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I can't accept full-time job offers, I mostly work remotely on small tasks, like these:

Decrypting a database, managing unknown type of files

Due to NDA agreement, I can't reveal many details about the last case, but the case in "[Encrypted database case #1](#)" article is heavily based on a real case.

Rewriting some kind of old EXE or DLL file back to C/C++

Dongles

Occasionally I do [software copy-protection dongle](#) replacements or dongle emulators. In general, it is somewhat unlawful to break software protection, so I can do this only if these conditions are met:

- software company who developed the software product does not exist anymore to my best knowledge;
- the software product is older than 10 years;
- you have a dongle to read information from it. In other words, I can only help to those who still uses some very old software, completely satisfied with it, but afraid of dongle electrical breakage and there are no company who can still sell the dongle replacement.

These includes ancient MS-DOS and UNIX software. Software for exotic computer architectures (like MIPS, DEC Alpha, PowerPC) accepted as well.

Examples of my work you may find here:

- My book devoted to reverse engineering has a part about copy-protection dongles: [81](#).
- [Finding unknown algorithm using only input/output pairs and Z3 SMT solver article](#)
- [About MicroPhar \(93c46-baseed dongle\) emulation in DosBox.](#)
- [Source code of DOS MicroPhar emulator using EMM386 I/O interception API](#)

Contact me

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Still want to hire reverse engineer/security researcher on full-time basis?

You may try [Reddit RE hiring thread](#). There is also Russian-speaking forum with a [section devoted to RE jobs](#).

Reverse Engineering for Beginners



Dennis Yurichev

Reverse Engineering for Beginners

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The latest version (and Russian edition) of this text is accessible at beginners.re. An e-book reader version is also available there.

The cover was made by Andy Nechaevsky: [facebook](#).

Call for translators!

You may want to help me with translation this work into languages other than English and Russian. Just send me any piece of translated text (no matter how short) and I'll put it into my LaTeX source code.

Speed isn't important, because this is open-source project, after all. Your name will be mentioned as project contributor. Korean, Chinese and Persian languages are reserved by publishers. English and Russian versions I do by myself, but my English is still that horrible, so I'm very grateful for any notes about grammar, etc. Even my Russian is also flawed, so I'm grateful for notes about Russian text as well!

So do not hesitate to contact me: [dennis\(a\)yurichev.com](mailto:dennis(a)yurichev.com).

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¹Instruction Set Architecture

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²Floating-point unit

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³Redundant Array of Independent Disks

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⁴Java virtual machine

⁵Pseudorandom number generator

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⁶Compact Disc File System

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⁷General Purpose Registers

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](#)⁸ structure. This book is about the first meaning.

Topics discussed in-depth

x86/x64, ARM/ARM64, MIPS, Java/JVM.

Topics touched upon

Oracle RDBMS ([84 on page 837](#)), Itanium ([96 on page 909](#)), copy-protection dongles ([81 on page 772](#)), LD_PRELOAD ([70.2 on page 707](#)), stack overflow, [ELF](#)⁹, win32 PE file format ([71.2 on page 713](#)), x86-64 ([27.1 on page 420](#)), critical sections ([71.4 on page 741](#)), syscalls ([69 on page 703](#)), [TLS](#)¹⁰, position-independent code ([PIC](#)¹¹) ([70.1 on page 705](#)), profile-guided optimization ([98.1 on page 913](#)), C++ STL ([53.4 on page 560](#)), OpenMP ([95 on page 903](#)), SEH ([71.3 on page 719](#)).

Exercises and tasks

...are all moved to the separate website: <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 *Reverse Engineering for Beginners*

- “It’s very well done .. and for free .. amazing.”¹² Daniel Bilar, Siege Technologies, LLC.
- “... excellent and free”¹³ Pete Finnigan, Oracle RDBMS security guru.
- “... book is interesting, great job!” Michael Sikorski, author of *Practical Malware Analysis: The Hands-On Guide to Dissecting Malicious Software*.
- “... my compliments for the very nice tutorial!” Herbert Bos, full professor at the Vrije Universiteit Amsterdam, co-author of *Modern Operating Systems (4th Edition)*.
- “... 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.

⁸Database management systems

⁹Executable file format widely used in *NIX systems including Linux

¹⁰Thread Local Storage

¹¹Position Independent Code: [70.1 on page 705](#)

¹²twitter.com/daniel_bilar/status/436578617221742593

¹³twitter.com/petefinnigan/status/400551705797869568

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-
- "... reasonable intro to some of the techniques."¹⁴ 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, plan to use it in graduate course."¹⁵ 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"¹⁶ Tanel Poder, Oracle RDBMS performance tuning expert .
 - "This book is some kind of Wikipedia to beginners..." Archer, Chinese Translator, IT Security Researcher.

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For patiently answering all my questions: Andrey "herm1t" Baranovich, Slava "Avid" Kazakov.

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Thanks a lot to every donor!

mini-FAQ

Q: Why should one learn assembly language these days?

¹⁴[reddit](#)

¹⁵[twitter.com/sergeybratus/status/505590326560833536](#)

¹⁶[twitter.com/TanelPoder/status/524668104065159169](#)

CONTENTS

A: Unless you are an OS¹⁷ developer, you probably don't need to code in assembly—modern compilers are much better at performing optimizations than humans¹⁸.

Also, modern CPU¹⁹s are very complex devices and assembly knowledge doesn't really help one to understand their internals.

That being said, there are at least two areas where a good understanding of assembly can be helpful: First and foremost, security/malware research. It is also a good way to gain a better understanding of your compiled code whilst 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.

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 many other free things.

A: In my own experience, authors of technical literature do this mostly for self-advertisement purposes. It's not possible to get 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 RE²⁰ ([2013 Q3](#), [2014](#)). Try looking there.

A somewhat related hiring thread can be found in the “netsec” subreddit: [2014 Q2](#).

Q: I have a question...

A: Send it to me by email ([dennis\(a\)yurichev.com](mailto:dennis(a)yurichev.com)).

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 my book (as it was in August 2014) into Korean.

It's now available at [their website](#).

The translator is Byungho Min ([twitter/tais9](#)). The cover art was done by my artistic friend, Andy Nechaevsky: [facebook/andy-dinka](#). They also hold the copyright to the Korean translation.

So, if you want to have a *real* book on your shelf in Korean and want to support my work, it is now available for purchase.

¹⁷Operating System

¹⁸A very good text about this topic: [\[Fog13b\]](#)

¹⁹Central processing unit

²⁰reddit.com/r/ReverseEngineering/

Part I

Code patterns

Everything is comprehended through comparison

Author unknown

Chapter 1

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.¹. He did it so many times that the relationship between the C/C++ code and what the compiler produced was imprinted deeply in his mind. It's easy to imagine instantly a rough outline of C code's appearance and function. Perhaps this technique could be helpful for others.

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

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 modern 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 disable optimization. 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 and direction, a compiler can include in the resulting file some debug information, thus producing code for easy debugging. One of the important features of the 'debug' code is that it might contain links between each line of the source code and the respective machine code addresses. 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, where possible.

¹In fact, he still does it when he can't understand what a particular bit of code does.

Chapter 2

Some basics

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**). ≈ 8 in x86, ≈ 16 in x86-64, ≈ 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**¹ 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 **CPU**s are not alike—it is much easier for humans to use a high-level **PL** like C/C++, Java, Python, etc., 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 **CPU**s 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*.

²

2.1.1 A couple of words about different **ISAs**

The x86 **ISA** has always been one with variable-length opcodes, 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**³ **CPU** designed with constant-length opcode in mind, which had some advantages in the past. In the very beginning, all ARM instructions were encoded in 4 bytes⁴. This is now referred to as “ARM mode”. Then they thought it wasn’t as frugal as they first imagined. In fact, most used **CPU** instructions⁵ in real world applications can be encoded using less information. They therefore added another **ISA**, called Thumb, where each instruction was encoded in just 2 bytes. This is now referred 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 may of course 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 (admittedly, largely due to the fact that Xcode does this by default). Later the 64-bit ARM came out. This **ISA** has 4-byte opcodes, 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

¹Programming language

²Old-school Russian literature also use term “translator”.

³Reduced instruction set computing

⁴By the way, 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 ([14.2.2 on page 173](#)) section.

⁵These are MOV/PUSH/CALL/Jcc

2.2. NUMERAL SYSTEMS

that they are different **ISAs**, rather than variations of the same one. Therefore, we would 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 opcodes, such as MIPS, PowerPC and Alpha AXP.

2.2 Numeral systems

Humans accustomed to decimal numeral system probably because almost all ones has 10 fingers. Nevertheless, number 10 has no significant meaning in science and mathematics. Natural numeral system in digital electronics is binary: 0 is for absence of current in wire and 1 for presence. 10 in binary is 2 in decimal, 100 in binary is 4 in decimal and so on.

How to convert from one system to another?

Positional notation is used almost everywhere, this means, the digit (number placed in single character) has some weight depending on where it is placed. If 2 is placed at the rightmost place, it's 2. If it is placed at the place one digit before rightmost, it's 20.

What 1234 stands for?

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

Same story for binary numbers, but base is 2 instead of 10. What 101011 stands for?

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

Positional notation can be opposed to non-positional notation such as Roman numeric system. Perhaps, humankind switched to positional notation because it's easier to do basic operations (addition, multiplication, etc) on paper by hand.

Indeed, 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 hexadecimal numeral system can be used. Hexadecimal system uses 0..9 numbers 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.

hexadecimal	binary	decimal
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
A	1010	10
B	1011	11
C	1100	12
D	1101	13
E	1110	14
F	1111	15

How to understand, which system is currently used?

Decimal numbers are usually written as is, i.e., 1234. But some assemblers allows to make emphasis on decimal system and this number can be written with "d" suffix: 1234d.

Binary numbers sometimes prepended with "0b" prefix: 0b100110111 ([GCC⁶](#) has non-standard language extension for this: <https://gcc.gnu.org/onlinedocs/gcc/Binary-constants.html>). There is also another way: "b" suffix, for example: 100110111b. I'll try to use "0b" prefix throughout the book for binary numbers.

Hexadecimal numbers are prepended with "0x" prefix in C/C++ and other **PLs**: 0x1234ABCD. Or they are has "h" suffix: 1234ABCDh - this is common way of representing them in assemblers and debuggers. If the number is started with A..F digit, 0 should be added before: 0ABCDEFh. I'll try to use "0x" prefix throughout the book for hexadecimal numbers.

⁶GNU Compiler Collection

2.2. NUMERAL SYSTEMS

Should one learn to convert numbers in mind? A table of 1-digit hexadecimal numbers can easily be memorized. As of larger numbers, probably, it's not worth to torment yourself.

2.2.1 Octal numeral system

Another numeral system heavily used in past of computer programming is 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 hexadecimal system almost everywhere, but surprisingly, there is *NIX utility used by many people often which takes octal number as argument: `chmod`.

As many *NIX users know, `chmod` argument can be a number of 3 digits. The first one is rights for owner of file, second is rights for group (to which file belongs), third is for everyone else. And each digit can be represented in binary form:

decimal	binary	meaning
7	111	rwx
6	110	rw-
5	101	r-x
4	100	r--
3	011	-wx
2	010	-w-
1	001	--x
0	000	---

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

Now the reason why I'm talking about `chmod` here is that the whole number in argument can be represented as octal number. Let's take for example, 664. When you run `chmod 664 file`, you set read/write permissions for owner, read permissions for group and again, read permissions for everyone else. Let's convert 664 octal number to binary, this will 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--`.

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 divisible by 3, so octal system was natural on that environment. Nowadays, all popular computers employs word/address size of 16, 32 or 64 bits, and these numbers are divisible by 4, so hexadecimal system is more natural here.

Octal numeral system is supported by all standard C/C++ compilers. This is source of confusion sometimes, because octal numbers are encoded with zero prepended, for example, 0277 is 255. And sometimes, you may make a typo and write "09" instead of 9, and the compiler wouldn't allow you. GCC may report something like that: `error: invalid digit "9" in octal`

2.2.2 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 two last digits are zeroes.

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

Binary number `0b1000101000` is divisible by `0b1000` (8), etc.

This property can be used often to realize quickly if a size of some block in memory is padded to some boundary. For example, sections in PE⁷ files are almost always started at addresses ending with 3 hexadecimal zeroes: `0x41000`, `0x10001000`, etc. The reason behind this is in the fact that almost all PE sections are padded to boundary of `0x1000` (4096) bytes.

⁷Portable Executable

Chapter 3

The simplest Function

The simplest possible function is arguably one that simply returns a constant value:

Here it is:

Listing 3.1: C/C++ Code

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

Lets compile it!

3.1 x86

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

Listing 3.2: Optimizing GCC/MSVC (assembly output)

```
f:
    mov     eax, 123
    ret
```

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.

3.2 ARM

There are a few differences on the ARM platform:

Listing 3.3: Optimizing Keil 6/2013 (ARM mode) ASM Output

```
f 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`.

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](#).

It is worth noting that `MOV` is a misleading name for the instruction in both x86 and ARM [ISAs](#).

The data is not in fact *moved*, but *copied*.

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 pseudoname (\$V0, \$A0, etc).

The GCC assembly output below lists registers by number:

Listing 3.4: Optimizing GCC 4.4.5 (assembly output)

```
j      $31
li     $2,123          # 0x7b
```

...while IDA¹ does it—by their pseudonames:

Listing 3.5: Optimizing GCC 4.4.5 (IDA)

```
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, jumping to the address in the \$31 (or \$RA) register.

This is the register analogous to LR² in ARM.

You might be wondering why positions of the 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 just need to remember 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 which must be executed beforehand.

3.3.1 A note about MIPS instruction/register names

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

¹ Interactive Disassembler and debugger developed by Hex-Rays

²Link Register

Chapter 4

Hello, world!

Let's use the famous example from the book "The C programming Language"[\[Ker88\]](#):

```
#include <stdio.h>

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

4.1 x86

4.1.1 MSVC

Let's compile it in MSVC 2010:

```
cl 1.cpp /Fa1.asm
```

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

Listing 4.1: 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 difference between Intel-syntax and AT&T-syntax will be discussed in [4.1.3 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[]` [\[Str13, p176, 7.3.2\]](#), 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.

4.1. X86

That is why the example may be rewritten as follows:

```
#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: [60.1.1 on page 666](#).

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)¹.

After the function prologue we see the call to the `printf()` function: `CALL _printf`. Before the call the 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 register².

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 probably 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 4.2: 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”³ 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*, which, in any case, results in zero.

The last instruction `RET` returns the control to the `caller`. Usually, this is C/C++ `CRT`⁴ code, which, in turn, returns control to the `OS`.

4.1.2 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-syntax⁵.

¹You can read more about it in the section about function prologues and epilogues ([5 on page 26](#)).

²CPU flags, however, are modified

³[wikipedia](#)

⁴C runtime library

⁵We could also have GCC produce assembly listings in Intel-syntax by applying the options `-S -masm=intel`.

Listing 4.3: 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

```

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 it is saved onto the stack. In addition, the function prologue contains `AND ESP, 0FFFFFFF0h` – 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)⁶.

`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, ...`).

4.1.3 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 4.4: let's compile in GCC 4.7.3

```
gcc -S 1_1.c
```

We get this:

Listing 4.5: GCC 4.7.3

```

.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
.cfi_offset 5, -8

```

⁶[Wikipedia: Data structure alignment](#)

4.1. X86

```

    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"
.section .note.GNU-stack,"",@progbits

```

The listing contains many macros (beginning with dot). These are not interesting for us at the moment.

For now, for the sake of simplification, we can ignore them (except the `.string` macro which encodes a null-terminated character sequence just like a C-string). Then we'll see this⁷:

Listing 4.6: GCC 4.7.3

```

.LC0:
.string "hello, world\n"
main:
    pushl  %ebp
    movl   %esp, %ebp
    andl   $-16, %esp
    subl   $16, %esp
    movl   $.LC0, (%esp)
    call   printf
    movl   $0, %eax
    leave
    ret

```

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 memorise 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 (→)⁸.

- 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)

Let's go back to the compiled result: it is identical to what we saw in [IDA](#). With one subtle difference: `0xFFFFFFFF0h` is presented as `$-16`. It is the same thing: `16` in the decimal system is `0x10` in hexadecimal. `-0x10` is equal to `0xFFFFFFFF0` (for a 32-bit data type).

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

⁷This GCC option can be used to eliminate “unnecessary” macros: `-fno-asynchronous-unwind-tables`

⁸By 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.

4.2 x86-64

4.2.1 MSVC-x86-64

Let's also try 64-bit MSVC:

Listing 4.7: 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 exists a popular way to pass function arguments via registers (*fastcall*) [67.3 on page 691](#). I.e., a part of the function arguments is passed in registers, the rest—via the stack. In Win64, 4 function arguments are passed in the `RCX`, `RDX`, `R8`, `R9` registers. That is what we see here: a pointer to the string for `printf()` is now passed not in the stack, but 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:

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
<code>RAX^{x64}</code>							
<code>EAX</code>							
<code>AX</code>							
<code>AH</code> <code>AL</code>							

The `main()` function returns an *int*-typed value, which is, in C/C++, for better backward compatibility and portability, still 32-bit, so that is why the `EAX` register is cleared at the function end (i.e., the 32-bit part of the register) instead of `RAX`. There are also 40 bytes allocated in the local stack. This is called the “shadow space”, about which we are going to talk later: [9.2.1 on page 100](#).

4.2.2 GCC-x86-64

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

Listing 4.8: 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
```

A method to pass function arguments in registers is also used in Linux, *BSD and Mac OS X is [[Mit13](#)].

The first 6 arguments are passed in the `RDI`, `RSI`, `RDX`, `RCX`, `R8`, `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). But why not 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 [[Int13](#)]. I.e., the `MOV EAX, 011223344h` writes a value into `RAX` correctly, since the higher bits will be cleared.

4.3. GCC—ONE MORE THING

If we open the compiled object file (.o), we can also see all the instructions' opcodes⁹:

Listing 4.9: 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:00000000004004D9 31 C0    xor   eax, eax
.text:00000000004004DB E8 D8 FE FF FF    call  _printf
.text:00000000004004E0 31 C0    xor   eax, eax
.text:00000000004004E2 48 83 C4 08    add   rsp, 8
.text:00000000004004E6 C3    retn
.text:00000000004004E6          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 was cleared before the `printf()` function call. This is done because the number of used vector registers is passed in `EAX` in *NIX systems on x86-64 ([Mit13]).

4.3 GCC—one more thing

The fact that an *anonymous* C-string has `const` type (4.1.1 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:

```
#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:

Listing 4.10: GCC 4.8.1 + IDA listing

```
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
```

⁹This must be enabled in Options → Disassembly → Number of opcode bytes

4.4. ARM

```
        mov    [esp+1Ch+s], offset aHello ; "hello "
        call    __puts
        add     esp, 1Ch
        retn
f2      endp

aHello      db 'hello '
s          db 'world',0xa,0
```

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.

4.4 ARM

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

- Popular in the embedded area: Keil Release 6/2013.
- Apple Xcode 4.6.3 IDE with the LLVM-GCC 4.2 compiler ¹⁰.
- 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.

4.4.1 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 ¹¹, but it is more important for us to see the instructions “as is” so let’s see the compiled result in [IDA](#).

Listing 4.11: 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:000001EC 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}` ¹², 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`¹⁴ 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`.

¹⁰It is indeed so: Apple Xcode 4.6.3 uses open-source GCC as front-end compiler and LLVM code generator

¹¹e.g. ARM mode lacks `PUSH / POP` instructions

¹²`STMFD`¹³

¹⁴`stack pointer`. `SP/ESP/RSP` in x86/x64. `SP` in ARM.

4.4. ARM

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.

The `ADR R0, aHelloWorld` instruction adds or subtracts the value in the `PC15` 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”¹⁶.

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 __2printf17` 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 CISC¹⁸-processors like x86, where the return address is usually stored on the stack. Read more about this in next section ([6 on page 27](#)).

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 remember, 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 $current_PC \pm \approx 32M$.

Next, the `MOV R0, #019` 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,PC20`. 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 was 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.

4.4.2 Non-optimizing Keil 6/2013 (Thumb mode)

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

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

We are getting (in IDA):

¹⁵Program Counter. IP/EIP/RIP in x86/64. PC in ARM.

¹⁶Read more about it in relevant section ([70.1 on page 705](#))

¹⁷Branch with Link

¹⁸Complex instruction set computing

¹⁹Meaning MOVe

²⁰`LDMFD21` is an inverse instruction of `STMFD`

Listing 4.12: Non-optimizing Keil 6/2013 (Thumb mode) + IDA

```
.text:00000000          main
.text:00000000 10 B5      PUSH   {R4,LR}
.text:00000002 C0 A0      ADR    R0, aHelloWorld ; "hello, world"
.text:00000004 06 F0 2E F9  BL     _2printf
.text:00000008 00 20      MOVS   R0, #0
.text:0000000A 10 BD      POP    {R4,PC}

.text:00000304 68 65 6C 6C+aHelloWorld  DCB "hello, world",0 ; DATA XREF: main+2
```

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 $\text{current_PC} \pm \approx 2M$.

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. `MOVS` writes 0 into the `R0` register in order to return zero.

4.4.3 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`.

Listing 4.13: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
_text:000028C4          _hello_world
.text:000028C4 80 40 2D E9  STMFD   SP!, {R7,LR}
.text:000028C8 86 06 01 E3  MOV      R0, #0x1686
.text:000028CC 0D 70 A0 E1  MOV      R7, SP
.text:000028D0 00 00 40 E3  MOVT    R0, #0
.text:000028D4 00 00 8F E0  ADD     R0, PC, R0
.text:000028D8 C3 05 00 EB  BL      _puts
.text:000028DC 00 00 A0 E3  MOV      R0, #0
.text:000028E0 80 80 BD E8  LDMFD   SP!, {R7,PC}

cstring:00003F62 48 65 6C 6C+aHelloWorld_0  DCB "Hello world!",0
```

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 [App10]) is a frame pointer. More on that below.

The `MOVT R0, #0` (`MVO` Top) 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.

Remember, 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, #0x1686` instruction above cleared the higher part of the register. This is probably 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()`.

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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 ²².

Why did the compiler replace the `printf()` with `puts()`? Probably because `puts()` is faster ²³.

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.

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

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

Listing 4.14: 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`²⁴ 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.

²²It 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.

²³ciselant.de/projects/gcc_printf/gcc_printf.html

²⁴Return Address

4.4. ARM

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()`.

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, `_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).

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:

"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".

([The Jargon File](#))

4.4.5 ARM64

GCC

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

Listing 4.15: Non-optimizing GCC 4.8.1 + objdump

```
1 0000000000400590 <main>:  
2 400590: a9bf7bfd      stp    x29, x30, [sp,#-16]!  
3 400594: 910003fd      mov    x29, sp  
4 400598: 90000000      adrp   x0, 400000 <_init-0x3b8>  
5 40059c: 91192000      add    x0, x0, #0x648  
6 4005a0: 97fffffa0     bl    400420 <puts@plt>  
7 4005a4: 52800000      mov    w0, #0x0          // #0  
8 4005a8: a8c17bfd      ldp    x29, x30, [sp],#16  
9 4005ac: d65f03c0      ret  
10  
11 ...
```

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12
13
14

Contents of section .rodata:
400640 01000200 00000000 48656c6c 6f210a00Hello!..

There are no Thumb and Thumb-2 modes in ARM64, only ARM, so there are 32-bit instructions only. The Register count is doubled: [B.4.1 on page 942](#). 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` in `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: [29.2 on page 441](#).

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 `FP25` 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 done 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: [29.3.1 on page 442](#)). So several instructions must be utilised. 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: [29.4 on page 443](#).

`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: [4.4.3 on page 17](#).

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

High 32-bit part	low 32-bit part
X0	
	W0

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:

Listing 4.16: `main()` returning a value of `uint64_t` type

```
#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 4.17: Non-optimizing GCC 4.8.1 + objdump

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

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

²⁵Frame Pointer

4.5. MIPS

There is no exclamation mark after the instruction: this implies that the value is 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.

4.5 MIPS

4.5.1 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 **.sbss** (“small **BSS**²⁶”) 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/.sbss**. Some old-school programmers may recall the MS-DOS memory model [97 on page 912](#) 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.

4.5.2 Optimizing GCC

Lets consider the following example, which illustrates the “global pointer” concept.

Listing 4.18: Optimizing GCC 4.4.5 (assembly output)

```
1 $LC0:  
2 ; \000 is zero byte in octal base:  
3     .ascii  "Hello, world!\012\000"  
4 main:  
5 ; function prologue.  
6 ; set the GP:  
7     lui      $28,%hi(__gnu_local_gp)  
8     addiu   $sp,$sp,-32  
9     addiu   $28,$28,%lo(__gnu_local_gp)  
10 ; save the RA to the local stack:  
11    sw      $31,28($sp)  
12 ; load the address of the puts() function from the GP to $25:  
13    lw      $25,%call16(puts)($28)  
14 ; load the address of the text string to $4 ($a0):  
15    lui      $4,%hi($LC0)  
16 ; jump to puts(), saving the return address in the link register:  
17    jalr   $25  
18    addiu   $4,$4,%lo($LC0) ; branch delay slot  
19 ; restore the RA:  
20    lw      $31,28($sp)  
21 ; copy 0 from $zero to $v0:  
22    move   $2,$0  
23 ; return by jumping to the RA:  
24    j      $31  
25 ; function epilogue:  
26    addiu   $sp,$sp,32 ; branch delay slot
```

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** the instruction (“Load Word”). Then the address of the text string is loaded to **\$4** using **LUI** (“Load Upper

²⁶Block Started by Symbol

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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 (remember *branch delay slots*?). The register \$4 is also called \$A0, which is used for passing the first function argument ²⁷.

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 pseudoinstructions and the ALU²⁸ 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 pseudoname:

Listing 4.19: Optimizing GCC 4.4.5 (IDA)

```

1 .text:00000000 main:
2 .text:00000000
3 .text:00000000 var_10      = -0x10
4 .text:00000000 var_4       = -4
5 .text:00000000
6 ; function prologue.
7 ; set the GP:
8 .text:00000000          lui    $gp, (__gnu_local_gp >> 16)
9 .text:00000004          addiu $sp, -0x20
10 .text:00000008         la     $gp, (__gnu_local_gp & 0xFFFF)
11 ; save the RA to the local stack:
12 .text:0000000C          sw    $ra, 0x20+var_4($sp)
13 ; save the GP to the local stack:
14 ; for some reason, this instruction is missing in the GCC assembly output:
15 .text:00000010          sw    $gp, 0x20+var_10($sp)
16 ; load the address of the puts() function from the GP to $t9:
17 .text:00000014          lw    $t9, (puts & 0xFFFF)($gp)
18 ; form the address of the text string in $a0:
19 .text:00000018          lui    $a0, ($LC0 >> 16) # "Hello, world!"
20 ; jump to puts(), saving the return address in the link register:
21 .text:0000001C          jalr $t9
22 .text:00000020          la     $a0, ($LC0 & 0xFFFF) # "Hello, world!"
23 ; restore the RA:
24 .text:00000024          lw    $ra, 0x20+var_4($sp)
25 ; copy 0 from $zero to $v0:
26 .text:00000028          move   $v0, $zero
27 ; return by jumping to the RA:
28 .text:0000002C          jr    $ra
29 ; function epilogue:
30 .text:00000030          addiu $sp, 0x20

```

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 ²⁹. 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.

²⁷The MIPS registers table is available in appendix C.1 on page 944

²⁸Arithmetic logic unit

²⁹Apparently, functions generating listings are not so critical to GCC users, so some unfixed errors may still exist.

4.5.3 Non-optimizing GCC

Non-optimizing GCC is more verbose.

Listing 4.20: Non-optimizing GCC 4.4.5 (assembly output)

```

1 $LC0:
2     .ascii  "Hello, world!\012\000"
3 main:
4 ; function prologue.
5 ; save the RA ($31) and FP in the stack:
6     addiu   $sp,$sp,-32
7     sw      $31,28($sp)
8     sw      $fp,24($sp)
9 ; set the FP (stack frame pointer):
10    move    $fp,$sp
11 ; set the GP:
12    lui     $28,%hi(__gnu_local_gp)
13    addiu   $28,$28,%lo(__gnu_local_gp)
14 ; load the address of the text string:
15    lui     $2,%hi($LC0)
16    addiu   $4,$2,%lo($LC0)
17 ; load the address of puts() using the GP:
18    lw      $2,%call16(puts)($28)
19    nop
20 ; call puts():
21    move    $25,$2
22    jalr    $25
23    nop ; branch delay slot
24
25 ; restore the GP from the local stack:
26    lw      $28,16($fp)
27 ; set register $2 ($V0) to zero:
28    move    $2,$0
29 ; function epilogue.
30 ; restore the SP:
31    move    $sp,$fp
32 ; restore the RA:
33    lw      $31,28($sp)
34 ; restore the FP:
35    lw      $fp,24($sp)
36    addiu   $sp,$sp,32
37 ; jump to the RA:
38    j      $31
39    nop ; branch delay slot

```

We see here that register FP is used as a pointer to the stack frame. We also see 3 NOP³⁰s. 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 4.21: Non-optimizing GCC 4.4.5 ([IDA](#))

```

1 .text:00000000 main:
2 .text:00000000
3 .text:00000000 var_10          = -0x10
4 .text:00000000 var_8           = -8
5 .text:00000000 var_4           = -4
6 .text:00000000
7 ; function prologue.
8 ; save the RA and FP in the stack:
9 .text:00000000            addiu   $sp, -0x20
10 .text:00000004             sw      $ra, 0x20+var_4($sp)
11 .text:00000008             sw      $fp, 0x20+var_8($sp)
12 ; set the FP (stack frame pointer):
13 .text:0000000C             move    $fp, $sp
14 ; set the GP:
15 .text:00000010             la      $gp, __gnu_local_gp

```

³⁰No OPeration

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```
16 .text:00000018          sw    $gp, 0x20+var_10($sp)
17 ; load the address of the text string:
18 .text:0000001C          lui   $v0, (aHelloWorld >> 16) # "Hello, world!"
19 .text:00000020          addiu $a0, $v0, (aHelloWorld & 0xFFFF) # "Hello, world!"
20 ; load the address of puts() using the GP:
21 .text:00000024          lw    $v0, (puts & 0xFFFF)($gp)
22 .text:00000028          or    $at, $zero ; NOP
23 ; call puts():
24 .text:0000002C          move  $t9, $v0
25 .text:00000030          jalr $t9
26 .text:00000034          or    $at, $zero ; NOP
27 ; restore the GP from local stack:
28 .text:00000038          lw    $gp, 0x20+var_10($fp)
29 ; set register $2 ($V0) to zero:
30 .text:0000003C          move  $v0, $zero
31 ; function epilogue.
32 ; restore the SP:
33 .text:00000040          move  $sp, $fp
34 ; restore the RA:
35 .text:00000044          lw    $ra, 0x20+var_4($sp)
36 ; restore the FP:
37 .text:00000048          lw    $fp, 0x20+var_8($sp)
38 .text:0000004C          addiu $sp, 0x20
39 ; jump to the RA:
40 .text:00000050          jr    $ra
41 .text:00000054          or    $at, $zero ; NOP
```

Interestingly, IDA recognized the LUI / ADDIU instructions pair and coalesced them into one LA ("Load Address") pseudoinstruction at line 15. We may also see that this pseudoinstruction has a size of 8 bytes! This is a pseudoinstruction (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.

4.5.4 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: [3.3 on page 8](#).

4.5.5 Optimizing GCC: load it into GDB

Listing 4.22: sample GDB session

```
root@debian-mips:~# gcc hw.c -O3 -o hw
root@debian-mips:~# gdb hw
GNU gdb (GDB) 7.0.1-debian
Copyright (C) 2009 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law. Type "show copying"
and "show warranty" for details.
This GDB was configured as "mips-linux-gnu".
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>...
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
```

4.6. CONCLUSION

```
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)
```

4.6 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.

4.7 Exercises

- <http://challenges.re/48>
- <http://challenges.re/49>

Chapter 5

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
```

What these instruction do: save the value in the `EBP` register, 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 [callee](#):

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

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

5.1 Recursion

Epilogues and prologues can negatively affect the recursion performance.

More about recursion in this book: [38.3 on page 469](#).

Chapter 6

Stack

The stack is one of the most fundamental data structures in computer science ¹.

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.

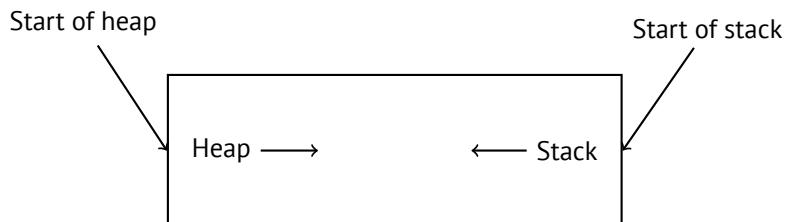
ARM supports both descending and ascending stacks.

For example the `STMFD/LDMFD`, `STMED2/LDMED3` instructions are intended to deal with a descending stack (grows downwards, starting with a high address and progressing to a lower one). The `STMFA4/LDMFA5`, `STMEA6/LDMEA7` instructions are intended to deal with an ascending stack (grows upwards, starting from a low address and progressing to a higher one).

6.1 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.



In [RT74] we can read:

¹[wikipedia.org/wiki/Call_stack](https://en.wikipedia.org/wiki/Call_stack)

²Store Multiple Empty Descending (ARM instruction)

³Load Multiple Empty Descending (ARM instruction)

⁴Store Multiple Full Ascending (ARM instruction)

⁵Load Multiple Full Ascending (ARM instruction)

⁶Store Multiple Empty Ascending (ARM instruction)

⁷Load Multiple Empty Ascending (ARM instruction)

6.2. WHAT IS THE STACK USED FOR?

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.

6.2 What is the stack used for?

6.2.1 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:

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

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:

```
?f@YAXXZ PROC ; f
; File c:\tmp6\ss.cpp
; Line 2
    push    ebp
    mov     ebp, esp
; Line 3
    call    ?f@YAXXZ ; f
; Line 4
    pop    ebp
    ret    0
?f@YAXXZ ENDP ; f
```

...Also if we turn on the compiler optimization (`/Ox` option) the optimized code will not overflow the stack and will work correctly⁸ instead:

```
?f@YAXXZ PROC ; f
; File c:\tmp6\ss.cpp
; Line 2
$LL3@f:
```

⁸irony here

6.2. WHAT IS THE STACK USED FOR?

```
; Line 3
    jmp      SHORT $LL3@f
?f@@YAXXZ ENDP
; f
```

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!” ([4.4 on page 15](#)), 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 function*⁹. 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 stack¹⁰. This can be also useful for situations when memory for the stack is not yet allocated or not available.

Some examples of leaf functions: [9.3.2 on page 103](#), [9.3.3 on page 103](#), [20.17 on page 313](#), [20.33 on page 330](#), [20.5.4 on page 331](#), [16.4 on page 208](#), [16.2 on page 206](#), [18.3 on page 225](#).

6.2.2 Passing function arguments

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

```
push arg3
push arg2
push arg1
call f
add esp, 12 ; 4*3=12
```

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:

ESP	return address
ESP+4	argument#1, marked in IDA as arg_0
ESP+8	argument#2, marked in IDA as arg_4
ESP+0xC	argument#3, marked in IDA as arg_8
...	...

For more information on other calling conventions see also section ([67 on page 690](#)). 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.

For example, it is possible to allocate a space for arguments in the **heap**, fill it and pass it to a function via a pointer to this block in the **EAX** register. This will work¹¹. However, it is a convenient custom in x86 and ARM to use the stack for this purpose.

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:

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

⁹infocenter.arm.com/help/index.jsp?topic=/com.arm.doc.faqs/ka13785.html

¹⁰Some 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](#) [Ray03, Chapter 4, Part II].

¹¹For example, in the “The Art of Computer Programming” book by Donald Knuth, in section 1.4.1 dedicated to subroutines [[Knu98](#), section 1.4.1], we could read that one way to supply arguments to a subroutine is simply to list them after the **JMP** instruction passing control to subroutine. Knuth explains that this method was particularly convenient on IBM System/360.

6.2. WHAT IS THE STACK USED FOR?

`printf()` will print 1234, and then two random numbers, 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:

```
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.

6.2.3 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.

6.2.4 x86: `alloca()` function

It is worth noting the `alloca()` function ¹². This function works like `malloc()`, but allocates memory directly on the stack. The allocated memory chunk does not need to be freed via a `free()` function call, since the function epilogue ([5 on page 26](#)) 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:

```
#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);  
};
```

`_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.

¹²In MSVC, the function implementation can be found in `alloca16.asm` and `chkstk.asm` in `C:\Program Files (x86)\Microsoft Visual Studio`

6.2. WHAT IS THE STACK USED FOR?

MSVC

Let's compile (MSVC 2010):

Listing 6.1: 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

push   esi
call   _puts
add    esp, 28          ; 0000001cH
...
```

The sole `alloca()` argument is passed via `EAX` (instead of pushing it into the stack) ¹³.

GCC + Intel syntax

GCC 4.4.1 does the same without calling external functions:

Listing 6.2: 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 6.3: GCC 4.7.3

```
.LC0:
```

¹³It is because `alloca()` is rather a compiler intrinsic ([93 on page 901](#)) 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 [MSVC¹⁴](#) `alloca()` implementation also has code which reads from the memory just allocated, in order to let the [OS](#) map physical memory to this [VM¹⁵](#) region. After the `alloca()` call, `ESP` points to the block of 600 bytes and we can use it as memory for the `buf` array.

6.3. A TYPICAL STACK LAYOUT

```
.string "hi! %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
    ret
```

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)`.

6.2.5 (Windows) SEH

SEH¹⁶ records are also stored on the stack (if they are present). Read more about it: ([71.3 on page 719](#)).

6.2.6 Buffer overflow protection

More about it here ([19.2 on page 274](#)).

6.2.7 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.

6.3 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:

...	...
ESP-0xC	local variable#2, marked in IDA as <code>var_8</code>
ESP-8	local variable#1, marked in IDA as <code>var_4</code>
ESP-4	saved value of EBP
ESP	Return Address
ESP+4	argument#1, marked in IDA as <code>arg_0</code>
ESP+8	argument#2, marked in IDA as <code>arg_4</code>
ESP+0xC	argument#3, marked in IDA as <code>arg_8</code>
...	...

¹⁶Structured Exception Handling

6.4 Noise in stack

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

```
#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);
}

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

Compiling ...

Listing 6.4: 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
```

6.4. NOISE IN STACK

```
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
Microsoft (R) Incremental Linker Version 10.00.40219.01
Copyright (C) Microsoft Corporation. All rights reserved.

/out:st.exe
st.obj
```

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.

6.4. NOISE IN STACK

Let's load the example into OllyDbg:

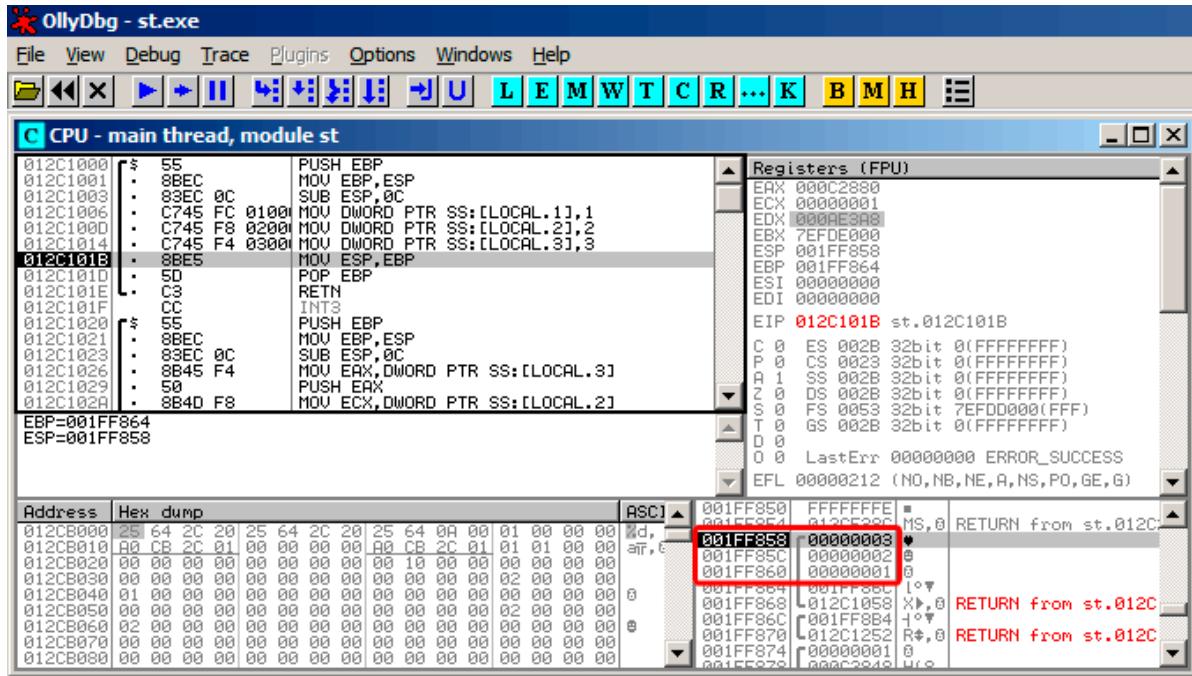


Figure 6.1: OllyDbg: `f1()`

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

6.4. NOISE IN STACK

And when `f2()` executes:

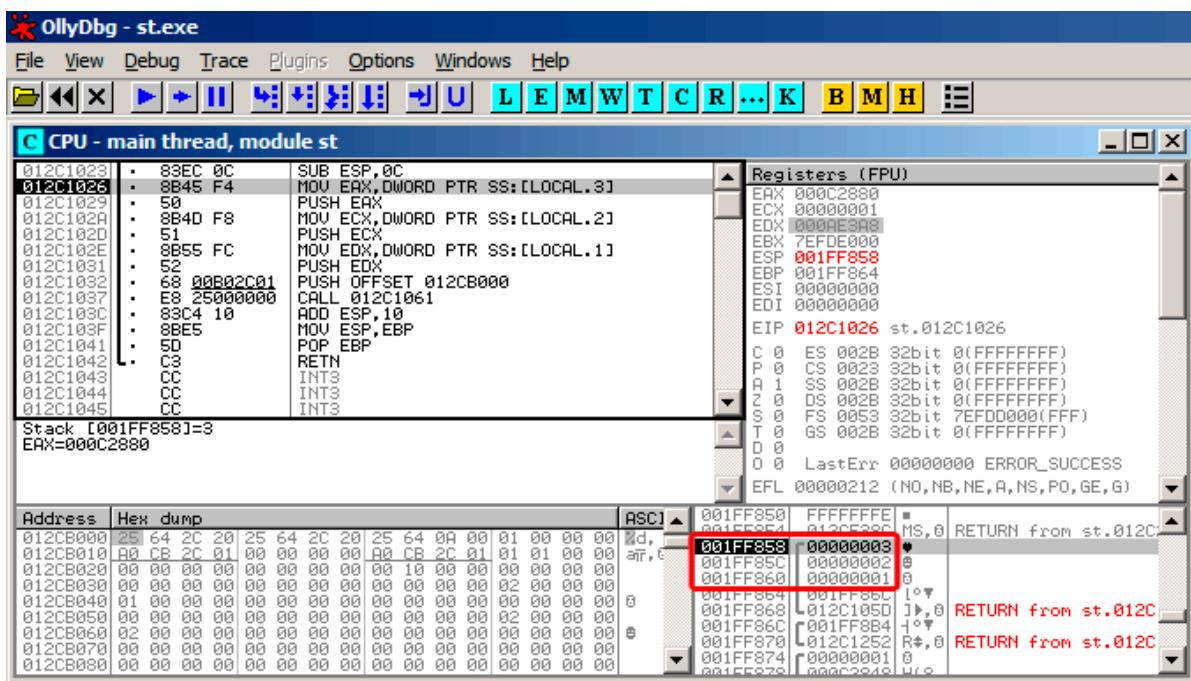


Figure 6.2: OllyDbg: `f2()`

... `a`, `b` and `c` of `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 `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 probably would be possible to clear portions of the stack before each function execution, but that's too much extra (and unnecessary) work.

6.4.1 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 6.5: MSVC 2013

```
_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
...
_f1 ENDP
```

6.5. EXERCISES

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 probably something changed inside of compiler guts, so it behaves slightly different.

6.5 Exercises

- <http://challenges.re/51>
- <http://challenges.re/52>

Chapter 7

printf() with several arguments

Now let's extend the *Hello, world!* ([4 on page 9](#)) example, replacing `printf()` in the `main()` function body with this:

```
#include <stdio.h>

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

7.1 x86

7.1.1 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. $4 * 4 = 16$ —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 ([67 on page 690](#)).

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:

```
push a1
push a2
call ...
```

7.1. X86

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

Here is a real-world example:

Listing 7.1: 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
```

MSVC and OllyDbg

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):

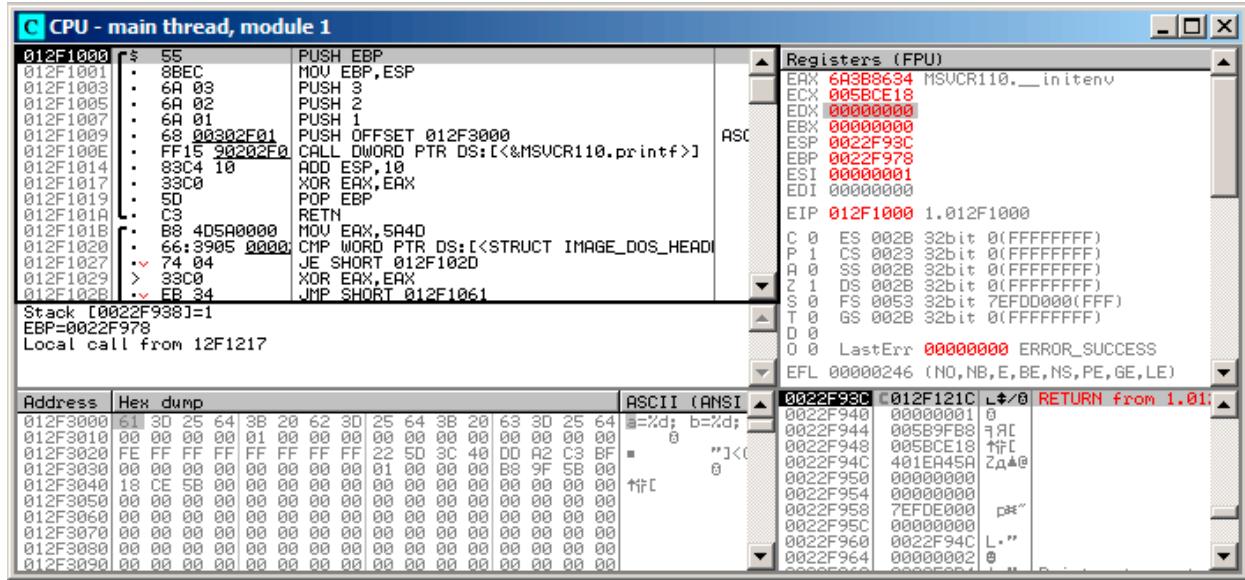


Figure 7.1: OllyDbg: the very start of the `main()` function

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

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

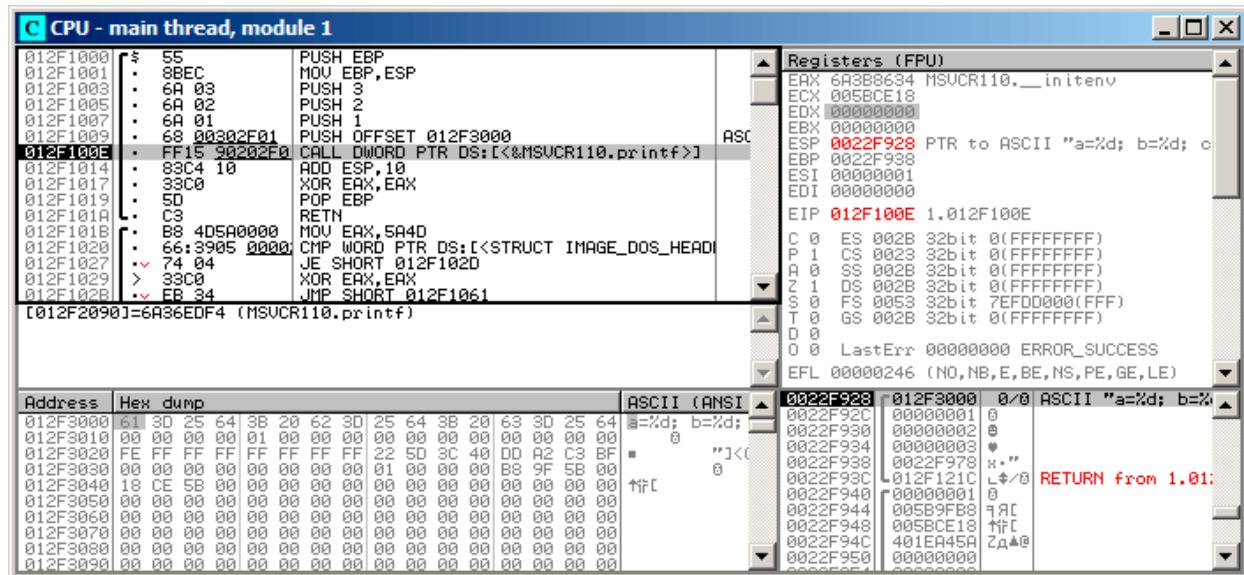


Figure 7.2: OllyDbg: before `printf()` execution

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:

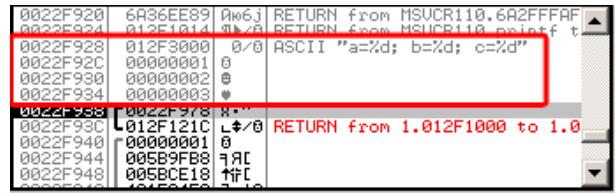


Figure 7.3: OllyDbg: stack after the argument values have been pushed (The red rectangular border was added by me in a graphics editor)

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.

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Press F8 (step over).

We see the following output in the console:

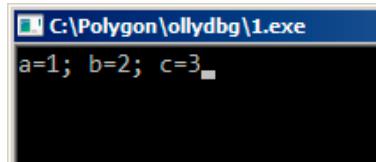


Figure 7.4: `printf()` function executed

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

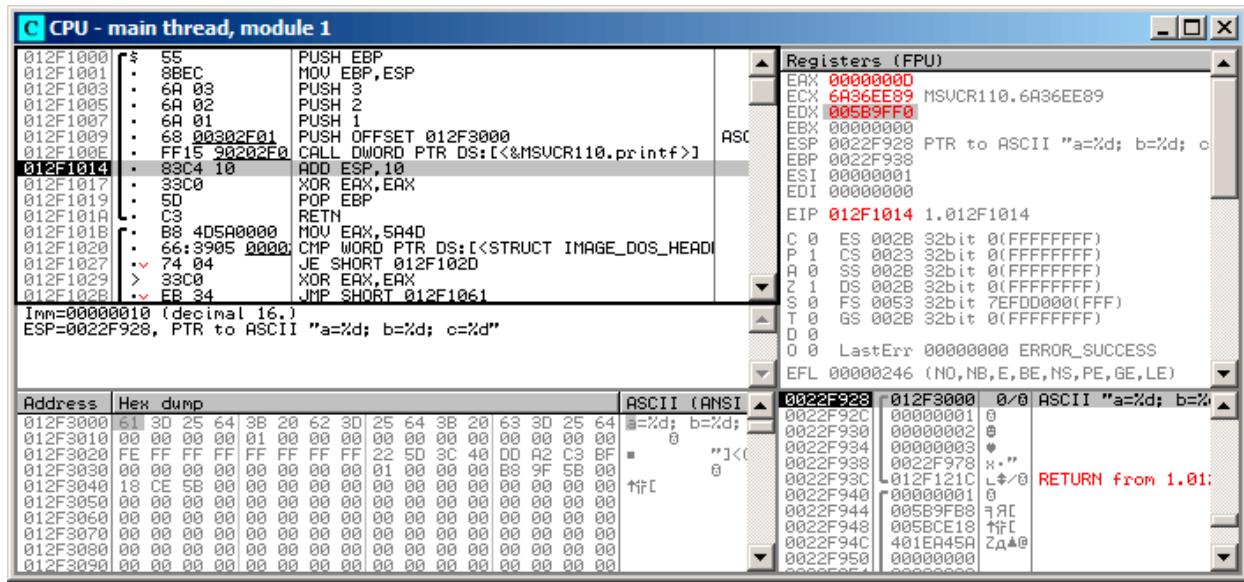


Figure 7.5: OllyDbg after `printf()` execution

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 behaviour: *callee* does not return `ESP` back to its previous value. The *caller* is responsible to do so.

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Press F8 again to execute ADD ESP, 10 instruction:

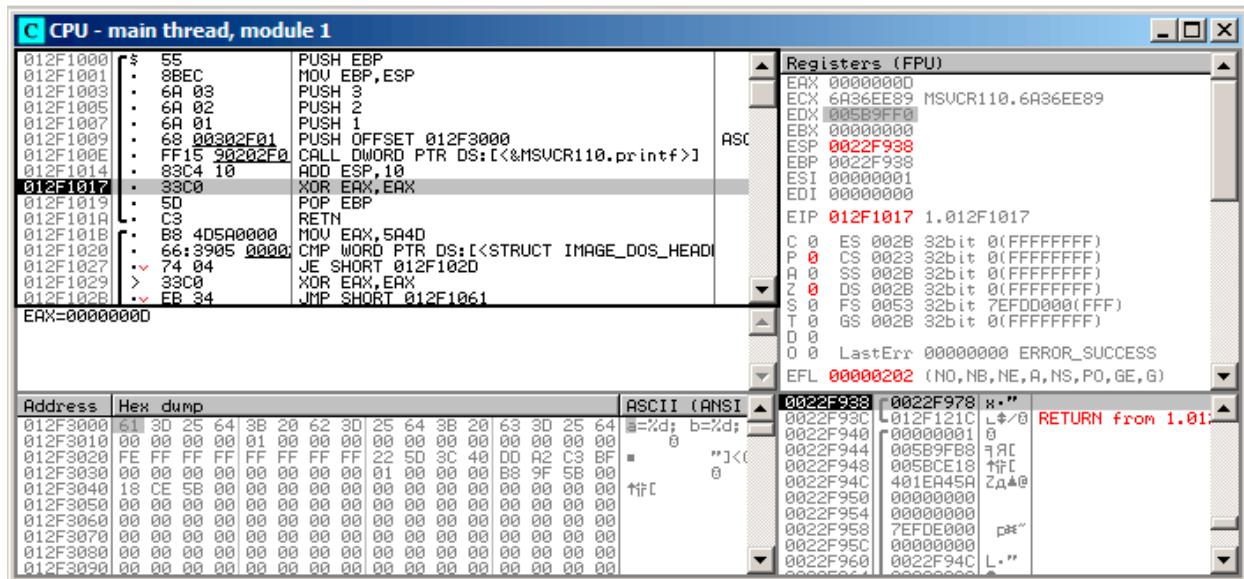


Figure 7.6: OllyDbg: after ADD ESP, 10 instruction execution

ESP has changed, but the values are still in the stack! Yes, of course; no one needs to set these values to zeroes 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:

```
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
retn
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

Let's try this example also in GDB¹ in Linux.

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

¹GNU debugger

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

```
$ gdb 1
GNU gdb (GDB) 7.6.1-ubuntu
Copyright (C) 2013 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law. Type "show copying"
and "show warranty" for details.
This GDB was configured as "i686-linux-gnu".
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>...
Reading symbols from /home/dennis/polygon/1...done.
```

Listing 7.2: 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      0x00000001
```

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 0x080484f0
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

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executed? This is due to the fact that the compiler, while generating debugging 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**:

```
(gdb) info registers
eax          0xd      13
ecx          0x0      0
edx          0x0      0
ebx          0xb7fc0000  -1208221696
esp          0xbfffff120  0xbfffff120
ebp          0xbfffff138  0xbfffff138
esi          0x0      0
edi          0x0      0
eip          0x804844a <main+45>
...

```

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

```
(gdb) disas
Dump of assembler code for function main:
0x0804841d <+0>:    push   %ebp
0x0804841e <+1>:    mov    %esp,%ebp
0x08048420 <+3>:    and    $0xffffffff0,%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:

```
(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,0xffffffff0
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.

