 32-bit architecture or by step 8 on 64-bit one, this probably sliding address of some elements of array.

It’s important to know that win32 doesn’t use addresses below 0x10000, so if you see some number below this constant, this cannot be an address (see also: https://msdn.microsoft.com/en-us/library/ms810627.aspx).

Anyway, many debuggers can show you if the value in a register can be an address to something. OllyDbg can also show an ASCII string if the value is an address of it.

Bit field

If you see a value where one (or more) bit(s) are flipping from time to time like 0xABCD1234 → 0xABCD1434 and back, this is probably a bit field (or bitmap).

Packed bytes

When strcmp() or memcmp() copies a buffer, it loads/stores 4 (or 8) bytes simultaneously, so if a string containing “4321”, and it would be copied to another place, at one point you’ll see 0x31323334 value in some register. This is 4 packed bytes into a 32-bit value.

2.2 Signed number representations

There are several methods for representing signed numbers\textsuperscript{13}, but “two’s complement” is the most popular one in computers.

\textsuperscript{13}Wikipedia
Here is a table for some byte values:

<table>
<thead>
<tr>
<th>binary</th>
<th>hexadecimal</th>
<th>unsigned</th>
<th>signed</th>
</tr>
</thead>
<tbody>
<tr>
<td>01111111</td>
<td>0x7f</td>
<td>127</td>
<td>127</td>
</tr>
<tr>
<td>01111110</td>
<td>0x7e</td>
<td>126</td>
<td>126</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>00000010</td>
<td>0x6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>00000101</td>
<td>0x5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>00000100</td>
<td>0x4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>00000011</td>
<td>0x3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>00000010</td>
<td>0x2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>00000001</td>
<td>0x1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>00000000</td>
<td>0x0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11111111</td>
<td>0xff</td>
<td>255</td>
<td>-1</td>
</tr>
<tr>
<td>11111110</td>
<td>0xfe</td>
<td>254</td>
<td>-2</td>
</tr>
<tr>
<td>11111101</td>
<td>0xfd</td>
<td>253</td>
<td>-3</td>
</tr>
<tr>
<td>11111100</td>
<td>0xfc</td>
<td>252</td>
<td>-4</td>
</tr>
<tr>
<td>11111011</td>
<td>0xfb</td>
<td>251</td>
<td>-5</td>
</tr>
<tr>
<td>11111010</td>
<td>0xfa</td>
<td>250</td>
<td>-6</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10000010</td>
<td>0x82</td>
<td>130</td>
<td>-126</td>
</tr>
<tr>
<td>10000001</td>
<td>0x81</td>
<td>129</td>
<td>-127</td>
</tr>
<tr>
<td>10000000</td>
<td>0x80</td>
<td>128</td>
<td>-128</td>
</tr>
</tbody>
</table>

The difference between signed and unsigned numbers is that if we represent 0xFFFFFFF&E and 0x00000002 as unsigned, then the first number (4294967294) is bigger than the second one (2). If we represent them both as signed, the first one becomes \(-2\), and it is smaller than the second (2). That is the reason why conditional jumps (1.14 on page 124) are present both for signed (e.g. JG, JL) and unsigned (JA, JB) operations.

For the sake of simplicity, this is what one needs to know:

- Numbers can be signed or unsigned.
- C/C++ signed types:
  - int64_t (-9,223,372,036,854,775,808 .. 9,223,372,036,854,775,807) (- 9.2.. 9.2 quintillions) or 0x8000000000000000..0x7FFFFFFFFFFFFFFF),
  - int (-2,147,483,648..2,147,483,647 (- 2.15.. 2.15Gb) or 0x80000000..0x7FFFFFFFFF),
  - char (-128..127 or 0x80..0x7F),
  - ssize_t.
- Unsigned:
  - uint64_t (0..18,446,744,073,709,551,615 ( 18 quintillions) or 0..0xFFFFFFFFFFFFFFFF),
  - unsigned int (0..4,294,967,295 ( 4.3Gb) or 0..0xFFFFFFFF),
  - unsigned char (0..255 or 0..0xFF),
  - size_t.
- Signed types have the sign in the MSB: 1 means “minus”, 0 means “plus”.
- Promoting to a larger data type is simple: 1.28.5 on page 405.
- Negation is simple: just invert all bits and add 1.
  We can keep in mind that a number of inverse sign is located on the opposite side at the same proximity from zero. The addition of one is needed because zero is present in the middle.
- The addition and subtraction operations work well for both signed and unsigned values. But for multiplication and division operations, x86 has different instructions: IDIV/IMUL for signed and DIV/MUL for unsigned.
- Here are some more instructions that work with signed numbers:
  CBW/CWD/CWDE/CDQ/CDQE (.1.6 on page 1031), MOVsx (.1.17.1 on page 201), SAR (.1.6 on page 1035).

A table of some negative and positive values (??) looks like thermometer with Celsius scale. This is why addition and subtraction works equally well for both signed and unsigned numbers: if the first addend is
2.2. SIGNED NUMBER REPRESENTATIONS

represented as mark on thermometer, and one need to add a second addend, and it's positive, we just shift mark up on thermometer by the value of second addend. If the second addend is negative, then we shift mark down to absolute value of the second addend.

Addition of two negative numbers works as follows. For example, we need to add -2 and -3 using 16-bit registers. -2 and -3 is 0xfffe and 0xfffd respectively. If we add these numbers as unsigned, we will get 0xfffe+0xfffd=0x1fffb. But we work on 16-bit registers, so the result is cut off, the first 1 is dropped, 0xfffb is left, and this is -5. This works because -2 (or 0xfffe) can be represented using plain English like this: “2 lacks in this value up to maximal value in 16-bit register + 1”. -3 can be represented as “…3 lacks in this value up to ...”. Maximal value of 16-bit register + 1 is 0x10000. During addition of two numbers and cutting off by \(2^{16} \mod 2\) will be lacking.

2.2.1 Using IMUL over MUL

Example like listing 3.21.2 where two unsigned values are multiplied compiles into listing 3.21.2 where IMUL is used instead of MUL.

This is important property of both MUL and IMUL instructions. First of all, they both produce 64-bit value if two 32-bit values are multiplied, or 128-bit value if two 64-bit values are multiplied (biggest possible product in 32-bit environment is 0xffffffff*0xffffffff=0xfffffffff00000001). But C/C++ standards have no way to access higher half of result, and a product always has the same size as multiplicands. And both MUL and IMUL instructions works in the same way if higher half is ignored, i.e., they both generate the same lower half. This is important property of “two’s complement” way of representing signed numbers.

So C/C++ compiler can use any of these instructions.

But IMUL is more versatile than MUL because it can take any register(s) as source, while MUL requires one of multiplicands stored in AX/EAX/RAX register. Even more than that: MUL stores result in EDX:EAX pair in 32-bit environment, or RDX:RAX in 64-bit one, so it always calculates the whole result. On contrary, it’s possible to set a single destination register while using IMUL instead of pair, and then CPU will calculate only lower half, which works faster [see Torbom Granlund, Instruction latencies and throughput for AMD and Intel x86 processors\(^{14}\)]

Given than, C/C++ compilers may generate IMUL instruction more often then MUL.

Nevertheless, using compiler intrinsic, it’s still possible to do unsigned multiplication and get full result. This is sometimes called extended multiplication. MSVC has intrinsic for this called _emul\(^{15}\) and another one: _umul128\(^{16}\). GCC offer __int128 data type, and if 64-bit multiplicands are first promoted to 128-bit ones, then a product is stored into another __int128 value, then result is shifted by 64 bits right, you’ll get higher half of result\(^{17}\).

MulDiv() function in Windows

Windows has MulDiv() function\(^{18}\), fused multiply/divide function, it multiplies two 32-bit integers into intermediate 64-bit value and then divides it by a third 32-bit integer. It is easier than to use two compiler intrinsic, so Microsoft developers made a special function for it. And it seems, this is busy function, judging by its usage.

2.2.2 Couple of additions about two’s complement form

Exercise 2-1. Write a program to determine the ranges of char, short, int, and long variables, both signed and unsigned, by printing appropriate values from standard headers and by direct computation.


---

15 https://msdn.microsoft.com/en-us/library/d2s81xt0(v=vs.80).aspx
16 https://msdn.microsoft.com/library/3daytv9%28v=vs.100%29.aspx
17 Example: http://stackoverflow.com/a/13187798
2.3. INTEGER OVERFLOW

Getting maximum number of some word

Maximum unsigned number is just a number where all bits are set: \texttt{0xFF....FF} (this is -1 if the \texttt{word} is treated as signed integer). So you take a \texttt{word}, set all bits and get the value:

```c
#include <stdio.h>
int main()
{
    unsigned int val=~0; // change to "unsigned char" to get maximal value for the unsigned
    // 8-bit byte
    // 0-1 will also work, or just -1
    printf ("%u\n", val); // %u for unsigned
}
```

This is 4294967295 for 32-bit integer.

Getting minimum number for some signed word

Minimum signed number is encoded as \texttt{0x80....00}, i.e., most significant bit is set, while others are cleared. Maximum signed number is encoded in the same way, but all bits are inverted: \texttt{0x7F....FF}.

Let’s shift a lone bit left until it disappears:

```c
#include <stdio.h>
int main()
{
    signed int val=1; // change to "signed char" to find values for signed byte
    while (val!=0)
    {
        printf ("%d %d\n", val, ~val);
        val=val<<1;
    }
}
```

Output is:

```
... 
536870912 -536870913
1073741824 -1073741825
-2147483648 2147483647
```

Two last numbers are minimum and maximum signed 32-bit \texttt{int} respectively.

2.3 Integer overflow

I intentionally put this section after the section about signed number representation.

First, take a look at this implementation of \texttt{itoa()} function from [Brian W. Kernighan, Dennis M. Ritchie, The C Programming Language, 2ed, (1988)]:

```c
void itoa(int n, char s[])
{
    int i, sign;
    if ((sign = n) < 0) /* record sign */
        n = -n; /* make \texttt{n} positive */
    i = 0;
    do { /* generate digits in reverse order */
        s[i++] = n % 10 + '0'; /* get next digit */
    } while ((n /= 10) > 0); /* delete it */
    if (sign < 0)
        s[i++] = '-';
    s[i] = '\0';
    strrev(s);
```
2.3. INTEGER OVERFLOW

( The full source code: https://github.com/DennisYurichev/RE-for-beginners/blob/master/fundamentals/itoa_KR.c )

It has a subtle bug. Try to find it. You can download source code, compile it, etc. The answer on the next page.
Exercise 3-4. In a two’s complement number representation, our version of itoa does not handle the largest negative number, that is, the value of \( n \) equal to \( -(2^{\text{wordsize}} - 1) \). Explain why not. Modify it to print that value correctly, regardless of the machine on which it runs.

The answer is: the function cannot process largest negative number (\texttt{INT\_MIN} or \texttt{0x80000000} or -2147483648) correctly.

How to change sign? Invert all bits and add 1. If to invert all bits in \texttt{INT\_MIN} value (\texttt{0x80000000}), this is \texttt{0x7fffffff}. Add 1 and this is \texttt{0x80000000} again. So changing sign has no effect. This is an important artifact of two’s complement system.

Further reading:
- blexim – Basic Integer Overflows\textsuperscript{19}
- Yannick Moy, Nikolaj Bjrner, and David Sielaff – Modular Bug-finding for Integer Overflows in the Large: Sound, Efficient, Bit-precise Static Analysis\textsuperscript{20}

2.4 AND

2.4.1 Checking if a value is on \( 2^n \) boundary

If you need to check if your value is divisible by \( 2^n \) number (like 1024, 4096, etc.) without remainder, you can use a \% operator in C/C++, but there is a simpler way. 4096 is \texttt{0x1000}, so it always has \( 4 \times 3 = 12 \) lower bits cleared.

What you need is just:

```c
if (value&0xFFF)
{
    printf ("value is not divisible by 0x1000 (or 4096)\n");
    printf ("by the way, remainder is %d\n", value&0xFFF);
}
else
    printf ("value is divisible by 0x1000 (or 4096)\n");
```

In other words, this code checks if there are any bit set among lower 12 bits. As a side effect, lower 12 bits is always a remainder from division a value by 4096 (because division by \( 2^n \) is merely a right shift, and shifted (and dropped) bits are bits of remainder).

Same story if you want to check if the number is odd or even:

```c
if (value&1)
    // odd
else
    // even
```

This is merely the same as if to divide by 2 and get 1-bit remainder.

2.4.2 KOI-8R Cyrillic encoding

It was a time when 8-bit ASCII table wasn’t supported by some Internet services, including email. Some supported, some others—not.

It was also a time, when non-Latin writing systems used second half of 8-bit ASCII table to accommodate non-Latin characters. There were several popular Cyrillic encodings, but KOI-8R (devised by Andrey “ache” Chernov) is somewhat unique in comparison with others.

\textsuperscript{19}http://phrack.org/issues/60/10.html  
\textsuperscript{20}https://yurichev.com/mirrors/SMT/z3prefix.pdf
2.5 AND OR as subtraction and addition

2.5.1 ZX Spectrum ROM text strings

Those who once investigated ZX Spectrum ROM internals, probably noticed that the last symbol of each text string is seemingly absent.
There are present, in fact. Here is excerpt of ZX Spectrum 128K ROM disassembled:

<table>
<thead>
<tr>
<th>Address</th>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>L048C</td>
<td>DEFM &quot;MERGE error&quot;</td>
<td>Report ‘a’.</td>
</tr>
<tr>
<td></td>
<td>DEFB 'r'+$80</td>
<td></td>
</tr>
<tr>
<td>L0497</td>
<td>DEFM &quot;Wrong file typ&quot;</td>
<td>Report ‘b’.</td>
</tr>
<tr>
<td></td>
<td>DEFB 'e'+$80</td>
<td></td>
</tr>
<tr>
<td>L04A6</td>
<td>DEFM &quot;CODE error&quot;</td>
<td>Report ‘c’.</td>
</tr>
<tr>
<td></td>
<td>DEFB 'r'+$80</td>
<td></td>
</tr>
<tr>
<td>L04B0</td>
<td>DEFM &quot;Too many bracket&quot;</td>
<td>Report ‘d’.</td>
</tr>
<tr>
<td></td>
<td>DEFB 's'+$80</td>
<td></td>
</tr>
<tr>
<td>L04C1</td>
<td>DEFM &quot;File already exist&quot;</td>
<td>Report ‘e’.</td>
</tr>
<tr>
<td></td>
<td>DEFB 's'+$80</td>
<td></td>
</tr>
</tbody>
</table>

(http://www.matthew-wilson.net/spectrum/rom/128_ROM0.html)

Last character has most significant bit set, which marks string end. Presumably, it was done to save some space? Old 8-bit computers have very tight environment.

Characters of all messages are always in standard 7-bit ASCII table, so it's guaranteed 8th bit is never used for characters.

To print such string, we must check MSB of each byte, and if it's set, we must clear it, then print character, and then stop. Here is a C example:

```c
unsigned char hw[] =
{
    'H',
    'e',
    'l',
    'l',
    'o' | 0x80
};

void print_string()
{
    for (int i=0; ;i++)
    {
        if (hw[i] & 0x80) // check MSB
        {
            // clear MSB
            // (in other words, clear all, but leave 7 lower bits intact)
            printf ("%c", hw[i] & 0x7F);
            // stop
        }
    }
}
```
Now what is interesting, since 8th bit is the most significant bit (in byte), we can check it, set it and remove it using arithmetical operations instead of logical.

I can rewrite my C example:

```c
unsigned char hw[] =
    {
        'H',
        'e',
        'l',
        'l',
        'o' + 0x80
    };

void print() {
    for (int i=0; ; i++) {
        // hw[] must have 'unsigned char' type
        if (hw[i] >= 0x80) // check for MSB
            { printf ("%c", hw[i]-0x80); // clear MSB
              // stop
              break;
            }
        printf ("%c", hw[i]);
    }
}
```

By default, `char` is signed type in C/C++, so to compare it with variable like 0x80 (which is negative \((-128)\) if treated as signed), we must treat each character in text message as unsigned.

Now if 8th bit is set, the number is always larger or equal to 0x80. If 8th bit is clear, the number is always smaller than 0x80.

Even more than that: if 8th bit is set, it can be cleared by subtracting 0x80, nothing else. If it’s not set beforehand, however, subtracting will destruct other bits.

Likewise, if 8th bit is clear, it’s possible to set it by adding 0x80. But if it’s set beforehand, addition operation will destruct some other bits.

In fact, this is valid for any bit. If the 4th bit is clear, you can set it just by adding 0x10: 0x100+0x10 = 0x110. If the 4th bit is set, you can clear it by subtracting 0x10: 0x1234-0x10 = 0x1224.

It works, because carry isn’t happened during addition/subtraction. It will, however, happen, if the bit is already set there before addition, or absent before subtraction.

Likewise, addition/subtraction can be replaced using OR/AND operation if two conditions are met: 1) you want to add/subtract by a number in form of \(2^n\); 2) this bit in source value is clear/set.

For example, addition of 0x20 is the same as ORing value with 0x20 under condition that this bit is clear before: 0x1204|0x20 = 0x1204+0x20 = 0x1224.

Subtraction of 0x20 is the same as ANDing value with \(0x20 (0x....FFDF)\), but if this bit is set before: 0x1234&(~0x20) = 0x1234&0xFFDF = 0x1234-0x20 = 0x1214.

Again, it works because carry not happened when you add \(2^n\) number and this bit isn’t set before.

This property of boolean algebra is important, worth understanding and keeping it in mind.

Another example in this book: 3.16.3 on page 537.
2.6. **XOR (exclusive OR)**

XOR is widely used when one needs just to flip specific bit(s). Indeed, the XOR operation applied with 1 effectively inverts a bit:

<table>
<thead>
<tr>
<th>input A</th>
<th>input B</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

And vice-versa, the XOR operation applied with 0 does nothing, i.e., it’s an idle operation. This is a very important property of the XOR operation and it’s highly recommended to memorize it.

### 2.6.1 Everyday speech

XOR operation present in common everyday speech. When someone asks “please buy apples or bananas”, this usually means “buy the first object or the second, but not both”—this is exactly exclusive OR, because logical OR would mean “both objects are also fine”.

Some people suggest “and/or” should be used in everyday speech to make emphasis that logical OR is used instead of exclusive OR: https://en.wikipedia.org/wiki/And/or.

### 2.6.2 Encryption

XOR is heavily used in both amateur (9.1) and real encryption (at least in Feistel network).

XOR is very useful here because: $\text{cipher}_{\text{text}} = \text{plain}_{\text{text}} \oplus \text{key}$ and then: $(\text{plain}_{\text{text}} \oplus \text{key}) \oplus \text{key} = \text{plain}_{\text{text}}$.

### 2.6.3 RAID

RAID4 offers a very simple method to protect hard disks. For example, there are several disks ($D_1$, $D_2$, $D_3$, etc.) and one parity disk ($P$). Each bit/byte written to parity disk is calculated and written on-fly:

$$P = D_1 \oplus D_2 \oplus D_3$$  

(2.1)

If any of disks is failed, for example, $D_2$, it’s restored using the very same way:

$$D_2 = D_1 \oplus P \oplus D_3$$  

(2.2)

If parity disk failed, it is restored using 2.1 way. If two of any disks are failed, then it wouldn’t be possible to restore both.

RAID5 is more advanced, but this XOR property is still exploited there.

That’s why RAID controllers has hardware “XOR accelerators” helping to XOR large chunks of written data on-fly. When computers get faster and faster, it now can be done at software level, using SIMD.

### 2.6.4 XOR swap algorithm

Hard to believe, but this code swaps values in EAX and EBX without aid of any other additional register or memory cell:

```assembly
xor eax, ebx
xor ebx, eax
xor eax, ebx
```

Let’s find out, how it works. First, we will rewrite it to step aside from x86 assembly language:
2.6. XOR (EXCLUSIVE OR)

\[
\begin{align*}
X &= X \oplus Y \\
Y &= Y \oplus X \\
X &= X \oplus Y
\end{align*}
\]

What \(X\) and \(Y\) has at each step? Just keep in mind the simple rule: \((X \oplus Y) \oplus Y = X\) for any values of \(X\) and \(Y\).

Let’s see, \(X\) after 1st step has \(X \oplus Y\); \(Y\) after 2nd step has \(Y \oplus (X \oplus Y) = X\); \(X\) after 3rd step has \((X \oplus Y) \oplus X = Y\).

Hard to say if anyone should use this trick, but it serves as a good demonstration example of XOR properties.

Wikipedia article (https://en.wikipedia.org/wiki/XOR_swap_algorithm) has also yet another explanation: addition and subtraction operations can be used instead of XOR:

\[
\begin{align*}
X &= X + Y \\
Y &= X - Y \\
X &= X - Y
\end{align*}
\]

Let’s see: \(X\) after 1st step has \(X + Y\); \(Y\) after 2nd step has \(X + Y - Y = X\); \(X\) after 3rd step has \(X + Y - X = Y\).

2.6.5 XOR linked list

Doubly linked list is a list in which each element has link to the previous element and to the next one. Hence, it’s easy to traverse list backwards or forward. \texttt{std::list} in C++ implements doubly linked list which also is examined in this book: 3.18.4.

So each element has two pointers. Is it possible, perhaps in environment of small RAM footprint, to preserve all functionality with one pointer instead of two? Yes, if a value of \(\text{prev} \oplus \text{next}\) will be stored in this memory cell, which is usually called “link”.

Maybe, we could say that address to the previous element is “encrypted” using address of next element and otherwise: next element address is “encrypted” using previous element address.

When we traverse this list forward, we always know address of the previous element, so we can “decrypt” this field and get address of the next element. Likewise, it’s possible to traverse this list backwards, “decrypting” this field using next element’s address.

But it’s not possible to find address of previous or next element of some specific element without knowing address of the first one.

Couple of things to complete this solution: first element will have address of next element without any XOR-ing, last element will have address of previous element without any XOR-ing.

Now let’s sum it up. This is example of doubly linked list of 5 elements. \(A \_x\) is address of element.

<table>
<thead>
<tr>
<th>address</th>
<th>link field contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A_0)</td>
<td>(A_1)</td>
</tr>
<tr>
<td>(A_1)</td>
<td>(A_0 \oplus A_2)</td>
</tr>
<tr>
<td>(A_2)</td>
<td>(A_1 \oplus A_3)</td>
</tr>
<tr>
<td>(A_3)</td>
<td>(A_2 \oplus A_4)</td>
</tr>
<tr>
<td>(A_4)</td>
<td>(A_3)</td>
</tr>
</tbody>
</table>

And again, hard to say if anyone should use this tricky hacks, but this is also a good demonstration of XOR properties. As with XOR swap algorithm, Wikipedia article about it also offers way to use addition or subtraction instead of XOR: https://en.wikipedia.org/wiki/XOR_linked_list.

2.6.6 Zobrist hashing / tabulation hashing

If you work on a chess engine, you traverse a game tree many times per second, and often, you can encounter the same position, which has already been processed.

So you have to use a method to store already calculated positions somewhere. But chess position can require a lot of memory, and a hash function would be used instead.

Here is a way to compress a chess position into 64-bit value, called Zobrist hashing:
2.7. POPULATION COUNT

// we have 8*8 board and 12 pieces (6 for white side and 6 for black)
uint64_t table[12][8][8]; // filled with random values

int position[8][8]; // for each square on board. 0 - no piece. 1..12 - piece

uint64_t hash;
for (int row=0; row<8; row++)
    for (int col=0; col<8; col++)
        {
            int piece=position[row][col];
            if (piece!=0)
                hash=hash^table[piece][row][col];
        }
return hash;

Now the most interesting part: if the next (modified) chess position differs only by one (moved) piece,
you don't need to recalculate hash for the whole position, all you need is:

hash=...; // (already calculated)

// subtract information about the old piece:
hash=hash^table[old_piece][old_row][old_col];

// add information about the new piece:
hash=hash^table[new_piece][new_row][new_col];

2.6.7 By the way

The usual OR also sometimes called inclusive OR (or even IOR), as opposed to exclusive OR. One place is
operator Python’s library: it’s called operator.ior here.

2.6.8 AND/OR/XOR as MOV

OR reg, 0xFFFFFFFF sets all bits to 1, hence, no matter what has been in register before, it will be set
to −1. OR reg, -1 is shorter than MOV reg, -1, so MSVC uses OR instead the latter, for example: 3.15.1
on page 527.
Likewise, AND reg, 0 always resets all bits, hence, it acts like MOV reg, 0.
XOR reg, reg, no matter what has been in register beforehand, resets all bits, and also acts like MOV reg, 0.

2.7 Population count

POPCNT instruction is population count (AKA Hamming weight). It just counts number of bits set in an input
value.

As a side effect, POPCNT instruction (or operation) can be used to determine, if the value has 2^n form.
Since, 2^n number always has just one single bit, POPCNT’s result will always be just 1.

For example, I once wrote a base64 strings scanner for hunting something interesting in binary files.
And there is a lot of garbage and false positives, so I add an option to filter out data blocks which has size
of 2^n bytes (i.e., 256 bytes, 512, 1024, etc.). The size of block is checked just like this:

if (popcnt(size)==1)
    // OK
...

21https://github.com/DennisYurichev/base64scanner
2.8. ENDIANNESS

The instruction is also known as “NSA\textsuperscript{22} instruction” due to rumors:

This branch of cryptography is fast-paced and very politically charged. Most designs are secret; a majority of military encryptions systems in use today are based on LFSRs. In fact, most Cray computers (Cray 1, Cray X-MP, Cray Y-MP) have a rather curious instruction generally known as “population count.” It counts the 1 bits in a register and can be used both to efficiently calculate the Hamming distance between two binary words and to implement a vectorized version of a LFSR. I’ve heard this called the canonical NSA instruction, demanded by almost all computer contracts.

[Bruce Schneier, \textit{Applied Cryptography}, (John Wiley & Sons, 1994)]

2.8 Endianness

The endianness is a way of representing values in memory.

2.8.1 Big-endian

The 0x12345678 value is represented in memory as:

<table>
<thead>
<tr>
<th>address in memory</th>
<th>byte value</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0</td>
<td>0x12</td>
</tr>
<tr>
<td>+1</td>
<td>0x34</td>
</tr>
<tr>
<td>+2</td>
<td>0x56</td>
</tr>
<tr>
<td>+3</td>
<td>0x78</td>
</tr>
</tbody>
</table>

Big-endian CPUs include Motorola 68k, IBM POWER.

2.8.2 Little-endian

The 0x12345678 value is represented in memory as:

<table>
<thead>
<tr>
<th>address in memory</th>
<th>byte value</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0</td>
<td>0x78</td>
</tr>
<tr>
<td>+1</td>
<td>0x56</td>
</tr>
<tr>
<td>+2</td>
<td>0x34</td>
</tr>
<tr>
<td>+3</td>
<td>0x12</td>
</tr>
</tbody>
</table>

Little-endian CPUs include Intel x86.

2.8.3 Example

Let’s take big-endian MIPS Linux installed and ready in QEMU\textsuperscript{23}.

And let’s compile this simple example:

```c
#include <stdio.h>

int main()
{
    int v;
    v=123;
    printf ("%02X %02X %02X %02X\n",
            *(char*)&v,
            *((char*)&v+1),
            *((char*)&v+2),
```

\textsuperscript{22} National Security Agency

\textsuperscript{23} Available for download here: \url{http://go.yurichev.com/17088}
2.9. MEMORY

```c
*(((char*)&v)+3));
```

After running it we get:

```
root@debian-mips:~# ./a.out
00 00 00 7B
```

That is it. 0x7B is 123 in decimal. In little-endian architectures, 7B is the first byte (you can check on x86 or x86-64), but here it is the last one, because the highest byte goes first.

That’s why there are separate Linux distributions for MIPS (“mips” (big-endian) and “mipsel” (little-endian)). It is impossible for a binary compiled for one endianness to work on an OS with different endianness.

There is another example of MIPS big-endiannes in this book: 1.24.4 on page 365.

2.8.4 Bi-endian

CPUs that may switch between endianness are ARM, PowerPC, SPARC, MIPS, IA64\(^{24}\), etc.

2.8.5 Converting data

The BSWAP instruction can be used for conversion.

TCP/IP network data packets use the big-endian conventions, so that is why a program working on a little-endian architecture has to convert the values. The htonl() and htons() functions are usually used.

In TCP/IP, big-endian is also called “network byte order”, while byte order on the computer “host byte order”. “host byte order” is little-endian on Intel x86 and other little-endian architectures, but it is big-endian on IBM POWER, so htonl() and htons() don’t shuffle any bytes on the latter.

2.9 Memory

There are 3 main types of memory:

- **Global memory AKA “static memory allocation”**. No need to allocate explicitly, the allocation is performed just by declaring variables/arrays globally. These are global variables, residing in the data or constant segments. They are available globally (hence, considered as an anti-pattern). Not convenient for buffers/arrays, because they must have a fixed size. Buffer overflows that occur here usually overwrite variables or buffers residing next to them in memory. There’s an example in this book: 1.9.3 on page 76.

- **Stack AKA “allocate on stack”**. The allocation is performed just by declaring variables/arrays locally in the function. These are usually local variables for the function. Sometimes these local variable are also available to descending functions (to callee functions, if caller passes a pointer to a variable to the callee to be executed). Allocation and deallocation are very fast, it just SP needs to be shifted.

  But they’re also not convenient for buffers/arrays, because the buffer size has to be fixed, unless alloca() (1.7.2 on page 35) (or a variable-length array) is used. Buffer overflows usually overwrite important stack structures: 1.20.2 on page 275.

- **Heap AKA “dynamic memory allocation”**. Allocation/deallocation is performed by calling malloc()/free() or new/delete in C++. This is the most convenient method: the block size may be set at runtime.

  Resizing is possible (using realloc()), but can be slow. This is the slowest way to allocate memory: the memory allocator must support and update all control structures while allocating and deallocating. Buffer overflows usually overwrite these structures. Heap allocations are also source of memory leak problems: each memory block has to be deallocated explicitly, but one may forget about it, or do it incorrectly.

\(^{24}\)Intel Architecture 64 (Itanium)
2.10. CPU

Another problem is the “use after free”—using a memory block after free() has been called on it, which is very dangerous.


2.10 CPU

2.10.1 Branch predictors

Some latest compilers try to get rid of conditional jump instructions. Examples in this book are: 1.14.1 on page 135, 1.14.3 on page 143, 1.22.5 on page 330.

This is because the branch predictor is not always perfect, so the compilers try to do without conditional jumps, if possible.

Conditional instructions in ARM (like ADRcc) are one way, another one is the CMOVcc x86 instruction.

2.10.2 Data dependencies

Modern CPUs are able to execute instructions simultaneously (OOE\textsuperscript{25}), but in order to do so, the results of one instruction in a group must not influence the execution of others. Hence, the compiler endeavors to use instructions with minimal influence on the CPU state.

That’s why the LEA instruction is so popular, because it does not modify CPU flags, while other arithmetic instructions does.

2.11 Hash functions

A very simple example is CRC32, an algorithm that provides “stronger” checksum for integrity checking purposes. It is impossible to restore the original text from the hash value, it has much less information:

But CRC32 is not cryptographically secure: it is known how to alter a text in a way that the resulting CRC32 hash value will be the one we need. Cryptographic hash functions are protected from this.

MD5, SHA1, etc. are such functions and they are widely used to hash user passwords in order to store them in a database. Indeed: an Internet forum database may not contain user passwords (a stolen database can compromise all users’ passwords) but only hashes (so a cracker can’t reveal the passwords).

Besides, an Internet forum engine does not need to know your password exactly, it needs only to check if its hash is the same as the one in the database, and give you access if they match. One of the simplest password cracking methods is just to try hashing all possible passwords in order to see which matches the resulting value that we need. Other methods are much more complex.

2.11.1 How do one-way functions work?

A one-way function is a function which is able to transform one value into another, while it is impossible (or very hard) to reverse it. Some people have difficulties while understanding how this is possible at all. Here is a simple demonstration.

We have a vector of 10 numbers in range 0..9, each is present only once, for example:

\begin{verbatim}
4 6 0 1 3 5 7 8 9 2
\end{verbatim}

The algorithm for the simplest possible one-way function is:

\begin{itemize}
  \item take the number at zeroth position (4 in our case);
  \item take the number at first position (6 in our case);
  \item swap numbers at positions of 4 and 6.
\end{itemize}

Let’s mark the numbers at positions 4 and 6:

\begin{verbatim}
25 Out-of-Order Execution
\end{verbatim}
Let's swap them and we get this result:

\[
\begin{array}{cccccccccc}
4 & 6 & 0 & 1 & 7 & 5 & 3 & 8 & 9 & 2 \\
\end{array}
\]

While looking at the result, and even if we know the algorithm, we can't know unambiguously the initial state, because the first two numbers could be 0 and/or 1, and then they could participate in the swapping procedure.

This is an utterly simplified example for demonstration. Real one-way functions are much more complex.
3.1 Double negation

A popular way\(^1\) to convert non-zero value into 1 (or boolean \textit{true}) and zero value into 0 (or boolean \textit{false}) is `!!statement`:

```c
int convert_to_bool(int a)
{
    return !!a;
};
```

Optimizing GCC 5.4 x86:

```assembly
convert_to_bool:
    mov edx, DWORD PTR [esp+4]
    xor eax, eax
    test edx, edx
    setne al
    ret
```

XOR always clears return value in EAX, even in case if SETNE will not trigger. I.e., XOR sets default return value to zero.

If the input value is not equal to zero (-NE suffix in SET instruction), 1 is set to AL, otherwise AL isn’t touched.

Why SETNE operates on low 8-bit part of EAX register? Because the matter is just in the last bit (0 or 1), while other bits are cleared by XOR.

Therefore, that C/C++ code could be rewritten like this:

```c
int convert_to_bool(int a)
{
    if (a!=0)
        return 1;
    else
        return 0;
};
```

...or even:

```c
int convert_to_bool(int a)
{
    if (a)
        return 1;
    else
        return 0;
};
```

Compilers targeting CPUs lacking instruction similar to SET, in this case, generates branching instructions, etc.

\(^1\)This way is also controversial, because it leads to hard-to-read code
3.2 \texttt{strstr()} example

Let's back to the fact that GCC sometimes can use part of string: \texttt{1.5.3 on page 18}.

The \texttt{strstr()} C/C++ standard library function is used to find any occurrence in a string. This is what we will do:

```c
#include <string.h>
#include <stdio.h>

int main()
{
    char *s="Hello, world!";
    char *w=strstr(s, "world");
    printf ("%p, [%s]\n", s, s);
    printf ("%p, [%s]\n", w, w);
}
```

The output is:

```
0x8048530, [Hello, world!]
0x8048537, [world!]
```

The difference between the address of the original string and the address of the substring that \texttt{strstr()} has returned is 7. Indeed, “Hello, ” string has length of 7 characters.

The \texttt{printf()} function during second call has no idea there are some other characters before the passed string and it prints characters from the middle of original string till the end (marked by zero byte).

3.3 Temperature converting

Another very popular example in programming books for beginners is a small program that converts Fahrenheit temperature to Celsius or back.

\[
C = 5 \cdot \frac{(F - 32)}{9}
\]

We can also add simple error handling: 1) we must check if the user has entered a correct number; 2) we must check if the Celsius temperature is not below -273 (which is below absolute zero, as we may recall from school physics lessons).

The \texttt{exit()} function terminates the program instantly, without returning to the \texttt{caller} function.

3.3.1 Integer values

```c
#include <stdio.h>
#include <stdlib.h>

int main()
{
    int celsius, fahr;
    printf ("Enter temperature in Fahrenheit:\n");
    if (scanf ("%d", &fahr)!="1)
    {
        printf ("Error while parsing your input\n");
        exit(0);
    };
    celsius = 5 * (fahr-32) / 9;
    if (celsius<-273)
    {
        printf ("Error: incorrect temperature!\n");
    }
}```
3.3. TEMPERATURE CONVERTING

```c
exit(0);

printf ("Celsius: \d\n", celsius);
```

Optimizing MSVC 2012 x86

Listing 3.1: Optimizing MSVC 2012 x86

```assembly
$SG4228 DB 'Enter temperature in Fahrenheit:', 0aH, 00H
$SG4230 DB '%d', 00H
$SG4231 DB 'Error while parsing your input', 0aH, 00H
$SG4233 DB 'Error: incorrect temperature!', 0aH, 00H
$SG4234 DB 'Celsius: %d', 0aH, 00H

_fahr$ = -4 ; size = 4
_main PROC
    push ecx
    push esi
    mov esi, DWORD PTR __imp__printf
    push OFFSET $SG4228 ; 'Enter temperature in Fahrenheit:'
    call esi ; call printf()
    lea eax, DWORD PTR _fahr$[esp+12]
    push eax
    push OFFSET $SG4230 ; '%d'
    call DWORD PTR __imp__scanf
    add esp, 12
    cmp eax, 1
    je SHORT $LN2@main
    push OFFSET $SG4231 ; 'Error while parsing your input'
    call esi ; call printf()
    add esp, 4
    push 0
    call DWORD PTR __imp__exit
$LN9@main:
$LN2@main:
    push eax
    push OFFSET $SG4234 ; 'Celsius: %d'
    call esi ; call printf()
    add esp, 8
; return 0 - by C99 standard
    xor eax, eax
    pop esi
    pop ecx
    ret 0
$LN8@main:
_main ENDP
```

What we can say about it:
3.3. TEMPERATURE CONVERTING

- The address of printf() is first loaded in the ESI register, so the subsequent printf() calls are done just by the CALL ESI instruction. It’s a very popular compiler technique, possible if several consequent calls to the same function are present in the code, and/or if there is a free register which can be used for this.

- We see the ADD EAX, -32 instruction at the place where 32 has to be subtracted from the value. \( EAX = EAX + (-32) \) is equivalent to \( EAX = EAX - 32 \) and somehow, the compiler decided to use ADD instead of SUB. Maybe it’s worth it, it’s hard to be sure.

- The LEA instruction is used when the value is to be multiplied by 5: \( \text{lea ecx, DWORD PTR [eax+eax*4]} \). Yes, \( i + i * 4 \) is equivalent to \( i * 5 \) and LEA works faster then IMUL.

- The division by multiplication trick (3.9 on page 497) is also used here.

- main() returns 0 if we don’t have return 0 at its end. The C99 standard tells us [ISO/IEC 9899:TC3 (C99 standard), (2007)5.1.2.2.3] that main() will return 0 in case the return statement is missing. This rule works only for the main() function.

Though, MSVC doesn’t officially support C99, but maybe it support it partially?

Optimizing MSVC 2012 x64

The code is almost the same, but we can find INT 3 instructions after each exit() call.

```assembly
xor ecx, ecx
call QWORD PTR __imp_exit
int 3
```

INT 3 is a debugger breakpoint.

It is known that exit() is one of the functions which can never return 2, so if it does, something really odd has happened and it’s time to load the debugger.

3.3.2 Floating-point values

```c
#include <stdio.h>
#include <stdlib.h>

int main()
{
    double celsius, fahr;
    printf("Enter temperature in Fahrenheit:\n");
    if (scanf("%lf", &fahr)!=1)
    {
        printf("Error while parsing your input\n");
        exit(0);
    }
    celsius = 5 * (fahr-32) / 9;
    if (celsius<-273)
    {
        printf("Error: incorrect temperature!\n");
        exit(0);
    }
    printf("Celsius: %lf\n", celsius);
}
```

MSVC 2010 x86 uses FPU instructions...

Listing 3.2: Optimizing MSVC 2010 x86

```assembly
SG4038 DB 'Enter temperature in Fahrenheit:', 0aH, 00H
SG4040 DB '%lf', 00H
```

2 another popular one is longjmp()
3.3. TEMPERATURE CONVERTING

Listing 3.3: Optimizing MSVC 2010 x86

...but MSVC 2012 uses SIMD instructions instead:
Of course, SIMD instructions are available in x86 mode, including those working with floating point numbers.

It’s somewhat easier to use them for calculations, so the new Microsoft compiler uses them.

We can also see that the \(-273\) value is loaded into \(XMM0\) register too early. And that’s OK, because the compiler may emit instructions not in the order they are in the source code.

### 3.4 Fibonacci numbers

Another widespread example used in programming textbooks is a recursive function that generates the Fibonacci numbers\(^3\). The sequence is very simple: each consecutive number is the sum of the previous two. The first two numbers are 0 and 1, or 1 and 1.

The sequence starts like this:

\[
0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, 610, 987, 1597, 2584, 4181, \ldots
\]

\(^3\)http://go.yurichev.com/17332
3.4. FIBONACCI NUMBERS

3.4.1 Example #1

The implementation is simple. This program generates the sequence until 21.

```c
#include <stdio.h>

void fib (int a, int b, int limit)
{
    printf ("%d\n", a+b);
    if (a+b > limit)
        return;
    fib (b, a+b, limit);
};

int main()
{
    printf ("0\n1\n1\n");
    fib (1, 1, 20);
};
```

Listing 3.4: MSVC 2010 x86

```
a$ = 8 ; size = 4
_b$ = 12 ; size = 4
_limit$ = 16 ; size = 4
_fib PROC
    push ebp
    mov ebp, esp
    mov eax, DWORD PTR _a$[ebp]
    add eax, DWORD PTR _b$[ebp]
    push eax
    push OFFSET $SG2643
    call DWORD PTR __imp__printf
    add esp, 8
    mov ecx, DWORD PTR _a$[ebp]
    add ecx, DWORD PTR _b$[ebp]
    cmp ecx, DWORD PTR _limit$[ebp]
    jle SHORT $LN1@fib
    jmp SHORT $LN2@fib
$LN1@fib:
    mov edx, DWORD PTR _limit$[ebp]
    push edx
    mov eax, DWORD PTR _a$[ebp]
    add eax, DWORD PTR _b$[ebp]
    push eax
    mov ecx, DWORD PTR _b$[ebp]
    push ecx
    call _fib
    add esp, 12
$LN2@fib:
    pop ebp
    ret 0
_fib ENDP

_main PROC
    push ebp
    mov ebp, esp
    push OFFSET $SG2647 ; "0\n1\n1\n"
    call DWORD PTR __imp__printf
    add esp, 4
    push 20
    push 1
    push 1
    call _fib
    add esp, 12
    xor eax, eax
    pop ebp
    ret 0
_main ENDP
```
3.4. FIBONACCI NUMBERS

We will illustrate the stack frames with this.
3.4. FIBONACCI NUMBERS

Let’s load the example in OllyDbg and trace to the last call of f():

![OllyDbg screenshot showing the last call of f()](image)

Figure 3.1: OllyDbg: last call of f()
Let’s investigate the stack more closely. Comments were added by the author of this book:

The function is recursive, hence stack looks like a “sandwich”. We see that the limit argument is always the same (0x14 or 20), but the a and b arguments are different for each call.

There are also the RA-s and the saved EBP values. OllyDbg is able to determine the EBP-based frames, so it draws these brackets. The values inside each bracket make the stack frame, in other words, the stack area which each function incarnation uses as scratch space.

We can also say that each function incarnation must not access stack elements beyond the boundaries of its frame (excluding function arguments), although it’s technically possible.

It’s usually true, unless the function has bugs.

Each saved EBP value is the address of the previous stack frame: this is the reason why some debuggers can easily divide the stack in frames and dump each function’s arguments.

As we see here, each function incarnation prepares the arguments for the next function call.

At the end we see the 3 arguments for main(). argc is 1 (yes, indeed, we have ran the program without command-line arguments).

This easily to lead to a stack overflow: just remove (or comment out) the limit check and it will crash with exception 0xC00000FD (stack overflow.)

### 3.4.2 Example #2

My function has some redundancy, so let’s add a new local variable next and replace all “a+b” with it:

```plaintext
My function has some redundancy, so let’s add a new local variable next and replace all “a+b” with it:
```

---

1. By the way, it’s possible to select several entries in OllyDbg and copy them to the clipboard (Ctrl-C). That’s what was done by author for this example.
2. i.e., it calls itself
#include <stdio.h>

void fib (int a, int b, int limit)
{
    int next=a+b;
    printf ("%d\n", next);
    if (next > limit)
        return;
    fib (b, next, limit);
}

int main()
{
    printf ("0\n1\n1\n");
    fib (1, 1, 20);
};

This is the output of non-optimizing MSVC, so the next variable is actually allocated in the local stack:

Listing 3.5: MSVC 2010 x86

_next$ = -4 ; size = 4
_a$ = 8 ; size = 4
_b$ = 12 ; size = 4
_limit$ = 16 ; size = 4
_fib PROC
    push ebp
    mov ebp, esp
    push ecx
    mov eax, DWORD PTR _a$[ebp]
    add eax, DWORD PTR _b$[ebp]
    mov DWORD PTR _next$[ebp], eax
    mov ecx, DWORD PTR _next$[ebp]
    push ecx
    push OFFSET $SG2751 ; '%d'
    call DWORD PTR __imp__printf
    add esp, 8
    mov edx, DWORD PTR _next$[ebp]
    cmp edx, DWORD PTR _limit$[ebp]
    jle SHORT $LN1@fib
    jmp SHORT $LN2@fib
$LN1@fib:
    mov eax, DWORD PTR _limit$[ebp]
    push eax
    mov edx, DWORD PTR _next$[ebp]
    call _fib
    add esp, 12
$LN2@fib:
    mov esp, ebp
    pop ebp
    ret 0
_fib ENDP

_main PROC
    push ebp
    mov ebp, esp
    push OFFSET $SG2753 ; "0\n1\n1\n"
    call DWORD PTR __imp__printf
    add esp, 4
    push 20
    push 1
    push 1
    call _fib
    add esp, 12
    xor eax, eax
    pop ebp
    ret 0
_main ENDP
3.4. FIBONACCI NUMBERS

main ENDP
3.4. FIBONACCI NUMBERS

Let's load it in OllyDbg once again:

![OllyDbg screenshot showing the last call of f()](image)

Now the next variable is present in each frame.
3.4. FIBONACCI NUMBERS

Let's investigate the stack more closely. The author has again added his comments:

Here we see it: the next value is calculated in each function incarnation, then passed as argument b to the next incarnation.

3.4.3 Summary

Recursive functions are aesthetically nice, but technically may degrade performance because of their heavy stack usage. Everyone who writes performance critical code probably should avoid recursion.

For example, the author of this book once wrote a function to seek a particular node in a binary tree. As a recursive function it looked quite stylish but since additional time was spent at each function call for the prologue/epilogue, it was working a couple of times slower than an iterative (recursion-free) implementation.

By the way, that is the reason that some functional PL\^6 compilers (where recursion is used heavily) use tail call. We talk about tail call when a function has only one single call to itself located at the end of it, like:

Listing 3.6: Scheme, example is copypasted from Wikipedia

```scheme
;; factorial : number -> number
;; to calculate the product of all positive
;; integers less than or equal to n.
(define (factorial n)
  (if (= n 1)
      1
      (* n (factorial (- n 1))))
```

\^6LISP, Python, Lua, etc.
3.5. CRC32 CALCULATION EXAMPLE
(* n (factorial (- n 1)))))

Tail call is important because compiler can rework this code easily into iterative one, to get rid of recursion.

3.5

CRC32 calculation example

This is a very popular table-based CRC32 hash calculation technique7 .
/* By Bob Jenkins, (c) 2006, Public Domain */
#include <stdio.h>
#include <stddef.h>
#include <string.h>
typedef
typedef

unsigned long
unsigned char

ub4;
ub1;

static const ub4 crctab[256] = {
0x00000000, 0x77073096, 0xee0e612c,
0x706af48f, 0xe963a535, 0x9e6495a3,
0xe0d5e91e, 0x97d2d988, 0x09b64c2b,
0x90bf1d91, 0x1db71064, 0x6ab020f2,
0x1adad47d, 0x6ddde4eb, 0xf4d4b551,
0x646ba8c0, 0xfd62f97a, 0x8a65c9ec,
0xfa0f3d63, 0x8d080df5, 0x3b6e20c8,
0xa2677172, 0x3c03e4d1, 0x4b04d447,
0x35b5a8fa, 0x42b2986c, 0xdbbbc9d6,
0x45df5c75, 0xdcd60dcf, 0xabd13d59,
0xc8d75180, 0xbfd06116, 0x21b4f4b5,
0xb8bda50f, 0x2802b89e, 0x5f058808,
0x2f6f7c87, 0x58684c11, 0xc1611dab,
0x01db7106, 0x98d220bc, 0xefd5102a,
0x9fbfe4a5, 0xe8b8d433, 0x7807c9a2,
0xe10e9818, 0x7f6a0dbb, 0x086d3d2d,
0x6b6b51f4, 0x1c6c6162, 0x856530d8,
0x1b01a57b, 0x8208f4c1, 0xf50fc457,
0x8bbeb8ea, 0xfcb9887c, 0x62dd1ddf,
0xfbd44c65, 0x4db26158, 0x3ab551ce,
0x4adfa541, 0x3dd895d7, 0xa4d1c46d,
0x346ed9fc, 0xad678846, 0xda60b8d0,
0xaa0a4c5f, 0xdd0d7cc9, 0x5005713c,
0xc90c2086, 0x5768b525, 0x206f85b3,
0x5edef90e, 0x29d9c998, 0xb0d09822,
0x2eb40d81, 0xb7bd5c3b, 0xc0ba6cad,
0x03b6e20c, 0x74b1d29a, 0xead54739,
0x73dc1683, 0xe3630b12, 0x94643b84,
0xe40ecf0b, 0x9309ff9d, 0x0a00ae27,
0x8708a3d2, 0x1e01f268, 0x6906c2fe,
0x196c3671, 0x6e6b06e7, 0xfed41b76,
0x67dd4acc, 0xf9b9df6f, 0x8ebeeff9,
0xd6d6a3e8, 0xa1d1937e, 0x38d8c2c4,
0xa6bc5767, 0x3fb506dd, 0x48b2364b,
0x36034af6, 0x41047a60, 0xdf60efc3,
0x4669be79, 0xcb61b38c, 0xbc66831a,
0xcc0c7795, 0xbb0b4703, 0x220216b9,
0xb2bd0b28, 0x2bb45a92, 0x5cb36a04,
0x2cd99e8b, 0x5bdeae1d, 0x9b64c2b0,
0x026d930a, 0x9c0906a9, 0xeb0e363f,
0x95bf4a82, 0xe2b87a14, 0x7bb12bae,
0xe5d5be0d, 0x7cdcefb7, 0x0bdbdf21,
0x68ddb3f8, 0x1fda836e, 0x81be16cd,
0x18b74777, 0x88085ae6, 0xff0f6a70,
0x8f659eff, 0xf862ae69, 0x616bffd3,
0xd70dd2ee, 0x4e048354, 0x3903b3c2,
0x4969474d, 0x3e6e77db, 0xaed16a4a,
0x37d83bf0, 0xa9bcae53, 0xdebb9ec5,
7 The

0x990951ba,
0x0edb8832,
0x7eb17cbd,
0xf3b97148,
0x83d385c7,
0x14015c4f,
0x4c69105e,
0xd20d85fd,
0xacbcf940,
0x26d930ac,
0x56b3c423,
0xc60cd9b2,
0xb6662d3d,
0x71b18589,
0x0f00f934,
0x91646c97,
0xf262004e,
0x65b0d9c6,
0x15da2d49,
0xa3bc0074,
0xd3d6f4fb,
0x44042d73,
0x270241aa,
0xb966d409,
0xc7d7a8b4,
0xedb88320,
0x9dd277af,
0x0d6d6a3e,
0x7d079eb1,
0xf762575d,
0x89d32be0,
0x17b7be43,
0x4fdff252,
0xd80d2bda,
0xa867df55,
0x256fd2a0,
0x5505262f,
0xc2d7ffa7,
0xec63f226,
0x72076785,
0x0cb61b38,
0x86d3d2d4,
0xf6b9265b,
0x66063bca,
0x166ccf45,
0xa7672661,
0xd9d65adc,
0x47b2cf7f,

0x076dc419,
0x79dcb8a4,
0xe7b82d07,
0x84be41de,
0x136c9856,
0x63066cd9,
0xd56041e4,
0xa50ab56b,
0x32d86ce3,
0x51de003a,
0xcfba9599,
0xb10be924,
0x76dc4190,
0x06b6b51f,
0x9609a88e,
0xe6635c01,
0x6c0695ed,
0x12b7e950,
0x8cd37cf3,
0xd4bb30e2,
0x4369e96a,
0x33031de5,
0xbe0b1010,
0xce61e49f,
0x59b33d17,
0x9abfb3b6,
0x04db2615,
0x7a6a5aa8,
0xf00f9344,
0x806567cb,
0x10da7a5a,
0x60b08ed5,
0xd1bb67f1,
0xaf0a1b4c,
0x316e8eef,
0x5268e236,
0xc5ba3bbe,
0xb5d0cf31,
0x756aa39c,
0x05005713,
0x92d28e9b,
0xf1d4e242,
0x6fb077e1,
0x11010b5c,
0xa00ae278,
0xd06016f7,
0x40df0b66,
0x30b5ffe9,

source code has been taken from here: http://go.yurichev.com/17327

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3.5. CRC32 CALCULATION EXAMPLE

```c
0xbdbdf21c, 0xcabac28a, 0x53b39330, 0x24b4a3a6, 0xbad03605,
0xcdd70693, 0x54de5729, 0x23d967bf, 0xb3667a2e, 0xc4614ab8,
0x5d681b02, 0x2a6f2b94, 0xb40bbe37, 0xc30c8ea1, 0x5a05df1b,
0x2d02ef8d
};
/* how to derive the values in crctab[] from polynomial 0xedb88320 */
void build_table()
{
  ub4 i, j;
  for (i=0; i<256; ++i) {
    j = i;
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
    printf("0x%.8lx, ", j);
    if (i%6 == 5) printf("\n");
  }
}
/* the hash function */
crc(const void *key, ub4 len, ub4 hash)
{
  ub4 i;
  const ub1 *k = key;
  for (hash=len, i=0; i<len; ++i)
    hash = (hash >> 8) ^ crctab[(hash & 0xff) ^ k[i]];
  return hash;
}
/* To use, try "gcc -O crc.c -o crc; crc < crc.c" */
int main()
{
  char s[1000];
  while (gets(s)) printf("%.8lx\n", crc(s, strlen(s), 0));
  return 0;
}

We are interested in the crc() function only. By the way, pay attention to the two loop initializers in the for() statement: hash=len, i=0. The C/C++ standard allows this, of course. The emitted code will contain two operations in the loop initialization part instead of one.

Let’s compile it in MSVC with optimization (/Ox). For the sake of brevity, only the crc() function is listed here, with my comments.

```
_key$ = 8 ; size = 4
_len$ = 12 ; size = 4
_hash$ = 16 ; size = 4
_crc PROC
  mov edx, DWORD PTR _len$[esp-4]
  xor ecx, ecx ; i will be stored in ECX
  mov eax, edx
  test edx, edx
  jbe SHORT $LN1@crc
  push ebx
  push esi
  mov esi, DWORD PTR _key$[esp+4] ; ESI = key
  push edi
  $LL3@crc:
  ; work with bytes using only 32-bit registers. byte from address key+i we store into EDI
  movzx edi, BYTE PTR [ecx+esi]
  mov ebx, eax ; EBX = (hash = len)
```

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3.5. CRC32 CALCULATION EXAMPLE

and ebx, 255 ; EBX = hash & 0xff

; XOR EDI, EBX (EDI=EDI*EBX) - this operation uses all 32 bits of each register
; but other bits (8-31) are cleared all time, so its OK'
; these are cleared because, as for EDI, it was done by MOVZX instruction above
; high bits of EBX was cleared by AND EBX, 255 instruction above (255 = 0xff)

xor edi, ebx

; EAX=EAX>>8; bits 24-31 taken from nowhere will be cleared
shr eax, 8

; EAX=EAX^crctab[EDI*4] - choose EDI-th element from crctab[] table
xor eax, DWORD PTR _crctab[edi*4]
inc ecx ; i++
cmp ecx, edx ; i<len ?
jb SHORT $LL3@crc ; yes
pop edi
pop esi
pop ebx

$LN1@crc:
ret 0
 crc ENDP

Let's try the same in GCC 4.4.1 with -O3 option:

public crc
crc proc near
key = dword ptr 8
hash = dword ptr 0Ch

push ebp
xor edx, edx
mov ebp, esp
push esi
mov esi, [ebp+key]
push ebx
mov ebx, [ebp+hash]
test ebx, ebx
jz short loc_8048D3
nop ; padding
lea esi, [esi+0] ; padding; works as NOP (ESI does not change here)

loc_8048B8:
mov ecx, eax ; save previous state of hash to ECX
xor al, [esi+edx] ; AL=*(key+i)
add edx, 1 ; i++
shr ecx, 8 ; ECX=hash>>8
movzx eax, al ; EAX=*(key+i)
mov eax, dword ptr ds:crctab[eax*4] ; EAX=crctab[EAX]
xor eax, ecx ; hash=EAX^ECX
cmp ebx, edx
ja short loc_8048B8

loc_8048D3:
pop ebx
pop esi
pop ebp
retn
crc endp
\

GCC has aligned the loop start on a 8-byte boundary by adding NOP and lea esi, [esi+0] (that is an idle operation too). Read more about it in npad section (.1.7 on page 1038).
3.6. NETWORK ADDRESS CALCULATION EXAMPLE

3.6

Network address calculation example

As we know, a TCP/IP address (IPv4) consists of four numbers in the 0 . . . 255 range, i.e., four bytes.
Four bytes can be ﬁt in a 32-bit variable easily, so an IPv4 host address, network mask or network address
can all be 32-bit integers.
From the user’s point of view, the network mask is deﬁned as four numbers and is formatted like 255.255.255.0
or so, but network engineers (sysadmins) use a more compact notation (CIDR8 ), like “/8”, “/16”, etc.
This notation just deﬁnes the number of bits the mask has, starting at the MSB.
Mask
/30
/29
/28
/27
/26
/24
/23
/22
/21
/20
/19
/18
/17
/16
/8

Hosts
4
8
16
32
64
256
512
1024
2048
4096
8192
16384
32768
65536
16777216

Usable
2
6
14
30
62
254
510
1022
2046
4094
8190
16382
32766
65534
16777214

Netmask
255.255.255.252
255.255.255.248
255.255.255.240
255.255.255.224
255.255.255.192
255.255.255.0
255.255.254.0
255.255.252.0
255.255.248.0
255.255.240.0
255.255.224.0
255.255.192.0
255.255.128.0
255.255.0.0
255.0.0.0

Hex mask
0xﬀﬀﬀfc
0xﬀﬀﬀf8
0xﬀﬀﬀf0
0xﬀﬀﬀe0
0xﬀﬀﬀc0
0xﬀﬀﬀ00
0xﬀﬀfe00
0xﬀﬀfc00
0xﬀﬀf800
0xﬀﬀf000
0xﬀﬀe000
0xﬀﬀc000
0xﬀﬀ8000
0xﬀﬀ0000
0xﬀ000000

class C network

class B network
class A network

Here is a small example, which calculates the network address by applying the network mask to the host
address.
#include <stdio.h>
#include <stdint.h>
uint32_t form_IP (uint8_t ip1, uint8_t ip2, uint8_t ip3, uint8_t ip4)
{
return (ip1<<24) | (ip2<<16) | (ip3<<8) | ip4;
};
void print_as_IP (uint32_t a)
{
printf ("%d.%d.%d.%d\n",
(a>>24)&0xFF,
(a>>16)&0xFF,
(a>>8)&0xFF,
(a)&0xFF);
};
// bit=31..0
uint32_t set_bit (uint32_t input, int bit)
{
return input=input|(1<<bit);
};
uint32_t form_netmask (uint8_t netmask_bits)
{
uint32_t netmask=0;
uint8_t i;
for (i=0; i<netmask_bits; i++)
netmask=set_bit(netmask, 31-i);
return netmask;
};
void calc_network_address (uint8_t ip1, uint8_t ip2, uint8_t ip3, uint8_t ip4, uint8_t ⤦
Ç netmask_bits)
{
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3.6. NETWORK ADDRESS CALCULATION EXAMPLE

```c
uint32_t netmask = form_netmask(netmask_bits);
uint32_t ip = form_IP(ip1, ip2, ip3, ip4);
uint32_t netw_adr;

printf("netmask=");
print_as_IP (netmask);

netw_adr = ip & netmask;
printf("network address=");
print_as_IP (netw_adr);
```

```c
int main()
{
    calc_network_address (10, 1, 2, 4, 24);  // 10.1.2.4, /24
    calc_network_address (10, 1, 2, 4, 8);  // 10.1.2.4, /8
    calc_network_address (10, 1, 2, 4, 25); // 10.1.2.4, /25
    calc_network_address (10, 1, 2, 64, 26); // 10.1.2.4, /26
}
```

3.6.1 calc_network_address()

`calc_network_address()` function is simplest one: it just ANDs the host address with the network mask, resulting in the network address.

```assembly
; opti..._Ob0

   _calc_network_address PROC
   push    edi
   push    DWORD PTR _netmask_bits$[esp]
   call    _form_netmask
   push    OFFSET $SG3045 ; 'netmask='
   mov     edi, eax
   call    DWORD PTR __imp__printf
   push    edi
   call    _print_as_IP
   push    OFFSET $SG3046 ; 'network address='
   call    DWORD PTR __imp__printf
   push    DWORD PTR _ip4$[esp+16]
   push    DWORD PTR _ip3$[esp+20]
   push    DWORD PTR _ip2$[esp+24]
   push    DWORD PTR _ip1$[esp+28]
   call    _form_IP
   and     eax, edi ; network address = host address & netmask
   push    eax
   call    _print_as_IP
   add     esp, 36
   pop     edi
   ret     0
   _calc_network_address ENDP
```

At line 22 we see the most important AND—here the network address is calculated.

3.6.2 form_IP()

The `form_IP()` function just puts all 4 bytes into a 32-bit value.

Here is how it is usually done:

- Allocate a variable for the return value. Set it to 0.
• Take the fourth (lowest) byte, apply OR operation to this byte and return the value. The return value contain the 4th byte now.

• Take the third byte, shift it left by 8 bits. You’ll get a value like 0x0000bb00 where bb is your third byte. Apply the OR operation to the resulting value and returning value. The return value has contained 0x000000aa so far, so ORing the values will produce a value like 0x0000bbaa.

• Take the second byte, shift it left by 16 bits. You’ll get a value like 0x00cc0000, where cc is your second byte. Apply the OR operation to the resulting value and returning value. The return value has contained 0x0000bbaa so far, so ORing the values will produce a value like 0x00ccbbaa.

• Take the first byte, shift it left by 24 bits. You’ll get a value like 0xdd000000, where dd is your first byte. Apply the OR operation to the resulting value and returning value. The return value has contained 0x00ccbbaa so far, so ORing the values will produce a value like 0xddccbbaa.

And this is how it’s done by non-optimizing MSVC 2012:

Listing 3.8: Non-optimizing MSVC 2012

```plaintext
; denote ip1 as "dd", ip2 as "cc", ip3 as "bb", ip4 as "aa".

_ip1$ = 8 ; size = 1
_ip2$ = 12 ; size = 1
_ip3$ = 16 ; size = 1
_ip4$ = 20 ; size = 1
_form_IP PROC
    push ebp
    mov ebp, esp
    movzx eax, BYTE PTR _ip1$[ebp]; EAX=000000dd
    shl eax, 24
    movzx ecx, BYTE PTR _ip2$[ebp]; ECX=000000cc
    shl ecx, 16
    or eax, ecx
    ; EAX=ddcc0000
    movzx edx, BYTE PTR _ip3$[ebp]; EDX=0000bb00
    or eax, edx
    ; EAX=ddccbb00
    movzx ecx, BYTE PTR _ip4$[ebp]; ECX=000000aa
    or eax, ecx
    ; EAX=ddccbbaa
    pop ebp
    ret 0
_form_IP ENDP
```

Well, the order is different, but, of course, the order of the operations doesn’t matter.

Optimizing MSVC 2012 does essentially the same, but in a different way:

Listing 3.9: Optimizing MSVC 2012 /Ob0

```plaintext
; denote ip1 as "dd", ip2 as "cc", ip3 as "bb", ip4 as "aa".

_ip1$ = 8 ; size = 1
_ip2$ = 12 ; size = 1
_ip3$ = 16 ; size = 1
_ip4$ = 20 ; size = 1
_form_IP PROC
    movzx eax, BYTE PTR _ip1$[esp-4]; EAX=000000dd
    movzx ecx, BYTE PTR _ip2$[esp-4]; ECX=000000cc
    shl eax, 8
    ; EAX=0000dd00
    or eax, ecx
    ; EAX=0000ddcc
    movzx edx, BYTE PTR _ip3$[esp-4]; EDX=0000bb00
    or eax, edx
    ; EAX=0000ccbb
    movzx ecx, BYTE PTR _ip4$[esp-4]; ECX=000000aa
    or eax, ecx
    ; EAX=0000ccbbaa
    pop ebp
    ret 0
_form_IP ENDP
```
We could say that each byte is written to the lowest 8 bits of the return value, and then the return value is shifted left by one byte at each step.

Repeat 4 times for each input byte.

That's it! Unfortunately, there are probably no other ways to do it.

There are no popular CPUs or ISAs which has instruction for composing a value from bits or bytes.

It's all usually done by bit shifting and ORing.

### 3.6.3 print_as_IP()

print_as_IP() does the inverse: splitting a 32-bit value into 4 bytes.

Slicing works somewhat simpler: just shift input value by 24, 16, 8 or 0 bits, take the bits from zeroth to seventh (lowest byte), and that's it:

#### Listing 3.10: Non-optimizing MSVC 2012

```assembly
_a$ = 8 ; size = 4

_print_as_IP PROC
push ebp
mov ebp, esp
mov eax, DWORD PTR _a$[ebp] ; EAX=ddccbbaa
and eax, 255 ; EAX=000000aa
push eax
mov ecx, DWORD PTR _a$[ebp] ; ECX=ddccbbaa
shr ecx, 8 ; ECX=00ddccbb
and ecx, 255 ; ECX=000000bb
push ecx
mov edx, DWORD PTR _a$[ebp] ; EDX=ddccbbaa
shr edx, 16 ; EDX=0000ddcc
and edx, 255 ; EDX=000000cc
push edx
mov eax, DWORD PTR _a$[ebp] ; EAX=ddccbbaa
shr eax, 24 ; EAX=000000dd
and eax, 255 ; probably redundant instruction
push eax
push OFFSET $SG2973 ; '%d.%d.%d.%d'
call DWORD PTR __imp__printf
add esp, 20
pop esp
ret 0

_print_as_IP ENDP
```
3.6. NETWORK ADDRESS CALCULATION EXAMPLE

Optimizing MSVC 2012 does almost the same, but without unnecessary reloading of the input value:

Listing 3.11: Optimizing MSVC 2012 /Ob0

```assembly
; size = 4
_print_as_IP PROC
    mov ecx, DWORD PTR _a$[esp-4]
    ; ECX=ddccbbaa
    movzx eax, cl
    ; EAX=000000aa
    push eax
    mov eax, ecx
    ; EAX=ddccbbaa
    shr eax, 8
    ; EAX=00ddccbb
    and eax, 255
    ; EAX=000000bb
    push eax
    mov eax, ecx
    ; EAX=ddccbbaa
    shr eax, 16
    ; EAX=0000ddcc
    and eax, 255
    ; EAX=000000cc
    push eax
    push ecx
    mov ecx, DWORD PTR _bit$[esp-4]
    shr ecx, 24
    push ecx
    push OFFSET $SG3020 ; '%d.%d.%d.%d'
    call DWORD PTR __imp__printf
    add esp, 20
    ret 0
_print_as_IP ENDP
```

3.6.4 form_netmask() and set_bit()

form_netmask() makes a network mask value from CIDR notation. Of course, it would be much effective to use here some kind of a precalculated table, but we consider it in this way intentionally, to demonstrate bit shifts.

We will also write a separate function set_bit(). It's a not very good idea to create a function for such primitive operation, but it would be easy to understand how it all works.

Listing 3.12: Optimizing MSVC 2012 /Ob0

```assembly
; size = 4
_set_bit PROC
    mov ecx, DWORD PTR _bit$[esp-4]
    mov eax, 1
    shl eax, cl
    or eax, DWORD PTR _input$[esp-4]
    ret 0
_set_bit ENDP

_netmask_bits$ = 8 ; size = 1
_form_netmask PROC
    push ebx
    push esi
    movzx esi, BYTE PTR _netmask_bits$[esp+4]
    xor ecx, ecx
    xor bl, bl
    test esi, esi
    jle SHORT $LN9@form_netma
    xor edx, edx
    $LL3@form_netma:
    mov eax, 31
    sub eax, edx
```
3.7. **LOOPS: SEVERAL ITERATORS**

```assembly
push   eax
push   ecx
call   _set_bit
inc    bl
movzx  edx, bl
add    esp, 8
mov    ecx, eax
cmp    edx, esi
jl     SHORT $LL3@form_netma

$LN9@form_netma:
    pop    esi
    mov    eax, ecx
    pop    ebx
    ret    0

_form_netmask ENDP
```

set_bit() is primitive: it just shift left 1 to number of bits we need and then ORs it with the “input” value. form_netmask() has a loop: it will set as many bits (starting from the MSB) as passed in the netmask_bits argument.

### 3.6.5 Summary

That’s it! We run it and getting:

- netmask=255.255.255.0
- network address=10.1.2.0
- netmask=255.0.0.0
- network address=10.0.0.0
- netmask=255.255.255.128
- network address=10.1.2.0
- netmask=255.255.255.192
- network address=10.1.2.64

### 3.7 Loops: several iterators

In most cases loops have only one iterator, but there could be several in the resulting code.

Here is a very simple example:

```c
#include <stdio.h>

void f(int *a1, int *a2, size_t cnt)
{
    size_t i;

    // copy from one array to another in some weird scheme
    for (i=0; i<cnt; i++)
        a1[i*3]=a2[i*7];
}
```

There are two multiplications at each iteration and they are costly operations. Can we optimize it somehow?

Yes, if we notice that both array indices are jumping on values that we can easily calculate without multiplication.

#### 3.7.1 Three iterators

Listing 3.13: Optimizing MSVC 2013 x64
3.7. **LOOPS: SEVERAL ITERATORS**

```assembly
; R8=cnt
    test    r8, r8      ; cnt==0? exit then
    je      SHORT $LN1@f
    npad   11
$LL3@f:
    mov    eax, DWORD PTR [rdx]
    lea    rcx, QWORD PTR [rcx+12]
    lea    rdx, QWORD PTR [rdx+28]
    mov    DWORD PTR [rcx-12], eax
    dec    r8
    jne    SHORT $LL3@f
$LN1@f:
    ret  0
f  ENDP
```

Now there are 3 iterators: the `cnt` variable and two indices, which are increased by 12 and 28 at each iteration. We can rewrite this code in C/C++:

```c
#include <stdio.h>

void f(int *a1, int *a2, size_t cnt)
{
    size_t i;
    size_t idx1=0; idx2=0;
    // copy from one array to another in some weird scheme
    for (i=0; i<cnt; i++)
    {
        a1[idx1]=a2[idx2];
        idx1+=3;
        idx2+=7;
    }
}
```

So, at the cost of updating 3 iterators at each iteration instead of one, we can remove two multiplication operations.

### 3.7.2 Two iterators

GCC 4.9 does even more, leaving only 2 iterators:

```assembly
Listing 3.14: Optimizing GCC 4.9 x64

; RDI=a1
; RSI=a2
; RDX=cnt
f:
    test    rdx, rdx      ; cnt==0? exit then
    je      .L1
    ; calculate last element address in "a2" and leave it in RDX
    lea    rax, [0+rdx*4]
    RAX=RDX*4=cnt*4
    sal    rdx, 5
    RDX=RDX<<5=cnt*32
    sub    rdx, rax
    RDX=RDX-RAX=cnt*32-cnt*4=cnt*28
    add    rdx, rsi
    RDX=RDX+RSI=a2+cnt*28
    .L3:
    mov    eax, DWORD PTR [rsi]
    add    rsi, 28
    add    rdi, 12
    mov    DWORD PTR [rdi-12], eax
    cmp    rsi, rdx
    jne    .L3
    .L1:
    rep    ret
```
3.7. LOOPS: SEVERAL ITERATORS

There is no counter variable any more: GCC concluded that it is not needed.

The last element of the a2 array is calculated before the loop begins (which is easy: \( cnt + 7 \)) and that’s how the loop is to be stopped: just iterate until the second index reaches this precalculated value.

You can read more about multiplication using shifts/additions/subtractions here: 1.18.1 on page 213.

This code can be rewritten into C/C++ like that:

```c
#include <stdio.h>

void f(int *a1, int *a2, size_t cnt)
{
    size_t idx1=0; idx2=0;
    size_t last_idx2=cnt*7;

    // copy from one array to another in some weird scheme
    for (;;) {
        a1[idx1]=a2[idx2];
        idx1+=3;
        idx2+=7;
        if (idx2==last_idx2)
            break;
    }
}
```

GCC (Linaro) 4.9 for ARM64 does the same, but it precalculates the last index of a1 instead of a2, which, of course has the same effect:

Listing 3.15: Optimizing GCC (Linaro) 4.9 ARM64

```assembly
X0=a1
X1=a2
X2=cnt
f:
    cbz x2, .L1 ; cnt==0? exit then
; calculate last element of "a1" array
    add x2, x2, x2, lsl 1
    X2=X2+X2<<1=X2+x2=2=X2*3
mov x3, 0
    lsl x2, x2, 2
; X2=X2<<2=X2*4=X2*3*4=X2*12
.L3:
    ldr w4, [x1],28 ; load at X1, add 28 to X1 (post-increment)
str w4, [x0,x3] ; store at X0+x3=a1+x3
    add x3, x3, 12 ; shift X3
    cmp x3, x2 ; end?
    bne .L3
.L1:
    ret
```

GCC 4.4.5 for MIPS does the same:

Listing 3.16: Optimizing GCC 4.4.5 for MIPS (IDA)

```assembly
; $a0=a1
; $a1=a2
; $a2=cnt
f:
; jump to loop check code:
    beqz $a2, locret_24
; initialize counter (i) at 0:
    move $v0, $zero ; branch delay slot, NOP
loc_8:
; load 32-bit word at $a1
    lw $a3, 0($a1)
; increment counter (i):
    addiu $v0, 1
; check for finish (compare "i" in $v0 and "cnt" in $a2):
    sltu $v1, $v0, $a2
```

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3.7. LOOPS: SEVERAL ITERATORS

; store 32-bit word at $a0:
    sw $a3, 0($a0)
; add 0x1C (28) to $a1 at each iteration:
    addiu $a1, 0x1C
; jump to loop body if i<cnt:
    bnez $v1, loc_8
; add 0xC (12) to $a0 at each iteration:
    addiu $a0, 0xC ; branch delay slot
locret_24:
    jr $ra
or $at, $zero ; branch delay slot, NOP

3.7.3 Intel C++ 2011 case

Compiler optimizations can also be weird, but nevertheless, still correct. Here is what the Intel C++ compiler 2011 does:

Listing 3.17: Optimizing Intel C++ 2011 x64

f PROC
; parameter 1: rcx = a1
; parameter 2: rdx = a2
; parameter 3: r8 = cnt
.B1.1::
    test r8, r8
    jbe exit
.B1.2::
    cmp r8, 6
    jbe just_copy
.B1.3::
    cmp rcx, rdx
    jbe .B1.5
.B1.4::
    mov r10, r8
    mov r9, rcx
    shl r10, 5
    lea rax, QWORD PTR [r8*4]
    sub r9, rdx
    sub r10, rax
    cmp r9, r10
    jge just_copy2
.B1.5::
    cmp rdx, rcx
    jbe just_copy
.B1.6::
    mov r9, rdx
    lea rax, QWORD PTR [r8*8]
    sub r9, rcx
    lea r10, QWORD PTR [rax+r8*4]
    cmp r9, r10
    jl just_copy
just_copy2::
; R8 = cnt
; RDX = a2
; RCX = a1
    xor r10d, r10d
    xor r9d, r9d
    xor eax, eax
.B1.8::
    mov r11d, DWORD PTR [rax+rdx]
First, there are some decisions taken, then one of the routines is executed.

Looks like it is a check if arrays intersect.

This is very well known way of optimizing memory block copy routines. But copy routines are the same!

This is has to be an error of the Intel C++ optimizer, which still produces workable code, though.

We intentionally considering such example code in this book so the reader would understand that compiler output is weird at times, but still correct, because when the compiler was tested, it passed the tests.

### 3.8 Duff’s device

Duff’s device \(^9\) is an unrolled loop with the possibility to jump to the middle of it. The unrolled loop is implemented using a fallthrough switch() statement. We would use here a slightly simplified version of Tom Duff’s original code. Let’s say, we have to write a function that clears a region in memory. One can come with a simple loop, clearing byte by byte. It’s obviously slow, since all modern computers have much wider memory bus. So the better way is to clear the memory region using 4 or 8 bytes blocks. Since we are going to work with a 64-bit example here, we are going to clear the memory in 8 bytes blocks. So far so good. But what about the tail? Memory clearing routine can also be called for regions of size that’s not a multiple of 8. So here is the algorithm:

- calculate the number of 8-bytes blocks, clear them using 8-bytes (64-bit) memory accesses;
- calculate the size of the tail, clear it using 1-byte memory accesses.

The second step can be implemented using a simple loop. But let’s implement it as an unrolled loop:

```c
#include <stdint.h>
#include <stdio.h>

void bzero(uint8_t* dst, size_t count)
{
    int i;

    if (count&(~7))
        // work out 8-byte blocks
        for (i=0; i<count>>3; i++)
        {
```
Let's first understand how the calculation is performed. The memory region size comes as a 64-bit value. And this value can be divided in two parts:

\[
\begin{align*}
\text{count} & = & 7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\
\text{B} & & \text{B} & & \text{B} & & \text{B} & & \text{S} & & \text{S} & & \text{S}
\end{align*}
\]

(“B” is number of 8-byte blocks and “S” is length of the tail in bytes).

When we divide the input memory region size by 8, the value is just shifted right by 3 bits. But to calculate the remainder, we can just to isolate the lowest 3 bits! So the number of 8-byte blocks is calculated as \( \text{count} \gg 3 \) and remainder as \( \text{count} \& 7 \). We also have to find out if we are going to execute the 8-byte procedure at all, so we need to check if the value of \( \text{count} \) is greater than 7. We do this by clearing the 3 lowest bits and comparing the resulting number with zero, because all we need here is to answer the question, is the high part of \( \text{count} \) non-zero. Of course, this works because 8 is \( 2^3 \) and division by numbers that are \( 2^n \) is easy. It’s not possible for other numbers. It’s actually hard to say if these hacks are worth using, because they lead to hard-to-read code. However, these tricks are very popular and a practicing programmer, even if he/she is not using them, nevertheless has to understand them.

So the first part is simple: get the number of 8-byte blocks and write 64-bit zero values to memory. The second part is an unrolled loop implemented as fallthrough switch() statement.

First, let’s express in plain English what we have to do here.

We have to “write as many zero bytes in memory, as \( \text{count} \& 7 \) value tells us”. If it's 0, jump to the end, there is no work to do. If it’s 1, jump to the place inside switch() statement where only one storage operation is to be executed. If it’s 2, jump to another place, where two storage operation are to be executed, etc. 7 as input value leads to the execution of all 7 operations. There is no 8, because a memory region of 8 bytes is to be processed by the first part of our function. So we wrote an unrolled loop. It was definitely faster on older computers than normal loops (and conversely, latest CPUs works better for short loops than for unrolled ones). Maybe this is still meaningful on modern low-cost embedded MCU\(^{10}\)’s.

Let’s see what the optimizing MSVC 2012 does:

```
<code>
dst$ = 8
count$ = 16
bzero PROC
    test rdx, -8
    je SHORT $LN11@bzero
; work out 8-byte blocks
    xor r10d, r10d
    mov r9, rdx
    shr r9, 3
    mov r8d, r10d
    test r9, r9
    je SHORT $LN11@bzero
    npad 5
$LL19@bzero:
    inc r8d
    mov QWORD PTR [rcx], r10
    add rcx, 8
</code>
```
The first part of the function is predictable. The second part is just an unrolled loop and a jump passing control flow to the correct instruction inside it. There is no other code between the MOV/INC instruction pairs, so the execution is to fall until the very end, executing as many pairs as needed. By the way, we can observe that the MOV/INC pair consumes a fixed number of bytes (3+3). So the pair consumes 6 bytes. Knowing that, we can get rid of the switch() jumptable, we can just multiple the input value by 6 and jump to current RIP + input_value * 6.

This can also be faster because we are not in need to fetch a value from the jumptable.

It’s possible that 6 probably is not a very good constant for fast multiplication and maybe it’s not worth it, but you get the idea. That is what old-school demomakers did in the past with unrolled loops.

### 3.8.1 Should one use unrolled loops?

Unrolled loops can have benefits if there is no fast cache memory between RAM and CPU, and the CPU, in order to get the code of the next instruction, must load it from RAM each time. This is a case of modern low-cost MCU and old CPUs.

---

11As an exercise, you can try to rework the code to get rid of the jumptable. The instruction pair can be rewritten in a way that it will consume 4 bytes or maybe 8. 1 byte is also possible (using STOSB instruction).
3.9. DIVISION USING MULTIPLICATION

Unrolled loops are slower than short loops if there is a fast cache between RAM and CPU and the body of loop can fit into cache, and CPU will load the code from it not touching the RAM. Fast loops are the loops which body’s size can fit into L1 cache, but even faster loops are those small ones which can fit into micro-operation cache.

3.9 Division using multiplication

A very simple function:

```c
int f(int a)
{
    return a/9;
}
```

3.9.1 x86

...is compiled in a very predictable way:

**Listing 3.18: MSVC**

```
a$ = 8 ; size = 4
_f PROC
    push ebp
    mov ebp, esp
    mov eax, DWORD PTR _a$[ebp]
    cdq ; sign extend EAX to EDX:EAX
    mov ecx, 9
    idiv ecx
    pop ebp
    ret 0
_f ENDP
```

IDIV divides the 64-bit number stored in the EDX:EAX register pair by the value in the ECX. As a result, EAX will contain the quotient, and EDX— the remainder. The result is returned from the f() function in the EAX register, so the value is not moved after the division operation, it is in right place already.

Since IDIV uses the value in the EDX:EAX register pair, the CDQ instruction (before IDIV) extends the value in EAX to a 64-bit value taking its sign into account, just as MOVVSX does.

If we turn optimization on (/Ox), we get:

**Listing 3.19: Optimizing MSVC**

```
a$ = 8 ; size = 4
_f PROC
    mov ecx, DWORD PTR _a$[esp-4]
    mov eax, 954437177 ; 38e38e39H
    imul ecx
    sar edx, 1
    mov eax, edx
    shr eax, 31 ; 0000001fH
    add eax, edx
    ret 0
_f ENDP
```

This is division by multiplication. Multiplication operations work much faster. And it is possible to use this trick \[12\] to produce code which is effectively equivalent and faster.

This is also called “strength reduction” in compiler optimizations.

GCC 4.4.1 generates almost the same code even without additional optimization flags, just like MSVC with optimization turned on:

\[12\] Read more about division by multiplication in [Henry S. Warren, Hacker’s Delight, (2002)10-3]
3.9.2 How it works

From school-level mathematics, we can remember that division by 9 can be replaced by multiplication by \( \frac{1}{9} \). In fact, sometimes compilers do so for floating-point arithmetics, for example, FDIV instruction in x86 code can be replaced by FMUL. At least MSVC 6.0 will replace division by 9 by multiplication by 0.111111... and sometimes it’s hard to be sure, what operation was in original source code.

But when we operate over integer values and integer CPU registers, we can’t use fractions. However, we can rework fraction like that:

\[
\text{result} = \frac{x}{9} = x \cdot \frac{1}{9} = x \cdot \frac{1}{9} \cdot \text{MagicNumber} = \frac{x \cdot \text{MagicNumber}}{9}
\]

Given the fact that division by \( 2^n \) is very fast (using shifts), we now should find that MagicNumber, for which the following equation will be true: \( 2^n = 9 \cdot \text{MagicNumber} \).

Division by \( 2^{32} \) is somewhat hidden: lower 32-bit of product in EAX is not used (dropped), only higher 32-bit of product (in EDX) is used and then shifted by additional 1 bit.

In other words, the assembly code we have just seen multiplicates by \( \frac{954437177}{2^{32}+1} \), or divides by \( \frac{2^{32}+1}{954437177} \). To find divisor we just have to divide numerator by denominator. Using Wolfram Alpha, we can get 8.9999999.... as result (which is close to 9).

Read more about it in [Henry S. Warren, Hacker’s Delight, (2002)10-3].

Couple of words about better understanding. Many people miss “hidden” division by \( 2^{32} \) or \( 2^{64} \), when lower 32-bit part (or 64-bit part) of product is not used. Also, there is misconception that modulo inverse is used here. This is close, but not the same thing. Extended Euclidean algorithm is usually used to find magic coefficient, but in fact, this algorithm is rather used to solve the equation. You can solve it using any other method. Anyway, Extended Euclidean algorithm is probably the most efficient way to solve it. Also, needless to mention, the equation is unsolvable for some divisors, because this is diophantine equation (i.e., equation allowing result to be only integer), since we work on integer CPU registers, after all.

3.9.3 ARM

The ARM processor, just like in any other “pure” RISC processor lacks an instruction for division. It also lacks a single instruction for multiplication by a 32-bit constant (recall that a 32-bit constant cannot fit into a 32-bit opcode).

By taking advantage of this clever trick (or hack), it is possible to do division using only three instructions: addition, subtraction and bit shifts (1.22 on page 304).

Here is an example that divides a 32-bit number by 10, from [Advanced RISC Machines Ltd, The ARM Cookbook, (1994)3.3 Division by a Constant]. The output consists of the quotient and the remainder.
3.9. DIVISION USING MULTIPLICATION

; takes argument in a1
; returns quotient in a1, remainder in a2
; cycles could be saved if only divide or remainder is required
SUB    a2, a1, #10    ; keep (x-10) for later
SUB    a1, a1, a1, lsr #2
ADD    a1, a1, a1, lsr #4
ADD    a1, a1, a1, lsr #8
ADD    a1, a1, a1, lsr #16
MOV    a1, a1, lsr #3
ADD    a3, a1, a1, asl #2
SUBS   a2, a2, a3, asl #1    ; calc (x-10) - (x/10)*10
ADDPL  a1, a1, #1    ; fix-up quotient
ADDMI  a2, a2, #10    ; fix-up remainder
MOV    pc, lr

Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOV R1, 0x38E38E39</td>
<td>Load 32-bit value into R1</td>
</tr>
<tr>
<td>SMMUL R0, R0, R1</td>
<td>Signed Most Significant Word Multiply</td>
</tr>
<tr>
<td>MOV R1, R0,ASR#1</td>
<td>Arithmetic Shift Right</td>
</tr>
<tr>
<td>ADD R0, R1, R0,LSR#31</td>
<td>Add with Logical Shift Right</td>
</tr>
</tbody>
</table>

This code is almost the same as the one generated by the optimizing MSVC and GCC. Apparently, LLVM uses the same algorithm for generating constants.

The observant reader may ask, how does MOV writes a 32-bit value in a register, when this is not possible in ARM mode.

it is impossible indeed, but, as we see, there are 8 bytes per instruction instead of the standard 4, in fact, there are two instructions.

The first instruction loads 0x8E39 into the low 16 bits of register and the second instruction is MOV, it loads 0x383E into the high 16 bits of the register. IDA is fully aware of such sequences, and for the sake of compactness reduces them to one single “pseudo-instruction”.

The SMMUL (Signed Most Significant Word Multiply) instruction two multiplies numbers, treating them as signed numbers and leaving the high 32-bit part of result in the R0 register, dropping the low 32-bit part of the result.

The“MOV R1, R0,ASR#1” instruction is an arithmetic shift right by one bit.

“ADD R0, R1, R0,LSR#31” is \( R0 = R1 + R0 >> 31 \)

There is no separate shifting instruction in ARM mode. Instead, an instructions like (MOV, ADD, SUB, RSB)\(^{13}\) can have a suffix added, that says if the second operand must be shifted, and if yes, by what value and how. ASR stands for Arithmetic Shift Right, LSR—Logical Shift Right.

Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOV R1, 0x38E38E39</td>
<td>Load 32-bit value into R1</td>
</tr>
<tr>
<td>SMMUL.W R0, R0, R1</td>
<td>Signed Most Significant Word Multiply</td>
</tr>
<tr>
<td>ASRS R1, R0, #1</td>
<td>Arithmetic Shift Right</td>
</tr>
<tr>
<td>ADD.W R0, R1, R0,LSR#31</td>
<td>Add with Logical Shift Right</td>
</tr>
<tr>
<td>BX LR</td>
<td></td>
</tr>
</tbody>
</table>

There are separate instructions for shifting in Thumb mode, and one of them is used here—ASRS (arithmetic shift right).

\(^{13}\)These instructions are also called “data processing instructions”
Non-optimizing Xcode 4.6.3 (LLVM) and Keil 6/2013

Non-optimizing LLVM does not generate the code we saw before in this section, but instead inserts a call to the library function \_\_divsi3. What about Keil: it inserts a call to the library function \_\_aeabi_idivmod in all cases.

3.9.4 MIPS

For some reason, optimizing GCC 4.4.5 generate just a division instruction:

Listing 3.21: Optimizing GCC 4.4.5 (IDA)

```
f:
    li $v0, 9
    bnez $v0, loc_10
    div $a0, $v0 ; branch delay slot
    break 0x1C00 ; “break 7” in assembly output and objdump
loc_10:
    mflo $v0
    jr $ra
    or $at, $zero ; branch delay slot, NOP
```

Here we see here a new instruction: BREAK. It just raises an exception. In this case, an exception is raised if the divisor is zero (it’s not possible to divide by zero in conventional math). But GCC probably did not do very well the optimization job and did not see that $V0 is never zero. So the check is left here. So if $V0 is zero somehow, BREAK is to be executed, signaling to the OS about the exception.

Otherwise, MFLO executes, which takes the result of the division from the LO register and copies it in $V0. By the way, as we may know, the MUL instruction leaves the high 32 bits of the result in register HI and the low 32 bits in register LO. DIV leaves the result in the LO register, and remainder in the HI register.

If we alter the statement to “a % 9”, the MFHI instruction is to be used here instead of MFLO.

3.9.5 Exercise

- [http://challenges.re/27](http://challenges.re/27)

3.10 String to number conversion (atoi())

Let's try to reimplement the standard atoi() C function.

3.10.1 Simple example

Here is the simplest possible way to read a number represented in ASCII encoding. It’s not error-prone: a character other than a digit leads to incorrect result.

```c
#include <stdio.h>

int my_atoi (char *s) {
    int rt=0;
    while (*s)
    {
```

```c
```
So what the algorithm does is just reading digits from left to right.
The zero ASCII character is subtracted from each digit.
The digits from “0” to “9” are consecutive in the ASCII table, so we do not even need to know the exact value of the “0” character.
All we have to know is that “0” minus “0” is 0, “9” minus “0” is 9 and so on.
Subtracting “0” from each character results in a number from 0 to 9 inclusive.
Any other character leads to an incorrect result, of course!
Each digit has to be added to the final result (in variable “rt”), but the final result is also multiplied by 10 at each digit.
In other words, the result is shifted left by one position in decimal form on each iteration.
The last digit is added, but there is no shift.

**Optimizing MSVC 2013 x64**

A character can be loaded in two places: the first character and all subsequent characters. This is arranged so for loop regrouping.
3.10. STRING TO NUMBER CONVERSION (ATOI())

There is no instruction for multiplication by 10, two LEA instruction do this instead.

MSVC sometimes uses the ADD instruction with a negative constant instead of SUB. This is the case. It’s very hard to say why this is better then SUB. But MSVC does this often.

Optimizing GCC 4.9.1 x64

Optimizing GCC 4.9.1 is more concise, but there is one redundant RET instruction at the end. One would be enough.

Listing 3.23: Optimizing GCC 4.9.1 x64

```assembly
my_atoi:
    ; load input character into EDX
    movsx edx, BYTE PTR [rdi]
    ; EAX is allocated for "rt" variable
    xor eax, eax
    ; exit, if loaded character is null byte
    test dl, dl
    je .L4
    .L3:
        lea eax, [rax+rax*4]
        ; EAX=RAX*5=rt*5
        ; shift pointer to the next character:
        add rdi, 1
        lea eax, [rdx-48+rax*2]
        ; EAX=input character - 48 + RAX*2 = input character - '0' + rt*10
        ; load next character:
        movsx edx, BYTE PTR [rdi]
        ; goto loop begin, if loaded character is not null byte
        test dl, dl
        jne .L3
    .L4:
        rep ret
```

Optimizing Keil 6/2013 (ARM mode)

Listing 3.24: Optimizing Keil 6/2013 (ARM mode)

```assembly
my_atoi PROC
    ; R1 will contain pointer to character
    MOV r1,r0
    ; R0 will contain "rt" variable
    MOV r0,#0
    B |L0.12|
    |L0.12|
    ADD r0,r0,r0,LSL #2
    ; R0=R0+R0<<2=rt*5
    ADD r0,r2,r0,LSL #1
    ; R0=input character + rt*5<<1 = input character + rt*10
    ; correct whole thing by subtracting '0' from rt:
    SUB r0,r0,#0x30
    ; shift pointer to the next character:
    ADD r1,r1,#1
    |L0.28|
    ; load input character to R2
    LDRB r2,[r1,#0]
    ; is it null byte? if no, jump to loop body.
    CMP r2,#0
    BNE |L0.12|
    ; exit if null byte.
    ; "rt" variable is still in R0 register, ready to be used in caller function
    BX lr
ENDP
```
my_atoi PROC
    ; R1 will be pointer to the input character
    MOV VS r1, r0
    ; R0 is allocated to "rt" variable
    MOV VS r0, #0
    B |L0.16|
    |L0.6|
    MOV VS r3, #0xa
    ; R3=10
    MULS r0, r3, r0
    ; shift pointer to the next character:
    ADDS r1, r1, #1
    ; correct whole thing by subtracting 0' character from it':
    SUBS r0, r0, #0x30
    ADDS r0, r2, r0
    ; rt=R2+R0=input character + (rt*10 - '0')
    |L0.16|
    ; load input character to R2
    LDRB r2, [r1, #0]
    ; is it zero?
    CMP r2, #0
    ; jump to loop body if it is not
    BNE |L0.6|
    ; rt variable in R0 now, ready to be used in caller function
    BX lr
    ENDP

Interestingly, from school mathematics we may recall that the order of addition and subtraction operations
doesn't matter.

That's our case: first, the \( rt \times 10 - '0' \) expression is computed, then the input character value is added to it.
Indeed, the result is the same, but the compiler did some regrouping.

**Optimizing GCC 4.9.1 ARM64**

The ARM64 compiler can use the pre-increment instruction suffix:

my_atoi:
    ; load input character into W1
    ldrb w1, [x0]
    mov x2, x0
    ; X2=address of input string
    ; is loaded character zero?
    ; jump to exit if its so
    ; W1 will contain 0 in this case.
    ; it will be reloaded into W0 at L4.
    cbz w1, .L4
    ; W0 will contain "rt" variable
    ; initialize it at zero:
    mov w0, 0
    .L3:
    ; subtract 48 or '0' from input variable and put result into W3:
    sub w3, w1, #48
    ; load next character at address X2+1 into W1 with pre-increment:
    ldrb w1, [x2,1]!
    add w0, w0, w0, lsl 2
    ; W0=W0+W0<<2=W0+W0*4=rt*5
    add w0, w3, w0, lsl 1
    ; W0=input digit + W0<<1 = input digit + rt*5*2 = input digit + rt*10
    ; if the character we just loaded is not null byte, jump to the loop begin
    cbnz w1, .L3

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### 3.10. STRING TO NUMBER CONVERSION (ATOI())

```asm
; variable to be returned (rt) is in W0, ready to be used in caller function
ret
.L4:
    mov   w0, w1
ret
```

### 3.10.2 A slightly advanced example

My new code snippet is more advanced, now it checks for the “minus” sign at the first character and reports an error if a non-digit has been found in the input string:

```c
#include <stdio.h>

int my_atoi (char *s)
{
    int negative=0;
    int rt=0;
    if (*s=='-')
    {
        negative=1;
        s++;
    }
    while (*s)
    {
        if (*s<'0' || *s>'9')
        {
            printf ("Error! Unexpected char: '%c'
", *s);
            exit(0);
        }
        rt=rt*10 + (*s-'0');
        s++;
    }
    if (negative)
        return -rt;
    return rt;
}

int main()
{
    printf ("%d\n", my_atoi ("1234");
    printf ("%d\n", my_atoi ("1234567890");
    printf ("%d\n", my_atoi ("-1234");
    printf ("%d\n", my_atoi ("-1234567890");
    printf ("%d\n", my_atoi ("-a1234567890"); // error
}
```

### Optimizing GCC 4.9.1 x64

Listing 3.27: Optimizing GCC 4.9.1 x64

```asm
.LC0:
    .string "Error! Unexpected char: '%c\n"
my_atoi:
    sub   rsp, 8
    movsx  edx, BYTE PTR [rdi]
    ; check for minus sign
    cmp    dl, 45 ; ' -'
    je     .L22
    xor    esi, esi
    test   dl, dl
    je     .L20
.L10:
```

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3.10. STRING TO NUMBER CONVERSION (ATOI())

; ESI=0 here if there was no minus sign and 1 if it was
lea eax, [rdx-48]
; any character other than digit will result in unsigned number greater than 9 after subtraction
; so if it is not digit, jump to L4, where error will be reported:
cmp al, 9
ja .L4
xor eax, eax
jmp .L6 .L7:
lea ecx, [rdx-48]
cmp cl, 9
ja .L4
.L6:
lea eax, [rax+rax*4]
add rdi, 1
lea eax, [rdx-48+rax*2]
movsx edx, BYTE PTR [rdi]
test dl, dl
jne .L7
;if there was no minus sign, skip NEG instruction
;if it was, execute it.
test esi, esi
je .L18
neg eax
.L18:
add rsp, 8
ret .L22:
movsx edx, BYTE PTR [rdi+1]
lea rax, [rdi+1]
test dl, dl
je .L20
mov rdi, rax
mov esi, 1
jmp .L10
.L20:
xor eax, eax
jmp .L18
.L4:
; report error. character is in EDX
mov edi, 1
mov esi, OFFSET FLAT:.LC0 ; "Error! Unexpected char: '%c'\n"
xor eax, eax
call __printf_chk
xor edi, edi
call exit

If the “minus” sign has been encountered at the string start, the NEG instruction is to be executed at the end. It just negates the number.

There is one more thing that needs mentioning.

How would a common programmer check if the character is not a digit? Just how we have it in the source code:

if (*s<'0' || *s>'9')
...

There are two comparison operations.

What is interesting is that we can replace both operations by single one: just subtract “0” from character value,
treat result as unsigned value (this is important) and check if it’s greater than 9.

For example, let’s say that the user input contains the dot character (“.”) which has ASCII code 46. 46 - 48 = -2 if we treat the result as a signed number.

Indeed, the dot character is located two places earlier than the “0” character in the ASCII table. But it is 0xFFFFFFFF (4294967294) if we treat the result as an unsigned value, and that’s definitely bigger than 9!
The compilers do this often, so it’s important to recognize these tricks.

Another example of it in this book: 3.16.1 on page 535.

Optimizing MSVC 2013 x64 does the same tricks.

**Optimizing Keil 6/2013 (ARM mode)**

Listing 3.28: Optimizing Keil 6/2013 (ARM mode)

```assembly
my_atoi PROC
  PUSH {r4-r6,lr}
  MOV r4,r0
  LDRB r0,[r0,#0]
  MOV r6,#0
  MOV r5,r6
  CMP r0,#0x2d '–'
  ; R6 will contain 1 if minus was encountered, 0 if otherwise
  MOVEQ r6,#1
  ADDEQ r4,r4,#1
  B |L0.80|
|L0.36|
  SUB r0,r1,#0x30
  CMP r0,#0xa
  BCC |L0.64|
  ADR r0,|L0.220|
  BL __2printf
  MOV r0,#0
  BL exit
|L0.64|
  LDRB r0,[r4],#1
  ADD r1,r5,r5,LSL #2
  ADD r0,r0,r1,LSL #1
  SUB r5,r0,#0x30
|L0.80|
  LDRB r1,[r4,#0]
  CMP r1,#0
  BNE |L0.36|
  CMP r6,#0
  ; negate result
  RSBNE r0,r5,#0
  MOVEQ r0,r5
  POP {r4-r6,pc}
ENDP
|L0.220|
DCB "Error! Unexpected char: '%c'\n",0
```

There is no NEG instruction in 32-bit ARM, so the “Reverse Subtraction” operation (line 31) is used here. It is triggered if the result of the CMP instruction (at line 29) has been “Not Equal” (hence -NE suffix).

So what RSBNE does is to subtract the resulting value from 0.

It works just like the regular subtraction operation, but swaps operands.

Subtracting any number from 0 results in negation: \(0 - x = -x\).

Thumb mode code is mostly the same.

GCC 4.9 for ARM64 can use the NEG instruction, which is available in ARM64.

### 3.10.3 Exercise

Oh, by the way, security researchers deal often with unpredictable behavior of program while handling of incorrect data.

For example, while fuzzing. As an exercise, you may try to enter non-digit characters and see what happens.
3.11 Inline functions

Inlined code is when the compiler, instead of placing a call instruction to a small or tiny function, just places its body right in-place.

Listing 3.29: A simple example

```c
#include <stdio.h>

int celsius_to_fahrenheit (int celsius)
{
    return celsius * 9 / 5 + 32;
};

int main(int argc, char *argv[])
{
    int celsius = atol(argv[1]);
    printf("%d
", celsius_to_fahrenheit (celsius));
};
```

...is compiled in very predictable way, however, if we turn on GCC optimizations (-O3), we’ll see:

Listing 3.30: Optimizing GCC 4.8.1

```
main:
push    ebp
mov     ebp, esp
and     esp, -16
sub     esp, 16
call    __main
mov     eax, DWORD PTR [ebp+12]
mov     eax, DWORD PTR [eax+4]
mov     DWORD PTR [esp], eax
call    _atol
mov     edx, 1717986919
mov     DWORD PTR [esp], OFFSET FLAT:LC2 ; "%d\12\0"
lea     ecx, [eax+eax*8]
mov     eax, ecx
imul    edx
sar     ecx, 31
sar     edx
sub     edx, ecx
add     edx, 32
mov     DWORD PTR [esp+4], edx
call    _printf
leave
ret
```

(Here the division is performed by multiplication( 3.9 on page 497).)

Yes, our small function `celsius_to_fahrenheit()` has just been placed before the `printf()` call.

Why? It can be faster than executing this function’s code plus the overhead of calling/returning.

Modern optimizing compilers are choosing small functions for inlining automatically. But it’s possible to force compiler additionally to inline some function, if to mark it with the “inline” keyword in its declaration.

3.11.1 Strings and memory functions

Another very common automatic optimization tactic is the inlining of string functions like `strcpy()`, `strncpy()`, `strlen()`, `memset()`, `memcpy()`, `memcmp()`, etc..

Sometimes it’s faster than to call a separate function.

These are very frequent patterns and it is highly advisable for reverse engineers to learn to detect automatically.
3.11. INLINE FUNCTIONS

strcmp()

Listing 3.31: strcmp() example

```c
bool is_bool (char *s)
{
    if (strcmp (s, "true")==0)
        return true;
    if (strcmp (s, "false")==0)
        return false;
    assert(0);
};
```

Listing 3.32: Optimizing GCC 4.8.1

```assembly
.LC0:       .string "true"
.LC1:       .string "false"
is_bool:
.LFB0:
push edi
mov ecx, 5
push esi
mov edi, OFFSET FLAT:.LC0
sub esp, 20
mov esi, DWORD PTR [esp+32]
repz cmpsb
je .L3
mov esi, DWORD PTR [esp+32]
mov ecx, 6
mov edi, OFFSET FLAT:.LC1
repz cmpsb
seta cl
setb dl
xor eax, eax
cmp cl, dl
jne .L8
add esp, 20
pop esi
pop edi
ret
.L8:
    mov DWORD PTR [esp], 0
call assert
add esp, 20
pop esi
pop edi
ret
.L3:
    add esp, 20
mov eax, 1
pop esi
pop edi
ret
```

Listing 3.33: Optimizing MSVC 2010

```assembly
$SG3454 DB 'true', 00H
$SG3456 DB 'false', 00H
_s$ = 8         ; size = 4
?is_bool@YA NPAD@Z PROC ; is_bool
push esi
mov esi, DWORD PTR _s$[esp]
mov ecx, OFFSET $SG3454 ; 'true'
mov eax, esi
npad 4 ; align next label
```

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3.11. INLINE FUNCTIONS

mov dl, BYTE PTR [eax]
cmp dl, BYTE PTR [ecx]
jne SHORT $LN7@is_bool
test dl, dl
je SHORT $LN8@is_bool
mov dl, BYTE PTR [eax+1]
cmp dl, BYTE PTR [ecx+1]
jne SHORT $LN7@is_bool
add eax, 2
add ecx, 2
test dl, dl
jne SHORT $LL6@is_bool

$LN8@is_bool:
xor eax, eax
jmp SHORT $LN9@is_bool

$LN7@is_bool:
sbb eax, eax
sbb eax, -1

test dl, dl
jne SHORT $LL6@is_bool

$LN9@is_bool:
xor eax, eax
jmp SHORT $LN10@is_bool

$LN10@is_bool:
add eax, 2
add ecx, 2
test dl, dl
jne SHORT $LL10@is_bool

$LN11@is_bool:
xor eax, eax
jmp SHORT $LN12@is_bool

$LN12@is_bool:
sbb eax, eax
sbb eax, -1

test eax, eax
jne SHORT $LN10@is_bool

$LN13@is_bool:
xor al, al
pop esi
ret 0

$LN1@is_bool:
push 11
push OFFSET $SG3458
push OFFSET $SG3459
call DWORD PTR __imp___wassert
add esp, 12
pop esi
ret 0

?is_bool@YA_NPAD@Z ENDP ; is_bool
### 3.11. INLINE FUNCTIONS

#### strlen()

**Listing 3.34: strlen() example**

```c
int strlen_test(char *s1)
{
    return strlen(s1);
};
```

**Listing 3.35: Optimizing MSVC 2010**

```assembly
_sl1$ = 8 ; size = 4
_strlen_test PROC
    mov eax, DWORD PTR _sl1$[esp-4]
    lea edx, DWORD PTR [eax+1]
$LL3@strlen_tes:
    mov cl, BYTE PTR [eax]
    inc eax
    test cl, cl
    jne SHORT $LL3@strlen_tes
    sub eax, edx
    ret 0
_strlen_test ENDP
```

#### strcpy()

**Listing 3.36: strcpy() example**

```c
void strcpy_test(char *s1, char *outbuf)
{
    strcpy(outbuf, s1);
};
```

**Listing 3.37: Optimizing MSVC 2010**

```assembly
_sl1$ = 8 ; size = 4
_outbuf$ = 12 ; size = 4
strcpy_test PROC
    mov eax, DWORD PTR _s1$[esp-4]
    mov edx, DWORD PTR _outbuf$[esp-4]
    sub edx, eax
    npad 6 ; align next label
$LL3@strcpy_tes:
    mov cl, BYTE PTR [eax]
    mov BYTE PTR [edx+eax], cl
    inc eax
    test cl, cl
    jne SHORT $LL3@strcpy_tes
    ret 0
strcpy_test ENDP
```

#### memset()

**Example#1**

**Listing 3.38: 32 bytes**

```c
#include <stdio.h>

void f(char *out)
{
    memset(out, 0, 32);
}
```

Many compilers don’t generate a call to memset() for short blocks, but rather insert a pack of MOVs:
3.11. INLINE FUNCTIONS

Listing 3.39: Optimizing GCC 4.9.1 x64

```assembly
f:
    mov    QWORD PTR [rdi], 0
    mov    QWORD PTR [rdi+8], 0
    mov    QWORD PTR [rdi+16], 0
    mov    QWORD PTR [rdi+24], 0
    ret
```

By the way, that remind us of unrolled loops: 1.16.1 on page 192.

Example#2

Listing 3.40: 67 bytes

```c
#include <stdio.h>

void f(char *out)
{
    memset(out, 0, 67);
}
```

When the block size is not a multiple of 4 or 8, the compilers can behave differently.

For instance, MSVC 2012 continues to insert MOVs:

Listing 3.41: Optimizing MSVC 2012 x64

```assembly
out$ = 8
f PROC
    xor    eax, eax
    mov    QWORD PTR [rcx], rax
    mov    QWORD PTR [rcx+8], rax
    mov    QWORD PTR [rcx+16], rax
    mov    QWORD PTR [rcx+24], rax
    mov    QWORD PTR [rcx+32], rax
    mov    QWORD PTR [rcx+40], rax
    mov    QWORD PTR [rcx+48], rax
    mov    QWORD PTR [rcx+56], rax
    mov    WORD PTR [rcx+64], ax
    mov    BYTE PTR [rcx+66], al
    ret    0
f ENDP
```

...while GCC uses REP STOSQ, concluding that this would be shorter than a pack of MOVs:

Listing 3.42: Optimizing GCC 4.9.1 x64

```assembly
f:
    mov    QWORD PTR [rdi], 0
    mov    QWORD PTR [rdi+59], 0
    mov    rcx, rdi
    lea    rdi, [rdi+8]
    xor    eax, eax
    and    rdi, -8
    sub    rcx, rdi
    add    ecx, 67
    shr    ecx, 3
    rep    stosq
    ret
```

memcpy()

Short blocks

The routine to copy short blocks is often implemented as a sequence of MOV instructions.
3.11. INLINE FUNCTIONS

Listing 3.43: memcpy() example

```c
void memcpy_7(char *inbuf, char *outbuf)
{
    memcpy(outbuf+10, inbuf, 7);
};
```

Listing 3.44: Optimizing MSVC 2010

```
inbuf$ = 8    ; size = 4
_outbuf$ = 12 ; size = 4
_memcpy_7 PROC
    mov ecx, DWORD PTR _inbuf$[esp-4]
    mov edx, DWORD PTR [ecx]
    mov eax, DWORD PTR _outbuf$[esp-4]
    mov DWORD PTR [eax+10], edx
    mov dx, WORD PTR [ecx+4]
    mov WORD PTR [eax+14], dx
    mov cl, BYTE PTR [ecx+6]
    mov BYTE PTR [eax+16], cl
    ret 0
_memcpy_7 ENDP
```

Listing 3.45: Optimizing GCC 4.8.1

```
memcpy_7:
    push ebx
    mov eax, DWORD PTR [esp+8]
    mov ecx, DWORD PTR [esp+12]
    mov ebx, DWORD PTR [eax]
    lea edx, [ecx+10]
    mov DWORD PTR [ecx+10], ebx
    movzx ecx, WORD PTR [eax+4]
    mov WORD PTR [edx+4], cx
    movzx eax, BYTE PTR [eax+6]
    mov BYTE PTR [edx+6], al
    pop ebx
    ret
```

That's usually done as follows: 4-byte blocks are copied first, then a 16-bit word (if needed), then the last byte (if needed).

Structures are also copied using MOV: 1.24.4 on page 361.

**Long blocks**

The compilers behave differently in this case.

Listing 3.46: memcpy() example

```
void memcpy_128(char *inbuf, char *outbuf)
{
    memcpy(outbuf+10, inbuf, 128);
};
void memcpy_123(char *inbuf, char *outbuf)
{
    memcpy(outbuf+10, inbuf, 123);
};
```

For copying 128 bytes, MSVC uses a single MOVSD instruction (because 128 divides evenly by 4):

Listing 3.47: Optimizing MSVC 2010

```
inbuf$ = 8    ; size = 4
_outbuf$ = 12 ; size = 4
_memcpy_128 PROC
    push esi
    mov esi, DWORD PTR _inbuf$[esp]
```
3.11. **INLINE_FUNCTIONS**

```assembly
push edi
mov edi, DWORD PTR _outbuf$[esp+4]
add edi, 10
mov ecx, 32
rep movsd
pop edi
pop esi
ret 0

_memcp_128 ENDP
```

When copying 123 bytes, 30 32-bit words are copied first using MOVSD (that’s 120 bytes), then 2 bytes are copied using MOVSW, then one more byte using MOVSB.

**Listing 3.48: Optimizing MSVC 2010**

```assembly
_inbuf$ = 8 ; size = 4
_outbuf$ = 12 ; size = 4
_memcp_123 PROC
push esi
mov esi, DWORD PTR _inbuf$[esp]
push edi
mov edi, DWORD PTR _outbuf$[esp+4]
add edi, 10
mov ecx, 30
rep movsd
movsw
movsb
pop edi
pop esi
ret 0

_memcp_123 ENDP
```

GCC uses one big universal functions, that works for any block size:

**Listing 3.49: Optimizing GCC 4.8.1**

```assembly
memcpy_123:
.LFB3:
push edi
mov eax, 123
push esi
mov edx, DWORD PTR [esp+16]
mov esi, DWORD PTR [esp+12]
lea edi, [edx+10]
test edi, 1
jne .L24
.test edi, 2
jne .L25
.L7:
mov ecx, eax
xor edx, edx
shr ecx, 2
test al, 2
rep movsd
je .L8
movzx edx, WORD PTR [esi]
mov WORD PTR [edi], dx
mov edx, 2
.L8:
test al, 1
je .L5
movzx eax, BYTE PTR [esi+edx]
mov BYTE PTR [edi+edx], al
.L5:
pop esi
pop edi
ret
.L24:
movzx eax, BYTE PTR [esi]
lea edi, [edx+11]
add esi, 1
```
Universal memory copy functions usually work as follows: calculate how many 32-bit words can be copied, then copy them using MOVSD, then copy the remaining bytes.

More advanced and complex copy functions use SIMD instructions and also take the memory alignment in consideration.

As an example of SIMD strlen() function: 1.29.2 on page 416.

**memcmp()**

Listing 3.50: memcmp() example

```c
int memcmp_1235(char *buf1, char *buf2)
{
    return memcmp(buf1, buf2, 1235);
}
```

For any block size, MSVC 2013 inserts the same universal function:

Listing 3.51: Optimizing MSVC 2010

```assembly
(buf1$ = 8 ; size = 4
(buf2$ = 12 ; size = 4
(memcmp_1235 PROC
    mov ecx, DWORD PTR _buf1$[esp-4]
    mov edx, DWORD PTR _buf2$[esp-4]
    push esi
    mov esi, 1231
    npad 2
$LL5@memcmp_123:
    mov eax, DWORD PTR [ecx]
    cmp eax, DWORD PTR [edx]
    jne SHORT $LN4@memcmp_123
    add ecx, 4
    add edx, 4
    sub esi, 4
    jae SHORT $LL5@memcmp_123
$LN4@memcmp_123:
    mov al, BYTE PTR [ecx]
    cmp al, BYTE PTR [edx]
    jne SHORT $LN6@memcmp_123
    add ecx, 1
    add edx, 1
    sub esi, 1
    jae SHORT $LL5@memcmp_123
$LN6@memcmp_123:
    mov al, BYTE PTR [ecx+1]
    cmp al, BYTE PTR [edx+1]
    jne SHORT $LN6@memcmp_123
    mov al, BYTE PTR [ecx+2]
    cmp al, BYTE PTR [edx+2]
    jne SHORT $LN6@memcmp_123
    mov al, BYTE PTR [ecx+3]
    cmp al, BYTE PTR [edx+3]
    jne SHORT $LN6@memcmp_123
$LN3@memcmp_123:
    xor eax, eax
    pop esi
    ret 0
```
3.12. C99 restrict

This is inlined strcat() as it has been generated by MSVC 6.0. There are 3 parts visible: 1) getting source string length (first scasb); 2) getting destination string length (second scasb); 3) copying source string into the end of destination string (movsd/movsb pair).

Listing 3.52: strcat()

<table>
<thead>
<tr>
<th>c99restrict</th>
<th>movsd</th>
<th>movsb</th>
</tr>
</thead>
<tbody>
<tr>
<td>src</td>
<td>dst</td>
<td></td>
</tr>
<tr>
<td>lea edi, [src]</td>
<td>or ecx, 0FFFFFFFFh</td>
<td></td>
</tr>
<tr>
<td>repne scasb</td>
<td>not ecx</td>
<td></td>
</tr>
<tr>
<td>sub edi, ecx</td>
<td>mov esi, edi</td>
<td></td>
</tr>
<tr>
<td>mov edi, [dst]</td>
<td>mov edx, ecx</td>
<td></td>
</tr>
<tr>
<td>or ecx, 0FFFFFFFFh</td>
<td>repne scasb</td>
<td></td>
</tr>
<tr>
<td>mov ecx, edx</td>
<td>dec edi</td>
<td></td>
</tr>
<tr>
<td>shr ecx, 2</td>
<td>rep movsd</td>
<td></td>
</tr>
<tr>
<td>mov ecx, edx</td>
<td>and ecx, 3</td>
<td></td>
</tr>
<tr>
<td>rep movsb</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IDA script

There is also a small IDA script for searching and folding such very frequently seen pieces of inline code: GitHub.

3.12 C99 restrict

Here is a reason why Fortran programs, in some cases, work faster than C/C++ ones.

```c
void f1 (int* x, int* y, int* sum, int* product, int* sum_product, int* update_me, size_t s) {
    for (int i=0; i<s; i++) {
        sum[i]=x[i]+y[i];
        product[i]=x[i]*y[i];
        update_me[i]=i*123; // some dummy value
        sum_product[i]=sum[i]+product[i];
    }
}
```

That's very simple example with one specific thing in it: the pointer to the update_me array could be a pointer to the sum array, product array, or even the sum_product array—nothing forbids that, right?

The compiler is fully aware of this, so it generates code with four stages in the loop body:

- calculate next sum[i]
- calculate next product[i]
- calculate next update_me[i]
3.12. C99 RESTRICT

- calculate next sum_product[i]—on this stage, we need to load from memory the already calculated sum[i] and product[i]

Is it possible to optimize the last stage? Since we have already calculated sum[i] and product[i] it is not necessary to load them again from memory.

Yes, but compiler is not sure that nothing has been overwritten at the 3rd stage! This is called “pointer aliasing”, a situation when the compiler cannot be sure that a memory to which a pointer is pointing hasn’t been changed.

restrict in the C99 standard [ISO/IEC 9899:TC3 (C99 standard), (2007) 6.7.3/1] is a promise, given by programmer to the compiler that the function arguments marked by this keyword always points to different memory locations and never intersects.

To be more precise and describe this formally, restrict shows that only this pointer is to be used to access an object, and no other pointer will be used for it.

It can be even said the object will be accessed only via one single pointer, if it is marked as restrict.

Let’s add this keyword to each pointer argument:

```c
void f2 (int* restrict x, int* restrict y, int* restrict sum, int* restrict product, int* restrict sum_product, int* restrict update_me, size_t s) {
    for (int i=0; i<s; i++) {
        sum[i]=x[i]+y[i];
        product[i]=x[i]*y[i];
        update_me[i]=i*123; // some dummy value
        sum_product[i]=sum[i]+product[i];
    }
};
```

Let’s see results:

**Listing 3.53: GCC x64: f1()**

```c
f1:
    push r15 r14 r13 r12 rbp rdi rsi rbx
    mov r13, QWORD PTR 120[rsp]
    mov rbp, QWORD PTR 104[rsp]
    mov r12, QWORD PTR 112[rsp]
    test r13, r13
    je .L1
    add r13, 1
    xor ebx, ebx
    mov edi, 1
    xor r11d, r11d
    jmp .L4
.L6:
    mov r11, rdi
    mov rdi, rax
.L4:
    lea rax, 0[0+r11*4]
    lea r10, [rcx+rax]
    lea r14, [rdx+rax]
    lea rsi, [r8+rax]
    add rax, r9
    mov r15d, DWORD PTR [r10]
    add r15d, DWORD PTR [r14]
    mov DWORD PTR [rsi], r15d ; store to sum[]
    mov r10d, DWORD PTR [r10]
    imul r10d, DWORD PTR [r14]
    mov DWORD PTR [rax], r10d ; store to product[]
    mov DWORD PTR [r12+r11*4], ebx ; store to update_me[]
    add ebx, 123
    add r10d, DWORD PTR [rsi] ; reload sum[i]
    add r10d, DWORD PTR [rax] ; reload product[i]
    lea rax, 1[rdi]
    cmp rax, r13
    mov DWORD PTR 0[rbp+r11*4], r10d ; store to sum_product[
```
The difference between the compiled \texttt{f1()} and \texttt{f2()} functions is as follows: in \texttt{f1()}, \texttt{sum[i]} and \texttt{product[i]} are reloaded in the middle of the loop, and in \texttt{f2()} there is no such thing, the already calculated values are used, since we “promised” the compiler that no one and nothing will change the values in \texttt{sum[i]} and \texttt{product[i]} during the execution of the loop’s body, so it is “sure” that there is no need to load the value from memory again.

Obviously, the second example works faster.

But what if the pointers in the function’s arguments intersect somehow? This is on the programmer’s conscience, and the results will be incorrect.

Let’s go back to Fortran.

Compilers of this programming language treats all pointers as such, so when it was not possible to set \texttt{restrict} in C, Fortran could generate faster code in these cases.

How practical is it?

In the cases when the function works with several big blocks in memory.

There are a lot of such in linear algebra, for instance.

Supercomputers/\textsc{HPC}\textsuperscript{14} are very busy with linear algebra, so probably that is why, traditionally, Fortran is still used there [Eugene Loh, \textit{The Ideal HPC Programming Language}, (2010)].

But when the number of iterations is not very big, certainly, the speed boost may not to be significant.

\textsuperscript{14}High-Performance Computing
Let’s revisit an example we considered earlier 1.14.2 on page 141 and ask ourselves, is it possible to make a branchless version of the function in x86 code?

```c
int my_abs (int i)
{
    if (i<0)
        return -i;
    else
        return i;
}
```

And the answer is yes.

### 3.13.1 Optimizing GCC 4.9.1 x64

We could see it if we compile it using optimizing GCC 4.9:

```assembly
Listing 3.55: Optimizing GCC 4.9 x64
my_abs:
    mov edx, edi
    mov eax, edi
    sar edx, 31
; EDX is 0xFFFFFFFF here if sign of input value is minus
; EDX is 0 if sign of input value is plus (including 0)
; the following two instructions have effect only if EDX is 0xFFFFFFFF
; or idle if EDX is 0
    xor eax, edx
    sub eax, edx
ret
```

This is how it works:

Arithmetically shift the input value right by 31.

Arithmetical shift implies sign extension, so if the MSB is 1, all 32 bits are to be filled with 1, or with 0 if otherwise.

In other words, the SAR REG, 31 instruction makes 0xFFFFFFFF if the sign has been negative or 0 if positive.

After the execution of SAR, we have this value in EDX.

Then, if the value is 0xFFFFFFFF (i.e., the sign is negative), the input value is inverted (because XOR REG, 0xFFFFFFFF is effectively an inverse all bits operation).

Then, again, if the value is 0xFFFFFFFF (i.e., the sign is negative), 1 is added to the final result (because subtracting −1 from some value resulting in incrementing it).

Inversion of all bits and incrementing is exactly how two’s complement value is negated: 2.2 on page 452.

We may observe that the last two instruction do something if the sign of the input value is negative. Otherwise (if the sign is positive) they do nothing at all, leaving the input value untouched.

The algorithm is explained in [Henry S. Warren, Hacker’s Delight, (2002)2-4].

It’s hard to say, how GCC did it, deduced it by itself or found a suitable pattern among known ones?

### 3.13.2 Optimizing GCC 4.9 ARM64

GCC 4.9 for ARM64 generates mostly the same, just decides to use the full 64-bit registers.

There are less instructions, because the input value can be shifted using a suffixed instruction (“asr”) instead of using a separate instruction.
### 3.14 Variadic functions

Functions like `printf()` and `scanf()` can have a variable number of arguments. How are these arguments accessed?

#### 3.14.1 Computing arithmetic mean

Let's imagine that we want to calculate arithmetic mean, and for some weird reason we want to specify all the values as function arguments. But it’s impossible to get the number of arguments in a variadic function in C/C++, so let’s denote the value of $-1$ as a terminator.

**Using va_arg macro**

There is the standard `stdarg.h` header file which define macros for dealing with such arguments.

The `printf()` and `scanf()` functions use them as well.

```c
#include <stdio.h>
#include <stdarg.h>

int arith_mean(int v, ...) {  
    va_list args;  
    int sum=v, count=1, i;  
    va_start(args, v);  
    while(1)  
    {  
        i=va_arg(args, int);  
        if (i==-1) // terminator  
            break;  
        sum=sum+i;  
        count++;  
    }  
    va_end(args);  
    return sum/count;  
};

int main() {  
    printf ("%d\n", arith_mean (1, 2, 7, 10, 15, -1 /* terminator */));  
};
```

The first argument has to be treated just like a normal argument.

All other arguments are loaded using the `va_arg` macro and then summed.

So what is inside?
3.14. VARIADIC FUNCTIONS

cdecl calling conventions

Listing 3.57: Optimizing MSVC 6.0

```
v$ = 8
_arith_mean PROC NEAR
    mov   eax, DWORD PTR _v$[esp-4] ; load 1st argument into sum
    push  esi
    mov   esi, 1 ; count=1
    lea   edx, DWORD PTR _v$[esp] ; address of the 1st argument
$L838:
    mov   ecx, DWORD PTR [edx+4] ; load next argument
    add   edx, 4 ; shift pointer to the next argument
    cmp   ecx, -1 ; is it -1?
    je    SHORT $L856 ; exit if so
    add   eax, ecx ; sum = sum + loaded argument
    inc   esi ; count++
    jmp   SHORT $L838
$L856:
    ; calculate quotient
    cdq
    idiv  esi
    pop   esi
    ret   0
_arith_mean ENDP

$SG851 DB '%d', 0aH, 00H

_main PROC NEAR
    push  -1
    push  15
    push  10
    push  7
    push  2
    push  1
    call  _arith_mean
    push  eax
    push  OFFSET FLAT:$SG851 ; '%d'
    call  _printf
    add   esp, 32
    ret   0
_main ENDP
```

The arguments, as we may see, are passed to main() one-by-one.
The first argument is pushed into the local stack as first.
The terminating value (−1) is pushed last.
The arith_mean() function takes the value of the first argument and stores it in the sum variable.
Then, it sets the EDX register to the address of the second argument, takes the value from it, adds it to sum, and does this in an infinite loop, until −1 is found.
When it’s found, the sum is divided by the number of all values (excluding −1) and the quotient is returned.
So, in other words, the function treats the stack fragment as an array of integer values of infinite length.
Now we can understand why the cdecl calling convention forces us to push the first argument into the stack as last.
Because otherwise, it would not be possible to find the first argument, or, for printf-like functions, it would not be possible to find the address of the format-string.

Register-based calling conventions

The observant reader may ask, what about calling conventions where the first few arguments are passed in registers? Let’s see:
Listing 3.58: Optimizing MSVC 2012 x64

```assembly
$SG3013 DB 'd', 0AH, 00H

v$ = 8

arith_mean PROC
    mov DWORD PTR [rsp+8], ecx ; 1st argument
    mov QWORD PTR [rsp+16], rdx ; 2nd argument
    mov QWORD PTR [rsp+24], r8 ; 3rd argument
    mov eax, ecx ; sum = 1st argument
    lea rcx, QWORD PTR v$[rsp+8] ; pointer to the 2nd argument
    mov QWORD PTR [rsp+32], r9 ; 4th argument
    mov edx, DWORD PTR [rcx] ; load 2nd argument
    mov r8d, 1 ; count=1
    cmp edx, -1 ; 2nd argument is -1?
    je SHORT $LN8@arith_mean ; exit if so
    $LL3@arith_mean:
        add eax, edx ; sum = sum + loaded argument
        mov edx, DWORD PTR [rcx+8] ; load next argument
        inc r8d ; count++
        cmp edx, -1 ; is loaded argument -1?
        jne SHORT $LL3@arith_mean ; go to loop begin if its not
    $LN8@arith_mean:
        ; calculate quotient
        cdq
        idiv r8d
        ret 0

arith_mean ENDP

main PROC
    sub rsp, 56
    mov edx, 2
    mov DWORD PTR [rsp+40], -1
    mov DWORD PTR [rsp+32], 15
    lea r9d, QWORD PTR [rdx+8]
    lea r8d, QWORD PTR [rdx-1]
    call arith_mean
    lea rcx, OFFSET FLAT:$SG3013
    mov edx, eax
    call printf
    xor eax, eax
    add rsp, 56
    ret 0

main ENDP
```

We see that the first 4 arguments are passed in the registers and two more—in the stack.

The `arith_mean()` function first places these 4 arguments into the *Shadow Space* and then treats the *Shadow Space* and stack behind it as a single continuous array!

What about GCC? Things are slightly clumsier here, because now the function is divided in two parts: the first part saves the registers into the “red zone”, processes that space, and the second part of the function processes the stack:

Listing 3.59: Optimizing GCC 4.9.1 x64

```assembly
arith_mean:
    lea rax, [rsp+8]
    ; save 6 input registers in
    ; red zone in the local stack
    mov QWORD PTR [rsp-40], rsi
    mov QWORD PTR [rsp-32], rdx
    mov QWORD PTR [rsp-16], r8
    mov QWORD PTR [rsp-24], rcx
    mov esi, 8
    mov QWORD PTR [rsp-64], rax
    lea rax, [rsp-48]
    mov QWORD PTR [rsp-8], r9
    mov DWORD PTR [rsp-72], 8
    lea rdx, [rsp+8]
```

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3.14. VARIADIC FUNCTIONS

```assembly
mov r8d, 1
mov QWORD PTR [rsp-56], rax
jmp .L5
.L7:
    ; work out saved arguments
lea rax, [rsp-48]
mov ecx, esi
add esi, 8
add rcx, rax
mov ecx, DWORD PTR [rcx]
cmp ecx, -1
je .L4
.L8:
add edi, ecx
add r8d, 1
.L5:
    ; decide, which part we will work out now.
    ; is current argument number less or equal 6?
cmp esi, 47
jbe .L7 ; no, process saved arguments then
    ; work out arguments from stack
mov rcx, rdx
add rdx, 8
mov ecx, DWORD PTR [rcx]
cmp ecx, -1
jne .L8
.L4:
mov eax, edi
cdq
idiv r8d
ret
.LC1:
.string "%d\n"
main:
sub rsp, 8
mov edx, 7
mov esi, 2
mov edi, 1
mov r9d, -1
mov r8d, 15
mov ecx, 10
xor eax, eax
call arith_mean
mov esi, OFFSET FLAT:.LC1
mov edx, eax
mov edi, 1
xor eax, eax
add rsp, 8
jmp __printf_chk
```

By the way, a similar usage of the Shadow Space is also considered here: 6.1.8 on page 740.

**Using pointer to the first function argument**

The example can be rewritten without va_arg macro:

```c
#include <stdio.h>

int arith_mean(int v, ...)
{
    int *i=&v;
    int sum=*i, count=1;
    i++;
    while(1)
    {
        if (*((i)==-1)) // terminator
```
3.14. VARIADIC FUNCTIONS

```c
break;
    sum=sum+(*i);
    count++;
    i++;
}
return sum/count;
}
int main()
{
    printf ("%d\n", arith_mean (1, 2, 7, 10, 15, -1 /* terminator */));
    // test: https://www.wolframalpha.com/input/?i=mean(1,2,7,10,15)
}
```

In other words, if an argument set is array of words (32-bit or 64-bit), we just enumerate array elements starting at first one.

### 3.14.2 vprintf() function case

Many programmers define their own logging functions which take a printf-like format string + a variable number of arguments.

Another popular example is the die() function, which prints some message and exits.

We need some way to pack input arguments of unknown number and pass them to the printf() function. But how?

That's why there are functions with “v” in name.