```
(gdb) step
7      };
```

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

```
(gdb) info registers
eax          0x0      0
ecx          0x0      0
edx          0x0      0
ebx          0xb7fc0000  -1208221696
esp          0xbfffff120  0xbfffff120
ebp          0xbfffff138  0xbfffff138
esi          0x0      0
edi          0x0      0
```

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eip	0x804844f	0x804844f <main+50>
...		

7.1.2 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):

```
#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 7.3: MSVC 2012 x64

```
$SG2923 DB      'a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d', 0aH, 00H

main PROC
    sub    rsp, 88

    mov    DWORD PTR [rsp+64], 8
    mov    DWORD PTR [rsp+56], 7
    mov    DWORD PTR [rsp+48], 6
    mov    DWORD PTR [rsp+40], 5
    mov    DWORD PTR [rsp+32], 4
    mov    r9d, 3
    mov    r8d, 2
    mov    edx, 1
    lea    rcx, OFFSET FLAT:$SG2923
    call   printf

    ; return 0
    xor    eax, eax

    add    rsp, 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 remember: 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: [4.2.2 on page 14](#).

We also noted earlier that the `EAX` register has been cleared before a `printf()` call: [4.2.2 on page 14](#).

Listing 7.4: 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
Copyright (C) 2013 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law. Type "show copying"
and "show warranty" for details.
This GDB was configured as "x86_64-linux-gnu".
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>...
Reading symbols from /home/dennis/polygon/2...done.
```

Listing 7.5: 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          0x7fffffffdf60 0x7fffffffdf60
rsp          0x7fffffffdf38 0x7fffffffdf38
```

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```
r8          0x4      4
r9          0x5      5
r10         0x7fffffffce0  140737488346336
r11         0x7fffff7a65f60  140737348263776
r12         0x400440  4195392
r13         0x7fffffff040  140737488347200
r14         0x0      0
r15         0x0      0
rip          0x7fffff7a65f60  0x7fffff7a65f60 <__printf>
...
```

Listing 7.6: 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: 0x00000000000400576      0x0000000000000000
0x7fffffffdf48: 0x0000000000000007      0x00007fff00000008
0x7fffffffdf58: 0x0000000000000000      0x0000000000000000
0x7fffffffdf68: 0x00007fffff7a33de5    0x0000000000000000
0x7fffffffdf78: 0x00007ffffffe048    0x0000000010000000
```

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 have *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 0x00000000000400576
Dump of assembler code for function main:
0x0000000000040052d <+0>:    push   rbp
0x0000000000040052e <+1>:    mov    rbp,rs
0x00000000000400531 <+4>:    sub    rsp,0x20
0x00000000000400535 <+8>:    mov    DWORD PTR [rsp+0x10],0x8
0x0000000000040053d <+16>:   mov    DWORD PTR [rsp+0x8],0x7
0x00000000000400545 <+24>:   mov    DWORD PTR [rsp],0x6
0x0000000000040054c <+31>:   mov    r9d,0x5
0x00000000000400552 <+37>:   mov    r8d,0x4
0x00000000000400558 <+43>:   mov    ecx,0x3
0x0000000000040055d <+48>:   mov    edx,0x2
0x00000000000400562 <+53>:   mov    esi,0x1
0x00000000000400567 <+58>:   mov    edi,0x400628
0x0000000000040056c <+63>:   mov    eax,0x0
0x00000000000400571 <+68>:   call   0x400410 <printf@plt>
0x00000000000400576 <+73>:   mov    eax,0x0
0x0000000000040057b <+78>:   leave 
0x0000000000040057c <+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
  ↳ d\n")
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
```

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```
rcx          0x26      38
rdx          0x7fffff7dd59f0  140737351866864
rsi          0x7fffffd9      2147483609
rdi          0x0        0
rbp          0x7fffffffdf60  0x7fffffffdf60
rsp          0x7fffffffdf40  0x7fffffffdf40
r8           0x7fffff7dd26a0  140737351853728
r9           0x7fffff7a60134  140737348239668
r10          0x7fffffffdf5b0  140737488344496
r11          0x7fffff7a95900  140737348458752
r12          0x400440 4195392
r13          0x7ffffffffe040  140737488347200
r14          0x0        0
r15          0x0        0
rip          0x40057b 0x40057b <main+78>
...
```

7.1.3 x64: 8 argomenti

Per vedere come altri argomenti sono passati tramite lo stack, cambiamo nuovamente l'esempio per aumentare il numero degli argomenti a 9 (format string di `printf()` + 8 variabili `int`):

```
#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

Come già detto in precedenza, i primi 4 argomenti devono essere passati tramite i registri `RCX`, `RDX`, `R8`, `R9` in Win64, mentre tutto il resto –tramite lo stack. È esattamente quello che vediamo qui. Tuttavia, l'istruzione `MOV` instruction è usata al posto di `PUSH` per preparare lo stack, in modo tale che i valori siano memorizzati nello stack in maniera diretta.

Listing 7.7: MSVC 2012 x64

```
$SG2923 DB      'a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d', 0aH, 00H

main PROC
    sub    rsp, 88

    mov    DWORD PTR [rsp+64], 8
    mov    DWORD PTR [rsp+56], 7
    mov    DWORD PTR [rsp+48], 6
    mov    DWORD PTR [rsp+40], 5
    mov    DWORD PTR [rsp+32], 4
    mov    r9d, 3
    mov    r8d, 2
    mov    edx, 1
    lea    rcx, OFFSET FLAT:$SG2923
    call   printf

    ; return 0
    xor    eax, eax

    add    rsp, 88
    ret    0

main ENDP
_TEXT ENDS
END
```

Il lettore attento potrebbe chiedere perché per i valori `int` sono allocati 8 byte quando ne bastano 4? Bisogna ricordare che per ogni tipo di dato più piccolo di 64 bit, sono allocati 8 byte. Questo è stabilito per convenienza: rende più facile calcolare

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l'indirizzo di argomenti arbitrari. E inoltre fa sì che tutti siano allocati ad indirizzi di memoria allineati. Succede lo stesso in ambienti a 32-bit environments: sono riservati 4 byte per ogni tipo di dato.

GCC

L'immagine è simile per i sistemi operativi x86-64 e *NIX, con l'eccezione che i primi 6 argomenti sono passati attraverso i registri RDI, RSI, RDX, RCX, R8, R9 registers. Tutto il resto –tramite lo stack. GCC genera il codice memorizzando il puntatore alla stringa in EDI invece che RDI –lo abbiamo visto in precedenza: [4.2.2 on page 14](#).

Abbiamo anche notato prima che il registro EAX è stato azzerato prima di una chiamata a `printf()`: [4.2.2 on page 14](#).

Listing 7.8: 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

Proviamo l'esempio in [GDB](#).

```
$ gcc -g 2.c -o 2
```

```
$ gdb 2
GNU gdb (GDB) 7.6.1-ubuntu
Copyright (C) 2013 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law. Type "show copying"
and "show warranty" for details.
This GDB was configured as "x86_64-linux-gnu".
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>...
Reading symbols from /home/dennis/polygon/2...done.
```

Listing 7.9: impostiamo il breakpoint su `printf()`, e avviamo

```
(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.
```

7.1. X86

I registri `RSI / RDX / RCX / R8 / R9` hanno i valori previsti. `RIP` ha l'indirizzo della prima istruzione della funzione `printf()`.

```
(gdb) info registers
rax          0x0      0
rbx          0x0      0
rcx          0x3      3
rdx          0x2      2
rsi          0x1      1
rdi          0x400628 4195880
rbp          0x7fffffffdf60 0x7fffffffdf60
rsp          0x7fffffffdf38 0x7fffffffdf38
r8           0x4      4
r9           0x5      5
r10          0x7fffffffdfce0 140737488346336
r11          0x7fffff7a65f60 140737348263776
r12          0x400440 4195392
r13          0x7ffffffffe040 140737488347200
r14          0x0      0
r15          0x0      0
rip          0x7fffff7a65f60 0x7fffff7a65f60 <__printf>
...
```

Listing 7.10: ispezioniamo la format string

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

Effettuiamo un dump dello stack, questa volta con il comando `x/g -g` sta per *giant words*, ovvero 64-bit words.

```
(gdb) x/10g $rsp
0x7fffffffdf38: 0x000000000000400576      0x0000000000000006
0x7fffffffdf48: 0x000000000000000007      0x00007fff00000008
0x7fffffffdf58: 0x000000000000000000      0x0000000000000000
0x7fffffffdf68: 0x00007fffff7a33de5      0x0000000000000000
0x7fffffffdf78: 0x00007fffffe048       0x0000000100000000
```

Il primo elemento dello stack, proprio come nel caso precedente, e' il RA. 3 valori vengono passati tramite lo stack : 6, 7, 8. Notiamo anche che 8 e' passato nei 32-bit alti non azzerati: `0x00007fff00000008`. Cio' va bene, perche' i valori hanno tipo *int*, che e' a 32-bit. Quindi, i registri alti o gli elementi alti dello stack potrebbero contenere "random garbage".

Se andiamo a vedere dove viene restituito il controllo dopo l'esecuzione di `printf()`, GDB mostrera' l'intera funzione `main()`:

```
(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.
```

Finiamo di eseguire `printf()`, eseguiamo l'istruzione che azzerà `EAX`, e notiamo che il registro `EAX` register ha esattamente il valore zero. `RIP` adesso punta all'istruzione `LEAVE`, ovvero la penultima nella funzione `main()`.

```
(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          0x7fffff7dd59f0  140737351866864
rsi          0x7fffffff9  2147483609
rdi          0x0      0
rbp          0x7fffffffdf60  0x7fffffffdf60
rsp          0x7fffffffdf40  0x7fffffffdf40
r8           0x7fffff7dd26a0  140737351853728
r9           0x7fffff7a60134  140737348239668
r10          0x7fffffffdf5b0  140737488344496
r11          0x7fffff7a95900  140737348458752
r12          0x400440 4195392
r13          0x7fffffff040  140737488347200
r14          0x0      0
r15          0x0      0
rip          0x40057b 0x40057b <main+78>
...

```

7.2 ARM

7.2.1 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 in fastcall ([67.3 on page 691](#)) or win64 ([67.5.1 on page 693](#)).

32-bit ARM

Non-optimizing Keil 6/2013 (ARM mode)

Listing 7.11: 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, aADBD_CD    ; "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 7.12: 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, aADBDCCD ; "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.

Optimizing Keil 6/2013 (ARM mode) + let's remove return

Let's rework example slightly by removing *return 0*:

```
#include <stdio.h>

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

The result is somewhat unusual:

Listing 7.13: 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, aADBDCCD ; "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 was called then the control from `printf()` will be returned to that point. Therefore we do not need to save `LR` because we do not need to modify `LR`. And we do not need to modify `LR` because there are no other function calls except `printf()`. Furthermore, after this call we do not 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: [14.1.1 on page 155](#).

ARM64

Non-optimizing GCC (Linaro) 4.9

Listing 7.14: 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
```

7.2. ARM

```
    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.

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.

7.2.2 ARM: 8 arguments

Let's use again the example with 9 arguments from the previous section: [7.1.3 on page 49](#).

```
#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 Keil 6/2013: ARM mode

```
.text:00000028          main
.text:00000028
.text:00000028          var_18 = -0x18
.text:00000028          var_14 = -0x14
.text:00000028          var_4  = -4
.text:00000028
.text:00000028 04 E0 2D E5  STR   LR, [SP,#var_4]!
.text:0000002C 14 D0 4D E2  SUB   SP, SP, #0x14
.text:00000030 08 30 A0 E3  MOV    R3, #8
.text:00000034 07 20 A0 E3  MOV    R2, #7
.text:00000038 06 10 A0 E3  MOV    R1, #6
.text:0000003C 05 00 A0 E3  MOV    R0, #5
.text:00000040 04 C0 8D E2  ADD   R12, SP, #0x18+var_14
.text:00000044 0F 00 8C E8  STMIA R12, {R0-R3}
.text:00000048 04 00 A0 E3  MOV    R0, #4
.text:0000004C 00 00 8D E5  STR   R0, [SP,#0x18+var_18]
.text:00000050 03 30 A0 E3  MOV    R3, #3
.text:00000054 02 20 A0 E3  MOV    R2, #2
.text:00000058 01 10 A0 E3  MOV    R1, #1
.text:0000005C 6F 0F 8F E2  ADR   R0, aADBDCDDDEFDGD ; "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d"
.text:00000060 BC 18 00 EB  BL    __2printf
.text:00000064 14 D0 8D E2  ADD   SP, SP, #0x14
.text:00000068 04 F0 9D E4  LDR   PC, [SP+4+var_4],#4
```

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*.

7.2. ARM

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: [29.2 on page 441](#).

The second **SUB SP, SP, #0x14** instruction decreases **SP** (the **stack pointer**) in order to allocate **0x14** (20) bytes on the stack. Indeed, we need 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.

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 cleaning the stack. Of course, what was 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*². 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 x86³.

Optimizing Keil 6/2013: Thumb mode

```
.text:0000001C          printf_main2
.text:0000001C
.text:0000001C          var_18 = -0x18
.text:0000001C          var_14 = -0x14
.text:0000001C          var_8  = -8
.text:0000001C
.text:0000001C 00 B5    PUSH   {LR}
.text:0000001E 08 23    MOVS   R3, #8
.text:00000020 85 B0    SUB    SP, SP, #0x14
.text:00000022 04 93    STR    R3, [SP, #0x18+var_8]
.text:00000024 07 22    MOVS   R2, #7
.text:00000026 06 21    MOVS   R1, #6
.text:00000028 05 20    MOVS   R0, #5
.text:0000002A 01 AB    ADD    R3, SP, #0x18+var_14
.text:0000002C 07 C3    STMIA  R3!, {R0-R2}
.text:0000002E 04 20    MOVS   R0, #4
.text:00000030 00 90    STR    R0, [SP, #0x18+var_18]
.text:00000032 03 23    MOVS   R3, #3
.text:00000034 02 22    MOVS   R2, #2
.text:00000036 01 21    MOVS   R1, #1
.text:00000038 A0 A0    ADR    R0, aADBDCDDDEDFDGD ; "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; ↴
     ↴ g=%"...
.text:0000003A 06 F0 D9 F8  BL     __2printf
```

²Read more about it: [29.2 on page 441](#).

³It is impossible to set **IP/EIP/RIP** value using **POP** in x86, but anyway, you got the analogy right.

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```
.text:0000003E          loc_3E    ; CODE XREF: example13_f+16
.text:0000003E          ADD      SP, SP, #0x14
.text:0000003E 05 B0      POP     {PC}
```

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

```
_text:0000290C          _printf_main2
_text:0000290C
_text:0000290C          var_1C = -0x1C
_text:0000290C          var_C = -0xC
_text:0000290C
_text:0000290C 80 40 2D E9  STMFD  SP!, {R7,LR}
_text:00002910 0D 70 A0 E1  MOV     R7, SP
_text:00002914 14 D0 4D E2  SUB    SP, SP, #0x14
_text:00002918 70 05 01 E3  MOV     R0, #0x1570
_text:0000291C 07 C0 A0 E3  MOV     R12, #7
_text:00002920 00 00 40 E3  MOVT   R0, #0
_text:00002924 04 20 A0 E3  MOV     R2, #4
_text:00002928 00 00 8F E0  ADD    R0, PC, R0
_text:0000292C 06 30 A0 E3  MOV     R3, #6
_text:00002930 05 10 A0 E3  MOV     R1, #5
_text:00002934 00 20 8D E5  STR    R2, [SP,#0x1C+var_1C]
_text:00002938 0A 10 8D E9  STMFA  SP, {R1,R3,R12}
_text:0000293C 08 90 A0 E3  MOV     R9, #8
_text:00002940 01 10 A0 E3  MOV     R1, #1
_text:00002944 02 20 A0 E3  MOV     R2, #2
_text:00002948 03 30 A0 E3  MOV     R3, #3
_text:0000294C 10 90 8D E5  STR    R9, [SP,#0x1C+var_C]
_text:00002950 A4 05 00 EB  BL     _printf
_text:00002954 07 D0 A0 E1  MOV     SP, R7
_text:00002958 80 80 BD E8  LDMFD  SP!, {R7,PC}
```

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

```
_text:00002BA0          _printf_main2
_text:00002BA0
_text:00002BA0          var_1C = -0x1C
_text:00002BA0          var_18 = -0x18
_text:00002BA0          var_C = -0xC
_text:00002BA0
_text:00002BA0 80 B5      PUSH    {R7,LR}
_text:00002BA2 6F 46      MOV     R7, SP
_text:00002BA4 85 B0      SUB    SP, SP, #0x14
```

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```

__text:00002BA6 41 F2 D8 20    MOVW    R0, #0x12D8
__text:00002BAA 4F F0 07 0C    MOV.W   R12, #7
__text:00002BAE C0 F2 00 00    MOVT.W  R0, #0
__text:00002BB2 04 22        MOVS    R2, #4
__text:00002BB4 78 44        ADD     R0, PC ; char *
__text:00002BB6 06 23        MOVS    R3, #6
__text:00002BB8 05 21        MOVS    R1, #5
__text:00002BBA 0D F1 04 0E    ADD.W   LR, SP, #0x1C+var_18
__text:00002BBE 00 92        STR     R2, [SP,#0x1C+var_1C]
__text:00002BC0 4F F0 08 09    MOV.W   R9, #8
__text:00002BC4 8E E8 0A 10    STMIA.W LR, {R1,R3,R12}
__text:00002BC8 01 21        MOVS    R1, #1
__text:00002BCA 02 22        MOVS    R2, #2
__text:00002BCC 03 23        MOVS    R3, #3
__text:00002BCE CD F8 10 90    STR.W   R9, [SP,#0x1C+var_C]
__text:00002BD2 01 F0 0A EA    BLX    _printf
__text:00002BD6 05 B0        ADD     SP, SP, #0x14
__text:00002BD8 80 BD        POP    {R7,PC}

```

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 7.15: Non-optimizing GCC (Linaro) 4.9

```

.LC2:
    .string "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n"
f3:
; grab more space in stack:
    sub    sp, sp, #32
; save FP and LR in stack frame:
    stp    x29, x30, [sp,16]
; set stack frame (FP=SP):
    add    x29, sp, 16
    adrp   x0, .LC2 ; "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d; h=%d\n"
    add    x0, x0, :lo12:.LC2
    mov    w1, 8          ; 9th argument
    str    w1, [sp]       ; store 9th argument in the stack
    mov    w1, 1
    mov    w2, 2
    mov    w3, 3
    mov    w4, 4
    mov    w5, 5
    mov    w6, 6
    mov    w7, 7
    bl    printf
    sub    sp, x29, #16
; restore FP and LR
    ldp    x29, x30, [sp,16]
    add    sp, sp, 32
    ret

```

The first 8 arguments are passed in X- or W-registers: [ARM13c]. A string pointer requires a 64-bit register, so it's passed in **X0**. All other values have a *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.

7.3 MIPS

7.3.1 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.

Listing 7.16: Optimizing GCC 4.4.5 (assembly output)

```
$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(sprintf)($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 7.17: Optimizing GCC 4.4.5 (IDA)

```
.text:00000000 main:
.text:00000000
.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, -0x20
.text:00000008          la      $gp, (__gnu_local_gp & 0xFFFF)
.text:0000000C          sw      $ra, 0x20+var_4($sp)
.text:00000010          sw      $gp, 0x20+var_10($sp)
; load address of printf():
.text:00000014          lw      $t9, (printf & 0xFFFF)($gp)
; load address of the text string and set 1st argument of printf():
.text:00000018          la      $a0, $LC0        # "a=%d; b=%d; c=%d"
; set 2nd argument of printf():
.text:00000020          li      $a1, 1
; set 3rd argument of printf():
.text:00000024          li      $a2, 2
; call printf():
.text:00000028          jalr   $t9
; set 4th argument of printf() (branch delay slot):
.text:0000002C          li      $a3, 3
; function epilogue:
.text:00000030          lw      $ra, 0x20+var_4($sp)
```

7.3. MIPS

```
; set return value to 0:
.text:00000034          move    $v0, $zero
; return
.text:00000038          jr     $ra
.text:0000003C          addiu  $sp, 0x20 ; branch delay slot
```

IDA has coalesced pair of LUI and ADDIU instructions into one LA pseudoinstruction. That's why there are no instruction at address 0x1C: because LA occupies 8 bytes.

Non-optimizing GCC 4.4.5

Non-optimizing GCC is more verbose:

Listing 7.18: Non-optimizing GCC 4.4.5 (assembly output)

```
$LC0:
    .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    $2,%hi($LC0)
    addiu $2,$2,%lo($LC0)
; 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(sprintf)($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 7.19: 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)
```

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```

.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, aADBD_CD      # "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
; set 4th argument of printf():
.text:00000030      li     $a3, 3
; get address of printf():
.text:00000034      lw     $v0, (printf & 0xFFFF)($gp)
.text:00000038      or     $at, $zero
; call printf():
.text:0000003C      move   $t9, $v0
.text:00000040      jalr   $t9
.text:00000044      or     $at, $zero ; NOP
; function epilogue:
.text:00000048      lw     $gp, 0x20+var_10($fp)
; set return value to 0:
.text:0000004C      move   $v0, $zero
.text:00000050      move   $sp, $fp
.text:00000054      lw     $ra, 0x20+var_4($sp)
.text:00000058      lw     $fp, 0x20+var_8($sp)
.text:0000005C      addiu $sp, 0x20
; return
.text:00000060      jr     $ra
.text:00000064      or     $at, $zero ; NOP

```

7.3.2 8 arguments

Let's use again the example with 9 arguments from the previous section: [7.1.3 on page 49](#).

```

#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 7.20: Optimizing GCC 4.4.5 (assembly output)

```

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

```

7.3. MIPS

```
; 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(sprintf)($28)
    sw      $2,28($sp)
; 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 7.21: Optimizing GCC 4.4.5 (IDA)

```
.text:00000000 main:
.text:00000000
.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_4           = -4
.text:00000000
; function prologue:
.text:00000000               lui      $gp, (__gnu_local_gp >> 16)
.text:00000004               addiu   $sp, -0x38
.text:00000008               la      $gp, (__gnu_local_gp & 0xFFFF)
.text:0000000C               sw      $ra, 0x38+var_4($sp)
.text:00000010               sw      $gp, 0x38+var_10($sp)
; pass 5th argument in stack:
.text:00000014               li      $v0, 4
.text:00000018               sw      $v0, 0x38+var_28($sp)
; pass 6th argument in stack:
.text:0000001C               li      $v0, 5
.text:00000020               sw      $v0, 0x38+var_24($sp)
; pass 7th argument in stack:
.text:00000024               li      $v0, 6
.text:00000028               sw      $v0, 0x38+var_20($sp)
; pass 8th argument in stack:
.text:0000002C               li      $v0, 7
.text:00000030               lw      $t9, (printf & 0xFFFF)($gp)
.text:00000034               sw      $v0, 0x38+var_1C($sp)
; prepare 1st argument in $a0:
.text:00000038               lui     $a0, ($LC0 >> 16) # "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d\n"
    ↴ ; g=%"...
; pass 9th argument in stack:
.text:0000003C               li      $v0, 8
.text:00000040               sw      $v0, 0x38+var_18($sp)
```

7.3. MIPS

```
; pass 1st argument in $a1:
.text:00000044          la      $a0, ($LC0 & 0xFFFF) # "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%d"...
; pass 2nd argument in $a1:
.text:00000048          li      $a1, 1
; pass 3rd argument in $a2:
.text:0000004C          li      $a2, 2
; call printf():
.text:00000050          jalr   $t9
; pass 4th argument in $a3 (branch delay slot):
.text:00000054          li      $a3, 3
; function epilogue:
.text:00000058          lw      $ra, 0x38+var_4($sp)
; set return value to 0:
.text:0000005C          move   $v0, $zero
; return
.text:00000060          jr      $ra
.text:00000064          addiu $sp, 0x38 ; branch delay slot
```

Non-optimizing GCC 4.4.5

Non-optimizing GCC is more verbose:

Listing 7.22: 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(sprintf)($28)
    nop
    move $25,$2
    jalr $25
    nop
; function epilogue:
    lw    $28,40($fp)
; set return value to 0:
```

7.3. MIPS

```

move    $2,$0
move    $sp,$fp
lw      $31,52($sp)
lw      $fp,48($sp)
addiu  $sp,$sp,56
; return
j       $31
nop

```

Listing 7.23: Non-optimizing GCC 4.4.5 (IDA)

```

.text:00000000 main:
.text:00000000
.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, aABDCDDDEDFDGD # "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%"...
; pass 5th argument in stack:
.text:00000024 li      $v1, 4
.text:00000028 sw      $v1, 0x38+var_28($sp)
; pass 6th argument in stack:
.text:0000002C li      $v1, 5
.text:00000030 sw      $v1, 0x38+var_24($sp)
; pass 7th argument in stack:
.text:00000034 li      $v1, 6
.text:00000038 sw      $v1, 0x38+var_20($sp)
; pass 8th argument in stack:
.text:0000003C li      $v1, 7
.text:00000040 sw      $v1, 0x38+var_1C($sp)
; pass 9th argument in stack:
.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

```

7.4. CONCLUSION

```
.text:0000008C          or      $at, $zero ; NOP
```

7.4 Conclusion

Here is a rough skeleton of the function call:

Listing 7.24: x86

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

Listing 7.25: 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 7.26: 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 7.27: 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 7.28: 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 CALL function  
; modify stack pointer (if needed)
```

Listing 7.29: MIPS (O32 calling convention)

```
LI $4, 1st argument ; AKA $A0  
LI $5, 2nd argument ; AKA $A1
```

7.5. BY THE WAY

```
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
```

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

MIPS \$A0 ...\$A3 registers are labelled 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 newcomer 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.

Chapter 8

scanf()

Now let's use `scanf()`.

8.1 Simple example

```
#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`.

8.1.1 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. 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 ([56 on page 607](#))).

`scanf()` function—is such a case.

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.

8.1. SIMPLE EXAMPLE

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

8.1.2 x86

MSVC

Here is what we get after compiling with MSVC 2010:

```
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.

Here is a typical [stack frame](#) layout in 32-bit environment:

8.1. SIMPLE EXAMPLE

...	...
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 ([A.6.2 on page 931](#)).

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.

8.1. SIMPLE EXAMPLE

8.1.3 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:

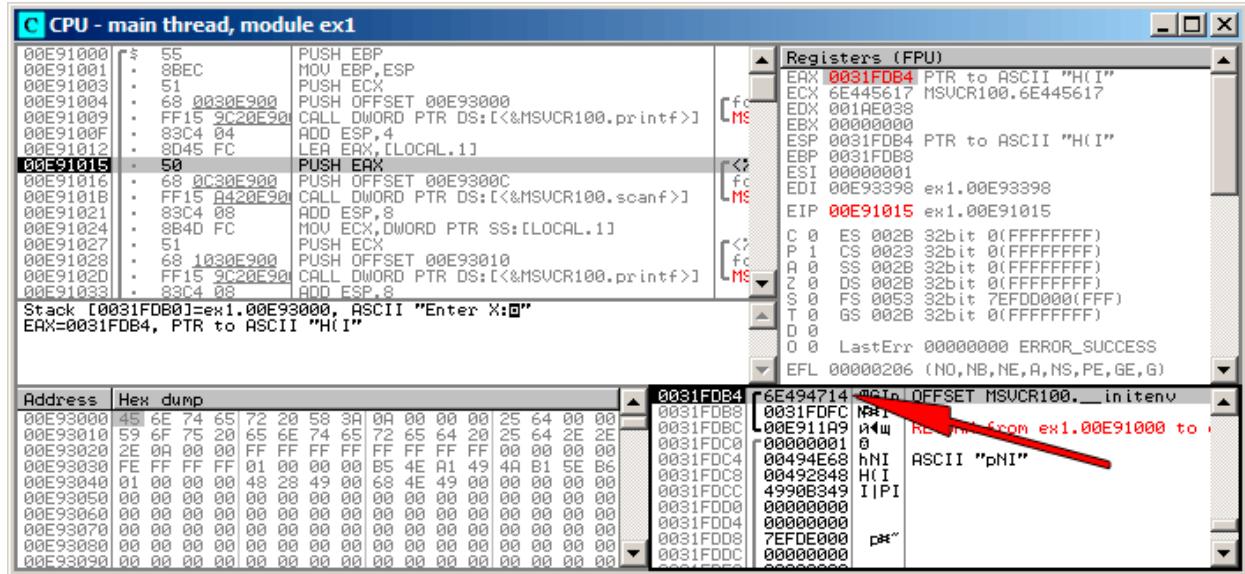


Figure 8.1: OllyDbg: The address of the local variable is calculated

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:

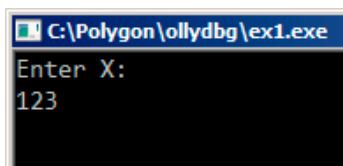


Figure 8.2: User input in the console window

8.1. SIMPLE EXAMPLE

`scanf()` completed its execution already:

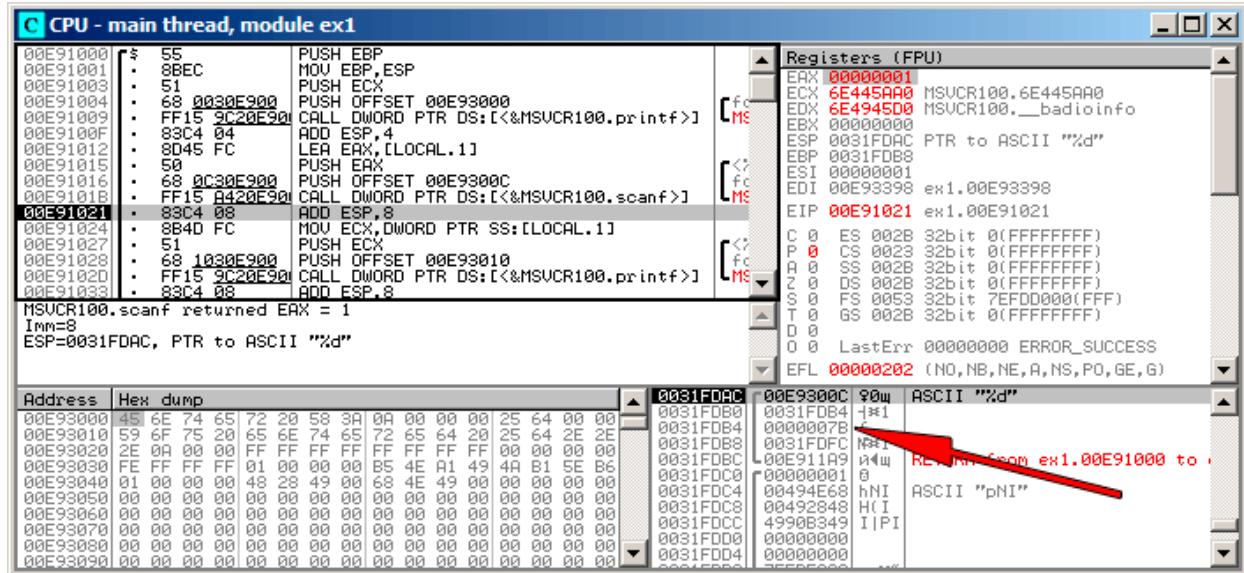


Figure 8.3: OllyDbg: `scanf()` executed

`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).

8.1. SIMPLE EXAMPLE

Later this value is copied from the stack to the `ECX` register and passed to `printf()`:

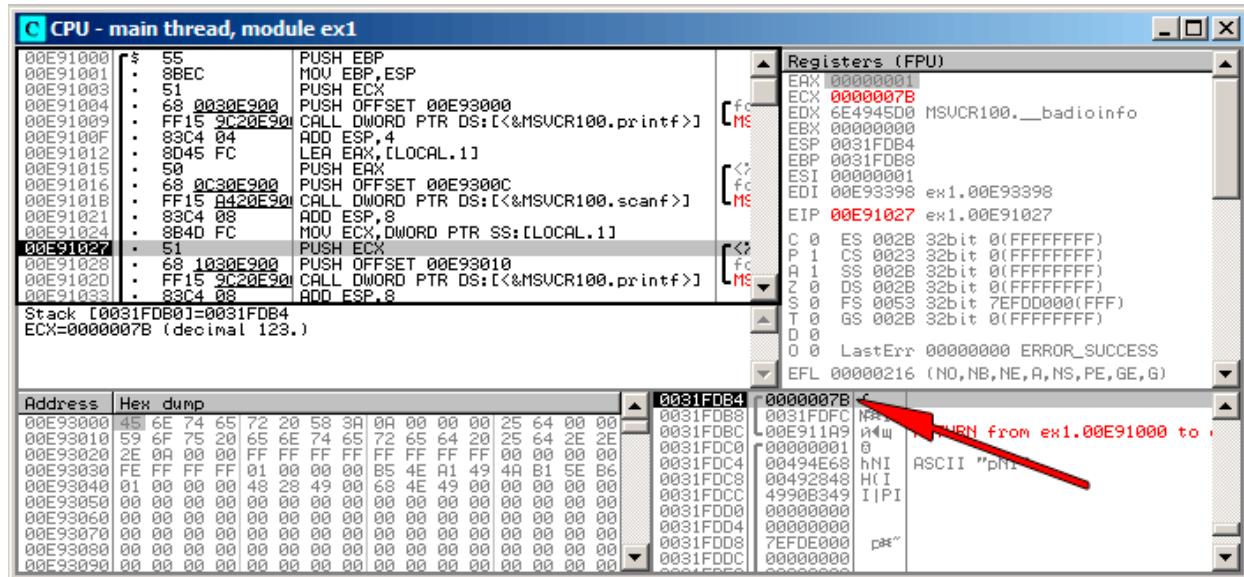


Figure 8.4: OllyDbg: preparing the value for passing to `printf()`

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...\n"
mov     [esp+20h+var_1C], edx
mov     [esp+20h+var_20], eax
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 ([4.4.3 on page 17](#)).

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

By the way

By the way, 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.

8.1. SIMPLE EXAMPLE

8.1.4 x64

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

MSVC

Listing 8.1: MSVC 2012 x64

```
_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 8.2: Optimizing GCC 4.4.6 x64

```
.LC0:
.string "Enter X:"
.LC1:
.string "%d"
.LC2:
.string "You entered %d...\n"

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...\n"
    xor    eax, eax
    call   printf

    ; return 0
    xor    eax, eax
    add    rsp, 24
    ret
```

8.1.5 ARM**Optimizing Keil 6/2013 (Thumb mode)**

```
.text:00000042          scanf_main
.text:00000042
.text:00000042          var_8        = -8
.text:00000042
.text:00000042 08 B5
.text:00000044 A9 A0
.text:00000046 06 F0 D3 F8
.text:0000004A 69 46
.text:0000004C AA A0
.text:0000004E 06 F0 CD F8
.text:00000052 00 99
.text:00000054 A9 A0
.text:00000056 06 F0 CB F8
.text:0000005A 00 20
.text:0000005C 08 BD

          PUSH   {R3,LR}
          ADR    R0, aEnterX      ; "Enter X:\n"
          BL     __2printf
          MOV    R1, SP
          ADR    R0, aD           ; "%d"
          BL     __0scanf
          LDR    R1, [SP,#8+var_8]
          ADR    R0, aYouEnteredD__ ; "You entered %d...\n"
          BL     __2printf
          MOVS   R0, #0
          POP    {R3,PC}
```

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 8.3: Non-optimizing GCC 4.9.1 ARM64

```
1 .LC0:
2     .string "Enter X:"
3 .LC1:
4     .string "%d"
5 .LC2:
6     .string "You entered %d...\n"
7 scanf_main:
8 ; subtract 32 from SP, then save FP and LR in stack frame:
9     stp    x29, x30, [sp, -32]!
10 ; set stack frame (FP=SP)
11     add    x29, sp, 0
12 ; load pointer to the "Enter X:" string:
13     adrp   x0, .LC0
14     add    x0, x0, :lo12:.LC0
15 ; X0=pointer to the "Enter X:" string
16 ; print it:
17     bl     puts
18 ; load pointer to the "%d" string:
19     adrp   x0, .LC1
20     add    x0, x0, :lo12:.LC1
21 ; find a space in stack frame for "x" variable (X1=FP+28):
22     add    x1, x29, 28
23 ; X1=address of "x" variable
24 ; pass the address to scanf() and call it:
25     bl     __isoc99_scanf
26 ; load 32-bit value from the variable in stack frame:
27     ldr    w1, [x29,28]
28 ; W1=x
29 ; load pointer to the "You entered %d...\n" string
30 ; printf() will take text string from X0 and "x" variable from X1 (or W1)
31     adrp   x0, .LC2
32     add    x0, x0, :lo12:.LC2
33     bl     printf
34 ; return 0
35     mov    w0, 0
```

8.1. SIMPLE EXAMPLE

```
36 ; restore FP and LR, then add 32 to SP:  
37     ldp    x29, x30, [sp], 32  
38     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 *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 *int*. The value is fetched at line 27 and then passed to `printf()`.

8.1.6 MIPS

A place in the local stack is allocated for the *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 `LW` ("Load Word") instruction and then passed to `printf()`.

Listing 8.4: Optimizing GCC 4.4.5 (assembly output)

```
$LC0:  
    .ascii  "Enter X:\000"  
$LC1:  
    .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      $4,%hi($LC0)  
    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(sprintf)($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:  
    j      $31  
    addiu   $sp,$sp,40      ; branch delay slot
```

IDA displays the stack layout as follows:

Listing 8.5: Optimizing GCC 4.4.5 (IDA)

```
.text:00000000 main:
```

8.2. GLOBAL VARIABLES

```
.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:0000000C               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:" ; branch delay slot
; 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 slot
; 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
```

8.2 Global variables

What if the `x` variable from the previous example was not 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.

```
#include <stdio.h>

// now x is global variable
int x;

int main()
{
    printf ("Enter X:\n");

    scanf ("%d", &x);

    printf ("You entered %d...\n", x);

    return 0;
};
```

8.2.1 MSVC: x86

8.2. GLOBAL VARIABLES

```

_DATA    SEGMENT
COMM    _x:DWORD
$SG2456   DB      'Enter X:', 0aH, 00H
$SG2457   DB      '%d', 00H
$SG2458   DB      'You entered %d...', 0aH, 00H
_DATA    ENDS
PUBLIC   _main
EXTRN   _scanf:PROC
EXTRN   _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

```

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 zeroes there¹.

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

```
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` was not set, you would see something like this:

```

.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:0040FA8C ; LPVOID lpMem
.data:0040FA8C 1pMem        dd ?           ; DATA XREF: __sbh_find_block+B
.data:0040FA8C                 ; __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

```

¹That is how a [VM](#) behaves

8.2. GLOBAL VARIABLES

`_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 zeroes [ISO07, 6.7.8p10]. But in the .exe file these uninitialized variables do not occupy anything. This is convenient for large arrays, for example.

8.2. GLOBAL VARIABLES

8.2.2 MSVC: x86 + OllyDbg

Things are even simpler here:

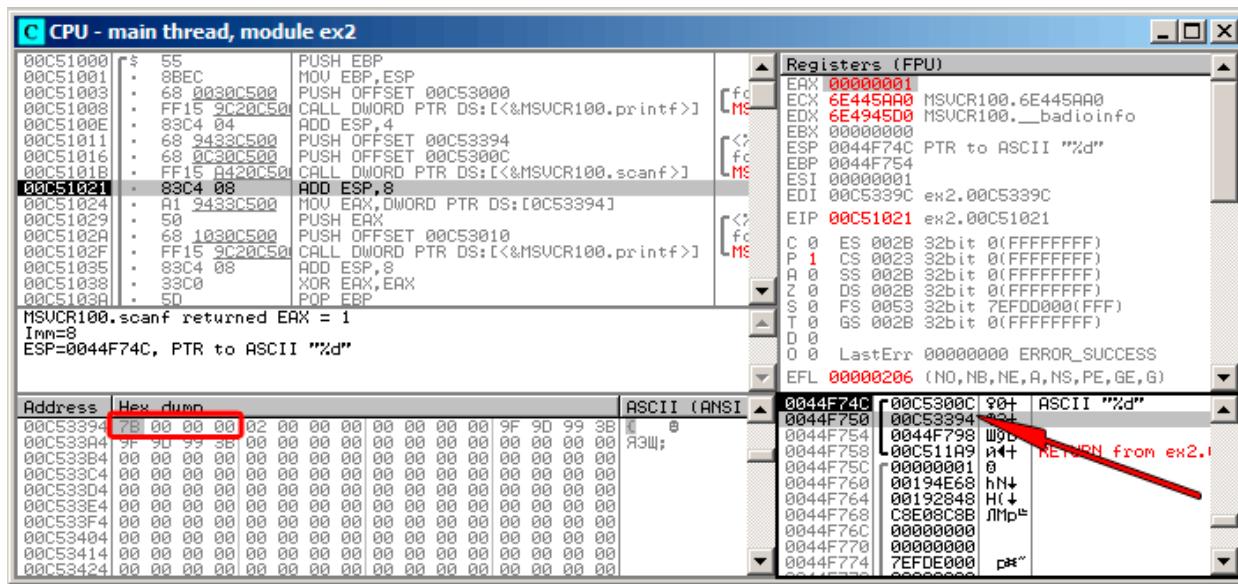


Figure 8.5: OllyDbg: after `scanf()` execution

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** should be there. The cause for this is referred as **endian-ness**, and x86 uses *little-endian*. This implies that the lowest byte is written first, and the highest written last. Read more about it at: [33 on page 452](#). 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 .

8.2. GLOBAL VARIABLES

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:

Address	Size	Owner	Section	Contains	Type	Access	Initial	Mapped as
00070000	00067000			Heap	Map	R	R	C:\Windows\System32\locale.nls
00190000	00005000				Priv	RW	RW	
00209000	00007000				Priv	RW	Guar	RW
0044C000	00001000				Priv	RW	Guar	RW
0044D000	00003000			Stack of main thread	Priv	RW	RW	
00590000	00007000				Priv	RW	RW	
00750000	0000C000	ex2		Default heap	Priv	RW	RW	
00C50000	00001000	ex2	.text	PE header	Img	R	RWE	Cop
00C51000	00001000	ex2	.rdata	Code	Img	R	E	RWE
00C52000	00001000	ex2	.data	Imports	Img	R	RWE	Cop
00C53000	00001000	ex2	.reloc	Data	Img	RW	RWE	Cop
00C54000	00001000	ex2	.text	Relocations	Img	R	RWE	Cop
6E3E0000	00001000	MSVCR100		PE header	Img	R	RWE	Cop
6E3E1000	00002000	MSVCR100	.text	Code, imports, exports	Img	R	E	RWE
6E493000	00006000	MSVCR100	.data	Data	Img	RW	Cop	RWE
6E499000	00001000	MSVCR100	.rsrc	Resources	Img	R	RWE	Cop
6E49A000	00005000	MSVCR100	.reloc	Relocations	Img	R	RWE	Cop
755D0000	00001000	Mod_7550		PE header	Img	R	RWE	Cop
755D1000	00003000				Img	R	E	RWE
755D4000	00001000				Img	RW	RWE	Cop
755D5000	00003000				Img	R	RWE	Cop
755E0000	00001000	Mod_755E		PE header	Img	R	RWE	Cop
755E1000	00004000				Img	R	E	RWE
7562E000	00005000				Img	RW	Cop	RWE
75633000	00009000				Img	R	RWE	Cop
75640000	00001000	Mod_7564		PE header	Img	R	RWE	Cop
75641000	00003000				Img	R	E	RWE
75679000	00002000				Img	RW	RWE	Cop
7567B000	00004000				Img	R	RWE	Cop
76F50000	00001000	kernel32		PE header	Img	R	RWE	Cop
76F60000	00000000	kernel32	.text	Code, imports, exports	Img	R	E	RWE
77030000	00010000	kernel32	.data	Data	Img	RW	Cop	RWE
77040000	00001000	kernel32	.rsrc	Resources	Img	R	RWE	Cop
77050000	00000000	kernel32	.reloc	Relocations	Img	R	RWE	Cop
77810000	00001000	KERNELBASE		PE header	Img	R	RWE	Cop
77811000	000040000	KERNELBASE	.text	Code, imports, exports	Img	R	E	RWE
77851000	00002000	KERNELBASE	.data	Data	Img	RW	RWE	Cop
77853000	00001000	KERNELBASE	.rsrc	Resources	Img	R	RWE	Cop
77854000	00000000	KERNELBASE	.reloc	Relocations	Img	R	RWE	Cop
77B20000	00001000	Mod_77B2		PE header	Img	R	RWE	Cop
77B21000	000102000				Img	R	E	RWE
77C23000	0002F000				Img	R	RWE	Cop
77C52000	00000000				Img	RW	Cop	RWE
77C5E000	000060000				Img	R	RWE	Cop
77D00000	00001000	ntdll		PE header	Img	R	RWE	Cop
77D10000	000060000	ntdll	.text	Code, exports	Img	R	E	RWE
77DF0000	00001000	ntdll	RT	Code	Img	R	E	RWE
77E00000	00009000	ntdll	.data	Data	Img	RW	Cop	RWE

Figure 8.6: OllyDbg: process memory map

8.2.3 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:

```
; Segment type: Uninitialized
; Segment permissions: Read/Write
```

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

```
; Segment type: Pure data
; Segment permissions: Read/Write
```

8.2.4 MSVC: x64

Listing 8.6: MSVC 2012 x64

```
_DATA SEGMENT
COMM x:DWORD
$SG2924 DB      'Enter X:', 0Ah, 00H
$SG2925 DB      '%d', 00H
$SG2926 DB      'You entered %d...', 0Ah, 00H
_DATA ENDS

_TEXT SEGMENT
main PROC
$LN3:
    sub    rsp, 40
    lea     rcx, OFFSET FLAT:$SG2924 ; 'Enter X:'
```

8.2. GLOBAL VARIABLES

```

call  printf
lea   rdx, OFFSET FLAT:x
lea   rcx, OFFSET FLAT:$SG2925 ; '%d'
call  scanf
mov   edx, DWORD PTR x
lea   rcx, OFFSET FLAT:$SG2926 ; 'You entered %d...'
call  printf

; return 0
xor   eax, eax

add   rsp, 40
ret   0
main ENDP
_TEXT ENDS

```

The code is almost the same as in x86. Please note that the address of the *x* variable is passed to `scanf()` using a `LEA` instruction, while the variable's value is passed to the second `printf()` using a `MOV` instruction. `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 `MOV` instruction has to be encoded accordingly.

8.2.5 ARM: Optimizing Keil 6/2013 (Thumb mode)

```

.text:00000000 ; Segment type: Pure code
.text:00000000          AREA .text, CODE
...
.text:00000000 main
.text:00000000          PUSH    {R4,LR}
.text:00000002          ADR     R0, aEnterX      ; "Enter X:\n"
.text:00000004          BL      __2printf
.text:00000008          LDR     R1, =x
.text:0000000A          ADR     R0, aD           ; "%d"
.text:0000000C          BL      __0scanf
.text:00000010          LDR     R0, =x
.text:00000012          LDR     R1, [R0]
.text:00000014          ADR     R0, aYouEnteredD__ ; "You entered %d...\n"
.text:00000016          BL      __2printf
.text:0000001A          MOVS   R0, #0
.text:0000001C          POP    {R4,PC}
...
.text:00000020 aEnterX      DCB "Enter X:",0xA,0      ; DATA XREF: main+2
.text:0000002A          DCB     0
.text:0000002B          DCB     0
.text:0000002C off_2C       DCD x                  ; DATA XREF: main+8
.text:0000002C          ; main+10
.text:00000030 aD           DCB "%d",0          ; DATA XREF: main+A
.text:00000033          DCB     0
.text:00000034 aYouEnteredD__ DCB "You entered %d...",0xA,0 ; DATA XREF: main+14
.text:00000047          DCB     0
.text:00000047 ; .text      ends
.text:00000047

...
.data:00000048 ; Segment type: Pure data
.data:00000048          AREA .data, DATA
.data:00000048          ; ORG 0x48
.data:00000048          EXPORT x
.data:00000048 x         DCD 0xA             ; DATA XREF: main+8
.data:00000048          ; main+10
.data:00000048 ; .data    ends

```

So, the `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 `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.

8.2. GLOBAL VARIABLES

The code segment might sometimes be located in a ROM² chip (remember, we now deal with embedded microelectronics, and memory scarcity is common here), and changeable variables –in RAM³.

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

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

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

That is because the `x` variable could be located somewhere far from this particular code fragment, so its address must be saved somewhere in close proximity to the code.

The `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 ±4095 bytes.

And so the address of the `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 `const`, the Keil compiler allocates it in the `.constdata` segment.

Perhaps thereafter, the linker could place this segment in ROM too, along with the code segment.

8.2.6 ARM64

Listing 8.7: Non-optimizing GCC 4.9.1 ARM64

```
1      .comm    x,4,4
2 .LC0:
3     .string "Enter X:"
4 .LC1:
5     .string "%d"
6 .LC2:
7     .string "You entered %d...\n"
8 f5:
9 ; save FP and LR in stack frame:
10    stp      x29, x30, [sp, -16]!
11 ; set stack frame (FP=SP)
12    add      x29, sp, 0
13 ; load pointer to the "Enter X:" string:
14    adrp    x0, .LC0
15    add     x0, x0, :lo12:.LC0
16    b1     puts
17 ; load pointer to the "%d" string:
18    adrp    x0, .LC1
19    add     x0, x0, :lo12:.LC1
20 ; form address of x global variable:
21    adrp    x1, x
22    add     x1, x1, :lo12:x
23    b1     __isoc99_scanf
24 ; form address of x global variable again:
25    adrp    x0, x
26    add     x0, x0, :lo12:x
27 ; load value from memory at this address:
28    ldr     w1, [x0]
29 ; load pointer to the "You entered %d...\n" string:
30    adrp    x0, .LC2
31    add     x0, x0, :lo12:.LC2
32    b1     printf
33 ; return 0
34    mov     w0, 0
35 ; restore FP and LR:
36    ldp     x29, x30, [sp], 16
37    ret
```

²Read-only memory

³Random-access memory

8.2. GLOBAL VARIABLES

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).

8.2.7 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"? [4.5.1 on page 21](#)), since the variable is not initialized at the start.

Listing 8.8: Optimizing GCC 4.4.5 (IDA)

```
.text:004006C0 main:
.text:004006C0
.text:004006C0 var_10      = -0x10
.text:004006C0 var_4       = -4
.text:004006C0
; function prologue:
.text:004006C0          lui      $gp, 0x42
.text:004006C4          addiu   $sp, -0x20
.text:004006C8          li      $gp, 0x410994
.text:004006CC          sw      $ra, 0x20+var_4($sp)
.text:004006D0          sw      $gp, 0x20+var_10($sp)
; call puts():
.text:004006D4          la      $t9, puts
.text:004006D8          lui      $a0, 0x40
.text:004006DC          jalr   $t9 ; puts
.text:004006E0          la      $a0, aEnterX    # "Enter X:" ; branch delay slot
; call scanf():
.text:004006E4          lw      $gp, 0x20+var_10($sp)
.text:004006E8          lui      $a0, 0x40
.text:004006EC          la      $t9, __isoc99_scanf
; prepare address of x:
.text:004006F0          la      $a1, x
.text:004006F4          jalr   $t9 ; __isoc99_scanf
.text:004006F8          la      $a0, aD          # "%d"           ; branch delay slot
; call printf():
.text:004006FC          lw      $gp, 0x20+var_10($sp)
.text:00400700          lui      $a0, 0x40
; get address of x:
.text:00400704          la      $v0, x
.text:00400708          la      $t9, printf
; load value from "x" variable and pass it to printf() in $a1:
.text:0040070C          lw      $a1, (x - 0x41099C)($v0)
.text:00400710          jalr   $t9 ; printf
.text:00400714          la      $a0, aYouEnteredD__ # "You entered %d...\n" ; branch ↴
    ↴ delay slot
; function epilogue:
.text:00400718          lw      $ra, 0x20+var_4($sp)
.text:0040071C          move   $v0, $zero
.text:00400720          jr      $ra
.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:

Listing 8.9: Optimizing GCC 4.4.5 (objdump)

```
1 004006c0 <main>:
2  ; function prologue:
3  4006c0: 3c1c0042          lui      gp,0x42
```

8.2. GLOBAL VARIABLES

```

4 4006c4:    27bdffe0      addiu   sp,sp,-32
5 4006c8:    279c8940      addiu   gp,gp,-30400
6 4006cc:    afbf001c      sw      ra,28(sp)
7 4006d0:    afbc0010      sw      gp,16(sp)
8 ; 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
13 ; call scanf():
14 4006e4:    8fb0010      lw      gp,16(sp)
15 4006e8:    3c040040     lui     a0,0x40
16 4006ec:    8f998038     lw      t9,-32712(gp)
17 ; 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
21 ; call printf():
22 4006fc:    8fb0010      lw      gp,16(sp)
23 400700:    3c040040     lui     a0,0x40
24 ; get address of x:
25 400704:    8f828044     lw      v0,-32700(gp)
26 400708:    8f99803c     lw      t9,-32708(gp)
27 ; load value from "x" variable and pass it to printf() in $a1:
28 40070c:    8c450000     lw      a1,0(v0)
29 400710:    0320f809     jalr    t9
30 400714:    24840900     addiu   a0,a0,2304 ; branch delay slot
31 ; function epilogue:
32 400718:    8fb001c      lw      ra,28(sp)
33 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 8.10: Optimizing GCC 4.4.5 (IDA)

```

.text:004006A0 main:
.text:004006A0
.text:004006A0 var_10      = -0x10
.text:004006A0 var_8       = -8
.text:004006A0 var_4       = -4
.text:004006A0
.text:004006A0             lui     $gp, 0x42
.text:004006A4             addiu $sp, -0x20
.text:004006A8             li     $gp, 0x418930
.text:004006AC             sw     $ra, 0x20+var_4($sp)
.text:004006B0             sw     $s0, 0x20+var_8($sp)
.text:004006B4             sw     $gp, 0x20+var_10($sp)
.text:004006B8             la     $t9, puts

```

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```

.text:004006BC          lui    $a0, 0x40
.text:004006C0          jalr   $t9 ; puts
.text:004006C4          la     $a0, aEnterX      # "Enter X:"
.text:004006C8          lw     $gp, 0x20+var_10($sp)
; prepare high part of x address:
.text:004006CC          lui    $s0, 0x41
.text:004006D0          la     $t9, __isoc99_scanf
.text:004006D4          lui    $a0, 0x40
; add low part of x address:
.text:004006D8          addiu $a1, $s0, (x - 0x410000)
; now address of x is in $a1.
.text:004006DC          jalr   $t9 ; __isoc99_scanf
.text:004006E0          la     $a0, aD          # "%d"
.text:004006E4          lw     $gp, 0x20+var_10($sp)
; get a word from memory:
.text:004006E8          lw     $a1, x
; value of x is now in $a1.
.text:004006EC          la     $t9, printf
.text:004006F0          lui    $a0, 0x40
.text:004006F4          jalr   $t9 ; printf
.text:004006F8          la     $a0, aYouEnteredD__ # "You entered %d...\n"
.text:004006FC          lw     $ra, 0x20+var_4($sp)
.text:00400700          move   $v0, $zero
.text:00400704          lw     $s0, 0x20+var_8($sp)
.text:00400708          jr     $ra
.text:0040070C          addiu $sp, 0x20

...
.data:00410920          .globl x
.data:00410920 x:       .word 0xA

```

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

Nevertheless, now *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 **LUI** ("Load Upper Immediate") and **ADDIU** ("Add Immediate Unsigned Word").

Here is also the objdump listing for close inspection:

Listing 8.11: Optimizing GCC 4.4.5 (objdump)

```

004006a0 <main>:
 4006a0: 3c1c0042    lui    gp,0x42
 4006a4: 27bdffe0    addiu $p,sp,-32
 4006a8: 279c8930    addiu gp,sp,-30416
 4006ac: afbf001c    sw     ra,28(sp)
 4006b0: afb00018    sw     s0,24(sp)
 4006b4: afbc0010    sw     gp,16(sp)
 4006b8: 8f998034    lw     t9,-32716(gp)
 4006bc: 3c040040    lui    a0,0x40
 4006c0: 0320f809    jalr   t9
 4006c4: 248408d0    addiu a0,a0,2256
 4006c8: 8fbcc0010   lw     gp,16(sp)
; prepare high part of x address:
 4006cc: 3c100041    lui    s0,0x41
 4006d0: 8f998038    lw     t9,-32712(gp)
 4006d4: 3c040040    lui    a0,0x40
; add low part of x address:
 4006d8: 26050920    addiu a1,s0,2336
; now address of x is in $a1.
 4006dc: 0320f809    jalr   t9
 4006e0: 248408dc    addiu a0,a0,2268
 4006e4: 8fbcc0010   lw     gp,16(sp)
; high part of x address is still in $s0.
; add low part to it and load a word from memory:
 4006e8: 8e050920    lw     a1,2336(s0)
; value of x is now in $a1.
 4006ec: 8f99803c    lw     t9,-32708(gp)
 4006f0: 3c040040    lui    a0,0x40

```

8.3. SCANF()

```
4006f4: 0320f809 jalr    t9
4006f8: 248408e0 addiu   a0,a0,2272
4006fc: 8fbff001c lw      ra,28(sp)
400700: 00001021 move    v0,zero
400704: 8fb00018 lw      s0,24(sp)
400708: 03e00008 jr      ra
40070c: 27bd0020 addiu   sp,sp,32
```

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 is need to be preserved before use in other functions (i.e., "saved").

That is why the value of `$S0` was set at address `0x4006cc` and was used again at address `0x4006e8`, after the `scanf()` call. The `scanf()` function does not change its value.

8.3 scanf()

As was noted before, it is slightly old-fashioned to use `scanf()` today. But if we have to, we need to at least 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()`⁴ 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`⁵) – 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?
```

8.3.1 MSVC: x86

Here is what we get in the assembly output (MSVC 2010):

⁴scanf, wscanf: [MSDN](#)

⁵End of file

8.3. SCANF()

```
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 flags⁶. `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 was 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*.

8.3.2 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 analysing code in **IDA**, it is very helpful to leave notes for oneself (and others). In instance, analysing 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
.text:00401000 var_4 = dword ptr -4
.text:00401000 argc  = dword ptr  8
.text:00401000 argv  = dword ptr  0Ch
```

⁶x86 flags, see also: [wikipedia](#).

8.3. SCANF()

```
.text:00401000 envp  = dword ptr  10h
.text:00401000
.text:00401000      push    ebp
.text:00401001      mov     ebp, esp
.text:00401003      push    ecx
.text:00401004      push    offset Format ; "Enter X:\n"
.text:00401009      call    ds:printf
.text:0040100F      add     esp, 4
.text:00401012      lea     eax, [ebp+var_4]
.text:00401015      push    eax
.text:00401016      push    offset aD ; "%d"
.text:0040101B      call    ds:scanf
.text:00401021      add     esp, 8
.text:00401024      cmp     eax, 1
.text:00401027      jnz    short error
.text:00401029      mov     ecx, [ebp+var_4]
.text:0040102C      push    ecx
.text:0040102D      push    offset aYou ; "You entered %d...\n"
.text:00401032      call    ds:printf
.text:00401038      add     esp, 8
.text:0040103B      jmp    short exit
.text:0040103D
.text:0040103D error: ; CODE XREF: _main+27
.text:0040103D      push    offset aWhat ; "What you entered? Huh?\n"
.text:00401042      call    ds:printf
.text:00401048      add     esp, 4
.text:0040104B
.text:0040104B exit: ; CODE XREF: _main+3B
.text:0040104B      xor    eax, eax
.text:0040104D      mov     esp, ebp
.text:0040104F      pop    ebp
.text:00401050      retn
.text:00401050 _main endp
```

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:

```
.text:00401000 _text segment para public 'CODE' use32
.text:00401000      assume cs:_text
.text:00401000      ;org 401000h
.text:00401000 ; ask for X
.text:00401012 ; get X
.text:00401024      cmp    eax, 1
.text:00401027      jnz    short error
.text:00401029 ; print result
.text:0040103B      jmp    short exit
.text:0040103D
.text:0040103D error: ; CODE XREF: _main+27
.text:0040103D      push    offset aWhat ; "What you entered? Huh?\n"
.text:00401042      call    ds:printf
.text:00401048      add     esp, 4
.text:0040104B
.text:0040104B exit: ; CODE XREF: _main+3B
.text:0040104B      xor    eax, eax
.text:0040104D      mov     esp, ebp
.text:0040104F      pop    ebp
.text:00401050      retn
.text:00401050 _main endp
```

To expand previously collapsed parts of the code, use “+” on the numerical pad.

8.3. SCANF()

By pressing "space", we can see how IDA represents a function as a graph:

```
; 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
```

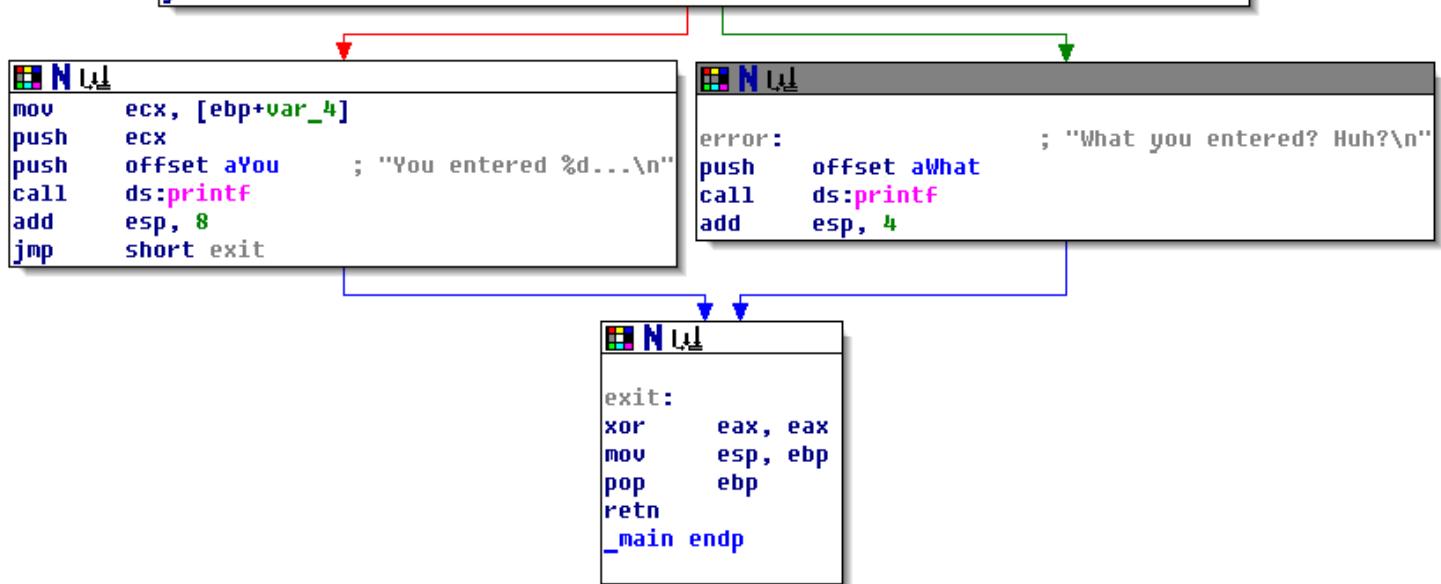


Figure 8.7: Graph mode in IDA

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.

8.3. 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:

```
; 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
```

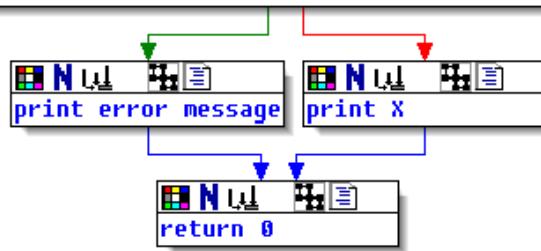


Figure 8.8: Graph mode in IDA with 3 nodes folded

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.

8.3. SCANF()

8.3.3 MSVC: x86 + OllyDbg

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`:

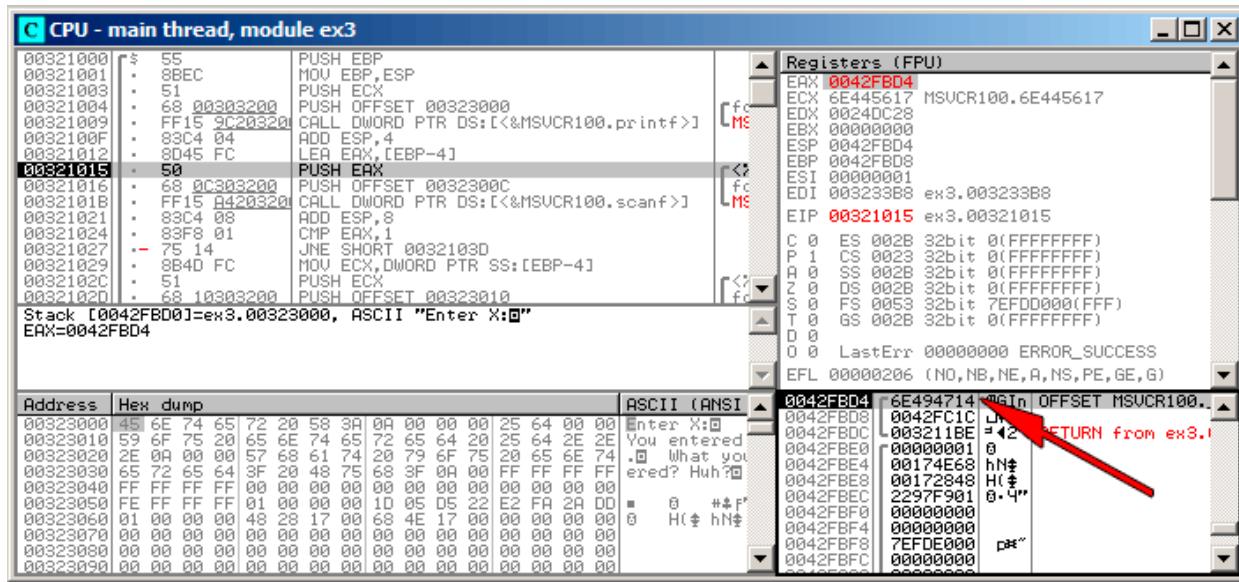


Figure 8.9: OllyDbg: passing variable address into `scanf()`

8.3. 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:

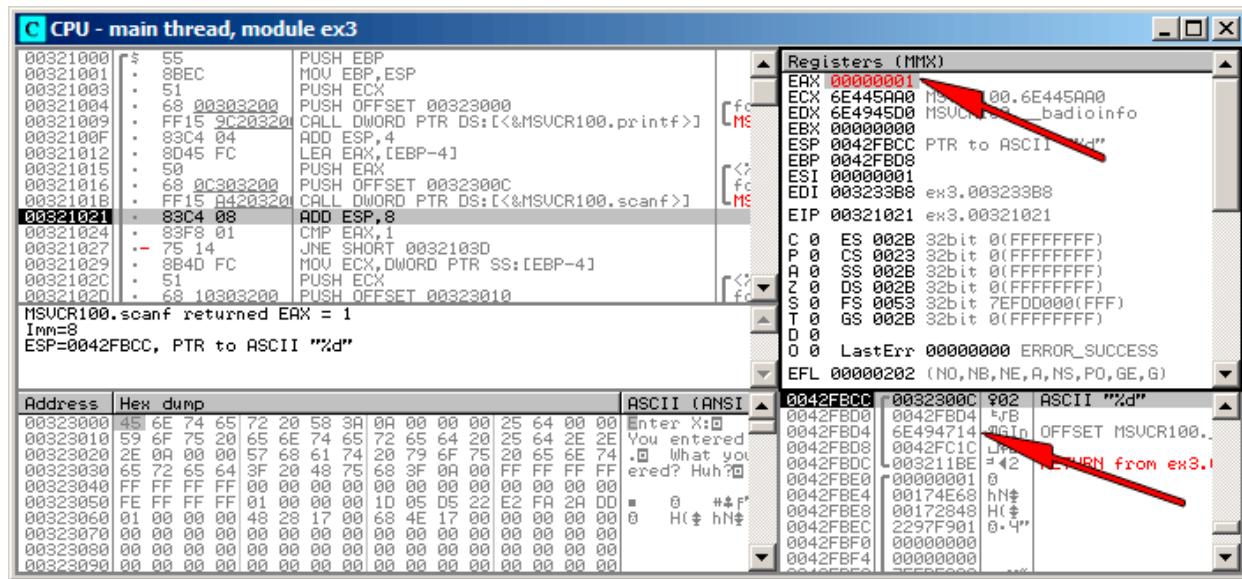


Figure 8.10: OllyDbg: `scanf()` returning error

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:

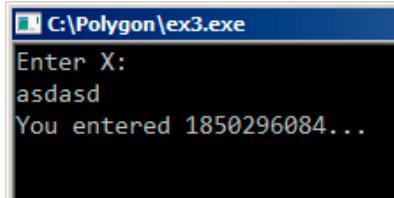


Figure 8.11: console window

Indeed, 1850296084 is a decimal representation of the number in the stack (0x00172948)!

8.3.4 MSVC: x86 + Hiew

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)⁷, 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 8.12: Hiew: main() function

Hiew finds ASCII⁸ strings and displays them, as it does with the imported functions' names.

⁷that's what also called "dynamic linking"

⁸ ASCII Zero (null-terminated ASCII string)

8.3. *SCANF()*

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):

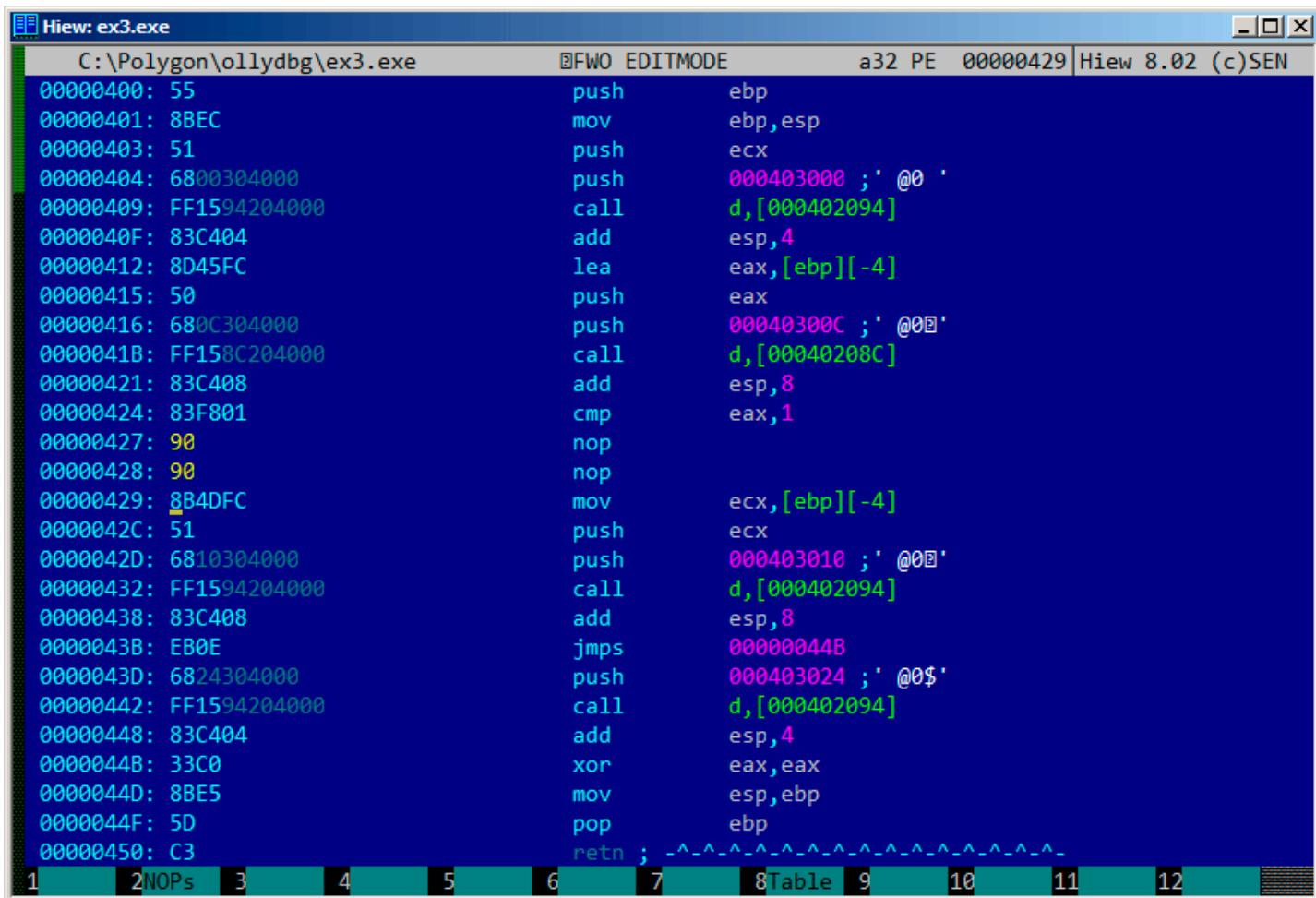


Figure 8.13: Hiew: replacing JNZ with two NOPs

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 æsthetic 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.

8.3.5 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- .

Listing 8.12: 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
```

8.3. SCANF()

```
$LN5:
    sub    rsp, 56
    lea     rcx, OFFSET FLAT:$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
    add    rsp, 56
    ret    0
main ENDP
_TEXT ENDS
END
```

8.3.6 ARM

ARM: Optimizing Keil 6/2013 (Thumb mode)

Listing 8.13: 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      MOVS   R0, #0
        POP    {R3,PC}

loc_1E      LDR    R1, [SP,#8+var_8]
        ADR    R0, aYouEnteredD__ ; "You entered %d...\n"
        BL     __2printf
        B     loc_1A
```

The new instructions here are **CMP** and **BEQ**⁹.

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 was 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.

⁹(PowerPC, ARM) Branch if Equal

Listing 8.14: Non-optimizing GCC 4.9.1 ARM64

```

1 .LC0:           .string "Enter X:"
2 .LC1:           .string "%d"
3 .LC2:           .string "You entered %d...\n"
4 .LC3:           .string "What you entered? Huh?"
5 f6:
6 ; save FP and LR in stack frame:
7     stp    x29, x30, [sp, -32]!
8 ; set stack frame (FP=SP)
9     add    x29, sp, 0
10 ; load pointer to the "Enter X:" string:
11     adrp   x0, .LC0
12     add    x0, x0, :lo12:.LC0
13     bl     puts
14 ; load pointer to the "%d" string:
15     adrp   x0, .LC1
16     add    x0, x0, :lo12:.LC1
17     bl     __isoc99_scanf
18 ; scanf() returned result in W0.
19 ; check it:
20     cmp    w0, 1
21 ; BNE is Branch if Not Equal
22 ; so if W0<>0, jump to L2 will be occurred
23     bne    .L2
24 ; at this moment W0=1, meaning no error
25 ; load x value from the local stack
26     ldr    w1, [x29,28]
27 ; load pointer to the "You entered %d...\n" string:
28     adrp   x0, .LC2
29     add    x0, x0, :lo12:.LC2
30     bl     printf
31 ; skip the code, which print the "What you entered? Huh?" string:
32     b      .L3
33 .L2:
34 ; load pointer to the "What you entered? Huh?" string:
35     adrp   x0, .LC3
36     add    x0, x0, :lo12:.LC3
37     bl     puts
38 .L3:
39 ; return 0
40     mov    w0, 0
41 ; restore FP and LR:
42     ldp    x29, x30, [sp], 32
43     ret
44

```

Code flow in this case forks with the use of **CMP / BNE** (Branch if Not Equal) instructions pair.

8.3.7 MIPS

Listing 8.15: Optimizing GCC 4.4.5 (IDA)

```

.text:004006A0 main:
.text:004006A0
.text:004006A0 var_18          = -0x18
.text:004006A0 var_10          = -0x10
.text:004006A0 var_4           = -4
.text:004006A0
.text:004006A0                 lui     $gp, 0x42
.text:004006A4                 addiu $sp, -0x28

```

8.4. EXERCISE

```
.text:004006A8        li      $gp, 0x418960
.text:004006AC        sw      $ra, 0x28+var_4($sp)
.text:004006B0        sw      $gp, 0x28+var_18($sp)
.text:004006B4        la      $t9, puts
.text:004006B8        lui    $a0, 0x40
.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...\n"
.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 `$V1` (`1` was stored in `$V1` earlier, at `0x004006DC`). `BEQ` stands for “Branch Equal”. If the two values are equal (i.e., success), the execution jumps to address `0x0040070C`.

8.3.8 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.

8.4 Exercise

- <http://challenges.re/53>

Chapter 9

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 9.1: simple example

```
#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;
}
```

9.1 x86

9.1.1 MSVC

Here is what we get after compilation (MSVC 2010 Express):

Listing 9.2: MSVC 2010 Express

```
_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
```

9.1. X86

```

call    _printf
add    esp, 8
; return 0
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`. 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 use it as an argument to `printf()`.

9.1.2 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.

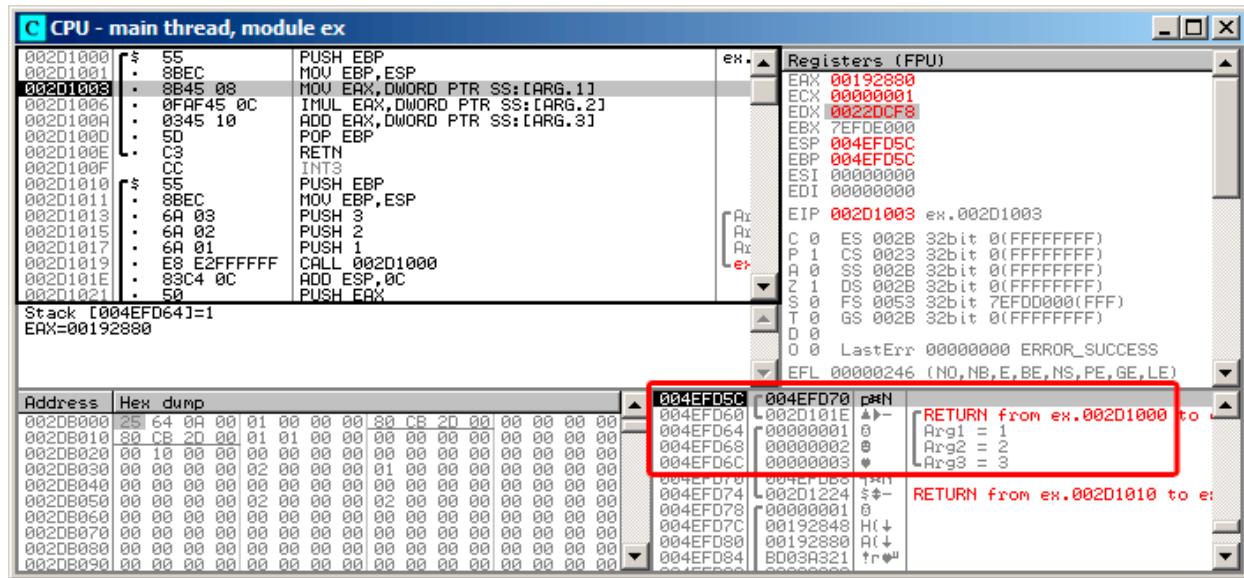


Figure 9.1: OllyDbg: inside of `f()` function

9.1.3 GCC

Let's compile the same in GCC 4.4.1 and see the results in IDA:

Listing 9.3: GCC 4.4.1

```

f          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
        retn
f
        endp

main
public 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](#) ([A.6.2 on page 931](#)) instruction takes care of this at the end.

9.2 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.

9.2.1 MSVC

Optimizing MSVC:

Listing 9.4: 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

```

9.2. X64

```
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 9.5: 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
        mov     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
        mov    edx, eax
        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”¹: 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 break².

So, some large functions can save their input arguments in the “shadows space” if they need 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.

¹MSDN

²MSDN

9.2.2 GCC

Optimizing GCC generates more or less understandable code:

Listing 9.6: Optimizing GCC 4.4.6 x64

```
f:
; EDI - 1st argument
; ESI - 2nd argument
; EDX - 3rd argument
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:

Listing 9.7: 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    eax, OFFSET FLAT:.LC0 ; "%d\n"
mov    esi, edx
mov    rdi, rax
mov    eax, 0 ; number of vector registers passed
call  printf
mov    eax, 0
leave
ret
```

There are no “shadow space” requirements in System V *NIX[[Mit13](#)], but the `callee` may need to save its arguments somewhere in case of registers shortage.

9.2.3 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-`).

9.3. ARM

It can be altered slightly in order to use 64-bit values:

```
#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,
                         0x1111111222222222,
                         0x3333333444444444));
    return 0;
}
```

Listing 9.8: Optimizing GCC 4.4.6 x64

```
f          proc near
imul      rsi, rdi
lea       rax, [rdx+rsi]
retn
f          endp

main      proc near
sub      rsp, 8
mov      rdx, 333333344444444h ; 3rd argument
mov      rsi, 111111122222222h ; 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.

9.3 ARM

9.3.1 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())`.

9.3. ARM

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.

Multiplication and addition at once³ (*Fused multiply-add*) is a very useful operation. By the way, there was no such instruction in x86 before FMA-instructions appeared in SIMD⁴.

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 was called from ARM code [ARM12, A2.3.2].

9.3.2 Optimizing Keil 6/2013 (ARM mode)

```
.text:00000098          f
.text:00000098 91 20 20 E0      MLA      R0, R1, R0, R2
.text:0000009C 1E 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.

9.3.3 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`.

9.3.4 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`.

Listing 9.9: Optimizing GCC (Linaro) 4.9

```
f:
    madd    w0, w0, w1, w2
    ret

main:
; save FP and LR to stack frame:
    stp    x29, x30, [sp, -16]!
    mov    w2, 3
    mov    w1, 2
    add    x29, sp, 0
    mov    w0, 1
```

³Wikipedia: Multiply–accumulate operation

⁴wikipedia

9.3. ARM

```
bl      f
mov    w1, w0
adrp   x0, .LC7
add    x0, x0, :lo12:.LC7
bl     printf
; return 0
    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:

```
#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,
                      0x3333333444444444));
    return 0;
}
```

```
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: [29.3.1 on page 442](#).

Non-optimizing GCC (Linaro) 4.9

The non-optimizing compiler is more redundant:

```
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
```

9.4. MIPS

```

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*. [ARM13c] The callee, however, is not obliged to save them. This is somewhat similar to "Shadow Space": 9.2.1 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`.

9.4 MIPS

Listing 9.10: Optimizing GCC 4.4.5

```

.text:00000000 f:
; $a0=a
; $a1=b
; $a2=c
.text:00000000          mult    $a1, $a0
.text:00000004          mflo   $v0
.text:00000008          jr     $ra
.text:0000000C          addu   $v0, $a2, $v0      ; branch delay slot
; result 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
; set a:
.text:00000028          li     $a0, 1
.text:0000002C          jal    f
; set b:
.text:00000030          li     $a1, 2      ; branch delay slot
; 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      ; branch delay slot
.text:0000004C          lw     $ra, 0x20+var_4($sp)
.text:00000050          move   $v0, $zero
.text:00000054          jr     $ra
.text:00000058          addiu $sp, 0x20      ; branch delay slot

```

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 `MFLO` and `MFHI` instructions.

`MFLO` 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.

9.4. MIPS

Finally, `ADDU` (“Add Unsigned”) adds the value of the third argument to the result.

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 useful⁵ 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.

⁵<http://go.yurichev.com/17326>

Chapter 10

More about results returning

In x86, the result of function execution is usually returned¹ 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.

10.1 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 was 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: [4.4.3 on page 17](#)), 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 10.1: GCC 4.8.1

```
.LC0:  
    .string "Hello, world!"  
main:
```

¹See also: MSDN: Return Values (C++): [MSDN](#)

10.2. WHAT IF WE DO NOT USE THE FUNCTION RESULT?

```
push    ebp
mov     ebp,  esp
and    esp, -16
sub    esp, 16
mov    DWORD PTR [esp], OFFSET FLAT:.LC0
call    puts
leave
ret
```

Let's write a bash script that shows the exit status:

Listing 10.2: tst.sh

```
#!/bin/sh
./hello_world
echo $?
```

And run it:

```
$ tst.sh
Hello, world!
14
```

14 is the number of characters printed.

10.2 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:

```
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.

10.3 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:

```
struct s
{
    int a;
    int b;
    int c;
};
```

10.3. RETURNING A STRUCTURE

```
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):

```
$T3853 = 8          ; size = 4
_a$ = 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:

```
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 10.3: GCC 4.8.1

```
_get_some_values proc near

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 was passed. So there are no performance drawbacks.

Chapter 11

Pointers

Pointers are often used to return values from functions (recall `scanf()` case ([8 on page 66](#))). For example, when a function needs to return two values.

11.1 Global variables example

```
#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:

Listing 11.1: Optimizing MSVC 2010 (/Ob0)

```
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
```

11.1. GLOBAL VARIABLES EXAMPLE

```
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         ; 0000001cH
xor    eax, eax
ret    0
_main  ENDP
```

11.1. GLOBAL VARIABLES EXAMPLE

Let's see this in OllyDbg:

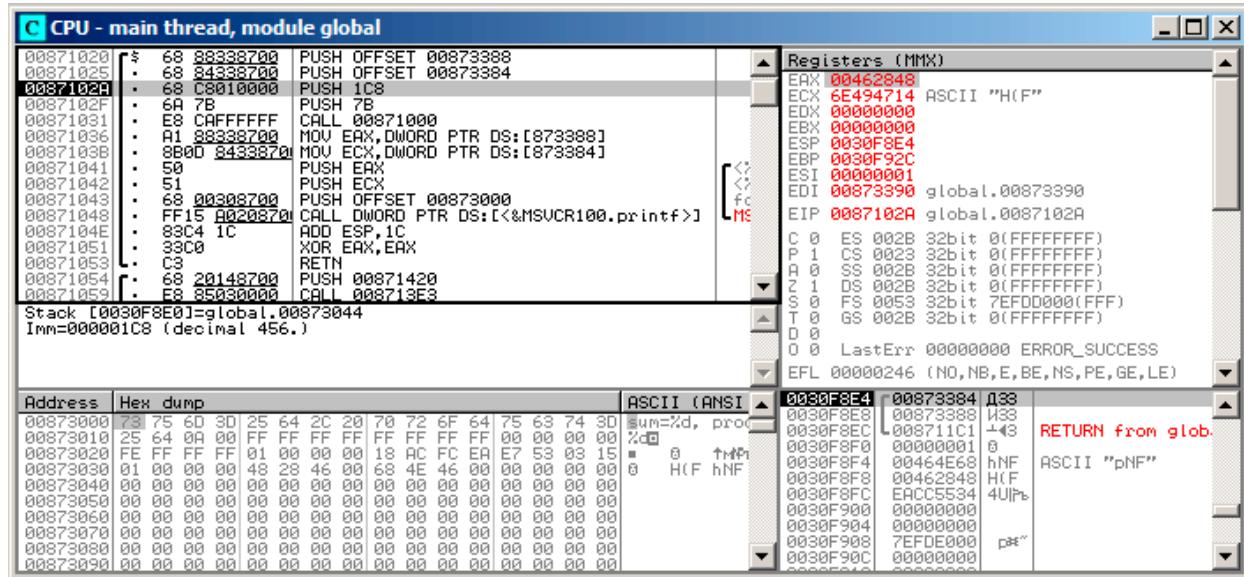


Figure 11.1: OllyDbg: global variables addresses are passed to `f1()`

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.

11.1. GLOBAL VARIABLES EXAMPLE

These variables are zeroed, because non-initialized data (from **BSS**) is cleared before the execution begins: [ISO07, 6.7.8p10]. They reside in the data segment, we can verify this by pressing Alt-M and reviewing the memory map:

Address	Size	Owner	Section	Contains	Type	Access	Initial	Mapped as
00050000	00004000				Map	R	R	
00060000	00001000				Priv	RW	RW	
00070000	00007000				Map	R	R	
00159000	00007000				Priv	RW	Guar	RW
00300000	00001000			Stack of main thread	Priv	RW	Guar	RW
0030E000	00002000			Heap	Priv	RW	Guar	RW
00460000	00005000				Priv	RW	RW	RW
004A0000	00007000				Priv	RW	RW	RW
006B0000	00000000			Default heap	Priv	RW	RW	RW
00870000	00001000	global	.text	PE header	Img	R	RWE	Cop
00871000	00001000	global	.rdata	Code	Img	R E	RWE	Cop
00872000	00001000	global	.data	Imports	Img	R	RWE	Cop
00873000	00001000	global	.data	Data	Img	RW	RWE	Cop
00874000	00001000	global	.reloc	Relocations	Img	R	RWE	Cop
6E3E0000	00001000	MSVCR100	.text	PE header	Img	R	RWE	Cop
6E3E1000	000082000	MSVCR100	.data	Code, imports, exports	Img	R E	RWE	Cop
6E493000	00006000	MSVCR100	.rsrc	Data	Img	RW	Cop	
6E499000	00001000	MSVCR100	.resources	Resources	Img	R	RWE	Cop
6E49A000	00005000	MSVCR100	.reloc	Relocations	Img	R	RWE	Cop
755D0000	00001000	Mod_7550		PE header	Img	R	RWE	Cop
755D1000	00003000				Img	R E	RWE	Cop
755D4000	00001000				Img	RW	RWE	Cop
755D5000	00003000				Img	R	RWE	Cop
755E0000	00001000	Mod_755E		PE header	Img	R E	RWE	Cop
755E1000	00040000				Img	RW	Cop	
7562E000	00005000				Img	R	RWE	Cop
75633000	00009000				Img	R	RWE	Cop

Figure 11.2: OllyDbg: memory map

11.1. GLOBAL VARIABLES EXAMPLE

Let's trace (F7) to the start of `f1()`:

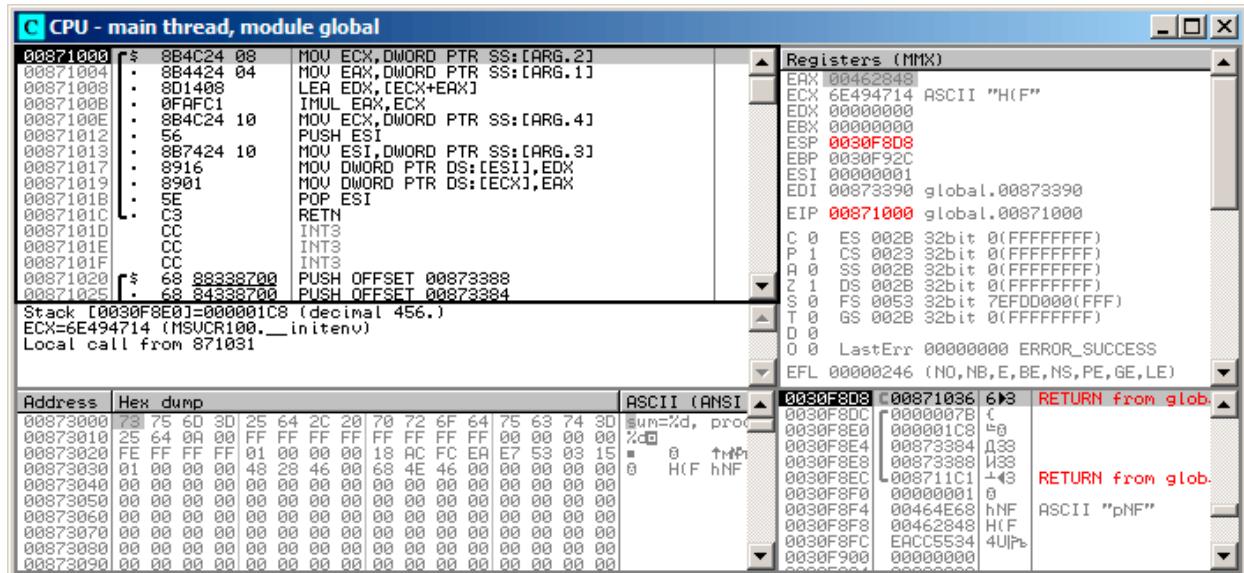


Figure 11.3: OllyDbg: `f1()` starts

Two values are visible in the stack 456 (0x1C8) and 123 (0x7B), and also the addresses of the two global variables.

11.1. GLOBAL VARIABLES EXAMPLE

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:

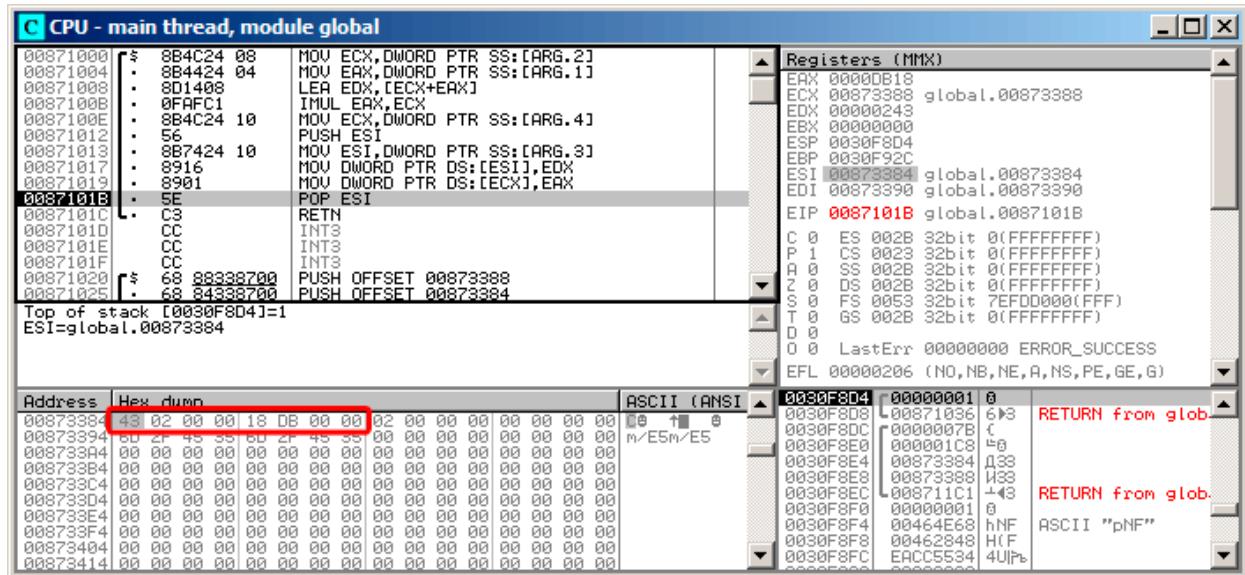


Figure 11.4: OllyDbg: `f1()` execution completed

11.2. LOCAL VARIABLES EXAMPLE

Now the global variables' values are loaded into registers ready for passing to `printf()` (via the stack):

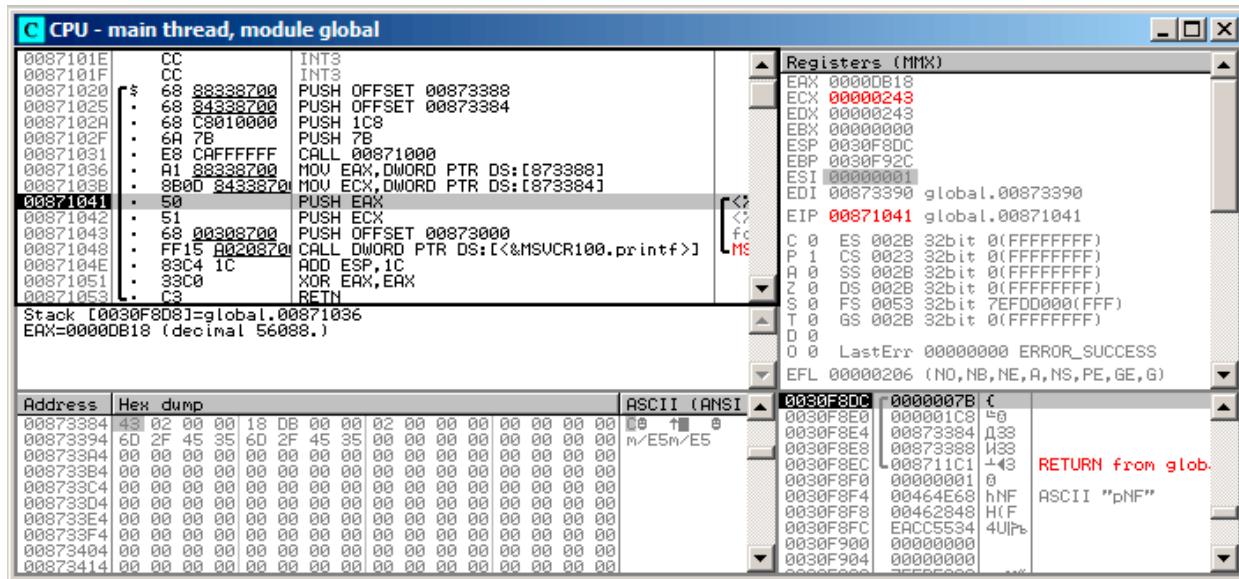


Figure 11.5: OllyDbg: global variables' addresses are passed into `printf()`

11.2 Local variables example

Let's rework our example slightly:

Listing 11.2: now the `sum` and `product` variables are local

```
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:

Listing 11.3: Optimizing MSVC 2010 (/Obo)

```
_product$ = -8                                ; size = 4
_sum$ = -4                                     ; size = 4
_main PROC
; 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$[esp+24]
    mov    eax, DWORD PTR _sum$[esp+24]
    push   edx
    push   eax
    push   OFFSET $SG2803
    call   DWORD PTR __imp__printf
; Line 15
    xor    eax, eax
    add    esp, 36                                  ; 00000024H
    ret
```

11.2. LOCAL VARIABLES EXAMPLE

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:

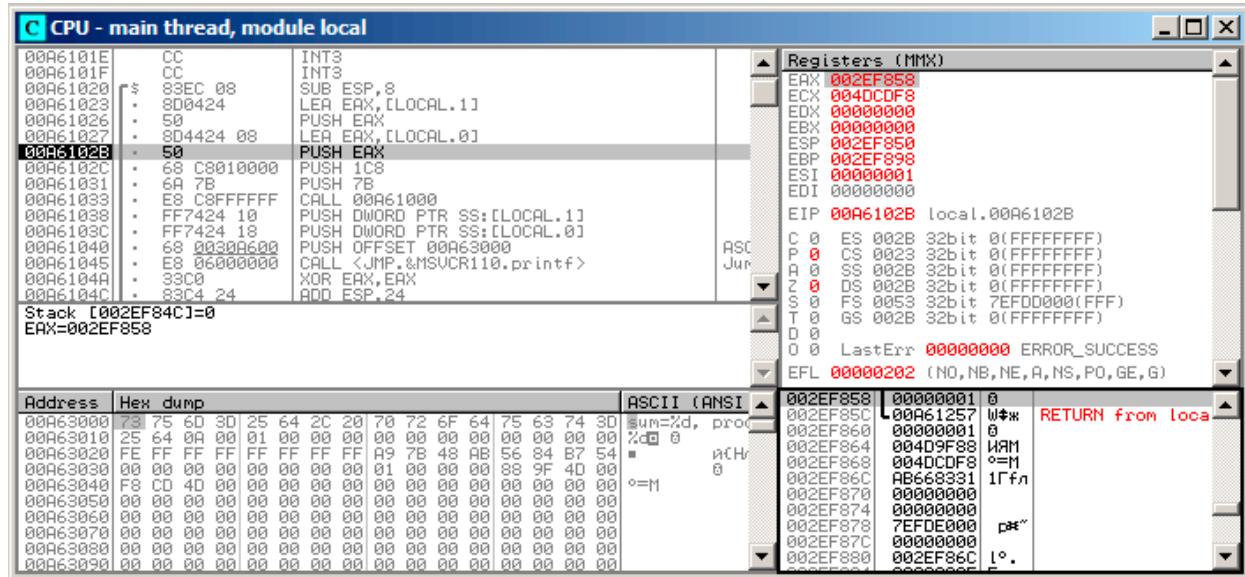


Figure 11.6: OllyDbg: local variables' addresses are pushed into the stack

11.2. LOCAL VARIABLES EXAMPLE

f1() starts. So far there is only random garbage in the stack at 0x2EF854 and 0x2EF858 :

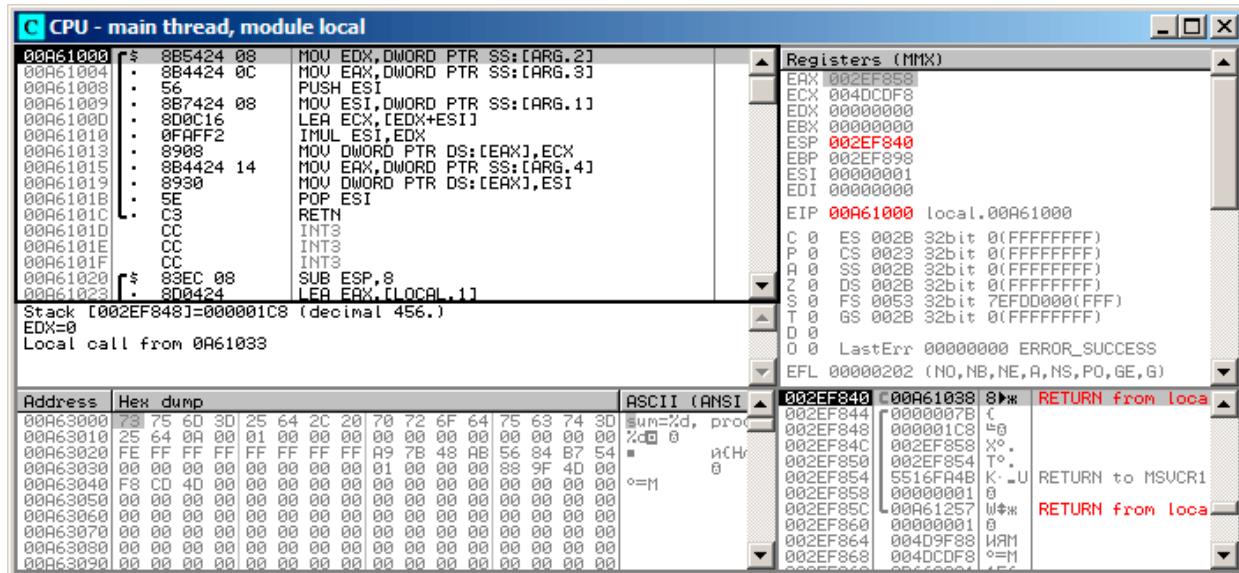


Figure 11.7: OllyDbg: f1() starting

11.3. CONCLUSION

f1() completes:

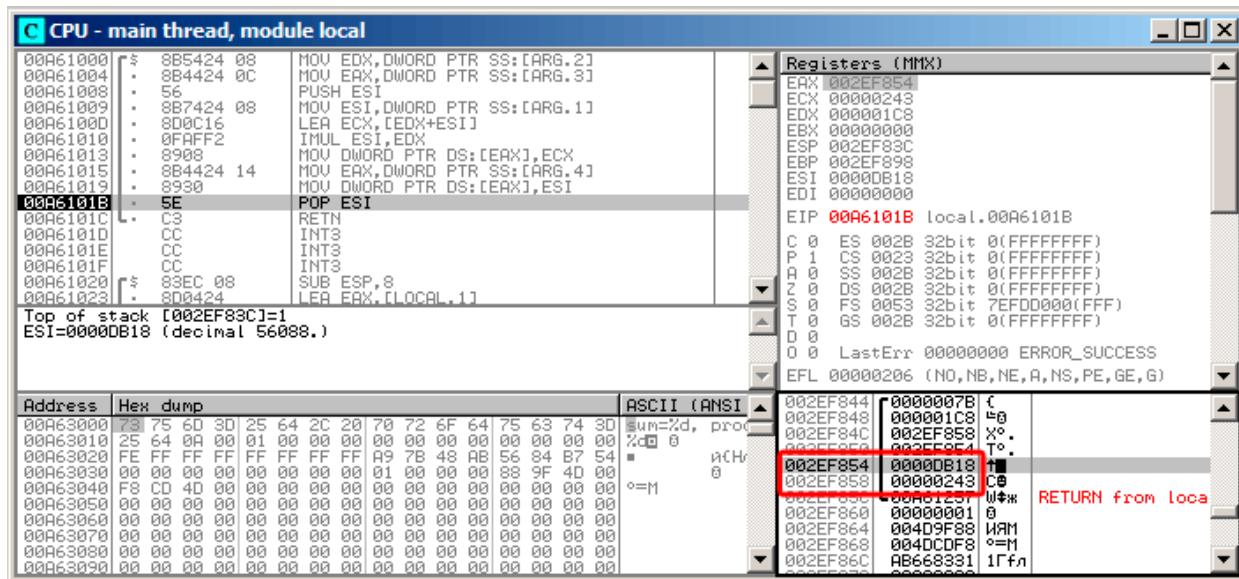


Figure 11.8: OllyDbg: f1() completes execution

We now find `0xDB18` and `0x243` at addresses `0x2EF854` and `0x2EF858`. These values are the `f1()` results.

11.3 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: ([53.3 on page 559](#)).

Chapter 12

GOTO operator

The GOTO operator is generally considered as anti-pattern. [Dij68], Nevertheless, it can be used reasonably [Knu74], [Yur13, p. 1.3.2].

Here is a very simple example:

```
#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 12.1: MSVC 2012

```
$SG2934 DB      'begin', 0aH, 00H
$SG2936 DB      'skip me!', 0aH, 00H
$SG2937 DB      'end', 0aH, 00H

_main PROC
    push    ebp
    mov     ebp, esp
    push    OFFSET $SG2934 ; 'begin'
    call    _printf
    add    esp, 4
    jmp    SHORT $exit$3
    push    OFFSET $SG2936 ; 'skip me!'
    call    _printf
    add    esp, 4
$exit$3:
    push    OFFSET $SG2937 ; 'end'
    call    _printf
    add    esp, 4
    xor    eax, eax
    pop    ebp
    ret    0
_main ENDP
```

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.

This could also be useful as a simple patching exercise. Let's open the resulting executable in Hiew:

Figure 12.1: Hiew

12.1. DEAD CODE

Place the cursor to address JMP (0x410), press F3 (edit), press zero twice, so the opcode becomes EB 00 :

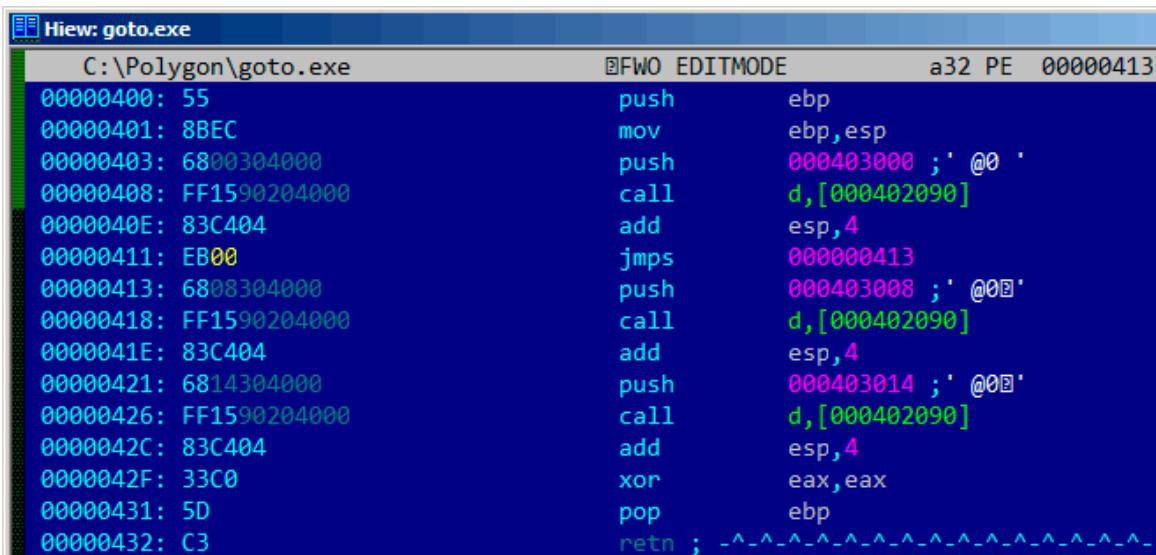


Figure 12.2: Hiew

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 should see this:

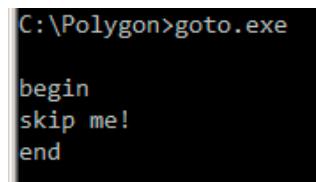


Figure 12.3: Patched executable output

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).

12.1 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:

Listing 12.2: Optimizing MSVC 2012

```
$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
        xor     eax, eax
```

12.2. EXERCISE

```
        ret      0  
_main    ENDP
```

However, the compiler forgot to remove the “skip me!” string.

12.2 Exercise

Try to achieve the same result using your favorite compiler and debugger.

Chapter 13

Conditional jumps

13.1 Simple example

```
#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;
}
```

13.1.1 x86

x86 + MSVC

Here is how the `f_signed()` function looks like:

Listing 13.1: 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
```

13.1. SIMPLE EXAMPLE

```

add    esp, 4
$LN3@f_signed:
    mov    ecx, DWORD PTR _a$[ebp]
    cmp    ecx, DWORD PTR _b$[ebp]
    jne    SHORT $LN2@f_signed
    push   OFFSET $SG739           ; 'a==b'
    call   _printf
    add    esp, 4
$LN2@f_signed:
    mov    edx, DWORD PTR _a$[ebp]
    cmp    edx, DWORD PTR _b$[ebp]
    jge    SHORT $LN4@f_signed
    push   OFFSET $SG741           ; 'a<b'
    call   _printf
    add    esp, 4
$LN4@f_signed:
    pop    ebp
    ret    0
_f_signed ENDP

```

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 specified in the instruction address or label. 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()`, with the exception that the `JBE` and `JAE` instructions are used instead of `JLE` and `JGE`, as follows:

Listing 13.2: GCC

```

_a$ = 8    ; size = 4
_b$ = 12   ; size = 4
_f_unsigned PROC
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _a$[ebp]
    cmp    eax, DWORD PTR _b$[ebp]
    jbe    SHORT $LN3@f_unsigned
    push   OFFSET $SG2761      ; 'a>b'
    call   _printf
    add    esp, 4
$LN3@f_unsigned:
    mov    ecx, DWORD PTR _a$[ebp]
    cmp    ecx, DWORD PTR _b$[ebp]
    jne    SHORT $LN2@f_unsigned
    push   OFFSET $SG2763      ; 'a==b'
    call   _printf
    add    esp, 4
$LN2@f_unsigned:
    mov    edx, DWORD PTR _a$[ebp]
    cmp    edx, DWORD PTR _b$[ebp]
    jae    SHORT $LN4@f_unsigned
    push   OFFSET $SG2765      ; 'a<b'
    call   _printf
    add    esp, 4
$LN4@f_unsigned:
    pop    ebp
    ret    0
_f_unsigned ENDP

```

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.