One of them is vprintf(): it takes a format-string and a pointer to a variable of type va_list:

```c
#include <stdlib.h>
#include <stdarg.h>
void die (const char * fmt, ...)
{
    va_list va;
    va_start (va, fmt);
    vprintf (fmt, va);
    exit(0);
};
```

By closer examination, we can see that va_list is a pointer to an array. Let's compile:

```
Listing 3.60: Optimizing MSVC 2010

_fmt$ = 8
_die PROC
    ; load 1st argument (format-string)
    mov ecx, DWORD PTR _fmt$[esp-4]
    ; get pointer to the 2nd argument
    lea eax, DWORD PTR _fmt$[esp]
    push eax ; pass a pointer
    push ecx
    call _vprintf
    add esp, 8
    push 0
    call _exit
$LN3@die:
    int 3
_die ENDP
```

We see that all our function does is just taking a pointer to the arguments and passing it to vprintf(), and that function is treating it like an infinite array of arguments!

```
Listing 3.61: Optimizing MSVC 2012 x64

_fmt$ = 48
```

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```assembly
die PROC
    ; save first 4 arguments in Shadow Space
    mov    QWORD PTR [rsp+8], rcx
    mov    QWORD PTR [rsp+16], rdx
    mov    QWORD PTR [rsp+24], r8
    mov    QWORD PTR [rsp+32], r9
    sub    rsp, 40
    lea    rdx, QWORD PTR fmt$[rsp+8] ; pass pointer to the 1st argument
    ; RCX here is still points to the 1st argument (format-string) of die()
    ; so vprintf() will take it right from RCX
    call   vprintf
    xor    ecx, ecx
    call   exit
    int    3
die ENDP
```

3.14.3 **Pin case**

It’s interesting to note how some functions from Pin DBI\(^\text{15}\) framework takes number of arguments:

```plaintext
INS_InsertPredicatedCall(
    ins, IPOINT_BEFORE, (AFUNPTR)RecordMemRead,
    IARG_INST_PTR,
    IARG_MEMORYOP_EA, memOp,
    IARG_END);
```

(pinatrace.cpp)

And this is how INS_InsertPredicatedCall() function is declared:

```plaintext
extern VOID INS_InsertPredicatedCall(INS ins, IPOINT ipoint, AFUNPTR funptr, ...);
```

(pin_client.PH)

Hence, constants with names starting with IARG_ are some kinds of arguments to the function, which are handled inside of INS_InsertPredicatedCall(). You can pass as many arguments, as you need. Some commands has additional argument(s), some are not. Full list of arguments: [https://software.intel.com/sites/landingpage/pintool/docs/58423/Pin/html/group__INST__ARGS.html](https://software.intel.com/sites/landingpage/pintool/docs/58423/Pin/html/group__INST__ARGS.html). And it has to be a way to detect an end of arguments list, so the list must be terminated with IARG_END constant, without which, the function will (try to) handle random noise in the local stack, treating it as additional arguments.

Also, in [Brian W. Kernighan, Rob Pike, *Practice of Programming*, (1999)](https://books.google.com/books?id=6rQrEAAAQBAJ) we can find a nice example of C/C++ routines very similar to `pack/unpack`\(^\text{16}\) in Python.

3.14.4 **Format string exploit**

It’s a popular mistake, to write `printf(string)` instead of `puts(string)` or `printf("%s", string)`. If the attacker can put his/her own text into `string`, he/she can crash process, or get insight into variables in the local stack.

Take a look at this:

```c
#include <stdio.h>

int main()
{
    char *s1="hello";
    char *s2="world";
    char buf[128];

    // do something mundane here
    strcpy (buf, s1);
    strcpy (buf, " ");
    strcpy (buf, s2);

    printf("Hi there!");
}
```

\(^{15}\)Dynamic Binary Instrumentation

\(^{16}\)https://docs.python.org/3/library/struct.html
printf ("%s");
{
    char c;
    size_t str_len;
    // work as long as \r or \n is at the end of string
    // stop if some other character there or its an empty string
    // (at start or due to our operation)
    for (str_len=strlen(s); str_len>0 && (c=s[str_len-1]); str_len--) {
        if (c=='\r' || c=='\n')
            s[str_len-1]=0;
        else
            s[str_len-1]=0;
    }

Please note, that printf() has no additional arguments besides single format string.

Now let's imagine, that was the attacker who put %s string into the last printf() first arguments. I compile this example using GCC 5.4.0 on x86 Ubuntu, and the resulting executable prints “world” string if it gets executed!

If I turn optimization on, printf() outputs some garbage, though—probably, strcpy() calls has been optimized and/or local variables as well. Also, result will be different for x64 code, different compiler, OS, etc.

Now, let's say, attacker could pass the following string to printf() call: %x %x %x %x %x. In may case, output is: “80485c6 b7751b48 1 0 80485c0” (these are just values from local stack). You see, there are 1 and 0 values, and some pointers (first is probably pointer to “world” string). So if the attacker passes %s %s %s %s %s string, the process will crash, because printf() treats 1 and/or 0 as pointer to string, tries to read characters from there and fails.

Even worse, there could be sprintf (buf, string) in code, where buf is a buffer in the local stack with size of 1024 bytes or so, attacker can craft string in such a way that buf will be overflown, maybe even in a way that would lead to code execution.

Many popular and well-known software was (or even still) vulnerable:

QuakeWorld went up, got to around 4000 users, then the master server exploded.
Disrupter and cohorts are working on more robust code now.
If anyone did it on purpose, how about letting us know... (It wasn’t all the people that tried %s as a name)

(John Carmack’s .plan file, 17-Dec-1996\footnote{https://github.com/ESWAT/john-carmack-plan-archive/blob/33ae52fdba46aa0d1abfed6fc7598233748541c0/by_day/johnc_plan_19961217.txt})

Nowadays, almost all decent compilers warn about this.

Another problem is the lesser known %n printf() argument: whenever printf() reaches it in a format string, it writes the number of characters printed so far into the corresponding argument: \url{http://stackoverflow.com/questions/3401156/what-is-the-use-of-the-n-format-specifier-in-c}. Thus, an attacker could zap local variables by passing many %n commands in format string.

3.15 Strings trimming

A very common string processing task is to remove some characters at the start and/or at the end.

In this example, we are going to work with a function which removes all newline characters (\texttt{CR\textsuperscript{18}/LF\textsuperscript{19}}) from the end of the input string:

\begin{verbatim}
#include <stdio.h>
#include <string.h>
char* str_trim (char *s)
{
    char c;
    size_t str_len;
    // work as long as \r or \n is at the end of string
    // stop if some other character there or its an empty string
    // (at start or due to our operation)
    for (str_len=strlen(s); str_len>0 && (c=s[str_len-1]); str_len--) {
        if (c=='\r' || c=='\n')
            s[str_len-1]=0;
        else
            s[str_len-1]=0;
    }
\end{verbatim}

\footnote{\texttt{Carriage Return (13 or ‘\r’ in C/C++)}}\footnote{\texttt{Line Feed (10 or ‘\n’ in C/C++)}}
3.15. STRINGS TRIMMING

```c
int main()
{
    // test
    // strdup() is used to copy text string into data segment,
    // because it will crash on Linux otherwise,
    // where text strings are allocated in constant data segment,
    // and not modifiable.

    printf ("[%s]\n", str_trim (strdup("")));    
    printf ("[%s]\n", str_trim (strdup("n")));    
    printf ("[%s]\n", str_trim (strdup("r")));    
    printf ("[%s]\n", str_trim (strdup("\n")));   
    printf ("[%s]\n", str_trim (strdup("\r\n"))); 
    printf ("[%s]\n", str_trim (strdup("test1\n\r"))); 
    printf ("[%s]\n", str_trim (strdup("test2\n\r\n"))); 
    printf ("[%s]\n", str_trim (strdup("test3\n\r\n\r"))); 
    printf ("[%s]\n", str_trim (strdup("test4\n\r\n\n\r"))); 
    printf ("[%s]\n", str_trim (strdup("test5\r\n\n\r\n"))); 
    printf ("[%s]\n", str_trim (strdup("test6\r\r\n\r\n\r\n\r"))); 
}
```

The input argument is always returned on exit, this is convenient when you want to chain string processing functions, like it has done here in the main() function.

The second part of for() (str_len=0 & c=s[str_len-1]) is the so called “short-circuit” in C/C++ and is very convenient [Dennis Yurichev, C/C++ programming language notes1.3.8].

The C/C++ compilers guarantee an evaluation sequence from left to right.

So if the first clause is false after evaluation, the second one is never to be evaluated.

### 3.15.1 x64: Optimizing MSVC 2013

Listing 3.62: Optimizing MSVC 2013 x64

```assembly
s$ = 8
str_trim PROC
    rcx is the first function argument and it always holds pointer to the string
    mov    rdx, rcx
    ; this is strlen() function inlined right here:
    ; set RAX to 0xFFFFFFFFFFFFFFFF (-1)
    or     rax, -1
$L14@str_trim:
    inc     rax
    cmp     BYTE PTR [rcx+rax], 0
    jne     SHORT $L14@str_trim
    ; is the input string length zero? exit then:
    test    rax, rax
    je      SHORT $L15@str_trim
    ; RAX holds string length
    dec     rcx
    ; RCX = s-1
    mov     r8d, 1
    add     rcx, rax
    ; RCX = s-1+strlen(s), i.e., this is the address of the last character in the string
    sub     r8, rdx
$L6@str_trim:
    ; load the last character of the string:
    ; jump, if its code is 13 or 10:
    movzx   eax, BYTE PTR [rcx]
    cmp     al, 13
```
3.15. STRINGS TRIMMING

```asm
je SHORT $LN2@str_trim
cmp al, 10
jne SHORT $LN15@str_trim
$LN2@str_trim:
; the last character has a 13 or 10 code
; write zero at this place:
    mov BYTE PTR [rcx], 0
; decrement address of the last character,
; so it will point to the character before the one which has just been erased:
    dec rcx
    lea rax, QWORD PTR [r8+rcx]
; RAX = 1 - s + address of the current last character
; thus we can determine if we reached the first character and we need to stop, if it is so
    test rax, rax
    jne SHORT $LL6@str_trim
$LN15@str_trim:
    mov rax, rdx
    ret 0
str_trim ENDP
```

First, MSVC inlined the strlen() function code, because it concluded this is to be faster than the usual strlen() work + the cost of calling it and returning from it. This is called inlining: 3.11 on page 507.

The first instruction of the inlined strlen() is

```
OR RAX, 0xFFFFFFFFFFFFFFFF
```

MSVC often uses OR instead of MOV RAX, 0xFFFFFFFFFFFFFFFF, because resulting opcode is shorter.

And of course, it is equivalent: all bits are set, and a number with all bits set is \(-1\) in two’s complement arithmetic: 2.2 on page 452.

Why would the \(-1\) number be used in strlen(), one might ask. Due to optimizations, of course. Here is the code that MSVC generated:

Listing 3.63: Inlined strlen() by MSVC 2013 x64

```asm
; RCX = pointer to the input string
; RAX = current string length
    or rax, -1
label:
    inc rax
    cmp BYTE PTR [rcx+rax], 0
    jne SHORT label
; RAX = string length
```

Try to write shorter if you want to initialize the counter at 0! OK, let’ try:

Listing 3.64: Our version of strlen()

```asm
; RCX = pointer to the input string
; RAX = current string length
    xor rax, rax
label:
    cmp byte ptr [rcx+rax], 0
    jz exit
    inc rax
    jmp label
exit:
; RAX = string length
```

We failed. We have to use additional JMP instruction!

So what the MSVC 2013 compiler did is to move the INC instruction to the place before the actual character loading.

If the first character is 0, that’s OK, RAX is 0 at this moment, so the resulting string length is 0.

The rest in this function seems easy to understand.

3.15.2 x64: Non-optimizing GCC 4.9.1
str_trim:
    push    rbp
    mov     rbp, rsp
    sub     rsp, 32
    mov     QWORD PTR [rbp-24], rdi

; for() first part begins here
    mov     rax, QWORD PTR [rbp-24]
    mov     rdi, rax
    call    strlen
    mov     QWORD PTR [rbp-8], rax ; str_len
; for() first part ends here
    jmp     .L2

; for() body begins here
.L5:
    cmp     BYTE PTR [rbp-9], 13 ; c=='\r'?
    je      .L3
    cmp     BYTE PTR [rbp-9], 10 ; c=='\n'?
    jne     .L4

.L3:
    mov     rax, QWORD PTR [rbp-8] ; str_len
    lea     rdx, [rax-1] ; EDX=str_len-1
    mov     rax, QWORD PTR [rbp-24] ; s
    add     rax, rdx ; RAX=s+str_len-1
    mov     BYTE PTR [rax], 0 ; s[str_len-1]=0

; for() body ends here
; for() third part begins here
    sub     QWORD PTR [rbp-8], 1 ; str_len--
; for() third part ends here
.L2:
; for() second part begins here
    cmp     QWORD PTR [rbp-8], 0 ; str_len==0?
    je      .L4 ; exit then
; check second clause, and load "c"
    mov     rax, QWORD PTR [rbp-8] ; RAX=str_len
    lea     rdx, [rax-1] ; RDX=str_len-1
    mov     rax, QWORD PTR [rbp-24] ; RAX=s
    add     rax, rdx ; RAX=s+str_len-1
    movzx   eax, BYTE PTR [rax] ; AL=s[str_len-1]
    mov     BYTE PTR [rbp-9], al ; store loaded char into "c"
    cmp     BYTE PTR [rbp-9], 0 ; is it zero?
    jne     .L5 ; yes? exit then
; for() second part ends here
.L4:
; return "s"
    mov     rax, QWORD PTR [rbp-24]
    leave
    ret

Comments are added by the author of the book.

After the execution of strlen(), the control is passed to the L2 label, and there two clauses are checked, one after another.

The second will never be checked, if the first one (str_len==0) is false (this is “short-circuit”).

Now let's see this function in short form:

- First for() part (call to strlen())
- goto L2
- L5: for() body. goto exit, if needed
- for() third part (decrement of str_len)
- L2: for() second part: check first clause, then second. goto loop body begin or exit.
- L4: // exit
- return s
3.15. STRINGS TRIMMING

3.15.3 x64: Optimizing GCC 4.9.1

str_trim:
    push rbx
    mov rbx, rdi
    ; RBX will always be "s"
    call strlen
    ; check for str_len==0 and exit if its so
    test rax, rax
    je .L9
    lea rdx, [rax-1]
    ; RDX will always contain str_len-1 value, not str_len
    ; so RDX is more like buffer index variable
    lea rsi, [rbx+rdx] ; RSI=s+str_len-1
    movzx ecx, BYTE PTR [rsi] ; load character
    test cl, cl
    je .L9 ; exit if its zero
    cmp cl, 10
    je .L4
    cmp cl, 13 ; exit if its not \n' and not \r'
    jne .L9
.L4:
    ; this is weird instruction. we need RSI=s-1 here.
    ; its possible to get it by MOV RSI, EBX / DEC RSI
    ; but this is two instructions instead of one
    sub rsi, rax
    ; RSI = s+str_len-1-str_len = s-1
    ; main loop begin
.L12:
    test rdx, rdx
    ; store zero at address s-1+str_len-1+1 = s-1+str_len = s+str_len-1
    mov BYTE PTR [rsi+1+rdx], 0
    ; check for str_len-1==0. exit if so.
    je .L9
    sub rdx, 1 ; equivalent to str_len--
    ; load next character at address s+str_len-1
    movzx ecx, BYTE PTR [rbx+rdx]
    test cl, cl ; is it zero? exit then
    je .L9
    cmp cl, 10 ; is it \n'?
    je .L12
    cmp cl, 13 ; is it \r'?
    je .L12
.L9:
    ; return "s"
    mov rax, rbx
    pop rbx
    ret

Now this is more complex.

The code before the loop's body start is executed only once, but it has the CR/LF characters check too! What is this code duplication for?

The common way to implement the main loop is probably this:

- (loop start) check for CR/LF characters, make decisions
- store zero character

But GCC has decided to reverse these two steps.

Of course, store zero character cannot be first step, so another check is needed:

- workout first character. match it to CR/LF, exit if character is not CR/LF
- (loop begin) store zero character
- check for CR/LF characters, make decisions

Now the main loop is very short, which is good for latest CPUs.

The code doesn’t use the str_len variable, but str_len-1. So this is more like an index in a buffer.
3.15. STRINGS TRIMMING

Apparently, GCC notices that the `str_len-1` statement is used twice.

So it’s better to allocate a variable which always holds a value that’s smaller than the current string length by one, and decrement it (this is the same effect as decrementing the `str_len` variable).

3.15.4 ARM64: Non-optimizing GCC (Linaro) 4.9

This implementation is straightforward:

```asm
Listing 3.65: Non-optimizing GCC (Linaro) 4.9

str_trim:
    stp    x29, x30, [sp, -48]!
    add    x29, sp, 0
    str    x0, [x29,24] ; copy input argument into local stack
    ldr    x0, [x29,24] ; s
    bl     strlen
    str    x0, [x29,40] ; str_len variable in local stack

; main loop begin
.L5:
    ldrb   w0, [x29,39]
    cmp    w0, 13 ; is it '\r'?
    beq    .L3
    ldrb   w0, [x29,39]
    cmp    w0, 10 ; is it '\n'?
    bne    .L4 ; goto exit if it is not
.L3:
    ldr    x0, [x29,40]
    X0=str_len
    sub    x0, x0, #1
    X0=str_len-1
    ldr    x1, [x29,24]
    X1=s
    add    x0, x1, x0
    X0=s+str_len-1
    strb   wzr, [x0] ; write byte at s+str_len-1
; decrement str_len:
    ldr    x0, [x29,40]
    X0=str_len
    sub    x0, x0, #1
    X0=str_len-1
    str    x0, [x29,40]
; save X0 (or str_len-1) to local stack
.L2:
    ldr    x0, [x29,40]
    str_len==0?
    cmp    x0, xzr
    ; goto exit then
    beq    .L4
    X0=str_len
    ldr    x0, [x29,40]
    X0=str_len-1
    ldr    x1, [x29,24]
    X1=s
    add    x0, x1, x0
    X0=s+str_len-1
; load byte at address s+str_len-1 to W0
    ldrb   w0, [x0]
    strb   w0, [x29,39] ; store loaded byte to "c"
    ldrb   w0, [x29,39] ; reload it
; is it zero byte?
    cmp    w0, wzr
    ; goto exit, if its zero or to L5 if its not
    bne    .L5
.L4:
```

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3.15.5 ARM64: Optimizing GCC (Linaro) 4.9

This is a more advanced optimization.

The first character is loaded at the beginning, and compared against 10 (the LF character).

Characters are also loaded in the main loop, for the characters after first one.

This is somewhat similar to the 3.15.3 on page 529 example.

Listing 3.66: Optimizing GCC (Linaro) 4.9

```
str_trim:
    stp x29, x30, [sp, -32]!
    add x29, sp, 0
    str x19, [sp,16]
    mov x19, x0
; X19 will always hold value of "s"
    bl strlen
; X0=str_len
    cbz x0, .L9 ; goto L9 (exit) if str_len==0
    sub x1, x0, #1
; X1=X0-1=str_len-1
    add x3, x19, x1
; X3=X19+X1=s+str_len-1
    ldrb w2, [x19,x1] ; load byte at address X19+X1=s+str_len-1
; W2=loaded character
    cbz w2, .L9 ; is it zero? jump to exit then
    cmp w2, 10 ; is it '\n'?
    bne .L15
.L12:
; main loop body. loaded character is always 10 or 13 at this moment!
    sub x2, x1, x0
; X2=X1-X0=str_len-1-str_len=-1
    add x2, x3, x2
; X2=X3+X2=s+str_len-1+(-1)=s+str_len-2
    strb wzr, [x2,1] ; store zero byte at address s+str_len-2+1=s+str_len-1
    cbz x1, .L9 ; str_len-1==0? goto exit, if so
    sub x1, x1, #1 ; str_len--
    ldrb w2, [x19,x1] ; load next character at address X19+X1=s+str_len-1
    cmp w2, 10 ; is it '\n'?
    cbz w2, .L9 ; jump to exit, if its zero
    beq .L12 ; jump to begin loop, if its '\n'
.L15:
    cmp w2, 13 ; is it '\r'?
    beq .L12 ; yes, jump to the loop body begin
.L9:
; return "s"
    mov x0, x19
    ldr x19, [sp,16]
    ldp x29, x30, [sp], 32
    ret
```

3.15.6 ARM: Optimizing Keil 6/2013 (ARM mode)

And again, the compiler took advantage of ARM mode’s conditional instructions, so the code is much more compact.

Listing 3.67: Optimizing Keil 6/2013 (ARM mode)

```
str_trim PROC
    PUSH {r4,lr}
```
3.15. STRINGS TRIMMING

; R0=s
MOV r4,r0
; R4=s
BL strlen ; strlen() takes "s" value from R0
; R0=str_len
MOV r3,#0
; R3 will always hold 0
L0.16:
CMP r0,#0 ; str_len==0?
ADDNE r2,r4,r0 ; (if str_len!=0) R2=R4+R0=s+str_len
LDRBNE r1,[r2,#-1] ; (if str_len!=0) R1=load byte at address R2-1=s+str_len-1
CMPNE r1,#0 ; (if str_len!=0) compare loaded byte against 0
BEQ [L0.56] ; jump to exit if str_len==0 or loaded byte is 0
CMP r1,#0xd ; is loaded byte ''?
CMPNE r1,#0xa ; (if loaded byte is not '\r') is loaded byte '\r'?
SUBEQ r0,r0,#1 ; (if loaded byte is '\r' or '\n') R0-- or str_len--
STRBEQ r3,[r2,#-1] ; (if loaded byte is '\r' or '\n') store R3 (zero) at address R2;
\_L0.56:
; return "s"
MOV r0,r4
POP {r4,pc}
ENDP

3.15.7 ARM: Optimizing Keil 6/2013 (Thumb mode)

There are less conditional instructions in Thumb mode, so the code is simpler.

But there are is really weird thing with the 0x20 and 0x1F offsets (lines 22 and 23). Why did the Keil
compiler do so? Honestly, it’s hard to say.

It has to be a quirk of Keil’s optimization process. Nevertheless, the code works correctly.

Listing 3.68: Optimizing Keil 6/2013 (Thumb mode)

1 str_trim PROC
2 PUSH {r4,lr}
3 MOVs r4,r0
4 ; R4=s
5 BL strlen ; strlen() takes "s" value from R0
6 ; R0=str_len
7 MOVs r3,#0
8 ; R3 will always hold 0
9 B [L0.24]
|L0.12|
10 CMP r1,#0xd ; is loaded byte '\r'?
11 BEQ [L0.20] ; is loaded byte '\r'?
12 CMP r1,#0xa ; is loaded byte '\n'?
13 BNE [L0.38] ; jump to exit, if no
14 |L0.20|
15 SUBS r0,r0,#1 ; R0-- or str_len--
16 STRB r3,[r2,#0x1f] ; store 0 at address R2+0x1F=s+str_len-0x20+0x1F=s+str_len-1
17 |L0.24|
18 CMP r0,#0 ; str_len==0?
19 BEQ [L0.38] ; yes? jump to exit
20 ADDS r2,r4,r0 ; R2=R4+R0=s+str_len
21 SUBS r2,r2,#0x20 ; R2=R2-0x20=s+str_len-0x20
22 LDRB r1,[r2,#0x1f] ; load byte at address R2+0x1F=s+str_len-0x20+0x1F=s+str_len-1
\_L0.38:
23 CMP r1,#0 ; is loaded byte 0?
24 BNE [L0.12] ; jump to loop begin, if its not 0
25 |L0.38|
26 ; return "s"
27 MOVs r0,r4
28 POP {r4,pc}
29 ENDP
Listing 3.69: Optimizing GCC 4.4.5 (IDA)

str_trim:
; IDA is not aware of local variable names, we gave them manually:
saved_GP = -0x10
saved_S0 = -8
saved_RA = -4

    lui $gp, (__gnu_local_gp >> 16)
    addiu $sp, -0x20
    la $gp, (__gnu_local_gp & 0xFFFF)
    sw $ra, 0x20+saved_RA($sp)
    sw $s0, 0x20+saved_S0($sp)
    sw $gp, 0x20+saved_GP($sp)

; call strlen(). input string address is still in $a0, strlen() will take it from there:
    lw $t9, (strlen & 0xFFFF)($gp)
    or $at, $zero ; load delay slot, NOP
    jalr $t9

; input string address is still in $a0, put it to $s0:
    move $s0, $a0 ; branch delay slot
; result of strlen() (i.e., length of string) is in $v0 now
; jump to exit if $v0==0 (i.e., if length of string is 0):
    beqz $v0, exit
    or $at, $zero ; branch delay slot, NOP
    addiu $a1, $v0, -1

; $a1 = $v0-1 = str_len-1
    addu $a1, $s0, $a1

; $a1 = input string address + $a1 = s+str_len-1
; load byte at address $a1:
    lb $a0, 0($a1)
    or $at, $zero ; load delay slot, NOP

; loaded byte is zero? jump to exit if its so:
    beqz $a0, exit
    or $at, $zero ; branch delay slot, NOP
    addiu $v1, $v0, -2

; $v1 = str_len-2
    addu $v1, $s0, $v1

; $v1 = $s0+$v1 = s+str_len-2
    li $a2, 0xD
; skip loop body:
    b loc_6C
    li $a3, 0xA ; branch delay slot
loc_5C:
; load next byte from memory to $a0:
    lb $a0, 0($v1)
    move $a1, $v1

; $a1=s+str_len-2
; jump to exit if loaded byte is zero:
    beqz $a0, exit
; decrement str_len:
    addiu $v1, -1 ; branch delay slot
loc_6C:
; at this moment, $a0=loaded byte, $a2=0xD (CR symbol) and $a3=0xA (LF symbol)
; loaded byte is CR? jump to loc_7C then:
    beq $a0, $a2, loc_7C
    addiu $v0, -1 ; branch delay slot

; loaded byte is LF? jump to exit if its not LF:
    bne $a0, $a3, exit
    or $at, $zero ; branch delay slot, NOP
loc_7C:
; loaded byte is CR at this moment
; jump to loc_5c (loop body begin) if str_len (in $v0) is not zero:
    bnez $v0, loc_5C
; simultaneously, store zero at that place in memory:
    sb $zero, 0($a1) ; branch delay slot
; "exit" label was named by me manually:
exit:
    lw $ra, 0x20+saved_RA($sp)
3.16. TOUPPER() FUNCTION

| move  | $v0, $s0
| lw    | $s0, 0x20+saved_S0($sp)
| jr    | $ra
| addiu | $sp, 0x20 ; branch delay slot |

Registers prefixed with S- are also called “saved temporaries”, so $S0 value is saved in the local stack and restored upon finish.

3.16 toupper() function

Another very popular function transforms a symbol from lower case to upper case, if needed:

```c
char toupper (char c)
{
    if(c>='a' && c<='z')
        return c-'a'+'A';
    else
        return c;
}
```

The 'a'+'A' expression is left in the source code for better readability, it will be optimized by compiler, of course.

The ASCII code of “a” is 97 (or 0x61), and 65 (or 0x41) for “A”.

The difference (or distance) between them in the ASCII table is 32 (or 0x20).

For better understanding, the reader may take a look at the 7-bit standard ASCII table:

![Figure 3.3: 7-bit ASCII table in Emacs](image)

3.16.1 x64

Two comparison operations

Non-optimizing MSVC is straightforward: the code checks if the input symbol is in [97..122] range (or in ['a'..'z'] range) and subtracts 32 if it's true.

There are also some minor compiler artifact:

```
Listing 3.70: Non-optimizing MSVC 2013 (x64)
1 c$ = 8
2 toupper PROC
3     mov     BYTE PTR [rsp+8], cl
4     movsx   eax, BYTE PTR c$[rsp]
5     cmp     eax, 97
6     jl      SHORT $LN2@toupper
7     movsx   eax, BYTE PTR c$[rsp]
8     cmp     eax, 122
9     jg      SHORT $LN2@toupper
```

\(^{20}\) However, to be meticulous, there still could be compilers which can't optimize such expressions and will leave them right in the code.
3.16. TOUPPER() FUNCTION

It’s important to notice that the input byte is loaded into a 64-bit local stack slot at line 3.

All the remaining bits ([8..63]) are untouched, i.e., contain some random noise (you’ll see it in debugger).

All instructions operate only on byte-level, so it’s fine.

The last MOVZX instruction at line 15 takes the byte from the local stack slot and zero-extends it to a int 32-bit data type.

Non-optimizing GCC does mostly the same:

Listing 3.71: Non-optimizing GCC 4.9 (x64)

toupper:
push  rbp
mov  rbp, rsp
mov  eax, edi
mov  BYTE PTR [rbp-4], al
cmp  BYTE PTR [rbp-4], 96
jle  .L2
cmp  BYTE PTR [rbp-4], 122
jg   .L2
movzx eax, BYTE PTR [rbp-4]
sub  eax, 32
jmp  .L3
.L2:
movzx eax, BYTE PTR [rbp-4]
.L3:
pop   rbp
ret

toupper ENDP

One comparison operation

Optimizing MSVC does a better job, it generates only one comparison operation:

Listing 3.72: Optimizing MSVC 2013 (x64)

toupper PROC
lea   eax, DWORD PTR [rcx-97]
cmp  al, 25
ja   SHORT $LN2@toupper
movsx eax, cl
sub  eax, 32
ret  0
$LN2@toupper:
movzx eax, cl
ret  0
toupper ENDP

toupper PROC

It was explained earlier how to replace the two comparison operations with a single one: 3.10.2 on page 505.

We will now rewrite this in C/C++:

```c
int tmp = c - 97;
if (tmp > 25)
    return c;
else
    return c - 32;
```
3.16. TOUPPER() FUNCTION

The tmp variable must be signed.

This makes two subtraction operations in case of a transformation plus one comparison.

In contrast the original algorithm uses two comparison operations plus one subtracting.

Optimizing GCC is even better, it gets rid of the jumps (which is good: 2.10.1 on page 466) by using the CMOVcc instruction:

Listing 3.73: Optimizing GCC 4.9 (x64)

```c
1 toupper:
2   lea edx, [rdi-97] ; 0x61
3   lea eax, [rdi-32] ; 0x20
4   cmp dl, 25
5   cmova eax, edi
6   ret
```

At line 3 the code prepares the subtracted value in advance, as if the conversion will always happen.

At line 5 the subtracted value in EAX is replaced by the untouched input value if a conversion is not needed. And then this value (of course incorrect) is dropped.

Advance subtracting is a price the compiler pays for the absence of conditional jumps.

### 3.16.2 ARM

Optimizing Keil for ARM mode also generates only one comparison:

Listing 3.74: Optimizing Keil 6/2013 (ARM mode)

```assembly
toupper PROC
    SUB r1, r0, #0x61
    CMP r1, #0x19
    SUBLS r0, r0, #0x20
    ANDLS r0, r0, #0xff
    BX lr
ENDP
```

The SUBLS and ANDLS instructions are executed only if the value in R1 is less than 0x19 (or equal). They also do the actual conversion.

Optimizing Keil for Thumb mode generates only one comparison operation as well:

Listing 3.75: Optimizing Keil 6/2013 (Thumb mode)

```assembly
toupper PROC
    MOV r1, r0
    SUBS r1, r1, #0x61
    CMP r1, #0x19
    BHI |L0.14|
    SUBS r0, r0, #0x20
    LSLS r0, r0, #24
    LSRS r0, r0, #24
|L0.14|
    BX lr
ENDP
```

The last two LSLS and LSRS instructions work like `AND reg, 0xFF`: they are equivalent to the C/C++ expression `(i << 24) >> 24`.

Seems like that Keil for Thumb mode deduced that two 2-byte instructions are shorter than the code that loads the 0xFF constant into a register plus an AND instruction.

### GCC for ARM64

Listing 3.76: Non-optimizing GCC 4.9 (ARM64)

```assembly
toupper:
    sub sp, sp, #16
```
3.16. **TOUPPER() FUNCTION**

```assembly
strb w0, [sp,15]
ldrb w0, [sp,15]
cmp w0, 96
bhi .L2
ldrb w0, [sp,15]
cmp w0, 122
bhi .L2
ldrb w0, [sp,15]
sub w0, w0, #32
uxtb w0, w0
b .L3
.L2:
ldrb w0, [sp,15]
.L3:
add sp, sp, 16
ret
```

Listing 3.77: Optimizing GCC 4.9 (ARM64)

```assembly
toupper:
    uxtb w0, w0
    sub w1, w0, #97
    uxtb w1, w1
    cmp w1, 25
    bhi .L2
    sub w0, w0, #32
    uxtb w0, w0
    add sp, sp, 16
    ret
```

Listing 3.78: Optimizing GCC 5.4 (x86)

3.16.3 **Using bit operations**

Given the fact that 5th bit (counting from 0th) is always present after the check, subtracting is merely clearing this sole bit, but the very same effect can be achieved with ANDing (2.5 on page 458).

Even simpler, with XOR-ing:

```c
char toupper (char c)
{
    if(c>='a' && c<='z')
        return c^0x20;
    else
        return c;
}
```

The code is close to what the optimized GCC has produced for the previous example (3.73 on the previous page):

```
...but XOR is used instead of SUB.
Flipping 5th bit is just moving a cursor in ASCII table up and down by two rows.
Some people say that lowercase/uppercase letters has been placed in the ASCII table in such a way deliberately, because:
```
3.17. OBFUSCATION

Very old keyboards used to do Shift just by toggling the 32 or 16 bit, depending on the key; this is why the relationship between small and capital letters in ASCII is so regular, and the relationship between numbers and symbols, and some pairs of symbols, is sort of regular if you squint at it.


Therefore, we can write this piece of code, which just flips the case of letters:

```c
#include <stdio.h>

char flip (char c)
{
    if((c>='a' && c<='z') || (c>='A' && c<='Z'))
        return c^0x20;
    else
        return c;
}

int main()
{
    // will produce "hELLO, WORLD!"
    for (char *s="Hello, world!"; *s; s++)
        printf ("%c", flip(*s));
}
```

3.16.4 Summary

All these compiler optimizations are very popular nowadays and a practicing reverse engineer usually sees such code patterns often.

3.17 Obfuscation

The obfuscation is an attempt to hide the code (or its meaning) from reverse engineers.

3.17.1 Text strings

As we saw in (5.4 on page 704), text strings may be really helpful.

Programmers who are aware of this try to hide them, making it impossible to find the string in IDA or any hex editor.

Here is the simplest method.

This is how the string can be constructed:

```
mov byte ptr [ebx], 'h'
mov byte ptr [ebx+1], 'e'
mov byte ptr [ebx+2], 'l'
mov byte ptr [ebx+3], 'l'
mov byte ptr [ebx+4], 'o'
mov byte ptr [ebx+5], '
'
mov byte ptr [ebx+6], 'w'
mov byte ptr [ebx+7], 'o'
mov byte ptr [ebx+8], 'r'
mov byte ptr [ebx+9], 'l'
mov byte ptr [ebx+10], 'd'
```

The string can also be compared with another one like this:
3.17. OBfuscation

In both cases, it is impossible to find these strings straightforwardly in a hex editor.

By the way, this is a way to work with the strings when it is impossible to allocate space for them in the data segment, for example in a PIC\(^1\) or in shellcode.

Another method is to use sprintf() for the construction:

```c
sprintf(buf, "%s%c%s%c%s", "hel","l","o w","o","rld");
```

The code looks weird, but as a simple anti-reversing measure, it may be helpful.

Text strings may also be present in encrypted form, then every string usage is to be preceded by a string decrypting routine. For example: 8.5.2 on page 822.

### 3.17.2 Executable code

**Inserting garbage**

Executable code obfuscation implies inserting random garbage code between real one, which executes but does nothing useful.

A simple example:

**Listing 3.79: original code**

```assembly
add eax, ebx
mul ecx
```

**Listing 3.80: obfuscated code**

```assembly
xor esi, 011223344h ; garbage
add esi, eax ; garbage
add eax, ebx
mov edx, eax ; garbage
shl edx, 4 ; garbage
mul ecx
xor esi, ecx ; garbage
```

Here the garbage code uses registers which are not used in the real code (ESI and EDX). However, the intermediate results produced by the real code may be used by the garbage instructions for some extra mess—why not?

**Replacing instructions with bloated equivalents**

- MOV op1, op2 can be replaced by the PUSH op2 / POP op1 pair.
- JMP label can be replaced by the PUSH label / RET pair. IDA will not show the references to the label.
- CALL label can be replaced by the following instructions triplet:
  PUSH label_after_CALL_instruction / PUSH label / RET.
- PUSH op can also be replaced with the following instructions pair:
  SUB ESP, 4 (or 8) / MOV [ESP], op.

\(^{21}\)Position Independent Code
3.17. OBFUSCATION

Always executed/never executed code

If the developer is sure that ESI at always 0 at that point:

```assembly
mov esi, 1
... ; some code not touching ESI
dec esi
... ; some code not touching ESI
cmp esi, 0
jz real_code
; fake luggage
real_code:
```

The reverse engineer needs some time to get into it.
This is also called an opaque predicate.

Another example (and again, the developer is sure that ESI is always zero):

```assembly
add eax, ebx ; real code
mul ecx ; real code
add eax, esi ; opaque predicate. XOR, AND or SHL, etc, can be here instead of ADD.
```

Making a lot of mess

instruction 1
instruction 2
instruction 3

Can be replaced with:

```assembly
begin: jmp ins1_label
ins2_label: instruction 2
            jmp ins3_label
ins3_label: instruction 3
            jmp exit:
ins1_label: instruction 1
            jmp ins2_label
exit:
```

Using indirect pointers

```assembly
dummy_data1 db 100h dup (0)
message1 db 'hello world',0
dummy_data2 db 200h dup (0)
message2 db 'another message',0
func proc...
mov eax, offset dummy_data1 ; PE or ELF reloc here
add eax, 100h
push eax
call dump_string
...
mov eax, offset dummy_data2 ; PE or ELF reloc here
add eax, 200h
push eax
call dump_string
...
func endp
```
IDA will show references only to dummy_data1 and dummy_data2, but not to the text strings. Global variables and even functions may be accessed like that.

### 3.17.3 Virtual machine / pseudo-code

A programmer can construct his/her own PL or ISA and interpreter for it.

(Like the pre-S.0 Visual Basic, .NET or Java machines). The reverse engineer will have to spend some time to understand the meaning and details of all of the ISA’s instructions.

He/she will also have to write a disassembler/decompiler of some sort.

### 3.17.4 Other things to mention

My own (yet weak) attempt to patch the Tiny C compiler to produce obfuscated code: [http://go.yurichev.com/17220](http://go.yurichev.com/17220).

Using the MOV instruction for really complicated things: [Stephen Dolan, *mov is Turing-complete*, (2013)]

22.

### 3.17.5 Exercise

- [http://challenges.re/29](http://challenges.re/29)

### 3.18 C++

#### 3.18.1 Classes

**A simple example**

Internally, the representation of C++ classes is almost the same as the structures.

Let’s try an example with two variables, two constructors and one method:

```cpp
#include <stdio.h>

class c {
private:
    int v1;
    int v2;
public:
    c() // default ctor
    {
        v1=667;
        v2=999;
    }
    c(int a, int b) // ctor
    {
        v1=a;
        v2=b;
    }
    void dump()
    {
        printf ("%d; %d\n", v1, v2);
    }
};
```

22 Also available as [http://www.cl.cam.ac.uk/~sd601/papers/mov.pdf](http://www.cl.cam.ac.uk/~sd601/papers/mov.pdf)
3.18. C++

```cpp
int main()
{
    class c c1;
    class c c2(5,6);

    c1.dump();
    c2.dump();

    return 0;
}
```

**MSVC: x86**

Here is how the `main()` function looks like, translated into assembly language:

```
Listing 3.81: MSVC

_c2$ = -16 ; size = 8
_c1$ = -8 ; size = 8
_main PROC
    push ebp
    mov ebp, esp
    sub esp, 16
    lea ecx, DWORD PTR _c1$[ebp]
    call ??0c@@QAE@XZ ; c::c
    push 6
    push 5
    lea ecx, DWORD PTR _c2$[ebp]
    call ??0c@@QAE@HH@Z ; c::c
    lea ecx, DWORD PTR _c1$[ebp]
    call ?dump@c@@QAEXXZ ; c::dump
    lea ecx, DWORD PTR _c2$[ebp]
    call ?dump@c@@QAEXXZ ; c::dump
    xor eax, eax
    mov esp, ebp
    pop ebp
    ret 0
_main ENDP
```

Here’s what’s going on. For each object (instance of class `c`) 8 bytes are allocated, exactly the size needed to store the 2 variables.

For `c1` a default argumentless constructor `??0c@@QAE@XZ` is called. For `c2` another constructor `??0c@@QAE@HH@Z` is called and two numbers are passed as arguments.

A pointer to the object (this in C++ terminology) is passed in the `ECX` register. This is called thiscall (3.18.1)—the method for passing a pointer to the object.

MSVC does it using the `ECX` register. Needless to say, it is not a standardized method, other compilers can do it differently, e.g., via the first function argument (like GCC).

Why do these functions have such odd names? That’s **name mangling**.

A C++ class may contain several methods sharing the same name but having different arguments—that is polymorphism. And of course, different classes may have their own methods with the same name.

**Name mangling** enable us to encode the class name + method name + all method argument types in one ASCII string, which is then used as an internal function name. That’s all because neither the linker, nor the DLL OS loader (mangled names may be among the DLL exports as well) knows anything about C++ or OOP23.

The `dump()` function is called two times.

Now let’s see the constructors’ code:

```
Listing 3.82: MSVC

_this$ = -4 ; size = 4
??0c@@QAE@XZ PROC ; c::c, COMDAT
```

---

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3.18. C++

```c
; _this$ = ecx
    push ebp
    mov ebp, esp
    push ecx
    mov DWORD PTR _this$[ebp], ecx
    mov eax, DWORD PTR _this$[ebp]
    mov DWORD PTR [eax], 667
    mov ecx, DWORD PTR _this$[ebp]
    mov DWORD PTR [ecx+4], 999
    mov esp, ebp
    pop ebp
    ret 0
??0c@@QAE@XZ ENDP ; c::c

_this$ = -4 ; size = 4
_a$ = 8 ; size = 4
_b$ = 12 ; size = 4
??0c@@QAEHH@Z PROC ; c::c, COMDAT
; _this$ = ecx
    push ebp
    mov ebp, esp
    push ecx
    mov DWORD PTR _this$[ebp], ecx
    mov eax, DWORD PTR _this$[ebp]
    mov ecx, DWORD PTR _a$[ebp]
    mov DWORD PTR [eax], ecx
    mov edx, DWORD PTR _this$[ebp]
    mov eax, DWORD PTR _b$[ebp]
    mov DWORD PTR [edx+4], eax
    mov esp, ebp
    pop ebp
    ret 8
??0c@@QAEHH@Z ENDP ; c::c
```

The constructors are just functions, they use a pointer to the structure in ECX, copying the pointer into their own local variable, however, it is not necessary.

From the C++ standard (C++11 12.1) we know that constructors are not required to return any values. In fact, internally, the constructors return a pointer to the newly created object, i.e., `this`.

Now the `dump()` method:

```c
 dump(c, COMDAT)
; _this$ = ecx
    push ebp
    mov ebp, esp
    push ecx
    mov DWORD PTR _this$[ebp], ecx
    mov eax, DWORD PTR _this$[ebp]
    mov ecx, DWORD PTR [eax+4]
    push ecx
    mov edx, DWORD PTR _this$[ebp]
    mov eax, DWORD PTR [edx]
    push eax
    push OFFSET ??_C@_07NJBDCIEC@?$CFd?$DL?5?$CFd?6?$AA@
call _printf
    add esp, 12
    mov esp, ebp
    pop ebp
    ret 0
??0c@@QAEHH@Z ENDP ; c::dump
```

Simple enough: `dump()` takes a pointer to the structure that contains the two int’s from ECX, takes both values from it and passes them to `printf()`.

The code is much shorter if compiled with optimizations (`/Ox`):
3.18. C++

That's all. The other thing we must note is that the stack pointer hasn't been corrected with add esp, X after the constructor has been called. At the same time, the constructor has ret 8 instead of RET at the end.

This is all because the thiscall (3.18.1 on page 542) calling convention is used here, which together with the stdcall (6.1.2 on page 734) method offers the callee to correct the stack instead of the caller. The ret x instruction adds X to the value in ESP, then passes the control to the caller function.

See also the section about calling conventions (6.1 on page 734).

It also has to be noted that the compiler decides when to call the constructor and destructor—but we already know that from the C++ language basics.

**MSVC: x86-64**

As we already know, the first 4 function arguments in x86-64 are passed in RCX, RDX, R8 and R9 registers, all the rest—via the stack.

Nevertheless, the this pointer to the object is passed in RCX, the first argument of the method in RDX, etc. We can see this in the c(int a, int b) method internals:

```assembly
??0c@@QAE@XZ PROC ; c::c, COMDAT
    _this$ = ecx
    mov eax, ecx
    mov DWORD PTR [eax], 667
    mov DWORD PTR [eax+4], 999
    ret 0
??0c@@QAE@XZ ENDP ; c::c

_a$ = 8 ; size = 4
_b$ = 12 ; size = 4
??0c@@QAE@HH@Z PROC ; c::c, COMDAT
    _this$ = ecx
    mov edx, DWORD PTR _b$[esp-4]
    mov eax, ecx
    mov ecx, DWORD PTR _a$[esp-4]
    mov DWORD PTR [eax], ecx
    mov DWORD PTR [eax+4], edx
    ret 8
??0c@@QAE@HH@Z ENDP ; c::c

?dump@??0c@@QAE@HH@Z PROC ; c::dump, COMDAT
    _this$ = ecx
    mov eax, DWORD PTR [rcx+4]
    mov ecx, DWORD PTR [ecx+4]
    push eax
    push ecx
    push OFFSET ??_C@_07NJBDCIEC@?$CFd?$DL?5?$CFd?6?$AA@ ; '%d; %d'
    call printf
    add esp, 12
    ret 0
?dump@??0c@@QAE@HH@Z ENDP ; c::dump
```

```assembly
??0c@@QAE@XZ PROC ; c::c, COMDAT
    _this$ = ecx
    mov eax, ecx
    mov DWORD PTR [eax], 667
    mov DWORD PTR [eax+4], 999
    ret 0
??0c@@QAE@XZ ENDP ; c::c

.a$ = 8 ; size = 4
.b$ = 12 ; size = 4
??0c@@QAE@HH@Z PROC ; c::c, COMDAT
    _this$ = ecx
    mov edx, DWORD PTR _b$[esp-4]
    mov eax, ecx
    mov ecx, DWORD PTR _a$[esp-4]
    mov DWORD PTR [eax], ecx
    mov DWORD PTR [eax+4], edx
    ret 8
??0c@@QAE@HH@Z ENDP ; c::c

?dump@??0c@@QAE@HH@Z PROC ; c::dump, COMDAT
    _this$ = ecx
    mov eax, DWORD PTR [rcx+4]
    mov ecx, DWORD PTR [rcx+4]
    push eax
    push ecx
    push OFFSET ??_C@_07NJBDCIEC@?$CFd?$DL?5?$CFd?6?$AA@ ; '%d; %d'
    call printf
    add esp, 12
    ret 0
?dump@??0c@@QAE@HH@Z ENDP ; c::dump
```

```assembly
; void dump()

?dump@??0c@@QAE@HH@Z PROC ; c::dump
    mov rdx, DWORD PTR [rcx+4]
    mov edx, DWORD PTR [rcx]
    lea rcx, OFFSET FLAT:??_C@_07NJBDCIEC@?$CFd?$DL?5?$CFd?6?$AA@ ; '%d; %d'
    jmp printf
?dump@??0c@@QAE@HH@Z ENDP ; c::dump

; c(int a, int b)

??0c@@QAE@HH@Z PROC ; c::c
    mov DWORD PTR [rcx], edx ; 1st argument: a
```
The int data type is still 32-bit in x64, so that is why 32-bit register parts are used here.

We also see JMP printf instead of RET in the dump() method, that hack we already saw earlier: 1.15.1 on page 154.

GCC: x86

It is almost the same story in GCC 4.4.1, with a few exceptions.

Here we see another name mangling style, specific to GNU. It can also be noted that the pointer to the object is passed as the first function argument—invisible to programmer, of course.

First constructor:

---

24 Apparently, for easier porting of 32-bit C/C++ code to x64.

25 There is a good document about the various name mangling conventions in different compilers: [Agner Fog, Calling conventions (2015)].
3.18. C++

```assembly
arg_0 = dword ptr 8
push ebp
mov ebp, esp
mov eax, [ebp+arg_0]
mov dword ptr [eax], 667
mov eax, [ebp+arg_0]
mov dword ptr [eax+4], 999
pop ebp
retn

_ZN1cC1Ev endp
```

It just writes two numbers using the pointer passed in the first (and only) argument.

Second constructor:

```assembly
public _ZN1cC1Eii
_ZN1cC1Eii proc near
arg_0 = dword ptr 8
arg_4 = dword ptr 0Ch
arg_8 = dword ptr 10h
push ebp
mov ebp, esp
mov eax, [ebp+arg_0]
mov edx, [ebp+arg_4]
mov [eax], edx
mov eax, [ebp+arg_0]
mov edx, [ebp+arg_8]
mov [eax+4], edx
pop ebp
retn
_ZN1cC1Eii endp
```

This is a function, the analog of which can look like this:

```c
void ZN1cC1Eii (int *obj, int a, int b) {
    *obj=a;
    *(obj+1)=b;
}
```

...and that is completely predictable.

Now the dump() function:

```assembly
public _ZN1c4dumpEv
_ZN1c4dumpEv proc near
var_18 = dword ptr -18h
var_14 = dword ptr -14h
var_10 = dword ptr -10h
arg_0 = dword ptr 8
push ebp
mov ebp, esp
sub esp, 18h
mov eax, [ebp+arg_0]
mov edx, [eax+4]
mov eax, [ebp+arg_0]
mov eax, [eax]
mov [esp+18h+var_10], edx
mov [esp+18h+var_14], eax
mov [esp+18h+var_18], offset aDD ; "; %d; %d\n"
call _printf
leave
retn
_ZN1c4dumpEv endp
```
This function in its internal representation has only one argument, used as pointer to the object (this).

This function could be rewritten in C like this:

```c
void ZN1c4dumpEv (int *obj)
{
    printf (%d; %d\n", *obj, *(obj+1));
};
```

Thus, if we base our judgment on these simple examples, the difference between MSVC and GCC is the style of the encoding of function names (name mangling) and the method for passing a pointer to the object (via the ECX register or via the first argument).

**GCC: x86-64**

The first 6 arguments, as we already know, are passed in the RDI, RSI, RDX, RCX, R8 and R9 ([Michael Matz, Jan Hubicka, Andreas Jaeger, Mark Mitchell, System V Application Binary Interface. AMD64 Architecture Processor Supplement, (2013)](https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf)) registers, and the pointer to this via the first one (RDI) and that is what we see here. The int data type is also 32-bit here.

The JMP instead of RET hack is also used here.

**Listing 3.87: GCC 4.4.6 x64**

```c
; default ctor

_ZN1cC2Ev:
    mov DWORD PTR [rdi], 667
    mov DWORD PTR [rdi+4], 999
    ret

; c(int a, int b)

_ZN1cC2Eii:
    mov DWORD PTR [rdi], esi
    mov DWORD PTR [rdi+4], edx
    ret

; dump()

_ZN1c4dumpEv:
    mov edx, DWORD PTR [rdi+4]
    mov esi, DWORD PTR [rdi]
    xor eax, eax
    mov edi, OFFSET FLAT:.LC0 ; "%d; %d\n"
    jmp printf
```

**Class inheritance**

Inherited classes are similar to the simple structures we already discussed, but extended in inheritable classes.

Let’s take this simple example:

```c
#include <stdio.h>

class object
{
    public:
        int color;
    object() { }
    object (int color) { this-&gt;color=color; }
    void print_color() { printf ("color=%d\n", color); }
};
```

__26Also available as [https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf](https://software.intel.com/sites/default/files/article/402129/mpx-linux64-abi.pdf)
3.18. C++

class box : public object
{
private:
    int width, height, depth;
public:
    box(int color, int width, int height, int depth)
    {
        this->color=color;
        this->width=width;
        this->height=height;
        this->depth=depth;
    }
    void dump()
    {
        printf ("this is box. color=%d, width=%d, height=%d, depth=%d\n", color, width, height, depth);
    }
};

class sphere : public object
{
private:
    int radius;
public:
    sphere(int color, int radius)
    {
        this->color=color;
        this->radius=radius;
    }
    void dump()
    {
        printf ("this is sphere. color=%d, radius=%d\n", color, radius);
    }
};

int main()
{
    box b(1, 10, 20, 30);
    sphere s(2, 40);
    b.print_color();
    s.print_color();
    b.dump();
    s.dump();
    return 0;
};

Let’s investigate the generated code of the dump() functions/methods and also object::print_color(), and see the memory layout for the structures-objects (for 32-bit code).

So, here are the dump() methods for several classes, generated by MSVC 2008 with /Ox and /Ob0 options.

Listing 3.88: Optimizing MSVC 2008 /Ob0

??_C@_09GCEDOLPA@color?$DN?$CFd76?$AA@ DB 'color=%d', 0aH, 00H ; `string'
?print_color@object@@QAEXXZ PROC ; object::print_color, COMDAT
    _this$ = ecx
    mov eax, DWORD PTR [ecx]
    push eax
    ; 'color=%d', 0aH, 00H
    push OFFSET ??_C@_09GCEDOLPA@color?$DN?$CFd76?$AA@
    call _printf
    add esp, 8
    ret 0
?print_color@object@@QAEXXZ ENDP ; object::print_color

27The /Ob0 option stands for disabling inline expansion since function inlining can make our experiment harder.
3.18. C++

Listing 3.89: Optimizing MSVC 2008 /Ob0

?dump@box@@QAEXXZ PROC ; box::dump, COMDAT
; _this$ = ecx
  mov eax, DWORD PTR [ecx+12]
  mov edx, DWORD PTR [ecx+8]
  push eax
  mov eax, DWORD PTR [ecx+4]
  mov ecx, DWORD PTR [ecx]
  push edx
  push eax
  push ecx

; 'this is box. color=%d, width=%d, height=%d, depth=%d', 0aH, 00H ; 'string'
  push OFFSET ??_C@_0DG@NCNGAADL@this?5is?5box?4?5color?$DN?$CFd?0?5width?$DN?$CFd?0?5depth?$DN?$CFd?0@
  call _printf
  add esp, 20
  ret 0
?dump@box@@QAEXXZ ENDP ; box::dump

Listing 3.90: Optimizing MSVC 2008 /Ob0

?dump@sphere@@QAEXXZ PROC ; sphere::dump, COMDAT
;  _this$ = ecx
  mov eax, DWORD PTR [ecx+4]
  mov ecx, DWORD PTR [ecx]
  push eax
  push ecx

; 'this is sphere. color=%d, radius=%d', 0aH, 00H
  push OFFSET ??_C@_0CF@EFEDJLDC@this?5is?5sphere?4?5color?$DN?$CFd?0?5radius@
  call _printf
  add esp, 12
  ret 0
?dump@sphere@@QAEXXZ ENDP ; sphere::dump

So, here is the memory layout:

(base class object)

<table>
<thead>
<tr>
<th>offset</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0x0</td>
<td>int color</td>
</tr>
</tbody>
</table>

(inherited classes)

box:

<table>
<thead>
<tr>
<th>offset</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0x0</td>
<td>int color</td>
</tr>
<tr>
<td>+0x4</td>
<td>int width</td>
</tr>
<tr>
<td>+0x8</td>
<td>int height</td>
</tr>
<tr>
<td>+0xC</td>
<td>int depth</td>
</tr>
</tbody>
</table>

sphere:

<table>
<thead>
<tr>
<th>offset</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0x0</td>
<td>int color</td>
</tr>
<tr>
<td>+0x4</td>
<td>int radius</td>
</tr>
</tbody>
</table>

Let's see main() function body:

Listing 3.91: Optimizing MSVC 2008 /Ob0

PUBLIC _main
_TEXT SEGMENT
_s$ = -24 ; size = 8
_b$ = -16 ; size = 16
_main PROC
  sub esp, 24
  push 30
  push 20
  push 10
  push 1
The inherited classes must always add their fields after the base classes' fields, to make it possible for the base class methods to work with their own fields.

When the `object::print_color()` method is called, a pointers to both the box and sphere objects are passed as this, and it can work with these objects easily since the color field in these objects is always at the pinned address (at offset +0x0).

It can be said that the `object::print_color()` method is agnostic in relation to the input object type as long as the fields are pinned at the same addresses, and this condition is always true.

And if you create inherited class of the box class, the compiler will add the new fields after the depth field, leaving the box class fields at the pinned addresses.

Thus, the box::dump() method will work fine for accessing the color, width, height and depths fields, which are always pinned at known addresses.

The code generated by GCC is almost the same, with the sole exception of passing the this pointer (as it has been explained above, it is passed as the first argument instead of using the ECX register).

**Encapsulation**

Encapsulation is hiding the data in the private sections of the class, e.g. to allow access to them only from this class methods.

However, are there any marks in code the about the fact that some field is private and some other—not?

No, there are no such marks.

Let's try this simple example:

```c++
#include <stdio.h>

class box {
    private:
        int color, width, height, depth;
    public:
        box(int color, int width, int height, int depth)
            {  
                this->color=color;
                this->width=width;
                this->height=height;
                this->depth=depth;
            }
        void dump()
            {  
                printf("this is box. color=%d, width=%d, height=%d, depth=%d\n", color, width, height, depth);
            }
};
```
3.18. C++

Let's compile it again in MSVC 2008 with /Ox and /Ob0 options and see the box::dump() method code:

```assembly
?dump@box@@QAEXXZ PROC ; box::dump, COMDAT
    _this$ = ecx
    mov eax, DWORD PTR [ecx+12]
    mov edx, DWORD PTR [ecx+8]
    push eax
    mov eax, DWORD PTR [ecx+4]
    mov ecx, DWORD PTR [ecx]
    push edx
    push eax
    push ecx
    ; 'this is box. color=%d, width=%d, height=%d, depth=%d', 0aH, 00H
    push OFFSET ??_C@_0DG@NCNGAADL@this?5is?5box?4?5color?$DN?$CFd?0?5width?$DN?$CFd?0@
    call _printf
    add esp, 20
    ret 0
?dump@box@@QAEXXZ ENDP ; box::dump
```

Here is a memory layout of the class:

<table>
<thead>
<tr>
<th>offset</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0x0</td>
<td>int color</td>
</tr>
<tr>
<td>+0x4</td>
<td>int width</td>
</tr>
<tr>
<td>+0x8</td>
<td>int height</td>
</tr>
<tr>
<td>+0xC</td>
<td>int depth</td>
</tr>
</tbody>
</table>

All fields are private and not allowed to be accessed from any other function, but knowing this layout, can we create code that modifies these fields?

To do this we'll add the hack_oop_encapsulation() function, which is not going to compile if it looked like this:

```c
void hack_oop_encapsulation(class box * o)
{
    o->width=1; // that code can't be compiled':
    // "error C2248: 'box::width' : cannot access private member declared in class '
    // \'box\''
}
```

Nevertheless, if we cast the box type to a pointer to an int array, and we modify the array of int-s that we have, we can succeed.

```c
void hack_oop_encapsulation(class box * o)
{
    unsigned int *ptr_to_object=reinterpret_cast<unsigned int*>(o);
    ptr_to_object[1]=123;
}
```

This function's code is very simple—it can be said that the function takes a pointer to an array of int-s for input and writes 123 to the second int:

```assembly
?hack_oop_encapsulation@@YAXPAVbox@@@Z PROC ; hack_oop_encapsulation
    mov eax, DWORD PTR _o$[esp-4]
    mov DWORD PTR [eax+4], 123
    ret 0
?hack_oop_encapsulation@@YAXPAVbox@@@Z ENDP ; hack_oop_encapsulation
```

Let's check how it works:

```c
int main()
{
    box b(1, 10, 20, 30);
    b.dump();
    hack_oop_encapsulation(&b);
    b.dump();
}
```
Let's run:

```cpp
this is box. color=1, width=10, height=20, depth=30
this is box. color=1, width=123, height=20, depth=30
```

We see that the encapsulation is just protection of class fields only in the compilation stage. The C++ compiler is not allowing the generation of code that modifies protected fields straightforwardly, nevertheless, it is possible with the help of dirty hacks.

## Multiple inheritance

Multiple inheritance is creating a class which inherits fields and methods from two or more classes. Let's write a simple example again:

```cpp
#include <stdio.h>

class box
{
    public:
        int width, height, depth;
      box() { };
      box(int width, int height, int depth)
      {
          this->width=width;
          this->height=height;
          this->depth=depth;
      };
      void dump()
      {
          printf ("this is box. width=%d, height=%d, depth=%d\n", width, height, depth);
      };
      int get_volume()
      {
          return width * height * depth;
      };
};

class solid_object
{
    public:
        int density;
      solid_object() { };
      solid_object(int density)
      {
          this->density=density;
      };
      int get_density()
      {
          return density;
      };
      void dump()
      {
          printf ("this is solid_object. density=%d\n", density);
      };
};

class solid_box: box, solid_object
{
    public:
      solid_box (int width, int height, int depth, int density)
      {
          this->width=width;
          this->height=height;
          this->depth=depth;
      };
};
```
3.18. C++

```cpp
this->density=density;
};
void dump()
{
    printf ("this is solid_box. width=%d, height=%d, depth=%d, density=%d\n", width, \\
    height, depth, density);
};
int get_weight() { return get_volume() * get_density(); }
};

int main()
{
    box b(10, 20, 30);
    solid_object so(100);
    solid_box sb(10, 20, 30, 3);
    b.dump();
    so.dump();
    sb.dump();
    printf ("%d\n", sb.get_weight());
    return 0;
}

Let's compile it in MSVC 2008 with the /Ox and /Ob0 options and see the code of box::dump(), solid_object::dump() and solid_box::dump():

Listing 3.92: Optimizing MSVC 2008 /Ob0

```
So, the memory layout for all three classes is:

**box class:**

<table>
<thead>
<tr>
<th>offset</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0x0</td>
<td>width</td>
</tr>
<tr>
<td>+0x4</td>
<td>height</td>
</tr>
<tr>
<td>+0x8</td>
<td>depth</td>
</tr>
</tbody>
</table>

**solid_object class:**

<table>
<thead>
<tr>
<th>offset</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0x0</td>
<td>density</td>
</tr>
</tbody>
</table>

It can be said that the *solid_box* class memory layout is *united*:

**solid_box class:**

<table>
<thead>
<tr>
<th>offset</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0x0</td>
<td>width</td>
</tr>
<tr>
<td>+0x4</td>
<td>height</td>
</tr>
<tr>
<td>+0x8</td>
<td>depth</td>
</tr>
<tr>
<td>+0xC</td>
<td>density</td>
</tr>
</tbody>
</table>

The code of the `box::get_volume()` and `solid_object::get_density()` methods is trivial:

**Listing 3.95: Optimizing MSVC 2008 /Ob0**

```c
?get_volume@box@@QAEHXZ PROC ; box::get_volume, COMDAT
 ; __this$ = ecx
   mov eax, DWORD PTR [ecx+8]
imul eax, DWORD PTR [ecx+4]
imul eax, DWORD PTR [ecx]
ret 0
?get_volume@box@@QAEHXZ ENDP ; box::get_volume
```

**Listing 3.96: Optimizing MSVC 2008 /Ob0**

```c
?get_density@solid_object@@QAEHXZ PROC ; solid_object::get_density, COMDAT
 ; __this$ = ecx
   mov eax, DWORD PTR [ecx]
ret 0
?get_density@solid_object@@QAEHXZ ENDP ; solid_object::get_density
```

But the code of the `solid_box::get_weight()` method is much more interesting:

**Listing 3.97: Optimizing MSVC 2008 /Ob0**

```c
?get_weight@solid_box@@QAEHXZ PROC ; solid_box::get_weight, COMDAT
 ; __this$ = ecx
   push esi
mov esi, ecx
push edi
lea ecx, DWORD PTR [esi+12]
call ?get_density@solid_object@@QAEHXZ ; solid_object::get_density
mov ecx, esi
mov edi, eax
call ?get_volume@box@@QAEHXZ ; box::get_volume
imul eax, edi
pop edi
pop esi
ret 0
?get_weight@solid_box@@QAEHXZ ENDP ; solid_box::get_weight
```

`get_weight()` just calls two methods, but for `get_volume()` it just passes pointer to `this`, and for `get_density()` it passes a pointer to this incremented by 12 (or `0xC`) bytes, and there, in the *solid_box* class memory layout, the fields of the *solid_object* class start.
3.18. C++

Thus, the solid_object::get_density() method will believe like it is dealing with the usual solid_object class, and the box::get_volume() method will work with its three fields, believing this is just the usual object of class box.

Thus, we can say, an object of a class, that inherits from several other classes, is representing in memory as a united class, that contains all inherited fields. And each inherited method is called with a pointer to the corresponding structure's part.

**Virtual methods**

Yet another simple example:

```c
#include <stdio.h>

class object {
  public:
    int color;
    object() {};
    object (int color) { this->color=color; };
    virtual void dump() {
      printf ("color=%d\n", color);
    };
};
class box : public object {
  private:
    int width, height, depth;
  public:
    box(int color, int width, int height, int depth) {
      this->color=color;
      this->width=width;
      this->height=height;
      this->depth=depth;
    }
    void dump() {
      printf ("this is box. color=%d, width=%d, height=%d, depth=%d\n", color, width, height, depth);
    };
};
class sphere : public object {
  private:
    int radius;
  public:
    sphere(int color, int radius) {
      this->color=color;
      this->radius=radius;
    }
    void dump() {
      printf ("this is sphere. color=%d, radius=%d\n", color, radius);
    };
};

int main() {
  box b(1, 10, 20, 30);
  sphere s(2, 40);
  object *o1=&b;
  object *o2=&s;
}  
```
Class object has a virtual method dump() that is being replaced in the inheriting box and sphere classes.

If we are in an environment where it is not known the type of an object, as in the main() function in example, where the virtual method dump() is called, the information about its type must be stored somewhere, to be able to call the relevant virtual method.

Let's compile it in MSVC 2008 with the /Ox and /Ob0 options and see the code of main():

```assembly
_main PROC
    sub esp, 32
    push 30
    push 20
    push 10
    push 1
    lea ecx, DWORD PTR _b$[esp+48]
    call ??0box@@QAE@HHHH@Z ; box::box
    push 40
    push 2
    lea ecx, DWORD PTR _s$[esp+40]
    call ??0sphere@@QAE@HH@Z ; sphere::sphere
    mov eax, DWORD PTR _b$[esp+32]
    mov edx, DWORD PTR [eax]
    lea ecx, DWORD PTR _b$[esp+32]
    call edx
    mov eax, DWORD PTR _s$[esp+32]
    mov edx, DWORD PTR [eax]
    lea ecx, DWORD PTR _s$[esp+32]
    call edx
    xor eax, eax
    add esp, 32
    ret 0
_main ENDP
```

A pointer to the dump() function is taken somewhere from the object. Where could we store the address of the new method? Only somewhere in the constructors: there is no other place since nothing else is called in the main() function. 28

Let's see the code of the constructor of the box class:

```assembly
??_R0?AVbox@@@8 DD FLAT:?_7type_info@@6B@ ; box `RTTI Type Descriptor'
    DD 00H
    DB '.?AVbox@@', 00H
??_R1@0A@EA@box@@8 DD FLAT:?_R0?AVbox@@@8 ; box::`RTTI Base Class Descriptor at (0,-1,0,64)'
    DD 01H
    DD 00H
    DD 0ffffffffH
    DD 00H
    DD 040H
    DD FLAT:?_R3box@@8
??_R2box@@8 DD FLAT:?_R1@0A@EA@box@@8 ; box::`RTTI Base Class Array'
    DD FLAT:?_R1@0A@EA@object@@
??_R3box@@8 DD 00H ; box::`RTTI Class Hierarchy Descriptor'
    DD 00H
    DD 02H
    DD FLAT:?_R2box@@8
??_R4box@@6B@ DD 00H ; box::`RTTI Complete Object Locator'
    DD 00H
    DD 00H
```

28You can read more about pointers to functions in the relevant section: (1.27 on page 384)
3.18. C++

Here we see a slightly different memory layout: the first field is a pointer to some table `box::`vftable'(the name has been set by the MSVC compiler).

In this table we see a link to a table named `box::`RTTI Complete Object Locator' and also a link to the `box::dump()` method.

These are called virtual methods table and `RTTI`. The table of virtual methods has the addresses of methods and the `RTTI` table contains information about types.

By the way, the `RTTI` tables are used while calling `dynamic_cast` and `typeid` in C++. You can also see here the class name as a plain text string.

Thus, a method of the base `object` class may call the virtual method `object::dump()`, which in turn will call a method of an inherited class, since that information is present right in the object's structure.

Some additional CPU time is needed for doing look-ups in these tables and finding the right virtual method address, thus virtual methods are widely considered as slightly slower than common methods.

In GCC-generated code the `RTTI` tables are constructed slightly differently.

3.18.2 ostream

Let's start again with a “hello world” example, but now we are going to use `ostream`:

```cpp
#include <iostream>

int main()
{
    std::cout << "Hello, world!\n";
}
```

Almost any C++ textbook tells us that the `<<` operation can be defined (overloaded) for other types. That is what is done in `ostream`. We see that operator `<<` is called for `ostream`:

```cpp
$SG37112 DB 'Hello, world!', 0aH, 00H
```

---

29Run-Time Type Information
Let's modify the example:

```cpp
#include <iostream>
int main()
{
    std::cout << "Hello, " << "world!\n";
}
```

And again, from many C++ textbooks we know that the result of each `operator<<` in `ostream` is forwarded to the next one. Indeed:

```cpp
Listing 3.99: MSVC 2012
$SG37112 DB 'world!', 0aH, 00H
$SG37113 DB 'Hello, ', 00H
_main PROC
    push OFFSET $SG37113 ; 'Hello, '
    push OFFSET ?cout@std@@3V?$basic_ostream@DU?$char_traits@D@std@@@1@A ; std::cout
call ??$?6U?$char_traits@D@std@@@std@@YAAAV?$basic_ostream@DU?$char_traits@D@std@@@0@AAV10@PBD@Z ; std::operator<<<std::char_traits<char> >
    add esp, 8
    xor eax, eax
    ret 0
_main ENDP
```

If we would rename `operator<<` method name to `f()`, that code will looks like:

```cpp
f(f(std::cout, "Hello, "), "world!");
```

GCC generates almost the same code as MSVC.

### 3.18.3 References

In C++, references are pointers ([3.21 on page 611](#)) as well, but they are called safe, because it is harder to make a mistake while dealing with them (C++11 8.3.2).

For example, reference must always be pointing to an object of the corresponding type and cannot be NULL [Marshall Cline, C++ FAQ 8.6].

Even more than that, references cannot be changed, it is impossible to point them to another object (reseat) [Marshall Cline, C++ FAQ 8.5].

If we are going to change the example with pointers ([3.21 on page 611](#)) to use references instead ...

```cpp
void f2 (int x, int y, int & sum, int & product)
{
    sum=x+y;
    product=x*y;
};
```
3.18. C++

...then we can see that the compiled code is just the same as in the pointers example (3.21 on page 611):

Listing 3.100: Optimizing MSVC 2010

```
x$ = 8 ; size = 4
_y$ = 12 ; size = 4
_sum$ = 16 ; size = 4
_product$ = 20 ; size = 4
?f2@@YAXHHAAH0@Z PROC ; f2
    mov ecx, DWORD PTR _y$[esp-4]
    mov eax, DWORD PTR _x$[esp-4]
    lea edx, DWORD PTR [eax+ecx]
    imul eax, ecx
    mov ecx, DWORD PTR _product$[esp-4]
    push esi
    mov esi, DWORD PTR _sum$[esp]
    mov DWORD PTR [esi], edx
    mov DWORD PTR [ecx], eax
    pop esi
    ret 0
?f2@@YAXHHAAH0@Z ENDP ; f2
```

(The reason why C++ functions has such strange names is explained here: 3.18.1 on page 542.)
Hence, C++ references are as much efficient as usual pointers.

3.18.4 STL

N.B.: all examples here were checked only in 32-bit environment. x64 wasn’t checked.

std::string

Internals

Many string libraries [Dennis Yurichev, C/C++ programming language notes2.2] implement a structure that contains a pointer to a string buffer, a variable that always contains the current string length (which is very convenient for many functions: [Dennis Yurichev, C/C++ programming language notes2.2.1]) and a variable containing the current buffer size.

The string in the buffer is usually terminated with zero, in order to be able to pass a pointer to the buffer into the functions that take usual C ASCIIZ strings.

It is not specified in the C++ standard how std::string has to be implemented, however, it is usually implemented as explained above.

The C++ string is not a class (as QString in Qt, for instance) but a template (basic_string), this is made in order to support various character types: at least char and wchar_t.

So, std::string is a class with char as its base type.

And std::wstring is a class with wchar_t as its base type.

MSVC

The MSVC implementation may store the buffer in place instead of using a pointer to a buffer (if the string is shorter than 16 symbols).

This implies that a short string is to occupy at least \(16 + 4 + 4 = 24\) bytes in 32-bit environment or at least \(16 + 8 + 8 = 32\) bytes in 64-bit one, and if the string is longer than 16 characters, we also have to add the length of the string itself.

Listing 3.101: example for MSVC

```
#include <string>
#include <stdio.h>
```

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Almost everything is clear from the source code.

A couple of notes:

If the string is shorter than 16 symbols, a buffer for the string is not to be allocated in the heap.

This is convenient because in practice, a lot of strings are short indeed.

Looks like that Microsoft’s developers chose 16 characters as a good balance.

One very important thing here can be seen at the end of main(): we’re not using the c_str() method, nevertheless, if we compile and run this code, both strings will appear in the console!

This is why it works.

In the first case the string is shorter than 16 characters and the buffer with the string is located in the beginning of the std::string object (it can be treated as a structure). printf() treats the pointer as a pointer to the null-terminated array of characters, hence it works.

Printing the second string (longer than 16 characters) is even more dangerous: it is a typical programmer’s mistake (or typo) to forget to write c_str().

This works because at the moment a pointer to buffer is located at the start of structure.

This may stay unnoticed for a long time, until a longer string appears there at some time, then the process will crash.

**GCC**

GCC’s implementation of this structure has one more variable—reference count.

One interesting fact is that in GCC a pointer an instance of std::string instance points not to the beginning of the structure, but to the buffer pointer. In `libstdc++-v3/include/bits/basic_string.h` we can read that it was done for more convenient debugging:

* The reason you want _M_data pointing to the character %array and not the _Rep is so that the debugger can see the string contents. (Probably we should add a non-inline member to get the _Rep for the debugger to use, so users can check the actual
3.18. C++

*b string length.*

**basic_string.h source code**

We consider this in our example:

**Listing 3.102: example for GCC**

```c
#include <string>
#include <stdio.h>

struct std_string
{
    size_t length;
    size_t capacity;
    size_t refcount;
};

void dump_std_string(std::string s)
{
    char *p1=*(char**)&s; // GCC type checking workaround
    struct std_string *p2=(struct std_string*)(p1-sizeof(struct std_string));
    printf ("[%s] size:%d capacity:%d\n", p1, p2->length, p2->capacity);
}

int main()
{
    std::string s1="short string";
    std::string s2="string longer that 16 bytes";
    dump_std_string(s1);
    dump_std_string(s2);
    // GCC type checking workaround:
    printf ("%s\n", *(char**)&s1);
    printf ("%s\n", *(char**)&s2);
}
```

A trickery has to be used to imitate the mistake we already have seen above because GCC has stronger type checking, nevertheless, printf() works here without c_str() as well.

**A more advanced example**

```c
#include <string>
#include <stdio.h>

int main()
{
    std::string s1="Hello, ";
    std::string s2="world!\n";
    std::string s3=s1+s2;
    printf ("%s\n", s3.c_str());
}
```

**Listing 3.103: MSVC 2012**

```
SG39512 DB 'Hello, ', 00H
SG39514 DB 'world!', 0aH, 00H
SG39581 DB '%s', 0aH, 00H
_s2$ = -72 ; size = 24
_s3$ = -48 ; size = 24
_s1$ = -24 ; size = 24
_main PROC
    sub esp, 72
    push 7
```
The compiler does not construct strings statically: it would not be possible anyway if the buffer needs to be located in the heap.

Instead, the `ASCIIZ` strings are stored in the data segment, and later, at runtime, with the help of the
“assign” method, the s1 and s2 strings are constructed. And with the help of operator+, the s3 string is constructed.

Please note that there is no call to the c_str() method, because its code is tiny enough so the compiler inlined it right there: if the string is shorter than 16 characters, a pointer to buffer is left in EAX, otherwise the address of the string buffer located in the heap is fetched.

Next, we see calls to the 3 destructors, they are called if the string is longer than 16 characters: then the buffers in the heap have to be freed. Otherwise, since all three std::string objects are stored in the stack, they are freed automatically, when the function ends.

As a consequence, processing short strings is faster, because of less heap accesses.

GCC code is even simpler (because the GCC way, as we saw above, is to not store shorter strings right in the structure):

Listing 3.104: GCC 4.8.1

```
.LC0:
.string "Hello, ",
.LC1:
.string "world!\n"
main:
push ebp
mov ebp, esp
push edi
push esi
push ebx
and esp, -16
sub esp, 32
lea ebx, [esp+28]
lea edi, [esp+20]
mov DWORD PTR [esp+8], ebx
lea edi, [esp+20]
mov DWORD PTR [esp+4], OFFSET FLAT:.LC0
mov DWORD PTR [esp], edi
call _ZNSsC1EPKcRKSaIcE
mov DWORD PTR [esp+8], ebx
mov DWORD PTR [esp+4], OFFSET FLAT:.LC1
mov DWORD PTR [esp], esi
call _ZNSsC1EPKcRKSaIcE
mov DWORD PTR [esp+4], edi
mov DWORD PTR [esp], ebx
call _ZNSsC1ERKSs
mov DWORD PTR [esp+4], esi
mov DWORD PTR [esp], ebx
call _ZNSs6appendERKSs
; inlined c_str():
mov eax, DWORD PTR [esp+28]
mov DWORD PTR [esp], eax
call puts
mov eax, DWORD PTR [esp+28]
lea ebx, [esp+19]
mov DWORD PTR [esp+4], ebx
sub eax, 12
mov DWORD PTR [esp], eax
call _ZNSs4_Rep10_M_disposeERKSaIcE
mov eax, DWORD PTR [esp+24]
mov DWORD PTR [esp+4], ebx
sub eax, 12
mov DWORD PTR [esp], eax
call _ZNSs4_Rep10_M_disposeERKSaIcE
```
It can be seen that it’s not a pointer to the object that is passed to destructors, but rather an address 12 bytes (or 3 words) before, i.e., a pointer to the real start of the structure.

### std::string as a global variable

Experienced C++ programmers know that global variables of STL types can be defined without problems.

Yes, indeed:

```cpp
#include <stdio.h>
#include <string>

std::string s="a string";

int main()
{
    printf ("%s\n", s.c_str());
}
```

But how and where std::string constructor will be called?

In fact, this variable is to be initialized even before `main()` start.

Listing 3.105: MSVC 2012: here is how a global variable is constructed and also its destructor is registered

```assembly
??__Es@@YAXXZ PROC
push 8
push OFFSET $SG39512 ; 'a string'
mov ecx, OFFSET ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A ; s
call ?assign@?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A@std@@AEEAV12@PBDI@Z ;
\std::basic_string<char,std::char_traits<char>,std::allocator<char> >::assign
push OFFSET ??__Fs@@YAXXZ ; `dynamic atexit destructor for 's'
call _atexit
pop ecx
ret 0
??__Es@@YAXXZ ENDP
```

Listing 3.106: MSVC 2012: here a global variable is used in `main()`

```assembly
$SG39512 DB 'a string', 00H
$SG39519 DB '%s', 0aH, 00H

_main PROC
    cmp DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A+20, 16
    mov eax, OFFSET ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A ; s
    cmovae eax, DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A ; s
    push eax
    push OFFSET $SG39519 ; '%s'
call _printf
    add esp, 8
    xor eax, eax
    ret 0
_main ENDP
```

\(^{30}\text{(C++) Standard Template Library}\)
In fact, a special function with all constructors of global variables is called from CRT, before main().

More than that: with the help of atexit() another function is registered, which contain calls to all destructors of such global variables.

GCC works likewise:
But it does not create a separate function for this, each destructor is passed to atexit(), one by one.

**std::list**

This is the well-known doubly-linked list: each element has two pointers, to the previous and next elements.

This implies that the memory footprint is enlarged by 2 words for each element (8 bytes in 32-bit environment or 16 bytes in 64-bit).

C++ STL just adds the “next” and “previous” pointers to the existing structure of the type that you want to unite in a list.

Let’s work out an example with a simple 2-variable structure that we want to store in a list.

Although the C++ standard does not say how to implement it, both MSVC’s and GCC’s implementations are straightforward and similar, so here is only one source code for both:

```cpp
cpp
#include <stdio.h>
#include <list>
#include <iostream>

struct a
{
    int x;
    int y;
};

struct List_node
{
    struct List_node* _Next;
    struct List_node* _Prev;
    int x;
    int y;
};

void dump_List_node (struct List_node *n)
{
    printf (“ptr=0x%p _Next=0x%p _Prev=0x%p x=%d y=%d
”,
            n, n->_Next, n->_Prev, n->x, n->y);
}

void dump_List_vals (struct List_node* n)
{
    struct List_node* current=n;
    for (;;)
    {
        dump_List_node (current);
        current=current->_Next;
        if (current==n) // end
            break;
    }
}

void dump_List_val (unsigned int *a)
{
    #ifdef _MSC_VER
        // GCC implementation does not have "size" field
        printf ("_Myhead=0x%p, _Mysize=%d
", a[0], a[1]);
    #endif
    dump_List_vals ((struct List_node*)a[0]);
}

int main()
```
3.18. C++
{
    std::list<struct a> l;
    printf("** empty list:\n\n");
    dump_List_val((unsigned int*)(void*)&l);

    struct a t1;
    t1.x=1;
    t1.y=2;
    l.push_front(t1);
    t1.x=3;
    t1.y=4;
    l.push_front(t1);
    t1.x=5;
    t1.y=6;
    l.push_back(t1);
    printf("** 3-elements list:\n\n");
    dump_List_val((unsigned int*)(void*)&l);

    std::list<struct a>::iterator tmp;
    printf("node at .begin:\n\n");
    tmp=l.begin();
    dump_List_node ((struct List_node *)*(void**)&tmp);
    printf("node at .end:\n\n");
    tmp=l.end();
    dump_List_node ((struct List_node *)(void**)&tmp);

    printf("* let's count from the beginning:\n\n");
    std::list<struct a>::iterator it=l.begin();
    printf("1st element: %d %d\n", (*it).x, (*it).y);
    it++;
    printf("2nd element: %d %d\n", (*it).x, (*it).y);
    it++;
    printf("3rd element: %d %d\n", (*it).x, (*it).y);
    it++;
    printf("element at .end(): %d %d\n", (*it).x, (*it).y);

    printf("* let's count from the end:\n\n");
    std::list<struct a>::iterator it2=l.end();
    printf("element at .end(): %d %d\n", (*it2).x, (*it2).y);
    it2--;
    printf("3rd element: %d %d\n", (*it2).x, (*it2).y);
    it2--;
    printf("2nd element: %d %d\n", (*it2).x, (*it2).y);
    it2--;
    printf("1st element: %d %d\n", (*it2).x, (*it2).y);

    printf("removing last element...\n");
    l.pop_back();
    dump_List_val((unsigned int*)(void*)&l);
};

GCC

Let's start with GCC.

When we run the example, we'll see a long dump, let's work with it in pieces.

* empty list:
ptr=0x0028fe90 _Next=0x0028fe90 _Prev=0x0028fe90 x=3 y=0

Here we see an empty list.

Despite the fact it is empty, it has one element with garbage (AKA dummy node) in \(x\) and \(y\). Both the "next" and "prev" pointers are pointing to the self node:
At this moment, the .begin and .end iterators are equal to each other. If we push 3 elements, the list internally will be:

```plaintext
* 3-elements list:
ptr=0x000349a0 _Next=0x00034988 _Prev=0x0028fe90 x=3 y=4
ptr=0x00034988 _Next=0x00034b40 _Prev=0x000349a0 x=1 y=2
ptr=0x00034b40 _Next=0x0028fe90 _Prev=0x00034988 x=5 y=6
ptr=0x0028fe90 _Next=0x000349a0 _Prev=0x00034b40 x=5 y=6
```

The last element is still at 0x0028fe90, it not to be moved until the list’s disposal. It still contain random garbage in \( x \) and \( y \) (5 and 6). By coincidence, these values are the same as in the last element, but it doesn’t mean that they are meaningful.

Here is how these 3 elements are stored in memory:

The \( l \) variable always points to the first node. The .begin() and .end() iterators are not variables, but functions, which when called return pointers to the corresponding nodes.

Having a dummy element (aka sentinel node) is a very popular practice in implementing doubly-linked lists. Without it, a lot of operations may become slightly more complex and, hence, slower.

The iterator is in fact just a pointer to a node. list.begin() and list.end() just return pointers.

```plaintext
node at .begin:
ptr=0x000349a0 _Next=0x00034988 _Prev=0x0028fe90 x=3 y=4
node at .end:
ptr=0x0028fe90 _Next=0x000349a0 _Prev=0x00034b40 x=5 y=6
```

The fact that the last element has a pointer to the first and the first element has a pointer to the last one remind us of circular lists.
This is very helpful here: having a pointer to the first list element, i.e., that is in the \( i \) variable, it is easy to get a pointer to the last one quickly, without the necessity to traverse the whole list.

Inserting an element at the end of the list is also quick, thanks to this feature.

\[
\text{operator-- and operator++ just set the current iterator's value to the current_node->prev or current_node->next values.}
\]

The reverse iterators (.begin, .rend) work just as the same, but in reverse.

\[
\text{operator* just returns a pointer to the point in the node structure, where the user's structure starts, i.e., a pointer to the first element of the structure (}\ x\text{).}
\]

The list insertion and deletion are trivial: just allocate a new node (or deallocate) and update all pointers to be valid.

That's why an iterator may become invalid after element deletion: it may still point to the node that has been already deallocated. This is also called a dangling pointer.

And of course, the information from the freed node (to which iterator still points) cannot be used anymore.

The GCC implementation (as of 4.8.1) doesn't store the current size of the list: this implies a slow .size() method: it has to traverse the whole list to count the elements, because it doesn't have any other way to get the information.

This means that this operation is \( O(n) \), i.e., it steadily gets slower as the list grows.

---

**Listing 3.109: Optimizing GCC 4.8.1 -fno-inline-small-functions**

```c
main proc near
  push ebp
  mov ebp, esp
  push esi
  push ebx
  and esp, 0FFFFFFF0h
  sub esp, 20h
  lea ebx, [esp+10h]
  mov dword ptr [esp], offset s ; "* empty list:" 
  mov [esp+10h], ebx
  mov [esp+14h], ebx
  call puts
  mov [esp], ebx
  call _Z13dump_List_valPj ; dump_List_val(uint *)
  lea esi, [esp+4]
  mov [esp+10h], esi
  mov [esp], ebx
  mov dword ptr [esp+10h], 1 ; X for new element
  mov dword ptr [esp+1Ch], 2 ; Y for new element
  call _ZNSt4listI1aSaIS0_EE10push_frontERKS0_ ; std::list<a,std::allocator<a>>::push_front(a, \\ const&)
  mov [esp+4], esi
  mov [esp], ebx
  mov dword ptr [esp+10h], 3 ; X for new element
  mov dword ptr [esp+1Ch], 4 ; Y for new element
  call _ZNSt4listI1aSaIS0_EE10push_frontERKS0_ ; std::list<a,std::allocator<a>>::push_front(a, \\ const&)
  mov dword ptr [esp], 10h
  mov dword ptr [esp+10h], 5 ; X for new element
  mov dword ptr [esp+1Ch], 6 ; Y for new element
  call _Znwj ; operator new(uint)
  cmp eax, 0FFFFFFF8h
  jz short loc_80002A6
  mov ecx, [esp+1Ch]
  mov edx, [esp+18h]
  mov [eax+0Ch], ecx
  mov [eax+8], edx
  loc_80002A6: ; CODE XREF: main+86
  mov [esp+4], ebx
  mov [esp], eax
  call _ZNSt8__detail15_List_node_base7_M_hookEPS0_ ; std::__detail::List_node_base::M_hook(\$, (std::__detail::List_node_base*))
  mov dword ptr [esp], offset a3ElementsList ; "* 3-elements list:" 
```
3.18. C++

call puts
mov [esp], ebx
    call Z13dump_List_valPj ; dump_List_val(uint *)
    mov dword ptr [esp], offset aNodeAt_begin ; "node at .begin:
    call puts
mov eax, [esp+10h]
mov [esp], eax
    call Z14dump_List_nodeP9List_node ; dump_List_node(List_node *)
mov dword ptr [esp], offset aNodeAt_end ; "node at .end:
    call puts
mov [esp], ebx
    call Z14dump_List_nodeP9List_node ; dump_List_node(List_node *)
mov dword ptr [esp], offset aLetSCountFromT ; "* let's count from the beginning:
    call puts
mov esi, [esp+10h]
mov eax, [esi+0Ch]
mov [esp+0Ch], eax
mov eax, [esi+8]
mov dword ptr [esp+4], offset a1stElementDD ; "1st element: %d %d
mov dword ptr [esp], 1
mov [esp+8], eax
    call __printf_chk
mov esi, [esi] ; operator++: get ->next pointer
mov eax, [esi+0Ch]
mov [esp+0Ch], eax
mov eax, [esi+8]
mov dword ptr [esp+4], offset a2ndElementDD ; "2nd element: %d %d
mov dword ptr [esp], 1
mov [esp+8], eax
    call __printf_chk
mov esi, [esi] ; operator++: get ->next pointer
mov eax, [esi+0Ch]
mov [esp+0Ch], eax
mov eax, [esi+8]
mov dword ptr [esp+4], offset a3rdElementDD ; "3rd element: %d %d
mov dword ptr [esp], 1
mov [esp+8], eax
    call __printf_chk
mov eax, [esi] ; operator++: get ->next pointer
mov edx, [eax+0Ch]
mov [esp+0Ch], edx
mov eax, [eax+8]
mov dword ptr [esp+4], offset aElementAt_endD ; "element at .end(): %d %d
mov dword ptr [esp], 1
mov [esp+8], eax
    call __printf_chk
mov dword ptr [esp], offset aLetSCountFro_0 ; "* let's count from the end:
    call puts
mov eax, [esp+1Ch]
mov dword ptr [esp+4], offset aElementAt_endD ; "element at .end(): %d %d
mov dword ptr [esp], 1
mov [esp+8], eax
    call __printf_chk
mov esi, [esp+14h]
mov eax, [esi+0Ch]
mov [esp+0Ch], eax
mov eax, [esi+8]
mov dword ptr [esp+4], offset a3rdElementDD ; "3rd element: %d %d
mov dword ptr [esp], 1
mov [esp+8], eax
    call __printf_chk
mov esi, [esi+4] ; operator--: get ->prev pointer
mov eax, [esi+0Ch]
mov [esp+0Ch], eax
mov eax, [esi+8]
mov dword ptr [esp+4], offset a2ndElementDD ; "2nd element: %d %d
mov dword ptr [esp], 1
mov [esp+8], eax
3.18. C++

call __printf_chk
mov eax, [esi+4]; operator--: get ->prev pointer
mov edx, [eax+0Ch]
mov [esp+0Ch], edx
mov eax, [eax+8]
mov dword ptr [esp+4], offset a1stElementDD ; "1st element: %d %d\n"
mov dword ptr [esp], 1
mov [esp+8], eax
call __printf_chk
mov dword ptr [esp], offset aRemovingLastEl; "removing last element..."
call puts
mov esi, [esp+14h]
mov [esp], esi
call _ZNSt8__detail15_List_node_base9_M_unhookEv; std::__detail::List_node_base::
ˌ M_unhook(void)
mov [esp], esi; void *
call _ZdlPv; operator delete(void *)
mov [esp], ebx
call _Z13dump List_valPj; dump_List_val(uint *)
mov [esp], ebx
call _ZNSt10_List_baseI1aSaIS0_EE8_M_clearEv; std::List_base<a,std::allocator<a>>::
ˌ M_clear(void)
lea esp, [ebp-8]
xor eax, eax
pop ebx
pop esi
pop ebp
retn
main endp

Listing 3.110: The whole output

* empty list:
ptr=0x0028fe90 _Next=0x0028fe90 _Prev=0x0028fe90 x=3 y=0
* 3-elements list:
ptr=0x000349a0 _Next=0x00034988 _Prev=0x0028fe90 x=3 y=4
ptr=0x00034988 _Next=0x00034b40 _Prev=0x000349a0 x=1 y=2
ptr=0x00034b40 _Next=0x0028fe90 _Prev=0x00034988 x=5 y=6
ptr=0x0028fe90 _Next=0x000349a0 _Prev=0x00034b40 x=5 y=6
node at .begin:
ptr=0x000349a0 _Next=0x00034988 _Prev=0x0028fe90 x=3 y=4
node at .end:
ptr=0x0028fe90 _Next=0x000349a0 _Prev=0x00034b40 x=5 y=6
* let’s count from the beginning:
1st element: 3 4
2nd element: 1 2
3rd element: 5 6
element at .end(): 5 6
* let’s count from the end:
element at .end(): 5 6
3rd element: 5 6
2nd element: 1 2
1st element: 3 4
removing last element...
ptr=0x000349a0 _Next=0x00034988 _Prev=0x0028fe90 x=3 y=4
ptr=0x00034988 _Next=0x0028fe90 _Prev=0x000349a0 x=1 y=2
ptr=0x0028fe90 _Next=0x00034988 _Prev=0x000349a0 x=5 y=6

MSVC

MSVC’s implementation (2012) is just the same, but it also stores the current size of the list. This implies that the .size() method is very fast (\(O(1)\)): it just reads one value from memory. On the other hand, the size variable must be updated at each insertion/deletion.

MSVC’s implementation is also slightly different in the way it arranges the nodes:
3.18. C++

GCC has its dummy element at the end of the list, while MSVC’s is at the beginning.

Listing 3.111: Optimizing MSVC 2012 /Fa2.asm /GS- /Ob1

```assembly
.ls = -16 ; size = 8
.tl$ = -8 ; size = 8

_main PROC
  sub esp, 16
  push ebx
  push esi
  push edi
  push 0
  push 0
  lea ecx, DWORD PTR _l$[esp+36]
  mov DWORD PTR _l$[esp+40], 0
  ; allocate first garbage element
  call ?_Buynode0@?$_List_alloc@$0A@U?$_List_base_types@Ua@@V?
  # $allocator@Ua@@std@@std@@std@@QAEPAU?$_List_node@Ua@@PAX@2@PAU32@0@Z ; std::
  # _List_alloc<a,std::List_base_types<a,std::allocator<a>> > >::_Buynode0
  mov edi, DWORD PTR __imp__printf
  mov ebx, eax
  push OFFSET $SG40685 ; '* empty list:
  mov DWORD PTR _l$[esp+32], ebx
  call edi ; printf
  lea eax, DWORD PTR _l$[esp+32]
  push eax
  call ?dump_List_val@@YAXPAI@Z ; dump_List_val
  mov esi, DWORD PTR [ebx]
  add esp, 8
  lea eax, DWORD PTR _tl$[esp+28]
  push eax
  push DWORD PTR [esi+4]
  lea ecx, DWORD PTR _l$[esp+36]
  push esi
  mov DWORD PTR _tl$[esp+40], 1 ; data for a new node
  mov DWORD PTR _tl$[esp+44], 2 ; data for a new node
  ; allocate new node
  call ??$_Buynode@ABUa@@@?$_List_buy@Ua@@V?$allocator@Ua@@std@@std@@std@@QAEPAU7@Z ; std::_List_buy<a,std::allocator<a>> > >::_Buynode<a>
  # $ allocator@Ua@@std@@std@@std@@QAEPAU7 @a > :>_List_node@Ua@@PAX01@PAU21@0ABU7@Z ; std::_List_node@Ua@@PAX01@PAU21@0ABU7 @a > :>_List_node@Ua@@PAX01@PAU21@0ABU7 @a > :>_Buynode<a>
  push eax
  push DWORD PTR [esi+4]
  lea ecx, DWORD PTR _l$[esp+28]
  push eax
  push DWORD PTR [esi+4]
  lea ecx, DWORD PTR [eax+4]
  mov DWORD PTR _tl$[esp+28], 3 ; data for a new node
  mov DWORD PTR [ecx], eax
  mov esi, DWORD PTR [ebx]
  lea eax, DWORD PTR _tl$[esp+28]
  push eax
  push DWORD PTR [esi+4]
  lea ecx, DWORD PTR _l$[esp+36]
  push esi
  mov DWORD PTR _tl$[esp+44], 4 ; data for a new node

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allocate new node

\begin{verbatim}
call ??$_Buynode@ABUa@@@?$_List_buy@Ua@@V?$allocator@Ua@@@std@@@std@@QAEPAU?
⤦/rcurvearrowse
$\_List_node@Ua@@PAX@1@PAU21@0ABUa@@@Z ; std::_List_buy<a,std::allocator<a> > :: Buynode<a >
\end{verbatim}

mov DWORD PTR [esi+4], eax
mov ecx, DWORD PTR [eax+4]
lea eax, DWORD PTR [ecx]
push eax
lea ecx, DWORD PTR _t1$[esp+28]
push ebx
lea eax, DWORD PTR _t1$[esp+28]
push eax
mov DWORD PTR _t1$[esp+44], 6 ; data for a new node
allocate new node
call ??$_Buynode@ABUa@@@?$_List_buy@Ua@@V?$allocator@Ua@@@std@@@std@@QAEPAU?
⤦/rcurvearrowse
$\_List_node@Ua@@PAX@1@PAU21@0ABUa@@@Z ; std::_List_buy<a,std::allocator<a> > :: Buynode<a >
\end{verbatim}

mov DWORD PTR [esi+4], eax
mov ecx, DWORD PTR [eax+4]
push OFFSET $SG40689 ; '* 3-elements list:
 mov DWORD PTR _l$[esp+36], 3
 mov DWORD PTR [ecx], eax
call edi ; printf
lea eax, DWORD PTR _l$[esp+32]
push eax
call ?dump_List_val@@YAXPAI@Z ; dump_List_val
push OFFSET $SG40831 ; 'node at .begin:'
call edi ; printf
push DWORD PTR [ebx] ; get next field of node $l$ variable points to
 call ??$_dump_List_node@YAXPAUList_node@@@std@@@std@@QAEPAU@
⤦/rcurvearrowse
$\_List_node@Ua@@PAX@1@PAU21@0ABUa@@@Z ; std::_List_buy<a,std::allocator<a> > :: Buynode<a >
\end{verbatim}

mov esi, DWORD PTR [esi+4] ; operator--: get ->prev pointer
add esp, 64
push DWORD PTR [eax+12]
push DWORD PTR [eax+8]
push OFFSET $SG40860 ; 'element at .end(): %d %d'
call edi ; printf
push OFFSET $SG40862 ; 'element at .end(): %d %d'
call edi ; printf
push DWORD PTR [ebx+12] ; use x and y fields from the node "l" variable points to
 push DWORD PTR [ebx+8]
push OFFSET $SG40860 ; 'element at .end(): %d %d'
call edi ; printf
mov esi, DWORD PTR [esi+4] ; operator--: get ->prev pointer
add esp, 64
push DWORD PTR [eax+12]
push DWORD PTR [eax+8]
push OFFSET $SG40850 ; '3rd element: %d %d'
call edi ; printf
mov eax, DWORD PTR [esi] ; operator++: get ->next pointer
add esp, 64
push DWORD PTR [eax+12]
push DWORD PTR [eax+8]
push OFFSET $SG40852 ; 'element at .end(): %d %d'
call edi ; printf
push OFFSET $SG40853 ; '* let''s count from the end:'
call edi ; printf

Unlike GCC, MSVC’s code allocates the dummy element at the start of the function with the help of the “Buynode” function, it is also used to allocate the rest of the nodes (GCC’s code allocates the first element in the local stack).

Listing 3.112: The whole output

* empty list:
  _Myhead=0x003CC258, _Mysize=0
  ptr=0x003CC258 _Next=0x003CC258 _Prev=0x003CC258 x=6226002 y=4522072
* 3-elements list:

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3.18. C++

Myhead=0x003CC258, _Mysize=3
ptr=0x003CC258 _Next=0x003CC288 _Prev=0x003CC2A0 x=6226002 y=4522072
ptr=0x003CC288 _Next=0x003CC270 _Prev=0x003CC258 x=3 y=4
ptr=0x003CC270 _Next=0x003CC2A0 _Prev=0x003CC288 x=1 y=2
ptr=0x003CC2A0 _Next=0x003CC258 _Prev=0x003CC270 x=5 y=6
node at .begin:
ptr=0x003CC288 _Next=0x003CC270 _Prev=0x003CC258 x=3 y=4
node at .end:
ptr=0x003CC258 _Next=0x003CC288 _Prev=0x003CC2A0 x=6226002 y=4522072
* let's count from the beginning:
  1st element: 3 4
  2nd element: 1 2
  3rd element: 5 6
element at .end(): 6226002 4522072
* let's count from the end:
  element at .end(): 6226002 4522072
  3rd element: 5 6
  2nd element: 1 2
  1st element: 3 4
removing last element...
_Myhead=0x003CC258, _Mysize=2
ptr=0x003CC258 _Next=0x003CC288 _Prev=0x003CC270 x=6226002 y=4522072
ptr=0x003CC288 _Next=0x003CC270 _Prev=0x003CC258 x=3 y=4
ptr=0x003CC270 _Next=0x003CC2A0 _Prev=0x003CC288 x=1 y=2

C++11 std::forward_list

The same thing as std::list, but singly-linked one, i.e., having only the “next” field at each node.
It has a smaller memory footprint, but also don’t offer the ability to traverse list backwards.

std::vector

We would call std::vector a safe wrapper of the PODT\textsuperscript{31} C array. Internally it is somewhat similar to
std::string (3.18.4 on page 559): it has a pointer to the allocated buffer, a pointer to the end of the
array, and a pointer to the end of the allocated buffer.
The array’s elements lie in memory adjacently to each other, just like in a normal array (1.20 on page 267).
In C++11 there is a new method called .data(), that returns a pointer to the buffer, like .c_str() in
std::string.
The buffer allocated in the heap can be larger than the array itself.
Both MSVC’s and GCC’s implementations are similar, just the names of the structure’s fields are slightly
different\textsuperscript{32}, so here is one source code that works for both compilers. Here is again the C-like code for
dumping the structure of std::vector:

```
#include <stdio.h>
#include <vector>
#include <algorithm>
#include <functional>

struct vector_of_ints
{
  // MSVC names:
  int *Myfirst;
  int *Mylast;
  int *Myend;

  // GCC structure is the same, but names are: _M_start, _M_finish, _M_end_of_storage
};

void dump(struct vector_of_ints *in)
{

\textsuperscript{31}(C++) Plain Old Data Type
\textsuperscript{32}GCC internals: http://go.yurichev.com/17086
```

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```c++
3.18. C++

```}

Here is the output of this program when compiled in MSVC:

```
Myfirst=00000000, Mylast=00000000, Myend=00000000
size=0, capacity=0

Myfirst=0051CF48, Mylast=0051CF4C, Myend=0051CF4C
size=1, capacity=1
  element 0: 1

Myfirst=0051CF58, Mylast=0051CF60, Myend=0051CF60
size=2, capacity=2
  element 0: 1
  element 1: 2

Myfirst=0051C278, Mylast=0051C284, Myend=0051C284
size=3, capacity=3
  element 0: 1
  element 1: 2
  element 2: 3

Myfirst=0051C290, Mylast=0051C2A0, Myend=0051C2A0
size=4, capacity=4
  element 0: 1
  element 1: 2
  element 2: 3
  element 3: 4

Myfirst=0051B180, Mylast=0051B190, Myend=0051B198
size=4, capacity=6
  element 0: 1
  element 1: 2
  element 2: 3
  element 3: 4

Myfirst=0051B180, Mylast=0051B194, Myend=0051B198
size=5, capacity=6
  element 0: 1
  element 1: 2
  element 2: 3
  element 3: 4
  element 4: 5

Myfirst=0051B180, Mylast=0051B198, Myend=0051B198
size=6, capacity=6
  element 0: 1
  element 1: 2
  element 2: 3
```

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As it can be seen, there is no allocated buffer when main() starts. After the first push_back() call, a buffer is allocated. And then, after each push_back() call, both array size and buffer size (capacity) are increased. But the buffer address changes as well, because push_back() reallocates the buffer in the heap each time. It is costly operation, that's why it is very important to predict the size of the array in the future and reserve enough space for it with the .reserve() method.

The last number is garbage: there are no array elements at this point, so a random number is printed. This illustrates the fact that operator[] of std::vector does not check of the index is in the array's bounds. The slower .at() method, however, does this checking and throws an std::out_of_range exception in case of error.

Let's see the code:

```assembly
Listing 3.113: MSVC 2012 /GS- /Ob1
```

```assembly
SG52650 DB 'd', 0A, 00H
SG52651 DB 'd', 0A, 00H
	.this$ = -4 ; size = 4
	.Pos$ = 8 ; size = 4

at?$vector@HV$allocator@H@std@@std@QAEAAHI@Z PROC ; std::vector<int,std::allocator<int> \
˓→.at, COMDAT
	.this$ = ecx
    push ebp
    mov ebp, esp
    push ecx
    mov DWORD PTR _this$[ebp], ecx
    mov eax, DWORD PTR _this$[ebp]
    mov ecx, DWORD PTR _this$[ebp]
    mov edx, DWORD PTR [eax+4]
    sar edx, 2
    cmp edx, DWORD PTR __Pos$[ebp]
    ja SHORT $LN1@at
    push OFFSET ??_C@_0BM@NMJKDPPO@invalid?5vector?$DMT?$DO?5subscript?$AA@
call DWORD PTR __imp_?_Xout_of_range@std@@YAXPBD@Z

$LN1@at:
    mov eax, DWORD PTR _this$[ebp]
    mov ecx, DWORD PTR [eax]
    mov edx, DWORD PTR __Pos$[ebp]
    lea eax, DWORD PTR [ecx+edx*4]

$LN3@at:
    mov esp, ebp
    pop ebp
    ret 4

at?$vector@HV$allocator@H@std@@std@QAEAAHI@Z ENDP ; std::vector<int,std::allocator<int> \
˓→.at

c$ = -36 ; size = 12
T1 = -24 ; size = 4
T2 = -20 ; size = 4
T3 = -16 ; size = 4
T4 = -12 ; size = 4
T5 = -8 ; size = 4
T6 = -4 ; size = 4

_main PROC
    push ebp
    mov ebp, esp
    sub esp, 36
    mov DWORD PTR _c$[ebp], 0 ; Myfirst
    mov DWORD PTR _c$[ebp+4], 0 ; Mylast
    mov DWORD PTR _c$[ebp+8], 0 ; Myend
    lea eax, DWORD PTR _c$[ebp]
    push eax
call ?dump@YAXPAUvector_of_ints@@@Z ; dump
```
C++

```c
add esp, 4
mov DWORD PTR $T6[ebp], 1
lea ecx, DWORD PTR $T6[ebp]
push ecx
lea ecx, DWORD PTR _c$[ebp]
call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::allocator<int> >::push_back
lea edx, DWORD PTR _c$[ebp]
push edx
call ?dump@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
mov DWORD PTR $T5[ebp], 2
lea eax, DWORD PTR $T5[ebp]
push eax
lea ecx, DWORD PTR _c$[ebp]
call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::allocator<int> >::push_back
lea ecx, DWORD PTR _c$[ebp]
push ecx
call ?dump@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
mov DWORD PTR $T4[ebp], 3
lea edx, DWORD PTR $T4[ebp]
push edx
lea ecx, DWORD PTR _c$[ebp]
call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::allocator<int> >::push_back
lea eax, DWORD PTR _c$[ebp]
push eax
call ?dump@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
mov DWORD PTR $T3[ebp], 4
lea ecx, DWORD PTR $T3[ebp]
push ecx
lea ecx, DWORD PTR _c$[ebp]
call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::allocator<int> >::push_back
lea edx, DWORD PTR _c$[ebp]
push edx
call ?dump@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
push 5
lea ecx, DWORD PTR _c$[ebp]
call ?reserve@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::allocator<int> >::reserve
lea eax, DWORD PTR _c$[ebp]
push eax
call ?dump@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
mov DWORD PTR $T2[ebp], 5
lea ecx, DWORD PTR $T2[ebp]
push ecx
lea ecx, DWORD PTR _c$[ebp]
call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::allocator<int> >::push_back
lea edx, DWORD PTR _c$[ebp]
push edx
call ?dump@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
mov DWORD PTR $T1[ebp], 6
lea eax, DWORD PTR $T1[ebp]
push eax
lea ecx, DWORD PTR _c$[ebp]
call ?push_back@?$vector@HV?$allocator@H@std@@@std@@QAEX$$QAH@Z ; std::vector<int,std::allocator<int> >::push_back
lea ecx, DWORD PTR _c$[ebp]
push ecx
call ?dump@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
push 5
```
We see how the `.at()` method checks the bounds and throws an exception in case of error. The number that the last `printf()` call prints is just taken from the memory, without any checks.

One may ask, why not use the variables like “size” and “capacity”, like it was done in `std::string`. Supposedly, this was done for faster bounds checking.

The code GCC generates is in general almost the same, but the `.at()` method is inlined:

```
Listing 3.114: GCC 4.8.1 -fno-inline-small-functions -O1
main proc near
push ebp
mov ebp, esp
push edi
push esi
push ebx
and esp, 0FFFFFFF0h
sub esp, 20h
mov dword ptr [esp+14h], 0
mov dword ptr [esp+18h], 0
mov dword ptr [esp+1Ch], 0
lea eax, [esp+14h]
mov [esp], eax
call Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
mov dword ptr [esp+10h], 1
lea eax, [esp+10h]
mov [esp+4], eax
lea eax, [esp+14h]
mov [esp], eax
call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(int const&)
lea eax, [esp+14h]
mov [esp], eax
call Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
mov dword ptr [esp+10h], 2
lea eax, [esp+10h]
mov [esp+4], eax
lea eax, [esp+14h]
mov [esp], eax
call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(int const&)
lea eax, [esp+14h]
mov [esp], eax
call Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
mov dword ptr [esp+10h], 3
lea eax, [esp+10h]
```
mov [esp+4], eax
lea eax, [esp+14h]
mov [esp], eax
call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(
  int const&
lea eax, [esp+14h]
mov [esp], eax
call Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
mov dword ptr [esp+10h], 4
lea eax, [esp+10h]
mov [esp+4], eax
lea eax, [esp+14h]
mov [esp], eax
call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(
  int const&
lea eax, [esp+14h]
mov [esp], eax
call Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
mov ebx, [esp+14h]
mov eax, [esp+1Ch]
sub eax, ebx
cmp eax, 17h
ja short loc_80001CF
mov edi, [esp+18h]
sub edi, ebx
sar edi, 2
mov dword ptr [esp], 18h
call _Znwj ; operator new(uint)
mov esi, eax
test edi, edi
jz short loc_80001AD
lea eax, ds:0[edi*4]
mov [esp+8], eax ; n
mov [esp+4], ebx ; src
mov [esp], esi ; dest
call memmove

loc_80001AD: ; CODE XREF: main+F8
mov eax, [esp+14h]
test eax, eax
jz short loc_80001BD
mov [esp], eax ; void *
call _ZdlPv ; operator delete(void *)

loc_80001BD: ; CODE XREF: main+117
mov [esp+14h], esi
lea eax, [esi+edi*4]
mov [esp+18h], eax
add esi, 18h
mov [esp+1Ch], esi

loc_80001CF: ; CODE XREF: main+DD
lea eax, [esp+14h]
mov [esp], eax
call Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
mov dword ptr [esp+10h], 5
lea eax, [esp+10h]
mov [esp+4], eax
lea eax, [esp+14h]
mov [esp], eax
call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(
  int const&
lea eax, [esp+14h]
mov [esp], eax
call Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
mov dword ptr [esp+10h], 6
lea eax, [esp+10h]
mov [esp+4], eax
lea eax, [esp+14h]
mov [esp], eax
3.18. C++

```c
3.18. C++
call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int,std::allocator<int>>::push_back(
\ int const&)
leax, [esp+14h]
mov[Rsp], eax
call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
mov[eax], [esp+14h]
mov edx, [esp+18h]
sub edx, eax
cmp edx, 17h
ja short loc_8000246
mov dword ptr [esp], offset aVector_m_range ; "vector:: M_range_check"
call _ZSt20__throw_out_of_rangePKc ; std::__throw_out_of_range(char const*)
loc_8000246: ; CODE XREF: main+19C
  mov[eax], [esp+14h]
  mov [esp+8], eax
  mov dword ptr [esp+4], offset aD ; "%d\n"
  mov dword ptr [esp], 1
call _printf_chk
  mov[eax], [esp+14h]
  mov[eax], [esp+20h]
  mov [esp+8], eax
  mov dword ptr [esp+4], offset aD ; "%d\n"
  mov dword ptr [esp], 1
call _printf_chk
  mov[eax], [esp+14h]
test eax, eax
  jz short loc_80002AC
  mov[esp], eax ; void *
call _ZdlPv ; operator delete(void *)
jmp short loc_80002AC

loc_80002A4: ; CODE XREF: main+1FE
  mov [esp], ebx
  call _Unwind_Resume
loc_80002AC: ; CODE XREF: main+1EA
  ; main+1F4
  mov[eax], 0
  leax, [ebp-0Ch]
pop ebx
pop esi
pop edi
pop ebp
loc_80002BB: ; DATA XREF: .eh_frame:08000510
  ; .eh_frame:080005BC
  retn
main endp
```

 réserve() is inlined as well. It calls new() if the buffer is too small for the new size, calls memmove() to copy the contents of the buffer, and calls delete() to free the old buffer.

Let's also see what the compiled program outputs if compiled with GCC:

```
_Myfirst=0x(nil), _Mylast=0x(nil), _Myend=0x(nil)
size=0, capacity=0
_Myfirst=0x8257008, _Mylast=0x825700c, _Myend=0x825700c
size=1, capacity=1
element 0: 1
_Myfirst=0x8257018, _Mylast=0x8257020, _Myend=0x8257020
size=2, capacity=2
```

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We can spot that the buffer size grows in a different way that in MSVC.
Simple experimentation shows that in MSVC’s implementation the buffer grows by ~50% each time it needs to be enlarged, while GCC’s code enlarges it by 100% each time, i.e., doubles it.

**std::map and std::set**

The binary tree is another fundamental data structure.
As its name states, this is a tree where each node has at most 2 links to other nodes. Each node has key and/or value: `std::set` provides only key at each node, `std::map` provides both key and value at each node.

Binary trees are usually the structure used in the implementation of “dictionaries” of key-values (AKA “associative arrays”).

There are at least three important properties that a binary trees has:
- All keys are always stored in sorted form.
- Keys of any types can be stored easily. Binary tree algorithms are unaware of the key’s type, only a key comparison function is required.
- Finding a specific key is relatively fast in comparison with lists and arrays.

Here is a very simple example: let’s store these numbers in a binary tree: 0, 1, 2, 3, 5, 6, 9, 10, 11, 12, 20, 99, 100, 101, 107, 1001, 1010.
All keys that are smaller than the node key's value are stored on the left side.
All keys that are bigger than the node key's value are stored on the right side.

Hence, the lookup algorithm is straightforward: if the value that you are looking for is smaller than the current node's key value: move left, if it is bigger: move right, stop if the value required is equal to the node key's value.

That is why the searching algorithm may search for numbers, text strings, etc., as long as a key comparison function is provided.

All keys have unique values.

Having that, one needs $\approx \log_2 n$ steps in order to find a key in a balanced binary tree with $n$ keys. This implies that $\approx 10$ steps are needed $\approx 1000$ keys, or $\approx 13$ steps for $\approx 10000$ keys.

Not bad, but the tree has always to be balanced for this: i.e., the keys has to be distributed evenly on all levels. The insertion and removal operations do some maintenance to keep the tree in a balanced state.

There are several popular balancing algorithms available, including the AVL tree and the red-black tree. The latter extends each node with a “color” value to simplify the balancing process, hence, each node may be “red” or “black”.

Both GCC's and MSVC's std::map and std::set template implementations use red-black trees.

std::set has only keys. std::map is the “extended” version of std::set: it also has a value at each node.

**MSVC**

```cpp
#include <map>
#include <set>
#include <string>
#include <iostream>

// Structure is not packed! Each field occupies 4 bytes.
struct tree_node
{
    struct tree_node *Left;
    struct tree_node *Parent;
    struct tree_node *Right;
    char Color; // 0 - Red, 1 - Black
    char Isnil;
    //std::pair Myval;
    unsigned int first; // called Myval in std::set
    const char *second; // not present in std::set
};

struct tree_struct
{
    struct tree_node *Myhead;
    size_t Mysize;
};
```
3.18. C++

```cpp
void dump_tree_node (struct tree_node *n, bool is_set, bool traverse) {
    printf ("ptr=0x%p Left=0x%p Parent=0x%p Right=0x%p Color=%d Isnil=%d\n",
            n, n->Left, n->Parent, n->Right, n->Color, n->Isnil);
    if (n->Isnil==0) {
        if (is_set)
            printf ("first=%d\n", n->first);
        else
            printf ("first=%d second=[%s]\n", n->first, n->second);
    }
    if (traverse) {
        if (n->Isnil==1)
            dump_tree_node (n->Parent, is_set, true);
        else {
            if (n->Left->Isnil==0)
                dump_tree_node (n->Left, is_set, true);
            if (n->Right->Isnil==0)
                dump_tree_node (n->Right, is_set, true);
        }
    }
}

const char* ALOT_OF_TABS="\t\t\t\t\t\t\t\t\t\t\t"

void dump_as_tree (int tabs, struct tree_node *n, bool is_set) {
    if (is_set)
        printf ("%d\n", n->first);
    else
        printf ("%d [%s]\n", n->first, n->second);
    if (n->Left->Isnil==0) {
        printf (%.*sL------", tabs, ALOT_OF_TABS);
        dump_as_tree (tabs+1, n->Left, is_set);
    }
    if (n->Right->Isnil==0) {
        printf (%.*sR------", tabs, ALOT_OF_TABS);
        dump_as_tree (tabs+1, n->Right, is_set);
    }
}

void dump_map_and_set(struct tree_struct *m, bool is_set) {
    printf ("ptr=0x%p, Myhead=0x%p, Mysize=%d\n", m, m->Myhead, m->Mysize);
    dump_tree_node (m->Myhead, is_set, true);
    printf ("As a tree:\n");
    printf ("root----");
    dump_as_tree (1, m->Myhead->Parent, is_set);
}

int main() {
    // map
    std::map<int, const char*> m;
    m[10]="ten";
    m[20]="twenty";
    m[3]="three";
    m[101]="one hundred one";
    m[100]="one hundred";
    m[12]="twelve";
    m[107]="one hundred seven";
    m[0]="zero";
```
3.18. C++

```c++
m[1]="one";
m[6]="six";
m[9]="ninety-nine";
m[5]="five";
m[11]="eleven";
m[1001]="one thousand one";
m[1010]="one thousand ten";
m[2]="two";
m[9]="nine";
printf ("dumping m as map:");
dump_map_and_set ((struct tree_struct *)(void*)&m, false);

std::map<int, const char*>::iterator it1=m.begin();
printf ("m.begin():");
dump_tree_node ((struct tree_node *)(void**)&it1, false, false);
it1=m.end();
printf ("m.end():");
dump_tree_node ((struct tree_node *)(void**)&it1, false, false);

// set
std::set<int> s;
s.insert(123);
s.insert(456);
s.insert(11);
s.insert(12);
s.insert(100);
s.insert(1001);
printf ("dumping s as set:");
dump_map_and_set ((struct tree_struct *)(void*)&s, true);
std::set<int>::iterator it2=s.begin();
printf ("s.begin():");
dump_tree_node ((struct tree_node *)(void**)&it2, true, false);
it2=s.end();
printf ("s.end():");
dump_tree_node ((struct tree_node *)(void**)&it2, true, false);
```

Listing 3.115: MSVC 2012

```c++
dumping m as map:
pTR=0x0020FE04, Myhead=0x005BB3A0, Mysize=17
ptr=0x005BB3A0 Left=0x005BB4A0 Parent=0x005BB3C0 Right=0x005BB500 Color=1 Isnil=1
ptr=0x005BB3C0 Left=0x005BB4C0 Parent=0x005BB3A0 Right=0x005BB440 Color=1 Isnil=0
first=10 second=[ten]
ptr=0x005BB4C0 Left=0x005BB4A0 Parent=0x005BB3C0 Right=0x005BB520 Color=1 Isnil=0
first=1 second=[one]
ptr=0x005BB4A0 Left=0x005BB3A0 Parent=0x005BB4C0 Right=0x005BB3A0 Color=1 Isnil=0
first=0 second=[zero]
ptr=0x005BB520 Left=0x005BB400 Parent=0x005BB4C0 Right=0x005BB4E0 Color=0 Isnil=0
first=5 second=[five]
ptr=0x005BB400 Left=0x005BB5A0 Parent=0x005BB520 Right=0x005BB3A0 Color=1 Isnil=0
first=3 second=[three]
ptr=0x005BB5A0 Left=0x005BB3A0 Parent=0x005BB400 Right=0x005BB3A0 Color=0 Isnil=0
first=2 second=[two]
ptr=0x005BB4E0 Left=0x005BB3A0 Parent=0x005BB520 Right=0x005BB5C0 Color=1 Isnil=0
first=6 second=[six]
ptr=0x005BB5C0 Left=0x005BB3A0 Parent=0x005BB4E0 Right=0x005BB3A0 Color=0 Isnil=0
first=9 second=[nine]
ptr=0x005BB440 Left=0x005BB3E0 Parent=0x005BB3C0 Right=0x005BB480 Color=1 Isnil=0
first=100 second=[one hundred]
ptr=0x005BB3E0 Left=0x005BB460 Parent=0x005BB440 Right=0x005BB500 Color=0 Isnil=0
first=20 second=[twenty]
ptr=0x005BB460 Left=0x005BB540 Parent=0x005BB3E0 Right=0x005BB3A0 Color=1 Isnil=0
first=12 second=[twelve]
ptr=0x005BB540 Left=0x005BB3A0 Parent=0x005BB460 Right=0x005BB3A0 Color=0 Isnil=0
first=11 second=[eleven]
ptr=0x005BB500 Left=0x005BB3A0 Parent=0x005BB3E0 Right=0x005BB3A0 Color=1 Isnil=0
first=99 second=[ninety-nine]
ptr=0x005BB420 Left=0x005BB400 Parent=0x005BB440 Right=0x005BB560 Color=0 Isnil=0
```
As a tree:

root----10 [ten]
  L-------0 [zero]
  R-------5 [five]
    L-------3 [three]
    R-------6 [six]
  R-------100 [one hundred]
    L-------20 [twenty]
    L-------12 [twelve]
    L-------11 [eleven]
    R-------99 [ninety-nine]
    R-------107 [one hundred seven]
    L-------101 [one hundred one]
    R-------1001 [one thousand one]
    R-------1010 [one thousand ten]

As for `std::map`, `first` and `second` can be viewed as a single value of type `std::pair`. `std::set` has only one value at this address in the structure instead.

The current size of the tree is always present, as in the case of the implementation of `std::list` in MSVC (3.18.4 on page 571).

As in the case of `std::list`, the iterators are just pointers to nodes. The `.begin()` iterator points to the minimal key.

That pointer is not stored anywhere (as in lists), the minimal key of the tree is looked up every time.
3.18. C++

operator-- and operator++ move the current node pointer to the predecessor or successor respectively, i.e., the nodes which have the previous or next key.

The algorithms for all these operations are explained in [Cormen, Thomas H. and Leiserson, Charles E. and Rivest, Ronald L. and Stein, Clifford, \textit{Introduction to Algorithms, Third Edition}, (2009)].

The .end() iterator points to the dummy node, it has 1 in Isnil, which implies that the node has no key and/or value. It can be viewed as a “landing zone” in HDD\textsuperscript{33} and often called \textit{sentinel} [see N. Wirth, \textit{Algorithms and Data Structures}, 1985]\textsuperscript{34}.

The “parent” field of the dummy node points to the root node, which serves as a vertex of the tree and contains information.

**GCC**

```c
#include <stdio.h>
#include <map>
#include <set>
#include <string>
#include <iostream>

struct map_pair
{
    int key;
    const char *value;
};

struct tree_node
{
    int M_color; // 0 - Red, 1 - Black
    struct tree_node *M_parent;
    struct tree_node *M_left;
    struct tree_node *M_right;
};

struct tree_struct
{
    int M_key_compare;
    struct tree_node M_header;
    size_t M_node_count;
};

void dump_tree_node (struct tree_node *n, bool is_set, bool traverse, bool dump_keys_and_values)
{
    printf ("ptr=0x%p M_left=0x%p M_parent=0x%p M_right=0x%p M_color=%d\n",
            n, n->M_left, n->M_parent, n->M_right, n->M_color);
    void *point_after_struct=((char*)n)+sizeof(struct tree_node);
    if (dump_keys_and_values)
    {
        if (is_set)
            printf ("key=%d\n", *(int*)point_after_struct);
        else
        {
            struct map_pair *p=(struct map_pair *)point_after_struct;
            printf ("key=%d value=[%s]\n", p->key, p->value);
        }
    }
    if (traverse==false)
        return;
    if (n->M_left)
        dump_tree_node (n->M_left, is_set, traverse, dump_keys_and_values);
    if (n->M_right)
        dump_tree_node (n->M_right, is_set, traverse, dump_keys_and_values);
}
```

\textsuperscript{33}Hard Disk Drive
\textsuperscript{34}http://www.ethoberon.ethz.ch/WirthPubl/AD.pdf
```c++
if (n->M_right)
    dump_tree_node (n->M_right, is_set, traverse, dump_keys_and_values);
};

const char* ALOT_OF_TABS="\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\\t\n```
```c++

```
### 3.18. C++

R-------100 [one hundred]
L-------20 [twenty]
  L-------12 [twelve]
  L-------11 [eleven]
R-------99 [ninety-nine]
R-------107 [one hundred seven]
L-------101 [one hundred one]
R-------1001 [one thousand one]
R-------1010 [one thousand ten]

```
m.begin():
ptr=0x007A4BE0 M_left=0x00000000 M_parent=0x007A4C00 M_right=0x00000000 M_color=1
key=0 value=[zero]
m.end():
ptr=0x0028FE40 M_left=0x007A4BE0 M_parent=0x007A4988 M_right=0x007A4CC0 M_color=0
```

### GCC’s implementation is very similar

```
The only difference is the absence of the IsnIL field, so the structure occupies slightly less space in memory than its implementation in MSVC.
```

The dummy node is also used as a place to point the .end() iterator also has no key and/or value.

### Rebalancing demo (GCC)

Here is also a demo showing us how a tree is rebalanced after some insertions.

```
Listing 3.117: GCC

#include <stdio.h>
#include <map>
#include <set>
#include <string>
#include <iostream>

struct map_pair
{
    int key;
    const char *value;
};

struct tree_node
{...}
```

[^17084]: [http://go.yurichev.com/17084]
```
int M_color; // 0 - Red, 1 - Black
struct tree_node *M_parent;
struct tree_node *M_left;
struct tree_node *M_right;
};

struct tree_struct
{
  int M_key_compare;
  struct tree_node M_header;
  size_t M_node_count;
};

const char* ALOT_OF_TABS="											";

void dump_as_tree (int tabs, struct tree_node *n)
{
  void *point_after_struct=((char*)n)+sizeof(struct tree_node);
  printf("%d
", *(int*)point_after_struct);
  if (n->M_left)
    {
      printf(".%sL-------", tabs, ALOT_OF_TABS);
      dump_as_tree (tabs+1, n->M_left);
    }
  if (n->M_right)
    {
      printf(".%sR-------", tabs, ALOT_OF_TABS);
      dump_as_tree (tabs+1, n->M_right);
    }
};

void dump_map_and_set(struct tree_struct *m)
{
  printf("root----");
  dump_as_tree (1, m->M_header.M_parent);
};

int main()
{
  std::set<int> s;
  s.insert(123);
  s.insert(456);
  printf("123, 456 has been inserted\n");
  dump_map_and_set ((struct tree_struct *) (void *)&s);
  s.insert(11);
  s.insert(12);
  printf("\n11, 12 has been inserted\n");
  dump_map_and_set ((struct tree_struct *) (void *)&s);
  s.insert(100);
  s.insert(1001);
  printf("\n100, 1001 has been inserted\n");
  dump_map_and_set ((struct tree_struct *) (void *)&s);
  s.insert(667);
  s.insert(1);
  s.insert(4);
  s.insert(7);
  printf("\n667, 1, 4, 7 has been inserted\n");
  dump_map_and_set ((struct tree_struct *) (void *)&s);
  printf("\n");
};
```
3.18.5 Memory

Sometimes you may hear from C++ programmers “allocate memory on stack” and/or “allocate memory on heap”.

Allocating object on stack:

```cpp
void f()
{
    ...
    Class o=Class(...);
    ...
}
```

The memory for object (or structure) is allocated in stack, using simple SP shift. The memory is deallocated upon function exit, or, more precisely, at the end of scope—SP is returning to its state (same as at the start of function) and destructor of Class is called. In the same manner, memory for allocated structure in C is deallocated upon function exit.

Allocating object on heap:

```cpp
void f1()
{
    ...
    Class *o=new Class(...);
    ...
}
void f2()
{
    ...
    delete o;
    ...
}
```
This is the same as allocating memory for a structure using *malloc()* call. In fact, *new* in C++ is wrapper for *malloc()* and *delete* is wrapper for *free()* . Since memory block has been allocated in *heap*, it must be deallocated explicitly, using *delete*. Class destructor will be automatically called right before that moment.

Which method is better? Allocating on stack is very fast, and good for small, short-lived object, which will be used only in the current function.

Allocating on heap is slower, and better for long-lived object, which will be used across many functions. Also, objects allocated in heap are prone to memory leakage, because they must to be freed explicitly, but one can forget about it.

Anyway, this is matter of taste.

### 3.19 Negative array indices

It’s possible to address the space before an array by supplying a negative index, e.g., *array[−1]* .

#### 3.19.1 Addressing string from the end

Python PL allows to address arrays and strings from the end. For example, *string[−1]* returns the last character, *string[−2]* returns penultimate, etc. Hard to believe, but this is also possible in C/C++:

```c
#include <string.h>
#include <stdio.h>

int main()
{
    char *s="Hello, world!";
    char *s_end=s+strlen(s);

    printf ("last character: %c\n", s_end[−1]);
    printf ("penultimate character: %c\n", s_end[−2]);
}
```

It works, but *s_end* must always has an address of terminating zero byte at the end of *s* string. If *s* string’s size get changed, *s_end* must be updated.

The trick is dubious, but again, this is a demonstration of negative indices.

#### 3.19.2 Addressing some kind of block from the end

Let’s first recall why stack grows backwards ( 1.7.1 on page 30 ). There is some kind of block in memory and you want to store both heap and stack there, and you are not sure, how big they both can grow during runtime.

You can set a heap pointer to the beginning of the block, then you can set a stack pointer to the end of the block (*heap* + *size_of_block*), and then you can address *nth* element of stack like *stack[−n]*. For example, *stack[−1]* for 1st element, *stack[−2]* for 2nd, etc.

This will work in the same fashion, as our trick of addressing string from the end.

You can easily check if the structures has not begun to overlap each other: just be sure that address of the last element in heap is below the address of the last element of stack.

Unfortunately, *−0* as index will not work, since two’s complement way of representing negative numbers ( 2.2 on page 452 ) don’t allow negative zero, so it cannot be distinguished from positive zero.

This method is also mentioned in “Transaction processing”, Jim Gray, 1993, “The Tuple-Oriented File System” chapter, p. 755.
3.19. NEGATIVE ARRAY INDICES

3.19.3 Arrays started at 1

Fortran and Mathematica defined first element of array as 1th, probably because this is tradition in mathematics. Other PLs like C/C++ defined it as 0th. Which is better? Edsger W. Dijkstra argued that latter is better 36.

But programmers may still have a habit after Fortran, so using this little trick, it’s possible to address the first element in C/C++ using index 1:

```
#include <stdio.h>

int main()
{
    int random_value=0x11223344;
    unsigned char array[10];
    int i;
    unsigned char *fakearray=&array[-1];

    for (i=0; i<10; i++)
        array[i]=i;

    printf ("first element %d\n", fakearray[1]);
    printf ("second element %d\n", fakearray[2]);
    printf ("last element %d\n", fakearray[10]);

    printf ("array[-1]=%02X, array[-2]=%02X, array[-3]=%02X, array[-4]=%02X\n",
            array[-1],
            array[-2],
            array[-3],
            array[-4]);
}
```

Listing 3.119: Non-optimizing MSVC 2010

36See https://www.cs.utexas.edu/users/EWD/transcriptions/EWD08xx/EWD831.html
### NEGATIVE ARRAY INDICES

3.19. NEGATIVEARRAYINDICES

```assembly
35      mov    ecx, DWORD PTR fakearray$[ebp]
36        ; ecx=address of fakearray[0], ecx+1 is fakearray[1] or array[0]
37      movzx   edx, BYTE PTR [ecx+1]
38      push   edx
39      push OFFSET $SG2751 ; 'first element %d'
40      call _printf
41      add esp, 8
42      mov eax, DWORD PTR fakearray$[ebp]
43        ; eax=address of fakearray[0], eax+2 is fakearray[2] or array[1]
44      movzx ecx, BYTE PTR [eax+2]
45      push ecx
46      push OFFSET $SG2752 ; 'second element %d'
47      call _printf
48      add esp, 8
49      mov edx, DWORD PTR fakearray$[ebp]
50        ; edx=address of fakearray[0], edx+10 is fakearray[10] or array[9]
51      movzx eax, BYTE PTR [edx+10]
52      push eax
53      push OFFSET $SG2753 ; 'last element %d'
54      call _printf
55      add esp, 8
56      lea ecx, DWORD PTR array$[ebp]
57      movzx edx, BYTE PTR [ecx-4]
58      push edx
59      lea eax, DWORD PTR array$[ebp]
60      movzx ecx, BYTE PTR [eax-3]
61      push ecx
62      lea edx, DWORD PTR array$[ebp]
63      movzx eax, BYTE PTR [edx-2]
64      push eax
65      lea ecx, DWORD PTR array$[ebp]
66      movzx edx, BYTE PTR [ecx-1]
67      push edx
68      push OFFSET $SG2754 ; 'array[-1]=%02X, array[-2]=%02X, array[-3]=%02X, array[-4]=%02X'
69      call _printf
70      add esp, 20
71      xor eax, eax
72      mov esp, ebp
73      pop ebp
74      ret 0
```

So we have `array[]` of ten elements, filled with `0...9` bytes.

Then we have the `fakearray[]` pointer, which points one byte before `array[]`.

`fakearray[1]` points exactly to `array[0]`. But we are still curious, what is there before `array[]`? We have added `random_value` before `array[]` and set it to `0x11223344`. The non-optimizing compiler allocated the variables in the order they were declared, so yes, the 32-bit `random_value` is right before the array.