13.1. SIMPLE EXAMPLE

See also the section about signed number representations ([31 on page 448](#)). 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:

Listing 13.3: `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
```

13.1. SIMPLE EXAMPLE

x86 + MSVC + OllyDbg

We can see how flags are set by running this example in OllyDbg. Let's begin with `f_unsigned()`, which works with unsigned numbers.

`CMP` is executed thrice here, but for the same arguments, so the flags are the same each time.

Result of the first comparison:

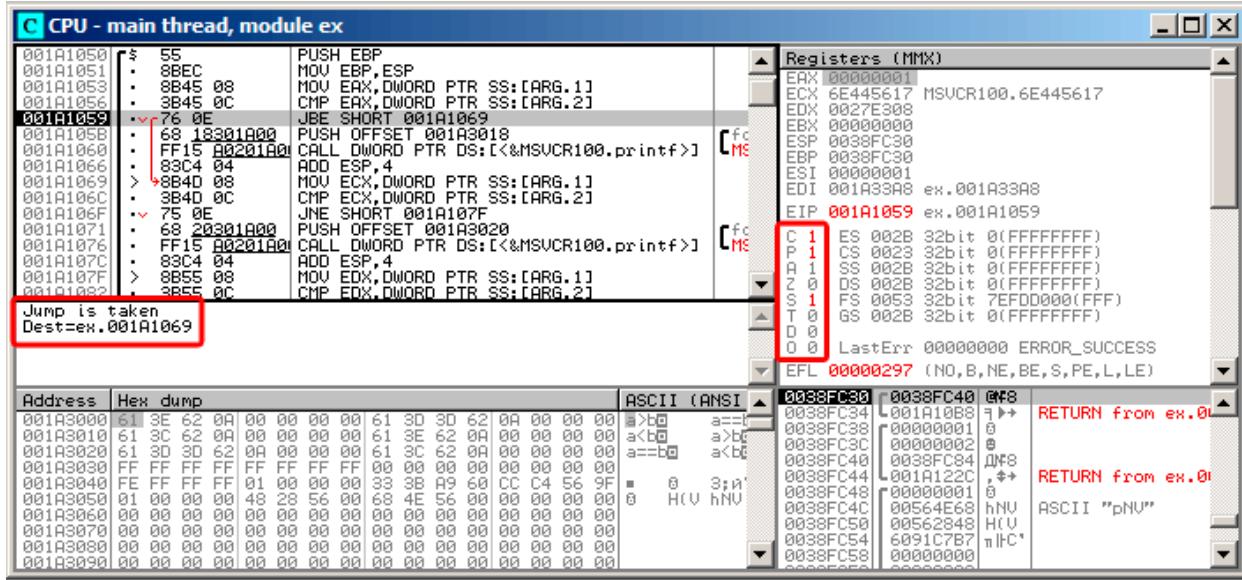


Figure 13.1: OllyDbg: `f_unsigned()`: first conditional jump

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 [Int13], we can read there that `JBE` is triggering if CF=1 or ZF=1. The condition is true here, so the jump is triggered.

13.1. SIMPLE EXAMPLE

The next conditional jump:

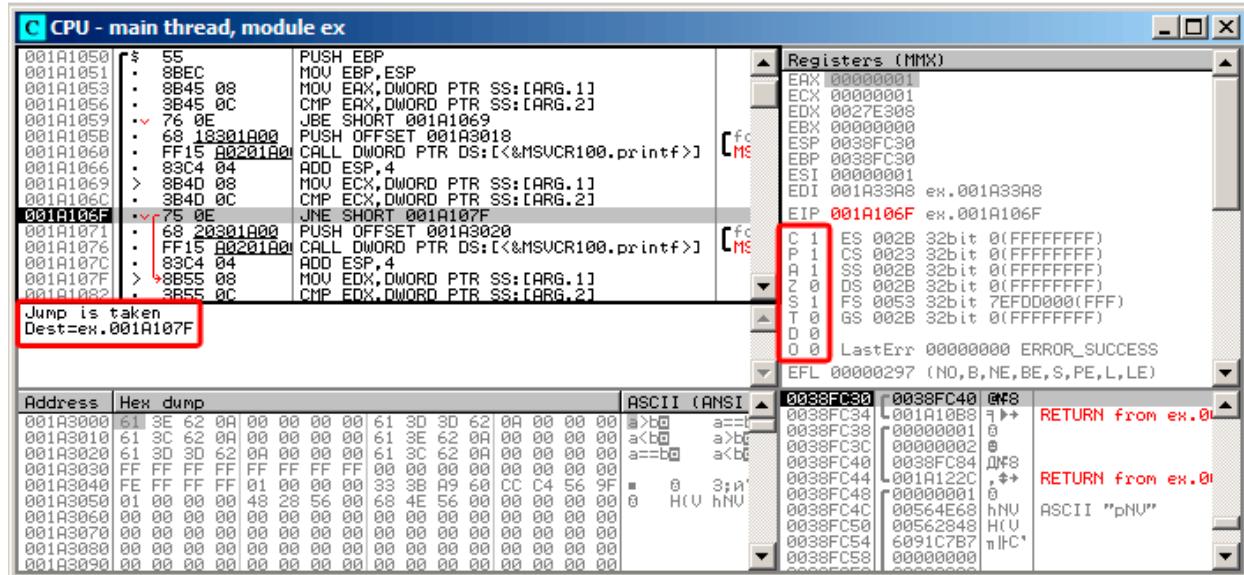


Figure 13.2: OllyDbg: `f_unsigned()`: second conditional jump

OllyDbg gives a hint that `JNZ` is to be triggered now. Indeed, `JNZ` triggering if ZF=0 (zero flag).

13.1. SIMPLE EXAMPLE

The third conditional jump, JNB :

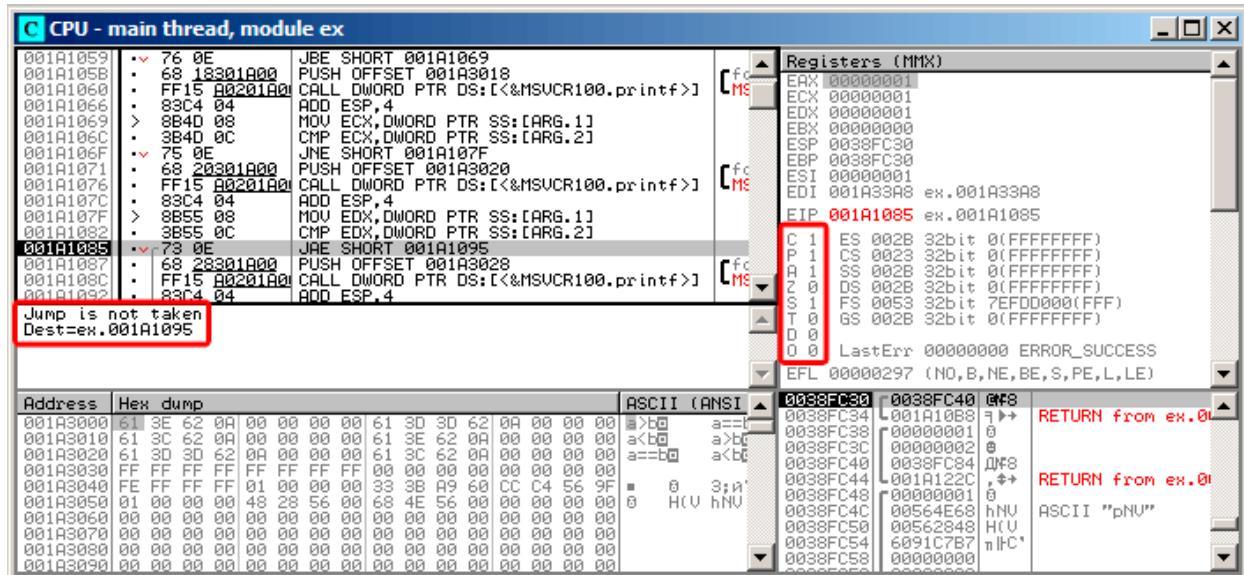


Figure 13.3: OllyDbg: f_unsigned() : third conditional jump

In [Int13] we can see that JNB triggers if CF=0 (carry flag). That is not true in our case, so the third printf() will execute.

13.1. SIMPLE EXAMPLE

Now let's review the `f_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:

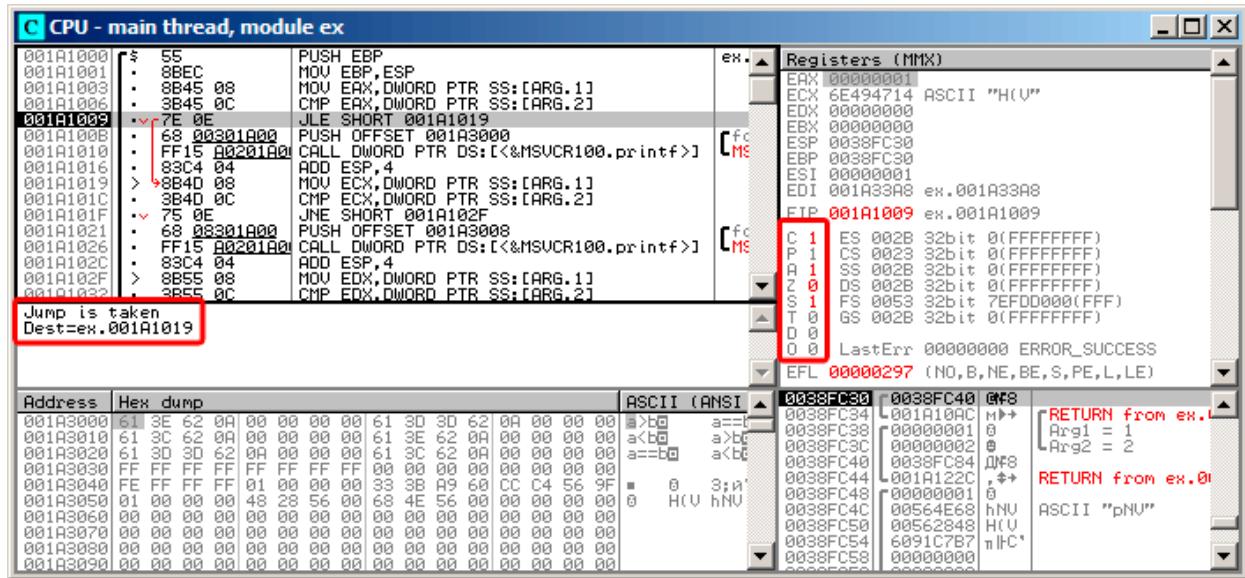


Figure 13.4: OllyDbg: `f_signed()` : first conditional jump

In [Int13] we find that this instruction is triggered if ZF=1 or SF≠OF. SF≠OF in our case, so the jump triggers.

13.1. SIMPLE EXAMPLE

The second JNZ conditional jump triggering: if ZF=0 (zero flag):

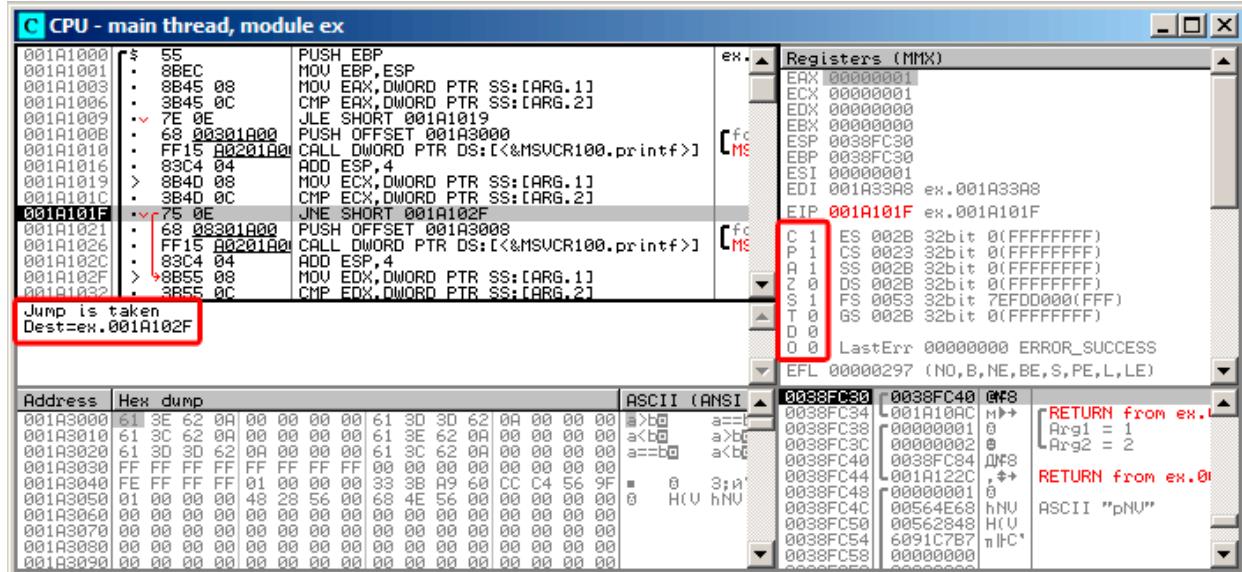


Figure 13.5: OllyDbg: `f_signed()`: second conditional jump

13.1. SIMPLE EXAMPLE

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:

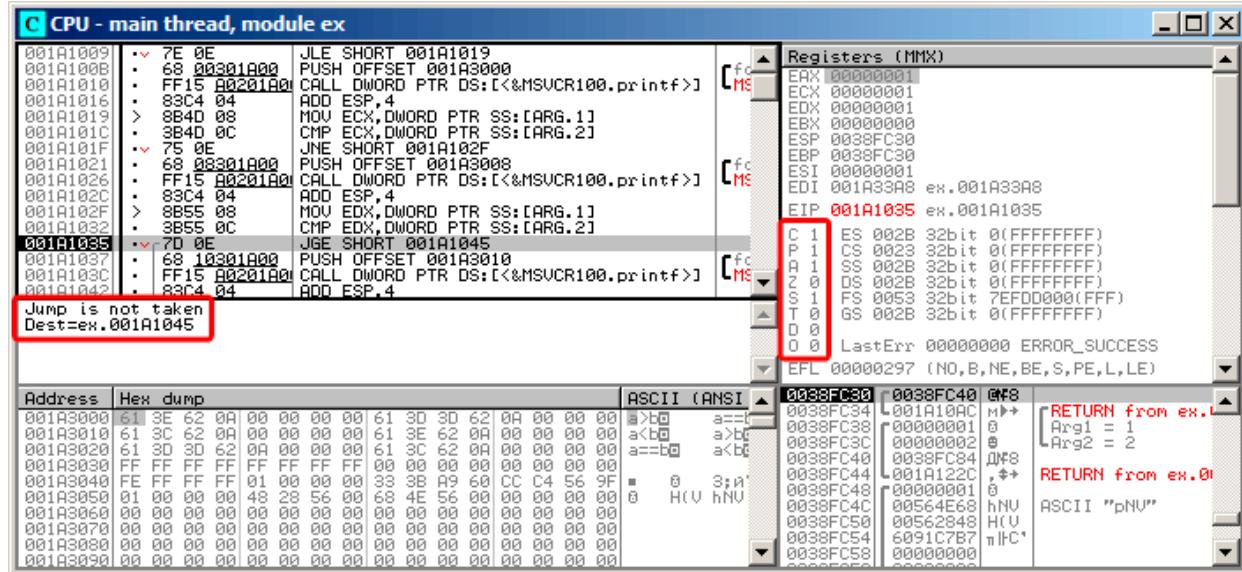


Figure 13.6: OllyDbg: `f_signed()` : third conditional jump

13.1. SIMPLE EXAMPLE

x86 + MSVC + Hiew

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:

The screenshot shows the assembly code for the `f_unsigned()` function in the Hiew debugger. The code is as follows:

```

C:\Polygon\ollydbg\7_1.exe      FRO -----      a32 PE .00401000 | Hiew 8.02 (c)SEN
.00401000: 55                 push    ebp
.00401001: 8BEC               mov     ebp,esp
.00401003: 8B4508             mov     eax,[ebp][8]
.00401006: 3B450C             cmp     eax,[ebp][00C]
.00401009: 7E0D               jle    .000401018 --①
.0040100B: 6800B04000         push   00040B000 --②
.00401010: E8AA000000         call   .0004010BF --③
.00401015: 83C404             add    esp,4
.00401018: 8B4D08             1mov   ecx,[ebp][8]
.0040101B: 3B4D0C             cmp    ecx,[ebp][00C]
.0040101E: 750D               jnz    .00040102D --④
.00401020: 6808B04000         push   00040B008 ;'a==b' --⑤
.00401025: E895000000         call   .0004010BF --③
.0040102A: 83C404             add    esp,4
.0040102D: 8B5508             4mov   edx,[ebp][8]
.00401030: 3B550C             cmp    edx,[ebp][00C]
.00401033: 7D0D               jge    .000401042 --⑥
.00401035: 6810B04000         push   00040B010 --⑦
.0040103A: E880000000         call   .0004010BF --③
.0040103F: 83C404             add    esp,4
.00401042: 5D                 6pop   ebp
.00401043: C3                 retn  ; -^_-^_-^_-^_-^_-^_-^_-^_-^_-^_
.00401044: CC
.00401045: CC
.00401046: CC
.00401047: CC
.00401048: CC

```

At the bottom of the window, there is a toolbar with various icons: Global, FillBlk, CryBlk, ReLoad, String, Direct, Table, byte, Leave, Naked, AddName.

Figure 13.7: Hiew: `f_unsigned()` function

Essentially, we need 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.

13.1. SIMPLE EXAMPLE

Here is the modified code:

The screenshot shows the Hiew 8.02 debugger interface with the assembly code for the `f_unsigned()` function. The code is as follows:

```
C:\Polygon\ollydbg\7_1.exe      FWO EDITMODE    a32 PE 00000434|Hiew 8.02 (c)SEN
00000400: 55                  push    ebp
00000401: 8BEC                mov     ebp,esp
00000403: 8B4508              mov     eax,[ebp][8]
00000406: 3B450C              cmp     eax,[ebp][00C]
00000409: EB0D                jmps   00000418
0000040B: 6800B04000          push   00040B000 ;' @@@ '
00000410: E8AA000000          call   0000004BF
00000415: 83C404              add    esp,4
00000418: 8B4D08              mov    ecx,[ebp][8]
0000041B: 3B4D0C              cmp    ecx,[ebp][00C]
0000041E: 7500                jnz   00000420
00000420: 6808B04000          push   00040B008 ;' @@@ '
00000425: E895000000          call   0000004BF
0000042A: 83C404              add    esp,4
0000042D: 8B5508              mov    edx,[ebp][8]
00000430: 3B550C              cmp    edx,[ebp][00C]
00000433: EB0D                jmps   00000442
00000435: 6810B04000          push   00040B010 ;' @@@ '
0000043A: E880000000          call   0000004BF
0000043F: 83C404              add    esp,4
00000442: 5D                  pop    ebp
00000443: C3                  retn  ; -^--^--^--^--^--^--^--^--^--^--^--^--^-
00000444: CC
00000445: CC
00000446: CC
00000447: CC
00000448: CC
```

The assembly code consists of several jumps (jmps) to different addresses (e.g., 00000418, 00000420, 00000442, 00000443), which likely correspond to the printf() calls mentioned in the text.

Figure 13.8: 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()` (4.4.3 on page 17) 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 can not do this, but optimizing GCC 4.8.1 can go deeper:

Listing 13.4: GCC 4.8.1 `f_signed()`

```
f_signed:
    mov    eax, DWORD PTR [esp+8]
    cmp    DWORD PTR [esp+4], eax
    jg     .L6
    je     .L7
    jge   .L1
    mov    DWORD PTR [esp+4], OFFSET FLAT:.LC2 ; "a<b"
    jmp    puts
.L6:
    mov    DWORD PTR [esp+4], OFFSET FLAT:.LC0 ; "a>b"
    jmp    puts
.L1:
    rep    ret
```

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.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: [14.1.1 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 aesthetically short:

Listing 13.5: GCC 4.8.1 `f_unsigned()`

```
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.

13.1.2 ARM

32-bit ARM

Optimizing Keil 6/2013 (ARM mode)

Listing 13.6: Optimizing Keil 6/2013 (ARM mode)

```
.text:000000B8          EXPORT f_signed
.text:000000B8          f_signed           ; CODE XREF: main+C
.text:000000B8 70 40 2D E9  STMFD   SP!, {R4-R6,LR}
.text:000000BC 01 40 A0 E1  MOV      R4, R1
.text:000000C0 04 00 50 E1  CMP      R0, R4
```

13.1. SIMPLE EXAMPLE

```
.text:000000C4 00 50 A0 E1      MOV    R5, R0
.text:000000C8 1A 0E 8F C2      ADRGT  R0, aAB          ; "a>b\n"
.text:000000CC A1 18 00 CB      BLGT   __2printf
.text:000000D0 04 00 55 E1      CMP    R5, R4
.text:000000D4 67 0F 8F 02      ADREQ  R0, aAB_0        ; "a==b\n"
.text:000000D8 9E 18 00 0B      BLEQ   __2printf
.text:000000DC 04 00 55 E1      CMP    R5, R4
.text:000000E0 70 80 BD A8      LDMGEFD SP!, {R4-R6,PC}
.text:000000E4 70 40 BD E8      LDMFD  SP!, {R4-R6,LR}
.text:000000E8 19 0E 8F E2      ADR    R0, aAB_1        ; "a<b\n"
.text:000000EC 99 18 00 EA      B     __2printf
.text:000000EC                 ; End of function f_signed
```

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 `ADRG` 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 was the same (*Greater Than*). `ADRG` 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`¹, 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* \geq *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 ([7.2.1 on page 53](#)).

`f_unsigned` is similar, only the `ADRHI`, `BLHI`, and `LDMCSFD` instructions are used there, these predicates (*H* = *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:

Listing 13.7: `main()`

```
.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:00000148                 ; End of function main
```

That is how you can get rid of conditional jumps in ARM mode.

Why is this so good? Read here: [35.1 on page 455](#).

¹`LDMFD`

13.1. SIMPLE EXAMPLE

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 13.8: Optimizing Keil 6/2013 (Thumb mode)

```
.text:00000072          f_signed ; CODE XREF: main+6
.text:00000072 70 B5      PUSH    {R4-R6,LR}
.text:00000074 0C 00      MOVS    R4, R1
.text:00000076 05 00      MOVS    R5, R0
.text:00000078 A0 42      CMP     R0, R4
.text:0000007A 02 DD      BLE    loc_82
.text:0000007C A4 A0      ADR     R0, aAB           ; "a>b\n"
.text:0000007E 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\n"
.text:00000088 06 F0 B2 F8  BL      __2printf
.text:0000008C
.loc_8C ; CODE XREF: f_signed+12
.text:0000008C A5 42      CMP     R5, R4
.text:0000008E 02 DA      BGE    locret_96
.text:00000090 A3 A0      ADR     R0, aAB_1         ; "a<b\n"
.text:00000092 06 F0 AD F8  BL      __2printf
.text:00000096
.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 13.9: `f_signed()`

```
f_signed:
; W0=a, W1=b
    cmp    w0, w1
    bgt   .L19    ; Branch if Greater Than (a>b)
    beq   .L20    ; Branch if Equal (a==b)
    bge   .L15    ; Branch if Greater than or Equal (a>=b) (impossible here)
    ; a<b
    adrp   x0, .LC11      ; "a<b"
    add    x0, x0, :lo12:.LC11
    b      puts
.L19:
    adrp   x0, .LC9       ; "a>b"
    add    x0, x0, :lo12:.LC9
    b      puts
.L15: ; impossible to get here
    ret
.L20:
    adrp   x0, .LC10      ; "a==b"
    add    x0, x0, :lo12:.LC10
    b      puts
```

13.1. SIMPLE EXAMPLE

Listing 13.10: 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
    bl       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.

13.1.3 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 13.11: Non-optimizing GCC 4.4.5 (IDA)

```
.text:00000000 f_signed:                                # CODE XREF: main+18
.text:00000000
.text:00000000 var_10        = -0x10
.text:00000000 var_8         = -8
.text:00000000 var_4         = -4
.text:00000000 arg_0         = 0
.text:00000000 arg_4         = 4
.text:00000000
.text:00000000 addiu   $sp, -0x20
```

13.1. SIMPLE EXAMPLE

```

.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)
; reload them.
.text:00000024          lw      $v1, 0x20+arg_0($fp)
.text:00000028          lw      $v0, 0x20+arg_4($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)
.text:0000005C          loc_5C:                                # CODE XREF: f_signed+34
.text:0000005C          lw      $v1, 0x20+arg_0($fp)
.text:00000060          lw      $v0, 0x20+arg_4($fp)
.text:00000064          or      $at, $zero ; NOP
; 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)
.text:00000090          loc_90:                                # CODE XREF: f_signed+68
.text:00000090          lw      $v1, 0x20+arg_0($fp)
.text:00000094          lw      $v0, 0x20+arg_4($fp)
.text:00000098          or      $at, $zero ; NOP
; check if $v1<$v0 (a<b), set $v0 to 1 if condition is true:
.text:0000009C          slt    $v0, $v1, $v0
; if condition is not true (i.e., $v0==0), jump to loc_c8:
.text:000000A0          beqz $v0, loc_C8
.text:000000A4          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)
.text:000000C8          loc_C8:                                # CODE XREF: f_signed+A0
.text:000000C8          move   $sp, $fp

```

13.1. SIMPLE EXAMPLE

```
.text:0000000CC          lw      $ra, 0x20+var_4($sp)
.text:0000000D0          lw      $fp, 0x20+var_8($sp)
.text:0000000D4          addiu $sp, 0x20
.text:0000000D8          jr      $ra
.text:0000000DC          or      $at, $zero ; branch delay slot, NOP
.text:0000000DC # End of function f_signed
```

`SLT REG0, REG0, REG1` is reduced by IDA to its shorter form `SLT REG0, REG1`.

We also see there `BEQZ` pseudoinstruction ("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 13.12: Non-optimizing GCC 4.4.5 (IDA)

```
.text:000000E0 f_unsigned:                                # CODE XREF: main+28
.text:000000E0
.text:000000E0 var_10          = -0x10
.text:000000E0 var_8           = -8
.text:000000E0 var_4           = -4
.text:000000E0 arg_0           = 0
.text:000000E0 arg_4           = 4
.text:000000E0
.text:000000E0                 addiu $sp, -0x20
.text:000000E4                 sw     $ra, 0x20+var_4($sp)
.text:000000E8                 sw     $fp, 0x20+var_8($sp)
.text:000000EC                 move  $fp, $sp
.text:000000F0                 la     $gp, __gnu_local_gp
.text:000000F8                 sw     $gp, 0x20+var_10($sp)
.text:000000FC                 sw     $a0, 0x20+arg_0($fp)
.text:00000100                 sw     $a1, 0x20+arg_4($fp)
.text:00000104                 lw     $v1, 0x20+arg_0($fp)
.text:00000108                 lw     $v0, 0x20+arg_4($fp)
.text:0000010C                 or     $at, $zero
.text:00000110                 sltu $v0, $v1
.text:00000114                 beqz $v0, loc_13C
.text:00000118                 or     $at, $zero
.text:0000011C                 lui   $v0, (unk_230 >> 16)
.text:00000120                 addiu $a0, $v0, (unk_230 & 0xFFFF)
.text:00000124                 lw     $v0, (puts & 0xFFFF)($gp)
.text:00000128                 or     $at, $zero
.text:0000012C                 move  $t9, $v0
.text:00000130                 jalr $t9
.text:00000134                 or     $at, $zero
.text:00000138                 lw     $gp, 0x20+var_10($fp)
.text:0000013C
.text:0000013C loc_13C:                                     # CODE XREF: f_unsigned+34
.text:0000013C                 lw     $v1, 0x20+arg_0($fp)
.text:00000140                 lw     $v0, 0x20+arg_4($fp)
.text:00000144                 or     $at, $zero
.text:00000148                 bne   $v1, $v0, loc_170
.text:0000014C                 or     $at, $zero
.text:00000150                 lui   $v0, (aAB >> 16) # "a==b"
.text:00000154                 addiu $a0, $v0, (aAB & 0xFFFF) # "a==b"
.text:00000158                 lw     $v0, (puts & 0xFFFF)($gp)
.text:0000015C                 or     $at, $zero
.text:00000160                 move  $t9, $v0
.text:00000164                 jalr $t9
.text:00000168                 or     $at, $zero
.text:0000016C                 lw     $gp, 0x20+var_10($fp)
.text:00000170
.text:00000170 loc_170:                                     # CODE XREF: f_unsigned+68
.text:00000170                 lw     $v1, 0x20+arg_0($fp)
.text:00000174                 lw     $v0, 0x20+arg_4($fp)
.text:00000178                 or     $at, $zero
.text:0000017C                 sltu $v0, $v1, $v0
.text:00000180                 beqz $v0, loc_1A8
.text:00000184                 or     $at, $zero
.text:00000188                 lui   $v0, (aAB_0 >> 16) # "a<b"
.text:0000018C                 addiu $a0, $v0, (aAB_0 & 0xFFFF) # "a<b"
```

13.2. CALCULATING ABSOLUTE VALUE

```
.text:00000190          lw      $v0, (puts & 0xFFFF)($gp)
.text:00000194          or      $at, $zero
.text:00000198          move   $t9, $v0
.text:0000019C          jalr   $t9
.text:000001A0          or      $at, $zero
.text:000001A4          lw      $gp, 0x20+var_10($fp)
.text:000001A8
.text:000001A8 loc_1A8:           # CODE XREF: f_unsigned+A0
.text:000001A8          move   $sp, $fp
.text:000001AC          lw      $ra, 0x20+var_4($sp)
.text:000001B0          lw      $fp, 0x20+var_8($sp)
.text:000001B4          addiu $sp, 0x20
.text:000001B8          jr      $ra
.text:000001BC          or      $at, $zero
.text:000001BC # End of function f_unsigned
```

13.2 Calculating absolute value

A simple function:

```
int my_abs (int i)
{
    if (i<0)
        return -i;
    else
        return i;
};
```

13.2.1 Optimizing MSVC

This is how the code is usually generated:

Listing 13.13: 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.

13.2.2 Optimizing Keil 6/2013: Thumb mode

Listing 13.14: Optimizing Keil 6/2013: Thumb mode

```
my_abs PROC
    CMP    r0,#0
; is input value equal to zero or greater than zero?
; skip RSBS instruction then
    BGE    |L0.6|
; subtract input value from 0:
    RSBS   r0,r0,#0
|L0.6|
    BX     lr
```

13.2. CALCULATING ABSOLUTE VALUE

```
ENDP
```

ARM lacks a negate instruction, so the Keil compiler uses the “Reverse Subtract” instruction, which just subtracts with reversed operands.

13.2.3 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:

Listing 13.15: Optimizing Keil 6/2013: ARM mode

```
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: [35.1 on page 455](#).

13.2.4 Non-optimizing GCC 4.9 (ARM64)

ARM64 has instruction **NEG** for negating:

Listing 13.16: Optimizing GCC 4.9 (ARM64)

```
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
    ldr   w0, [sp,12]
    neg   w0, w0
    b     .L3
.L2:
    ldr   w0, [sp,12]
.L3:
    add   sp, sp, 16
    ret
```

13.2.5 MIPS

Listing 13.17: Optimizing GCC 4.4.5 (IDA)

```
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
```

Here we see a new instruction: **BLTZ** (“Branch if Less Than Zero”).

There is also the **NEGU** pseudoinstruction, 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.

13.2.6 Branchless version?

You could have also a branchless version of this code. This we will review later: [47 on page 512](#).

13.3 Ternary conditional operator

The ternary conditional operator in C/C++ has the following syntax:

```
expression ? expression : expression
```

Here is an example:

```
const char* f (int a)
{
    return a==10 ? "it is ten" : "it is not ten";
}
```

13.3.1 x86

Old and non-optimizing compilers generate assembly code just as if an `if/else` statement was used:

Listing 13.18: 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 13.19: 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
    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
```

13.3. TERNARY CONDITIONAL OPERATOR

Newer compilers are more concise:

Listing 13.20: 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.

13.3.2 ARM

Optimizing Keil for ARM mode also uses the conditional instructions `ADRcc`:

Listing 13.21: 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

|L0.16|
    DCB    "it is ten",0
|L0.28|
    DCB    "it is not ten",0
```

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 13.22: Optimizing Keil 6/2013 (Thumb mode)

```
f PROC
; compare input value with 10
    CMP    r0,#0xa
; jump to |L0.8| if EEqual
    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

|L0.12|
    DCB    "it is not ten",0
|L0.28|
    DCB    "it is ten",0
```

13.3.3 ARM64

Optimizing GCC (Linaro) 4.9 for ARM64 also uses conditional jumps:

Listing 13.23: Optimizing GCC (Linaro) 4.9

```
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`)[\[ARM13a\]](#), p390, C5.5], but GCC 4.9 does not seem to be smart enough to use it in such piece of code.

13.3.4 MIPS

Unfortunately, GCC 4.4.5 for MIPS is not very smart, either:

Listing 13.24: Optimizing GCC 4.4.5 (assembly output)

```
$LC0:
    .ascii  "it is not ten\000"
$LC1:
    .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    $2,%hi($LC0)
    j     $31
    addiu $2,$2,%lo($LC0)

$L2:
; leave address of "it is ten" string in $v0 and return:
    lui    $2,%hi($LC1)
    j     $31
    addiu $2,$2,%lo($LC1)
```

13.3.5 Let's rewrite it in an `if/else` way

```
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 13.25: Optimizing GCC 4.8

```
.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 [13.21](#).

But the optimizing MSVC 2012 is not that good (yet).

13.3.6 Conclusion

Why optimizing compilers try to get rid of conditional jumps? Read here about it: [35.1 on page 455](#).

13.4 Getting minimal and maximal values

13.4.1 32-bit

```
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 13.26: Non-optimizing MSVC 2013

```
_a$ = 8
_b$ = 12
_my_min PROC
    push    ebp
    mov     ebp, esp
    mov     eax, DWORD PTR _a$[ebp]
; compare A and B:
    cmp    eax, DWORD PTR _b$[ebp]
; jump, if A is greater or equal to B:
    jge    SHORT $LN2@my_min
; reload A to EAX if otherwise and jump to exit
    mov    eax, DWORD PTR _a$[ebp]
    jmp    SHORT $LN3@my_min
    jmp    SHORT $LN3@my_min ; this is redundant JMP
$LN2@my_min:
; return B
    mov    eax, DWORD PTR _b$[ebp]
$LN3@my_min:
    pop    ebp
```

13.4. GETTING MINIMAL AND MAXIMAL VALUES

```

        ret      0
_my_min ENDP

_a$ = 8
_b$ = 12
_my_max PROC
    push    ebp
    mov     ebp, esp
    mov     eax, DWORD PTR _a$[ebp]
; compare A and B:
    cmp     eax, DWORD PTR _b$[ebp]
; jump if A is less or equal to B:
    jle     SHORT $LN2@my_max
; reload A to EAX if otherwise and jump to exit
    mov     eax, DWORD PTR _a$[ebp]
    jmp     SHORT $LN3@my_max
    jmp     SHORT $LN3@my_max ; this is redundant JMP
$LN2@my_max:
; return B
    mov     eax, DWORD PTR _b$[ebp]
$LN3@my_max:
    pop    ebp
    ret      0
_my_max ENDP

```

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 probably left by mistake.

Branchless

ARM for Thumb mode reminds us of x86 code:

Listing 13.27: Optimizing Keil 6/2013 (Thumb mode)

```

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|
; return
    BX      lr
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:

13.4. GETTING MINIMAL AND MAXIMAL VALUES

Listing 13.28: Optimizing Keil 6/2013 (ARM mode)

```

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 13.29: Optimizing MSVC 2013

```

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

```

13.4.2 64-bit

```

#include <stdint.h>

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)
{

```

13.4. GETTING MINIMAL AND MAXIMAL VALUES

```
if (a<b)
    return a;
else
    return b;
};
```

There is some unneeded value shuffling, but the code is comprehensible:

Listing 13.30: 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 13.31: 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)
    cmovge rax, rdi
    ret

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)
```

13.4. GETTING MINIMAL AND MAXIMAL VALUES

```
cmovele 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 13.32: Optimizing GCC 4.9.1 ARM64

```
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  
  
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
```

13.4.3 MIPS

Unfortunately, GCC 4.4.5 for MIPS is not that good:

Listing 13.33: Optimizing GCC 4.4.5 (IDA)

```
my_max:  
; set $v1 $a1<$a0:  
    slt      $v1, $a1, $a0  
; jump, if $a1<$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  
  
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 wasn't taken.

13.5 Conclusion

13.5.1 x86

Here's the rough skeleton of a conditional jump:

Listing 13.34: 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:
```

13.5.2 ARM

Listing 13.35: 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:
```

13.5.3 MIPS

Listing 13.36: Check for zero

```
BEQZ REG, label
...
```

Listing 13.37: Check for less than zero:

```
BLTZ REG, label
...
```

Listing 13.38: Check for equal values

```
BEQ REG1, REG2, label
...
```

Listing 13.39: Check for non-equal values

```
BNE REG1, REG2, label
...
```

Listing 13.40: Check for less than, greater than (signed)

```
SLT REG1, REG2, REG3
BEQ REG1, label
...
```

Listing 13.41: Check for less than, greater than (unsigned)

```
SLTU REG1, REG2, REG3
BEQ REG1, label
...
```

13.5.4 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 13.42: 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: [18.7.2 on page 262](#).

Listing 13.43: 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
```

13.6 Exercise

(ARM64) Try rewriting the code in listing [13.23](#) by removing all conditional jump instructions and using the `CSEL` instruction.

Chapter 14

switch()/case/default

14.1 Small number of cases

```
#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()
{
    f (2); // test
}
```

14.1.1 x86

Non-optimizing MSVC

Result (MSVC 2010):

Listing 14.1: 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:
```

14.1. SMALL NUMBER OF CASES

```
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
```

Our function with a few cases in switch() is in fact analogous to this construction:

```
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");
};
```

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. 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`¹.

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`

Listing 14.2: 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 $SG789 ; '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
```

¹Local variables in stack are prefixed with `tv` –that's how MSVC names internal variables for its needs

14.1. SMALL NUMBER OF CASES

```
_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` was 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 does 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 need 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 `callee`, 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()`² function. And of course, it is all done for the sake of speed.

A similar case with the ARM compiler is described in "printf() with several arguments" section, here ([7.2.1 on page 53](#)).

²wikipedia

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OllyDbg

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 in the beginning, that's the function's input value:

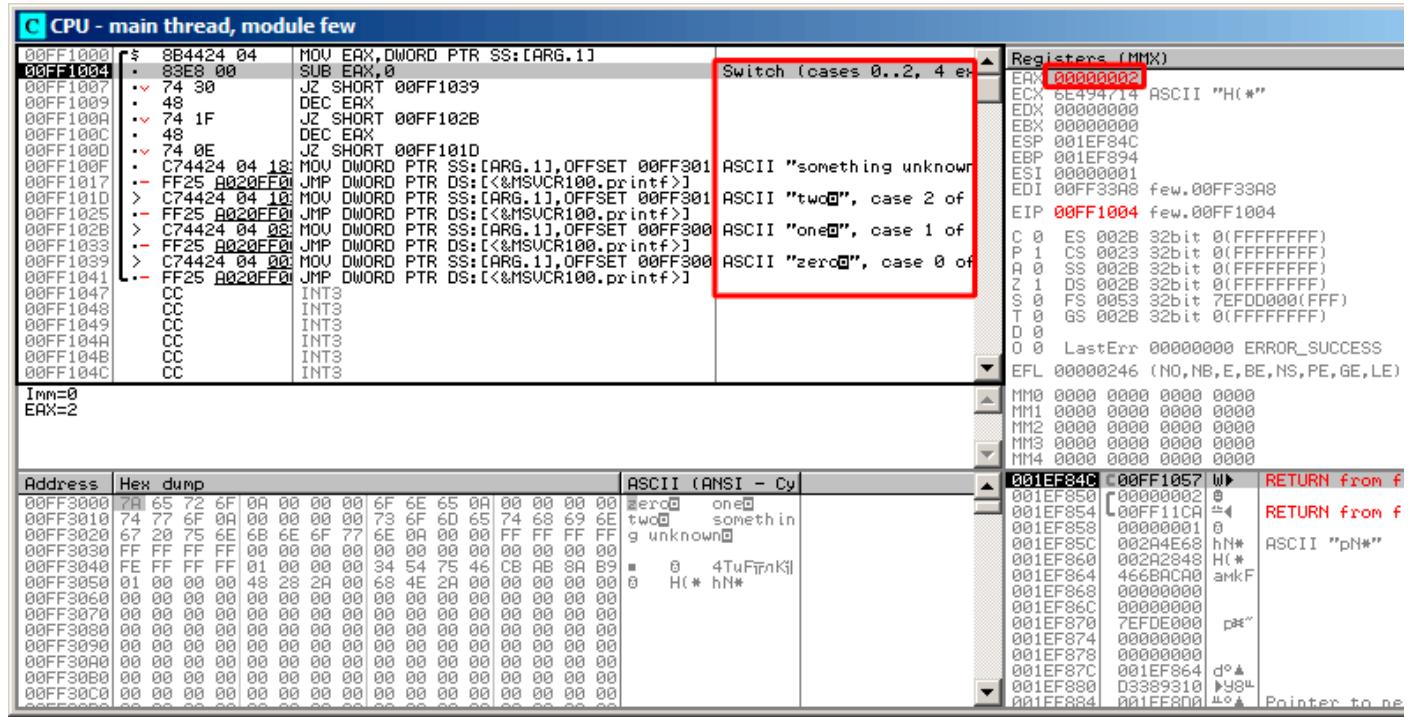


Figure 14.1: OllyDbg: **EAX** now contain the first (and only) function argument

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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:

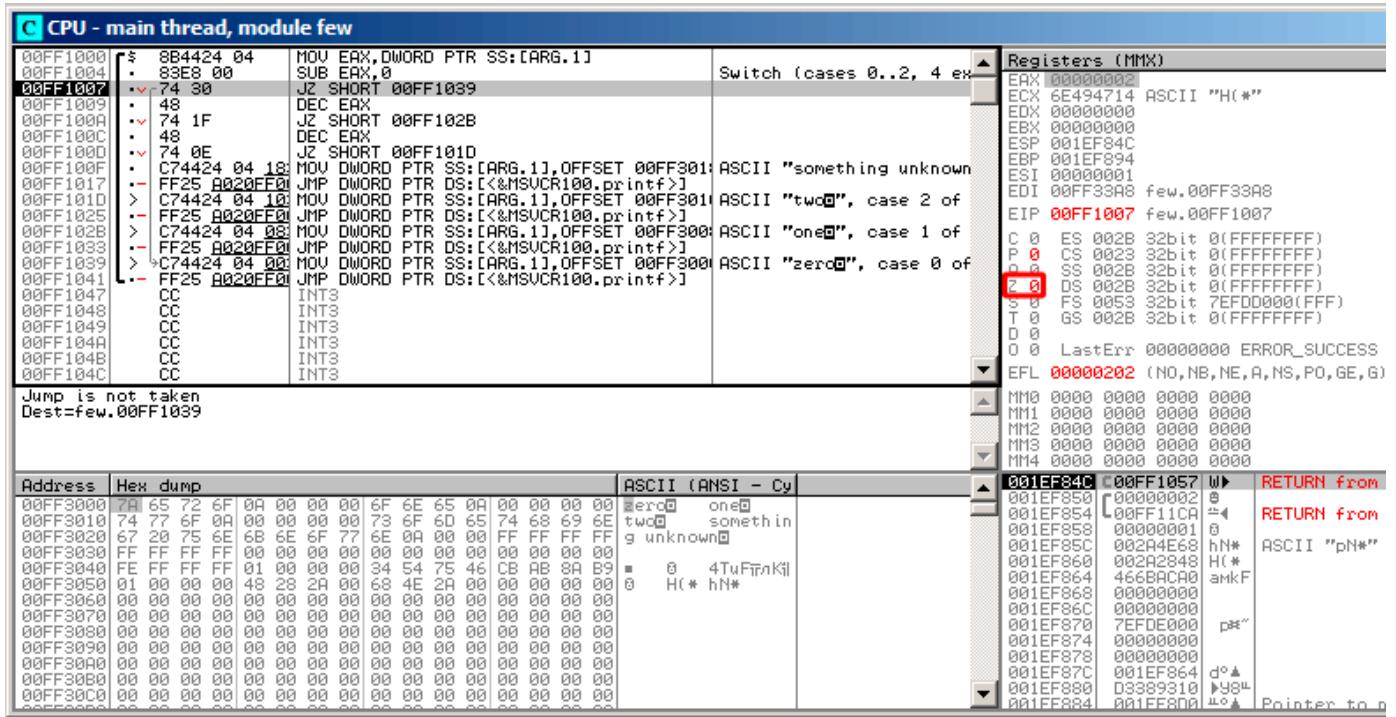


Figure 14.2: OllyDbg: `SUB` executed

14.1. SMALL NUMBER OF CASES

`DEC` is executed and `EAX` now contains 1. But 1 is non-zero, so the `ZF` flag is still 0:

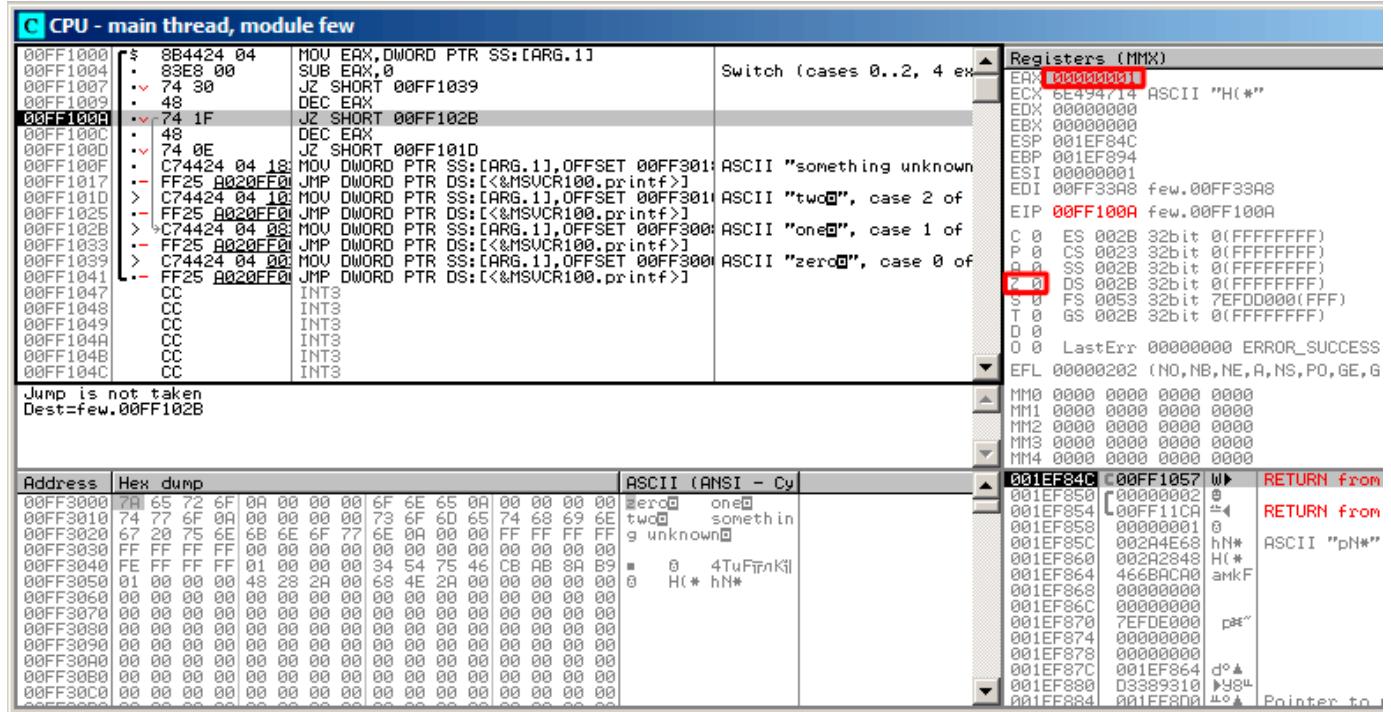


Figure 14.3: OllyDbg: first `DEC` executed

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Next DEC is executed. EAX is finally 0 and the ZF flag gets set, because the result is zero:

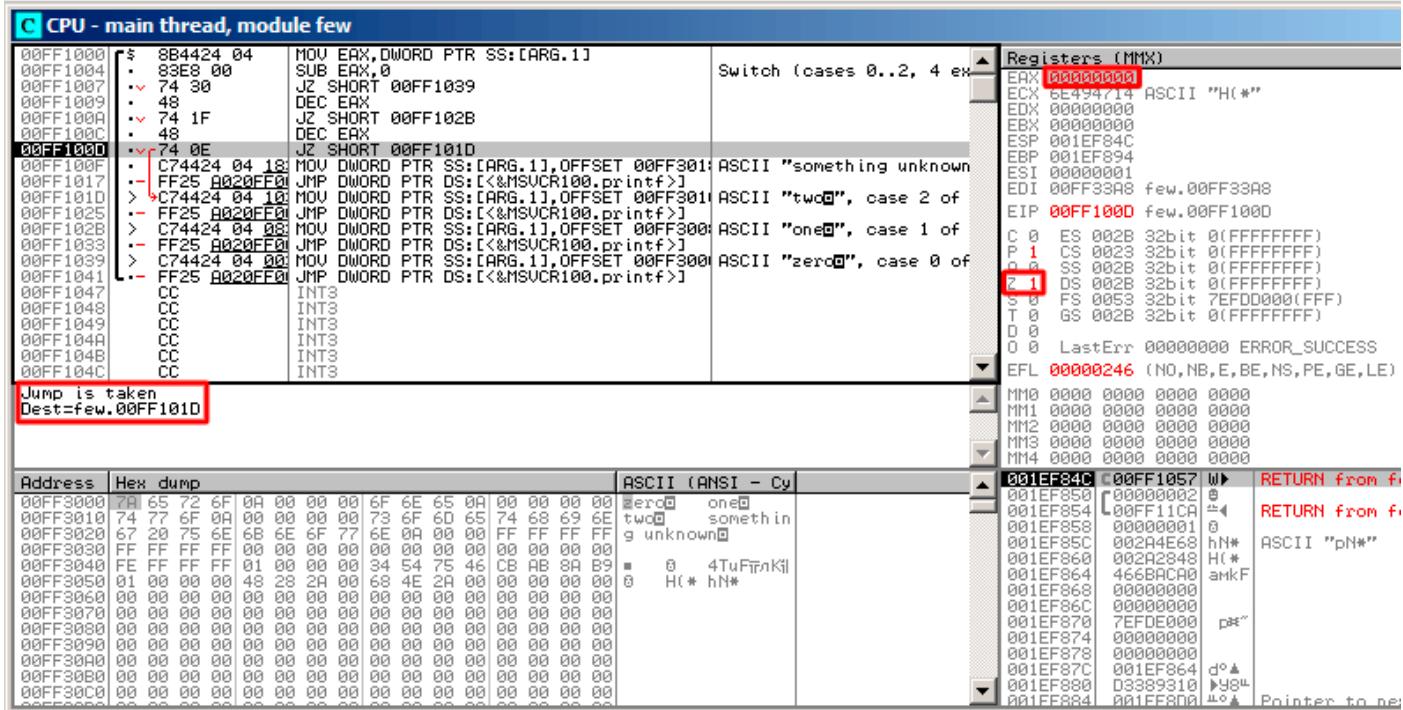


Figure 14.4: OllyDbg: second DEC executed

OllyDbg shows that this jump is to be taken now.

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A pointer to the string "two" is to be written into the stack now:

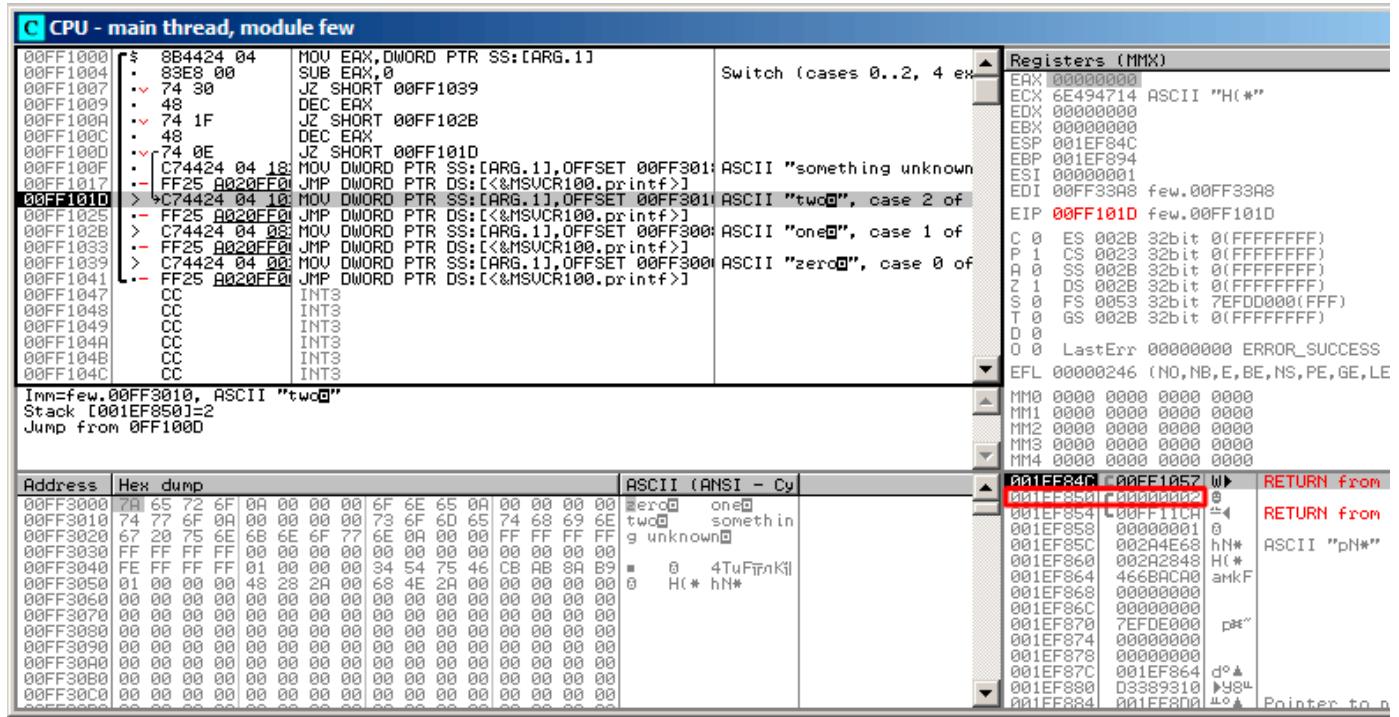


Figure 14.5: OllyDbg: pointer to the string is to be written at the place of the first argument

Please note: the current argument of the function is 2 and 2 is now in the stack at the address 0x001EF850.

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`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):

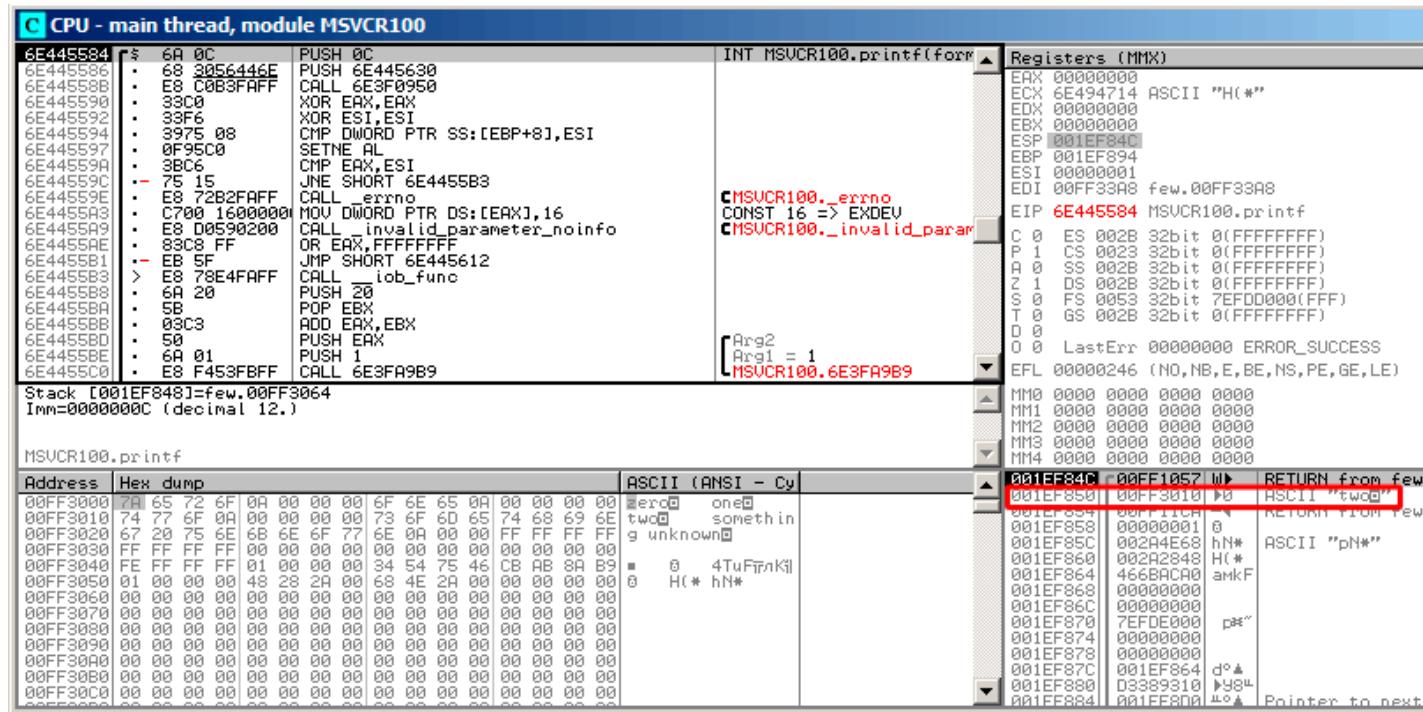


Figure 14.6: OllyDbg: first instruction of `printf()` in MSVCR100.DLL

Now `printf()` treats the string at `0x00FF3010` as its only argument and prints the string.

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This is the last instruction of `printf()`:

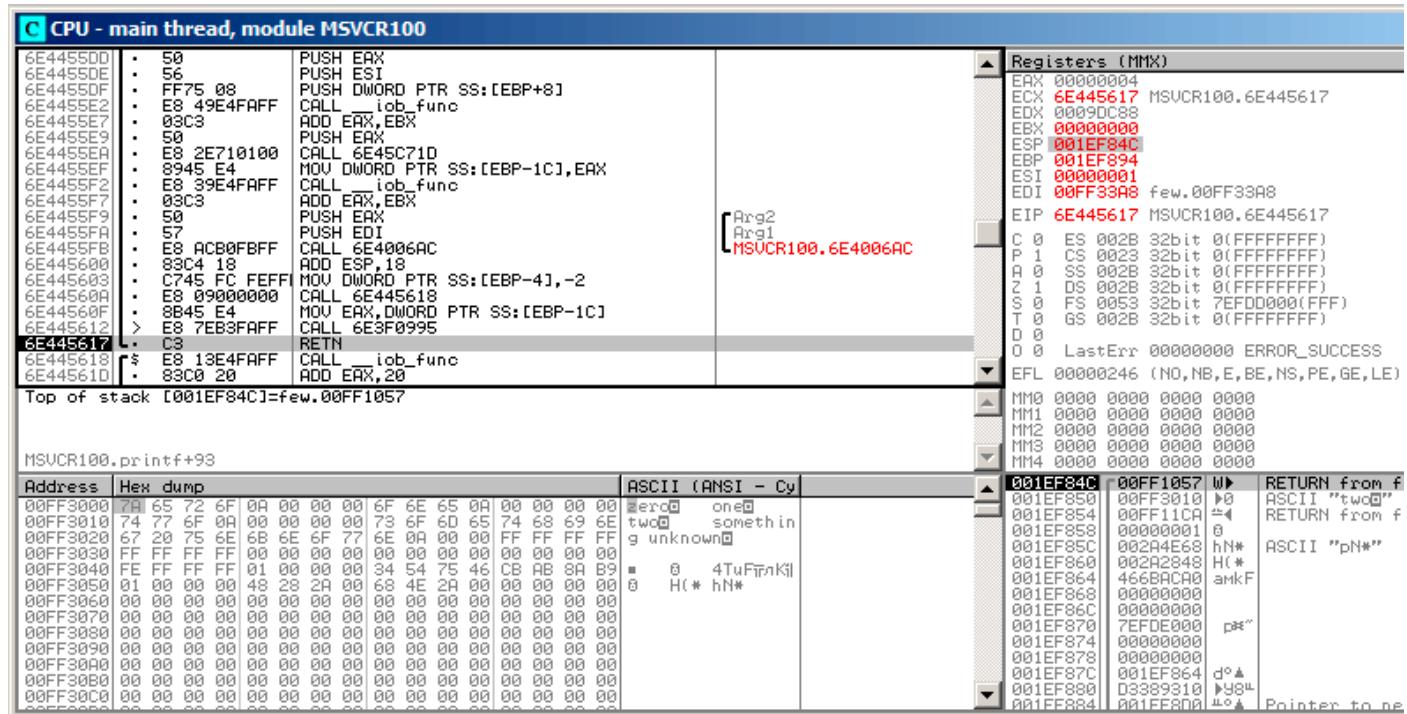


Figure 14.7: OllyDbg: last instruction of `printf()` in MSVCR100.DLL

The string "two" was just printed to the console window.

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Now let's press F7 or F8 (step over) and return...not to `f()`, but rather to `main()`:

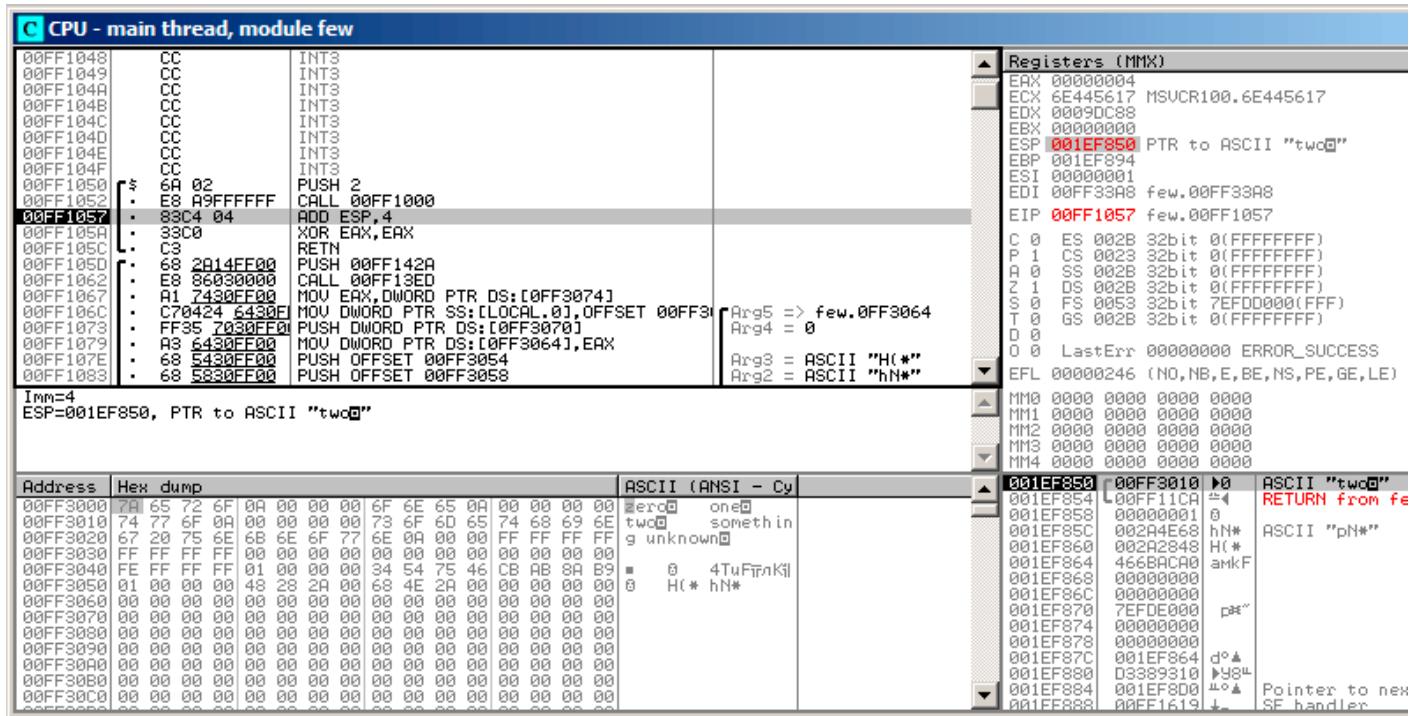


Figure 14.8: OllyDbg: return to `main()`

Yes, the jump was direct, from the guts of `printf()` to `main()`. Because RA in the stack points not to some place in `f()`, but rather to `main()`. And `CALL 0x00FF1000` was the actual instruction which called `f()`.

14.1.2 ARM: Optimizing Keil 6/2013 (ARM mode)

```
.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 02  ADREQ R0, aOne  ; "one\n"
.text:00000160 02 00 00 0A  BEQ    loc_170
.text:00000164 02 00 50 E3  CMP    R0, #2
.text:00000168 4A 0F 8F 12  ADRNE  R0, aSomethingUnkno ; "something unknown\n"
.text:0000016C 4E 0F 8F 02  ADREQ R0, aTwo   ; "two\n"
.text:00000170
.loc_170: ; CODE XREF: 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 (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 `loc_170`, if `R0 = 0`.