We ran it, and:

- first element 0
- second element 1
- last element 9

Here is the stack fragment we will copypaste from OllyDbg’s stack window (with comments added by the author):

**CPU Stack**

<table>
<thead>
<tr>
<th>Address</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>001DFBCC</td>
<td>001DFBD3</td>
</tr>
<tr>
<td>001DFBD0</td>
<td>11223344</td>
</tr>
<tr>
<td>001DFBD4</td>
<td>03020100</td>
</tr>
<tr>
<td>001DFBD8</td>
<td>07860504</td>
</tr>
</tbody>
</table>

Listing 3.120: Non-optimizing MSVC 2010
3.20. PACKING 12-BIT VALUES INTO ARRAY

|001DFBDC | 00CB0908 ; random garbage + 2 last bytes of array[]
|001DFBE0 | 00000000 ; last i value after loop was finished
|001DFBE4 | 001DFC2C ; saved EBP value
|001DFBE8 \00CB129D ; Return Address

The pointer to the fake array[] (0x001DFBD3) is indeed the address of array[] in the stack (0x001DFBD4), but minus 1 byte.

It’s still very hackish and dubious trick. Doubtfully anyone should use it in production code, but as a demonstration, it fits perfectly here.

3.20 Packing 12-bit values into array using bit operations (x64, ARM/ARM64, MIPS)

(This part has been first appeared in my blog at 4-Sep-2015.)

3.20.1 Introduction

File Allocation Table (FAT) was a widely popular filesystem. Hard to believe, but it’s still used on flash drives, perhaps, for the reason of simplicity and compatibility. The FAT table itself is array of elements, each of which points to the next cluster number of a file (FAT supports files scattered across the whole disk). That implies that maximum of each element is maximum number of clusters on the disk. In MS-DOS era, most hard disks has FAT16 filesystem, because cluster number could be packed into 16-bit value. Hard disks then become cheaper, and FAT32 emerged, where 32-bit value was allocated for cluster number. But there were also a times, when floppy diskettes were not that cheap and has no much space, so FAT12 were used on them, for the reason of packing all filesystem structures as tight as possible.

So the FAT table in FAT12 filesystem is an array where each two subsequent 12-bit elements are stored into 3 bytes (triplet). Here is how 6 12-bit values (AAA, BBB, CCC, DDD, EEE and FFF) are packed into 9 bytes:

```
+0 +1 +2 +3 +4 +5 +6 +7 +8
|AA|AB|BB|CC|CD|DD|EE|EF|FF|...
```

Pushing values into array and pulling them back can be good example of bit twiddling operations (in both C/C++ and low-level machine code), so that’s why I’ll use FAT12 as an example here.

3.20.2 Data structure

We can quickly observe that each byte triplet will store 2 12-bit values: the first one is located at the left side, second one is at right:

```
+0 +1 +2
|11|12|22|...
```

We will pack nibbles (4 bit chunks) in the following way (1 - highest nibble, 3 - lowest):

(Even)

```
+0 +1 +2
|12|3.|2|...
```

(Odd)

```
+0 +1 +2
|.1|23|...
```
3.20. PACKING 12-BIT VALUES INTO ARRAY

3.20.3 The algorithm

So the algorithm can be as follows: if the element’s index is even, put it at left side, if the index is odd, place it at right side. The middle byte: if the element’s index is even, place part of it in high 4 bits, if it’s odd, place its part in low 4 bits. But first, find the right triplet, this is easy: $\frac{\text{index}}{2}$. Finding the address of right byte in array of bytes is also easy: $\frac{\text{index}}{2} \cdot 3$ or $\frac{\text{index}}{2} \cdot 2$ or just $\text{index} \cdot 1.5$.

Pulling values from array: if index is even, get leftmost and middle bytes and combine its parts. If index is odd, get middle and rightmost bytes and combine them. Do not forget to isolate unneeded bits in middle byte.

Pushing values is almost the same, but be careful not to overwrite some other’s bits in the middle byte, correcting only yours.

3.20.4 The C/C++ code

```c
#include <stdio.h>
#include <stdint.h>
#include <assert.h>

#define ARRAY_SIZE (0x1000/2*3)
uint8_t array[ARRAY_SIZE]; // big enough array of triplets

unsigned int get_from_array (unsigned int idx)
{
    // find right triple in array:
    int triple=(idx>>1);
    int array_idx=triple*3;
    //assert (array_idx<ARRAY_SIZE);
    if (idx&1)
    {
        // this is odd element
        // compose value using middle and rightmost bytes:
        return ((array[array_idx+1]&0xF) << 8)|array[array_idx+2];
    }
    else
    {
        // this is even element
        // compose value using rightmost and middle bytes:
        return array[array_idx]<<4 | ((array[array_idx+1]>>4)&0xF);
    }
}

void put_to_array (unsigned int idx, unsigned int val)
{
    //assert (val<=0xFFF);
    // find right triple in array:
    int triple=(idx>>1);
    int array_idx=triple*3;
    //assert (array_idx<ARRAY_SIZE);
    if (idx&1)
    {
        // this is odd element
        // put value into middle and rightmost bytes:
        // decompose value to be stored:
        uint8_t val_lowest_byte=val&0xFF; // isolate lowest 8 bits
        uint8_t val_highest_nibble=val>>8; // no need to apply &0xF, we already know \$
        \text{\textbackslash}\text{\textbackslash}$ the val<=0xFFF
        // clear low 4 bits in the middle byte:
        array[array_idx+1]=array[array_idx+1]&0xF0;
    }
    else
    {
        // this is even element
        // put value into rightmost and middle bytes:
        // decompose value to be stored:
        uint8_t val_lowest_byte=val&0xFF; // isolate lowest 8 bits
        uint8_t val_highest_nibble=val>>8; // no need to apply \&0xF, we already know \$
        \text{\textbackslash}\text{\textbackslash}$ the val<=0xFFF
        // clear low 4 bits in the middle byte:
        array[array_idx+1]=array[array_idx+1]&0xF0;
    }
}
```

3.20. PACKING 12-BIT VALUES INTO ARRAY

    array[array_idx+1]=array[array_idx+1]|val_highest_nibble;
array[array_idx+2]=val_lowest_byte;

} else
{
    // this is even element
    // put value into leftmost and middle bytes:

    // decompose value to be stored:
uint8_t val_highest_byte=val>>4;
uint8_t val_lowest_nibble=val&0xF;

array[array_idx]=val_highest_byte;

// clear high 4 bits in the middle byte:
array[array_idx+1]=array[array_idx+1]&0xF;
array[array_idx+1]=array[array_idx+1]|val_lowest_nibble<<4;
}

int main()
{
    int i;

    // test
    for (i=0; i<0x1000; i++)
    {
        put_to_array(i, i);
    }

    for (i=0; i<0x1000; i++)
    {
        assert(get_from_array(i)==i);
    }

    // put_to_array(0x1000, 1); // will fail due to assert()

    // print triples:
    for (int i=0;i<0x1000/2;i++)
    {
        printf("0x%02X%02X%02X\n",array[i*3],array[i*3+1],array[i*3+2]);
    }
}

During test, all 12-bit elements are filled with values in 0..0xFFF range. And here is a dump of all triplets, each line has 3 bytes:

| 0x000001 0x002003 0x004005 |
| 0x006007 0x008009 0x00A00B |
| 0x00C00D 0x00E00F 0x010011 |
| 0x012013 0x014015 ... |
| 0xFECDF 0xFEECEEFF 0xFFF0FF1 |
| 0xFFF2FF3 0xFFF4FF5 0xFFF6FF7 |
| 0xFFF8FF9 0xFFFAFFB 0xFFFCCFD |
| 0xFFFEEFF |

Here is also GDB byte-level output of 300 bytes (or 100 triplets) started at 512/2*3, i.e., it’s address where
3.20. PACKING 12-BIT VALUES INTO ARRAY

512th element (0x200) is beginning. I added square brackets in my text editor to show triplets explicitly. Take a notice at the middle bytes, where the last element is ended and the next is started. In other words, each middle byte has lowest 4 bits of even element and highest 4 bits of odd element.

(gdb) x/300xb array+512/2*3
0x601380 <array+768>: [ 0x20 0x02 0x01 ][ 0x20 0x22 0x03 ][ 0x20 0x42 0x601388 <array+776>: 0x05 ][ 0x20 0x62 0x07 ][ 0x20 0x82 0x09 ][ 0x20 0x601380 <array+784>: 0xa2 0x0b ][ 0x20 0xc2 0x0d ][ 0x20 0xe2 0x0f ][ 0x20 0x601388 <array+792>: 0x21 0x02 0x11 ][ 0x21 0x22 0x13 ][ 0x21 0x42 0x601390 <array+800>: 0x15 ][ 0x21 0x62 0x17 ][ 0x21 0x82 0x19 ][ 0x21 0x601390 <array+808>: 0xa2 0x1b ][ 0x21 0xc2 0x1d ][ 0x21 0xe2 0x1f ][ 0x21 0x601398 <array+816>: 0x22 0x02 0x21 ][ 0x22 0x22 0x23 ][ 0x22 0x42 0x6013a0 <array+824>: 0x15 ][ 0x22 0x62 0x27 ][ 0x22 0x82 0x29 ][ 0x22 0x6013a0 <array+832>: 0xa2 0x2b ][ 0x22 0xc2 0x2d ][ 0x22 0xe2 0x2f ][ 0x22 0x6013a8 <array+840>: 0x23 0x02 0x31 ][ 0x23 0x22 0x33 ][ 0x23 0x42 0x6013b0 <array+848>: 0x25 0x0b ][ 0x23 0xc2 0x3d ][ 0x23 0xe2 0x3f ][ 0x23 0x6013b8 <array+856>: 0x24 0x02 0x41 ][ 0x24 0x22 0x43 ][ 0x24 0x42 0x6013c0 <array+864>: 0x25 0x02 0x51 ][ 0x25 0x22 0x53 ][ 0x25 0x42 0x6013c8 <array+872>: 0x45 ][ 0x25 0x62 0x57 ][ 0x25 0x82 0x59 ][ 0x25 0x6013c8 <array+880>: 0xa2 0x5b ][ 0x25 0xc2 0x5d ][ 0x25 0xe2 0x5f ][ 0x25 0x6013d0 <array+888>: [ 0x26 0x02 0x61 ][ 0x26 0x22 0x63 ][ 0x26 0x42 0x6013d8 <array+896>: [ 0x27 0x02 0x71 ][ 0x27 0x22 0x73 ][ 0x27 0x42 0x6013e0 <array+904>: [ 0x28 0x02 0x81 ][ 0x28 0x22 0x83 ][ 0x28 0x42 0x6013e8 <array+912>: [ 0x29 0x02 0x91 ][ 0x29 0x22 0x93 ][ 0x29 0x42 0x6013f0 <array+920>: [ 0x2a 0x02 0xa1 ][ 0x2a 0x22 0xa3 ][ 0x2a 0x42 0x6013f8 <array+928>: [ 0x2b 0x02 0xb1 ][ 0x2b 0x22 0xb3 ][ 0x2b 0x42 0x601400 <array+936>: [ 0x2c 0x02 0xc1 ][ 0x2c 0x22 0xc3 ][ 0x2c 0x42 0x601408 <array+944>: [ 0x2d 0x02 0xd1 ][ 0x2d 0x22 0xd3 ][ 0x2d 0x42 0x601410 <array+952>: [ 0x2e 0x02 0xe1 ][ 0x2e 0x22 0xe3 ][ 0x2e 0x42 0x601418 <array+960>: [ 0x2f 0x02 0xf1 ][ 0x2f 0x22 0xf3 ][ 0x2f 0x42 0x601420 <array+968>: [ 0x30 0x02 0x10 ][ 0x30 0x22 0x12 ][ 0x30 0x42 0x601428 <array+976>: [ 0x31 0x02 0x20 ][ 0x31 0x22 0x22 ][ 0x31 0x42 0x601430 <array+984>: [ 0x32 0x02 0x30 ][ 0x32 0x22 0x32 ][ 0x32 0x42 0x601438 <array+992>: [ 0x33 0x02 0x40 ][ 0x33 0x22 0x42 ][ 0x33 0x42 0x601440 <array+1000>: [ 0x34 0x02 0x50 ][ 0x34 0x22 0x52 ][ 0x34 0x42 0x601448 <array+1008>: [ 0x35 0x02 0x60 ][ 0x35 0x22 0x62 ][ 0x35 0x42 0x601450 <array+1016>: [ 0x36 0x02 0x70 ][ 0x36 0x22 0x72 ][ 0x36 0x42 0x601458 <array+1024>: [ 0x37 0x02 0x80 ][ 0x37 0x22 0x82 ][ 0x37 0x42 0x601460 <array+1032>: [ 0x38 0x02 0x90 ][ 0x38 0x22 0x92 ][ 0x38 0x42 0x601468 <array+1040>: [ 0x39 0x02 0xa0 ][ 0x39 0x22 0xa2 ][ 0x39 0x42 0x601470 <array+1048>: [ 0x3a 0x02 0xb0 ][ 0x3a 0x22 0xb2 ][ 0x3a 0x42 0x601478 <array+1056>: [ 0x3b 0x02 0xc0 ][ 0x3b 0x22 0xc2 ][ 0x3b 0x42 0x601480 <array+1064>: [ 0x3c 0x02 0xd0 ][ 0x3c 0x22 0xd2 ][ 0x3c 0x42

3.20.5 How it works

Let array be a global buffer to make simpler access to it.

**Getter**

Let’s first start at the function getting values from the array, because it’s simpler. The method of finding triplet’s number is just division input index by 2, but we can do it just by shifting right by 1 bit. This is a very common way of dividing/multiplication by numbers in form of $2^n$.

I can demonstrate how it works. Let’s say, you want to divide 123 by 10. Just drop last digit (3, which is remainder of division) and 12 is left. Division by 2 is just dropping least significant bit. Dropping can be done by shifting right.

Now the functions must decide if the input index even (so 12-bit value is placed at the left) or odd (at the right). Simplest way to do so is to isolate lowest bit ($x$&1). If it’s zero, our value is even, otherwise it’s odd.

This fact can be illustrated easily, take a look at the lowest bit:

<table>
<thead>
<tr>
<th>decimal</th>
<th>binary</th>
<th>even/odd</th>
</tr>
</thead>
<tbody>
<tr>
<td>599</td>
<td>0b111100111</td>
<td>odd</td>
</tr>
</tbody>
</table>
Zero is also even number, it’s so in two’s complement system, where it’s located between two odd numbers (-1 and 1).

For math geeks, I could also say that even or odd sign is also remainder of division by 2. Division of a number by 2 is merely dropping the last bit, which is remainder of division. Well, we do not have to do shifts here, just isolate lowest bit.

If the element is odd, we take middle and right bytes (array[array_idx+1] and array[array_idx+2]). Lowest 4 bits of the middle byte is isolated. Right byte is taken as a whole. Now we have to combine these parts into 12-bit value. To do so, shift 4 bits from the middle byte by 8 bits left, so these 4 bits will be allocated right behind highest 8th bit of byte. Then, using OR operation, we just add these parts.

If the element is even, high 8 bits of 12-bit value is located in left byte, while lowest 4 bits are located in the high 4 bits of middle byte. We isolate highest 4 bits in the middle byte by shifting it 4 bits right and then applying AND operation, just to be sure that nothing is left there. We also take left byte and shift its value 4 bits left, because it has bits from 11th to 4th (inclusive, starting at 0), Using OR operation, we combine these two parts.

**Setter**

Setter calculates triplet’s address in the same way. It also operates on left/right bytes in the same way. But it’s not correct just to write to the middle byte, because write operation will destroy the information related to the other element. So the common way is to load byte, drop bits where you’ll write, write it there, but leave other part intact. Using AND operation (& in C/C++), we drop everything except our part. Using OR operation (| in C/C++), we then update the middle byte.

### 3.20.6 Optimizing GCC 4.8.2 for x86-64

Let’s see what optimizing GCC 4.8.2 for Linux x64 will do. I added comments. Sometimes readers are confused because instructions order is not logical. It’s OK, because optimizing compilers take CPU out-of-order-execution mechanisms into considerations, and sometimes, swapped instructions performing better.

**Getter**

```assembly
get_from_array:
    ; EDI=idx
    ; make a copy:
        mov   eax, edi
    ; calculate idx>>1:
        shr   eax
    ; determine if the element even or odd by isolation of the lowest bit:
        and   edi, 1
    ; calculate (idx>>1)*3.
    ; multiplication is slow in general, and can be replaced by one shifting and addition operation
    ; LEA is capable to do both:
        lea   edx, [rax+rax*2]
```
3.20. PACKING 12-BIT VALUES INTO ARRAY

; EDX now is (idx>>1)*3
; point EAX to the middle byte:
  lea eax, [rdx+1]
; sign-extend EAX value to RDX:
  cdqe
; get middle byte into EAX:
  movzx eax, BYTE PTR array[rax]
; finally check the value of the lowest bit in index.
; jump if index is odd (NE is the same as NZ (Not Zero)):
  jne .L9

; this is even element, go on
; sign-extend EDX to RDX:
  movsx rdx, edx
; shift middle byte 4 bits right:
  shr al, 4
; AL now has 4 highest bits of middle byte
; load left byte into EDX:
  movzx edx, BYTE PTR array[rdx]
; sign-extend AL (where high 4 bits of middle byte are now)
  movzx eax, al
; EAX has 4 high bits bits of middle byte
; EDX now has left byte
; shift left byte 4 bits left:
  sal edx, 4
; 4 lowest bits in EDX after shifting is cleared to zero
; finally merge values:
  or eax, edx
  ret

.L9:
; this is odd element, go on
; calculate address of right byte:
  add edx, 2
; isolate lowest 4 bits in middle byte:
  and eax, 15 ; 15=0xF
; sign-extend EDX (where address of right byte is) to RDX:
  movsx rdx, edx
; shift 4 bits we got from middle bytes 8 bits left:
  sal eax, 8
; load right byte:
  movzx edx, BYTE PTR array[rdx]
; merge values:
  or eax, edx
  ret

Setter

put to array:
; EDI=idx
; ESI=val
; copy idx to EAX:
  mov eax, edi
; calculate idx>>1 and put it to EAX:
  shr eax
; isolate lowest bit in idx:
  and edi, 1
; calculate (idx>>2)*3 and put it to EAX:
  lea eax, [rax+rax*2]
; jump if index is odd (NE is the same as NZ (Not Zero)):
  jne .L5

; this is even element, go on
; sign-extend address of triplet in EAX to RDX:
  movsx rdx, eax
; copy val value to ECX:
  mov ecx, esi
; calculate address of middle byte:
  add eax, 1
Other comments

All addresses in Linux x64 are 64-bit ones, so during pointer arithmetic, all values should also be 64-bit. The code calculating offsets inside of array operates on 32-bit values (input \texttt{idx} argument has type of \texttt{int}, which has width of 32 bits), and so these values must be converted to 64-bit addresses before actual memory load/store. So there are a lot of sign-extending instructions (like \texttt{CDQE}, \texttt{MOVSX}) used for conversion. Why to extend sign? By C/C++ standards, pointer arithmetic can operate on negative values (it’s possible to access array using negative index like \texttt{array[-123]}, see: \texttt{3.19 on page 593}). Since GCC compiler cannot be sure if all indices are always positive, it adds sign-extending instructions.

3.20.7 Optimizing Keil 5.05 (Thumb mode)

Getter

The following code has final OR operation in the function epilogue. Indeed, it executes at the end of both branches, so it’s possible to save some space.
3.20. PACKING 12-BIT VALUES INTO ARRAY

; R1 = R0<>1 = idx<>1
; R1 is now number of triplet
  LSLS  r2,r1,#1
; R2 = R1<<1 = (R0<>1)<<1 = R0&(~1) = idx&(~1)
; the operation (x<>1)<<1 looks senseless, but it's intended to clear the lowest bit in x (or \\ idx)
  LSLS  r5,r0,#31
; R5 = R0<<31 = idx<<31
; thus, R5 will contain 0x80000000 in case of even idx or zero if odd
  ADDS  r4,r1,r2
; R4 = R1+R2 = idx<>1 + idx&(~1) = offset of triplet begin (or offset of left byte)
; the expression looks tricky, but it's equal to multiplication by 1.5
  LSRS  r0,r0,#1
; R0 = R0<>1 = idx<>1
; load pointer to array:
  LDR  r3,array
; R3 = offset of array table
  LSLS  r1,r0,#1
; R1 = R0<<1 = (idx<>1)<<1 = idx&(~1)
  ADDS  r0,r0,r1
; R0 = idx<>1 + idx&(~1) = idx*1.5 = offset of triple begin
  ADDS  r1,r3,r0
; R1 = R3+R0 = offset of array + idx*1.5
; in other words, R1 now contains absolute address of triplet
; load middle byte (at address R1+1):
  LDRB  r2,[r1,#1]
; R2 = middle byte
; finally check if the idx even or odd:
  CMP  r5,#0
; jump if even:
  BEQ  |L0.92|
; idx is odd, go on:
  LSLS  r0,r2,#28
; R0 = R2<<28 = middle_byte<<28
; load right byte at R1+2:
  LDRB  r1,[r1,#2]
; R1 = right byte
  LSRS  r0,r0,#20
; R0 = R0<>20 = (R2<<28)>>20
; this is the same as R2<>8, but Keil compiler generates more complex code in order to drop all\ bits behind these 4
  B  |L0.98|
|L0.92|
; idx is even, go on:
; load left byte. R3=array now and R4=address of it
  LDRB  r0,[r3,r4]
; R0 = left byte
  LSLS  r0,r0,#4
; R0 = left_byte<<4
; shift middle_byte in R2 4 bits right:
  LSRS  r1,r2,#4
; R1=middle_byte<>4
|L0.98|
; function epilogue:
; current R0 value is shifted left byte or part of middle byte
; R1 is shifted part of middle byte or right byte
; now merge values and leave merged result in R0:
  ORRS  r0,r0,r1
; R0 = R0|R1
POP  {r4,r5,pc}
ENDP

There are at least of redundancy: idx*1.5 is calculated twice. As an exercise, reader may try to rework assembly function to make it shorter. Do not forget about testing!

Another thing to mention is that it’s hard to generate big constants in 16-bit Thumb instructions, so Keil compiler often generates tricky code using shifting instructions to achieve the same effect. For example, it’s tricky to generate AND Rdest, Rsrc, 1 or TST Rsrc, 1 code in Thumb mode, so Keil generates the code which shifts input idx by 31 bits left and then check, if the resulting value zero or not.
3.20. PACKING 12-BIT VALUES INTO ARRAY

Setter

The first half of setter code is very similar to getter, address of triplet is calculated first, then the jump is occurred in order to dispatch to the right handler’s code.

```
put_to_array PROC
  PUSH {r4,r5,lr}
  ; R0 = idx
  ; R1 = val
  LSRS  r2,r0,#1
  ; R2 = R0>>1 = idx>>1
  LSLs  r3,r2,#1
  ; R3 = R2<<1 = (idx>>1)<<1 = idx&(-1)
  LSLs  r4,r0,#31
  ; R4 = R0<<31 = idx<<31
  ADDS  r3,r2,r3
  ; R3 = R2+R3 = idx>>1 + idx&(-1) = idx*1.5
  LSRS  r0,r4,#1
  ; R0 = R0+1 = idx>>1
  LDR  r2,|array|
  LSLS  r5,r0,#1
  ; R5 = R0<<1 = (idx>>1)<<1 = idx&(-1)
  ADDS  r0,r0,r5
  ; R0 = R0+R5 = idx>>1 + idx&(-1) = idx*1.5
  ADDS  r0,r2,r0
  ; R0 = R2+R0 = array + idx*1.5, in other words, this is address of triplet
  ; finally test shifted lowest bit in idx:
  CMP  r4,#0
  ; jump if idx is even:
  BEQ  |L0.40|
  ; idx is odd, go on:
  ; load middle byte at R0+1:
  LDRB  r3,[r0,#1]
  ; R3 = middle byte
  LSRS  r2,r1,#8
  ; R2 = R1>>8 = val>>8
  LSRS  r3,r3,#4
  ; R3 = R3<<4 = middle_byte<<4
  LSLs  r3,r3,#4
  ; R3 = R3<<4 = (middle_byte<<4)<<4
  ; this two shift operations are used to drop low 4 bits in middle_byte
  ; merge high 4 bits in middle byte (in R3) with val>>8 (in R2):
  ORRS  r3,r3,r2
  ; store it at R0+1:
  STRB  r3,[r0,#1]
  ; store low 8 bits of val (val&0xFF) at R0+2:
  STRB  r1,[r0,#2]
  POP  {r4,r5,pc}
  |L0.40|
  ; idx is even, go on:
  LSRS  r4,r1,#4
  ; R4 = R1>>4 = val>>4
  ; store val>>4 at R2+R3 (address of left byte or beginning of triplet):
  STRB  r4,[r2,r3]
  ; load middle byte at R0+1:
  LDRB  r3,[r0,#1]
  ; R3 = middle byte
  LSLs  r2,r1,#4
  ; R2 = R1<<4 = val<<4
  LSLs  r1,r3,#28
  ; R1 = R3<<28 = middle_byte<<28
  LSRS  r1,r1,#28
  ; R1 = R1<<28 = (middle_byte<<28)<<28
  ; these two shifting operation are used to drop all bits in register except lowest 4
  ; merge lowest 4 bits (in R1) and val<<4 (in R2):
  ORRS  r1,r1,r2
  ; store it at R0+1:
  STRB  r1,[r0,#1]
```

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### 3.20.8 Optimizing Keil 5.05 (ARM mode)

**Getter**

Getter function for ARM mode has no conditional branches at all! Thanks to the suffixes (like `-EQ`, `-NE`), which can be supplied to many instructions in ARM mode, so the instruction will be only executed if the corresponding flag(s) are set.

Many arithmetical instructions in ARM mode can have shifting suffix like `LSL #1` (it means, the last operand is shifted left by 1 bit).

```
get_from_array PROC
  ; R0 = idx
  LSR r1,r0,#1
  ; R1 = R0>>1 = idx>>1
  ; check lowest bit in idx and set flags:
  TST r0,#1
  ADD r2,r1,r1,LSL #1
  ; R2 = R1+R1<<1 = R1+R1*2 = R1*3
  ; thanks to shifting suffix, a single instruction in ARM mode can multiplicate by 3
  LDR r1,[array]!
  ; R1 = address of array
  LSR r0,r0,#1
  ; R0 = R0>>1 = idx>>1
  ADD r0,r0,r0,LSL #1
  ; R0 = R0+R0<<1 = R0+R0*2 = R0*3 = (idx>>1)*3 = idx*1.5
  ; load middle byte at R0+1:
  LDRB r3,[r0,#1]
  ; R3 = middle byte

  ; the following 3 instructions executed if index is odd, otherwise all of them are skipped:
  ; load right byte at R0+2:
  LDRBNE r0,[r0,#2]
  ; R0 = right byte
  ANDNE r1,r3,#0xf
  ; R1 = R3&0xF = middle_byte&0xF
  ORRNE r0,r0,r1,LSR #8
  ; R0 = R0 | (R3<<8) = right_byte | (middle_byte&0xF)<<8
  ; this is the result returned

  ; the following 3 instructions executed if index is even, otherwise all of them are skipped:
  ; load at R1+R2 = array + (idx>>1)*3 = array + idx*1.5
  LDRBEQ r0,[r1,r2]
  ; R0 = left byte
  LSLEQ r0,r0,#4
  ; R0 = R0<<4 = left_byte << 4
  ORREQ r0,r0,r3,LSR #4
  ; R0 = R0 | R3>>4 = left_byte << 4 | middle_byte >> 4
  ; this is the result returned
  BX lr
ENDP
```

**Setter**

```
put_to_array PROC
  ; R0 = idx
  ; R1 = val
  LSR r2,r0,#1
  ; R2 = R0>>1 = idx>>1
  ; check the lowest bit of idx and set flags:
  TST r0,#1
  ADD r2,r1,r1,LSL #1
  ; R2 = R1+R1<<1 = R1+R1*2 = R1*3
  ; thanks to shifting suffix, a single instruction in ARM mode can multiplicate by 3
  LDR r1,[array]!
  ; R1 = address of array
  LSR r0,r0,#1
  ; R0 = R0>>1 = idx>>1
  ADD r0,r0,r0,LSL #1
  ; R0 = R0+R0<<1 = R0+R0*2 = R0*3 = (idx>>1)*3 = idx*1.5
  ; load middle byte at R0+1:
  LDRB r3,[r0,#1]
  ; R3 = middle byte

  ; the following 3 instructions executed if index is odd, otherwise all of them are skipped:
  ; load right byte at R0+2:
  LDRBNE r0,[r0,#2]
  ; R0 = right byte
  ANDNE r1,r3,#0xf
  ; R1 = R3&0xF = middle_byte&0xF
  ORRNE r0,r0,r1,LSR #8
  ; R0 = R0 | (R3<<8) = right_byte | (middle_byte&0xF)<<8
  ; this is the result returned

  ; the following 3 instructions executed if index is even, otherwise all of them are skipped:
  ; load at R1+R2 = array + (idx>>1)*3 = array + idx*1.5
  LDRBEQ r0,[r1,r2]
  ; R0 = left byte
  LSLEQ r0,r0,#4
  ; R0 = R0<<4 = left_byte << 4
  ORREQ r0,r0,r3,LSR #4
  ; R0 = R0 | R3>>4 = left_byte << 4 | middle_byte >> 4
  ; this is the result returned
  BX lr
ENDP
```


3.20. PACKING 12-BIT VALUES INTO ARRAY

```
TST r0,#1
LDR r12,[array]
; R12 = address of array
LSR r0,r0,#1
; R0 = R0>>1 = idx>>1
ADD r0,r0,r0,LSL #1
; R0 = R0+R0<<1 = R0+R0*2 = R0*3 = (idx>>1)*3 = idx/2*3 = idx*1.5
ADD r3,r2,r2,LSL #1
; R3 = R2+R2<<1 = R2+R2*2 = R2*3 = (idx>>1)*3 = idx/2*3 = idx*1.5
ADD r0,r0,r12
; R0 = R0+R12 = idx*1.5 + array
; jump if idx is even:
BEQ |L0.56|
; idx is odd, go on:
; load middle byte at R0+1:
LDRB r3,[r0,#1]
; R3 = middle byte
AND r3,r3,#0xf0
; R3 = middle_byte&0xF0
ORR r2,r3,r1,LSR #8
; R2 = middle_byte&0xF0 | val>>8
; store middle_byte&0xF0 | val>>8 at R0+1 (at the place of middle byte):
STRB r2,[r0,#1]
; store low 8 bits of val (or val&0xFF) at R0+2 (at the place of right byte):
STRB r1,[r0,#2]
BX lr
|L0.56|
; idx is even, go on:
LSR r2,r1,#4
; R2 = R1>>4 = val>>4
; store val>>4 at R12+R3 or array + idx*1.5 (place of left byte):
STRB r2,[r12,r3]
; load byte at R0+1 (middle byte):
LDRB r2,[r0,#1]
; R2 = middle_byte
; drop high 4 bits of middle byte:
AND r2,r2,#0xf
; R2 = middle_byte&0xF
; update middle byte:
ORR r1,r2,r1,LSR #4
; R1 = middle_byte&0xF | val<<4
; store updated middle byte at R0+1:
STRB r1,[r0,#1]
BX lr
ENDP
```

Value of \(\text{idx} \times 1.5\) is calculated twice, this is redundancy Keil compiler produced can be eliminated. You can rework assembly function as well to make it shorter. Do not forget about tests!

3.20.9 (32-bit ARM) Comparison of code density in Thumb and ARM modes

Thumb mode in ARM CPUs was introduced to make instructions shorter (16-bits) instead of 32-bit instructions in ARM mode. But as we can see, it’s hard to say, if it was worth it: code in ARM mode is always shorter (however, instructions are longer).

3.20.10 Optimizing GCC 4.9.3 for ARM64

**Getter**

```
<get_from_array>:
; W0 = idx
  0: lsr w2, w0, #1
  W2 = W0>>1 = idx>>1
  4: lsl w1, w2, #2
  W1 = W2<<2 = (W0>>1)<<2 = (idx&(-1))<<1
```
3.20. **PACKING 12-BIT VALUES INTO ARRAY**

```assembly
8: sub w1, w1, w2
; W1 = W1-W2 = (idx&(-1))<<1 - idx>>1 = idx*1.5
; now test lowest bit of idx and jump if it is present.
; (ARM64 has single instruction for these operations: TBNZ (Test and Branch Not Zero)).
c: tbnz w0, #0, 30 <get_from_array+0x30>

; idx is even, go on:
10: adrp x2, page of array
14: add w3, w1, #0x1
; W3 = W1+1 = idx*1.5 + 1, i.e., offset of middle byte
18: add x2, x2, offset of array within page
; load left byte at X2+W1 = array + idx*1.5 with sign-extension ("sxtw")
1c: ldrb w0, [x2,w1,sxtw]
; load middle byte at X2+W3 = array + idx*1.5 + 1 with sign-extension ("sxtw")
20: ldrb w1, [x2,w3,sxtw]
; W0 = left byte
; W1 = middle byte
24: lsl w0, w0, #4
; merge parts:
28: orr w0, w0, w1, lsr #4
; W0 = W0<4 | left_byte << 4 | middle_byte >> 4
; value in W0 is returned
2c: ret

; idx is odd, go on:
30: adrp x2, page of array
34: add w0, w1, #0x1
; W0 = W1+1 = idx*1.5+1, i.e., offset of middle byte
38: add x2, x2, address of array within page
3c: add w1, w1, #0x2
; W1 = W1+2 = idx*1.5+2, i.e., offset of right byte
; load middle byte at X2+W0 = array+idx*1.5+1 with sign-extension ("sxtw")
40: ldrb w0, [x2,w0,sxtw]
; load right byte at X2+W1 = array+idx*1.5+2 with sign-extension ("sxtw")
44: ldrb w1, [x2,w1,sxtw]
; W0 = middle byte
; W1 = right byte
48: ubfiz w0, w0, #8, #4
; W0 = middle_byte<<8
; now merge parts:
4c: orr w0, w0, w1
; W0 = W0 | W1 = middle_byte<<8 | right_byte
; value in W0 is returned
50: ret
```

ARM64 has new cool instruction **UBFIZ** *(Unsigned bitfield insert in zero, with zeros to left and right)*, which can be used to place specified number of bits from one register to another. It’s alias of another instruction, **UBFM** *(Unsigned bitfield move, with zeros to left and right)*. **UBFM** is the instruction used internally in ARM64 instead of LSL/LSR (bit shifts).

**Setter**

```assembly
<put_to_array>:
W0 = idx
W1 = val
54: lsr w3, w0, #1
; W3 = W0>>1 = idx>>1
58: lsl w2, w3, #2
; W2 = W3<<2 = (W0)>>1 <<2 = (idx&(-1))<<1
5c: sub w2, w2, w3
; W2 = W2-W3 = (idx&(-1))<<1 - idx>>1 = idx*1.5
; jump if lowest bit in idx is 1:
60: tbnz w0, #0, 94 <put_to_array+0x40>

; idx is even, go on:
64: adrp x0, page of array
68: add w3, w2, #0x1
```
3.20. PACKING 12-BIT VALUES INTO ARRAY

; W3 = W2+1 = idx*1.5+1, i.e., offset of middle byte
6c:  add   x0, x0, offset of array within page
; X0 = address of array
70:  lsr   w4, w1, #4
; W4 = W1>>4 = val>>4
74:  sxtw  x3, w3
; X3 = sign-extended 32-bit W3 (idx*1.5+1) to 64-bit
; sign-extension is needed here because the value will be used as offset within array,
; and negative offsets are possible in standard C/C++
78:  ubfiz w1, w1, #4, #4
; W1 = W1<<4 = val<<4
; store W4 (val>>4) at X0+W2 = array + idx*1.5, i.e., address of left byte:
7c:  strb  w4, [x0,w2,sxtw]
; load middle byte at X0+X3 = array+idx*1.5+1
80:  ldrb  w2, [x0,x3]
; W2 = middle byte
84:  and   w2, w2, #0xf
; W2 = W2&0xF = middle_byte&0xF (high 4 bits in middle byte are dropped)
; merge parts of new version of middle byte:
88:  orr   w3, w1, w1
; W1 = W2|W1 = middle_byte&0xF | val<<4
; store W2 (new middle byte) at X0+X3 = array+idx*1.5+1
8c:  strb  w1, [x0,x3]
90:  ret

; idx is odd, go on:
94:  add   w4, w2, #0x1
; W4 = W2+1 = idx*1.5+1, i.e., offset of middle byte
98:  adrp  x0, page of array
9c:  add   x0, x0, offset of array within page
; X0 = address of array
a0:  add   w2, w2, #0x2
; W2 = W2+2 = idx*1.5+2, i.e., offset of right byte
a4:  sxtw  x4, w4
; X4 = sign-extended 64-bit version of 32-bit W4
a8:  ldrb  w3, [x0,x4]
; load at X0+X4 = array+idx*1.5+1:
ac:  and   w3, w3, #0xfffffff0
; W3 = W3&0xFFFF0 = middle_byte&0xFFFF0, i.e., clear lowest 4 bits
b0:  orr   w3, w3, w1, lsr #8
; W3 = W3|W1>>8 = middle_byte&0xFFFF0 | val>>8
; store new version of middle byte at X0+X4=array+idx*1.5+1:
b4:  strb  w3, [x0,x4]
; now store lowest 8 bits of val. (in W1) at X0+W2=array+idx*1.5+2, i.e., place of right byte
; SXTW suffix means W2 will be sign-extended to 64-bit value before summing with X0
b8:  strb  w1, [x0,w2,sxtw]
bc:  ret

3.20.11 Optimizing GCC 4.4.5 for MIPS

Needless to keep in mind that each instruction after jump/branch instruction is executed first. It’s called branch delay slot in RISC CPUs lingo. To make things simpler, just swap instructions (mentally) in each instruction pair which is started with branch or jump instruction.

MIPS has no flags (apparently, to simplify data dependencies), so branch instructions (like BNE) does both comparison and branching.

There is also GP (Global Pointer) set up code in the function prologue, which can be ignored so far.

**Getter**

gget_from_array:
; $4 = idx
3c:  srl   $2,$4,1
; $2 = $4>>1 = idx>>1

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3.20. PACKING 12-BIT VALUES INTO ARRAY

```assembly
lui $28, %hi(__gnu_local_gp)
sll $3, $2, 1
; $3 = $2 << 1 = (idx>>1)<<1 = idx&(~1)
andi $4, $4, 0x1
; $4 = $4&1 = idx&1
addiu $28, $28, %lo(__gnu_local_gp)

; jump if $4 (idx&1) is not zero (if idx is odd):
bne $4, $0, $L6
; $2 = $3+$2 = idx>>1 + idx&(-1) = idx*1.5
addu $2, $3, $2 ; branch delay slot - this instruction executed before BNE

; idx is even, go on:
lw $3, %got(array)($28)
nop
addu $2, $3, $2
; $2 = $3+$2 = array + idx*1.5
; load byte at $2+0 = array + idx*1.5 (left byte):
lbu $3, 0($2)
; $3 = left byte
; load byte at $2+1 = array + idx*1.5+1 (middle byte):
lbu $2, 1($2)

; $2 = middle byte
sll $2, $3, 4
; $3 = $3<<4 = left_byte<<4
srl $2, $2, 4
; $2 = $2>>4 = middle_byte>>4
j $31
or $2, $2, $3 ; branch delay slot - this instruction executed before J
; $2 = $2|$3 = middle_byte>>4 | left_byte<<4
; $2=returned result

$L6:
; idx is odd, go on:
lw $3, %got(array)($28)

; $3 = array
nop
addu $2, $3, $2
; $2 = $3+$2 = array + idx*1.5
; load byte at $2+1 = array + idx*1.5 + 1 (middle byte):
lbu $4, 1($2)
; $4 = middle byte

; load byte at $2+1 = array + idx*1.5 + 2 (right byte):
lbu $3, 2($2)
; $3 = right byte
andi $2, $4, 0xf
; $2 = $4&0xf = middle_byte&0xf
sll $2, $2, 8
; $2 = $2<<8 = middle_byte&0xf << 8
j $31
or $2, $2, $3 ; branch delay slot - this instruction executed before J
; $2 = $2|$3 = middle_byte&0xf << 8 | right byte
; $2=returned result

Setter

put_to_array:
; $4=idx
; $5=val
srl $2, $4, 1
; $2 = $4>>1 = idx>>1
lui $28, %hi(__gnu_local_gp)
sll $3, $2, 1
; $3 = $2<<1 = (idx>>1)<<1 = idx&(~1)
andi $4, $4, 0x1
; $4 = $4&1 = idx&1
addiu $28, $28, %lo(__gnu_local_gp)
```

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3.20. PACKING 12-BIT VALUES INTO ARRAY

; jump if $4=idx&1 is not zero (i.e., if idx is odd):
  bne $4,$0,$L11
  addu $2,$3,$2 ; branch delay slot, this instruction is executed before BNE
; $2 = $3+$2 = idx&(-1) + idx>>>1 = idx*1.5

; idx is even, go on
  lw $3,%got(array)($28)
  $3 = array
  addiu $4,$2,1
; $4 = $2+1 = idx*1.5+1, i.e., offset of middle byte in array
  srl $6,$5,4
; $6 = $5>>4 = val>>4
  addu $2,$3,$2
; $2 = $3+$2 = array + idx*1.5 (offset of left byte)
; store $6 (val>>4) as left byte:
    sb $6,0($2)
    addu $2,$3,$4
; $2 = $3+$4 = array + idx*1.5+1 (absolute address of middle byte)
; load middle byte at $2+0 = array + idx*1.5 + 1
  lbu $3,0($2)
; $3 = middle byte
  andi $5,$5,0xf
; $5 = $5&0xF = val&0xF
  andi $3,$3,0xf
; $3 = $3&0xF = middle_byte&0xF
  sll $5,$5,4
; $5 = $5<<4 = (val&0xF)<<4
  or $5,$3,$5
; $5 = $5|$5 = middle_byte&0xF | (val&0xF)<<4 (new version of middle byte)
  j $31
; store $5 (new middle byte) at $2 (array + idx*1.5 + 1)
    sb $5,0($2) ; branch delay slot, this instruction is executed before J
$L11:
; idx is odd, go on
  lw $4,%got(array)($28)
; $4 = array
  addiu $3,$2,1
; $3 = $2+1 = idx*1.5+1 (offset of middle byte)
  addu $3,$4,$3
; $3 = $4+$3 = array + idx*1.5+1
; load middle byte at $3 (array + idx*1.5+1)
  lbu $6,0($3)
; $6 = middle byte
  srl $7,$5,8
; $7 = $5>>8 = val>>8
  andi $6,$6,0xf0
; $6 = $6&0xF0 = middle_byte&0xF0
  or $6,$6,$7
; $6 = $6|$7 = middle_byte&0xF0 | val>>8
  addu $2,$4,$2
; store updated middle byte at $3 (array + idx*1.5+1)
    sb $6,0($3)
    j $31
; store low 8 bits of val at $2+2=idx*1.5+2 (place of right byte)
    sb $5,2($2) ; branch delay slot, this instruction is executed before J

3.20.12 Difference from the real FAT12

The real FAT12 table is slightly different: https://en.wikipedia.org/wiki/Design_of_the_FAT_file_system#Cluster_map.

For even elements:

<table>
<thead>
<tr>
<th>+0</th>
<th>+1</th>
<th>+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>1</td>
<td>..</td>
</tr>
</tbody>
</table>

For odd elements:
Here are FAT12-related functions in Linux Kernel:
fat12_ent_get(), fat12_ent_put().

Nevertheless, I did as I did because values are better visible and recognizable in byte-level GDB dump, for the sake of demonstration.

### 3.20.13 Exercise

Perhaps, there could be a way to store data in a such way, so getter/setter functions would be faster. If we would place values in this way:

(Even elements)

<table>
<thead>
<tr>
<th>+0</th>
<th>+1</th>
<th>+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>1</td>
<td>..</td>
</tr>
</tbody>
</table>

(Odd elements)

<table>
<thead>
<tr>
<th>+0</th>
<th>+1</th>
<th>+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>..</td>
<td>1</td>
<td>23</td>
</tr>
</tbody>
</table>

This schema of storing data will allow to eliminate at least one shift operation. As an exercise, you may rework my C/C++ code in that way and see what compiler will produce.

### 3.20.14 Summary

Bit shifts (<< and >> in C/C++, SHL/SHR/SAL/SAR in x86, LSL/LSR in ARM, SLL/SRL in MIPS) are used to place bit(s) to specific place.

AND operation (& in C/C++, AND in x86/ARM) is used to drop unneeded bits, also during isolation.

OR operation (| in C/C++, OR in x86/ARM) is used to merge or combine several values into one. One input value must have zero space at the place where another value has its information-caring bits.

ARM64 has new instructions UBFM, UFBIZ to move specific bits from one register to another.

### 3.20.15 Conclusion

FAT12 is hardly used somewhere nowadays, but if you have space constraints and you have to store values limited to 12 bits, you may consider tightly-packed array in the manner it’s done in FAT12 table.

### 3.21 More about pointers

The way C handles pointers, for example, was a brilliant innovation; it solved a lot of problems that we had before in data structuring and made the programs look good afterwards.

Donald Knuth, interview (1993)

For those, who still have hard time understanding C/C++ pointers, here are more examples. Some of them are weird and serves only demonstration purpose: use them in production code only if you really know what you’re doing.
3.21. MORE ABOUT POINTERS

3.21.1 Working with addresses instead of pointers

Pointer is just an address in memory. But why do we write `char* string` instead of something like `address string`? Pointer variable is supplied with a type of the value to which pointer points. So then compiler will be able to catch data typization bugs during compilation.

To be pedantic, data typing in programming languages is all about preventing bugs and self-documentation. It's possible to use maybe two of data types like `int` (or `int64_t`) and byte—these are the only types which are available to assembly language programmers. But it's just very hard task to write big and practical assembly programs without nasty bugs. Any small typo can lead to hard-to-find bug.

Data type information is absent in a compiled code (and this is one of the main problems for decompilers), and I can demonstrate this.

This is what a sane C/C++ programmer can write:

```c
#include <stdio.h>
#include <stdint.h>

void print_string (char *s)
{
    printf ((address: 0x%llx)
    printf (%s
    }
}

int main()
{
    char *s="Hello, world!"
    print_string (s);
}
```

This is what I can write:

```c
#include <stdio.h>
#include <stdint.h>

void print_string (uint64_t address)
{
    printf ((address: 0x%llx)
    puts ((char*)address);
}

int main()
{
    char *s="Hello, world!"
    print_string ((uint64_t)s);
}
```

I use `uint64_t` because I run this example on Linux x64. `int` would work for 32-bit OS-es. First, a pointer to character (the very first in the greeting string) is casted to `uint64_t`, then it's passed further. `print_string()` function casts back incoming `uint64_t` value into pointer to a character.

What is interesting is that GCC 4.8.4 produces identical assembly output for both versions:

```
gcc 1.c -S -masm=intel -O3 -fno-inline
```

```
.LC0:
    .string "(address: 0x%llx)"

print_string:
    push rbx
    mov rdx, rdi
    mov rbx, rdi
    mov esi, OFFSET FLAT:.LC0
    mov edi, 1
    xor eax, eax
    call __printf_chk
    mov rdi, rbx
    pop rbx
```
3.21. MORE ABOUT POINTERS

jmp puts
.LC1:
.string "Hello, world!"
main:
    sub    rsp, 8
    mov    edi, OFFSET FLAT:.LC1
    call   print_string
    add    rsp, 8
    ret

(I've removed all insignificant GCC directives.)

I also tried UNIX diff utility and it shows no differences at all.

Let's continue to abuse C/C++ programming traditions heavily. Someone may write this:

```c
#include <stdio.h>
#include <stdint.h>

uint8_t load_byte_at_address (uint8_t* address)
{
    return *address;
    //this is also possible: return address[0];
};

void print_string (char *s)
{
    char* current_address=s;
    while (1)
    {
        char current_char=load_byte_at_address(current_address);
        if (current_char==0)
            break;
        printf("%c", current_char);
        current_address++;
    }
};

int main()
{
    char *s="Hello, world!";
    print_string (s);
};
```

It can be rewritten like this:

```c
#include <stdio.h>
#include <stdint.h>

uint8_t load_byte_at_address (uint64_t address)
{
    return *(uint8_t*)address;
    //this is also possible: return address[0];
};

void print_string (uint64_t address)
{
    uint64_t current_address=address;
    while (1)
    {
        char current_char=load_byte_at_address(current_address);
        if (current_char==0)
            break;
        printf("%c", current_char);
        current_address++;
    }
};

int main()
{
    char *s="Hello, world!";
    print_string (s);
};
```
3.21. MORE ABOUT POINTERS

char *s="Hello, world!";
print_string ((uint64_t)s);
};

Both source codes resulting in the same assembly output:

```c
load_byte_at_address:
  movzx  eax, BYTE PTR [rdi]
  ret

print_string:
  .LFB15:
    push rbx
    mov rbx, rdi
    jmp .L4
  .L7:
    movsx  edi, al
    add rbx, 1
    call putchar
  .L4:
    mov rdi, rbx
    call load_byte_at_address
    test al, al
    jne .L7
    pop rbx
    ret
  .LC0:
    .string "Hello, world!"
main:
    sub rsp, 8
    mov edi, OFFSET FLAT:.LC0
    call print_string
    add rsp, 8
    ret
```

(I have also removed all insignificant GCC directives.)

No difference: C/C++ pointers are essentially addresses, but supplied with type information, in order to prevent possible mistakes at the time of compilation. Types are not checked during runtime—it would be huge (and unneeded) overhead.

3.21.2 Passing values as pointers; tagged unions

Here is an example on how to pass values in pointers:

```c
#include <stdio.h>
#include <stdint.h>

uint64_t multiply1 (uint64_t a, uint64_t b)
{    return a*b;
};

uint64_t* multiply2 (uint64_t *a, uint64_t *b)
{    return (uint64_t*)((uint64_t)a*(uint64_t)b);
};

int main()
{
    printf ("%d\n", multiply1(123, 456));
    printf ("%d\n", (uint64_t)multiply2((uint64_t*)123, (uint64_t*)456));
};
```

It works smoothly and GCC 4.8.4 compiles both multiply1() and multiply2() functions identically!
As long as you do not dereference pointer (in other words, you don’t read any data from the address stored in pointer), everything will work fine. Pointer is a variable which can store anything, like usual variable.

Signed multiplication instruction (IMUL) is used here instead of unsigned one (MUL), read more about it here: 2.2.1.

By the way, it’s well-known hack to abuse pointers a little called tagged pointers. In short, if all your pointers points to blocks of memory with size of, let’s say, 16 bytes (or it is always aligned on 16-byte boundary), 4 lowest bits of pointer is always zero bits and this space can be used somehow. It’s very popular in LISP compilers and interpreters. They store cell/object type in these unused bits, this can save some memory. Even more, you can judge about cell/object type using just pointer, with no additional memory access. Read more about it: [Dennis Yurichev, C/C++ programming language notes1.3].

### 3.21.3 Pointers abuse in Windows kernel

The resource section of PE executable file in Windows OS is a section containing pictures, icons, strings, etc. Early Windows versions allowed to address resources only by IDs, but then Microsoft added a way to address them using strings.

So then it would be possible to pass ID or string to `FindResource()` function. Which is declared like this:

```c
HRSRC WINAPI FindResource(
    _In_opt_ HMODULE hModule,
    _In_ LPCTSTR lpName,
    _In_ LPCTSTR lpType
);
```

`lpName` and `lpType` has `char*` or `wchar*` types, and when someone still wants to pass ID, he/she have to use `MAKEINTRESOURCE` macro, like this:

```c
result = FindResource(..., MAKEINTRESOURCE(1234), ...);
```

It’s interesting fact that `MAKEINTRESOURCE` is merely casting integer to pointer. In MSVC 2013, in the file `Microsoft SDKs\Windows\v7.1A\Include\Ks.h` we can find this:

```c
#if (!defined( MAKEINTRESOURCE ))
#define MAKEINTRESOURCE( res ) ((ULONG_PTR) (USHORT) res)
#endif
```

Sounds insane. Let’s peek into ancient leaked Windows NT4 source code. In `private/windows/base/client/module.c` we can find `FindResource()` source code:

```c
HRSRC FindResourceA(
    HMODULE hModule,
    LPCSTR lpName,
    LPCSTR lpType
)
...
{
    NTSTATUS Status;
```
Let's proceed to `BaseDllMapResourceIdA()` in the same source file:

```c
ULONG BaseDllMapResourceIdA(LPCSTR lpId)
{
    NTSTATUS Status;
    ULONG Id;
    UNICODE_STRING UnicodeString;
    ANSI_STRING AnsiString;
    PWSTR s;

    try {
        if (((ULONG)lpId & LDR_Resource_ID_Name_MASK) == 0)
        {
            Status = RtlCharToInteger(lpId+1, 10, &Id);
            if (!NT_SUCCESS(Status))
                Id = (ULONG)-1;
        }
        else
        {
            RtlInitAnsiString(&AnsiString, lpId);
            Status = RtlAnsiStringToUnicodeString(&UnicodeString, &AnsiString, TRUE);
            if (!NT_SUCCESS(Status))
                Id = (ULONG)-1;
            else
            {  
                s = UnicodeString.Buffer;
                while (*s != UNICODE_NULL)
                {  
                    *s = RtlUpcaseUnicodeChar(*s);
                    s++;
                }
                Id = (ULONG)UnicodeString.Buffer;
            }
        }
    except (EXCEPTION_EXECUTE_HANDLER) {
        BaseSetLastNTErrror(GetExceptionCode());
        Id = (ULONG)-1;
    }
    return Id;
}
```
3.21. MORE ABOUT POINTERS

lpId is ANDed with LDR_RESOURCE_ID_NAME_MASK. Which we can find in public/sdk/inc/ntldr.h:

```c
#define LDR_RESOURCE_ID_NAME_MASK 0xFFFF0000
```

So lpId is ANDed with 0xFFFF0000 and if some bits beyond lowest 16 bits are still present, first half of function is executed (lpId is treated as an address of string). Otherwise—second half (lpId is treated as 16-bit value).

Still, this code can be found in Windows 7 kernel32.dll file:

```asm
.text:0000000078D24510 ; __int64 __fastcall BaseDllMapResourceIdA(PCSZ SourceString)
.text:0000000078D24510 BaseDllMapResourceIdA proc near ; CODE XREF: FindResourceExA+34
.text:0000000078D24510 ; FindResourceExA+4B
.text:0000000078D24510
.text:0000000078D24510 var_38 = qword ptr -38h
.text:0000000078D24510 var_30 = qword ptr -30h
.text:0000000078D24510 var_28 = _UNICODE_STRING ptr -28h
.text:0000000078D24510 DestinationString= _STRING ptr -18h
.text:0000000078D24510 arg_8 = dword ptr 10h
.text:0000000078D24510 ; FUNCTION CHUNK AT .text:0000000078D42FB4 SIZE 000000D5 BYTES
.text:0000000078D24510
.text:0000000078D24510 push rbx
.text:0000000078D24512 sub rsp, 50h
.text:0000000078D24516 cmp rcx, 10000h
.text:0000000078D2451D jnb loc_78D42FB4
.text:0000000078D24523 mov [rsp+58h+var_38], rcx
.text:0000000078D24528 jmp short $+2
.text:0000000078D2452A ;
```

...
If value in input pointer is greater than 0x10000, jump to string processing is occurred. Otherwise, input value of lpId is returned as is. 0xFFFF0000 mask is not used here any more, because this is 64-bit code after all, but still, 0xFFFFFFFFFFFF0000 could work here.

Attentive reader may ask, what if address of input string is lower than 0x10000? This code relied on the fact that in Windows there are nothing on addresses below 0x10000, at least in Win32 realm. Raymond Chen writes about this:

```
How does MAKEINTRESOURCE work? It just stashes the integer in the bottom 16 bits of a pointer, leaving the upper bits zero. This relies on the convention that the first 64KB of address space is never mapped to valid memory, a convention that is enforced starting in Windows 7.
```

In short words, this is dirty hack and probably one should use it only if there is a real necessity. Perhaps, FindResource() function in past had SHORT type for its arguments, and then Microsoft has added a way to pass strings there, but older code must also be supported.

Now here is my short distilled example:

```c
#include <stdio.h>
#include <stdint.h>

void f(char* a)
{
    if (((uint64_t)a)>0x10000)
        printf("Pointer to string has been passed: %s\n", a);
    else
        printf("16-bit value has been passed: %d\n", (uint64_t)a);
};

int main()
{
    f("Hello!"); // pass string
    f((char*)1234); // pass 16-bit value
};
```

It works!

**Pointers abuse in Linux kernel**

As it has been noted in comments on Hacker News, Linux kernel also has something like that. For example, this function can return both error code and pointer:

```c
struct kernfs_node *kernfs_create_link(struct kernfs_node *parent,
    const char *name,
    struct kernfs_node *target)
{
    struct kernfs_node *kn;
    int error;

    kn = kernfs_new_node(parent, name, S_IFLNK|S_IRWXUGO, KERNFS_LINK);
    if (!kn)
        return ERR_PTR(-ENOMEM);
    if (kernfs_ns_enabled(parent))
        kn->ns = target->ns;
    kn->symlink.target_kn = target;
    kernfs_get(target); /* ref owned by symlink */

    error = kernfs_add_one(kn);
    if (!error)
        return kn;
}
```
### 3.21. MORE ABOUT POINTERS

```c
kernfs_put(kn);
return ERR_PTR(error);
```

(https://github.com/torvalds/linux/blob/fceef393a538134f03b778c5d2519e670269342f/fs/kernfs/symlink.c#L25)

**ERR_PTR** is a macro to cast integer to pointer:

```c
static inline void * __must_check ERR_PTR(long error) {
    return (void *) error;
}
```

(https://github.com/torvalds/linux/blob/61d0b5a4b2777df5d5aef245e212b3c1fa8091ca/tools/virtio/linux/err.h)

This header file also has a macro helper to distinguish error code from pointer:

```c
#define IS_ERR_VALUE(x) unlikely((x) >= (unsigned long)-MAX_ERRNO)
```

This means, error codes are the “pointers” which are very close to -1 and, hopefully, there are nothing in kernel memory on the addresses like 0xFFFFFFFFFFFFFFFF, 0xFFFFFFFFFFFFFFFE, 0xFFFFFFFFFFFFFFFD, etc.

Much more popular solution is to return NULL in case of error and to pass error code via additional argument. Linux kernel authors don’t do that, but everyone who use these functions must always keep in mind that returning pointer must always be checked with **IS_ERR_VALUE** before dereferencing.

For example:

```c
fman->cam_offset = fman_muram_alloc(fman->muram, fman->cam_size);
if (IS_ERR_VALUE(fman->cam_offset)) {
    dev_err(fman->dev, "%s: MURAM alloc for DMA CAM failed\n", __func__);
    return -ENOMEM;
}
```

(https://github.com/torvalds/linux/blob/aa00edc1287a693eadc7bc67a3d735555d969b35d/drivers/net/ethernet/freescale/fman/fman.c#L826)

**Pointers abuse in UNIX userland**

mmap() function returns -1 in case of error (or MAP_FAILED, which equals to -1). Some people say, mmap() can map a memory at zeroth address in rare situations, so it can’t use 0 or NULL as error code.

### 3.21.4 Null pointers

"Null pointer assignment" error of MS-DOS era

Some oldschoolers may recall a weird error message of MS-DOS era: “Null pointer assignment”. What does it mean?

It’s not possible to write a memory at zeroth address in *NIX and Windows OSes, but it was possible to do so in MS-DOS due to absence of memory protection whatsoever.

So I’ve pulled my ancient Turbo C++ 3.0 (later it was renamed to Borland C++) from early 1990s and tried to compile this:

```c
#include <stdio.h>

int main() {
    int *ptr=NULL;
    *ptr=1234;
    printf ("Now let's read at NULL\n");
}
```

```c
Now let's read at NULL
```

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3.21. MORE ABOUT POINTERS

```c
    printf("%d\n", *ptr);
```

Hard to believe, but it works, with error upon exit, though:

Listing 3.121: Ancient Turbo C 3.0

```
C:\TC30\BIN\1
Now let's read at NULL
1234
Null pointer assignment
C:\TC30\BIN>_
```

Let's dig deeper into the source code of CRT of Borland C++ 3.1, file c0.asm:

```asm
; _checknull() check for null pointer zapping copyright message
...

; Check for null pointers before exit
__checknull PROC DIST
PUBLIC __checknull

IF LDATA EQ false
    IFNDEF __TINY__
        push si
        push di
        mov es, cs:DGROUP@*
        xor ax, ax
        mov si, ax
        mov cx, lgth_CopyRight
    ComputeChecksum label near
        add al, es:[si]
        adc ah, 0
        inc si
        loop ComputeChecksum
        sub ax, CheckSum
        jz @@SumOK
        mov cx, lgth_NullCheck
        mov dx, offset DGROUP: NullCheck
        call ErrorDisplay
    @@SumOK:
        pop di
        pop si
    ENDIF
ENDIF

_DATA SEGMENT

; Magic symbol used by the debug info to locate the data segment
public DATASEG@
DATASEG@ label byte

; The CopyRight string must NOT be moved or changed without
; changing the null pointer check logic
CopyRight db 4 dup(0)
db 'Borland C++ - Copyright 1991 Borland Intl.',0
lgth_CopyRight equ $ - CopyRight

IF LDATA EQ false
    IFNDEF __TINY__
        CheckSum equ 00D5Ch
        NullCheck db 'Null pointer assignment', 13, 10
        lgth_NullCheck equ $ - NullCheck
    ENDIF
ENDIF
```

...
The MS-DOS memory model was really weird (11.6) and probably not worth looking into it unless you’re fan of retrocomputing or retrogaming. One thing we have to keep in mind is that memory segment (included data segment) in MS-DOS is a memory segment in which code or data is stored, but unlike “serious” OSes, it’s started at address 0.

And in Borland C++ CRT, the data segment is started with 4 zero bytes and the copyright string “Borland C++ - Copyright 1991 Borland Intl.”. The integrity of the 4 zero bytes and text string is checked upon exit, and if it’s corrupted, the error message is displayed.

But why? Writing at null pointer is common mistake in C/C++, and if you do so in *NIX or Windows, your application will crash. MS-DOS has no memory protection, so CRT has to check this post-factum and warn about it upon exit. If you see this message, this means, your program at some point has written at address 0.

Our program did so. And this is why 1234 number has been read correctly: because it was written at the place of the first 4 zero bytes. Checksum is incorrect upon exit (because the number has been left there), so error message has been displayed.

Am I right? I’ve rewritten the program to check my assumptions:

```c
#include <stdio.h>

int main()
{
    int *ptr=NULL;
    *ptr=1234;
    printf ("Now let's read at NULL\n");
    printf ("%d\n", *ptr);
    *ptr=0; // psst, cover our tracks!
}
```

This program executes without error message upon exit.

Though method to warn about null pointer assignment is relevant for MS-DOS, perhaps, it can still be used today in low-cost MCU37 with no memory protection and/or MMU37.

### Why would anyone write at address 0?

But why would sane programmer write a code which writes something at address 0? It can be done accidentally: for example, a pointer must be initialized to newly allocated memory block and then passed to some function which returns data through pointer.

```c
int *ptr=NULL;
... we forgot to allocate memory and initialize ptr
strcpy (ptr, buf); // strcpy() terminates silently because MS-DOS has no memory protection
```

Even worse:

```c
int *ptr=malloc(1000);
... we forgot to check if memory has been really allocated: this is MS-DOS after all and \<
... and RAM shortage was very common.
... if malloc() returned NULL, the ptr will also be NULL.
strcpy (ptr, buf); // strcpy() terminates silently because MS-DOS has no memory protection
```

### NULL in C/C++

NULL in C/C++ is just a macro which is often defined like this:

```c
#define NULL ((void*)0)
```

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3.21. MORE ABOUT POINTERS

(void*) is a data type reflecting the fact it’s the pointer, but to a value of unknown data type (void).

NULL is usually used to show absence of an object. For example, you have a single-linked list, and each node has a value (or pointer to a value) and next pointer. To show that there are no next node, 0 is stored to next field. Other solutions are just worse. Perhaps, you may have some crazy environment where you need to allocate memory blocks at zero address. How would you indicate absence of the next node? Some kind of magic number? Maybe -1? Or maybe using additional bit?

In Wikipedia we may find this:

In fact, quite contrary to the zero page’s original preferential use, some modern operating systems such as FreeBSD, Linux and Microsoft Windows[2] actually make the zero page inaccessible to trap uses of NULL pointers.


Null pointer to function

It’s possible to call function by its address. For example, I compile this by MSVC 2010 and run it in Windows 7:

```c
#include <windows.h>
#include <stdio.h>

int main()
{
    printf ("0x%x\n", &MessageBoxA);
}
```

The result is 0x7578feae and doesn’t changing after several times I run it, because user32.dll (where MessageBoxA function resides) is always loads at the same address. And also because ASLR is not enabled (result would be different each time in that case).

Let’s call MessageBoxA() by address:

```c
#include <windows.h>
#include <stdio.h>

typedef int (*msgboxtype)(HWND hWnd, LPCTSTR lpText, LPCTSTR lpCaption, UINT uType);

int main()
{
    msgboxtype msgboxaddr=0x7578feae;
    // force to load DLL into process memory,
    // since our code doesn't use any function from user32.dll,
    // and DLL is not imported
    LoadLibrary ("user32.dll");

    msgboxaddr(NULL, "Hello, world!", "hello", MB_OK);
}
```

Weird, but works in Windows 7 x86.

This is commonly used in shellcodes, because it’s hard to call DLL functions by name from there. And ASLR is a countermeasure.

Now what is really weird, some embedded C programmers may be familiar with a code like that:

```c
int reset()
{
    void (*foo)(void) = 0;
    foo();
}
```

38 Address Space Layout Randomization
3.21. MORE ABOUT POINTERS

Who will want to call a function at address 0? This is a portable way to jump at zero address. Many low-cost cheap microcontrollers also have no memory protection or MMU and after reset, they start to execute code at address 0, where some kind of initialization code is stored. So jumping to address 0 is a way to reset itself. One could use inline assembly, but if it’s not possible, this portable method can be used.

It even compiles correctly by my GCC 4.8.4 on Linux x64:

```markdown
reset:
    sub    rsp, 8
    xor    eax, eax
    call   rax
    add    rsp, 8
    ret
```

The fact that stack pointer is shifted is not a problem: initialization code in microcontrollers usually completely ignores registers and RAM state and boots from scratch.

And of course, this code will crash on *NIX or Windows because of memory protection and even in absence of protection, there are no code at address 0.

GCC even has non-standard extension, allowing to jump to a specific address rather than call a function there: [http://gcc.gnu.org/onlinedocs/gcc/Labels-as-Values.html](http://gcc.gnu.org/onlinedocs/gcc/Labels-as-Values.html).

### 3.21.5 Array as function argument

Someone may ask, what is the difference between declaring function argument type as array and as pointer?

As it seems, there are no difference at all:

```c
void write_something1(int a[16])
{
    a[5]=0;
};
void write_something2(int *a)
{
    a[5]=0;
};
int f()
{
    int a[16];
    write_something1(a);
    write_something2(a);
};
```

Optimizing GCC 4.8.4:

```c
write_something1:
    mov     DWORD PTR [rdi+20], 0
    ret
write_something2:
    mov     DWORD PTR [rdi+20], 0
    ret
```

But you may still declare array instead of pointer for self-documenting purposes, if the size of array is always fixed. And maybe, some static analysis tool will be able to warn you about possible buffer overflow. Or is it possible with some tools today?


C99 standard also have static keyword [ISO/IEC 9899:TC3 (C C99 standard), (2007) 6.7.5.3]:
If the keyword static also appears within the [ and ] of the array type derivation, then for each call to the function, the value of the corresponding actual argument shall provide access to the first element of an array with at least as many elements as specified by the size expression.

### 3.21.6 Pointer to function

A function name in C/C++ without brackets, like “printf” is a pointer to function of void (*)() type. Let’s try to read function’s contents and patch it:

```c
#include <memory.h>
#include <stdio.h>

void print_something ()
{
    printf ("we are in %s()\n", __FUNCTION__);
};

int main()
{
    print_something();
    printf ("first 3 bytes: %x %x %x...\n",
            *(unsigned char*)print_something,
            *((unsigned char*)print_something+1),
            *((unsigned char*)print_something+2));

    *(unsigned char*)print_something=0xC3; // opecode of RET
    printf ("going to call patched print_something():\n");
    print_something();
    printf ("it must exit at this point\n");
};
```

It tells, that the first 3 bytes of functions are 55 89 e5. Indeed, these are opcodes of PUSH EBP and MOV EBP, ESP instructions (these are x86 opcodes). But then our program crashes, because text section is readonly.

We can recompile our example and make text section writable:  

```bash
gcc --static -g -Wl,--omagic -o example example.c
```

That works!

```c
we are in print_something()
first 3 bytes: 55 89 e5...
going to call patched print_something():
it must exit at this point
```

### 3.21.7 Pointer as object identifier

Both assembly language and C has no OOP features, but it’s possible to write a code in OOP style (just treat structure as an object).

It’s interesting, that sometimes, pointer to an object (or its address) is called as ID (in sense of data hiding/encapsulation).

For example, LoadLibrary(), according to MSDN\(^\text{40}\), returns “handle to the module” \(^\text{41}\). Then you pass this “handle” to other functions like GetProcAddress(). But in fact, LoadLibrary() returns pointer to DLL file mapped into memory \(^\text{42}\). You can read two bytes from the address LoadLibrary() returns, and that would be “MZ” (first two bytes of any .EXE/.DLL file in Windows).

\(^{39}\)http://stackoverflow.com/questions/27581279/make-text-segment-writable-elf
\(^{40}\)Microsoft Developer Network
\(^{41}\)https://msdn.microsoft.com/ru-ru/library/windows/desktop/ms684175(v=vs.85).aspx
\(^{42}\)https://blogs.msdn.microsoft.com/oldnewthing/20041025-00/?p=37483
3.22. LOOP OPTIMIZATIONS

Apparently, Microsoft “hides” that fact to provide better forward compatibility. Also, HMODULE and HINSTANCE data types had another meaning in 16-bit Windows.

Probably, this is reason why printf() has “%p” modifier, which is used for printing pointers (32-bit integers on 32-bit architectures, 64-bit on 64-bit, etc) in hexadecimal form. Address of a structure dumped into debug log may help in finding it in another place of log.

Here is also from SQLite source code:

```c
struct Pager {
    sqlite3_vfs *pVfs; /* OS functions to use for IO */
u8 exclusiveMode; /* Boolean. True if locking_mode==EXCLUSIVE */
u8 journalMode; /* One of the PAGER_JOURNALMODE_* values */
u8 useJournal; /* Use a rollback journal on this file */
u8 noSync; /* Do not sync the journal if true */
...

static int pagerLockDb(Pager *pPager, int eLock){
    int rc = SQLITE_OK;
    assert( eLock==SHARED_LOCK || eLock==RESERVED_LOCK || eLock==EXCLUSIVE_LOCK );
    if( pPager->eLock<eLock || pPager->eLock==UNKNOWN_LOCK ){
        rc = sqlite3OsLock(pPager->fd, eLock);
        if( rc==SQLITE_OK && (pPager->eLock!=UNKNOWN_LOCK||eLock==EXCLUSIVE_LOCK) ){
            pPager->eLock = (u8)eLock;
            IOTRACE(("LOCK %p %d\n", pPager, eLock))
        }
    }
    return rc;
}

PAGER_INCR(sqlite3_pager_readdb_count);
PAGER_INCR(pPager->nRead);
IOTRACE("PGIN %p %d\n", pPager, pgno);
PAGERTRACE("FETCH %d page %d hash(%08x)\n",
            PAGERID(pPager), pgno, pager_pagehash(pPg));
...```

3.22  Loop optimizations

3.22.1  Weird loop optimization

This is a simplest ever memcpy() function implementation:

```c
void memcpy (unsigned char* dst, unsigned char* src, size_t cnt)
{
    size_t i;
    for (i=0; i<cnt; i++)
        dst[i]=src[i];
}
```

At least MSVC 6.0 from the end of 1990s till MSVC 2013 can produce a really weird code (this listing is generated by MSVC 2013 x86):

```c
_dst$ = 8 ; size = 4
_src$ = 12 ; size = 4
_cnt$ = 16 ; size = 4
_memcpy PROC
    mov    edx, DWORD PTR _cnt$[esp-4]
    test   edx, edx
```
3.22. LOOP OPTIMIZATIONS

This is weird, because how humans work with two pointers? They store two addresses in two registers or two memory cells. MSVC compiler in this case stores two pointers as one pointer (sliding dst in EAX) and difference between src and dst pointers (left unchanged over the span of loop body execution in ESI). (By the way, this is a rare case when ptrdiff_t data type can be used.) When it needs to load a byte from src, it loads it at diff + sliding dst and stores byte at just sliding dst.

This has to be some optimization trick. But I've rewritten this function to:

```assembly
_f2 PROC
    mov edx, DWORD PTR _cnt$[esp-4]
    test edx, edx
    je SHORT $LN1@f
    mov eax, DWORD PTR _dst$[esp-4]
    push esi
    mov esi, DWORD PTR _src$[esp]
    ; eax=dst; esi=src
$LL8@f:
    mov cl, BYTE PTR [esi+edx]
    mov BYTE PTR [eax+edx], cl
    dec edx
    jne SHORT $LL8@f
    pop esi
$LN1@f:
    ret 0
_f2 ENDP
```

...and it works as efficient as the optimized version on my Intel Xeon E31220 @ 3.10GHz. Maybe, this optimization was targeted some older x86 CPUs of 1990s era, since this trick is used at least by ancient MS VC 6.0?

Any idea?

Hex-Rays 2.2 have a hard time recognizing patterns like that (hopefully, temporary?):

```c
void __cdecl f1(char *dst, char *src, size_t size)
{
    size_t counter; // edx@1
    char *sliding_dst; // eax@2
    char tmp; // cl@3

    counter = size;
    if ( size )
    {
        sliding_dst = dst;
        do
        {
            tmp = (sliding_dst++)[src - dst]; // difference (src-dst) is calculated once,
            *(sliding_dst - 1) = tmp;
            --counter;
        } while (--counter);
    }
```
3.22. LOOP OPTIMIZATIONS

```c
while ( counter );
```

Nevertheless, this optimization trick is often used by MSVC (not just in Do It Yourself homebrew memcpy() routines, but in many loops which uses two or more arrays), so it’s worth for reverse engineers to keep it in mind.

### 3.22.2 Another loop optimization

If you process all elements of some array which happens to be located in global memory, compiler can optimize it. For example, let’s calculate a sum of all elements of array of 128 `int`'s:

```c
#include <stdio.h>

int a[128];

int sum_of_a()
{
    int rt=0;
    for (int i=0; i<128; i++)
        rt=rt+a[i];
    return rt;
};

int main()
{
    // initialize
    for (int i=0; i<128; i++)
        a[i]=i;
    // calculate the sum
    printf (%d\n", sum_of_a());
};
```

Optimizing GCC 5.3.1 (x86) can produce this (IDA):

```
.text:00048480 sum_of_a proc near
 .text:00048480 mov edx, offset a
 .text:00048485 xor eax, eax
 .text:00048487 mov esi, esi
 .text:00048489 lea edi, [edi+0]
 .text:000484ca loc_80484c0: ; CODE XREF: sum_of_a+1b
 .text:000484c0 add eax, [edx]
 .text:000484c2 add edx, 4
 .text:000484c5 cmp edx, offset __libc_start_main@@GLIBC_2_0
 .text:000484cb jnz short loc_80484c0
 .text:000484cd rep retn
 .text:000484cd sum_of_a endp

...```

43Do It Yourself
What the heck is `__libc_start_main@@GLIBC_2_0` at 0x080484C5? This is a label just after end of a[] array. The function can be rewritten like this:

```c
int sum_of_a_v2()
{
    int *tmp=a;
    int rt=0;
    do
    {
        rt=rt+(*tmp);
        tmp++;
    }while (tmp<(a+128));
    return rt;
}
```

First version has `i` counter, and the address of each element of array is to be calculated at each iteration. The second version is more optimized: the pointer to each element of array is always ready and is sliding 4 bytes forward at each iteration. How to check if the loop is ended? Just compare the pointer with the address just behind array's end, which is, in our case, is happens to be address of imported `__libc_start_main()` function from Glibc 2.0. Sometimes code like this is confusing, and this is very popular optimizing trick, so that's why I made this example.

My second version is very close to what GCC did, and when I compile it, the code is almost the same as in first version, but two first instructions are swapped:

```c
.text:080484D0 public sum_of_a_v2
.text:080484D0 sum_of_a_v2 proc near
.text:080484D0 xor eax, eax
.text:080484D2 mov edx, offset a
.text:080484D7 mov esi, esi
.text:080484D9 lea edi, [edi+0]
.text:080484E0 .text:080484E0 loc_80484E0: ; CODE XREF: sum_of_a_v2+1B
.text:080484E0 add eax, [edx]
.text:080484E2 add edx, 4
.text:080484E5 cmp edx, offset __libc_start_main@@GLIBC_2_0
.text:080484EB jnz short loc_80484E0
.text:080484ED rep retn
.text:080484ED sum_of_a_v2 endp
```

Needless to say, this optimization is possible if the compiler can calculate address of the end of array during compilation time. This happens if the array is global and it's size is fixed.

However, if the address of array is unknown during compilation, but size is fixed, address of the label just behind array's end can be calculated at the beginning of the loop.

### 3.23 More about structures

#### 3.23.1 Sometimes a C structure can be used instead of array

**Arithmetic mean**

```c
#include <stdio.h>

int mean(int *a, int len)
{
    int sum=0;
```
for (int i=0; i<len; i++)
    sum=sum+a[i];
return sum/len;
}

struct five_ints
{
    int a0;
    int a1;
    int a2;
    int a3;
    int a4;
};

int main()
{
    struct five_ints a;
    a.a0=123;
    a.a1=456;
    a.a2=789;
    a.a3=10;
    a.a4=100;
    printf (%d\n", mean(&a, 5));
    // test: https://www.wolframalpha.com/input/?i=mean(123,456,789,10,100)
}

This works: mean() function will never access behind the end of five_ints structure, because 5 is passed, meaning, only 5 integers will be accessed.

Putting string into structure

#include <stdio.h>

struct five_chars
{
    char a0;
    char a1;
    char a2;
    char a3;
    char a4;
} __attribute__ ((aligned (1),packed));

int main()
{
    struct five_chars a;
    a.a0='h';
    a.a1='i';
    a.a2='!';
    a.a3='\n';
    a.a4=0;
    printf (&a); // prints "hi"
}

((aligned (1),packed)) attribute must be used, because otherwise, each structure field will be aligned on 4-byte or 8-byte boundary.

Summary

This is just another example of how structures and arrays are stored in memory. Perhaps, no sane programmer will do something like in this example, except in case of some specific hack. Or maybe in case of source code obfuscation?
3.23. MORE ABOUT STRUCTURES

3.23.2 Unsized array in C structure

In some win32 structures we can find ones with last field defined as an array of one element:

```c
typedef struct _SYMBOL_INFO {
    ULONG SizeOfStruct;
    ULONG TypeIndex;
    ...
    ULONG MaxNameLen;
    TCHAR Name[1];
} SYMBOL_INFO, *PSYMBOL_INFO;

```

This is a hack, meaning, the last field is array of unknown size, which is to be calculated at the time of structure allocation.

Why: Name field may be short, so why to define it with some kind of MAX_NAME constant which can be 128, 256, or even bigger?

Why not to use pointer instead? Then you have to allocate two blocks: one for structure and the other one for string. This may be slower and may require larger memory overhead. Also, you need dereference pointer (i.e., read address of the string from the structure)—not a big deal, but some people say this is still surplus cost.

This is also known as struct hack: http://c-faq.com/struct/structhack.html.

Example:

```c
#include <stdio.h>

struct st {
    int a;
    int b;
    char s[];
};

void f (struct st *s) {
    printf ("%d %d %s\n", s->a, s->b, s->s);
    // f() can't replace s[] with bigger string - size of allocated block is unknown at this point
};

int main() {
    #define STRING "Hello!"
    struct st *s=malloc(sizeof(struct st)+strlen(STRING)+1); // incl. terminating zero
    s->a=1;
    s->b=2;
    strcpy (s->s, STRING);
    f(s);
};
```

In short, it works because C has no array boundary checks. Any array is treated as having infinite size.

Problem: after allocation, the whole size of allocated block for structure is unknown (except for memory manager), so you can't just replace string with larger string. You would still be able to do so if the field would be declared as something like s[MAX_NAME].

In other words, you have a structure plus an array (or string) fused together in the single allocated memory block. Another problem is what you obviously can't declare two such arrays in single structure, or to declare another field after such array.

Older compilers require to declare array with at least one element: s[1], newer allows to declare it as variable-sized array: s[]. This is also called flexible array member in C99 standard.

44https://en.wikipedia.org/wiki/Flexible_array_member
3.23. MORE ABOUT STRUCTURES

Read more about it in GCC documentation\(^45\), MSDN documentation\(^46\).

Dennis Ritchie (one of C creators) called this trick “unwarranted chumminess with the C implementation” (perhaps, acknowledging hackish nature of the trick).

Like it or not, use it or not: it is still another demonstration on how structures are stored in memory, that’s why I write about it.

### 3.23.3 Version of C structure

Many Windows programmers have seen this is MSDN:

<table>
<thead>
<tr>
<th><strong>SizeOfStruct</strong></th>
<th>The size of the structure, in bytes. This member must be set to sizeof(SYMBOL_INFO).</th>
</tr>
</thead>
</table>


Some structures like SYMBOL_INFO has started with this field indeed. Why? This is some kind of structure version.

Imagine you have a function which draws circle. It takes a single argument—a pointer to a structure with only two fields: X and Y. And then color displays flooded a market, sometimes in 1980s. And you want to add color argument to the function. But, let’s say, you cannot add another argument to it (a lot of software use your API\(^47\) and cannot be recompiled). And if the old piece of software uses your API with color display, let your function draw a circle in (default) black and white colors.

Another day you add another feature: circle now can be filled, and brush type can be set.

Here is one solution to the problem:

```c
#include <stdio.h>

struct ver1 {
    size_t SizeOfStruct;
    int coord_X;
    int coord_Y;
};

struct ver2 {
    size_t SizeOfStruct;
    int coord_X;
    int coord_Y;
    int color;
};

struct ver3 {
    size_t SizeOfStruct;
    int coord_X;
    int coord_Y;
    int color;
    int fill_brush_type; // 0 - do not fill circle
};

void draw_circle(struct ver3 *s) // latest struct version is used here
{
    // we presume SizeOfStruct, coord_X and coord_Y fields are always present
    printf ("We are going to draw a circle at %d:%d\n", s->coord_X, s->coord_Y);

    if (s->SizeOfStruct>=sizeof(int)*4) {
        // this is at least ver2, color field is present
        printf ("We are going to set color %d\n", s->color);
    }
}
```

\(^45\)https://gcc.gnu.org/onlinedocs/gcc/Zero-Length.html
\(^47\)Application Programming Interface
if (s->SizeOfStruct>=sizeof(int)*5)
{
    // this is at least ver3, fill_brush_type field is present
    printf ("We are going to fill it using brush type %d\n", s->fill_brush_type);
}

// early software version
void call_as_ver1()
{
    struct ver1 s;
    s.SizeOfStruct=sizeof(s);
    s.coord_X=123;
    s.coord_Y=456;
    printf (** %s()\n", __FUNCTION__);
    draw_circle(&s);
}

// next software version
void call_as_ver2()
{
    struct ver2 s;
    s.SizeOfStruct=sizeof(s);
    s.coord_X=123;
    s.coord_Y=456;
    s.color=1;
    printf (** %s()\n", __FUNCTION__);
    draw_circle(&s);
}

// latest, most advanced version
void call_as_ver3()
{
    struct ver3 s;
    s.SizeOfStruct=sizeof(s);
    s.coord_X=123;
    s.coord_Y=456;
    s.color=1;
    s.fill_brush_type=3;
    printf (** %s()\n", __FUNCTION__);
    draw_circle(&s);
}

int main()
{
    call_as_ver1();
    call_as_ver2();
    call_as_ver3();
}

In other words, SizeOfStruct field takes a role of version of structure field. It could be enumerate type (1, 2, 3, etc.), but to set SizeOfStruct field to sizeof(struct...) is less prone to mistakes/bugs.

In C++, this problem is solved using inheritance (3.18.1 on page 547). You just extend your base class (let’s call it Circle), and then you will have ColoredCircle and then FilledColoredCircle, and so on. A current version of an object (or, more precisely, current type) will be determined using C++ RTTI.

So when you see SizeOfStruct somewhere in MSDN—perhaps this structure was extended at least once in past.

3.23.4 High-score file in “Block out” game and primitive serialization

Many videogames has high-score file, sometimes called “Hall of fame”. Ancient “Block out” game (3D tetris from 1989) isn’t exception, here is what we see at the end:

[^48]: http://www.bestoldgames.net/eng/old-games/blockout.php
3.23. MORE ABOUT STRUCTURES

Figure 3.4: High score table

Now we can see that the file has changed after we added our name is BLSCORE.DAT.

% xxd -g 1 BLSCORE.DAT

All entries are clearly visible. The very first byte is probably number of entries. Second is zero and, in fact, number of entries can be 16-bit value spanning over first two bytes.

Next, after “Xenia” name we see 0xDF and 0x01 bytes. Xenia has score of 479, and this is exactly 0x1DF in hexadecimal radix. So a high score value is probably 16-bit integer, or maybe 32-bit integer: there are two more zero bytes after.

Now let’s think about the fact that both array elements and structure elements are always placed in memory adjacently to each other. That enables us to write the whole array/structure to the file using simple write() or fwrite() function, and then restore it using read() or fread(), as simple as that. This is what is called serialization nowadays.

Read

Now let’s write C program to read highscore file:

```c
#include <assert.h>
#include <stdio.h>
#include <stdint.h>
#include <string.h>

struct entry
{
```

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MORE ABOUT STRUCTURES

```c
char name[11]; // incl. terminating zero
uint32_t score;
char date[11]; // incl. terminating zero
} __attribute__((aligned (1),packed));

struct highscore_file
{
    uint8_t count;
    uint8_t unknown;
    struct entry entries[10];
} __attribute__((aligned (1), packed));

struct highscore_file file;

int main(int argc, char* argv[])
{
    FILE* f=fopen(argv[1], "rb");
    assert (f!=NULL);
    size_t got=fread(&file, 1, sizeof(struct highscore_file), f);
    assert (got==sizeof(struct highscore_file));
    fclose(f);
    for (int i=0; i<file.count; i++)
    {
        printf("name=%s score=%d date=%s\n",
               file.entries[i].name,
               file.entries[i].score,
               file.entries[i].date);
    }
}
```

We need GCC `((aligned (1),packed))` attribute so that all structure fields will be packed on 1-byte boundary.

Of course it works:

```
name=Xenia..... score=479 date=03-27-2018
name=Paul...... score=353 date=03-27-2018
name=John...... score=326 date=03-27-2018
name=James...... score=324 date=03-27-2018
name=Charlie... score=234 date=03-27-2018
name=Mike...... score=181 date=03-27-2018
name=Phil...... score=172 date=03-27-2018
name=Mary...... score=123 date=03-27-2018
name=Tom....... score=119 date=03-27-2018
name=Bob....... score=119 date=03-27-2018
```

(Needless to say, each name is padded with dots, both on screen and in the file, perhaps, for æsthetical reasons.)

Write

Let’s check if we right about width of score value. Is it really has 32 bits?

```
int main(int argc, char* argv[])
{
    FILE* f=fopen(argv[1], "rb");
    assert (f!=NULL);
    size_t got=fread(&file, 1, sizeof(struct highscore_file), f);
    assert (got==sizeof(struct highscore_file));
    fclose(f);

    strcpy (file.entries[1].name, "Mallory...");
    file.entries[1].score=12345678;
    strcpy (file.entries[1].date, "08-12-2016");

    f=fopen(argv[1], "wb");
    assert (f!=NULL);
    got=fwrite(&file, 1, sizeof(struct highscore_file), f);
    assert (got==sizeof(struct highscore_file));
    fclose(f);
```
3.23. MORE ABOUT STRUCTURES

Let’s run Blockout:

![High score table](image1)

**Figure 3.5**: High score table

First two digits (1 or 2) are choked. Perhaps, this is formatting issues... but the number is almost correct. Now I'm changing it to 999999 and run again:

![High score table](image2)

**Figure 3.6**: High score table

Now it’s correct. Yes, high score value is 32-bit integer.

**Is it serialization?**

...almost. Serialization like this is highly popular in scientific and engineering software, where efficiency and speed is much more important than converting into XML\(^{49}\) or JSON\(^{50}\) and back.

One important thing is that you obviously cannot serialize pointers, because each time you load the file into memory, all the structures may be allocated in different places.

\(^{49}\text{Extensible Markup Language}\)

\(^{50}\text{JavaScript Object Notation}\)
But: if you work on some kind of low-cost MCU with simple OS on it and you have your structures allocated at always same places in memory, perhaps you can save and restore pointers as well.

Random noise

When I prepared this example, I had to run “Block out” many times and played for it a bit to fill high-score table with random names.

And when there were just 3 entries in the file, I saw this:

```
00000000: 03 00 54 6f 6d 61 73 2e 2e 2e 2e 2e 00 da 2a 00 ..Tomas.......*.
00000010: 00 30 38 2d 31 32 2d 32 30 31 36 00 43 68 61 72 .08-12-2016.Char
00000020: 6c 69 65 2e 2e 2e 00 8b 1e 00 00 30 38 2d 31 32 lie........08-12
00000030: 2d 32 30 31 36 00 4a 6f 68 6e 2e 2e 2e 2e 2e 2e -2016.John......
00000040: 00 00 00 00 00 00 00 30 38 2d 31 32 2d 32 30 31 36 00 .....08-12-2016.
00000050: 00 00 57 c8 a2 01 06 01 ba f9 47 c7 05 00 f8 4f ..W.......G....0
00000060: 06 01 06 01 a6 32 00 00 00 00 00 00 00 00 00 00 ..........2.
00000070: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ............
00000080: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ............
00000090: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ............
000000a0: 00 00 00 00 00 00 00 00 39 c6 a2 01 46 72 ............Fr
000000b0: 8c f9 f6 c5 05 00 fb 4f 00 02 06 01 a6 32 0e 01 ........0....2..
000000c0: 00 00 98 f9 f2 c0 05 00 fb 4f 00 02 a6 32 a2 09 ..........0...2..
000000d0: 80 c1 a6 32 a6 32 fb 4f ba f9 39 c1 a6 32 0e 01 ...2..O...9..2..
000000e0: b4 f9 2b c5 a6 32 e1 4f 05 00 00 00 00 a6 32 d4 f9 76 2d 0.........2..v-
000000f0: a6 32 00 00 00 00 .2....
```

The first byte has value of 3, meaning there are 3 entries. And there are 3 entries present. But then we see a random noise at the second half of file.

The noise is probably has its origins in uninitialized data. Perhaps, “Block out” allocated memory for 10 entries somewhere in heap, where, obviously, some pseudorandom noise (left from something else) was present. Then it set first/second byte, fill 3 entries, and then it never touched 7 entries left, so they are written to the file as is.

When “Block out” loads high score file at the next run, it reads number of entries from the first/second byte (3) and then completely ignores what is after it.

This is common problem. Not a problem in strict sense: it’s not a bug, but information can be exposed outwards.

Microsoft Word versions from 1990s has been often left pieces of previously edited texts into the *.doc* files. It was some kind of amusement back then, to get a .doc file from someone, then open it in a hexadecimal editor and read something else, what has been edited on that computer before.

The problem can be even much more serious: Heartbleed bug in OpenSSL.

Homework

“Block out” has several polycubes (flat/basic/extended), size of pit can be configured, etc. And it seems, for each configuration, “Block out” has its own high score table. I’ve noticed that some information is probably stored in BLSCORE.IDX file. This can be a homework for hardcore “Block out” fans—to understand its structure as well.

The “Block out” files are here: [http://beginners.re/examples/blockout.zip](http://beginners.re/examples/blockout.zip) (including the binary high score files I’ve used in this example). You can use DosBox to run it.

### 3.24 memmove() and memcpy()

The difference between these standard functions is that `memcpy()` blindly copies a block to another place, while `memmove()` correctly handles overlapping blocks. For example, you want to tug a string two bytes forward:

[51](https://en.wikipedia.org/wiki/Heartbleed)
3.25. SETJMP/LONGJMP

memcpy() which copies 32-bit or 64-bit words at once, or even SIMD, will obviously fail here, a byte-wise copy routine must be used instead.

Now even more advanced example, insert two bytes in front of string:

```
`|.|.|h|e|l|l|o|...`  ->  `|h|e|l|l|o|...`
```

Now even byte-wise memory copy routine will fail, you have to copy bytes starting at the end.

That’s a rare case where DF x86 flag is to be set before REP MOVSB instruction: DF defines direction, and now we must move backwardly.

The typical memmove() routine works like this: 1) if source is below destination, copy forward; 2) if source is above destination, copy backward.

This is memmove() from uClibc:

```c
void *memmove(void *dest, const void *src, size_t n)
{
    int eax, ecx, esi, edi;
    asm volatile(
        " movl \%eax, \%edi\n"
        " cmpl \%esi, \%eax\n"
        " je 2f\n" /* (optional) src == dest -> NOP */
        " jb 1f\n" /* src > dest -> simple copy */
        " leal \-%esi,\%ecx\n"
        " leal \-%eax,\%ecx\n"
        " std\n"
        "1: rep; movsb\n"
        " cld\n"
        "2:\n"
    :
        " =&c" (ecx), " =65" (esi), " =6a" (eax), " =6d" (edi)
        " =0" (n), " =1" (src), " =2" (dest)
        " =memory"
    :
    );
    return (void*)eax;
}
```

In the first case, REP MOVSB is called with DF flag cleared. In the second, DF is set, then cleared.

More complex algorithm has the following piece in it:

“if difference between source and destination is larger than width of word, copy using words rather than bytes, and use byte-wise copy to copy unaligned parts”.

This how it happens in Glibc 2.24 in non-optimized C part.

Given all that, memmove() may be slower than memcpy(). But some people, including Linus Torvalds, argue\(^{32}\) that memcpy() should be an alias (or synonym) of memmove(), and the latter function must just check at start, if the buffers are overlapping or not, and then behave as memcpy() or memmove(). Nowadays, check for overlapping buffers is very cheap, after all.

3.24.1 Anti-debugging trick

I’ve heard about anti-debugging trick where all you need is just set DF to crash the process: the very next memcpy() routine will lead to crash because it copies backwardly. But I can’t check this: it seems all memory copy routines clear/set DF as they want to. On the other hand, memmove() from uClibc I cited here, has no explicit clear of DF (it assumes DF is always clear?), so it can really crash.

3.25 setjmp/longjmp

setjmp/longjmp is a mechanism in C which is very similar to throw/catch mechanism in C++ and other higher-level PLs. Here is an example from zlib:

---

\(^{32}\)https://bugzilla.redhat.com/show_bug.cgi?id=638477#c132
```c
#include <stdio.h>
#include <setjmp.h>

jmp_buf env;

void f2()
{
    printf ("%s() begin\n", __FUNCTION__);  
    // something odd happened here
    longjmp (env, 1234);
    printf ("%s() end\n", __FUNCTION__);
}

void f1()
{
    printf ("%s() begin\n", __FUNCTION__);  
    f2();
    printf ("%s() end\n", __FUNCTION__);
}

int main()
{
    int err=setjmp(env);
    if (err==0)
    {
        f1();
    }
    else
    {
        printf ("Error %d\n", err);
    }
}
```

If we run it, we will see:

```
f1() begin
f2() begin
Error 1234
```
jmp_buf structure usually comes undocumented, to preserve forward compatibility.

Let's see how `setjmp()` implemented in MSVC 2013 x64:

```assembly
... ; RCX = address of jmp_buf
    mov [rcx], rax
    mov [rcx+8], rbx
    mov [rcx+18h], rbp
    mov [rcx+28h], rdi
    mov [rcx+30h], r12
    mov [rcx+38h], r13
    mov [rcx+40h], r14
    mov [rcx+48h], r15
    lea r8, [rsp+arg_0]
    mov [rcx+10h], r8
    mov r8, [rsp+0] ; get saved RA from stack
    mov [rcx+50h], r8 ; save it
    stmxcsr dword ptr [rcx+58h]
    fnstcw word ptr [rcx+5Ch]
    movq xmmword ptr [rcx+60h], xmm6
    movq xmmword ptr [rcx+70h], xmm7
    movq xmmword ptr [rcx+80h], xmm8
    movq xmmword ptr [rcx+90h], xmm9
    movq xmmword ptr [rcx+0A0h], xmm10
    movq xmmword ptr [rcx+0B0h], xmm11
    movq xmmword ptr [rcx+0C0h], xmm12
    movq xmmword ptr [rcx+0D0h], xmm13
    movq xmmword ptr [rcx+0E0h], xmm14
    movq xmmword ptr [rcx+0F0h], xmm15
    ret
```

It just populates jmp_buf structure with current values of almost all registers. Also, current value of RA is taken from the stack and saved in jmp_buf: it will be used as new value of PC in future.

Now `longjmp()`:

```assembly
... ; RCX = address of jmp_buf
    mov rax, rdx
    mov rbx, [rcx+8]
    mov rsi, [rcx+20h]
    mov rdi, [rcx+28h]
    mov r12, [rcx+30h]
    mov r13, [rcx+38h]
    mov r14, [rcx+40h]
    mov r15, [rcx+48h]
    ldmxcsr dword ptr [rcx+58h]
    fnclcx
    fldcw word ptr [rcx+5Ch]
    movq xmm6, xmmword ptr [rcx+60h]
    movq xmm7, xmmword ptr [rcx+70h]
    movq xmm8, xmmword ptr [rcx+80h]
    movq xmm9, xmmword ptr [rcx+90h]
    movq xmm10, xmmword ptr [rcx+0A0h]
    movq xmm11, xmmword ptr [rcx+0B0h]
    movq xmm12, xmmword ptr [rcx+0C0h]
    movq xmm13, xmmword ptr [rcx+0D0h]
    movq xmm14, xmmword ptr [rcx+0E0h]
    movq xmm15, xmmword ptr [rcx+0F0h]
    mov rdx, [rcx+50h] ; get PC (RIP)
    mov rbp, [rcx+18h]
    mov rsp, [rcx+10h]
    jmp rdx ; jump to saved PC
```

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It just restores (almost) all registers, takes RA from structure and jumps there. This effectively works as if setjmp() returned to caller. Also, RAX is set to be equal to the second argument of longjmp(). This works as if setjmp() returned non-zero value at first place.

As a side effect of SP restoration, all values in stack which has been set and used between setjmp() and longjmp() calls are just dropped. They will not be used anymore. Hence, longjmp() usually jumps backwards\(^{53}\).

This implies that, unlike in throw/catch mechanism in C++, no memory will be freed, no destructors will be called, etc. Hence, this technique sometimes can be dangerous. Nevertheless, it’s still quite popular. It’s still used in Oracle RDBMS.

It also has an unexpected side-effect: if some buffer has been overflown inside of a function (maybe due to remote attack), and a function wants to report error, and it calls longjmp(), overwritten stack part just gets unused.

As an exercise, you can try to understand, why not all registers are saved. Why XMM0-XMMS and other registers are skipped?

### 3.26 Other weird stack hacks

#### 3.26.1 Accessing arguments/local variables of caller

From C/C++ basics we know that this is impossible for a function to access arguments of caller function or its local variables.

Nevertheless, it’s possible using dirty hacks. For example:

```c
#include <stdio.h>

void f(char *text)
{
    // print stack
    int *tmp=&text;
    for (int i=0; i<20; i++)
    {
        printf ("0x%\n", *tmp);
        tmp++;
    }
};

void draw_text(int X, int Y, char* text)
{
    f(text);
    printf ("We are going to draw [%s] at %d:%d\n", text, X, Y);
};

int main()
{
    printf ("address of main()=0x%\n", &main);
    printf ("address of draw_text()=0x%\n", &draw_text);
    draw_text(100, 200, "Hello!");
};
```

On 32-bit Ubuntu 16.04 and GCC 5.4.0, I got this:

```
address of main()=0x80484f8
address of draw_text()=0x80484cb
0x8048645  ~ first argument to f()
0x8048628
0xbf8ab98
```

\(^{53}\)However, there are some people who can use it for much more complicated things, imitating coroutines, etc: https://www.embeddedrelated.com/showarticle/455.php, http://fanf.livejournal.com/105413.html
Since \( f() \) starting to enumerate stack elements at its first argument, the first stack element is indeed a pointer to “Hello!” string. We see its address is also used as third argument to \( \text{draw}_\text{text}() \) function.

In \( f() \) we could read all functions arguments and local variables if we know exact stack layout, but it’s always changed, from compiler to compiler. Various optimization levels affect stack layout greatly.

But if we can somehow detect information we need, we can use it and even modify it. As an example, I’ll rework \( f() \) function:

```c
void f(char *text)
{
    ...
    // find 100, 200 values pair and modify the second on
    tmp=&text;
    for (int i=0; i<20; i++)
    {
        if (*tmp==100 && *(tmp+1)==200)
        {
            printf("found\n");
            *(tmp+1)=210; // change 200 to 210
            break;
        }
        tmp++;
    }
}
```

Holy moly, it works:

```
found
We are going to draw [Hello!] at 100:210
```

### Summary

It’s extremely dirty hack, intended to demonstrate stack internals. I never ever seen or heard that anyone used this in a real code. But still, this is a good example.

### Exercise

The example has been compiled without optimization on 32-bit Ubuntu using GCC 5.4.0 and it works. But when I turn on -O3 maximum optimization, it’s failed. Try to find why.

Use your favorite compiler and OS, try various optimization levels, find if it works and if it doesn’t, find why.
This is classic bug from Brian W. Kernighan, Rob Pike, *Practice of Programming*, (1999):

```c
#include <stdio.h>

char* amsg(int n, char* s)
{
    char buf[100];
    sprintf (buf, "error %d: %s
", n, s);
    return buf;
}

int main()
{
    amsg ("%s
", interim (1234, "something wrong!
");
}
```

It would crash. First, let's understand, why.

This is a stack state before `amsg()` return:

(lower addresses)

[amsg(): 100 bytes]  <- current SP
[RA]
[two amsg arguments]
[something else]
[main() local variables]

(upper addresses)

When `amsg()` returns control flow to `main()`, so far so good. But `printf()` is called from `main()`, which is, in turn, use stack for its own needs, zapping 100-byte buffer. A random garbage will be printed at the best.

Hard to believe, but I know how to fix this problem:

```c
#include <stdio.h>

char* amsg(int n, char* s)
{
    char buf[100];
    sprintf (buf, "error %d: %s
", n, s);
    return buf;
}

char* interim (int n, char* s)
{
    char large_buf[8000];
    // make use of local array.
    // it will be optimized away otherwise, as useless.
    large_buf[0]=0;
    return amsg (n, s);
}

int main()
{
    printf ("%s
", interim (1234, "something wrong!
");
}
```

It will work if compiled by MSVC 2013 with no optimizations and with `/GS-` option\(^{54}\). MSVC will warn: "warning C4172: returning address of local variable or temporary", but the code will run and message will be printed. Let's see stack state at the moment when `amsg()` returns control to `interim()`:

\(^{54}\)Turn off buffer security check
Now the stack state at the moment when interim() returns control to main():

So when main() calls printf(), it uses stack at the place where interim()'s buffer was allocated, and doesn’t zap 100 bytes with error message inside, because 8000 bytes (or maybe much less) is just enough for everything printf() and other descending functions do!

It may also work if there are many functions between, like: main() → f1() → f2() → f3() ... → amsg(), and then the result of amsg() is used in main(). The distance between SP in main() and address of buf[] must be long enough,

This is why bugs like these are dangerous: sometimes your code works (and bug can be hiding unnoticed), sometimes not. Bugs like these are jokingly called heisenbugs or schrödinbugs.

3.27 OpenMP

OpenMP is one of the simplest ways to parallelize simple algorithms.

As an example, let’s try to build a program to compute a cryptographic nonce.

In my simplistic example, the nonce is a number added to the plain unencrypted text in order to produce a hash with some specific features.

For example, at some step, the Bitcoin protocol requires to find such nonce so the resulting hash contains a specific number of consecutive zeros. This is also called “proof of work” (i.e., the system proves that it did some intensive calculations and spent some time for it).

My example is not related to Bitcoin in any way, it will try to add numbers to the “hello, world!_” string in order to find such number that when “hello, world!_<number>” is hashed with the SHA512 algorithm, it will contain at least 3 zero bytes.

Let’s limit our brute-force to the interval in 0..INT32_MAX-1 (i.e., 0x7FFFFFFE or 2147483646).

The algorithm is pretty straightforward:

```c
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <time.h>
#include "sha512.h"

int found=0;
int32_t checked=0;
int32_t* __min;
```

---

56 [wikipedia](https://en.wikipedia.org/wiki/Heisenbug)
```c
int32_t* __max;

time_t start;

#ifdef __GNUC__
#define min(X,Y) ((X) < (Y) ? (X) : (Y))
#define max(X,Y) ((X) > (Y) ? (X) : (Y))
#endif

void check_nonce (int32_t nonce)
{
    uint8_t buf[32];
    struct sha512_ctx ctx;
    uint8_t res[64];

    // update statistics
    int t=omp_get_thread_num();
    if (__min[t]==-1)
        __min[t]=nonce;
    if (__max[t]==-1)
        __max[t]=nonce;
    __min[t]=min(__min[t], nonce);
    __max[t]=max(__max[t], nonce);

    // idle if valid nonce found
    if (found)
        return;

    memset (buf, 0, sizeof(buf));
    sprintf (buf, "hello, world!_%d", nonce);
    sha512_init_ctx (&ctx);
    sha512_process_bytes (buf, strlen(buf), &ctx);
    sha512_finish_ctx (&ctx, &res);
    if (res[0]==0 && res[1]==0 && res[2]==0)
    {
        printf ("found (thread %d): [%s]. seconds spent=%d\n", t, buf, time(NULL)-start);
        found=1;
    }
    #pragma omp atomic
    checked++;
    #pragma omp critical
    if ((checked % 100000)==0)
        printf ("checked=%d\n", checked);
}

int main()
{
    int32_t i;
    int threads=omp_get_max_threads();
    printf ("threads=%d\n", threads);

    __min=(int32_t*)malloc(threads*sizeof(int32_t));
    __max=(int32_t*)malloc(threads*sizeof(int32_t));
    for (i=0; i<threads; i++)
        __min[i]=__max[i]=-1;

    start=time(NULL);

    #pragma omp parallel for
    for (i=0; i<INT32_MAX; i++)
        check_nonce (i);

    for (i=0; i<threads; i++)
        printf ("__min[%d]=0x%08x __max[%d]=0x%08x\n", i, __min[i], i, __max[i]);
```
The check_nonce() function just adds a number to the string, hashes it with the SHA512 algorithm and checks for 3 zero bytes in the result.

A very important part of the code is:

```c
#pragma omp parallel for
for (i=0; i<INT32_MAX; i++)
    check_nonce (i);
```

Yes, that simple, without #pragma we just call check_nonce() for each number from 0 to INT32_MAX (0x7fffffff or 2147483647). With #pragma, the compiler adds some special code which slices the loop interval into smaller ones, to run them on all CPU cores available.\(^57\)

The example can be compiled\(^58\) in MSVC 2012:

```
cl openmp_example.c sha512.obj /openmp /O1 /Zi /Faopenmp_example.asm
```

Or in GCC:

```
gcc -fopenmp 2.c sha512.c -S -masm=intel
```

### 3.27.1 MSVC

Now this is how MSVC 2012 generates the main loop:

Listing 3.122: MSVC 2012

```
push OFFSET _main$omp$1
push 0
push 1
call __vcomp_fork
add esp, 16
```

All functions prefixed by vcomp are OpenMP-related and are stored in the vcomp*.dll file. So here a group of threads is started.

Let's take a look on _main$omp$1:

Listing 3.123: MSVC 2012

```
$T1 = -8 ; size = 4
$T2 = -4 ; size = 4
_main$omp$1 PROC
push ebp
mov ebp, esp
push ecx
push ecx
push esi
lea eax, DWORD PTR $T2[ebp]
push eax
lea eax, DWORD PTR $T1[ebp]
push eax
push 1
push 1
push 2147483646 ; 7fffffffH
push 0
call __vcomp_for_static_simple_init
mov esi, DWORD PTR $T1[ebp]
add esp, 24
jmp SHORT $LN6@main$omp$1
$LL2@main$omp$1:
push esi
call __check_nonce
```

---

\(^{57}\)N.B.: This is intentionally simplest possible example, but in practice, the usage of OpenMP can be harder and more complex

\(^{58}\)sha512.(c|h) and u64.h files can be taken from the OpenSSL library: [http://go.yurichev.com/17324](http://go.yurichev.com/17324)
This function is to be started \( n \) times in parallel, where \( n \) is the number of CPU cores. vcomp_for_static_simple_init() calculates the interval for the for() construct for the current thread, depending on the current thread’s number.

The loop’s start and end values are stored in the $T1$ and $T2$ local variables. You may also notice 7fffffff (or 2147483646) as an argument to the vcomp_for_static_simple_init() function—this is the number of iterations for the whole loop, to be divided evenly.

Then we see a new loop with a call to the check_nonce() function, which does all the work.

Let’s also add some code at the beginning of the check_nonce() function to gather statistics about the arguments with which the function has been called.

This is what we see when we run it:

```
threads=4
...
checked=2800000
checked=3000000
checked=3200000
checked=3300000
found (thread 3): [hello, world!_1611446522]. seconds spent=3
__min[0]=0x00000000 __max[0]=0xffffffff
__min[1]=0x20000000 __max[1]=0x3fffffff
__min[2]=0x40000000 __max[2]=0x5fffffff
__min[3]=0x60000000 __max[3]=0x7fffffff
```
3.27. OPENMP

```plaintext
add esp, 12
; Line 56
mov ecx, DWORD PTR _checked
mov eax, ecx
cdq
mov esi, 100000 ; 000186a0H
test edx, edx
jne SHORT $LN1@check_nonc
; Line 57
push ecx
push OFFSET ??_C@_0M@NPNHLIOO@checked?$DN?$CFd?6?$AA@
call _printf
pop ecx
pop ecx
$LN1@check_nonc:
push DWORD PTR _$vcomp$critsect$
call __vcomp_leave_critsect
pop ecx
```

As it turns out, the vcomp_atomic_add_i4() function in the vcomp*.dll is just a tiny function with the LOCK XADD instruction\(^{59}\) in it.

vcomp_enter_critsect() eventually calling win32 API function EnterCriticalSection()\(^{60}\).

3.27.2 GCC

GCC 4.8.1 produces a program which shows exactly the same statistics table, so, GCC’s implementation divides the loop in parts in the same fashion.

```
Listing 3.125: GCC 4.8.1
```

```
mov edi, OFFSET FLAT:main._omp_fn.0
call GOMP_parallel_start
mov edi, 0
call main._omp_fn.0
call GOMP_parallel_end
```

Unlike MSVC’s implementation, what GCC code does is to start 3 threads, and run the fourth in the current thread. So there are 4 threads instead of the 5 in MSVC.

Here is the main._omp_fn.0 function:

```
Listing 3.126: GCC 4.8.1
```

```
main._omp_fn.0:
push rbp
mov rbp, rsp
push rbx
sub rsp, 40
mov QWORD PTR [rbp-40], rdi
call omp_get_num_threads
mov ebx, eax
call omp_get_thread_num
mov esi, eax
mov eax, 2147483647 ; 0x7FFFFFFF
cdq
idiv ebx
mov ecx, eax
mov eax, 2147483647 ; 0x7FFFFFFF
cdq
idiv ebx
mov eax, edx
cmp esi, eax
jl .L15
```

\(^{59}\)Read more about LOCK prefix: .1.6 on page 1026

\(^{60}\)You can read more about critical sections here: 6.5.4 on page 787
Here we see the division clearly: by calling `omp_get_num_threads()` and `omp_get_thread_num()`
we get the number of threads running, and also the current thread’s number, and then determine the
loop’s interval. Then we run `check_nonce()`.

GCC also inserted the `LOCK ADD`
instruction right in the code, unlike MSVC, which generated a call to a separate DLL function:

```
Listing 3.127: GCC 4.8.1

lock add DWORD PTR checked[rip], 1
call GOMP_critical_start
mov ecx, DWORD PTR checked[rip]
add ecx, 1
imul edx
sar edx, 13
mov eax, ecx
sar eax, 31
sub edx, eax
imul eax, eax, 100000
sub ecx, eax
mov eax, ecx
test eax, eax
jne .L7
mov eax, DWORD PTR checked[rip]
mov esi, eax
mov edi, OFFSET FLAT:.LC2 ; "checked=%d\n"
mov eax, 0
call printf
.L7:
call GOMP_critical_end
```

The functions prefixed with GOMP are from GNU OpenMP library. Unlike vcomp*.dll, its source code is freely available: GitHub.

### 3.28 Another heisenbug

Sometimes, array (or buffer) can overflow due to fencepost error:
### 3.29. WINDOWS 16-BIT

16-bit Windows programs are rare nowadays, but can be used in the cases of retrocomputing or dongle hacking (8.5 on page 815).

16-bit Windows versions were up to 3.11. 95/98/ME also support 16-bit code, as well as the 32-bit versions of the Windows NT line. The 64-bit versions of Windows NT line do not support 16-bit executable code at all.

The code resembles MS-DOS’s one.

Executable files are of type NE-type (so-called “new executable”).
3.29. WINDOWS 16-BIT

All examples considered here were compiled by the OpenWatcom 1.9 compiler, using these switches:

```
wcl.exe -i=C:/WATCOM/h/win/ -s -os -bt=windows -bcl=windows example.c
```

### 3.29.1 Example#1

```c
#include <windows.h>

int PASCAL WinMain( HINSTANCE hInstance,
                     HINSTANCE hPrevInstance,
                     LPSTR lpCmdLine,
                     int nCmdShow )
{
    MessageBeep(MB_ICONEXCLAMATION);
    return 0;
}
```

```
WinMain proc near
    push   bp
    mov    bp, sp
    mov    ax, 30h ; '0' ; MB_ICONEXCLAMATION constant
    push   ax
    call   MESSAGEBEEP
    xor    ax, ax ; return 0
    pop    bp
    retn   0Ah
WinMain endp
```

Seems to be easy, so far.

### 3.29.2 Example #2

```c
#include <windows.h>

int PASCAL WinMain( HINSTANCE hInstance,
                     HINSTANCE hPrevInstance,
                     LPSTR lpCmdLine,
                     int nCmdShow )
{
    MessageBox (NULL, "hello, world", "caption", MB_YESNOCANCEL);
    return 0;
}
```

```
WinMain proc near
    push   bp
    mov    bp, sp
    xor    ax, ax ; NULL
    push   ax
    push   ds
    mov    ax, offset aHelloWorld ; 0x18. "hello, world"
    push   ax
    push   ds
    mov    ax, offset aCaption ; 0x10. "caption"
    push   ax
    push   ax
    mov    ax, 3 ; MB_YESNOCANCEL
    call   MESSAGEBOX
    xor    ax, ax ; return 0
    pop    bp
    retn   0Ah
WinMain endp
```

dseg02:0010 aCaption db 'caption',0
dseg02:0018 aHelloWorld db 'hello, world',0
3.29. WINDOWS 16-BIT

Couple important things here: the PASCAL calling convention dictates passing the first argument first (MB_YESNOCANCEL), and the last argument—last (NULL). This convention also tells the callee to restore the stack pointer: hence the RETN instruction has 0Ah as argument, which implies that the pointer has to be increased by 10 bytes when the function exits. It is like stdcall (6.1.2 on page 734), but the arguments are passed in “natural” order.

The pointers are passed in pairs: first the data segment is passed, then the pointer inside the segment. There is only one segment in this example, so DS always points to the data segment of the executable.

3.29.3 Example #3

```c
#include <windows.h>

int PASCAL WinMain( HINSTANCE hInstance,
                    HINSTANCE hPrevInstance,
                    LPSTR lpCmdLine,
                    int nCmdShow )
{
    int result=MessageBox (NULL, "hello, world", "caption", MB_YESNOCANCEL);
    if (result==IDCANCEL)
        MessageBox (NULL, "you pressed cancel", "caption", MB_OK);
    else if (result==IDYES)
        MessageBox (NULL, "you pressed yes", "caption", MB_OK);
    else if (result==IDNO)
        MessageBox (NULL, "you pressed no", "caption", MB_OK);
    return 0;
};
```

```assembly
WinMain proc near
push bp
mov bp, sp
xor ax, ax ; NULL
push ax
push ds
mov ax, offset aHelloWorld ; "hello, world"
push ax
push ds
mov ax, offset aCaption ; "caption"
push ax
mov ax, 3 ; MB_YESNOCANCEL
push ax
call MESSAGEBOX
cmp ax, 2 ; IDCANCEL
jnz short loc_2F
xor ax, ax
push ax
push ds
mov ax, offset aYouPressedCanc ; "you pressed cancel"
jmp short loc_49
loc_2F:
cmp ax, 6 ; IDYES
jnz short loc_3D
xor ax, ax
push ax
push ds
mov ax, offset aYouPressedYes ; "you pressed yes"
jmp short loc_49
loc_3D:
cmp ax, 7 ; IDNO
jnz short loc_57
xor ax, ax
push ax
push ds
mov ax, offset aYouPressedNo ; "you pressed no"
loc_49:
push ax
```

651
Somewhat extended example from the previous section.

### 3.29.4 Example #4

```c
#include <windows.h>

int PASCAL func1 (int a, int b, int c)
{
    return a*b+c;
};

long PASCAL func2 (long a, long b, long c)
{
    return a*b+c;
};

long PASCAL func3 (long a, long b, long c, int d)
{
    return a*b+c-d;
};

int PASCAL WinMain( HINSTANCE hInstance,
                  HINSTANCE hPrevInstance,
                  LPSTR lpCmdLine,
                  int nCmdShow )
{
    func1 (123, 456, 789);
    func2 (600000, 700000, 800000);
    func3 (600000, 700000, 800000, 123);
    return 0;
};

func1 proc near
    c = word ptr 4
    b = word ptr 6
    a = word ptr 8

    push bp
    mov bp, sp
    mov ax, [bp+a]
    imul [bp+b]
    add ax, [bp+c]
    pop bp
    retn 6
func1 endp

func2 proc near
    arg_0 = word ptr 4
    arg_2 = word ptr 6
    arg_4 = word ptr 8
    arg_6 = word ptr 0Ah
    arg_8 = word ptr 0Ch
    arg_A = word ptr 0Eh
```
push bp
mov bp, sp
mov ax, [bp+arg_8]
mov dx, [bp+arg_A]
mov bx, [bp+arg_4]
mov cx, [bp+arg_6]
call sub_B2 ; long 32-bit multiplication
add ax, [bp+arg_0]
adc dx, [bp+arg_2]
pop bp
retn 12

func2 endp

func3 proc near
arg_0 = word ptr 4
arg_2 = word ptr 6
arg_4 = word ptr 8
arg_6 = word ptr 0Ah
arg_8 = word ptr 0Ch
arg_A = word ptr 0Eh
arg_C = word ptr 10h
push bp
mov bp, sp
mov ax, [bp+arg_A]
mov dx, [bp+arg_C]
mov bx, [bp+arg_6]
mov cx, [bp+arg_8]
call sub_B2 ; long 32-bit multiplication
mov cx, [bp+arg_2]
add cx, ax
mov bx, [bp+arg_4]
adc bx, dx  ; BX=high part, CX=low part
mov ax, [bp+arg_0]
cwd  ; AX=low part d, DX=high part d
sub cx, ax
mov ax, cx
sbb bx, dx
mov dx, bx
pop bp
retn 14
func3 endp

WinMain proc near
push bp
mov bp, sp
mov ax, 123
push ax
mov ax, 456
push ax
mov ax, 789
push ax
call func1
mov ax, 9  ; high part of 600000
push ax
mov ax, 27C0h  ; low part of 600000
push ax
mov ax, 0Ah  ; high part of 700000
push ax
mov ax, 0AE60h ; low part of 700000
push ax
mov ax, 0Ch  ; high part of 800000
push ax
mov ax, 3500h ; low part of 800000
push ax
call func2
mov ax, 9  ; high part of 600000
push ax
32-bit values (the long data type implies 32 bits, while int is 16-bit) in 16-bit code (both MS-DOS and Win16) are passed in pairs. It is just like when 64-bit values are used in a 32-bit environment (1.28 on page 396).

sub_B2 here is a library function written by the compiler’s developers that does “long multiplication”, i.e., multiplies two 32-bit values. Other compiler functions that do the same are listed here: .5 on page 1043, .4 on page 1043.

The ADD/ADC instruction pair is used for addition of compound values: ADD may set/clear the CF flag, and ADC uses it after.

The SUB/SBB instruction pair is used for subtraction: SUB may set/clear the CF flag, SBB uses it after.

32-bit values are returned from functions in the DX:AX register pair.

Constants are also passed in pairs in WinMain() here.

The int-typed 123 constant is first converted according to its sign into a 32-bit value using the CWD instruction.

### 3.29.5 Example #5

```c
#include <windows.h>

int PASCAL string_compare (char *s1, char *s2)
{
    while (1)
    {
        if (*s1!=*s2) return 0;
        if (*s1==0 || *s2==0) return 1; // end of string
        s1++;
        s2++;
    }
}

int PASCAL string_compare_far (char far *s1, char far *s2)
{
    while (1)
    {
        if (*s1!=*s2) return 0;
        if (*s1==0 || *s2==0) return 1; // end of string
        s1++;
        s2++;
    }
}
```
void PASCAL remove_digits (char *s)
{
    while (*s)
    {
        if (*s>='0' && *s<='9')
            *s='.';
        s++;
    }
};

char str[]="hello 1234 world";

int PASCAL WinMain( HINSTANCE hInstance,
                      HINSTANCE hPrevInstance,
                      LPSTR lpCmdLine,
                      int nCmdShow )
{
    string_compare ("asd", "def");
    string_compare_far ("asd", "def");
    remove_digits (str);
    MessageBox (NULL, str, "caption", MB_YESNOCANCEL);
    return 0;
};

string_compare proc near
arg_0 = word ptr 4
arg_2 = word ptr 6

push bp
mov bp, sp
push si
mov si, [bp+arg_0]
mov bx, [bp+arg_2]

loc_12: ; CODE XREF: string_compare+21j
mov al, [bx]
cmp al, [si]
jz short loc_1C
xor ax, ax
jmp short loc_2B

loc_1C: ; CODE XREF: string_compare+Ej
test al, al
jz short loc_22
jnz short loc_27

loc_22: ; CODE XREF: string_compare+16j
mov ax, 1
jmp short loc_2B

loc_27: ; CODE XREF: string_compare+18j
inc bx
inc si
jmp short loc_12

loc_2B: ; CODE XREF: string_compare+12j
; string_compare+1Dj
pop si
pop bp
retn 4

string_compare far proc near ; CODE XREF: WinMain+18p
arg_0 = word ptr 4
arg_2 = word ptr 6
arg_4 = word ptr 8
arg_6 = word ptr 0Ah

    push   bp
    mov    bp, sp
    push   si
    mov    si, [bp+arg_0]
    mov    bx, [bp+arg_4]

loc_3A: ; CODE XREF: string_compare_far+35j
    mov    es, [bp+arg_6]
    mov    al, es:[bx]
    mov    es, [bp+arg_2]
    cmp    al, es:[si]
    jz     short loc_4C
    xor    ax, ax
    jmp    short loc_67

loc_4C: ; CODE XREF: string_compare_far+16j
    mov    es, [bp+arg_6]
    cmp    byte ptr es:[bx], 0
    jz     short loc_5E
    mov    es, [bp+arg_2]
    cmp    byte ptr es:[si], 0
    jnz    short loc_63

loc_5E: ; CODE XREF: string_compare_far+23j
    mov    ax, 1
    jmp    short loc_67

loc_63: ; CODE XREF: string_compare_far+2Cj
    inc    bx
    inc    si
    jmp    short loc_3A

loc_67: ; CODE XREF: string_compare_far+1Aj
    pop    si
    pop    bp
    retn   0

string_compare_far endp

remove_digits proc near ; CODE XREF: WinMain+1Fp

arg_0 = word ptr 4

    push   bp
    mov    bp, sp
    mov    bx, [bp+arg_0]

loc_72: ; CODE XREF: remove_digits+18j
    mov    al, [bx]
    test   al, al
    jz     short loc_86
    cmp    al, 30h ; '0'
    jb     short loc_83
    cmp    al, 39h ; '9'
    ja     short loc_83
    mov    byte ptr [bx], 2Dh ; '-'

loc_83: ; CODE XREF: remove_digits+Ej
    ; remove_digits+12j
    inc    bx
    jmp    short loc_72

remove_digits endp
Here we see a difference between the so-called “near” pointers and the “far” pointers: another weird artifact of segmented memory in 16-bit 8086.

You can read more about it here: 11.6 on page 1003.

“near” pointers are those which point within the current data segment. Hence, the `string_compare()` function takes only two 16-bit pointers, and accesses the data from the segment that DS points to (The `mov al, [bx]` instruction actually works like `mov al, ds:[bx]`—DS is implicit here).

“far” pointers are those which may point to data in another memory segment. Hence `string_compare_far()` takes the 16-bit pair as a pointer, loads the high part of it in the ES segment register and accesses the data through it (`mov al, es:[bx]`). “far” pointers are also used in my `MessageBox()` win16 example: 3.29.2 on page 650. Indeed, the Windows kernel is not aware which data segment to use when accessing text strings, so it need the complete information.

The reason for this distinction is that a compact program may use just one 64kb data segment, so it doesn’t need to pass the high part of the address, which is always the same. A bigger program may use several 64kb data segments, so it needs to specify the segment of the data each time.

It’s the same story for code segments. A compact program may have all executable code within one 64kb-segment, then all functions in it will be called using the `CALL NEAR` instruction, and the code flow will be returned using `RETN`. But if there are several code segments, then the address of the function is to be specified by a pair, it is to be called using the `CALL FAR` instruction, and the code flow is to be returned using `RETF`.

This is what is set in the compiler by specifying “memory model”.

The compilers targeting MS-DOS and Win16 have specific libraries for each memory model: they differ by pointer types for code and data.
```c
#include <windows.h>
#include <time.h>
#include <stdio.h>

char strbuf[256];

int PASCAL WinMain( HINSTANCE hInstance,
                     HINSTANCE hPrevInstance,
                     LPSTR lpCmdLine,
                     int nCmdShow )
{
    struct tm *t;
    time_t unix_time;
    unix_time=time(NULL);
    t=localtime (&unix_time);
    sprintf (strbuf, "%04d-%02d-%02d %02d:%02d:%02d", t->tm_year+1900, t->tm_mon, t->
             \tm_mday,
             t->tm_hour, t->tm_min, t->tm_sec);
    MessageBox (NULL, strbuf, "caption", MB_OK);
    return 0;
}
```

```
WinMain          proc near
var_4 = word ptr -4
var_2 = word ptr -2
    push    bp
    mov     bp, sp
    push    ax
    push    ax
    xor     ax, ax
    call    time_
    mov     [bp+var_4], ax ; low part of UNIX time
    mov     [bp+var_2], dx ; high part of UNIX time
    lea     ax, [bp+var_4] ; take a pointer of high part
    call    localtime_
    mov     bx, ax          ; t
    push    word ptr [bx]  ; second
    push    word ptr [bx+2]; minute
    push    word ptr [bx+4]; hour
    push    word ptr [bx+6]; day
    push    word ptr [bx+8]; month
    mov     ax, [bx+0Ah]    ; year
    add     ax, 1900
    push    ax
    mov     ax, offset a04d02d02d02d02d ; "%04d-%02d-%02d %02d:%02d:%02d"
    push    ax
    mov     ax, offset strbuf
    push    ax
    call    sprintf_
    add     sp, 10h
    xor     ax, ax          ; NULL
    push    ax
    push    ds
    mov     ax, offset strbuf
    push    ax
    push    ds
    mov     ax, offset aCaption ; "caption"
    push    ax
    xor     ax, ax          ; MB_OK
    push    ax
```
UNIX time is a 32-bit value, so it is returned in the DX:AX register pair and stored in two local 16-bit variables. Then a pointer to the pair is passed to the localtime() function. The localtime() function has a struct tm allocated somewhere in the guts of the C library, so only a pointer to it is returned.

By the way, this also implies that the function cannot be called again until its results are used.

For the time() and localtime() functions, a Watcom calling convention is used here: the first four arguments are passed in the AX, DX, BX and CX, registers, and the rest arguments are via the stack.

The functions using this convention are also marked by underscore at the end of their name.

sprintf() does not use the PASCAL calling convention, nor the Watcom one, so the arguments are passed in the normal cdecl way (6.1.1 on page 734).

**Global variables**

This is the same example, but now these variables are global:

```c
#include <windows.h>
#include <time.h>
#include <stdio.h>

char strbuf[256];
struct tm *t;
time_t unix_time;

int PASCAL WinMain( HINSTANCE hInstance,
                    HINSTANCE hPrevInstance,
                    LPSTR lpCmdLine,
                    int nCmdShow )
{
    unix_time=time(NULL);
    t=localtime (&unix_time);
    strftime (strbuf, "%04d-%02d-%02d %02d:%02d:%02d", t->tm_year+1900, t->tm_mon, t->tm_mday,
               t->tm_hour, t->tm_min, t->tm_sec);
    MessageBox (NULL, strbuf, "caption", MB_OK);
    return 0;
}
```

unix_time_low   dw 0
unix_time_high  dw 0
t   dw 0

WinMain      proc near
            push bp
            mov bp, sp
            xor ax, ax
            call time_
            mov unix_time_low, ax
            mov unix_time_high, dx
            mov ax, offset unix_time_low
            call localtime_
            mov bx, ax
            mov t, ax ; will not be used in future...
            push word ptr [bx] ; seconds
            push word ptr [bx+2] ; minutes
            push word ptr [bx+4] ; hour

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push word ptr [bx+6] ; day
push word ptr [bx+8] ; month
mov ax, [bx+0Ah] ; year
add ax, 1900
push ax
mov ax, offset a04d02d02d02d02 ; "%04d-%02d-%02d %02d:%02d:%02d"
push ax
mov ax, offset strbuf
push ax
call sprintf_
add sp, 10h
xor ax, ax ; NULL
push ax
push ds
mov ax, offset strbuf
push ax
push ds
mov ax, offset aCaption ; "caption"
push ax
xor ax, ax ; MB_OK
push ax
call MESSAGEBOX
xor ax, ax ; return 0
pop bp
retn 0Ah
WinMain endp

t is not to be used, but the compiler emitted the code which stores the value. Because it is not sure, maybe that value will eventually be used in some other module.
Chapter 4

Java

4.1 Java

4.1.1 Introduction

There are some well-known decompilers for Java (or JVM bytecode in general)\(^1\). The reason is the decompilation of JVM-bytecode is somewhat easier than for lower level x86 code:

- There is much more information about the data types.
- The JVM memory model is much more rigorous and outlined.
- The Java compiler don’t do any optimizations (the JVM JIT\(^2\) does them at runtime), so the bytecode in the class files is usually pretty readable.

When can the knowledge of JVM be useful?

- Quick-and-dirty patching tasks of class files without the need to recompile the decompiler’s results.
- Analyzing obfuscated code.
- Building your own obfuscator.
- Building a compiler codegenerator (back-end) targeting JVM (like Scala, Clojure, etc.\(^3\)).

Let’s start with some simple pieces of code. JDK 1.7 is used everywhere, unless mentioned otherwise. This is the command used to decompile class files everywhere:

```
javap -c -verbose
```

This is the book I used while preparing all examples: [Tim Lindholm, Frank Yellin, Gilad Bracha, Alex Buckley, The Java(R) Virtual Machine Specification / Java SE 7 Edition]\(^4\).

4.1.2 Returning a value

Probably the simplest Java function is the one which returns some value.

Oh, and we must keep in mind that there are no “free” functions in Java in common sense, they are “methods”.

Each method is related to some class, so it’s not possible to define a method outside of a class.

But we’ll call them “functions” anyway, for simplicity.

```java
public class ret
{
    public static int main(String[] args)
    {
        return 0;
    }
}
```

---

\(^1\)For example, JAD: [http://varaneckas.com/jad/](http://varaneckas.com/jad/)

\(^2\)Just-In-Time compilation


\(^4\)Also available as [https://docs.oracle.com/javase/specs/jvms/se7/jvms7.pdf](https://docs.oracle.com/javase/specs/jvms/se7/jvms7.pdf); [http://docs.oracle.com/javase/specs/jvms/se7/html/](http://docs.oracle.com/javase/specs/jvms/se7/html/)
4.1. JAVA

Let's compile it:

```
javac ret.java
```

...and decompile it using the standard Java utility:

```
javap -c -verbose ret.class
```

And we get:

```
Listing 4.1: JDK 1.7 (excerpt)

public static int main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
    stack=1, locals=1, args_size=1
0: iconst_0
1: ireturn

The Java developers decided that 0 is one of the busiest constants in programming, so there is a separate short one-byte iconst_0 instruction which pushes 0.

5. There are also iconst_1 (which pushes 1), iconst_2, etc., up to iconst_5.

There is also iconst_m1 which pushes -1.

The stack is used in JVM for passing data to called functions and also for return values. So iconst_0 pushes 0 into the stack. ireturn returns an integer value (i in name means integer) from the TOS6.

Let's rewrite our example slightly, now we return 1234:

```
public class ret
{
    public static int main(String[] args)
    {
        return 1234;
    }
}
```

...we get:

```
Listing 4.2: JDK 1.7 (excerpt)

public static int main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
    stack=1, locals=1, args_size=1
0: sipush 1234
3: ireturn

sipush (short integer) pushes 1234 into the stack. short in name implies a 16-bit value is to be pushed. The number 1234 indeed fits well in a 16-bit value.

What about larger values?

```
public class ret
{
    public static int main(String[] args)
    {
        return 12345678;
    }
}
```

---

5. Just like in MIPS, where a separate register for zero constant exists: 1.5.5 on page 26.

6. Top of Stack
It's not possible to encode a 32-bit number in a JVM instruction opcode, the developers didn't leave such possibility.