An astute reader may ask, will `BEQ` trigger correctly since `ADREQ` before it has already filled the `R0` register 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 ([7.2.1 on page 53](#)). In the end, there are three paths to `printf()`.

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` was already checked to be equal to 0 or 1, and we can be sure that the `a` variable is

14.1. SMALL NUMBER OF CASES

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**.

14.1.3 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    ADR    R0, aSomethingUnkno ; "something unknown\n"
.text:000000E4 04 E0    B      default_case

.text:000000E6          zero_case: ; CODE XREF: f1+4
.text:000000E6 95 A0    ADR    R0, aZero ; "zero\n"
.text:000000E8 02 E0    B      default_case

.text:000000EA          one_case: ; CODE XREF: f1+8
.text:000000EA 96 A0    ADR    R0, aOne ; "one\n"
.text:000000EC 00 E0    B      default_case

.text:000000EE          two_case: ; CODE XREF: f1+C
.text:000000EE 97 A0    ADR    R0, aTwo ; "two\n"
.text:000000F0          default_case ; CODE XREF: f1+10
.text:000000F0           ; f1+14
.text:000000F0 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.

14.1.4 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
    b1    puts
    b     .L32
.L34:
    adrp   x0, .LC13       ; "one"
    add    x0, x0, :lo12:.LC13
    b1    puts
    b     .L32
.L35:
    adrp   x0, .LC14       ; "two"
    add    x0, x0, :lo12:.LC14
```

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```
b1      puts
b      .L32
.L38:
    adrp    x0, .LC15      ; "something unknown"
    add     x0, x0, :lo12:.LC15
    b1     puts
    nop
.L32:
    ldp    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: [4.4.5 on page 20](#).

14.1.5 ARM64: Optimizing GCC (Linaro) 4.9

```
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: [14.1.1 on page 154](#).

14.1.6 MIPS

Listing 14.3: 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:
    lui    $a0, ($LC0 >> 16) # "zero"
    lw    $t9, (puts & 0xFFFF)($gp)
    or     $at, $zero ; load delay slot, NOP
    jr    $t9 ; branch delay slot, NOP
```

14.2. A LOT OF CASES

```
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: [14.1.1 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.

14.1.7 Conclusion

A `switch()` with few cases is indistinguishable from an *if/else* construction, for example: listing [14.1.1](#).

14.2 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
}
```

14.2.1 x86**Non-optimizing MSVC**

We get (MSVC 2010):

Listing 14.4: 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], 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.

14.2. A LOT OF CASES

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. $2 * 4 = 8$ (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*³.

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 * 4`*.

`npad` ([91 on page 898](#)) is assembly language macro that aligning the next label so that it is to be stored at an address aligned on a 4 byte (or 16 byte) 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.

³The whole method was once called *computed GOTO* in early versions of FORTRAN: [wikipedia](#). Not quite relevant these days, but what a term!

OllyDbg

Let's try this example in OllyDbg. The input value of the function (2) is loaded into **EAX**:

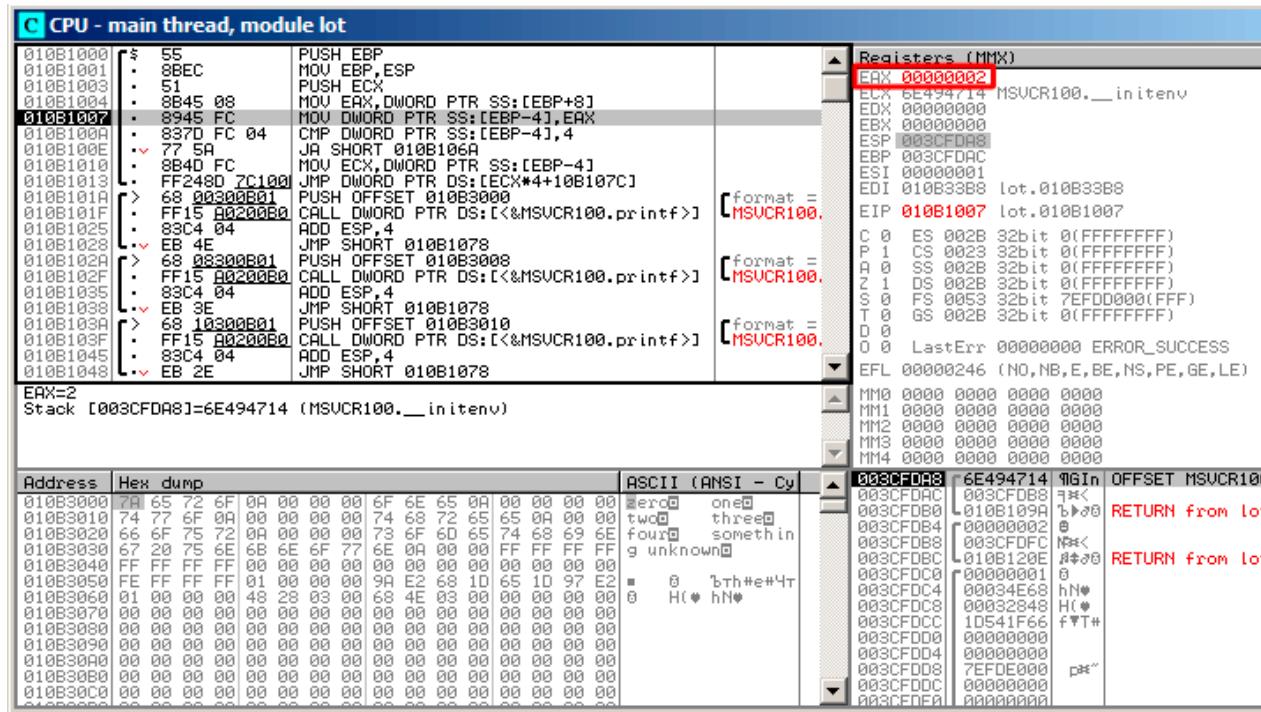


Figure 14.9: OllyDbg: function's input value is loaded in **EAX**

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The input value is checked, is it bigger than 4? If not, the “default” jump is not taken:

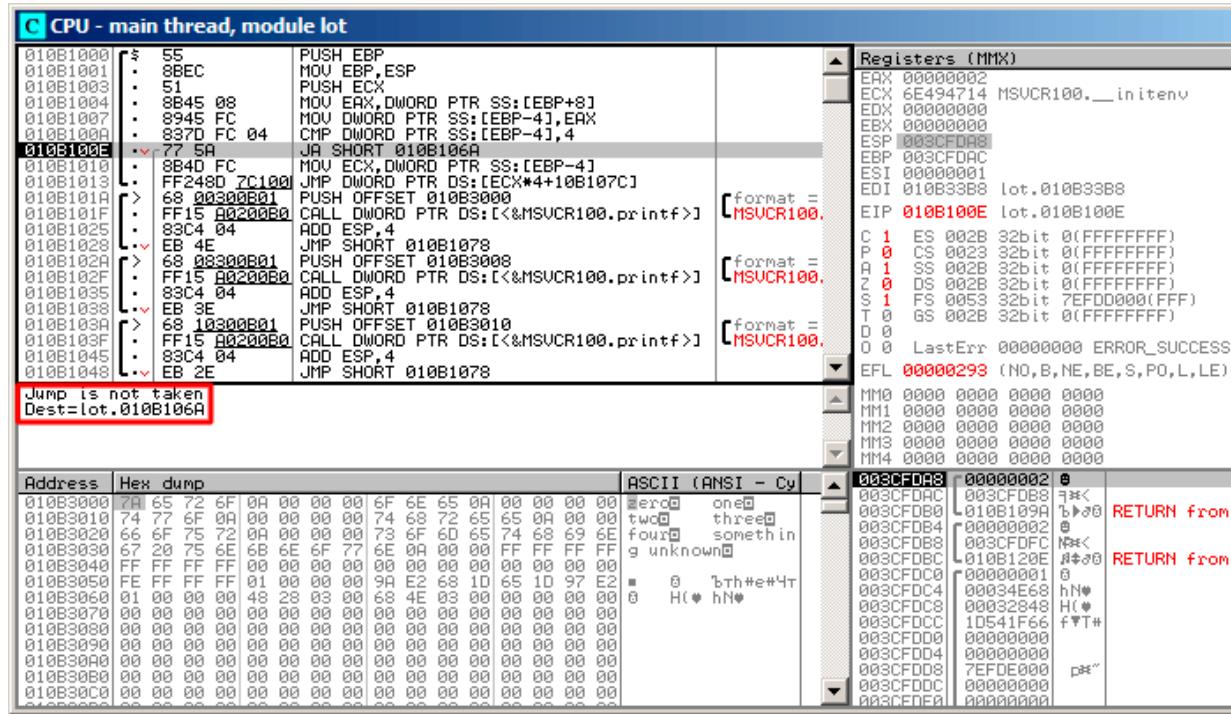


Figure 14.10: OllyDbg: 2 is no bigger than 4: no jump is taken

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Here we see a jumptable:

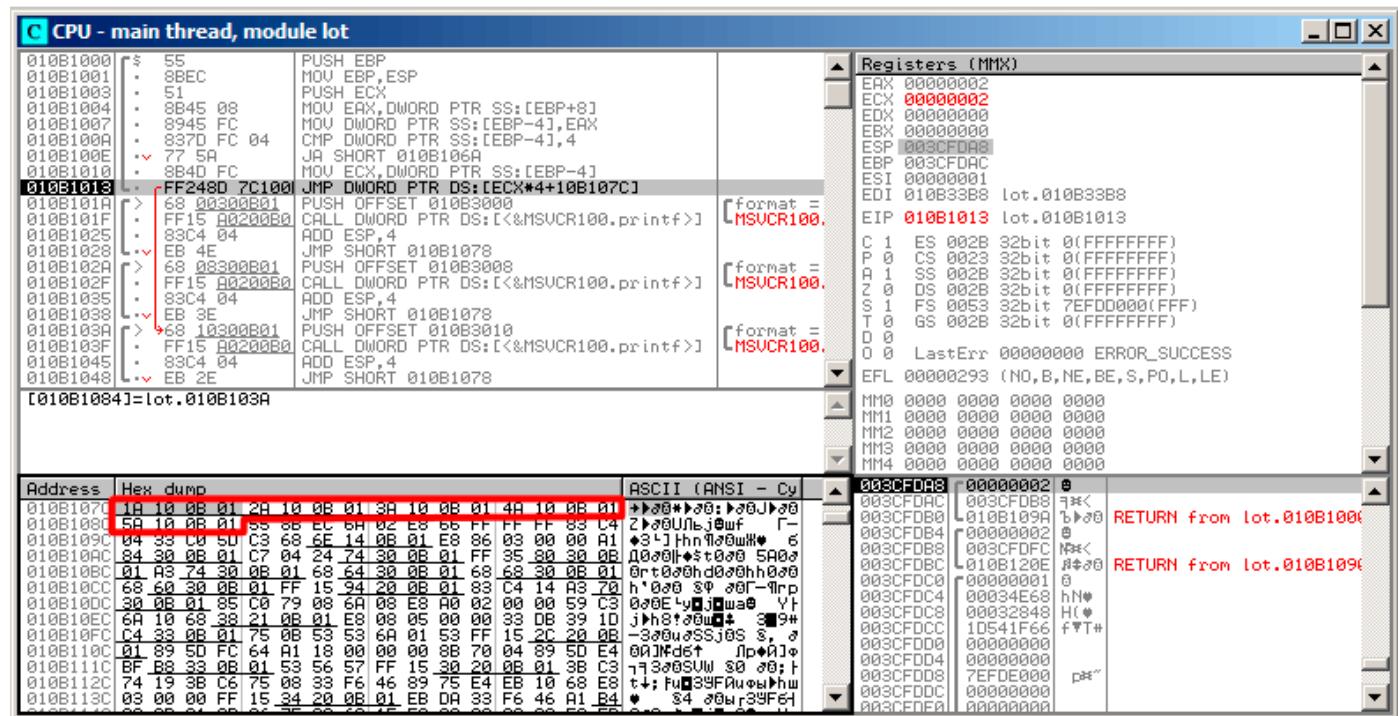


Figure 14.11: OllyDbg: calculating destination address using jumptable

Here we've clicked "Follow in Dump" → "Address constant", so now we see the *jumptable* in the data window. These are 5 32-bit values⁴. ECX is now 2, so the second element (counting from zero) 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 .

⁴They are underlined by OllyDbg because these are also FIXUPS: [71.2.6 on page 716](#), we are going to come back to them later

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After the jump we are at `0x010B103A`: the code printing "two" will now be executed:

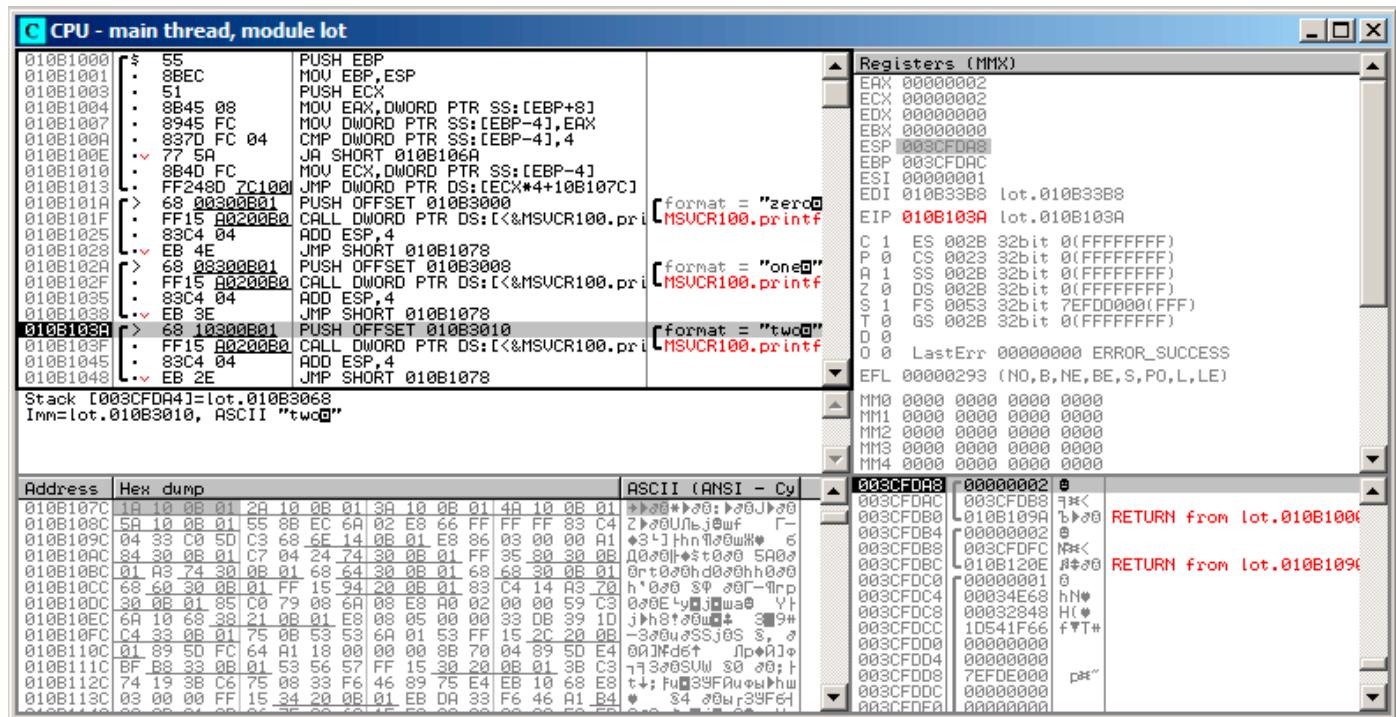


Figure 14.12: OllyDbg: now we at the *case*: label

Non-optimizing GCC

Let's see what GCC 4.4.1 generates:

Listing 14.5: GCC 4.4.1

```

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

```

14.2. A LOT OF CASES

```

    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
    ; f+34...
    leave
    retn
f    endp

off_804855C dd offset loc_80483FE ; DATA XREF: f+12
    dd offset loc_804840C
    dd offset loc_804841A
    dd offset loc_8048428
    dd offset loc_8048436

```

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) ([17.2.1 on page 215](#)). Then the address of the label is taken from the `off_804855C` array, stored in `EAX`, and then `JMP EAX` does the actual jump.

14.2.2 ARM: Optimizing Keil 6/2013 (ARM mode)

Listing 14.6: Optimizing Keil 6/2013 (ARM mode)

```

00000174      f2
00000174 05 00 50 E3    CMP    R0, #5           ; switch 5 cases
00000178 00 F1 8F 30    ADDCC  PC, PC, R0,LSL#2 ; switch jump
0000017C 0E 00 00 EA    B      default_case     ; jumptable 00000178 default case

00000180
00000180          loc_180 ; CODE XREF: f2+4
00000180 03 00 00 EA    B      zero_case       ; jumptable 00000178 case 0

00000184
00000184          loc_184 ; CODE XREF: f2+4
00000184 04 00 00 EA    B      one_case        ; jumptable 00000178 case 1

00000188
00000188          loc_188 ; CODE XREF: f2+4
00000188 05 00 00 EA    B      two_case        ; jumptable 00000178 case 2

0000018C
0000018C          loc_18C ; CODE XREF: f2+4
0000018C 06 00 00 EA    B      three_case      ; jumptable 00000178 case 3

00000190
00000190          loc_190 ; CODE XREF: f2+4
00000190 07 00 00 EA    B      four_case       ; jumptable 00000178 case 4

00000194
00000194          zero_case ; CODE XREF: f2+4
00000194          ; f2:loc_180
00000194 EC 00 8F E2    ADR    R0, aZero      ; jumptable 00000178 case 0
00000198 06 00 00 EA    B      loc_1B8

0000019C
0000019C          one_case ; CODE XREF: f2+4
0000019C          ; f2:loc_184

```

14.2. A LOT OF CASES

```
0000019C EC 00 8F E2      ADR    R0, aOne          ; jumptable 00000178 case 1
000001A0 04 00 00 EA      B      loc_1B8

000001A4
000001A4      two_case ; CODE XREF: f2+4
000001A4          ; f2:loc_188
000001A4 01 0C 8F E2      ADR    R0, aTwo          ; jumptable 00000178 case 2
000001A8 02 00 00 EA      B      loc_1B8

000001AC
000001AC      three_case ; CODE XREF: f2+4
000001AC          ; f2:loc_18C
000001AC 01 0C 8F E2      ADR    R0, aThree        ; jumptable 00000178 case 3
000001B0 00 00 00 EA      B      loc_1B8

000001B4
000001B4      four_case ; CODE XREF: f2+4
000001B4          ; f2:loc_190
000001B4 01 0C 8F E2      ADR    R0, aFour         ; jumptable 00000178 case 4
000001B8
000001B8      loc_1B8   ; CODE XREF: f2+24
000001B8          ; f2+2C
000001B8 66 18 00 EA      B      __2printf

000001BC
000001BC      default_case ; CODE XREF: f2+4
000001BC          ; f2+8
000001BC D4 00 8F E2      ADR    R0, aSomethingUnkno ; jumptable 00000178 default case
000001C0 FC FF FF EA      B      loc_1B8
```

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\n*» string to be printed.

The first `CMP R0, #5` instruction compares the input value of a with 5.

The next `ADCC PC, PC, R0, LSL#2`⁵ instruction is being executed only if $R0 < 5$ (*CC=Carry clear / Less than*). Consequently, if `ADCC` does not trigger (it is a $R0 \geq 5$ case), a jump to `default_case` label will occur.

But if $R0 < 5$ and `ADCC` 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 ([17.2.1 on page 215](#)) in section “Shifts”, shift left by 2 bits is equivalent to multiplying by 4.

Then we add $R0 * 4$ to the current value in `PC`, thus jumping to one of the `B` (*Branch*) instructions located below.

At the moment of the execution of `ADCC`, the value in `PC` is 8 bytes ahead (0x180) than the address at which the `ADCC` instruction is located (0x178), or, in other words, 2 instructions ahead.

This is how the pipeline in ARM processors works: when `ADCC` 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 `ADCC` instruction is.

If $a = 1$, then $PC + 8 + a * 4 = PC + 8 + 1 * 4 = PC + 12 = 0x184$ 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.

14.2.3 ARM: Optimizing Keil 6/2013 (Thumb mode)

⁵ADD-addition

Listing 14.7: Optimizing Keil 6/2013 (Thumb mode)

```

000000F6          EXPORT f2
000000F6          f2
000000F6 10 B5    PUSH   {R4,LR}
000000F8 03 00    MOVS   R3, R0
000000FA 06 F0 69 F8  BL     __ARM_common_switch8_thumb ; switch 6 cases

000000FE 05      DCB 5
000000FF 04 06 08 0A 0C 10  DCB 4, 6, 8, 0xA, 0xC, 0x10 ; jump table for switch statement
00000105 00      ALIGN 2

00000106          zero_case ; CODE XREF: f2+4
00000106 8D A0    ADR    R0, aZero ; jumptable 000000FA case 0
00000108 06 E0    B      loc_118

0000010A          one_case ; CODE XREF: f2+4
0000010A 8E A0    ADR    R0, aOne ; jumptable 000000FA case 1
0000010C 04 E0    B      loc_118

0000010E          two_case ; CODE XREF: f2+4
0000010E 8F A0    ADR    R0, aTwo ; jumptable 000000FA case 2
00000110 02 E0    B      loc_118

00000112          three_case ; CODE XREF: f2+4
00000112 90 A0    ADR    R0, aThree ; jumptable 000000FA case 3
00000114 00 E0    B      loc_118

00000116          four_case ; CODE XREF: f2+4
00000116 91 A0    ADR    R0, aFour ; jumptable 000000FA case 4
00000118          loc_118 ; CODE XREF: f2+12
00000118          ; f2+16
00000118 06 F0 6A F8  BL     __2printf
0000011C 10 BD    POP    {R4,PC}

0000011E          default_case ; CODE XREF: f2+4
0000011E 82 A0    ADR    R0, aSomethingUnkno ; jumptable 000000FA default case
00000120 FA E7    B      loc_118

000061D0          EXPORT __ARM_common_switch8_thumb
000061D0          __ARM_common_switch8_thumb ; CODE XREF: example6_f2+4
000061D0 78 47    BX     PC

000061D2 00 00    ALIGN 4
000061D2          ; End of function __ARM_common_switch8_thumb
000061D2
000061D4          __32__ARM_common_switch8_thumb ; CODE XREF: ↴
    ↴ __ARM_common_switch8_thumb
000061D4 01 C0 5E E5  LDRB   R12, [LR,#-1]
000061D8 0C 00 53 E1  CMP    R3, R12
000061DC 0C 30 DE 27  LDRCSB R3, [LR,R12]
000061E0 03 30 DE 37  LDRCCB R3, [LR,R3]
000061E4 83 C0 8E E0  ADD    R12, LR, R3,LSL#1
000061E8 1C FF 2F E1  BX     R12
000061E8          ; End of function __32__ARM_common_switch8_thumb

```

One cannot be sure that all instructions in Thumb and Thumb-2 modes has 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 case.

A special function is present here in order to deal with the table and pass control, named `__ARM_common_switch8_thumb`. It starts with `BX PC`, whose function is to switch the processor to ARM-mode. Then you see the function for table processing.

14.2. A LOT OF CASES

It is too complex 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 `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 not generates 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.`

14.2.4 MIPS

Listing 14.8: Optimizing GCC 4.4.5 (IDA)

```
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
; jump to the address we got in jumptable:
    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
    lui      $a0, ($LC0 >> 16) # "zero"
    lw       $t9, (puts & 0xFFFF)($gp)
    or      $at, $zero ; NOP
    jr      $t9
    la      $a0, ($LC0 & 0xFFFF) # "zero" ; branch delay slot

sub_80:                      # DATA XREF: .rodata:00000124
```

14.2. A LOT OF CASES

```
; print "one" and finish
    lui      $a0, ($LC1 >> 16) # "one"
    lw       $t9, (puts & 0xFFFF)($gp)
    or       $at, $zero ; NOP
    jr       $t9
    la       $a0, ($LC1 & 0xFFFF) # "one" ; branch delay slot

sub_94:                                # DATA XREF: .rodata:00000128
; print "two" and finish
    lui      $a0, ($LC2 >> 16) # "two"
    lw       $t9, (puts & 0xFFFF)($gp)
    or       $at, $zero ; NOP
    jr       $t9
    la       $a0, ($LC2 & 0xFFFF) # "two" ; branch delay slot

; may be placed in .rodata section:
off_120:        .word sub_6C
                .word sub_80
                .word sub_94
                .word sub_44
                .word sub_58
```

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 “l” 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.

14.2.5 Conclusion

Rough skeleton of *switch()*:

Listing 14.9: x86

```
MOV REG, input
CMP REG, 4 ; maximal number of cases
JA default
SHL REG, 2 ; find element in table. shift for 3 bits in x64.
MOV REG, jump_table[REG]
JMP REG

case1:
    ; 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:
    ...

exit:
    .....

jump_table dd case1
            dd case2
```

14.3. WHEN THERE ARE SEVERAL CASE STATEMENTS IN ONE BLOCK

```
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 *jumtable* is just array of pointers, like the one described later: [19.5 on page 285](#).

14.3 When there are several *case* statements in one block

Here is a very widespread construction: several *case* statements for a single block:

```
#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.

14.3.1 MSVC

Listing 14.10: Optimizing MSVC 2010

```
1 $SG2798 DB      '1, 2, 7, 10', 0aH, 00H  
2 $SG2800 DB      '3, 4, 5', 0aH, 00H  
3 $SG2802 DB      '8, 9, 21', 0aH, 00H  
4 $SG2804 DB      '22', 0aH, 00H  
5 $SG2806 DB      'default', 0aH, 00H  
6  
7 _a$ = 8
```

14.3. WHEN THERE ARE SEVERAL CASE STATEMENTS IN ONE BLOCK

```

8 _f      PROC
9      mov     eax, DWORD PTR _a$[esp-4]
10     dec    eax
11     cmp    eax, 21
12     ja     SHORT $LN1@f
13     movzx  eax, BYTE PTR $LN10@f[eax]
14     jmp    DWORD PTR $LN11@f[eax*4]
15 $LN5@f:
16     mov     DWORD PTR _a$[esp-4], OFFSET $SG2798 ; '1, 2, 7, 10'
17     jmp    DWORD PTR __imp__printf
18 $LN4@f:
19     mov     DWORD PTR _a$[esp-4], OFFSET $SG2800 ; '3, 4, 5'
20     jmp    DWORD PTR __imp__printf
21 $LN3@f:
22     mov     DWORD PTR _a$[esp-4], OFFSET $SG2802 ; '8, 9, 21'
23     jmp    DWORD PTR __imp__printf
24 $LN2@f:
25     mov     DWORD PTR _a$[esp-4], OFFSET $SG2804 ; '22'
26     jmp    DWORD PTR __imp__printf
27 $LN1@f:
28     mov     DWORD PTR _a$[esp-4], OFFSET $SG2806 ; 'default'
29     jmp    DWORD PTR __imp__printf
30     npad   2 ; align $LN11@f table on 16-byte boundary
31 $LN11@f:
32     DD     $LN5@f ; print '1, 2, 7, 10'
33     DD     $LN4@f ; print '3, 4, 5'
34     DD     $LN3@f ; print '8, 9, 21'
35     DD     $LN2@f ; print '22'
36     DD     $LN1@f ; print 'default'
37 $LN10@f:
38     DB     0 ; a=1
39     DB     0 ; a=2
40     DB     1 ; a=3
41     DB     1 ; a=4
42     DB     1 ; a=5
43     DB     1 ; a=6
44     DB     0 ; a=7
45     DB     2 ; a=8
46     DB     2 ; a=9
47     DB     0 ; a=10
48     DB     4 ; a=11
49     DB     4 ; a=12
50     DB     4 ; a=13
51     DB     4 ; a=14
52     DB     4 ; a=15
53     DB     4 ; a=16
54     DB     4 ; a=17
55     DB     4 ; a=18
56     DB     4 ; a=19
57     DB     2 ; a=20
58     DB     2 ; a=21
59     DB     3 ; a=22
60 _f      ENDP

```

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.

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 ([14.2.1 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.

14.3.2 GCC

GCC does the job in the way we already discussed ([14.2.1 on page 172](#)), using just one table of pointers.

14.3.3 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 using 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 14.11: Optimizing GCC 4.9.1 ARM64

```
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:
    adr     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
    .byte   (.L3 - .Lrtx4) / 4      ; case 10
    .byte   (.L2 - .Lrtx4) / 4      ; case 11
    .byte   (.L2 - .Lrtx4) / 4      ; case 12
    .byte   (.L2 - .Lrtx4) / 4      ; case 13
    .byte   (.L2 - .Lrtx4) / 4      ; case 14
    .byte   (.L2 - .Lrtx4) / 4      ; case 15
    .byte   (.L2 - .Lrtx4) / 4      ; case 16
    .byte   (.L2 - .Lrtx4) / 4      ; case 17
    .byte   (.L2 - .Lrtx4) / 4      ; case 18
    .byte   (.L2 - .Lrtx4) / 4      ; case 19
    .byte   (.L6 - .Lrtx4) / 4      ; case 20
    .byte   (.L6 - .Lrtx4) / 4      ; case 21
    .byte   (.L7 - .Lrtx4) / 4      ; case 22
    .text
; everything after ".text" statement is allocated in the code (text) segment:
```

14.3. WHEN THERE ARE SEVERAL CASE STATEMENTS IN ONE BLOCK

```
.L7:
; print "22"
    adrp    x0, .LC3
    add     x0, x0, :lo12:.LC3
    b      puts

.L6:
; print "8, 9, 21"
    adrp    x0, .LC2
    add     x0, x0, :lo12:.LC2
    b      puts

.L5:
; print "3, 4, 5"
    adrp    x0, .LC1
    add     x0, x0, :lo12:.LC1
    b      puts

.L3:
; print "1, 2, 7, 10"
    adrp    x0, .LC0
    add     x0, x0, :lo12:.LC0
    b      puts

.LC0:
.string "1, 2, 7, 10"
.LC1:
.string "3, 4, 5"
.LC2:
.string "8, 9, 21"
.LC3:
.string "22"
.LC4:
.string "default"
```

Let's compile this example to object file and open it in [IDA](#). Here is the jump table:

Listing 14.12: jumptable in IDA

.rodata:000000000000000064	AREA .rodata, DATA, READONLY
.rodata:000000000000000064	; ORG 0x64
.rodata:000000000000000064 \$d	DCB 9 ; case 1
.rodata:000000000000000065	DCB 9 ; case 2
.rodata:000000000000000066	DCB 6 ; case 3
.rodata:000000000000000067	DCB 6 ; case 4
.rodata:000000000000000068	DCB 6 ; case 5
.rodata:000000000000000069	DCB 6 ; case 6
.rodata:00000000000000006A	DCB 9 ; case 7
.rodata:00000000000000006B	DCB 3 ; case 8
.rodata:00000000000000006C	DCB 3 ; case 9
.rodata:00000000000000006D	DCB 9 ; case 10
.rodata:00000000000000006E	DCB 0xF7 ; case 11
.rodata:00000000000000006F	DCB 0xF7 ; case 12
.rodata:000000000000000070	DCB 0xF7 ; case 13
.rodata:000000000000000071	DCB 0xF7 ; case 14
.rodata:000000000000000072	DCB 0xF7 ; case 15
.rodata:000000000000000073	DCB 0xF7 ; case 16
.rodata:000000000000000074	DCB 0xF7 ; case 17
.rodata:000000000000000075	DCB 0xF7 ; case 18
.rodata:000000000000000076	DCB 0xF7 ; case 19
.rodata:000000000000000077	DCB 3 ; case 20
.rodata:000000000000000078	DCB 3 ; case 21
.rodata:000000000000000079	DCB 0 ; case 22
.rodata:00000000000000007B ; .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 need 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).

14.4 Fall-through

Another very popular usage of `switch()` is the fall-through. Here is a small example:

```

1 #define R 1
2 #define W 2
3 #define RW 3
4
5 void f(int type)
6 {
7     int read=0, write=0;
8
9     switch (type)
10    {
11        case RW:
12            read=1;
13        case W:
14            write=1;
15            break;
16        case R:
17            read=1;
18            break;
19        default:
20            break;
21    }
22    printf ("read=%d, write=%d\n", read, write);
23 }
```

If `type = 1 (R)`, `read` is to be set to 1, if `type = 2 (W)`, `write` is to be set to 1. In case of `type = 3 (RW)`, both `read` and `write` is to be set to 1.

The code at line 14 is executed in two cases: if `type = RW` or if `type = W`. There is no “break” for “case RW”x and that’s OK.

14.4.1 MSVC x86

Listing 14.13: MSVC 2012

```
$SG1305 DB      'read=%d, write=%d', 0aH, 00H

_write$ = -12 ; size = 4
_read$ = -8  ; size = 4
tv64 = -4   ; size = 4
_type$ = 8   ; size = 4
_f      PROC
    push    ebp
    mov     ebp, esp
    sub     esp, 12
    mov     DWORD PTR _read$[ebp], 0
    mov     DWORD PTR _write$[ebp], 0
    mov     eax, DWORD PTR _type$[ebp]
    mov     DWORD PTR tv64[ebp], eax
    cmp     DWORD PTR tv64[ebp], 1 ; R
    je      SHORT $LN2@f
    cmp     DWORD PTR tv64[ebp], 2 ; W
    je      SHORT $LN3@f
    cmp     DWORD PTR tv64[ebp], 3 ; RW
    je      SHORT $LN4@f
    jmp     SHORT $LN5@f
$LN4@f: ; case RW:
    mov     DWORD PTR _read$[ebp], 1
$LN3@f: ; case W:
    mov     DWORD PTR _write$[ebp], 1
    jmp     SHORT $LN5@f
$LN2@f: ; case R:
    mov     DWORD PTR _read$[ebp], 1
$LN5@f: ; default
    mov     ecx, DWORD PTR _write$[ebp]
    push    ecx
```

14.5. EXERCISES

```
    mov    edx, DWORD PTR _read$[ebp]
    push   edx
    push   OFFSET $SG1305 ; 'read=%d, write=%d'
    call   _printf
    add    esp, 12
    mov    esp, ebp
    pop    ebp
    ret    0
_f      ENDP
```

The code mostly resembles what is in the source. There are no jumps between labels `$LN4@f` and `$LN3@f`: so when code flow is at `$LN4@f`, `read` is first set to 1, then `write`. This is why it's called fall-through: code flow falls through one piece of code (setting `read`) to another (setting `write`). If `type = W`, we land at `$LN3@f`, so no code setting `read` to 1 is executed.

14.4.2 ARM64

Listing 14.14: GCC (Linaro) 4.9

```
.LC0:
    .string "read=%d, write=%d\n"
f:
    stp    x29, x30, [sp, -48]!
    add    x29, sp, 0
    str    w0, [x29,28]
    str    wzr, [x29,44] ; set "read" and "write" local variables to zero
    str    wzr, [x29,40]
    ldr    w0, [x29,28] ; load "type" argument
    cmp    w0, 2          ; type=W?
    beq   .L3
    cmp    w0, 3          ; type=RW?
    beq   .L4
    cmp    w0, 1          ; type=R?
    beq   .L5
    b     .L6             ; otherwise...
.L4: ; case RW
    mov    w0, 1
    str    w0, [x29,44] ; read=1
.L3: ; case W
    mov    w0, 1
    str    w0, [x29,40] ; write=1
    b     .L6
.L5: ; case R
    mov    w0, 1
    str    w0, [x29,44] ; read=1
    nop
.L6: ; default
    adrp   x0, .LC0 ; "read=%d, write=%d\n"
    add    x0, x0, :lo12:.LC0
    ldr    w1, [x29,44] ; load "read"
    ldr    w2, [x29,40] ; load "write"
    bl     printf
    ldp    x29, x30, [sp], 48
    ret
```

Merely the same thing. There are no jumps between labels `.L4` and `.L3`.

14.5 Exercises

14.5.1 Exercise #1

It's possible to rework the C example in [14.2 on page 166](#) in such way that the compiler can produce even smaller code, but will work just the same. Try to achieve it.

Chapter 15

Loops

15.1 Simple example

15.1.1 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 done at each iteration (`increment/decrement`) and of course loop body.

```
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:

```
#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 15.1: MSVC 2010

```
_i$ = -4
_main    PROC
    push    ebp
    mov     ebp, esp
    push    ecx
```

15.1. SIMPLE EXAMPLE

```

    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
    mov    esp, ebp
    pop    ebp
    ret    0
_main  ENDP

```

As we see, nothing special.

GCC 4.4.1 emits almost the same code, with one subtle difference:

Listing 15.2: GCC 4.4.1

```

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 15.3: Optimizing MSVC

```

_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

```

15.1. SIMPLE EXAMPLE

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 15.4: Optimizing GCC 4.4.1

```
main          proc near
var_10        = dword ptr -10h
              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 footprint¹.

OK, let's increase the maximum value of the *i* variable to 100 and try again. GCC does:

Listing 15.5: GCC

```
main          public 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
```

¹A very good article about it: [[Dre07](#)]. Another recommendations about loop unrolling from Intel are here: [[Int14](#), p. 3.4.1.7].

15.1. SIMPLE EXAMPLE

```
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
```

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 `main()` function.

15.1. SIMPLE EXAMPLE

15.1.2 x86: OllyDbg

Let's compile our example in MSVC 2010 with `/Ox` and `/Obo` options and load it into OllyDbg.

It seems that OllyDbg is able to detect simple loops and show them in square brackets, for convenience:

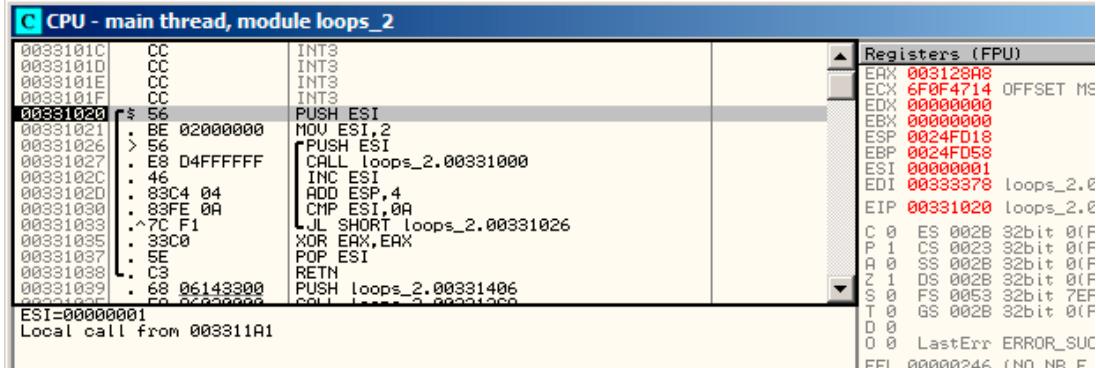


Figure 15.1: OllyDbg: `main()` begin

By tracing (F8 – step over) we see `ESI` incrementing. Here, for instance, $ESI = i = 6$:

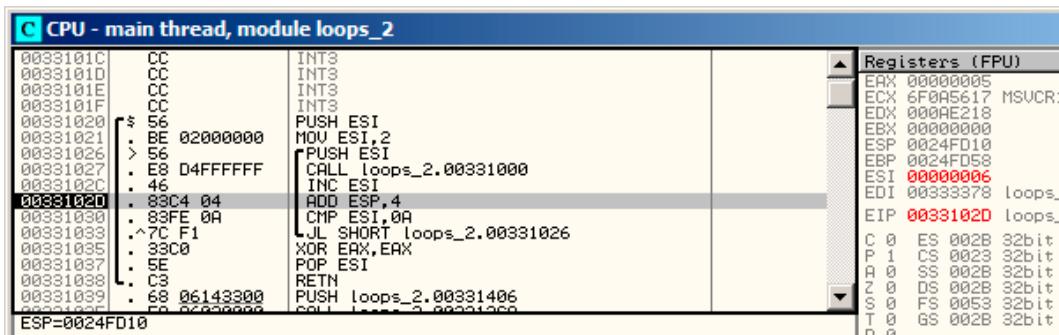


Figure 15.2: OllyDbg: loop body just executed with $i = 6$

9 is the last loop value. That's why `JL` is not triggering after the increment, and the function will finish:

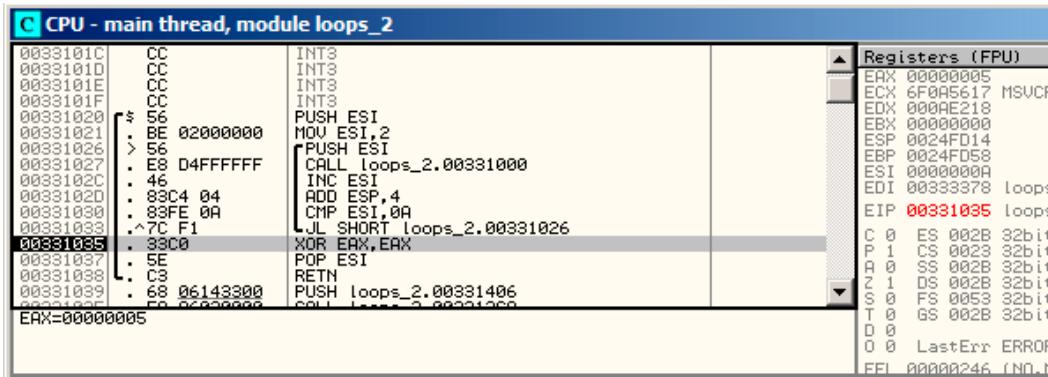


Figure 15.3: OllyDbg: $ESI = 10$, loop end

15.1.3 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
```

15.1. SIMPLE EXAMPLE

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:

```
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 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 AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000008 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF AF SF IF
(0) loops_2.exe!0x401026
EAX=0x00000005 EBX=0x00000000 ECX=0x6f0a5617 EDX=0x000ee188
ESI=0x00000009 EDI=0x00333378 EBP=0x0024fbfc ESP=0x0024fbb8
EIP=0x00331026
FLAGS=CF PF AF SF IF
PID=12884|Process loops_2.exe exited. ExitCode=0 (0x0)
```

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.

15.1. SIMPLE EXAMPLE

We load `loops_2.exe.idc` into [IDA](#) and see:

```
.text:00401020 ; ===== S U B R O U T I N E =====
.text:00401020 ; int __cdecl main(int argc, const char **argv, const char **envp)
.text:00401020 _main proc near ; CODE XREF: __tmainCRTStartup+11D↓p
.text:00401020     argc      = dword ptr  4
.text:00401020     argv      = dword ptr  8
.text:00401020     envp      = dword ptr  0Ch
.text:00401020
.text:00401020         push    esi          ; ESI=1
.text:00401021         mov     esi, 2
.text:00401026 loc_401026:           ; CODE XREF: _main+13↓j
.text:00401026         push    esi          ; ESI=2..9
.text:00401027         call    sub_401000 ; tracing nested maximum level (1) reached,
.text:0040102C         inc    esi          ; ESI=2..9
.text:0040102D         add    esp, 4          ; ESP=0x38FcBC
.text:00401030         cmp    esi, 0Ah        ; ESI=3..0xA
.text:00401033         jl    short loc_401026 ; SF=false,true OF=false
.text:00401035         xor    eax, eax
.text:00401037         pop    esi
.text:00401038         retn
.text:00401038 _main endp          ; EAX=0
```

Figure 15.4: IDA with .idc-script loaded

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 was executed and register values:

Listing 15.6: loops_2.exe.txt

```
0x401020 (.text+0x20), e= 1 [PUSH ESI] ESI=1
0x401021 (.text+0x21), e= 1 [MOV ESI, 2]
0x401026 (.text+0x26), e= 8 [PUSH ESI] ESI=2..9
0x401027 (.text+0x27), e= 8 [CALL 8D1000h] tracing nested maximum level (1) reached, ↴
    ↴ skipping this CALL 8D1000h=0x8d1000
0x40102c (.text+0x2c), e= 8 [INC ESI] ESI=2..9
0x40102d (.text+0x2d), e= 8 [ADD ESP, 4] ESP=0x38FcBC
0x401030 (.text+0x30), e= 8 [CMP ESI, 0Ah] ESI=3..0xA
0x401033 (.text+0x33), e= 8 [JL 8D1026h] SF=false,true OF=false
0x401035 (.text+0x35), e= 1 [XOR EAX, EAX]
0x401037 (.text+0x37), e= 1 [POP ESI]
0x401038 (.text+0x38), e= 1 [RETN] EAX=0
```

We can use grep here.

15.1.4 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
```

15.1. SIMPLE EXAMPLE

```
loc_368 ; CODE XREF: main+8
    CMP    R4, #0xA
    BLT    loc_35C
    MOV    R0, #0
    LDMFD  SP!, {R4,PC}
```

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)

```
_main
    PUSH   {R4,LR}
    MOVS   R4, #2

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)

```
_main
    PUSH   {R4,R7,LR}
    MOVW   R4, #0x1124 ; "%d\n"
    MOVS   R1, #2
    MOVT.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
    MOVS   R0, #0
    POP    {R4,R7,PC}
```

15.1. SIMPLE EXAMPLE

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 15.7: 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 15.8: 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
```

15.1. SIMPLE EXAMPLE

```
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"
```

15.1.5 MIPS

Listing 15.9: 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
```

15.2. MEMORY BLOCKS COPYING ROUTINE

```
; check counter, is it 10?
    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 pseudoinstruction (**BEQ**).

15.1.6 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 Keil, Xcode (LLVM), MSVC in optimization mode).

15.2 Memory blocks copying routine

Real-world memory copy routines may copy 4 or 8 bytes at each iteration, use SIMD², 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];
}
```

15.2.1 Straight-forward implementation

Listing 15.10: 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
```

²Single instruction, multiple data

15.2. MEMORY BLOCKS COPYING ROUTINE

```
.L2:
; 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 15.11: 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 X1+i:
    strb    w4, [x0,x3]
    add     x3, x3, 1 ; i++
    b       .L2
.L5:
    ret
```

Listing 15.12: 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
    MOVS   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 R1+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
```

15.2.2 ARM in ARM mode

Keil in ARM mode takes full advantage of conditional suffixes:

Listing 15.13: Optimizing Keil 6/2013 (ARM mode)

15.2. MEMORY BLOCKS COPYING ROUTINE

```

my_memcpy PROC
; 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 R1+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.

15.2.3 MIPS

Listing 15.14: 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”).

15.3. CONCLUSION

On the other hand, **LB** (“Load Byte”) instruction sign-extends the loaded byte to a 32-bit value.

SB just writes a byte from lowest 8 bits of register to memory.

15.2.4 Vectorization

Optimizing GCC can do much more on this example: [26.1.2 on page 412](#).

15.3 Conclusion

Rough skeleton of loop from 2 to 9 inclusive:

Listing 15.15: 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 15.16: 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 15.17: 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 15.18: x86

```
MOV [counter], 2 ; initialization
JMP label_check
label_increment:
ADD [counter], 1 ; increment
label_check:
CMP [counter], 10
JGE exit
```

15.4. EXERCISES

```
; loop body  
; do something here  
; use counter variable in local stack  
JMP label_increment  
exit:
```

Usually the condition is checked *before* loop body, but the compiler may rearrange it in a way that the condition is checked *after* loop body.

This is done when the compiler is sure that the condition is always *true* on the first iteration, so the body of the loop is to be executed at least once:

Listing 15.19: x86

```
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
```

Using the `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 15.20: x86

```
; 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
```

ARM.

The `R4` register is dedicated to counter variable in this example:

Listing 15.21: ARM

```
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
```

15.4 Exercises

- <http://challenges.re/54>
- <http://challenges.re/55>
- <http://challenges.re/56>
- <http://challenges.re/57>

Chapter 16

Simple C-strings processing

16.1 `strlen()`

Let's talk about loops one more time. Often, the `strlen()` function¹ is implemented using a `while()` statement. Here is how it is done in the MSVC standard libraries:

```
int my_strlen (const char * str)
{
    const char *eos = str;

    while( *eos++ ) ;

    return( eos - str - 1 );
}

int main()
{
    // test
    return my_strlen("hello!");
};
```

16.1.1 x86

Non-optimizing MSVC

Let's compile:

```
_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_:
```

¹counting the characters in a string in the C language

16.1. 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 it 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 need to transfer `0xFE` from a variable of *char* type to *int*, we need to identify its sign and extend it. That is what `MOVsx` does.

You can also read about it in “*Signed number representations*” section ([31 on page 448](#)).

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 ([20 on page 303](#)). 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

        push    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     eax, [ebp+arg_0]
        mov     ecx, edx
        sub    ecx, eax
        mov     eax, ecx
        sub    eax, 1
        leave
        retn
strlen endp
```

16.1. STRLEN()

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`):