So the 32-bit number 12345678 is stored in so called “constant pool” which is, let's say, the library of most used constants (including strings, objects, etc.).

This way of passing constants is not unique to JVM.

MIPS, ARM and other RISC CPUs also can't encode a 32-bit number in a 32-bit opcode, so the RISC CPU code (including MIPS and ARM) has to construct the value in several steps, or to keep it in the data segment: 1.32.3 on page 440, 1.33.1 on page 443.

MIPS code also traditionally has a constant pool, named “literal pool”, the segments are called “.lit4” (for 32-bit single precision floating point number constants) and “.lit8” (for 64-bit double precision floating point number constants).

Let's try some other data types!

Boolean:

```java
public class ret {
    public static boolean main(String[] args) {
        return true;
    }
}
```

This JVM bytecode is no different from one returning integer 1.

32-bit data slots in the stack are also used here for boolean values, like in C/C++.

But one could not use returned boolean value as integer or vice versa — type information is stored in the class file and checked at runtime.

It's the same story with a 16-bit short:

```java
public class ret {
    public static short main(String[] args) {
        return 1234;
    }
}
```
4.1. JAVA

...and char!

```java
public class ret {
    public static char main(String[] args) {
        return 'A';
    }
}
```

```java
public static char main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
    stack=1, locals=1, args_size=1
  0: bipush 65
  2: ireturn
```

bipush means “push byte”. Needless to say that a char in Java is 16-bit UTF-16 character, and it’s equivalent to short, but the ASCII code of the “A” character is 65, and it’s possible to use the instruction for pushing a byte in the stack.

Let’s also try a byte:

```java
public class retc {
    public static byte main(String[] args) {
        return 123;
    }
}
```

```java
public static byte main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
    stack=1, locals=1, args_size=1
  0: bipush 123
  2: ireturn
```

One may ask, why bother with a 16-bit short data type which internally works as a 32-bit integer? Why use a char data type if it is the same as a short data type?

The answer is simple: for data type control and source code readability.

A char may essentially be the same as a short, but we quickly grasp that it’s a placeholder for an UTF-16 character, and not for some other integer value.

When using short, we show everyone that the variable’s range is limited by 16 bits.

It’s a very good idea to use the boolean type where needed to, instead of the C-style int.

There is also a 64-bit integer data type in Java:

```java
public class ret3 {
    public static long main(String[] args) {
        return 1234567890123456789L;
    }
}
```

Listing 4.4: Constant pool

```java
...  #2 = Long 1234567890123456789L...
```

```java
public static long main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
    stack=2, locals=1, args_size=1
```

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4.1. JAVA

```java
0: ldc2_w #2 // long 1234567890123456789l
3: lreturn
```

The 64-bit number is also stored in a constant pool, `ldc2_w` loads it and `lreturn` (long return) returns it. The `ldc2_w` instruction is also used to load double precision floating point numbers (which also occupy 64 bits) from a constant pool:

```java
class ret {
    public static double main(String[] args) {
        return 123.456d;
    }
}
```

Listing 4.5: Constant pool

```java
... #2 = Double 123.456d ...
```

dreturn stands for “return double”.

And finally, a single precision floating point number:

```java
class ret {
    public static float main(String[] args) {
        return 123.456f;
    }
}
```

Listing 4.6: Constant pool

```java
... #2 = Float 123.456f ...
```

The `ldc` instruction used here is the same one as for loading 32-bit integer numbers from a constant pool.

freturn stands for “return float”.

Now what about function that return nothing?

```java
class ret {
    public static void main(String[] args) {
        return;
    }
}
```
public static void main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
    stack=0, locals=1, args_size=1
    0: return

This means that the return instruction is used to return control without returning an actual value.
Knowing all this, it’s very easy to deduce the function’s (or method’s) returning type from the last instruction.

### 4.1.3 Simple calculating functions

Let's continue with a simple calculating functions.

```java
public class calc
{
    public static int half(int a)
    {
        return a/2;
    }
}
```

Here's the output when the `iconst_2` instruction is used:

```java
public static int half(int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
    stack=2, locals=1, args_size=1
    0: iload_0
    1: iconst_2
    2: idiv
    3: ireturn
```

`iload_0` takes the zeroth function argument and pushes it to the stack.
`iconst_2` pushes 2 in the stack. After the execution of these two instructions, this is how stack looks like:

```
+---+
TOS ->| 2 |
+---+
| a |
+---+
```

`idiv` just takes the two values at the TOS, divides one by the other and leaves the result at TOS:

```
+---------+
TOS ->| result |
+---------+
```

`ireturn` takes it and returns.

Let's proceed with double precision floating point numbers:

```java
public class calc
{
    public static double half_double(double a)
    {
        return a/2.0;
    }
}
```

Listing 4.7: Constant pool

```java
...  #2 = Double 2.0d ...
...
4.1. JAVA

```java
public static double half_double(double);
flags: ACC_PUBLIC, ACC_STATIC
Code:
  stack=4, locals=2, args_size=1
  0: dload_0
  1: ldc2_w #2 // double 2.0d
  4: ddiv
  5: dreturn
```

It's the same, but the ldc2_w instruction is used to load the constant 2.0 from the constant pool.

Also, the other three instructions have the d prefix, meaning they work with double data type values.

Let's now use a function with two arguments:

```java
public class calc
{
  public static int sum(int a, int b)
  {
    return a+b;
  }
}
```

```java
public static int sum(int, int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
  stack=2, locals=2, args_size=2
  0: iload_0
  1: iload_1
  2: iadd
  3: ireturn
```

iload_0 loads the first function argument (a), iload_1—second (b).

Here is the stack after the execution of both instructions:

```
+---+
TOS ->| b |
  +---+
| a |
  +---+
```

iadd adds the two values and leaves the result at TOS:

```
+--------+
TOS ->| result |
  +--------+
```

Let's extend this example to the long data type:

```java
public static long lsum(long a, long b)
{
  return a+b;
}
```

...we got:

```java
public static long lsum(long, long);
flags: ACC_PUBLIC, ACC_STATIC
Code:
  stack=4, locals=4, args_size=2
  0: iload_0
  1: iload_1
  2: ladd
  3: lreturn
```

The second iload instruction takes the second argument from the 2nd slot. That's because a 64-bit long value occupies exactly two 32-bit slots.

Slightly more advanced example:
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```java
public class calc {
    public static int mult_add(int a, int b, int c) {
        return a*b+c;
    }
}
```

```java
public static int mult_add(int, int, int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
  stack=2, locals=3, args_size=3
  0: iload_0
  1: iload_1
  2: imul
  3: iload_2
  4: iadd
  5: ireturn
```

The first step is multiplication. The product is left at the TOS:

```
+---------+
<table>
<thead>
<tr>
<th>product</th>
</tr>
</thead>
</table>
```

`iload_2` loads the third argument (c) in the stack:

```
+---------+
<table>
<thead>
<tr>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>product</td>
</tr>
<tr>
<td>---------</td>
</tr>
</tbody>
</table>
```

Now the `iadd` instruction can add the two values.

### 4.1.4 JVM memory model

x86 and other low-level environments use the stack for argument passing and as a local variables storage. JVM is slightly different.

It has:

- Local variable array (LVA\(^7\)). Used as storage for incoming function arguments and local variables.
  
  Instructions like `iload_0` load values from it.

  `istore` stores values in it. At the beginning the function arguments are stored: starting at 0 or at 1 (if the zeroth argument is occupied by `this` pointer).

  Then the local variables are allocated.

  Each slot has size of 32-bit.

  Hence, values of `long` and `double` data types occupy two slots.

- Operand stack (or just “stack”). It’s used for computations and passing arguments while calling other functions.

  Unlike low-level environments like x86, it’s not possible to access the stack without using instructions which explicitly pushes or pops values to/from it.

- Heap. It is used as storage for objects and arrays.

These 3 areas are isolated from each other.

\(^7\) (Java) Local Variable Array
4.1. JAVA

4.1.5 Simple function calling

Math.random() returns a pseudorandom number in range of [0.0 …1.0), but let’s say that for some reason we need to devise a function that returns a number in range of [0.0 …0.5):

```java
public class HalfRandom {
    public static double f() {
        return Math.random()/2;
    }
}
```

Listing 4.8: Constant pool

```
... #2 = Methodref #18.#19 // java/lang/Math.random:()D
#3 = Double 2.0d
...
#12 = Utf8 ()D
...
#18 = Class #22 // java/lang/Math
#19 = NameAndType #23:#12 // random:()D
#22 = Utf8 java/lang/Math
#23 = Utf8 random
```

public static double f();
flags: ACC_PUBLIC, ACC_STATIC
Code:
`stack=4, locals=0, args_size=0`
0: invokestatic #2 // Method java/lang/Math.random():D
3: ldc2_w #3 // double 2.0d
6: ddiv
7: dreturn

invokestatic calls the Math.random() function and leaves the result at the TOS.
Then the result is divided by 2.0 and returned.
But how is the function name encoded?
It’s encoded in the constant pool using a Methodref expression.
It defines the class and method names.
The first field of Methodref points to a Class expression which, in turn, points to the usual text string (“java/lang/Math”).
The second Methodref expression points to a NameAndType expression which also has two links to the strings.
The first string is “random”, which is the name of the method.
The second string is “()D”, which encodes the function’s type. It means that it returns a double value (hence the D in the string).
This is the way 1) JVM can check data for type correctness; 2) Java decompilers can restore data types from a compiled class file.
Now let’s try the “Hello, world!” example:

```java
public class HelloWorld {
    public static void main(String[] args) {
        System.out.println("Hello, World");
    }
}
```

Listing 4.9: Constant pool

...
### 4.1. JAVA

| #2 = Fieldref | #16.#17 | // java/lang/System.out:Ljava/io/PrintStream; |
| #3 = String    | #18    | // Hello, World |
| #4 = Methodref | #19.#20 | // java/io/PrintStream.println:(Ljava/lang/String;)V |

...  

| #16 = Class    | #23    | // java/lang/System |
| #17 = NameAndType | #24:#25 | // out:Ljava/io/PrintStream; |
| #18 = Utf8     | Hello, World |
| #19 = Class    | #26    | // java/io/PrintStream |
| #20 = NameAndType | #27:#28 | // println:(Ljava/lang/String;)V |

...  

| #23 = Utf8 | java/lang/System |
| #24 = Utf8 | out |
| #25 = Utf8 | Ljava/io/PrintStream; |
| #26 = Utf8 | java/io/PrintStream |
| #27 = Utf8 | println |
| #28 = Utf8 | (Ljava/lang/String;)V |

```java
public static void main(java.lang.String[])
flags: ACC_PUBLIC, ACC_STATIC
Code:
  stack=2, locals=1, args_size=1
  0: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
  3: ldc #3    // String Hello, World
  5: invokevirtual #4 // Method java/io/PrintStream.println:(Ljava/lang/String;)V
  8: return
```

ldc at offset 3 takes a pointer to the “Hello, World” string in the constant pool and pushes it in the stack.

It’s called a reference in the Java world, but it’s rather a pointer, or an address.

The familiar invokevirtual instruction takes the information about the println function (or method) from the constant pool and calls it.

As we may know, there are several println methods, one for each data type.

Our case is the version of println intended for the String data type.

But what about the first getstatic instruction?

This instruction takes a reference (or address of) a field of the object System.out and pushes it in the stack.

This value is acts like the this pointer for the println method.

Thus, internally, the println method takes two arguments for input: 1) this, i.e., a pointer to an object; 2) the address of the “Hello, World” string.

Indeed, println() is called as a method within an initialized System.out object.

For convenience, the javap utility writes all this information in the comments.

#### 4.1.6 Calling beep()

This is a simple calling of two functions without arguments:

```java
public static void main(String[] args)
{
    java.awt.Toolkit.getDefaultToolkit().beep();
}
```

```java
public static void main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
  stack=1, locals=1, args_size=1
  0: invokestatic #2 // Method java/awt/Toolkit.getDefaultToolkit:()Ljava/awt/Toolkit;
```
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First invokevirtual at offset 0 calls java.awt.Toolkit.getDefaultToolkit(), which returns a reference to an object of class Toolkit. The invokevirtual instruction at offset 3 calls the beep() method of this class.

4.1.7 Linear congruential PRNG

Let's try a simple pseudorandom numbers generator, which we already considered once in the book (1.23 on page 338):

```java
public class LCG {
    public static int rand_state;
    public void my_srand (int init) {
        rand_state=init;
    }
    public static int RNG_a=1664525;
    public static int RNG_c=1013904223;
    public int my_rand () {
        rand_state=rand_state*RNG_a;
        rand_state=rand_state+RNG_c;
        return rand_state & 0x7fff;
    }
}
```

There are couple of class fields which are initialized at start.

But how? In javap output we can find the class constructor:

```java
static {};
flags: ACC_STATIC
Code:
    stack=1, locals=0, args_size=0
0: ldc #5 // int 1664525
2: putstatic #3 // Field RNG_a:I
5: ldc #6 // int 1013904223
7: putstatic #4 // Field RNG_c:I
10: return
```

That's the way variables are initialized.

RNG_a occupies the 3rd slot in the class and RNG_c—4th, and putstatic puts the constants there.

The my_srand() function just stores the input value in rand_state:

```java
public void my_srand(int);
flags: ACC_PUBLIC
Code:
    stack=1, locals=2, args_size=2
0: iload_1
1: putstatic #2 // Field rand_state:I
4: return
```

Iload_1 takes the input value and pushes it into stack. But why not iload_0?

It's because this function may use fields of the class, and so this is also passed to the function as a zeroth argument.

The field rand_state occupies the 2nd slot in the class, so putstatic copies the value from the TOS into the 2nd slot.

Now my_rand():

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public int my_rand();
flags: ACC_PUBLIC
Code:
  stack=2, locals=1, args_size=1
  0: getstatic #2 // Field rand_state:I
  3: getstatic #3 // Field RNG_a:I
  6: imul
  7: putstatic #2 // Field rand_state:I
 10: getstatic #2 // Field rand_state:I
 13: getstatic #4 // Field RNG_c:I
 16: iadd
 17: putstatic #2 // Field rand_state:I
 20: getstatic #2 // Field rand_state:I
 23: sipush 32767
 26: iand
 27: ireturn

It just loads all the values from the object’s fields, does the operations and updates rand_state’s value using the putstatic instruction.

At offset 20, rand_state is reloaded again (because it has been dropped from the stack before, by putstatic).

This looks like non-efficient code, but be sure, the JVM is usually good enough to optimize such things really well.

4.1.8 Conditional jumps

Now let’s proceed to conditional jumps.

public class abs
{
  public static int abs(int a)
  {
    if (a<0)
      return -a;
    return a;
  }
}

public static int abs(int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
  stack=1, locals=1, args_size=1
  0: iload_0
  1: ifge 7
  4: iload_0
  5: ineg
  6: ireturn
  7: iload_0
  8: ireturn

ifge jumps to offset 7 if the value at TOS is greater or equal to 0.
Don’t forget, any ifXX instruction pops the value (to be compared) from the stack.

ineg just negates value at TOS.

Another example:

public static int min (int a, int b)
{
  if (a>b)
    return b;
  return a;
}

We get:
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```java
public static int min(int a, int b) {
    if (a > b) return a;
    return b;
}
```

If `if_icmple` pops two values and compares them. If the second one is lesser than (or equal to) the first, a jump to offset 7 is performed.

When we define `max()` function ...

```java
public static int max(int a, int b) {
    if (a > b) return a;
    return b;
}
```

...the resulting code is the same, but the last two `iload` instructions (at offsets 5 and 7) are swapped:

```java
public static int max(int a, int b) {
    if (a > b) return a;
    return b;
}
```

A more advanced example:

```java
public class cond {
    public static void f(int i) {
        if (i<100) System.out.print("<100");
        if (i==100) System.out.print("==100");
        if (i>100) System.out.print(">100");
        if (i==0) System.out.print("==0");
    }
}
```

```java
public static void f(int); 
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=2, locals=1, args_size=1
  0: iload_0
  1: bipush 100
  3: if_icmpge 14
  6: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
  9: ldc #3 // String <100
11: invokevirtual #4 // Method java/io/PrintStream.print:(Ljava/lang/String;)V
14: iload_0
15: bipush 100
17: if_icmpne 28
20: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
```

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```java
23: ldc #5 // String ==100
25: invokevirtual #4 // Method java/io/PrintStream.print:(Ljava/lang/String;)V
28: iload_0
29: bipush 100
31: if_icmple 42
34: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
37: ldc #6 // String >100
39: invokevirtual #4 // Method java/io/PrintStream.print:(Ljava/lang/String;)V
42: iload_0
43: ifne 54
46: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
49: ldc #7 // String ==0
51: invokevirtual #4 // Method java/io/PrintStream.print:(Ljava/lang/String;)V
54: return
```

if _icmpge pops two values and compares them. If the second one is larger than the first, a jump to offset 14 is performed.

if _icmpne and _icmple work just the same, but implement different conditions.

There is also a _ifne instruction at offset 43.

Its name is misnomer, it would’ve be better to name it _ifnz (jump if the value at TOS is not zero).

And that is what it does: it jumps to offset 54 if the input value is not zero.

If zero, the execution flow proceeds to offset 46, where the “==0” string is printed.

N.B.: JVM has no unsigned data types, so the comparison instructions operate only on signed integer values.

4.1.9 Passing arguments

Let’s extend our min() / max() example:

```java
public class minmax
{
    public static int min (int a, int b)
    {
        if (a>b)
            return b;
        return a;
    }

    public static int max (int a, int b)
    {
        if (a>b)
            return a;
        return b;
    }

    public static void main(String[] args)
    {
        int a=123, b=456;
        int max_value=max(a, b);
        int min_value=min(a, b);
        System.out.println(min_value);
        System.out.println(max_value);
    }
}
```

Here is main() function code:

```java
  public static void main(java.lang.String[])
  flags: ACC_PUBLIC, ACC_STATIC
  Code:
    stack=2, locals=5, args_size=1
    0: bipush      123
    2: istore_1
    3: sipush      456
```
Arguments are passed to the other function in the stack, and the return value is left on TOS.

### 4.1.10 Bitfields

All bit-wise operations work just like in any other ISA:

```java
public static int set (int a, int b) {
    return a | 1<<b;
}

public static int clear (int a, int b) {
    return a & (~(1<<b));
}
```

iconst\_m1 loads \(-1\) in the stack, it’s the same as the 0xFFFFFFFF number.

XORing with 0xFFFFFFFF has the same effect of inverting all bits (2.6 on page 461).

Let’s extend all data types to 64-bit long:

```java
public static long lset (long a, int b) {
    return a | 1<<b;
}
```
public static long lclear (long a, int b) {
    return a & ~(1<<b);
}

public static long lset(long, int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=4, locals=3, args_size=2
0: lload_0
1: iconst_1
2: iload_2
3: ishl
4: l2l
5: lor
6: lreturn

The code is the same, but instructions with \texttt{l} prefix are used, which operate on 64-bit values.
Also, the second argument of the function still is of type \texttt{int}, and when the 32-bit value in it needs to be promoted to 64-bit value the \texttt{i2l} instruction is used, which essentially extend the value of an \texttt{integer} type to a \texttt{long} one.

### 4.1.11 Loops

public class Loop {
    public static void main(String[] args) {
        for (int i = 1; i <= 10; i++) {
            System.out.println(i);
        }
    }
}

public static void main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=2, locals=2, args_size=1
0: iconst_1
1: istore_1
2: iload_1
3: bipush 10
5: if_icmpgt 21 // Field java/lang/System.out:Ljava/io/PrintStream;
8: getstatic #2 // Method java/io/PrintStream.println:(I)V
11: iload_1
12: invokevirtual #3 // Method java/io/PrintStream.println:(I)V
15: iinc 1, 1
18: goto 2
21: return

\texttt{iconst\_1} loads 1 into \texttt{TOS}, \texttt{istore\_1} stores it in the \texttt{LVA} at slot 1.
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Why not the zeroth slot? Because the main() function has one argument (array of String) and a pointer to it (or reference) is now in the zeroth slot.

So, the $i$ local variable will always be in 1st slot.

Instructions at offsets 3 and 5 compare $i$ with 10.

If $i$ is larger, execution flow passes to offset 21, where the function ends.

If it's not, println is called.

$i$ is then reloaded at offset 11, for println.

By the way, we call the println method for an integer, and we see this in the comments: “(I)V” ($I$ means integer and $V$ means the return type is void).

When println finishes, $i$ is incremented at offset 15.

The first operand of the instruction is the number of a slot (1), the second is the number (1) to add to the variable.

goto is just GOTO, it jumps to the beginning of the loop's body offset 2.

Let's proceed with a more complex example:

```java
public class Fibonacci {
    public static void main(String[] args) {
        int limit = 20, f = 0, g = 1;
        for (int i = 1; i <= limit; i++) {
            f = f + g;
            g = f - g;
            System.out.println(f);
        }
    }
}
```

Here is a map of the LVA slots:

- 0 — the sole argument of main()
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- 1 — limit, always contains 20
- 2 — f
- 3 — g
- 4 — i

We can see that the Java compiler allocates variables in LVA slots in the same order they were declared in the source code.

There are separate istore instructions for accessing slots 0, 1, 2 and 3, but not for 4 and larger, so there is istore with an additional operand at offset 8 which takes the slot number as an operand.

It’s the same with iload at offset 10.

But isn’t it dubious to allocate another slot for the limit variable, which always contains 20 (so it’s a constant in essence), and reload its value so often?

JVM JIT compiler is usually good enough to optimize such things.

Manual intervention in the code is probably not worth it.

4.1.12 switch()

The switch() statement is implemented with the tableswitch instruction:

```java
public static void f(int a)
{
    switch (a)
    {
    case 0: System.out.println("zero"); break;
    case 1: System.out.println("one\n"); break;
    case 2: System.out.println("two\n"); break;
    case 3: System.out.println("three\n"); break;
    case 4: System.out.println("four\n"); break;
    default: System.out.println("something unknown\n"); break;
    }
}
```

As simple, as possible:

```java
public static void f(int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=2, locals=1, args_size=1
0: iload_0
1: tableswitch { // 0 to 4
    0: 36
    1: 47
    2: 58
    3: 69
    4: 80
    default: 91
}
36: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
39: ldc #3 // String zero
41: invokevirtual #4 // Method java/io/PrintStream.println:(Ljava/lang/String;)V
44: goto 99
47: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
50: ldc #5 // String one\n
52: invokevirtual #4 // Method java/io/PrintStream.println:(Ljava/lang/String;)V
55: goto 99
58: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
61: ldc #6 // String two\n
63: invokevirtual #4 // Method java/io/PrintStream.println:(Ljava/lang/String;)V
66: goto 99
69: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
72: ldc #7 // String three\n
74: invokevirtual #4 // Method java/io/PrintStream.println:(Ljava/lang/String;)V
77: goto 99
```

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80: getstatic  #2  // Field java/lang/System.out:Ljava/io/PrintStream;
83: ldc       #8  // String four\n85: invokevirtual #4  // Method java/io/PrintStream.println:(Ljava/lang/String;)V
88: goto      99
91: getstatic  #2  // Field java/lang/System.out:Ljava/io/PrintStream;
94: ldc       #9  // String something unknown\n96: invokevirtual #4  // Method java/io/PrintStream.println:(Ljava/lang/String;)V
99: return

4.1.13 Arrays

Simple example

Let’s first create an array of 10 integers and fill it:

```java
public static void main(String[] args)
{
    int a[] = new int[10];
    for (int i=0; i<10; i++)
        a[i]=i;
    dump (a);
}
```

The newarray instruction creates an array object of 10 int elements. The array’s size is set with bipush and left at TOS. The array’s type is set in newarray instruction’s operand. After newarray’s execution, a reference (or pointer) to the newly created array in the heap is left at the TOS. astore_1 stores the reference to the 1st slot in LVA. The second part of the main() function is the loop which stores i into the corresponding array element. aload_1 gets a reference of the array and places it in the stack. istore then stores the integer value from the stack in the array, reference of which is currently in TOS. The third part of the main() function calls the dump() function. An argument for it is prepared by aload_1 (offset 23).

Now let’s proceed to the dump() function:
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```java
public static void dump(int a[])
{
    for (int i=0; i<a.length; i++)
        System.out.println(a[i]);
}
```

```java
public static void dump(int[]);
``` flags: ACC_PUBLIC, ACC_STATIC

Code:

```
stack=3, locals=2, args_size=1
0: iconst_0
1: istore_1
2: iload_1
3: aiaload
4: arraylength
5: if_icmpge 23 // Field java/lang/System.out:Ljava/io/PrintStream;
8: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
11: iload_1
12: iload_1
13: iiaload
14: invokevirtual #3 // Method java/io/PrintStream.println:(I)V
17: iinc 1, 1
20: goto 2
23: return
```

The incoming reference to the array is in the zeroth slot.

The `a.length` expression in the source code is converted to an `arraylength` instruction: it takes a reference to the array and leaves the array size at TOS.

`iaload` at offset 13 is used to load array elements, it requires to array reference be present in the stack (prepared by `aload_0` at 11), and also an index (prepared by `iload_1` at offset 12).

Needless to say, instructions prefixed with `a` may be mistakenly comprehended as array instructions.

It's not correct. These instructions works with references to objects.

And arrays and strings are objects too.

**Summing elements of array**

Another example:

```java
public class ArraySum
{
    public static int f (int[] a)
    {
        int sum=0;
        for (int i=0; i<a.length; i++)
            sum=sum+a[i];
        return sum;
    }
}
```

```java
public static int f(int[]);
``` flags: ACC_PUBLIC, ACC_STATIC

Code:

```
stack=3, locals=3, args_size=1
0: iconst_0
1: istore_1
2: iconst_0
3: istore_2
4: iload_2
5: aiaload
6: arraylength
7: if_icmpge 22
10: iload_1
11: aiaload
```
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```
12: iload_2
13: iaload
14: iadd
15: istore_1
16: iinc 2, 1
19: goto 4
22: iload_1
23: ireturn
```

**LVA** slot 0 contains a *reference* to the input array.

**LVA** slot 1 contains the local variable *sum*.

**The only argument of the main() function is an array too**

We'll be using the only argument of the main() function, which is an array of strings:

```java
class UseArgument {
    public static void main(String[] args) {
        System.out.print("Hi, ");
        System.out.print(args[1]);
        System.out.println(" . How are you?");
    }
}
```

The zeroth argument is the program's name (like in C/C++, etc.), so the 1st argument supplied by the user is 1st.

```java
public static void main(java.lang.String[]); flags: ACC_PUBLIC, ACC_STATIC
Code:
    stack=3, locals=1, args_size=1
    0: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
    3: ldc #3 // String Hi,
    5: invokevirtual #4 // Method java/io/PrintStream.print:(Ljava/lang/String;)V
    8: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
   11: aload_0
   12: iconst_1
   13: aaload
   14: invokevirtual #4 // Method java/io/PrintStream.print:(Ljava/lang/String;)V
   17: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
   20: ldc #5 // String . How are you?
   22: invokevirtual #6 // Method java/io/PrintStream.println:(Ljava/lang/String;)V
   25: return
```

`aload_0` at 11 loads a *reference* of the zeroth **LVA** slot (1st and only main() argument).

`iconst_1` and `aaload` at 12 and 13 take a *reference* to the first (counting at 0) element of array.

The *reference* to the string object is at **TOS** at offset 14, and it is taken from there by `println` method.

**Pre-initialized array of strings**

```java
class Month {
    public static String[] months = {
        "January",
        "February",
        "March",
        "April",
        "May",
        "June",
        "July",
        "August",
    }
}
```
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```java
"September",
"October",
"November",
"December"
};

public String get_month (int i)
{
    return months[i];
}
```

The `get_month()` function is simple: Функция `get_month()` проста:

```java
public java.lang.String get_month(int);
flags: ACC_PUBLIC
Code:
    stack=2, locals=2, args_size=2
0: getstatic #2 // Field months:[Ljava/lang/String;
3: iload_1
4: aaload
5: areturn
```

Java String are objects, so the `a`-instructions are used to operate on them. `areturn` returns a reference to a String object.

How is the `months[]` array initialized?

```java
static {
    flags: ACC_STATIC
Code:
    stack=4, locals=0, args_size=0
0: bipush 12
2: anewarray #3 // class java/lang/String
5: dup
6: iconst_0
7: ldc #4 // String January
9: aastore
10: dup
11: iconst_1
12: ldc #5 // String February
14: aastore
15: dup
16: iconst_2
17: ldc #6 // String March
19: aastore
20: dup
21: iconst_3
22: ldc #7 // String April
24: aastore
25: dup
26: iconst_4
27: ldc #8 // String May
29: aastore
30: dup
31: iconst_5
32: ldc #9 // String June
34: aastore
35: dup
36: bipush 6
38: ldc #10 // String July
40: aastore
41: dup
42: bipush 7
44: ldc #11 // String August
46: aastore
47: dup
48: bipush 8
```

```
```
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```java
50: ldc #12 // String September
52: aastore
53: dup
54: bipush 9
56: ldc #13 // String October
58: aastore
59: dup
60: bipush 10
62: ldc #14 // String November
64: aastore
65: dup
66: bipush 11
68: ldc #15 // String December
70: aastore
71: putstatic #2 // Field months:[Ljava/lang/String;
74: return
```

`anewarray` creates a new array of references (hence a prefix).

The object’s type is defined in the `anewarray`’s operand, it is the “java/lang/String” string.

The `bipush 12` before `anewarray` sets the array’s size.

We see here a new instruction for us: `dup`.

It’s a standard instruction in stack computers (including the Forth programming language) which just duplicates the value at TOS.

By the way, FPU 80x87 is also a stack computer and it has similar instruction – `FDUP`.

It is used here to duplicate a reference to an array, because the `aastore` instruction pops the reference to array from the stack, but subsequent `aastore` will need it again.

The Java compiler concluded that it’s better to generate a `dup` instead of generating a `getstatic` instruction before each array store operation (i.e., 11 times).

`aastore` puts a reference (to string) into the array at an index which is taken from TOS.

Finally, `putstatic` puts reference to the newly created array into the second field of our object, i.e., `months` field.

**Variadic functions**

Variadic functions actually use arrays:

```java
public static void f(int... values)
{
    for (int i=0; i<values.length; i++)
        System.out.println(values[i]);
}

public static void main(String[] args)
{
    f (1,2,3,4,5);
}
```

```java
public static void f(int...);
flags: ACC_PUBLIC, ACC_STATIC, ACC_VARARGS
Code:
stack=3, locals=2, args_size=1
0: iconst_0
1: istore_1
2: iload_1
3: aaload
4: arraylength
5: if_icmpge 23
8: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
11: aaload
12: iastore
13: iload
```

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```java
14: invokevirtual #3 // Method java/io/PrintStream.println:(I)V
17: iinc 1, 1
20: goto 2
23: return
```

f() just takes an array of integers using `aload_0` at offset 3.

Then it gets the array's size, etc.

```java
public static void main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=4, locals=1, args_size=1
0: iconst_5
1: newarray int
3: dup
4: iconst_0
5: iconst_1
6: iastore
7: dup
8: iconst_1
9: iconst_2
10: iastore
11: dup
12: iconst_2
13: iconst_3
14: iastore
15: dup
16: iconst_3
17: iconst_4
18: iastore
19: dup
20: iconst_4
21: iconst_5
22: iastore
23: invokestatic #4 // Method f:([I)V
26: return
```

The array is constructed in `main()` using the `newarray` instruction, then it's filled, and f() is called.

Oh, by the way, array object is not destroyed at the end of `main()`.

There are no destructors in Java at all, because the JVM has a garbage collector which does this automatically, when it feels it needs to.

What about the `format()` method?

It takes two arguments at input: a string and an array of objects:

```java
public PrintStream format(String format, Object... args)
```

( [http://docs.oracle.com/javase/tutorial/java/data/numberformat.html](http://docs.oracle.com/javase/tutorial/java/data/numberformat.html) )

Let's see:

```java
public static void main(String[] args)
{
    int i=123;
    double d=123.456;
    System.out.format("int: %d double: %f%n", i, d);
}
```

```java
public static void main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=7, locals=4, args_size=1
0: bipush 123
2: istore_1
3: ldc2_w #2 // double 123.456d
6: dstore_2
7: getstatic #4 // Field java/lang/System.out:Ljava/io/PrintStream;
```

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So values of the *int* and *double* types are first promoted to *Integer* and *Double* objects using the `valueOf` methods.

The `format()` method needs objects of type *Object* at input, and since the *Integer* and *Double* classes are derived from the root *Object* class, they suitable for elements in the input array.

On the other hand, an array is always homogeneous, i.e., it can't hold elements of different types, which makes it impossible to push *int* and *double* values in it.

An array of *Object* objects is created at offset 13, an *Integer* object is added to the array at offset 22, and a *Double* object is added to the array at offset 29.

The penultimate pop instruction discards the element at TOS, so when return is executed, the stack becomes empty (or balanced).

### Two-dimensional arrays

Two-dimensional arrays in Java are just one-dimensional arrays of *references* to another one-dimensional arrays.

Let's create a two-dimensional array:

```java
public static void main(String[] args)
{
    int[][] a = new int[5][10];
    a[1][2]=3;
}
```

It's created using the `multianewarray` instruction: the object's type and dimensionality are passed as operands.

The array's size (10*5) is left in stack (using the instructions `iconst_5` and `bipush`).

A *reference* to row #1 is loaded at offset 10 (`iconst_1` and `aaload`).

The column is chosen using `iconst_2` at offset 11.
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The value to be written is set at offset 12.
iastore at 13 writes the array’s element.

How it is an element accessed?

```java
public static int get12 (int[][] in)
{
    return in[1][2];
}
```

```java
public static int get12(int[][]);  
flags: ACC_PUBLIC, ACC_STATIC  
Code:  
    stack=2, locals=1, args_size=1  
        0: aload_0  
        1: iconst_1  
        2: aaload  
        3: iconst_2  
        4: iaload  
        5: ireturn
```

A Reference to the array’s row is loaded at offset 2, the column is set at offset 3, then iaload loads the array’s element.

Three-dimensional arrays

Three-dimensional arrays are just one-dimensional arrays of references to one-dimensional arrays of references.

```java
public static void main(String[] args)
{
    int[][][][] a = new int[5][10][15];
    a[1][2][3]=4;
    get_elem(a);
}
```

```java
public static void main(java.lang.String[]);  
flags: ACC_PUBLIC, ACC_STATIC  
Code:  
    stack=3, locals=2, args_size=1  
        0: iconst_5  
        1: bipush 10  
        2: bipush 15  
        3: multianewarray #2, 3 // class "[[[I"  
        4: astore_1  
        5: aload_1  
        6: iconst_1  
        7: aaload  
        8: iconst_2  
        9: aaload  
       10: iconst_3  
       11: aaload  
       12: iconst_4  
       13: aaload  
       14: iconst_5  
       15: astore_1  
       16: aaload  
       17: iastore  
       18: aload_1  
       19: invokestatic #3 // Method get_elem:([[[I)I  
       20: pop  
       21: return
```

Now it takes two aaload instructions to find right reference:

```java
public static int get_elem (int[][][] a)
{
    return a[1][2][3];
}
```
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```java
public static int get_elem(int[][][][]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=2, locals=1, args_size=1
    0: aload_0
    1: iconst_1
    2: aaload
    3: iconst_2
    4: aaload
    5: iconst_3
    6: iaload
    7: ireturn
```

Summary

Is it possible to do a buffer overflow in Java?

No, because the array’s length is always present in an array object, array bounds are controlled, and an exception is to be raised in case of out-of-bounds access.

There are no multi-dimensional arrays in Java in the C/C++ sense, so Java is not very suited for fast scientific computations.

4.1.14 Strings

First example

Strings are objects and are constructed in the same way as other objects (and arrays).

```java
public static void main(String[] args)
{
    System.out.println("What is your name?"yo
    String input = System.console().readLine();
    System.out.println("Hello, " + input);
}
```

```java
public static void main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=3, locals=2, args_size=1
    0: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
    3: ldc #3 // String What is your name?
    5: invokevirtual #4 // Method java/io/PrintStream.println:(Ljava/lang/String;)V
    8: invokestatic #5 // Method java/lang/System.console:()Ljava/io/Console;
   11: invokevirtual #6 // Method java/io/Console.readLine:()Ljava/lang/String;
   14: astore_1
   15: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;
   18: new #7 // class java/lang/StringBuilder
   21: dup
   22: invokespecial #8 // Method java/lang/StringBuilder.<init>():V
   25: ldc #9 // String Hello,
          // Method java/lang/StringBuilder.append:(Ljava/lang/String;
   30: aload_1
   31: invokevirtual #10 // Method java/lang/StringBuilder.append:(Ljava/lang/String;
          // Method java/lang/StringBuilder.append:(Ljava/lang/String;
   34: invokevirtual #11 // Method java/lang/StringBuilder.toString:()Ljava/lang/String;
   37: invokevirtual #4 // Method java/io/PrintStream.println:(Ljava/lang/String;)
   40: return
```

The `readLine()` method is called at offset 11, a `reference` to string (which is supplied by the user) is then stored at TOS.

At offset 14 the `reference` to string is stored in slot 1 of LVA.

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The string the user entered is reloaded at offset 30 and concatenated with the “Hello, ” string using the 
StringBuilder class.
The constructed string is then printed using println at offset 37.

**Second example**

Another example:

```java
public class strings {
    public static char test (String a) {
        return a.charAt(3);
    };
    public static String concat (String a, String b) {
        return a+b;
    }
}
```

The string concatenation is performed using StringBuilder:

```java
public static java.lang.String concat(java.lang.String, java.lang.String);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=2, locals=2, args_size=2
0: new #3 // class java/lang/StringBuilder
3: dup
4: invokespecial #4 // Method java/lang/StringBuilder."<init">:(())V
7: aload_0
8: invokevirtual #5 // Method java/lang/StringBuilder.append:(Ljava/lang/String;)Ljava/lang/StringBuilder;
11: aload_1
12: invokevirtual #5 // Method java/lang/StringBuilder.append:(Ljava/lang/String;)Ljava/lang/StringBuilder;
15: invokevirtual #6 // Method java/lang/StringBuilder.toString:()Ljava/lang/String;
18: areturn
```

Another example:

```java
public static void main(String[] args) {
    String s="Hello!";
    int n=123;
    System.out.println("s" + s + " n=" + n);
}
```

And again, the strings are constructed using the StringBuilder class and its append method, then the 
constructed string is passed to println:

```java
public static void main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=3, locals=3, args_size=1
0: ldc #2 // String Hello!
2: astore_1
```
4.1. JAVA

| 3: bipush 123 |
| 5: istore 2 |
| 6: getstatic #3 // Field java/lang/System.out:Ljava/io/PrintStream; |
| 9: new #4 // class java/lang/StringBuilder |
| 12: dup |
| 13: invokespecial #5 // Method java/lang/StringBuilder."<init>"():V |
| 16: ldc #6 // String s= |
| 18: invokevirtual #7 // Method java/lang/StringBuilder.append:(Ljava/lang/String;)Ljava/lang/StringBuilder; |
| 21: aload_1 |
| 25: ldc #8 // String n= |
| 27: invokevirtual #7 // Method java/lang/StringBuilder.append:(Ljava/lang/String;)Ljava/lang/StringBuilder; |
| 30: iload_2 |
| 31: invokevirtual #9 // Method java/lang/StringBuilder.append:(I)Ljava/lang/StringBuilder; |
| 34: invokevirtual #10 // Method java/lang/StringBuilder.toString():Ljava/lang/String; |
| 37: invokevirtual #11 // Method java/io/PrintStream.println:(Ljava/lang/String;)V |
| 40: return |

4.1.15 Exceptions

Let's rework our Month example (4.1.13 on page 681) a bit:

Listing 4.10: IncorrectMonthException.java

```java
public class IncorrectMonthException extends Exception {
    private int index;

    public IncorrectMonthException(int index) {
        this.index = index;
    }

    public int getIndex() {
        return index;
    }
}
```

Listing 4.11: Month2.java

```java
class Month2 {
    public static String[] months = {
        "January",
        "February",
        "March",
        "April",
        "May",
        "June",
        "July",
        "August",
        "September",
        "October",
        "November",
        "December"
    };

    public static String get_month (int i) throws IncorrectMonthException {
        if (i<0 || i>11)
            throw new IncorrectMonthException(i);
        return months[i];
    }
}
```
public static void main (String[] args) {
    try {
        System.out.println(get_month(100));
    } catch (IncorrectMonthException e) {
        System.out.println("incorrect month index: "+ e.getIndex());
        e.printStackTrace();
    }
}

Essentially, IncorrectMonthException.class has just an object constructor and one getter method.

The IncorrectMonthException class is derived from Exception, so the IncorrectMonthException constructor first calls the constructor of the Exception class, then it puts incoming integer value into the sole IncorrectMonthException class field:

```java
public IncorrectMonthException(int);
flags: ACC_PUBLIC
Code:
stack=2, locals=2, args_size=2
0: aload_0
1: invokespecial #1 // Method java/lang/Exception."<init>":()V
4: aload_0
5: iload_1
6: putfield  #2 // Field index:I
9: return
```

getIndex() is just a getter. A reference to IncorrectMonthException is passed in the zeroth LVA slot (this), aload_0 takes it, getfield loads an integer value from the object, ireturn returns it.

```java
public int getIndex();
flags: ACC_PUBLIC
Code:
stack=1, locals=1, args_size=1
0: aload_0
1: getfield    #2 // Field index:I
4: ireturn
```

Now let's take a look at get_month() in Month2.class:

```java
public static java.lang.String get_month(int) throws IncorrectMonthException;
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=3, locals=1, args_size=1
0: iload_0
1: iflt   10
4: iload_0
5: bipush 11
7: if_icmpe 19
10: new   #2 // class IncorrectMonthException
13: dup
14: iload_0
15: invokespecial #3 // Method IncorrectMonthException."<init>":(I)V
18: athrow
19: getstatic  #4 // Field months:[Ljava/lang/String;
22: iload_0
23: aaload
24: areturn
```

iflt at offset 1 is if less than.

In case of invalid index, a new object is created using the new instruction at offset 10.
4.1. JAVA

The object’s type is passed as an operand to the instruction (which is IncorrectMonthException).

Then its constructor is called, and index is passed via TOS (offset 15).

When the control flow is offset 18, the object is already constructed, so now the athrow instruction takes a reference to the newly constructed object and signals to JVM to find the appropriate exception handler.

The athrow instruction doesn't return the control flow here, so at offset 19 there is another basic block, not related to exceptions business, where we can get from offset 7.

How do handlers work?

main() in Month2.class:

```java
public static void main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=3, locals=2, args_size=1
0: getstatic #5 // Field java/lang/System.out:Ljava/io/PrintStream;
3: bipush 100
5: invokestatic #6 // Method get_month:(I)Ljava/lang/String;
8: invokevirtual #7 // Method java/io/PrintStream.println:(Ljava/lang/String;)V
11: goto 47
14: astore_1
15: getstatic #5 // Field java/lang/System.out:Ljava/io/PrintStream;
18: new #8 // class java/lang/StringBuilder
21: dup
22: invokespecial #9 // Method java/lang/StringBuilder.<init>:()V
25: ldc #10 // String incorrect month index: 
30: aload_1
31: invokevirtual #12 // Method IncorrectMonthException.getIndex:()I
34: invokevirtual #13 // Method java/lang/StringBuilder.append:(I)Ljava/lang/String;
37: invokevirtual #14 // Method java/lang/StringBuilder.toString:()Ljava/lang/String;
40: invokevirtual #7 // Method java/io/PrintStream.println:(Ljava/lang/String;)V
43: aload_1
44: invokevirtual #15 // Method IncorrectMonthException.printStackTrace:()V
47: return
```

Exception table:

<table>
<thead>
<tr>
<th>from</th>
<th>to</th>
<th>target</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11</td>
<td>14</td>
<td>Class IncorrectMonthException</td>
</tr>
</tbody>
</table>

Here is the Exception table, which defines that from offsets 0 to 11 (inclusive) an exception IncorrectMonthException may happen, and if it does, the control flow is to be passed to offset 14.

Indeed, the main program ends at offset 11.

At offset 14 the handler starts. It’s not possible to get here, there are no conditional/unconditional jumps to this area.

But JVM will transfer the execution flow here in case of an exception.

The very first astore_1 (at 14) takes the incoming reference to the exception object and stores it in LVA slot 1.

Later, the getIndex() method (of this exception object) will be called at offset 31.

The reference to the current exception object is passed right before that (offset 30).

The rest of the code is does just string manipulation: first the integer value returned by getIndex() is converted to string by the toString() method, then it's concatenated with the “incorrect month index: ” text string (like we saw before), then println() and printStackTrace() are called.

After printStackTrace() finishes, the exception is handled and we can continue with the normal execution.

At offset 47 there is a return which finishes the main() function, but there could be any other code which would execute as if no exceptions were raised.

Here is an example on how IDA shows exception ranges:
4.1. JAVA

4.1.16 Classes

Simple class:

```java
public class test {
    public static int a;
    private static int b;

    public test() {
        a=0;
        b=0;
    }

    public static void set_a (int input) {
        a=input;
    }

    public static int get_a () {
        return a;
    }

    public static void set_b (int input) {
        b=input;
    }

    public static int get_b () {
        return b;
    }
}
```

The constructor just sets both fields to zero:

```java
public test();
flags: ACC_PUBLIC
Code:
    stack=1, locals=1, args_size=1
    0: aload_0
    1: invokespecial #1 // Method java/lang/Object."<init>"():V
    4: iconst_0
    5: putstatic #2 // Field a:I
    8: iconst_0
    9: putstatic #3 // Field b:I
   12: return
```

Setter of a:

```java
public static void set_a(int);
flags: ACC_PUBLIC, ACC_STATIC
```
4.1. JAVA

Code:
```
stack=1, locals=1, args_size=1
0: iload_0
1: putstatic #2 // Field a:I
4: return
```

Getter of a:
```
public static int get_a();
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=1, locals=0, args_size=0
0: getstatic #2 // Field a:I
3: ireturn
```

Setter of b:
```
public static void set_b(int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=1, locals=1, args_size=1
0: iload_0
1: putstatic #3 // Field b:I
4: return
```

There is no difference in the code which works with public and private fields. But this type information is present in the .class file, and it's not possible to access private fields from everywhere.

Let's create an object and call its method:

Listing 4.16: ex1.java
```
public class ex1 {
    public static void main(String[] args) {
        test obj=new test();
        obj.set_a (1234);
        System.out.println(obj.a);
    }
}
```

public static void main(java.lang.String[]); flags: ACC_PUBLIC, ACC_STATIC
```
stack=2, locals=2, args_size=1
0: new #2 // class test
3: dup
4: invokespecial #3 // Method test."<init>"():V
7: astore_1
8: aload_1
9: pop
10: sipush 1234
13: invokestatic #4 // Method test.set_a:(I)V
16: getstatic #5 // Field java/lang/System.out:Ljava/io/PrintStream;
19: aload_1
20: pop
21: getstatic #6 // Field test.a:I
24: invokevirtual #7 // Method java/io/PrintStream.println:(I)V
27: return
```
4.1. JAVA

The new instruction creates an object, but doesn’t call the constructor (it is called at offset 4).
The `set_a()` method is called at offset 16.
The a field is accessed using the `getstatic` instruction at offset 21.

4.1.17 Simple patching

First example

Let’s proceed with a simple code patching task.

```java
class nag {
    public static void nag_screen() {
        System.out.println("This program is not registered");
    }
    public static void main(String[] args) {
        System.out.println("Greetings from the mega-software");
        nag_screen();
    }
}
```

How would we remove the printing of “This program is not registered” string?

Let’s load the .class file into IDA:

![IDA](image)

Let’s patch the first byte of the function to 177 (which is the return instruction’s opcode):
4.1. JAVA

But that doesn't work (JRE 1.7):

Figure 4.2: IDA

Exception in thread "main" java.lang.VerifyError: Expecting a stack map frame
Exception Details:
Location:
  nag.nag_screen()V @1: nop
Reason:
  Error exists in the bytecode
Bytecode:
  0000000: b100 0212 03b6 0004 b1

at java.lang.Class.getDeclaredMethods0(Native Method)
at java.lang.Class.privateGetDeclaredMethods(Class.java:2615)
at java.lang.Class.getMethod0(Class.java:2856)
at java.lang.Class.getMethod(Class.java:1668)
at sun.launcher.LauncherHelper.getMainMethod(LauncherHelper.java:494)
at sun.launcher.LauncherHelper.checkAndLoadMain(LauncherHelper.java:486)

Perhaps JVM has some other checks related to the stack maps.
OK, let's patch it differently by removing the call to nag():

Figure 4.3: IDA

0 is the opcode for NOP.
Now that works!
4.1. JAVA

Second example

Another simple crackme example:

```java
public class password {
    public static void main(String[] args) {
        System.out.println("Please enter the password");
        String input = System.console().readLine();
        if (input.equals("secret"))
            System.out.println("password is correct");
        else
            System.out.println("password is not correct");
    }
}
```

Let's load it in IDA:

![IDA](Figure 4.4: IDA)

We see here the `ifeq` instruction which does the job.

Its name stands for *if equal*, and this is misnomer, a better name would be *ifz* (*if zero*), i.e., if value at TOS is zero, then do the jump.

In our example, it jumps if the password is not correct (the equals method returns `false`, which is 0).

The very first idea is to patch this instruction.

There are two bytes in `ifeq` opcode, which encode the jump offset.

To make this instruction a NOP, we must set the 3rd byte to the value of 3 (because by adding 3 to the current address we will always jump to the next instruction, since the `ifeq` instruction’s length is 3 bytes):
4.1. JAVA

That doesn't work (JRE 1.7):

Exception in thread "main" java.lang.VerifyError: Expecting a stackmap frame at branch target 24
Exception Details:
Location: password.main([Ljava/lang/String;)V @21: ifeq
Reason: Expected stackmap frame at this location.
Bytecode:
0000000: b200 0212 03b6 0004 b800 05b6 0006 4c2b
0000010: 1207 b600 0899 0003 b200 0212 09b6 0004
0000020: a700 0bb2 0002 120a b600 04b1
Stackmap Table:
append_frame(@35,Object[#20])
same_frame(@43)

But it must be mentioned that it worked in JRE 1.6.
We can also try to replace to all 3 ifeq opcode bytes with zero bytes (NOP), and it still won't work.
Seems like there are more stack map checks in JRE 1.7.
OK, we'll replace the whole call to the equals method with the icnst_1 instruction plus a pack of NOPs:

Figure 4.5: IDA
4.1. JAVA

1 needs always to be in the TOS when the ifeq instruction is executed, so ifeq would never jump.

This works.

4.1.18 Summary

What is missing in Java in comparison to C/C++?

- Structures: use classes.
- Unions: use class hierarchies.
- Unsigned data types. By the way, this makes cryptographic algorithms somewhat harder to implement in Java.
- Function pointers.
Chapter 5

Finding important/interesting stuff in the code

Minimalism it is not a prominent feature of modern software.

But not because the programmers are writing a lot, but because a lot of libraries are commonly linked statically to executable files. If all external libraries were shifted into an external DLL files, the world would be different. (Another reason for C++ are the STL and other template libraries.)

Thus, it is very important to determine the origin of a function, if it is from standard library or well-known library (like Boost\textsuperscript{1}, libpng\textsuperscript{2}), or if it is related to what we are trying to find in the code.

It is just absurd to rewrite all code in C/C++ to find what we’re looking for.

One of the primary tasks of a reverse engineer is to find quickly the code he/she needs.

The IDA disassembler allow us to search among text strings, byte sequences and constants. It is even possible to export the code to .lst or .asm text files and then use grep, awk, etc.

When you try to understand what some code is doing, this easily could be some open-source library like libpng. So when you see some constants or text strings which look familiar, it is always worth to google them. And if you find the opensource project where they are used, then it’s enough just to compare the functions. It may solve some part of the problem.

For example, if a program uses XML files, the first step may be determining which XML library is used for processing, since the standard (or well-known) libraries are usually used instead of self-made one.

For example, the author of these lines once tried to understand how the compression/decompression of network packets works in SAP 6.0. It is a huge software, but a detailed PDB with debugging information is present, and that is convenient. He finally came to the idea that one of the functions, that was called CsDecomprLZC, was doing the decompression of network packets. Immediately he tried to google its name and he quickly found the function was used in MaxDB (it is an open-source SAP project)\textsuperscript{3}.

http://www.google.com/search?q=CsDecomprLZC

Astoundingly, MaxDB and SAP 6.0 software shared likewise code for the compression/decompression of network packets.

5.1 Identification of executable files

5.1.1 Microsoft Visual C++

MSVC versions and DLLs that can be imported:

\textsuperscript{1}http://go.yurichev.com/17036
\textsuperscript{2}http://go.yurichev.com/17037
\textsuperscript{3}More about it in relevant section (8.10.1 on page 884)
5.1. IDENTIFICATION OF EXECUTABLE FILES

<table>
<thead>
<tr>
<th>Marketing ver.</th>
<th>Internal ver.</th>
<th>CLI.EXE ver.</th>
<th>DLLs imported</th>
<th>Release date</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>6.0</td>
<td>12.00</td>
<td>msvcr.dll</td>
<td>June 1998</td>
</tr>
<tr>
<td>.NET (2002)</td>
<td>7.0</td>
<td>13.00</td>
<td>msvcr70.dll,</td>
<td>February 13,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>msvcp70.dll</td>
<td>2002</td>
</tr>
<tr>
<td>.NET 2003</td>
<td>7.1</td>
<td>13.10</td>
<td>msvcr71.dll,</td>
<td>April 24,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>msvcp71.dll</td>
<td>2003</td>
</tr>
<tr>
<td>2005</td>
<td>8.0</td>
<td>14.00</td>
<td>msvcr80.dll,</td>
<td>November 7,</td>
</tr>
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<td>16.00</td>
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<td>2012</td>
</tr>
<tr>
<td>2013</td>
<td>12.0</td>
<td>18.00</td>
<td>msvcr120.dll,</td>
<td>October 17,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>msvcp120.dll</td>
<td>2013</td>
</tr>
</tbody>
</table>

msvcp*.dll has C++-related functions, so if it is imported, this is probably a C++ program.

Name mangling

The names usually start with the ? symbol.
You can read more about MSVC’s name mangling here: 3.18.1 on page 542.

5.1.2 GCC

Aside from *NIX targets, GCC is also present in the win32 environment, in the form of Cygwin and MinGW.

Name mangling

Names usually start with the _Z symbols.
You can read more about GCC’s name mangling here: 3.18.1 on page 542.

Cygwin

cygwin1.dll is often imported.

MinGW

msvcr1.dll may be imported.

5.1.3 Intel Fortran

libifcoremd.dll, libifportmd.dll and libiomp5md.dll (OpenMP support) may be imported.
libifcoremd.dll has a lot of functions prefixed with for_, which means Fortran.

5.1.4 Watcom, OpenWatcom

Name mangling

Names usually start with the W symbol.
For example, that is how the method named “method” of the class “class” that does not have any arguments and returns void is encoded:
5.1. IDENTIFICATION OF EXECUTABLE FILES

5.1.5 Borland

Here is an example of Borland Delphi's and C++Builder's name mangling:

@TApplication@IdleAction$qv
@TApplication@ProcessMDIAccels$qp6tagMSG
@TModule@$bctr$qpcpvt1
@TModule@$bdtr$qv
@TModule@ValidWindow$qp14TWindowsObject
@TrueColorTo8BitN$qpviiiiiit1iiiiii
@TrueColorTo16BitN$qpviiiiiit1iiiiii
@DIB24BitTo8BitBitmap$qpviiiiiit1iiiii
@TrueBitmap@$bctr$qpcl
@TrueBitmap@$bctr$qpvl
@TrueBitmap@$bctr$qiilll

The names always start with the @ symbol, then we have the class name came, method name, and encoded the types of the arguments of the method.

These names can be in the .exe imports, .dll exports, debug data, etc.

Borland Visual Component Libraries (VCL) are stored in .bpl files instead of .dll ones, for example, vcl50.dll, rtl60.dll.

Another DLL that might be imported: BORLNDMM.DLL.

Delphi

Almost all Delphi executables has the “Boolean” text string at the beginning of the code segment, along with other type names.

This is a very typical beginning of the CODE segment of a Delphi program, this block came right after the win32 PE file header:

```
00000400 04 10 40 00 03 07 42 6f 6f 6c 65 61 6e 01 00 00 |.@...Boolean|
00000410 00 00 01 00 00 00 00 10 40 00 05 46 61 6c 73 65 |...@..False|
00000420 04 54 72 75 65 8d 40 00 09 08 57 69 64 65 6c 69 |.True.@...W|
00000430 64 65 43 68 61 72 03 00 00 00 00 ff ff 00 00 90 |...Char........|
00000440 44 6f 75 62 6c 65 01 8d 40 00 40 11 40 00 00 00 |..Double..@.|
00000450 04 11 40 00 04 08 45 78 74 65 64 65 64 02 90 |..Currency..|
00000460 14 11 40 00 04 06 44 44 6f 75 62 6c 65 01 8d 40 |..String..|
00000470 00 00 00 ff ff ff ff ff ff ff ff ff 7f 90 |...Char........|
00000480 0b 0a 57 69 64 65 53 74 72 69 6e 67 30 11 40 00 |..WideString0.@|
00000490 0c 07 49 6e 74 65 72 66 61 63 65 00 00 00 00 00 |.@...IInterface|
000004a0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 |................|
000004b0 00 00 00 00 00 00 00 00 18 4d 40 00 00 00 00 00 |...System..|
```

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### 5.2. Communication with outer world (function level)

It’s often advisable to track function arguments and return values in debugger or DBI. For example, the author once tried to understand meaning of some obscure function, which happens to be incorrectly implemented bubble sort\(^4\). (It worked correctly, but slower.) Meanwhile, watching inputs and outputs of this function helps instantly to understand what it does.

Often, when you see division by multiplication (3.9 on page 497), but forgot all details about its mechanics, you can just observe input and output and quickly find divisor.

#### 5.3 Communication with the outer world (win32)

Sometimes it’s enough to observe some function’s inputs and outputs in order to understand what it does. That way you can save time.

Files and registry access: for the very basic analysis, Process Monitor\(^5\) utility from SysInternals can help. For the basic analysis of network accesses, Wireshark\(^6\) can be useful. But then you will have to look inside anyway.

The first thing to look for is which functions from the OS’s APIs and standard libraries are used. If the program is divided into a main executable file and a group of DLL files, sometimes the names of the functions in these DLLs can help.

If we are interested in exactly what can lead to a call to `MessageBox()` with specific text, we can try to find this text in the data segment, find the references to it and find the points from which the control may be passed to the `MessageBox()` call we’re interested in.

\(^4\)https://yurichev.com/blog/weird_sort/
\(^5\)http://go.yurichev.com/17301
\(^6\)http://go.yurichev.com/17303
5.3. COMMUNICATION WITH THE OUTER WORLD (WIN32)

If we are talking about a video game and we’re interested in which events are more or less random in it, we may try to find the `rand()` function or its replacements (like the Mersenne twister algorithm) and find the places from which those functions are called, and more importantly, how are the results used. One example: 8.2.

But if it is not a game, and `rand()` is still used, it is also interesting to know why. There are cases of unexpected `rand()` usage in data compression algorithms (for encryption imitation): blog.yurichev.com.

5.3.1 Often used functions in the Windows API

These functions may be among the imported. It is worth to note that not every function might be used in the code that was written by the programmer. A lot of functions might be called from library functions and CRT code.

Some functions may have the -A suffix for the ASCII version and -W for the Unicode version.

- Registry access (advapi32.dll): RegEnumKeyEx, RegEnumValue, RegGetValue, RegOpenKeyEx, RegQueryValueEx.
- Dialog boxes (user32.dll): MessageBox, MessageBoxEx, CreateDialog, SetDlgItemText, GetDlgItemText.
- Resources access (6.5.2 on page 763) (user32.dll): LoadMenu.
- TCP/IP networking (ws2_32.dll): WSARecv, WSASend.
- File access (kernel32.dll): CreateFile, ReadFile, ReadFileEx, WriteFile, WriteFileEx.
- High-level access to the Internet (wininet.dll): WinHttpOpen.
- Checking the digital signature of an executable file (wintrust.dll): WinVerifyTrust.
- The standard MSVC library (if it’s linked dynamically) (msvcr*.dll): assert, itoa, ltoa, open, printf, read, strcmp, atol, atoi, fopen, fread, fwrite, memcmp, rand, strlen, strstr, strchr.

5.3.2 Extending trial period

Registry access functions are frequent targets for those who try to crack trial period of some software, which may save installation date/time into registry.

Another popular target are GetLocalTime() and GetSystemTime() functions: a trial software, at each startup, must check current date/time somehow anyway.

5.3.3 Removing nag dialog box

A popular way to find out what causing popping nag dialog box is intercepting MessageBox(), CreateDialog() and CreateWindow() functions.

5.3.4 tracer: Intercepting all functions in specific module

There are INT3 breakpoints in the tracer, that are triggered only once, however, they can be set for all functions in a specific DLL.

```
--one-time-INT3-bp:somedll.dll!.*
```

Or, let’s set INT3 breakpoints on all functions with the xml prefix in their name:

```
--one-time-INT3-bp:somedll.dll!xml.*
```

On the other side of the coin, such breakpoints are triggered only once. Tracer will show the call of a function, if it happens, but only once. Another drawback—it is impossible to see the function’s arguments. Nevertheless, this feature is very useful when you know that the program uses a DLL, but you do not know which functions are actually used. And there are a lot of functions.
5.4. Strings

5.4.1 Text strings

C/C++

The normal C strings are zero-terminated (ASCIIZ-strings).

The reason why the C string format is as it is (zero-terminated) is apparently historical. In [Dennis M. Ritchie, *The Evolution of the Unix Time-sharing System*, (1979)] we read:

A minor difference was that the unit of I/O was the word, not the byte, because the PDP-7 was a word-addressed machine. In practice this meant merely that all programs dealing with character streams ignored null characters, because null was used to pad a file to an even number of characters.

In Hiew or FAR Manager these strings look like this:

```c
int main()
{
    printf("Hello, world!\n");
}
```

![Figure 5.1: Hiew](image-url)
5.4. STRINGS

Borland Delphi

The string in Pascal and Borland Delphi is preceded by an 8-bit or 32-bit string length.
For example:

Listing 5.1: Delphi

| CODE:00518AC8       | dd 19h |
| CODE:00518ACC aLoading__Plea db 'Loading... , please wait.',0 |
| ... |
| CODE:00518AFC       | dd 10h |
| CODE:00518B00 aPreparingRun__ db 'Preparing run...',0 |

Unicode

Often, what is called Unicode is a methods for encoding strings where each character occupies 2 bytes or 16 bits. This is a common terminological mistake. Unicode is a standard for assigning a number to each character in the many writing systems of the world, but does not describe the encoding method.

The most popular encoding methods are: UTF-8 (is widespread in Internet and *NIX systems) and UTF-16LE (is used in Windows).

UTF-8

UTF-8 is one of the most successful methods for encoding characters. All Latin symbols are encoded just like in ASCII, and the symbols beyond the ASCII table are encoded using several bytes. 0 is encoded as before, so all standard C string functions work with UTF-8 strings just like any other string.

Let's see how the symbols in various languages are encoded in UTF-8 and how it looks like in FAR, using the 437 codepage:

```
How much? 100€?
(English) I can eat glass and it doesn't hurt me.
(Greek) Μπορώ να φάω παραθύρα γυαλίων χωρίς να πάθω τίμητα.
(Hungarian) Meg tudom énni az üveget, nem lesz tőle bajom.
(Icelandic) Eg get eitri glér án þess að melda mig.
(Polish) Mogę jeść szkło i mi nie szkodzi.
(Russian) Я могу есть стекло, мне не вредит.
(Arabic) انا قادر على كل الزجاج وهذا لا يضر لي.
(Hebrew) אני יכול לאכול זכוכית ואינני נפגיע.
(Chinese) 我能吞下玻璃而不伤身体。
(Japanese) 私はガラスを食べられます。それは私を傷つけません。
(Hindi) मैं क्यूप खा सकता हूँ और मुझे उससे कोई घोट नहीं पहुँचता.
```

The example and translations was taken from here: http://go.yurichev.com/17304
5.4. STRINGS

As you can see, the English language string looks the same as it is in ASCII.

The Hungarian language uses some Latin symbols plus symbols with diacritic marks. These symbols are encoded using several bytes, these are underscored with red. It’s the same story with the Icelandic and Polish languages.

There is also the “Euro” currency symbol at the start, which is encoded with 3 bytes.

The rest of the writing systems here have no connection with Latin.

At least in Russian, Arabic, Hebrew and Hindi we can see some recurring bytes, and that is not surprise: all symbols from a writing system are usually located in the same Unicode table, so their code begins with the same numbers.

At the beginning, before the “How much?” string we see 3 bytes, which are in fact the BOM. The BOM defines the encoding system to be used.

UTF-16LE

Many win32 functions in Windows have the suffixes -A and -W. The first type of functions works with normal strings, the other with UTF-16LE strings (wide).

In the second case, each symbol is usually stored in a 16-bit value of type short.

The Latin symbols in UTF-16 strings look in Hiew or FAR like they are interleaved with zero byte:

```c
int wmain()
{
    wprintf (L"Hello, world!\n");
}
```

---

8Byte Order Mark
5.4. STRINGS

We can see this often in Windows NT system files:

![Figure 5.4: Hiew](image)

Strings with characters that occupy exactly 2 bytes are called “Unicode” in IDA:

```
.data:0040E000 aHelloWorld:
.data:0040E000 unicode 0, <Hello, world!>
.data:0040E000 dw 0Ah, 0
```

Here is how the Russian language string is encoded in UTF-16LE:

![Figure 5.5: Hiew: UTF-16LE](image)

What we can easily spot is that the symbols are interleaved by the diamond character (which has the ASCII code of 4). Indeed, the Cyrillic symbols are located in the fourth Unicode plane. Hence, all Cyrillic symbols in UTF-16LE are located in the 0x400-0x4FF range.

Let's go back to the example with the string written in multiple languages. Here is how it looks like in UTF-16LE.

---

9 wikipedia
Here we can also see the **BOM** at the beginning. All Latin characters are interleaved with a zero byte. Some characters with diacritic marks (Hungarian and Icelandic languages) are also underscored in red.

### Base64

The base64 encoding is highly popular for the cases when you have to transfer binary data as a text string. In essence, this algorithm encodes 3 binary bytes into 4 printable characters: all 26 Latin letters (both lower and upper case), digits, plus sign (“+”) and slash sign (“/”), 64 characters in total.

One distinctive feature of base64 strings is that they often (but not always) end with 1 or 2 padding equality symbol(s) (“=”), for example:

```
AVjbbVSVfcUMu1xvjaMgjNTueRwBbxnyJw8dpGnLW8Zw8aKG3v4Y0icuQT+qEJAp9lAoW=
WVjbbVSVfcUMu1xvjaMgjNTueRwBbxnyJw8dpGnLW8Zw8aKG3v4Y0icuQT+qEJAp9lAoQ==
```

The equality sign (“=”) is never encounter in the middle of base64-encoded strings.

Now example of manual encoding. Let’s encode 0x00, 0x11, 0x22, 0x33 hexadecimal bytes into base64 string:

```
$ echo -n \"\x00\x11\x22\x33\" | base64
ABEiMw==
```

Let’s put all 4 bytes in binary form, then regroup them into 6-bit groups:

```
| 00 || 11 || 22 || 33 || || |
| 000000000010010100010001100111111111111111111111111111111111111111111111 |
| A || B || E || i || M || w || = || = |
```

Three first bytes (0x00, 0x11, 0x22) can be encoded into 4 base64 characters (“ABEi”), but the last one (0x33) — cannot be, so it’s encoded using two characters (“Mw”) and padding symbol (“=”) is added twice to pad the last group to 4 characters. Hence, length of all correct base64 strings are always divisible by 4.
5.4. STRINGS

Base64 is often used when binary data needs to be stored in XML. “Armored” (i.e., in text form) PGP keys and signatures are encoded using base64.


There are utilities for scanning an arbitrary binary files for base64 strings. One such utility is base64scanner.

Another encoding system which was much more popular in UseNet and FidoNet is Uuencoding. Binary files are still encoded in Uuencode format in Phrack magazine. It offers mostly the same features, but is different from base64 in the sense that file name is also stored in header.

By the way: there is also close sibling to base64: base32, alphabet of which has 10 digits and 26 Latin characters. One well-known usage of it is onion addresses, like: http://3g2upl4pq6kufc4m.onion/.

URL can’t have mixed-case Latin characters, so apparently, this is why Tor developers used base32.

5.4.2 Finding strings in binary

Actually, the best form of Unix documentation is frequently running the strings command over a program’s object code. Using strings, you can get a complete list of the program’s hard-coded file name, environment variables, undocumented options, obscure error messages, and so forth.

The standard UNIX strings utility is quick-n-dirty way to see strings in file. For example, these are some strings from OpenSSH 7.2 sshd executable file:

```plaintext
...
0123
0123456789
0123456789abcdefABCDEF./
%02x
...
%.100s, line %lu: Bad permitopen specification <%.100s>
%.100s, line %lu: invalid criteria
%.100s, line %lu: invalid tun device
...
%.200s/.ssh/environment
...
2886173b9c9b6fddbeda7a247cd636db38deaa.debug
\$2a\$06$\r3.juUaHZdIbQaO2dS9FuYxL1W9MB1R1Tc92PoSNmzvpEqLkLGrK
...
3des-cbc
...
Bind to port %s on %s.
Bind to port %s on %s failed: %.200s.
/bin/login
/bin/sh
/bin/sh /etc/ssh/sshrc
...
D$4PQWR1
D$4PUj
D$4PV
D$4PVj
D$4PW
D$4PWj
D$4X
D$4XZj
D$4Y
...
diffie-hellman-group-exchange-sha1
```
5.4. STRINGS

diffie-hellman-group-exchange-sha256
digests
D$iPV
direct-streamlocal
direct-streamlocal@openssh.com
...
FFFFFFFFFFFFFFFFFC90FDAA22168C234C4C6628B80DC1CD29024E088A6...
...

There are options, error messages, file paths, imported dynamic modules and functions, some other
strange strings (keys?) There is also unreadable noise—x86 code sometimes has chunks consisting of
printable ASCII characters, up to 8 characters.

Of course, OpenSSH is open-source program. But looking at readable strings inside of some unknown
binary is often a first step of analysis.

grep can be applied as well.

Hiew has the same capability (Alt-F6), as well as Sysinternals ProcessMonitor.

5.4.3 Error/debug messages

Debugging messages are very helpful if present. In some sense, the debugging messages are reporting
what’s going on in the program right now. Often these are printf()-like functions, which write to log-files,
or sometimes do not writing anything but the calls are still present since the build is not a debug one but
release one.

If local or global variables are dumped in debug messages, it might be helpful as well since it is possible
to get at least the variable names. For example, one of such function in Oracle RDBMS is ksdwr

Meaningful text strings are often helpful. The IDA disassembler may show from which function and from
which point this specific string is used. Funny cases sometimes happen.

The error messages may help us as well. In Oracle RDBMS, errors are reported using a group of functions.
You can read more about them here: blog.yurichev.com.

It is possible to find quickly which functions report errors and in which conditions.

By the way, this is often the reason for copy-protection systems to inarticulate cryptic error messages
or just error numbers. No one is happy when the software cracker quickly understand why the copy-
protection is triggered just by the error message.

One example of encrypted error messages is here: 8.5.2 on page 822.

5.4.4 Suspicious magic strings

Some magic strings which are usually used in backdoors look pretty suspicious.

For example, there was a backdoor in the TP-Link WR740 home router. The backdoor can activated
using the following URL:
http://192.168.0.1/userRpmNatDebugRpm26525557/start_art.html.

Indeed, the “userRpmNatDebugRpm26525557” string is present in the firmware.

This string was not googleable until the wide disclosure of information about the backdoor.

You would not find this in any RFC.

You would not find any computer science algorithm which uses such strange byte sequences.

And it doesn’t look like an error or debugging message.

So it’s a good idea to inspect the usage of such weird strings.

---

13 blog.yurichev.com
14 http://sekurak.pl/tp-link-httptftp-backdoor/
15 Request for Comments
5.5 CALLSTOASSERT()

Sometimes, such strings are encoded using base64.
So it’s a good idea to decode them all and to scan them visually, even a glance should be enough.

More precise, this method of hiding backdoors is called “security through obscurity”.

5.5 Calls to assert()

Sometimes the presence of the assert() macro is useful too: commonly this macro leaves source file name, line number and condition in the code.

The most useful information is contained in the assert’s condition, we can deduce variable names or structure field names from it. Another useful piece of information are the file names—we can try to deduce what type of code is there. Also it is possible to recognize well-known open-source libraries by the file names.

Listing 5.2: Example of informative assert() calls

```
.text:107D4B29 mov dx, [ecx+42h]
.text:107D4B2D cmp edx, 1
.text:107D4B30 jz short loc_107D4B4A
.text:107D4B32 push 1ECh
.text:107D4B37 push offset aWrite_c ; "write.c"
.text:107D4B3C push offset aTdTd_planarcon ; "td->td_planarconfig == PLANARCONFIG_CON"
.text:107D4B41 call ds:_assert
...
.text:107D52CA mov edx, [ebp-4]
.text:107D52CD and edx, 3
.text:107D52D0 test edx, edx
.text:107D52D2 jz short loc_107D52E9
.text:107D52D4 push 58h
.text:107D52D6 push offset aDumpmode_c ; "dumpmode.c"
.text:107D52DB push offset aN30 ; "(n & 3) == 0"
.text:107D52E0 call ds:_assert
...
.text:107D6759 mov cx, [eax+6]
.text:107D675D cmp ecx, 0Ch
.text:107D6760 jle short loc_107D677A
.text:107D6762 push 2D8h
.text:107D6767 push offset aLzw_c ; "lzw.c"
.text:107D676C push offset aSpLzw_nbitsBit ; "sp->lzw_nbits <= BITS_MAX"
.text:107D6771 call ds:_assert
```

It is advisable to “google” both the conditions and file names, which can lead us to an open-source library. For example, if we “google” “sp->lzw_nbits <= BITS_MAX”, this predictably gives us some open-source code that’s related to the LZW compression.

5.6 Constants

Humans, including programmers, often use round numbers like 10, 100, 1000, in real life as well as in the code.

The practicing reverse engineer usually know them well in hexadecimal representation: 10=0xA, 100=0x64, 1000=0x3E8, 10000=0x2710.

The constants 0xAAAAAAAA (0b10101010101010101010101010101010) and 0x55555555 (0b01010101010101010101010101010101) are also popular—those are composed of alternating bits.
5.6. CONSTANTS

That may help to distinguish some signal from a signal where all bits are turned on (0b1111 ...) or off (0b0000 ...). For example, the 0x55AA constant is used at least in the boot sector, MBR\(^\text{16}\), and in the ROM of IBM-compatible extension cards.

Some algorithms, especially cryptographical ones use distinct constants, which are easy to find in code using IDA.

For example, the MD5\(^\text{17}\) algorithm initializes its own internal variables like this:

```c
var int h0 := 0x67452301
var int h1 := 0xEFCDAB89
var int h2 := 0x98BADCFE
var int h3 := 0x10325476
```

If you find these four constants used in the code in a row, it is highly probable that this function is related to MD5.

Another example are the CRC16/CRC32 algorithms, whose calculation algorithms often use precomputed tables like this one:

```
/** CRC table for the CRC-16. The poly is 0x8005 (x^16 + x^15 + x^2 + 1) */
const u16 crc16_table[256] = {
  0x0000, 0xC0C1, 0xC181, 0x0140, 0xC301, 0x03C0, 0x0280, 0xC241,
  0xC601, 0x06C0, 0x0780, 0xC741, 0x0500, 0xC5C1, 0xC481, 0x0440,
  0xCC01, 0x0CC0, 0x0D80, 0xCD41, 0x0F00, 0xCF81, 0xCE40, 0xCDE2,
  …
};
```

See also the precomputed table for CRC32: \(^\text{3.5 on page 482}\).

In tableless CRC algorithms well-known polynomials are used, for example, 0xEDB88320 for CRC32.

5.6.1 Magic numbers

A lot of file formats define a standard file header where a magic number(s)\(^\text{18}\) is used, single one or even several.

For example, all Win32 and MS-DOS executables start with the two characters “MZ”\(^\text{19}\).

At the beginning of a MIDI file the “MThd” signature must be present. If we have a program which uses MIDI files for something, it’s very likely that it must check the file for validity by checking at least the first 4 bytes.

This could be done like this: (buf points to the beginning of the loaded file in memory)

```c
cmp [buf], 0x646854D ; "MThd"
```

...or by calling a function for comparing memory blocks like memcmp() or any other equivalent code up to a CMPSB (\(^\text{1.6 on page 1032}\)) instruction.

When you find such point you already can say where the loading of the MIDI file starts, also, we could see the location of the buffer with the contents of the MIDI file, what is used from the buffer, and how.

Dates

Often, one may encounter number like 0x19870116, which is clearly looks like a date (year 1987, 1th month (January), 16th day). This may be someone’s birthday (a programmer, his/her relative, child), or some other important date. The date may also be written in a reverse order, like 0x01161987. American-style dates are also popular, like 0x01161987.

Well-known example is 0x19540119 (magic number used in UFS2 superblock structure), which is a birthday of Marshall Kirk McKusick, prominent FreeBSD contributor.

\(^{16}\)Master Boot Record
\(^{17}\)wikipedia
\(^{18}\)wikipedia
\(^{19}\)wikipedia
5.6. **CONSTANTS**

Stuxnet uses the number “19790509” (not as 32-bit number, but as string, though), and this led to speculation that the malware is connected to Israel.

Also, numbers like those are very popular in amateur-grade cryptography, for example, excerpt from the secret function internals from HASP3 dongle:

```c
void xor_pwd(void)
{
    int i;
    pwd ^= 0x09071966;
    for(i=0;i<8;i++)
    {
        al_buf[i] = pwd & 7; pwd = pwd >> 3;
    }
}

void emulate_func2(unsigned short seed)
{
    int i, j;
    for(i=0;i<8;i++)
    {
        ch[i] = 0;
        for(j=0;j<8;j++)
        {
            seed *= 0x1989;
            seed += 5;
            ch[i] |= (tab[(seed>>9)&0x3f]) << (7-j);
        }
    }
}
```

**DHCP**

This applies to network protocols as well. For example, the DHCP protocol’s network packets contains the so-called magic cookie: 0x63538263. Any code that generates DHCP packets somewhere must embed this constant into the packet. If we find it in the code we may find where this happens and, not only that. Any program which can receive DHCP packet must verify the magic cookie, comparing it with the constant.

For example, let’s take the dhcpcore.dll file from Windows 7 x64 and search for the constant. And we can find it, twice: it seems that the constant is used in two functions with descriptive names DhcpExtractOptionsForValidation() and DhcpExtractFullOptions():

```c
Listing 5.4: dhcpcore.dll (Windows 7 x64)
.rdata:000007FF6483CBE8 dword_7FF6483CBE8 dd 63538263h ; DATA XREF: ↵
    \DhcpExtractOptionsForValidation+79
.rdata:000007FF6483CBEC dword_7FF6483CBEC dd 63538263h ; DATA XREF: ↵
    \DhcpExtractFullOptions+97
```

And here are the places where these constants are accessed:

```c
Listing 5.5: dhcpcore.dll (Windows 7 x64)
.text:000007FF6480875F mov eax, [rsi]
.text:000007FF64808761 cmp eax, cs:dword_7FF6483CBE8
.text:000007FF64808767 jnz loc_7FF64817179
```

And:

```c
Listing 5.6: dhcpcore.dll (Windows 7 x64)
.text:000007FF64808757 mov eax, [r12]
.text:000007FF64808761 cmp eax, cs:dword_7FF6483CBEC
.text:000007FF64808767 jnz loc_7FF648173AF
```

---

20This is a date of execution of Habib Elghanian, persian jew.
5.6.2 Specific constants

Sometimes, there is a specific constant for some type of code. For example, the author once dug into a code, where number 12 was encountered suspiciously often. Size of many arrays is 12, or multiple of 12 (24, etc). As it turned out, that code takes 12-channel audio file at input and process it.

And vice versa: for example, if a program works with text field which has length of 120 bytes, there has to be a constant 120 or 119 somewhere in the code. If UTF-16 is used, then \(2 \cdot 120\). If a code works with network packets of fixed size, it’s good idea to search for this constant in the code as well.

This is also true for amateur cryptography (license keys, etc). If encrypted block has size of \(n\) bytes, you may want to try to find occurences of this number throughout the code. Also, if you see a piece of code which is been repeated \(n\) times in loop during execution, this may be encryption/decryption routine.

5.6.3 Searching for constants

It is easy in IDA: Alt-B or Alt-I. And for searching for a constant in a big pile of files, or for searching in non-executable files, there is a small utility called binary grep\(^22\).

5.7 Finding the right instructions

If the program is utilizing FPU instructions and there are very few of them in the code, one can try to check each one manually with a debugger.

For example, we may be interested how Microsoft Excel calculates the formulae entered by user. For example, the division operation.

If we load excel.exe (from Office 2010) version 14.0.4756.1000 into IDA, make a full listing and to find every FDIV instruction (except the ones which use constants as a second operand—obviously, they do not suit us):

```
cat EXCEL.lst | grep fdiv | grep -v dbl_ > EXCEL.fdiv
```

...then we see that there are 144 of them.

We can enter a string like \((1/3)\) in Excel and check each instruction.

By checking each instruction in a debugger or tracer (one may check 4 instruction at a time), we get lucky and the sought-for instruction is just the 14th:

```
.text:3011E919 DC 33 fdiv qword ptr [ebx]
```

ST(0) holds the first argument (1) and second one is in [EBX].

The instruction after FDIV (FSTP) writes the result in memory:

```
.text:3011E91B DD 1E fstp qword ptr [esi]
```

If we set a breakpoint on it, we can see the result:

\(^{22}\)GitHub
5.8 Suspicious code patterns

5.8.1 XOR instructions

Instructions like XOR op, op (for example, XOR EAX, EAX) are usually used for setting the register value to zero, but if the operands are different, the “exclusive or” operation is executed.
This operation is rare in common programming, but widespread in cryptography, including amateur one. It's especially suspicious if the second operand is a big number. This may point to encrypting/decrypting, checksum computing, etc.

One exception to this observation worth noting is the “canary” (\ref{sec:canary}) Its generation and checking are often done using the XOR instruction.

This AWK script can be used for processing IDA listing (.lst) files:

\begin{verbatim}
gawk -e '$2=="xor" { tmp=substr($3, 0, length($3)-1); if (tmp!=$4) if($4!="esp") if ($4!="ebp")/rcurvearrowse
⤦ { print $1, $2, tmp, ",", $4 } }' filename.lst
\end{verbatim}

It is also worth noting that this kind of script can also match incorrectly disassembled code (\ref{sec:incorrect}).

\section{Hand-written assembly code}

Modern compilers do not emit the LOOP and RCL instructions. On the other hand, these instructions are well-known to coders who like to code directly in assembly language. If you spot these, it can be said that there is a high probability that this fragment of code was hand-written. Such instructions are marked as (M) in the instructions list in this appendix:\ref{sec:appendix}.

Also the function prologue/epilogue are not commonly present in hand-written assembly. Commonly there is no fixed system for passing arguments to functions in the hand-written code.

Example from the Windows 2003 kernel (ntoskrnl.exe file):

\begin{verbatim}
MultiplyTest proc near ; CODE XREF: Get386Stepping
    xor cx, cx
loc_620555:
    push cx
    call Multiply
    pop cx
    jb short locret_620563
    loop loc_620555
    clc
locret_620563: ; CODE XREF: MultiplyTest+C
    retn
MultiplyTest endp

Multiply proc near ; CODE XREF: MultiplyTest+5
    mov ecx, 81h
    mov eax, 417A000h
    mul ecx
    cmp edx, 2
    stc
    jnz short locret_62057F
    cmp eax, 0FE7A000h
    stc
    jnz short locret_62057F
    clc
locret_62057F: ; CODE XREF: Multiply+10
    ; Multiply+18
    retn
Multiply endp
\end{verbatim}

Indeed, if we look in the WRK\textsuperscript{23} v1.2 source code, this code can be found easily in file WRK-v1.2\base\ntos\ke\i386\cpu.asm.

\footnote{\textsuperscript{23}Windows Research Kernel}
5.9 Using magic numbers while tracing

Often, our main goal is to understand how the program uses a value that has been either read from file or received via network. The manual tracing of a value is often a very labor-intensive task. One of the simplest techniques for this (although not 100% reliable) is to use your own magic number.

This resembles X-ray computed tomography in some sense: a radiocontrast agent is injected into the patient’s blood, which is then used to improve the visibility of the patient’s internal structure in to the X-rays. It is well known how the blood of healthy humans percolates in the kidneys and if the agent is in the blood, it can be easily seen on tomography, how blood is percolating, and are there any stones or tumors.

We can take a 32-bit number like 0x0badf00d, or someone’s birth date like 0x11101979 and write this 4-byte number to some point in a file used by the program we investigate.

Then, while tracing this program with tracer in code coverage mode, with the help of grep or just by searching in the text file (of tracing results), we can easily see where the value has been used and how.

Example of grepable tracer results in cc mode:

```
0x150bf66 (_kziaia+0x14), e= 1 [MOV EBX, [EBP+8]] [EBP+8]=0xf59c934
0x150bf69 (_kziaia+0x17), e= 1 [MOV EDX, [69AEB08h]] [69AEB08h]=0
0x150bf6f (_kziaia+0x1d), e= 1 [FS: MOV EAX, [2Ch]]
0x150bf75 (_kziaia+0x23), e= 1 [MOV ECX, [EAX+EDX*4]] [EAX+EDX*4]=0xf1ac360
0x150bf78 (_kziaia+0x26), e= 1 [MOV [EBP-4], ECX] ECX=0xf1ac360
```

This can be used for network packets as well. It is important for the magic number to be unique and not to be present in the program’s code.

Aside of the tracer, DosBox (MS-DOS emulator) in heavydebug mode is able to write information about all registers’ states for each executed instruction of the program to a plain text file, so this technique may be useful for DOS programs as well.

5.10 Loops

Whenever your program works with some kind of file, or buffer of some size, it has to be some kind of decrypting/processing loop inside of the code.

This is a real example of tracer tool output. There was a code which loads some kind of encrypted file of 258 bytes. I run it with the intention to get each instruction counts (a DBI tool will serve much better these days). And I quickly found a piece of code, which executed 259/258 times:

```
...  
0x45a6b5 e= 1 [FS: MOV [0], EAX] EAX=0x218fb08
0x45a6bb e= 1 [MOV [EBP-254h], ECX] ECX=0x218fbd8
0x45a6c1 e= 1 [MOV EAX, [EBP-254h]] [EBP-254h]=0x218fbd8
0x45a6c7 e= 1 [CMP [EAX+14h], 0] [EAX+14h]=0x102
0x45a6cb e= 1 [JZ 45A9F2h] ZF=false
0x45a6d1 e= 1 [MOV [EBP-00h], 1]
0x45a6d5 e= 1 [XOR ECX, ECX] ECX=0x218fbd8
0x45a6d7 e= 1 [MOV [EBP-14h], CX] CX=0
0x45a6db e= 1 [MOV [EBP-18h], 0]
0x45a6e2 e= 1 [JMP 45A6EDh]
0x45a6e4 e= 258 [MOV EDX, [EBP-18h]] [EBP-18h]=0..5 (248 items skipped) 0xfd..0x101
0x45a6e7 e= 258 [ADD EDX, 1] EDX=0..5 (248 items skipped) 0xfd..0x101
0x45a6ea e= 258 [MOV [EBP-18h], EDX] EDX=1..6 (248 items skipped) 0xfe..0x102
0x45a6ed e= 259 [MOV EAX, [EBP-254h]] [EBP-254h]=0x218fbd8
0x45a6f3 e= 259 [MOV ECX, [EBP-18h]] [EBP-18h]=0..5 (249 items skipped) 0xfe..0x102
0x45a6f6 e= 259 [CMP ECX, [EAX+14h]] ECX=0..5 (249 items skipped) 0xfe..0x102 [EAX+14h]=0x102
0x45a6f9 e= 259 [JNB 45A727h] CF=false, true
0x45a701 e= 258 [MOV EAX, [EBP-254h]] [EBP-254h]=0x218fbd8
0x45a704 e= 258 [MOV EAX, [EDX+10h]] [EDX+10h]=0x21ee4c8
0x45a707 e= 258 [ADD ECX, 1] ECX=0..5 (248 items skipped) 0xfd..0x101
0x45a70a e= 258 [IMUL ECX, ECX, 1] ECX=1..6 (248 items skipped) 0xfe..0x102
```

24 See also my blog post about this DosBox feature: blog.yurichev.com
5.10. LOOPS

As it turns out, this is the decrypting loop.

5.10.1 Some binary file patterns

All examples here were prepared on the Windows with active code page 437 in console. Binary files internally may look visually different if another code page is set.

5.10. LOOPS

Arrays

Sometimes, we can clearly spot an array of 16/32/64-bit values visually, in hex editor.

Here is an example of array of 16-bit values. We see that the first byte in pair is 7 or 8, and the second looks random:

![Figure 5.8: FAR: array of 16-bit values](image)

I used a file containing 12-channel signal digitized using 16-bit ADC\(^{26}\).

---

\(^{26}\)Analog-to-Digital Converter
5.10. **LOOPS**

And here is an example of very typical MIPS code.

As we may recall, every MIPS (and also ARM in ARM mode or ARM64) instruction has size of 32 bits (or 4 bytes), so such code is array of 32-bit values.

By looking at this screenshot, we may see some kind of pattern.

Vertical red lines are added for clarity:

---

**Figure 5.9:** Hiew: very typical MIPS code

Another example of such pattern here is book: **9.5 on page 973.**
This is sparse file with data scattered amidst almost empty file. Each space character here is in fact zero byte (which is looks like space). This is a file to program FPGA (Altera Stratix GX device). Of course, files like these can be compressed easily, but formats like this one are very popular in scientific and engineering software where efficient access is important while compactness is not.

Figure 5.10: FAR: Sparse file
This file is just some compressed archive. It has relatively high entropy and visually looks just chaotic. This is how compressed and/or encrypted files looks like.
OS installations are usually distributed as ISO files which are copies of CD/DVD discs. Filesystem used is named CDFS, here you see file names mixed with some additional data. This can be file sizes, pointers to another directories, file attributes, etc. This is how typical filesystems may look internally.

---

**Figure 5.12:** FAR: ISO file: Ubuntu 15 installation

---

Footnote: Compact Disc File System
This is how 32-bit x86 executable code looks like. It has not very high entropy, because some bytes occurred more often than others.

Figure 5.13: FAR: Executable 32-bit x86 code
BMP graphics files

BMP files are not compressed, so each byte (or group of bytes) describes each pixel. I’ve found this picture somewhere inside my installed Windows 8.1:

![Example picture](image)

Figure 5.14: Example picture

You see that this picture has some pixels which unlikely can be compressed very good (around center), but there are long one-color lines at top and bottom. Indeed, lines like these also looks as lines during viewing the file:

![BMP file fragment](image)

Figure 5.15: BMP file fragment

5.10.2 Memory “snapshots” comparing

The technique of the straightforward comparison of two memory snapshots in order to see changes was often used to hack 8-bit computer games and for hacking “high score” files.
5.11. ISA DETECTION

For example, if you had a loaded game on an 8-bit computer (there isn't much memory on these, but the game usually consumes even less memory) and you know that you have now, let's say, 100 bullets, you can do a “snapshot” of all memory and back it up to some place. Then shoot once, the bullet count goes to 99, do a second “snapshot” and then compare both: it must be a byte somewhere which has been 100 at the beginning, and now it is 99.

Considering the fact that these 8-bit games were often written in assembly language and such variables were global, it can be said for sure which address in memory has holding the bullet count. If you searched for all references to the address in the disassembled game code, it was not very hard to find a piece of code decrementing the bullet count, then to write a NOP instruction there, or a couple of NOP-s, and then have a game with 100 bullets forever. Games on these 8-bit computers were commonly loaded at the constant address, also, there were not much different versions of each game (commonly just one version was popular for a long span of time), so enthusiastic gamers knew which bytes must be overwritten (using the BASIC’s instruction POKE at which address in order to hack it. This led to “cheat” lists that contained POKE instructions, published in magazines related to 8-bit games. See also: wikipedia.

Likewise, it is easy to modify “high score” files, this does not work with just 8-bit games. Notice your score count and back up the file somewhere. When the “high score” count gets different, just compare the two files, it can even be done with the DOS utility FC29 (“high score” files are often in binary form).

There will be a point where a couple of bytes are different and it is easy to see which ones are holding the score number. However, game developers are fully aware of such tricks and may defend the program against it.

Somewhat similar example in this book is: 9.3 on page 961.

Windows registry

It is also possible to compare the Windows registry before and after a program installation.

It is a very popular method of finding which registry elements are used by the program. Perhaps, this is the reason why the “windows registry cleaner” shareware is so popular.

Blink-comparator

Comparison of files or memory snapshots remind us blink-comparator 30: a device used by astronomers in past, intended to find moving celestial objects.

Blink-comparator allows to switch quickly between two photographies shot in different time, so astronomer would spot the difference visually.

By the way, Pluto was discovered by blink-comparator in 1930.

5.11  ISA detection

Often, you can deal with a binary file for an unknown ISA. Perhaps, easiest way to detect ISA is to try various ones in IDA, objdump or another disassembler.

To achieve this, one should understand a difference between incorrectly disassembled code and correctly one.

5.11.1  Incorrectly disassembled code

Practicing reverse engineers often have to deal with incorrectly disassembled code.

29MS-DOS utility for comparing binary files
30http://go.yurichev.com/17348
Disassembling from an incorrect start (x86)

Unlike ARM and MIPS (where any instruction has a length of 2 or 4 bytes), x86 instructions have variable size, so any disassembler that starts in the middle of a x86 instruction may produce incorrect results.

As an example:

```
add [ebp-31F7Bh], cl
dec dword ptr [ecx-3277Bh]
dec dword ptr [ebp-2CF7Bh]
inc dword ptr [ebx-7A76F33Ch]
fdiv st(4), st
db 0FFh
dec dword ptr [ecx-21F7Bh]
dec dword ptr [ecx-22373h]
dec dword ptr [ecx-2276Bh]
dec dword ptr [ecx-22B63h]
dec dword ptr [ecx-22F4Bh]
dec dword ptr [ecx-23343h]
jmp dword ptr [esi-74h]
xchg eax, ebp
clc
std
db 0FFh
db 0FFh
mov word ptr [ebp-214h], cs ; <- disassembler finally found right track here
mov word ptr [ebp-238h], ds
mov word ptr [ebp-23Ch], es
mov word ptr [ebp-240h], fs
mov word ptr [ebp-244h], gs
pushf
pop dword ptr [ebp-210h]
mov eax, [ebp+4]
mov [ebp-218h], eax
lea eax, [ebp+4]
mov [ebp-20Ch], eax
mov dword ptr [ebp-200h], 10001h
mov eax, [eax-4]
mov [ebp-21Ch], eax
mov eax, [ebp+0Ch]
mov [ebp-320h], eax
mov eax, [ebp+10h]
mov [ebp-31Ch], eax
mov eax, [ebp+4]
mov [ebp-314h], eax
call ds:IsDebuggerPresent
mov edi, eax
lea eax, [ebp-328h]
push eax
call sub_407663
pop ecx
test eax, eax
jnz short loc_402D7B
```

There are incorrectly disassembled instructions at the beginning, but eventually the disassembler gets on the right track.

**How does random noise look disassembled?**

Common properties that can be spotted easily are:

- Unusually big instruction dispersion. The most frequent x86 instructions are PUSH, MOV, CALL, but here we see instructions from all instruction groups: FPU instructions, IN/OUT instructions, rare and system instructions, everything mixed up in one single place.

- Big and random values, offsets and immediates.

- Jumps having incorrect offsets, often jumping in the middle of another instructions.
Listing 5.7: random noise (x86)

```assembly
mov bl, 0Ch
mov ecx, 0D38558Dh
mov eax, ds:2C869A86h
db 67h
mov dl, 0CCh
insb
movsb
push eax
xor [edx-53h], ah
fcom qword ptr [edi-45A0EF72h]
pop esp
pop ss
in eax, dx
dec ebx
push esp
lds esp, [esi-41h]
retf
rcl dword ptr [eax], cl
mov cl, 9Ch
mov ch, 0DFh
push cs
insb
mov esi, 0D9C65E4Dh
imul ebp, [ecx], 66h
pushf
sal dword ptr [ebp-64h], cl
sub eax, 0AC433D64h
out 8Ch, eax
pop ss
sbb [eax], ebx
aas
xchg cl, [ebx+ebx*4+14B31Eh]
jecxz short near ptr loc_58+1
xor al, 0C6h
inc edx
db 36h
pusha
stosb
test [ebx], ebx
sub al, 0D3h ; 'L'
pop eax
stosb
loc_58: ; CODE XREF: seg000:0000004A
test [esi], eax
inc ebp
das
db 64h
pop ecx
das
hlt
pop edx
out 080h, al
lodsb
push ebx
cdq
out dx, al
sub al, 0Ah
sti
outsd
add dword ptr [edx], 96FCBE4Bh
and eax, 0E537EE4Fh
inc esp
stosd
cdq
push ecx
in al, 0CBh
mov ds:0D114C45Ch, al
```
5.11. ISA DETECTION

mov esi, 659D1985h

Listing 5.8: random noise (x86-64)

lea esi, [rax+rdx*4+43558D29h]
loc_AF3: ; CODE XREF: seg000:00000000000000846
rcl byte ptr [rsi+rax*8+29B8423Ah], 1
lea ecx, cs:0FFFFFFFB2A6780Fh
mov al, 96h
mov ah, 0CEh
push rsp
lods byte ptr [esi]

db 2Fh ; /
pop rsp
db 64h
retf 0E993h
cmp ah, [rax+4Ah]
movzx rsi, dword ptr [rbp-25h]
push 4Ah
movzx rdi, dword ptr [rdi+rdx*8]
db 9Ah
rcr byte ptr [rax+1Dh], cl
lodsd
xor [rbp+6CF20173h], edx
xor [rbp+66F8B593h], edx
push rbx
sbb ch, [rbx-0Fh]
ostd
int 87h
db 46h, 4Ch
out dx, eax
test ecx, ebp
movsdl
leave
push rsp

db 16h
xchg eax, esi
pop rdi

loc_B3D: ; CODE XREF: seg000:00000000000000BF
mov ds:93CA685DF98A90F9h, eax
jnz short near ptr loc_AF3+6
out dx, eax
cwde
mov bh, 5Dh ; ']' 
movsb
pop rbp

Listing 5.9: random noise (ARM (ARM mode))

BLNE 0xFE16A9D8
BGE 0x1634D0C
SVCCS 0x450685
STRNVT R5, [PC], #0x964
LDCGE p6, c14, [R0], #0x168
STCCSL p9, c9, [LR], #0x14C
CMNHP R5, R0, LSL#22
FLDMADVN LR!, {D4}
MCR p5, 2, R2, c15, c6, 4
BLGE 0x1139558
BLGT 0xFF9146E4
5.11. ISA DETECTION

Listing 5.10: random noise (ARM (Thumb mode))
### 5.12. TEXT STRINGS RIGHT IN THE MIDDLE OF COMPRESSED DATA

It is also important to keep in mind that cleverly constructed unpacking and decryption code (including self-modifying) may look like noise as well, but still execute correctly.

#### 5.11.2 Correctly disassembled code

Each ISA has a dozen of a most used instructions, all the rest are used much less often. As of x86, it is interesting to know that the fact that function calls (PUSH/CALL/ADD) and MOV instructions are the most frequently executed pieces of code in almost all programs we use. In other words, CPU is very busy passing information between levels of abstractions, or, it can be said, it’s very busy switching between these levels. Regardless type of ISA. This is a cost of splitting problems into several levels of abstractions (so humans could work with them easier).

### 5.12 Text strings right in the middle of compressed data

You can download Linux kernels and find English words right in the middle of compressed data:

```sh
% wget https://www.kernel.org/pub/linux/kernel/v4.x/linux-4.10.2.tar.gz
```
5.12. TEXT STRINGS RIGHT IN THE MIDDLE OF COMPRESSED DATA

% xxd -g 1 -seek 0x515c550 -l 0x30 linux-4.10.2.tar.gz
0515c550: c5 59 43 cf 41 27 85 54 35 4a 57 90 73 89 b7 6a .YC.A'.T5JW.s..j
0515c560: 15 af 03 db 20 df 6a 51 f9 56 49 52 55 3d da .... .jQ.VIRUS=.
0515c570: 0e b9 29 24 cc 6a 38 e2 78 66 09 32 72 aa 88 df ..$).j8.xf.3r...

% wget https://cdn.kernel.org/pub/linux/kernel/v2.3/linux-2.3.3.tar.bz2
% xxd -g 1 -seek 0xa93086 -l 0x30 linux-2.3.3.tar.bz2
00a93086: 4d 54 54 41 55 4e 45 4c 4d 45 54 41 4c cd 44 4e 03 2c 95 dc 65 eb 31 d3 f1 METAL.DE-,AAT...
00a93096: 5d 2b d8 d0 bd d8 06 91 74 ab 41 a0 0a 8a 94 68 ]+....t.A.....h
00a930a6: 66 56 86 81 68 0d 0e 25 6b b6 80 a4 28 1a 00 a4 fV..h..%k...(...

One of Linux kernel patches in compressed form has the “Linux” word itself:

% wget https://cdn.kernel.org/pub/linux/kernel/v4.x/testing/patch-4.6-rc4.gz
% xxd -g 1 -seek 0x4d03f -l 0x30 patch-4.6-rc4.gz
004d03f: c7 40 24 bd ae ef ee 03 2c 95 dc 65 eb 31 d3 f1 .@$.....,..e.1..
004d04f: 4c 69 6e 75 78 f2 f3 70 3c 3a bd 3e bd f8 59 7e Linux..<:.>..Y~
004d05f: cd 76 55 74 2b cb d5 af 7a 35 56 d7 5e 07 5a 67 .vUt+...z5V.~Zg

Other English words I’ve found in other compressed Linux kernel trees:

<table>
<thead>
<tr>
<th>Kernel Tree</th>
<th>Example Bytes</th>
</tr>
</thead>
<tbody>
<tr>
<td>linux-4.6.2.tar.gz: [maybe]</td>
<td>0x68e78ec</td>
</tr>
<tr>
<td>linux-4.10.14.tar.xz: [OCEAN]</td>
<td>0x6bf0a8</td>
</tr>
<tr>
<td>linux-4.7.8.tar.gz: [FUNNY]</td>
<td>0x29e6e20</td>
</tr>
<tr>
<td>linux-4.6.4.tar.gz: [DRINK]</td>
<td>0x68dc314</td>
</tr>
<tr>
<td>linux-2.6.11.8.tar.bz2: [LUCKY]</td>
<td>0x1ab5be7</td>
</tr>
<tr>
<td>linux-3.0.68.tar.gz: [BOOST]</td>
<td>0x11238c7</td>
</tr>
<tr>
<td>linux-3.0.16.tar.bz2: [APPLE]</td>
<td>0x34c091</td>
</tr>
<tr>
<td>linux-3.0.26.tar.xz: [magic]</td>
<td>0x29f6f7d9</td>
</tr>
<tr>
<td>linux-3.11.8.tar.bz2: [TRUTH]</td>
<td>0x2f635ba</td>
</tr>
<tr>
<td>linux-3.10.11.tar.bz2: [logic]</td>
<td>0x4a7f794</td>
</tr>
</tbody>
</table>

There is a nice illustration of apophenia and pareidolia There is a nice illustration of apophenia and pareidolia (human’s mind ability to see faces in clouds, etc) in Lurkmore, Russian counterpart of Encyclopedia Dramatica. As they wrote in the article about electronic voice phenomenon31, you can open any long enough compressed file in hex editor and find well-known 3-letter Russian obscene word, and you’ll find it a lot: but that means nothing, just a mere coincidence.

And I was interested in calculation, how big compressed file must be to contain all possible 3-letter, 4-letter, etc, words? In my naive calculations, I’ve got this: probability of the first specific byte in the middle of compressed data stream with maximal entropy is $\frac{1}{256}$, probability of the 2nd is also $\frac{1}{256}$, and probability of specific byte pair is $\frac{1}{256} \cdot \frac{1}{256} = \frac{1}{256^2}$. Probability of specific triple is $\frac{1}{256^3}$. If the file has maximal entropy (which is almost unachievable, but …) and we live in an ideal world, you’ve got to have a file of size just $256^3 = 16777216$, which is 16-17MB. You can check: get any compressed file, and use rafind2 to search for any 3-letter word (not just that Russian obscene one).

It took $\approx 8$-9 GB of my downloaded movies/TV series files to find the word “beer” in them (case sensitive). Perhaps, these movies wasn’t compressed good enough? This is also true for a well-known 4-letter English obscene word.

My approach is naive, so I googled for mathematically grounded one, and have find this question: “Time until a consecutive sequence of ones in a random bit sequence” 32. The answer is: $(p^{-n}-1)/(1-p)$, where $p$ is probability of each event and $n$ is number of consecutive events. Plug $\frac{1}{256}$ and 3 and you’ll get almost the same as my naive calculations.

So any 3-letter word can be found in the compressed file (with ideal entropy) of length $256^3 = 17MB$, any 4-letter word $- 256^4 = 4.7GB$ (size of DVD). Any 5-letter word $- 256^5 = 17B$.

For the piece of text you are reading now, I mirrored the whole kernel.org website (hopefully, sysadmins can forgive me), and it has $\approx 430$GB of compressed Linux Kernel source trees. It has enough compressed

---

31 [http://archive.is/gYnFL](http://archive.is/gYnFL)
5.13. OTHER THINGS

data to contain these words, however, I cheated a bit: I searched for both lowercase and uppercase strings, thus compressed data set I need is almost halved.

This is quite interesting thing to think about: 1TB of compressed data with maximal entropy has all possible 5-byte chains, but the data is encoded not in chains itself, but in the order of chains (no matter of compression algorithm, etc).

Now the information for gamblers: one should throw a dice \( \approx 42 \) times to get a pair of six, but no one will tell you, when exactly this will happen. I don’t remember, how many times coin was tossed in the “Rosencrantz & Guildenstern Are Dead” movie, but one should toss it \( \approx 2048 \) times and at some point, you’ll get 10 heads in a row, and at some other point, 10 tails in a row. Again, no one will tell you, when exactly this will happen.

Compressed data can also be treated as a stream of random data, so we can use the same mathematics to determine probabilities, etc.

If you can live with strings of mixed case, like “bEeR”, probabilities and compressed data sets are much lower: \( 128^3 = 2MB \) for all 3-letter words of mixed case, \( 128^4 = 268MB \) for all 4-letter words, \( 128^5 = 34GB \) for all 5-letter words, etc.

Moral of the story: whenever you search for some patterns, you can find it in the middle of compressed blob, but that means nothing else then coincidence. In philosophical sense, this is a case of selection/confirmation bias: you find what you search for in “The Library of Babel”\(^\text{33}\).

5.13 Other things

5.13.1 General idea

A reverse engineer should try to be in programmer’s shoes as often as possible. To take his/her viewpoint and ask himself, how would one solve some task the specific case.

5.13.2 Order of functions in binary code

All functions located in a single .c or .cpp-file are compiled into corresponding object (.o) file. Later, linker puts all object files it needs together, not changing order or functions in them. As a consequence, if you see two or more consecutive functions, it means, that they were placed together in a single source code file (unless you’re on border of two object files, of course.) This means these functions have something in common, that they are from the same API level, from same library, etc.

5.13.3 Tiny functions

Tiny functions like empty functions (1.3 on page 5) or function which returns just “true” (1) or “false” (0) (1.4 on page 7) are very common, and almost all decent compilers tend to put only one such function into resulting executable code even if there were several similar functions in source code. So, whenever you see a tiny function consisting just of \( \text{mov eax, 1} / \text{ret} \) which is referenced (and can be called) from many places, which are seems unconnected to each other, this may be a result of such optimization.

5.13.4 C++

RTTI (3.18.1 on page 557)-data may be also useful for C++ class identification.

\(^{33}\)Short story by Jorge Luis Borges
Chapter 6

OS-specific

6.1 Arguments passing methods (calling conventions)

6.1.1 cdecl

This is the most popular method for passing arguments to functions in the C/C++ languages.

The glscaller also must return the value of the stack pointer (ESP) to its initial state after the callee function exits.

Listing 6.1: cdecl

push arg3
push arg2
push arg1
call function
add esp, 12 ; returns ESP

6.1.2 stdcall

It’s almost the same as cdecl, with the exception that the callee must set ESP to the initial state by executing the RET x instruction instead of RET, where x = arguments number * sizeof(int). The caller is not adjusting the stack pointer, there are no add esp, x instruction.

Listing 6.2: stdcall

push arg3
push arg2
push arg1
call function
function:
  ... do something ...
ret 12

The method is ubiquitous in win32 standard libraries, but not in win64 (see below about win64).

For example, we can take the function from 1.86 on page 97 and change it slightly by adding the __stdcall modifier:

```c
int __stdcall f2 (int a, int b, int c) {
  return a*b+c;
};
```

It is to be compiled in almost the same way as 1.87 on page 97, but you will see RET 12 instead of RET. SP is not updated in the caller.

---

1 The size of an int type variable is 4 in x86 systems and 8 in x64 systems
As a consequence, the number of function arguments can be easily deduced from the RETN \( n \) instruction: just divide \( n \) by 4.

Listing 6.3: MSVC 2010

```assembly
a$ = 8 ; size = 4
_b$ = 12 ; size = 4
_c$ = 16 ; size = 4
_f2@12 PROC
push ebp
mov ebp, esp
mov eax, DWORD PTR _a$[ebp]
imul eax, DWORD PTR _b$[ebp]
add eax, DWORD PTR _c$[ebp]
pop ebp
ret 12
_f2@12 ENDP

push 3
push 2
push 1
```

Function with variable number of arguments

printf()-like functions are, probably, the only case of functions with a variable number of arguments in C/C++, but it is easy to illustrate an important difference between cdecl and stdcall with their help. Let’s start with the idea that the compiler knows the argument count of each printf() function call.

However, the called printf(), which is already compiled and located in MSVCRT.DLL (if we talk about Windows), does not have any information about how much arguments were passed, however it can determine it from the format string.

Thus, if printf() would be a stdcall function and restored stack pointer to its initial state by counting the number of arguments in the format string, this could be a dangerous situation, when one programmer’s typo can provoke a sudden program crash. Thus it is not suitable for such functions to use stdcall, cdecl is better.

6.1.3 fastcall

That’s the general naming for the method of passing some arguments via registers and the rest via the stack. It worked faster than cdecl/stdcall on older CPUs (because of smaller stack pressure). It may not help to gain any significant performance on latest (much more complex) CPUs, however.

It is not standardized, so the various compilers can do it differently. It’s a well known caveat: if you have two DLLs and the one uses another one, and they are built by different compilers with different fastcall calling conventions, you can expect problems.

Both MSVC and GCC pass the first and second arguments via ECX and EDX and the rest of the arguments via the stack.

The stack pointer must be restored to its initial state by the callee (like in stdcall).

Listing 6.4: fastcall

```assembly
push arg3
mov edx, arg2
mov ecx, arg1
call function
```

function:
.. do something ..
ret 4
6.1. ARGUMENTS PASSING METHODS (CALLING CONVENTIONS)

For example, we may take the function from 1.86 on page 97 and change it slightly by adding a __fastcall modifier:

```c
int __fastcall f3 (int a, int b, int c)
{
    return a*b+c;
}
```

Here is how it is to be compiled:

```assembly
Listing 6.5: Optimizing MSVC 2010 /Ob0
_c$ = 8 ; size = 4
@f3@12 PROC
; _a$ = ecx
; _b$ = edx
    mov eax, ecx
    imul eax, edx
    add eax, DWORD PTR _c$[esp-4]
    ret 4
@f3@12 ENDP
; ...
    mov edx, 2
    push 3
    lea ecx, DWORD PTR [edx-1]
    call @f3@12
    push eax
    push OFFSET $SG81390
    call _printf
    add esp, 8

We see that the callee returns SP by using the RETN instruction with an operand.
Which implies that the number of arguments can be deduced easily here as well.

**GCC regparm**

It is the evolution offastcall\(^2\) in some sense. With the -mregparm option it is possible to set how many arguments are to be passed via registers (3 is the maximum). Thus, the EAX, EDX and ECX registers are to be used.

Of course, if the number the of arguments is less than 3, not all 3 registers are to be used.
The caller restores the stack pointer to its initial state.
For example, see (1.22.1 on page 306).

**Watcom/OpenWatcom**

Here it is called “register calling convention”. The first 4 arguments are passed via the EAX, EDX, EBX and ECX registers. All the rest—via the stack.

These functions have an underscore appended to the function name in order to distinguish them from those having a different calling convention.

6.1.4 thiscall

This is passing the object’s this pointer to the function-method, in C++.
In MSVC, this is usually passed in the ECX register.
In GCC, the this pointer is passed as the first function-method argument. Thus it will be visible that all functions in assembly code have an extra argument, in comparison with the source code.
For an example, see (3.18.1 on page 542).

\(^2\)http://go.yurichev.com/17040
Windows x64

The method of for passing arguments in Win64 somewhat resembles fast call. The first 4 arguments are passed via RCX, RDX, R8 and R9, the rest—via the stack. The caller also must prepare space for 32 bytes or 4 64-bit values, so then the callee can save there the first 4 arguments. Short functions may use the arguments’ values just from the registers, but larger ones may save their values for further use.

The caller also must return the stack pointer into its initial state.

This calling convention is also used in Windows x86-64 system DLLs (instead of stdcall in win32).

Example:

```c
#include <stdio.h>

void f1(int a, int b, int c, int d, int e, int f, int g)
{
    printf(“%d %d %d %d %d %d %d
”, a, b, c, d, e, f, g);
}

int main()
{
    f1(1, 2, 3, 4, 5, 6, 7);
}
```

Listing 6.6: MSVC 2012 /0b

```assembly
$SG2937 DB '%d %d %d %d %d %d %d', 0aH, 00H
main PROC
    sub rsp, 72
    mov DWORD PTR [rsp+48], 7
    mov DWORD PTR [rsp+40], 6
    mov DWORD PTR [rsp+32], 5
    mov R9D, 4
    mov R8D, 3
    mov EDX, 2
    mov ECX, 1
    call f1
    xor eax, eax
    add rsp, 72
    ret 0
main ENDP

a$ = 80
b$ = 88
c$ = 96
d$ = 104
e$ = 112
f$ = 120
g$ = 128
f1 PROC
$LN3:
    mov DWORD PTR [rsp+32], R9D
    mov DWORD PTR [rsp+24], R8D
    mov DWORD PTR [rsp+16], EDX
    mov DWORD PTR [rsp+8], ECX
    sub rsp, 72
    mov eax, DWORD PTR g$[rsp]
    mov DWORD PTR [rsp+56], eax
    mov eax, DWORD PTR f$[rsp]
    mov DWORD PTR [rsp+48], eax
    mov eax, DWORD PTR e$[rsp]
    mov DWORD PTR [rsp+40], eax
    mov eax, DWORD PTR d$[rsp]
```

737
Here we clearly see how 7 arguments are passed: 4 via registers and the remaining 3 via the stack.

The code of the f1() function's prologue saves the arguments in the “scratch space”—a space in the stack intended exactly for this purpose.

This is arranged so because the compiler cannot be sure that there will be enough registers to use without these 4, which will otherwise be occupied by the arguments until the function’s execution end.

The “scratch space” allocation in the stack is the caller’s duty.
If we compile the example with optimizations, it is to be almost the same, but the “scratch space” will not be used, because it won’t be needed.

Also take a look on how MSVC 2012 optimizes the loading of primitive values into registers by using LEA (.1.6 on page 1028). MOV would be 1 byte longer here (5 instead of 4).

Another example of such thing is: 8.1.1 on page 797.

**Windows x64: Passing this (C/C++)**

The this pointer is passed in RCX, the first argument of the method is in RDX, etc. For an example see: 3.18.1 on page 544.

**Linux x64**

The way arguments are passed in Linux for x86-64 is almost the same as in Windows, but 6 registers are used instead of 4 (RDI, RSI, RDX, RCX, R8, R9) and there is no “scratch space”, although the callee may save the register values in the stack, if it needs/wants to.

Listing 6.8: Optimizing GCC 4.7.3

```c
.LC0:
    .string "%d %d %d %d %d %d %d\n"

f1:
    sub    rsp, 40
    mov    eax, DWORD PTR [rsp+48]
    mov    DWORD PTR [rsp+8], r9d
    mov    r9d, ecx
    mov    DWORD PTR [rsp], r8d
    mov    ecx, esi
    mov    r8d, edx
    mov    esi, OFFSET FLAT:.LC0
    mov    edx, edi
    xor    eax, eax
    call   __printf_chk
    add    rsp, 40
    ret

main:
    sub    rsp, 24
    mov    r9d, 6
    mov    r8d, 5
    mov    DWORD PTR [rsp], 7
    mov    ecx, 4
    mov    edx, 3
    mov    esi, 2
    mov    edi, 1
    call   f1
    add    rsp, 24
    ret
```

N.B.: here the values are written into the 32-bit parts of the registers (e.g., EAX) but not in the whole 64-bit register (RAX). This is because each write to the low 32-bit part of a register automatically clears the high 32 bits. Supposedly, it was decided in AMD to do so to simplify porting code to x86-64.

**6.1.6 Return values of float and double type**

In all conventions except in Win64, the values of type float or double are returned via the FPU register ST(0).

In Win64, the values of float and double types are returned in the low 32 or 64 bits of the XMM0 register.
6.1.7 Modifying arguments

Sometimes, C/C++ programmers (not limited to these PLs, though), may ask, what can happen if they modify the arguments?

The answer is simple: the arguments are stored in the stack, that is where the modification takes place. The calling functions is not using them after the callee’s exit (the author of these lines has never seen any such case in his practice).

```c
#include <stdio.h>
void f(int a, int b)
{
    a=a+b;
    printf ("%d\n", a);
}
```

Listing 6.9: MSVC 2012

```assembly
_ a$ = 8 ; size = 4
_ b$ = 12 ; size = 4
_f PROC
    push ebp
    mov ebp, esp
    mov eax, DWORD PTR _a$[ebp]
    add eax, DWORD PTR _b$[ebp]
    mov DWORD PTR _a$[ebp], eax
    mov ecx, DWORD PTR _a$[ebp]
    push ecx
    push OFFSET $SG2938 ; '%d', 0aH
    call _printf
    add esp, 8
    pop ebp
    ret 0
_f ENDP
```

So yes, one can modify the arguments easily. Of course, if it is not references in C++ (3.18.3 on page 558), and if you don’t modify data to which a pointer points to, then the effect will not propagate outside the current function.

Theoretically, after the callee’s return, the caller could get the modified argument and use it somehow. Maybe if it is written directly in assembly language.

For example, code like this will be generated by usual C/C++ compiler:

```assembly
push 456 ; will be b
push 123 ; will be a
call f ; f() modifies its first argument
add esp, 2*4
```

We can rewrite this code like:

```assembly
push 456 ; will be b
push 123 ; will be a
call f ; f() modifies its first argument
pop eax
add esp, 4
; EAX=1st argument of f() modified in f()
```

Hard to imagine, why anyone would need this, but this is possible in practice. Nevertheless, the C/C++ languages standards don’t offer any way to do so.

6.1.8 Taking a pointer to function argument

...even more than that, it’s possible to take a pointer to the function’s argument and pass it to another function:
#include <stdio.h>

// located in some other file
void modify_a (int *a);

void f (int a)
{
    modify_a (&a);
    printf ("%d\n", a);
};

It’s hard to understand how it works until we can see the code:

Listing 6.10: Optimizing MSVC 2010

$SG2796 DB '%d', 0aH, 00H
_a$ = 8
_f PROC
    lea eax, DWORD PTR _a$[esp-4] ; just get the address of value in local stack
    push eax ; and pass it to modify_a()
    call _modify_a
    mov ecx, DWORD PTR _a$[esp] ; reload it from the local stack
    push ecx ; and pass it to printf()
    push OFFSET $SG2796 ; '%d'
    call _printf
    add esp, 12
ret 0
_f ENDP

The address of the place in the stack where a has been passed is just passed to another function. It modifies the value addressed by the pointer and then printf() prints the modified value.

The observant reader might ask, what about calling conventions where the function’s arguments are passed in registers?

That’s a situation where the Shadow Space is used.

The input value is copied from the register to the Shadow Space in the local stack, and then this address is passed to the other function:

Listing 6.11: Optimizing MSVC 2012 x64

$SG2994 DB '%d', 0aH, 00H
a$ = 48
_f PROC
    mov DWORD PTR [rsp+8], ecx ; save input value in Shadow Space
    sub rsp, 40
    lea rcx, QWORD PTR a$[rsp] ; get address of value and pass it to modify_a()
    call modify_a
    mov edx, DWORD PTR a$[rsp] ; reload value from Shadow Space and pass it to printf()
\( \)
    lea rcx, OFFSET FLAT:$SG2994 ; '%d'
    call printf
    add rsp, 40
ret 0
_f ENDP

GCC also stores the input value in the local stack:

Listing 6.12: Optimizing GCC 4.9.1 x64

.LC0:
    .string "%d\n"
_f:
    sub rsp, 24
    mov DWORD PTR [rsp+12], edi ; store input value to the local stack
    lea rdi, [rsp+12] ; take an address of the value and pass it to modify_a
\( \)
    call modify_a
6.2. THREAD LOCAL STORAGE

GCC for ARM64 does the same, but this space is called Register Save Area here:

Listing 6.13: Optimizing GCC 4.9.1 ARM64

By the way, a similar usage of the Shadow Space is also considered here: 3.14.1 on page 520.

6.2 Thread Local Storage

TLS is a data area, specific to each thread. Every thread can store what it needs there. One well-known example is the C standard global variable errno.

Multiple threads may simultaneously call functions which return an error code in errno, so a global variable will not work correctly here for multi-threaded programs, so errno must be stored in the TLS.

In the C++11 standard, a new thread_local modifier was added, showing that each thread has its own version of the variable, it can be initialized, and it is located in the TLS 3:

Listing 6.14: C++11

```cpp
#include <iostream>
#include <thread>

thread_local int tmp=3;
int main()
{
    std::cout << tmp << std::endl;
}
```

Compiled in MinGW GCC 4.8.1, but not in MSVC 2012.

If we talk about PE files, in the resulting executable file, the tmp variable is to be allocated in the section devoted to the TLS.

6.2.1 Linear congruential generator revisited

The pseudorandom number generator we considered earlier 1.23 on page 338 has a flaw: it’s not thread-safe, because it has an internal state variable which can be read and/or modified in different threads simultaneously.

3 C11 also has thread support, optional though
6.2. THREAD LOCAL STORAGE

Win32

Uninitialized TLS data

One solution is to add __declspec(thread) modifier to the global variable, then it will be allocated in the TLS (line 9):

```c
#include <stdint.h>
#include <windows.h>
#include <winnt.h>

// from the Numerical Recipes book:
#define RNG_a 1664525
#define RNG_c 1013904223

__declspec(thread) uint32_t rand_state;

void my_srand(uint32_t init)
{
    rand_state = init;
}

int my_rand()
{
    rand_state = rand_state * RNG_a;
    rand_state = rand_state + RNG_c;
    return rand_state & 0x7fff;
}

int main()
{
    my_srand(0x12345678);
    printf("%d\n", my_rand());
}
```

Hiew shows us that there is a new PE section in the executable file: .tls.

```
Listing 6.15: Optimizing MSVC 2013 x86

_TLS SEGMENT
_rand_state DD 01H DUP (?)
_TLS ENDS

_DATA SEGMENT
$SG84851 DB '%d', 0aH, 00H
_DATA ENDS

_TEXT SEGMENT

_init$ = 8 ; size = 4
_my_srand PROC
    ; FS:0=address of TIB
    mov eax, DWORD PTR fs:__tls_array ; displayed in IDA as FS:2Ch
    ; EAX=address of TLS of process
    mov ecx, DWORD PTR __tls_index
    mov ecx, DWORD PTR [eax+ecx*4]
    ; ECX=current TLS segment
    mov eax, DWORD PTR _init$[esp-4]
    mov DWORD PTR _rand_state[ecx], eax
    ret 0
_my_srand ENDP

_my_rand PROC
    ; FS:0=address of TIB
    mov eax, DWORD PTR fs:__tls_array ; displayed in IDA as FS:2Ch
    ; EAX=address of TLS of process
    mov ecx, DWORD PTR __tls_index
    mov ecx, DWORD PTR [eax+ecx*4]
    ; ECX=current TLS segment
    imul eax, DWORD PTR _rand_state[ecx], 1664525
    add eax, 1013904223 ; 3c6ef35fH
```
6.2. THREAD LOCAL STORAGE

```
 mov DWORD PTR _rand_state[ecx], eax
 and eax, 32767 ; 00007fffH
 ret 0
_my_rand ENDP

_TEXT ENDS
```

`rand_state` is now in the **TLS** segment, and each thread has its own version of this variable.

Here is how it's accessed: load the address of the **TIB** from FS:2Ch, then add an additional index (if needed), then calculate the address of the **TLS** segment.

Then it's possible to access the `rand_state` variable through the ECX register, which points to an unique area in each thread.

The FS: selector is familiar to every reverse engineer, it is specially used to always point to **TIB**, so it would be fast to load the thread-specific data.

The GS: selector is used in Win64 and the address of the **TLS** is 0x58:

```
LISTING 6.16: Optimizing MSVC 2013 x64

_TLS SEGMENT
rand_state DD 01H DUP (?)
_TLS ENDS

_DATA SEGMENT
$SG85451 DB '%d', 0aH, 00H
_DATA ENDS

_TEXT SEGMENT
init$ = 8
my_srand PROC
    mov edx, DWORD PTR _tls_index
    mov rax, QWORD PTR gs:88 ; 58h
    mov r8d, OFFSET FLAT:rand_state
    mov rax, QWORD PTR [rax+rdx*8]
    mov DWORD PTR [r8+rax], ecx
    ret 0
my_srand ENDP

my_rand PROC
    mov rax, QWORD PTR gs:88 ; 58h
    mov ecx, DWORD PTR _tls_index
    mov edx, OFFSET FLAT:rand_state
    mov rcx, QWORD PTR [rax+rcx*8]
    imul eax, DWORD PTR [rcx+rdx], 1664525 ; 0019660dH
    add eax, 1013904223 ; 3c6ef35fH
    mov DWORD PTR [rcx+rdx], eax
    and eax, 32767 ; 00007fffH
    ret 0
my_rand ENDP

_TEXT ENDS
```

**Initialized TLS data**

Let's say, we want to set some fixed value to `rand_state`, so in case the programmer forgets to, the `rand_state` variable would be initialized to some constant anyway (line 9):

```
#include <stdint.h>
#include <windows.h>
#include <winnt.h>

// from the Numerical Recipes book:
#define RNG_a 1664525
#define RNG_c 1013904223
```
6.2. THREAD LOCAL STORAGE
9
10
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19
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25
26

__declspec( thread ) uint32_t rand_state=1234;
void my_srand (uint32_t init)
{
rand_state=init;
}
int my_rand ()
{
rand_state=rand_state*RNG_a;
rand_state=rand_state+RNG_c;
return rand_state & 0x7fff;
}
int main()
{
printf ("%d\n", my_rand());
};

The code is not diﬀerent from what we already saw, but in IDA we see:
.tls:00404000
.tls:00404000
.tls:00404000
.tls:00404000
.tls:00404000
.tls:00404000
.tls:00404001
.tls:00404002
.tls:00404003
.tls:00404004
.tls:00404008
...

; Segment type: Pure data
; Segment permissions: Read/Write
_tls
segment para public 'DATA' use32
assume cs:_tls
;org 404000h
TlsStart
db
0
; DATA XREF: .rdata:TlsDirectory
db
0
db
0
db
0
dd 1234
TlsEnd
db
0
; DATA XREF: .rdata:TlsEnd_ptr

1234 is there and every time a new thread starts, a new TLS is allocated for it, and all this data, including
1234, will be copied there.
This is a typical scenario:
• Thread A is started. A TLS is created for it, 1234 is copied to rand_state.
• The my_rand() function is called several times in thread A.
rand_state is diﬀerent from 1234.
• Thread B is started. A TLS is created for it, 1234 is copied to rand_state, while thread A has a
diﬀerent value in the same variable.

TLS callbacks
But what if the variables in the TLS have to be ﬁlled with some data that must be prepared in some unusual
way?
Let’s say, we’ve got the following task: the programmer can forget to call the my_srand() function to
initialize the PRNG, but the generator has to be initialized at start with something truly random, instead
of 1234. This is a case in which TLS callbacks can be used.
The following code is not very portable due to the hack, but nevertheless, you get the idea.
What we do here is deﬁne a function (tls_callback()) which is to be called before the process and/or
thread start.
The function initializes the PRNG with the value returned by GetTickCount() function.
#include <stdint.h>
#include <windows.h>
#include <winnt.h>
// from the Numerical Recipes book:
#define RNG_a 1664525
#define RNG_c 1013904223

745


6.2. THREAD LOCAL STORAGE

```c
__declspec( thread ) uint32_t rand_state;

void my_srand (uint32_t init)
{
    rand_state=init;
}

void NTAPI tls_callback(PVOID a, DWORD dwReason, PVOID b)
{
    my_srand (GetTickCount());
}

#pragma data_seg(".CRT$XLB")
PIMAGE_TLS_CALLBACK p_thread_callback = tls_callback;
#pragma data_seg()

int my_rand ()
{
    rand_state=rand_state*RNG_a;
    rand_state=rand_state+RNG_c;
    return rand_state & 0x7fff;
}

int main()
{
    // rand_state is already initialized at the moment (using GetTickCount())
    printf ("%d\n", my_rand());
};
```

Let's see it in IDA:

Listing 6.17: Optimizing MSVC 2013

```
.text:00401020 TlsCallback_0 proc near ; DATA XREF: .rdata:TlsCallbacks
.text:00401020 call ds:GetTickCount
.text:00401026 push eax
.text:00401027 call my_srand
.text:0040102C pop ecx
.text:0040102D retn 0Ch
.text:0040102D TlsCallback_0 endp
```

```
.rdata:004020C0 TlsCallbacks dd offset TlsCallback_0 ; DATA XREF: .rdata:TlsCallbacks_ptr
```

```
.rdata:00402118 TlsDirectory dd offset TlsStart
.rdata:0040211C TlsEnd_ptr dd offset TlsEnd
.rdata:00402120 TlsIndex_ptr dd offset TlsIndex
.rdata:00402124 TlsCallbacks_ptr dd offset TlsCallbacks
.rdata:00402128 TlsSizeOfZeroFill dd 0
.rdata:0040212C TlsCharacteristics dd 300000h
```

TLS callback functions are sometimes used in unpacking routines to obscure their processing. Some people may be confused and be in the dark that some code executed right before the OEP\(^4\).

**Linux**

Here is how a thread-local global variable is declared in GCC:

```c
__thread uint32_t rand_state=1234;
```

This is not the standard C/C++ modifier, but a rather GCC-specific one \(^5\).

\(^4\)Original Entry Point
\(^5\)http://go.yurichev.com/17062
6.3. SYSTEM CALLS (SYSCALL-S)

The GS: selector is also used to access the TLS, but in a somewhat different way:

```
Listing 6.18: Optimizing GCC 4.8.1 x86

.text:08048460 my_srand proc near
.text:08048460 .text:08048460 .text:08048460 arg_0 = dword ptr 4
.text:08048460 .text:08048460 .text:08048460 mov eax, [esp+arg_0]
.text:08048460 .text:08048464 mov gs:0FFFFFFFCh, eax
.text:08048464 retn
.text:08048464A my_srand endp

.text:08048470 my_rand proc near
.text:08048470 .text:08048470 .text:08048470 imul eax, gs:0FFFFFFFCh, 19660Dh
.text:08048470 .text:0804847B add eax, 3C6EF35Fh
.text:0804847B .text:0804847B .text:0804847B mov gs:0FFFFFFFCh, eax
.text:08048486 .text:08048486 .text:08048486 and eax, 7FFFh
.text:08048486 .text:0804848B retn
.text:0804848B my_rand endp

.text:0804848B my_rand endp
```


### 6.3 System calls (syscall-s)

As we know, all running processes inside an OS are divided into two categories: those having full access to the hardware (“kernel space”) and those that do not (“user space”).

The OS kernel and usually the drivers are in the first category.

All applications are usually in the second category.

For example, Linux kernel is in kernel space, but Glibc in user space.

This separation is crucial for the safety of the OS: it is very important not to give to any process the possibility to screw up something in other processes or even in the OS kernel. On the other hand, a failing driver or error inside the OS’s kernel usually leads to a kernel panic or BSOD.

The protection in the x86 processors allows to separate everything into 4 levels of protection (rings), but both in Linux and in Windows only two are used: ring0 (“kernel space”) and ring3 (“user space”).

System calls (syscall-s) are a point where these two areas are connected.

It can be said that this is the main API provided to applications.

As in Windows NT, the syscalls table resides in the SSDT.

The usage of syscalls is very popular among shellcode and computer viruses authors, because it is hard to determine the addresses of needed functions in the system libraries, but it is easier to use syscalls. However, much more code has to be written due to the lower level of abstraction of the API.

It is also worth noting that the syscall numbers may be different in various OS versions.

#### 6.3.1 Linux

In Linux, a syscall is usually called via int 0x80. The call’s number is passed in the EAX register, and any other parameters—in the other registers.

```
Listing 6.19: A simple example of the usage of two syscalls

section .text
global _start

_start:    mov edx,len ; buffer len
           mov ecx,msg ; buffer

Also available as [http://go.yurichev.com/17272](http://go.yurichev.com/17272)

Blue Screen of Death

System Service Dispatch Table
6.4. LINUX

```assembly
mov ebx,1 ; file descriptor. 1 is for stdout
mov eax,4 ; syscall number. 4 is for sys_write
int 0x80
mov eax,1 ; syscall number. 1 is for sys_exit
int 0x80
section .data
msg db 'Hello, world!',0xa
len equ $ - msg
```

Compilation:
```
nasm -f elf32 1.s
ld 1.o
```

The full list of syscalls in Linux: http://go.yurichev.com/17319.
For system calls interception and tracing in Linux, strace( 7.2.3 on page 791) can be used.

6.3.2 Windows

Here they are called via int 0x2e or using the special x86 instruction SYSENTER.
Further reading:

6.4 Linux

6.4.1 Position-independent code

While analyzing Linux shared (.so) libraries, one may frequently spot this code pattern:

```assembly
Listing 6.20: libc-2.17.so x86
.text:0012D5E3 __x86_get_pc_thunk_bx proc near ; CODE XREF: sub_17350+3
.text:0012D5E3 ; sub_173CC+4 ...
.text:0012D5E3 mov ebx, [esp+0]
.text:0012D5E6 retn
.text:0012D5E6 __x86_get_pc_thunk_bx endp
...
.text:000576C0 sub_576C0 proc near ; CODE XREF: tmpfile+73
...
.text:000576C0 push ebp
.text:000576C1 mov ecx, large gs:0
.text:000576C8 push edi
.text:000576C9 push esi
.text:000576CA push ebx
.text:000576CB call __x86_get_pc_thunk_bx
.text:000576D0 add ebx, 157930h
.text:000576D6 sub esp, 9Ch
...
.text:000579F0 lea eax, (a__gen_tempname - 1AF000h)[ebx] ; "a__gen_tempname"
.text:000579F6 mov [esp+0ACH+var_A0], eax
.text:000579FA lea eax, (a__SysdepsPosix - 1AF000h)[ebx] ; "../sysdeps/
\posix/tempname.c"
.text:00057A00 mov [esp+0ACH+var_A8], eax
```

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All pointers to strings are corrected by some constants and the value in EBX, which is calculated at the beginning of each function.

This is the so-called PIC, it is intended to be executable if placed at any random point of memory, that is why it cannot contain any absolute memory addresses.

PIC was crucial in early computer systems and is still crucial today in embedded systems without virtual memory support (where all processes are placed in a single continuous memory block).

It is also still used in *NIX systems for shared libraries, since they are shared across many processes while loaded in memory only once. But all these processes can map the same shared library at different addresses, so that is why a shared library has to work correctly without using any absolute addresses.

Let's do a simple experiment:

```c
#include <stdio.h>

int global_variable=123;

int f1(int var)
{
    int rt=global_variable+var;
    printf("returning %d\n", rt);
    return rt;
}
```

Let's compile it in GCC 4.7.3 and see the resulting .so file in IDA:

```
gcc -fPIC -shared -O3 -o 1.so 1.c
```

Let's do a simple experiment:
That’s it: the pointers to «returning %d\n» and global_variable are to be corrected at each function execution.

The __x86_get_pc_thunk_bx() function returns in EBX the address of the point after a call to itself (0x57C here).

That’s a simple way to get the value of the program counter (EIP) at some point. The 0x1A84 constant is related to the difference between this function’s start and the so-called Global Offset Table Procedure Linkage Table (GOT PLT), the section right after the Global Offset Table (GOT), where the pointer to global_variable is. IDA shows these offsets in their processed form to make them easier to understand, but in fact the code is:

```
.text:00000577 call __x86_get_pc_thunk_bx
.text:0000057C add ebx, 1A84h
.text:00000582 mov [esp+1Ch+var_4], esi
.text:00000586 mov eax, [ebx-0Ch]
.text:0000058C mov esi, [eax]
.text:0000058E lea eax, [ebx-1A30h]
```

Here EBX points to the GOT PLT section and to calculate a pointer to global_variable (which is stored in the GOT), 0xC must be subtracted.

To calculate pointer to the «returning %d\n» string, 0x1A30 must be subtracted.

By the way, that is the reason why the AMD64 instruction set supports RIP relative addressing — to simplify PIC-code.

Let’s compile the same C code using the same GCC version, but for x64.

IDA would simplify the resulting code but would suppress the RIP-relative addressing details, so we are going to use objdump instead of IDA to see everything:

```
0000000000000720 <f1>:
  720: 48 8b 05 b9 08 20 00 mov rax,QWORD PTR [rip+0x20b9] # 200fe0 <_DYNAMIC+0>

  727: 53 push rbx
  728: 89 fb mov ebx,edi
  72a: 48 8d 35 20 00 00 00 lea rsi,[rip+0x20] # 751 <_fini+0x9>
  731: bf 01 00 00 00 mov edi,0x1
  736: 03 18 add ebx,DWORD PTR [rax]
  738: 31 c0 xor eax,eax
  73a: 89 da mov edx,ebx
  73c: e8 df ff ff ff call 620 <__printf_chk@plt>
  741: 89 d8 mov eax,ebx
  743: 5b pop rbx
  744: c3 ret
```

0x20b9 is the difference between the address of the instruction at 0x720 and global_variable, and 0x20 is the difference between the address of the instruction at 0x72A and the «returning %d\n» string.

As you might see, the need to recalculate addresses frequently makes execution slower (it is better in x64, though).

So it is probably better to link statically if you care about performance [see: Agner Fog, Optimizing software in C++ (2015)].

**Windows**

The PIC mechanism is not used in Windows DLLs. If the Windows loader needs to load DLL on another base address, it “patches” the DLL in memory (at the FIXUP places) in order to correct all addresses.

This implies that several Windows processes cannot share an once loaded DLL at different addresses in different processes’ memory blocks — since each instance that’s loaded in memory is fixed to work only at these addresses.

9 program counter in AMD64
6.4. LINUX

6.4.2 LD_PRELOAD hack in Linux

This allows us to load our own dynamic libraries before others, even before system ones, like libc.so.6.

This, in turn, allows us to “substitute” our written functions before the original ones in the system libraries. For example, it is easy to intercept all calls to time(), read(), write(), etc.

Let’s see if we can fool the uptime utility. As we know, it tells how long the computer has been working. With the help of strace (7.2.3 on page 791), it is possible to see that the utility takes this information the /proc/uptime file:

$ strace uptime
...  
open("/proc/uptime", O_RDONLY) = 3
lseek(3, 0, SEEK_SET) = 0
read(3, "416166.86 414629.38\n", 2047) = 20
...

It is not a real file on disk, it is a virtual one and its contents are generated on fly in the Linux kernel. There are just two numbers:

$ cat /proc/uptime
416690.91 415152.03

What we can learn from Wikipedia:

The first number is the total number of seconds the system has been up. The second number is how much of that time the machine has spent idle, in seconds.

Let’s try to write our own dynamic library with the open(), read(), close() functions working as we need.

At first, our open() will compare the name of the file to be opened with what we need and if it is so, it will write down the descriptor of the file opened.

Second, read(), if called for this file descriptor, will substitute the output, and in the rest of the cases will call the original read() from libc.so.6. And also close(), will note if the file we are currently following is to be closed.

We are going to use the dlopen() and dlsym() functions to determine the original function addresses in libc.so.6.

We need them because we must pass control to the “real” functions.

On the other hand, if we intercepted strcmp() and monitored each string comparisons in the program, then we would have to implement our version of strcmp(), and not use the original function, that would be easier.

```c
#include <stdio.h>
#include <stdarg.h>
#include <stdlib.h>
#include <stdbool.h>
#include <unistd.h>
#include <dlfcn.h>
#include <string.h>

void *libc_handle = NULL;
int (*open_ptr)(const char *, int) = NULL;
int (*close_ptr)(int) = NULL;
ssize_t (*read_ptr)(int, void*, size_t) = NULL;
bool inited = false;

_Noreturn void die (const char * fmt, ...)
{
    va_list va;
    va_start (va, fmt);
    va_print (va, fmt);
    va_end (va);
    die (0);
}
```

---

10 Wikipedia
11 For example, here is how simple strcmp() interception works in this article written by Yong Huang
6.4. LINUX

```c
vprintf (fmt, va);
exit(0);
};

static void find_original_functions ()
{
    if (inited)
        return;

    libc_handle = dlopen ("libc.so.6", RTLD_LAZY);
    if (libc_handle==NULL)
        die ("can't open libc.so.6\n");

    open_ptr = dladdr (libc_handle, "open");
    if (open_ptr==NULL)
        die ("can't find open()\n");

    close_ptr = dladdr (libc_handle, "close");
    if (close_ptr==NULL)
        die ("can't find close()\n");

    read_ptr = dladdr (libc_handle, "read");
    if (read_ptr==NULL)
        die ("can't find read()\n");

    inited = true;
}

static int opened_fd=0;

int open(const char *pathname, int flags)
{
    find_original_functions();

    int fd=(*open_ptr)(pathname, flags);
    if (strcmp(pathname, "/proc/uptime")==0)
        opened_fd=fd; // that's our file! record its file descriptor
    else
        opened_fd=0;
    return fd;
};

int close(int fd)
{
    find_original_functions();

    if (fd==opened_fd)
        opened_fd=0; // the file is not opened anymore
    return (*close_ptr)(fd);
};

ssize_t read(int fd, void *buf, size_t count)
{
    find_original_functions();

    if (opened_fd!=0 && fd==opened_fd)
    {
        // that's our file!
        return snprintf (buf, count, "%d %d", 0x7fffffff, 0x7fffffff)+1;
    }; // not our file, go to real read() function
    return (*read_ptr)(fd, buf, count);
};
```

(Source code at GitHub)

Let’s compile it as common dynamic library:

```
gcc -fpic -shared -Wall -o fool_uptime.so fool_uptime.c -ldl
```

752
Let's run `uptime` while loading our library before the others:

```bash
LD_PRELOAD=`pwd`/fool_uptime.so uptime
```

And we see:

```
01:23:02 up 24855 days, 3:14, 3 users, load average: 0.00, 0.01, 0.05
```

If the `LD_PRELOAD` environment variable always points to the filename and path of our library, it is to be loaded for all starting programs.

More examples:

- Very simple interception of the `strcmp()` (Yong Huang) [http://go.yurichev.com/17143](http://go.yurichev.com/17143)
- Kevin Pulo—Fun with `LD_PRELOAD`. A lot of examples and ideas. [yurichev.com](http://yurichev.com)

## 6.5 Windows NT

### 6.5.1 CRT (win32)

Does the program execution start right at the `main()` function? No, it does not.

If we would open any executable file in IDA or HIEW, we can see OEP pointing to some another code block. This code is doing some maintenance and preparations before passing control flow to our code. It is called startup-code or CRT code (C RunTime).

The `main()` function takes an array of the arguments passed on the command line, and also one with environment variables. But in fact a generic string is passed to the program, the CRT code finds the spaces in it and cuts it in parts. The CRT code also prepares the environment variables array `envp`.

As for GUI13 win32 applications, `WinMain` is used instead of `main()`, having its own arguments:

```c
int CALLBACK WinMain(
    _In_ HINSTANCE hInstance,
    _In_ HINSTANCE hPrevInstance,
    _In_ LPSTR lpCmdLine,
    _In_ int nCmdShow
);
```

The CRT code prepares them as well.

Also, the number returned by the `main()` function is the exit code.

It may be passed in CRT to the `ExitProcess()` function, which takes the exit code as an argument.

Usually, each compiler has its own CRT code.

Here is a typical CRT code for MSVC 2008.

```assembly
____tmainCRTStartup proc near
    var_24 = dword ptr -24h
    var_20 = dword ptr -20h
    var_1C = dword ptr -1Ch
    ms_exc = CPPEH_RECORD ptr -18h
    push 14h
    push offset stru_4092D0
    call __SEH_prolog4
    mov eax, 5A4Dh
    __tmainCRTStartup endp
```

---

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cmp ds:400000h, ax
jnz short loc_401096
mov eax, ds:40003Ch
cmp dword ptr [eax+400000h], 4550h
jnz short loc_401096
cmp ds:400018h, cx
jnz short loc_401096
cmp dword ptr [eax+400074h], 0Eh
jbe short loc_401096
xor ecx, ecx
mov [ebp+var_1C], ecx
jmp short loc_40109A

loc_401096: ; CODE XREF: ___tmainCRTStartup+18
            ; ___tmainCRTStartup+29 ...
            and [ebp+var_1C], 0

loc_40109A: ; CODE XREF: ___tmainCRTStartup+50
            push 1
            call __heap_init
            pop ecx
            test eax, eax
            jnz short loc_4010AE

loc_4010AE: ; CODE XREF: ___tmainCRTStartup+60
            call __mtinit
            test eax, eax
            jnz short loc_4010BF
            push 10h
            call __fast_error_exit
            pop ecx

loc_4010BF: ; CODE XREF: ___tmainCRTStartup+71
            call sub_401F2B
            and [ebp+ms_exc.disabled], 0
            call __ioinit
            test eax, eax
            jge short loc_4010D9
            push 1Bh
            call __amsg_exit
            pop ecx

loc_4010D9: ; CODE XREF: ___tmainCRTStartup+8B
            call ds:GetCommandLineA
            mov dword_40B7F8, eax
            call __crtGetEnvironmentStringsA
            mov dword_40AC60, eax
            call __setargv
            test eax, eax
            jge short loc_4010FF
            push 8
            call __amsg_exit
            pop ecx

loc_4010FF: ; CODE XREF: ___tmainCRTStartup+81
            call __setenvp
            test eax, eax
            jge short loc_401110
            push 9
            call __amsg_exit
            pop ecx

loc_401110: ; CODE XREF: ___tmainCRTStartup+C2
Here we can see calls to GetCommandLineA() (line 62), then to setargv() (line 66) and setenvp() (line 74), which apparently fill the global variables argc, argv, envp.

Finally, main() is called with these arguments (line 97).

There are also calls to functions with self-describing names like heap_init() (line 35), ioinit() (line 54). The heap is indeed initialized in the CRT. If you try to use malloc() in a program without CRT, it will exit.
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abnormally with the following error:

\begin{verbatim}
runtime error R6030
- CRT not initialized
\end{verbatim}

Global object initializations in C++ is also occur in the CRT before the execution of \texttt{main()}: \ref{page:3.18.4}.

The value that \texttt{main()} returns is passed to \texttt{cexit()}, or in $\texttt{LN32}$, which in turn calls \texttt{doexit()}.

Is it possible to get rid of the CRT? Yes, if you know what you are doing.

The MSVC’s linker has the /ENTRY option for setting an entry point.

\begin{verbatim}
#include <windows.h>
int main()
{     MessageBox (NULL, "hello, world", "caption", MB_OK);
}
\end{verbatim}

Let’s compile it in MSVC 2008.

\begin{verbatim}
cl no_crt.c user32.lib /link /entry:main
\end{verbatim}

We are getting a runnable .exe with size 2560 bytes, that has a PE header in it, instructions calling \texttt{MessageBox}, two strings in the data segment, the \texttt{MessageBox} function imported from user32.dll and nothing else.

This works, but you cannot write \texttt{WinMain} with its 4 arguments instead of \texttt{main()}.

To be precise, you can, but the arguments are not prepared at the moment of execution.

By the way, it is possible to make the .exe even shorter by aligning the PE sections at less than the default 4096 bytes.

\begin{verbatim}
cl no_crt.c user32.lib /link /entry:main /align:16
\end{verbatim}

Linker says:

\begin{verbatim}
LINK : warning LNK4108: /ALIGN specified without /DRIVER; image may not run
\end{verbatim}

We get an .exe that’s 720 bytes. It can be executed in Windows 7 x86, but not in x64 (an error message will be shown when you try to execute it).

With even more efforts, it is possible to make the executable even shorter, but as you can see, compatibility problems arise quickly.

6.5.2 \textbf{Win32 PE}

\textbf{PE} is an executable file format used in Windows. The difference between .exe, .dll and .sys is that .exe and .sys usually do not have exports, only imports.

A DLL\footnote{Dynamic-Link Library}, just like any other PE-file, has an entry point (OEP) (the function DllMain() is located there) but this function usually does nothing. .sys is usually a device driver. As of drivers, Windows requires the checksum to be present in the PE file and for it to be correct\footnote{For example, Hiew (7.1 on page 789) can calculate it}.

Starting at Windows Vista, a driver’s files must also be signed with a digital signature. It will fail to load otherwise.

Every PE file begins with tiny DOS program that prints a message like “This program cannot be run in DOS mode.”—if you run this program in DOS or Windows 3.1 (OS-es which are not aware of the PE format), this message will be printed.
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Terminology

- Module—a separate file, .exe or .dll.
- Process—a program loaded into memory and currently running. Commonly consists of one .exe file and bunch of .dll files.
- Process memory—the memory a process works with. Each process has its own. There usually are loaded modules, memory of the stack, heap(s), etc.
- VA\textsuperscript{16}—an address which is to be used in program while runtime.
- Base address (of module)—the address within the process memory at which the module is to be loaded. OS loader may change it, if the base address is already occupied by another module just loaded before.
- RVA\textsuperscript{17}—the VA-address minus the base address.

Many addresses in PE-file tables use RVA-addresses.

- IAT\textsuperscript{18}—an array of addresses of imported symbols\textsuperscript{19}. Sometimes, the IMAGE_DIRECTORY_ENTRY_IAT data directory points at the IAT. It is worth noting that IDA (as of 6.1) may allocate a pseudo-section named .idata for IAT, even if the IAT is a part of another section!
- INT\textsuperscript{20}—an array of names of symbols to be imported\textsuperscript{21}.

Base address

The problem is that several module authors can prepare DLL files for others to use and it is not possible to reach an agreement which addresses is to be assigned to whose modules.

So that is why if two necessary DLLs for a process have the same base address, one of them will be loaded at this base address, and the other—at some other free space in process memory, and each virtual addresses in the second DLL will be corrected.

With MSVC the linker often generates the .exe files with a base address of 0x400000\textsuperscript{22}, and with the code section starting at 0x401000. This means that the RVA of the start of the code section is 0x1000.

DLLs are often generated by MSVC’s linker with a base address of 0x10000000\textsuperscript{23}.

There is also another reason to load modules at various base addresses, in this case random ones. It is ASLR\textsuperscript{24}.

A shellcode trying to get executed on a compromised system must call system functions, hence, know their addresses.

In older OS (in Windows NT line: before Windows Vista), system DLL (like kernel32.dll, user32.dll) were always loaded at known addresses, and if we also recall that their versions rarely changed, the addresses of functions were fixed and shellcode could call them directly.

In order to avoid this, the ASLR method loads your program and all modules it needs at random base addresses, different every time.

ASLR support is denoted in a PE file by setting the flag IMAGE_DLL_CHARACTERISTICS_DYNAMIC_BASE [see Mark Russinovich, Microsoft Windows Internals].

Subsystem

There is also a subsystem field, usually it is:

- native\textsuperscript{25} (.sys-driver),

\textsuperscript{16}Virtual Address
\textsuperscript{17}Relative Virtual Address
\textsuperscript{18}Import Address Table
\textsuperscript{19}Matt Pietrek, An In-Depth Look into the Win32 Portable Executable File Format, (2002)]
\textsuperscript{20}Import Name Table
\textsuperscript{21}Matt Pietrek, An In-Depth Look into the Win32 Portable Executable File Format, (2002)]
\textsuperscript{22}This can be changed by the /BASE linker option
\textsuperscript{23}wikipedia
\textsuperscript{24}Meaning, the module use Native API instead of Win32
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- console (console application) or
- GUI (non-console).

OS version

A PE file also specifies the minimal Windows version it needs in order to be loadable.

The table of version numbers stored in the PE file and corresponding Windows codenames is here\(^{26}\).

For example, MSVC 2005 compiles .exe files for running on Windows NT4 (version 4.00), but MSVC 2008 does not (the generated files have a version of 5.00, at least Windows 2000 is needed to run them).

MSVC 2012 generates .exe files of version 6.00 by default, targeting at least Windows Vista. However, by changing the compiler’s options\(^{27}\), it is possible to force it to compile for Windows XP.

Sections

Division in sections, as it seems, is present in all executable file formats.

It is devised in order to separate code from data, and data—from constant data.

- Either the \texttt{IMAGE\_SCN\_CNT\_CODE} or \texttt{IMAGE\_SCN\_MEM\_EXECUTE} flags will be set on the code section—this is executable code.

- On data section—\texttt{IMAGE\_SCN\_CNT\_INITIALIZED\_DATA}, \texttt{IMAGE\_SCN\_MEM\_READ} and \texttt{IMAGE\_SCN\_MEM\_WRITE} flags.

- On an empty section with uninitialized data—\texttt{IMAGE\_SCN\_CNT\_UNINITIALIZED\_DATA}, \texttt{IMAGE\_SCN\_MEM\_READ} and \texttt{IMAGE\_SCN\_MEM\_WRITE}.

- On a constant data section (one that’s protected from writing), the flags \texttt{IMAGE\_SCN\_CNT\_INITIALIZED\_DATA} and \texttt{IMAGE\_SCN\_MEM\_READ} can be set, but not \texttt{IMAGE\_SCN\_MEM\_WRITE}. A process going to crash if it tries to write to this section.

Each section in PE-file may have a name, however, it is not very important. Often (but not always) the code section is named .text, the data section—.data, the constant data section — .rdata (readable data). Other popular section names are:

- .idata—imports section. IDA may create a pseudo-section named like this: 6.5.2 on the preceding page.

- .edata—exports section (rare)

- .pdata—section holding all information about exceptions in Windows NT for MIPS, IA64 and x64: 6.5.3 on page 783

- .reloc—relocs section

- .bss—uninitialized data (BSS)

- .tls—thread local storage (TLS)

- .rsrc—resources

- .CRT—may present in binary files compiled by ancient MSVC versions

PE file packers/encryptors often garble section names or replace the names with their own.

MSVC allows you to declare data in arbitrarily named section\(^ {28}\).

Some compilers and linkers can add a section with debugging symbols and other debugging information (MinGW for instance). However it is not so in latest versions of MSVC (separate PDB files are used there for this purpose).

That is how a PE section is described in the file:

\(^{26}\) wikipedia

\(^{27}\) MSDN

\(^{28}\) MSDN
6.5. WINDOWS NT

typedef struct _IMAGE_SECTION_HEADER {
    BYTE Name[IMAGE_SIZEOF_SHORT_NAME];
    union {
        DWORD PhysicalAddress;
        DWORD VirtualSize;
    } Misc;
    DWORD VirtualAddress;
    DWORD SizeOfRawData;
    DWORD PointerToRawData;
    DWORD PointerToRelocations;
    DWORD PointerToLinenumbers;
    WORD NumberOfRelocations;
    WORD NumberOfLinenumbers;
    DWORD Characteristics;
} IMAGE_SECTION_HEADER, *PIMAGE_SECTION_HEADER;

A word about terminology: PointerToRawData is called “Offset” in Hiew and VirtualAddress is called “RVA” there.

Data section

Data section in file can be smaller than in memory. For example, some variables can be initialized, some are not. Compiler and linker will collect them all into one section, but the first part of it is initialized and allocated in file, while another is absent in file (of course, to make it smaller). VirtualSize will be equal to the size of section in memory, and SizeOfRawData — to size of section in file.

IDA can show the border between initialized and not initialized parts like that:

```
... .data:10017FFA db 0 .data:10017FFB db 0 .data:10017FFC db 0 .data:10017FFD db 0 .data:10017FFE db 0 .data:10017FFF db 0 .data:10018000 db ? ; .data:10018001 db ? ; .data:10018002 db ? ; .data:10018003 db ? ; .data:10018004 db ? ; .data:10018005 db ? ; ...
```

Relocations (reloc)

AKA FIXUP-s (at least in Hiew).

They are also present in almost all executable file formats 30. Exceptions are shared dynamic libraries compiled with PIC, or any other PIC-code.

What are they for?

Obviously, modules can be loaded on various base addresses, but how to deal with global variables, for example? They must be accessed by address. One solution is position-independent code (6.4.1 on page 748). But it is not always convenient.

That is why a relocations table is present. There the addresses of points that must be corrected are enumerated, in case of loading at a different base address.

For example, there is a global variable at address 0x410000 and this is how it is accessed:

29MSDN
30Even in .exe files for MS-DOS
The base address of the module is 0x400000, the RVA of the global variable is 0x10000.
If the module is loaded at base address 0x500000, the real address of the global variable must be 0x510000.
As we can see, the address of variable is encoded in the instruction MOV, after the byte 0xA1.
That is why the address of the 4 bytes after 0xA1, is written in the relocs table.
If the module is loaded at a different base address, the OS loader enumerates all addresses in the table, finds each 32-bit word the address points to, subtracts the original base address from it (we get the RVA here), and adds the new base address to it.
If a module is loaded at its original base address, nothing happens.
All global variables can be treated like that.
Relocs may have various types, however, in Windows for x86 processors, the type is usually IMAGE_REL_BASED_HIGHLOW.
By the way, relocs are darkened in Hiew, for example: fig.1.21.
OllyDbg underlines the places in memory to which relocs are to be applied, for example: fig.1.52.

Exports and imports

As we all know, any executable program must use the OS’s services and other DLL-libraries somehow.
It can be said that functions from one module (usually DLL) must be connected somehow to the points of their calls in other modules (.exe-file or another DLL).
For this, each DLL has an “exports” table, which consists of functions plus their addresses in a module.
And every .exe file or DLL has “imports”, a table of functions it needs for execution including list of DLL filenames.
After loading the main .exe-file, the OS loader processes imports table: it loads the additional DLL-files, finds function names among the DLL exports and writes their addresses down in the IAT of the main .exe-module.
As we can see, during loading the loader must compare a lot of function names, but string comparison is not a very fast procedure, so there is a support for “ordinals” or “hints”, which are function numbers stored in the table, instead of their names.
That is how they can be located faster when loading a DLL. Ordinals are always present in the “export” table.
For example, a program using the MFC library usually loads mfc*.dll by ordinals, and in such programs there are no MFC function names in INT.
When loading such programs in IDA, it will ask for a path to the mfc*.dll files in order to determine the function names.
If you don’t tell IDA the path to these DLLs, there will be mfc80_123 instead of function names.

Imports section

Often a separate section is allocated for the imports table and everything related to it (with name like .idata), however, this is not a strict rule.
Imports are also a confusing subject because of the terminological mess. Let’s try to collect all information in one place.

31 Microsoft Foundation Classes
The main structure is the array `IMAGE_IMPORT_DESCRIPTOR`. Each element for each DLL being imported. Each element holds the RVA address of the text string (DLL name) (Name).

`OriginalFirstThunk` is the RVA address of the INT table. This is an array of RVA addresses, each of which points to a text string with a function name. Each string is prefixed by a 16-bit integer (“hint”)—“ordinal” of function.

While loading, if it is possible to find a function by ordinal, then the strings comparison will not occur. The array is terminated by zero.

There is also a pointer to the IAT table named `FirstThunk`, it is just the RVA address of the place where the loader writes the addresses of the resolved functions.

The points where the loader writes addresses are marked by IDA like this: `__imp_CreateFileA`, etc.

There are at least two ways to use the addresses written by the loader.

- The code will have instructions like `call __imp_CreateFileA`, and since the field with the address of
the imported function is a global variable in some sense, the address of the call instruction (plus 1 or 2) is to be added to the relocations table, for the case when the module is loaded at a different base address.

But, obviously, this may enlarge relocations table significantly.

Because there are might be a lot of calls to imported functions in the module.

Furthermore, large relocations table slows down the process of loading modules.

• For each imported function, there is only one jump allocated, using the JMP instruction plus a reloc to it. Such points are also called “thunks”.

All calls to the imported functions are just CALL instructions to the corresponding “thunk”. In this case, additional relocations are not necessary because these CALL-s have relative addresses and do not need to be corrected.

These two methods can be combined.

Possible, the linker creates individual “thunk”s if there are too many calls to the function, but not done by default.

By the way, the array of function addresses to which FirstThunk is pointing is not necessary to be located in the IAT section. For example, the author of these lines once wrote the PE_add_import utility for adding imports to an existing .exe-file.

Some time earlier, in the previous versions of the utility, at the place of the function you want to substitute with a call to another DLL, my utility wrote the following code:

```
MOV EAX, [yourdll.dll!function]
JMP EAX
```

FirstThunk points to the first instruction. In other words, when loading yourdll.dll, the loader writes the address of the function right in the code.

It also worth noting that a code section is usually write-protected, so my utility adds the IMAGE_SCN_MEM_WRITE flag for code section. Otherwise, the program to crash while loading with error code 5 (access denied).

One might ask: what if I supply a program with a set of DLL files which is not supposed to change (including addresses of all DLL functions), is it possible to speed up the loading process?

Yes, it is possible to write the addresses of the functions to be imported into the FirstThunk arrays in advance. The Timestamp field is present in the IMAGE_IMPORT_DESCRIPTOR structure.

If a value is present there, then the loader compares this value with the date-time of the DLL file.

If the values are equal, then the loader does not do anything, and the loading of the process can be faster. This is called “old-style binding” 33.

The BIND.EXE utility in Windows SDK is for this. For speeding up the loading of your program, Matt Pietrek in Matt Pietrek, An In-Depth Look into the Win32 Portable Executable File Format, (2002)] 34, suggests to do the binding shortly after your program installation on the computer of the end user.

PE-files packers/encryptors may also compress/encrypt imports table.

In this case, the Windows loader, of course, will not load all necessary DLLs.

Therefore, the packer/encryptor does this on its own, with the help of LoadLibrary() and the GetProcAddress() functions.

That is why these two functions are often present in IAT in packed files.

In the standard DLLs from the Windows installation, IAT often is located right at the beginning of the PE file. Supposedly, it is made so for optimization.

While loading, the .exe file is not loaded into memory as a whole (recall huge install programs which are started suspiciously fast), it is “mapped”, and loaded into memory in parts as they are accessed.

Probably, Microsoft developers decided it will be faster.

---

32 yurichev.com
33 MSDN. There is also the “new-style binding”.
34 Also available as http://go.yurichev.com/17318
Resources in a PE file are just a set of icons, pictures, text strings, dialog descriptions. Perhaps they were separated from the main code, so all these things could be multilingual, and it would be simpler to pick text or picture for the language that is currently set in the OS.

As a side effect, they can be edited easily and saved back to the executable file, even if one does not have special knowledge, by using the ResHack editor, for example (6.5.2).

.NET

.NET programs are not compiled into machine code but into a special bytecode. Strictly speaking, there is bytecode instead of the usual x86 code in the .exe file, however, the entry point (OEP) points to this tiny fragment of x86 code:

```sql
jmp    mscoree.dll!_CorExeMain
```

The .NET loader is located in mscoree.dll, which processes the PE file.

It was so in all pre-Windows XP OSes. Starting from XP, the OS loader is able to detect the .NET file and run it without executing that JMP instruction 35.

TLS

This section holds initialized data for the TLS (6.2 on page 742) (if needed). When a new thread start, its TLS data is initialized using the data from this section.

Aside from that, the PE file specification also provides initialization of the TLS section, the so-called TLS callbacks.

If they are present, they are to be called before the control is passed to the main entry point (OEP).

This is used widely in the PE file packers/encryptors.

Tools

- objdump (present in cygwin) for dumping all PE-file structures.
- Hiew (7.1 on page 789) as editor.
- pefile—Python-library for PE-file processing 36.
- PE_add_import38—simple tool for adding symbol(s) to PE executable import table.
- PE_patcher39—simple tool for patching PE executables.
- PE_search_str.refs40—simple tool for searching for a function in PE executables which use some text string.

Further reading

- Daniel Pistelli—The .NET File Format 41

35 MSDN
36 http://go.yurichev.com/17052
37 http://go.yurichev.com/17052
38 http://go.yurichev.com/17049
39 yurichev.com
40 yurichev.com
41 http://go.yurichev.com/17056
Let’s forget about MSVC

In Windows, the SEH is intended for exceptions handling, nevertheless, it is language-agnostic, not related to C++ or OOP in any way.

Here we are going to take a look at SEH in its isolated (from C++ and MSVC extensions) form.

Each running process has a chain of SEH handlers, each TIB has the address of the most recently defined handler.

When an exception occurs (division by zero, incorrect address access, user exception triggered by calling the RaiseException() function), the OS finds the last handler in the TIB and calls it, passing exception kind and all information about the CPU state (register values, etc.) at the moment of the exception.

The exception handler considering the exception, does it see something familiar? If so, it handles the exception.

If not, it signals to the OS that it cannot handle it and the OS calls the next handler in the chain, until a handler which is able to handle the exception is be found.

At the very end of the chain there a standard handler that shows the well-known dialog box, informing the user about a process crash, some technical information about the CPU state at the time of the crash, and offering to collect all information and send it to developers in Microsoft.

![crash.exe](image)

**Figure 6.2: Windows XP**
6.5. WINDOWS NT

Figure 6.3: Windows XP

Figure 6.4: Windows 7
Earlier, this handler was called Dr. Watson\(^\text{42}\).

By the way, some developers make their own handler that sends information about the program crash to themselves. It is registered with the help of `SetUnhandledExceptionFilter()` and to be called if the OS does not have any other way to handle the exception. An example is Oracle RDBMS—it saves huge dumps reporting all possible information about the CPU and memory state.

Let's write our own primitive exception handler. This example is based on the example from [Matt Pietrek, *A Crash Course on the Depths of Win32™ Structured Exception Handling*, (1997)](http://go.yurichev.com/17293)\(^\text{43}\). It must be compiled with the SAFESEH option: `cl seh1.cpp /link /safeseh:no`. More about SAFESEH here: [MSDN](http://msdn.microsoft.com).

```c
#include <windows.h>
#include <stdio.h>

DWORD new_value = 1234;

EXCEPTION_DISPOSITION __cdecl except_handler(
    struct _EXCEPTION_RECORD *ExceptionRecord,
    void * EstablisherFrame,
    struct _CONTEXT *ContextRecord,
    void * DispatcherContext)
{
    unsigned i;

    printf( "%s\n", __FUNCTION__);
    printf( "ExceptionRecord->ExceptionCode=0x%p\n", ExceptionRecord->ExceptionCode);
    printf( "ExceptionRecord->ExceptionFlags=0x%p\n", ExceptionRecord->ExceptionFlags);
    printf( "ExceptionRecord->ExceptionAddress=0x%p\n", ExceptionRecord->ExceptionAddress);

    if (ExceptionRecord->ExceptionCode == 0xE1223344)
    {
        printf( "That's for us\n");
        // yes, we "handled" the exception
        return ExceptionContinueExecution;
    }
    else if (ExceptionRecord->ExceptionCode == EXCEPTION_ACCESS_VIOLATION)
    {
        printf( "ContextRecord->Eax=0x%08X\n", ContextRecord->Eax);
        // will it be possible to 'fix' it?
        printf( "Trying to fix wrong pointer address\n");
        ContextRecord->Eax = (DWORD)&new_value;
        // yes, we "handled" the exception
        return ExceptionContinueExecution;
    }
    else
    {
        printf( "We do not handle this\n");
        // someone else's problem
        return ExceptionContinueSearch;
    }
}
```

\(^{42}\text{wikipedia}\)

\(^{43}\text{Also available as http://go.yurichev.com/17293}\)
int main()
{
    DWORD handler = (DWORD)except_handler; // take a pointer to our handler

    // install exception handler
    __asm
    {
        // make EXCEPTION_REGISTRATION record:
        push handler // address of handler function
        push FS:[0] // address of previous handler
        mov FS:[0],ESP // add new EXCEPTION_REGISTRATION
    }
    RaiseException (0xE1223344, 0, 0, NULL);

    // now do something very bad
    int* ptr=NULL;
    int val=0;
    val=*ptr;
    printf( "val=%.d\n", val);

    // deinstall exception handler
    __asm
    {
        // remove our EXCEPTION_REGISTRATION record
        mov eax,[ESP] // get pointer to previous record
        mov FS:[0], EAX // install previous record
        add esp, 8 // clean our EXCEPTION_REGISTRATION off stack
    }
    return 0;
}

The FS: segment register is pointing to the TIB in win32.
The very first element in the TIB is a pointer to the last handler in the chain. We save it in the stack and store the address of our handler there. The structure is named _EXCEPTION_REGISTRATION, it is a simple singly-linked list and its elements are stored right in the stack.

Listing 6.22: MSVC/VC/crt/src/exsup.inc

\_EXCEPTION\_REGISTRATION struc
    prev dd ?
    handler dd ?
\_EXCEPTION\_REGISTRATION ends

So each “handler” field points to a handler and an each “prev” field points to the previous record in the chain of exception handlers. The last record has 0xFFFFFFFF (-1) in the “prev” field.
After our handler is installed, we call `RaiseException()`[^44]. This is an user exception. The handler checks the code. If the code is 0xE1223344, it returning `ExceptionContinueExecution`, which means that handler corrected the CPU state (it is usually a correction of the EIP/ESP registers) and the OS can resume the execution of the thread. If you alter slightly the code so the handler returns `ExceptionContinueSearch`, then the OS will call the other handlers, and it’s unlikely that one who can handle it will be found, since no one will have any information about it (rather about its code). You will see the standard Windows dialog about a process crash.

What is the difference between a system exceptions and a user one? Here are the system ones:

<table>
<thead>
<tr>
<th>System Exception</th>
<th>User Code</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXCEPTION_ACCESS_VIOLATION</td>
<td>STATUS_ACCESS_VIOLATION</td>
<td>0xC0000005</td>
</tr>
<tr>
<td>EXCEPTION_DATATYPE_MISALIGNMENT</td>
<td>STATUS_DATATYPE_MISALIGNMENT</td>
<td>0x80000002</td>
</tr>
<tr>
<td>EXCEPTION_BREAKPOINT</td>
<td>STATUS_BREAKPOINT</td>
<td>0x80000003</td>
</tr>
<tr>
<td>EXCEPTION_SINGLE_STEP</td>
<td>STATUS_SINGLE_STEP</td>
<td>0x80000004</td>
</tr>
<tr>
<td>EXCEPTION_ARRAY_BOUNDS_EXCEEDED</td>
<td>STATUS_ARRAY_BOUNDS_EXCEEDED</td>
<td>0xC0000008C</td>
</tr>
<tr>
<td>EXCEPTION_FLT_DENORMAL_OPERAND</td>
<td>STATUS_FLOAT_DENORMAL_OPERAND</td>
<td>0xC000008D</td>
</tr>
<tr>
<td>EXCEPTION_FLT_DIVIDE_BY_ZERO</td>
<td>STATUS_FLOAT_DIVIDE_BY_ZERO</td>
<td>0xC000008E</td>
</tr>
<tr>
<td>EXCEPTION_FLT_INEXACT_RESULT</td>
<td>STATUS_FLOAT_INEXACT_RESULT</td>
<td>0xC000008F</td>
</tr>
<tr>
<td>EXCEPTION_FLT_INVALID_OPERATION</td>
<td>STATUS_FLOAT_INVALID_OPERATION</td>
<td>0xC0000090</td>
</tr>
<tr>
<td>EXCEPTION_FLT_OVERFLOW</td>
<td>STATUS_FLOAT_OVERFLOW</td>
<td>0xC0000091</td>
</tr>
<tr>
<td>EXCEPTION_FLT_STACK_CHECK</td>
<td>STATUS_FLOAT_STACK_CHECK</td>
<td>0xC0000092</td>
</tr>
<tr>
<td>EXCEPTION_FLT_UNDERFLOW</td>
<td>STATUS_FLOAT_UNDERFLOW</td>
<td>0xC0000093</td>
</tr>
<tr>
<td>EXCEPTION_INT_DIVIDE_BY_ZERO</td>
<td>STATUS_INTEGER_DIVIDE_BY_ZERO</td>
<td>0xC0000094</td>
</tr>
<tr>
<td>EXCEPTION_INT_OVERFLOW</td>
<td>STATUS_INTEGER_OVERFLOW</td>
<td>0xC0000095</td>
</tr>
<tr>
<td>EXCEPTION_PRIV_INSTRUCTION</td>
<td>STATUS_PRIVILEGED_INSTRUCTION</td>
<td>0xC0000096</td>
</tr>
<tr>
<td>EXCEPTION_IN_PAGE_ERROR</td>
<td>STATUS_IN_PAGE_ERROR</td>
<td>0xC0000006</td>
</tr>
<tr>
<td>EXCEPTION_ILLEGAL_INSTRUCTION</td>
<td>STATUS_ILLEGAL_INSTRUCTION</td>
<td>0xC000001D</td>
</tr>
<tr>
<td>EXCEPTION_NONCONTINUABLE_EXCEPTION</td>
<td>STATUS_NONCONTINUABLE_EXCEPTION</td>
<td>0xC0000025</td>
</tr>
<tr>
<td>EXCEPTION_STACK_OVERFLOW</td>
<td>STATUS_STACK_OVERFLOW</td>
<td>0xC000005D</td>
</tr>
<tr>
<td>EXCEPTION_INVALID_DISPOSITION</td>
<td>STATUS_INVALID_DISPOSITION</td>
<td>0xC0000026</td>
</tr>
<tr>
<td>EXCEPTION_GUARD_PAGE</td>
<td>STATUS_GUARD_PAGE</td>
<td>0x80000001</td>
</tr>
<tr>
<td>EXCEPTION_INVALID_HANDLE</td>
<td>STATUS_INVALID_HANDLE</td>
<td>0xC0000008</td>
</tr>
<tr>
<td>EXCEPTION_POSSIBLE_DEADLOCK</td>
<td>STATUS_POSSIBLE_DEADLOCK</td>
<td>0xC00000194</td>
</tr>
<tr>
<td>CONTROL_C_EXIT</td>
<td>STATUS_CONTROL_C_EXIT</td>
<td>0xC0000013A</td>
</tr>
</tbody>
</table>

That is how the code is defined:

<table>
<thead>
<tr>
<th>S</th>
<th>U</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S is a basic status code: 11—error; 10—warning; 01—informational; 00—success. U—whether the code is user code.

[^44]: MSDN
That is why we chose 0xE123344—E16 (11102) 0xE (1110b) means that it is 1) user exception; 2) error. But to be honest, this example works fine without these high bits.

Then we try to read a value from memory at address 0.

Of course, there is nothing at this address in win32, so an exception is raised.

The very first handler is to be called—yours, and it will know about it first, by checking the code if it’s equal to the EXCEPTION_ACCESS_VIOLATION constant.

The code that’s reading from memory at address 0 is looks like this:

```
Listing 6.23: MSVC 2010
...
xor eax, eax
mov eax, DWORD PTR [eax] ; exception will occur here
push eax
push OFFSET msg
call _printf
add esp, 8
...
```

Will it be possible to fix this error “on the fly” and to continue with program execution?

Yes, our exception handler can fix the EAX value and let the OS execute this instruction once again. So that is what we do. printf() prints 1234, because after the execution of our handler EAX is not 0, but contains the address of the global variable new_value. The execution will resume.

That is what is going on: the memory manager in the CPU signals about an error, the CPU suspends the thread, finds the exception handler in the Windows kernel, which, in turn, starts to call all handlers in the SEH chain, one by one.

We use MSVC 2010 here, but of course, there is no any guarantee that EAX will be used for this pointer.

This address replacement trick is showy, and we considering it here as an illustration of SEH’s internals. Nevertheless, it’s hard to recall any case where it is used for “on-the-fly” error fixing.

Why SEH-related records are stored right in the stack instead of some other place? Supposedly because the OS is not needing to care about freeing this information, these records are simply disposed when the function finishes its execution. This is somewhat like alloca(): (1.7.2 on page 35).

**Now let’s get back to MSVC**

Supposedly, Microsoft programmers needed exceptions in C, but not in C++ (for use in Windows NT kernel, which is written in C), so they added a non-standard C extension to MSVC. It is not related to C++ PL exceptions.

```
__try
{
...
}
__except(filter code)
{
handler code
}
```

“Finally” block may be instead of handler code:

```
__try
{
...
}
__finally
{
...
}
```

45 MSDN
6.5. WINDOWS NT

The filter code is an expression, telling whether this handler code corresponds to the exception raised.

If your code is too big and cannot fit into one expression, a separate filter function can be defined.

There are a lot of such constructs in the Windows kernel. Here are a couple of examples from there (WRK):

Listing 6.24: WRK-v1.2/base/ntos/ob/obwait.c

```c
try {
    KeReleaseMutant( (PKMUTANT)SignalObject, MUTANT_INCREMENT, FALSE, TRUE );
} except((GetExceptionCode () == STATUS_ABANDONED || GetExceptionCode () == STATUS_MUTANT_NOT_OWNED)? EXCEPTION_EXECUTE_HANDLER : EXCEPTION_CONTINUE_SEARCH) {
    Status = GetExceptionCode();
    goto WaitExit;
}
```

Listing 6.25: WRK-v1.2/base/ntos/cache/cachesub.c

```c
try {
    RtlCopyBytes( (PVOID)((PCHAR)CacheBuffer + PageOffset), UserBuffer, MorePages ? (PAGE_SIZE - PageOffset) : (ReceivedLength - PageOffset) );
} except( CcCopyReadExceptionFilter( GetExceptionInformation(), &Status ) ) {
```

Here is also a filter code example:

Listing 6.26: WRK-v1.2/base/ntos/cache/copysup.c

```c
LONG CcCopyReadExceptionFilter(
    IN PEXCEPTION_POINTERS ExceptionPointer,
    IN PNTSTATUS ExceptionCode
)

/**+
Routine Description:

    This routine serves as an exception filter and has the special job of extracting the "real" I/O error when Mm raises STATUS_IN_PAGE_ERROR beneath us.

Arguments:

    ExceptionPointer - A pointer to the exception record that contains the real Io Status.

    ExceptionCode - A pointer to an NTSTATUS that is to receive the real status.

Return Value:

    EXCEPTION_EXECUTE_HANDLER

-*/
```
6.5. **WINDOWS NT**

```c
*ExceptionCode = ExceptionPointer->ExceptionRecord->ExceptionCode;
if ( (*ExceptionCode == STATUS_IN_PAGE_ERROR) &&
    (ExceptionPointer->ExceptionRecord->NumberParameters >= 3) ) {
    *ExceptionCode = (NTSTATUS) ExceptionPointer->ExceptionRecord->ExceptionInformation[2];
}
ASSERT( !NT_SUCCESS(*ExceptionCode) );
return EXCEPTION_EXECUTE_HANDLER;
}
```

Internally, SEH is an extension of the OS-supported exceptions. But the handler function is _except_handler3 (for SEH3) or _except_handler4 (for SEH4).

The code of this handler is MSVC-related, it is located in its libraries, or in msvcr*.dll. It is very important to know that SEH is a MSVC thing.

Other win32-compilers may offer something completely different.

**SEH3**

SEH3 has _except_handler3 as a handler function, and extends the _EXCEPTION_REGISTRATION table, adding a pointer to the *scope table* and *previous try level* variable. SEH4 extends the *scope table* by 4 values for buffer overflow protection.

The *scope table* is a table that consists of pointers to the filter and handler code blocks, for each nested level of *try/except*. 
Again, it is very important to understand that the OS takes care only of the prev/handle fields, and nothing more.
It is the job of the _except_handler3 function to read the other fields and scope table, and decide which handler to execute and when.

The source code of the _except_handler3 function is closed.

However, Sanos OS, which has a win32 compatibility layer, has the same functions reimplemented, which are somewhat equivalent to those in Windows 46. Another reimplementation is present in Wine 47 and ReactOS 48.

If the filter pointer is NULL, the handler pointer is the pointer to the finally code block.

During execution, the previous try level value in the stack changes, so _except_handler3 can get information about the current level of nestedness, in order to know which scope table entry to use.

SEH3: one try/except block example

```c
#include <stdio.h>
#include <windows.h>
#include <excp.h>

int main()
{
    int* p = NULL;
    ...
```
6.5. WINDOWS NT

```c
__try
{
    printf("hello #1!\n");
    *p = 13; // causes an access violation exception;
    printf("hello #2!\n");
}
__except(GetExceptionCode()==EXCEPTION_ACCESS_VIOLATION ?
    EXCEPTION_EXECUTE_HANDLER : EXCEPTION_CONTINUE_SEARCH)
{
    printf("access violation, can't recover\n");
}

Listing 6.27: MSVC 2003

$SG74605 DB 'hello #1!', 0aH, 00H
$SG74606 DB 'hello #2!', 0aH, 00H
$SG74608 DB 'access violation, can't recover', 0aH, 00H
_DATA ENDS

; scope table:
CONST SEGMENT
$T74622 DD 0xffffffffH ; previous try level
DD FLAT:$L74617 ; filter
DD FLAT:$L74618 ; handler
CONST ENDS
_TEXT SEGMENT
$L74621 = -32 ; size = 4
_p$ = -28 ; size = 4
__$SEHRec$ = -24 ; size = 24
_main PROC NEAR
push ebp
mov ebp, esp
push -1 ; previous try level
push OFFSET FLAT:$T74622 ; scope table
push OFFSET FLAT:_except_handler3 ; handler
mov eax, DWORD PTR fs:__except_list
push eax ; prev
mov DWORD PTR fs:__except_list, esp
add esp, -16
; 3 registers to be saved:
push ebx
push esi
push edi
mov DWORD PTR__$SEHRec$[ebp], esp
mov DWORD PTR_p$[ebp], 0
mov DWORD PTR__$SEHRec$[ebp+20], 0 ; previous try level
push OFFSET FLAT:$SG74605 ; 'hello #1'
call _printf
add esp, 4
mov eax, DWORD PTR_p$[ebp]
mov DWORD PTR [eax], 13
push OFFSET FLAT:$SG74606 ; 'hello #2'
call _printf
add esp, 4
mov DWORD PTR__$SEHRec$[ebp+20], -1 ; previous try level
jmp SHORT $L74616

; filter code:
$L74617:
$L74627:
mov ecx, DWORD PTR__$SEHRec$[ebp+4]
mov edx, DWORD PTR [ecx]
mov eax, DWORD PTR [edx]
mov DWORD PTR $T74621[ebp], eax
mov eax, DWORD PTR $T74621[ebp]
sub eax, -1073741819; c0000005H
neg eax
sbb eax, eax
```

773
Here we see how the SEH frame is constructed in the stack. The *scope table* is located in the CONST segment—indeed, these fields are not to be changed. An interesting thing is how the *previous try level* variable has changed. The initial value is 0xFFFFFFFF (−1). The moment when the body of the *try* statement is opened is marked with an instruction that writes 0 to the variable. The moment when the body of the *try* statement is closed, −1 is written back to it. We also see the addresses of filter and handler code. Thus we can easily see the structure of the *try/except* constructs in the function.

Since the SEH setup code in the function prologue may be shared between many functions, sometimes the compiler inserts a call to the SEH_prolog() function in the prologue, which does just that.

The SEH cleanup code is in the SEH_epilog() function.

Let's try to run this example in *tracer*:

```
tracer.exe -l:2.exe --dump-seh
```

<table>
<thead>
<tr>
<th>Listing 6.28: tracer.exe output</th>
</tr>
</thead>
</table>

```plaintext
EXCEPTION ACCESS VIOLATION at 2.exe!main+0x44 (0x401054) ExceptionInformation[0]=1
EAX=0x00000000 EBX=0x7efde000 ECX=0x0040cbc8 EDX=0x0000e3c8
ESI=0x00001db1 EDI=0x00000000 EBP=0x0018feac ESP=0x0018fe80
EIP=0x00401054
FLAGS=AF IF RF
* SEH frame at 0x18fe9c prev=0x18ff78 handler=0x401204 (2.exe!_except_handler3)
  SEH3 frame. previous trylevel=0
    scopetable entry[0]. previous try level=-1, filter=0x401070 (2.exe!main+0x60) handler=0x401088  \(2.exe!main+0x78)  
* SEH frame at 0x18ff78 prev=0x18fffc4 handler=0x401204 (2.exe!_except_handler3)
  SEH3 frame. previous trylevel=0
    scopetable entry[0]. previous try level=-1, filter=0x401531 (2.exe!mainCRTStartup+0x18d)  \(2.exe!mainCRTStartup+0x1a1)
* SEH frame at 0x18fffc4 prev=0x18ffe4 handler=0x771f90eb (ntdll.dll!__safe_se_handler_table+0x20)
  SEH4 frame. previous trylevel=0
    scopetable entry[0]. previous try level=-2, filter=0x771f7fd0 (ntdll.dll!_TppTerminateProcess@4+0x43)  
    __safe_se_handler_table+0x20 handler=0x771f90eb (ntdll.dll!__safe_se_handler_table+0x20)  
* SEH frame at 0x18ffe4 prev=0xffffffff handler=0x77247428 (ntdll.dll!_FinalExceptionHandler@16)  

We see that the SEH chain consists of 4 handlers.
```
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The first two are located in our example. "Two? But we made only one? Yes, another one has been set up in the CRT function _mainCRTStartup(), and as it seems that it handles at least FPU exceptions. Its source code can be found in the MSVC installation: crt/src/winxfltr.c.

The third is the SEH4 one in ntdll.dll, and the fourth handler is not MSVC-related and is located in nt.dll.dll, and has a self-describing function name.

As you can see, there are 3 types of handlers in one chain:
one is not related to MSVC at all (the last one) and two MSVC-related: SEH3 and SEH4.

SEH3: two try/except blocks example

```c
#include <stdio.h>
#include <windows.h>
#include <excpt.h>

int filter_user_exceptions (unsigned int code, struct _EXCEPTION_POINTERS *ep)
{
    printf("in filter. code=0x%08X\n", code);
    if (code == 0x112233)
    {
        printf("yes, that is our exception\n");
        return EXCEPTION_EXECUTE_HANDLER;
    }
    else
    {
        printf("not our exception\n");
        return EXCEPTION_CONTINUE_SEARCH;
    }
}

int main()
{
    int* p = NULL;
    __try
    {
        __try
        {
            printf("hello!\n");
            RaiseException (0x112233, 0, 0, NULL);
            printf("0x112233 raised. now let's crash\n");
            *p = 13; // causes an access violation exception;
        }
        __except(GetExceptionCode()==EXCEPTION_ACCESS_VIOLATION ?
                  EXCEPTION_EXECUTE_HANDLER : EXCEPTION_CONTINUE_SEARCH)
        {
            printf("access violation, can't recover\n");
        }
        __except(filter_user_exceptions(GetExceptionCode(), GetExceptionInformation()))
        {
            // the filter_user_exceptions() function answering to the question
            // "is this exception belongs to this block?"
            // if yes, do the follow:
            printf("user exception caught\n");
        }
    }
}
```

Now there are two try blocks. So the scope table now has two entries, one for each block. Previous try level changes as execution flow enters or exits the try block.

Listing 6.29: MSVC 2003

```
$SG74606 DB 'in filter. code=0x%08X', 0AH, 00H
$SG74608 DB 'yes, that is our exception', 0AH, 00H
$SG74610 DB 'not our exception', 0AH, 00H
$SG74617 DB 'hello!', 0AH, 00H
$SG74619 DB '0x112233 raised. now let's crash', 0AH, 00H
```
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$SG74621 DB 'access violation, can''t recover', 0AH, 00H
$SG74623 DB 'user exception caught', 0AH, 00H

_code$ = 8 ; size = 4
_ep$ = 12 ; size = 4

_filter_user_exceptions PROC NEAR
push ebp
mov ebp, esp
mov eax, DWORD PTR _code$[ebp]
push eax
push OFFSET FLAT:$SG74606 ; 'in filter. code=0x%08X'
call _printf
add esp, 8
cmp DWORD PTR _code$[ebp], 1122867 ; 00112233H
jne SHORT $L74607
push OFFSET FLAT:$SG74608 ; 'yes, that is our exception'
call _printf
add esp, 4
mov eax, 1
jmp SHORT $L74605
$L74607:
push OFFSET FLAT:$SG74610 ; 'not our exception'
call _printf
add esp, 4
xor eax, eax
$L74605:
pop ebp
ret 0

_filter_user_exceptions ENDP

; scope table:
CONST SEGMENT
$T74644 DD 0ffffffffH ; previous try level for outer block
DD FLAT:$L74634 ; outer block filter
DD FLAT:$L74635 ; outer block handler
DD 00H ; previous try level for inner block
DD FLAT:$L74638 ; inner block filter
DD FLAT:$L74639 ; inner block handler
CONST ENDS

$T74643 = -36 ; size = 4
$T74642 = -32 ; size = 4
_p$ = -28 ; size = 4
__$SEHRec$ = -24 ; size = 24

_main PROC NEAR
push ebp
mov ebp, esp
push -1 ; previous try level
push OFFSET FLAT:$T74644
push OFFSET FLAT:_except_handler3
mov eax, DWORD PTR fs:_except_list
push eax
mov DWORD PTR __$SEHRec$[ebp], esp
add esp, -20
push ebx
push esi
push edi
mov DWORD PTR __$SEHRec$[ebp], esp
mov DWORD PTR _p$[ebp], 0
mov DWORD PTR __$SEHRec$[ebp+20], 0 ; outer try block entered. set previous try level to
\0
mov DWORD PTR __$SEHRec$[ebp+20], 1 ; inner try block entered. set previous try level to
\1
push OFFSET FLAT:$SG74617 ; 'hello!'
call _printf
add esp, 4
push 0
push 0
push 0
push 1122867 ; 00112233H

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call DWORD PTR __imp_RaiseException@16
push OFFSET FLAT:$SG74619 ; '0x112233 raised. now let''s crash'
call _printf
add esp, 4
mov eax, DWORD PTR __$SEHRec$[ebp+20], 0 ; inner try block exited. set previous try level ✓
\back to 0
jmp SHORT $L74615

; inner block filter:
$L74638:
$L74650:
mov ecx, DWORD PTR __$SEHRec$[ebp+4]
mov edx, DWORD PTR [ecx]
mov eax, DWORD PTR [edx]
mov DWORD PTR $T74643[ebp], eax
mov eax, DWORD PTR $T74643[ebp]
sub eax, -1073741819; c0000005H
neg eax
sbb eax, eax
inc eax
$L74640:
$L74648:
ret 0

; inner block handler:
$L74639:
push OFFSET FLAT:$SG74621 ; 'access violation, can''t recover'
call _printf
add esp, 4
mov DWORD PTR __$SEHRec$[ebp+20], 0 ; inner try block exited. set previous try level ✓
\back to 0
$L74615:
mov DWORD PTR __$SEHRec$[ebp+20], -1 ; outer try block exited, set previous try level ✓
\back to -1
jmp SHORT $L74633

; outer block filter:
$L74634:
$L74651:
mov ecx, DWORD PTR __$SEHRec$[ebp+4]
mov edx, DWORD PTR [ecx]
mov eax, DWORD PTR [edx]
mov DWORD PTR $T74642[ebp], eax
mov ecx, DWORD PTR $T74642[ebp]
push ecx
mov edx, DWORD PTR $T74642[ebp]
push edx
call _filter_user_exceptions
add esp, 8
$L74636:
$L74649:
ret 0

; outer block handler:
$L74635:
push OFFSET FLAT:$SG74623 ; 'user exception caught'
call _printf
add esp, 4
mov DWORD PTR __$SEHRec$[ebp+20], -1 ; both try blocks exited. set previous try level ✓
\back to -1
$L74633:
xor eax, eax
mov ecx, DWORD PTR __$SEHRec$[ebp+8]
mov DWORD PTR fs:_except_list, ecx
pop edi
777
If we set a breakpoint on the `printf()` function, which is called from the handler, we can also see how yet another SEH handler is added.

Perhaps it’s another machinery inside the SEH handling process. Here we also see our `scope table` consisting of 2 entries.

```
tracer.exe -l:3.exe bpx=3.exe!printf --dump-seh
```

Listing 6.30: tracer.exe output

```
(0) 3.exe!printf
EAX=0x0000001b EBX=0x00000000 ECX=0x0040cc58 EDX=0x0008e3c8
ESI=0x00000000 EDI=0x00000000 EBP=0x0018f840 ESP=0x0018f838
EIP=0x004011b6
FLAGS=PF ZF IF
* SEH frame at 0x18f88c prev=0x18fe9c handler=0x771db4ad (ntdll.dll!ExecuteHandler2@20+0x3a)
* SEH frame at 0x18fe9c prev=0x18ff78 handler=0x4012e0 (3.exe!_except_handler3)
SEH3 frame. previous trylevel=1
scopeetable entry[0]. previous try level=-1, filter=0x401120 (3.exe!main+0xb0) handler=0x40113b
\<\ (3.exe!main+0xcb)
scopeetable entry[1]. previous try level=0, filter=0x4010e8 (3.exe!main+0x78) handler=0x401100
\<\ (3.exe!main+0x90)
* SEH frame at 0x18ff78 prev=0x18fffc4 handler=0x4012e0 (3.exe!_except_handler3)
SEH3 frame. previous trylevel=0
scopeetable entry[0]. previous try level=-1, filter=0x40160d (3.exe!mainCRTStartup+0x18d) \<\ handler=0x401621 (3.exe!mainCRTStartup+0x1a1)
* SEH frame at 0x18fffc4 prev=0x18ffe4 handler=0x771f71f5 (ntdll.dll!__except_handler4)
SEH4 frame. previous try level=0
SEH4 header: GSCookieOffset=0xffffffff GSCookieXOROffset=0x0
\> EHCookieOffset=0xffffffff EHCookieXOROffset=0x0
scopeetable entry[0]. previous try level=-2, filter=0x771f74d0 (ntdll.dll!__safe_se_handler_table+0x20) handler=0x771f90eb (ntdll.dll!_TpTerminateProcess@4+0x43)
* SEH frame at 0x18ffe4 prev=0xffffffff handler=0x77247428 (ntdll.dll!_FinalExceptionHandler@16
\> )
```

**SEH4**

During a buffer overflow (1.20.2 on page 275) attack, the address of the `scope table` can be rewritten, so starting from MSVC 2005, SEH3 was upgraded to SEH4 in order to have buffer overflow protection. The pointer to the `scope table` is now `xored` with a [security cookie](#). The `scope table` was extended to have a header consisting of two pointers to [security cookies](#).

Each element has an offset inside the stack of another value: the address of the `stack frame` (EBP) xored with the `security_cookie`, placed in the stack.

This value will be read during exception handling and checked for correctness. The `security cookie` in the stack is random each time, so hopefully a remote attacker can’t predict it.

The initial `previous try level` is −2 in SEH4 instead of −1.
Here are both examples compiled in MSVC 2012 with SEH4:

Listing 6.31: MSVC 2012: one try block example

```assembly
$SG85485 DB 'hello #1!', 0aH, 00H
$SG85486 DB 'hello #2!', 0aH, 00H
$SG85488 DB 'access violation, can"t recover', 0aH, 00H

; scope table:
xdata$x SEGMENT
__sehtable$main DD 0fffffffeH ; GS Cookie Offset
  DD 00H ; GS Cookie XOR Offset
  DD 0ffffffccH ; EH Cookie Offset
  DD 00H ; EH Cookie XOR Offset
  DD 0fffffffeH ; previous try level
  DD FLAT:$LN12@main ; filter
  DD FLAT:$LN8@main ; handler
xdata$x ENDS

$T2 = -36 ; size = 4
_p$ = -32 ; size = 4
tv68 = -28 ; size = 4
__$SEHRec$ = -24 ; size = 24
```
main PROC
    push ebp
    mov ebp, esp
    push -2
    push OFFSET __sehtable$main
    push OFFSET __except_handler4
    mov eax, DWORD PTR fs:0
    push eax
    add esp, -20
    push ebx
    push esi
    push edi
    mov eax, DWORD PTR ___security_cookie
    xor DWORD PTR __$SEHRec$[ebp+16], eax ; xored pointer to scope table
    xor eax, ebp
    push eax ; ebp ^ security_cookie
    lea eax, DWORD PTR __$SEHRec$[ebp+8] ; pointer to VC_EXCEPTION_REGISTRATION_RECORD
    mov DWORD PTR fs:0, eax
    mov DWORD PTR __$SEHRec$[ebp], esp
    mov DWORD PTR _p$[ebp], 0
    mov DWORD PTR __$SEHRec$[ebp+20], 0 ; previous try level
    push OFFSET $SG85485 ; 'hello #1!'
    call _printf
    add esp, 4
    mov eax, DWORD PTR _p$[ebp]
    mov DWORD PTR [eax], 13
    push OFFSET $SG85486 ; 'hello #2!'
    call _printf
    add esp, 4
    mov DWORD PTR __$SEHRec$[ebp+20], -2 ; previous try level
    jmp SHORT $LN6@main
; filter:
$LN7@main:
$LN12@main:
    mov ecx, DWORD PTR __$SEHRec$[ebp+4]
    mov edx, DWORD PTR [ecx]
    mov eax, DWORD PTR [edx]
    mov DWORD PTR $T2$[ebp], eax
    cmp DWORD PTR $T2$[ebp], -1073741819 ; c0000005H
    jne SHORT $LN4@main
    mov DWORD PTR tv68$[ebp], 1
    jmp SHORT $LN5@main
$LN4@main:
$LN5@main:
    mov DWORD PTR tv68$[ebp], 0
$LN9@main:
$LN11@main:
    ret 0
; handler:
$LN8@main:
$LN6@main:
    xor eax, eax
    mov ecx, DWORD PTR __$SEHRec$[ebp+8]
    mov DWORD PTR fs:0, ecx
    pop ecx
    pop edi
    pop esi
    pop ebx
    mov esp, ebp
    pop ebp
    ret 0
main ENDP
Listing 6.32: MSVC 2012: two try blocks example

xdata$x SEGMENT
__sehtable$_main DD 0fffffffeH ; GS Cookie Offset
    DD 00H ; GS Cookie XOR Offset
    DD 0ffffffc8H ; EH Cookie Offset
    DD 00H ; EH Cookie Offset
    DD 0fffffffeH ; previous try level for outer block
    DD FLAT:$LN19@main ; outer block filter
    DD FLAT:$LN9@main ; outer block handler
    DD 00H ; previous try level for inner block
    DD FLAT:$LN18@main ; inner block filter
    DD FLAT:$LN13@main ; inner block handler
xdata$x ENDS

$T2 = -40 ; size = 4
$T3 = -36 ; size = 4
_p$ = -32 ; size = 4
tv72 = -28 ; size = 4
__$SEHRec$ = -24 ; size = 24

_main PROC
    push ebp
    mov ebp, esp
    push -2 ; initial previous try level
    push OFFSET __sehtable$_main
    push OFFSET __except_handler4
    mov eax, DWORD PTR fs:0
    push eax ; prev
    add esp, -24
    push ebx
    push esi
    push edi
    mov eax, DWORD PTR ___security_cookie
    xor DWORD PTR __$SEHRec$[ebp+16], eax ; xored pointer to scope table
    xor eax, ebp ; ebp ^ security_cookie
    push eax
    lea eax, DWORD PTR __$SEHRec$[ebp+8] ; pointer to
      VC_EXCEPTION_REGISTRATION_RECORD
    mov DWORD PTR fs:0, eax
    mov DWORD PTR __$SEHRec$[ebp], esp
    mov DWORD PTR _p$[ebp], 0
    mov DWORD PTR __$SEHRec$[ebp+20], 0 ; entering outer try block, setting previous try
    mov DWORD PTR __$SEHRec$[ebp+20], 1 ; entering inner try block, setting previous try
    push OFFSET $SG85497 ; 'hello!'
call _printf
    add esp, 4
    push 0
    push 0
    push 0
    push 1122867 ; 00112233H
call DWORD PTR __imp__RaiseException@16
    push OFFSET $SG85499 ; '0x112233 raised. now let's crash'
call _printf
    add esp, 4
    mov eax, DWORD PTR _p$[ebp]
    mov DWORD PTR [eax], 13
    mov DWORD PTR __$SEHRec$[ebp+20], 0 ; exiting inner try block, set previous try level
    jmp back to 0
jmp SHORT $LN2@main

; inner block filter:
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$L12@main:
$LN18@main:
  mov  ecx, DWORD PTR __SEHRec$[ebp+4]
  mov  edx, DWORD PTR [ecx]
  mov  eax, DWORD PTR [edx]
  mov  DWORD PTR $T3[ebp], eax
  cmp  DWORD PTR $T3[ebp], -1073741819 ; c0000005H
  jne  SHORT $LN5@main
  mov  DWORD PTR tv72[ebp], 1
  jmp  SHORT $LN6@main
$LN5@main:
  mov  DWORD PTR tv72[ebp], 0
$LN6@main:
  mov  eax, DWORD PTR tv72[ebp]
$LN14@main:
$LN16@main:
  ret 0

; inner block handler:
$L13@main:
  mov  esp, DWORD PTR __SEHRec$[ebp]
  push  OFFSET $SG85501 ; 'access violation, can't recover'
  call  _printf
  add  esp, 4
  mov  DWORD PTR __SEHRec$[ebp+20], 0 ; exiting inner try block, setting previous try level back to 0
$LN2@main:
  mov  DWORD PTR __SEHRec$[ebp+20], -2 ; exiting both blocks, setting previous try level back to -2
  jmp  SHORT $LN7@main

; outer block filter:
$L19@main:
  mov  ecx, DWORD PTR __SEHRec$[ebp+4]
  mov  edx, DWORD PTR [ecx]
  mov  eax, DWORD PTR [edx]
  mov  DWORD PTR $T2[ebp], eax
  mov  ecx, DWORD PTR __SEHRec$[ebp+4]
  push  ecx
  mov  edx, DWORD PTR $T2[ebp]
  push  edx
  call  _filter_user_exceptions
  add  esp, 8
$L10@main:
$LN17@main:
  ret 0

; outer block handler:
$L9@main:
  mov  esp, DWORD PTR __SEHRec$[ebp]
  push  OFFSET $SG85503 ; 'user exception caught'
  call  _printf
  add  esp, 4
  mov  DWORD PTR __SEHRec$[ebp+20], -2 ; exiting both blocks, setting previous try level back to -2
$L7@main:
  xor  eax, eax
  mov  ecx, DWORD PTR __SEHRec$[ebp+8]
  mov  DWORD PTR fs:0, ecx
  pop  ecx
  pop  edi
  pop  esi
  pop  ebx
  mov  esp, ebp
  pop  ebp
  ret 0
$main  ENDP

_code$ = 8 ; size = 4
Here is the meaning of the cookies: Cookie Offset is the difference between the address of the saved EBP value in the stack and the EBP⊕security_cookie value in the stack. Cookie XOR Offset is an additional difference between the EBP⊕security_cookie value and what is stored in the stack.

If this equation is not true, the process is to halt due to stack corruption:

\[
\text{security_cookie} \oplus (\text{Cookie XOR Offset} + \text{address of saved EBP}) = \text{stack[address of saved EBP + Cookie Offset]}
\]

If Cookie Offset is −2, this implies that it is not present.

Cookies checking is also implemented in my tracer, see GitHub for details.

It is still possible to fall back to SEH3 in the compilers after (and including) MSVC 2005 by setting the /GS- option, however, the CRT code use SEH4 anyway.

### Windows x64

As you might think, it is not very fast to set up the SEH frame at each function prologue. Another performance problem is changing the previous try level value many times during the function’s execution.

So things are changed completely in x64: now all pointers to try blocks, filter and handler functions are stored in another PE segment .pdata, and from there the OS’s exception handler takes all the information.

Here are the two examples from the previous section compiled for x64:

#### Listing 6.33: MSVC 2012

```
$SG86276 DB 'hello #1!', 0aH, 00H
$SG86277 DB 'hello #2!', 0aH, 00H
$SG86279 DB 'access violation, can''t recover', 0aH, 00H
pdata SEGMENT
pdata$main DD imagerel $LN9
          DD imagerel $LN9+61
          DD imagerel $unwind$main
pdata ENDS
pdata SEGMENT
pdata$main$filt$0 DD imagerel main$filt$0
          DD imagerel main$filt$0+32
          DD imagerel $unwind$main$filt$0
pdata ENDS
xdata SEGMENT
$xunwind$main DD 020609H
```
Listing 6.34: MSVC 2012

```
SG86277 DB 'in filter. code=0x%08X', 0aH, 00H
SG86279 DB 'yes, that is our exception', 0aH, 00H
SG86281 DB 'not our exception', 0aH, 00H
SG86288 DB 'hello!', 0aH, 00H
SG86290 DB '0x112233 raised. now let''s crash', 0aH, 00H
SG86292 DB 'access violation, can''t recover', 0aH, 00H
SG86294 DB 'user exception caught', 0aH, 00H
```

```
pdata SEGMENT
pdata$filter_user_exceptions DD imagerel $LN6
DD imagerel $LN6+73
DD imagerel unwind$filter_user_exceptions
pdata$main DD imagerel $LN14
DD imagerel $LN14+95
```

```
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 DD  030023206H
 DD  imagerel _C_specific_handler
 DD  01H
 DD  imagerel $LN9+8
 DD  imagerel $LN9+40
 DD  imagerel main$filt$0
 DD  imagerel $LN9+40
unwind$main$filt$0 DD 020601H
 DD  050023206H
xdata ENDS

_TEXT SEGMENT
main PROC
$LN9:
  push rbx
  sub rsp, 32
  xor ebx, ebx
  lea rcx, OFFSET FLAT:$SG86276 ; 'hello #1!'
  call printf
  mov DWORD PTR [rbx], 13
  lea rcx, OFFSET FLAT:$SG86277 ; 'hello #2!'
  call printf
  jmp SHORT $LN8@main
$LN6@main:
  lea rcx, OFFSET FLAT:$SG86279 ; 'access violation, can''t recover'
  call printf
  npad 1 ; align next label
$LN8@main:
  xor eax, eax
  add rsp, 32
  pop rbx
  ret 0
main ENDP
_TEXT ENDS

text$x SEGMENT
main$filt$0 PROC
push rbp
sub rsp, 32
mov rbp, rdx
$LN5@main$filt$:
  mov rax, QWORD PTR [rcx]
  xor ecx, ecx
  cmp DWORD PTR [rax], -1073741819; c0000005H
  sete cl
$LN7@main$filt$:
  add rsp, 32
  pop rbp
  ret 0
int 3
main$filt$0 ENDP
text$x ENDS

```

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DD imagerel unwind$main
pdata ENDS
pdata SEGMENT
pdata main$filt$0 DD imagerel main$filt$0
  DD imagerel main$filt$0+32
  DD imagerel unwind$main$filt$0
pdata main$filt$1 DD imagerel main$filt$1
  DD imagerel main$filt$1+30
  DD imagerel unwind$main$filt$1
pdata ENDS

xdata SEGMENT
$unwind$filter_user_exceptions DD 020601H
  DD 030023206H
$unwind$main DD 020609H
  DD 030023206H
  DD imagerel __C_specific_handler
  DD 02H
  DD imagerel $LN14+8
  DD imagerel $LN14+59
  DD imagerel main$filt$0
  DD imagerel $LN14+59
  DD imagerel $LN14+8
  DD imagerel $LN14+74
  DD imagerel main$filt$1
  DD imagerel $LN14+74
$unwind$main$filt$0 DD 020601H
  DD 050023206H
$unwind$main$filt$1 DD 020601H
  DD 050023206H
xdata ENDS

_TEXT SEGMENT
main PROC
$LN14:
push rbx
  sub rsp, 32
  xor ebx, ebx
  lea rcx, OFFSET FLAT:$SG86288 ; 'hello'
call printf
  xor r9d, r9d
  xor r8d, r8d
  xor edx, edx
  mov ecx, 1122867 ; 00112233H
call QWORD PTR __imp_RaiseException
  lea rcx, OFFSET FLAT:$SG86290 ; '0x112233 raised. now let's crash'
call printf
  mov DWORD PTR [rbx], 13
  jmp SHORT $LN13@main
$LN11@main:
  lea rcx, OFFSET FLAT:$SG86292 ; 'access violation, can't recover'
call printf
  npad 1 ; align next label
$LN13@main:
  jmp SHORT $LN9@main
$LN7@main:
  lea rcx, OFFSET FLAT:$SG86294 ; 'user exception caught'
call printf
  npad 1 ; align next label
$LN9@main:
  xor eax, eax
  add rsp, 32
  pop rbx
  ret 0
main ENDP

_TEXT SEGMENT
main$filt$0 PROC
push rbp
  sub rsp, 32

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Read [Igor Skochinsky, Compiler Internals: Exceptions and RTTI, (2012)](http://go.yurichev.com/17294) for more detailed information about this.

Aside from exception information, .pdata is a section that contains the addresses of almost all function starts and ends, hence it may be useful for a tools targeted at automated analysis.

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49Also available as http://go.yurichev.com/17294
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Read more about SEH


6.5.4 Windows NT: Critical section

Critical sections in any OS are very important in multithreaded environment, mostly for giving a guarantee that only one thread can access some data in a single moment of time, while blocking other threads and interrupts.

That is how a CRITICAL_SECTION structure is declared in Windows NT line OS:

```c
Listing 6.35: (Windows Research Kernel v1.2) public/sdk/inc/nturtl.h

typedef struct _RTL_CRITICAL_SECTION {
    PRTL_CRITICAL_SECTION_DEBUG DebugInfo;

    // The following three fields control entering and exiting the critical section for the resource
    //
    // LONG LockCount;
    LONG RecursionCount;
    HANDLE OwningThread; // from the thread's ClientId->UniqueThread
    HANDLE LockSemaphore;
    ULONG_PTR SpinCount; // force size on 64-bit systems when packed
} RTL_CRITICAL_SECTION, *PRTL_CRITICAL_SECTION;
```

That's is how EnterCriticalSection() function works:

```c
Listing 6.36: Windows 2008/ntdll.dll/x86 (begin)

_RtlEnterCriticalSection@4

var_C = dword ptr -0Ch
var_8 = dword ptr -8
var_4 = dword ptr -4
arg_0 = dword ptr 8

mov edi, edi
push ebp
mov ebp, esp
sub esp, 0Ch
push esi
push edi
mov edi, [ebp+arg_0]
lea esi, [edi+4]; LockCount
mov eax, esi
lock btr dword ptr [eax], 0
jnb wait; jump if CF=0

loc_7DE922DD:

mov eax, large fs:18h
mov ecx, [eax+24h]
mov [edi+0Ch], ecx
mov dword ptr [edi+8], 1
pop edi
xor eax, eax
pop esi
mov esp, ebp
pop ebp
retn 4

... skipped
```

50 Also available as [http://go.yurichev.com/17293](http://go.yurichev.com/17293)
51 Also available as [http://go.yurichev.com/17294](http://go.yurichev.com/17294)
The most important instruction in this code fragment is BTR (prefixed with LOCK):
the zeroth bit is stored in the CF flag and cleared in memory. This is an atomic operation,
blocking all other CPUs’ access to this piece of memory (see the LOCK prefix before the BTR instruction).
If the bit at LockCount is 1,
fine, reset it and return from the function: we are in a critical section.
If not—the critical section is already occupied by other thread, so wait.
The wait is performed there using WaitForSingleObject().

And here is how the LeaveCriticalSection() function works:

Listing 6.37: Windows 2008/ntdll.dll/x86 (begin)

XADD is “exchange and add”.
In this case, it adds 1 to LockCount, meanwhile saves initial value of LockCount in the EBX register. However, value in EBX is to incremented with a help of subsequent INC EBX, and it also will be equal to the updated value of LockCount.
This operation is atomic since it is prefixed by LOCK as well, meaning that all other CPUs or CPU cores in system are blocked from accessing this point in memory.
The LOCK prefix is very important:
without it two threads, each of which works on separate CPU or CPU core can try to enter a critical section and to modify the value in memory, which will result in non-deterministic behavior.
Chapter 7

Tools

Now that Dennis Yurichev has made this book free (libre), it is a contribution to the world of free knowledge and free education. However, for our freedom’s sake, we need free (libre) reverse engineering tools to replace the proprietary tools described in this book.

Richard M. Stallman

7.1 Binary analysis

Tools you use when you don’t run any process.

- (Free, open-source) ent\(^1\): entropy analyzing tool. Read more about entropy: 9.2 on page 948.
- Hiew\(^2\): for small modifications of code in binary files. Has assembler/disassembler.
- (Free, open-source) GHex\(^3\): simple hexadecimal editor for Linux.
- (Free, open-source) xxod: standard UNIX utilities for dumping.
- (Free, open-source) strings: *NIX tool for searching for ASCII strings in binary files, including executable ones. Sysinternals has alternative\(^4\) supporting wide char strings (UTF-16, widely used in Windows).
- (Free, open-source) Binwalk\(^5\): analyzing firmware images.
- (Free, open-source) binary grep: a small utility for searching any byte sequence in a big pile of files, including non-executable ones: GitHub. There is also rafind2 in rada.re for the same purpose.

7.1.1 Disassemblers

- IDA. An older freeware version is available for download \(^6\). Hot-keys cheatsheet: .6.1 on page 1044
- Binary Ninja\(^7\)
- (Free, open-source) zynamics BinNavi\(^8\)
- (Free, open-source) objdump: simple command-line utility for dumping and disassembling.
- (Free, open-source) readelf\(^9\): dump information about ELF file.

\(^1\)http://www.fourmilab.ch/random/
\(^2\)hiew.ru
\(^3\)https://wiki.gnome.org/Apps/Ghex
\(^4\)https://technet.microsoft.com/en-us/sysinternals/strings
\(^5\)http://binwalk.org/
\(^6\)hex-rays.com/products/ida/support/download_freeware.shtml
\(^7\)http://binary.ninja/
\(^8\)https://www.zynamics.com/binnavi.html
\(^9\)https://sourceware.org/binutils/docs/binutils/readelf.html
7.2. **LIVE ANALYSIS**

### 7.1.2 Decompilers

There is only one known, publicly available, high-quality decompiler to C code: *Hex-Rays*: [hex-rays.com/products/decompiler/](http://hex-rays.com/products/decompiler/)

Read more about it: 11.8 on page 1006.

### 7.1.3 Patch comparison/diffing

You may want to use it when you compare original version of some executable and patched one, in order to find what has been patched and why.

- (Free) *zynamics BinDiff*[^10]
- (Free, open-source) *Diaphora*[^11]

### 7.2 Live analysis

Tools you use on a live system or during running of a process.

#### 7.2.1 Debuggers

- (Free) *OllyDbg*. Very popular user-mode win32 debugger[^12]. Hot-keys cheatsheet: .6.2 on page 1044
- (Free, open-source) *GDB*. Not quite popular debugger among reverse engineers, because it’s intended mostly for programmers. Some commands: .6.5 on page 1045. There is a visual interface for GDB, “*GDB dashboard*”[^13].
- (Free, open-source) *LLDB*[^14].
- *WinDbg*[^15]: kernel debugger for Windows.
- *IDA* has internal debugger.
- (Free, open-source) *Radare AKA rada.re AKA r2*[^16]. A GUI also exists: *ragu*[^17].
- (Free, open-source) *tracer*. The author often uses *tracer*[^18] instead of a debugger.

The author of these lines stopped using a debugger eventually, since all he needs from it is to spot function arguments while executing, or registers state at some point. Loading a debugger each time is too much, so a small utility called *tracer* was born. It works from command line, allows intercepting function execution, setting breakpoints at arbitrary places, reading and changing registers state, etc.

N.B.: the *tracer* isn’t evolving, because it was developed as a demonstration tool for this book, not as everyday tool.

#### 7.2.2 Library calls tracing

*ltrace*[^19].

[^12]: ollydbg.de
[^15]: [https://github.com/yurichev/ragui](https://github.com/yurichev/ragui)
[^16]: yurichev.com
7.2.3 System calls tracing

strace / dtruss

It shows which system calls (syscalls( 6.3 on page 747)) are called by a process right now.

For example:

```
# strace df -h
...
access("/etc/ld.so.nohwcap", F_OK) = -1 ENOENT (No such file or directory)
open("/lib/i386-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\1\1\1\0\0\0\0\0\0\0\0\0\3\0\3\0\1\0\0\0\220\232\1\0004\0\0\0"..., 512) = 512
fstat64(3, {st_mode=S_IFREG|0755, st_size=1770984, ...}) = 0
mmap2(NULL, 1780508, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0xb75b3000
```

Mac OS X has dtruss for doing the same.

Cygwin also has strace, but as far as it's known, it works only for .exe-files compiled for the cygwin environment itself.

7.2.4 Network sniffing

Sniffing is intercepting some information you may be interested in.

(Free, open-source) Wireshark\(^{20}\) for network sniffing. It has also capability for USB sniffing\(^{21}\).

Wireshark has a younger (or older) brother tcpdump\(^{22}\), simpler command-line tool.

7.2.5 Sysinternals

(Free) Sysinternals (developed by Mark Russinovich)\(^{23}\). At least these tools are important and worth studying: Process Explorer, Handle, VMMAP, TCPView, Process Monitor.

7.2.6 Valgrind

(Free, open-source) a powerful tool for detecting memory leaks: http://valgrind.org/. Due to its powerful JIT mechanism, Valgrind is used as a framework for other tools.

7.2.7 Emulators

- (Free, open-source) QEMU\(^{24}\): emulator for various CPUs and architectures.
- (Free, open-source) DosBox\(^{25}\): MS-DOS emulator, mostly used for retrogaming.
- (Free, open-source) SimH\(^{26}\): emulator of ancient computers, mainframes, etc.

\(^{20}\)https://www.wireshark.org/
\(^{21}\)https://wiki.wireshark.org/CaptureSetup/USB
\(^{22}\)http://www.tcpdump.org/
\(^{23}\)https://technet.microsoft.com/en-us/sysinternals/bb842062
\(^{24}\)http://qemu.org
\(^{25}\)https://www.dosbox.com/
\(^{26}\)http://simh.trailing-edge.com/
7.3. OTHER TOOLS

7.3 Other tools

Microsoft Visual Studio Express 27: Stripped-down free version of Visual Studio, convenient for simple experiments.

Some useful options: 6.3 on page 1044.

There is a website named “Compiler Explorer”, allowing to compile small code snippets and see output in various GCC versions and architectures (at least x86, ARM, MIPS): http://godbolt.org/—I would have used it myself for the book if I would know about it!

7.3.1 Calculators

Good calculator for reverse engineer’s needs should support at least decimal, hexadecimal and binary bases, as well as many important operations like XOR and shifts.

• IDA has built-in calculator (“?”).
• rada.re has rax2.
• https://github.com/DennisYurichev/progcaltc
• As a last resort, standard calculator in Windows has programmer’s mode.

7.4 Do You Think Something Is Missing Here?

If you know a great tool not listed here, please drop a note:
dennis@yurichev.com.

27 visualstudio.com/en-US/products/visual-studio-express-vs
Chapter 8

Case studies
8.1. TASKMANAGERPRACTICALJOKE(WINDOWSVISTA)

Instead of epigraph:

Seibel: How do you tackle reading source code? Even reading something in a programming language you already know is a tricky problem.

Knuth: But it’s really worth it for what it builds in your brain. So how do I do it? There was a machine called the Bunker Ramo 300 and somebody told me that the Fortran compiler for this machine was really amazingly fast, but nobody had any idea why it worked. I got a copy of the source-code listing for it. I didn’t have a manual for the machine, so I wasn’t even sure what the machine language was.

But I took it as an interesting challenge. I could figure out BEGIN and then I would start to decode. The operation codes had some two-letter mnemonics and so I could start to figure out “This probably was a load instruction, this probably was a branch.” And I knew it was a Fortran compiler, so at some point it looked at column seven of a card, and that was where it would tell if it was a comment or not.

After three hours I had figured out a little bit about the machine. Then I found these big, branching tables. So it was a puzzle and I kept just making little charts like I’m working at a security agency trying to decode a secret code. But I knew it worked and I knew it was a Fortran compiler—it wasn’t encrypted in the sense that it was intentionally obscure; it was only in code because I hadn’t gotten the manual for the machine.

Eventually I was able to figure out why this compiler was so fast. Unfortunately it wasn’t because the algorithms were brilliant; it was just because they had used unstructured programming and hand optimized the code to the hilt.

It was just basically the way you solve some kind of an unknown puzzle— make tables and charts and get a little more information here and make a hypothesis. In general when I’m reading a technical paper, it’s the same challenge. I’m trying to get into the author’s mind, trying to figure out what the concept is. The more you learn to read other people’s stuff, the more able you are to invent your own in the future, it seems to me.

(Peter Seibel — Coders at Work: Reflections on the Craft of Programming)

8.1 Task manager practical joke (Windows Vista)

Let’s see if it’s possible to hack Task Manager slightly so it would detect more CPU cores.

Let us first think, how does the Task Manager know the number of cores?

There is the GetSystemInfo() win32 function present in win32 userspace which can tell us this. But it’s not imported in taskmgr.exe.

There is, however, another one in NTAPI, NtQuerySystemInformation(), which is used in taskmgr.exe in several places.

To get the number of cores, one has to call this function with the SystemBasicInformation constant as a first argument (which is zero 1).

The second argument has to point to the buffer which is getting all the information.

So we have to find all calls to the NtQuerySystemInformation(0, ?, ?, ?) function. Let’s open taskmgr.exe in IDA.

What is always good about Microsoft executables is that IDA can download the corresponding PDB file for this executable and show all function names.

It is visible that Task Manager is written in C++ and some of the function names and classes are really speaking for themselves. There are classes CAdapter, CNetPage, CPerfPage, CProcInfo, CProcPage, CSvcPage, CTaskPage, CUserPage.

Apparently, each class corresponds to each tab in Task Manager.

Let’s visit each call and add comment with the value which is passed as the first function argument. We will write “not zero” at some places, because the value there was clearly not zero, but something really different (more about this in the second part of this chapter).

And we are looking for zero passed as argument, after all.

1MSDN
8.1. TASK MANAGER PRACTICAL JOKE (WINDOWS VISTA)

Figure 8.1: IDA: cross references to NtQuerySystemInformation()

Yes, the names are really speaking for themselves.

When we closely investigate each place where NtQuerySystemInformation(0, ?, ?, ?) is called, we quickly find what we need in the InitPerfInfo() function:

Listing 8.1: taskmgr.exe (Windows Vista)

```assembly
.text:10000B4B3 xor r9d, r9d
.text:10000B4B6 lea rdx, [rsp+0C78h+var_C58] ; buffer
.text:10000B4BB xor ecx, ecx
.text:10000B4BD lea ebp, [r9+40h]
.text:10000B4C1 mov r8d, ebp
.text:10000B4C4 call cs:__imp_NtQuerySystemInformation ; 0
.text:10000B4D0 ; CODE XREF: InitPerfInfo(void)+97
.text:10000B4D0 mov eax, [rsp+0C78h+var_C50]
.text:10000B4D0 mov esi, ebx
.text:10000B4D0 mov r12d, 3E80h
.text:10000B4D3 mov cs:?g_PageSize@@3KA, eax ; ulong g_PageSize
.text:10000B4D9 shr eax, 0Ah
.text:10000B4DD lea r13, __ImageBase
.text:10000B4E3 imul eax, [rsp+0C78h+var_C4C]
.text:10000B4E8 cmp [rsp+0C78h+var_C20], bpl
.text:10000B4E9 mov cs:?g_MEMMax@@3_JA, rax ; __int64 g_MEMMax
.text:10000B4F3 mov al, [esp+0C78h+var_C20] ; number of CPUs
.text:10000B4F9 cmp eax, ebx
.text:10000B4FD mov cs:?g_cProcessors@@3EA, al ; uchar g_cProcessors
.text:10000B504 movzx eax, [esp+0C78h+var_C20]
.text:10000B509 cmp eax, ebx
.text:10000B50C cmp al, bl
.text:10000B50E mov eax, [esp+0C78h+var_C20]
```

g_cProcessors is a global variable, and this name has been assigned by IDA according to the PDB loaded from Microsoft’s symbol server.
The byte is taken from var_C20. And var_C58 is passed to NtQuerySystemInformation() as a pointer to the receiving buffer. The difference between 0xC20 and 0xC58 is 0x38 (56).

Let’s take a look at format of the return structure, which we can find in MSDN:

```c
typedef struct _SYSTEM_BASIC_INFORMATION {
    BYTE Reserved1[24];
    PVOID Reserved2[4];
    UCHAR NumberOfProcessors;
} SYSTEM_BASIC_INFORMATION;
```

This is a x64 system, so each PVOID takes 8 bytes.

All reserved fields in the structure take $24 + 4 \times 8 = 56$ bytes.

Oh yes, this implies that var_C20 is the local stack is exactly the NumberOfProcessors field of the SYSTEM_BASIC_INFORMATION structure.

Let’s check our guess. Copy taskmgr.exe from C:\Windows\System32 to some other folder (so the Windows Resource Protection will not try to restore the patched taskmgr.exe).

Let’s open it in Hiew and find the place:

![Figure 8.2: Hiew: find the place to be patched](image)

Let’s replace the MOVZ X instruction with ours. Let’s pretend we’ve got 64 CPU cores.

Add one additional NOP (because our instruction is shorter than the original one):

![Figure 8.3: Hiew: patch it](image)

And it works! Of course, the data in the graphs is not correct.

At times, Task Manager even shows an overall CPU load of more than 100%.
The biggest number Task Manager does not crash with is 64.
Apparently, Task Manager in Windows Vista was not tested on computers with a large number of cores. So there are probably some static data structure(s) inside it limited to 64 cores.

### 8.1.1 Using LEA to load values

Sometimes, LEA is used in taskmgr.exe instead of MOV to set the first argument of NtQuerySystemInformation():

Listing 8.2: taskmgr.exe (Windows Vista)

```assembly
xor r9d, r9d
div dword ptr [rsp+4C8h+WndClass.lpfnWndProc]
lea rdx, [rsp+4C8h+VersionInformation]
lea ecx, [r9+2] ; put 2 to ECX
mov r8d, 138h
mov ebx, eax ; ECX=SystemPerformanceInformation
    call cs:__imp_NtQuerySystemInformation ; 2
...

mov r8d, 30h
lea r9, [rsp+298h+var_268]
lea rdx, [rsp+298h+var_258]
lea ecx, [r8-20h] ; put 3 to ECX
; ECX=SystemTimeOfDayInformation
    call cs:__imp_NtQuerySystemInformation ; not zero
```
...  
`mov rbp, [rsi+8]
mov r8d, 20h
lea r9, [rsp+98h+arg_0]
lea rdx, [rsp+98h+var_78]
lea ecx, [r8+2Fh] ; put 0x4F to ECX
mov [rsp+98h+var_60], ebx
mov [rsp+98h+var_68], rbp
; ECX=SystemSuperfetchInformation
call cs:__imp_NtQuerySystemInformation ; not zero

Perhaps **MSVC** did so because machine code of **LEA** is shorter than **MOV REG, 5** (would be 5 instead of 4). LEA with offset in −128..127 range (offset will occupy 1 byte in opcode) with 32-bit registers is even shorter (for lack of REX prefix)—3 bytes.

Another example of such thing is: **6.1.5 on page 739**.
This is a very popular game with several implementations in existence. We can take one of them, called BallTriX, from 1997, available freely at http://go.yurichev.com/17311\(^2\). Here is how it looks:

![BallTriX game screenshot](image)

Figure 8.5: This is how the game is usually looks like

So let's see, is it possible to find the random generator and do some trick with it. IDA quickly recognize the standard \_rand function in balltrix.exe at 0x00403DA0. IDA also shows that it is called only from one place:

```
.text:00402C9C sub_402C9C proc near ; CODE XREF: sub_402ACA+52
.text:00402C9C ; sub_402ACA+64 ...
.text:00402C9C arg_0 = dword ptr 8
.text:00402C9C push ebp
.text:00402C9D mov ebp, esp
.text:00402CA0 push ebx
.text:00402CA1 push esi
.text:00402CA2 mov eax, dword_40D430
.text:00402CA7 imul eax, dword_40D440
.text:00402CAE add eax, dword_40D5C8
.text:00402CB4 mov ecx, 32000
.text:00402CB9 cdq
.text:00402CBA idiv ecx
.text:00402CBC mov dword_40D440, edx
.text:00402CC2 call _rand
.text:00402CC7 cdq
.text:00402CC8 idiv [ebp+arg_0]
.text:00402CCB mov dword_40D440, edx
.text:00402CD1 mov eax, dword_40D430
.text:00402CD6 jmp $+5
.text:00402CDB pop edi
.text:00402CDC pop esi
.text:00402CDE leave
.text:00402CDF retn
.text:00402CDF sub_402C9C endp
```

We'll call it “random”. Let's not to dive into this function’s code yet.

This function is referred from 3 places.

Here are the first two:

```
.text:00402B16 mov eax, dword_40C03C ; 10 here
.text:00402B1B push eax
.text:00402B1C call random
.text:00402B21 add esp, 4
.text:00402B24 inc eax
.text:00402B25 mov [ebp+var_C], eax
.text:00402B28 mov eax, dword_40C040 ; 10 here
.text:00402B2D push eax
.text:00402B2E call random
.text:00402B33 add esp, 4
```

Here is the third one:

```
.text:00402B88 mov eax, dword_40C058 ; 5 here
.text:00402B8B push eax
.text:00402B8C call random
.text:00402B90 add esp, 4
.text:00402B94 inc eax
```

So the function has only one argument.

10 is passed in first two cases and 5 in third. We can also notice that the board has a size of 10*10 and there are 5 possible colors. This is it! The standard rand() function returns a number in the $0..0x7FFF$ range and this is often inconvenient, so many programmers implement their own random functions which returns a random number in a specified range. In our case, the range is $0..n−1$ and \(n\) is passed as the sole argument of the function. We can quickly check this in any debugger.

So let's fix the third function call to always return zero. First, we will replace three instructions (PUSH/CALL/ADD) by NOPs. Then we'll add XOR EAX, EAX instruction, to clear the EAX register.
So what we did is we replaced a call to the `random()` function by a code which always returns zero.
Let's run it now:

![Minesweeper Game](image)

**Figure 8.6: Practical joke works**

Oh yes, it works.\(^3\)

But why are the arguments to the `random()` functions global variables? That's just because it's possible to change the board size in the game's settings, so these values are not hardcoded. The 10 and 5 values are just defaults.

### 8.3 Minesweeper (Windows XP)

For those who are not very good at playing Minesweeper, we could try to reveal the hidden mines in the debugger.

As we know, Minesweeper places mines randomly, so there has to be some kind of random number generator or a call to the standard `rand()` C-function.

What is really cool about reversing Microsoft products is that there are PDB file with symbols (function names, etc). When we load `winmine.exe` into IDA, it downloads the PDB file exactly for this executable and shows all names.

So here it is, the only call to `rand()` is this function:

```assembly
.text:01003940 ; __stdcall Rnd(x)
.text:01003940 _Rnd@4 proc near ; CODE XREF: StartGame()+53
.text:01003940 ; StartGame()+61
.text:01003940 arg_0 = dword ptr 4
.text:01003940 call ds:__imp__rand
.text:01003940 cdq
.text:01003940 idiv [esp+arg_0]
.text:01003940 mov eax, edx
.text:01003940 retn 4
.text:01003940 _Rnd@4 endp
```

IDA named it so, and it was the name given to it by Minesweeper's developers.

The function is very simple:

\(^3\)Author of this book once did this as a joke for his coworkers with the hope that they would stop playing. They didn't.
int Rnd(int limit)
{
    return rand() % limit;
};

(There is no “limit” name in the PDB file; we manually named this argument like this.)

So it returns a random value from 0 to a specified limit.

Rnd() is called only from one place, a function called StartGame(), and as it seems, this is exactly the code which place the mines:

Minesweeper allows you to set the board size, so the X (xBoxMac) and Y (yBoxMac) of the board are global variables. They are passed to Rnd() and random coordinates are generated. A mine is placed by the OR instruction at 0x010036FA. And if it has been placed before (it’s possible if the pair of Rnd() generates a coordinates pair which has been already generated), then TEST and JNZ at 0x010036E6 jumps to the generation routine again.

cBombStart is the global variable containing total number of mines. So this is loop.

The width of the array is 32 (we can conclude this by looking at the SHL instruction, which multiplies one of the coordinates by 32).

The size of the rgBlk global array can be easily determined by the difference between the rgBlk label in the data segment and the next known one. It is 0x360 (864):

864/32 = 27.

So the array size is 27 * 32? It is close to what we know: when we try to set board size to 100 * 100 in Minesweeper settings, it fallbacks to a board of size 24 * 30. So this is the maximal board size here. And the array has a fixed size for any board size.

So let’s see all this in OllyDbg. We will ran Minesweeper, attaching OllyDbg to it and now we can see the memory dump at the address of the rgBlk array (0x01005340) a.

So we got this memory dump of the array:

---

aAll addresses here are for Minesweeper for Windows XP SP3 English. They may differ for other service packs.
8.3. MINESWEEPER (WINDOWS XP)

OllyDbg, like any other hexadecimal editor, shows 16 bytes per line. So each 32-byte array row occupies exactly 2 lines here.

This is beginner level (9*9 board).

There is some square structure can be seen visually (0x10 bytes).

We will click “Run” in OllyDbg to unfreeze the Minesweeper process, then we’ll clicked randomly at the Minesweeper window and trapped into mine, but now all mines are visible:

![Minesweeper](image)

Figure 8.7: Mines

By comparing the mine places and the dump, we can conclude that 0x10 stands for border, 0x0F—empty block, 0x8F—mine. Perhaps, 0x10 is just a sentinel value.

Now we’ll add comments and also enclose all 0x8F bytes into square brackets:
8.3. MINESWEEPER (WINDOWS XP)

Now we'll remove all *border bytes* (0x10) and what's beyond those:

Yes, these are mines, now it can be clearly seen and compared with the screenshot.
8.3. MINESWEEPER (WINDOWS XP)

What is interesting is that we can modify the array right in OllyDbg. We can remove all mines by changing all 0x8F bytes by 0x0F, and here is what we’ll get in Minesweeper:

We can also move all of them to the first line:

Well, the debugger is not very convenient for eavesdropping (which is our goal anyway), so we’ll write a small utility to dump the contents of the board:

```c
// Windows XP MineSweeper cheater
// written by dennis(a)yurichev.com for http://beginners.re/ book
#include <windows.h>
#include <assert.h>
#include <stdio.h>

int main (int argc, char * argv[]) {
    int i, j;
    HANDLE h;
    DWORD PID, address, rd;
    BYTE board[27][32];
```
if (argc!=3)
{
    printf ("Usage: %s <PID> <address>\n", argv[0]);
    return 0;
}

assert (argv[1]!=NULL);
assert (argv[2]!=NULL);
assert (sscanf (argv[1], "%d", &PID)==1);
assert (sscanf (argv[2], "%x", &address)==1);

h=OpenProcess (PROCESS_VM_OPERATION | PROCESS_VM_READ | PROCESS_VM_WRITE, FALSE, PID);
if (h==NULL)
{
    DWORD e=GetLastError();
    printf ("OpenProcess error: %08X\n", e);
    return 0;
}

if (ReadProcessMemory (h, (LPVOID)address, board, sizeof(board), &rd)!=TRUE)
{
    printf ("ReadProcessMemory() failed\n");
    return 0;
}

for (i=1; i<26; i++)
{
    if (board[i][0]==0x10 && board[i][1]==0x10)
        break; // end of board
    for (j=1; j<31; j++)
    {
        if (board[i][j]==0x10)
            break; // board border
        if (board[i][j]==0x8F)
            printf ("*");
        else
            printf (" ");
    }
    printf ("\n");
}

CloseHandle (h);

Just set the PID\(^5\)\(^6\) and the address of the array (0x01005340 for Windows XP SP3 English) and it will dump it\(^7\).

It attaches itself to a win32 process by PID and just reads process memory at the address.

### 8.3.1 Finding grid automatically

This is kind of nuisance to set address each time when we run our utility. Also, various Minesweeper versions may have the array on different address. Knowing the fact that there is always a border (0x10 bytes), we can just find it in memory:

```c
// find frame to determine the address
process_mem=(BYTE*)malloc(process_mem_size);
assert (process_mem!=NULL);
if (ReadProcessMemory (h, (LPVOID)start_addr, process_mem, process_mem_size, &rd)!=TRUE)
```

\(^5\)Program/process ID  
\(^6\)PID it can be seen in Task Manager (enable it in "View → Select Columns")  
\(^7\)The compiled executable is here: beginners.re
8.4. HACKING WINDOWS CLOCK

```c
{    printf ("ReadProcessMemory() failed\n");    return 0;
};
// for 9*9 grid.    // FIXME: slow!    for (i=0; i<process_mem_size; i++){
    if (memcmp(process_mem+i, "\x10\x10\x10\x10\x10\x10\x10\x10\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x0F\x10", 32)>
        ==0)    {
        // found
        address=start_addr+i;
        break;
    }
};
if (address==0)    {
    printf ("Can't determine address of frame (and grid)\n");    return 0;
} else    {
    printf ("Found frame and grid at 0x%x\n", address);
};
```


8.3.2 Exercises

- Why do the border bytes (or sentinel values) (0x10) exist in the array? What they are for if they are not visible in Minesweeper’s interface? How could it work without them?
- As it turns out, there are more values possible (for open blocks, for flagged by user, etc). Try to find the meaning of each one.
- Modify my utility so it can remove all mines or set them in a fixed pattern that you want in the Minesweeper process currently running.

8.4 Hacking Windows clock

Sometimes I do some kind of first April prank for my coworkers.

Let’s find, if we could do something with Windows clock? Can we force to go clock hands backwards?

First of all, when you click on date/time in status bar, a C:\WINDOWS\SYSTEM32\TIMEDATE.CPL module gets executed, which is usual executable PE-file.

Let’s see, how it draw hands? When I open the file (from Windows 7) in Resource Hacker, there are clock faces, but with no hands:
OK, what we know? How to draw a clock hand? All they are started at the middle of circle, ending with its border. Hence, we must calculate coordinates of a point on circle’s border. From school-level mathematics we may recall that we have to use sine/cosine functions to draw circle, or at least square root. There are no such things in TIMEDATE.CPL, at least at first glance. But, thanks to Microsoft debugging PDB files, I can find a function named CAnalogClock::DrawHand(), which calls Gdiplus::Graphics::DrawLine() at least twice.

Here is its code:

```assembly
.text:6EB9DBC7 ; private: enum Gdiplus::Status __thiscall CAnalogClock::DrawHand(class 
	\ Gdiplus::Graphics *, int, struct ClockHand const &, class Gdiplus::Pen *)
.text:6EB9DBC7 ? DrawHand@CAnalogClock@@QAEXPAVGraphics@@HABUClockHand@@PAVPen@3@@Z proc near
.text:6EB9DBC7 ; CODE XREF: CAnalogClock::_ClockPaint(HDC__ *)+163
.text:6EB9DBC7 ; CAnalogClock::_ClockPaint(HDC__ *)+18B

.var_10 = dword ptr -10h
.var_C = dword ptr -0Ch
.var_8 = dword ptr -8h
.var_4 = dword ptr -4h
.arg_0 = dword ptr 0h
.arg_4 = dword ptr 0Ch
.arg_8 = dword ptr 10h
.arg_C = dword ptr 14h

.text:6EB9D8C7 var_10 = dword ptr -10h
.text:6EB9D8C7 var_C = dword ptr -0Ch
.text:6EB9D8C7 var_8 = dword ptr -8h
.text:6EB9D8C7 var_4 = dword ptr -4h
.text:6EB9D8C7 arg_0 = dword ptr 0h
.text:6EB9D8C7 arg_4 = dword ptr 0Ch
.text:6EB9D8C7 arg_8 = dword ptr 10h
.text:6EB9D8C7 arg_C = dword ptr 14h

.text:6EB9D8C7 mov edi, edi
.text:6EB9D9C9 push ebp
.text:6EB9D9CA mov ebp, esp
.text:6EB9D9CC sub esp, 10h
.text:6EB9D9CF mov eax, [ebp+arg_4]
.text:6EB9D9D2 push ebx
.text:6EB9D9D3 push esi
```
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```汇编
push edi
    cdq
push 3Ch
    mov esi, ecx
pop ecx
    idiv ecx
push 2
    lea ebx, table[edx*8]
lea eax, [edx+1Eh]
    cdq
    idiv ecx
    mov ecx, [ebp+arg_0]
    mov [ebp+var_4], ebx
    lea eax, table[edx*8]
    mov [ebp+arg_4], eax
    call ?SetInterpolationMode@Graphics@Gdiplus@@QAE?
\ A4Status@2@W4InterpolationMode@2@Z ; Gdiplus::Graphics::SetInterpolationMode(Gdiplus::/
\ InterpolationMode)
    mov eax, [esi+70h]
    mov edi, [ebp+arg_8]
    mov [ebp+var_10], eax
    mov eax, [esi+74h]
    mov [ebp+var_C], eax
    mov eax, [edi]
    sub eax, [edi+8]
push 8000 ; nDenominator
    push eax ; nNumerator
    push dword ptr [ebx+4] ; nNumber
    mov ebx, ds:__imp__MulDiv@12 ; MulDiv(x,x,x)
call ebx ; MulDiv(x,x,x)
    add eax, [esi+74h]
push 8000 ; nDenominator
    mov [ebp+arg_8], eax
    mov eax, [edi]
    sub eax, [edi+8]
push eax ; nNumerator
    mov eax, [ebp+var_4]
call ebx ; MulDiv(x,x,x)
    add eax, [esi+70h]
    mov ecx, [ebp+arg_0]
mov eax, [ebp+arg_8]
mov [ebp+var_4], eax
    mov eax, [ebp+var_C], eax
push eax
    lea eax, [ebp+var_8]
push eax
    push [ebp+arg_C]
call ?DrawLine@Graphics@Gdiplus@@QAE?
\ A4Status@2@PBVPen@2@ABVPoint@2@1@Z ; Gdiplus::Graphics::DrawLine(Gdiplus::Pen const *, Gdiplus::/
\ Point const &)
push 8000 ; nDenominator
    push ecx ; nNumerator
    push dword ptr [eax+4] ; nNumber
    mov ebx, ds:__imp__MulDiv@12 ; MulDiv(x,x,x)
call ebx ; MulDiv(x,x,x)
    add eax, [esi+74h]
push 8000 ; nDenominator
    push dword ptr [edi+8] ; nNumerator
    mov [ebp+arg_8], eax
    mov eax, [ebp+arg_4]
push eax
    push [ebp+arg_8]
call ebx ; MulDiv(x,x,x)
    add eax, [esi+70h]
```

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8.4. HACKING WINDOWS CLOCK

We can see that \texttt{DrawLine()} arguments are dependent on result of \texttt{MulDiv()} function and a table[] table (name is mine), which has 8-byte elements (look at LEA’s second operand).

What is inside of table[]?

It’s referenced only from \texttt{DrawHand()} function. It has 120 32-bit words or 60 32-bit pairs... wait, 60? Let’s take a closer look at these values. First of all, I’ll zap 6 pairs or 12 32-bit words with zeros, and then I’ll put patched \texttt{TIMEDATE.CPL} into C:\WINDOWS\SYSTEM32. (You may need to set owner of the \texttt{TIMEDATE.CPL} file to your primary user account (instead of TrustedInstaller), and also, boot in safe mode with command prompt so you can copy the file, which is usually locked.)
8.4. HACKING WINDOWS CLOCK

Now when any hand is located at 0..5 seconds/minutes, it’s invisible! However, opposite (shorter) part of second hand is visible and moving. When any hand is outside of this area, hand is visible as usual.

Let’s take even closer look at the table in Mathematica. I have copied-pasted table from the TIMEDATE.CPL to a tbl file (480 bytes). We will take for granted the fact that these are signed values, because half of elements are below zero (0FFFFE0C1h, etc.). If these values would be unsigned, they would be suspiciously huge.

```
In[1]:= tbl = BinaryReadList["~/.../tbl", "Integer32"]
Out[1]= {0, -7999, 836, -7956, 1663, -7825, 2472, -7608, 3253, -7308, 3999, 
-6928, 4702, -6472, 5353, -5945, 5945, -5353, 6472, -4702, 6928, 
-4000, 7308, -3253, 7608, -2472, 7825, -1663, 7956, -836, 8000, 0, 
7956, 836, 7825, 1663, 7608, 2472, 7308, 3253, 6928, 4000, 6472, 
4702, 5945, 5353, 5353, 5945, 4702, 6472, 3999, 6928, 3253, 7308, 
2472, 7608, 1663, 7825, 836, 7956, 0, 7999, -836, 7956, -1663, 7825, 
-2472, 7608, -3253, 7308, -4000, 6928, -4702, 6472, -5353, 5945, 
-5945, 5353, -6472, 4702, -6928, 3999, -7308, 3253, -7608, 2472, 
-7825, 1663, -7956, 836, -7999, 0, -7956, -836, -7608, -2472, -3253, 
-6928, -4000, -6472, -5353, -5945, -5945, -4702, -6472, -3999, -6928, 
-3253, -7308, -2472, -7608, -1663, 
-7825, -836, -7956}

In[]:= Length[tbl]
Out[]= 120
```

Let’s treat two consecutive 32-bit values as pair:

```
In[]:= pairs = Partition[tbl, 2]
{3253, -7308}, {3999, -6928}, {4702, -6472}, {5353, -5945}, {5945, 
-5353}, {6472, -4702}, {6928, -4000}, {7308, -3253}, {7608, -2472}, 
{7825, -1663}, {7956, -836}, {8000, 0}, {7956, 836}, {7825, 
1663}, {7608, 2472}, {7308, 3253}, {6928, 4000}, {6472, 
4702}, {5945, 5353}, {5353, 5945}, {4702, 6472}, {3999, 
6928}, {3253, 7308}, {2472, 7608}, {1663, 7825}, {836, 7956}, {0, 
7999}, {-836, 7956}, {-1663, 7825}, {-2472, 7608}, {-3253, 
7308}, {-4000, 6928}, {-4702, 6472}, {-5353, 5945}, {-5945, 
5353}, {-6472, 4702}, {-6928, 3999}, {-7308, 3253}, {-7608, 
2472}, {-7825, 1663}, {-7956, 836}, {-7999, 
0}, {-7956, -836}, {-7825, -1663}, {-7608, -2472}, {-7308, -3253, 
{-6928, -4000}, {-6472, -4702}, {-5945, -5353}, {-5353, -5945}, 
{-4702, -6472}, {-3999, -6928}, {-3253, -7308}, {-2472, -7608}, 
{-1663, -7825}, {-836, -7956}}

In[]:= Length[pairs]
```

Figure 8.11: Attempt to run
Let's try to treat each pair as X/Y coordinate and draw all 60 pairs, and also first 15 pairs:

![Figure 8.12: Mathematica](image)

Now this is something! Each pair is just coordinate. First 15 pairs are coordinates for $\frac{1}{4}$ of circle. Perhaps, Microsoft developers precalculated all coordinates and put them into table.

Now I can understand why when I zapped first 6 pairs, hands were invisible at that area: in fact, hands were drawn, they just had zero length, because hand started at 0:0 coordinate and ended there.

**The prank (practical joke)**

Given all that, how would we force hands to go counterclockwise? In fact, this is simple, we need just to rotate the table, so each hand, instead of drawing at place of zeroth second, would be drawing at place of 59th second.
8.4. HACKING WINDOWS CLOCK

I made the patcher a long time ago, at the very beginning of 2000s, for Windows 2000. Hard to believe, it still works for Windows 7, perhaps, the table hasn’t been changed since then!


Now I can see all hands goes backwards:

![Clock Image]

Figure 8.13: Now it works

Well, there is no animation in this book, but if you look closer, you can see, that hands are in fact shows correct time, but the whole clock face is rotated vertically, like we see it from the inside of clock.

Windows 2000 leaked source code

So I did the patcher and then Windows 2000 source code has been leaked (I can’t force you to trust me, though). Let’s take a look on source code if that function and table.

The file is win2k/private/shell/cpls/utc/clock.c:

```c
// Array containing the sine and cosine values for hand positions.
//
POINT rCircleTable[] =
{
    { 0,   -7999},
    { 836, -7956},
    { 1663, -7825},
    { 2472, -7608},
    { 3253, -7308},
    ...  
    { -4702, -6472},
    { -3999, -6928},
    { -3253, -7308},
    { -2472, -7608},
    { -1663, -7825},
    {  -836,  -7956},
};

////////////////////////////////////////////////////////////////////////////
// DrawHand
// Draws the hands of the clock.
//////////////////////////////////////////////////////////////////////////////
```
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```c
void DrawHand(
    HDC hDC,
    int pos,
    HPEN hPen,
    int scale,
    int patMode,
    PCLOCKSTR np)
{
    LPOINT lppt;
    int radius;

    MoveTo(hDC, np->clockCenter.x, np->clockCenter.y);
    radius = MulDiv(np->clockRadius, scale, 100);
    lppt = rCircleTable + pos;
    SetROP2(hDC, patMode);
    SelectObject(hDC, hPen);
    LineTo( hDC,
            np->clockCenter.x + MulDiv(lppt->x, radius, 8000),
            np->clockCenter.y + MulDiv(lppt->y, radius, 8000));
}
```

Now it's clear: coordinates has been precalculated as if clock face has height and width of $2 \cdot 8000$, and then it's rescaled to current clock face radius using `MulDiv()` function.

POINT structure is a structure of two 32-bit values, first is $x$, second is $y$.

8.5 Dongles

The author of these lines, occasionally did software copy-protection dongle replacements, or “dongle emulators” and here are couple examples of how it’s happening.

About one of the cases about Rocket and Z3 that is not present here, you can read here: [http://yurichev.com/tmp/SAT_SMT_DRAFT.pdf](http://yurichev.com/tmp/SAT_SMT_DRAFT.pdf).

8.5.1 Example #1: MacOS Classic and PowerPC

Here is an example of a program for MacOS Classic, for PowerPC. The company who developed the software product has disappeared a long time ago, so the (legal) customer was afraid of physical dongle damage.

While running without a dongle connected, a message box with the text “Invalid Security Device” appeared.

Luckily, this text string could easily be found in the executable binary file.

Let's pretend we are not very familiar both with Mac OS Classic and PowerPC, but will try anyway.

IDA opened the executable file smoothly, reported its type as “PEF (Mac OS or Be OS executable)” (indeed, it is a standard Mac OS Classic file format).

By searching for the text string with the error message, we've got into this code fragment:

```assembly
... seg000:000C87FC 38 60 00 01 li %r3, 1
seg000:000C8800 48 03 93 40 bl check1
seg000:000C8804 60 00 00 00 nop
seg000:000C8808 54 60 06 3F crlwi. %r0, %r3, 24
seg000:000C880C 40 82 00 40 bne OK
seg000:000C8810 80 62 9F D8 lwz %r3, TC_aInvalidSecurityDevice
...
```

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Yes, this is PowerPC code.

The CPU is a very typical 32-bit RISC of 1990s era.

Each instruction occupies 4 bytes (just as in MIPS and ARM) and the names somewhat resemble MIPS instruction names.

check1() is a function name we'll give to it later. BL is Branch Link instruction, e.g., intended for calling subroutines.

The crucial point is the BNE instruction which jumps if the dongle protection check passes or not if an error occurs: then the address of the text string gets loaded into the r3 register for the subsequent passing into a message box routine.

From the [Steve Zucker, SunSoft and Kari Karhi, IBM, SYSTEM V APPLICATION BINARY INTERFACE: PowerPC Processor Supplement, (1995)]10 we will found out that the r3 register is used for return values (and r4, in case of 64-bit values).

Another yet unknown instruction is CLRLWI. From [PowerPC(tm) Microprocessor Family: The Programming Environments for 32-Bit Microprocessors, (2000)]11 we’ll learn that this instruction does both clearing and loading. In our case, it clears the 24 high bits from the value in r3 and puts them in r0, so it is analogical to MOVZX in x86 (1.17.1 on page 202), but it also sets the flags, so BNE can check them afterwards.

Let’s take a look into the check1() function:

```
check1: # CODE XREF: check1+Cp
    set arg_8, 8
    mflr %r0
    stw %r0, arg_8(%sp)
    stwu %sp, -0x40(%sp)
    bl check2
    mtlr %r0
    blr
```

As you can see in IDA, that function is called from many places in the program, but only the r3 register’s value is checked after each call.

All this function does is to call the other function, so it is a thunk function: there are function prologue and epilogue, but the r3 register is not touched, so check1() returns what check2() returns.

BLR12 looks like the return from the function, but since IDA does the function layout, we probably do not need to care about this.

Since it is a typical RISC, it seems that subroutines are called using a link register, just like in ARM.

The check2() function is more complex:

```
check2: # CODE XREF: check1+Cp
    set var_18, -0x18
    set var_C, -0xC
    set var_8, -8
    set var_4, -4
    mflr %r0
    lwz %r31, 0x40+arg_8(%sp)
    stw %r30, var_8(%sp)
    stw %r29, var_C(%sp)
    mr %r29, %r3
    stw %r0, arg_8(%sp)
```

10Also available as http://yurichev.com/mirrors/PowerPC/elfspec_ppc.pdf
11Also available as http://yurichev.com/mirrors/PowerPC/6xx_pem.pdf
12(PowerPC) Branch to Link Register

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We are lucky again: some function names are left in the executable (debug symbols section? Hard to say while we are not very familiar with the file format, maybe it is some kind of PE exports? (6.5.2 on page 760)), like .RBEFINDNEXT() and .RBEFINDFIRST().

Eventually these functions call other functions with names like .GetNextDeviceViaUSB(), .USBSendPKT(), so these are clearly dealing with an USB device.

There is even a function named .GetNextEve3Device()—sounds familiar, there was a Sentinel Eve3 dongle for ADB port (present on Macs) in 1990s.

Let’s first take a look on how the r3 register is set before return, while ignoring everything else.

We know that a “good” r3 value has to be non-zero, zero r3 leads the execution flow to the message box with an error message.

There are two li %r3, 1 instructions present in the function and one li %r3, 0 (Load Immediate, i.e.,
8.5. **DONGLES**

Loading a value into a register). The first instruction is at 0x001186B0—and frankly speaking, it’s hard to say what it means.

What we see next is, however, easier to understand: `.RBEFINDFIRST()` is called: if it fails, 0 is written into r3 and we jump to exit, otherwise another function is called (check3())—if it fails too, `.RBEFINDNEXT()` is called, probably in order to look for another USB device.

N.B.: `.clrlwi. %r0, %r3, 16` it is analogical to what we already saw, but it clears 16 bits, i.e., `.RBEFINDFIRST()` probably returns a 16-bit value.

B (stands for branch) unconditional jump.

**BEQ** is the inverse instruction of **BNE**.

Let’s see check3():

```assembly
seg000:0011873C     check3: # CODE XREF: check2+88p
seg000:0011873C     .set var_18, -0x18
seg000:0011873C     .set var_C, -0xC
seg000:0011873C     .set var_8, -8
seg000:0011873C     .set var_4, -4
seg000:0011873C     .set arg_8, 8
seg000:0011873C     93 E1 FF FC stw %r31, var_4(%sp)
seg000:0011873C     7C 08 02 A6 mflr %r0
seg000:0011873C     38 A0 00 00 li %r5, 0
seg000:0011873C     93 C1 FF F8 stw %r30, var_8(%sp)
seg000:0011873C     83 C2 95 A8 lwz %r30, off_1485E8 # dword_24B704
seg000:0011873C     93 A1 FF F4 stw %r29, var_C(%sp)
seg000:0011873C     3B A3 00 00 addi %r29, %r3, 0
seg000:0011873C     38 60 00 00 li %r3, 0
seg000:0011873C     90 01 00 08 stw %r0, arg_8(%sp)
seg000:0011873C     48 00 C0 5D bl .RBEREAD
seg000:0011873C     54 60 04 3F clrlwi. %r0, %r3, 16
seg000:0011873C     41 82 00 0C beq loc_1187C0
seg000:0011873C     38 60 00 00 li %r3, 0
seg000:0011873C     48 00 02 F0 b exit
seg000:0011873C     4B F9 F3 D9 bl sub_B7BAC
```

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seg000:00118980  80 DE 00 00 lwz  %r6, dword_24B704
seg000:00118984  38 81 00 38 addi  %r4, %sp, 0x50+var_18
seg000:00118988  3B E0 00 00 li   %r31, 0
seg000:0011898C  38 81 00 04 li   %r3, 4
seg000:00118990  38 A0 00 00 li   %r5, 0
seg000:00118994  48 00 BE 35 bl  .RBEREAD
seg000:00118998  60 00 00 00 nop
seg000:0011899C  54 60 04 3F clrlwi. %r0, %r3, 16
seg000:001189A0  41 82 00 0C beq  loc_1189AC
seg000:001189A4  38 60 00 00 li   %r3, 0
seg000:001189A8  48 00 00 CB b   exit
seg000:001189AC  
seg000:001189AC A0 01 00 38 lhz  %r0, 0x50+var_18(%sp)
seg000:001189B0  28 00 00 6A cmplwi %r0, 0xAED0
seg000:001189B4  40 82 00 0C bne  loc_1189C0
seg000:001189B8  3B E0 00 00 li   %r31, 1
seg000:001189BC  48 00 00 14 b   exit
seg000:001189D0  
seg000:001189D0 loc_1189D0:  
seg000:001189D0 57 A0 06 3E clrlwi %r0, %r29, 24
seg000:001189D4  28 00 00 02 cmplwi %r0, 2
seg000:001189D8  40 82 00 20 bne  loc_1189F8
seg000:001189DC  38 60 00 00 li   %r3, 5
seg000:001189E0  41 82 00 10 beq  good2
seg000:001189E4  48 00 4C 69 bl  sub_11D64C
seg000:001189E8  60 00 00 00 nop
seg000:001189EC  48 00 00 84 b   exit
seg000:001189F0  
seg000:001189F0 good2:  
seg000:001189F0 38 60 00 01 li   %r3, 1
seg000:001189F4  48 00 00 7C b   exit
seg000:001189F8  
seg000:001189F8 loc_1189F8:  
seg000:001189F8 80 DE 00 00 lwz  %r6, dword_24B704
seg000:001189FC  38 81 00 38 addi  %r4, %sp, 0x50+var_18
seg000:00118A00  38 60 00 05 li   %r3, 5
seg000:00118A04  38 A0 00 00 li   %r5, 0
seg000:00118A08  48 00 BD C1 bl  .RBEREAD
seg000:00118A0C  60 00 00 00 nop
seg000:00118A10  54 60 04 3F clrlwi. %r0, %r3, 16
seg000:00118A14  41 82 00 0C beq  loc_118A20
seg000:00118A18  38 60 00 00 li   %r3, 0
seg000:00118A1C  48 00 00 54 b   exit
seg000:00118A20  
seg000:00118A20 loc_118A20:  
seg000:00118A20 A0 01 00 38 lhz  %r0, 0x50+var_18(%sp)
seg000:00118A24  28 00 11 03 cmplwi %r0, 0xD300
seg000:00118A28  40 82 00 0C bne  loc_118A34
seg000:00118A2C  3B E0 00 01 li   %r31, 1
seg000:00118A30  48 00 00 14 b   good1
seg000:00118A34  
seg000:00118A34 loc_118A34:  
seg000:00118A34 28 00 1A EB cmplwi %r0, 0xEBA1
seg000:00118A38  41 82 00 0C beq  good1
seg000:00118A3C  38 60 00 00 li   %r3, 0
seg000:00118A40  48 00 00 30 b   exit
seg000:00118A44  
seg000:00118A44 good1:  
seg000:00118A44 57 A0 06 3E clrlwi %r0, %r29, 24
seg000:00118A48  28 00 00 03 cmplwi %r0, 3
There are a lot of calls to .RBEREAD().

Perhaps, the function returns some values from the dongle, so they are compared here with some hard-coded variables using CMPLWI.

We also see that the r3 register is also filled before each call to .RBEREAD() with one of these values: 0, 1, 8, 0xA, 0xB, 0xC, 0xD, 4, 5. Probably a memory address or something like that?

Yes, indeed, by googling these function names it is easy to find the Sentinel Eve3 dongle manual!

Perhaps we don’t even have to learn any other PowerPC instructions: all this function does is just call .RBEREAD(), compare its results with the constants and returns 1 if the comparisons are fine or 0 otherwise.

OK, all we’ve got is that check1() has always to return 1 or any other non-zero value.

But since we are not very confident in our knowledge of PowerPC instructions, we are going to be careful: we will patch the jumps in check2() at 0x001186FC and 0x00118718.

At 0x001186FC we’ll write bytes 0x48 and 0 thus converting the BEQ instruction in an B (unconditional jump): we can spot its opcode in the code without even referring to [PowerPC(tm) Microprocessor Family: The Programming Environments for 32-Bit Microprocessors, (2000)]

At 0x00118718 we’ll write 0x60 and 3 zero bytes, thus converting it to a NOP instruction: Its opcode we could spot in the code too.

And now it all works without a dongle connected.

In summary, such small modifications can be done with IDA and minimal assembly language knowledge.

8.5.2 Example #2: SCO OpenServer

An ancient software for SCO OpenServer from 1997 developed by a company that disappeared a long time ago.

There is a special dongle driver to be installed in the system, that contains the following text strings: “Copyright 1989, Rainbow Technologies, Inc., Irvine, CA” and “Sentinel Integrated Driver Ver. 3.0”.

After the installation of the driver in SCO OpenServer, these device files appear in the /dev filesystem:

/dev/rbsl8
/dev/rbsl9
/dev/rbsl10

Also available as http://yurichev.com/mirrors/PowerPC/6xx_pem.pdf
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The program reports an error without dongle connected, but the error string cannot be found in the executables.

Thanks to IDA, it is easy to load the COFF executable used in SCO OpenServer.

Let's also try to find “rbsl” string and indeed, found it in this code fragment:

```
.text:00022AB8 public SSQC
.text:00022AB8 SSQC proc near ; CODE XREF: SSQ+7p
.text:00022AB8 .text:00022AB8 var_44 = byte ptr -44h
.text:00022AB8 var_29 = byte ptr -29h
.text:00022AB8 arg_0 = dword ptr 8
.text:00022AB8
.text:00022AB8 push ebp
.text:00022AB9 mov ebp, esp
.text:00022ABB sub esp, 44h
.text:00022ABE push edi
.text:00022ABF mov edi, offset unk_4035D0
.text:00022AC4 push esi
.text:00022AC5 mov esi, [ebp+arg_0]
.text:00022AC8 push ebx
.text:00022AC9 push esi
.text:00022ACA call strlen
.text:00022ACF add esp, 4
.text:00022AD2 cmp eax, 2
.text:00022AD7 jnz loc_22BA4
.text:00022ADD inc esi
.text:00022ADE mov al, [esi-1]
.text:00022AEE cmp al, '3'
.text:00022AF4 jz loc_22B94
.text:00022AFA cmp al, '4'
.text:00022AFF jnz short loc_22B6B
.text:00022B01 movsx ebx, byte ptr [esi]
.text:00022B04 sub ebx, '0'
.text:00022B07 mov eax, 7
.text:00022B0C add eax, ebx
.text:00022B0E push eax
.text:00022B0F lea eax, [ebp+var_44]
.text:00022B12 push offset aDevSlD ; "/dev/sl%d"
.text:00022B17 push eax
.text:00022B18 call nl_sprintf
.text:00022B1D push 0 ; int
.text:00022B1F push offset aDevRbsl8 ; char *
.text:00022B24 call _access
.text:00022B29 add esp, 14h
.text:00022B2C cmp eax, 0FFFFFFFFh
.text:00022B31 jz short loc_22B48
.text:00022B33 lea eax, [ebx+7]
.text:00022B36 push eax
.text:00022B37 lea eax, [ebp+var_44]
.text:00022B3A push offset aDevRbslD ; "/dev/rbsl%d"
.text:00022B3F push eax
.text:00022B40 call nl_sprintf
.text:00022B45 add esp, 0Ch
.text:00022B48 loc_22B48: ; CODE XREF: SSQC+79j
.text:00022B48 mov edx, [edi]
.text:00022B4A test edx, edx
.text:00022B4C jle short loc_22B57
.text:00022B4E push edx ; int
.text:00022B4F call _close
.text:00022B54 add esp, 4
.text:00022B57 loc_22B57: ; CODE XREF: SSQC+94j
.text:00022B57 push 2 ; int
.text:00022B59 lea eax, [ebp+var_44]
.text:00022B5C push eax ; char *
```
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.text:0002B5D     call _open
.text:0002B62     add esp, 8
.text:0002B65     test eax, eax
.text:0002B67     mov [edi], eax
.text:0002B69     jge short loc_22B78
.text:0002B6B     loc_22B6B: ; CODE XREF: SSQC+47j
.text:0002B6B     mov eax, 0FFFFFFFh
.text:0002B70     pop ebx
.text:0002B71     pop esi
.text:0002B72     pop edi
.text:0002B73     mov esp, ebp
.text:0002B75     pop ebp
.text:0002B76     retn
.text:0002B78     loc_22B78: ; CODE XREF: SSQC+B1j
.text:0002B78     pop ebx
.text:0002B79     pop esi
.text:0002B7A     pop edi
.text:0002B7B     xor eax, eax
.text:0002B7D     mov esp, ebp
.text:0002B7F     pop ebp
.text:0002B80     retn
.text:0002B84     loc_22B84: ; CODE XREF: SSQC+31j
.text:0002B84     mov al, [esi]
.text:0002B86     pop ebx
.text:0002B87     pop esi
.text:0002B88     pop edi
.text:0002B89     mov ds:byte_407224, al
.text:0002B8E     mov esp, ebp
.text:0002B90     xor eax, eax
.text:0002B92     pop ebp
.text:0002B93     retn
.text:0002B94     loc_22B94: ; CODE XREF: SSQC+3Cj
.text:0002B94     mov al, [esi]
.text:0002B96     pop ebx
.text:0002B97     pop esi
.text:0002B98     pop edi
.text:0002B99     mov ds:byte_407225, al
.text:0002B9E     mov esp, ebp
.text:0002BA0     xor eax, eax
.text:0002BA2     pop ebp
.text:0002BA3     retn
.text:0002BA4     loc_22BA4: ; CODE XREF: SSQC+1Fj
.text:0002BA4     movsx eax, ds:byte_407225
.text:0002BAC     push esi
.text:0002BAC     push eax
.text:0002BAD     movsx eax, ds:byte_407224
.text:0002BB4     push eax
.text:0002BB5     lea eax, [ebp+var_44]
.text:0002BB8     push offset a46CC5 ; "46%c%c%s"
.text:0002BBB     push eax
.text:0002BBE     call nl_sprintf
.text:0002BC3     lea eax, [ebp+var_44]
.text:0002BC6     push eax
.text:0002BC7     call strlen
.text:0002BCC     add esp, 18h
.text:0002BCF     cmp eax, 18h
.text:0002BDA     jle short loc_22BDA
.text:0002BDD     mov [ebp+var_29], 0
.text:0002BDA     loc_22BDA: ; CODE XREF: SSQC+11Cj
.text:0002BDA     lea eax, [ebp+var_44]
.text:0002BDD     push eax
.text:0002BDE     call strlen
.text:0002BEE     push eax ; unsigned int
.text:0002BE4     lea eax, [ebp+var_44]
Yes, indeed, the program needs to communicate with the driver somehow.