Listing 16.1: Optimizing MSVC 2012 /Ob0

```
_str$ = 8          ; size = 4
_strlen PROC
    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 substract 1 to/from a variable.

16.1. STRLEN()

Optimizing MSVC + OllyDbg

We can try this (optimized) example in OllyDbg. Here is the first iteration:

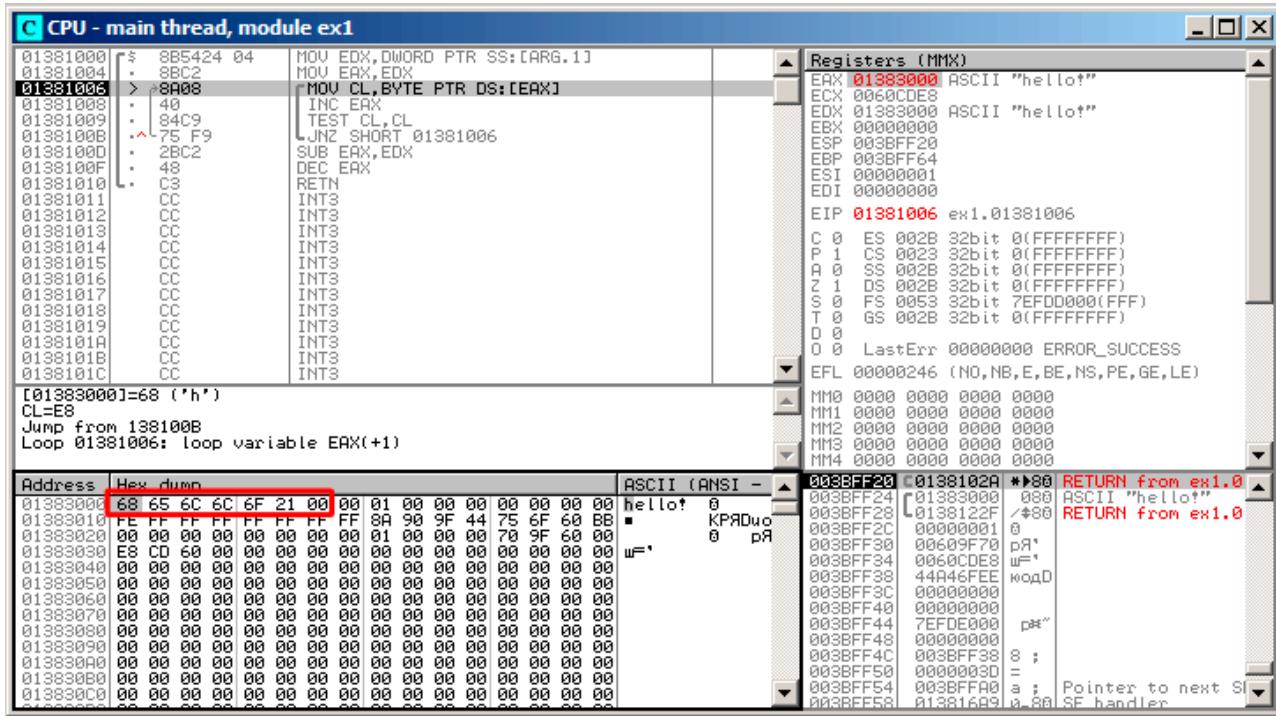


Figure 16.1: OllyDbg: first iteration start

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.

16.1. *STRLEN()*

Let's press F8 (step over) a few times, to get to the start of the body of the loop:

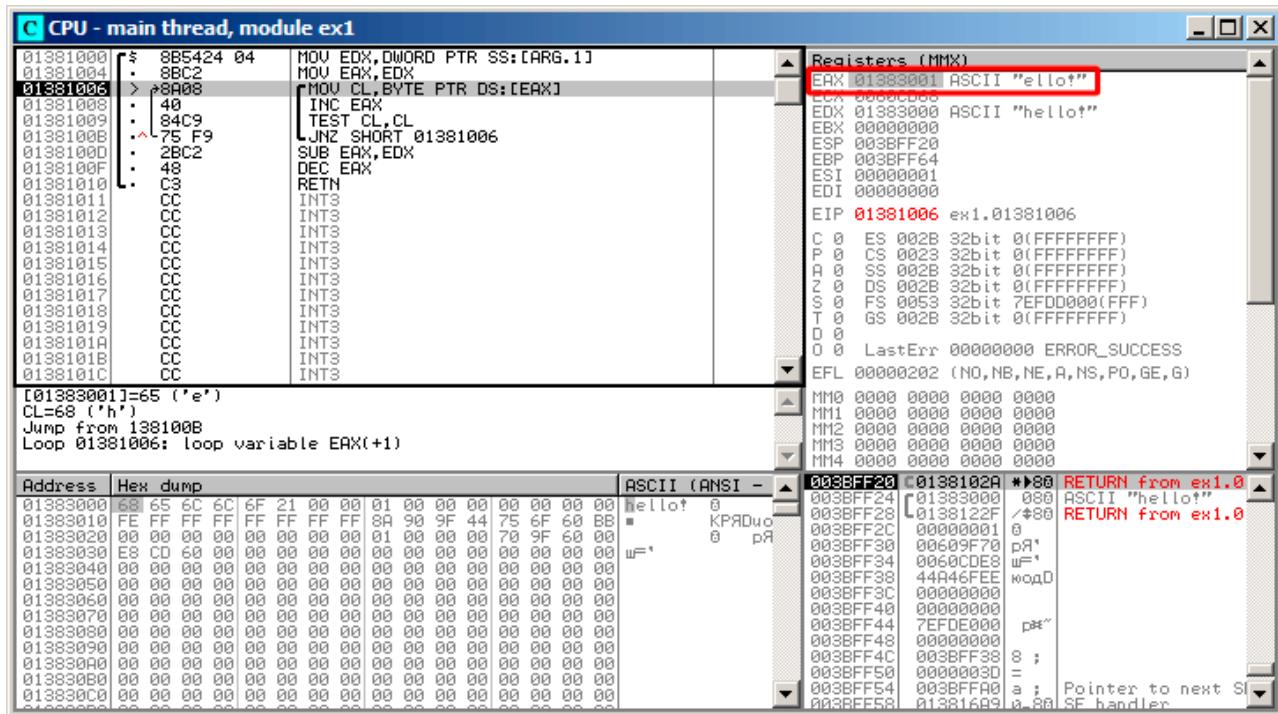


Figure 16.2: OllyDbg: second iteration start

We see that **EAX** contains the address of the second character in the string.

16.1. STRLEN()

We have to press F8 enough number of times in order to escape from the loop:

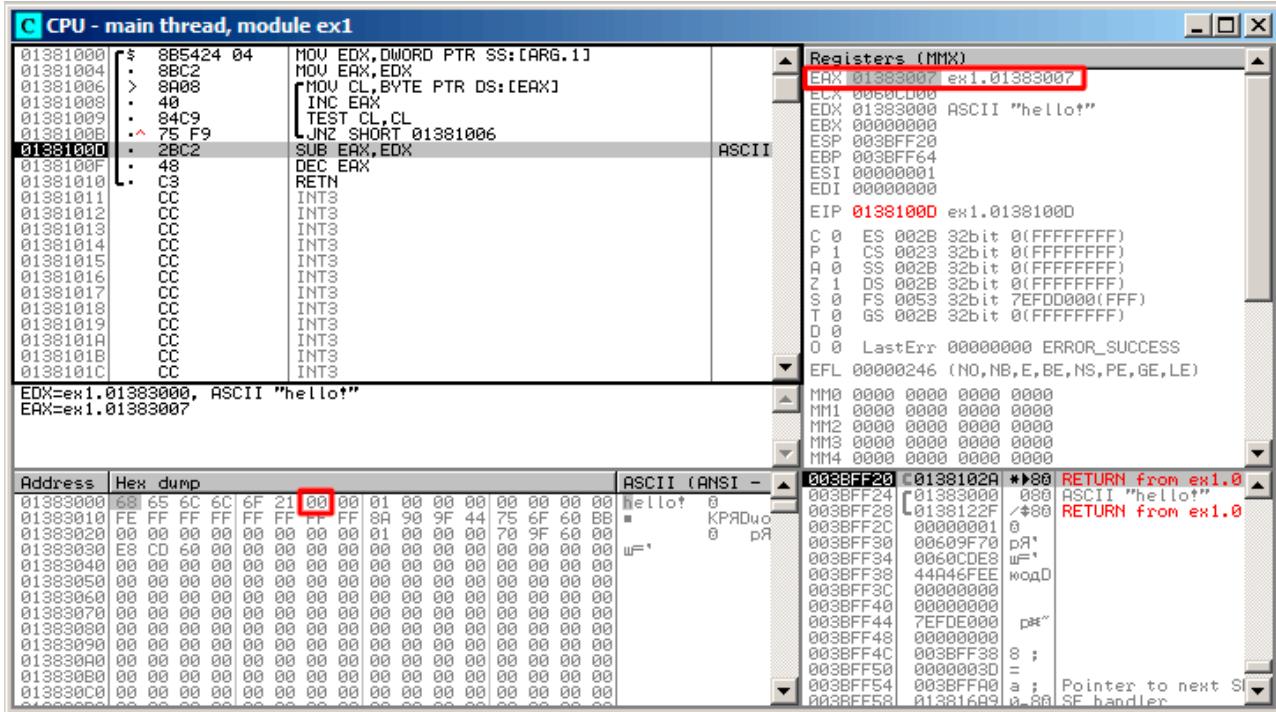


Figure 16.3: OllyDbg: pointers difference to be calculated now

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.

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The `SUB` instruction just got executed:

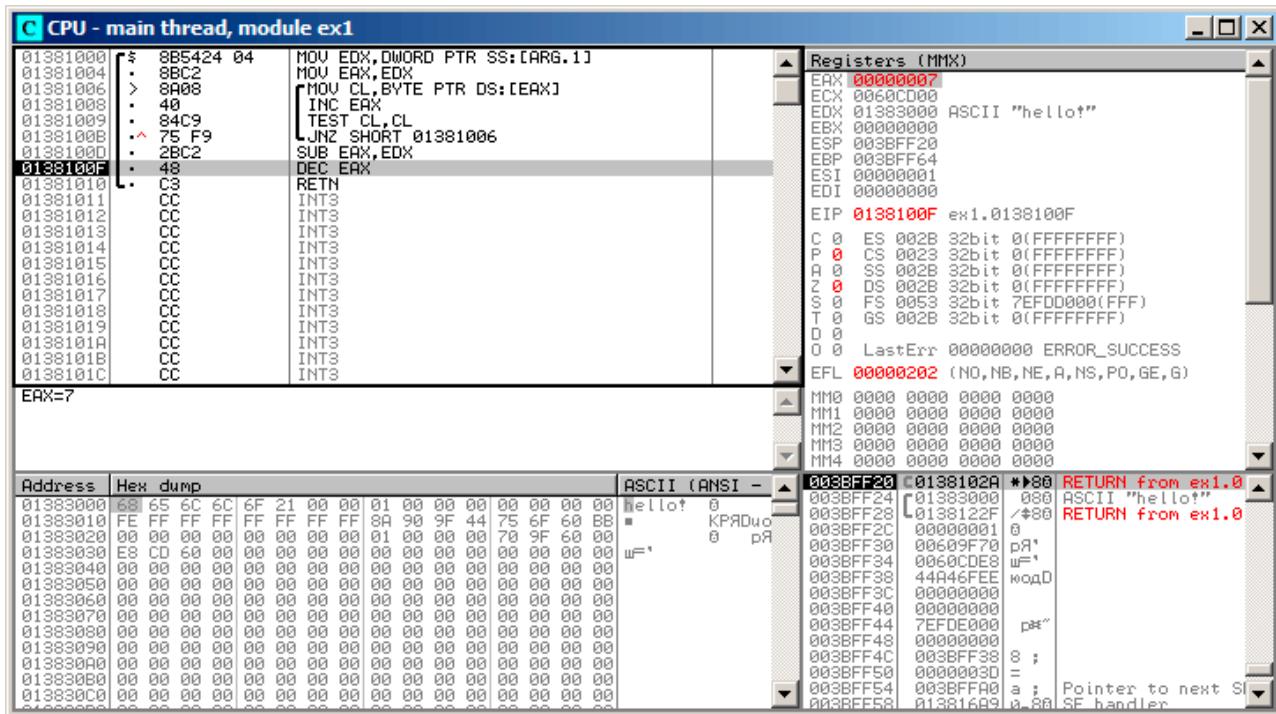


Figure 16.4: OllyDbg: `EAX` to be decremented now

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
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]`.

Probably 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

16.1. STRLEN()

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” ([31 on page 448](#)).

In other words, at the end of the function just after loop body, these operations are executed:

```
ecx=str;
eax=eos;
ecx=(-ecx)-1;
eax=eax+ecx
return eax
```

... and this is effectively equivalent to:

```
ecx=str;
eax=eos;
eax=eax-ecx;
eax=eax-1;
return eax
```

Why did GCC decide it would be better? Hard to guess. But perhaps the both variants are equivalent in efficiency.

16.1.2 ARM

32-bit ARM

Non-optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 16.2: 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+str]
        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`.

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 instruction 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.

16.1. STRLEN()

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-bit². This is similar to the `MOVsx` 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 ([16.1.1 on page 200](#)) 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 `BEQ` 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 16.3: Optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

```
_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 is implies "Post-indexed addressing", which means that 1 is to be added to `R1` after the byte is loaded. Read more about it: [29.2 on page 441](#).

Then you can see `CMP` and `BNE`³ in the body of the loop, these instructions continue looping until 0 is found in the string.

`MVNS`⁴ (inverts all bits, like `NOT` in x86) and `ADD` instructions compute $eos - str - 1$. In fact, these two instructions compute $R0 = str + eos$, which is effectively equivalent to what was in the source code, and why it is so, was already explained here ([16.1.1 on page 205](#)).

Apparently, LLVM, just like GCC, concludes that this code can be shorter (or faster).

Optimizing Keil 6/2013 (ARM mode)

²The Keil compiler treats the `char` type as signed, just like MSVC and GCC.

³(PowerPC, ARM) Branch if Not Equal

⁴MoVe Not

```

_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

```

Almost the same as what we saw before, with the exception that the $str - eos - 1$ 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 was executed before were equal to each other. Thus, if **R0** contains 0, both **SUBEQ** instructions executes and result is left in the **R0** register.

ARM64

Optimizing GCC (Linaro) 4.9

```

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

```

The algorithm is the same as in [16.1.1 on page 201](#): 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: **my_strlen()** returns 32-bit *int*, while it has to return **size_t** or another 64-bit type.

The reason is that, theoretically, **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 **SUB** instruction operates on a 32-bit part of register, while the penultimate **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.

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

```

16.1. STRLEN()

```
    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.

16.1.3 MIPS

Listing 16.5: 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:
    bne    $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 electronics⁵, but isn't very popular in computer programming. So, the NOT operation is implemented here as **NOR DST, \$ZERO, SRC**.

From fundamentals [31 on page 448](#) 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.

⁵NOR is called “universal gate”. For example, the Apollo Guidance Computer used in the Apollo program, was built by only using 5600 NOR gates: [\[Eic11\]](#).

Chapter 17

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 54.1.

For example, the `LEA` instruction is often used for simple arithmetic calculations: A.6.2 on page 931.

17.1 Multiplication

17.1.1 Multiplication using addition

Here is a simple example:

Listing 17.1: Optimizing MSVC 2010

```
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.

```
_TEXT SEGMENT
_a$ = 8                                ; size = 4
_f    PROC
; 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
```

17.1.2 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 17.2: Non-optimizing MSVC 2010

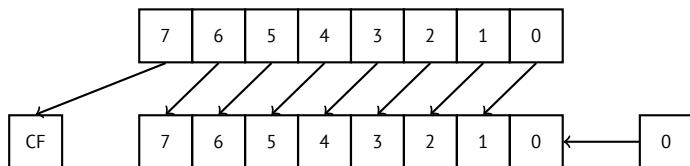
```
_a$ = 8      ; size = 4
_f    PROC
    push    ebp
```

17.1. MULTIPLICATION

```
    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 need to just add two zeroes at the right.

That's how the shift left instruction works:



The added bits at right are always zeroes.

Multiplication by 4 in ARM:

Listing 17.3: Non-optimizing Keil 6/2013 (ARM mode)

```
f PROC
    LSL      r0,r0,#2
    BX       lr
ENDP
```

Multiplication by 4 in MIPS:

Listing 17.4: Optimizing GCC 4.4.5 (IDA)

```
jr      $ra
sll     $v0, $a0, 2 ; branch delay slot
```

SLL is “Shift Left Logical”.

17.1.3 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.

32-bit

```
#include <stdint.h>

int f1(int a)
{
    return a*7;
};

int f2(int a)
{
    return a*28;
};

int f3(int a)
{
    return a*17;
};
```

Listing 17.5: Optimizing MSVC 2012

```

; 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:

Listing 17.6: 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      1r
        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      1r
        ENDP

; a*17
||f3|| PROC
        ADD     r0,r0,r0,LSL #4
; R0=R0+R0<<4=R0+R0*16=R0*17=a*17

```

17.1. MULTIPLICATION

```
BX      lr  
ENDP
```

But there are no such modifiers in Thumb mode. It also can't optimize `f2()`:

Listing 17.7: 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  
; R1=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 17.8: 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  
; $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)
```

17.1. MULTIPLICATION

```
{  
    return a*7;  
};  
  
int64_t f2(int64_t a)  
{  
    return a*28;  
};  
  
int64_t f3(int64_t a)  
{  
    return a*17;  
};
```

x64

Listing 17.9: 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
```

ARM64

GCC 4.9 for ARM64 is also terse, thanks to the shift modifiers:

Listing 17.10: Optimizing GCC (Linaro) 4.9 ARM64

```
; 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
```

17.2. DIVISION

```
ret  
;  
; a*17  
f3:  
    add      x0, x0, x0, lsl 4  
; X0=X0+X0<<4=a+a*16=a*17  
    ret
```

17.2 Division

17.2.1 Division using shifts

Example of division by 4:

```
unsigned int f(unsigned int a)  
{  
    return a/4;  
}
```

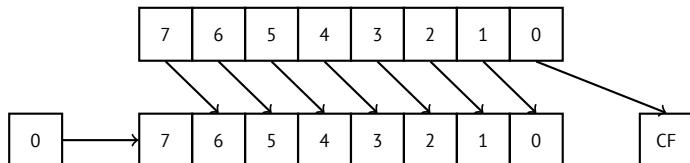
We get (MSVC 2010):

Listing 17.11: MSVC 2010

```
_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:

Listing 17.12: Non-optimizing Keil 6/2013 (ARM mode)

```
f PROC  
    LSR      r0,r0,#2  
    BX       lr  
ENDP
```

Division by 4 in MIPS:

Listing 17.13: Optimizing GCC 4.4.5 (IDA)

```
jr      $ra  
srl     $v0, $a0, 2 ; branch delay slot
```

The SRL instruction is “Shift Right Logical”.

17.3 Exercise

- <http://challenges.re/59>

Chapter 18

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](#).

18.1 IEEE 754

A number in the IEEE 754 format consists of a *sign*, a *significand* (also called *fraction*) and an *exponent*.

18.2 x86

It is worth looking into stack machines¹ or learning the basics of the Forth language², 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 it³.

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](#) is done 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.

The FPU has a stack capable to holding 8 80-bit registers, and each register can hold a number in the IEEE 754⁴ 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”.

18.3 ARM, MIPS, x86/x64 SIMD

In ARM and MIPS the FPU is not a stack, but a set of registers.

The same ideology is used in the SIMD extensions of x86/x64 CPUs.

¹[wikipedia.org/wiki/Stack_machine](https://en.wikipedia.org/wiki/Stack_machine)

²[wikipedia.org/wiki/Forth_\(programming_language\)](https://en.wikipedia.org/wiki/Forth_(programming_language))

³For example, John Carmack used fixed-point arithmetic ([wikipedia.org/wiki/Fixed-point_arithmetic](https://en.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.

⁴[wikipedia.org/wiki/IEEE_floating_point](https://en.wikipedia.org/wiki/IEEE_floating_point)

18.4 C/C++

The standard C/C++ languages offer at least two floating number types, *float* (*single-precision*⁵, 32 bits)⁶ and *double* (*double-precision*⁷, 64 bits).

GCC also supports the *long double* type (*extended precision*⁸, 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.

18.5 Simple example

Let's consider this simple example:

```
#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));
}
```

18.5.1 x86

MSVC

Compile it in MSVC 2010:

Listing 18.1: 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
_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:
```

⁵[wikipedia.org/wiki/Single-precision_floating-point_format](https://en.wikipedia.org/wiki/Single-precision_floating-point_format)

⁶the single precision floating point number format is also addressed in the *Working with the float type as with a structure* (22.6.2 on page 371) section

⁷[wikipedia.org/wiki/Double-precision_floating-point_format](https://en.wikipedia.org/wiki/Double-precision_floating-point_format)

⁸[wikipedia.org/wiki/Extended_precision](https://en.wikipedia.org/wiki/Extended_precision)

18.5. SIMPLE EXAMPLE

```
; 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 language⁹, you can quickly understand that this is a stack machine¹⁰.

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 numer 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**.

⁹[wikipedia.org/wiki/Forth_\(programming_language\)](https://en.wikipedia.org/wiki/Forth_(programming_language))

¹⁰[wikipedia.org/wiki/Stack_machine](https://en.wikipedia.org/wiki/Stack_machine)

18.5. SIMPLE EXAMPLE

MSVC + OllyDbg

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)`:

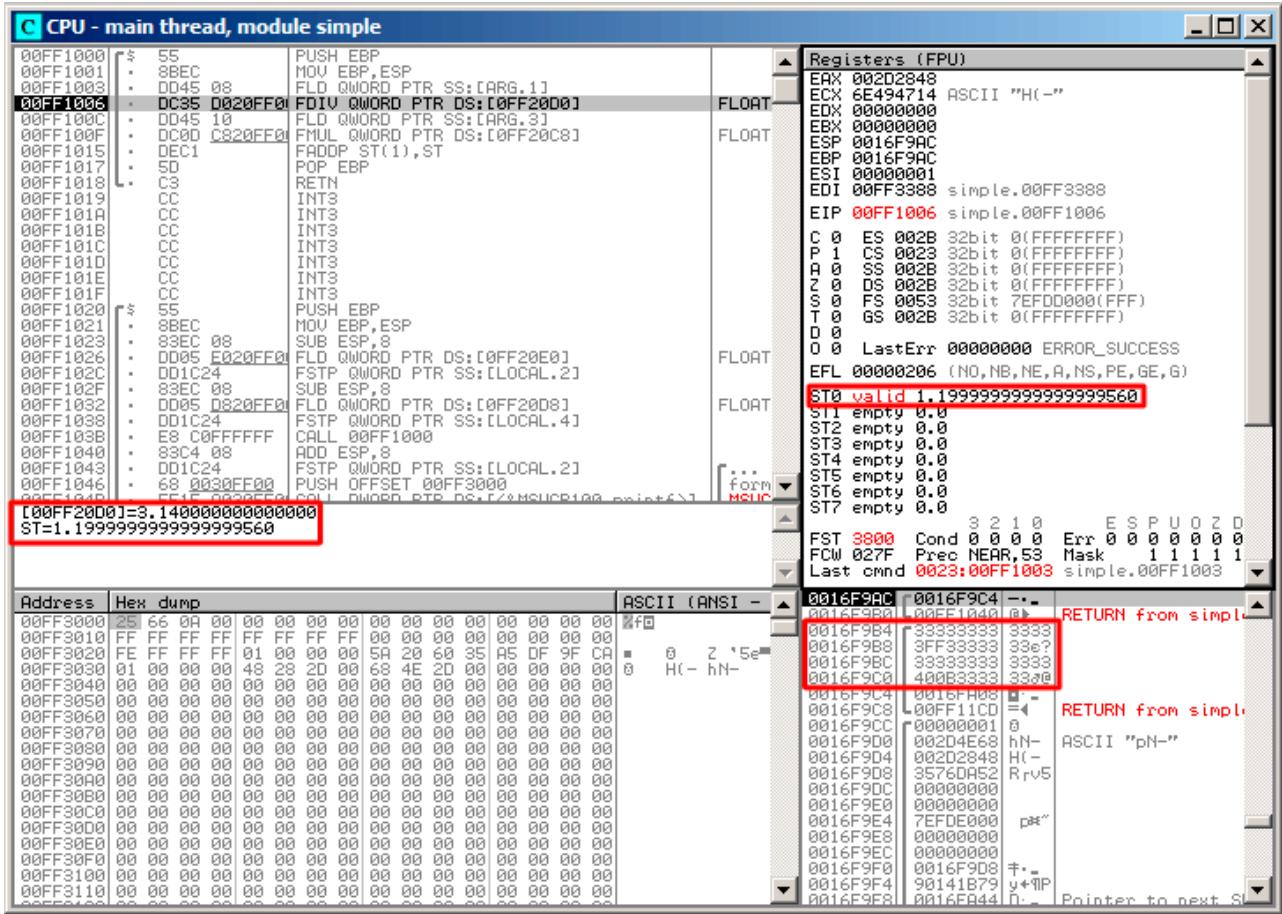


Figure 18.1: OllyDbg: first `FLD` executed

Because of unavoidable conversion errors from 64-bit IEEE 754 floating point to 80-bit (used internally in the FPU), here we see 1.999..., 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

18.5. SIMPLE EXAMPLE

Let's trace further. FDIV was executed, now ST(0) contains 0.382...(quotient):

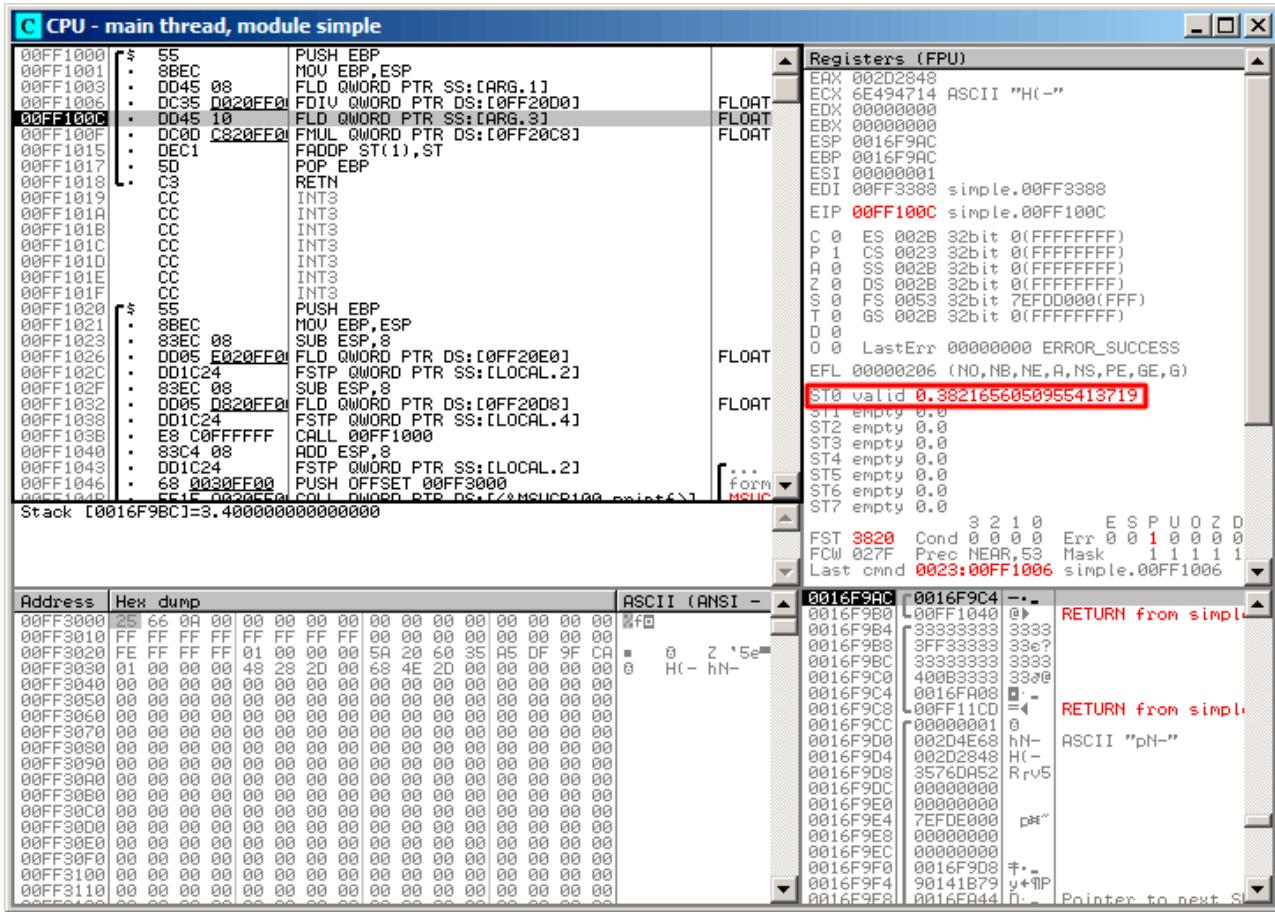


Figure 18.2: OllyDbg: FDIV executed

18.5. SIMPLE EXAMPLE

Third step: the next FLD

was executed, loading 3.4 into **ST(0)** (here we see the approximate value 3.39999...):

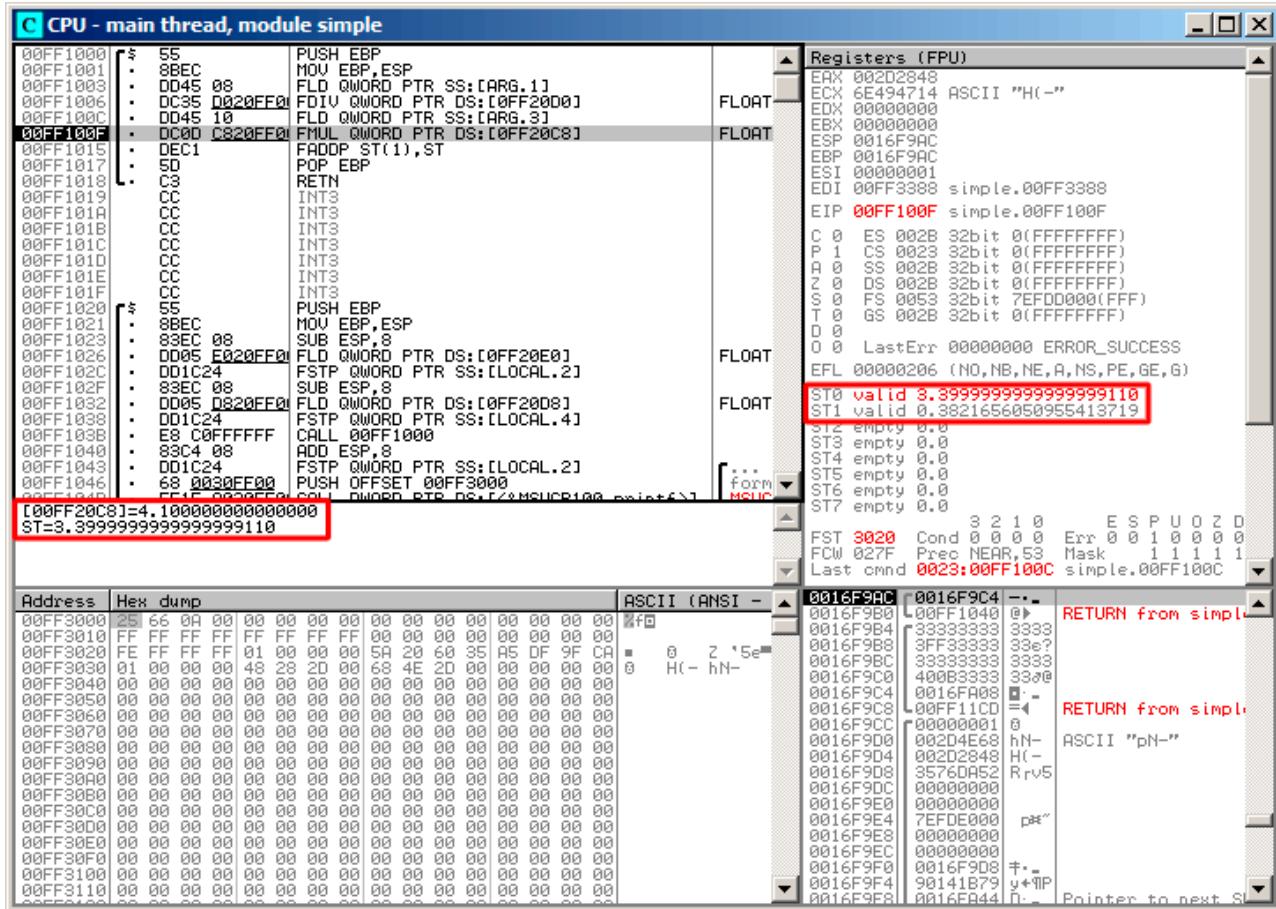


Figure 18.3: OllyDbg: second FLD executed

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:

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Next: `FMUL` was executed, so now the `product` is in `ST(0)`:

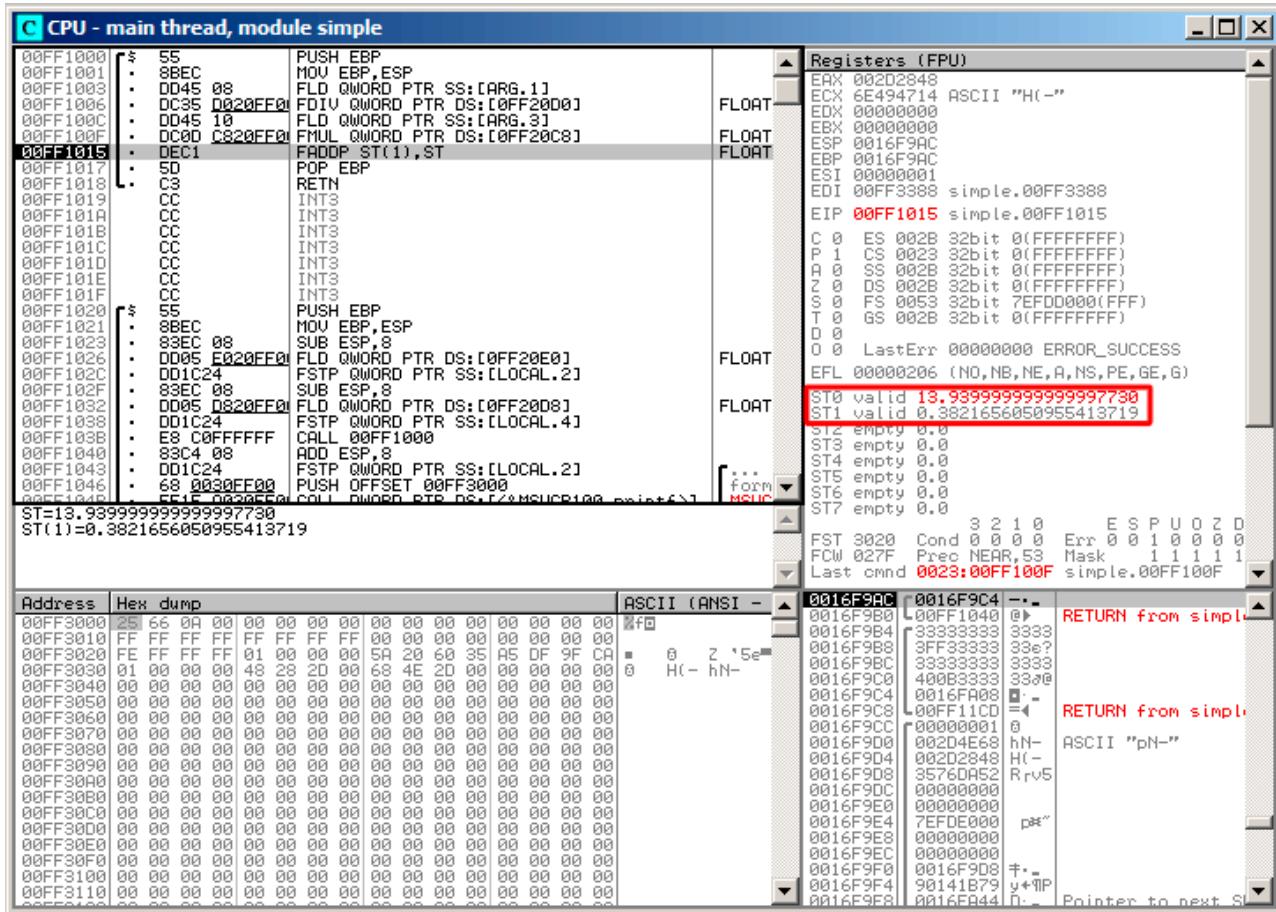


Figure 18.4: OllyDbg: `FMUL` executed

18.5. SIMPLE EXAMPLE

Next: `FADDP` was executed, now the result of the addition is in `ST(0)`, and `ST(1)` is cleared:

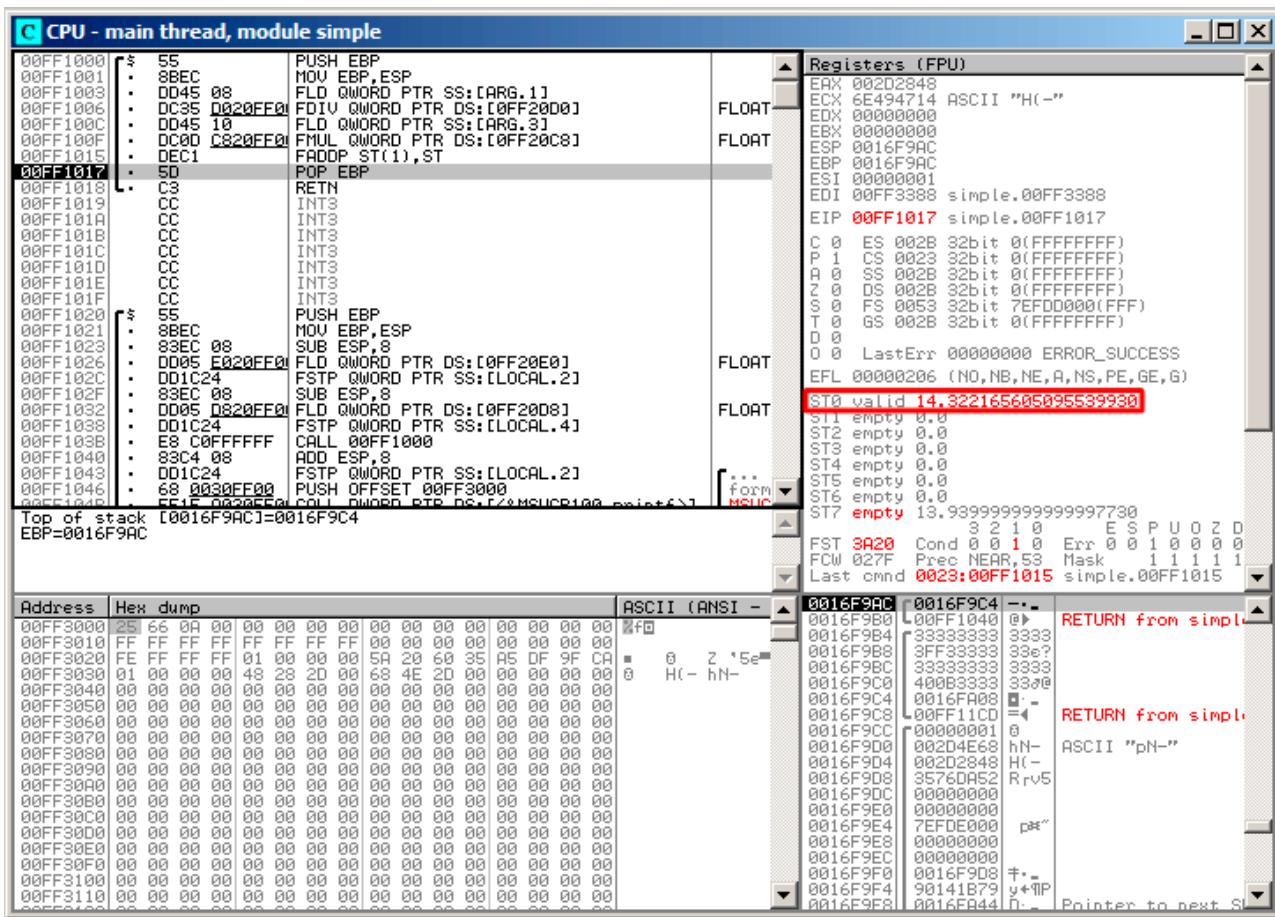


Figure 18.5: OllyDbg: `FADDP` executed

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: [18.2 on page 217](#). 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 was 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

GCC 4.4.1 (with `-O3` option) emits the same code, just slightly different:

Listing 18.2: Optimizing GCC 4.4.1

```
f          public f
          proc near
```

18.5. SIMPLE EXAMPLE

```

arg_0      = qword ptr  8
arg_8      = qword ptr  10h

        push    ebp
        fld     ds:dbl_8048608 ; 3.14

; stack state now: ST(0) = 3.14

        mov     ebp, esp
        fdivr [ebp+arg_0]

; stack state now: ST(0) = result of division

        fld     ds:dbl_8048610 ; 4.1

; stack state now: ST(0) = 4.1, ST(1) = result of division

        fmul   [ebp+arg_8]

; stack state now: ST(0) = result of multiplication, ST(1) = result of division

        pop    ebp
        faddp st(1), st

; stack state now: ST(0) = result of addition

        retn
f
        endp

```

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.

18.5.2 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 18.3: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```

f
        VLDR      D16, =3.14
        VMOV      D17, R0, R1 ; load "a"
        VMOV      D18, R2, R3 ; load "b"
        VDIV.F64  D16, D17, D16 ; a/3.14
        VLDR      D17, =4.1
        VMUL.F64  D17, D18, D17 ; b*4.1
        VADD.F64  D16, D17, D16 ; +
        VMOV      R0, R1, D16
        BX       LR

dbl_2C98  DCFD 3.14           ; DATA XREF: f
dbl_2CA0  DCFD 4.1           ; DATA XREF: f+10

```

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 remember: D-registers are for double precision numbers, while S-registers—for single precision numbers. More about it: [B.3.3 on page 942](#).

18.5. SIMPLE EXAMPLE

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 was 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.

18.5.3 ARM: Optimizing Keil 6/2013 (Thumb mode)

```
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.

Of course, that is slower than FPU-coprocessor, but 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*.

18.5.4 ARM64: Optimizing GCC (Linaro) 4.9

Very compact code:

Listing 18.4: 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
```

18.5.5 ARM64: Non-optimizing GCC (Linaro) 4.9

Listing 18.5: 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
; D0 = a/3.14
    fmov   d1, x0
; D1 = X0 = b*4.1
    fadd   d0, d0, d1
; D0 = D0+D1 = a/3.14 + b*4.1

    fmov   x0, d0 ; \ redundant code
    fmov   d0, x0 ; /
```

18.5. SIMPLE EXAMPLE

```
    add    sp, sp, 16
    ret
.LC25:
    .word 1374389535      ; 3.14
    .word 1074339512
.LC26:
    .word 1717986918      ; 4.1
    .word 1074816614
```

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 *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`.

18.5.6 MIPS

MIPS can support several coprocessors (up to 4), the zeroth of which 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): [C.1.2 on page 944](#).

When one needs to work with 64-bit *double* values, a pair of 32-bit F-registers is used.

Listing 18.6: 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:
        lwc1    $f0, dword_BC
        or       $at, $zero           ; load delay slot, NOP
; load high 32-bit part of 3.14 constant to $f1:
        lwc1    $f1, $LC0
        lui      $v0, ($LC1 >> 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:
        lwc1    $f2, dword_C4
        or       $at, $zero           ; load delay slot, NOP
; load high 32-bit part of 4.1 to $f3:
        lwc1    $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

.rodata.cst8:000000B8 $LC0:          .word 0x40091EB8      # DATA XREF: f+C
.rodata.cst8:000000BC dword_BC:     .word 0x51EB851F      # DATA XREF: f+4
.rodata.cst8:000000C0 $LC1:          .word 0x40106666      # DATA XREF: f+10
.rodata.cst8:000000C4 dword_C4:     .word 0x66666666      # DATA XREF: f
```

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` pseudoinstruction.
- `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)

18.6. PASSING FLOATING POINT NUMBERS VIA ARGUMENTS

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 author¹¹.

18.6 Passing floating point numbers via arguments

```
#include <math.h>
#include <stdio.h>

int main ()
{
    printf ("32.01 ^ 1.54 = %lf\n", pow (32.01,1.54));

    return 0;
}
```

18.6.1 x86

Let's see what we get in (MSVC 2010):

Listing 18.7: MSVC 2010

```
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
```

`FLD` and `FSTP` move variables between the data segment and the FPU stack. `pow()`¹² takes both values from the stack of the FPU 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: [18.6.2 on the following page](#).

¹¹dennis(a)yurichev.com

¹²a standard C function, raises a number to the given power (exponentiation)

18.6.2 ARM + Non-optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```

_main
var_C      = -0xC

        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}

dbl_2F90  DCFD 32.01          ; DATA XREF: _main+6
dbl_2F98  DCFD 1.54           ; DATA XREF: _main+E

```

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.

18.6.3 ARM + Non-optimizing Keil 6/2013 (ARM mode)

```

_main
        STMFDE 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}

y      DCD 0xA3D70A4          ; DATA XREF: _main+4
dword_520 DCD 0x3FF8A3D7       ; DATA XREF: _main+8
x      DCD 0xAE147AE1         ; DATA XREF: _main+C
dword_528 DCD 0x40400147       ; DATA XREF: _main+10
a32_011_54Lf DCB "32.01 ^ 1.54 = %lf",0xA,0
                                         ; DATA XREF: _main+24

```

D-registers are not used here, just R-register pairs.

18.6.4 ARM64 + Optimizing GCC (Linaro) 4.9

Listing 18.8: Optimizing GCC (Linaro) 4.9

```
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
    b1    pow
; result of pow() in D0
    adrp   x0, .LC2
    add    x0, x0, :lo12:.LC2
    b1    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\n"
```

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.

18.6.5 MIPS

Listing 18.9: Optimizing GCC 4.4.5 (IDA)

```
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:
    lwc1  $f12, dword_9C
; load address of pow() function:
    lw    $t9, (pow & 0xFFFF)($gp)
; load high 32-bit part of 32.01:
    lwc1  $f13, $LC0
    lui    $v0, ($LC1 >> 16) ; ?
; load low 32-bit part of 1.54:
    lwc1  $f14, dword_A4
    or     $at, $zero ; load delay slot, NOP
; load high 32-bit part of 1.54:
    lwc1  $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"
```

18.7. COMPARISON EXAMPLE

```
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<0>

; 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                .word 0x00000000      # main+18
; 1.54:
.rodata.cst8:000000A0 $LC1:          .word 0x3FF8A3D7      # DATA XREF: main+24
.rodata.cst8:000000A0                .word 0x00000000      # 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 in the end the result from `pow()` is moved to registers `$A3` and `$A2`, and `printf()` takes a 64-bit double value from this register pair.

18.7 Comparison example

Let's try this:

```
#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.

18.7.1 x86

Non-optimizing MSVC

MSVC 2010 generates the following:

Listing 18.10: Non-optimizing MSVC 2010

```
PUBLIC _d_max
_TEXT SEGMENT
_a$ = 8           ; size = 8
_b$ = 16          ; size = 8
_d_max PROC
    push ebp
    mov ebp, esp
    fld QWORD PTR _b$[ebp]
```

18.7. COMPARISON EXAMPLE