The only place where the SSQC() function is called is the thunk function:

SSQC() can be called from at least 2 functions.

One of these is:

; these names we gave to the labels:
.data:004016C0 answers1 dd 6805h ; DATA XREF: sys_info+286r
.data:004016C4 answers2 dd 3Ch ; DATA XREF: sys_info+296r
.data:004016CC answers3 dd 832h ; DATA XREF: sys_info+2A3r
.data:004016D0 _C_and_B db 0Ch ; DATA XREF: sys_info+2BAr
.data:004016D0 answers4 dd 832h ; DATA XREF: sys_info+2A3r
.data:004016D0 byte_4016D1 db 0Bh ; DATA XREF: sys_info+2CDr
.data:004016D2 db 0

...
“3C” and “3E” sound familiar: there was a Sentinel Pro dongle by Rainbow with no memory, providing only one crypto-hashing secret function.

You can read a short description of what hash function is here: 2.11 on page 466.

But let’s get back to the program.

So the program can only check the presence or absence of a connected dongle.

No other information can be written to such dongle, as it has no memory. The two-character codes are commands (we can see how the commands are handled in the SSQC() function) and all other strings are...
hashed inside the dongle, being transformed into a 16-bit number. The algorithm was secret, so it was not possible to write a driver replacement or to remake the dongle hardware that would emulate it perfectly. However, it is always possible to intercept all accesses to it and to find what constants the hash function results are compared to.

But we need to say that it is possible to build a robust software copy protection scheme based on secret cryptographic hash-function: let it encrypt/decrypt the data files your software uses.

But let’s get back to the code.

Codes 51/52/53 are used for LPT printer port selection. 3x/4x are used for “family” selection (that’s how Sentinel Pro dongles are differentiated from each other: more than one dongle can be connected to a LPT port).

The only non-2-character string passed to the hashing function is “0123456789”.

Then, the result is compared against the set of valid results.

If it is correct, 0xC or 0xB is to be written into the global variable ctl_model.

Another text string that gets passed is “PRESS ANY KEY TO CONTINUE: ”, but the result is not checked. Hard to say why, probably by mistake.

Let’s see where the value from the global variable ctl_mode is used.

One such place is:

```
.text:0000D708 prep_sys proc near ; CODE XREF: init_sys+46Ap
.text:0000D708 .text:0000D708 var_14 = dword ptr -14h
.text:0000D708 .text:0000D708 var_10 = byte ptr -10h
.text:0000D708 .text:0000D708 var_8 = dword ptr -8
.text:0000D708 .text:0000D708 var_2 = word ptr -2
.text:0000D708 .text:0000D708 push ebp
.text:0000D708 .text:0000D709 mov eax, ds:net_env
.text:0000D70E .text:0000D70E mov ebp, esp
.text:0000D710 .text:0000D710 sub esp, 1Ch
.text:0000D713 .text:0000D713 test eax, eax
.text:0000D715 .text:0000D715 jnz short loc_D734
.text:0000D717 .text:0000D717 mov al, ds:ctl_model
.text:0000D71C .text:0000D71C test al, al
.text:0000D71E .text:0000D71E jnz short loc_D77E
.text:0000D720 .text:0000D720 mov [ebp+var_8], offset aIeCvulnv0kgT_ ; "Ie-cvulnv\bOKG\T_"
.text:0000D727 .text:0000D727 mov edx, 7
.text:0000D72C .text:0000D72C jmp loc_D7E7

...  

.text:0000D7E7 loc_D7E7: ; CODE XREF: prep_sys+24j
.text:0000D7E7 .text:0000D7E7 ; prep_sys+33j
.text:0000D7E7 .text:0000D7E7 push edx
.text:0000D7E8 .text:0000D7E8 mov edx, [ebp+var_8]
.text:0000D7EB .text:0000D7EB push 20h
.text:0000D7ED .text:0000D7ED push edx
.text:0000D7EE .text:0000D7EE push 16h
.text:0000D7F0 .text:0000D7F0 call err_warn
.text:0000D7F5 .text:0000D7F5 push offset station_sem
.text:0000D7FA .text:0000D7FA call ClosSem
.text:0000D7FF .text:0000D7FF call startup_err
```

If it is 0, an encrypted error message is passed to a decryption routine and printed.

The error string decryption routine seems a simple xoring:

```
.text:0000A43C err_warn proc near ; CODE XREF: prep_sys+E8p
.text:0000A43C ; prep_sys2+2Fp ...
.text:0000A43C .text:0000A43C var_55 = byte ptr -55h
.text:0000A43C .text:0000A43C var_54 = byte ptr -54h
.text:0000A43C .text:0000A43C arg_0 = dword ptr 8
```

\[\text{14What a strange feeling: to find bugs in such ancient software.}\]
That's why we were unable to find the error messages in the executable files, because they are encrypted (which is is popular practice).

Another call to the SSQ() hashing function passes the “offln” string to it and compares the result with 0xFE81 and 0x12A9.

If they don’t match, it works with some timer() function (maybe waiting for a poorly connected dongle to be reconnected and check again?) and then decrypts another error message to dump.
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.text:0000DA55 loc_DA55: ; CODE XREF: sync_sys+24Cj
    push offset aOffln ; "offln"
    call SSQ
    add esp, 4
    mov dl, [ebx]
    mov esi, eax
    cmp dl, 0Bh
    jnz short loc_DA83
    cmp esi, 0FE81h
    jz OK
    cmp esi, 0FFFFF8EFh
    jz OK
.loc_DA83: ; CODE XREF: sync_sys+201j
    mov cl, [ebx]
    cmp cl, 0Ch
    jnz short loc_DA9F
    cmp esi, 12A9h
    jz OK
    cmp esi, 0FFFFFFF5h
    jz OK
.loc_DA9F: ; CODE XREF: sync_sys+220j
    mov eax, [ebp+var_18]
    test eax, eax
    jz short loc_DAB0
    push 24h
    call timer
    add esp, 4
.loc_DAB0: ; CODE XREF: sync_sys+23Cj
    inc edi
    cmp edi, 3
    jle short loc_DA55
    mov eax, ds:net_env
    test eax, eax
    jz short error

.error: ; CODE XREF: sync_sys+255j
    mov [ebp+var_8], offset encrypted_error_message2
    mov [ebp+var_C], 17h ; decrypting key
    jmp decrypt_end_print_message

.decrypt_end_print_message: ; CODE XREF: sync_sys+29Dj
    mov eax, [ebp+var_18]
    test eax, eax
    jnz short loc_D9FB
    mov edx, [ebp+var_C] ; key
    push edx
    push 18h
    call err_warn
    push 0Fh
    push 190h
    push 18h
.call sound
    push eax
    test eax, eax
    jz short loc_D9FB

; this name we gave to label:
.decrypt_end_print_message: ; CODE XREF: sync_sys+2ABj
    mov eax, [ebp+var_18]
    test eax, eax
    jnz short loc_D9FB
    mov edx, [ebp+var_C] ; key
    push edx
    push 18h
    call err_warn
    push 0Fh
    push 190h
    push 18h
    call sound
    push [ebp+var_18], 1
    add esp, 18h
    call pcv_kbhit
    push eax
    test eax, eax
    jz short loc_D9FB

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Bypassing the dongle is pretty straightforward: just patch all jumps after the relevant CMP instructions. Another option is to write our own SCO OpenServer driver, containing a table of questions and answers, all of those which present in the program.

Decrypting error messages

By the way, we can also try to decrypt all error messages. The algorithm that is located in the err_warn() function is very simple, indeed:

```
Listing 8.3: Decryption function

.text:0000A44D mov esi, [ebp+arg_C] ; key
.text:0000A450 mov edx, [ebp+arg_4] ; string
.text:0000A453 loc_A453:
.text:0000A453 xor eax, eax
.text:0000A455 mov al, [edx+edi] ; load encrypted byte
.text:0000A458 xor eax, esi ; decrypt it
.text:0000A45A add esi, 3 ; change key for the next byte
.text:0000A45D inc edi
.text:0000A45E cmp edi, ecx
.text:0000A460 mov [ebp+edi+var_55], al
.text:0000A464 jl short loc_A453
```

As we can see, not just string is supplied to the decryption function, but also the key:

```
Listing 8.4: Python 3.x

#!/usr/bin/python
import sys
msg=[0x74, 0x72, 0x78, 0x43, 0x48, 0x6, 0x5A, 0x49, 0x4C, 0x47, 0x47,
0x51, 0x4F, 0x47, 0x61, 0x20, 0x22, 0x3C, 0x24, 0x33, 0x36, 0x76,
0x3A, 0x33, 0x31, 0x0C, 0x0, 0x0B, 0x1F, 0x7, 0x1E, 0x1A]
```

The algorithm is a simple xoring: each byte is xored with a key, but the key is increased by 3 after the processing of each byte.

We can write a simple Python script to check our hypothesis:
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key=0x17
tmp=key
for i in msg:
    sys.stdout.write("%c" % (i^tmp))
    tmp=tmp+3
sys.stdout.flush()

And it prints: “check security device connection”. So yes, this is the decrypted message.

There are also other encrypted messages with their corresponding keys. But needless to say, it is possible
to decrypt them without their keys. First, we can see that the key is in fact a byte. It is because the core
decryption instruction (XOR) works on byte level. The key is located in the ESI register, but only one byte
part of ESI is used. Hence, a key may be greater than 255, but its value is always to be rounded.

As a consequence, we can just try brute-force, trying all possible keys in the 0..255 range. We are also
going to skip the messages that has unprintable characters.

Listing 8.5: Python 3.x

```python
#!/usr/bin/python
import sys, curses.ascii
msgs=[
    [0x74, 0x72, 0x78, 0x43, 0x48, 0x6, 0x5A, 0x49, 0x4C, 0x47, 0x47,
    0x51, 0x4F, 0x47, 0x61, 0x20, 0x22, 0x3C, 0x24, 0x31, 0x33, 0x36, 0x76,
    0x7A, 0x33, 0x31, 0x0C, 0x0B, 0x01F, 0x07, 0x01E, 0x01A],
    [0x49, 0x65, 0x20, 0x63, 0x76, 0x75, 0x6C, 0x6E, 0x76, 0x77, 0x75, 0x65, 0x6E, 0x76, 0x56, 0x55, 0x5F, 0x1D, 0x26, 0x2C, 0x33,
    0x27, 0x28, 0x6F, 0x72, 0x75, 0x78, 0x77, 0x7E, 0x41, 0x44],
    [0x45, 0x61, 0x31, 0x67, 0x72, 0x79, 0x68, 0x52, 0x4A, 0x52, 0x50,
    0x0C, 0x4B, 0x57, 0x43, 0x51, 0x58, 0x5B, 0x61, 0x37, 0x33, 0x2B,
    0x39, 0x39, 0x3C, 0x38, 0x79, 0x3A, 0x30, 0x17, 0x0B, 0x0C],
    [0x40, 0x64, 0x79, 0x75, 0x6F, 0x09, 0x4C, 0x40, 0x9, 0x4D, 0x5A,
    0x46, 0x50, 0x49, 0x57, 0x49, 0x57, 0x3B, 0x21, 0x23, 0x6A, 0x38, 0x23,
    0x36, 0x24, 0x2A, 0x7C, 0x3A, 0x1A, 0x6, 0x8D, 0x0E, 0x0A, 0x14, 0x10],
    [0x72, 0x7C, 0x72, 0x79, 0x76, 0x0,
    0x50, 0x43, 0x4A, 0x59, 0x5D, 0x5B, 0x41, 0x41, 0x1B, 0x5A, 0x24,
    0x32, 0x2E, 0x29, 0x2B, 0x70, 0x20, 0x22, 0x38, 0x28, 0x36, 0x0D, 0x0B, 0x48, 0x04B, 0x04E]]

def is_string_printable(s):
    return all(list(map(lambda x: curses.ascii.isprint(x), s)))

for msg in msgs:
    print("message #" + str(cnt) + ":")
    for key in range(0,256):
        result=[]
        tmp=key
        for i in msg:
            result.append (i^tmp)
            tmp=tmp+3
        if is_string_printable (result):
            print("key: ", key, "value: ", ", ".join(list(map(chr, result)))
        cnt=cnt+1
```

And we get:

Listing 8.6: Results

<table>
<thead>
<tr>
<th>message</th>
<th>key</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>20</td>
<td><code>eb``h%</code>'<code>\</code>hudwlj. af{~f`ljmSblwlpk</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td><code>ajci</code>`cawtgv<code>bgto</code>g`millcmvkqkh</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td><code>bkd\j#rbbvsfuz\cduhj</code>d#bhomdlunj</td>
</tr>
</tbody>
</table>
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There is some garbage, but we can quickly find the English-language messages!

By the way, since the algorithm is a simple xoring encryption, the very same function can be used to encrypt messages. If needed, we can encrypt our own messages, and patch the program by inserting them.

8.5.3 Example #3: MS-DOS

Another very old software for MS-DOS from 1995 also developed by a company that disappeared a long time ago.

In the pre-DOS extenders era, all the software for MS-DOS mostly relied on 16-bit 8086 or 80286 CPUs, so the code was 16-bit en masse.

The 16-bit code is mostly same as you already saw in this book, but all registers are 16-bit and there are less instructions available.

The MS-DOS environment has no system drivers, and any program can deal with the bare hardware via ports, so here you can see the OUT/IN instructions, which are present in mostly in drivers in our times (it is impossible to access ports directly in user mode on all modern OSes).

Given that, the MS-DOS program which works with a dongle has to access the LPT printer port directly.

So we can just search for such instructions. And yes, here they are:

```
seg030:0034  out_port proc far ; CODE XREF: sent_pro+22p
seg030:0034  ; sent_pro+2Ap ...
seg030:0034
seg030:0034  arg_0 = byte ptr 6
seg030:0034
seg030:0034  55 push bp
seg030:0035  8B EC mov bp, sp
seg030:0037  8B 16 7E E7 mov dx, _out_port ; 0x378
seg030:003B  8A 46 06 mov al, [bp+arg_0]
seg030:003E  EE out dx, al
seg030:003F  5D pop bp
seg030:0040  CB retf
seg030:0040  out_port endp
```

(All label names in this example were given by me).

```
out_port() is referenced only in one function:
```

```
seg030:0041  sent_pro proc far ; CODE XREF: check_dongle+34p
seg030:0041
seg030:0041  var_3 = byte ptr -3
seg030:0041  var_2 = word ptr -2
seg030:0041  arg_0 = dword ptr 6
seg030:0041
seg030:0041  C8 04 00 00 enter 4, 0
seg030:0045  56 push si
```

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```
seg030:0046 07 push di
seg030:0047 8B 16 82 E7 mov dx, _in_port_1 ; 0x37A
seg030:004B EC in al, dx
seg030:004E 80 E3 04 or bl, 4
seg030:0054 8A C3 mov al, bl
seg030:0056 88 46 FD mov [bp+var_3], al
seg030:0059 80 E3 1F and bl, 1Fh
seg030:005C 8A C3 mov al, bl
seg030:005F 68 FF 00 push 0FFh
seg030:0062 0E push cs
seg030:0063 E8 CE FF call near ptr out_port
seg030:0066 59 pop cx
seg030:0067 68 D3 00 push 0D3h
seg030:006A 0E push cs
seg030:006B E8 C6 FF call near ptr out_port
seg030:006E 59 pop cx
seg030:006F 33 F6 xor si, si
seg030:0071 EB 01 jmp short loc_359D4
seg030:0073 46 inc si
seg030:0074 BE 04 00 mov si, 4
seg030:007A 83 CF 01 or di, 1
seg030:007D F7 46 FE 08+ test [bp+var_2], 8
seg030:0080 74 05 jz short loc_35A2C
seg030:0083 68 D7 00 push 007h ; '+'
```
This is again a Sentinel Pro “hashing” dongle as in the previous example. It is noticeably because text
8.5. DONGLES

Strings are passed here, too, and 16 bit values are returned and compared with others.

So that is how Sentinel Pro is accessed via ports.

The output port address is usually 0x378, i.e., the printer port, where the data to the old printers in pre-USB era was passed to.

The port is uni-directional, because when it was developed, no one imagined that someone will need to transfer information from the printer.\(^{15}\)

The only way to get information from the printer is a status register on port 0x379, which contains such bits as “paper out”, “ack”, “busy”—thus the printer may signal to the host computer if it is ready or not and if paper is present in it.

So the dongle returns information from one of these bits, one bit at each iteration.

\_in\_port\_2 contains the address of the status word (0x379) and \_in\_port\_1 contains the control register address (0x37A).

It seems that the dongle returns information via the “busy” flag at seg030:00B9: each bit is stored in the DI register, which is returned at the end of the function.

What do all these bytes sent to output port mean? Hard to say. Perhaps, commands to the dongle.

But generally speaking, it is not necessary to know: it is easy to solve our task without that knowledge.

Here is the dongle checking routine:

```
00000000 struct_0 struc ; (sizeof=0x1B)
00000000 field_0 db 25 dup(?) ; string(C)
00000019 _A dw ?
0000001B struct_0 ends

dseg:3CBC 61 63 72 75+_Q struct_0 <'hello', 01122h>
dseg:3CBC 6E 00 00 00+ ; DATA XREF: check_dongle+2Eo
... skipped ...

dseg:3E00 63 6F 66 66+ struct_0 <'coffee', 7EB7h>
dseg:3E1B 64 6F 67 00+ struct_0 <'dog', 0FFAdh>
dseg:3E36 63 61 74 00+ struct_0 <'cat', 0F5Fh>
dseg:3E51 70 61 70 65+ struct_0 <'paper', 0FFDfh>
dseg:3E6C 63 6F 6B 00+ struct_0 <'coke', 0FF68h>
dseg:3E87 63 6C 6F 63+ struct_0 <'clock', 55EAh>
dseg:3EA2 64 69 72 00+ struct_0 <'dir', 0FFAEh>
dseg:3EBD 63 6F 70 79+ struct_0 <'copy', 0F557h>

seg030:0145 check_dongle proc far ; CODE XREF: sub_3771D+3EP
seg030:0145 seg030:0145 var_6 = dword ptr -6
seg030:0145 seg030:0145 var_2 = word ptr -2
seg030:0145 seg030:0145 seg030:0145 C8 06 00 00 enter 6, 0
seg030:0149 seg030:0149 56 push si
seg030:014A seg030:014A 66 6A 00 push large 0 ; newtime
seg030:014D seg030:014D 6A 00 push 0 ; cmd
seg030:0151 seg030:0151 9A C1 18 00+ call _biostime
seg030:0154 seg030:0154 52 push dx
seg030:0155 seg030:0155 50 push ax
seg030:0156 seg030:0156 66 58 pop eax
seg030:0158 seg030:0158 83 C4 06 add sp, 6
seg030:015B seg030:015B 66 89 46 FA mov [bp+var_6], eax
seg030:015F seg030:015F 66 3B 06 D8+ cmp eax, _expiration
seg030:0164 seg030:0164 7E 44 jle short loc_35B0A
seg030:0166 seg030:0166 6A 14 push 14h
seg030:0168 seg030:0168 90 nop
seg030:0169 seg030:0169 0E push cs
seg030:016A seg030:016A EB 52 00 call near ptr get_rand
seg030:016D seg030:016D 59 pop cx
seg030:016E seg030:016E 8B F0 mov si, ax
seg030:0170 seg030:0170 6B C0 1B imul ax, 1Bh
```

\(^{15}\)If we consider Centronics only. The following IEEE 1284 standard allows the transfer of information from the printer.
8.5. DONGLES

Since the routine can be called very frequently, e.g., before the execution of each important software feature, and accessing the dongle is generally slow (because of the slow printer port and also slow MCU in the dongle), they probably added a way to skip some dongle checks, by checking the current time in the biostime() function.

The get_rand() function uses the standard C function:

So the text string is selected randomly, passed into the dongle, and then the result of the hashing is compared with the correct value.

The text strings seem to be constructed randomly as well, during software development.

And this is how the main dongle checking function is called:
8.6 “QR9”: Rubik’s cube inspired amateur crypto-algorithm

Sometimes amateur cryptosystems appear to be pretty bizarre.

The author of this book was once asked to reverse engineer an amateur cryptoalgorithm of some data encryption utility, the source code for which was lost.

Here is the listing exported from IDA for the original encryption utility:

```
.text:00541000 set_bit proc near ; CODE XREF: rotate1+42
.text:00541000 ; rotate2+42 ...
.text:00541000
.text:00541000 arg_0 = dword ptr 4
.text:00541000 arg_4 = dword ptr 8
.text:00541000 arg_8 = dword ptr 0Ch
.text:00541000 arg_C = byte ptr 10h
.text:00541000
.text:00541000 mov al, [esp+arg_C]  
.text:00541004 mov ecx, [esp+arg_8]  
.text:00541008 push esi     
.text:00541009 mov esi, [esp+4+arg_0] 
.text:0054100D test al, al  
.text:0054100F mov eax, [esp+4+arg_4]  
.text:00541013 mov dl, 1  
.text:00541015 jz short loc_54102B  
.text:00541017 shl dl, cl
```

16 He also got permission from the customer to publish the algorithm’s details.
8.6. “QR9”: RUBIK’S CUBE INSPIRED AMATEUR CRYPTO-ALGORITHM

\text{mov} cl, \text{cube64[eax+esi*8]}
\text{or} cl, dl
\text{mov} \text{cube64[eax+esi*8]}, cl
\pop\  esi
\text{return}

\text{mov} cl, \text{cube64[eax+esi*8]}
\text{or} cl, dl
\text{mov} \text{cube64[eax+esi*8]}, cl
\pop\  esi
\text{return}
\text{set_bit}

\align\ 10h
\text{get_bit proc near ; CODE XREF: rotate1+16}
\text{rotate2+16 ...}
\align\ 10h
\text{rotate1 proc near ; CODE XREF: rotate_all_with_password+8E}
\align\ 10h
\text{internal_array_64= byte ptr -40h}
\align\ 10h
\text{first_loop1_begin: ; CODE XREF: rotate1+2E}
\text{first_loop2_begin: ; CODE XREF: rotate2+25}
\text{push}\  esi
\text{return}
8.6. “QR9”: RUBIK’S CUBE INSPIRED AMATEUR CRYPTO-ALGORITHM

.text:0054109B     add    ebx, 8
.text:0054109B     cmp    edi, 8
.text:0054109E     jl     short first_loop1_begin
.text:005410A0     lea    ebx, [esp+50h+internal_array_64]
.text:005410A4     mov    edi, 7 ; EDI is loop1 counter, initial state is 7
.text:005410A9
.text:005410A9 second_loop1_begin: ; CODE XREF: rotate1+57
.text:005410A9     xor    esi, esi ; ESI is loop2 counter
.text:005410AB     mov    al, [ebx+esi] ; value from internal array
.text:005410AE     push   eax
.text:005410AF     push   ebp ; arg_0
.text:005410B0     push   edi
.text:005410B1     push   esi
.text:005410B2     call    set_bit
.text:005410B7     add    esp, 10h
.text:005410BA     inc    esi ; increment loop2 counter
.text:005410BB     cmp    esi, 8
.text:005410BE     jl     short second_loop2_begin
.text:005410C0     dec    edi ; decrement loop2 counter
.text:005410C1     add    ebx, 8
.text:005410C4     cmp    edi, 0FFFFFFFFh
.text:005410C7     jg     short second_loop1_begin
.text:005410C9     pop    edi
.text:005410CA     pop    esi
.text:005410CC     pop    ebp
.text:005410CD     add    esp, 40h
.text:005410D0     retn
.text:005410D0     rotate1 endp
.text:005410D0
.text:005410D1     align 10h
.text:005410E0
.text:005410E0 ;============ SUBROUTINE ================================
.text:005410E0 rotate2 proc near ; CODE XREF: rotate_all_with_password+7A
.text:005410E0 internal_array_64= byte ptr -40h
.text:005410E0 arg_0 = dword ptr 4
.text:005410E0 sub    esp, 40h
.text:005410E3     push   ebx
.text:005410E4     push   ebp
.text:005410E5     mov    ebp, [esp+48h+arg_0]
.text:005410E9     push   esi
.text:005410EA     push   edi
.text:005410EB     xor    edi, edi ; loop1 counter
.text:005410ED     lea    ebx, [esp+50h+internal_array_64]
.text:005410F1     loc_5410F1: ; CODE XREF: rotate2+2E
.text:005410F1     xor    esi, esi ; loop2 counter
.text:005410F3     loc_5410F3: ; CODE XREF: rotate2+25
.text:005410F3     push   esi ; loop2
.text:005410F4     push   edi ; loop1
.text:005410F5     push   ebp ; arg_0
.text:005410F6     call    get_bit
.text:005410FB     add    esp, 0Ch
.text:005410FE     mov    [ebx+esi], al ; store to internal array
.text:00541101     inc    esi ; increment loop1 counter
.text:00541102     cmp    esi, 8
.text:00541105     jl     short loc_5410F3
.text:00541107     inc    edi ; increment loop2 counter
.text:00541108     add    ebx, 8
.text:0054110B     cmp    edi, 8
.text:0054110E     jl     short loc_5410F1
.text:00541110     lea    ebx, [esp+50h+internal_array_64]
.text:00541114     mov    edi, 7 ; loop1 counter is initial state 7
8.6. “QR9”: RUBIK’S CUBE INSPIRED AMATEUR CRYPTO-ALGORITHM

.loc_541119: ; CODE XREF: rotate2+57
xor esi, esi ; loop2 counter

.loc_54111B: ; CODE XREF: rotate2+4E
mov al, [ebx+esi] ; get byte from internal array
push eax
push edi ; loop1 counter
push esi ; loop2 counter
push ebp ; arg_0

.call set_bit
add esp, 10h
inc esi ; increment loop2 counter
cmp esi, 8
jl short loc_54111B
dec edi ; decrement loop2 counter
add ebx, 8
cmp edi, 0FFFFFFFFh
jg short loc_541119
pop edi
pop esi
pop ebp
pop ebx
add esp, 40h
retn

rotate2 endp

.align 10h

rotate3 proc near ; CODE XREF: rotate_all_with_password+66

var_40 = byte ptr -40h
arg_0 = dword ptr 4
sub esp, 40h
push ebx
push ebp
mov ebp, [esp+48h+arg_0]
push esi
push edi
xor edi, edi
lea ebx, [esp+50h+var_40]

loc_541161: ; CODE XREF: rotate3+2E
xor esi, esi

loc_541163: ; CODE XREF: rotate3+25
push esi
push ebp
push edi
call get_bit
add esp, 0Ch
mov [ebx+esi], al
inc esi
cmp esi, 8
jl short loc_541163
inc edi
add ebx, 8
cmp edi, 8
jl short loc_541161
xor ebx, ebx
lea edi, [esp+50h+var_40]

loc_541186: ; CODE XREF: rotate3+54
mov esi, 7

loc_54118B: ; CODE XREF: rotate3+4E

8.6. “QR9”: RUBIK’S CUBE INSPIRED AMATEUR CRYPTO-ALGORITHM

```assembly
.text:0054118B  mov  al, [edi]
.text:0054118D  push eax
.text:0054118E  push ebx
.text:0054118F  push ebp
.text:00541190  push esi
.text:00541191  call set_bit
.text:00541196  add esp, 10h
.text:00541199  inc edi
.text:0054119A  dec esi
.text:0054119B  cmp esi, 0FFFFFFFFh
.text:0054119E  jg short loc_54118B
.text:005411A0  inc ebx
.text:005411A1  cmp ebx, 8
.text:005411A4  jl short loc_541186
.text:005411A6  pop edi
.text:005411A7  pop esi
.text:005411A8  pop ebp
.text:005411A9  pop ebx
.text:005411AA  add esp, 40h
.text:005411AD  retn
.text:005411AD rotate3 endp
.text:005411AE  align 10h
.text:005411B0  ; =============== SUBROUTINE ===============================
.text:005411B0 rotate_all_with_password proc near ; CODE XREF: crypt+1F
.text:005411B0 ; decrypt+36
.text:005411B0 arg_0 = dword ptr 4
.text:005411B0 arg_4 = dword ptr 8
.text:005411B0
.text:005411B0 mov eax, [esp+arg_0]
.text:005411B4 push ebp
.text:005411B5 mov ebp, eax
.text:005411B7 cmp byte ptr [eax], 0
.text:005411BA jz exit
.text:005411C0 push ebx
.text:005411C1 mov ebx, [esp+8+arg_4]
.text:005411C5 push esi
.text:005411C6 push edi
.text:005411C7
.text:005411C7 loop_begin: ; CODE XREF: rotate_all_with_password+9F
.text:005411C7 movsx eax, byte ptr [ebp+0]
.text:005411CB push eax ; C
.text:005411CC call _tolower
.text:005411D1 add esp, 4
.text:005411D4 cmp al, 'a'
.text:005411D6 jl short next_character_in_password
.text:005411D8 cmp al, 'z'
.text:005411DA jg short next_character_in_password
.text:005411DC movsx ecx, al
.text:005411DF sub ecx, 'a'
.text:005411E2 cmp ecx, 24
.text:005411E5 jle short skip_subtracting
.text:005411E7 sub ecx, 24
.text:005411EA skip_subtracting: ; CODE XREF: rotate_all_with_password+35
.text:005411EA mov eax, 55555556h
.text:005411EF imul ecx
.text:005411F1 mov eax, edx
.text:005411F3 shr eax, 1Fh
.text:005411F6 add edx, eax
.text:005411F8 mov eax, ecx
.text:005411FA mov esi, edx
.text:005411FC mov ecx, 3
.text:00541201 cdq
.text:00541202 idiv ecx
.text:00541204 sub edx, 0
```
8.6. “QR9”: RUBIK’S CUBE INSPIRED AMATEUR CRYPTO-ALGORITHM

.text:00541207 jz  short call_rotate1
.text:00541209 dec edx
.text:0054120A jz  short call_rotate2
.text:0054120C dec edx
.text:0054120D jnz short next_character_in_password
.text:0054120F test ebx, ebx
.text:00541211 jle short next_character_in_password
.text:00541213 mov edi, ebx
.text:00541215 call_rotate1: ; CODE XREF: rotate_all_with_password+57
.text:00541215 push esi
.text:00541216 call rotate1
.text:0054121B add esp, 4
.text:0054121C dec edi
.text:0054121D jnz short call_rotate1
.text:00541221 jmp short next_character_in_password
.text:00541223 call_rotate2: ; CODE XREF: rotate_all_with_password+5A
.text:00541223 test ebx, ebx
.text:00541225 jle short next_character_in_password
.text:00541227 mov edi, ebx
.text:00541229 call_rotate3: ; CODE XREF: rotate_all_with_password+6F
.text:00541229 push esi
.text:0054122A call rotate3
.text:0054122F add esp, 4
.text:00541232 dec edi
.text:00541233 jnz short call_rotate3
.text:00541237 call_rotate1: ; CODE XREF: rotate_all_with_password+57
.text:00541237 test ebx, ebx
.text:00541239 jle short next_character_in_password
.text:0054123B mov edi, ebx
.text:0054123D call_rotate2: ; CODE XREF: rotate_all_with_password+5A
.text:0054123D test ebx, ebx
.text:0054123F jle short next_character_in_password
.text:00541241 mov edi, ebx
.text:00541243 loc_541243: ; CODE XREF: rotate_all_with_password+97
.text:00541243 push esi
.text:00541244 call rotate2
.text:00541249 add esp, 4
.text:0054124A dec edi
.text:0054124B jnz short loc_541243
.text:0054124D next_character_in_password: ; CODE XREF: rotate_all_with_password+26
.text:0054124D ; rotate_all_with_password+2A ...
.text:0054124D mov al, [ebp+1]
.text:0054124C inc ebp
.text:0054124D test al, al
.text:0054124F jnz loop_begin
.text:00541254 pop edi
.text:00541255 pop esi
.text:00541256 pop ebx
.text:00541257 ret
.text:00541259 exit: ; CODE XREF: rotate_all_with_password+A
.text:0054125B retn
.text:0054125D rotate_all_with_password endp
.text:0054125E align 10h
.text:00541260 ; =============== S U B R O U T I N E ===============
.text:00541261 crypt proc near ; CODE XREF: crypt_file+8A
.text:00541261 arg_0 = dword ptr 4
.text:00541261 arg_4 = dword ptr 8
.text:00541261 arg_8 = dword ptr 0Ch
.text:00541261 push ebx
.text:00541261 mov ebx, [esp+4+arg_0]
8.6. “QR9”: RUBIK’S CUBE INSPIRED AMATEUR CRYPTO-ALGORITHM

.text:00541265    push    ebp
.text:00541266    push    esi
.text:00541267    push    edi
.text:00541268    xor    ebp, ebp
.text:0054126A
.text:0054126A    loc_54126A:    ; CODE XREF: crypt+41
.text:0054126A    mov    eax, [esp+10h+arg_8]
.text:0054126E    mov    ecx, 10h
.text:00541273    mov    esi, ebx
.text:00541275    mov    edi, offset cube64
.text:0054127A    push    1
.text:0054127C    push    eax
.text:0054127D    rep movsd
.text:0054127F    call    rotate_all_with_password
.text:00541284    mov    eax, [esp+18h+arg_4]
.text:00541288    mov    edi, ebx
.text:0054128A    add    ebp, 40h
.text:0054128D    add    esp, 8
.text:00541290    mov    ecx, 10h
.text:00541295    mov    esi, offset cube64
.text:0054129A    add    ebx, 40h
.text:0054129D    cmp    ebp, eax
.text:0054129F    rep movsd
.text:005412A1    jl    short loc_54126A
.text:005412A3    pop    edi
.text:005412A4    pop    esi
.text:005412A5    pop    ebp
.text:005412A6    pop    ebx
.text:005412A7    ret
.text:005412A7    | crypt endp |
.text:005412A8    | align 10h |
.text:005412B0    | crypt endp |
.text:005412B0    | =============== S U B R O U T I N E =============== |
.text:005412B0    | decrypt proc near |
.text:005412B0    | CODE XREF: decrypt_file+99 |
.text:005412B0    | decrypt proc near |
.text:005412B0    | arg_0 = dword ptr 4 |
.text:005412B0    | arg_4 = dword ptr 8 |
.text:005412B0    | Src = dword ptr 0Ch |
.text:005412B0    | mov    eax, [esp+Src] |
.text:005412B4    | push    ebx |
.text:005412B5    | push    ebp |
.text:005412B6    | push    esi |
.text:005412B7    | push    edi |
.text:005412B8    | push    eax    ; Src |
.text:005412B9    | call    __strdup |
.text:005412BE    | push    eax    ; Str |
.text:005412BF    | mov    [esp+18h+Src], eax |
.text:005412C3    | call    __strrev |
.text:005412C8    | mov    ebx, [esp+18h+arg_0] |
.text:005412CC    | add    esp, 8 |
.text:005412CF    | xor    ebp, ebp |
.text:005412D1    | loc_5412D1:    ; CODE XREF: crypt+58 |
.text:005412D1    | mov    ecx, 10h |
.text:005412D6    | mov    esi, ebx |
.text:005412D8    | mov    edi, offset cube64 |
.text:005412DD    | push    3 |
.text:005412DF    | rep movsd |
.text:005412E1    | mov    ecx, [esp+14h+Src] |
.text:005412E5    | push    ecx |
.text:005412E6    | call    rotate_all_with_password |
.text:005412EB    | mov    eax, [esp+18h+arg_4] |
.text:005412EF    | mov    edi, ebx |
.text:005412F1    | add    ebp, 40h |
.text:005412F4    | add    esp, 8 |
8.6. “QR9”: RUBIK’S CUBE INSPIRED AMATEUR CRYPTO-ALGORITHM

.text:00512F7    mov    ecx, 10h
.text:00512FC    mov    esi, offset cube64
.text:0051301    add    ebx, 40h
.text:0051304    cmp    ebp, eax
.text:0051306    rep movsd
.text:0051308    jl     short loc_5412D1
.text:005130A    mov    edx, [esp+10h+Src]
.text:005130E    push   edx ; Memory
.text:005130F    call   _free
.text:0051314    add    esp, 4
.text:0051317    pop    edi
.text:0051318    pop    esi
.text:0051319    pop    ebp
.text:005131A    pop    ebx
.text:005131B    retn
.text:005131B decrypt endp
.text:005131C      align 10h
.text:0051320 ; =============== SUBROUTINE ===============================
.text:0051320
.text:0051320 crypt_file proc near ; CODE XREF: _main+42
.text:0051320
.text:0051320 Str = dword ptr 4
.text:0051320 Filename = dword ptr 8
.text:0051320 password = dword ptr 0Ch
.text:0051320
.text:0051320 mov    eax, [esp+Str]
.text:0051324 push   ebp
.text:0051325 push    offset Mode ; "rb"
.text:005132A push    eax ; Filename
.text:005132B call   _fopen ; open file
.text:0051330 mov    ebp, eax
.text:0051332 add    esp, 8
.text:0051335 test    ebp, ebp
.text:0051337 jnz    short loc_541348
.text:0051339 push    offset Format ; "Cannot open input file!
.text:005133E call   _printf
.text:0051343 add    esp, 4
.text:0051346 pop    ebp
.text:0051347 retn
.text:0051347 loc_541348: ; CODE XREF: crypt_file+17
.text:005134A push   ebx
.text:0051349 push    esi
.text:005134A push    edi
.text:005134B push    2 ; Origin
.text:005134D push    0 ; Offset
.text:005134F push    ebp ; File
.text:0051350 call   _fseek
.text:0051355 push    ebp ; File
.text:0051356 call   _ftell ; get file size
.text:005135B push    0 ; Origin
.text:005135D push    0 ; Offset
.text:005135F push    ebp ; File
.text:0051360 mov    [esp+2Ch+Str], eax
.text:0051364 call   _fseek ; rewind to start
.text:0051366 mov    esi, [esp+2Ch+Str]
.text:0051369 mov    esi, 0FFFFFFC0h ; reset all lowest 6 bits
.text:0051370 add    esi, 40h ; align size to 64-byte border
.text:0051373 push    esi ; Size
.text:0051374 call   _malloc
.text:0051379 mov    ecx, esi
.text:005137B mov    ebx, eax ; allocated buffer pointer -> to EBX
.text:005137D mov    edx, ecx
.text:005137F xor    eax, eax
.text:0051381 mov    edi, ebx
.text:0051383 push   ebp ; File

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```
.text:00541384  shr   ecx, 2
.text:00541387  rep stosd
.text:00541389  mov   ecx, edx
.text:0054138B  push  1   ; Count
.text:0054138D  and  ecx, 3
.text:00541390  rep stosb ; memset (buffer, 0, aligned_size)
.text:00541392  mov   eax, [esp+38h+Str]
.text:00541396  push  eax ; ElementSize
.text:00541397  push  ebx ; DstBuf
.text:00541398  call  _fread ; read file
.text:0054139D  push  ebp ; File
.text:0054139E  call  __fclose
.text:005413A3  mov   ecx, [esp+44h+password]
.text:005413A7  push  ecx ; password
.text:005413A8  push  esi ; aligned size
.text:005413A9  push  ebx ; buffer
.text:005413AA  call  crypt ; do crypt
.text:005413AF  mov   edx, [esp+50h+Filename]
.text:005413B3  add  esp, 40h
.text:005413B6  push  offset aWb ; "wb"
.text:005413B8  push  edx ; Filename
.text:005413BC  call  __fopen
.text:005413C1  mov   edi, eax
.text:005413C3  push  edi ; File
.text:005413C4  push  1   ; Count
.text:005413C6  push  3   ; Size
.text:005413C8  push  offset aQr9 ; "QR9"
.text:005413CD  call  __fwrite ; write file signature
.text:005413D2  push  edi ; File
.text:005413D3  push  1   ; Count
.text:005413D5  lea  eax, [esp+30h+Str]
.text:005413D9  push  4   ; Size
.text:005413DB  push  eax ; Str
.text:005413DC  call  __fwrite ; write original file size
.text:005413E1  push  edi ; File
.text:005413E2  push  1   ; Count
.text:005413E4  push  esi ; Size
.text:005413E5  push  ebx ; Str
.text:005413E6  call  __fwrite ; write encrypted file
.text:005413E9  push  edi ; File
.text:005413ED  call  __fclose
.text:005413F1  push  ebx ; Memory
.text:005413F2  call  __free
.text:005413F7  add  esp, 40h
.text:005413FA  pop   edi
.text:005413FB  pop   esi
.text:005413FC  pop   ebx
.text:005413FD  pop   ebp
.text:005413FE  ret
.text:005413FE  crypt_file  endp
.text:005413FF  .align 10h
.text:00541400  .---------- S U B R O U T I N E ----------
.text:00541400  decrypt_file proc near ; CODE XREF: _main+6E
.text:00541400  Filename   = dword ptr 4
.text:00541400  arg_4    = dword ptr 8
.text:00541400  Src      = dword ptr 0Ch
.text:00541400  mov    eax, [esp+Filename]
.text:00541404  push   ebx
.text:00541405  push   ebp
.text:00541406  push   esi
.text:00541407  push   edi
.text:00541408  push   offset aRb ; "rb"
.text:0054140D  push   eax ; Filename
```
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.text:0054140E call _fopen
.text:00541413 mov esi, eax
.text:00541415 add esp, 8
.text:00541418 test esi, esi
.text:0054141A jnz short loc_54142E
.text:0054141C push offset aCannotOpenIn_0 ; "Cannot open input file!\n"
.text:00541421 call _printf
.text:00541426 add esp, 4
.text:00541429 pop edi
.text:0054142A pop esi
.text:0054142B pop ebp
.text:0054142C pop ebx
.text:0054142D retn

.text:0054142E loc_54142E: ; CODE XREF: decrypt_file+1A
.text:0054142E push 2 ; Origin
.text:00541430 push 0 ; Offset
.text:00541432 push esi ; File
.text:00541433 call __fseek
.text:00541438 push esi ; File
.text:00541439 call _ftell
.text:0054143E push 0 ; Origin
.text:00541440 push 0 ; Offset
.text:00541442 push esi ; File
.text:00541443 mov ebp, eax
.text:00541445 call __fseek
.text:0054144A push ebp ; Size
.text:0054144B call _malloc
.text:00541450 push esi ; File
.text:00541451 mov ebx, eax
.text:00541453 push 1 ; Count
.text:00541455 push ebp ; ElementSize
.text:00541456 push ebx ; DstBuf
.text:00541457 call __fread
.text:0054145C push esi ; File
.text:0054145D call __fclose
.text:00541462 add esp, 34h
.text:00541465 mov ecx, 3
.text:00541466 mov edi, offset aQr9_0 ; "QR9"
.text:0054146F mov esi, ebx
.text:00541471 xor edx, edx
.text:00541473 repe cmpsb
.text:00541475 jz short loc_541489
.text:00541477 push offset aFileIsNotCrypt ; "File is not encrypted!\n"
.text:0054147C call _printf
.text:00541481 add esp, 4
.text:00541484 pop edi
.text:00541485 pop esi
.text:00541486 pop ebp
.text:00541487 pop ebx
.text:00541488 retn

.text:00541489 loc_541489: ; CODE XREF: decrypt_file+75
.text:00541489 mov eax, [esp+10h+Src]
.text:0054148D mov edi, [ebx+3]
.text:00541490 add ebp, 0FFFFFFF9h
.text:00541493 lea esi, [ebx+7]
.text:00541496 push eax ; Src
.text:00541497 push ebp ; int
.text:00541498 push esi ; int
.text:00541499 call decrypt
.text:0054149E mov ecx, [esp+1Ch+arg_4]
.text:005414AE push offset aWb_0 ; "wb"
.text:005414B7 push ecx ; Filename
.text:005414B8 call _fopen
.text:005414AD mov ebp, eax
.text:005414AF push ebp ; File
.text:005414B0 push 1 ; Count
.text:005414B2 push edi ; Size
.text:005414B3 push esi ; Str
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All function and label names were given by me during the analysis.

Let’s start from the top. Here is a function that takes two file names and password.

```assembly
; int __cdecl crypt_file(int Str, char *Filename, int password)
crypt_file proc near

Str = dword ptr 4
Filename = dword ptr 8
password = dword ptr 0Ch

Open the file and report if an error occurs:

mov eax, [esp+Str]
push ebp
push offset Mode ; "rb"
push eax ; Filename
call _fopen ; open file
mov ebp, eax
add esp, 8
test ebp, ebp
jnz short loc_541348
push offset Format ; "Cannot open input file!\n"
call _printf
add esp, 4
pop ebp
retn

loc_541348:

Get the file size via fseek()/ftell():

push ebx
push esi
push edi
push 2 ; Origin
push 0 ; Offset
push ebp ; File

; move current file position to the end
call _fseek
push ebp ; File
call _ftell ; get current file position
push 0 ; Origin
push 0 ; Offset
push ebp ; File
mov [esp+2Ch+Str], eax

; move current file position to the start
call _fseek
```

This fragment of code calculates the file size aligned on a 64-byte boundary. This is because this cryptographic algorithm works only with 64-byte blocks. The operation is pretty straightforward: divide the file size by 64, forget about the remainder and add 1, then multiply by 64. The following code removes the remainder as if the value has already been divided by 64 and adds 64. It is almost the same.
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Allocate buffer with aligned size:

```
.text:00541373    push    esi    ; Size
.text:00541374    call    _malloc
```

Call memset(), e.g., clear the allocated buffer:\footnote{\texttt{malloc()} + \texttt{memset()} could be replaced by \texttt{calloc()}}.

```
.text:00541379    mov    ecx, esi
.text:0054137b    mov    ebx, eax    ; allocated buffer pointer -> to EBX
.text:0054137d    mov    edx, ecx
.text:0054137f    xor    eax, eax
.text:00541381    push    ebp    ; File
.text:00541383    shr    ecx, 2
.text:00541387    rep    stosd
.text:00541389    mov    ecx, edx
.text:0054138b    push    1    ; Count
.text:0054138d    push    ecx, edx
.text:00541390    rep    stosb    ; memset (buffer, 0, aligned_size)
```

Read file via the standard C function \texttt{fread()}.

```
.text:00541392    mov    eax, [esp+38h+Str]
.text:00541396    push    eax    ; ElementSize
.text:00541397    push    ebx    ; DstBuf
.text:00541398    call    _fread    ; read file
.text:0054139d    push    ebp    ; File
.text:0054139e    call    _fclose
```

Call \texttt{crypt()}. This function takes a buffer, buffer size (aligned) and a password string.

```
.text:005413a3    mov    ecx, [esp+44h+password]
.text:005413a7    push    ecx    ; password
.text:005413a8    push    esi    ; aligned size
.text:005413aa    push    ebx    ; buffer
.text:005413ab    call    crypt    ; do crypt
```

Create the output file. By the way, the developer forgot to check if it has been created correctly! The file opening result is being checked, though.

```
.text:005413af    mov    edx, [esp+50h+Filename]
.text:005413b3    add    esp, 40h
.text:005413b6    push    offset aWb    ; "wb"
.text:005413bb    push    edx    ; Filename
.text:005413bc    call    _fopen
.text:005413c1    mov    edi, eax
```

The newly created file handle is in the \texttt{EDI} register now. Write signature “QR9”.

```
.text:005413c3    push    edi    ; File
.text:005413c4    push    1    ; Count
.text:005413c6    push    3    ; Size
.text:005413c8    push    offset aQr9    ; "QR9"
.text:005413cd    call    _fwrite    ; write file signature
```

Write the actual file size (not aligned):

```
.text:005413d2    push    edi    ; File
.text:005413d3    push    1    ; Count
.text:005413d5    lea    eax, [esp+30h+Str]
.text:005413d9    push    4    ; Size
```
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Write the encrypted buffer:

```
.text:005413DB    push eax        ; Str
.text:005413DC    call _fwrite       ; write original file size
```

Close the file and free the allocated buffer:

```
.text:005413E1    push edi        ; File
.text:005413E2    push 1          ; Count
.text:005413E4    push esi        ; Size
.text:005413E5    push ebx        ; Str
.text:005413E6    call _fwrite     ; write encrypted file
```

Here is the reconstructed C code:

```c
void crypt_file(char *fin, char* fout, char *pw)
{
    FILE *f;
    int flen, flen_aligned;
    BYTE *buf;

    f=fopen(fin, "rb");
    if (f==NULL)
    {
        printf ("Cannot open input file!\n");
        return;
    }

    fseek (f, 0, SEEK_END);
    flen=ftell (f);
    fseek (f, 0, SEEK_SET);
    flen_aligned=(flen&0xFFFFFFC0)+0x40;
    buf=(BYTE*)malloc (flen_aligned);
    memset (buf, 0, flen_aligned);
    fread (buf, flen, 1, f);
    fclose (f);
    crypt (buf, flen_aligned, pw);

    f=fopen(fout, "wb");
    fwrite ("QR9", 3, 1, f);
    fwrite (&flen, 4, 1, f);
    fwrite (buf, flen_aligned, 1, f);
    fclose (f);
    free (buf);
}
```

The decryption procedure is almost the same:
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```assembly
.text:00541400 ; int cdecl decrypt_file(char *Filename, int, void *Src)
.text:00541400 decrypt_file proc near
.text:00541400 Filename = dword ptr 4
.text:00541400 arg_4 = dword ptr 8
.text:00541400 Src = dword ptr 0Ch
.text:00541400 mov eax, [esp+Filename]
.text:00541404 push ebx
.text:00541405 push ebp
.text:00541406 push esi
.text:00541407 push edi
.text:00541408 push offset aRb ; "rb"
.text:0054140D push eax ; Filename
.text:0054140E call _fopen
.text:00541413 mov esi, eax
.text:00541415 add esp, 8
.text:00541418 test esi, esi
.text:0054141A jnz short loc_54142E
.text:0054141C push offset aCannotOpenIn_0 ; "Cannot open input file!\n"
.text:00541421 call _printf
.text:00541426 add esp, 4
.text:0054142A pop edi
.text:0054142C pop esi
.text:0054142E pop ebp
.text:0054142F push 2 ; Origin
.text:00541430 push 0 ; Offset
.text:00541432 push esi ; File
.text:00541433 call _fseek
.text:00541438 push esi ; File
.text:00541439 call _ftell
.text:0054143E push 0 ; Origin
.text:00541440 push 0 ; Offset
.text:00541442 push esi ; File
.text:00541443 mov ebp, eax
.text:00541445 call _fseek
.text:00541444A push ebp ; Size
.text:0054144B call _malloc
.text:00541450 push esi ; File
.text:00541451 mov ebx, eax
.text:00541453 push 1 ; Count
.text:00541455 push ebx ; ElementSize
.text:00541456 push ebx ; DstBuf
.text:00541457 call _fread
.text:0054145C push esi ; File
.text:0054145D call _fclose

Check signature (first 3 bytes):

.text:00541462 add esp, 34h
.text:00541465 mov ecx, 3
.text:0054146A mov edi, offset aQR9_0 ; "QR9"
.text:0054146F mov esi, ebx
.text:00541471 xor edx, edx
.text:00541473 repe cmpsb
.text:00541475 jz short loc_541489

Report an error if the signature is absent:

.text:00541477 push offset aFileIsNotCrypt ; "File is not encrypted!\n"
.text:0054147C call _printf
.text:00541481 add esp, 4
.text:00541484 pop edi
.text:00541486 pop ebp
```

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Call decrypt().

Here is the reconstructed C code:

```c
void decrypt_file(char *fin, char* fout, char *pw)
{
    FILE *f;
    int real_flen, flen;
    BYTE *buf;

    f=fopen(fin, "rb");
    if (f==NULL)
    {
        printf ("Cannot open input file!\n");
        return;
    }

    fseek (f, 0, SEEK_END);
    flen=ftell (f);
    fseek (f, 0, SEEK_SET);
    buf=(BYTE*)malloc (flen);
    fread (buf, flen, 1, f);

    fclose (f);

    if (memcmp (buf, "QR9", 3)!=0)
    {
        printf ("File is not encrypted!\n");
        return;
    }

    memcpy (&real_flen, buf+3, 4);
}
```

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decrypt (buf+(3+4), flen-(3+4), pw);
f=fopen(fout, "wb");
fwrite (buf+(3+4), real_flen, 1, f);
fclose (f);
free (buf);

OK, now let’s go deeper.

Function crypt():

This fragment of code copies a part of the input buffer to an internal array we later name “cube64”. The size is in the ECX register. MOVSD stands for move 32-bit dword, so, 16 32-bit dwords are exactly 64 bytes.

Call rotate_all_with_password():

Copy encrypted contents back from “cube64” to buffer:

If EBP is not bigger that the size input argument, then continue to the next block.

Reconstructed crypt() function:
void crypt (BYTE *buf, int sz, char *pw)
{
    int i=0;
    do
    {
        memcpy (cube, buf+i, 8*8);
        rotate_all (pw, 1);
        memcpy (buf+i, cube, 8*8);
        i+=64;
    }
    while (i<sz);
};

OK, now let's go deeper in function rotate_all_with_password(). It takes two arguments: password string and a number.

In crypt(), the number 1 is used, and in the decrypt() function (where rotate_all_with_password() function is called too), the number is 3.

Check the current character in the password. If it is zero, exit:

Call tolower(), a standard C function.

Hmm, if the password has non-Latin character, it is skipped! Indeed, when we run the encryption utility and try non-Latin characters in the password, they seem to be ignored.

Subtract the value of “a” (97) from the character.

After subtracting, we'll get 0 for “a” here, 1 for “b”, etc. And 25 for “z”.

It seems, “y” and “z” are exceptional characters too. After that fragment of code, “y” becomes 0 and “z” — 1. This implies that the 26 Latin alphabet symbols become values in the range of 0..23, (24 in total).
This is actually division via multiplication. You can read more about it in the “Division using multiplication” section (3.9 on page 497).

The code actually divides the password character’s value by 3.

EDX is the remainder of the division.

If the remainder is 2, call rotate3(). EDI is the second argument of the rotate_all_with_password() function. As we already noted, 1 is for the encryption operations and 3 is for the decryption. So, here is a loop. When encrypting, rotate1/2/3 are to be called the same number of times as given in the first argument.
Fetch the next character from the password string.

Increment the character pointer in the password string:

Here is the reconstructed C code:

```c
void rotate_all (char *pwd, int v)
{
    char *p=pwd;
    while (*p)
    {
        char c=*p;
        int q;
        c=tolower (c);
        if (c>='a' && c<='z')
        {
            q=c-'a';
            if (q>24)
                q-=24;
            int quotient=q/3;
            int remainder=q % 3;

            switch (remainder)
            {
                case 0: for (int i=0; i<v; i++) rotate1 (quotient); break;
                case 1: for (int i=0; i<v; i++) rotate2 (quotient); break;
                case 2: for (int i=0; i<v; i++) rotate3 (quotient); break;
            };
            p++;
        }
    }
}
```

Now let's go deeper and investigate the rotate1/2/3 functions. Each function calls another two functions. We eventually will name them set_bit() and get_bit().

Let's start with get_bit():

```c
.get_bit proc near
.text:00541050 get_bit proc near
.text:00541050 arg_0 = dword ptr 4
.text:00541050 arg_4 = dword ptr 8
.text:00541050 arg_8 = byte ptr 0Ch
.text:00541050
.text:00541050 mov eax, [esp+arg_4]
.text:00541054 mov ecx, [esp+arg_0]
.text:00541058 mov al, cube64[eax+ecx*8]
.text:0054105F mov cl, [esp+arg_8]
.text:00541063 shr al, cl
.text:00541065 and al, 1
.text:00541067 retn
```

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...in other words: calculate an index in the cube64 array: \( \text{arg}_4 + \text{arg}_0 \times 8 \). Then shift a byte from the array by \( \text{arg}_8 \) bits right. Isolate the lowest bit and return it.

Let's see another function, \text{set_bit}():

```
.text:00541000 set_bit proc near
.text:00541000
.text:00541000 arg_0 = dword ptr 4
.text:00541000 arg_4 = dword ptr 8
.text:00541000 arg_8 = dword ptr 0Ch
.text:00541000 arg_C = byte ptr 10h
.text:00541000
.text:00541000 mov al, [esp+arg_C]
.text:00541004 mov ecx, [esp+arg_8]
.text:00541008 push esi
.text:00541009 mov esi, [esp+4+arg_0]
.text:0054100D test al, al
.text:0054100F mov eax, [esp+4+arg_4]
.text:00541013 mov dl, 1
.text:00541015 jz short loc_54102B
.text:00541017 shl dl, cl
.text:00541019 mov cl, cube64[eax+esi*8]
.text:00541020 or cl, dl
.text:00541022 mov cube64[eax+esi*8], cl
.text:00541029 pop esi
.text:0054102A retn
.text:0054102B loc_54102B:
.text:0054102B shl dl, cl
```

The value in the DL is 1 here. It gets shifted left by \( \text{arg}_8 \). For example, if \( \text{arg}_8 \) is 4, the value in the DL register is to be 0x10 or 1000b in binary form.

```
.text:00541017 shl dl, cl
.text:00541019 mov cl, cube64[eax+esi*8]
```

Get a bit from array and explicitly set it.

```
.text:00541020 or cl, dl
```

Store it back:

```
.text:00541022 mov cube64[eax+esi*8], cl
.text:00541029 pop esi
.text:0054102A retn
```

If \( \text{arg}_C \) is not zero...

```
.text:0054102D mov cl, cube64[eax+esi*8]
```

...invert DL. For example, if DL's state after the shift is 0x10 or 0b1000, there is 0xEF to be after the NOT instruction (or 0b11101111b).

```
.text:00541034 not dl
```

This instruction clears the bit, in other words, it saves all bits in CL which are also set in DL except those in DL which are cleared. This implies that if DL is 11101111b in binary form, all bits are to be saved except the 5th (counting from lowest bit).

```
.text:00541036 and cl, dl
```

Store it back:

```
.text:00541038 mov cube64[eax+esi*8], cl
.text:0054103F pop esi
.text:00541040 retn
```

It is almost the same as \text{get_bit}(), except, if \( \text{arg}_C \) is zero, the function clears the specific bit in the array, or sets it otherwise.

We also know that the array's size is 64. The first two arguments both in the \text{set_bit}() and \text{get_bit}() functions could be seen as 2D coordinates. Then the array is to be an 8*8 matrix.

Here is a C representation of what we know up to now:
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```c
#define IS_SET(flag, bit)   ((flag) & (bit))
#define SET_BIT(var, bit)   ((var) |= (bit))
#define REMOVE_BIT(var, bit)  ((var) &= ~(bit))

static BYTE cube[8][8];

void set_bit (int x, int y, int shift, int bit)
{
    if (bit)
        SET_BIT (cube[x][y], 1<<shift);
    else
        REMOVE_BIT (cube[x][y], 1<<shift);
}

bool get_bit (int x, int y, int shift)
{
    if ((cube[x][y]>>shift)&1==1)
        return 1;
    return 0;
}

Now let’s get back to the rotate1/2/3 functions.

Internal array allocation in the local stack, with size of 64 bytes:

```assembly
.text:00541070 rotate1 proc near
.text:00541070
Internal array allocation in the local stack, with size of 64 bytes:

.text:00541070 internal_array_64= byte ptr -40h
.text:00541070 arg_0 = dword ptr 4
.text:00541070 .text:00541070 ...
.text:00541077 move edx, 8 ; increment internal array pointer by 8 at each loop 1 iteration
.text:0054108f add ebx, 8
.text:00541097 jmp short first_loop1_begin

EBX is a pointer to the internal array:

.text:0054107D lea ebx, [esp+50h+internal_array_64]
.text:00541081

Here we have two nested loops:

.text:00541081 first_loop1_begin:
.text:00541081 ...
.text:0054108f add esp, 0Ch
.text:00541098 mov [ebx+esi], al ; store to internal array
.text:0054109f inc esi ; increment loop 1 counter
.text:005410a0 cmp esi, 8
.text:005410a3 jl short first_loop2_begin
.text:005410a7 inc edi ; increment loop 2 counter

...we see that both loops’ counters are in the range of 0..7. Also they are used as the first and second argument for the get_bit() function. The third argument to get_bit() is the only argument of rotate1(). The return value from get_bit() is placed in the internal array.
8.6. “QR9”: RUBIK’S CUBE INSPIRED AMATEUR CRYPTO-ALGORITHM

Prepare a pointer to the internal array again:

```
.text:005410A0  lea  ebx, [esp+50h+internal_array_64]
.text:005410A4  mov  edi, 7    ; EDI is loop 1 counter, initial state is 7
.text:005410A9  .text:005410A9  second_loop1_begin:
.text:005410A9  xor  esi, esi    ; ESI is loop 2 counter
.text:005410AB  .text:005410AB  second_loop2_begin:
.text:005410AB  mov  al, [ebx+esi] ; value from internal array
.text:005410AE  push eax
.text:005410AF  push ebp    ; arg_0
.text:005410B0  push edi    ; loop 1 counter
.text:005410B1  push esi    ; loop 2 counter
.text:005410B2  call  set_bit
.text:005410B7  add esp, 10h
.text:005410BA  inc esi     ; increment loop 2 counter
.text:005410BB  cmp  esi, 8
.text:005410BE  jl  short second_loop2_begin
.text:005410C0  dec  edi     ; decrement loop 1 counter
.text:005410C1  add  ebx, 8    ; increment pointer in internal array
.text:005410C4  cmp  edi, 0FFFFFFFh
.text:005410C7  jg  short second_loop1_begin
.text:005410C9  pop  edi
.text:005410CA  pop  esi
.text:005410CB  pop  ebp
.text:005410CC  pop  ebx
.text:005410CD  add  esp, 40h
.text:005410D0  retn
.text:005410D0  rotate1 endp
```

...this code is placing the contents of the internal array to the cube global array via the set_bit() function, but in a different order! Now the counter of the first loop is in the range of 7 to 0, decrementing at each iteration!

The C code representation looks like:

```c
void rotate1 (int v)
{
    bool tmp[8][8]; // internal array
    int i, j;

    for (i=0; i<8; i++)
        for (j=0; j<8; j++)
            tmp[i][j]=get_bit (i, j, v);

    for (i=0; i<8; i++)
        for (j=0; j<8; j++)
            set_bit (j, 7-i, v, tmp[x][y]);
}
```

Not very understandable, but if we take a look at rotate2() function:
8.6. “QR9”: RUBIK’S CUBE INSPIRED AMATEUR CRYPTO-ALGORITHM

It is almost the same, except the order of the arguments of the get_bit() and set_bit() is different. Let's rewrite it in C-like code:

```c
void rotate2 (int v) {
    bool tmp[8][8]; // internal array
    int i, j;

    for (i=0; i<8; i++)
        for (j=0; j<8; j++)
            tmp[i][j]=get_bit (v, i, j);

    for (i=0; i<8; i++)
        for (j=0; j<8; j++)
            set_bit (v, j, 7-i, tmp[i][j]);
}
```

Let's also rewrite the rotate3() function:

```c
void rotate3 (int v) {
    bool tmp[8][8];
    int i, j;

    for (i=0; i<8; i++)
        for (j=0; j<8; j++)
            tmp[i][j]=get_bit (i, v, j);
```
Well, now things are simpler. If we consider cube64 as a 3D cube of size 8*8*8, where each element is a bit, `get_bit()` and `set_bit()` take just the coordinates of a bit as input.

The rotate1/2/3 functions are in fact rotating all bits in a specific plane. These three functions are one for each cube side and the v argument sets the plane in the range of 0..7.

Maybe the algorithm’s author was thinking of a 8*8*8 Rubik’s cube?! Yes, indeed.

Let’s look closer into the `decrypt()` function, here is its rewritten version:

```c
void decrypt (BYTE *buf, int sz, char *pw)
{
    char *p=strdup (pw);
    strrev (p);
    int i=0;
    do
    {
        memcpy (cube, buf+i, 8*8);
        rotate_all (p, 3);
        memcpy (buf+i, cube, 8*8);
        i+=64;
    } while (i<sz);
    free (p);
}
```

It is almost the same as for `crypt()`, but the password string is reversed by the `strrev()` standard C function and `rotate_all()` is called with argument 3.

This implies that in case of decryption, each corresponding rotate1/2/3 call is to be performed thrice.

This is almost as in Rubik’c cube! If you want to get back, do the same in reverse order and direction! If you want to undo the effect of rotating one place in clockwise direction, rotate it once in counter-clockwise direction, or thrice in clockwise direction.

`rotate1()` is apparently for rotating the “front” plane. `rotate2()` is apparently for rotating the “top” plane. `rotate3()` is apparently for rotating the “left” plane.

Let’s get back to the core of the `rotate_all()` function:

```c
q=c-'a';
if (q>24) 
    q-=24;
int quotient=q/3; // in range 0..7
int remainder=q % 3;
switch (remainder)
{
    case 0: for (int i=0; i<v; i++) rotate1 (quotient); break; // front
    case 1: for (int i=0; i<v; i++) rotate2 (quotient); break; // top
    case 2: for (int i=0; i<v; i++) rotate3 (quotient); break; // left
}
```

Now it is much simpler to understand: each password character defines a side (one of three) and a plane (one of 8). 3*8 = 24, that is why two the last two characters of the Latin alphabet are remapped to fit an alphabet of exactly 24 elements.

The algorithm is clearly weak: in case of short passwords you can see that in the encrypted file there are the original bytes of the original file in a binary file editor.

18 wikipedia  
19 MSDN
#include <windows.h>
#include <stdio.h>
#include <assert.h>

#define IS_SET(flag, bit)  ((flag) & (bit))
#define SET_BIT(var, bit)  ((var) |= (bit))
#define REMOVE_BIT(var, bit)  ((var) &= ~(bit))

static BYTE cube[8][8];

void set_bit (int x, int y, int z, bool bit)
{
    if (bit)
        SET_BIT (cube[x][y], 1<<z);
    else
        REMOVE_BIT (cube[x][y], 1<<z);
}

bool get_bit (int x, int y, int z)
{
    if ((cube[x][y]>>z)&1==1)
        return true;
    return false;
}

void rotate_f (int row)
{
    bool tmp[8][8];
    int x, y;

    for (x=0; x<8; x++)
        for (y=0; y<8; y++)
            tmp[x][y]=get_bit (x, y, row);

    for (x=0; x<8; x++)
        for (y=0; y<8; y++)
            set_bit (y, 7-x, row, tmp[x][y]);
}

void rotate_t (int row)
{
    bool tmp[8][8];
    int y, z;

    for (y=0; y<8; y++)
        for (z=0; z<8; z++)
            tmp[y][z]=get_bit (row, y, z);

    for (y=0; y<8; y++)
        for (z=0; z<8; z++)
            set_bit (row, z, 7-y, tmp[y][z]);
}

void rotate_l (int row)
{
    bool tmp[8][8];
    int x, z;

    for (x=0; x<8; x++)
        for (z=0; z<8; z++)
            tmp[x][z]=get_bit (x, row, z);

    for (x=0; x<8; x++)
        for (z=0; z<8; z++)
            set_bit (7-z, row, x, tmp[x][z]);
}
void rotate_all (char *pwd, int v)
{
    char *p=pwd;
    while (*p)
    {
        char c=*p;
        int q;
        c=tolower (c);
        if (c>='a' &c<='z')
        {
            q=c-'a';
            if (q>24)
                q-=24;
            int quotient=q/3;
            int remainder=q % 3;
            switch (remainder)
            {
            case 0: for (int i=0; i<v; i++) rotate_f (quotient); break;
            case 1: for (int i=0; i<v; i++) rotate_t (quotient); break;
            case 2: for (int i=0; i<v; i++) rotate_l (quotient); break;
            };
        }
        p++;
    }
};

void crypt (BYTE *buf, int sz, char *pw)
{
    int i=0;
    do
    {
        memcpy (cube, buf+i, 8*8);
        rotate_all (pw, 1);
        memcpy (buf+i, cube, 8*8);
        i+=64;
    } while (i<sz);
};

void decrypt (BYTE *buf, int sz, char *pw)
{
    char *p=strdup (pw);
    strrev (p);
    int i=0;
    do
    {
        memcpy (cube, buf+i, 8*8);
        rotate_all (p, 3);
        memcpy (buf+i, cube, 8*8);
        i+=64;
    } while (i<sz);
    free (p);
};

void crypt_file(char *fin, char* fout, char *pw)
{
    FILE *f;
    int flen, flen_aligned;
    BYTE *buf;
8.6. “QR9”: RUBIK’S CUBE INSPIRED AMATEUR CRYPTO-ALGORITHM

```c
f=fopen(fin, "rb");
if (f==NULL)
{
    printf ("Cannot open input file!\n");
    return;
};

fseek (f, 0, SEEK_END);
flen=ftell (f);
fseek (f, 0, SEEK_SET);
flen_aligned=(flen&0xFFFFFFC0)+0x40;
buf=(BYTE*)malloc (flen_aligned);
memset (buf, 0, flen_aligned);

fread (buf, flen, 1, f);
fclose (f);
crypt (buf, flen_aligned, pw);

f=fopen(fout, "wb");
fwrite ("QR9", 3, 1, f);
fwrite (&flen, 4, 1, f);
fwrite (buf, flen_aligned, 1, f);
fclose (f);
free (buf);
};

void decrypt_file(char *fin, char* fout, char *pw)
{
    FILE *f;
    int real_flen, flen;
    BYTE *buf;

    f=fopen(fin, "rb");
    if (f==NULL)
    {
        printf ("Cannot open input file!\n");
        return;
    };

    fseek (f, 0, SEEK_END);
    flen=ftell (f);
    fseek (f, 0, SEEK_SET);

    buf=(BYTE*)malloc (flen);
    fread (buf, flen, 1, f);
    fclose (f);

    if (memcmp (buf, "QR9", 3)!=0)
    {
        printf ("File is not encrypted!\n");
        return;
    };

    memcpy (&real_flen, buf+3, 4);
    decrypt (buf+(3+4), flen-(3+4), pw);
    f=fopen(fout, "wb");
```
8.7. Encrypted Database Case #1

(This part has been first appeared in my blog at 26-Aug-2015. Some discussion: https://news.ycombinator.com/item?id=10128684.)

8.7.1 Base64 and entropy

I've got the XML file containing some encrypted data. Perhaps, it's related to some orders and/or customers information.

```xml
<?xml version = "1.0" encoding = "UTF-8"?>
<Orders>
  <Order>
    <OrderID>1</OrderID>
    <Data>yjmxhXUbhB/5MV45chPsXZWAIwIh1S0aD9lFn3xuJMSxJ3/E+UE3hsnH</Data>
  </Order>
  <Order>
    <OrderID>2</OrderID>
    <Data>0KGe/wnypFBjsy+U0C2P9fC5nDZP3XDZLMPCRaiBw9oJik6Tu5U</Data>
  </Order>
  <Order>
    <OrderID>3</OrderID>
    <Data>mqkXfdzvQKvEArduzh+zD9oETVGBFvcTBLs2ph1b5bYddExzp</Data>
  </Order>
  <Order>
    <OrderID>4</OrderID>
    <Data>FCx6JhIDqnEsyT3HaeplE1BJ3cJd7wCk+APCRUeuNtZdpCvQ2M/7kLXtfUHuA==</Data>
  </Order>
  ...
</Orders>
```

The file is available here.

This is clearly base64-encoded data, because all strings consisting of Latin characters, digits, plus (+) and slash (/) symbols. There can be 1 or 2 padding symbols (=), but they are never occurred in the middle of string. Keeping in mind these base64 properties, it's very easy to recognize them.
8.7. ENCRYPTED DATABASE CASE #1

Let’s decode them and calculate entropies (9.2 on page 948) of these blocks in Wolfram Mathematica:

\[
\text{In[1]} := \text{ListOfBase64Strings = Map[First[#[[3]]] & , Cases[Import["encrypted.xml"], XMLElement["Data", _, _, Infinity]]];}
\]
\[
\text{In[2]} := \text{BinaryStrings = Map[ImportString[#, \{"Base64", "String"\}] & , ListOfBase64Strings];}
\]
\[
\text{In[3]} := \text{Entropies = Map[N[Entropy[2, \#]] & , BinaryStrings];}
\]
\[
\text{In[4]} := \text{Variance[Entropies]}
\]
\[
\text{Out[4]} = 0.0238614
\]

Variance is low. This means the entropy values are not very different from each other. This is visible on graph:

\[
\text{In[5]} := \text{ListPlot[Entropies]}
\]

Most values are between 5.0 and 5.4. This is a sign that the data is compressed and/or encrypted.

To understand variance, let’s calculate entropies of all lines in Conan Doyle’s *The Hound of the Baskervilles* book:

\[
\text{In[6]} := \text{BaskervillesLines = Import["http://www.gutenberg.org/cache/epub/2852/pg2852.txt", \"List\"]};
\]
\[
\text{In[7]} := \text{EntropiesT = Map[N[Entropy[2, \#]] & , BaskervillesLines];}
\]
\[
\text{In[8]} := \text{Variance[EntropiesT]}
\]
\[
\text{Out[8]} = 2.73883
\]
\[
\text{In[9]} := \text{ListPlot[EntropiesT]}
\]
Most values are gathered around value of 4, but there are also values which are smaller, and they are influenced final variance value.

Perhaps, shortest strings has smaller entropy, let's take short string from the Conan Doyle's book:

```plaintext
In[] := Entropy[2, "Yes, sir."] // N
Out[] = 2.9477
```

Let's try even shorter:

```plaintext
In[] := Entropy[2, "Yes"] // N
Out[] = 1.58496

In[] := Entropy[2, "No"] // N
Out[] = 1.
```

### 8.7.2 Is data compressed?

OK, so our data is compressed and/or encrypted. Is it compressed? Almost all data compressors put some header at the start, signature, or something like that. As we can see, there are no consistent data at the start of each block. It's still possible that this is a handmade data compressor, but they are very rare. On the other hand, handmade cryptoalgorithms are much more popular, because it's very easy to make it work. Even primitive keyless cryptosystems like `memfrob`\(^{20}\) and ROT13 works fine without errors. It's a serious challenge to write data compressor from scratch using only fantasy and imagination in a way so it will have no evident bugs. Some programmers implements data compression functions by reading textbooks, but this is also rare. The most popular two ways are: 1) just take open-source library like zlib; 2) copy&paste something from somewhere. Open-source data compressions algorithms usually puts some kind of header, and so do algorithms from sites like [http://www.codeproject.com/](http://www.codeproject.com/).

\(^{20}\)http://linux.die.net/man/3/memfrob
8.7.3 Is data encrypted?

Major data encryption algorithms process data in blocks. DES—8 bytes, AES—16 bytes. If the input buffer is not divided evenly by block size, it’s padded by zeroes (or something else), so encrypted data will be aligned by cryptoalgorithm’s block size. This is not our case.

Using Wolfram Mathematica, I analyzed block’s lengths:

```
In[1]:= Counts[Map[StringLength[#] &, BinaryStrings]]
Out[1]= <|42 -> 1858, 38 -> 1235, 36 -> 699, 46 -> 1151, 40 -> 1784,
    44 -> 1558, 50 -> 366, 34 -> 291, 32 -> 74, 56 -> 15, 48 -> 716,
    30 -> 13, 52 -> 156, 54 -> 71, 60 -> 3, 58 -> 6, 28 -> 4|>
```

1858 blocks has size of 42 bytes, 1235 blocks has size of 38 bytes, etc.

I made a graph:

```
ListPlot[Counts[Map[StringLength[#] &, BinaryStrings]]]
```

So, most blocks has size between ~36 and ~48. There is also another thing to notice: all block sizes are even. No single block with odd size.

There are, however, stream ciphers which can operate on byte level or even on bit level.

8.7.4 CryptoPP

The program which can browse this encrypted database is written C# and the .NET code is heavily obfuscated. Nevertheless, there is DLL with x86 code, which, after brief examination, has parts of the CryptoPP popular open-source library! (I just spotted “CryptoPP” strings inside.) Now it’s very easy to find all functions inside of DLL because CryptoPP library is open-source.

CryptoPP library has a lot of crypto-functions, including AES (AKA Rijndael). Newer x86 CPUs has AES helper instructions like AESENCE, AESDEC and AESKEYGENASSIST. They are not performing encryption/decryption completely, but they do significant amount of job. And newer CryptoPP versions use them. For example, here: 1, 2. To my surprise, during decryption, AESENCE gets executed, while AESDEC is not (I just

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checked with my tracer utility, but any debugger can be used). I checked, if my CPU really supports AES instructions. Some Intel i3 CPUs are not. And if not, CryptoPP library falling back to AES functions implemented in old way. But my CPU supports them. Why AESDEC is still not executed? Why the program use AES encryption in order to decrypt database?

OK, it’s not a problem to find a function which encrypts block. It is called CryptoPP::Rijndael::Enc::ProcessAndXorBlock().

https://github.com/mmoss/cryptopp/blob/2772f7b57182b31a41659b48d5f35a7b6c5d34d/src/rijndael.cpp#L349, and it can call from another function: Rijndael::Enc::AdvancedProcessBlocks()

https://github.com/mmoss/cryptopp/blob/2772f7b57182b31a41659b48d5f35a7b6c5d34d/src/rijndael.cpp#L1179, which, in turn, can be call the two functions (AESNI_Enc_Block and AESNI_Enc_4_Blocks) which has AESENC instructions.

So, judging by CryptoPP internals, CryptoPP::Rijndael::Enc::ProcessAndXorBlock() encrypts one 16-byte block. Let’s set breakpoint on it and see, what happens during decryption. I use my simple tracer tool again. The software must decrypt first data block now. Oh, by the way, here is the first data block converted from base64 encoding to hexadecimal data, let’s have it at hand:

00000000: CA 39 B1 85 75 1B 84 1F F9 31 5E 39 72 13 EC .9..u....1^9r..
00000010: 95 80 27 02 21 D5 2D 1A 0F D9 45 9F 75 EE 24 .'.!.-...E.u.$.
00000020: B1 27 7F 84 FE 41 37 86 C9 C0 ...A7...

These are also arguments of the function from CryptoPP source files:

size_t Rijndael::Enc::AdvancedProcessBlocks(const byte *inBlocks, const byte *xorBlocks, byte *outBlocks, size_t length, word32 flags);

So it has 5 arguments. Possible flags are:

enum {BT_InBlockIsCounter=1, BT_DontIncrementInOutPointers=2, BT_XorInput=4, BT_ReverseDirection=8, BT_AllowParallel=16} FlagsForAdvancedProcessBlocks;

OK, run tracer on ProcessAndXorBlock() function:

... tracer.exe -l:filename.exe bpf=filename.exe!0x4339a0,args:5,dump_args:0x10

Warning: no tracer.cfg file.
PID=1984|New process software.exe
no module registered with image base 0x77320000
no module registered with image base 0x76e20000
no module registered with image base 0x77320000
no module registered with image base 0x77220000
Warning: unknown (to us) INT3 breakpoint at ntdll.dll!LdrVerifyImageMatchesChecksum+0x96c (0x776c103b)
(0) software.exe!0x4339a0(0x38b920, 0x0, 0x38b978, 0x10, 0x0) (called from software.exe!0x13e4c0d)
Argument 1/5
0038B920: 01 00 00 00 FF FF FF F7 FF 79 C1 69 08 67 C1 04 7D ".........y.i.g..}"
Argument 3/5
0038B978: CD CD CD CD CD CD CD CD CD CD CD CD CD CD CD CD CD "............."
(0) software.exe!0x4339a0() -> 0x0
Argument 3/5 difference
00000000: C7 39 4E 7B 39 1B D6 31 10 39 39 13 A5 5D ".9N{3....1.99.}"
(0) software.exe!0x4339a0(0x38a828, 0x38a838, 0x38bb40, 0x0, 0x8) (called from software.exe!0x13e4c0d)
Argument 1/5
0038B828: 95 80 27 02 21 D5 2D 1A 0F D9 45 9F 75 EE 24 C4 ".'.!.-...E.u.$.
Argument 2/5
0038B838: B1 27 7F 84 FE 41 37 86 C9 C0 00 CD CD CD CD CD ....A7........
Argument 3/5
0038BB40: CD CD CD CD CD CD CD CD CD CD CD CD CD CD CD CD CD "............."
(0) software.exe!0x4339a0() -> 0x0
(0) software.exe!0x4339a0(0x38b920, 0x38a828, 0x38bb30, 0x10, 0x0) (called from software.exe!0x13e4c0d)
Argument 1/5
0038B920: CA 39 B1 85 75 1B 84 1F-F9 31 5E 39 72 13 EC 5D ".9..u....1^9r..
Argument 2/5
0038B828: 95 80 27 02 21 D5 2D 1A-0F D9 45 9F 75 EE 24 C4 ".....E.u.$.

22https://github.com/mmoss/cryptopp/blob/2772f7b57182b31a41659b48d5f35a7b6c5d34d/src/rijndael.cpp#L355
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Here we can see inputs to the `ProcessAndXorBlock()` function, and outputs from it.

This is output from the function during first call:

```
00000000: C7 39 4E 7B 33 1B D6 31 10 39 39 13 A5 5D ".9N{3....1.99..}"
```

Then the `ProcessAndXorBlock()` is called with zero-length block, but with 8 flag (`BT_ReverseDirection`). Second call:

```
00000000: 45 00 20 00 4A 00 4F 00 48 00 4E 00 53 00 00 00 "E. .J.O.H.N.S...
```

Wow, there is some string familiar to us!

Third call:

```
00000000: B1 27 7F E4 9F 01 E3 81-CF C6 12 FB B9 7C F1 BC ".'. ............|.."
```

The first output is very similar to the first 16 bytes of the encrypted buffer.

Output of the first call of `ProcessAndXorBlock()`:

```
00000000: C7 39 4E 7B 33 1B D6 31 10 39 39 13 A5 5D ".9N{3....1.99..}"
```

First 16 bytes of encrypted buffer:

```
00000000: CA 39 B1 85 75 1B 84 1F F9 31 5E 39 72 13 EC 5D .9...u....1^9r..]
```

There are too much equal bytes! How come AES encryption result can be very similar to the encrypted buffer while this is not encryption but rather decryption?!

### 8.7.5 Cipher Feedback mode

The answer is **CFB**\(^2\): in this mode, AES algorithm used not as encryption algorithm, but as a device which generates cryptographically secure random data. The actual encryption is happening using simple XOR operation.

Here is encryption algorithm (images are taken from Wikipedia):

\(^2\)Cipher Feedback
And decryption:

Now let's see: AES encryption operation generates 16 bytes (or 128 bits) of random data to be used while XOR-ing, who forces us to use all 16 bytes? If at the last iteration we've got 1 byte of data, let's xor 1 byte of data with 1 byte of generated random data? This leads to important property of CFB mode: data can be not padded, data of arbitrary size can be encrypted and decrypted.

Oh, that's why all encrypted blocks are not padded. And that's why AESDEC instruction is never called.

Let's try to decrypt first block manually, using Python. CFB mode also use IV, as a seed for CSPRNG. In our case, IV is the block which is encrypted at first iteration:

```plaintext
0038B920: 01 00 00 FF FF FF FF 79 C1 69 0B 67 C1 04 7D "........y.i.g..}"
```

Oh, and we also have to recover encryption key. There is AESKEYGENASSIST is DLL, and it is called, and it is used in the `Rijndael::Base::UncheckedSetKey()` function:

https://github.com/mmoss/cryptopp/blob/2772f7b57182b31a41659b48d5f35a7b6cedd34d/src/rijndael.cpp#L198 It's easy to find it in IDA and set breakpoint. Let's see:

```plaintext
... tracer.exe -l:filename.exe bpf=filename.exe!0x435c30,args:3,dump_args:0x10
```

Warning: no tracer.cfg file.
PID=2068|New process software.exe
no module registered with image base 0x77320000

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no module registered with image base 0x76e20000
no module registered with image base 0x77320000
no module registered with image base 0x77220000
Warning: unknown (to us) INT3 breakpoint at ntdll.dll!LdrVerifyImageMatchesChecksum+0x96c (0x776c103b)
(0) software.exe!0x435c30(0x15e8000, 0x10, 0x14f808) (called from software.exe!.text+0x22fa1 (0x776c103b))
Argument 1/3
015E8000: CD C5 7E AD 28 5F 6D E1-CE 29 B1 21 88 8E "...(.m....)..."
Argument 3/3
0014F808: 38 82 58 01 C8 B9 46 00-01 D1 3C 01 00 F8 14 00 "8.X...F<......"
Argument 3/3 +0x0: software.exe!.rdata+0x5238
Argument 3/3 +0x8: software.exe!.text+0x1c101
(0) software.exe!0x435c30() -> 0x13c28f1
PID=2068|Process software.exe exited. ExitCode=0 (0x0)

So this is the key: CDC57EAD285F6DE1-CE8FCC29B121888E.
During manual decryption we've got this:

<table>
<thead>
<tr>
<th>Argument 1/3</th>
<th>Argument 3/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>015E8000: CD C5 7E AD 28 5F 6D E1-CE 29 B1 21 88 8E</td>
<td>0014F808: 38 82 58 01 C8 B9 46 00-01 D1 3C 01 00 F8 14 00</td>
</tr>
</tbody>
</table>

Now this is something readable! And now we can see why there were so many equal bytes at the first decryption iteration: because plaintext has so many zero bytes!
Let's decrypt the second block:

<table>
<thead>
<tr>
<th>Argument 1/3</th>
<th>Argument 3/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>00000000: 0D 00 FF FE 46 00 52 00 41 00 4E 00 4B 00 49 00</td>
<td>00000000: 17 98 D0 84 3A E9 72 4F DB 82 3F AD E9 3E 2A A8</td>
</tr>
</tbody>
</table>

Third, fourth and fifth:

<table>
<thead>
<tr>
<th>Argument 1/3</th>
<th>Argument 3/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>00000000: 5D 90 59 06 EF F4 96 B4 7C 33 A7 4A BE FF 66 AB</td>
<td>00000000: 41 00 20 00 4A 00 4F 00 4E 00 CD CC CC CC CC</td>
</tr>
</tbody>
</table>

All blocks decrypted seems correctly except of first 16 bytes part.

8.7.6 Initializing Vector

What can affect first 16 bytes?
Let's back to CFB decryption algorithm again: 8.7.5 on the preceding page.
We can see that IV can affect to first block decryption operation, but not the second, because during the second iteration, ciphertext from the first iteration is used, and in case of decryption, it's the same, no matter what IV has!
So probably, IV is different each time. Using my tracer, I’ll take a look at the first input during decryption of the second block of XML file:

| 0038B920: 02 00 00 00 FE FF FF FF-79 C1 69 0B 67 C1 04 7D | 0038B920: 03 00 00 00 FD FF FF FF-79 C1 69 0B 67 C1 04 7D |

...third:
It seems, first and fifth byte are changed each time. I finally concluded that the first 32-bit integer is just OrderID from the XML file, and the second 32-bit integer is also OrderID, but negated. All other 8 bytes are same for each operation. Now I have decrypted the whole database: [https://raw.githubusercontent.com/DennisYurichev/RE-for-beginners/master/examples/encrypted_DB1/decrypted.full.txt](https://raw.githubusercontent.com/DennisYurichev/RE-for-beginners/master/examples/encrypted_DB1/decrypted.full.txt).

The Python script used for this is: [https://github.com/DennisYurichev/RE-for-beginners/blob/master/examples/encrypted_DB1/decrypt_blocks.py](https://github.com/DennisYurichev/RE-for-beginners/blob/master/examples/encrypted_DB1/decrypt_blocks.py).

Perhaps, the author wanted each block encrypted differently, so he/she used OrderID as part of key. It would be also possible to make different AES key instead of IV.

So now we know that IV only affects first block during decryption in CFB mode, this is feature of it. All other blocks can be decrypted without knowledge IV, but using the key.


It is very likely, program's author(s) just copied/pasted the example from CryptoPP wiki page. Many programmers do so.

The only difference that IV is chosen randomly in CryptoPP wiki example, while this indeterminism wasn't allowable to programmers of the software we are dissecting now, so they choose to initialize IV using Order ID.

Now we can proceed to analyzing matter of each byte in the decrypted block.

### 8.7.7 Structure of the buffer

Let's take first four decrypted blocks:

<table>
<thead>
<tr>
<th>Hex</th>
<th>Ascii</th>
</tr>
</thead>
<tbody>
<tr>
<td>00000000: 0D 00 FF FE 46 00 52 00 41 00 4E 00 4B 00 49 00</td>
<td>....F.R.A.N.K.I.</td>
</tr>
<tr>
<td>00000010: 45 00 20 00 4A 00 4F 00 48 00 53 00 53 00 66 66 9E</td>
<td>E. .J.O.H.N.S.ff</td>
</tr>
<tr>
<td>00000020: 66 66 66 41 00 4E 00 4B 00 49 00 0D 07 06 01</td>
<td>fff.a@....</td>
</tr>
<tr>
<td>00000030: 08 00 FF FE 4C 00 4F 00 52 00 49 00 20 00 42 00</td>
<td>....L.O.R.I. .B.</td>
</tr>
<tr>
<td>00000040: 41 00 52 00 52 00 4F 00 4E 00 CD CC CC CC CC</td>
<td>A.R.R.O.N........</td>
</tr>
<tr>
<td>00000050: 00 01 0D 07 06 01</td>
<td>.@....</td>
</tr>
<tr>
<td>00000060: 0D 00 FF FE 47 00 41 00 4D 00 4F 00 48 00 53 00 53 00 66 66</td>
<td>....G.A.R.Y. .B.</td>
</tr>
<tr>
<td>00000070: 49 00 47 00 47 00 53 00 00 00 00 00 00 00 00 00</td>
<td>C0 65 40 I.G.G.S.......</td>
</tr>
<tr>
<td>00000080: 1B D4 07 06 01</td>
<td>@....</td>
</tr>
<tr>
<td>00000090: 00 00 FF FE 4D 00 45 00 4C 00 49 00 53 00 44 00 49 00 4E 00 4B 00 49 00 0D 07 06 01</td>
<td>....M.E.L.I.N.D.</td>
</tr>
<tr>
<td>000000A0: 41 00 20 00 44 00 4F 00 48 00 53 00 53 00 66 66 66 66</td>
<td>A. .D.O.H.E.R.T.</td>
</tr>
<tr>
<td>000000B0: 59 00 48 E1 7A 14 AE FF 68 40 D4 07 06 02</td>
<td>Y.H.z...h@....</td>
</tr>
</tbody>
</table>

UTF-16 encoded text strings are clearly visible, these are names and surnames. The first byte (or 16-bit word) is seems string length, we can visually check it. FF FE is seems Unicode BOM.

There are 12 more bytes after each string.

Using this script ([https://github.com/DennisYurichev/RE-for-beginners/blob/master/examples/encrypted_DB1/dump_buffer_rest.py](https://github.com/DennisYurichev/RE-for-beginners/blob/master/examples/encrypted_DB1/dump_buffer_rest.py)) I've got random selection of the tails:

```
00000000: 4B 00 48 E1 7A 14 AE FF 68 40 D4 07 06 02 | Y.H.z...h@.... |
00000010: 59 00 48 E1 7A 14 AE FF 68 40 D4 07 06 02 | Y.H.z...h@.... |
00000020: 0F 00 FF FE 4D 00 45 00 4C 00 49 00 4E 00 4B 00 49 00 0D 07 06 01 | ....M.E.L.I.N.D. |
```

 UTF-16 encoded text strings are clearly visible, these are names and surnames. The first byte (or 16-bit word) is seems string length, we can visually check it. FF FE is seems Unicode BOM.

There are 12 more bytes after each string.

Using this script ([https://github.com/DennisYurichev/RE-for-beginners/blob/master/examples/encrypted_DB1/dump_buffer_rest.py](https://github.com/DennisYurichev/RE-for-beginners/blob/master/examples/encrypted_DB1/dump_buffer_rest.py)) I've got random selection of the tails:

```
dennis@...:$ python decrypt.py encrypted.xml | shuf | head -20
00000000: 4B 00 48 E1 7A 14 AE FF 68 40 D4 07 06 02 | Y.H.z...h@.... |
00000010: 59 00 48 E1 7A 14 AE FF 68 40 D4 07 06 02 | Y.H.z...h@.... |
00000020: 0F 00 FF FE 4D 00 45 00 4C 00 49 00 4E 00 4B 00 49 00 0D 07 06 01 | ....M.E.L.I.N.D. |
```

 UTF-16 encoded text strings are clearly visible, these are names and surnames. The first byte (or 16-bit word) is seems string length, we can visually check it. FF FE is seems Unicode BOM.
8.7. ENCRYPTED DATABASE CASE #1

We first see the 0x40 and 0x07 bytes present in each tail. The very last byte's always in 1..0x1F (1..31) range, I've checked. The penultimate byte is always in 1..0xC (1..12) range. Wow, that looks like a date! Year can be represented as 16-bit value, and maybe last 4 bytes is date (16 bits for year, 8 bits for month and 8 more for day)? 0x7DD is 2013, 0x7D5 is 2005, etc. Seems fine. This is a date. There are 8 more bytes. Judging by the fact this is database named orders, maybe some kind of sum is present here? I made attempt to interpret it as double-precision IEEE 754 floating point and dump all values!

Some are:

71.0
134.0
51.95
53.0
121.99
96.95
98.95
85.95
184.99
94.95
29.95
85.0
36.0
130.99
115.95
87.99
127.95
114.0
150.95

Looks like real!

Now we can dump names, sums and dates.

plain:

OrderID= 1 name= FRANKIE JOHNS sum= 140.95 date= 2004 / 6 / 1

plain:

OrderID= 2 name= LORI BARRON sum= 6.95 date= 2004 / 6 / 1

plain:

OrderID= 3 name= GARY BIGGS sum= 174.0 date= 2004 / 6 / 1

plain:

OrderID= 4 name= MELINDA DOHERTY sum= 199.99 date= 2004 / 6 / 2

plain:
8.7. ENCRYPTED DATABASE CASE #1

OrderID= 5 name= LENA MARCUS sum= 179.0 date= 2004 / 6 / 3


This is some kind of OOP serialization, i.e., packing differently typed values into binary buffer for storing and/or transmitting.

8.7.8 Noise at the end

The only question remaining is that sometimes, tail is bigger:

```
00000000: 0E 00 FF FE 54 00 54 00 54 00 54 00 54 00 54 00 ....T.H.E.R.E.S.
00000010: 45 00 20 00 54 00 4C 00 45 00 4C 00 45 00 4C 00 E. .T.U.T.T.L.E.
00000020: 66 66 66 66 66 66 63 63 63 40 D4 07 07 07 07 20 30 fffff.c@........
OrderID= 172 name= THERESE TUTTLE sum= 152.95 date= 2004 / 7 / 26
```

(00070719 bytes are not used and is ballast.)

```
00000000: 0C 00 FF FE 4D 00 45 00 4C 00 45 00 4C 00 45 00 4C 00 ....M.E.L.A.N.I.
00000010: 45 00 20 00 4B 00 4A 00 4C 00 4C 00 4C 00 4C 00 E. .K.I.R.K.....
00000020: 00 20 64 40 D4 07 09 02 00 02 . d@......
OrderID= 286 name= MELANIE KIRK sum= 161.0 date= 2004 / 9 / 2
```

(00 02 are not used.)

After close examination, we can see, that the noise at the end of tail is just left from previous encryption!

Here are two subsequent buffers:

```
00000000: 10 00 FF FE 4F 00 4F 00 4E 00 4E 00 4E 00 4E 00 4E 00 ....B.O.N.N.I.E.
00000010: 20 00 4F 00 54 00 54 00 54 00 54 00 54 00 54 00 54 00 .G.O.L.D.S.T.E.
00000020: 66 66 66 66 66 66 63 63 63 40 D4 07 07 07 07 20 30 fffff.c@........
OrderID= 171 name= BONNIE GOLDSTEIN sum= 44.95 date= 2004 / 7 / 25
```

(The last 07 07 19 bytes are copied from the previous plaintext buffer.)

Another two subsequent buffers:

```
00000000: 10 00 FF FE 4B 00 4B 00 4B 00 4B 00 4B 00 4B 00 4B 00 ....T.H.E.R.E.S.
00000010: 20 00 4B 00 54 00 54 00 54 00 54 00 54 00 54 00 54 00 .G.O.L.D.S.T.E.
00000020: 66 66 66 66 66 66 63 63 63 40 D4 07 07 07 07 20 30 fffff.c@........
OrderID= 172 name= THERESE TUTTLE sum= 152.95 date= 2004 / 7 / 26
```

The last 02 byte has been copied from the previous plaintext buffer.

It's possible if the buffer used while encrypting is global and/or isn't clearing before each encryption. The final buffer size is also chaotic, nevertheless, the bug left uncaught because it doesn't affect decrypting process, which just ignores noise at the end. This is common mistake. It's been present in OpenSSL (Heartbleed bug).

8.7.9 Conclusion

Summary: every practicing reverse engineer should be familiar with major crypto algorithms and also major cryptographical modes. Some books about it: 12.1.10 on page 1014.
8.8. OVERCLOCKING COINTERRA BITCOIN MINER

Encrypted database contents has been artificially constructed by me for the sake of demonstration. I’ve got most popular USA names and surnames from there: http://stackoverflow.com/questions/1803628/raw-list-of-person-names, and combined them randomly. Dates and sums were also generated randomly.

All files used in this part are here: https://github.com/DennisYurichev/RE-for-beginners/tree/master/examples/encrypted_DB1.

Nevertheless, many features like these I’ve observed in real-world software applications. This example is based on them.

8.7.10 Post Scriptum: brute-forcing IV

The case you have just seen has been artificially constructed, but is based on a real application I’ve reverse engineered. When I’ve been working on it, I first noticed that IV has been generating using some 32-bit number, and I wasn’t able to find a link between this value and OrderID. So I prepared to use brute-force, which is indeed possible here.

It’s not a problem to enumerate all 32-bit values and try each as a base for IV. Then you decrypt the first 16-byte block and check for zero bytes, which are always at fixed places.

8.8 Overclocking Cointerra Bitcoin miner

There was Cointerra Bitcoin miner, looking like that:

![Figure 8.14: Board](image)

875
And there was also (possibly leaked) utility\(^2\) which can set clock rate for the board. It runs on additional BeagleBone Linux ARM board (small board at bottom of the picture).

And the author was once asked, is it possible to hack this utility to see, which frequency can be set and which are not. And is it possible to tweak it?

The utility must be executed like that: \(./\text{cointool-overclock} \ \ 0 \ \ 0 \ 900\), where 900 is frequency in MHz. If the frequency is too high, utility will print “Error with arguments” and exit.

This is a fragment of code around reference to “Error with arguments” text string:

\[
\text{\texttt{...}}
\text{\texttt{.text:0000ABC4 STR R3, [R11,#var_28]}}
\text{\texttt{.text:0000ABC8 MOV R3, #optind}}} \\
\text{\texttt{.text:0000ABD0 LDR R3, [R3]}}} \\
\text{\texttt{.text:0000ABD4 ADD R3, R3, #1}}} \\
\text{\texttt{.text:0000ABD8 MOV R3, R3,LSL#2}}} \\
\text{\texttt{.text:0000ABDC LDR R2, [R11,#argv]}}} \\
\text{\texttt{.text:0000ABE0 ADD R3, R2, R3}}} \\
\text{\texttt{.text:0000ABE4 LDR R3, [R3]}}} \\
\text{\texttt{.text:0000ABE8 MOV R0, R3 ; nptr}}} \\
\text{\texttt{.text:0000ABEC MOV R1, #0 ; endptr}}} \\
\text{\texttt{.text:0000ABF0 MOV R2, #0 ; base}}} \\
\text{\texttt{.text:0000ABF4 BL strtoll}}} \\
\text{\texttt{.text:0000ABF8 MOV R2, R0}}} \\
\text{\texttt{.text:0000ABFC MOV R3, R1}}} \\
\text{\texttt{.text:0000AC00 MOV R3, R2}}} \\
\text{\texttt{.text:0000AC04 STR R3, [R11,#var_2C]}}} \\
\text{\texttt{.text:0000AC08 MOV R3, #optind}}} \\
\text{\texttt{.text:0000AC10 LDR R3, [R3]}}} \\
\text{\texttt{.text:0000AC14 ADD R3, R3, #2}}} \\
\text{\texttt{.text:0000AC18 MOV R3, R3,LSL#2}}} \\
\text{\texttt{.text:0000AC1C LDR R2, [R11,#argv]}}} \\
\text{\texttt{.text:0000AC20 ADD R3, R2, R3}}} \\
\text{\texttt{.text:0000AC24 LDR R3, [R3]}}} \\
\text{\texttt{.text:0000AC28 MOV R0, R3 ; nptr}}} \\
\text{\texttt{.text:0000AC2C MOV R1, #0 ; endptr}}} \\
\text{\texttt{.text:0000AC30 MOV R2, #0 ; base}}} \\
\text{\texttt{.text:0000AC34 BL strtoll}}} \\
\text{\texttt{.text:0000AC38 MOV R2, R0}}} \\
\text{\texttt{.text:0000AC3C MOV R3, R1}}} \\
\text{\texttt{.text:0000AC40 MOV R3, R2}}} \\
\text{\texttt{.text:0000AC44 STR R3, [R11,#third_argument]}}} \\
\text{\texttt{.text:0000AC48 LDR R3, [R11,#var_28]}}} \\
\text{\texttt{.text:0000AC4C CMP R3, #0}}} \\
\text{\texttt{.text:0000AC50 BLT errors_with_arguments}}} \\
\text{\texttt{.text:0000AC54 LDR R3, [R11,#var_28]}}} \\
\text{\texttt{.text:0000AC58 CMP R3, #1}}} \\
\text{\texttt{.text:0000AC5C BGT errors_with_arguments}}} \\
\text{\texttt{.text:0000AC60 LDR R3, [R11,#var_2C]}}} \\
\text{\texttt{.text:0000AC64 CMP R3, #0}}} \\
\text{\texttt{.text:0000AC68 BLT errors_with_arguments}}} \\
\text{\texttt{.text:0000AC6C LDR R3, [R11,#var_2C]}}} \\
\text{\texttt{.text:0000AC70 CMP R3, #3}}} \\
\text{\texttt{.text:0000AC74 BGT errors_with_arguments}}} \\
\text{\texttt{.text:0000AC78 LDR R3, [R11,#third_argument]}}} \\
\text{\texttt{.text:0000AC7C CMP R3, #0x31}}} \\
\text{\texttt{.text:0000AC80 BLE errors_with_arguments}}} \\
\text{\texttt{.text:0000AC84 LDR R2, [R11,#third_argument]}}} \\
\text{\texttt{.text:0000AC88 MOV R3, #950}}} \\
\text{\texttt{.text:0000AC8C CMP R2, R3}}} \\
\text{\texttt{.text:0000AC90 BGT errors_with_arguments}}} \\
\text{\texttt{.text:0000AC94 LDR R2, [R11,#third_argument]}}} \\
\text{\texttt{.text:0000AC98 MOV R3, #0x51EB851F}}} \\
\text{\texttt{.text:0000AC9C SBULER R1, R3, R2}}} \\
\text{\texttt{.text:0000ACA0 MOV R1, R3,ASR#4}}} \\
\text{\texttt{.text:0000ACA4 MOV R3, R2,ASR#31}}\]

\(^2\)Can be downloaded here: https://github.com/DennisYurichev/RE-for-beginners/raw/master/examples/bitcoin_miner/files/cointool-overclock
OVERCLOCKING COINTERRA BITCOIN MINER

.text:0000ACAC  RSB  R3, R3, R1
.text:0000ACB0  MOV  R1, #50
.text:0000ACB4  MUL  R3, R1, R3
.text:0000ACB8  RSB  R3, R3, R2
.text:0000ACBC  CMP  R3, #0
.text:0000ACC0  BEQ  loc_ACEC
.text:0000ACC4  errors_with_arguments
.text:0000ACC4  LDR  R3, [R11,#argv]
.text:0000ACC8  MOV  R0, R3 ; path
.text:0000ACD0  BL  __xpg_basename
.text:0000ACD4  MOV  R0, R3
.text:0000ACD8  MOV  R3, #aSErrorWithArgu ; format
.text:0000ACE0  MOV  R1, R3
.text:0000ACE4  BL  printf
.text:0000ACE8  B  loc_ADD4
.text:0000ACEC  ; -------------------------------------------------------------
.text:0000ACEC  loc_ACEC ; CODE XREF: main+66C
.text:0000ACEC  LDR  R2, [R11,#third_argument]
.text:0000ACFC  MOV  R3, #0x64
.text:0000AD00  STR  R3, [R11,#unk_constant]
.text:0000AD04  B  jump_to_write_power
.text:0000AD08 ; -------------------------------------------------------------
.text:0000AD08  loc_AD08 ; CODE XREF: main+6A4
.text:0000AD08  LDR  R2, [R11,#third_argument]
.text:0000AD10  MOV  R3, #799
.text:0000AD14  BGT  loc_AD24
.text:0000AD18  MOV  R3, #0x5F
.text:0000AD1C  STR  R3, [R11,#unk_constant]
.text:0000AD20  B  jump_to_write_power
.text:0000AD24 ; -------------------------------------------------------------
.text:0000AD24  loc_AD24 ; CODE XREF: main+6C0
.text:0000AD24  LDR  R2, [R11,#third_argument]
.text:0000AD28  MOV  R3, #899
.text:0000AD2C  CMP  R2, R3
.text:0000AD30  BGT  loc_AD40
.text:0000AD34  MOV  R3, #0x5A
.text:0000AD38  STR  R3, [R11,#unk_constant]
.text:0000AD3C  B  jump_to_write_power
.text:0000AD40 ; -------------------------------------------------------------
.text:0000AD40  loc_AD40 ; CODE XREF: main+6DC
.text:0000AD40  LDR  R2, [R11,#third_argument]
.text:0000AD44  MOV  R3, #999
.text:0000AD48  CMP  R2, R3
.text:0000AD50  BGT  loc_AD5C
.text:0000AD54  MOV  R3, #0x55
.text:0000AD58  STR  R3, [R11,#unk_constant]
.text:0000AD5C  B  jump_to_write_power
.text:0000AD5C ; -------------------------------------------------------------
.text:0000AD5C  loc_AD5C ; CODE XREF: main+6F8
.text:0000AD5C  LDR  R2, [R11,#third_argument]
.text:0000AD60  MOV  R3, #1099
.text:0000AD64  CMP  R2, R3
.text:0000AD68  BGT  jump_to_write_power
.text:0000AD6C  MOV  R3, #0x50
.text:0000AD70  STR  R3, [R11,#unk_constant]
.text:0000AD74  jump_to_write_power ; CODE XREF: main+6B0
.text:0000AD74 ; main+6CC ...
8.8. OVERCLOCKING COINTERRA BITCOIN MINER

Function names were present in debugging information of the original binary, like write_power, read_loop. But labels inside functions were named by me.

optind name looks familiar. It is from getopt *NIX library intended for command-line parsing—well, this is exactly what happens inside. Then, the 3rd argument (where frequency value is to be passed) is converted from a string to a number using a call to strtol() function.

The value is then checked against various constants. At 0xACEC, it's checked, if it is lesser or equal to 499, and if it is so, 0x64 is to be passed to write_power() function (which sends a command through USB using send_msg()). If it is greater than 499, jump to 0xAD08 is occurred.

At 0xAD08 it's checked, if it's lesser or equal to 799. 0x5F is then passed to write_power() function in case of success.

There are more checks: for 899 at 0xAD24, for 0x999 at 0xAD40 and finally, for 1099 at 0xAD5C. If the input frequency is lesser or equal to 1099, 0x50 will be passed (at 0xAD6C) to write_power() function.

As it seems, a value passed to the board is gradually decreasing during frequency increasing.

Now we see that value of 950MHz is a hardcoded limit, at least in this utility. Can we trick it?

Let's back to this piece of code:

<table>
<thead>
<tr>
<th>MHz</th>
<th>hexadecimal</th>
<th>decimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>499MHz</td>
<td>0x64</td>
<td>100</td>
</tr>
<tr>
<td>799MHz</td>
<td>0x5f</td>
<td>95</td>
</tr>
<tr>
<td>899MHz</td>
<td>0x5a</td>
<td>90</td>
</tr>
<tr>
<td>999MHz</td>
<td>0x55</td>
<td>85</td>
</tr>
<tr>
<td>1099MHz</td>
<td>0x50</td>
<td>80</td>
</tr>
</tbody>
</table>

As it seems, a value passed to the board is gradually decreasing during frequency increasing.

Now we see that value of 950MHz is a hardcoded limit, at least in this utility. Can we trick it?

Let's back to this piece of code:

We must disable BGT branch instruction at 0xAC90 somehow. And this is ARM in ARM mode, because, as we see, all addresses are increasing by 4, i.e., each instruction has size of 4 bytes. NOP (no operation) instruction in ARM mode is just four zero bytes: 00 00 00 00. So by writing four zeros at 0xAC90 address (or physical offset in file 0x2C90) we can disable the check.
8.9. **BREAKING SIMPLE EXECUTABLE CRYPTOR**

Now it's possible to set frequencies up to 1050MHz. Even more is possible, but due to the bug, if input value is greater than 1099, a value as is in MHz will be passed to the board, which is incorrect.

I didn’t go further, but if I had to, I would try to decrease a value which is passed to write_power() function.

Now the scary piece of code which I skipped at first:

```
.text:0000AC94  LDR  R2, [R11,#third_argument]
.text:0000AC98  MOV  R3, #0x51EB851F
.text:0000ACA0  SMULL R1, R3, R3, R2 ; R3=3rg_arg/3.125
.text:0000ACA4  MOV  R1, R3,ASR#4 ; R1=R3/16=3rg_arg/50
.text:0000ACA8  MOV  R3, R2,ASR#31 ; R3=MSB(3rg_arg)
.text:0000ACAC  RSB  R3, R3, R1 ; R3=3rd_arg/50
.text:0000ACB0  MOV  R1, #50
.text:0000ACB4  MUL  R3, R1, R3 ; R3=50*(3rd_arg/50)
.text:0000ACBC  CMP  R3, #0
.text:0000ACC0  BEQ  loc_ACEC
.text:0000ACC4  errors_with_arguments
```

Division via multiplication is used here, and constant is 0x51EB851F. I wrote a simple programmer’s calculator26 for myself. And I have there a feature to calculate modulo inverse.

```
modinv32(0x51EB851F)
Warning, result is not integer: 3.125000
(unsigned) dec: 3 hex: 0x3 bin: 11
```

That means that SMULL instruction at 0xACa0 is basically divides 3rd argument by 3.125. In fact, all modinv32() function in my calculator does, is this:

\[
\frac{1}{\text{input}} = \frac{2^{32}}{\text{input}}
\]

Then there are additional shifts and now we see than 3rg argument is just divided by 50. And then it’s multiplied by 50 again. Why? This is simplest check, if the input value is can be divided by 50 evenly. If the value of this expression is non-zero, \(x\) can’t be divided by 50 evenly:

\[
x - \left( \frac{x}{50} \right) \cdot 50
\]

This is in fact simple way to calculate remainder of division.

And then, if the remainder is non-zero, error message is displayed. So this utility takes frequency values in form like 850, 900, 950, 1000, etc., but not 855 or 911.

That’s it! If you do something like that, please be warned that you may damage your board, just as in case of overclocking other devices like **CPU**s, **GPU**s, etc. If you have a Cointerra board, do this on your own risk!

### 8.9 Breaking simple executable cryptor

I’ve got an executable file which is encrypted by relatively simple encryption. Here is it (only executable section is left here).

First, all encryption function does is just adds number of position in buffer to the byte. Here is how this can be encoded in Python:

```
Listing 8.7: Python script

#!/usr/bin/env python
def e(i, k):
    return chr ((ord(i)+k) % 256)
```

26 [https://github.com/DennisYurichev/progcalc](https://github.com/DennisYurichev/progcalc)  
27 Graphics Processing Unit
8.9. BREAKING SIMPLE EXECUTABLE CRYPTOR

```python
def encrypt(buf):
    return e(buf[0], 0) + e(buf[1], 1) + e(buf[2], 2) + e(buf[3], 3) + e(buf[4], 4) + e(buf[5], 5) +
            e(buf[6], 6) + e(buf[7], 7) +
            e(buf[8], 8) + e(buf[9], 9) + e(buf[10], 10) + e(buf[11], 11) + e(buf[12], 12) + e(buf[
            13], 13) + e(buf[14], 14) + e(buf[15], 15)
```

Hence, if you encrypt buffer with 16 zeros, you’ll get 0, 1, 2, 3 ... 12, 13, 14, 15.

Propagating Cipher Block Chaining (PCBC) is also used, here is how it works:

![Propagating Cipher Block Chaining (PCBC) mode encryption](image)

Figure 8.15: Propagating Cipher Block Chaining encryption (image is taken from Wikipedia article)

The problem is that it’s too boring to recover IV (Initialization Vector) each time. Brute-force is also not an option, because IV is too long (16 bytes). Let’s see, if it’s possible to recover IV for arbitrary encrypted executable file?

Let’s try simple frequency analysis. This is 32-bit x86 executable code, so let’s gather statistics about most frequent bytes and opcodes. I tried huge oracle.exe file from Oracle RDBMS version 11.2 for windows x86 and I’ve found that the most frequent byte (no surprise) is zero (10%). The next most frequent byte is (again, no surprise) 0xFF (5%). The next is 0x8B (5%).

0x8B is opcode for `MOV`, this is indeed one of the most busy x86 instructions. Now what about popularity of zero byte? If compiler needs to encode value bigger than 127, it has to use 32-bit displacement instead of 8-bit one, but large values are very rare, so it is padded by zeros. This is at least in `LEA`, `MOV`, `PUSH`, `CALL`.

For example:

```
8D B0 28 01 00 00  lea esi, [eax+128h]
8D BF 40 38 00 00  lea edi, [edi+3840h]
```

Displacements bigger than 127 are very popular, but they are rarely exceeds 0x10000 (indeed, such large memory buffers/structures are also rare).

Same story with `MOV`, large constants are rare, the most heavily used are 0, 1, 10, 100, $2^n$, and so on. Compiler has to pad small constants by zeros to represent them as 32-bit values:

```
BF 02 00 00 00  mov    edi, 2
BF 01 00 00 00  mov    edi, 1
```

Now about 00 and FF bytes combined: jumps (including conditional) and calls can pass execution flow forward or backwards, but very often, within the limits of the current executable module. If forward, displacement is not very big and also padded with zeros. If backwards, displacement is represented as negative value, so padded with FF bytes. For example, transfer execution flow forward:

```
E8 43 0C 00 00  call _function1
E8 5C 00 00 00  call _function2
0F 84 F0 0A 00 00  jz  loc_4F09A0
```
8.9. BREAKING SIMPLE EXECUTABLE CRYPTOR

Backwards:

<table>
<thead>
<tr>
<th>Opcode</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>E8 79 0C FE FF</td>
<td>call _function1</td>
</tr>
<tr>
<td>E8 F4 16 FF FF</td>
<td>call _function2</td>
</tr>
<tr>
<td>0F 84 F8 F8 FF FF</td>
<td>jz loc_8212BC</td>
</tr>
<tr>
<td>0F 84 06 FD FF FF</td>
<td>jz loc_FF1E7D</td>
</tr>
</tbody>
</table>

FF byte is also very often occurred in negative displacements like these:

<table>
<thead>
<tr>
<th>Opcode</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>8D 85 1E FF FF FF</td>
<td>lea eax, [ebp-0E2h]</td>
</tr>
<tr>
<td>8D 95 F8 5C FF FF</td>
<td>lea edx, [ebp-0A308h]</td>
</tr>
</tbody>
</table>

So far so good. Now we have to try various 16-byte keys, decrypt executable section and measure how often 00, FF ad 8B bytes are occurred. Let's also keep in sight how PCBC decryption works:

Propagating Cipher Block Chaining (PCBC) mode decryption

Figure 8.16: Propagating Cipher Block Chaining decryption (image is taken from Wikipedia article)

The good news is that we don't really have to decrypt whole piece of data, but only slice by slice, this is exactly how I did in my previous example: 9.1.5 on page 943.

Now I'm trying all possible bytes (0..255) for each byte in key and just pick the byte producing maximal amount of 00/FF/8B bytes in a decrypted slice:

```python
#!/usr/bin/env python
import sys, hexdump, array, string, operator

KEY_LEN=16

def chunks(l, n):
    # split n by l-byte chunks
    n = max(1, n)
    return [l[i:i + n] for i in range(0, len(l), n)]

def read_file(fname):
    with open(fname, mode='rb') as file:
        content = file.read()
        file.close()
    return content

def decrypt_byte (c, key):
    return chr((ord(c)-key) % 256)

def XOR_PCBC_step (IV, buf, k):
```
8.9. \textit{BREAKING SIMPLE EXECUTABLE CRYPTOR}

```python
prev=IV
rt=""
for c in buf:
    new_c=decrypt_byte(c, k)
    plain=chr(ord(new_c)^ord(prev))
    prev=chr(ord(c)^ord(plain))
    rt=rt+plain
return rt
```

```python
each_Nth_byte=[""]*KEY_LEN
content=read_file(sys.argv[1])
# split input by 16-byte chunks:
all_chunks=chunks(content, KEY_LEN)
for c in all_chunks:
    for i in range(KEY_LEN):
        each_Nth_byte[i]=each_Nth_byte[i] + c[i]

# try each byte of key
for N in range(KEY_LEN):
    print "N=", N
    stat={}
    for i in range(256):
        tmp_key=chr(i)
        tmp=XOR_PCBC_step(tmp_key,each_Nth_byte[N], N)
        # count 0, FFs and 8Bs in decrypted buffer:
        important_bytes=tmp.count(\'\x00\')+tmp.count(\'\xFF\')+tmp.count(\'\x8B\')
        stat[i]=important_bytes
    sorted_stat = sorted(stat.iteritems(), key=operator.itemgetter(1), reverse=True)
    print sorted_stat[0]
```

(Source code can downloaded \url{here}.)

I run it and here is a key for which 00/FF/8B bytes presence in decrypted buffer is maximal:

<table>
<thead>
<tr>
<th>N</th>
<th>count</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(147, 1224)</td>
</tr>
<tr>
<td>1</td>
<td>(94, 1327)</td>
</tr>
<tr>
<td>2</td>
<td>(252, 1223)</td>
</tr>
<tr>
<td>3</td>
<td>(218, 1266)</td>
</tr>
<tr>
<td>4</td>
<td>(38, 1209)</td>
</tr>
<tr>
<td>5</td>
<td>(192, 1378)</td>
</tr>
<tr>
<td>6</td>
<td>(199, 1204)</td>
</tr>
<tr>
<td>7</td>
<td>(213, 1332)</td>
</tr>
<tr>
<td>8</td>
<td>(225, 1251)</td>
</tr>
<tr>
<td>9</td>
<td>(112, 1223)</td>
</tr>
<tr>
<td>10</td>
<td>(143, 1177)</td>
</tr>
<tr>
<td>11</td>
<td>(108, 1286)</td>
</tr>
<tr>
<td>12</td>
<td>(10, 1164)</td>
</tr>
<tr>
<td>13</td>
<td>(3, 1271)</td>
</tr>
<tr>
<td>14</td>
<td>(128, 1253)</td>
</tr>
<tr>
<td>15</td>
<td>(232, 1330)</td>
</tr>
</tbody>
</table>

Let’s write decryption utility with the key we got:
8.9. BREAKING SIMPLE EXECUTABLE CRYPTOR

```python
#!/usr/bin/env python
import sys, hexdump, array

def xor_strings(s,t):
    # https://en.wikipedia.org/wiki/XOR_cipher#Example_implementation
    return ''.join(chr(ord(a)^ord(b)) for a,b in zip(s,t))

IV=array.array('B', [147, 94, 252, 218, 38, 192, 199, 213, 225, 112, 143, 108, 10, 3, 128, \ 232]).tostring()

def chunks(l, n):
    n = max(1, n)
    return [l[i:i + n] for i in range(0, len(l), n)]

def read_file(fname):
    file=open(fname, mode='rb')
    content=file.read()
    file.close()
    return content

def decrypt_byte(i, k):
    return chr ((ord(i)-k) % 256)

def decrypt(buf):
    return ''.join(decrypt_byte(buf[i], i) for i in range(16))

fout=open(sys.argv[2], mode='wb')
prev=IV
content=read_file(sys.argv[1])
tmp=chunks(content, 16)
for c in tmp:
    new_c=decrypt(c)
    p=xor_strings (new_c, prev)
    prev=xor_strings(c, p)
    fout.write(p)
fout.close()

(Source code can downloaded here.)

Let's check resulting file:

$ objdump -b binary -m i386 -D decrypted.bin
...
  5:  8b ff       mov  %edi,%edi
  7:  55         push  %ebp
  8:  8b ec       mov  %esp,%ebp
  a:  51         push  %ecx
  b:  53         push  %ebx
  c:  33 db       xor  %ebx,%ebx
  e:  43         inc  %ebx
  f:  84 1d a0 e2 05 01  test  %bl,0x105e2a0
 15:  75 09       jne  0x20
 17:  ff 75 08   pushl  0x8(%ebp)
 1a:  ff 15 b0 13 00 01  call  *0x10013b0
 20:  6a 6c       push  $0x6c
 22:  ff 35 54 d0 01 01  pushl  0x101d054
 28:  ff 15 b4 13 00 01  call  *0x10013b4
 2e:  89 45 fc   mov   0x10013bc,%esi
 31:  85 c9       test  %eax,%eax
 33:  0f 84 d9 00 00 00  je  0x112
 39:  56         push  %esi
 3a:  57         push  %edi
 3b:  6a 00       push  $0x0
 3d:  50         push  %eax
 3e:  ff 15 b8 13 00 01  call  *0x10013bb
 44:  8b 35 bc 13 00 01  mov  0x10013bc,%esi
```

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| 4a: | 8b f8 | mov %eax,%edi |
| 4c: | a1 e0 e2 05 01 | mov 0x105e2e0,%eax |
| 51: | 3b 05 e4 e2 05 01 | cmp 0x105e2e4,%eax |
| 57: | 75 12 | jne 0x6b |
| 59: | 73 | push %ebx |
| 5a: | 6a 03 | push $0x3 |
| 5c: | 57 | push %edi |
| 5d: | ff d6 | call *%esi |

Yes, this is seems correctly disassembled piece of x86 code. The whole dectyped file can be downloaded [here](#).

In fact, this is text section from regedit.exe from Windows 7. But this example is based on a real case I encountered, so just executable is different (and key), algorithm is the same.

### 8.9.1 Other ideas to consider

What if I would fail with such simple frequency analysis? There are other ideas on how to measure correctness of decrypted/decompressed x86 code:

- Many modern compilers aligns functions on 0x10 border. So the space left before is filled with NOPs (0x90) or other NOP instructions with known opcodes: [1.7 on page 1038](#).
- Perhaps, the most frequent pattern in any assembly language is function call:  
  
  PUSH chain / CALL / ADD ESP, X. This sequence can easily detected and found. I’ve even gathered statistics about average number of function arguments: [11.2 on page 999](#). (Hence, this is average length of PUSH chain.)

Read more about incorrectly/correctly disassembled code: [5.11 on page 726](#).

### 8.10 SAP

#### 8.10.1 About SAP client network traffic compression

(Tracing the connection between the TDW_NOCOMPRESS SAPGUI[28](http://go.yurichev.com/17221) environment variable and the pesky annoying pop-up window and the actual data compression routine.)

It is known that the network traffic between SAPGUI and SAP is not encrypted by default, but compressed (see here[29](http://go.yurichev.com/17221) and here[30](http://go.yurichev.com/17221)).

It is also known that by setting the environment variable *TDW_NOCOMPRESS* to 1, it is possible to turn the network packet compression off.

But you will see an annoying pop-up window that cannot be closed:

---

[28] SAP GUI client  
[29] [http://go.yurichev.com/17221](http://go.yurichev.com/17221)  
[30] [blog.yurichev.com](http://go.yurichev.com/17221)
Let's see if we can remove the window somehow.

But before this, let's see what we already know.

First: we know that the environment variable `TDW_NOCOMPRESS` is checked somewhere inside the SAPGUI client.

Second: a string like “data compression switched off” must be present somewhere in it.

With the help of the FAR file manager\(^\text{31}\) we can find that both of these strings are stored in the SAPguilib.dll file.

So let's open SAPguilib.dll in IDA and search for the “`TDW_NOCOMPRESS`” string. Yes, it is present and there is only one reference to it.

We see the following fragment of code (all file offsets are valid for SAPGUI 720 win32, SAPguilib.dll file version 7200,1,0,9009):

```assembly
.text:6440D51B lea eax, [ebp+2108h+var_211C]
.text:6440D51E push eax ; int
.text:6440D51F push offset aTdw_nocompress ; "TDW_NOCOMPRESS"
.text:6440D524 mov byte ptr [edi+15h], 0
.text:6440D528 call chk_env
.text:6440D52D pop ecx
.text:6440D52E pop ecx
.text:6440D534 lea ecx, [ebp+2108h+var_211C]

; demangled name: int ATL::CStringT::Compare(char const *)const
.text:6440D537 call ds:mfc90_1603
.text:6440D53D test eax, eax
.text:6440D53F jz short loc_6440D55A
.text:6440D541 lea ecx, [ebp+2108h+var_211C]

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
.text:6440D544 call ds:mfc90_910
```

\(^\text{31}\)http://go.yurichev.com/17347
The string returned by `chk_env()` via its second argument is then handled by the MFC string functions and then `atoi()` is called. After that, the numerical value is stored in `edi+15h`.

Also take a look at the `chk_env()` function (we gave this name to it manually):

```assembly
chk_env proc near
    DstSize = dword ptr -0Ch
    var_8 = dword ptr -8
    DstBuf = dword ptr -4
    VarName = dword ptr 8
    arg_4 = dword ptr 0Ch
    push ebp
    mov ebp, esp
    sub esp, 0Ch
    mov [ebp+DstSize], 0
    mov [ebp+DstBuf], 0
    push offset unk_6444C88C
    mov ecx, [ebp+arg_4]
    push offset unk_6444C88C
    mov ecx, [ebp+dstSize]
    push ecx ; DstSize
    push edx ; DstBuf
    lea ecx, [ebp+DstSize]
    push edx ; ReturnSize
    mov ecx, [ebp+VarName]
    push ecx ; VarName
    mov eax, [ebp+DstSize]
    push eax ; DstSize
    mov edx, [ebp+VarName]
    push edx ; VarName
    mov [ebp+DstSize], 0
    jz short loc_64413F68
    xor eax, eax
    jmp short loc_64413FBC
    loc_64413F68:
    cmp [ebp+DstSize], 0
    jnz short loc_64413F72
    xor eax, eax
    jmp short loc_64413FBC
    loc_64413F72:
    mov ecx, [ebp+DstSize]
    push ecx
    mov ecx, [ebp+arg_4]
    lea ecx, [ebp+dstSize]
    jmp short loc_64413FBC
    loc_64413FBC:
    ...
```

32standard C library function that converts the digits in a string to a number
Yes. The `getenv_s()` function is a Microsoft security-enhanced version of `getenv()`.

There are also some MFC string manipulations.

Lots of other environment variables are checked as well. Here is a list of all variables that are being checked and what SAPGUI would write to its trace log when logging is turned on:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Message</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPTRACE</td>
<td>“GUI-OPTION: Trace set to %d”</td>
</tr>
<tr>
<td>TDW.HEXDUMP</td>
<td>“GUI-OPTION: Hexdump enabled”</td>
</tr>
<tr>
<td>TDW.WORKDIR</td>
<td>“GUI-OPTION: working directory %s”</td>
</tr>
<tr>
<td>TDW.SPLASHSCREENOFF</td>
<td>“GUI-OPTION: Splash Screen Off”</td>
</tr>
<tr>
<td>TDW.REPLYTIMEOUT</td>
<td>“GUI-OPTION: reply timeout %d milliseconds”</td>
</tr>
<tr>
<td>TDW.PLAYBACKTIMEOUT</td>
<td>“GUI-OPTION: PlaybackTimeout set to %d milliseconds”</td>
</tr>
<tr>
<td>TDW.NOCOMPRESS</td>
<td>“GUI-OPTION: no compression read”</td>
</tr>
<tr>
<td>TDW.EXPERT</td>
<td>“GUI-OPTION: expert mode”</td>
</tr>
<tr>
<td>TDW.PLAYBACKPROGRESS</td>
<td>“GUI-OPTION: PlaybackProgress”</td>
</tr>
<tr>
<td>TDW.PLAYBACKNETTRAFFIC</td>
<td>“GUI-OPTION: PlaybackNetTraffic”</td>
</tr>
<tr>
<td>TDW.PLAYLOG</td>
<td>“GUI-OPTION: /PlayLog is YES, file %s”</td>
</tr>
<tr>
<td>TDW.PLAYTIME</td>
<td>“GUI-OPTION: /PlayTime set to %d milliseconds”</td>
</tr>
<tr>
<td>TDW.LOGFILE</td>
<td>“GUI-OPTION: TDW_LOGFILE &quot;%d&quot;”</td>
</tr>
<tr>
<td>TDW.WAN</td>
<td>“GUI-OPTION: WAN - low speed connection enabled”</td>
</tr>
<tr>
<td>TDW_FULLSCREEN</td>
<td>“GUI-OPTION: FullMenu enabled”</td>
</tr>
<tr>
<td>SAP.CP / SAP.CODEPAGE</td>
<td>“GUI-OPTION: SAP_CODEPAGE %d”</td>
</tr>
<tr>
<td>UPDOWNLOAD_CP</td>
<td>“GUI-OPTION: UPDOWNLOAD_CP %d”</td>
</tr>
<tr>
<td>SNC_PARTNERNAME</td>
<td>“GUI-OPTION: SNC name %s”</td>
</tr>
<tr>
<td>SNC_QOP</td>
<td>“GUI-OPTION: SNC_QOP %s”</td>
</tr>
<tr>
<td>SNC_LIB</td>
<td>“GUI-OPTION: SNC is set to: %s”</td>
</tr>
<tr>
<td>SAPGUI_INPLACE</td>
<td>“GUI-OPTION: environment variable SAPGUI_INPLACE is on”</td>
</tr>
</tbody>
</table>

The settings for each variable are written in the array via a pointer in the EDI register. EDI is set before the function call:

<table>
<thead>
<tr>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>.text:6440EE00 lea edi, [ebp+2884h+var_2884]; options here like +0x15...</td>
</tr>
<tr>
<td>.text:6440EE03 lea ecx, [esi+24h]</td>
</tr>
<tr>
<td>.text:6440EE06 call load_command_line</td>
</tr>
<tr>
<td>.text:6440EE09 mov edi, eax</td>
</tr>
<tr>
<td>.text:6440EE0D xor ebx, ebx</td>
</tr>
<tr>
<td>.text:6440EE0F cmp edi, ebx</td>
</tr>
<tr>
<td>.text:6440EE11 jz short loc_6440EE42</td>
</tr>
<tr>
<td>.text:6440EE13 push edi</td>
</tr>
</tbody>
</table>

---

33 MSDN
34 Standard C library returning environment variable
Now, can we find the “data record mode switched on” string?

Yes, and the only reference is in

CDwsGui::PrepareInfoWindow().

How do we get know the class/method names? There are a lot of special debugging calls that write to the log files, like:

```
.Call: CDwsGui::PrepareInfoWindow::
pvParam = byte ptr -3Ch
var_38 = dword ptr -38h
var_34 = dword ptr -34h
rc = tagRECT ptr -2Ch
cy = dword ptr -1Ch
h = dword ptr -18h
var_14 = dword ptr -14h
var_10 = dword ptr -10h
var_4 = dword ptr -4
push 30h
mov eax, offset loc_64438E00
_call __EH_prolog3
mov esi, ecx ; ECX is pointer to object
xor ebx, ebx
lea ecx, [ebp+var_14]
mov [ebp+var_10], ebx
```

It is very useful.

So let’s see the contents of this pesky annoying pop-up window’s function:

```
.Call: CDwsGui::PrepareInfoWindow::
```

---

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---

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; demangled name: ATL::CStringT::Format(char const *,...)  
.text:64404F98  call ebx ; mfc90_2539  
.text:64404F9A  add esp, 0Ch  
.text:64404F9D  lea eax, [ebp-var_14]  
.text:64404FA0  push eax  
.text:64404FA1  mov ecx, edi  

; demangled name: ATL::CStringT::operator+=(class ATL::CSimpleStringT<char, 1> const &)  
.text:64404FA3  call ds:mfc90_941  
.text:64404FA9  loc_64404FA9:  
.text:64404FA9  mov eax, [esi+38h]  
.text:64404FAC  test eax, eax  
.text:64404FAE  jbe short loc_64404FD3  
.text:64404FB0  push eax  
.text:64404FB1  lea eax, [ebp-var_14]  
.text:64404FB4  push offset aTraceLevelDAct ; "trace level \%d activated\n"  
.text:64404FB9  push eax  

; demangled name: ATL::CStringT::Format(char const *,...)  
.text:64404FBA  call ebx ; mfc90_2539  
.text:64404FBC  add esp, 0Ch  
.text:64404FBD  lea eax, [ebp+var_14]  
.text:64404FBE  push eax  
.text:64404FBB  mov ecx, edi  

; demangled name: ATL::CStringT::operator+=(class ATL::CSimpleStringT<char, 1> const &)  
.text:64404FC5  call ds:mfc90_941  
.text:64404FBC  add esp, 0Ch  
.text:64404FBD  lea eax, [ebp-var_14]  
.text:64404FBE  push eax  
.text:64404FCF  mov [ebp+var_10], ebx  
.text:64404FD1  jmp short loc_64404FD6  
.text:64404FD3  loc_64404FD3:  
.text:64404FD3  xor ebx, ebx  
.text:64404FD5  inc ebx  
.text:64404FD6  mov ecx, edi  

; demangled name: ATL::CStringT::operator+=(char const *)  
.text:64404FEB  call ds:mfc90_945  
.text:64404FE1  loc_64404FE1:  
.text:64404FE1  cmp byte ptr [esi+78h], 0  
.text:64404FFE  push offset aDataCompressio ; "data compression switched off\n"  
.text:64405004  mov ecx, edi  

; demangled name: ATL::CStringT::operator+=(char const *)  
.text:64405004  mov [ebp+var_10], ebx  
.text:64405007  loc_64405007:  
.text:64405007  cmp byte ptr [esi+3Dh], 0  
.text:6440500B  push offset aDataCompressio ; "data compression switched off\n"  
.text:64405012  mov ecx, edi  

; demangled name: ATL::CStringT::operator+=(char const *)  
.text:64405014  call ds:mfc90_945  
.text:6440501A  mov [ebp+var_10], ebx  

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.text:6440501D bypass:
  mov   eax, [esi+20h]
  test  eax, eax
  jz    short loc_6440503A
  cmp   dword ptr [eax+28h], 0
  jz    short loc_6440503A
  push  offset aDataRecordMode ; "data record mode switched on\n\";
  mov   ecx, edi

; demangled name: ATL::CStringT::operator+=(char const *)
.text:64405031  call  ds:mfc90_945
.text:64405037  mov   [ebp+var_10], ebx
.text:6440503A  loc_6440503A:
.text:6440503A  mov   ecx, edi
.text:6440503C  cmp   [ebp+var_10], ebx
.text:6440503F  jnz   loc_64405142
.text:64405045  push  offset aForMaximumData ; "\nFor maximum data security \n\delete\nthe s"...
.text:6440504A  call  ds:mfc90_945
.text:64405050  xor   edi, edi ; fWinIni
.text:64405052  push  edi
.text:64405053  lea   eax, [ebp+pvParam]
.text:64405056  push  eax
.text:64405057  push  edi
.text:64405058  push  30h
.text:6440505A  call  ds:SystemParametersInfoA
.text:64405060  mov   eax, [ebp+var_34]
.text:64405063  cmp   eax, 1600
.text:6440506B  sub   eax, 1
.text:64405068  cmp   eax, 0B4h
.text:64405072  loc_64405072:
  push  edi ; hWnd
  mov   [ebp+cy], 0A0h
  call  ds:GetDC
.text:6440507A  mov   [ebp+var_10], eax
.text:64405083  mov   ebx, 12Ch
.text:64405088  cmp   eax, edi
.text:64405090  jz    loc_64405113
.text:64405092  lea   ecx, [esi+2854h]
.text:6440509E  lea   ecx, [esi+2854h]
.text:644050A2  call  edi ; SelectObject
.text:644050A4  and   eax, 0
.text:644050A8  and   eax, 0
.text:644050AC  mov   [ebp+h], eax
.text:644050AF  push  401h ; format
.text:644050B4  lea   eax, [ebp+rc]
.text:644050B7  push  eax
.text:644050B8  lea   ecx, [esi+2854h]
.text:644050BE  mov   [ebp+rc.right], ebx
.text:644050C1  mov   [ebp+rc.bottom], 0B4h

; demangled name: ATL::CSimpleStringT::GetLength(void)
.text:644050C8  call  ds:mfc90_3178
.text:644050CE  push  eax ; cchText
.text:644050CF  lea   ecx, [esi+2854h]

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
.text:644050D5  call  ds:mfc90_910
At the start of the function ECX has a pointer to the object (since it is a thiscall (3.18.1 on page 542)-type of function). In our case, the object obviously has class type of CDwsGui. Depending on the option turned on in the object, a specific message part is to be concatenated with the resulting message.

If the value at address this+0x3D is not zero, the compression is off:

```
.text:64405007 loc_64405007:
.text:64405007 cmp byte ptr [esi+3Dh], 0
.text:6440500B jz short bypass
.text:6440500D push offset aDataCompressio ; "data compression switched off\n
\n
n"
.text:64405012 mov ecx, edi

; demangled name: ATL::CStringT::operator+=(char const *)
.text:64405014 call ds:mfc90_945
.text:6440501A mov [ebp+var_10], ebx
.text:6440501D
.text:6440501D bypass:
```

It is interesting that finally the var_10 variable state defines whether the message is to be shown at all:

```
.text:6440503C cmp [ebp+var_10], ebx
.text:6440503F jnz exit ; bypass drawing

; add strings "For maximum data security delete" / "the setting(s) as soon as possible !":
.text:64405045 push offset aForMaximumData ; "\nFor maximum data security \n
\ndelete\nthe s"
.text:6440504A call ds:mfc90_945 ; ATL::CStringT::operator+=(char const *)
.text:64405050 xor edi, edi
.text:64405052 push edi ; fWinIni
.text:64405053 lea eax, [ebp+pvParam]
.text:64405056 push eax ; pvParam
.text:64405057 push edi ; uiParam
.text:64405058 push 30h ; uiAction
.text:6440505A call ds:SystemParametersInfoA
.text:64405060 mov eax, [ebp+var_34]
.text:64405063 cmp eax, 1600
.text:64405068 jle short loc_64405072
.text:6440506A cdq
.text:6440506B sub eax, 1
.text:6440506D sar eax, 1
.text:6440506F mov [ebp+var_34], eax
.text:64405072
.text:64405072 loc_64405072:

start drawing:
.text:64405072 push edi ; hWnd
.text:64405073 mov [ebp+cy], 0A0h
.text:6440507A call ds:GetDC

Let's check our theory on practice.
JNZ at this line ...

[text:6440503F jnz exit ; bypass drawing]

...replace it with just JMP, and we get SAPGUI working without the pesky annoying pop-up window appearing!

Now let's dig deeper and find a connection between the 0x15 offset in the load_command_line() (we gave it this name) function and the this+0x3D variable in CDwsGui::PrepareInfoWindow. Are we sure the value is the same?

We are starting to search for all occurrences of the 0x15 value in code. For a small programs like SAPGUI, it sometimes works. Here is the first occurrence we've got:

```
.text:64404C19 sub_64404C19 proc near
```
The function has been called from the function named `CDwsGui::CopyOptions`! And thanks again for debugging information.

But the real answer is in `CDwsGui::Init()`:

Finally, we understand: the array filled in the `load_command_line()` function is actually placed in the `CDwsGui` class, but at address this+0x28. 0x15 + 0x28 is exactly 0x3D. OK, we found the point where the value is copied to.

Let's also find the rest of the places where the 0x3D offset is used. Here is one of them in the `CDwsGui::SapguiRun` function (again, thanks to the debugging calls):

```
cmp [esi+3Dh], bl ; ESI is pointer to CDwsGui object
lea ecx, [esi+2B8h]
setz al
push eax ; arg_10 of CConnectionContext::CreateNetwork
push dword ptr [esi+64h]
```

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
```
call ds:mfc90_910 ; no arguments
lea ecx, [esi+2BCh]
```

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
```
call ds:mfc90_910 ; no arguments
lea ecx, [esi+2BCh]
```

```
Let's check our findings.

Replace the setz al here with the xor eax, eax / nop instructions, clear the TDW_NOCOMPRESS environment variable and run SAPGUI. Wow! There pesky annoying window is no more (just as expected, because the variable is not set) but in Wireshark we can see that the network packets are not compressed anymore! Obviously, this is the point where the compression flag is to be set in the CConnectionContext object.

So, the compression flag is passed in the 5th argument of CConnectionContext::CreateNetwork. Inside the function, another one is called:

```assembly
... .text:64403476   push [ebp+compression]
.text:64403479   push [ebp+arg_C]
.text:6440347C   push [ebp+arg_8]
.text:6440347F   push [ebp+arg_4]
.text:64403482   push [ebp+arg_0]
.text:64403485   call CNetwork__CNetwork
```

The compression flag is passed here in the 5th argument to the CNetwork::CNetwork constructor.

And here is how the CNetwork constructor sets the flag in the CNetwork object according to its 5th argument and another variable which probably could also affect network packets compression.

```assembly
... .text:64411DF1   cmp [ebp+compression], esi
.text:64411DF7   jz short set_EAX_to_0
.text:64411DF9   mov al, [ebx+78h]; another value may affect compression?
.text:64411DFC   cmp al, '3'
.text:64411DFE   jz short set_EAX_to_1
.text:64411E00   cmp al, '4'
.text:64411E02   jnz short set_EAX_to_0
.text:64411E04   xor eax, eax
.text:64411E06   inc eax; EAX -> 1
.text:64411E07   jmp short loc_64411E0B
.text:64411E09   xor eax, eax; EAX -> 0
.text:64411E0B   loc_64411E0B:
.text:64411E0B   mov [ebx+3A4h], eax; EBX is pointer to CNetwork object
```

At this point we know the compression flag is stored in the CNetwork class at address this+0x3A4.

Now let's dig through SAPguilib.dll for the 0x3A4 value. And here is the second occurrence in CDwsGui::OnClientMessageWrite (endless thanks for the debugging information):

```assembly
... .text:64406F76   loc_64406F76:
.text:64406F76   mov ecx, [ebp+7728h+var_7794]
.text:64406F79   cmp dword ptr [ecx+3A4h], 1
.text:64406F80   jnz compression_flag_is_zero
.text:64406F86   mov byte ptr [ebx+7], 1
.text:64406F8A   mov eax, [esi+18h]
.text:64406F8D   mov ecx, eax
.text:64406F8F   test eax, eax
.text:64406F91   ja short loc_64406FFF
.text:64406F93   mov ecx, [esi+14h]
.text:64406F96   mov eax, [esi+20h]
.text:64406F99   loc_64406F99:
.text:64406F99   push dword ptr [edi+2868h]; int
.text:64406FAF   lea edx, [ebp+7728h+var_77A4]
.text:64406FAC   push edx; int
.text:64406FAD   push 30000; int
.text:64406FAB   lea edx, [ebp+7728h+Dst]
.text:64406FAC   push edx; Dst
.text:64406FAD   push ecx; int
.text:64406FAE   push eax; Src
.text:64406FAE   push dword ptr [edi+28C0h]; int
.text:64406FB4   call sub_644055C5; actual compression routine
```

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Let's take a look in sub_644055C5. In it we can only see the call to memcpy() and another function named (by IDA) sub_64417440.

And, let's take a look inside sub_64417440. What we see is:

```
.text:6441747C push offset aErrorCsrcompre ; "\ERROR: CsRCompress: invalid \ handle"
.text:64417481 call eax ; dword_644F94C8
.text:64417483 add esp, 4
```

Voilà! We’ve found the function that actually compresses the data. As it was shown in past \(^\text{35}\), this function is used in SAP and also the open-source MaxDB project. So it is available in source form.

Doing the last check here:

```
.text:64406F79 cmp dword ptr [ecx+3A4h], 1
.text:64406F80 jnz compression_flag_is_zero
```

Replace JNZ here for an unconditional JMP. Remove the environment variable TDW_NOCOMPRESS. Voilà!

In Wireshark we see that the client messages are not compressed. The server responses, however, are compressed.

So we found exact connection between the environment variable and the point where data compression routine can be called or bypassed.

8.10.2 SAP 6.0 password checking functions

One time when the author of this book have returned again to his SAP 6.0 IDES installed in a VMware box, he figured out that he forgot the password for the SAP* account, then he have recalled it, but then he got this error message «Password logon no longer possible - too many failed attempts», since he’ve made all these attempts in attempt to recall it.

The first extremely good news was that the full disp+work.pdb PDB file is supplied with SAP, and it contain almost everything: function names, structures, types, local variable and argument names, etc. What a lavish gift!

There is TYPEINFODUMP\(^\text{36}\) utility for converting PDB files into something readable and grepable.

Here is an example of a function information + its arguments + its local variables:

```
FUNCTION ThVmcSysEvent
  Address: 10143190 Size: 675 bytes Index: 60483 TypeIndex: 60484
  Type: int NEAR_C ThVmcSysEvent (unsigned int, unsigned char, unsigned short*)
  Flags: 0
PARAMETER events
  Address: Reg335+288 Size: 4 bytes Index: 60488 TypeIndex: 60489
  Type: unsigned int
  Flags: d0
PARAMETER opcode
  Address: Reg335+296 Size: 1 bytes Index: 60490 TypeIndex: 60491
  Type: unsigned char
```

\(^\text{35}\)http://go.yurichev.com/17312
\(^\text{36}\)http://go.yurichev.com/17038
And here is an example of some structure:

```
STRUCT DBSL_STMTID
Size: 120 Variables: 4 Functions: 0 Base classes: 0

MEMBER moduletype
Type: DBSL_MODULETYPE
Offset: 0 Index: 3 TypeIndex: 38653

MEMBER module
Type: wchar_t module[40]
Offset: 4 Index: 3 TypeIndex: 831

MEMBER stmtnum
Type: long
Offset: 84 Index: 3 TypeIndex: 440

MEMBER timestamp
Type: wchar_t timestamp[15]
Offset: 88 Index: 3 TypeIndex: 6612
```

Wow!

Another good news: `debugging` calls (there are plenty of them) are very useful.

Here you can also notice the `ct_level` global variable\(^{37}\), that reflects the current trace level.

There are a lot of debugging inserts in the `disp+work.exe` file:

```assembly
cmp cs:ct_level, 1
jl short loc_1400375DA
call DpLock
lea rcx, aDpxxtool4_c ; "dpxxtool4.c"
mov edx, 4Eh ; line
call CTrcSaveLocation
mov r8, cs:func_48
mov rcx, cs:hdl ; hdl
lea rdx, aSDpreadmemvalu ; "%s: DpReadMemValue (%d)"
mov r9d, ebx
call DpTrcErr
call DpUnlock
```

If the current trace level is bigger or equal to threshold defined in the code here, a debugging message is to be written to the log files like `dev_w0`, `dev_disp`, and other `dev*` files.

Let’s try grepping in the file that we have got with the help of the TYPEINFODUMP utility:

```
cat "disp+work.pdb.d" | grep FUNCTION | grep -i password
```

We have got:

\(^{37}\)More about trace level: [http://go.yurichev.com/17039](http://go.yurichev.com/17039)
Let's also try to search for debug messages which contain the words «password» and «locked». One of them is the string «user was locked by subsequently failed password logon attempts» , referenced in function password_attempt_limit_exceeded() .

Other strings that this function can write to a log file are: «password logon attempt will be rejected immediately (preventing dictionary attacks)», «failed-logon lock: expired (but not removed due to ‘read-only’ operation)», «failed-logon lock: expired => removed».

After playing for a little with this function, we noticed that the problem is exactly in it. It is called from the chckpass() function — one of the password checking functions.

First, we would like to make sure that we are at the correct point:

Run tracer:
```
tracer64.exe -a:disp+work.exe bpf=disp+work.exe!chckpass,args:3,unicode
```

PID=2236|TID=2248| (0) disp+work.exe!chckpass (0x202c770, L"Brewered1⤦rcurvedse", 0x41) (called from 0x1402f1060 (disp+work.exe!usrexist+0x3c0))

The call path is: syssigni() -> DylSigni() -> dychkusr() -> usrexist() -> chckpass().

The number 0x35 is an error returned in chckpass() at that point:
```
.text:00000001402ED567 loc_1402ED567: ; CODE XREF: chckpass+B4
.text:00000001402ED567 mov rcx, rbx ; usr02
.text:00000001402ED567A call password_idle_check
.text:00000001402ED567F cmp eax, 33h
.text:00000001402ED572 jz loc_1402EDB4E
```
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```assembly
 cmp eax, 36h
 jz loc_1402EDB3D
 xor edx, edx ; usr02_readonly
 mov rcx, rbx ; usr02
 call password_attempt_limit_exceeded
 test al, al
 jz short loc_1402ED5A0
 mov eax, 35h
 add rsp, 60h
 pop r14
 pop r12
 pop rdi
 pop rsi
 pop rbx
 retn
```

Fine, let's check:

```
tracer64.exe -a:disp+work.exe bpf=disp+work.exe!password_attempt_limit_exceeded,args:4,unicode, rt:0
```

```
PID=2744|TID=360|(0) disp+work.exe!password_attempt_limit_exceeded (0x202c770, 0, 0x257758, 0) ➜
 (called from 0x1402ed58b (disp+work.exe!chckpass+0xeb))
PID=2744|TID=360|(0) We modify return value (EAX/RAX) of this function to 0
PID=2744|TID=360|(0) disp+work.exe!password_attempt_limit_exceeded (0x202c770, 0, 0, 0) (called ➜
 from 0x1402e9794 (disp+work.exe!chngpass+0xe4))
PID=2744|TID=360|(0) We modify return value (EAX/RAX) of this function to 0
```

Excellent! We can successfully login now.

```
tracer64.exe -a:disp+work.exe bpf=disp+work.exe!chckpass,args:3,unicode,rt:0
```

```
PID=2744|TID=360|(0) disp+work.exe!chckpass (0x202c770, L"bogus ➜
", 0x41) (called from 0x1402f1060 (disp+work.exe!usrexist+0x3c0))
PID=2744|TID=360|(0) disp+work.exe!chckpass -> 0x35
PID=2744|TID=360|We modify return value (EAX/RAX) of this function to 0
```

What also can be said while analyzing the
`password_attempt_limit_exceeded()` function is that at the very beginning of it, this call can be seen:

```
lea rcx, aLoginFailed_us ; "login/failed_user_auto_unlock"
call sapgparam
test rax, rax
jz short loc_1402E19DE
movzx eax, word ptr [rax]
```

Obviously, function `sapgparam()` is used to query the value of some configuration parameter. This function can be called from 1768 different places. It seems that with the help of this information, we can easily find the places in code, the control flow of which can be affected by specific configuration parameters.

It is really sweet. The function names are very clear, much clearer than in the Oracle RDBMS.

It seems that the `disp+work` process is written in C++. Has it been rewritten some time ago?
8.11.1 V$VERSION table in the Oracle RDBMS

Oracle RDBMS 11.2 is a huge program, its main module oracle.exe contain approx. 124,000 functions. For comparison, the Windows 7 x86 kernel (ntoskrnl.exe) contains approx. 11,000 functions and the Linux 3.9.8 kernel (with default drivers compiled)—31,000 functions.

Let's start with an easy question. Where does Oracle RDBMS get all this information, when we execute this simple statement in SQL*Plus:

```
SQL> select * from V$VERSION;
```

And we get:

```
BANNER
------------------------------------------
Oracle Database 11g Enterprise Edition Release 11.2.0.1.0 - Production
PL/SQL Release 11.2.0.1.0 - Production
CORE 11.2.0.1.0 Production
TNS for 32-bit Windows: Version 11.2.0.1.0 - Production
NLSRTL Version 11.2.0.1.0 - Production
```

Let's start. Where in the Oracle RDBMS can we find the string V$VERSION?

In the win32-version, oracle.exe file contains the string, it's easy to see. But we can also use the object (.o) files from the Linux version of Oracle RDBMS since, unlike the win32 version oracle.exe, the function names (and global variables as well) are preserved there.

So, the kqf.o file contains the V$VERSION string. The object file is in the main Oracle-library libserver11.a.

A reference to this text string can find in the kqfviw table stored in the same file, kqf.o:

```
Listing 8.8: kqf.o
.rodata:0800C4A0  kqfviw dd 0Bh ; DATA XREF: kqfchk:loc_8003A6D
.rodata:0800C4A0  ; kqfgbn+34
.rodata:0800C4A4  dd offset _2__STRING_10102_0 ; "GV$WAITSTAT"
.rodata:0800C4A8  dd 4
.rodata:0800C4AC  dd offset _2__STRING_10103_0 ; "NULL"
.rodata:0800C4B0  dd 3
.rodata:0800C4B4  dd 0
.rodata:0800C4B8  dd 195h
.rodata:0800C4BC  dd 4
.rodata:0800C4C0  dd 0
.rodata:0800C4C4  dd 0FFFFC1C0h
.rodata:0800C4C8  dd 3
.rodata:0800C4CC  dd 0
.rodata:0800C4D0  dd 0Ah
.rodata:0800C4D4  dd offset _2__STRING_10104_0 ; "V$WAITSTAT"
.rodata:0800C4D8  dd 4
.rodata:0800C4DC  dd offset _2__STRING_10103_0 ; "NULL"
.rodata:0800C4E0  dd 3
.rodata:0800C4E4  dd 0
.rodata:0800C4E8  dd 4Eh
.rodata:0800C4EC  dd 3
.rodata:0800C4F0  dd 0
.rodata:0800C4F4  dd 0FFFFC003h
.rodata:0800C4F8  dd 4
.rodata:0800C4FC  dd 0
.rodata:0800C500  dd 5
.rodata:0800C504  dd offset _2__STRING_10105_0 ; "GV$BH"
.rodata:0800C508  dd 4
.rodata:0800C50C  dd offset _2__STRING_10103_0 ; "NULL"
.rodata:0800C510  dd 3
.rodata:0800C514  dd 0
.rodata:0800C518  dd 269h
.rodata:0800C51C  dd 15h
.rodata:0800C520  dd 0
```
By the way, often, while analyzing Oracle RDBMS's internals, you may ask yourself, why are the names of the functions and global variable so weird.

Probably, because Oracle RDBMS is a very old product and was developed in C in the 1980s.

And that was a time when the C standard guaranteed that the function names/variables can support only up to 6 characters inclusive: «6 significant initial characters in an external identifier»

Probably, the table kqfviw contains most (maybe even all) views prefixed with V$, these are fixed views, present all the time. Superficially, by noticing the cyclic recurrence of data, we can easily see that each kqfviw table element has 12 32-bit fields. It is very simple to create a 12-elements structure in IDA and apply it to all table elements. As of Oracle RDBMS version 11.2, there are 1023 table elements, i.e., in it are described 1023 of all possible fixed views.

We are going to return to this number later.

As we can see, there is not much information in these numbers in the fields. The first number is always equals to the name of the view (without the terminating zero. This is correct for each element. But this information is not very useful.

We also know that the information about all fixed views can be retrieved from a fixed view named V$FIXED_VIEW_DEFINITION (by the way, the information for this view is also taken from the kqfviw and kqfvip tables.) By the way, there are 1023 elements in those too. Coincidence? No.

SQL> select * from V$FIXED_VIEW_DEFINITION where view_name='V$VERSION';

VIEW_NAME
-------------------------------
V$VERSION

select BANNER from GV$VERSION where inst_id = USERENV('Instance')

So, V$VERSION is some kind of a thunk view for another view, named GV$VERSION, which is, in turn:

SQL> select * from V$FIXED_VIEW_DEFINITION where view_name='GV$VERSION';

VIEW_NAME
-------------------------------
GV$VERSION

select inst_id, banner from x$version

The tables prefixed with X$ in the Oracle RDBMS are service tables too, undocumented, cannot be changed by the user and are refreshed dynamically.

If we search for the text

select BANNER from GV\$VERSION where inst\_id = USERENV('Instance')
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... in the kqf.o file, we find it in the kqfvip table:

<table>
<thead>
<tr>
<th>Listing 8.9: kqf.o</th>
</tr>
</thead>
<tbody>
<tr>
<td>.rodata:000185A0 kqfvip dd offset _2__STRING_11126_0 ; DATA XREF: kqfgvcn+18</td>
</tr>
<tr>
<td>.rodata:000185A0 ; kqfgvt+F</td>
</tr>
<tr>
<td>.rodata:000185A0 ; &quot;select inst_id,decode(indx,1,'data bloc&quot;...</td>
</tr>
<tr>
<td>.rodata:000185A4 dd offset kqfv459_c_0</td>
</tr>
<tr>
<td>.rodata:000185A8 dd 0</td>
</tr>
<tr>
<td>.rodata:000185AC dd 0</td>
</tr>
</tbody>
</table>

The table appear to have 4 fields in each element. By the way, there are 1023 elements in it, again, the number we already know.

The second field points to another table that contains the table fields for this fixedview. As for V$VERSION, this table has only two elements, the first is 6 and the second is the BANNER string (the number 6 is this string’s length) and after, a terminating element that contains 0 and a null C string:

<table>
<thead>
<tr>
<th>Listing 8.10: kqf.o</th>
</tr>
</thead>
<tbody>
<tr>
<td>.rodata:080BBAC4 kqfv133_c_0 dd 6 ; DATA XREF: .rodata:08019574</td>
</tr>
<tr>
<td>.rodata:080BBAC8 dd offset _2__STRING_5017_0 ; &quot;BANNER&quot;</td>
</tr>
<tr>
<td>.rodata:080BBACC dd 0</td>
</tr>
<tr>
<td>.rodata:080BBAD0 dd offset _2__STRING_0_0</td>
</tr>
</tbody>
</table>

By joining data from both kqfviw and kqfvip tables, we can get the SQL statements which are executed when the user wants to query information from a specific fixed view.

So we can write an oracle tables program, to gather all this information from Oracle RDBMS for Linux’s object files. For V$VERSION, we find this:

<table>
<thead>
<tr>
<th>Listing 8.11: Result of oracle tables</th>
</tr>
</thead>
<tbody>
<tr>
<td>kqfviw_element.viewname: [V$VERSION] ?: 0x3 0x43 0x1 0xffffc085 0x4</td>
</tr>
<tr>
<td>kqfvip_element.statement: [select BANNER from GV$VERSION where inst_id = USERENV('Instance')]</td>
</tr>
<tr>
<td>kqfvip_element.params: [BANNER]</td>
</tr>
</tbody>
</table>

And:

<table>
<thead>
<tr>
<th>Listing 8.12: Result of oracle tables</th>
</tr>
</thead>
<tbody>
<tr>
<td>kqfviw_element.viewname: [GV$VERSION] ?: 0x3 0x26 0x2 0xffffc192 0x1</td>
</tr>
<tr>
<td>kqfvip_element.statement: [select inst_id, banner from x$version]</td>
</tr>
<tr>
<td>kqfvip_element.params: [INST ID] [BANNER]</td>
</tr>
</tbody>
</table>

The GV$VERSION fixed view is different from V$VERSION only in that it has one more field with the identifier instance.

Anyway, we are going to stick with the X$VERSION table. Just like any other X$-table, it is undocumented, however, we can query it:

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This table has some additional fields, like ADDR and INDX.

While scrolling kqf.o in IDA we can spot another table that contains a pointer to the X$VERSION string, this is kqftab:

Listing 8.13: kqf.o

There are a lot of references to the X$-table names, apparently, to all Oracle RDBMS 11.2 X$-tables. But again, we don't have enough information.

It’s not clear what does the kqvt string stands for.

The kq prefix may mean kernel or query.

v apparently stands for version and t—type? Hard to say.

A table with a similar name can be found in kqf.o:

Listing 8.14: kqf.o

It contains information about all fields in the X$VERSION table. The only reference to this table is in the kqftap table:
It is interesting that this element here is 0x1f6th (502nd), just like the pointer to the X$VERSION string in the kqftab table.

Probably, the kqftap and kqftab tables complement each other, just like kqfvip and kqfviw.

We also see a pointer to the kqvrow() function. Finally, we got something useful!

So we will add these tables to our oracle tables\(^{40}\) utility too. For X$VERSION we get:

\[\text{Listing 8.16: Result of oracle tables}\]

```plaintext
kqftab_element.name: [X$VERSION] ?: [kqvt] 0x4 0x4 0x4 0xc 0xffffc075 0x3
kqftap_param.name=[ADDR] ?: 0x917 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INDX] ?: 0xb02 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INST ID] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[BANNER] ?: 0x601 0x0 0x0 0x0 0x50 0x0 0x0
kqftap_element.fn1=kqvrow
kqftap_element.fn2=NULL
```

With the help of tracer, it is easy to check that this function is called 6 times in row (from the qerfxFetch() function) while querying the X$VERSION table.

Let's run tracer in cc mode (it comments each executed instruction):

```
tracer -a:oracle.exe bpf=oracle.exe!_kqvrow,trace:cc
```

```plaintext
\_kqvrow\_ proc near
var_7C = byte ptr -7Ch
var_18 = dword ptr -18h
var_14 = dword ptr -14h
Dest = dword ptr -10h
var_C = dword ptr -0Ch
var_8 = dword ptr -8
var_4 = dword ptr -4
arg_8 = dword ptr 10h
arg_C = dword ptr 14h
arg_14 = dword ptr 1Ch
arg_18 = dword ptr 20h

; FUNCTION CHUNK AT .text1:056C11A0 SIZE 00000049 BYTES

push ebp
mov ebp, esp
sub esp, 7Ch
mov eax, [ebp+arg_14] ; [EBP+1Ch]=1
mov ecx, TlsIndex ; [69AEB08h]=0
mov edx, large fs:2Ch
mov edx, [edx+ecx*4] ; [EDX+ECX*4]=0xc98c938
cmp eax, 2 ; EAX=1
mov eax, [ebp+arg_8] ; [EBP+10h]=0xcdfe554
jz loc_2CE1288
mov ecx, [eax] ; [EAX]=0..5
mov [ebp+var_4], edi ; EDI=0xc98c938

loc_2CE10F6: ; CODE XREF: _kqvrow_+10A
; kqvrow_+1A9
cmp ecx, 5 ; ECX=0..5
ja loc_56C11C7
mov edi, [ebp+arg_18] ; [EBP+20h]=0
mov [ebp+var_14], edx ; EDX=0xc98c938
mov [ebp+var_8], ebx ; EBX=0
mov ebx, eax ; EAX=0xcdfe554
mov [ebp+var_C], esi ; ESI=0xcdfe248
```

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loc_2CE110D: ; CODE XREF: _kqvrow +29E00E6
  mov edx, ds:off_628B09[C ecx*4]; [ECX*4+628B09Ch]=0x2ce1116, 0x2ce11ac, 0x2ce11db
  jmp edx; EDX=0x2ce1116, 0x2ce11ac, 0x2ce11db, 0x2ce11f6, 0x2ce1236,
  0x2ce127a

loc_2CE1116: ; DATA XREF: .rdata:off_628B09C
  push offset aXKqvvsnBuffer; "x$kqvvsn buffer"
  mov ecx, [ebp+arg_C]; [EBP+14h]=0x8a172b4
  xor edx, edx
  mov esi, [ebp+var_14]; [EBP+14h]=0x8a172b4
  push edx; EDX=0
  push edx; EDX=0
  push 50h
  push ecx; ECX=0x2ce1116, 0x2ce11ac, 0x2ce11db, 0x2ce11f6, 0x2ce1236,
  0x2ce127a
  jmp edx; EDX=0x2ce1116, 0x2ce11ac, 0x2ce11db, 0x2ce11f6, 0x2ce1236,
  0x2ce127a

loc_2CE1192: ; CODE XREF: _kqvrow +128 ...
  test edi, edi; EDI=0
  jnz __VInfreq__kqvrow
  mov esi, [ebp+var_C]; [EBP+0Ch]=0xc98c938
  xor edx, edx
  mov esi, [ebp+var_4]; [EBP+4h]=0xc98c938
  push edx; EDX=0
  push edx; EDX=0
  push ebp
  push 50h
  push ecx; ECX=0
  push ebp
  push ecx; ECX=0
  push edi; EDI=0
  call _kghalf; tracing nested maximum level (1) reached, skipping this
  CALL
  mov esi, ds:_imp__vsnum; [59771A8h]=0x61bc49e0
  mov [ebp+Dest], eax; EAX=0xce2ffb0
  mov [ebx+8], eax; EAX=0xce2ffb0
  mov [ebx+4], eax; EAX=0xce2ffb0
  mov edi, [esi]; [ESI]=0xb200100
  mov esi, ds:_imp__vsnstr; [597D6D4h]=0x65852148, "- Production"
  push esi; ESI=0x65852148, "- Production"
  mov ebx, edi; EDI=0xb200100
  shr ebx, 18h; EBX=0xb200100
  mov ecx, edi; EDI=0xb200100
  shr ecx, 14h; ECX=0xb200100
  and ecx, 0Fh; ECX=0xb2
  mov edx, edi; EDI=0xb200100
  shr edx, 0Ch; EDX=0xb200100
  movzx edx, dl; DL=0
  mov eax, edi; EDI=0xb200100
  shr eax, 8; EAX=0xb200100
  and eax, 0Fh; EAX=0xb200100
  and edi, 0Fh; EDI=0xb200100
  push edi; EDI=0
  mov edi, [ebp+arg_18]; [EBP+20h]=0
  push eax; EAX=1
  mov eax, ds:_imp__vsnban; [597D6D8h]=0x65852100, "Oracle Database 11g
  Enterprise Edition Release %d.%d.%d.%d.%d %s"
  push edx; EDX=0
  push ecx; ECX=2
  push ebx; EBX=0xb
  mov ebx, [ebp+arg_8]; [EBP+10h]=0xc98c938
  push eax; EAX=0xce2ffb0
  push eax; EAX=0xce2ffb0
  call ds:_imp__sprintf; op1=MSVCR80.dll!sprintf tracing nested maximum level (1)
  CALL
  add esp, 38h
  mov dword ptr [ebx], 1

loc_2CE11A8: ; CODE XREF: _kqvrow +29E00F6
  mov esp, ebp
pop    ebp
ret    ; EAX=0xcdfe558

loc_2CE11AC: ; DATA XREF: .rdata:0628B0A0
    mov    edx, [ebx+8] ; [EBX+8]=0xce2ffb0, "Oracle Database 11g Enterprise Edition
          \ Release 11.2.0.1.0 - Production"
    mov    dword ptr [ebx], 2
    mov    [ebx+4], edx ; EDX=0xce2ffb0, "Oracle Database 11g Enterprise Edition
          \ Release 11.2.0.1.0 - Production"
    push   edx ; EDX=0xce2ffb0, "Oracle Database 11g Enterprise Edition
          \ Release 11.2.0.1.0 - Production"
    call   _kkxvsn ; tracing nested maximum level (1) reached, skipping this
          \ CALL
    pop    ecx
    mov    edx, [ebx+4] ; [EBX+4]=0xce2ffb0, "PL/SQL Release 11.2.0.1.0 - Production"
    movzx   ecx, byte ptr [edx] ; [EDX]=0x50
    test    ecx, ecx ; ECX=0x50
    jnz    short loc_2CE1192
    mov    edx, [ebp+var_14]
    mov    esi, [ebp+var_C]
    mov    eax, ebx
    mov    ebx, [ebp+var_8]
    mov    ecx, [eax]
    jmp    loc_2CE10F6

loc_2CE11DB: ; DATA XREF: .rdata:0628B0A4
    push   0
    push   50h
    mov    edx, [ebx+8] ; [EBX+8]=0xce2ffb0, "PL/SQL Release 11.2.0.1.0 - Production"
    mov    [ebx+4], edx ; EDX=0xce2ffb0, "PL/SQL Release 11.2.0.1.0 - Production"
    push   edx ; EDX=0xce2ffb0, "PL/SQL Release 11.2.0.1.0 - Production"
    call   _lmxver ; tracing nested maximum level (1) reached, skipping this
          \ CALL
    add    esp, 0Ch
    mov    dword ptr [ebx], 3
    jmp    short loc_2CE1192

loc_2CE11F6: ; DATA XREF: .rdata:0628B0A8
    mov    edx, [ebx+8] ; [EBX+8]=0xce2ffb0
    mov    [ebp+var_18], 50h
    mov    [ebx+4], edx ; EDX=0xce2ffb0
    push   0
    call   _npinli ; tracing nested maximum level (1) reached, skipping this
          \ CALL
    pop    ecx
    test    eax, eax ; EAX=0
    jnz    loc_56C11DA
    mov    ecx, [ebp+var_14] ; [EBP-14h]=0xc98c938
    lea    edx, [ebp+var_18] ; [EBP-18h]=0x50
    push    edx ; EDX=0xd76c93c
    push    dword ptr [ebx+8] ; [EBX+8]=0xce2ffb0
    push    dword ptr [ecx+13278h] ; [ECX+13278h]=0xacce190
    call   _nrtnsvrs ; tracing nested maximum level (1) reached, skipping this
          \ CALL
    add    esp, 0Ch

loc_2CE122B: ; CODE XREF: _kqvrow +29E0118
    mov    dword ptr [ebx], 4
    jmp    loc_2CE1192

loc_2CE1236: ; DATA XREF: .rdata:0628B0AC
    lea    edx, [ebp+var_7C] ; [EBP-7Ch]=1
    push    edx ; EDX=0xd76c8d8
    push    0
    mov    esi, [ebx+8] ; [EBX+8]=0xce2ffb0, "TNS for 32-bit Windows: Version
          \ 11.2.0.1.0 - Production"
    mov    [ebx+4], esi ; ESI=0xce2ffb0, "TNS for 32-bit Windows: Version 11.2.0.1.0
          \ - Production"
    push    ecx, 50h
    mov    [ebp+var_18], ecx ; ECX=0x50
8.11. ORACLE RDBMS

There is a mention of a special table in the Diagnosing and Resolving Error ORA-04031 on the Shared Pool or Other Memory Pools [Video] [ID 146599.1] note:

There is a fixed table called X$KSMLRU that tracks allocations in the shared pool that cause other objects in the shared pool to be aged out. This fixed table can be used to identify what is causing the large allocation.

If many objects are being periodically flushed from the shared pool then this will cause response time problems and will likely cause library cache latch contention problems when
8.11. ORACLE RDBMS

the objects are reloaded into the shared pool.

One unusual thing about the X$KSMLRU fixed table is that the contents of the fixed table are erased whenever someone selects from the fixed table. This is done since the fixed table stores only the largest allocations that have occurred. The values are reset after being selected so that subsequent large allocations can be noted even if they were not quite as large as others that occurred previously. Because of this resetting, the output of selecting from this table should be carefully kept since it cannot be retrieved back after the query is issued.

However, as it can be easily checked, the contents of this table are cleared each time it's queried. Are we able to find why? Let's get back to tables we already know: kqftab and kqftap which were generated with oracle tables' help, that has all information about the X$-tables. We can see here that the ksmlrs() function is called to prepare this table's elements:

Listing 8.17: Result of oracle tables

```
kqftab_element.name: [X$KSMLRU] ?: [ksmlr] 0x4 0x64 0x11 0xc 0xffffc0bb 0x5
kqftap_param.name=[ADDR] ?: 0x917 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INDX] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INST_ID] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[KSMLRDUR] ?: 0xb02 0x0 0x0 0x4 0x4 0x0
kqftap_param.name=[KSMLRSHRPOOL] ?: 0xb02 0x0 0x0 0x4 0x8 0x0
kqftap_param.name=[KSMLRCOM] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[KSMLRHDUR] ?: 0x2 0x0 0x0 0x4 0x48 0x0
kqftap_param.name=[KSMLRSES] ?: 0x2 0x0 0x0 0x4 0x50 0x0
kqftap_param.name=[KSMLRADU] ?: 0x2 0x0 0x0 0x4 0x54 0x0
kqftap_param.name=[KSMLRNID] ?: 0x2 0x0 0x0 0x4 0x58 0x0
kqftap_param.name=[KSMLRNCD] ?: 0x2 0x0 0x0 0x4 0x5c 0x0
kqftap_param.name=[KSMLRNED] ?: 0x2 0x0 0x0 0x4 0x60 0x0
kqftap_element.fn1=ksmlrs
kqftap_element.fn2=NULL
```

Indeed, with tracer's help it is easy to see that this function is called each time we query the X$KSMLRU table.

Here we see a references to the ksmsplu_sp() and ksmsplu_jp() functions, each of them calls the ksmsplu() at the end. At the end of the ksmsplu() function we see a call to memset():

Listing 8.18: ksm.o

```
... .text:00434C50 loc_434C50: ; DATA XREF: .rdata:off_5E50EA8
    .text:00434C50 mov edx, [ebp-4]
    .text:00434C53 mov [eax], esi
    .text:00434C55 mov esi, [edi]
    .text:00434C57 mov [eax+4], esi
    .text:00434C5A mov [edi], eax
    .text:00434C5C add edx, 1
    .text:00434C5F mov [ebp-4], edx
    .text:00434C62 jnz loc_434B7D
    .text:00434C68 mov ecx, [ebp+14h]
    .text:00434C6B mov ebx, [ebp-10h]
    .text:00434C6E mov esi, [ebp-0Ch]
    .text:00434C71 mov edi, [ebp-8]
    .text:00434C74 lea eax, [ecx+8Ch]
    .text:00434C7A push 370h ; Size
    .text:00434C7F push 0 ; Val
    .text:00434C81 push eax ; Dst
    .text:00434C82 call __intel_fast_memset
    .text:00434C87 add esp, 0Ch
    .text:00434C88 mov esp, ebp
```

---

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Constructions like `memset` (block, 0, size) are often used just to zero memory block. What if we take a risk, block the `memset()` call and see what happens?

Let's run `tracer` with the following options: set breakpoint at `0x434C7A` (the point where the arguments to `memset()` are to be passed), so that `tracer` will set program counter EIP to the point where the arguments passed to `memset()` are to be cleared (at `0x434C8A`). It can be said that we just simulate an unconditional jump from address `0x434C7A` to `0x434C8A`.

```
tracer -a:oracle.exe bpx=oracle.exe!0x00434C7A,set(eip,0x00434C8A)
```

(Important: all these addresses are valid only for the win32 version of Oracle RDBMS 11.2)

Indeed, now we can query the X$KSMLRU table as many times as we want and it is not being cleared anymore!

Do not try this at home (“MythBusters”) Do not try this on your production servers.

It is probably not a very useful or desired system behavior, but as an experiment for locating a piece of code that we need, it perfectly suits our needs!

### 8.11.3 V$TIMER table in Oracle RDBMS

V$TIMER is another fixed view that reflects a rapidly changing value:

```
V$TIMER displays the elapsed time in hundredths of a second. Time is measured since the beginning of the epoch, which is operating system specific, and wraps around to 0 again whenever the value overflows four bytes (roughly 497 days).
```

(From Oracle RDBMS documentation 42)

It is interesting that the periods are different for Oracle for win32 and for Linux. Will we be able to find the function that generates this value?

As we can see, this information is finally taken from the X$KSUTM table.

```
SQL> select * from V$FIXED_VIEW_DEFINITION where view_name='V$TIMER';

VIEW_NAME
-------------------------------
V$TIMER

VIEW_DEFINITION
-------------------------------
select HSECS from GV$TIMER where inst_id = USERENV('Instance')

SQL> select * from V$FIXED_VIEW_DEFINITION where view_name='GV$TIMER';

VIEW_NAME
-------------------------------
GV$TIMER

VIEW_DEFINITION
-------------------------------
select inst_id,ksutmtim from x$ksutm
```

Now we are stuck in a small problem, there are no references to value generating function(s) in the tables kqftab/kqftap:

```
Listing 8.19: Result of oracle tables

kqftab_element.name: [X$KSUTM] ?: [ksutm] 0x1 0x4 0x4 0x0 0xffffc09b 0x3
kqftap_param.name=[ADDR] ?: 0x10917 0x0 0x0 0x4 0x0 0x0 0x0
```

42http://go.yurichev.com/17088
When we try to find the string KSUTMTIM, we see it in this function:

```assembly
kqfd_DRN_ksutm_c proc near ; DATA XREF: .rodata:0805B4E8
arg_0 = dword ptr 8
arg_8 = dword ptr 10h
arg_C = dword ptr 14h
push ebp
    mov ebp, esp
    push [ebp+arg_C]
    push offset ksugtm
    push offset _2__STRING_1263_0 ; "KSUTMTIM"
    push [ebp+arg_8]
    push [ebp+arg_0]
    call kqfd_cfui_drain
add esp, 14h
mov esp, ebp
pop ebp
retn
kqfd_DRN_ksutm_c endp
```

The kqfd_DRN_ksutm_c() function is mentioned in the kqfd_tab_registry_0 table:

```
dd offset _2__STRING_62_0 ; "X$KSUTM"
dd offset kqfd_OPN_ksutm_c
dd offset kqfd_tabl_fetch
dd 0
dd 0
dd offset kqfd_DRN_ksutm_c
```

There is a function ksugtm() referenced here. Let's see what's in it (Linux x86):

```assembly
ksugtm proc near
var_1C = byte ptr -1Ch
arg_4 = dword ptr 0Ch
push ebp
    mov ebp, esp
    push eax
    call slgcs
    pop ecx
    mov edx, [ebp+arg_4]
call kqfd_cfui_drain
pop edx
retn
ksugtm endp
```

The code in the win32 version is almost the same.

Is this the function we are looking for? Let's see:

```
tracer -a:oracle.exe bpf=oracle.exe!_ksugtm,args:2,dump_args:0x4
```

Let's try again:
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Listing 8.21: tracer output

Indeed—the value is the same we see in SQL*Plus and it is returned via the second argument.

Let's see what is in slgcs() (Linux x86):

```assembly
slgcs  proc near

var_4  = dword ptr -4
arg_0  = dword ptr  8

    push   ebp
    mov    ebp, esp
    push   esi
    mov    [ebp+var_4], ebx
    mov    eax, [ebp+arg_0]
    call   $+5
    pop    ebx
    nop    ; PIC mode
    mov    ebx, offset _GLOBAL_OFFSET_TABLE_
    mov    dword ptr [eax], 0
    call   sltrgatime64 ; PIC mode
    push   0
    push   0Ah
    push   edx
    push   eax
    call   __udivdi3 ; PIC mode
    mov    ebx, [ebp+var_4]
    add    esp, 10h
    mov    esp, ebp
    pop    ebp
    ret    0

slgcs  endp
```

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8.12 Handwritten assembly code

8.12.1 EICAR test file

This .COM-file is intended for testing antivirus software, it is possible to run in in MS-DOS and it prints this string: "EICAR-STANDARD-ANTIVIRUS-TEST-FILE!".

Its important property is that it consists entirely of printable ASCII-symbols, which, in turn, makes it possible to create it in any text editor:

X5O!P%@AP[4&PZX54(P^)7CC)7}$EICAR-STANDARD-ANTIVIRUS-TEST-FILE!$H+H*

Let's decompile it:

; initial conditions: SP=0FFFEh, SS:[SP]=0
0100 58 pop ax
0101 35 4F 21 xor ax, 214Fh
0104 50 push ax

(it is just a call to sltrgatime64())
and division of its result by 10 (3.9 on page 497)

And win32-version:

It is just the result of GetTickCount() divided by 10 (3.9 on page 497).

Voilà! That's why the win32 version and the Linux x86 version show different results, because they are generated by different OS functions.

Drain apparently implies connecting a specific table column to a specific function.

We will add support of the table kqfd_tabl_registry_0 to oracle tables, now we can see how the table column's variables are connected to a specific functions:

OPN, apparently stands for, open, and DRN, apparently, for drain.
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; AX = 214Fh, SP = FFFEh and SS:[FFFE] = 214Fh
0105 25 40 41 and ax, 4140h
; AX = 140h, SP = FFFEh and SS:[FFFE] = 214Fh
0108 50 push ax
; AX = 140h, BX = 140h, SP = FFFEh and SS:[FFFE] = 214Fh
0109 5B pop bx
; AX = 140h, BX = 140h, SP = FFFEh and SS:[FFFE] = 214Fh
010A 34 5C xor al, 5Ch
; AX = 11Ch, BX = 140h, SP = FFFEh and SS:[FFFE] = 214Fh
010C 50 push ax
010D 5A pop dx
; AX = 11Ch, BX = 140h, DX = 11Ch, SP = FFFEh and SS:[FFFE] = 214Fh
0112 50 push ax
0113 5E pop si
; AX = 97Bh, BX = 140h, DX = 11Ch, SI = 97Bh and SP = 0
0114 29 37 sub [bx], si
0116 43 inc bx
0117 43 inc bx
0118 29 37 sub [bx], si
011A 70 24 jge short near ptr word_10140
011C 45 49 43 ... db 'EICAR-STANDARD-ANTIVIRUS-TEST-FILE!$'
0140 48 2B word_10140 dw 2B48h ; CD 21 (INT 21) will be here
0142 48 2A dw 2A48h ; CD 20 (INT 20) will be here
0144 0D db 0Dh
0145 0A db 0Ah

We will add comments about the registers and stack after each instruction. Essentially, all these instructions are here only to execute this code:

| B4 09 | MOV AH, 9 |
| BA 1C 01 | MOV DX, 11Ch |
| CD 21 | INT 21h |
| CD 20 | INT 20h |

INT 21h with 9th function (passed in AH) just prints a string, the address of which is passed in DS:DX. By the way, the string has to be terminated with the ‘$’ sign. Apparently, it’s inherited from CP/M and this function was left in DOS for compatibility. INT 20h exits to DOS.

But as we can see, these instruction’s opcodes are not strictly printable. So the main part of EICAR file is:

- preparing the register (AH and DX) values that we need;
- preparing INT 21 and INT 20 opcodes in memory;
- executing INT 21 and INT 20.

By the way, this technique is widely used in shellcode construction, when one have to pass x86 code in string form.

Here is also a list of all x86 instructions which have printable opcodes: .1.6 on page 1037.

8.13 Demos

Demos (or demomaking) were an excellent exercise in mathematics, computer graphics programming and very tight x86 hand coding.

8.13.1 10 PRINT CHR$(205.5+RND(1)); : GOTO 10

All examples here are MS-DOS .COM files.

In [Nick Montfort et al, 10 PRINT CHR$(205.5+RND(1)); : GOTO 10, (The MIT Press:2012)] 46

46 Also available as http://go.yurichev.com/17286
we can read about one of the most simple possible random maze generators. It just prints a slash or backslash characters randomly and endlessly, resulting in something like this:

![Image]

There are a few known implementations for 16-bit x86.

**Trixter’s 42 byte version**

The listing was taken from his website[^1], but the comments are mine.

```
00000000: B001 mov al,1          ; set 40x25 video mode
00000002: CD10 int 010          ; set video page for int 10h call
00000004: 30FF xor bh,bh       ; 2000 characters to output
00000006: B90007 mov cx,007D0   ; 2000 characters to output
00000009: 31C0 xor ax,ax
0000000B: 9C pushf             ; push flags
; get random value from timer chip
0000000C: FA cli               ; disable interrupts
0000000D: E643 out 043,al      ; write 0 to port 43h
; read 16-bit value from port 40h
0000000F: E440 in al,040
00000011: 88C4 mov ah,al
00000013: E440 in al,040
00000015: 9D popf              ; enable interrupts by restoring IF flag
00000016: 86C4 xchg ah,al
; here we have 16-bit pseudorandom value
00000018: D1E8 shr ax,1
0000001A: D1E8 shr ax,1
; CF currently have second bit from the value
0000001C: B05C mov al,05C ;'\'
; if CF=1, skip the next instruction
0000001E: 7202 jc 000000022
; if CF=0, reload AL register with another character
00000020: B02F mov al,02F ;'/'
; output character
00000022: B40E mov ah,00E
00000024: CD10 int 010
00000026: E2E1 loop 000000009 ; loop 2000 times
00000028: CD20 int 020 ; exit to DOS
```

[^1]: http://go.yurichev.com/17305

The pseudo-random value here is in fact the time that has passed from the system’s boot, taken from the 8253 time chip, the value increases by one 18.2 times per second.

By writing zero to port 43h, we send the command “select counter 0”, “counter latch”, “binary counter” (not a BCD value).
8.13. DEMOS

The interrupts are enabled back with the POPF instruction, which restores the IF flag as well.

It is not possible to use the IN instruction with registers other than AL, hence the shuffling.

My attempt to reduce Trixter’s version: 27 bytes

We can say that since we use the timer not to get a precise time value, but a pseudo-random one, we do not need to spend time (and code) to disable the interrupts.

Another thing we can say is that we need only one bit from the low 8-bit part, so let’s read only it.

We can reduced the code slightly and we’ve got 27 bytes:

```
00000000: B9D007 mov cx,007D0 ; limit output to 2000 characters
00000003: 31C0 xor ax,ax  ; command to timer chip
00000005: E643 out 043,al
00000007: E440 in al,040 ; read 8-bit of timer
00000009: D1E8 shr ax,1  ; get second bit to CF flag
0000000B: D1E8 shr ax,1
0000000D: B05C mov al,05C ; prepare '\' 
0000000F: 7202 jc 000000013
00000011: B02F mov al,02F ; prepare '/'
; output character to screen
00000013: E40E move ah,00E
00000015: CD10 int 010
00000017: E2EA loop 00000003
; exit to DOS
00000019: CD20 int 020
```

Taking random memory garbage as a source of randomness

Since it is MS-DOS, there is no memory protection at all, we can read from whatever address we want. Even more than that: a simple LODSB instruction reads a byte from the DS:SI address, but it’s not a problem if the registers’ values are not set up, let it read 1) random bytes; 2) from a random place in memory!

It is suggested in Trixter’s webpage\(^48\) to use LODSB without any setup.

It is also suggested that the SCASB instruction can be used instead, because it sets a flag according to the byte it reads.

Another idea to minimize the code is to use the INT 29h DOS syscall, which just prints the character stored in the AL register.

That is what Peter Ferrie and Andrey “herm1lt” Baranovich did (11 and 10 bytes)\(^49\):

```
00000000: B05C mov al,05C  ; \'
; read AL byte from random place of memory
00000002: AE scasb
; PF = parity (AL - random_memory_byte) = parity (5Ch - random_memory_byte)
00000003: 7A02 jp 00000007
00000005: B02F mov al,02F ; '/'
00000007: CD29 int 029 ; output AL to screen
00000009: EBFS jmp 00000000 ; loop endlessly
```

SCASB also uses the value in the AL register, it subtract a random memory byte’s value from the 5Ch value in AL. JP is a rare instruction, here it used for checking the parity flag (PF), which is generated by the formulae in the listing. As a consequence, the output character is determined not by some bit in a random memory byte, but by a sum of bits, this (hopefully) makes the result more distributed.

It is possible to make this even shorter by using the undocumented x86 instruction SALC (AKA SETALC) (“Set AL CF”). It was introduced in the NEC V20 CPU and sets AL to 0xFF if CF is 1 or to 0 if otherwise.

\(^48\)http://go.yurichev.com/17305
\(^49\)http://go.yurichev.com/17087
So it is possible to get rid of conditional jumps at all. The ASCII code of backslash ("\") is 0x5C and 0x2F for slash ("/"). So we have to convert one (pseudo-random) bit in the CF flag to a value of 0x5C or 0x2F.

This is done easily: by AND-ing all bits in AL (where all 8 bits are set or cleared) with 0x2D we have just 0 or 0x2D.

By adding 0x2F to this value, we get 0x5C or 0x2F.

Then we just output it to the screen.

Conclusion

It is also worth mentioning that the result may be different in DOSBox, Windows NT and even MS-DOS, due to different conditions: the timer chip can be emulated differently and the initial register contents may be different as well.
Mandelbrot set is a fractal, which exhibits self-similarity. When you increase scale, you see that this characteristic pattern repeating infinitely.

Here is a demo written by “Sir_Lagsalot” in 2009, that draws the Mandelbrot set, which is just a x86 program with executable file size of only 64 bytes. There are only 30 16-bit x86 instructions.

Here it is what it draws:

Let’s try to understand how it works.

Theory

A word about complex numbers

A complex number is a number that consists of two parts—real (Re) and imaginary (Im).

The complex plane is a two-dimensional plane where any complex number can be placed: the real part is one coordinate and the imaginary part is the other.

Some basic rules we have to keep in mind:

- **Addition:** \((a + bi) + (c + di) = (a + c) + (b + d)i\)

  In other words: ________________________________

50Download it [here](#)
Re(sum) = Re(a) + Re(b)
Im(sum) = Im(a) + Im(b)

- **Multiplication:** \((a + bi)(c + di) = (ac - bd) + (bc + ad)i\)
  
  In other words:
  
  Re(product) = Re(a) \cdot Re(c) - Re(b) \cdot Re(d)
  
  Im(product) = Im(b) \cdot Im(c) + Im(a) \cdot Im(d)

- **Square:** \((a + bi)^2 = (a + bi)(a + bi) = (a^2 - b^2) + (2ab)i\)
  
  In other words:
  
  Re(square) = Re(a)^2 - Im(a)^2
  
  Im(square) = 2 \cdot Re(a) \cdot Im(a)

---

**How to draw the Mandelbrot set**

The Mandelbrot set is a set of points for which the \(z_{n+1} = z_n^2 + c\) recursive sequence (where \(z\) and \(c\) are complex numbers and \(c\) is the starting value) does not approach infinity.

In plain English language:

- Enumerate all points on screen.
- Check if the specific point is in the Mandelbrot set.
- Here is how to check it:
  - Represent the point as a complex number.
  - Calculate the square of it.
  - Add the starting value of the point to it.
  - Does it go off limits? If yes, break.
  - Move the point to the new place at the coordinates we just calculated.
  - Repeat all this for some reasonable number of iterations.
- The point is still in limits? Then draw the point.
- The point has eventually gone off limits?
  - (For a black-white image) do not draw anything.
  - (For a colored image) transform the number of iterations to some color. So the color shows the speed with which point has gone off limits.

Here is Pythonesque algorithm for both complex and integer number representations:

**Listing 8.24: For complex numbers**

```python
def check_if_is_in_set(P):
    P_start=P
    iterations=0
    while True:
        if (P>bounds):
            break
        P=P^2+P_start
        if iterations > max_iterations:
            break
        iterations++
    return iterations
```

# black-white
for each point on screen P:
    if check_if_is_in_set (P) < max_iterations:
        draw point
8.13. DEMOS

# colored
for each point on screen P:
    iterations = if check_if_is_in_set (P)
    map iterations to color
    draw color point

The integer version is where the operations on complex numbers are replaced with integer operations according to the rules which were explained above.

Listing 8.25: For integer numbers

```python
def check_if_is_in_set(X, Y):
    X_start=X
    Y_start=Y
    iterations=0
    while True:
        if (X^2 + Y^2 > bounds):
            break
        new_X=X^2 - Y^2 + X_start
        new_Y=2*X*Y + Y_start
        if iterations > max_iterations:
            break
        iterations++
    return iterations

# black-white
for X = min_X to max_X:
    for Y = min_Y to max_Y:
        if check_if_is_in_set (X,Y) < max_iterations:
            draw point at X, Y

# colored
for X = min_X to max_X:
    for Y = min_Y to max_Y:
        iterations = if check_if_is_in_set (X,Y)
        map iterations to color
        draw color point at X,Y
```

Here is also a C# source which is present in the Wikipedia article\(^{51}\), but we’ll modify it so it will print the iteration numbers instead of some symbol \(^{52}\):

```csharp
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;

namespace Mnoj
{
    class Program
    {
        static void Main(string[] args)
        {
            double realCoord, imagCoord;
            double realTemp, imagTemp, realTemp2, arg;
            int iterations;
            for (imagCoord = 1.2; imagCoord >= -1.2; imagCoord -= 0.05)
            {
                for (realCoord = -0.6; realCoord <= 1.77; realCoord += 0.03)
                {
                    iterations = 0;
                    realTemp = realCoord;
                    imagTemp = imagCoord;
                    arg = (realCoord * realCoord) + (imagCoord * imagCoord);
                    while ((arg < 2*2) && (iterations < 40))
                    {
```
realTemp2 = (realTemp * realTemp) - (imagTemp * imagTemp) - realCoord;
imagTemp = (2 * realTemp * imagTemp) - imagCoord;
realTemp = realTemp2;
arg = (realTemp * realTemp) + (imagTemp * imagTemp);
iterations += 1;
} Console.Write("{0,2:D} ", iterations);
} Console.Write("\n");
} Console.ReadKey();
}

Here is the resulting file, which is too wide to be included here: beginners.re.

The maximal number of iterations is 40, so when you see 40 in this dump, it means that this point has been wandering for 40 iterations but never got off limits.

A number \( n \) less than 40 means that point remained inside the bounds only for \( n \) iterations, then it went outside them.
There is a cool demo available at http://go.yurichev.com/17309, which shows visually how the point moves on the plane at each iteration for some specific point. Here are two screenshots.

First, we've clicked inside the yellow area and saw that the trajectory (green line) eventually swirls at some point inside:

![Click inside yellow area](image)

This implies that the point we've clicked belongs to the Mandelbrot set.
8.13. DEMOS

Then we've clicked outside the yellow area and saw a much more chaotic point movement, which quickly went off bounds:

![Diagram showing chaotic point movement](image)

Figure 8.19: Click outside yellow area

This means the point doesn't belong to Mandelbrot set.

Another good demo is available here: [http://go.yurichev.com/17310](http://go.yurichev.com/17310).
8.13. DEMOS

Let's get back to the demo

The demo, although very tiny (just 64 bytes or 30 instructions), implements the common algorithm described here, but using some coding tricks.

The source code is easily downloadable, so here it is, but let's also add comments:

```
Listing 8.26: Commented source code

; X is column on screen
; Y is row on screen

X=0, Y=0            X=319, Y=0
+------------------->

; switch to VGA 320*200*256 graphics mode
mov al,13h
int 10h

; initial BX is 0
; initial DI is 0xFFFF
; DS:BX (or DS:0) is pointing to Program Segment Prefix at this moment
; ... first 4 bytes of which are CD 20 FF 9F
les ax,[bx]
ES:AX=0xFFFF:20CD

FillLoop:
; set DX to 0. CWD works as: DX:AX = sign_extend(AX).
; AX here 0x20CD (at startup) or less then 320 (when getting back after loop),
; so DX will always be 0.
cwd
mov ax,di

; AX is current pointer within VGA buffer
; divide current pointer by 320
mov cx,320
div cx

; DX (start_X) - remainder (column: 0..319); AX - result (row: 0..199)
sub ax,100

; AX=AX-100, so AX (start_Y) now is in range -100..99
; DX is in range 0..319 or 0x0000..0x013F
dec dh

xor bx,bx
xor si,si

BX (temp_X)=0; SI (temp_Y)=0

; get maximal number of iterations
; CX is still 320 here, so this is also maximal number of iteration

MandelLoop:
mov bp,si
imul si,bx
add si,si
add bp,si
imul bx,bx
imul bp,bp
add bx,bp
add bx,bx
add bx,bp
add bx,bx
add bx,bp
```
8.13. DEMOS

; correct scale:
63    sar bx,6    ; BX=BX/64
64    add bx,dx    ; BX=BX+start_X
65    ; now temp_X = temp_X^2 - temp_Y^2 + start_X
66    sar si,6    ; SI=SI/64
67    add si,ax    ; SI=SI+start_Y
68    ; now temp_Y = (temp_X*temp_Y)*2 + start_Y
69    loop MandelLoop
70
71 MandelBreak:
72    ; CX=iterations
73    xchg ax,cx
74    ; AX=iterations. store AL to VGA buffer at ES:[DI]
75    stosb
76    ; stosb also increments DI, so DI now points to the next point in VGA buffer
77    ; jump always, so this is eternal loop here
78    jmp FillLoop

Algorithm:

- Switch to 320*200 VGA video mode, 256 colors. 320*200 = 64000 (0xFA00).

Each pixel is encoded by one byte, so the buffer size is 0xFA00 bytes. It is addressed using the ES:DI registers pair.

ES must be 0xA000 here, because this is the segment address of the VGA video buffer, but storing 0xA000 to ES requires at least 4 bytes (PUSH 0A000h / POP ES). You can read more about the 16-bit MS-DOS memory model here: 11.6 on page 1003.

Assuming that BX is zero here, and the Program Segment Prefix is at the zeroth address, the 2-byte LES AX,[BX] instruction stores 0x20CD to AX and 0x9FFF to ES.

So the program starts to draw 16 pixels (or bytes) before the actual video buffer. But this is MS-DOS, there is no memory protection, so a write happens into the very end of conventional memory, and usually, there is nothing important. That’s why you see a red strip 16 pixels wide at the right side. The whole picture is shifted left by 16 pixels. This is the price of saving 2 bytes.

- An infinite loop processes each pixel.

Probably, the most common way to enumerate all pixels on the screen is with two loops: one for the X coordinate, another for the Y coordinate. But then you’ll need to multiply the coordinates to address a byte in the VGA video buffer.

The author of this demo decided to do it otherwise: enumerate all bytes in the video buffer by using one single loop instead of two, and get the coordinates of the current point using division. The resulting coordinates are: X in the range of $-256..63$ and Y in the range of $-100..99$. You can see on the screenshot that the picture is somewhat shifted to the right part of screen.

That’s because the biggest heart-shaped black hole usually appears on coordinates 0,0 and these are shifted here to right. Could the author just subtract 160 from the value to get X in the range of $-160..159$? Yes, but the instruction SUB DX, 160 takes 4 bytes, while DEC DH—2 bytes (which subtracts 0x100 (256) from DX). So the whole picture is shifted for the cost of another 2 bytes of saved space.

- Check, if the current point is inside the Mandelbrot set. The algorithm is the one that has been described here.

- The loop is organized using the LOOP instruction, which uses the CX register as counter.

The author could set the number of iterations to some specific number, but he didn’t: 320 is already present in CX (has been set at line 35), and this is good maximal iteration number anyway. We save here some space by not the reloading CX register with another value.

- IMUL is used here instead of MUL, because we work with signed values: keep in mind that the 0,0 coordinates has to be somewhere near the center of the screen.

It’s the same with SAR (arithmetic shift for signed values): it’s used instead of SHR.

- Another idea is to simplify the bounds check. We must check a coordinate pair, i.e., two variables. What the author does is to checks thrice for overflow: two squaring operations and one addition.
Indeed, we use 16-bit registers, which hold signed values in the range of -32768..32767, so if any of the coordinates is greater than 32767 during the signed multiplication, this point is definitely out of bounds: we jump to the MandelBreak label.

- There is also a division by 64 (SAR instruction). 64 sets scale.

Try to increase the value and you can get a closer look, or to decrease if for a more distant look.

- We are at the MandelBreak label, there are two ways of getting here: the loop ended with CX=0 (the point is inside the Mandelbrot set); or because an overflow has happened (CX still holds some value). Now we write the low 8-bit part of CX (CL) to the video buffer.

The default palette is rough, nevertheless, 0 is black: hence we see black holes in the places where the points are in the Mandelbrot set. The palette can be initialized at the program’s start, but keep in mind, this is only a 64 bytes program!

- The program runs in an infinite loop, because an additional check where to stop, or any user interface will result in additional instructions.

Some other optimization tricks:

- The 1-byte CWD is used here for clearing DX instead of the 2-byte XOR DX, DX or even the 3-byte MOV DX, 0.

- The 1-byte XCHG AX, CX is used instead of the 2-byte MOV AX,CX. The current value of AX is not needed here anyway.

- DI (position in video buffer) is not initialized, and it is 0xFFFFE at the start.

That’s OK, because the program works for all DI in the range of 0..0xFFFFF eternally, and the user can’t notice that it is started off the screen (the last pixel of a 320*200 video buffer is at address 0xF9FF). So some work is actually done off the limits of the screen.

Otherwise, you’ll need an additional instructions to set DI to 0 and check for the video buffer’s end.

My “fixed” version

```
org 100h
mov al,13h
int 10h

; set palette
mov dx, 3c8h
mov al, 0
out dx, al
mov cx, 100h
inc dx
l00:
mov al, cl
shl ax, 2
out dx, al ; red
out dx, al ; green
out dx, al ; blue
loop l00

push 0a000h
pop es
xor di, di
FillLoop:
cwd
mov ax,di
mov cx,320
div cx
sub ax,100
sub dx,160
```

53 More information about initial register values: http://go.yurichev.com/17084
The author of these lines made an attempt to fix all these oddities: now the palette is smooth grayscale, the video buffer is at the correct place (lines 19..20), the picture is drawn on center of the screen (line 30), the program eventually ends and waits for the user’s keypress (lines 58..68).

But now it’s much bigger: 105 bytes (or 54 instructions) \(^{54}\).

\(^{54}\)You can experiment by yourself: get DosBox and NASM and compile it as: nasm fiole.asm -fbin -o file.com
8.14 Other examples

An example about Z3 and manual decompilation was here. It is (temporarily) moved there: http://yurichev.com/tmp/SAT_SMT_DRAFT.pdf.
Chapter 9

Examples of reversing proprietary file formats

9.1 Primitive XOR-encryption

9.1.1 Simplest ever XOR encryption

I once saw a software where all debugging messages has been encrypted using XOR by value of 3. In other words, two lowest bits of all characters has been flipped.

“Hello, world” would become “Kfool/#tlqog”:

```python
#!/usr/bin/python
msg="Hello, world!"
print ",.join(map(lambda x: chr(ord(x)^3), msg))
```

This is quite interesting encryption (or rather obfuscation), because it has two important properties: 1) single function for encryption/decryption, just apply it again; 2) resulting characters are also printable, so the whole string can be used in source code without escaping characters.

The second property exploits the fact that all printable characters organized in rows: 0x2x-0x7x, and when you flip two lowest bits, character moving 1 or 3 characters left or right, but never moved to another (maybe non-printable) row:

```
Figure 9.1: 7-bit ASCII table in Emacs
```

...with a single exception of 0x7F character.

For example, let’s encrypt characters in A-Z range:

```python
#!/usr/bin/python
msg="@ABCDEFGHIJKLMO"
print ",.join(map(lambda x: chr(ord(x)^3), msg))
```
9.1. PRIMITIVE XOR-ENCRYPTION

Result:

CBA@GFEDKJIHONML

It’s like “@” and “C” characters has been swapped, and so are “B” and “a”.

Yet again, this is interesting example of exploiting XOR properties, rather than encryption: the very same effect of *preserving printableness* can be achieved while flipping any of lowest 4 bits, in any combination.
Norton Guide\(^1\) was popular in the epoch of MS-DOS, it was a resident program that worked as a hypertext reference manual.

Norton Guide’s databases are files with the extension `.ng`, the contents of which look encrypted:

![Very typical look](image)

**Figure 9.2: Very typical look**

Why did we think that it’s encrypted but not compressed?

We see that the 0x1A byte (looking like “→”) occurs often, it would not be possible in a compressed file. We also see long parts that consist only of Latin letters, and they look like strings in an unknown language.

---

\(^1\)wikipedia
Since the 0x1A byte occurs so often, we can try to decrypt the file, assuming that it’s encrypted by the simplest XOR-encryption.

If we apply XOR with the 0x1A constant to each byte in Hiew, we can see familiar English text strings:

XOR encryption with one single constant byte is the simplest possible encryption method, which is, nevertheless, encountered sometimes.

Now we understand why the 0x1A byte is occurring so often: because there are so many zero bytes and they were replaced by 0x1A in encrypted form.

But the constant might be different. In this case, we could try every constant in the 0..255 range and look for something familiar in the decrypted file. 256 is not so much.


**Entropy**

A very important property of such primitive encryption systems is that the information entropy of the encrypted/decrypted block is the same.

Here is my analysis in Wolfram Mathematica 10.
9.1. PRIMITIVE XOR-ENCRYPTION

Listing 9.1: Wolfram Mathematica 10

```mathematica
In[1]:= input = BinaryReadList["X86.NG"];

In[2]:= Entropy[2, input] // N
Out[2]= 5.62724

In[3]:= decrypted = Map[BitXor[#, 16^^1A] &, input];

In[4]:= Export["X86_decrypted.NG", decrypted, "Binary"];

In[5]:= Entropy[2, decrypted] // N
Out[5]= 5.62724

In[6]:= Entropy[2, ExampleData["Text", "ShakespearesSonnets"]]] // N
```

What we do here is load the file, get its entropy, decrypt it, save it and get the entropy again (the same!). Mathematica also offers some well-known English language texts for analysis.

So we also get the entropy of Shakespeare’s sonnets, and it is close to the entropy of the file we just analyzed.

The file we analyzed consists of English language sentences, which are close to the language of Shakespeare.

And the XOR-ed bitwise English language text has the same entropy.

However, this is not true when the file is XOR-ed with a pattern larger than one byte.

The file we analyzed can be downloaded here: [http://go.yurichev.com/17350](http://go.yurichev.com/17350).

One more word about base of entropy

Wolfram Mathematica calculates entropy with base of $e$ (base of the natural logarithm), and the UNIX `ent` utility\(^2\) uses base 2.

So we set base 2 explicitly in `Entropy` command, so Mathematica will give us the same results as the `ent` utility.

\(^2\)[http://www.fourmilab.ch/random/]

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9.1.3 Simplest possible 4-byte XOR encryption

If a longer pattern was used for XOR-encryption, for example a 4 byte pattern, it’s easy to spot as well. For example, here is the beginning of the kernel32.dll file (32-bit version from Windows Server 2008):

Figure 9.4: Original file
Here it is "encrypted" with a 4-byte key:

It’s very easy to spot the recurring 4 symbols.

Indeed, the header of a PE-file has a lot of long zero areas, which are the reason for the key to become visible.
9.1. PRIMITIVE XOR-ENCRYPTION

Here is the beginning of a PE-header in hexadecimal form:

Figure 9.6: PE-header
9.1. PRIMITIVE XOR-ENCRYPTION

Here it is “encrypted”:

Figure 9.7: “Encrypted” PE-header

It’s easy to spot that the key is the following 4 bytes: 8C 61 D2 63.

With this information, it’s easy to decrypt the whole file.

So it is important to keep in mind these properties of PE-files: 1) PE-header has many zero-filled areas; 2) all PE-sections are padded with zeros at a page boundary (4096 bytes), so long zero areas are usually present after each section.

Some other file formats may contain long zero areas.

It’s typical for files used by scientific and engineering software.

For those who want to inspect these files on their own, they are downloadable here: http://go.yurichev.com/17352.

Exercise

- http://challenges.re/50

There is a file inside (named castle.dbf) which is clearly encrypted, but not by a real crypto algorithm, nor it's compressed, this is something rather simpler. I wouldn't even measure entropy level (9.2 on page 948) of the file, because I'm sure it's low. Here is how it looks like in Midnight Commander:

```
Figure 9.8: Encrypted file in Midnight Commander
```


Will it be possible to decrypt it without accessing to the program, using just this file?

There is a clearly visible pattern of repeating string. If a simple encryption by XOR mask was applied, such repeating strings is a prominent signature, because, probably, there were a long lacunas of zero bytes, which, in turn, are present in many executable files as well as in binary data files.

Here I'll dump the file's beginning using `xxd` UNIX utility:

```
...
00000030: 09 61 0d 63 0f 77 14 69 75 62 67 76 01 7e 1d 61
00000040: 7a 11 0f 72 6e 03 05 7d 7d 63 7e 77 66 1e 7a 02
00000050: 75 50 02 4a 31 71 31 33 5c 27 08 5c 51 74 3e 39
00000060: 50 2e 28 72 24 4b 38 21 4c 09 37 38 3b 51 41 2d
00000070: 1c 3c 37 5d 27 5a 1c 7c 6a 10 14 68 77 08 6d 1a
```

---

9.1.4 Simple encryption using XOR mask

I've found an old interactive fiction game while diving deep into if-archive:

The New Castle v3.5 - Text/Adventure Game in the style of the original Infocom (tm) type games, Zork, Collosal Cave (Adventure), etc. Can you solve the mystery of the abandoned castle?


There is a file inside (named castle.dbf) which is clearly encrypted, but not by a real crypto algorithm, nor it's compressed, this is something rather simpler. I wouldn't even measure entropy level (9.2 on page 948) of the file, because I'm sure it's low. Here is how it looks like in Midnight Commander:
Let's stick at visible repeating iubgv string. By looking at this dump, we can clearly see that the period of the string occurrence is 0x51 or 81. Probably, 81 is size of block? The size of the file is 1658961, and it can be divided evenly by 81 (and there are 20481 blocks then).

Now I'll use Mathematica to analyze, are there repeating 81-byte blocks in the file? I'll split input file by 81-byte blocks and then I'll use \texttt{Tally[]} function which just counts, how many times some item has been occurred in the input list. Tally's output is not sorted, so I also add \texttt{Sort[]} function to sort it by number of occurrences in descending order.

```
input = BinaryReadList["/home/dennis/.../castle.dbf"];
blocks = Partition[input, 81];
stat = Sort[Tally[blocks], #1[[2]] > #2[[2]] &]
```

And here is output:

```
```

\footnote{https://reference.wolfram.com/language/ref/Tally.html}
9.1. PRIMITIVE XOR-ENCRYPTION
29, 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, 102,
30, 122, 2, 117}, 1},
{{80, 1, 74, 59, 113, 45, 56, 86, 52, 91, 19, 64, 60, 60, 63,
25, 38, 59, 59, 42, 14, 53, 38, 77, 66, 38, 113, 38, 75, 4, 43, 84,
63, 101, 64, 43, 79, 64, 40, 57, 16, 91, 46, 119, 69, 40, 84, 117,
9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118, 1, 126, 29,
97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, 102, 30,
122, 2, 117}, 1},
{{80, 2, 74, 49, 113, 49, 51, 92, 39, 8, 92, 81, 116, 62, 57,
80, 46, 40, 114, 36, 75, 56, 33, 76, 9, 55, 56, 59, 81, 65, 45, 28,
60, 55, 93, 39, 90, 28, 124, 106, 16, 20, 104, 119, 8, 109, 26,
106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118, 1, 126,
29, 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, 102,
30, 122, 2, 117}, 1}}

Tally’s output is a list of pairs, each pair has 81-byte block and number of times it has been occurred in
the ﬁle. We see that the most frequent block is the ﬁrst, it has been occurred 1739 times. The second
one has been occurred 1422 times. There are others: 1012 times, 377 times, etc. 81-byte blocks which
has been occurred just once are at the end of output.
Let’s try to compare these blocks. The ﬁrst and the second. Is there a function in Mathematica which
compares lists/arrays? Certainly is, but for educational purposes, I’ll use XOR operation for comparison.
Indeed: if bytes in two input arrays are identical, XOR result is 0. If they are non-equal, result will be
non-zero.
Let’s compare ﬁrst block (occurred 1739 times) and the second (occurred 1422 times):
In[]:= BitXor[stat[[1]][[1]], stat[[2]][[1]]]
Out[]= {0, 3, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}

They are diﬀer only in the second byte.
Let’s compare the second block (occurred 1422 times) and the third (occurred 1012 times):
In[]:= BitXor[stat[[2]][[1]], stat[[3]][[1]]]
Out[]= {0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, \
0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}

They are also diﬀer only in the second byte.
Anyway, let’s try to use the most occurred block as a XOR key and try to decrypt four ﬁrst 81-byte blocks
in the ﬁle:
In[]:= key = stat[[1]][[1]]
Out[]= {80, 103, 2, 116, 113, 102, 118, 25, 99, 8, 19, 23,
125, 107, 25, 99, 109, 114, 102, 14, 121, 115, 31, 9, 117,
5, 4, 127, 28, 122, 101, 8, 110, 14, 18, 124, 106, 16, 20,
8, 109, 26, 106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98,
1, 126, 29, 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99,
102, 30, 122, 2, 117}

116,
113,
104,
103,
126,

\
111,
119,
118,
119,

\
\
\
\

In[]:= ToASCII[val_] := If[val == 0, " ", FromCharacterCode[val, "PrintableASCII"]]
In[]:= DecryptBlockASCII[blk_] := Map[ToASCII[#] &, BitXor[key, blk]]
In[]:= DecryptBlockASCII[blocks[[1]]]
Out[]= {" ", " ", " ", " ", " ", " ",
", " ", " ", " ", " ", " ", " ", " ",
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In[]:= DecryptBlockASCII[blocks[[2]]]

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9.1. PRIMITIVE XOR-ENCRYPTION

In[1]:= DecryptBlockASCII[blocks[[3]]]
Out[1]= {"", "?", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "", "",  

(I've replaced unprintable characters by “?”.)

So we see that the first and the third blocks are empty (or almost empty), but the second and the fourth has clearly visible English language words/phrases. It seems that our assumption about key is correct (at least partially). This means that the most occurred 81-byte block in the file can be found at places of lacunas of zero bytes or something like that.

Let's try to decrypt the whole file:

DecryptBlock[blk_] := BitXor[key, blk]
decrypted = Map[DecryptBlock[#] &, blocks];
BinaryWrite["/home/dennis/.../tmp", Flatten[decrypted]]
Close["/home/dennis/.../tmp"]
9.1. PRIMITIVE XOR-ENCRYPTION

Looks like some kind of English phrases from some game, but something wrong. First of all, cases are inverted: phrases and some words are started with lowercase characters, while other characters are in upper case. Also, some phrases started with wrong letters. Take a look at the very first phrase: “eHE WEED OF CRIME BEARS BITTER FRUIT”. What is “eHE”? Isn’t “tHE” have to be here? Is it possible that our decryption key has wrong byte at this place?

Let’s look again at the second block in the file, at key and at decryption result:

| In[1]:= blocks[[2]] | Out[1]:={80, 2, 74, 49, 113, 49, 51, 92, 39, 8, 92, 81, 116, 62, |
| 57, 50, 46, 40, 114, 36, 75, 56, 33, 76, 9, 55, 59, 81, 65, 45, |
| 28, 60, 55, 93, 39, 90, 28, 124, 106, 16, 20, 104, 119, 8, 109, 26, |
| 106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118, 1, 126, 29, |
| 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, 102, 30, |
| 122, 2, 117} |

| In[1]:= key | Out[1]:={80, 103, 2, 116, 113, 102, 118, 25, 99, 8, 19, 23, 116, |
| 125, 107, 25, 99, 109, 114, 102, 14, 121, 115, 31, 9, 117, 113, 111, |
| 5, 4, 127, 28, 122, 101, 8, 110, 14, 18, 124, 106, 16, 20, 104, 119, |
| 8, 109, 26, 106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118, |
| 1, 126, 29, 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, |
| 102, 30, 122, 2, 117} |

| In[1]:= BitXor[key, blocks[[2]]] | Out[1]:={0, 101, 72, 69, 0, 87, 69, 69, 68, 0, 79, 70, 0, 67, 82, |
| 73, 77, 69, 0, 66, 69, 65, 82, 83, 0, 66, 73, 84, 84, 69, 82, 0, 70, |
| 82, 85, 73, 84, 14, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, |
| 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0} |
9.1. PRIMITIVE XOR-ENCRYPTION

Encrypted byte is 2, the byte from the key is 103, \(2 \oplus 103 = 101\) is ASCII code for “e” character. What byte of a key must be equal to, so the resulting ASCII code will be 116 (for “t” character)? \(2 \oplus 116 = 118\), let’s put 118 in key at the second byte ...

\[ \text{key} = \{80, 118, 2, 116, 113, 102, 118, 25, 99, 8, 19, 23, 116, 125, 107, 25, 99, 109, 114, 102, 14, 121, 115, 31, 9, 117, 113, 111, 5, 4, 127, 28, 122, 101, 8, 110, 14, 18, 124, 106, 16, 20, 104, 119, 8, 109, 26, 106, 9, 97, 13, 99, 15, 119, 20, 105, 117, 98, 103, 118, 1, 126, 29, 97, 122, 17, 15, 114, 110, 3, 5, 125, 125, 99, 126, 119, 102, 30, 122, 2, 117\} \]

...and decrypt the whole file again.

![Figure 9.10: Decrypted file in Midnight Commander, 2nd attempt](image)

Wow, now the grammar is correct, all phrases started with correct letters. But still, case inversion is suspicious. Why would game’s developer write them in such a manner? Maybe our key is still incorrect?

While observing ASCII table we can notice that uppercase and lowercase letter’s ASCII codes are differ in just one bit (6th bit starting at 1st, 0b100000):

![Figure 9.11: 7-bit ASCII table in Emacs](image)

6th bit set in a zero byte has decimal form of 32. But 32 is ASCII code for space!
Indeed, one can switch case just by XOR-ing ASCII character code with 32 (more about it: 3.16.3 on page 537).

It is possible that the empty lacunas in the file are not zero bytes, but rather spaces? Let's modify XOR key one more time (I'll XOR each byte of key by 32):

\[
(* \text{"32" is scalar and \"key\" is vector, but that's OK *} *)
\]

\[
\text{In}[] := \text{key3} = \text{BitXor}[32, \text{key}]
\]

\[
\text{Out}[] = \{112, 86, 34, 84, 81, 70, 86, 57, 67, 40, 51, 55, 84, 93, 75, 57, 67, 82, 70, 86, 89, 83, 63, 41, 85, 81, 79, 37, 36, 95, 60, 90, 69, 40, 78, 46, 50, 92, 74, 48, 52, 72, 87, 40, 77, 58, 74, 41, 65, 45, 67, 47, 87, 52, 73, 85, 66, 71, 86, 33, 94, 61, 65, 90, 49, 47, 82, 78, 35, 37, 93, 93, 67, 94, 87, 70, 62, 90, 34, 85\}
\]

\[
\text{In}[] := \text{DecryptBlock}[\text{blk}_\text{\_}] := \text{BitXor}[\text{key3}, \text{blk}]
\]

Let's decrypt the input file again:

```
/home/dennis/P/RE-book/decrypt_dat_file/tmp3

The Shadow knows!
I keep it in a glass jar on my desk.

All positioning is RELATIVE and not ABSOLUTE.
This is a kludge to make this

(So is running head-first into brick walls!!)
And from within the tomb of the undead, vampires begin their feast as to

hlike figure appears before you, seeming to float in the air. In a low, the
nature of the world has changed, and the dungeon cannot be found. All
well, he fades into the spreading darkness. In his place appears a tasteful

INITIALIZATION FAILURE
The darkness becomes all encompassing, and your vision for

CRATCH Paper.
Keep it up and we'll both go out for a beer.
No, odd addresses don't occur on the South side of the street.

In
```

Figure 9.12: Decrypted file in Midnight Commander, final attempt

(Decrypted file is available here: https://github.com/DennisYurichev/RE-for-beginners/blob/master/ff/XOR/mask_1/files/decrypted.dat.bz2.)

This is undoubtedly a correct source file. Oh, and we see numbers at the start of each block. It has to be a source of our erroneous XOR key. As it seems, the most occurred 81-byte block in the file is a block filled with spaces and containing “1” character at the place of second byte. Indeed, somehow, many blocks here are interleaved with this one. Maybe it's some kind of padding for short phrases/messages? Other frequently occurred 81-byte blocks are also space-filled blocks, but with different digit, hence, they are differ only at the second byte.

That's all! Now we can write an utility to encrypt the file back, and maybe modify it before.
9.1. PRIMITIVE XOR-ENCRYPTION


Summary: XOR encryption like that is not robust at all. It has been intended by game’s developer(s), probably, just to prevent gamer(s) to peek into internals of game, nothing else more serious. Still, encryption like that is extremely popular due to its simplicity and many reverse engineers are usually familiar with it.

9.1.5 Simple encryption using XOR mask, case II

I’ve got another encrypted file, which is clearly encrypted by something simple, like XOR-ing:

![Figure 9.13: Encrypted file in Midnight Commander](image)

The encrypted file can be downloaded here.

ent Linux utility reports about ~7.5 bits per byte, and this is high level of entropy (9.2 on page 948), close to compressed or properly encrypted file. But still, we clearly see some pattern, there are some blocks with size of 17 bytes, and you can see some kind of ladder, shifting by 1 byte at each 16-byte line.

It’s also known that the plain text is just English language text.

Now let’s assume that this piece of text is encrypted by simple XOR-ing with 17-byte key.

I tried to find some repeating 17-byte blocks using Mathematica, like I did before in my previous example (9.1.4 on page 936):

```
/home/dennis/tmp/cipher.txt  0x00000000
00000000 0D 26 0F 70 1C E7 9E 8D  E9 EC AC 3D  61 5A 15 95 .p a =a2.
00000010 5C F5 D3 70 78 38 E7 94  DF F2 E2 BC  76 34 61 8F \.p =v$a.
00000020 98 5D FC D9 01 26 2A FD  82 DF E9 E2  88 33 61 7B 1 .& 3a.$
00000030 14 D9 45 F8 C5 01 3D 20  FD 95 96 EB  E4 BC 7A 61 .E ..= za
00000040 61 18 0F 54 9D AA 54 20  28 E1 DB 8B  ED EC BC 33 e T T  .
00000050 61 1C 15 8D 11 F9 CE 47  22 2A FE 8E  9A EB 7F EF el.. G*~
00000060 39 22 71 1B 8A 58 FF CE 52 78 38 E7  9E 91 A5 EB 5"q . X Rp66
00000070 AA 76 35 73 09 09 44 E0  80 40 3C 23  AF RF 96 E2 v6$s. D @#
00000080 EB BB 7A 61 65 18 0A 11  E3 C5 40 24  2A EB F6 F5 zae.. @@*
00000090 E4 F7 EF 22 29 77 5A 9B  43 F5 C1 4A 36 2E FC 8F 　”)wz  C J6.
000000A0 DF F1 E2 AD 3A 24 3C 5A  B0 11 E3 D4  4E 3F 2B AF 　”$z C N+.+
000000B0 8E BF EA ED EF 22 29 77 5A 91 54 F1  D2 55 38 62 　”)wz  T U8b
000000C0 FD BE 93 A5 E2 A1 32 61  62 13 9A 5A  F5 C4 01 25  2ab . Z ,%
000000D0 3F AF 8F 97 E9 BE C5 25  35 7B 19 92  11 E7 C8 4B .% 5< . H
000000E0 33 27 AF 94 8A F7 B3 B9  3F 32 7B 0E  96 43 B0 C8 3' .%2 C .
000000F0 40 34 6F E3 9E 99 F1 A3  AD 33 29 7B  14 9D 11 F8 @4o属 3) . .
00000100 C9 4C 70 38 E7 9E DF EB  EA RA 3E 35  32 18 9C 57 Lp; . 52 . W
00000110 FF D2 44 7E 6F C6 6F DF  F2 E2 BC 7C  20 1F 70 9F D*oa v.p
00000120 5B FE C5 0D 7B 3B E7 92  9C EE A3 BF 3F 24 71 1F x .p ;明； ？q.$
00000130 D9 5E F6 80 55 3F 20 EB  D7 DF E7 F6  A3 34 2E 67 . V? . 4g
00000140 09 D4 59 F5 C1 45 35 2B  A3 DB 90 E3  A3 BB 3E 24 . Y . 5+ 4*>
00000150 32 09 95 43 E4 00 56 38  26 EC 9D FC ED F0 EF 3D 3c . C . V8$b
00000160 2F 7D 0D 97 11 F1 D3 2C  5A 2E AF D9  AF ED ED AE /) . . . 3. 2.,
00000170 38 26 32 16 98 46 E9 C5  S3 7E 6D HF  B1 8A F6 F7 62& . F s’m
00000180 EF 23 2F 76 1F 8B 11 E4  C8 44 77 27  2A 97 9B 48 H/s . b:. Dp’
00000190 F4 RE 25 61 73 5A 9B 48  FF CI 45 70  3C EC 97 89 .%asZ C Epёp
000001A0 E0 F1 EF 34 23 7C 1E D9  5F FC 51 93  3C 36 2B F1 4 I . S\<
000001B0 9E RE A3 R6 38 22 7A 5A  98 52 E2 CF 52 23 61 AF 8"R Z R Ha.
000001C0 D9 RE RA E3 85 37 2C 77  09 D9 7C FF  D2 55 39 22 . . 7.w l U9b
000001D0 EA 89 D3 RA CE E1 04 6F  51 54 RA 1F BC 80 47 22 . u .ot . G”
000001E0 2B E2 D3 97 EC F0 EF 30  33 7B 1F 97 55 E3 80 4E v01. U H
000001F0 36 6F FB 93 9A 88 89 8C  78 02 3C 32 07 1D B2 80 6g . x . k2 .
```

Listing 9.2: Mathematica

The encrypted file can be downloaded here.

ent Linux utility reports about ~7.5 bits per byte, and this is high level of entropy (9.2 on page 948), close to compressed or properly encrypted file. But still, we clearly see some pattern, there are some blocks with size of 17 bytes, and you can see some kind of ladder, shifting by 1 byte at each 16-byte line.

It’s also known that the plain text is just English language text.

Now let’s assume that this piece of text is encrypted by simple XOR-ing with 17-byte key.

I tried to find some repeating 17-byte blocks using Mathematica, like I did before in my previous example (9.1.4 on page 936):

Listing 9.2: Mathematica

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9.1. PRIMITIVE XOR-ENCRYPTION

In[9]:= input = BinaryReadList["/home/dennis/tmp/cipher.txt"];

In[10]:= blocks = Partition[input, 17];

In[11]:= Sort[Tally[blocks], #1[[2]] > #2[[2]] &]

    {{226, 207, 67, 60, 42, 226, 219, 150, 246, 163, 166, 56, 97, 101, 18, 144, 82}, 1},
    {{252, 217, 1, 39, 39, 238, 143, 223, 241, 235, 170, 91, 75, 119, 2, 152, 82}, 1},
    {{244, 204, 88, 112, 59, 234, 151, 147, 165, 238, 170, 118, 49, 126, 27, 144, 95}, 1},
    {{241, 196, 78, 112, 54, 224, 142, 223, 242, 236, 186, 58, 37, 50, 17, 144, 95}, 1},
    {{176, 201, 71, 112, 56, 230, 143, 151, 234, 246, 187, 118, 44, 125, 8, 156, 17}, 1},
    ...,
    {{249, 206, 71, 34, 42, 254, 142, 154, 235, 247, 239, 57, 34, 113, 27, 138, 88}, 1},
    {{157, 170, 84, 32, 32, 225, 139, 237, 236, 188, 51, 97, 124, 21, 141, 17}, 1},
    {{248, 197, 1, 61, 32, 253, 149, 150, 235, 226, 188, 122, 97, 97, 27, 143, 64}, 1},
    {{252, 217, 1, 38, 42, 253, 130, 223, 223, 226, 187, 51, 97, 123, 20, 217, 69}, 1},
    {{245, 211, 13, 112, 56, 231, 148, 223, 242, 226, 188, 118, 52, 97, 15, 152, 93}, 1},
    {{221, 210, 15, 112, 28, 231, 158, 141, 233, 236, 172, 61, 97, 90, 21, 149, 92}, 1}}

No luck, each 17-byte block is unique within the file and occurred only once. Perhaps, there are no 17-byte zero lacunas, or lacunas containing only spaces. It is possible indeed: such long space indentation and padding may be absent in tightly typeset text.

The first idea is to try all possible 17-byte keys and find those, which will result in readable text after decryption. Bruteforce is not an option, because there are $2^{56}$ possibilities ($\approx 10^{40}$), that’s too much. But there are good news: who said we have to test 17-byte key as a whole, why can’t we test each byte of key separately? It is possible indeed.

Now the algorithm is:

- try all 256 bytes for 1st byte of key;
- decrypt 1st byte of each 17-byte blocks in the file;
- are all decrypted bytes we got are printable? keep tabs on it;
- do so for all 17 bytes of key.

I’ve written the following Python script to check this idea:

```
Listing 9.3: Python script
each_Nth_byte=['']*KEY_LEN
content=read_file(sys.argv[1])
# split input by 17-byte chunks:
all_chunks=chunks(content, KEY_LEN)
for c in all_chunks:
    for i in range(KEY_LEN):
        each_Nth_byte[i]=each_Nth_byte[i] + c[i]

# try each byte of key
for N in range(KEY_LEN):
    print "N=", N
    possible_keys=[]
    for i in range(256):
        tmp_key=chr(i)*len(each_Nth_byte[N])
        tmp=xor_strings(tmp_key,each_Nth_byte[N])
        # are all characters in tmp[] are printable?
        if is_string_printable(tmp)==False:
            continue
        possible_keys.append(i)
    print possible_keys, "len=", len(possible_keys)
```

(Full version of the source code is here.)

Here is its output:

```
N= 0
[144, 145, 151] len= 3
```

944
9.1. PRIMITIVE XOR-ENCRYPTION

So there are 2 or 3 possible bytes for each byte of 17-byte key. This is much better than 256 possible bytes for each byte, but still too much. There are up to 1 million of possible keys:

Listing 9.4: Mathematica

In[4]:= 3*2*3*3*2*2*3*2*3*2*2*2*2*2*2
Out[4]= 995328

It's possible to check all of them, but then we must check visually, if the decrypted text is looks like English language text.

Let's also take into consideration the fact that we deal with 1) natural language; 2) English language. Natural languages has some prominent statistical features. First of all, punctuation and word lengths. What is average word length in English language? Let's just count spaces in some well-known English language texts using Mathematica.

Here is “The Complete Works of William Shakespeare” text file from Gutenberg Library:

Listing 9.5: Mathematica

In[5]:= input = BinaryReadList["/home/dennis/tmp/pg100.txt"];
9.1. PRIMITIVE XOR-ENCRYPTION

In[] := Length[input]/1285884 // N
Out[] = 4.34712

There are 1285884 spaces in the whole file, and the frequency of space occurrence is 1 space per ~4.3 characters.

Now here is Alice’s Adventures in Wonderland, by Lewis Carroll from the same library:

In[] := input = BinaryReadList["/home/dennis/tmp/pg11.txt"]; In[] := Tally[input]

In[] := Length[input]/27964 // N
Out[] = 5.99049

The result is different probably because of different formatting of these texts (maybe indentation and/or padding).

OK, so let's assume the average frequency of space in English language is 1 space per 4.7 characters.

Now the good news again: we can measure frequency of spaces while decrypting our file gradually. Now I count spaces in each slice and throw away 1-byte keys which produce results with too small number of spaces (or too large, but this is almost impossible given so short key):

Listing 9.7: Python script

each_Nth_byte=""*KEY_LEN

content=read_file(sys.argv[1])
# split input by 17-byte chunks:
all_chunks=chunks(content, KEY_LEN)
for c in all_chunks:
   for i in range(KEY_LEN):
      each_Nth_byte[i]=each_Nth_byte[i] + c[i]

# try each byte of key
for N in range(KEY_LEN):
   possible_keys=[]
   for i in range(256):
      tmp_key=chr(i)*len(each_Nth_byte[N])
      tmp=xor_strings(tmp_key,each_Nth_byte[N])
      # are all characters in tmp[] are printable?
      if is_string_printable(tmp)==False:
         continue
      # count spaces in decrypted buffer:
      spaces=tmp.count(' ')
      if spaces==0:
9.1. PRIMITIVE XOR-ENCRYPTION

continue
spaces_ratio=len(tmp)/spaces
if spaces_ratio<4:
    continue
if spaces_ratio>7:
    continue
possible_keys.append(i)
print possible_keys, "len=", len(possible_keys)

(Full version of the source code is here.)

This reports just one single possible byte for each byte of key:

<table>
<thead>
<tr>
<th>N</th>
<th>len</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
</tr>
</tbody>
</table>

Let's check this key in Mathematica:

Listing 9.8: Mathematica

In[1]:= input = BinaryReadList["/home/dennis/tmp/cipher.txt"];  
In[2]:= blocks = Partition[input, 17];  
In[3]:= key = {144, 160, 33, 80, 79, 143, 251, 255, 133, 131, 207, 86, 65, 18, 122, 249, 49};  
In[4]:= EncryptBlock[blk_ := BitXor[key, blk]  
In[5]:= encrypted = Map[EncryptBlock[#] &, blocks];  
In[6]:= BinaryWrite["/home/dennis/tmp/plain2.txt", Flatten[encrypted]]  
In[7]:= Close["/home/dennis/tmp/plain2.txt"]

And the plain text is:

Mr. Sherlock Holmes, who was usually very late in the mornings, save upon those not infrequent occasions when he was up all night, was seated at the breakfast table. I stood upon the hearth-rug and picked up the
9.2. INFORMATION ENTROPY

stick which our visitor had left behind him the night before. It was a fine, thick piece of wood, bulbous-headed, of the sort which is known as a "Penang lawyer." Just under the head was a broad silver band nearly an inch across. "To James Mortimer, M.R.C.S., from his friends of the C.C.H.," was engraved upon it, with the date "1884." It was just such a stick as the old-fashioned family practitioner used to carry--dignified, solid, and reassuring.

"Well, Watson, what do you make of it?"

Holmes was sitting with his back to me, and I had given him no sign of my occupation.

... (Full version of the text is here.)

The text looks correct. Yes, I made up this example and choose well-known text of Conan Doyle, but it’s very close to what I had in my practice some time ago.

Other ideas to consider

If we would fail with space counting, there are other ideas to try:

• Take into consideration the fact that lowercase letters are much more frequent than uppercase ones.
• Frequency analysis.
• There is also a good technique to detect language of a text: trigrams. Each language has some very frequent letter triplets, these may be “the” and “tha” for English. Read more about it: N-Gram-Based Text Categorization, http://code.activestate.com/recipes/326576/. Interestingly enough, trigrams detection can be used when you decrypt a ciphertext gradually, like in this example (you just have to test 3 adjacent decrypted characters).

For non-Latin writing systems encoded in UTF-8, things may be easier. For example, Russian text encoded in UTF-8 has each byte interleaved with 0xD0/0xD1 byte. It is because Cyrillic characters are placed in 4th block of Unicode table. Other writing systems has their own blocks.

9.2 Information entropy

For the sake of simplification, I would say, information entropy is a measure, how tightly some piece of data can be compressed. For example, it is usually not possible to compress already compressed archive file, so it has high entropy. On the other hand, 1MiB of zero bytes can be compressed to a tiny output file. Indeed, in plain English language, one million of zeros can be described just as “resulting file is one million zero bytes”. Compressed files are usually a list of instructions to decompressor, like this: “put 1000 zeros, then 0x23 byte, then 0x45 byte, then put a block of size 10 bytes which we’ve seen 500 bytes back, etc.”

Texts written in natural languages are also can be compressed tightly, because natural languages has a lot of redundancy (otherwise, a tiny typo will always lead to misunderstanding, like any toggled bit in compressed archive make decompression nearly impossible), some words are used very often, etc. In everyday speech, it’s possible to drop up to half of words and it still be recognizable.

Code for CPUs is also can be compressed, because some ISA instructions are used much more often than others. In x86, most used instructions are MOV/PUSH/CALL (5.11.2 on page 731).

Data compressors and ciphers tend to produce very high entropy results. Good PRNG also produce data which cannot be compressed (it is possible to measure their quality by this sign).

So, in other words, entropy is a measure which can help to probe contents of unknown data block.

9.2.1 Analyzing entropy in Mathematica

(This part has been first appeared in my blog at 13-May-2015. Some discussion: https://news.ycombinator.com/item?id=9545276.)
9.2. INFORMATION ENTROPY

It is possible to slice a file by blocks, calculate entropy of each and draw a graph. I did this in Wolfram Mathematica for demonstration and here is a source code (Mathematica 10):

```mathematica
(* loading the file *)
input=BinaryReadList["file.bin"];

(* setting block sizes *)
BlockSize=4096;BlockSizeToShow=256;

(* slice blocks by 4k *)
blocks=Partition[input,BlockSize];

(* how many blocks we've got? *)
Length[blocks]

(* calculate entropy for each block. 2 in Entropy[] (base) is set with the intention so Entropy[] function will produce the same results as Linux ent utility does *)
entropies=Map[N[Entropy[2,#]]&,blocks];

(* helper functions *)
fBlockToShow[input_,offset_]:=Take[input,{1+offset,1+offset+BlockSizeToShow}]
fToASCII[val_]:=FromCharacterCode[val,"PrintableASCII"]
fToHex[val_]:=IntegerString[val,16]
fPutASCIIWindow[data_]:=Framed[Grid[Partition[Map[fToASCII,data],16]]]
fPutHexWindow[data_]:=Framed[Grid[Partition[Map[fToHex,data],16],Alignment->Right]]

(* that will be the main knob here *)
{Slider[Dynamic[offset],{0,Length[input]-BlockSize,BlockSize}],Dynamic[BaseForm[offset,16]]}

(* main UI part *)
Dynamic[{ListLinePlot[entropies,GridLines->{{-1,offset/BlockSize,1}},Filling->Axis,AxesLabel->{"offset","entropy"}],
CurrentBlock=fBlockToShow[input,offset];
fPutHexWindow[CurrentBlock],
fPutASCIIWindow[CurrentBlock]]}

GeoIP ISP database

Let's start with the GeoIP file (which assigns ISP to the block of IP addresses). This binary file GeoIPISP.dat has some tables (which are IP address ranges perhaps) plus some text blob at the end of the file (containing ISP names).

When I load it to Mathematica, I see this:
9.2. INFORMATION ENTROPY

There are two parts in graph: first is somewhat chaotic, second is more steady.

0 in horizontal axis in graph means lowest entropy (the data which can be compressed very tightly, ordered in other words) and 8 is highest (cannot be compressed at all, chaotic or random in other words). Why 0 and 8? 0 means 0 bits per byte (byte as a container is not filled at all) and 8 means 8 bits per byte, i.e., the whole byte container is filled with the information tightly.

So I put slider to point in the middle of the first block, and I clearly see some array of 32-bit integers. Now I put slider in the middle of the second block and I see English text:
Indeed, this are names of ISPs. So, entropy of English text is 4.5-5.5 bits per byte? Yes, something like this. Wolfram Mathematica has some well-known English literature corpus embedded, and we can see entropy of Shakespeare’s sonnets:

\[
\text{In}[] := \text{Entropy[2, ExampleData["Text", "ShakespearesSonnets"]] // N}
\]

\[
\text{Out}[] = 4.42366
\]

4.4 is close to what we’ve got (4.7-5.3). Of course, classic English literature texts are somewhat different from ISP names and other English texts we can find in binary files (debugging/logging/error messages), but this value is close.

**TP-Link WR941 firmware**

Next example. I’ve got firmware for TP-Link WR941 router:
We see here 3 blocks with empty lacunas. Then the first block with high entropy (started at address 0) is small, second (address somewhere at 0x22000) is bigger and third (address 0x123000) is biggest. I can't be sure about exact entropy of the first block, but 2nd and 3rd has very high entropy, meaning that these blocks are either compressed and/or encrypted.

I tried binwalk for this firmware file:

We find:

Indeed: there are some stuff at the beginning, but two large LZMA compressed blocks are started at 0x20400 and 0x120200. These are roughly addresses we have seen in Mathematica. Oh, and by the way, binwalk can show entropy information as well (-E option):
9.2. INFORMATION ENTROPY

Rising edges are corresponding to rising edges of block on our graph. Falling edges are the points where empty lacunas are started.

Binwalk can also generate PNG graphs (-E -J):

What can we say about lacunas? By looking in hex editor, we see that these are just filled with 0xFF bytes. Why developers put them? Perhaps, because they weren’t able to calculate precise compressed blocks sizes, so they allocated space for them with some reserve.

**Notepad**

Another example is notepad.exe I’ve picked in Windows 8.1:
There is cavity at \( \approx 0x19000 \) (absolute file offset). I've opened the executable file in hex editor and found imports table there (which has lower entropy than x86-64 code in the first half of graph). There are also high entropy block started at \( \approx 0x20000 \):
In hex editor I can see PNG file here, embedded in the PE file resource section (it is a large image of notepad icon). PNG files are compressed, indeed.

**Unnamed dashcam**

Now the most advanced example in this part is the firmware of some unnamed dashcam I've received from friend:
9.2. INFORMATION ENTROPY

The cavity at the very beginning is an English text: debugging messages. I checked various ISAs and I found that the first third of the whole file (with the text segment inside) is in fact MIPS (little-endian) code.

For instance, this is very distinctive MIPS function epilogue:

```
move $sp, $fp
lw $ra, 0x1C($sp)
lw $fp, 0x18($sp)
lw $s1, 0x14($sp)
lw $s0, 0x10($sp)
jr $ra
addiu $sp, 0x20
```

From our graph we can see that MIPS code has entropy of 5-6 bits per byte. Indeed, I once measured various ISAs entropy and I've got these values:

- x86: .text section of ntoskrnl.exe file from Windows 2003: 6.6
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- x64: .text section of ntoskrnl.exe file from Windows 7 x64: 6.5
- ARM (thumb mode), Angry Birds Classic: 7.05
- ARM (ARM mode) Linux Kernel 3.8.0: 6.03
- MIPS (little endian), .text section of user32.dll from Windows NT 4: 6.09

So the entropy of executable code is higher than of English text, but still can be compressed.

Now the second third is started at 0xF5000. I don't know what this is. I tried different ISAs but without success. The entropy of the block is looks even steadier than for executable one. Maybe some kind of data?

There is also a spike at \( \approx 0x213000 \). I checked it in hex editor and I found JPEG file there (which, of course, compressed)! I also don’t know what is at the end. Let’s try Binwalk for this file:

% binwalk FW96650A.bin

<table>
<thead>
<tr>
<th>DECIMAL</th>
<th>HEXADECIMAL</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>167698</td>
<td>0x28F12</td>
<td>Unix path: /15/20/24/25/30/60/120/240fps can be served.</td>
</tr>
<tr>
<td>280286</td>
<td>0x446DE</td>
<td>Copyright string: &quot;Copyright (c) 2012 Novatek Microelectronic Corp.&quot;</td>
</tr>
<tr>
<td>2169199</td>
<td>0x21196F</td>
<td>JPEG image data, JFIF standard 1.01</td>
</tr>
<tr>
<td>2300847</td>
<td>0x231BAF</td>
<td>MySQL MISAM compressed data file Version 3</td>
</tr>
</tbody>
</table>

% binwalk -E FW96650A.bin

<table>
<thead>
<tr>
<th>DECIMAL</th>
<th>HEXADECIMAL</th>
<th>ENTROPY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0x0</td>
<td>Falling entropy edge (0.579792)</td>
</tr>
<tr>
<td>2170880</td>
<td>0x212000</td>
<td>Rising entropy edge (0.967373)</td>
</tr>
<tr>
<td>2267136</td>
<td>0x229800</td>
<td>Falling entropy edge (0.882974)</td>
</tr>
<tr>
<td>2426880</td>
<td>0x250800</td>
<td>Falling entropy edge (0.846639)</td>
</tr>
<tr>
<td>2490368</td>
<td>0x260000</td>
<td>Falling entropy edge (0.849804)</td>
</tr>
<tr>
<td>2560000</td>
<td>0x271000</td>
<td>Rising entropy edge (0.974340)</td>
</tr>
<tr>
<td>2574336</td>
<td>0x274800</td>
<td>Rising entropy edge (0.970958)</td>
</tr>
<tr>
<td>2588672</td>
<td>0x278000</td>
<td>Falling entropy edge (0.763507)</td>
</tr>
<tr>
<td>2592768</td>
<td>0x279000</td>
<td>Rising entropy edge (0.951883)</td>
</tr>
<tr>
<td>2596864</td>
<td>0x27A000</td>
<td>Falling entropy edge (0.712814)</td>
</tr>
<tr>
<td>2600960</td>
<td>0x27B000</td>
<td>Rising entropy edge (0.968167)</td>
</tr>
<tr>
<td>2607104</td>
<td>0x27C800</td>
<td>Rising entropy edge (0.958582)</td>
</tr>
<tr>
<td>2609152</td>
<td>0x27D000</td>
<td>Falling entropy edge (0.760989)</td>
</tr>
<tr>
<td>2654208</td>
<td>0x288000</td>
<td>Rising entropy edge (0.954127)</td>
</tr>
<tr>
<td>2670592</td>
<td>0x28C000</td>
<td>Rising entropy edge (0.967883)</td>
</tr>
<tr>
<td>2676736</td>
<td>0x28D800</td>
<td>Rising entropy edge (0.975779)</td>
</tr>
<tr>
<td>2684928</td>
<td>0x28F800</td>
<td>Falling entropy edge (0.744369)</td>
</tr>
</tbody>
</table>

Yes, it found JPEG file and even MySQL data! But I’m not sure if it’s true—I didn’t check it yet.

It’s also interesting to try clusterization in Mathematica:
9.2. INFORMATION ENTROPY

Here is an example of how Mathematica grouped various entropy values into distinctive groups. Indeed, there is something credible. Blue dots in range of 5.0-5.5 are supposedly related to English text. Yellow dots in 5.5-6 are MIPS code. A lot of green dots in 6.0-6.5 is the unknown second third. Orange dots close to 8.0 are related to compressed JPEG file. Other orange dots are supposedly related to the end of the firmware (unknown to us data).

Links


9.2.2 Conclusion

Information entropy can be used as a quick-n-dirty method for inspecting unknown binary files. In particular, it is a very quick way to find compressed/encrypted pieces of data. Someone say it’s possible to find RSA\(^6\) (and other asymmetric cryptographic algorithms) public/private keys in executable code (keys has high entropy as well), but I didn’t try this myself.

9.2.3 Tools

Handy Linux ent utility to measure entropy of a file\(^7\).


radare2 framework has #entropy command for this.

A tool for IDA: IDAtropy\(^8\).

---

\(^6\)Rivest Shamir Adleman  
\(^7\)http://www.fourmilab.ch/random/  
\(^8\)https://github.com/danigargu/IDAtropy
9.2.4 A word about primitive encryption like XORing

It's interesting that simple XOR encryption doesn't affect entropy of data. I've shown this in Norton Guide example in the book (9.1.2 on page 929).

Generalizing: encryption by substitution cipher also doesn't affect entropy of data (and XOR can be viewed as substitution cipher). The reason of that is because entropy calculation algorithm view data on byte-level. On the other hand, the data encrypted by 2 or 4-byte XOR pattern will result in another level of entropy.

Nevertheless, low entropy is usually a good sign of weak amateur cryptography (which is also used in license keys/files, etc.).

9.2.5 More about entropy of executable code

It is quickly noticeable that probably a biggest source of high-entropy in executable code are relative offsets encoded in opcodes. For example, these two consequent instructions will have different relative offsets in their opcodes, while they are in fact pointing to the same function:

```plaintext
function proc
...
function endp
...
CALL function
...
CALL function
```

Ideal executable code compressor would encode information like this: there is a CALL to a “function” at address X and the same CALL at address Y without necessity to encode address of the function twice.

To deal with this, executable compressors are sometimes able to reduce entropy here. One example is UPX: http://sourceforge.net/p/upx/code/ci/default/tree/doc/filter.txt.

9.2.6 PRNG

When I run GnuPG to generate new private (secret) key, it asking for some entropy ...

We need to generate a lot of random bytes. It is a good idea to perform some other action (type on the keyboard, move the mouse, utilize the disks) during the prime generation; this gives the random number generator a better chance to gain enough entropy.

Not enough random bytes available. Please do some other work to give the OS a chance to collect more entropy! (Need 169 more bytes)

This means that good a PRNG produces long high-entropy results, and this is what the secret asymmetrical cryptographical key needs. But CPRNG\(^9\) is tricky (because computer is highly deterministic device itself), so the GnuPG asking for some additional randomness from the user.

9.2.7 More examples

Here is a case where I try to calculate entropy of some blocks with unknown contents: 8.7 on page 864.

9.2.8 Entropy of various files

Entropy of random data is close to 8:

```plaintext
% dd bs=1M count=1 if=/dev/urandom | ent
Entropy = 7.999803 bits per byte.
```

\(^9\)Cryptographically secure PseudoRandom Number Generator
9.2. INFORMATION ENTROPY

This means, almost all available space inside of byte is filled with information.

256 bytes in range of 0..255 gives exact value of 8:

```python
#!/usr/bin/env python
import sys
for i in range(256):
    sys.stdout.write(chr(i))
```

```
% python 1.py | ent
Entropy = 8.000000 bits per byte.
```

Order of bytes doesn’t matter. This means, all available space inside of byte is filled.

Entropy of any block filled with zero bytes is 0:

```
% dd bs=1M count=1 if=/dev/zero | ent
Entropy = 0.000000 bits per byte.
```

Entropy of a string consisting of a single (any) byte is 0:

```
% echo -n "aaaaaaaaaaaaaaaaaaa" | ent
Entropy = 0.000000 bits per byte.
```

Entropy of base64 string is the same as entropy of source data, but multiplied by $\frac{3}{4}$. This is because base64 encoding uses 64 symbols instead of 256.

```
% dd bs=1M count=1 if=/dev/urandom | base64 | ent
Entropy = 6.022068 bits per byte.
```

Perhaps, 6.02 not that close to 6 because padding symbols (=) spoils our statistics for a little.

Uuencode also uses 64 symbols:

```
% dd bs=1M count=1 if=/dev/urandom | uuencode - | ent
Entropy = 6.013162 bits per byte.
```

This means, any base64 and Uuencode strings can be transmitted using 6-bit bytes or characters.

Any random information in hexadecimal form has entropy of 4 bits per byte:

```
% openssl rand -hex $$(( 2**16 )) | ent
Entropy = 4.000013 bits per byte.
```

Entropy of randomly picked English language text from Gutenberg library has entropy $\approx 4.5$. The reason of this is because English texts uses mostly 26 symbols, and $\log_2(26) \approx 5.1$, i.e., you would need 5-bit bytes to transmit uncompressed English texts, that would be enough (it was indeed so in teletype era).

Randomly chosen Russian language text from [http://lib.ru](http://lib.ru) library is F.M.Dostoevsky “Idiot”¹⁰, internally encoded in CP1251 encoding.

And this file has entropy of $\approx 4.98$. Russian language has 33 characters, and $\log_2(33) \approx 5.04$. But it has unpopular and rare “ё” character. And $\log_2(32) = 5$ (Russian alphabet without this rare character)—now this close to what we’ve got.

However, the text we studying uses “ё” letter, but, probably, it’s still rarely used there.

The very same file transcoded from CP1251 to UTF-8 gave entropy of $\approx 4.23$. Each Cyrillic character encoded in UTF-8 is usually encoded as a pair, and the first byte is always one of: 0xD0 or 0xD1. Perhaps, this caused bias.

Let’s generate random bits and output them as “T” and “F” characters:

```python
#!/usr/bin/env python
import random, sys
rt=""
for i in range(102400):
    if random.randint(0,1)==1:
        rt+="T"
    else:
        rt+="F"
```

```
10[http://az.lib.ru/d/dostoewskij_f_m/text_0070.shtml](http://az.lib.ru/d/dostoewskij_f_m/text_0070.shtml)
```
Sample: ...TTTFTFTTTFTTTTTTTTFTFTTTTFTFFTFFFFF ...
Entropy is very close to 1 (i.e., 1 bit per byte).
Let’s generate random decimal digits:

```python
#!/usr/bin/env python
import random, sys
rt=""
for i in range(102400):
    rt=rt+"%d" % random.randint(0,9)
print rt
```

Sample: ...52203466119390328807552582367031963888032 ...
Entropy will be close to 3.32, indeed, this is $\log_2(10)$.

### 9.2.9 Making lower level of entropy

The author of these lines once saw a software which stored each byte of encrypted data in 3 bytes: each has $\approx \frac{\text{byte}}{3}$ value, so reconstructing encrypted byte back involving summing up 3 consecutive bytes. Looks absurdly.

But some people say this was done in order to conceal the very fact the data has something encrypted inside: measuring entropy of such block will show much lower level of it.

### 9.3 Millenium game save file

The “Millenium Return to Earth” is an ancient DOS game (1991), that allows you to mine resources, build ships, equip them and send them on other planets, and so on\(^\text{11}\).

Like many other games, it allows you to save all game state into a file.
Let’s see if we can find something in it.

---

\(^{11}\)It can be downloaded for free [here](#).
So there is a mine in the game. Mines at some planets work faster, or slower on others. The set of resources is also different.

Here we can see what resources are mined at the time:

![Figure 9.14: Mine: state 1](image)

Let's save a game state. This is a file of size 9538 bytes.

Let's wait some “days” here in the game, and now we’ve got more resources from the mine:
Let's save game state again.

Now let’s try to just do binary comparison of the save files using the simple DOS/Windows FC utility:

```bash
...> FC /b 2200save.i.v1 2200SAVE.I.V2
Comparing files 2200save.i.v1 and 2200SAVE.I.V2
00000016: 0D 04
00000017: 03 04
0000001C: 1F 1E
00000146: 27 3B
00000BDA: 0E 16
00000BDC: 66 9B
00000BDE: 0E 16
00000BE0: 0E 16
00000BE6: DB 4C
00000BE7: 00 01
00000BE8: 99 E8
00000BEC: A1 F3
00000BEE: B3 C7
00000BF: A8 2B
00000BF: 98 18
00000BFF: A8 2B
00000C01: A8 2B
00000C07: D8 5B
00000C09: E4 A4
00000C0D: 3B 8B
00000C0F: EB 68
...
```

The output is incomplete here, there are more differences, but we will cut result to show the most interesting.

In the first state, we have 14 “units” of hydrogen and 102 “units” of oxygen.
9.3. MILLENIUM GAME SAVE FILE

We have 22 and 155 “units” respectively in the second state. If these values are saved into the save file, we would see this in the difference. And indeed we do. There is 0x0E (14) at position 0xBDA and this value is 0x16 (22) in the new version of the file. This is probably hydrogen. There is 0x66 (102) at position 0xBDC in the old version and 0x9B (155) in the new version of the file. This seems to be the oxygen.

Both files are available on the website for those who wants to inspect them (or experiment) more: beginners.re.
9.3. **MILLENIUM GAME SAVE FILE**

Here is the new version of file opened in Hiew, we marked the values related to the resources mined in the game:

![Figure 9.16: Hiew: state 1](image)

Let's check each of them.

These are clearly 16-bit values: not a strange thing for 16-bit DOS software where the `int` type has 16-bit width.
Let’s check our assumptions. We will write the 1234 (0x4D2) value at the first position (this must be hydrogen):

![Figure 9.17: Hiew: let’s write 1234 (0x4D2) there](image)

Then we will load the changed file in the game and took a look at mine statistics:

![Figure 9.18: Let’s check for hydrogen value](image)

So yes, this is it.
9.3. MILLENIUM GAME SAVE FILE

Now let’s try to finish the game as soon as possible, set the maximal values everywhere:

![Hiew: let’s set maximal values](image1)

0xFFFF is 65535, so yes, we now have a lot of resources:

![All resources are 65535 (0xFFFF) indeed](image2)
Let’s skip some “days” in the game and oops! We have a lower amount of some resources:

That’s just overflow.
The game’s developer supposedly didn’t think about such high amounts of resources, so there are probably no overflow checks, but the mine is “working” in the game, resources are added, hence the overflows. Apparently, it is a bad idea to be that greedy.

There are probably a lot of more values saved in this file.

So this is very simple method of cheating in games. High score files often can be easily patched like that.

More about files and memory snapshots comparing: 5.10.2 on page 725.

9.4  *fortune* program indexing file

(This part was first appeared in my blog at 25-Apr-2015.)

*fortune* is well-known UNIX program which shows random phrase from a collection. Some geeks are often set up their system in such way, so *fortune* can be called after logging on. *fortune* takes phrases from the text files laying in `/usr/share/games/fortunes` (as of Ubuntu Linux). Here is example (“fortunes” text file):

```
A day for firm decisions!!!!!! Or is it?
%
A few hours grace before the madness begins again.
%
A gift of a flower will soon be made to you.
%
A long-forgotten loved one will appear soon.
%
Buy the negatives at any price.
```
A tall, dark stranger will have more fun than you.

So it is just phrases, sometimes multiline ones, divided by percent sign. The task of fortune program is to find random phrase and to print it. In order to achieve this, it must scan the whole text file, count phrases, choose random and print it. But the text file can get bigger, and even on modern computers, this naive algorithm is a bit uneconomical to computer resources. The straightforward way is to keep binary index file containing offset of each phrase in text file. With index file, fortune program can work much faster: just to choose random index element, take offset from there, set offset in text file and read phrase from it. This is actually done in fortune program. Let's inspect what is in its index file inside (these are .dat files in the same directory) in hexadecimal editor. This program is open-source of course, but intentionally, I will not peek into its source code.

```
% od -t x1 --address-radix=x fortunes.dat
000000 00 00 00 02 00 00 01 af 00 00 00 bb 00 00 00 0f
000010 00 00 00 00 25 00 00 00 00 00 00 00 00 00 02
000020 00 00 00 08 00 00 00 0f 00 00 00 0d 00 00 00 07
000030 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000040 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000050 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000060 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000070 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000080 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000090 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0000a0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0000b0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0000c0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0000d0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0000e0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0000f0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000100 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000110 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000120 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000130 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000140 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000150 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000160 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000170 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000180 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
000190 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0001a0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0001b0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0001c0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
...```

Without any special aid we could see that there are four 4-byte elements on each 16-byte line. Perhaps, it's our index array. I'm trying to load the whole file in Wolfram Mathematica as 32-bit integer array:

```
In[]:= BinaryReadList["c:/tmp/fortunes.dat", "UnsignedInteger32"]
Out[]= {33554432, 2936078336, 3137393932, 251658240, 0, 37, 0,   
721420288, 1610612736, 2399141888, 3741319168, 335609856, 1208025088,  
2080440320, 2868969472, 3858825216, 537001984, 989986816, 2046951424,  
3305242624, 67305472, 1023606784, 1745027072, 2801991680, 3775070208,  
419692544, 755236864, 2139688576, 2902720512, 3573809152, 84213760,  
990183424, 1678042980, 2181365760, 2902786048, 3456434176,  
414430032, 470155264, 1627783168, 2047213568, 3506831360, 168230912,  
1392967680, 2584150016, 4161208320, 654835712, 1493696512,  
2323557312, 2684878848, 3288858624, 3775397888, 4178051072,  
...```

Nope, something wrong. Numbers are suspiciously big. But let's back to od output: each 4-byte element has two zero bytes and two non-zero bytes, so the offsets (at least at the beginning of the file) are 16-bit at maximum. Probably different endianness is used in the file? Default endianness in Mathematica is little-endian, as used in Intel CPUs. Now I'm changing it to big-endian:

```
In[]:= BinaryReadList["c:/tmp/fortunes.dat", "UnsignedInteger32",  
ByteOrdering -> 1]   
969`
Yes, this is something readable. I choose random element (3066) which is 0xBFA in hexadecimal form. I’m opening ‘fortunes’ text file in hex editor, I’m setting 0xBFA as offset and I see this phrase:

```
% od -t x1 -c --skip-bytes=0xbfa --address-radix=x fortunes
000bfa 44 6f 20 77 68 61 74 20 63 6f 6d 65 73 20 6e 61
do what comes naturally. see the and fume and throw a tantrum.
```

Or:
```
Do what comes naturally. Seethe and fume and throw a tantrum.
```

Other offset are also can be checked, yes, they are valid offsets.

I can also check in Mathematica that each subsequent element is bigger than previous. I.e., elements of array are ascending. In mathematics lingo, this is called \textit{strictly increasing monotonic function}.

```
In[1]:= Differences[input]
Out[1]= {429, -244, -172, -15, 620756992, -620756992, 43, 53, 47, 22, 43, 35, 102, 53, 80, 65, 45, 31, 29, 
33, 48, 65, 35, 59, 47, 55, 22, 43, 35, 102, 53, 80, 65, 45, 31, 29, 
69, 32, 25, 38, 34, 35, 49, 59, 39, 41, 18, 43, 41, 83, 37, 31, 34, 
95, 72, 72, 81, 77, 53, 53, 50, 51, 45, 53, 39, 70, 54, 103, 33, 70, 
91, 59, 67, 54, 55, 65, 61, 54, 54, 53, 45, 100, 63, 48, 65, 71, 23, 
28, 43, 51, 61, 101, 69, 78, 66, 43, 43, 56, 50, 40, 67, 92, 65, 61, 
31, 45, 52, 94, 82, 82, 91, 46, 76, 55, 19, 58, 68, 41, 75, 30, 67, 
92, 54, 52, 100, 61, 56, 76, 41, 79, 54, 65, 74, 112, 76, 47, 53, 61, 
66, 53, 28, 41, 81, 75, 69, 69, 63, 60, 18, 18, 50, 79, 92, 37, 63, 
88, 52, 81, 60, 80, 26, 46, 80, 64, 78, 70, 75, 46, 91, 22, 63, 46, 
34, 81, 75, 59, 62, 66, 74, 76, 111, 55, 73, 40, 61, 55, 38, 56, 47, 
78, 81, 62, 37, 41, 60, 68, 40, 33, 54, 34, 41, 36, 49, 44, 68, 51, 
50, 52, 36, 53, 66, 46, 41, 45, 51, 44, 44, 33, 72, 40, 71, 57, 55, 
39, 66, 40, 56, 68, 43, 88, 78, 30, 54, 64, 36, 55, 35, 88, 45, 56, 
76, 61, 66, 29, 76, 53, 96, 36, 46, 54, 28, 51, 82, 53, 60, 77, 21, 
84, 53, 43, 104, 85, 50, 47, 39, 66, 78, 81, 94, 70, 49, 67, 61, 37, 
51, 91, 99, 58, 51, 49, 46, 68, 72, 40, 56, 63, 65, 41, 62, 47, 41, 
43, 30, 43, 67, 78, 80, 101, 61, 73, 70, 41, 82, 69, 45, 65, 38, 41, 
57, 82, 66}
```

As we can see, except of the very first 6 values (which is probably belongs to index file header), all numbers are in fact length of all text phrases (offset of the next phrase minus offset of the current phrase is in fact length of the current phrase).

It’s very important to keep in mind that bit-endianess can be confused with incorrect array start. Indeed, from \texttt{od} output we see that each element started with two zeros. But when shifted by two bytes in either side, we can interpret this array as little-endian:

```
Out[1]= {2, 431, 187, 15, 0, 620756992, 0, 43, 96, 143, 223, 276, 
328, 380, 427, 486, 544, 571, 634, 709, 772, 829, 872, 935, 993, 
1049, 1069, 1151, 1197, 1237, 1285, 1339, 1380, 1410, 1453, 1486, 
1527, 1564, 1633, 1658, 1745, 1802, 1875, 1946, 2040, 2087, 2137, 
2187, 2208, 2244, 2273, 2297, 2343, 2371, 2425, 2467, 2531, 2581, 
2637, 2654, 2698, 2726, 2751, 2799, 2840, 2883, 2913, 2958, 3023, 
3066, 3131, 3174, 3205, 3257, 3282, 3330, 3387, 3431, 3500, 3552, 
...}
```

9.4. FORTUNE PROGRAM INDEXING FILE
If we would interpret this array as little-endian, the first element is 0x4801, second is 0x7C01, etc. High 8-bit part of each of these 16-bit values are seems random to us, and the lowest 8-bit part is seems ascending.

But I'm sure that this is big-endian array, because the very last 32-bit element of the file is big-endian (00 00 5fc4 here):

```
% od -t x1 --address-radix=x fortunes.dat
... 000660 00 00 59 0d 00 00 59 55 00 00 59 7d 00 00 59 b5
000670 00 00 59 f4 00 00 5a 35 00 00 5a 5e 00 00 5a 9c
000680 00 00 5a cb 00 00 5a f4 00 00 5b 1f 00 00 5b 3d
000690 00 00 5b 68 00 00 5b ab 00 00 5b f9 00 00 5c 49
0006a0 00 00 5c ae 00 00 5c eb 00 00 5d 34 00 00 5d 7a
0006b0 00 00 5d a3 00 00 5d f5 00 00 5e 3a 00 00 5e 67
0006c0 00 00 5e a8 00 00 5e ce 00 00 5f f7 00 00 5f 30
0006d0 00 00 5f 82 00 00 5f c4 0006d8
```

Perhaps, \textit{fortune} program developer had big-endian computer or maybe it was ported from something like it.

OK, so the array is big-endian, and, judging by common sense, the very first phrase in the text file must be started at zeroth offset. So zero value should be present in the array somewhere at the very beginning. We've got couple of zero elements at the beginning. But the second is most appealing: 43 is going right after it and 43 is valid offset to valid English phrase in the text file.

The last array element is 0x5FC4, and there are no such byte at this offset in the text file. So the last array element is pointing behind the end of file. It's supposedly done because phrase length is calculated as difference between offset to the current phrase and offset to the next phrase. This can be faster than traversing phrase string for percent character. But this wouldn't work for the last element. So the dummy element is also added at the end of array.

So the first 6 32-bit integer values are supposedly some kind of header.

Oh, I forgot to count phrases in text file:

```
% cat fortunes | grep % | wc -l
432
```

The number of phrases can be present in index, but may be not. In case of very simple index files, number of elements can be easily deduced from index file size. Anyway, there are 432 phrases in the text file. And we see something very familiar at the second element (value 431). I've checked other files (literature.dat and riddles.dat in Ubuntu Linux) and yes, the second 32-bit element is indeed number of phrases minus 1. Why \textit{minus 1}? Perhaps, this is not number of phrases, but rather the number of the last phrase (starting at zero)?

And there are some other elements in the header. In Mathematica, I'm loading each of three available files and I'm taking a look on the header:
I have no idea what other values mean, except the size of index file. Some fields are the same for all files, some are not. From my own experience, there could be:

- file signature;
- file version;
- checksum;
- some flags;
- maybe even text language identifier;
- text file timestamp, so the fortune program will regenerate index file if a user modified text file.

For example, Oracle .SYM files (9.5 on the next page) which contain symbols table for DLL files, also contain timestamp of corresponding DLL file, so to be sure it is still valid.

On the other hand, text file and index file timestamps can gone out of sync after archiving/unarchiving/installing/deploying/etc.

But there are no timestamp, in my opinion. The most compact way of representing date and time is UNIX time value, which is big 32-bit number. We don’t see any of such here. Other ways of representation are even less compact.

So here is algorithm, how fortune supposedly works:

- take number of last phrase from the second element;
- generate random number in range of 0..number_of_last_phrase;
- find corresponding element in array of offsets, take also following offset;
- output to stdout all characters from the text file starting at the offset until the next offset minus 2 (so to ignore terminating percent sign and character of the following phrase).

### 9.4.1 Hacking

Let’s try to check some of our assumptions. I will create this text file under the path and name /usr/share/games/fortunes/fortunes:

```
Phrase one.
%
Phrase two.
%```

9.5. Oracle RDBMS: .SYM-files

When an Oracle RDBMS process experiences some kind of crash, it writes a lot of information into log files, including stack trace, like this:

```
----- Call Stack Trace -----
calling    call    entry    argument values in hex
location   type    point

------------------------ ------------------------------
_kqvrow() 00000000   _opifch2()+2729 00000000 23D4B914 E47F264 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2 1F19AE2
__opifch2()+2729 CALLptr 00000000 89 5 EB1CC74
__opifch2()+2729 CALLrel __opifch2() 89 5 EB1CC74
```

12 Gibibyte

9.4.2 The files

For the sake of demonstration, I still didn’t take a look in fortune source code. If you want to try to understand meaning of other values in index file header, you may try to achieve it without looking into source code as well. Files I took from Ubuntu Linux 14.04 are here: http://beginners.re/examples/fortune/, hacked files are also here.

Oh, and I took the files from x64 version of Ubuntu, but array elements are still has size of 32 bit. It is because fortune text files are probably never exceeds 4GiB size. But if it will, all elements must have size of 64 bit so to be able to store offset to the text file larger than 4GiB.