```

; current stack state: ST(0) = _b
; compare _b (ST(0)) and _a, and pop register

    fcomp  QWORD PTR _a$[ebp]
; stack is empty here

    fnstsw ax
    test    ah, 5
    jp      SHORT $LN1@d_max

; we are here only if a>b

    fld    QWORD PTR _a$[ebp]
    jmp    SHORT $LN2@d_max
$LN1@d_max:
    fld    QWORD PTR _b$[ebp]
$LN2@d_max:
    pop    ebp
    ret    0
_d_max    ENDP

```

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.

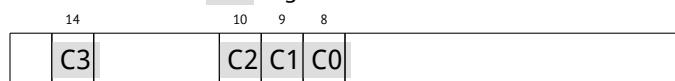
After the bits are set, the `FCOMP` instruction also pops one variable from the stack. This is what distinguishes it from `FCOM`, which is just compares values, leaving the stack in the same state.

Unfortunately, CPUs before Intel P6¹³ don't have any conditional jumps instructions which check the C3 / C2 / C0 bits. Probably, it is a matter of history (remember: FPU was 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:



This is how C3 / C2 / C0 bits are located in the AH register:



After the execution of `test ah, 514`, only C0 and C2 bits (on 0 and 2 position) are considered, all other bits are just ignored.

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 Wikipedia¹⁵:

¹³ Intel P6 is Pentium Pro, Pentium II, etc

Intel 10
145=101b

¹⁵ wikipedia.org/wiki/Parity_flag

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 can not 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 was cleared by the test ah, 5 instruction).

It is all simple after that. If the conditional jump was triggered, FLD loads the value of _b in ST(0), and if it was not 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.

18.7. COMPARISON EXAMPLE

First OllyDbg example: a=1.2 and b=3.4

Let's load the example into OllyDbg:

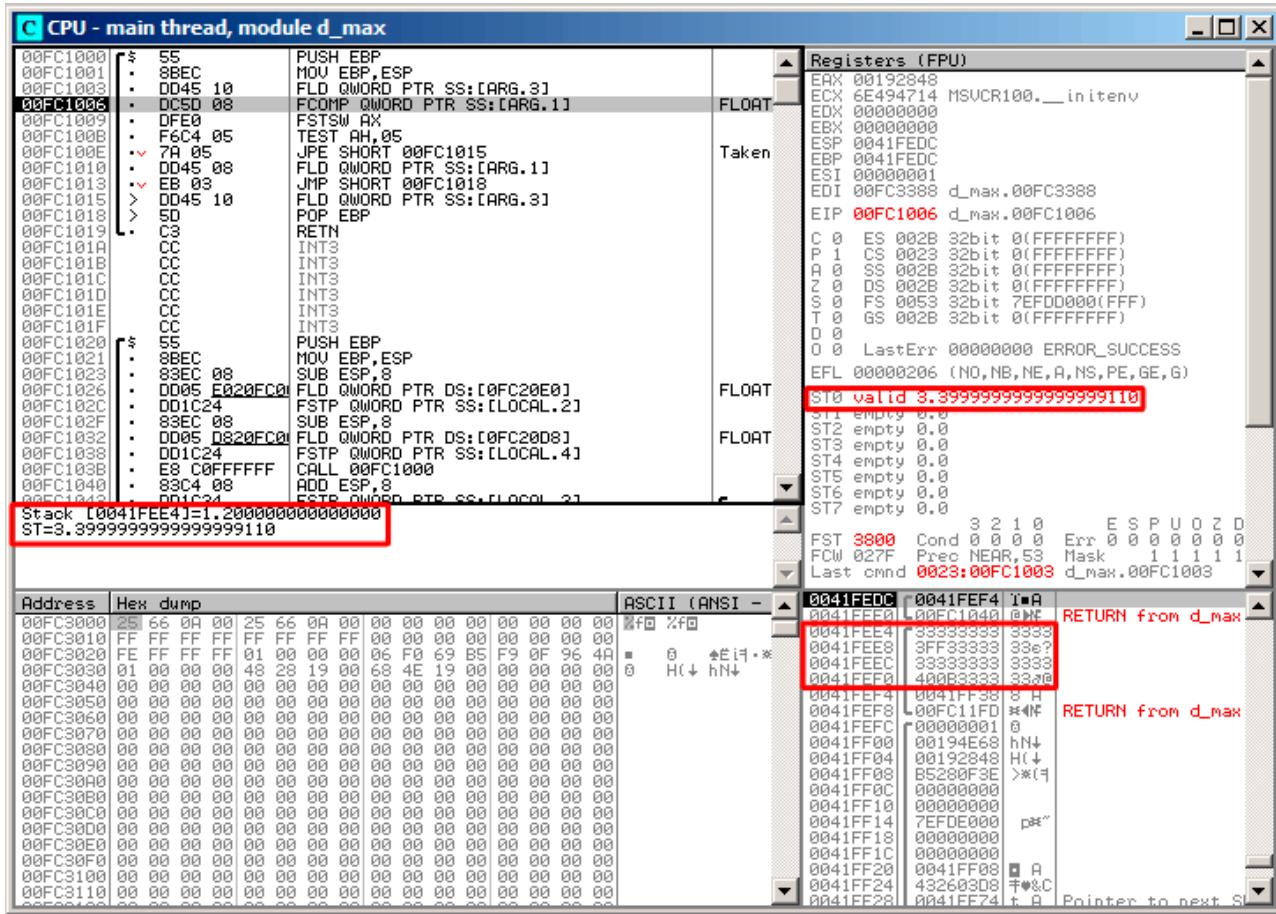


Figure 18.6: OllyDbg: first `FLD` is executed

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.

18.7. COMPARISON EXAMPLE

FCOMP is executed:

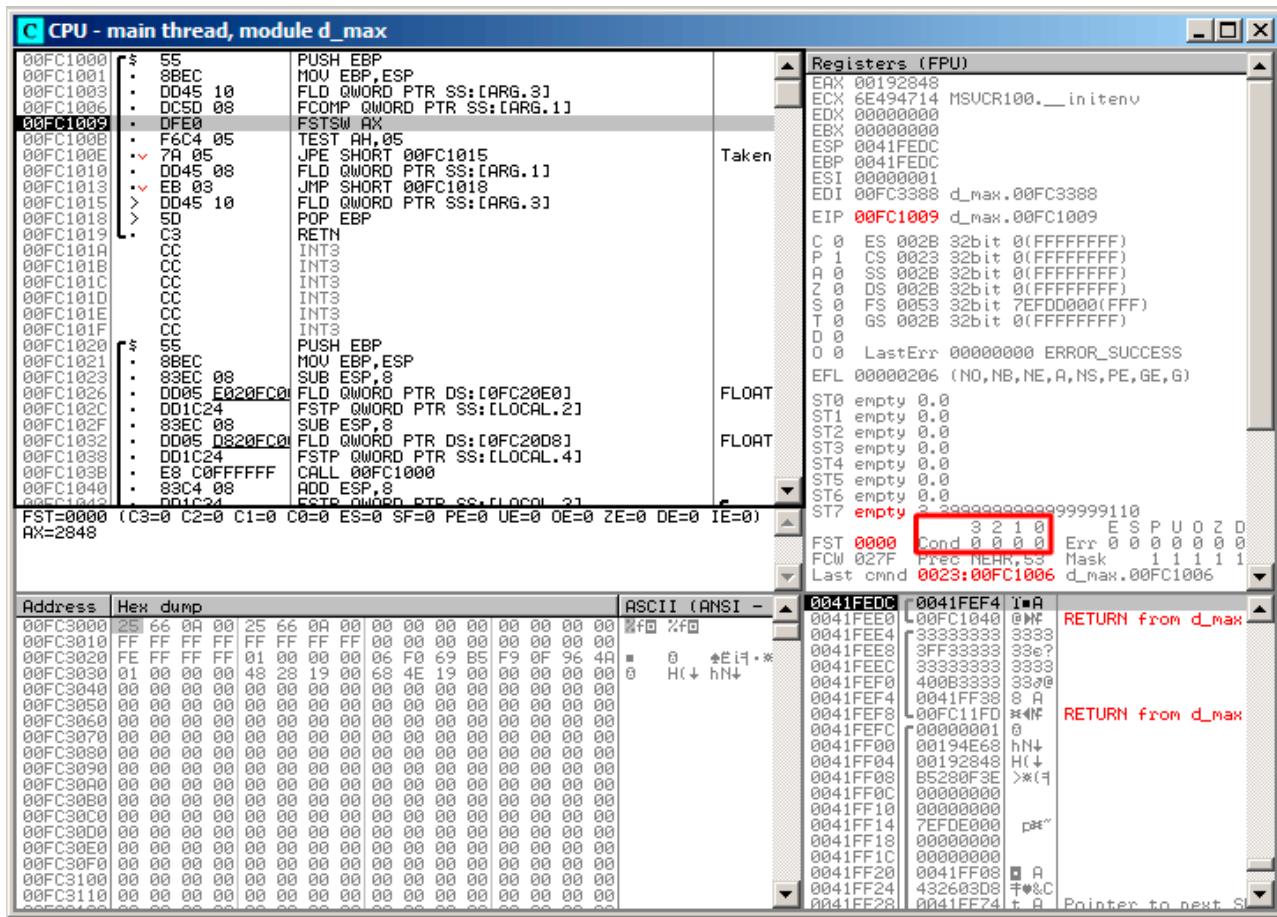


Figure 18.7: OllyDbg: FCOMP is executed

We see the state of the FPU's condition flags: all zeroes. The popped value is reflected as ST(7), it was written earlier about reason for this: [18.5.1 on page 224](#).

18.7. COMPARISON EXAMPLE

FNSTSW is executed:

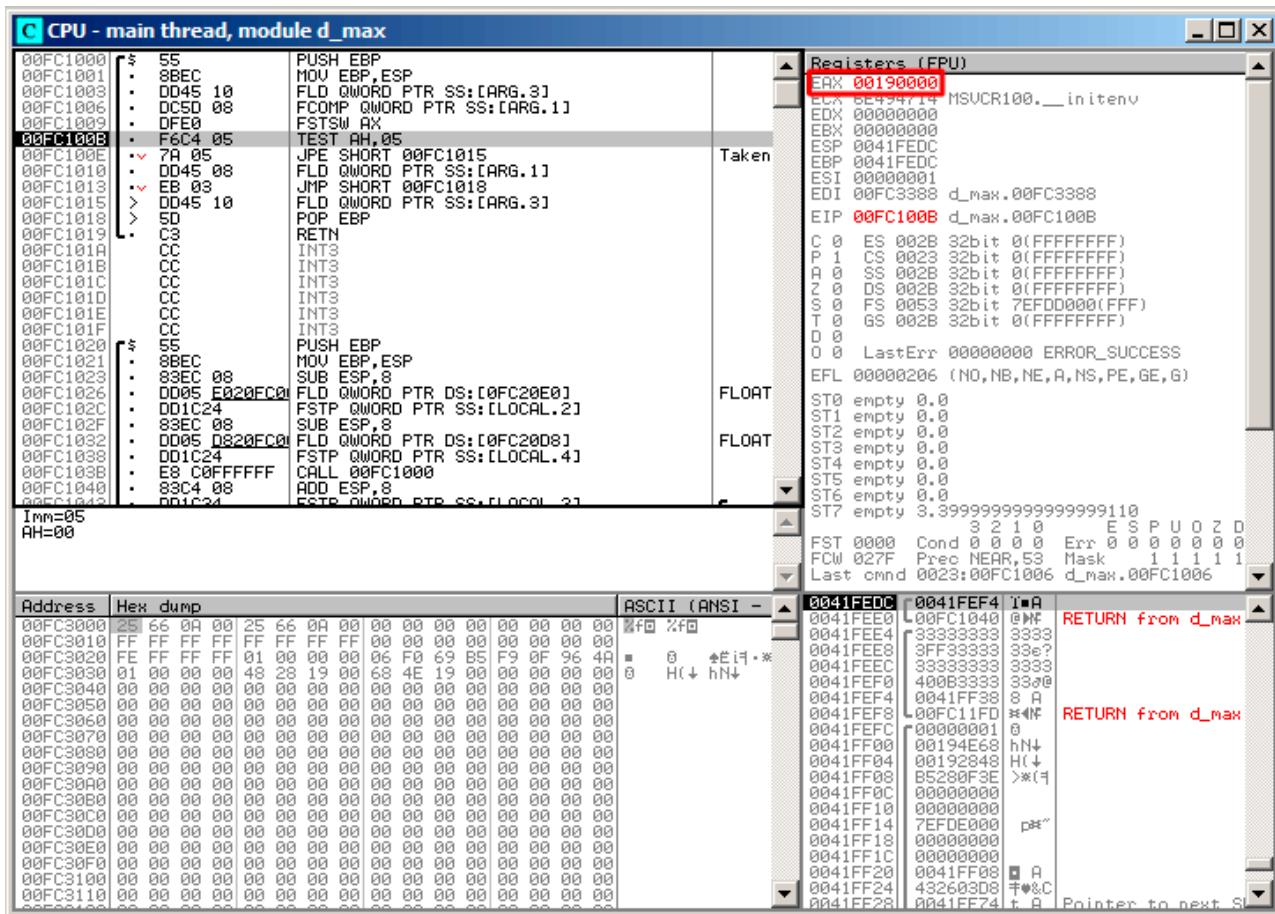


Figure 18.8: OllyDbg: FNSTSW is executed

We see that the `AX` register contain zeroes: indeed, all condition flags are zero. (OllyDbg disassembles the `FNSTSW` instruction as `FSTSW` –they are synonyms).

18.7. COMPARISON EXAMPLE

TEST is executed:

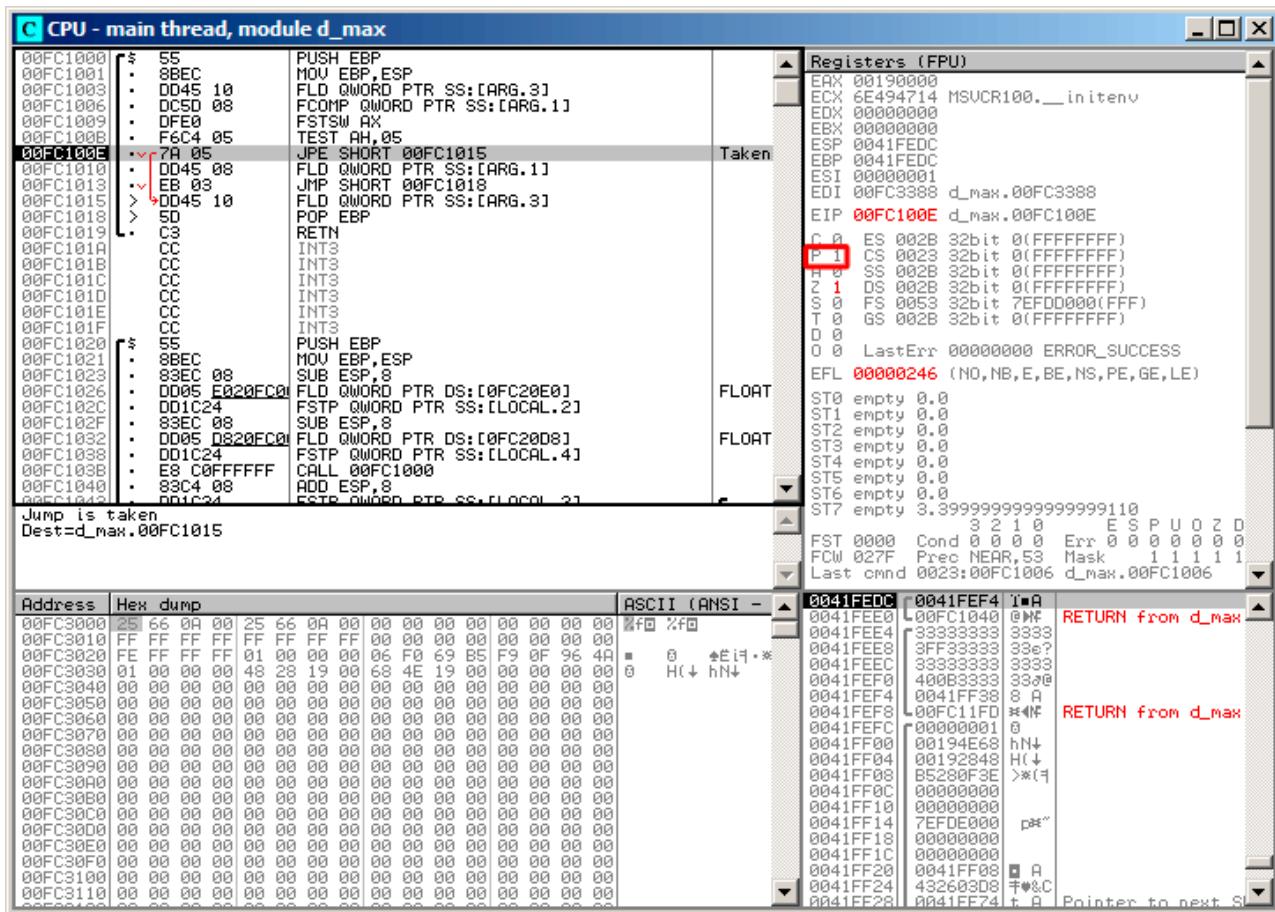


Figure 18.9: OllyDbg: TEST is executed

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 JPE¹⁶—they are synonyms. And it is about to trigger now.

¹⁶Jump Parity Even (x86 instruction)

18.7. COMPARISON EXAMPLE

JPE triggered, FLD loads the value of *b* (3.4) in ST(0) :

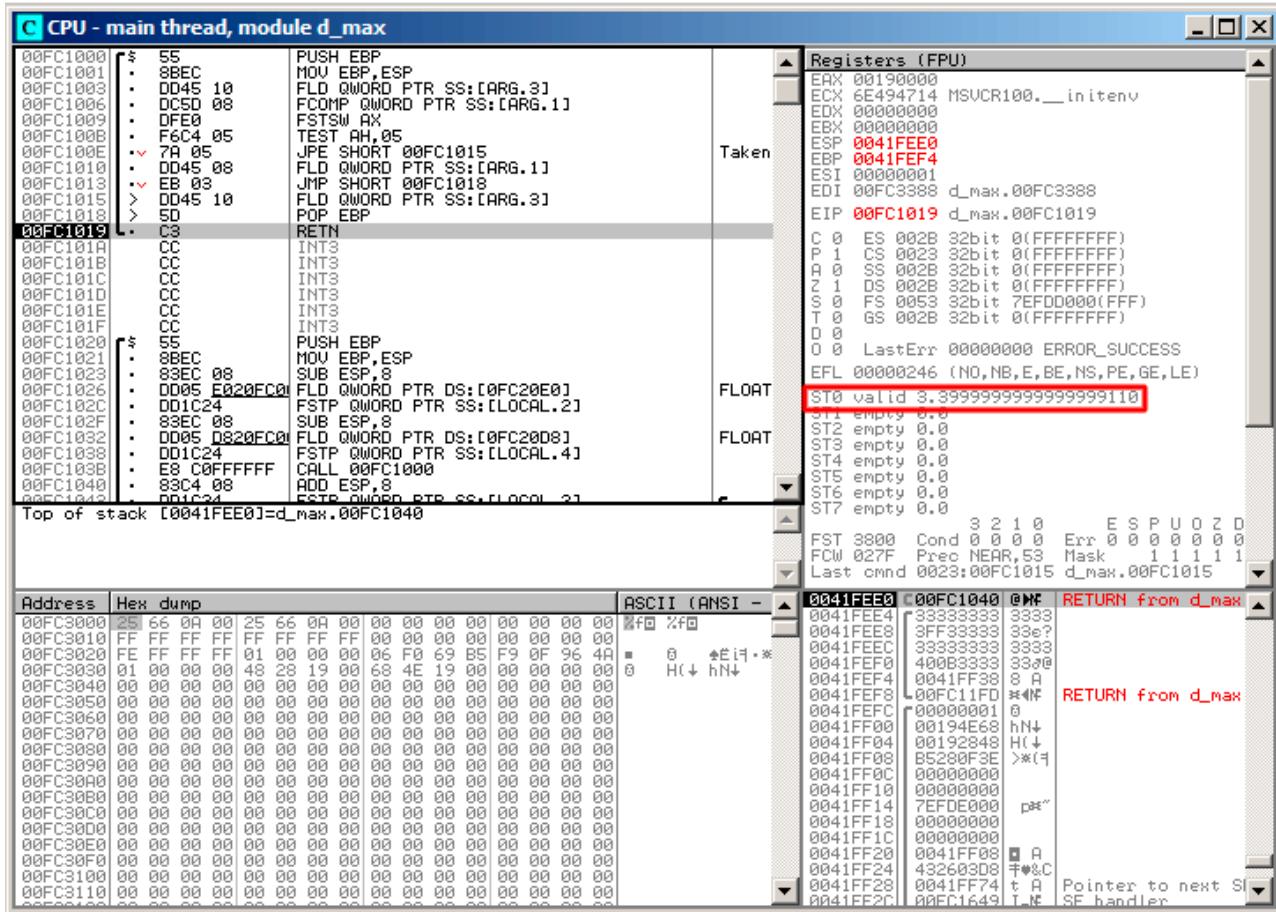


Figure 18.10: OllyDbg: second FLD is executed

The function finishes its work.

18.7. COMPARISON EXAMPLE

Second OllyDbg example: $a=5.6$ and $b=-4$

Let's load example into OllyDbg:

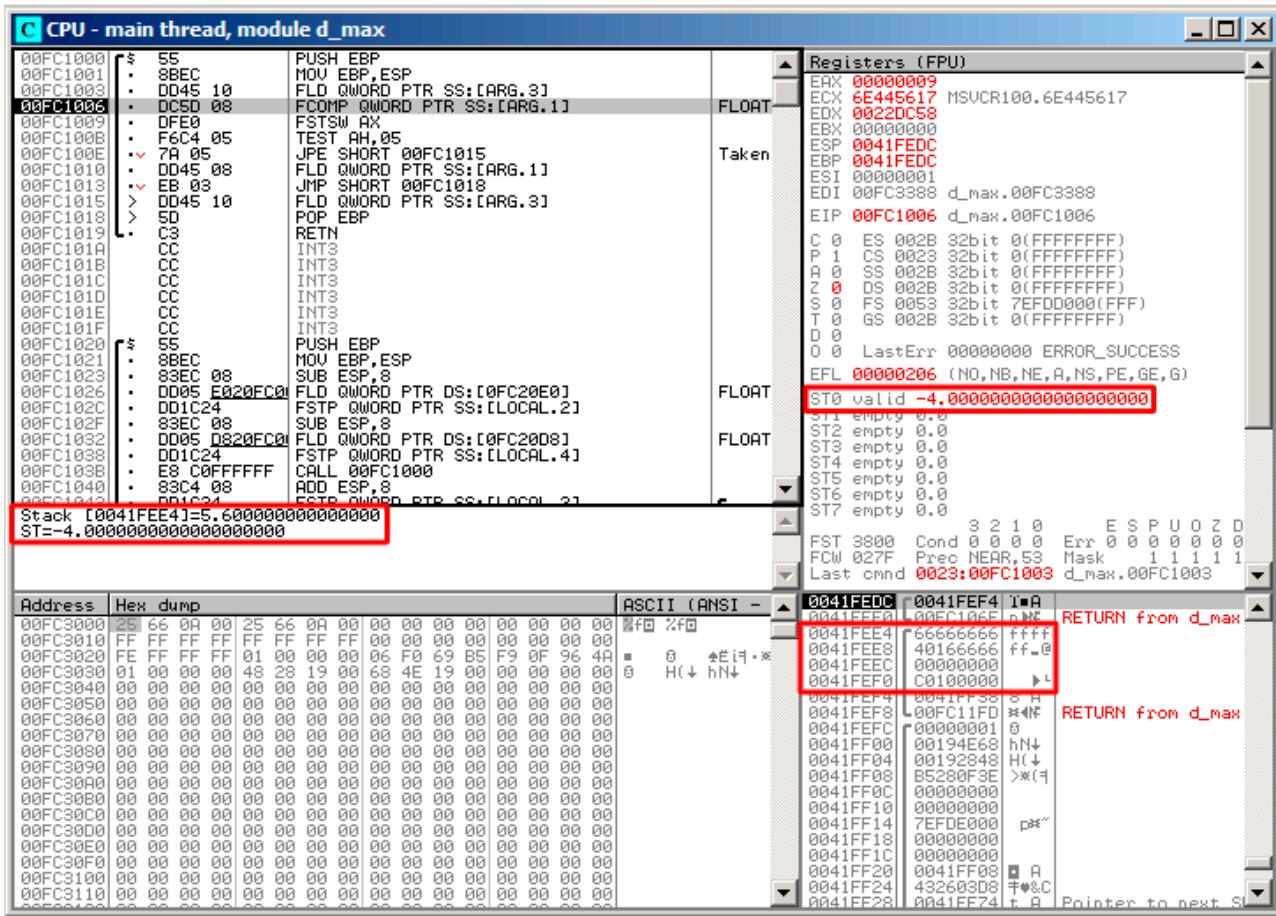


Figure 18.11: OllyDbg: first `FLD` executed

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.

18.7. COMPARISON EXAMPLE

FCOMP executed:

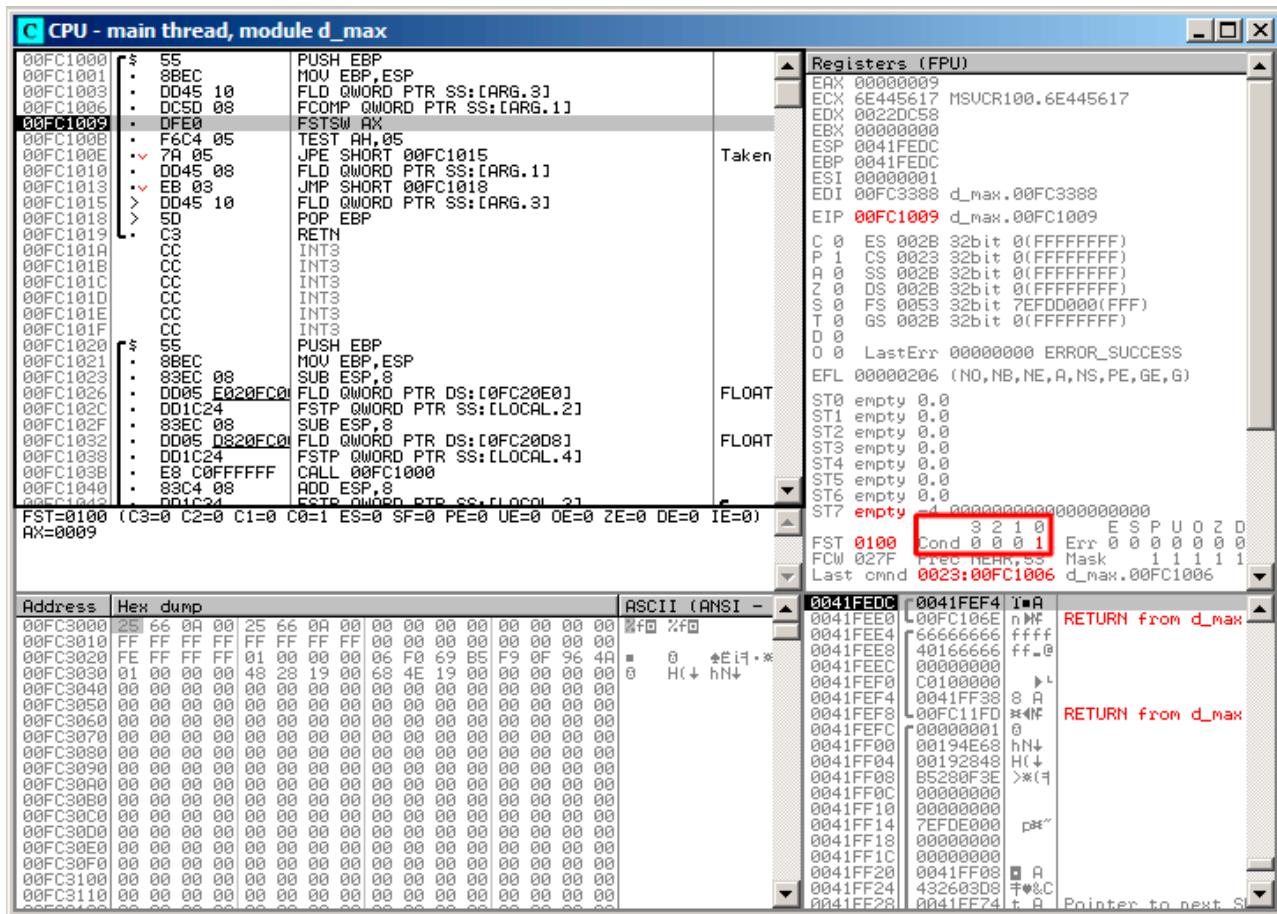


Figure 18.12: OllyDbg: FCOMP executed

We see the state of the FPU's condition flags: all zeroes except C0 .

18.7. COMPARISON EXAMPLE

FNSTSW executed:

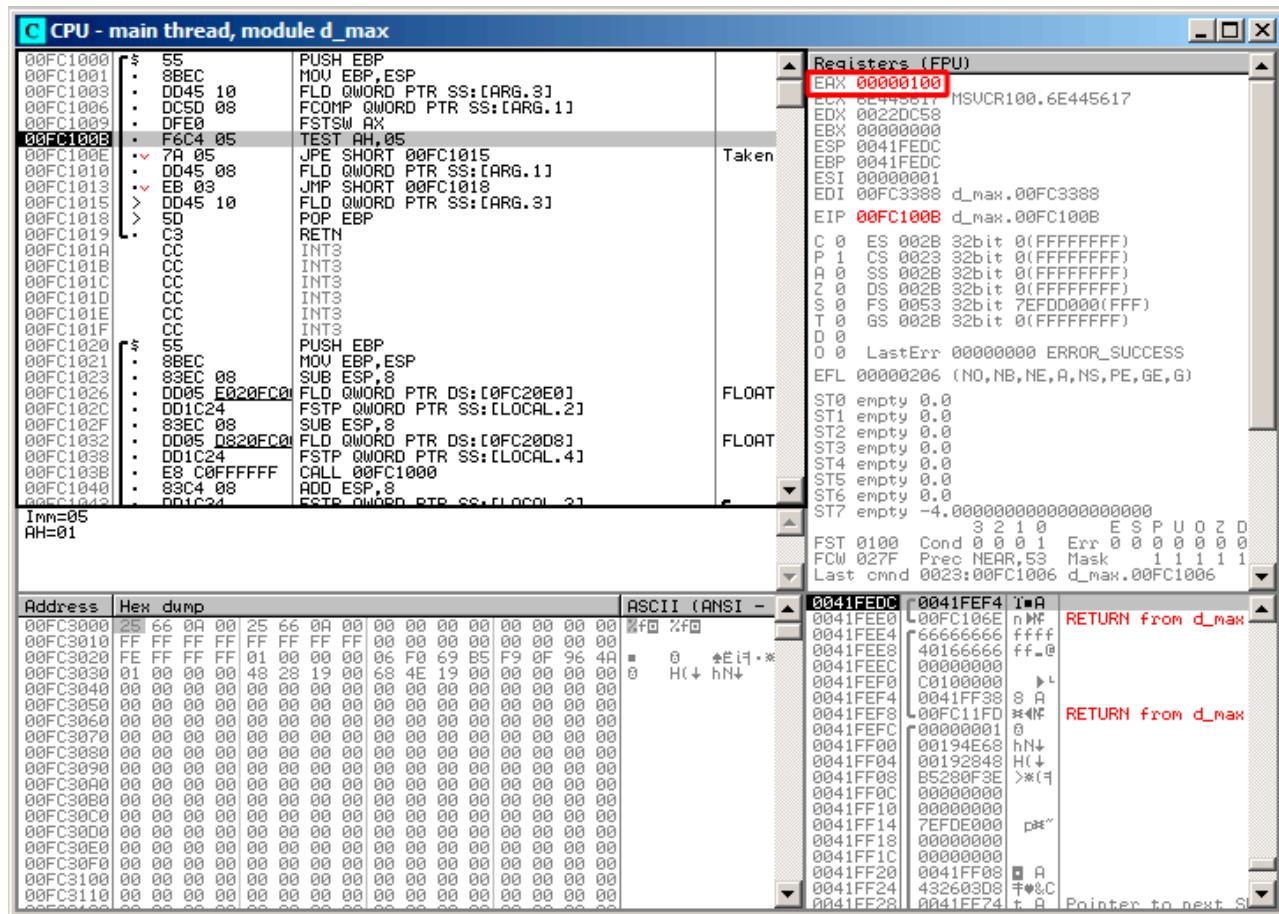


Figure 18.13: OllyDbg: FNSTSW executed

We see that the `AX` register contains `0x100`: the `C0` flag is at the 16th bit.

18.7. COMPARISON EXAMPLE

TEST executed:

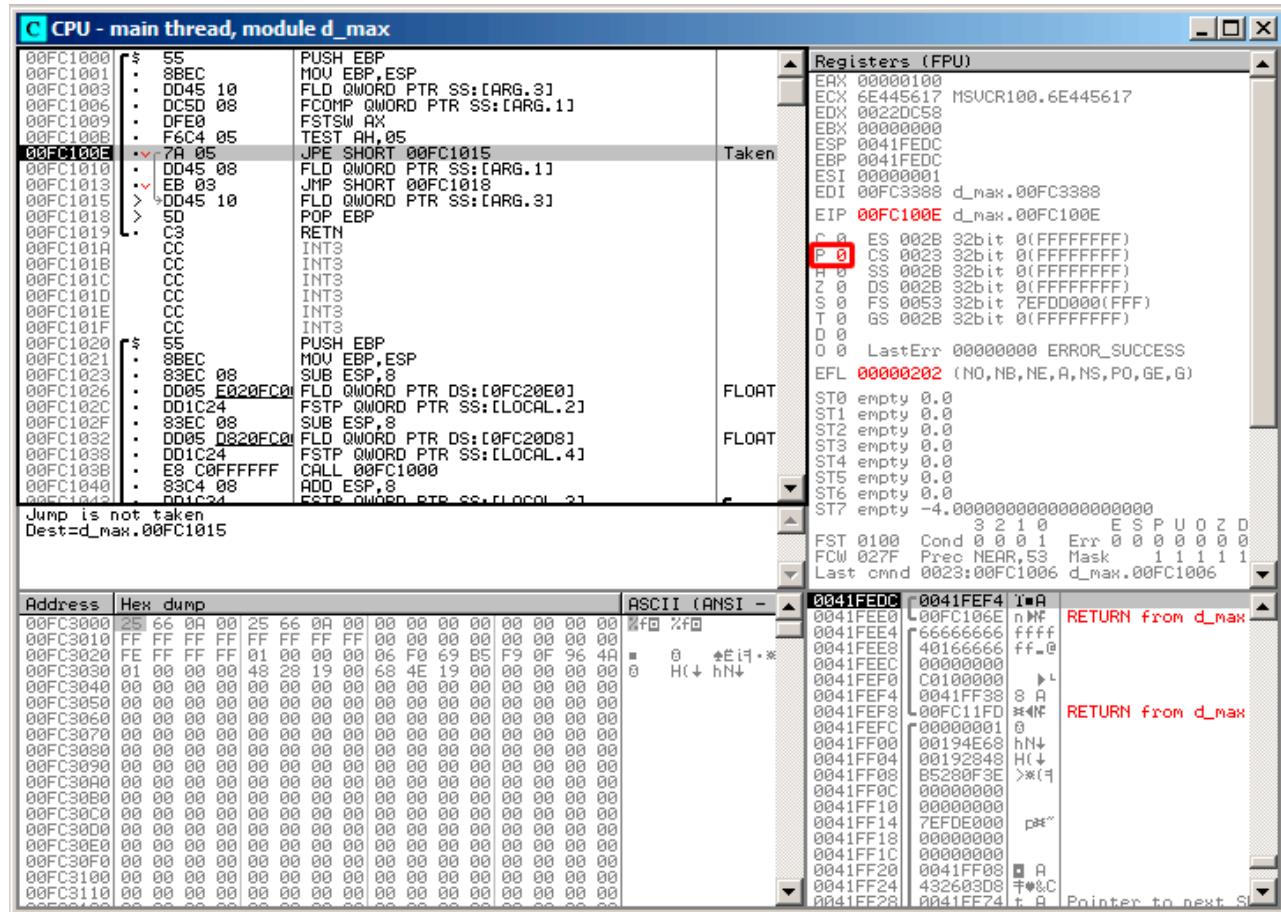


Figure 18.14: OllyDbg: TEST executed

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.

18.7. COMPARISON EXAMPLE

JPE wasn't triggered, so FLD loads the value of *a* (5.6) in ST(0) :

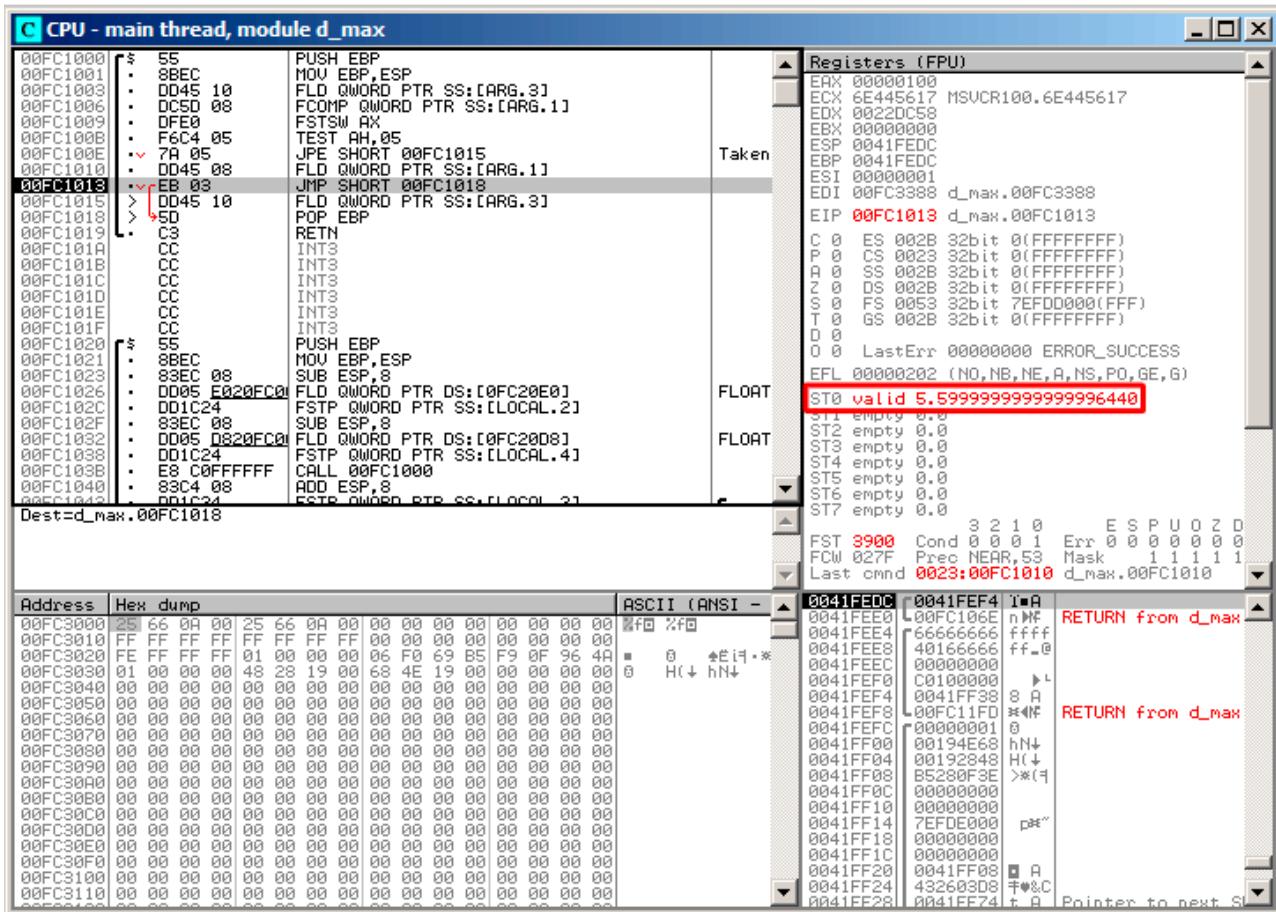


Figure 18.15: OllyDbg: second FLD executed

The function finishes its work.

Optimizing MSVC 2010

Listing 18.11: Optimizing MSVC 2010

```

_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 ; 00000041H
    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,
; leave (_b) on top
    fstp   ST(0)

; current stack state: ST(0) = _b

```

18.7. COMPARISON EXAMPLE

```
    ret      0  
_d_max    ENDP
```

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 finished.

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 was 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.

18.7. COMPARISON EXAMPLE

First OllyDbg example: a=1.2 and b=3.4

Both FLD are executed:

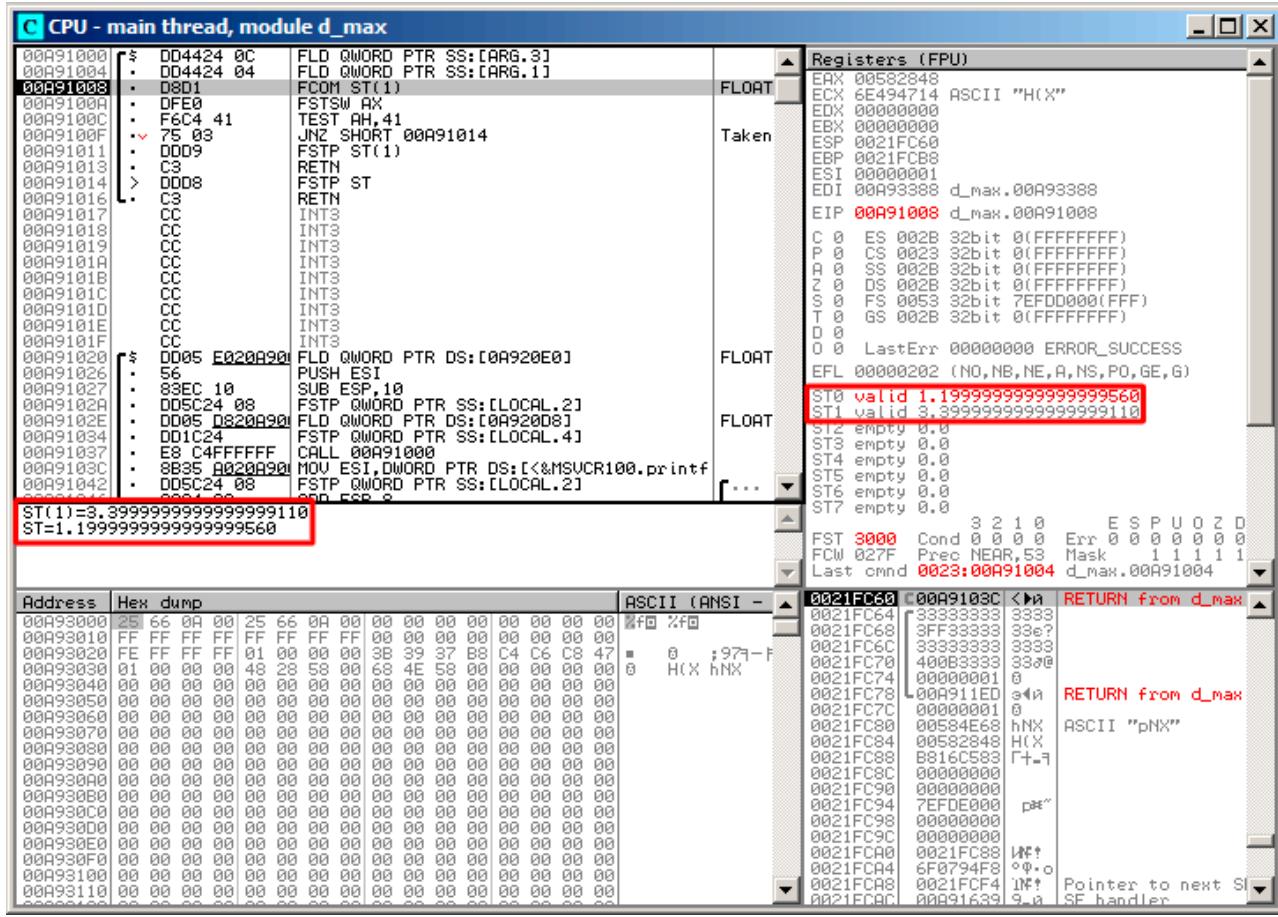


Figure 18.16: OllyDbg: both FLD are executed

FCOM being executed: OllyDbg shows the contents of ST(0) and ST(1) for convenience.

18.7. COMPARISON EXAMPLE

FCOM is done:

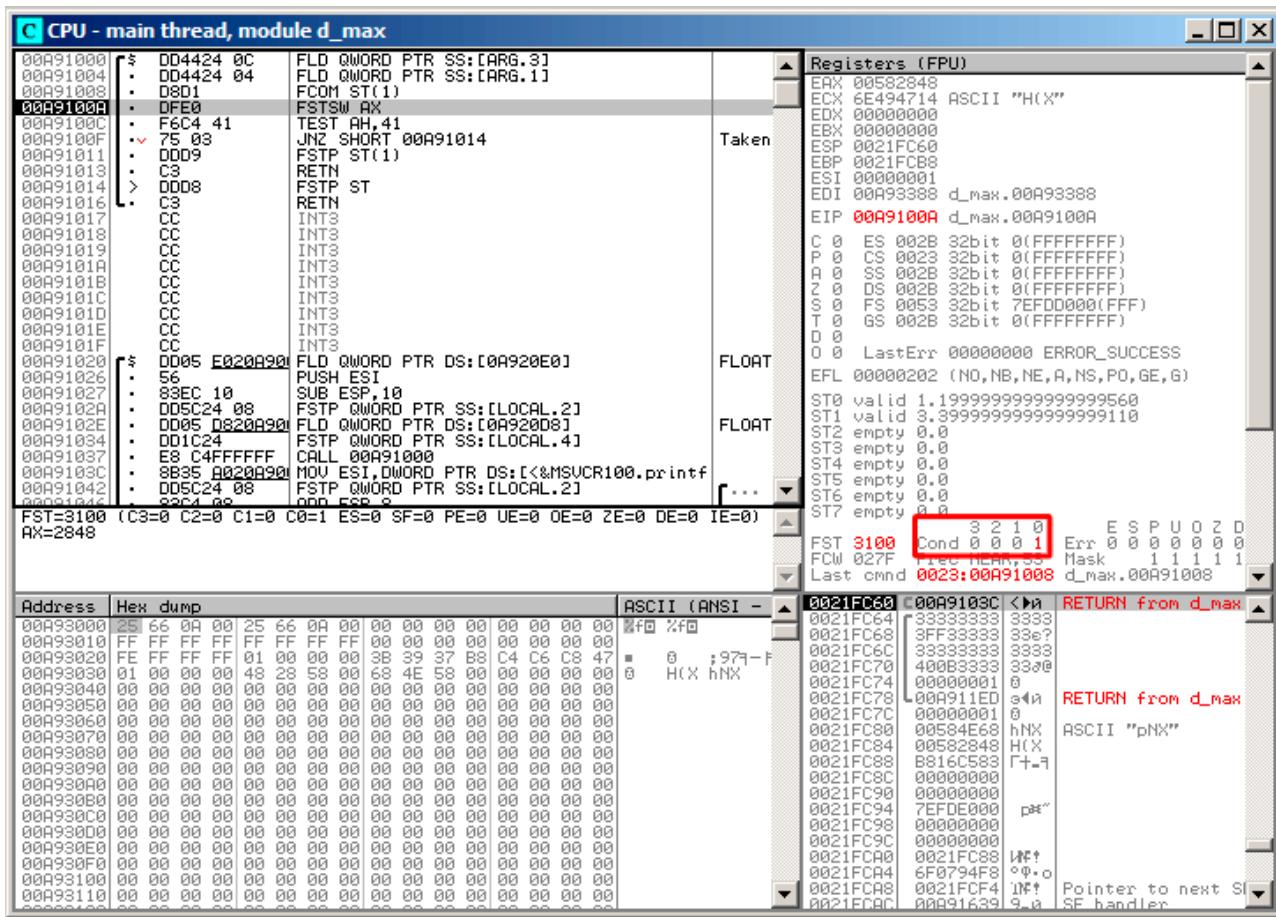


Figure 18.17: OllyDbg: FCOM is done

C0 is set, all other condition flags are cleared.

18.7. COMPARISON EXAMPLE

FNSTSW is done, AX =0x3100:

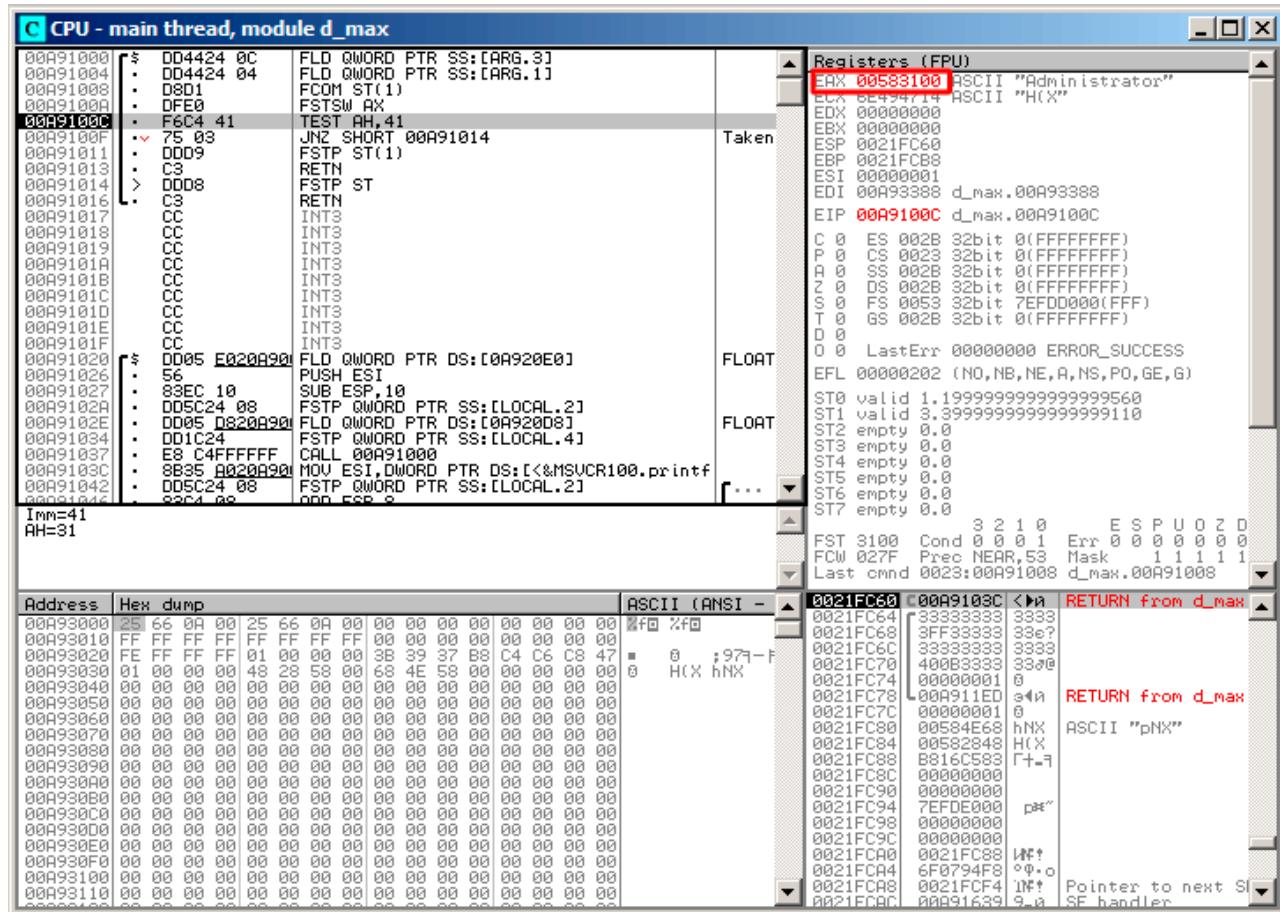


Figure 18.18: OllyDbg: FNSTSW is executed

18.7. COMPARISON EXAMPLE

TEST is executed:

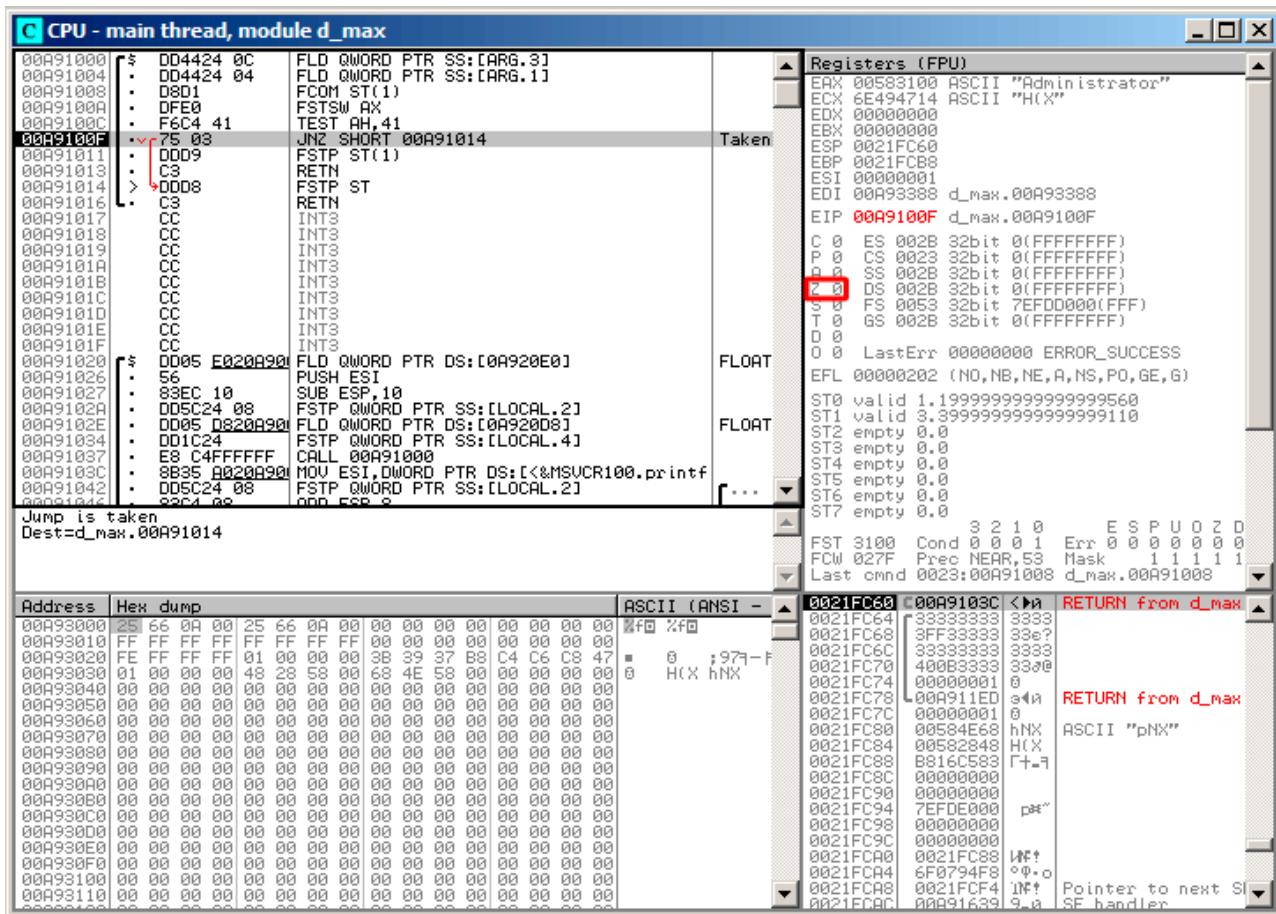


Figure 18.19: OllyDbg: TEST is executed

ZF=0, conditional jump is about to trigger now.

18.7. COMPARISON EXAMPLE

`FSTP ST` (or `FSTP ST(0)`) was executed –1.2 was popped from the stack, and 3.4 was left on top:

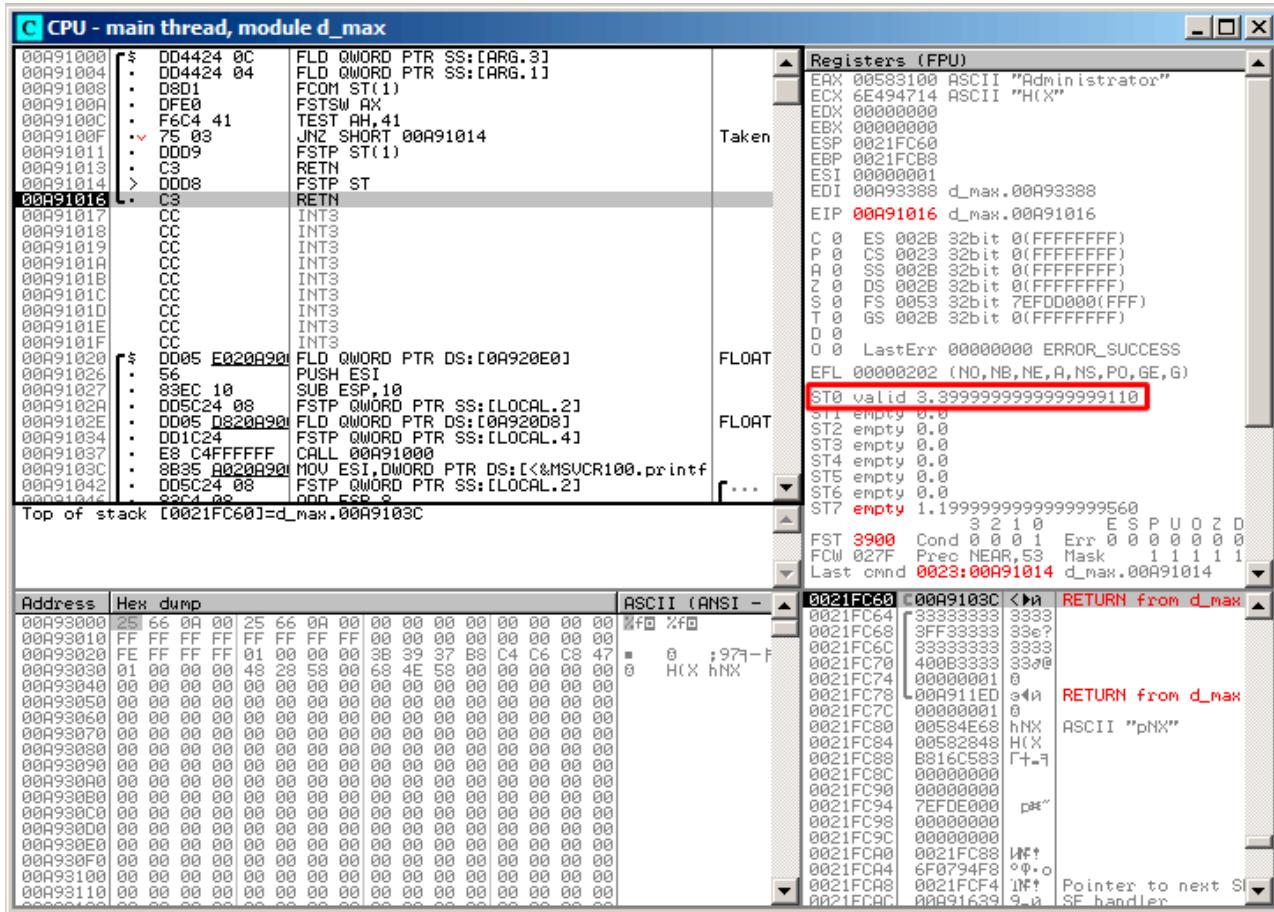


Figure 18.20: OllyDbg: `FSTP` is executed

We see that the `FSTP ST`

instruction works just like popping one value from the FPU stack.

18.7. COMPARISON EXAMPLE

Second OllyDbg example: a=5.6 and b=-4

Both **FLD** are executed:

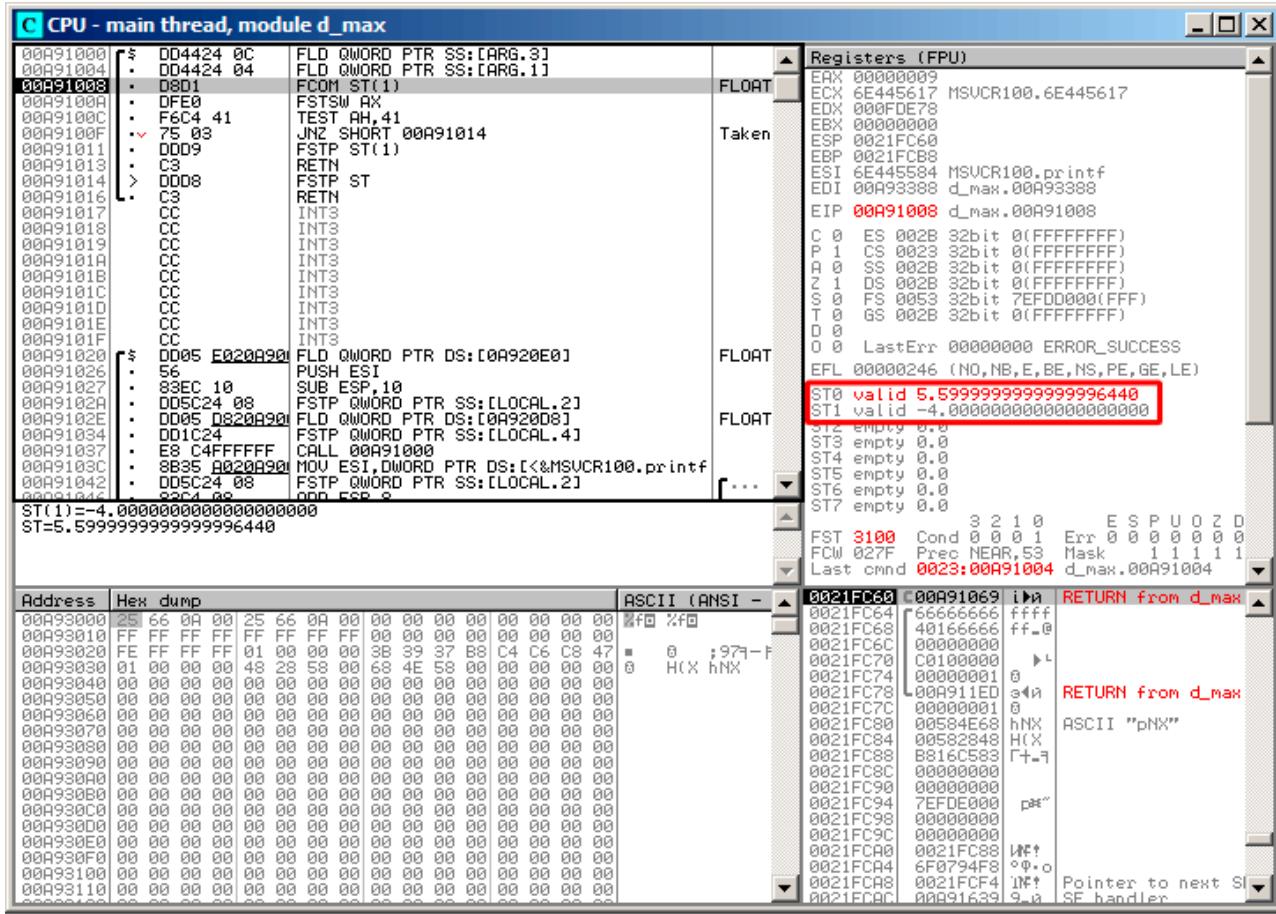


Figure 18.21: OllyDbg: both **FLD** are executed

FCOM is about to execute.

18.7. COMPARISON EXAMPLE

FCOM is done:

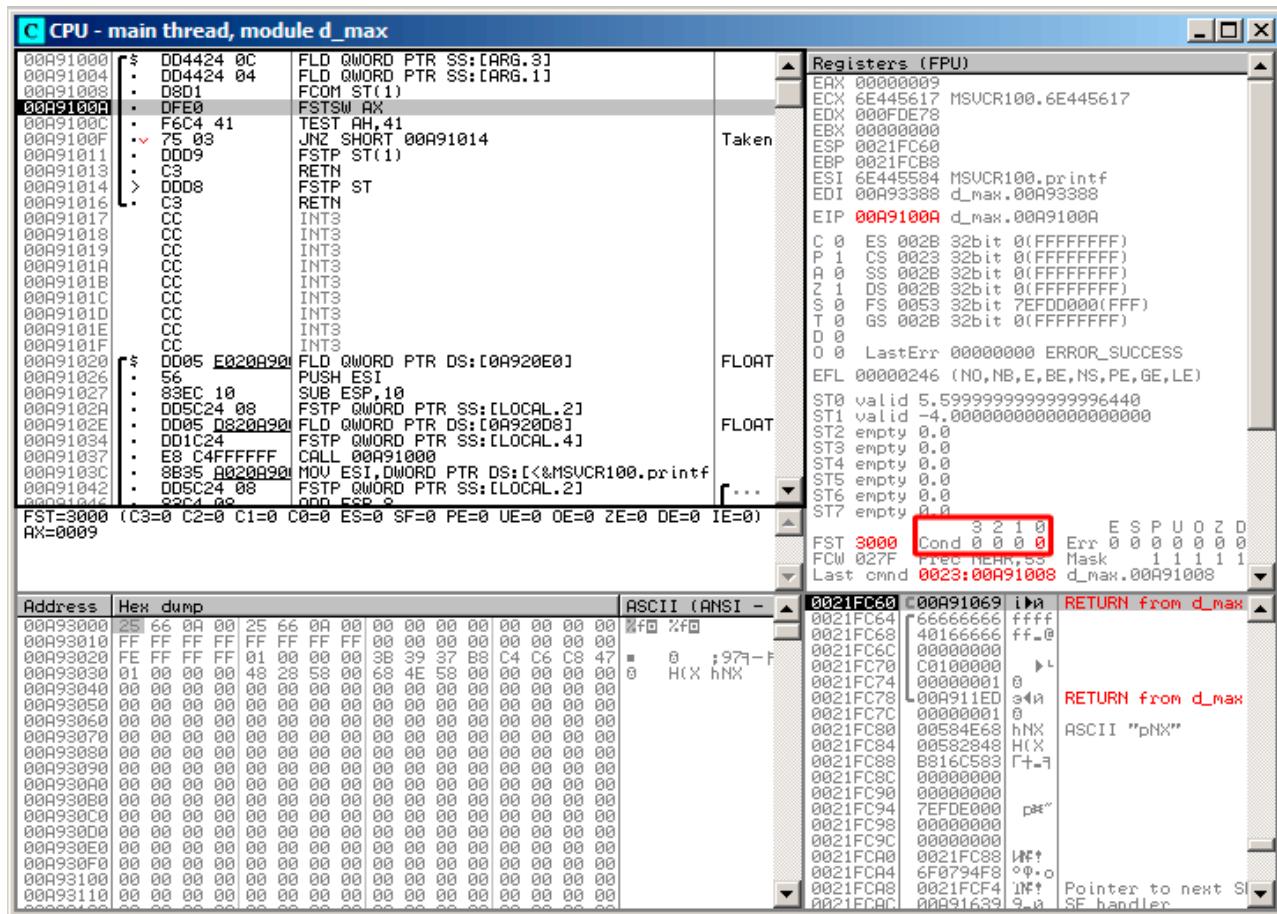


Figure 18.22: OllyDbg: FCOM is finished

All conditional flags are cleared.

18.7. COMPARISON EXAMPLE

FNSTSW done, AX =0x3000:

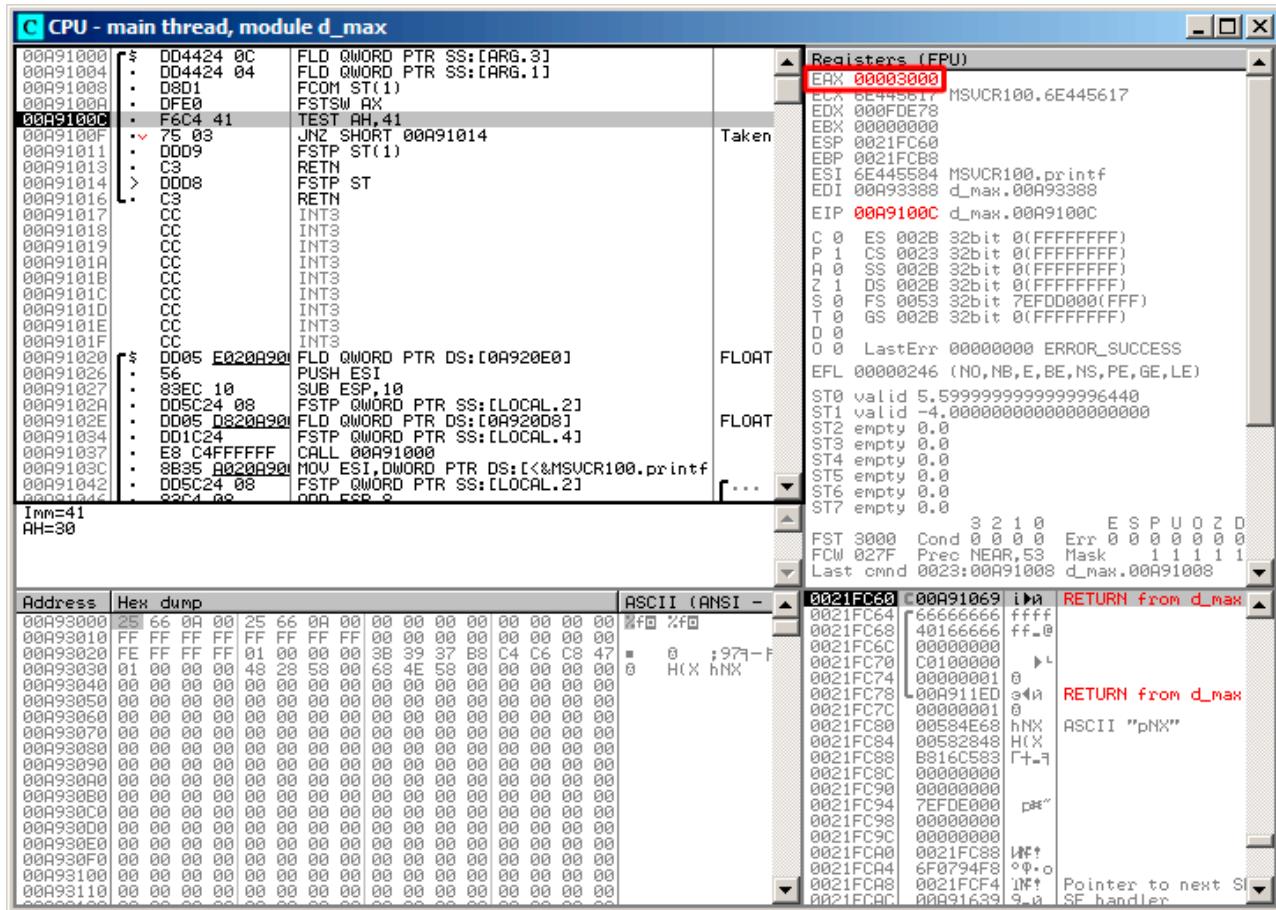


Figure 18.23: OllyDbg: FNSTSW was executed

18.7. COMPARISON EXAMPLE

TEST is done:

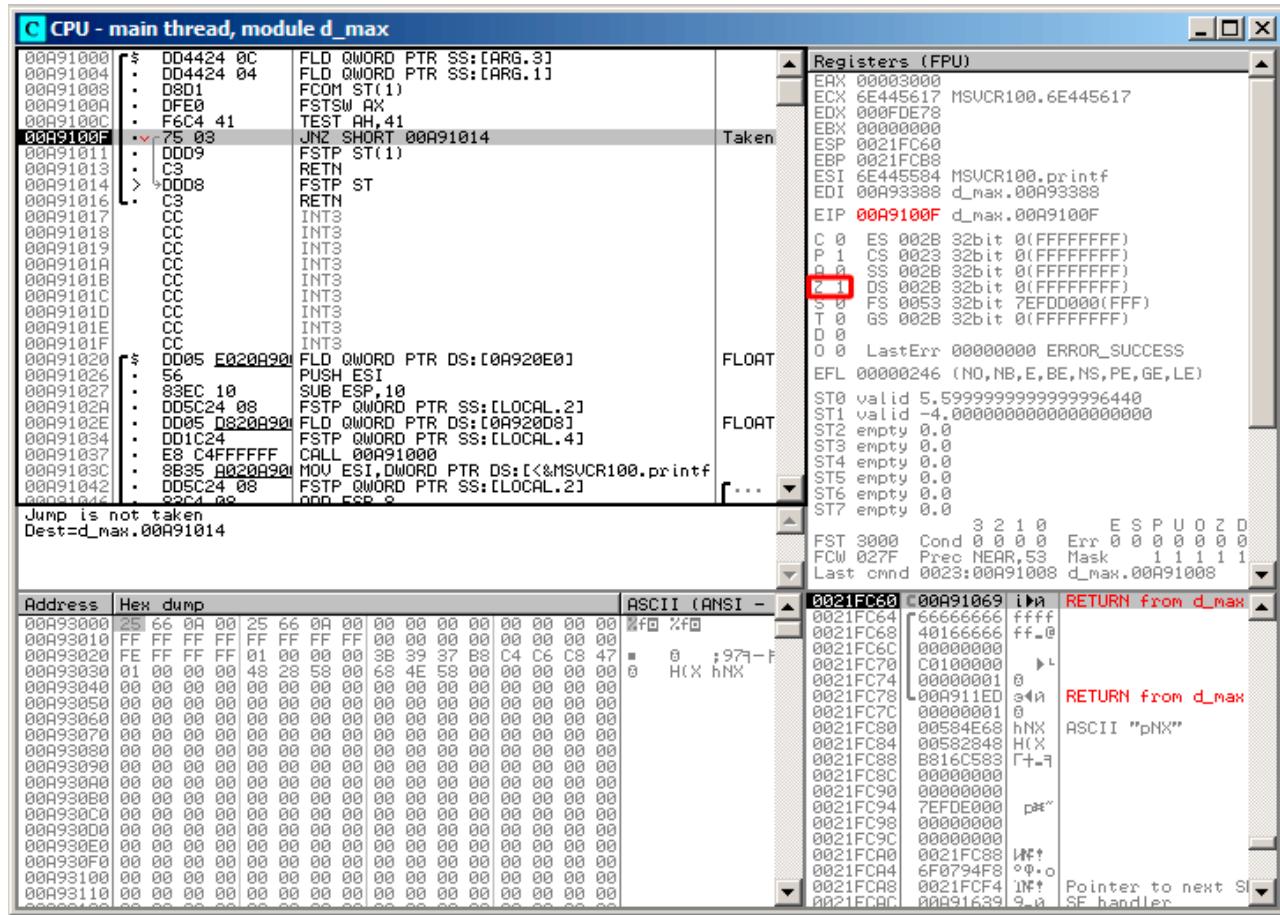


Figure 18.24: OllyDbg: TEST was executed

ZF=1, jump will not happen now.

18.7. COMPARISON EXAMPLE

FSTP ST(1) was executed: a value of 5.6 is now at the top of the FPU stack.

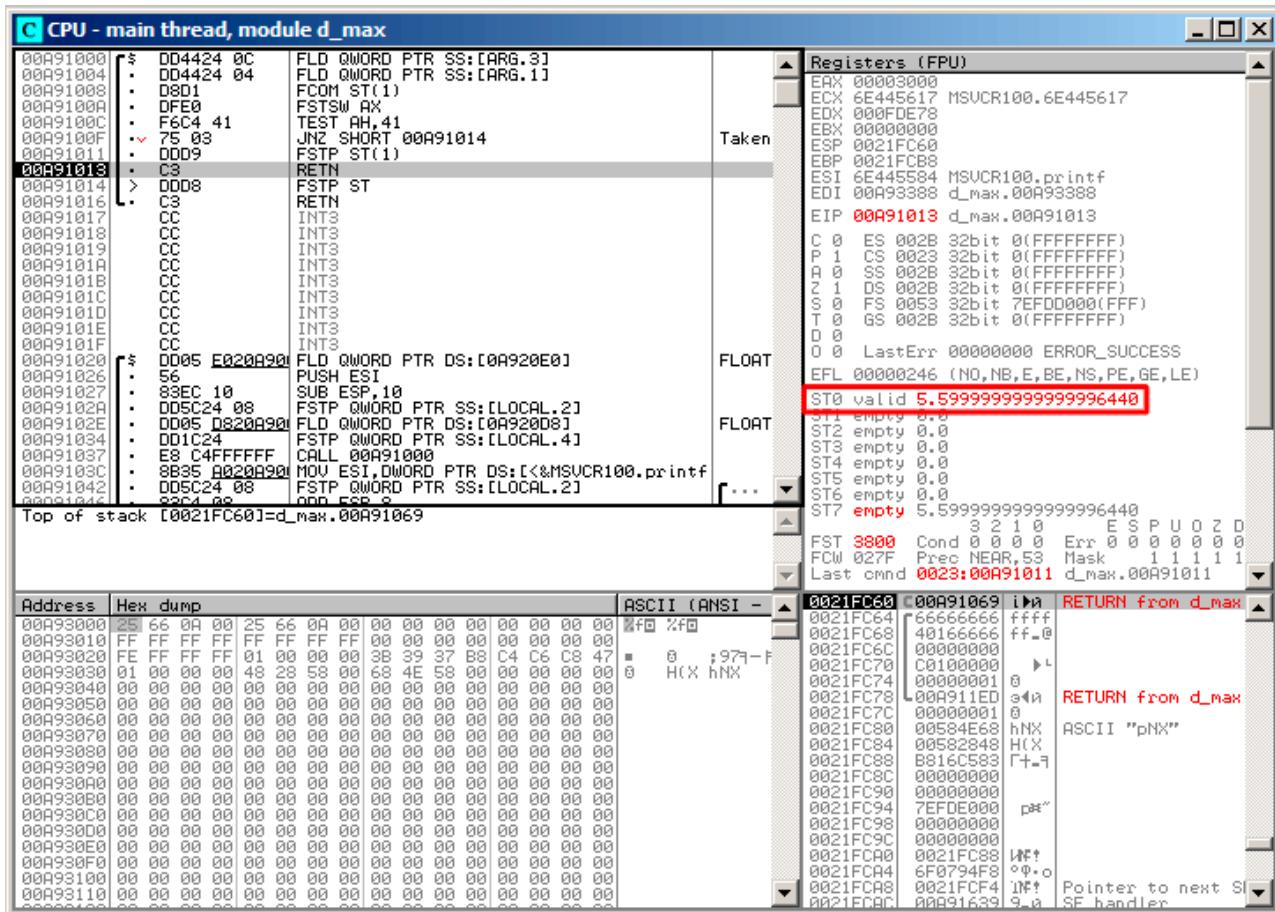


Figure 18.25: OllyDbg: `FSTP` was executed

We now see that the `FSTP ST(1)`

instruction works as follows: it leaves what was at the top of the stack, but clears `ST(1)`.

GCC 4.4.1

Listing 18.12: GCC 4.4.1