For impatient readers, the source code of fortune is here: https://launchpad.net/ubuntu/+source/fortune-mod/1:1.99.1-3.1ubuntu4.
### 9.5. ORACLE RDBMS: .SYM-FILES

<table>
<thead>
<tr>
<th>Function</th>
<th>Call Type</th>
<th>Address 1</th>
<th>Address 2</th>
<th>Address 3</th>
<th>Address 4</th>
<th>Address 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>_opiode() + 1248</td>
<td>CALLreg</td>
<td>00000000</td>
<td>5E 1C EB1F0A0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>_ttcpip() + 1051</td>
<td>CALLreg</td>
<td>00000000</td>
<td>5E 1C EB1F0A0 0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>_opitsk() + 1404</td>
<td>CALL???</td>
<td>00000000</td>
<td>C96C040 5E EB1F0A0 0 EB1ED30 EB1F1CC 53E52E 0 EB1F1F8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>_opiino() + 980</td>
<td>CALLrel _opitsk()</td>
<td>0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>_opiode() + 1248</td>
<td>CALLreg</td>
<td>00000000</td>
<td>3C 4 EB1FBF4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>_opidrv() + 1201</td>
<td>CALLrel _opiode()</td>
<td>3C 4 EB1FBF4 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>_sou2o() + 55</td>
<td>CALLrel _opidrv()</td>
<td>3C 4 EB1FBF4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>_opimai_real() + 124</td>
<td>CALLrel _sou2o()</td>
<td>EB1FC04 3C 4 EB1FBF4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>_opimai() + 125</td>
<td>CALLrel _opimai_real()</td>
<td>2 EB1FC2C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OracleThreadStart@</td>
<td>CALLrel _opimai()</td>
<td>2 EB1FF6C 7C88A7F4 EB1FC34 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4() + 830</td>
<td>CALL???</td>
<td>00000000</td>
<td>77E6481C CALLreg 00000000 E41FF9C 0 0 E41FF9C 0 EB1FFC4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>00000000</td>
<td>CALL???</td>
<td>00000000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

But of course, Oracle RDBMS’s executables must have some kind of debug information or map files with symbol information included or something like that.

Windows NT Oracle RDBMS has symbol information in files with .SYM extension, but the format is proprietary. (Plain text files are good, but needs additional parsing, hence offer slower access.)

Let’s see if we can understand its format.

We will pick the shortest ora_wtc8.sym file that comes with the ora_wtc8.dll file in Oracle 8.1.7.¹³

¹³We can chose an ancient Oracle RDBMS version intentionally due to the smaller size of its modules.
9.5. ORACLE RDBMS: .SYM-FILES

Here is the file opened in Hiew:

![The whole file in Hiew](image)

Figure 9.22: The whole file in Hiew

By comparing the file with other .SYM files, we can quickly see that OSYM is always header (and footer), so this is maybe the file’s signature.

We also see that basically, the file format is: OSYM + some binary data + zero delimited text strings + OSYM. The strings are, obviously, function and global variable names.
We will mark the OSYM signatures and strings here:

Well, let’s see. In Hiew, we will mark the whole strings block (except the trailing OSYM signatures) and put it into a separate file. Then we run UNIX `strings` and `wc` utilities to count the text strings:

```
strings strings_block | wc -l
66
```

So there are 66 text strings. Please note that number.

We can say, in general, as a rule, the number of anything is often stored separately in binary files.

It’s indeed so, we can find the 66 value (0x42) at the file’s start, right after the OSYM signature:

```
$ hexdump -C orawtc8.sym
00000000 4f 53 59 4d 00 00 00 00 00 10 00 10 00 10 00 10 |OSYMB...........|
00000010 f0 10 00 10 50 11 00 10 60 11 00 10 c0 11 00 10 |....P...`.......|
00000020 d0 11 00 10 70 13 00 10 40 15 00 10 50 15 00 10 |....p...@...P...|
00000030 60 15 00 10 80 15 00 10 a0 15 00 10 a6 15 00 10 |`...............|
```

Of course, 0x42 here is not a byte, but most likely a 32-bit value packed as little-endian, hence we see 0x42 and then at least 3 zero bytes.

Why do we believe it’s 32-bit? Because, Oracle RDBMS’s symbol files may be pretty big.

The oracle.sym file for the main oracle.exe (version 10.2.0.4) executable contains 0x3A38E (238478) symbols. A 16-bit value isn’t enough here.

We can check other .SYM files like this and it proves our guess: the value after the 32-bit OSYM signature always reflects the number of text strings in the file.
It’s a general feature of almost all binary files: a header with a signature plus some other information about the file.

Now let’s investigate closer what this binary block is.

Using Hiew again, we put the block starting at address 8 (i.e., after the 32-bit count value) ending at the strings block, into a separate binary file.
Let's see the binary block in Hiew:

![Binary block](image)

There is a clear pattern in it.

---

Figure 9.24: Binary block
9.5. ORACLE RDBMS: SYM-FILES

We will add red lines to divide the block:

![Binary block patterns](image)

**Figure 9.25: Binary block patterns**

Hiew, like almost any other hexadecimal editor, shows 16 bytes per line. So the pattern is clearly visible: there are 4 32-bit values per line.

The pattern is visually visible because some values here (till address 0x104) are always in 0x1000xxxx form, started with 0x10 and zero bytes.

Other values (starting at 0x108) are in 0x0000xxxx form, so always started with two zero bytes.

Let’s dump the block as an array of 32-bit values:

**Listing 9.9: first column is address**

```
$ od -v -t x4 binary_block
0000000 10001000 10001080 100010f0 10001150
0000020 10001160 100011c0 100011d0 10001370
0000040 10001540 10001550 10001560 10001580
0000060 100015a0 100015a6 100015ac 100015b2
0000080 100015b8 100015be 100015c4 100015ca
0000100 100015d0 100015e0 100016b0 10001760
0000120 10001766 1000176c 10001780 100017b0
0000140 100017d0 100017e0 10001810 10001816
0000180 10002000 10002004 10002008 1000200c
0000200 10002010 10002014 10002018 1000201c
```

979
There are 132 values, that’s 66*2. Probably, there are two 32-bit values for each symbol, but maybe there are two arrays? Let’s see.

Values starting with 0x1000 may be addresses.

This is a .SYM file for a DLL after all, and the default base address of win32 DLLs is 0x10000000, and the code usually starts at 0x10001000.

When we open the orawtc8.dll file in IDA, the base address is different, but nevertheless, the first function is:

```
.text:60351000  sub_60351000  proc near
.text:60351000  arg_0 = dword ptr 8
.text:60351000  arg_4 = dword ptr 0Ch
.text:60351000  arg_8 = dword ptr 10h
.text:60351000  push ebp
.text:60351001  mov ebp, esp
.text:60351003  mov eax, dword_60353014
.text:60351008  cmp eax, 0FFFFFFFFh
.text:6035100B  jnz short loc_6035104F
.text:6035100D  mov ecx, hModule
.text:60351013  xor eax, eax
.text:60351015  cmp ecx, 0FFFFFFFFh
.text:60351018  mov dword_60353014, eax
.text:6035101D  jnz short loc_6035104F
.text:60351021  mov ecx, hModule
.text:60351024  mov eax, dword_60353014
.text:60351026  mov hModule, ecx
.text:60351031  loc_60351031: ; CODE XREF: sub_60351000+1D
.text:60351031  test ecx, ecx
.text:60351033  jbe short loc_6035104F
.text:60351035  push offset ProcName ; "ax_reg"
.text:6035103A  push ecx ; hModule
.text:6035103B  call ds:GetProcAddress ...
```

Wow, “ax_reg” string sounds familiar.

It’s indeed the first string in the strings block! So the name of this function seems to be “ax_reg”.

The second function is:
The “ax_unreg” string is also the second string in the strings block!

The starting address of the second function is 0x60351080, and the second value in the binary block is 10001080. So this is the address, but for a DLL with the default base address.

We can quickly check and be sure that the first 66 values in the array (i.e., the first half of the array) are just function addresses in the DLL, including some labels, etc. Well, what’s the other part of array then? The other 66 values that start with 0x0000? These seem to be in range [0...0x3F8]. And they do not look like bitfields: the series of numbers is increasing.

The last hexadecimal digit seems to be random, so, it’s unlikely the address of something (it would be divisible by 4 or maybe 8 or 0x10 otherwise).

Let’s ask ourselves: what else Oracle RDBMS’s developers would save here, in this file?

Quick wild guess: it could be the address of the text string (function name).

It can be quickly checked, and yes, each number is just the position of the first character in the strings block.

This is it! All done.

We will write an utility to convert these .SYM files into IDA script, so we can load the .idc script and it sets the function names:

```c
#include <stdio.h>
#include <stdint.h>
#include <string.h>
#include <assert.h>
#include <malloc.h>
#include <fcntl.h>

int main (int argc, char *argv[]) {

    uint32_t sig, cnt, offset;
    uint32_t *d1, *d2;
    int h, i, remain, file_len;
    char *d3;
    uint32_t array_size_in_bytes;

    assert (argv[1]); // file name
    assert (argv[2]); // additional offset (if needed)

    // Read the file
    // ...
// additional offset
assert (sscanf (argv[2], "%X", &offset)==1);

// get file length
assert ((h=open (argv[1], _O_RDONLY | _O_BINARY, 0))!=-1);
assert ((file_len=lseek (h, 0, SEEK_END))!=-1);
assert (lseek (h, 0, SEEK_SET)!=-1);

// read signature
assert (read (h, &sig, 4)==4);
// read count
assert (read (h, &cnt, 4)==4);

assert (sig==0x4D59534F); // OSYM

// skip timedatestamp (for 11g)
//_lseek (h, 4, 1);

array_size_in_bytes=cnt*sizeof(uint32_t);

// load symbol addresses array
d1=(uint32_t*)malloc (array_size_in_bytes);
assert (d1);
assert (read (h, d1, array_size_in_bytes)==array_size_in_bytes);

// load string offsets array
d2=(uint32_t*)malloc (array_size_in_bytes);
assert (d2);
assert (read (h, d2, array_size_in_bytes)==array_size_in_bytes);

// calculate strings block size
remain=file_len-(8+4)-(cnt*8);

// load strings block
assert (d3=(char*)malloc (remain));
assert (read (h, d3, remain)==remain);

printf ("#include <idc.idc>

static main() {
	for (i=0; i<cnt; i++)
		MakeName(0x%08X, "%s");
}
"\n"

}@\n"

free (d1); free (d2); free (d3);
};

Here is an example of its work:

#include <idc.idc>

static main() {
	MakeName(0x60351000, "_ax_reg");
	MakeName(0x60351080, "_ax_unreg");
	MakeName(0x603510F0, "_loaddll");
	MakeName(0x60351150, "_wtcsrin0");
	MakeName(0x60351160, "_wtcsrin");
	MakeName(0x603511D0, "_wtcsrfre");
	MakeName(0x603511C0, "_wtclkm");
	MakeName(0x60351370, "_wtcstu");
...
}

The example files were used in this example are here: beginners.re.
Oh, let’s also try Oracle RDBMS for win64. There has to be 64-bit addresses instead, right?

The 8-byte pattern is visible even easier here:

![Figure 9.26: .SYM-file example from Oracle RDBMS for win64](image)

So yes, all tables now have 64-bit elements, even string offsets!

The signature is now OSYMAM64, to distinguish the target platform, apparently.

This is it!

Here is also library which has functions to access Oracle RDBMS.SYM-files: [GitHub](https://github.com).

### 9.6 Oracle RDBMS: .MSB-files

When working toward the solution of a problem, it always helps if you know the answer.

---

**Murphy’s Laws, Rule of Accuracy**

This is a binary file that contains error messages with their corresponding numbers. Let’s try to understand its format and find a way to unpack it.
There are Oracle RDBMS error message files in text form, so we can compare the text and packed binary files.

This is the beginning of the ORAUS.MSG text file with some irrelevant comments stripped:

Listing 9.10: Beginning of ORAUS.MSG file without comments

<table>
<thead>
<tr>
<th>Error Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>00000</td>
<td>&quot;normal, successful completion&quot;</td>
</tr>
<tr>
<td>00001</td>
<td>&quot;unique constraint (%s.%s) violated&quot;</td>
</tr>
<tr>
<td>00017</td>
<td>&quot;session requested to set trace event&quot;</td>
</tr>
<tr>
<td>00018</td>
<td>&quot;maximum number of sessions exceeded&quot;</td>
</tr>
<tr>
<td>00019</td>
<td>&quot;maximum number of session licenses exceeded&quot;</td>
</tr>
<tr>
<td>00020</td>
<td>&quot;maximum number of processes (%s) exceeded&quot;</td>
</tr>
<tr>
<td>00021</td>
<td>&quot;session attached to some other process; cannot switch session&quot;</td>
</tr>
<tr>
<td>00022</td>
<td>&quot;invalid session ID; access denied&quot;</td>
</tr>
<tr>
<td>00023</td>
<td>&quot;session references process private memory; cannot detach session&quot;</td>
</tr>
<tr>
<td>00024</td>
<td>&quot;logins from more than one process not allowed in single-process mode&quot;</td>
</tr>
<tr>
<td>00025</td>
<td>&quot;failed to allocate %s&quot;</td>
</tr>
<tr>
<td>00026</td>
<td>&quot;missing or invalid session ID&quot;</td>
</tr>
<tr>
<td>00027</td>
<td>&quot;cannot kill current session&quot;</td>
</tr>
<tr>
<td>00028</td>
<td>&quot;your session has been killed&quot;</td>
</tr>
<tr>
<td>00029</td>
<td>&quot;session is not a user session&quot;</td>
</tr>
<tr>
<td>00030</td>
<td>&quot;User session ID does not exist.&quot;</td>
</tr>
<tr>
<td>00031</td>
<td>&quot;session marked for kill&quot;</td>
</tr>
</tbody>
</table>

The first number is the error code. The second is perhaps maybe some additional flags.

---

14 Open-source text files don’t exist in Oracle RDBMS for every .MSB file, so that’s why we will work on their file format.
Now let’s open the ORAUS.MSB binary file and find these text strings. And there are:

![Figure 9.27: Hiew: first block](image)

We see the text strings (including those from the beginning of the ORAUS.MSG file) interleaved with some binary values. By quick investigation, we can see that main part of the binary file is divided by blocks of size 0x200 (512) bytes.
9.6. ORACLE RDBMS: .MSB-FILES

Let’s see the contents of the first block:

Here we see the texts of the first messages errors. What we also see is that there are no zero bytes between the error messages. This implies that these are not null-terminated C strings. As a consequence, the length of each error message must be encoded somehow. Let’s also try to find the error numbers. The ORAUS.MSG files starts with these: 0, 1, 17 (0x11), 18 (0x12), 19 (0x13), 20 (0x14), 21 (0x15), 22 (0x16), 23 (0x17), 24 (0x18)... We will find these numbers at the beginning of the block and mark them with red lines. The period between error codes is 6 bytes.

This implies that there are probably 6 bytes of information allocated for each error message.

The first 16-bit value (0xA here or 10) means the number of messages in each block: this can be checked by investigating other blocks. Indeed: the error messages have arbitrary size. Some are longer, some are shorter. But block size is always fixed, hence, you never know how many text messages can be packed in each block.

As we already noted, since these are not null-terminated C strings, their size must be encoded somewhere. The size of the first string “normal, successful completion” is 29 (0x1D) bytes. The size of the second string “unique constraint (%s.%s) violated” is 34 (0x22) bytes. We can’t find these values (0x1D or/and 0x22) in the block.

There is also another thing. Oracle RDBMS has to determine the position of the string it needs to load in the block, right? The first string “normal, successful completion” starts at position 0x1444 (if we count starting at the beginning of the file) or at 0x44 (from the block’s start). The second string “unique constraint
So, each 6-byte block is:

- 16-bit error number;
- 16-bit zero (maybe additional flags);
- 16-bit starting position of the text string within the current block.

We can quickly check the other values and be sure our guess is correct. And there is also the last “dummy” 6-byte block with an error number of zero and starting position beyond the last error message’s last character. Probably that’s how text message length is determined? We just enumerate 6-byte blocks to find the error number we need, then we get the text string’s position, then we get the position of the text string by looking at the next 6-byte block! This way we determine the string’s boundaries! This method allows to save some space by not saving the text string’s size in the file!

It’s not possible to say it saves a lot of space, but it’s a clever trick.
Let’s back to the header of .MSB-file:

Figure 9.29: Hiew: file header

Now we can quickly find the number of blocks in the file (marked by red). We can checked other .MSB-files and we see that it’s true for all of them.

There are a lot of other values, but we will not investigate them, since our job (an unpacking utility) is done.

If we have to write a .MSB file packer, we would probably have to understand the meaning of the other values.
There is also a table that came after the header which probably contains 16-bit values:

![Hiew: last_errnos table](image)

Their size can be determined visually (red lines are drawn here).

While dumping these values, we have found that each 16-bit number is the last error code for each block. So that's how Oracle RDBMS quickly finds the error message:

- load a table we will call last_errnos (that contains the last error number for each block);
- find a block that contains the error code we need, assuming all error codes increase across each block and across the file as well;
- load the specific block;
- enumerate the 6-byte structures until the specific error number is found;
- get the position of the first character from the current 6-byte block;
- get the position of the last character from the next 6-byte block;
- load all characters of the message in this range.

This is C program that we wrote which unpacks .MSB-files: beginners.re.

There are also the two files which were used in the example (Oracle RDBMS 11.1.0.6): beginners.re, beginners.re.
9.7. **EXERCISES**

9.6.1 **Summary**

The method is probably too old-school for modern computers. Supposedly, this file format was developed in the mid-80’s by someone who also coded for *big iron* with memory/disk space economy in mind. Nevertheless, it has been an interesting and yet easy task to understand a proprietary file format without looking into Oracle RDBMS’s code.

9.7 **Exercises**

Try to reverse engineer of any binary files of your favorite game, including high-score files, resources, etc. There are also binary files with known structure: utmp/wtmp files, try to understand its structure without documentation.

The EXIF header in JPEG file is documented, but you can try to understand its structure without help, just shoot photos at various date/time, places, and try to find date/time and GPS location in EXIF. Try to patch GPS location, upload JPEG file to Facebook and see, how it will put your picture on the map.

Try to patch any information in MP3 file and see how your favorite MP3-player will react.

9.8 **Further reading**

Pierre Capillon – Black-box cryptanalysis of home-made encryption algorithms: a practical case study.
Chapter 10

Dynamic binary instrumentation

DBI tools can be viewed as highly advanced and fast debuggers.

10.1 Using PIN DBI for XOR interception

PIN from Intel is a DBI tool. That means, it takes compiled binary and inserts your instructions in it, where you want.

Let's try to intercept all XOR instructions. These are heavily used in cryptography, and we can try to run WinRAR archiver in encryption mode with a hope that some XOR instruction is indeed is used while encryption.

Here is the source code of my PIN tool: https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/XOR/files/XOR_ins.cpp.

The code is almost self-explanatory: it scans input executable file for all XOR/PXOR instructions and inserts a call to our function before each. log_info() function first checks, if operands are different (since XOR is often used just to clear register, like XOR EAX, EAX), and if they are different, it increments a counter at this EIP/RIP, so the statistics will be gathered.

I have prepared two files for test: test1.bin (30720 bytes) and test2.bin (5547752 bytes), I’ll compress them by RAR with password and see difference in statistics.

You’ll also need to turn off ASLR\(^1\), so the PIN tool will report the same RIPS as in RAR executable.

Now let’s run it:

c:\pin-3.2-81205-msvc-windows\pin.exe -t XOR_ins.dll -- rar a -pLongPassword tmp.rar test1.bin
c:\pin-3.2-81205-msvc-windows\pin.exe -t XOR_ins.dll -- rar a -pLongPassword tmp.rar test2.bin

Now here is statistics for the test1.bin:
https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/XOR/files/XOR_ins.out. test1. ... and for test2.bin:
https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/XOR/files/XOR_ins.out. test2. So far, you can ignore all addresses other than ip=0x1400xxxxx, which are in other DLLs.

Now let’s see a difference: https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/XOR/files/XOR_ins.diff.

Some XOR instructions executed more often for test2.bin (which is bigger) than for test1.bin (which is smaller). So these are clearly related to file size!

The first block of differences is:

```
< ip=0x140017b21 count=0xd84
< ip=0x140017b48 count=0x81f
< ip=0x140017b59 count=0x858
< ip=0x140017b6a count=0xc13
< ip=0x140017b7b count=0xe4c
< ip=0x140017b8a count=0xe4d
< ip=0x140017b92 count=0xb86
```

\(^1\)https://stackoverflow.com/questions/9560993/how-do-you-disable-aslr-address-space-layout-randomization-on-windows
10.1. USING PIN DBI FOR XOR INTERCEPTION

< ip=0x140017ba1 count=0xf01
---
> ip=0x140017b21 count=0x9eab5
> ip=0x140017b48 count=0x79863
> ip=0x140017b59 count=0x862e8
> ip=0x140017b6a count=0x99495
> ip=0x140017b7b count=0xa891c
> ip=0x140017b8a count=0xa89f4
> ip=0x140017b92 count=0x8ed72
> ip=0x140017ba1 count=0xa8a8a

This is indeed some kind of loop inside of RAR.EXE:

```
.text:0000000140017B21 loc_140017B21:
.text:0000000140017B21 xor r11d, [rbx]
.text:0000000140017B24 mov r9d, [rbx+4]
.text:0000000140017B28 add rbx, 8
.text:0000000140017B2C mov eax, r9d
.text:0000000140017B2F shr eax, 18h
.text:0000000140017B32 movzx edx, al
.text:0000000140017B35 mov eax, r9d
.text:0000000140017B38 shr eax, 10h
.text:0000000140017B3B movzx ecx, al
.text:0000000140017B3E mov eax, r9d
.text:0000000140017B41 shr eax, 8
.text:0000000140017B44 mov r8d, [rsi+rdx*4]
.text:0000000140017B45 xor r8d, [rsi+rcx*4+400h]
.text:0000000140017B46 movzx ecx, al
.text:0000000140017B4E mov r11d, r8d
.text:0000000140017B56 shr eax, 18h
.text:0000000140017B59 xor r8d, [rsi+rcx*4+800h]
.text:0000000140017B5A movzx ecx, al
.text:0000000140017B62 xor r8d, [rsi+rcx*4+1000h]
.text:0000000140017B63 movzx ecx, al
.text:0000000140017B66 mov eax, r11d
.text:0000000140017B6D shr eax, 10h
.text:0000000140017B6E xor r8d, [rsi+rcx*4+1400h]
.text:0000000140017B71 movzx ecx, al
.text:0000000140017B74 mov eax, r11d
.text:0000000140017B7B shr eax, 8
.text:0000000140017B7C xor r8d, [rsi+rcx*4+1800h]
.text:0000000140017B7D movzx ecx, al
.text:0000000140017B7F xor r8d, [rsi+rcx*4+1C00h]
.text:0000000140017B86 movzx eax, r9b
.text:0000000140017B8D movzx eax, r9b
.text:0000000140017B94 xor r8d, [rsi+rcx*4+1800h]
.text:0000000140017B9A movzx eax, r11b
.text:0000000140017B9E mov r11d, r8d
.text:0000000140017BA1 xor r11d, [rsi+rcx*4+1C00h]
.text:0000000140017BA9 sub rdi, 1
.text:0000000140017BAD jnz loc_140017B21
```

What does it do? No idea yet.

The next:

< ip=0x14002c4f1 count=0x4fce
---
> ip=0x14002c4f1 count=0x4463be

0x4fce is 20430, which is close to size of test1.bin (30720 bytes). 0x4463be is 4481982 which is close to size of test2.bin (5547752 bytes). Not equal, but close.

This is a piece of code with that XOR instruction:

```
.text:0000000140017B21 loc_140017B21:
.text:0000000140017B21 xor r11d, [rbx]
.text:0000000140017B24 mov r9d, [rbx+4]
.text:0000000140017B28 add rbx, 8
.text:0000000140017B2C mov eax, r9d
.text:0000000140017B2F shr eax, 18h
.text:0000000140017B32 movzx edx, al
.text:0000000140017B35 mov eax, r9d
.text:0000000140017B38 shr eax, 10h
.text:0000000140017B3B movzx ecx, al
.text:0000000140017B3E mov eax, r9d
.text:0000000140017B41 shr eax, 8
.text:0000000140017B44 mov r8d, [rsi+rdx*4]
.text:0000000140017B45 xor r8d, [rsi+rcx*4+400h]
.text:0000000140017B46 movzx ecx, al
.text:0000000140017B4E mov r11d, r8d
.text:0000000140017B56 shr eax, 18h
.text:0000000140017B59 xor r8d, [rsi+rcx*4+800h]
.text:0000000140017B5A movzx ecx, al
.text:0000000140017B62 xor r8d, [rsi+rcx*4+1000h]
.text:0000000140017B63 movzx ecx, al
.text:0000000140017B66 mov eax, r11d
.text:0000000140017B6D shr eax, 10h
.text:0000000140017B6E xor r8d, [rsi+rcx*4+1400h]
.text:0000000140017B71 movzx ecx, al
.text:0000000140017B74 xor r8d, [rsi+rcx*4+1800h]
.text:0000000140017B7A movzx eax, r11b
.text:0000000140017B7E mov r11d, r8d
.text:0000000140017BA1 xor r11d, [rsi+rcx*4+1C00h]
.text:0000000140017BA9 sub rdi, 1
.text:0000000140017BAD jnz loc_140017B21
```
10.1. USING PIN DBI FOR XOR INTERCEPTION

Loop body can be written as:

\[
\text{state} = \text{input\_byte} \uparrow (\text{state} \ll 5) \land \text{0x7FFF}).
\]

state is then used as index in some table. Is this some kind of CRC\(^2\)? I don’t know, but this could be a checksumming routine. Or maybe optimized CRC routine? Any ideas?

The next block:

```
< ip=0x14004104a count=0x367
< ip=0x140041057 count=0x367
...
> ip=0x14004104a count=0x24193
> ip=0x140041057 count=0x24193
```

```
.loc_140041039:
mov rax, r10
add r10, 10h
cmp byte ptr [rcx+1], 0
movdqu xmm0, xmmword ptr [rax]
jz short loc_14004104E
pxor xmm0, xmm1
movdqu xmm1, xmmword ptr [rcx+18h]
movsx r8, dword ptr [rcx+4]
pxor xmm1, xmm0
jle short loc_14004107C
lea rdx, [rcx+28h]
lea r9d, [r8-1]
loc_140041069:
movdqu xmm0, xmmword ptr [rdx]
lea rdx, [rdx+10h]
aesenc xmm1, xmm0
sub r9, 1
jnz short loc_140041069
```

This piece has both PXOR and AESENC instructions (the last is AES\(^3\) encryption instruction). So yes, we found encryption function, RAR uses AES.

There is also another big block of almost contiguous XOR instructions:

```
< ip=0x140043e10 count=0x23006
...
> ip=0x140043e10 count=0x23004
499c510
< ip=0x140043e56 count=0x22ffd
...
> ip=0x140043e56 count=0x23002
```

But, its count is not very different during compressing/encrypting test1.bin/test2.bin. What is on these addresses?

```
xor ecx, r9d
mov r1ld, eax
and ecx, r10d
xor ecx, r8d
rol eax, 8
and eax, esi
ror r1ld, 8
add edx, 5A827999h
```

\(^2\)Cyclic redundancy check
\(^3\)Advanced Encryption Standard
10.2. CRACKING MINESWEEPER WITH PIN

Let's google 5A827999h constant... this looks like SHA-1! But why would RAR use SHA-1 during encryption?

Here is the answer:

In comparison, WinRAR uses its own key derivation scheme that requires \((\text{password length} * 2 + 11) \times 4096\) SHA-1 transformations. That's why it takes longer to brute-force attack encrypted WinRAR archives.

(http://www.tomshardware.com/reviews/password-recovery-gpu,2945-8.html)

This is key scheduling: input password hashed many times and the hash is then used as AES key. This is why we see the count of XOR instruction is almost unchanged during we switched to bigger test file.

This is it, it took couple of hours for me to write this tool and to get at least 3 points: 1) probably checksumming; 2) AES encryption; 3) SHA-1 calculation. The first function is still unknown for me.

Still, this is impressive, because I didn't dig into RAR code (which is proprietary, of course). I didn't even peek into UnRAR source code (which is available).

The files, including test files and RAR executable I've used (win64, 5.40):
https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/XOR/files

10.2 Cracking Minesweeper with PIN

In this book, I wrote about cracking Minesweeper for Windows XP: 8.3 on page 802.

The Minesweeper in Windows Vista and 7 is different: probably it was (re)written to C++, and a cell information is now stored not in global array, but rather in malloc'ed heap blocks.

This is a case when we can try PIN DBI tool.

10.2.1 Intercepting all rand() calls

First, since Minesweeper places mines randomly, it has to call rand() or similar function. Let's intercept all rand() calls:
https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/minesweeper/minesweeper1.dll

Now we can run it:
c:\pin-3.2-81205-msvc-windows\pin.exe -t minesweeper1.dll -- C:\PATH\TO\MineSweeper.exe

During startup, PIN searches for all calls to rand() function and adds a hook right after each call. The hook is the RandAfter() function we defined: it is logging about return value and also about return address. Here is a log I got during run of standard 9*9 configuration (10 mines): https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/minesweeper/minesweeper1.out.10mines. The rand() function was called many times from several places, but was called from 0x10002770d just 10 times. I switched Minesweeper to 16*16 configuration (40 mines) and rand() was called from 0x10002770d 40 times. So yes, this is our point. When I load minesweeper.exe (from Windows 7) into IDA and PDB from Microsoft website is fetched, the function which calls rand() at 0x10002770d called Board::placeMines().

10.2.2 Replacing rand() calls with our function

Let's now try to replace rand() function with our version, let it always return zero: https://github.com/DennisYurichev/RE-for-beginners/tree/master/DBI/minesweeper/minesweeper2.cpp. During startup, PIN replaces all calls to rand() to calls to our function, which writes to log and returns zero. OK, I run it, and clicked on leftmost/topmost cell:
Yes, unlike Minesweeper from Windows XP, mines are places randomly after user’s click on cell, so to guarantee there is no mine at the cell user first clicked. So Minesweeper placed cells on cells other than leftmost/topmost (where I clicked).

Now I clicked on rightmost/topmost cell:

This can be some kind of practical joke? I don’t know.

I clicked on 5th cell (right at the middle) at the 1st row:

This is nice, because Minesweeper can do some correct placement even with such a broken PRNG!
10.2. CRACKING MINESWEEPER WITH PIN

10.2.3 Peeking into placement of mines

How can we get information about where mines are placed? rand()’s result is seems to be useless: it returned zero all the time, but Minesweeper somehow managed to place mines in different cells, though, lined up.

This Minesweeper also written in C++ tradition, so it has no global arrays.

Let us put ourselves in the position of programmer. It has to be loop like:

```c++
for (int i; i<mines_total; i++)
{
    // get coordinates using rand()
    // put a cell: in other words, modify a block allocated in heap
}
```

How can we get information about heap block which gets modified at the 2nd step? What we need to do:
1) track all heap allocations by intercepting malloc()/realloc()/free(). 2) track all memory writes (slow). 3) intercept calls to rand().

Now the algorithm: 1) mark all heap blocks gets modified between 1st and 2nd call to rand() from 0x10002770d; 2) whenever heap block gets freed, dump its contents.

Tracking all memory writes is slow, but after 2nd call to rand(), we don’t need to track it (since we’ve got already a list of blocks of interest at this point), so we turn it off.


As it turns out, only 4 heap blocks gets modified between first two rand() calls, this is how they looks like:

```c
free(0x20aa6360)
free(): we have this block in our records, size=0x20
0x20AA6360: 36 00 00 00 4E 00 00 00-20 00 00 00 29 00 00 00 "6...N... ."
0x20AA6370: 06 00 00 00 37 00 00 00-35 00 00 00 19 00 00 00 "...7...5....."
0x20AA6380: 46 00 00 00 08 00 00 00-

free(0x20af9d10)
free(): we have this block in our records, size=0x18
0x20AF9D10: 0A 00 00 00 0A 00 00 00-0A 00 00 00 00 00 00 00 "................"
0x20AF9D20: 60 63 AA 20 00 00 00 00-

free(0x20b28b20)
free(): we have this block in our records, size=0x140
0x20B28B20: 02 00 00 00 03 00 00 00-04 00 00 00 00 00 00 00 "................"
0x20B28B30: 07 00 00 00 08 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B28B40: 0E 00 00 00 0F 00 00 00-00 00 00 00 11 00 00 00 "................"
0x20B28B50: 12 00 00 00 13 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B28B60: 16 00 00 00 17 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B28B70: 18 00 00 00 1C 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B28B80: 1F 00 00 00 20 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B28B90: 23 00 00 00 24 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B28BA0: 27 00 00 00 28 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B28BB0: 2C 00 00 00 2E 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B28BC0: 31 00 00 00 32 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B28BD0: 38 00 00 00 39 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B28BE0: 3C 00 00 00 3D 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B28BF0: 40 00 00 00 41 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B2BC00: 44 00 00 00 45 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B2BCC0: 49 00 00 00 4A 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B2BCE0: 4D 00 00 00 4F 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B2BCC0: 50 00 00 00 50 00 00 00-00 00 00 00 00 00 00 00 "................"
0x20B2BCC0: 50 00 00 00 50 00 00 00-00 00 00 00 00 00 00 00 "................"
```
10.3 WHY “INSTRUMENTATION”?

We can easily see that the biggest blocks (with size 0x28 and 0x140) are just arrays of values up to \( \approx 0x50 \). Wait... 0x50 is 80 in decimal representation. And 9*9=81 (standard minesweeper configuration).

After quick investigation, I’ve found that each 32-bit element is indeed cell coordinate. A cell is represented using a single number, it’s a number inside of 2D-array. Row and column of each mine is decoded like that:

\[
\text{row} = n \div \text{WIDTH}; \quad \text{col} = n \mod \text{HEIGHT};
\]

So when I tried to decode these two biggest blocks, I’ve got these cell maps:

```
try_to_dump_cells(). unique elements=0xa
......*..
..........*
.........
.........
.........
*.........*
**.*......
..........*
.........*
.........
...

try_to_dump_cells(). unique elements=0x44
*.*.*.*.**
...*****
*******.*
**********
*****.*.***
..*******
*******.*
******.**
.........

```

It seems that the first block is just a list of mines placed, while the second block is a list of free cells, but, the second is somewhat out of sync with the first one, and it’s negative version of the first one coincides only partially. Nevertheless, the first map is correct - we can peek into it in log file when Minesweeper is still loaded and almost all cells are hidden, and click safely on cells marked as dots here.

So it seems, when user first clicked somewhere, Minesweeper places 10 mines, than destroys the block with a list of it (perhaps, it copies all the data to another block before?), so we can see it during free() call.

Another fact: the method `Array<NodeType>::Add(NodeType)` modifies blocks we observed, and is called from various places, including `Board::placeMines()`. But what is cool: I never got into its details, everything has been resolved using just PIN.


### 10.2.4 Exercise

Try to understand how rand()'s result being converted into coordinate(s). As a practical joke, make rand() to output such results, so mines will be placed in shape of some symbol or figure.

### 10.3 Why “instrumentation”?

Perhaps, this is term of code profiling. There are at least two methods: 1) “sampling”: you break into running code as many times as possible (hundreds per second), and see, where it is executed at the moment; 2) “instrumentation”: compiled code is interleaved with other code, which can increment counters, etc. Perhaps, DBI tools inherited the term?
Chapter 11

Other things

11.1 Executable files patching

11.1.1 Text strings

The C strings are the thing that is the easiest to patch (unless they are encrypted) in any hex editor. This technique is available even for those who are not aware of machine code and executable file formats. The new string has not to be bigger than the old one, because there’s a risk of overwriting another value or code there.

Using this method, a lot of software was localized in the MS-DOS era, at least in the ex-USSR countries in 80’s and 90’s. It was the reason why some weird abbreviations were present in the localized software: there was no room for longer strings.

As for Delphi strings, the string’s size must also be corrected, if needed.

11.1.2 x86 code

Frequent patching tasks are:

- One of the most frequent jobs is to disable some instruction. It is often done by filling it using byte 0x90 (NOP).
- Conditional jumps, which have an opcode like 74 xx (JZ), can be filled with two NOPs. It is also possible to disable a conditional jump by writing 0 at the second byte (jump offset).
- Another frequent job is to make a conditional jump to always trigger: this can be done by writing 0xEB instead of the opcode, which stands for JMP.
- A function’s execution can be disabled by writing RETN (0xC3) at its beginning. This is true for all functions excluding stdcall (6.1.2 on page 734). While patching stdcall functions, one has to determine the number of arguments (for example, by finding RETN in this function), and use RETN with a 16-bit argument (0xC2).
- Sometimes, a disabled functions has to return 0 or 1. This can be done by MOV EAX, 0 or MOV EAX, 1, but it’s slightly verbose.
  A better way is XOR EAX, EAX (2 bytes 0x31 0xC0) or XOR EAX, EAX / INC EAX (3 bytes 0x31 0xC0 0x40).

A software may be protected against modifications.

This protection is often done by reading the executable code and calculating a checksum. Therefore, the code must be read before protection is triggered.

This can be determined by setting a breakpoint on reading memory.

tracer has the BPM option for this.

PE executable file relocs (6.5.2 on page 759) must not to be touched while patching, because the Windows loader may overwrite your new code. (They are grayed in Hiew, for example: fig.1.21).
11.2 Function arguments number statistics

I've always been interesting in what is average number of function arguments.
I've analyzed many Windows 7 32-bit DLLs (crypt32.dll, mfc71.dll, msvcr100.dll, shell32.dll, user32.dll, d3d11.dll, mshtml.dll, msxml6.dll, sqlncli11.dll, wininet.dll, mfc120.dll, msvbvm60.dll, ole32.dll, themeui.dll, wmp.dll) (because they use *stdcall* convention, and so it is easy to *grep* disassembly output just by RETN X).

- no arguments: ≈ 29%
- 1 argument: ≈ 23%
- 2 arguments: ≈ 20%
- 3 arguments: ≈ 11%
- 4 arguments: ≈ 7%
- 5 arguments: ≈ 3%
- 6 arguments: ≈ 2%
- 7 arguments: ≈ 1%

Figure 11.1: Function arguments number statistics

This is heavily dependent on programming style and may be very different for other software products.

11.3 Compiler intrinsic

A function specific to a compiler which is not an usual library function. The compiler generates a specific machine code instead of a call to it. It is often a pseudofunction for specific CPU instruction.

For example, there are no cyclic shift operations in C/C++ languages, but they are present in most CPUs.
11.4. COMPILER’S ANOMALIES

For programmer’s convenience, at least MSVC has pseudofunctions \_\_rotl() and \_\_rotr()\(^1\) which are translated by the compiler directly to the ROL/ROR x86 instructions.

Another example are functions to generate SSE-instructions right in the code.

Full list of MSVC intrinsics: [MSDN](https://msdn.microsoft.com).

### 11.4 Compilation’s anomalies

#### 11.4.1 Oracle RDBMS 11.2 and Intel C++ 10.1

Intel C++ 10.1, which was used for Oracle RDBMS 11.2 Linux x86 compilation, may emit two JZ in row, and there are no references to the second JZ. The second JZ is thus meaningless.

Listing 11.1: kdli.o from libserver11.a

```
.loc_8114CF1: ; CODE XREF: __PGOSF539_kdlimemSer+89A
.loc_8114CF1: ; __PGOSF539_kdlimemSer+3994
.loc_8114CF1 8B 45 08 mov eax, [ebp+arg_0]
.loc_8114CF4 0F B6 50 14 movzx edx, byte ptr [eax+14h]
.loc_8114CF8 F6 C2 01 test dl, 1
.loc_8114CFB 0F 85 17 08 00 00 jnz loc_8115518
.loc_8114D01 85 C9 test ecx, ecx
.loc_8114D03 0F 84 8A 00 00 00 jz loc_8114D93
.loc_8114D09 0F 84 09 08 00 00 jz loc_8115518
.loc_8114D0F 8B 53 08 mov edx, [ebx+8]
.loc_8114D12 09 55 FC mov [ebp+var_4], edx
.loc_8114D15 31 C0 xor eax, eax
.loc_8114D17 6A 00 push 0
.loc_8114D1B FF 71 08 push dword ptr [ecx+8]
.loc_8114D21 E8 03 54 00 00 call len2nbytes
```

Listing 11.2: from the same code

```
.loc_811A2A5: ; CODE XREF: kdliSerLengths+11C
.loc_811A2A5: ; kdliSerLengths+1C1
.loc_811A2A5 8B 7D 08 mov edi, [ebp+arg_0]
.loc_811A2A8 8B 7F 10 mov edi, [edi+10h]
.loc_811A2AB 0F B6 57 14 movzx edx, byte ptr [edi+14h]
.loc_811A2AF F6 C2 01 test dl, 1
.loc_811A2B2 75 3E jnz short loc_811A2F2
.loc_811A2B4 83 E0 01 add eax, 1
.loc_811A2B7 0F 84 03 54 00 00 push dword ptr [ecx+8]
.loc_811A2B9 E8 5F FE FF FF call len2nbytes
```

It is supposedly a code generator bug that was not found by tests, because resulting code works correctly anyway.

#### 11.4.2 MSVC 6.0

Just found in some old code:

```
fabs fild [esp+50h+var_34]
fabs fxch st(1); first instruction
fxch st(1); second instruction
faddp st(1), st
```

\(^1\) [MSDN](https://msdn.microsoft.com)
11.5. ITANIUM

The first FXCH instruction swaps ST(0) and ST(1), the second do the same, so both do nothing. This is a program uses MFC42.dll, so it could be MSVC 6.0, 5.0 or maybe even MSVC 4.2 from 1990s.
This pair do nothing, so it probably wasn’t caught by MSVC compiler tests. Or maybe I wrong?

11.4.3 Summary

Other compiler anomalies here in this book: 1.22.2 on page 315, 3.7.3 on page 493, 3.15.7 on page 532, 1.20.7 on page 302, 1.14.4 on page 147, 1.22.5 on page 332.
Such cases are demonstrated here in this book, to show that such compilers errors are possible and sometimes one should not to rack one’s brain while thinking why did the compiler generate such strange code.

11.5 Itanium

Although almost failed, Intel Itanium (IA64) is a very interesting architecture.

While OOE CPUs decides how to rearrange their instructions and execute them in parallel, EPIC² was an attempt to shift these decisions to the compiler: to let it group the instructions at the compile stage.

This resulted in notoriously complex compilers.

Here is one sample of IA64 code: simple cryptographic algorithm from the Linux kernel:

```
# define TEA_ROUNDS 32
# define TEA_DELTA 0x9e3779b9

static void tea_encrypt(struct crypto_tfm *tfm, u8 *dst, const u8 *src)
{
    u32 y, z, n, sum = 0;
    u32 k0, k1, k2, k3;
    struct tea_ctx *ctx = crypto_tfm_ctx(tfm);
    const __le32 *in = (const __le32 *)src;
    __le32 *out = (__le32 *)dst;

    y = le32_to_cpu(in[0]);
    z = le32_to_cpu(in[1]);

    k0 = ctx->KEY[0];
    k1 = ctx->KEY[1];
    k2 = ctx->KEY[2];
    k3 = ctx->KEY[3];

    n = TEA_ROUNDS;

    while (n-- > 0) {
        sum += TEA_DELTA;
        y += ((z << 4) + k0) ^ (z + sum) ^ ((z >> 5) + k1);
        z += ((y << 4) + k2) ^ (y + sum) ^ ((y >> 5) + k3);
    }

    out[0] = cpu_to_le32(y);
    out[1] = cpu_to_le32(z);
}
```

Here is how it was compiled:

²Explicitly Parallel Instruction Computing
First of all, all IA64 instructions are grouped into 3-instruction bundles.

Each bundle has a size of 16 bytes (128 bits) and consists of template code (5 bits) + 3 instructions (41 bits for each).

IDA shows the bundles as 6+6+4 bytes—you can easily spot the pattern.

All 3 instructions from each bundle usually executes simultaneously, unless one of instructions has a “stop bit”.

Supposedly, Intel and HP engineers gathered statistics on most frequent instruction patterns and decided to bring bundle types (AKA “templates”): a bundle code defines the instruction types in the bundle. There are 12 of them.

For example, the zeroth bundle type is MII, which implies the first instruction is Memory (load or store), the second and third ones are I (integer instructions).

Another example is the bundle of type 0x1d: MFB: the first instruction is Memory (load or store), the second one is Float (FPU instruction), and the third is Branch (branch instruction).

If the compiler cannot pick a suitable instruction for the relevant bundle slot, it may insert a NOP: you
11.6. 8086 MEMORY MODEL

can see here the nop.i instructions (NOP at the place where the integer instruction might be) or nop.m (a memory instruction might be at this slot).

NOPs are inserted automatically when one uses assembly language manually.

And that is not all. Bundles are also grouped.

Each bundle may have a “stop bit”, so all the consecutive bundles with a terminating bundle which has the “stop bit” can be executed simultaneously.

In practice, Itanium 2 can execute 2 bundles at once, resulting in the execution of 6 instructions at once.

So all instructions inside a bundle and a bundle group cannot interfere with each other (i.e., must not have data hazards).

If they do, the results are to be undefined.

Each stop bit is marked in assembly language as two semicolons (;;) after the instruction.

So, the instructions at [90-ac] may be executed simultaneously: they do not interfere. The next group is [b0-cc].

We also see a stop bit at 10c. The next instruction at 110 has a stop bit too.

This implies that these instructions must be executed isolated from all others (as in CISC).

Indeed: the next instruction at 110 uses the result from the previous one (the value in register r26), so they cannot be executed at the same time.

Apparently, the compiler was not able to find a better way to parallelize the instructions, in other words, to load CPU as much as possible, hence too much stop bits and NOPs.

Manual assembly programming is a tedious job as well: the programmer has to group the instructions manually.

The programmer is still able to add stop bits to each instructions, but this will degrade the performance that Itanium was made for.

An interesting examples of manual IA64 assembly code can be found in the Linux kernel’s sources:


Another introductory paper on Itanium assembly: [Mike Burrell, Writing Efficient Itanium 2 Assembly Code (2010)]³, [papasutra of haquebright, WRITING SHELLCODE FOR IA-64 (2001)]⁴.

Another very interesting Itanium feature is the speculative execution and the NaT (“not a thing”) bit, somewhat resembling NaN numbers:

MSDN.

11.6 8086 memory model

When dealing with 16-bit programs for MS-DOS or Win16 (8.5.3 on page 832 or 3.29.5 on page 654), we can see that the pointers consist of two 16-bit values. What do they mean? Oh yes, that is another weird MS-DOS and 8086 artifact.

8086/8088 was a 16-bit CPU, but was able to address 20-bit address in RAM (thus being able to access 1MB of external memory).

The external memory address space was divided between RAM (640KB max), ROM, windows for video memory, EMS cards, etc.

Let's also recall that 8086/8088 was in fact an inheritor of the 8-bit 8080 CPU.

The 8080 has a 16-bit memory space, i.e., it was able to address only 64KB.

And probably because of reason of old software porting⁵, 8086 can support many 64KB windows simultaneously, placed within the 1MB address space.

This is some kind of a toy-level virtualization.

³Also available as http://yurichev.com/mirrors/RE/itanium.pdf
⁴Also available as http://phrack.org/issues/57/5.html
⁵The author is not 100% sure here
11.7. BASIC BLOCKS REORDERING

All 8086 registers are 16-bit, so to address more, special segment registers (CS, DS, ES, SS) were introduced.

Each 20-bit pointer is calculated using the values from a segment register and an address register pair (e.g., DS:BX) as follows:

\[
\text{real_address} = (\text{segment_register} \ll 4) + \text{address_register}
\]

For example, the graphics (EGA\textsuperscript{6}, VGA\textsuperscript{7}) video RAM window on old IBM PC-compatibles has a size of 64KB.

To access it, a value of 0xA000 has to be stored in one of the segment registers, e.g. into DS.

Then DS:0 will address the first byte of video RAM and DS:0xFFFF — the last byte of RAM.

The real address on the 20-bit address bus, however, will range from 0xA0000 to 0xAFFFF.

The program may contain hard-coded addresses like 0x1234, but the OS may need to load the program at arbitrary addresses, so it recalculates the segment register values in a way that the program does not have to care where it’s placed in the RAM.

So, any pointer in the old MS-DOS environment in fact consisted of the segment address and the address inside segment, i.e., two 16-bit values. 20-bit was enough for that, though, but we needed to recalculate the addresses very often: passing more information on the stack seemed a better space/convenience balance.

By the way, because of all this it was not possible to allocate a memory block larger than 64KB.

The segment registers were reused at 80286 as selectors, serving a different function.

When the 80386 CPU and computers with bigger RAM were introduced, MS-DOS was still popular, so the DOS extenders emerged: these were in fact a step toward a “serious” OS, switching the CPU in protected mode and providing much better memory APIs for the programs which still needed to run under MS-DOS.

Widely popular examples include DOS/4GW (the DOOM video game was compiled for it), Phar Lap, PMODE.

By the way, the same way of addressing memory was used in the 16-bit line of Windows 3.x, before Win32.

11.7 Basic blocks reordering

11.7.1 Profile-guided optimization

This optimization method can move some basic blocks to another section of the executable binary file.

Obviously, there are parts of a function which are executed more frequently (e.g., loop bodies) and less often (e.g., error reporting code, exception handlers).

The compiler adds instrumentation code into the executable, then the developer runs it with a lot of tests to collect statistics.

Then the compiler, with the help of the statistics gathered, prepares final the executable file with all infrequently executed code moved into another section.

As a result, all frequently executed function code is compacted, and that is very important for execution speed and cache usage.

An example from Oracle RDBMS code, which was compiled with Intel C++:

```
public _skgfsync
_skgfsync      proc near
 ; address 0x6030D86A
    db   66h
    nop
    push ebp
    mov   ebp, esp
    mov   edx, [ebp+0Ch]
    test edax, edx
```

\textsuperscript{6}Enhanced Graphics Adapter

\textsuperscript{7}Video Graphics Array
11.7. BASIC BLOCKS REORDERING

The distance of addresses between these two code fragments is almost 9 MB.
All infrequently executed code was placed at the end of the code section of the DLL file, among all function parts.
This part of the function was marked by the Intel C++ compiler with the VInfreq prefix.
Here we see that a part of the function that writes to a log file (presumably in case of error or warning or something like that) which was probably not executed very often when Oracle’s developers gathered statistics (if it was executed at all).
The writing to log basic block eventually returns the control flow to the “hot” part of the function. Another “infrequent” part is the basic block returning error code 27050.
In Linux ELF files, all infrequently executed code is moved by Intel C++ into the separate text.unlikely section, leaving all “hot” code in the text.hot section.
From a reverse engineer’s perspective, this information may help to split the function into its core and error handling parts.

...
11.8. MY EXPERIENCE WITH HEX-RAYS 2.2.0

11.8 My experience with Hex-Rays 2.2.0

11.8.1 Bugs

There are couple of bugs.

First of all, Hex-Rays is getting lost when FPU instructions are interleaved (by compiler codegenerator) with others.

For example, this:

```
lea eax, [esp+4]
fild dword ptr [eax]
lea eax, [esp+8]
fild dword ptr [eax]
fabs fcompp
fnstsw ax
test ah, 1
jz l01
mov eax, 1
retn
l01:
    mov eax, 2
retn
```

...will be correctly decompiled to:

```
signed int __cdecl f(signed int a1, signed int a2)
{
    signed int result; // eax@2

    if ( fabs((double)a2) >= (double)a1 )
        result = 2;
    else
        result = 1;
    return result;
}
```

But let’s comment one of the instructions at the end:

```
    ;mov eax, 2
```

...we getting an obvious bug:

```
void __cdecl f(char a1, char a2)
{
    fabs((double)a2);
}
```

This is another bug:

```
extrn f1:dword
extrn f2:dword

proc near
    fld dword ptr [esp+4]
fadd dword ptr [esp+8]
fst dword ptr [esp+12]
```
11.8. MY EXPERIENCE WITH HEX-RAYS 2.2.0

```assembly
fcomp  ds:const_100
fld    dword ptr [esp+16] ; comment this instruction and it will be OK
fnstsw ax
test ah, 1
jnz    short l01
call f1
retn
l01:
call f2
retn
f      endp
...

const_100 dd 42C80000h ; 100.0
```

Result:

```
int __cdecl f(float a1, float a2, float a3, float a4)
{
    double v5; // st7@1
    char v6; // c0@1
    int result; // eax@2
    v5 = a4;
    if ( v6 )
        result = f2(v5);
    else
        result = f1(v5);
    return result;
}
```

v6 variable has char type and if you’ll try to compile this code, compiler will warn you about variable usage before assignment.

Another bug: FPATAN instruction is correctly decompiled into atan2(), but arguments are swapped.

### 11.8.2 Odd peculiarities

Hex-Rays too often promotes 32-bit int to 64-bit one. Here is example:

```assembly
f proc near
    mov   eax, [esp+4]
    cdq
    xor   eax, edx
    sub   eax, edx
    ; EAX=abs(a1)
    sub   eax, [esp+8]
    ; EAX=EAX-a2
    ; EAX at this point somehow gets promoted to 64-bit (RAX)
    cdq
    xor   eax, edx
    sub   eax, edx
    ; EAX=abs(abs(a1)-a2)
    retn
f endp
```

Result:
int __cdecl f(int a1, int a2)
{
    __int64 v2; // rax@1
    v2 = abs(a1) - a2;
    return (HIDWORD(v2) ^ v2) - HIDWORD(v2);
}

Perhaps, this is result of CDQ instruction? I'm not sure. Anyway, whenever you see __int64 type in 32-bit code, pay attention.

This is also weird:

```assembly
f proc near
    mov esi, [esp+4]
    lea ebx, [esi+10h]
    cmp esi, ebx
    jge short l00
    cmp esi, 1000
    jg short l00
    mov eax, 2
    retn
l00:
    mov eax, 1
    retn
f endp
```

Result:

```c
signed int __cdecl f(signed int a1)
{
    signed int result; // eax@3
    if ( __OFSUB__(a1, a1 + 16) ^ 1 && a1 <= 1000 )
        result = 2;
    else
        result = 1;
    return result;
}
```

The code is correct, but needs manual intervention.

Sometimes, Hex-Rays doesn’t fold (or reduce) division by multiplication code:

```assembly
f proc near
    mov eax, [esp+4]
    mov edx, 2AAAAAABh
    imul edx
    mov eax, edx
    retn
f endp
```

Result:

```c
int __cdecl f(int a1)
{
    return (unsigned __int64)(715827883i64 * a1) >> 32;
}
```

This can be folded (rewritten) manually.
Many of these peculiarities can be solved by manual reordering of instructions, recompiling assembly code, and then feeding it to Hex-Rays again.

### 11.8.3 Silence

```assembly
extrn some_func:dword

f proc near
    mov ecx, [esp+4]
    mov eax, [esp+8]
    push eax
    call some_func
    add esp, 4
    ; use ECX
    mov eax, ecx
    retn

f endp

Result:

```c
int __cdecl f(int a1, int a2)
{
    int v2; // ecx@1
    some_func(a2);
    return v2;
}
```

v2 variable (from ECX) is lost ...Yes, this code is incorrect (ECX value doesn’t saved during call to another function), but it would be good for Hex-Rays to give a warning.

Another one:

```assembly
extrn some_func:dword

f proc near
    call some_func
    jnz l01
    mov eax, 1
    retn
l01:
    mov eax, 2
    retn

f endp

Result:

```c
signed int f()
{
    char v0; // zf@1
    signed int result; // eax@2
    some_func();
    if ( v0 )
        result = 1;
    else
        result = 2;
    return result;
}
```
11.8. MY EXPERIENCE WITH HEX-RAYS 2.2.0

Again, warning would be great.

Anyway, whenever you see variable of char type, or variable which is used without initialization, this is clear sign that something went wrong and needs manual intervention.

11.8.4 Comma

Comma in C/C++ has a bad fame, because it can lead to a confusing code.

Quick quiz, what does this C/C++ function return?

```c
int f()
{
    return 1, 2;
};
```

It’s 2: when compiler encounters comma-expression, it generates code which executes all sub-expressions, and returns value of the last sub-expression.

I’ve seen something like that in production code:

```c
if (cond)
    return global_var=123, 456; // 456 is returned
else
    return global_var=789, 321; // 321 is returned
```

Apparently, programmer wanted to make code slightly shorter without additional curly brackets. In other words, comma allows to pack couple of expressions into one, without forming statement/code block inside of curly brackets.

Comma in C/C++ is close to begin in Scheme/Racket: https://docs.racket-lang.org/guide/begin.html.

Perhaps, the only widely accepted usage of comma is in for() statements:

```c
char *s="hello, world";
for(int i=0; *s; s++, i++);
; i = string length
```

Both s++ and i++ are executed at each loop iteration.


I’m writing all this because Hex-Rays produces (at least in my case) code which is rich with both commas and short-circuit expressions. For example, this is real output from Hex-Rays:

```c
if ( a >= b || (c = a, (d[a] - e) >> 2 > f) )
{
...
```

This is correct, it compiles and works, and let god help you to understand it. Here is it rewritten:

```c
if (cond1 || (comma_expr, cond2))
{
...
```

Short-circuit is effective here: first cond1 is checked, if it’s true, if() body is executed, the rest of if() expression is ignored completely. If cond1 is false, comma_expr is executed (in the previous example, a gets copied to c), then cond2 is checked. If cond2 is true, if() body gets executed, or not. In other words, if() body gets executed if cond1 is true or cond2 is true, but if the latter is true, comma_expr is also executed.

Now you can see why comma is so notorious.

**A word about short-circuit.** A common beginner’s misconception is that sub-conditions are checked in some unspecified order, which is not true. In a | b | c expression, a, b and c gets evaluated in unspecified order, so that is why || has also been added to C/C++, to apply short-circuit explicitly.
11.8. MY EXPERIENCE WITH HEX-RAYS 2.2.0

11.8.5 Data types

Data types is a problem for decompilers.

Hex-Rays can be blind to arrays in local stack, if they weren’t set correctly before decompilation. Same story about global arrays.

Another problem is too big functions, where a single slot in local stack can be used by several variables across function’s execution. It’s not a rare case when a slot is used for int-variable, then for pointer, then for float-variable. Hex-Rays correctly decompiles it: it creates a variable with some type, then cast it to another type in various parts of functions. This problem has been solved by me by manual splitting big function into several smaller. Just make local variables as global ones, etc, etc. And don’t forget about tests.

11.8.6 Long and messed expressions

Sometimes, during rewriting, you can end up with long and hard to understand expressions in if() constructs, like:

```c
if((! (v38 && v30 <= 5 && v27 != -1)) && (! (v38 && v30 <= 5) && v27 != -1) || (v24 >= 5 || v26)) && v25)
{
...
}
```

Wolfram Mathematica can minimize some of them, using BooleanMinimize[] function:

```mathematica
In[1]:= BooleanMinimize[(! (v38 && v30 <= 5 && v27 != -1)) && v38 && v30 <= 5 && v25 == 0]  
Out[1]:= v38 && v25 == 0 && v27 == -1 && v30 <= 5
```

There is even better way, to find common subexpressions:

```mathematica
In[2]:= Experimental`OptimizeExpression[(! (v38 && v30 <= 5 && v27 != -1)) && (! (v38 && v30 <= 5) && v27 != -1) || (v24 >= 5 || v26)) && v25
```

Experiment`OptimizedExpression[

```mathematica
Block[{Compile`$1, Compile`$2}, Compile`$1 = v30 <= 5;  
Compile`$2 = v27 != -1; (! (v38 && Compile`$1 && Compile`$2) && (! (v38 && Compile`$1 && Compile`$2) || v24 >= 5 || v26) && v25])
```

Mathematica adds two new variables: `Compile`$1 and `Compile`$2, values of which will be used several times in expression. So we can add two additional variables.

11.8.7 My plan

- Split big functions (and don’t forget about tests). Sometimes it’s very helpful to form new functions out of big loop bodies.
- Check/set data type of variables, arrays, etc.
- If you see odd result, dangling variable (which used before initialization), try to swap instructions manually, recompile it and feed to Hex-Rays again.

11.8.8 Summary

Nevertheless, quality of Hex-Rays 2.2.0 is very, very good. It makes life way easier.
Chapter 12

Books/blogs worth reading

12.1 Books and other materials

12.1.1 Reverse Engineering


Also, Kris Kaspersky’s books.

12.1.2 Windows

- Mark Russinovich, *Microsoft Windows Internals*

Blogs:

- Microsoft: Raymond Chen
- nynaeve.net

12.1.3 C/C++

- *ISO/IEC 9899:TC3 (C C99 standard)*, (2007)\(^1\)
- C++11 standard\(^2\)
- Agner Fog, *Optimizing software in C++* (2015)\(^3\)
- Marshall Cline, C++ FAQ\(^4\)
- Dennis Yurichev, C/C++ programming language notes\(^5\)
- JPL Institutional Coding Standard for the C Programming Language\(^6\)

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\(^1\)Also available as [http://go.yurichev.com/17274](http://go.yurichev.com/17274)
\(^3\)Also available as [http://agner.org/optimize/optimizing_cpp.pdf](http://agner.org/optimize/optimizing_cpp.pdf).
\(^4\)Also available as [http://go.yurichev.com/17291](http://go.yurichev.com/17291).
\(^5\)Also available as [http://yurichev.com/C-book.html](http://yurichev.com/C-book.html).
\(^6\)Also available as [https://yurichev.com/mirrors/C/JPL_Coding_Standard_C.pdf](https://yurichev.com/mirrors/C/JPL_Coding_Standard_C.pdf).
12.1. BOOKS AND OTHER MATERIALS

12.1.4 x86 / x86-64

- Intel manuals
- AMD manuals
- [Intel® 64 and IA-32 Architectures Optimization Reference Manual, (2014)]
- [Software Optimization Guide for AMD Family 16h Processors, (2013)]

Somewhat outdated, but still interesting to read:

Michael Abrash, *Graphics Programming Black Book*, 1997 (he is known for his work on low-level optimization for such projects as Windows NT 3.1 and id Quake).

12.1.5 ARM

- ARM manuals
- [ARM Architecture Reference Manual, ARMv8, for ARMv8-A architecture profile, (2013)]

12.1.6 Assembly language

Richard Blum — Professional Assembly Language.

12.1.7 Java


12.1.8 UNIX


12.1.9 Programming in general

- Henry S. Warren, *Hacker's Delight*, (2002). Some people say tricks and hacks from the book are not relevant today because they were good only for RISC CPUs, where branching instructions are expensive. Nevertheless, these can help immensely to understand boolean algebra and what all the mathematics near it.

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9Also available as [http://agner.org/optimize/microarchitecture.pdf](http://agner.org/optimize/microarchitecture.pdf)
10Also available as [http://www.agner.org/optimize/calling_conventions.pdf](http://www.agner.org/optimize/calling_conventions.pdf)
11Also available as [https://github.com/jagregory/abrash-black-book](https://github.com/jagregory/abrash-black-book)
14Also available as [http://go.yurichev.com/17273](http://go.yurichev.com/17273)
15Also available as [https://docs.oracle.com/javase/specs/jvms/se7/html/index.html](https://docs.oracle.com/javase/specs/jvms/se7/html/index.html)
• (For hard-core geeks with computer science and mathematical background) Donald E. Knuth, *The Art of Computer Programming*. Some people arguing, if it worth for mediocre programmer to try hard to read these quite hard fundamental books. I would say, it’s worth just to skim them, to learn what CS!\(^{16}\) consists of.

### 12.1.10 Cryptography

• (Free) lvh, *Crypto 101*\(^ {17} \)
• (Free) Dan Boneh, Victor Shoup, *A Graduate Course in Applied Cryptography*\(^ {18} \).

\(^{16}\) CS!

\(^{17}\) Also available as [https://www.crypto101.io/](https://www.crypto101.io/)

\(^{18}\) Also available as [https://crypto.stanford.edu/~dabo/cryptobook/](https://crypto.stanford.edu/~dabo/cryptobook/)
There are two excellent RE\textsuperscript{1}-related subreddits on reddit.com: reddit.com/r/ReverseEngineering/ and reddit.com/r/remath (on the topics for the intersection of RE and mathematics).

There is also a RE part of the Stack Exchange website: reverseengineering.stackexchange.com.

On IRC there’s a ##re channel on FreeNode\textsuperscript{2}.

\textsuperscript{1}Reverse Engineering

\textsuperscript{2}freenode.net
Afterword
13.1. *QUESTIONS?*

**13.1 Questions?**

Do not hesitate to mail any questions to the author: <dennis@yurichev.com>. Do you have any suggestion on new content for the book? Please do not hesitate to send any corrections (including grammar (you see how horrible my English is?)), etc.

The author is working on the book a lot, so the page and listing numbers, etc., are changing very rapidly. Please do not refer to page and listing numbers in your emails to me. There is a much simpler method: make a screenshot of the page, in a graphics editor underline the place where you see the error, and send it to the author. He’ll fix it much faster. And if you familiar with git and \LaTeX{} you can fix the error right in the source code:

GitHub.

Do not worry to bother me while writing me about any petty mistakes you found, even if you are not very confident. I’m writing for beginners, after all, so beginners’ opinions and comments are crucial for my job.
Appendix
### .1 X86

#### .1.1 Terminology

Common for 16-bit (8086/80286), 32-bit (80386, etc.), 64-bit.

**byte** 8-bit. The DB assembly directive is used for defining variables and arrays of bytes. Bytes are passed in the 8-bit part of registers: AL/BL/CL/DL/AH/BH/CH/DH/SIL/DIL/R*L.

**word** 16-bit. DW assembly directive —”—. Words are passed in the 16-bit part of the registers: AX/BX/CX/DX/SI/DI/R*W.

**double word** (”dword”) 32-bit. DD assembly directive —”—. Double words are passed in registers (x86) or in the 32-bit part of registers (x64). In 16-bit code, double words are passed in 16-bit register pairs.

**quad word** (”qword”) 64-bit. DQ assembly directive —”—. In 32-bit environment, quad words are passed in 32-bit register pairs.

**tbyte** (10 bytes) 80-bit or 10 bytes (used for IEEE 754 FPU registers).

**paragraph** (16 bytes)—term was popular in MS-DOS environment.

Data types of the same width (BYTE, WORD, DWORD) are also the same in Windows API.

#### .1.2 General purpose registers

It is possible to access many registers by byte or 16-bit word parts.

It is all inheritance from older Intel CPUs (up to the 8-bit 8080) still supported for backward compatibility. Older 8-bit CPUs (8080) had 16-bit registers divided by two.

Programs written for 8080 could access the low byte part of 16-bit registers, high byte part or the whole 16-bit register.

Perhaps, this feature was left in 8086 as a helper for easier porting.

This feature is usually not present in RISC CPUs.

Registers prefixed with R- appeared in x86-64, and those prefixed with E —in 80386.

Thus, R-registers are 64-bit, and E-registers—32-bit.

8 more GPR’s were added in x86-86: R8-R15.

N.B.: In the Intel manuals the byte parts of these registers are prefixed by L, e.g.: RBL, but IDA names these registers by adding the B suffix, e.g.: R8B.

**RAX/EAX/AX/AL**

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AKA accumulator. The result of a function is usually returned via this register.

**RBX/EBX/BX/BL**

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### RCX/ECX/CX/CL

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**AKA** counter: in this role it is used in REP prefixed instructions and also in shift instructions (SHL/SHR/RxL/RxR).

### RDX/EDX/DX/DL

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### RSI/ESI/SI/SIL

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**AKA** “source index”. Used as source in the instructions REP MOV\textit{Sx}, REP CMPS\textit{x}.

### RDI/EDI/DI/DIL

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**AKA** “destination index”. Used as a pointer to the destination in the instructions REP MOV\textit{Sx}, REP STOS\textit{x}.

### R8/R8D/R8W/R8L

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### X86

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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### R13/R13D/R13W/R13L

<table>
<thead>
<tr>
<th>Byte number:</th>
<th>7th</th>
<th>6th</th>
<th>5th</th>
<th>4th</th>
<th>3rd</th>
<th>2nd</th>
<th>1st</th>
<th>0th</th>
</tr>
</thead>
<tbody>
<tr>
<td>R13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R13D</td>
</tr>
<tr>
<td>R13D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R13W</td>
</tr>
<tr>
<td>R13W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R13L</td>
</tr>
<tr>
<td>R13L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### R14/R14D/R14W/R14L

<table>
<thead>
<tr>
<th>Byte number:</th>
<th>7th</th>
<th>6th</th>
<th>5th</th>
<th>4th</th>
<th>3rd</th>
<th>2nd</th>
<th>1st</th>
<th>0th</th>
</tr>
</thead>
<tbody>
<tr>
<td>R14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R14D</td>
</tr>
<tr>
<td>R14D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R14W</td>
</tr>
<tr>
<td>R14W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R14L</td>
</tr>
<tr>
<td>R14L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### R15/R15D/R15W/R15L

<table>
<thead>
<tr>
<th>Byte number:</th>
<th>7th</th>
<th>6th</th>
<th>5th</th>
<th>4th</th>
<th>3rd</th>
<th>2nd</th>
<th>1st</th>
<th>0th</th>
</tr>
</thead>
<tbody>
<tr>
<td>R15</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R15D</td>
</tr>
<tr>
<td>R15D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R15W</td>
</tr>
<tr>
<td>R15W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>R15L</td>
</tr>
<tr>
<td>R15L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
.1. X86

**RSP/ESP/SP/SPL**

<table>
<thead>
<tr>
<th>Byte number:</th>
</tr>
</thead>
<tbody>
<tr>
<td>7th</td>
</tr>
<tr>
<td>RSP</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

**AKA stack pointer.** Usually points to the current stack except in those cases when it is not yet initialized.

**RBP/EBP/BP/BPL**

<table>
<thead>
<tr>
<th>Byte number:</th>
</tr>
</thead>
<tbody>
<tr>
<td>7th</td>
</tr>
<tr>
<td>RBP</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

**AKA frame pointer.** Usually used for local variables and accessing the arguments of the function. More about it: (1.9.1 on page 67).

**RIP/EIP/IP**

<table>
<thead>
<tr>
<th>Byte number:</th>
</tr>
</thead>
<tbody>
<tr>
<td>7th</td>
</tr>
<tr>
<td>RIPx64</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

**AKA “instruction pointer.”** Usually always points to the instruction to be executed right now. Cannot be modified, however, it is possible to do this (which is equivalent):

| MOV EAX, ...  
| JMP EAX  |

Or:

| PUSH value  
| RET  |

**CS/DS/ES/SS/FS/GS**

16-bit registers containing code selector (CS), data selector (DS), stack selector (SS).

FS in win32 points to TLS, GS took this role in Linux. It is made so for faster access to the TLS and other structures like the TIB.

In the past, these registers were used as segment registers (11.6 on page 1003).

**Flags register**

**AKA EFLAGS.**

3Sometimes also called “program counter”
### Bit (mask) | Abbreviation (meaning) | Description
---|---|---
0 (1) | CF (Carry) | The CLC/STC/CMC instructions are used for setting/resetting/toggling this flag.
2 (4) | PF (Parity) | (See 1.19.7 on page 234).
4 (0x10) | AF (Adjust) | Exist solely for work with BCD-numbers.
6 (0x40) | ZF (Zero) | Setting to 0 if the last operation's result is equal to 0.
7 (0x80) | SF (Sign) | Used for debugging. If turned on, an exception is to be generated after each instruction's execution.
8 (0x100) | TF (Trap) | Are interrupts enabled. The CLI/STI instructions are used for setting/resetting the flag.
9 (0x200) | IF (Interrupt enable) | A directions is set for the REP MOVsx/CMPSx/LODSx/SCASx instructions. The CLD/STD instructions are used for setting/resetting the flag. See also: 3.24 on page 636.
10 (0x400) | DF (Direction) | Used for debugging. The CPU ignores the hardware breakpoint in DRx if the flag is set.
11 (0x800) | OF (Overflow) | IOPL (I/O privilege level)\textsuperscript{i286}
12, 13 (0x3000) | IOPL (I/O privilege level)\textsuperscript{i286} | NT (Nested task)\textsuperscript{i286}
16 (0x10000) | RF (Resume)\textsuperscript{i386} | Used for debugging.
17 (0x20000) | VM (Virtual 8086 mode)\textsuperscript{i386} | AC (Alignment check)\textsuperscript{i486}
18 (0x40000) | AC (Alignment check)\textsuperscript{i486} | VIF (Virtual interrupt)\textsuperscript{i586}
19 (0x80000) | VIF (Virtual interrupt)\textsuperscript{i586} | VIP (Virtual interrupt pending)\textsuperscript{i586}
20 (0x100000) | VIP (Virtual interrupt pending)\textsuperscript{i586} | ID (Identification)\textsuperscript{i586}
21 (0x200000) | ID (Identification)\textsuperscript{i586} | All the rest flags are reserved.

### 1.3 FPU registers

8 80-bit registers working as a stack: ST(0)-ST(7). N.B.: IDA calls ST(0) as just ST. Numbers are stored in the IEEE 754 format.

**long double** value format:

![IEEE 754 long double format](image)

(S—sign, I—integer part)

**Control Word**

Register controlling the behavior of the **FPU**.
### Bit Abbreviation (meaning) Description

<table>
<thead>
<tr>
<th>0</th>
<th>IM (Invalid operation Mask)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DM (Denormalized operand Mask)</td>
</tr>
<tr>
<td>2</td>
<td>ZM (Zero divide Mask)</td>
</tr>
<tr>
<td>3</td>
<td>OM (Overflow Mask)</td>
</tr>
<tr>
<td>4</td>
<td>UM (Underflow Mask)</td>
</tr>
<tr>
<td>5</td>
<td>PM (Precision Mask)</td>
</tr>
<tr>
<td>7</td>
<td>IEM (Interrupt Enable Mask)</td>
</tr>
</tbody>
</table>

| 8, 9 | PC (Precision Control) | 00 — 24 bits (REAL4) |
|      |                       | 10 — 53 bits (REAL8) |
|      |                       | 11 — 64 bits (REAL10) |

| 10, 11 | RC (Rounding Control) | 00 — (by default) round to nearest |
|        |                       | 01 — round toward \(-\infty\) |
|        |                       | 10 — round toward \(+\infty\) |
|        |                       | 11 — round toward 0 |

| 12 | IC (Infinity Control) | 0 — (by default) treat \(+\infty\) and \(-\infty\) as unsigned |
|    |                       | 1 — respect both \(+\infty\) and \(-\infty\) |

The PM, UM, OM, ZM, DM, IM flags define if to generate exception in the case of a corresponding error.

## Status Word

Read-only register.

<table>
<thead>
<tr>
<th>Bit</th>
<th>Abbreviation (meaning)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>B (Busy)</td>
<td>Is FPU doing something (1) or results are ready (0)</td>
</tr>
<tr>
<td>14</td>
<td>C3</td>
<td></td>
</tr>
<tr>
<td>13, 12, 11</td>
<td>TOP</td>
<td>points to the currently zeroth register</td>
</tr>
<tr>
<td>10</td>
<td>C2</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>C1</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>C0</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>IR (Interrupt Request)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>SF (Stack Fault)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>P (Precision)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>U (Underflow)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>O (Overflow)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Z (Zero)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>D (Denormalized)</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>I (Invalid operation)</td>
<td></td>
</tr>
</tbody>
</table>

The SF, P, U, O, Z, D, I bits signal about exceptions.

About the C3, C2, C1, C0 you can read more here: [1.19.7 on page 234].

N.B.: When ST(x) is used, the FPU adds \(x\) to TOP (by modulo 8) and that is how it gets the internal register’s number.

## Tag Word

The register has current information about the usage of numbers registers.

<table>
<thead>
<tr>
<th>Bit</th>
<th>Abbreviation (meaning)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15, 14</td>
<td>tag(7)</td>
</tr>
<tr>
<td>13, 12</td>
<td>tag(6)</td>
</tr>
<tr>
<td>11, 10</td>
<td>tag(5)</td>
</tr>
<tr>
<td>9, 8</td>
<td>tag(4)</td>
</tr>
<tr>
<td>7, 6</td>
<td>tag(3)</td>
</tr>
<tr>
<td>5, 4</td>
<td>tag(2)</td>
</tr>
<tr>
<td>3, 2</td>
<td>tag(1)</td>
</tr>
<tr>
<td>1, 0</td>
<td>tag(0)</td>
</tr>
</tbody>
</table>

Each tag contains information about a physical FPU register (R(x)), not logical (ST(x)).

For each tag:

- 00 — The register contains a non-zero value
01 — The register contains 0
10 — The register contains a special value (\textit{NAN}^4, \(\infty\), or denormal)
11 — The register is empty

### 1.4 SIMD registers

#### MMX registers

8 64-bit registers: MM0..MM7.

#### SSE and AVX registers

SSE: 8 128-bit registers: XMM0..XMM7. In the x86-64 8 more registers were added: XMM8..XMM15. AVX is the extension of all these registers to 256 bits ist eine Erweiterung all Register auf 256 Bit.

### 1.5 Debugging registers

Used for hardware breakpoints control.

- **DR0** — address of breakpoint #1
- **DR1** — address of breakpoint #2
- **DR2** — address of breakpoint #3
- **DR3** — address of breakpoint #4
- **DR6** — a cause of break is reflected here
- **DR7** — breakpoint types are set here

#### DR6

<table>
<thead>
<tr>
<th>Bit (mask)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (1)</td>
<td>B0 — breakpoint #1 has been triggered</td>
</tr>
<tr>
<td>1 (2)</td>
<td>B1 — breakpoint #2 has been triggered</td>
</tr>
<tr>
<td>2 (4)</td>
<td>B2 — breakpoint #3 has been triggered</td>
</tr>
<tr>
<td>3 (8)</td>
<td>B3 — breakpoint #4 has been triggered</td>
</tr>
<tr>
<td>13 (0x2000)</td>
<td>BD — modification attempt of one of the DRx registers. may be raised if GD is enabled</td>
</tr>
<tr>
<td>14 (0x4000)</td>
<td>BS — single step breakpoint (TF flag has been set in EFLAGS). Highest priority. Other bits may also be set.</td>
</tr>
<tr>
<td>15 (0x8000)</td>
<td>BT (task switch flag)</td>
</tr>
</tbody>
</table>

N.B. A single step breakpoint is a breakpoint which occurs after each instruction. It can be enabled by setting TF in EFLAGS (\textit{.1.2 on page 1022}).

#### DR7

Breakpoint types are set here.

---

\(^4\)Not a Number
<table>
<thead>
<tr>
<th>Bit (mask)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (1)</td>
<td>L0 — enable breakpoint #1 for the current task</td>
</tr>
<tr>
<td>1 (2)</td>
<td>G0 — enable breakpoint #1 for all tasks</td>
</tr>
<tr>
<td>2 (4)</td>
<td>L1 — enable breakpoint #2 for the current task</td>
</tr>
<tr>
<td>3 (8)</td>
<td>G1 — enable breakpoint #2 for all tasks</td>
</tr>
<tr>
<td>4 (0x10)</td>
<td>L2 — enable breakpoint #3 for the current task</td>
</tr>
<tr>
<td>5 (0x20)</td>
<td>G2 — enable breakpoint #3 for all tasks</td>
</tr>
<tr>
<td>6 (0x40)</td>
<td>L3 — enable breakpoint #4 for the current task</td>
</tr>
<tr>
<td>7 (0x80)</td>
<td>G3 — enable breakpoint #4 for all tasks</td>
</tr>
<tr>
<td>8 (0x100)</td>
<td>LE — not supported since P6</td>
</tr>
<tr>
<td>9 (0x200)</td>
<td>GE — not supported since P6</td>
</tr>
<tr>
<td>13 (0x2000)</td>
<td>GD — exception is to be raised if any MOV instruction tries to modify one of the DRx registers</td>
</tr>
<tr>
<td>16,17 (0x30000)</td>
<td>breakpoint #1: R/W — type</td>
</tr>
<tr>
<td>18,19 (0xCO000)</td>
<td>breakpoint #1: LEN — length</td>
</tr>
<tr>
<td>20,21 (0x300000)</td>
<td>breakpoint #2: R/W — type</td>
</tr>
<tr>
<td>22,23 (0xCO0000)</td>
<td>breakpoint #2: LEN — length</td>
</tr>
<tr>
<td>24,25 (0x3000000)</td>
<td>breakpoint #3: R/W — type</td>
</tr>
<tr>
<td>26,27 (0xCO00000)</td>
<td>breakpoint #3: LEN — length</td>
</tr>
<tr>
<td>28,29 (0x30000000)</td>
<td>breakpoint #4: R/W — type</td>
</tr>
<tr>
<td>30,31 (0xCO000000)</td>
<td>breakpoint #4: LEN — length</td>
</tr>
</tbody>
</table>

The breakpoint type is to be set as follows (R/W):
  - 00 — instruction execution
  - 01 — data writes
  - 10 — I/O reads or writes (not available in user-mode)
  - 11 — on data reads or writes

N.B.: breakpoint type for data reads is absent, indeed.

Breakpoint length is to be set as follows (LEN):
  - 00 — one-byte
  - 01 — two-byte
  - 10 — undefined for 32-bit mode, eight-byte in 64-bit mode
  - 11 — four-byte

### .1.6 Instructions

Instructions marked as (M) are not usually generated by the compiler: if you see one of them, it is probably a hand-written piece of assembly code, or a compiler intrinsic (11.3 on page 999).

Only the most frequently used instructions are listed here. You can read 12.1.4 on page 1013 for a full documentation.

Do you have to know all instruction’s opcodes by heart? No, only those which are used for code patching (11.1.2 on page 998). All the rest of the opcodes don’t need to be memorized.

#### Prefixes

LOCK forces CPU to make exclusive access to the RAM in multiprocessor environment. For the sake of simplification, it can be said that when an instruction with this prefix is executed, all other CPUs in a multiprocessor system are stopped. Most often it is used for critical sections, semaphores, mutexes. Commonly used with ADD, AND, BTR, BTS, CMPXCHG, OR, XADD, XOR. You can read more about critical sections here (6.5.4 on page 787).

REP is used with the MOVSx and STOSx instructions: execute the instruction in a loop, the counter is located in the CX/ECX/RCX register. For a detailed description, read more about the MOVSx (1.6 on page 1029) and STOSx (.1.6 on page 1030) instructions.

The instructions prefixed by REP are sensitive to the DF flag, which is used to set the direction.
**REPE/REPNE** (AKA REPZ/REPNZ) used with CMPSx and SCASx instructions: execute the last instruction in a loop, the count is set in the CX/ECX/RCX register. It terminates prematurely if ZF is 0 (REPE) or if ZF is 1 (REPNE).

For a detailed description, you can read more about the CMPSx (.1.6 on page 1032) and SCASx (.1.6 on page 1030) instructions.

Instructions prefixed by REPE/REPNE are sensitive to the DF flag, which is used to set the direction.

### Most frequently used instructions

These can be memorized in the first place.

**ADC** *(add with carry)* add values, **increment** the result if the CF flag is set. ADC is often used for the addition of large values, for example, to add two 64-bit values in a 32-bit environment using two ADD and ADC instructions. For example:

```
; work with 64-bit values: add val1 to val2.
; .lo means lowest 32 bits, .hi means highest.
ADD val1.lo, val2.lo
ADC val1.hi, val2.hi ; use CF set or cleared at the previous instruction
```

One more example: 1.28 on page 396.

**ADD** add two values

**AND** logical “and”

**CALL** call another function:
```
PUSH address_after_CALL_instruction; JMP label
```

**CMP** compare values and set flags, the same as SUB but without writing the result

**DEC** decrement. Unlike other arithmetic instructions, DEC doesn’t modify CF flag.

**IMUL** signed multiply IMUL often used instead of MUL, read more about it: 2.2.1.

**INC** increment. Unlike other arithmetic instructions, INC doesn’t modify CF flag.

**JCEXZ, JECXZ, JRCXZ** (M) jump if CX/ECX/RCX=0

**JMP** jump to another address. The opcode has a jump offset.

**Jcc** *(where cc—condition code)*

A lot of these instructions have synonyms (denoted with AKA), this was done for convenience. Synonymous instructions are translated into the same opcode. The opcode has a jump offset.

**JAE** AKA JNC: jump if above or equal (unsigned): CF=0

**JA** AKA JNBE: jump if greater (unsigned): CF=0 and ZF=0

**JBE** jump if lesser or equal (unsigned): CF=1 or ZF=1

**JB** AKA JC: jump if below (unsigned): CF=1

**JC** AKA JB: jump if CF=1

**JE** AKA JZ: jump if equal or zero: ZF=1

**JGE** jump if greater or equal (signed): SF=OF

**JG** jump if greater (signed): ZF=0 and SF=OF

**JLE** jump if lesser or equal (signed): ZF=1 or SF≠OF

**JL** jump if lesser (signed): SF≠OF

**JNAE** AKA JC: jump if not above or equal (unsigned) CF=1

**JNA** jump if not above (unsigned) CF=1 and ZF=1

**JNBE** jump if not below or equal (unsigned): CF=0 and ZF=0

**JNB** AKA JNC: jump if not below (unsigned): CF=0

**JNC** AKA JAE: jump CF=0 synonymous to JNB.
JNE  AKA JNZ: jump if not equal or not zero: ZF=0
JNGE  jump if not greater or equal (signed): SF≠OF
JNG  jump if not greater (signed): ZF=1 or SF≠OF
JNL  jump if not lesser (signed): SF=OF
JNO  jump if not overflow: OF=0
JNS  jump if SF flag is cleared
JNZ  AKA JNE: jump if not equal or not zero: ZF=0
JO   jump if overflow: OF=1
JPO  jump if PF flag is cleared (Jump Parity Odd)
JP   AKA JPE: jump if PF flag is set
JS   jump if SF flag is set
JZ   AKA JE: jump if equal or zero: ZF=1
LAHF  copy some flag bits to AH:

<table>
<thead>
<tr>
<th>SF</th>
<th>ZF</th>
<th>AF</th>
<th>PF</th>
<th>CF</th>
</tr>
</thead>
</table>

This instruction is often used in FPU-related code.

LEAVE  equivalent of the MOV ESP, EBP and POP EBP instruction pair—in other words, this instruction sets the stack pointer (ESP) back and restores the EBP register to its initial state.

LEA (Load Effective Address) form an address

This instruction was intended not for summing values and multiplication but for forming an address, e.g., for calculating the address of an array element by adding the array address, element index, with multiplication of element size\(^3\).

So, the difference between MOV and LEA is that MOV forms a memory address and loads a value from memory or stores it there, but LEA just forms an address.

But nevertheless, it is can be used for any other calculations.

LEA is convenient because the computations performed by it does not alter CPU flags. This may be very important for OOE processors (to create less data dependencies).

Aside from this, starting at least at Pentium, LEA instruction is executed in 1 cycle.

```c
int f(int a, int b)
{
    return a*8+b;
}
```

### Listing 1: Optimizing MSVC 2010

```c
int f1(int a)
{
    return a*13;
}
```

\(^3\)See also: [wikipedia](https://en.wikipedia.org/wiki/LEA_instruction)
These two instructions performs faster than one IMUL.

MOVSB/MOVSW/MOVS/D/MOVSD/MOVSS Q copy byte/ 16-bit word/ 32-bit word/ 64-bit word from the address which is in SI/ESI/RSI into the address which is in DI/EDI/RDI.

Together with the REP prefix, it is to be repeated in a loop, the count is to be stored in the CX/ECX/RCX register: it works like memcpy() in C. If the block size is known to the compiler in the compile stage, memcpy() is often inlined into a short code fragment using REP MOVSX, sometimes even as several instructions.

The memcpy(EDI, ESI, 15) equivalent is:

```
; copy 15 bytes from ESI to EDI
CLD ; set direction to forward
MOV ECX, 3
REP MOVSD ; copy 12 bytes
MOVSW ; copy 2 more bytes
MOVSX ; copy remaining byte
```

( Supposedly, it works faster than copying 15 bytes using just one REP MOVSB).

**MOVZX** load with sign extension see also: ( 1.17.1 on page 201)

**MOV** load value. this instruction name is misnomer, resulting in some confusion (data is not moved but copied), in other architectures the same instructions is usually named “LOAD” and/or “STORE” or something like that.

One important thing: if you set the low 16-bit part of a 32-bit register in 32-bit mode, the high 16 bits remains as they were. But if you modify the low 32-bit part of the register in 64-bit mode, the high 32 bits of the register will be cleared.

Supposedly, it was done to simplify porting code to x86-64.

**MUL** unsigned multiply. IMUL often used instead of MUL, read more about it: 2.2.1.

**NEG** negation: \( op = \neg op \). Same as NOT op / ADD op, 1.

**NOP**. Its opcode is 0x90, it is in fact the XCHG EAX, EAX idle instruction. This implies that x86 does not have a dedicated NOP instruction (as in many RISC). This book has at least one listing where GDB shows NOP as 16-bit XCHG instruction: 1.8.1 on page 48.

More examples of such operations: ( .1.7 on page 1038).

**NOP** may be generated by the compiler for aligning labels on a 16-byte boundary. Another very popular usage of NOP is to replace manually (patch) some instruction like a conditional jump to NOP in order to disable its execution.

**NOT** \( op_1 \): \( op_1 = \neg op_1 \). logical inversion Important feature—the instruction doesn’t change flags.

**OR** logical “or”

**POP** get a value from the stack: \( value=SS:\{ESP\} \); ESP=ESP+4 (or 8)

**PUSH** push a value into the stack: ESP=ESP-4 (or 8); \( SS:\{ESP\}=value \)

**RET** return from subroutine: POP \( tmp \); JMP \( tmp \).

In fact, RET is an assembly language macro, in Windows and *NIX environment it is translated into RETN (“return near”) or, in MS-DOS times, where the memory was addressed differently ( 11.6 on page 1003), into RETF (“return far”).

RET can have an operand. Then it works like this:

POP \( tmp \); ADD ESP \( op_1 \); JMP \( tmp \). RET with an operand usually ends functions in the stdcall calling convention, see also: 6.1.2 on page 734.

**SAHF** copy bits from AH to CPU flags:
This instruction is often used in FPU-related code.

**SBB** (subtraction with borrow) subtract values, decrement the result if the CF flag is set. SBB is often used for subtraction of large values, for example, to subtract two 64-bit values in 32-bit environment using two SUB and SBB instructions. For example:

```plaintext
; work with 64-bit values: subtract val2 from val1.
; .lo means lowest 32 bits, .hi means highest.
SUB val1.lo, val2.lo
SBB val1.hi, val2.hi ; use CF set or cleared at the previous instruction
```

One more example: 1.28 on page 396.

**SCASB/SCASW/SCASD/SCASQ** (M) compare byte/ 16-bit word/ 32-bit word/ 64-bit word that’s stored in AX/EAX/RAX with a variable whose address is in DI/EDI/RDI. Set flags as CMP does.

This instruction is often used with the REPNE prefix: continue to scan the buffer until a special value stored in AX/EAX/RAX is found. Hence “NE” in REPNE: continue to scan while the compared values are not equal and stop when equal.

It is often used like the strlen() C standard function, to determine an ASCIIZ string’s length:

Example:

```plaintext
lea   edi, string
mov   ecx, 0FFFFFFFFh ; scan 2^32−1 bytes, i.e., almost infinitely
xor   eax, eax ; 0 is the terminator
repne scasb
add   edi, 0FFFFFFFFh ; correct it

; now EDI points to the last character of the ASCIIIZ string.

; lets determine string length
; current ECX = -1-strlen
not   ecx
dec   ecx

; now ECX contain string length
```

If we use a different AX/EAX/RAX value, the function acts like the memchr() standard C function, i.e., it finds a specific byte.

**SHL** shift value left

**SHR** shift value right:

```plaintext
SHL:

<table>
<thead>
<tr>
<th>7</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

SHR:

<table>
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<tr>
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<th>6</th>
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<th>4</th>
<th>3</th>
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<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
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<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
```

These instructions are frequently used for multiplication and division by 2^n. Another very frequent application is processing bit fields: 1.22 on page 304.

**SHRD** op1, op2, op3: shift value in op2 right by op3 bits, taking bits from op1.

Example: 1.28 on page 396.

**STOSB/STOSW/STOSD/STOSQ** store byte/ 16-bit word/ 32-bit word/ 64-bit word from AX/EAX/RAX into the address which is in DI/EDI/EDI.
Together with the REP prefix, it is to be repeated in a loop, the counter is in the CX/ECX/RCX register: it works like memset() in C. If the block size is known to the compiler on compile stage, memset() is often inlined into a short code fragment using REP MOVSx, sometimes even as several instructions.

memset(EDI, 0xAA, 15) equivalent is:

```assembly
; store 15 0xAA bytes to EDI
CLD ; set direction to forward
MOV EAX, 0AAAAAAAAh
MOV ECX, 3
REP STOSD ; write 12 bytes
STOSW ; write 2 more bytes
STOSB ; write remaining byte
```

(Supposedly, it works faster than storing 15 bytes using just one REP STOSB).

**SUB** subtract values. A frequently occurring pattern is SUB reg, reg, which implies zeroing of reg.

**TEST** same as AND but without saving the result, see also: 1.22 on page 304

**XOR** op1, op2: XOR\(^6\) values. \(op1 = op1 \oplus op2\). A frequently occurring pattern is XOR reg, reg, which implies zeroing of reg. See also: 2.6 on page 461.

### Less frequently used instructions

**BSF** bit scan forward, see also: 1.29.2 on page 419

**BSR** bit scan reverse

**BSWAP** (byte swap), change value endianness.

**BTC** bit test and complement

**BTR** bit test and reset

**BTS** bit test and set

**BT** bit test

**CBW/CWD/CWDE/CDQ/CDQE** Sign-extend value:

- **CBW** convert byte in AL to word in AX
- **CWD** convert word in AX to doubleword in DX:AX
- **CWDE** convert word in AX to doubleword in EAX
- **CDQ** convert doubleword in EAX to quadword in EDX:EAX
- **CDQE** (x64) convert doubleword in EAX to quadword in RAX

These instructions consider the value’s sign, extending it to high part of the newly constructed value. See also: 1.28.5 on page 405.

Interestingly to know these instructions was initially named as **SEX** (Sign EXtend), as Stephen P. Morse (one of Intel 8086 CPU designers) wrote in [Stephen P. Morse, *The 8086 Primer*, (1980)]\(^7\):

> The process of stretching numbers by extending the sign bit is called sign extension. The 8086 provides instructions (Fig. 3.29) to facilitate the task of sign extension. These instructions were initially named SEX (Sign extend) but were later renamed to the more conservative CBW (convert byte to word) and CWD (convert word to double word).

**CLD** clear DF flag.

**CLI** (M) clear IF flag

**CMC** (M) toggle CF flag

**CMOVcc** conditional MOV: load if the condition is true. The condition codes are the same as in the Jcc instructions (.1.6 on page 1027).

---

\(^6\)eXclusive OR

\(^7\)Also available as [https://archive.org/details/The8086Primer](https://archive.org/details/The8086Primer)
**CMPSB/CMPSW/CMPSD/CMPSQ** (M) compare byte/ 16-bit word/ 32-bit word/ 64-bit word from the address which is in SI/ESI/RSI with the variable at the address stored in DI/EDI/RDI. Set flags as CMP does.

Together with the REP prefix, it is to be repeated in a loop, the counter is stored in the CX/ECX/RCX register, the process will run until the ZF flag is zero (e.g., until the compared values are equal to each other, hence “E” in REPE).

It works like memcmp() in C.

Example from the Windows NT kernel (WRK v1.2):

Listing 3: base\ntos\rtl\i386\movemem.asm

```asm
; ULONG
; RtlCompareMemory (  
;  IN PVOID Source1,  
;  IN PVOID Source2,  
;  IN ULONG Length  
; )
;
; Routine Description:
;
; This function compares two blocks of memory and returns the number
; of bytes that compared equal.
;
; Arguments:
;
;  Source1 (esp+4) - Supplies a pointer to the first block of memory to
;                      compare.
;
;  Source2 (esp+8) - Supplies a pointer to the second block of memory to
;                      compare.
;
;  Length (esp+12) - Supplies the Length, in bytes, of the memory to be
;                    compared.
;
; Return Value:
;
;  The number of bytes that compared equal is returned as the function
;  value. If all bytes compared equal, then the length of the original
;  block of memory is returned.
;
;--
RcmSource1 equ [esp+12]
RcmSource2 equ [esp+16]
RcmLength equ [esp+20]

CODE_ALIGNMENT
cPublicProc _RtlCompareMemory,3
  push esi ; save registers
  push edi ;
  cld ; clear direction
  mov esi,RcmSource1 ; (esi) -> first block to compare
  mov edi,RcmSource2 ; (edi) -> second block to compare

;  Compare dwords, if any.
;
rcml0: mov ecx,RcmLength ; (ecx) = length in bytes
  shr ecx,2 ; (ecx) = length in dwords
  jz rcm20 ; no dwords, try bytes
  repe cmppsd ; compare dwords
  jnz rcm40 ; mismatch, go find byte

;  Compare residual bytes, if any.

; 1032
```
.1. X86

rcm20: mov ecx,RcmLength ; (ecx) = length in bytes
and ecx,3 ; (ecx) = length mod 4
jz rcm30 ; 0 odd bytes, go do dwords
repe cmpsb ; compare odd bytes
jnz rcm50 ; mismatch, go report how far we got
;
; All bytes in the block match.
;
rcm30: mov eax,RcmLength ; set number of matching bytes
pop edi ; restore registers
pop esi ;
stdRET _RtlCompareMemory
;
; When we come to rcm40, esi (and edi) points to the dword after the
; one which caused the mismatch. Back up 1 dword and find the byte.
; Since we know the dword didn't match, we can assume one byte won't.
;
rcm40: sub esi,4 ; back up
sub edi,4 ; back up
mov ecx,5 ; ensure that ecx doesn't count out
repe cmpsb ; find mismatch byte
;
; When we come to rcm50, esi points to the byte after the one that
; did not match, which is TWO after the last byte that did match.
;
rcm50: dec esi ; back up
sub esi,RcmSource1 ; compute bytes that matched
mov eax,esi ;
pop edi ; restore registers
pop esi ;
stdRET _RtlCompareMemory
stdENDP _RtlCompareMemory

N.B.: this function uses a 32-bit word comparison (CMPSD) if the block size is a multiple of 4, or
per-byte comparison (CMPSB) otherwise.

CPUID get information about the CPU's features. see also: (1.24.6 on page 369).

DIV unsigned division

IDIV signed division

INT (M): INT x is analogous to PUSHF; CALL dword ptr [x*4] in 16-bit environment. It was widely
used in MS-DOS, functioning as a syscall vector. The registers AX/BX/CX/DX/SI/DI were filled with
the arguments and then the flow jumped to the address in the Interrupt Vector Table (located at the
beginning of the address space). It was popular because INT has a short opcode (2 bytes) and the
program which needs some MS-DOS services is not bother to determine the address of the service’s
entry point. The interrupt handler returns the control flow to caller using the IRET instruction.

The most busy MS-DOS interrupt number was 0x21, serving a huge part of its API. See also: [Ralf
Brown Ralf Brown’s Interrupt List], for the most comprehensive interrupt lists and other MS-DOS
information.

In the post-MS-DOS era, this instruction was still used as syscall both in Linux and Windows (6.3 on
page 747), but was later replaced by the SYSENTER or SYSCALL instructions.

INT3 (M): this instruction is somewhat close to INT, it has its own 1-byte opcode (0xCC), and is actively
used while debugging. Often, the debuggers just write the 0xCC byte at the address of the breakpoint
to be set, and when an exception is raised, the original byte is restored and the original instruction
at this address is re-executed.

As of Windows NT, an EXCEPTION_BREAKPOINT exception is to be raised when the CPU executes this
instruction. This debugging event may be intercepted and handled by a host debugger, if one is
If it is not loaded, Windows offers to run one of the registered system debuggers. If MSVS is installed, its debugger may be loaded and connected to the process. In order to protect from reverse engineering, a lot of anti-debugging methods check integrity of the loaded code.

MSVC has compiler intrinsic for the instruction: __debugbreak().

There is also a win32 function in kernel32.dll named DebugBreak(), which also executes INT 3.

IN (M) input data from port. The instruction usually can be seen in OS drivers or in old MS-DOS code, for example (8.5.3 on page 832).

IRET: was used in the MS-DOS environment for returning from an interrupt handler after it was called by the INT instruction. Equivalent to POP tmp; POPF; JMP tmp.

LOOP (M) decrement CX/ECX/RCX, jump if it is still not zero.

LOOP instruction was often used in DOS-code which works with external devices. To add small delay, this was done:

\[
\begin{align*}
\text{MOV} & \quad \text{CX}, \quad \text{nnnn} \\
\text{LABEL} & : \quad \text{LOOP} \quad \text{LABEL}
\end{align*}
\]

Drawback is obvious: length of delay depends on CPU speed.

OUT (M) output data to port. The instruction usually can be seen in OS drivers or in old MS-DOS code, for example (8.5.3 on page 832).

POPA (M) restores values of (R|E)DI, (R|E)SI, (R|E)BP, (R|E)BX, (R|E)DX, (R|E)CX, (R|E)AX registers from the stack.

POPCNT population count. Counts the number of 1 bits in the value.

See: 2.7 on page 463.

POPF restore flags from the stack (AKA EFLAGS register)

PUSHA (M) pushes the values of the (R|E)AX, (R|E)CX, (R|E)DX, (R|E)BX, (R|E)BP, (R|E)SI, (R|E)DI registers to the stack.

PUSHF push flags (AKA EFLAGS register)

RCL (M) rotate left via CF flag:

\[
\begin{array}{cccccccc}
7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\
\hline
\text{CF} & & & & & & & \\
\end{array}
\]

RCR (M) rotate right via CF flag:

\[
\begin{array}{cccccccc}
7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\
\hline
\text{CF} & & & & & & & \\
\end{array}
\]

ROL/ROR (M) cyclic shift

ROL: rotate left:

\[
\begin{array}{cccccccc}
7 & 6 & 5 & 4 & 3 & 2 & 1 & 0 \\
\hline
\text{CF} & & & & & & & \\
\end{array}
\]

ROR: rotate right:

---

\(^{9}\) Microsoft Visual Studio
\(^{9}\) MSDN
\(^{10}\) MSDN
Despite the fact that almost all CPUs have these instructions, there are no corresponding operations in C/C++, so the compilers of these PLs usually do not generate these instructions.

For the programmer’s convenience, at least MSVC has the pseudofunctions (compiler intrinsics) `_rotl()` and `_rotr()`\(^\text{11}\), which are translated by the compiler directly to these instructions.

**SAL**  Arithmetic shift left, synonymous to SHL

**SAR**  Arithmetic shift right

Hence, the sign bit always stays at the place of the MSB.

**SETcc** \(\text{op: load 1 to operand (byte only) if the condition is true or zero otherwise. The condition codes are the same as in the Jcc instructions (}.1.6\text{ on page 1027).}

**STC**  \(\text{(M) set CF flag}

**STD**  \(\text{(M) set DF flag. This instruction is not generated by compilers and generally rare. For example, it can be found in the ntoskrnl.exe Windows kernel file, in the hand-written memory copy routines.}

**STI**  \(\text{(M) set IF flag}

**SYSCALL**  \(\text{(AMD) call syscall (}.6.3\text{ on page 747)}

**SYSENTER**  \(\text{(Intel) call syscall (}.6.3\text{ on page 747)}

**UD2**  \(\text{(M) undefined instruction, raises exception. Used for testing.}

**XCHG**  \(\text{(M) exchange the values in the operands}

This instruction is rare: compilers don’t generate it, because starting at Pentium, XCHG with address in memory in operand executes as if it has LOCK prefix ([Michael Abrash, *Graphics Programming Black Book*, 1997chapter 19]). Perhaps, Intel engineers did so for compatibility with synchronizing primitives. Hence, XCHG starting at Pentium can be slow. On the other hand, XCHG was very popular in assembly language programmers. So if you see XCHG in code, it can be a sign that this piece of code is written manually. However, at least Borland Delphi compiler generates this instruction.

**FPU instructions**

-\(R\) suffix in the mnemonic usually implies that the operands are reversed, \(-P\) suffix implies that one element is popped from the stack after the instruction’s execution, \(-PP\) suffix implies that two elements are popped.

-\(P\) instructions are often useful when we do not need the value in the FPU stack to be present anymore after the operation.

**FABS**  replace value in ST(0) by absolute value in ST(0)

**FADD**  \(\text{op: ST(0)=op+ST(0)}

**FADD**  \(\text{ST(0), ST(i): ST(0)=ST(0)+ST(i)}

**FADDP**  \(\text{ST(1)=ST(0)+ST(1); pop one element from the stack, i.e., the values in the stack are replaced by their sum}

**FCHS**  \(\text{ST(0)=−ST(0)}

**FCOM**  compare ST(0) with ST(1)

**FCOM**  \(\text{op: compare ST(0) with op}

**FCOMP**  compare ST(0) with ST(1); pop one element from the stack

\(^{11}\text{MSDN}\)
FCOMPP compare ST(0) with ST(1); pop two elements from the stack
FDIVR op: ST(0)=op/ST(0)
FDIVR ST(i), ST(j): ST(i)=ST(j)/ST(i)
FDIVRP op: ST(0)=op/ST(0); pop one element from the stack
FDIVRP ST(i), ST(j): ST(i)=ST(j)/ST(i); pop one element from the stack
FDIV op: ST(0)=ST(0)/op
FDIV ST(i), ST(j): ST(i)=ST(i)/ST(j)
FDIVP ST(1)=ST(0)/ST(1); pop one element from the stack, i.e., the dividend and divisor values in the stack are replaced by quotient
FILD op: convert integer and push it to the stack.
FIST op: convert ST(0) to integer op
FISTP op: convert ST(0) to integer op; pop one element from the stack
FLD1 push 1 to stack
FLDCW op: load FPU control word (.1.3 on page 1023) from 16-bit op.
FLDZ push zero to stack
FLD op: push op to the stack.
FMUL op: ST(0)=ST(0)*op
FMUL ST(i), ST(j): ST(i)=ST(i)*ST(j)
FMULP op: ST(0)=ST(0)*op; pop one element from the stack
FMULP ST(i), ST(j): ST(i)=ST(i)*ST(j); pop one element from the stack
FSINCOS: tmp=ST(0); ST(1)=sin(tmp); ST(0)=cos(tmp)
FSQRT: \( ST(0) = \sqrt{ST(0)} \)
FSTCW op: store FPU control word (.1.3 on page 1023) into 16-bit op after checking for pending exceptions.
FNSTCW op: store FPU control word (.1.3 on page 1023) into 16-bit op.
FSTSW op: store FPU status word (.1.3 on page 1024) into 16-bit op after checking for pending exceptions.
FNSTSW op: store FPU status word (.1.3 on page 1024) into 16-bit op.
FST op: copy ST(0) to op
FSTP op: copy ST(0) to op; pop one element from the stack
FSUBR op: ST(0)=op-ST(0)
FSUBR ST(0), ST(i): ST(0)=ST(i)-ST(0)
FSUBRP ST(1)=ST(0)-ST(1); pop one element from the stack, i.e., the value in the stack is replaced by the difference
FSUB op: ST(0)=ST(0)-op
FSUB ST(0), ST(i): ST(0)=ST(0)-ST(i)
FSUBP ST(1)=ST(1)-ST(0); pop one element from the stack, i.e., the value in the stack is replaced by the difference
FUCOM ST(i): compare ST(0) and ST(i)
FUCOM compare ST(0) and ST(1)
FUCOMP compare ST(0) and ST(1); pop one element from stack.
FUCOMPP compare ST(0) and ST(1); pop two elements from stack.

The instructions perform just like FCOM, but an exception is raised only if one of the operands is SNaN, while QNaN numbers are processed smoothly.
FXCH ST(i) exchange values in ST(0) and ST(i)
Instructions having printable ASCII opcode

(In 32-bit mode).
These can be suitable for shellcode construction. See also: 8.12.1 on page 911.

<table>
<thead>
<tr>
<th>ASCII character</th>
<th>hexadecimal code</th>
<th>x86 instruction</th>
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</thead>
<tbody>
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<td>XOR</td>
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<tr>
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<tr>
<td>T</td>
<td>54</td>
<td>PUSH</td>
</tr>
<tr>
<td>U</td>
<td>55</td>
<td>PUSH</td>
</tr>
<tr>
<td>V</td>
<td>56</td>
<td>PUSH</td>
</tr>
<tr>
<td>W</td>
<td>57</td>
<td>PUSH</td>
</tr>
<tr>
<td>X</td>
<td>58</td>
<td>POP</td>
</tr>
<tr>
<td>Y</td>
<td>59</td>
<td>POP</td>
</tr>
<tr>
<td>Z</td>
<td>5a</td>
<td>POP</td>
</tr>
<tr>
<td>[</td>
<td>5b</td>
<td>POP</td>
</tr>
<tr>
<td>\</td>
<td>5c</td>
<td>POP</td>
</tr>
<tr>
<td>]</td>
<td>5d</td>
<td>POP</td>
</tr>
<tr>
<td>^</td>
<td>5e</td>
<td>POP</td>
</tr>
<tr>
<td>_</td>
<td>5f</td>
<td>POP</td>
</tr>
<tr>
<td>`</td>
<td>60</td>
<td>PUSHA</td>
</tr>
<tr>
<td>a</td>
<td>61</td>
<td>POPA</td>
</tr>
<tr>
<td>f</td>
<td>66</td>
<td>(in 32-bit mode) switch to 16-bit operand size</td>
</tr>
<tr>
<td>g</td>
<td>67</td>
<td>(in 32-bit mode) switch to 16-bit address size</td>
</tr>
<tr>
<td>h</td>
<td>68</td>
<td>PUSH</td>
</tr>
<tr>
<td>i</td>
<td>69</td>
<td>IMUL</td>
</tr>
<tr>
<td>j</td>
<td>6a</td>
<td>PUSH</td>
</tr>
</tbody>
</table>
In summary: AAA, AAS, CMP, DEC, IMUL, INC, JA, JAE, JB, JBE, JE, JNE, JNO, JNS, JO, JP, JS, POP, POPA, PUSH, PUSHA, XOR.

.1.7 npad

It is an assembly language macro for aligning labels on a specific boundary.

That's often needed for the busy labels to where the control flow is often passed, e.g., loop body starts. So the CPU can load the data or code from the memory effectively, through the memory bus, cache lines, etc.

Taken from listing.inc (MSVC):

By the way, it is a curious example of the different NOP variations. All these instructions have no effects whatsoever, but have a different size.

Having a single idle instruction instead of couple of NOP-s, is accepted to be better for CPU performance.

```assembly
;; Listing. Inc
;;
;; This file contains assembler macros and is included by the files created
;; with the -FA compiler switch to be assembled by MASM (Microsoft Macro
;; Assembler).
;;
;; Copyright (c) 1993-2003, Microsoft Corporation. All rights reserved.

;; non destructive nops
npad macro size
if size eq 1
    nop
else
if size eq 2
    mov edi, edi
else
if size eq 3
    ; lea ecx, [ecx+00]
    DB 8DH, 49H, 00H
else
if size eq 4
    ; lea esp, [esp+00]
    DB 8DH, 64H, 24H, 00H
else
if size eq 5
    add eax, DWORD PTR 0
else
if size eq 6
    ; lea ebx, [ebx+00000000]
    DB 8DH, 9BH, 00H, 00H, 00H, 00H
else
if size eq 7
    ; lea esp, [esp+00000000]
    DB 8DH, 0A4H, 24H, 00H, 00H, 00H
else
```
.2 ARM

.2.1 Terminology

ARM was initially developed as 32-bit CPU, so that's why a word here, unlike x86, is 32-bit.

byte 8-bit. The DB assembly directive is used for defining variables and arrays of bytes.

halfword 16-bit. DCW assembly directive —””—.

word 32-bit. DCD assembly directive —“”—.

doubleword 64-bit.

quadword 128-bit.
.2. ARM

.2.2 Versions

- ARMv4: Thumb mode introduced.
- ARMv6: used in iPhone 1st gen., iPhone 3G (Samsung 32-bit RISC ARM 1176JZ(F)-S that supports Thumb-2)
- ARMv7: Thumb-2 was added (2003). was used in iPhone 3GS, iPhone 4, iPad 1st gen. (ARM Cortex-A8), iPad 2 (Cortex-A9), iPad 3rd gen.
- ARMv7s: New instructions added. Was used in iPhone 5, iPhone 5c, iPad 4th gen. (Apple A6).
- ARMv8: 64-bit CPU, AKA ARM64 AKA AArch64. Was used in iPhone 5S, iPad Air (Apple A7). There is no Thumb mode in 64-bit mode, only ARM (4-byte instructions).

.2.3 32-bit ARM (AArch32)

General purpose registers

- R0— function result is usually returned using R0
- R1...R12— GPRs
- R13— AKA SP (stack pointer)
- R14— AKA LR (link register)
- R15— AKA PC (program counter)

R0-R3 are also called “scratch registers”: the function’s arguments are usually passed in them, and the values in them are not required to be restored upon the function’s exit.

Current Program Status Register (CPSR)

<table>
<thead>
<tr>
<th>Bit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0..4</td>
<td>M—processor mode</td>
</tr>
<tr>
<td>5</td>
<td>T—Thumb state</td>
</tr>
<tr>
<td>6</td>
<td>F—FIQ disable</td>
</tr>
<tr>
<td>7</td>
<td>I—IRQ disable</td>
</tr>
<tr>
<td>8</td>
<td>A—imprecise data abort disable</td>
</tr>
<tr>
<td>9</td>
<td>E—data endianness</td>
</tr>
<tr>
<td>10..15, 25, 26</td>
<td>IT—if-then state</td>
</tr>
<tr>
<td>16..19</td>
<td>GE—greater-than-or-equal-to</td>
</tr>
<tr>
<td>20..23</td>
<td>DNM—do not modify</td>
</tr>
<tr>
<td>24</td>
<td>J—Java state</td>
</tr>
<tr>
<td>27</td>
<td>Q—sticky overflow</td>
</tr>
<tr>
<td>28</td>
<td>V—overflow</td>
</tr>
<tr>
<td>29</td>
<td>C—carry/borrow/extend</td>
</tr>
<tr>
<td>30</td>
<td>Z—zero bit</td>
</tr>
<tr>
<td>31</td>
<td>N—negative/less than</td>
</tr>
</tbody>
</table>

VFP (floating point) and NEON registers

<table>
<thead>
<tr>
<th>0..31 bits</th>
<th>32..64</th>
<th>65..96</th>
<th>97..127</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q0</td>
<td>D0</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td>S0</td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
</tr>
</tbody>
</table>

S-registers are 32-bit, used for the storage of single precision numbers.
D-registers are 64-bit ones, used for the storage of double precision numbers.
D- and S-registers share the same physical space in the CPU—it is possible to access a D-register via the S-registers (it is senseless though).
Likewise, the NEON Q-registers are 128-bit ones and share the same physical space in the CPU with the other floating point registers.

In VFP 32 S-registers are present: S0..S31.

In VFPv2 there 16 D-registers are added, which in fact occupy the same space as S0..S31.

In VFPv3 (NEON or “Advanced SIMD”) there are 16 more D-registers, D0..D31, but the D16..D31 registers are not sharing space with any other S-registers.

In NEON or “Advanced SIMD” another 16 128-bit Q-registers were added, which share the same space as D0..D31.

.2.4 64-bit ARM (AArch64)

General purpose registers

The number of registers was doubled since AArch32.

• X0—function result is usually returned using X0
• X0...X7—Function arguments are passed here.
• X8
• X9...X15—are temporary registers, the callee function can use and not restore them.
• X16
• X17
• X18
• X19...X29—callee function can use them, but must restore them upon exit.
• X29—used as FP (at least GCC)
• X30—“Procedure Link Register” AKA LR (link register).
• X31—register always contains zero AKA XZR or “Zero Register”. It's 32-bit part is called WZR.
• SP, not a general purpose register anymore.

See also: [Procedure Call Standard for the ARM 64-bit Architecture (AArch64), (2013)]12.

The 32-bit part of each X-register is also accessible via W-registers (W0, W1, etc.).

<table>
<thead>
<tr>
<th>High 32-bit part</th>
<th>low 32-bit part</th>
</tr>
</thead>
<tbody>
<tr>
<td>X0</td>
<td>W0</td>
</tr>
</tbody>
</table>

.2.5 Instructions

There is a -S suffix for some instructions in ARM, indicating that the instruction sets the flags according to the result. Instructions which lacks this suffix are not modify flags. For example ADD unlike ADDS will add two numbers, but the flags will not be touched. Such instructions are convenient to use between CMP where the flags are set and, e.g. conditional jumps, where the flags are used. They are also better in terms of data dependency analysis (because less number of registers are modified during execution).

12Also available as http://go.yurichev.com/17287
### Conditional codes table

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
<th>Flags</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ</td>
<td>Equal</td>
<td>Z == 1</td>
</tr>
<tr>
<td>NE</td>
<td>Not equal</td>
<td>Z == 0</td>
</tr>
<tr>
<td>CS AKA HS (Higher or Same)</td>
<td>Carry set / Unsigned, Greater than, equal</td>
<td>C == 1</td>
</tr>
<tr>
<td>CC AKA LO (LOwer)</td>
<td>Carry clear / Unsigned, Less than</td>
<td>C == 0</td>
</tr>
<tr>
<td>MI</td>
<td>Minus, negative / Less than</td>
<td>N == 1</td>
</tr>
<tr>
<td>PL</td>
<td>Plus, positive or zero / Greater than, equal</td>
<td>N == 0</td>
</tr>
<tr>
<td>VS</td>
<td>Overflow</td>
<td>V == 1</td>
</tr>
<tr>
<td>VC</td>
<td>No overflow</td>
<td>V == 0</td>
</tr>
<tr>
<td>HI</td>
<td>Unsigned higher / Greater than</td>
<td>C == 1 and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Z == 0</td>
</tr>
<tr>
<td>LS</td>
<td>Unsigned lower or same / Less than or equal</td>
<td>C == 0 or</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Z == 1</td>
</tr>
<tr>
<td>GE</td>
<td>Signed greater than or equal / Greater than equal</td>
<td>N == V</td>
</tr>
<tr>
<td>LT</td>
<td>Signed less than / Less than</td>
<td>N !== V</td>
</tr>
<tr>
<td>GT</td>
<td>Signed greater than / Greater than</td>
<td>Z == 0 and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N == V</td>
</tr>
<tr>
<td>LE</td>
<td>Signed less than or equal / Less than, equal</td>
<td>Z == 1 or</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N != V</td>
</tr>
<tr>
<td>None / AL</td>
<td>Always</td>
<td>Any</td>
</tr>
</tbody>
</table>

### .3 MIPS

#### .3.1 Registers

(O32 calling convention)

**General purpose registers GPR**

<table>
<thead>
<tr>
<th>Number</th>
<th>Pseudoname</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0</td>
<td>$ZERO</td>
<td>Always zero. Writing to this register is like NOP.</td>
</tr>
<tr>
<td>$1</td>
<td>$AT</td>
<td>Used as a temporary register for assembly macros and pseudo instructions.</td>
</tr>
<tr>
<td>$2 ...$3</td>
<td>$V0 ...$V1</td>
<td>Function result is returned here.</td>
</tr>
<tr>
<td>$4 ...$7</td>
<td>$A0 ...$A3</td>
<td>Function arguments.</td>
</tr>
<tr>
<td>$8 ...$15</td>
<td>$T0 ...$T7</td>
<td>Used for temporary data.</td>
</tr>
<tr>
<td>$16 ...$23</td>
<td>$S0 ...$S7</td>
<td>Used for temporary data.</td>
</tr>
<tr>
<td>$24 ...$25</td>
<td>$T8 ...$T9</td>
<td>Used for temporary data.</td>
</tr>
<tr>
<td>$26 ...$27</td>
<td>$K0 ...$K1</td>
<td>Reserved for OS kernel.</td>
</tr>
<tr>
<td>$28</td>
<td>$GP</td>
<td>Global Pointer++.</td>
</tr>
<tr>
<td>$29</td>
<td>$SP</td>
<td>SP*.</td>
</tr>
<tr>
<td>$30</td>
<td>$FP</td>
<td>FP*.</td>
</tr>
<tr>
<td>$31</td>
<td>$RA</td>
<td>RA.</td>
</tr>
<tr>
<td>n/a</td>
<td>PC</td>
<td>PC.</td>
</tr>
<tr>
<td>n/a</td>
<td>HI</td>
<td>high 32 bit of multiplication or division remainder***.</td>
</tr>
<tr>
<td>n/a</td>
<td>LO</td>
<td>low 32 bit of multiplication and division remainder***.</td>
</tr>
</tbody>
</table>

**Floating-point registers**

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F0..$F1</td>
<td>Function result returned here.</td>
</tr>
<tr>
<td>$F2..$F3</td>
<td>Not used.</td>
</tr>
<tr>
<td>$F4..$F11</td>
<td>Used for temporary data.</td>
</tr>
<tr>
<td>$F12..$F15</td>
<td>First two function arguments.</td>
</tr>
<tr>
<td>$F16..$F19</td>
<td>Used for temporary data.</td>
</tr>
<tr>
<td>$F20..$F31</td>
<td>Used for temporary data*.</td>
</tr>
</tbody>
</table>

---Callee must preserve the value.

---Callee must preserve the value (except in PIC code).
3.2 Instructions

There are 3 kinds of instructions:

- **R-type**: those which have 3 registers. R-instruction usually have the following form:

  ```
  instruction destination, source1, source2
  ```

  One important thing to keep in mind is that when the first and second register are the same, IDA may show the instruction in its shorter form:

  ```
  instruction destination/source1, source2
  ```

  That somewhat reminds us of the Intel syntax for x86 assembly language.

- **I-type**: those which have 2 registers and a 16-bit immediate value.

- **J-type**: jump/branch instructions, have 26 bits for encoding the offset.

### Jump instructions

What is the difference between B- instructions (BEQ, B, etc.) and J- ones (JAL, JALR, etc.)?

The B-instructions have an I-type, hence, the B-instructions’ offset is encoded as a 16-bit immediate. JR and JALR are R-type and jump to an absolute address specified in a register. J and JAL are J-type, hence the offset is encoded as a 26-bit immediate.

In short, B-instructions can encode a condition (B is in fact pseudo instruction for BEQ $ZERO, $ZERO, LABEL), while J-instructions can’t.

### Some GCC library functions

<table>
<thead>
<tr>
<th>name</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>__divdi3</td>
<td>signed division</td>
</tr>
<tr>
<td>__moddi3</td>
<td>getting remainder (modulo) of signed division</td>
</tr>
<tr>
<td>__udivdi3</td>
<td>unsigned division</td>
</tr>
<tr>
<td>__umoddi3</td>
<td>getting remainder (modulo) of unsigned division</td>
</tr>
</tbody>
</table>

### Some MSVC library functions

_ll in function name stands for “long long”, e.g., a 64-bit data type.

<table>
<thead>
<tr>
<th>name</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>__alldiv</td>
<td>signed division</td>
</tr>
<tr>
<td>__allmul</td>
<td>multiplication</td>
</tr>
<tr>
<td>__allrem</td>
<td>remainder of signed division</td>
</tr>
<tr>
<td>__allshl</td>
<td>shift left</td>
</tr>
<tr>
<td>__allshr</td>
<td>signed shift right</td>
</tr>
<tr>
<td>__aulldiv</td>
<td>unsigned division</td>
</tr>
<tr>
<td>__aullrem</td>
<td>remainder of unsigned division</td>
</tr>
<tr>
<td>__aullshr</td>
<td>unsigned shift right</td>
</tr>
</tbody>
</table>

Multiplication and shift left procedures are the same for both signed and unsigned numbers, hence there is only one function for each operation here.

The source code of these function can be found in the installed MSVS, in VC/crt/src/intel/*.asm.
.6. CHEATSHEETS

.6 Cheatsheets

.6.1 IDA

Hot-keys cheatsheet:

<table>
<thead>
<tr>
<th>key</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space</td>
<td>switch listing and graph view</td>
</tr>
<tr>
<td>C</td>
<td>convert to code</td>
</tr>
<tr>
<td>D</td>
<td>convert to data</td>
</tr>
<tr>
<td>A</td>
<td>convert to string</td>
</tr>
<tr>
<td>*</td>
<td>convert to array</td>
</tr>
<tr>
<td>U</td>
<td>undefine</td>
</tr>
<tr>
<td>O</td>
<td>make offset of operand</td>
</tr>
<tr>
<td>H</td>
<td>make decimal number</td>
</tr>
<tr>
<td>R</td>
<td>make char</td>
</tr>
<tr>
<td>B</td>
<td>make binary number</td>
</tr>
<tr>
<td>Q</td>
<td>make hexadecimal number</td>
</tr>
<tr>
<td>N</td>
<td>rename identifier</td>
</tr>
<tr>
<td>?</td>
<td>calculator</td>
</tr>
<tr>
<td>G</td>
<td>jump to address</td>
</tr>
<tr>
<td>Ctrl-X</td>
<td>show references to the current function, label, variable (incl. in local stack)</td>
</tr>
<tr>
<td>X</td>
<td>show references to the function, label, variable, etc.</td>
</tr>
<tr>
<td>Alt-I</td>
<td>search for constant</td>
</tr>
<tr>
<td>Ctrl-I</td>
<td>search for the next occurrence of constant</td>
</tr>
<tr>
<td>Alt-B</td>
<td>search for byte sequence</td>
</tr>
<tr>
<td>Ctrl-B</td>
<td>search for the next occurrence of byte sequence</td>
</tr>
<tr>
<td>Alt-T</td>
<td>search for text (including instructions, etc.) Text suchen (inkl. Anweisungen, usw.)</td>
</tr>
<tr>
<td>Ctrl-T</td>
<td>search for the next occurrence of text</td>
</tr>
<tr>
<td>Alt-P</td>
<td>edit current function</td>
</tr>
<tr>
<td>Enter</td>
<td>jump to function, variable, etc.</td>
</tr>
<tr>
<td>Esc</td>
<td>get back</td>
</tr>
<tr>
<td>Num -</td>
<td>fold function or selected area</td>
</tr>
<tr>
<td>Num +</td>
<td>unhide function or area</td>
</tr>
</tbody>
</table>

Function/area folding may be useful for hiding function parts when you realize what they do. This is used in my script\(^\text{13}\) for hiding some often used patterns of inline code.

.6.2 OllyDbg

Hot-keys cheatsheet:

<table>
<thead>
<tr>
<th>hot-key</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>F7</td>
<td>trace into</td>
</tr>
<tr>
<td>F8</td>
<td>step over</td>
</tr>
<tr>
<td>F9</td>
<td>run</td>
</tr>
<tr>
<td>Ctrl-F2</td>
<td>restart</td>
</tr>
</tbody>
</table>

.6.3 MSVC

Some useful options which were used through this book.  

\(^{13}\)GitHub
.6. CHEATSHEETS

<table>
<thead>
<tr>
<th>option</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>/O1</td>
<td>minimize space</td>
</tr>
<tr>
<td>/Ob0</td>
<td>no inline expansion</td>
</tr>
<tr>
<td>/Ox</td>
<td>maximum optimizations</td>
</tr>
<tr>
<td>/GS-</td>
<td>disable security checks (buffer overflows)</td>
</tr>
<tr>
<td>/Fa(file)</td>
<td>generate assembly listing</td>
</tr>
<tr>
<td>/Zi</td>
<td>enable debugging information</td>
</tr>
<tr>
<td>/Zp(n)</td>
<td>pack structs on $n$-byte boundary</td>
</tr>
<tr>
<td>/MD</td>
<td>produced executable will use MSVCR*.DLL MSVCR*.DLL</td>
</tr>
</tbody>
</table>

Some information about MSVC versions: 5.1.1 on page 699.

.6.4 GCC

Some useful options which were used through this book.

<table>
<thead>
<tr>
<th>option</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>-Os</td>
<td>code size optimization</td>
</tr>
<tr>
<td>-O3</td>
<td>maximum optimization</td>
</tr>
<tr>
<td>-regparm=</td>
<td>how many arguments are to be passed in registers</td>
</tr>
<tr>
<td>-o file</td>
<td>set name of output file</td>
</tr>
<tr>
<td>-g</td>
<td>produce debugging information in resulting executable</td>
</tr>
<tr>
<td>-S</td>
<td>generate assembly listing file</td>
</tr>
<tr>
<td>-masm=intel</td>
<td>produce listing in Intel syntax</td>
</tr>
<tr>
<td>-fno-inline</td>
<td>do not inline functions</td>
</tr>
</tbody>
</table>

.6.5 GDB

Some of commands we used in this book:
<table>
<thead>
<tr>
<th>option</th>
<th>meaning</th>
</tr>
</thead>
<tbody>
<tr>
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GiB  Gibibyte ....................................................................................... 973
CRC  Cyclic redundancy check ............................................................. 993
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Glossary

heap usually, a big chunk of memory provided by the OS so that applications can divide it by themselves as they wish. malloc()/free() work with the heap. 30, 348, 560, 562, 563, 575, 577, 592, 593, 636, 755, 757

real number numbers which may contain a dot. this is float and double in C/C++. 218, 329

decrement Decrease by 1. 19, 184, 203, 440, 726, 858, 1027, 1030, 1034

increment Increase by 1. 16, 20, 184, 188, 203, 209, 326, 329, 440, 855, 1027

integral data type usual numbers, but not a real ones. may be used for passing variables of boolean data type and enumerations. 232

product Multiplication result. 97, 224, 227, 407, 431, 454

arithmetic mean a sum of all values divided by their count. 519

stack pointer A register pointing to a place in the stack. 10, 11, 20, 30, 35, 42, 54, 55, 73, 99, 544, 651, 734–737, 1022, 1028, 1040, 1048

tail call It is when the compiler (or interpreter) transforms the recursion (with which it is possible: tail recursion) into an iteration for efficiency: wikipedia. 481

quotient Division result. 218, 220, 222, 223, 227, 430, 497, 520

anti-pattern Generally considered as bad practice. 32, 76, 465

atomic operation “\textit{atōmos}” stands for “indivisible” in Greek, so an atomic operation is guaranteed not to be interrupted by other threads. 646, 788

basic block a group of instructions that do not have jump/branch instructions, and also don’t have jumps inside the block from the outside. In IDA it looks just like as a list of instructions without empty lines. 691, 1004, 1005

callee A function being called by another. 32, 33, 46, 66, 86, 97, 99, 101, 420, 465, 544, 651, 734–737, 739, 740, 1042

caller A function calling another. 6, 8, 10, 30, 46, 86, 97, 98, 100, 108, 154, 420, 469, 544, 734, 736, 737, 740

compiler intrinsic A function specific to a compiler which is not an usual library function. The compiler generates a specific machine code instead of a call to it. Often, it’s a pseudofunction for a specific CPU instruction. Read more: (11.3 on page 999). 1034

CP/M Control Program for Microcomputers: a very basic disk OS used before MS-DOS. 912

dongle Dongle is a small piece of hardware connected to LPT printer port (in past) or to USB. Its function was similar to a security token, it has some memory and, sometimes, a secret (crypto-)hashing algorithm. 815

endianness Byte order: 2.8 on page 464. 22, 78, 346, 1031

GiB Gibabyte: $2^{30}$ or 1024 mebibytes or 1073741824 bytes. 15

jump offset a part of the JMP or Jcc instruction’s opcode, to be added to the address of the next instruction, and this is how the new PC is calculated. May be negative as well. 93, 133, 1027
Glossary

**kernel mode** A restrictions-free CPU mode in which the OS kernel and drivers execute. cf. **user mode**. 1054

**leaf function** A function which does not call any other function. 28, 32

**link register** (RISC) A register where the return address is usually stored. This makes it possible to call leaf functions without using the stack, i.e., faster. 32, 816, 1040, 1041

**loop unwinding** It is when a compiler, instead of generating loop code for n iterations, generates just n copies of the loop body, in order to get rid of the instructions for loop maintenance. 186

**name mangling** used at least in C++, where the compiler needs to encode the name of class, method and argument types in one string, which will become the internal name of the function. You can read more about it here: 3.18.1 on page 542. 542, 700, 701

**NaN** not a number: a special cases for floating point numbers, usually signaling about errors. 235, 257, 1003

**NEON** AKA “Advanced SIMD”—SIMD from ARM. 1041

**NOP** “no operation”, idle instruction. 726

**NTAPI** API available only in the Windows NT line. Largely not documented by Microsoft. 794

**padding** Padding in English language means to stuff a pillow with something to give it a desired (bigger) form. In computer science, padding means to add more bytes to a block so it will have desired size, like $2^n$ bytes. 708

**PDB** (Win32) Debugging information file, usually just function names, but sometimes also function arguments and local variables names. 699, 758, 794, 795, 802, 803, 895

**POKE** BASIC language instruction for writing a byte at a specific address. 726

**register allocator** The part of the compiler that assigns CPU registers to local variables. 202, 307, 420

**reverse engineering** act of understanding how the thing works, sometimes in order to clone it. v, 1034

**security cookie** A random value, different at each execution. You can read more about it here: 1.20.3 on page 283. 778

**stack frame** A part of the stack that contains information specific to the current function: local variables, function arguments, RA, etc. 67, 68, 97, 98, 477, 778

**stdout** standard output. 22, 35, 154

**thunk function** Tiny function with a single role: call another function. 23, 393, 816, 825

**tracer** My own simple debugging tool. You can read more about it here: 7.2.1 on page 790. 189-191, 703, 714, 717, 774, 783, 897, 903, 907, 908, 910, 998

**user mode** A restricted CPU mode in which it all application software code is executed. cf. **kernel mode**. 832, 1054

**Windows NT** Windows NT, 2000, XP, Vista, 7, 8, 10. 293, 418, 649, 707, 747, 757, 787, 915, 1033

**word** data type fitting in GPR. In the computers older than PCs, the memory size was often measured in words rather than bytes. 447-450, 455, 566, 637

**xoring** often used in the English language, which implying applying the XOR operation. 778, 827, 830
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