```
d_max proc near

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     eax, [ebp+b_second_half]
mov     dword ptr [ebp+b+4], eax
```

18.7. COMPARISON EXAMPLE

```

; load a and b to FPU stack:
fld      [ebp+a]
fld      [ebp+b]

; current stack state: ST(0) - b; ST(1) - a
fxch    st(1) ; this instruction swapping ST(1) and ST(0)

; current stack state: ST(0) - a; ST(1) - b

fucompp   ; compare a and b and pop two values from stack, i.e., a and b
fnstsw  ax ; store FPU status to AX
sahf     ; load SF, ZF, AF, PF, and CF flags state from AH
setnbe  al ; store 1 to AL, if CF=0 and ZF=0
test    al, al        ; AL==0 ?
jz      short loc_8048453 ; yes
fld      [ebp+a]
jmp      short locret_8048456

loc_8048453:
fld      [ebp+b]

locret_8048456:
leave
retn
d_max endp

```

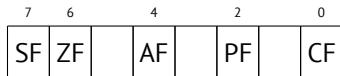
FUCOMPP is almost like **FCOM**, but pops both values from the stack and handles “not-a-numbers” differently.

A bit about *not-a-numbers*.

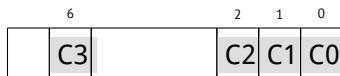
The FPU is able to deal with special values which are *not-a-numbers* or **NaN**¹⁷. These are infinity, result of division by 0, etc. Not-a-numbers can be “quiet” and “signaling”. It is possible to continue to work with “quiet” NaNs, but if one tries to do any operation with “signaling” NaNs, an exception 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:



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:



In other words, the **fnstsw ax / 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**.
- And if $a = b$, then: **ZF=1, PF=0, CF=0**.

¹⁷[wikipedia.org/wiki/NaN](https://en.wikipedia.org/wiki/NaN)

18.7. COMPARISON EXAMPLE

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`¹⁸ 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 18.13: Optimizing GCC 4.4.1

```

d_max          public 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

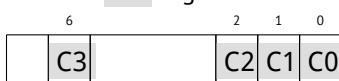
loc_8048448:
; store _a to ST(0), pop value at top of stack, leave _a at top
                fstp   st(1)

loc_804844A:
                pop    ebp
                retn
d_max          endp

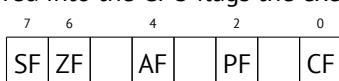
```

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`:



Let's also recall, how the bits from `AH` are stored into the CPU flags the execution of `SAHF`:



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.

Thereby, the conditional jumps instructions listed here can be used after a `FNSTSW / SAHF` instruction pair.

¹⁸cc is condition code

18.7. COMPARISON EXAMPLE

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 family¹⁹. 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 18.14: Optimizing GCC 4.8.1

```
fld    QWORD PTR [esp+4]      ; load "a"
fld    QWORD PTR [esp+12]     ; load "b"
; ST0=b, ST1=a
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*) <= 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 18.15: Optimizing GCC 4.8.1 and GDB

```
1 dennis@ubuntuvm:~/polygon$ gcc -O3 d_max.c -o d_max -fno-inline
2 dennis@ubuntuvm:~/polygon$ gdb d_max
3 GNU gdb (GDB) 7.6.1-ubuntu
4 Copyright (C) 2013 Free Software Foundation, Inc.
5 License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
6 This is free software: you are free to change and redistribute it.
7 There is NO WARRANTY, to the extent permitted by law. Type "show copying"
8 and "show warranty" for details.
9 This GDB was configured as "i686-linux-gnu".
10 For bug reporting instructions, please see:
11 <http://www.gnu.org/software/gdb/bugs/>...
12 Reading symbols from /home/dennis/polygon/d_max...(no debugging symbols found)...done.
13 (gdb) b d_max
14 Breakpoint 1 at 0x80484a0
15 (gdb) run
16 Starting program: /home/dennis/polygon/d_max
17
18 Breakpoint 1, 0x080484a0 in d_max ()
19 (gdb) ni
20 0x080484a4 in d_max ()
21 (gdb) disas $eip
```

¹⁹Starting at Pentium Pro, Pentium-II, etc.

18.7. COMPARISON EXAMPLE

```

22 Dump of assembler code for function d_max:
23   0x080484a0 <+0>:    fldl  0x4(%esp)
24 => 0x080484a4 <+4>:    fldl  0xc(%esp)
25   0x080484a8 <+8>:    fxch  %st(1)
26   0x080484aa <+10>:   fucomi %st(1),%st
27   0x080484ac <+12>:   fcmovbe %st(1),%st
28   0x080484ae <+14>:   fstp   %st(1)
29   0x080484b0 <+16>:   ret
30 End of assembler dump.
31 (gdb) ni
32 0x080484a8 in d_max ()
33 (gdb) info float
34   R7: Valid  0x3fff999999999999800 +1.19999999999999956
35 =>R6: Valid  0x4000d99999999999800 +3.39999999999999911
36   R5: Empty   0x00000000000000000000000000000000
37   R4: Empty   0x00000000000000000000000000000000
38   R3: Empty   0x00000000000000000000000000000000
39   R2: Empty   0x00000000000000000000000000000000
40   R1: Empty   0x00000000000000000000000000000000
41   R0: Empty   0x00000000000000000000000000000000
42
43 Status Word:      0x3000
44           TOP: 6
45 Control Word:     0x037f  IM DM ZM OM UM PM
46           PC: Extended Precision (64-bits)
47           RC: Round to nearest
48 Tag Word:          0xffff
49 Instruction Pointer: 0x73:0x080484a4
50 Operand Pointer:   0x7b:0xbfffff118
51 Opcode:            0x0000
52 (gdb) ni
53 0x080484aa in d_max ()
54 (gdb) info float
55   R7: Valid  0x4000d99999999999800 +3.39999999999999911
56 =>R6: Valid  0x3fff999999999999800 +1.19999999999999956
57   R5: Empty   0x00000000000000000000000000000000
58   R4: Empty   0x00000000000000000000000000000000
59   R3: Empty   0x00000000000000000000000000000000
60   R2: Empty   0x00000000000000000000000000000000
61   R1: Empty   0x00000000000000000000000000000000
62   R0: Empty   0x00000000000000000000000000000000
63
64 Status Word:      0x3000
65           TOP: 6
66 Control Word:     0x037f  IM DM ZM OM UM PM
67           PC: Extended Precision (64-bits)
68           RC: Round to nearest
69 Tag Word:          0xffff
70 Instruction Pointer: 0x73:0x080484a8
71 Operand Pointer:   0x7b:0xbfffff118
72 Opcode:            0x0000
73 (gdb) disas $eip
74 Dump of assembler code for function d_max:
75   0x080484a0 <+0>:    fldl  0x4(%esp)
76   0x080484a4 <+4>:    fldl  0xc(%esp)
77   0x080484a8 <+8>:    fxch  %st(1)
78 => 0x080484aa <+10>:   fucomi %st(1),%st
79   0x080484ac <+12>:   fcmovbe %st(1),%st
80   0x080484ae <+14>:   fstp   %st(1)
81   0x080484b0 <+16>:   ret
82 End of assembler dump.
83 (gdb) ni
84 0x080484ac in d_max ()
85 (gdb) info registers
86 eax            0x1          1
87 ecx            0xbffff1c4      -1073745468
88 edx            0x8048340       134513472
89 ebx            0xb7fbf000      -1208225792
90 esp            0xbffff10c      0xbffff10c
91 ebp            0xbffff128      0xbffff128

```

18.7. COMPARISON EXAMPLE

```

92  esi          0x0      0
93  edi          0x0      0
94  eip          0x80484ac      0x80484ac <d_max+12>
95  eflags       0x203    [ CF IF ]
96  cs           0x73     115
97  ss           0x7b     123
98  ds           0x7b     123
99  es           0x7b     123
100 fs           0x0      0
101 gs           0x33     51
102 (gdb) ni
103 0x080484ae in d_max ()
104 (gdb) info float
105   R7: Valid   0x4000d9999999999999800 +3.399999999999999911
106 =>R6: Valid   0x4000d9999999999999800 +3.399999999999999911
107   R5: Empty   0x00000000000000000000000000000000
108   R4: Empty   0x00000000000000000000000000000000
109   R3: Empty   0x00000000000000000000000000000000
110   R2: Empty   0x00000000000000000000000000000000
111   R1: Empty   0x00000000000000000000000000000000
112   R0: Empty   0x00000000000000000000000000000000
113
114 Status Word:      0x3000
115                 TOP: 6
116 Control Word:     0x037f  IM DM ZM OM UM PM
117                 PC: Extended Precision (64-bits)
118                 RC: Round to nearest
119 Tag Word:          0xffff
120 Instruction Pointer: 0x73:0x080484ac
121 Operand Pointer:   0x7b:0xbfffff118
122 Opcode:            0x0000
123 (gdb) disas $eip
124 Dump of assembler code for function d_max:
125  0x080484a0 <+0>:    fldl   0x4(%esp)
126  0x080484a4 <+4>:    fldl   0xc(%esp)
127  0x080484a8 <+8>:    fxch   %st(1)
128  0x080484aa <+10>:   fucomi %st(1),%st
129  0x080484ac <+12>:   fcmovbe %st(1),%st
130 => 0x080484ae <+14>:  fstp   %st(1)
131  0x080484b0 <+16>:   ret
132 End of assembler dump.
133 (gdb) ni
134 0x080484b0 in d_max ()
135 (gdb) info float
136 =>R7: Valid   0x4000d9999999999999800 +3.399999999999999911
137   R6: Empty   0x4000d9999999999999800
138   R5: Empty   0x00000000000000000000000000000000
139   R4: Empty   0x00000000000000000000000000000000
140   R3: Empty   0x00000000000000000000000000000000
141   R2: Empty   0x00000000000000000000000000000000
142   R1: Empty   0x00000000000000000000000000000000
143   R0: Empty   0x00000000000000000000000000000000
144
145 Status Word:      0x3800
146                 TOP: 7
147 Control Word:     0x037f  IM DM ZM OM UM PM
148                 PC: Extended Precision (64-bits)
149                 RC: Round to nearest
150 Tag Word:          0x3fff
151 Instruction Pointer: 0x73:0x080484ae
152 Operand Pointer:   0x7b:0xbfffff118
153 Opcode:            0x0000
154 (gdb) quit
155 A debugging session is active.
156
157     Inferior 1 [process 30194] will be killed.
158
159 Quit anyway? (y or n) y
160 dennis@ubuntuvm:~/polygon$
```

18.7. COMPARISON EXAMPLE

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 ([18.5.1 on page 224](#)). 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.

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.

18.7.2 ARM

Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 18.16: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
VMOV      D16, R2, R3 ; b
VMOV      D17, R0, R1 ; a
VCMPE.F64 D17, D16
VMRS      APSR_nzcv, FPSCR
VMOVGT.F64 D16, D17 ; copy "b" to D16
VMOV      R0, R1, D16
BX       LR
```

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`²⁰), since there is a need 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`²¹).

`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 *b* is to be written into `D16` (that is currently stored in `D17`). Otherwise the value of *a* 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)

Listing 18.17: Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```
VMOV      D16, R2, R3 ; b
VMOV      D17, R0, R1 ; a
VCMPE.F64 D17, D16
VMRS      APSR_nzcv, FPSCR
IT GT
VMOVGT.F64 D16, D17
VMOV      R0, R1, D16
BX       LR
```

²⁰(ARM) Floating-Point Status and Control Register

²¹(ARM) Application Program Status Register

18.7. COMPARISON EXAMPLE

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.

In fact, the usual `VMOV` 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 18.18: Angry Birds Classic

```
...
ITE NE          R2, R3, D16
VMOVNE
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 `VMOV` (or `VMOVEQ`) is a normal one, not suffixed (`BLX`).

One more that's slightly harder, which is also from Angry Birds:

Listing 18.19: 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 be, for example, `ITEEEE 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 18.20: Angry Birds Classic

```
...
CMP.W          R0, #0xFFFFFFFF
ITTE LE
SUBLE.W        R10, R0, #1
NEGLE
MOVGT          R10, R0
MOVS           R6, #0      ; not suffixed
```

18.7. COMPARISON EXAMPLE

```
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**, **ITE**, **ITT**, **ITTE**, **ITTT**, **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 18.21: 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 18.22: Optimizing Keil 6/2013 (Thumb mode)

```
PUSH {R3-R7,LR}  
MOVS R4, R2
```

18.7. COMPARISON EXAMPLE

```
    MOVS    R5, R3
    MOVS    R6, R0
    MOVS    R7, R1
    BL      __aeabi_cdrcmple
    BCS    loc_1C0
    MOVS    R0, R6
    MOVS    R1, R7
    POP     {R3-R7,PC}

loc_1C0
    MOVS    R0, R4
    MOVS    R1, R5
    POP     {R3-R7,PC}
```

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.

18.7.3 ARM64

Optimizing GCC (Linaro) 4.9

```
d_max:
; D0 - a, D1 - b
    fcmpe d0, d1
    fcSEL d0, d0, d1, gt
; now result in D0
    ret
```

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

```
d_max:
; save input arguments in "Register Save Area"
    sub    sp, sp, #16
    str    d0, [sp,8]
    str    d1, [sp]
; reload values
    ldr    x1, [sp,8]
    ldr    x0, [sp]
    fmov  d0, x1
    fmov  d1, x0
; D0 - a, D1 - b
    fcmpe d0, d1
    ble   .L76
; a>b; load D0 (a) into X0
    ldr    x0, [sp,8]
    b     .L74
.L76:
; a<=b; load D1 (b) into X0
    ldr    x0, [sp]
.L74:
```

18.7. COMPARISON EXAMPLE

```
; result in X0
    fmov    d0, x0
; result in D0
    add     sp, sp, 16
    ret
```

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 ($a \leq b$), 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*.

```
float f_max (float a, float b)
{
    if (a>b)
        return a;

    return b;
};
```

```
f_max:
; S0 - a, S1 - b
    fcmpe    s0, s1
    fcsel    s0, s0, s1, gt
; now result in S0
    ret
```

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).

18.7.4 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.

Listing 18.23: Optimizing GCC 4.4.5 (IDA)

```
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
    bc1t   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

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** mean 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.

18.8 Stack, calculators and reverse Polish notation

Now we understand why some old calculators used reverse Polish notation ²².

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.

18.9 x64

On how floating point numbers are processed in x86-64, read more here: [28 on page 428](#).

18.10 Exercises

- <http://challenges.re/60>
- <http://challenges.re/61>

²²[wikipedia.org/wiki/Reverse_Polish_notation](https://en.wikipedia.org/wiki/Reverse_Polish_notation)

Chapter 19

Arrays

An array is just a set of variables in memory that lie next to each other and that have the same type¹.

19.1 Simple example

```
#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;
}
```

19.1.1 x86

MSVC

Let's compile:

Listing 19.1: MSVC 2008

```
_TEXT      SEGMENT
_i$ = -84                      ; size = 4
_a$ = -80                      ; size = 80
_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
```

¹ AKA² “homogeneous container”

19.1. SIMPLE EXAMPLE

```
    mov    edx, DWORD PTR _i$[ebp]
    mov    DWORD PTR _a$[ebp+edx*4], ecx
    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:
    xor    eax, eax
    mov    esp, ebp
    pop    ebp
    ret    0
_main    ENDP
```

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 [17.2.1 on page 215](#).

80 bytes are allocated on the stack for the array, 20 elements of 4 bytes.

19.1. SIMPLE EXAMPLE

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:

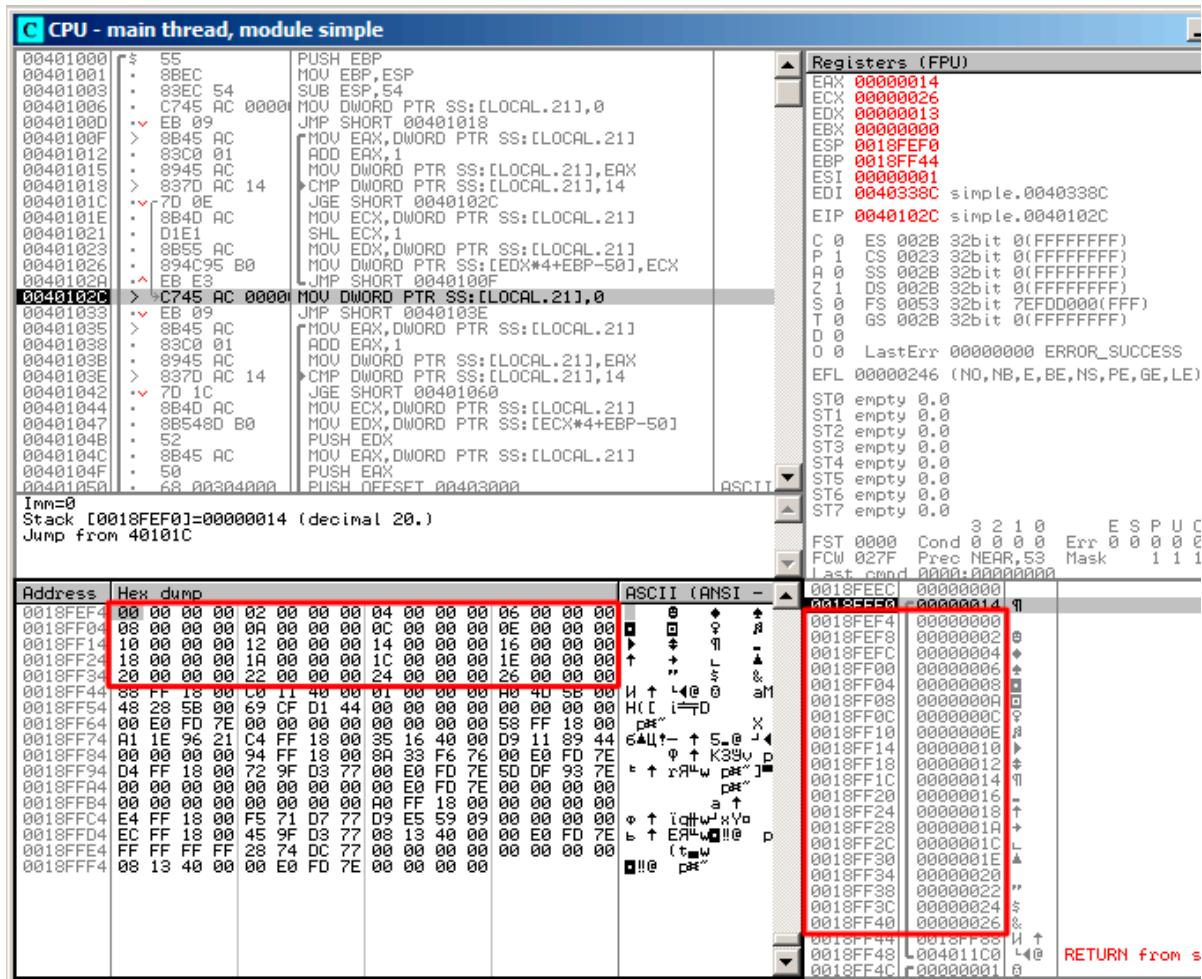


Figure 19.1: OllyDbg: after array filling

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:

Listing 19.2: GCC 4.4.1

```

public main
main    proc near           ; DATA XREF: _start+17

var_70     = dword ptr -70h
var_6C     = dword ptr -6Ch
var_68     = dword ptr -68h
i_2       = dword ptr -54h
i         = dword ptr -4

push    ebp
mov     ebp, esp
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

```

19.1. SIMPLE EXAMPLE

```
        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
        mov    eax, 0
        leave
        retn
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!

19.1.2 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
loc_4A0
    CMP    R4, #20             ; i<20?
    BLT    loc_494             ; yes, run loop body again
; second loop
    MOV    R4, #0              ; i
    B     loc_4C4
loc_4B0
    LDR    R2, [SP,R4,LSL#2]  ; (second printf argument) R2=*(SP+R4<<4) (same as
    *(SP+R4*4))
    MOV    R1, R4              ; (first printf argument) R1=i
```

19.1. SIMPLE EXAMPLE

```

        ADR    R0, aADD      ; "a[%d]=%d\n"
        BL     __2printf
        ADD    R4, R4, #1     ; i=i+1

loc_4C4
        CMP    R4, #20       ; i<20?
        BLT    loc_4B0       ; yes, run loop body again
        MOV    R0, #0         ; value to return
        ADD    SP, SP, #0x50   ; deallocate chunk, allocated for 20 int variables
        LDMFD  SP!, {R4,PC}

```

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 $i * 2$, 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#2]` 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#2]` instruction. It loads the value we need from the array, and the pointer to it is calculated likewise.

Optimizing Keil 6/2013 (Thumb mode)

```

_main
    PUSH    {R4,R5,LR}
; allocate place for 20 int variables + one more variable
    SUB    SP, SP, #0x54

; first loop

        MOVS   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

loc_1DC
        MOVS   R4, #0      ; i=0
        LSLS   R0, R4, #2    ; R0=i<<2 (same as i*4)
        LDR    R2, [R5,R0]    ; load from *(R5+R0) (same as R5+i*4)
        MOVS   R1, R4
        ADR    R0, aADD      ; "a[%d]=%d\n"
        BL    __2printf
        ADDS   R4, R4, #1     ; i=i+1
        CMP    R4, #20       ; i<20?
        BLT    loc_1DC       ; yes, i<20, run loop body again
        MOVS   R0, #0         ; value to return
; deallocate chunk, allocated for 20 int variables + one more variable
        ADD    SP, SP, #0x54
        POP    {R4,R5,PC}

```

Thumb code is very similar. Thumb mode has special instructions for bit shifting (like `LSLS`), which calculates the value to be written into the array and the address of each element in the array as well.

The compiler allocates slightly more space in the local stack, however, the last 4 bytes are not used.

19.1. SIMPLE EXAMPLE

Non-optimizing GCC 4.9.1 (ARM64)

Listing 19.3: 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
; jump to L3 (loop body begin) if not:
    ble   .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]
; 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
; jump to the loop body begin if not:
    ble   .L5
; return 0
    mov    w0, 0
; restore FP and LR:
```

19.1. SIMPLE EXAMPLE

```
1dp      x29, x30, [sp], 112
ret
```

19.1.3 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 19.4: 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
        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)
```

19.2. BUFFER OVERFLOW

```
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

$LCO: .ascii "a[%d]=%d\n"<0> # DATA XREF: main+44
```

Something interesting: there are two loops and the first one doesn't need i , it needs only $i * 2$ (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 `printf()` is called and it reports the value of 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: [41 on page 479](#). Their goal is to get rid of of multiplications.

19.2 Buffer overflow

19.2.1 Reading outside array bounds

So, array indexing is just `array[index]`. If you study the generated code closely, you'll probably note the missing index bounds checking, which could check *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:

```
#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):

Listing 19.5: Non-optimizing MSVC 2008

```
$SG2474 DB      'a[20]=%d', 0aH, 00H

_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], 20
    jge    SHORT $LN1@main
    mov    ecx, DWORD PTR _i$[ebp]
    shl    ecx, 1
    mov    edx, DWORD PTR _i$[ebp]
```

19.2. BUFFER OVERFLOW

```
    mov    DWORD PTR _a$[ebp+edx*4], ecx
    jmp    SHORT $LN2@main
$LN1@main:
    mov    eax, DWORD PTR _a$[ebp+80]
    push   eax
    push   OFFSET $SG2474 ; 'a[20]=%d'
    call   DWORD PTR __imp__printf
    add    esp, 8
    xor    eax, eax
    mov    esp, ebp
    pop    ebp
    ret    0
_main    ENDP
_TEXT    ENDS
END
```

The code produced this result:

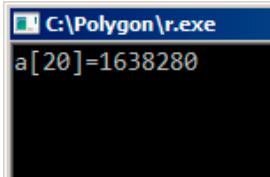


Figure 19.2: OllyDbg: console output

It is just *something* that was lying in the stack near to the array, 80 bytes away from its first element.

19.2. BUFFER OVERFLOW

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:

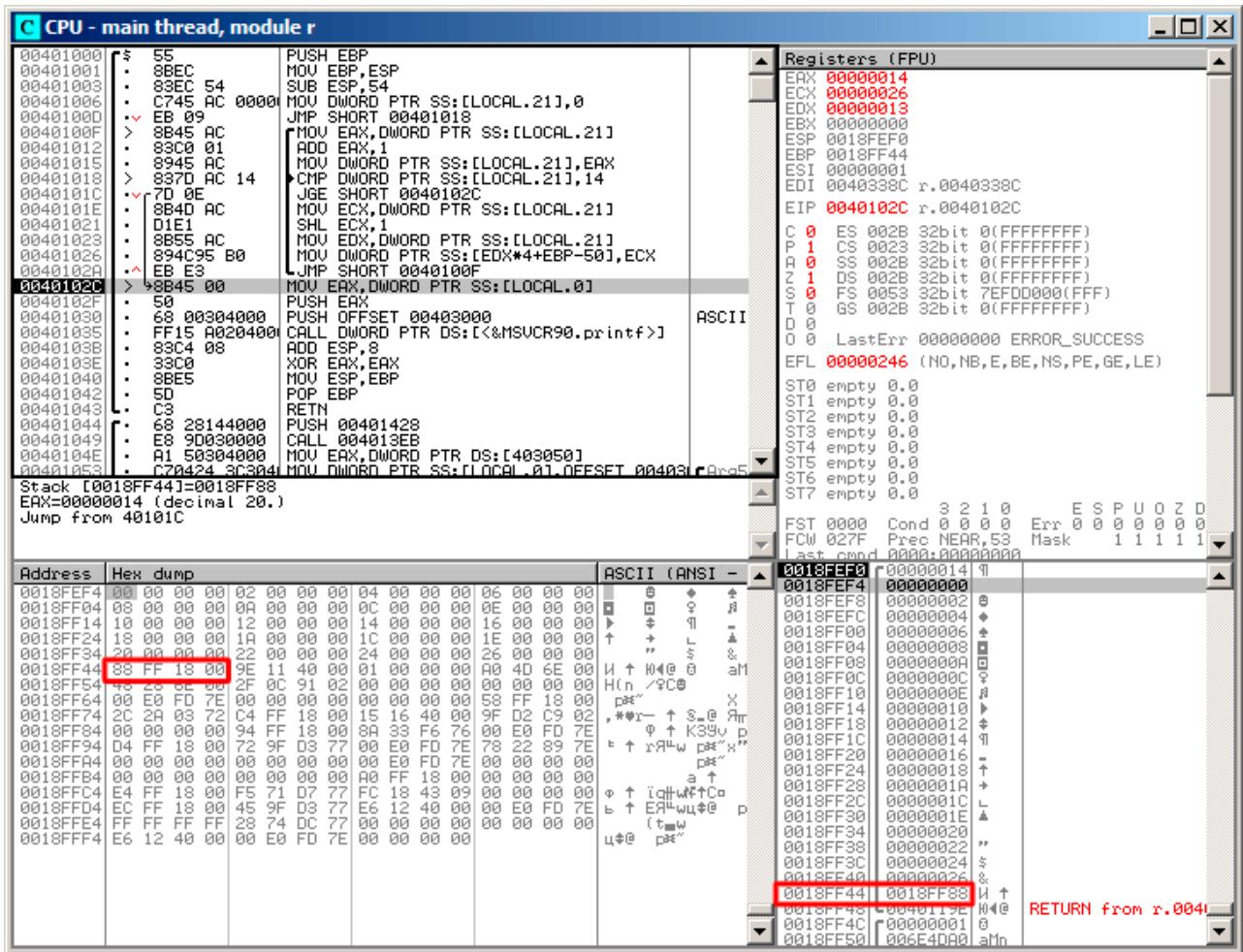


Figure 19.3: OllyDbg: reading of the 20th element and execution of `printf()`

What is this? Judging by the stack layout, this is the saved value of the EBP register.

19.2. BUFFER OVERFLOW

Let's trace further and see how it gets restored:

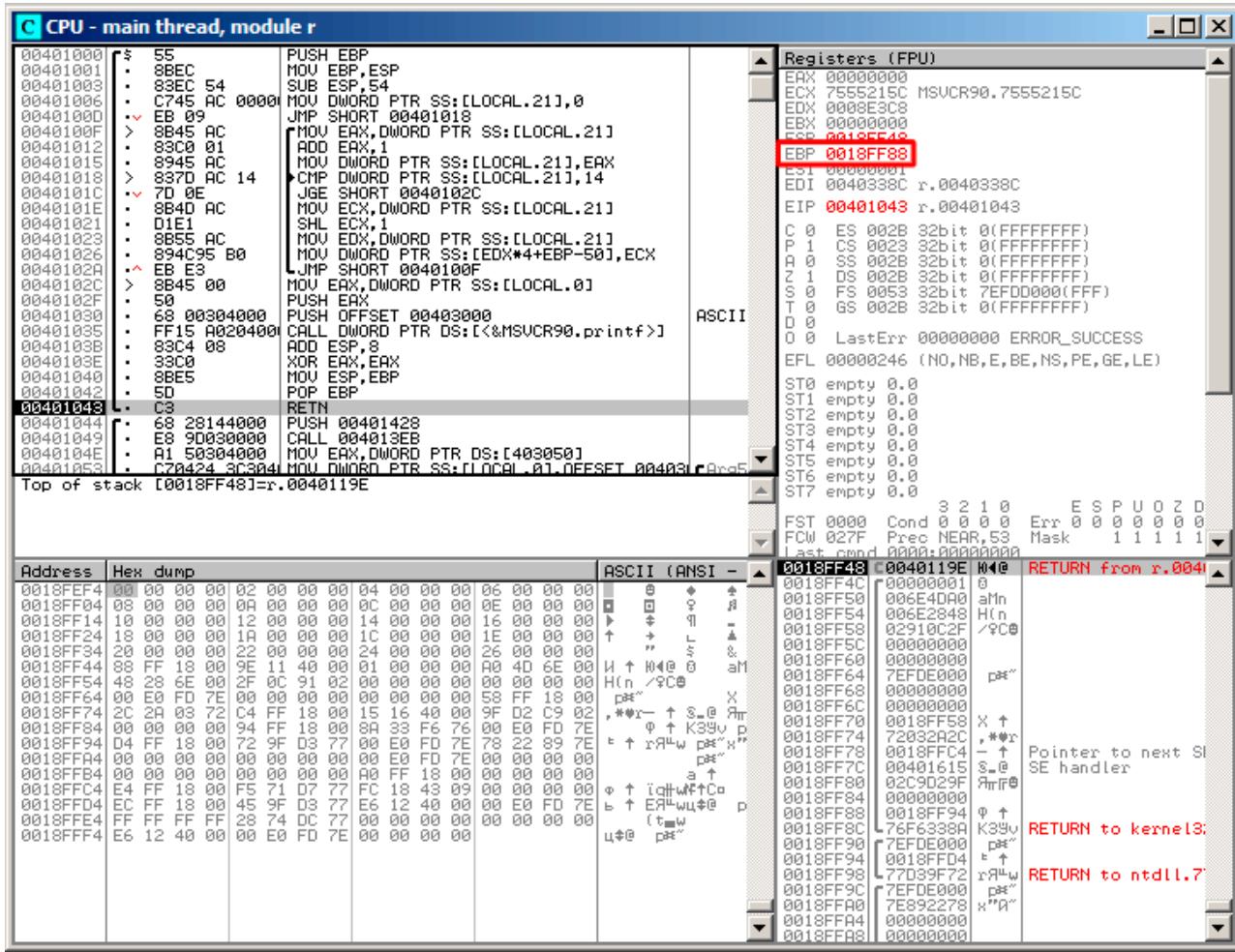


Figure 19.4: OllyDbg: restoring value of EBP

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 languages³) but this makes the code slower.

19.2.2 Writing beyond array bounds

OK, we read some values from the stack *illegally*, but what if we could write something to it?

Here is what we have got:

```
#include <stdio.h>

int main()
{
    int a[20];
    int i;

    for (i=0; i<30; i++)
        a[i]=i;

    return 0;
}
```

MSVC

And what we get:

³Java, Python, etc

```
_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.

19.2. BUFFER OVERFLOW

Let's load it into OllyDbg, and trace until all 30 elements are written:

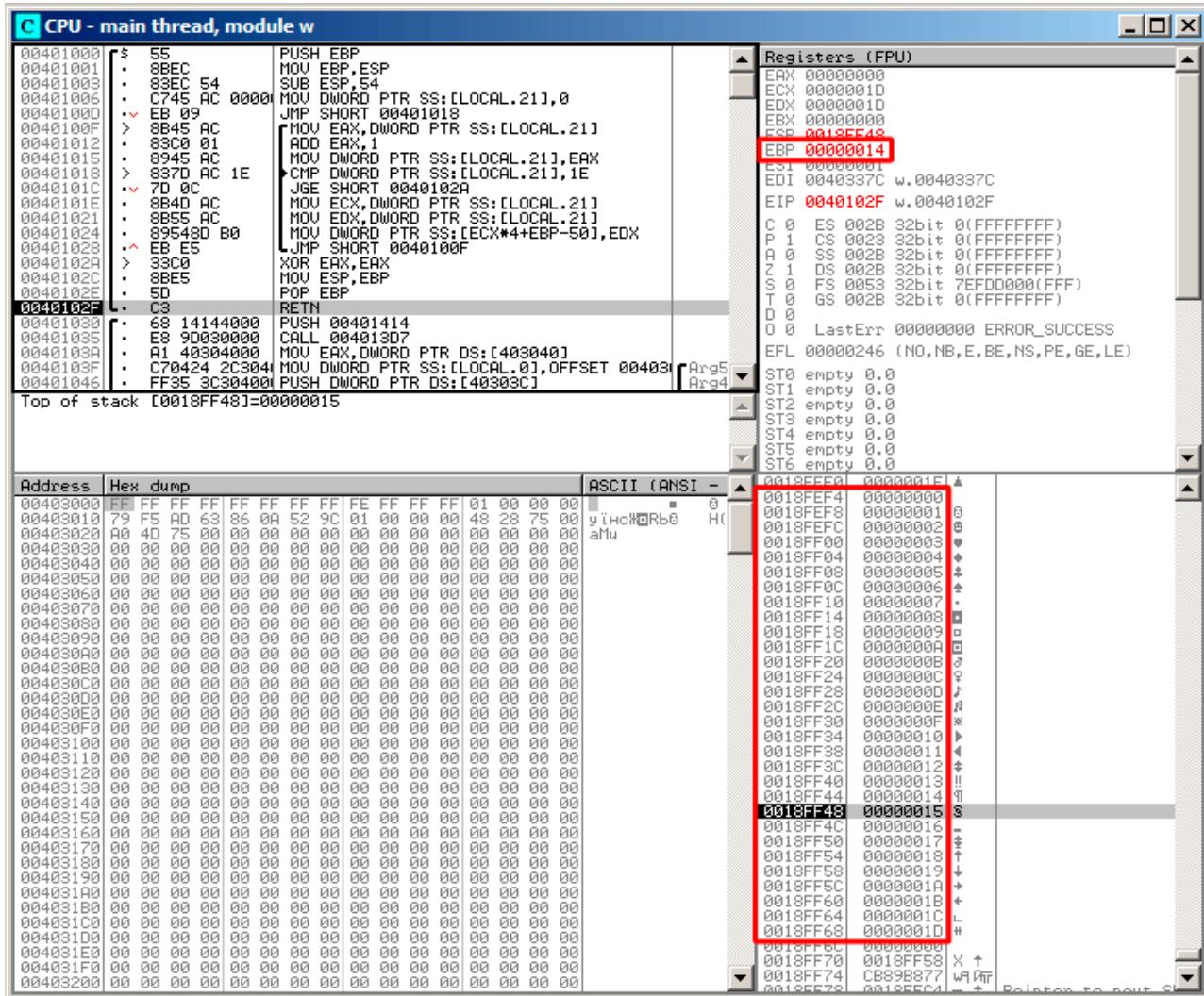


Figure 19.5: OllyDbg: after restoring the value of EBP

19.2. BUFFER OVERFLOW

Trace until the function end:

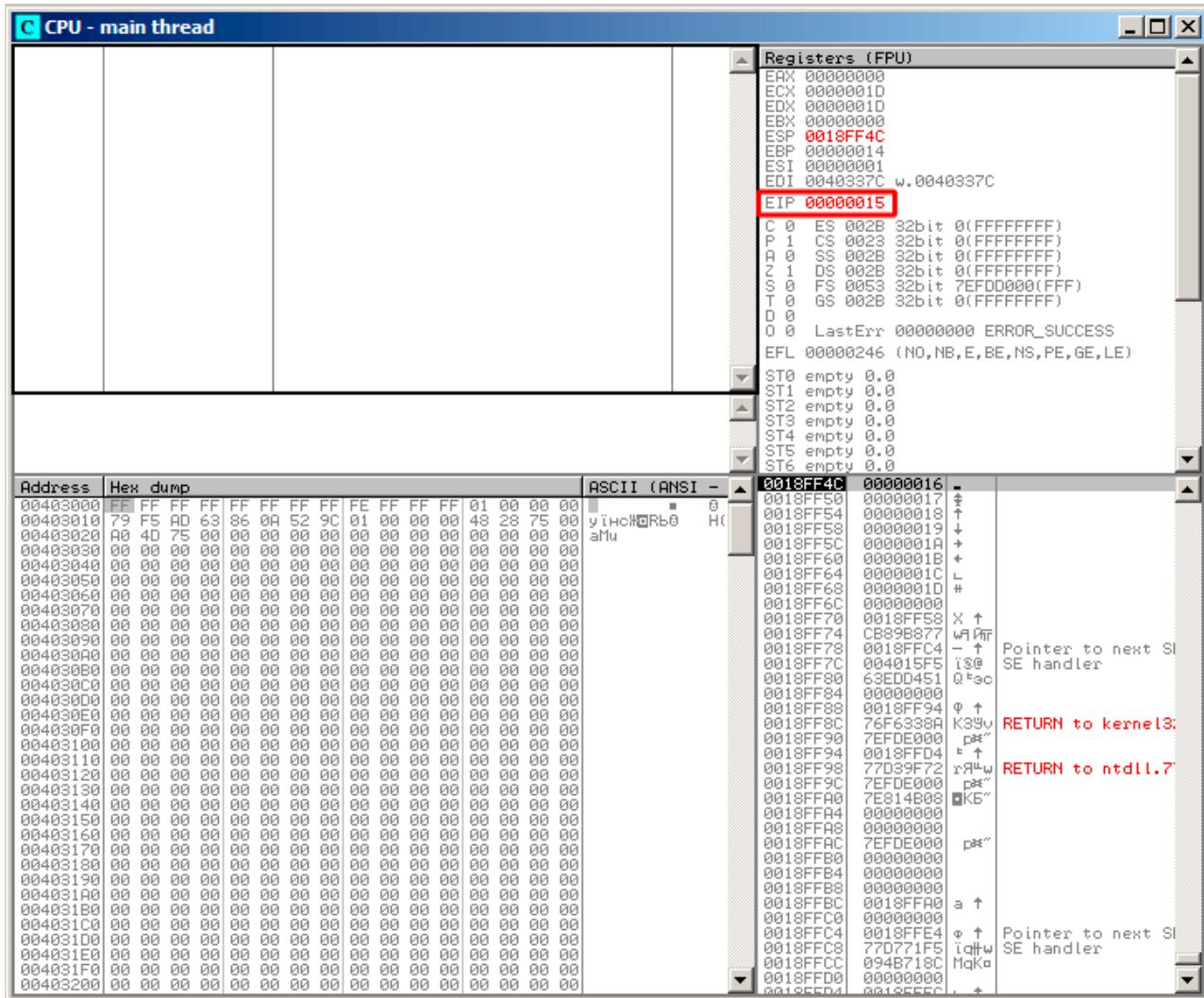


Figure 19.6: OllyDbg: EIP was restored, but OllyDbg can't disassemble at 0x15

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 was 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 $(20+1)*\text{sizeof}(int)$. 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>i</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 was written in the 20th element. At the function end, the function epilogue restores the original EBP value. (20 in decimal is 0x14 in hexadecimal). Then RET gets executed, which is effectively equivalent to POP EIP instruction.

19.2. BUFFER OVERFLOW

The `RET` instruction takes the return address from the stack (that is the address in `CRT`), which was called `main()`, and 21 iss 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*⁴.

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 emerged⁵

GCC

Let's try the same code in GCC 4.4.1. We get:

```
main          public 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
              retn
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            0x26efff4  2551796
esp            0xbfffff4b0      0xbfffff4b0
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
(gdb)
```

⁴[wikipedia](#)

⁵Classic article about it: [\[One96\]](#).

19.3. BUFFER OVERFLOW PROTECTION METHODS

The register values are slightly different than in win32 example, since the stack layout is slightly different too.

19.3 Buffer overflow protection methods

There are several methods to protect against this scourge, regardless of the C/C++ programmers' negligence. MSVC has options like⁶:

```
/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’ canary⁷, 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 ([19.1 on page 267](#)) 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()` ([6.2.4 on page 30](#)) example:

```
#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 19.7: 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  
    mov     DWORD PTR [esp], ebx  
    mov     eax, DWORD PTR gs:20           ; canary  
    mov     DWORD PTR [ebp-12], eax  
    xor     eax, eax  
    call    _snprintf
```

⁶compiler-side buffer overflow protection methods: wikipedia.org/wiki/Buffer_overflow_protection

⁷wikipedia.org/wiki/Domestic_canary#Miner.27s_canary

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```
    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)[0xb7606e5c]
/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]
===== Memory map: =====
08048000-08049000 r-xp 00000000 08:01 2097586 /home/dennis/2_1
08049000-0804a000 r--p 00000000 08:01 2097586 /home/dennis/2_1
0804a000-0804b000 rw-p 00001000 08:01 2097586 /home/dennis/2_1
094d1000-094f2000 rw-p 00000000 00:00 0 [heap]
b7560000-b757b000 r-xp 00000000 08:01 1048602 /lib/i386-linux-gnu/libgcc_s.so.1
b757b000-b757c000 r--p 0001a000 08:01 1048602 /lib/i386-linux-gnu/libgcc_s.so.1
b757c000-b757d000 rw-p 0001b000 08:01 1048602 /lib/i386-linux-gnu/libgcc_s.so.1
b7592000-b7593000 rw-p 00000000 00:00 0
b7593000-b7740000 r-xp 00000000 08:01 1050781 /lib/i386-linux-gnu/libc-2.17.so
b7740000-b7742000 r--p 001ad000 08:01 1050781 /lib/i386-linux-gnu/libc-2.17.so
b7742000-b7743000 rw-p 001af000 08:01 1050781 /lib/i386-linux-gnu/libc-2.17.so
b7743000-b7746000 rw-p 00000000 00:00 0
b775a000-b775d000 rw-p 00000000 00:00 0
b775d000-b775e000 r-xp 00000000 00:00 0 [vdso]
b775e000-b777e000 r-xp 00000000 08:01 1050794 /lib/i386-linux-gnu/ld-2.17.so
b777e000-b777f000 r--p 0001f000 08:01 1050794 /lib/i386-linux-gnu/ld-2.17.so
b777f000-b7780000 rw-p 00020000 08:01 1050794 /lib/i386-linux-gnu/ld-2.17.so
bff35000-bff56000 rw-p 00000000 00:00 0 [stack]
Aborted (core dumped)
```

`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](#) ([68 on page 698](#))—some information specific to thread is stored there. By the way, in win32 the `fs` register plays the same role, pointing to [TIB](#)⁸⁹.

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.

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

Let's get back to our simple array example ([19.1 on page 267](#)), again, now we can see how LLVM checks the correctness of the “canary”:

```
_main
var_64      = -0x64
var_60      = -0x60
var_5C      = -0x5C
```

⁸Thread Information Block

⁹wikipedia.org/wiki/Win32_Thread_Information_Block

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```

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
MOVW   R0, #aobjc_methtype ; "objc_methtype"
MOVS   R2, #0
MOVT.W R0, #0
MOVS   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]
MOVS   R0, #0x1C
STR    R0, [SP,#0x64+var_2C]
MOVS   R0, #0x1E
STR    R0, [SP,#0x64+var_28]
MOVS   R0, #0x20
STR    R0, [SP,#0x64+var_24]
MOVS   R0, #0x22
STR    R0, [SP,#0x64+var_20]
MOVS   R0, #0x24
STR    R0, [SP,#0x64+var_1C]
MOVS   R0, #0x26

```

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```
STR      R0, [SP,#0x64+var_18]
MOV      R4, 0xFDA ; "a[%d]=%d\n"
MOV      R0, SP
ADDS    R6, R0, #4
ADD     R4, PC
B       loc_2F1C

; second loop begin

loc_2F14
ADDS    R0, R5, #1
LDR.W   R2, [R6,R5,LSL#2]
MOV     R5, R0

loc_2F1C
MOV     R0, R4
MOV     R1, R5
BLX    _printf
CMP     R5, #0x13
BNE    loc_2F14
LDR.W   R0, [R8]
LDR     R1, [SP,#0x64+canary]
CMP     R0, R1
ITTTT EQ      ; canary still correct?
MOVEQ   R0, #0
ADDEQ   SP, SP, #0x54
LDREQ.W R8, [SP+0x64+var_64],#4
POPEQ   {R4-R7,PC}
BLX    __stack_chk_fail
```

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 `R8` points. If they are equal to each other, a 4-instruction block is triggered by `ITTTT EQ`, which contains writing 0 in `R0`, the function epilogue and exit. If the “canaries” are not equal, the block being skipped, and the jump to `__stack_chk_fail` function will occur, which, perhaps will halt execution.

19.4 One more word about arrays

Now we understand why it is impossible to write something like this in C/C++ code:

```
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 `malloc()`, then access the allocated memory block as an array of variables of the type you need.

Or use the C99 standard feature[[ISO07](#), pp. 6.7.5/2], and it works like `alloca()` ([6.2.4 on page 30](#)) internally.

It's also possible to use garbage collecting libraries for C. And there are also libraries supporting smart pointers for C++.

19.5 Array of pointers to strings

Here is an example for an array of pointers.

Listing 19.8: Get month name

```
#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];
}
```

19.5.1 x64

Listing 19.9: 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
$SG3156 DB      '%s', 0aH, 00H
$SG3131 DB      'October', 00H
$SG3132 DB      'November', 00H
$SG3133 DB      'December', 00H
_DATA ENDS

month$ = 8
get_month1 PROC
    movsx rax, ecx
    lea    rcx, OFFSET FLAT:month1
    mov    rax, QWORD PTR [rcx+rax*8]
    ret    0
get_month1 ENDP
```

The code is very simple:

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- The first `MOVSDX` 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-bit¹⁰.
- 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 * 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 better¹¹:

Listing 19.10: Optimizing GCC 4.9 x64

```
movsx rdi, edi
mov    rax, QWORD PTR month1[0+rdi*8]
ret
```

32-bit MSVC

Let's also compile it in the 32-bit MSVC compiler:

Listing 19.11: Optimizing MSVC 2013 x86

```
_month$ = 8
_get_month1 PROC
    mov    eax, DWORD PTR _month$[esp-4]
    mov    eax, DWORD PTR _month1[eax*4]
    ret    0
_get_month1 ENDP
```

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.

19.5.2 32-bit ARM

ARM in ARM mode

Listing 19.12: Optimizing Keil 6/2013 (ARM mode)

```
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
    DCB    "June",0
    DCB    "July",0
    DCB    "August",0
    DCB    "September",0
    DCB    "October",0
    DCB    "November",0
    DCB    "December",0
```

¹⁰It is somewhat weird, but negative array index could be passed here as `month` (negative array indices will have been explained later: [54 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.

¹¹"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.

```

AREA ||.data||, DATA, ALIGN=2
month1
    DCD    ||.conststring||
    DCD    ||.conststring||+0x8
    DCD    ||.conststring||+0x11
    DCD    ||.conststring||+0x17
    DCD    ||.conststring||+0x1d
    DCD    ||.conststring||+0x21
    DCD    ||.conststring||+0x26
    DCD    ||.conststring||+0x2b
    DCD    ||.conststring||+0x32
    DCD    ||.conststring||+0x3c
    DCD    ||.conststring||+0x44
    DCD    ||.conststring||+0x4d

```

The address of the table is loaded in R1. All the rest is done using just one `LDR` instruction. Then input value `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.

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:

```

get_month1 PROC
    LSLS    r0,r0,#2
    LDR    r1,|L0.64|
    LDR    r0,[r1,r0]
    BX    lr
ENDP

```

19.5.3 ARM64

Listing 19.13: Optimizing GCC 4.9 ARM64

```

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
    .xword  .LC11
    .xword  .LC12
    .xword  .LC13
.LC2:
    .string "January"
.LC3:
    .string "February"
.LC4:
    .string "March"
.LC5:
    .string "April"
.LC6:

```

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```

.string "May"
.LC7:
.string "June"
.LC8:
.string "July"
.LC9:
.string "August"
.LC10:
.string "September"
.LC11:
.string "October"
.LC12:
.string "November"
.LC13:
.string "December"

```

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 *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.

19.5.4 MIPS

Listing 19.14: 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"

    .data # .rodata.str1.4
aJanuary:
.ascii "January"<0>
aFebruary:
.ascii "February"<0>
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>

```

19.5.5 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 19.15: 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 should 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 19.16: 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
              ; .data:off_140011000
aFebruary_1 db 'February',0 ; DATA XREF: .data:0000000140011008
              align 4
aMarch_1 db 'March',0 ; DATA XREF: .data:0000000140011010
```

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

19.5. ARRAY OF POINTERS TO STRINGS

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 stop. One such method in C/C++ is assertions. We can modify our program to fail if an incorrect value is passed:

Listing 19.17: assert() added

```
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 19.18: Optimizing MSVC 2013 x64

```
$SG3143 DB      'm', 00H, 'o', 00H, 'n', 00H, 't', 00H, 'h', 00H, '.', 00H
        DB      'c', 00H, 00H, 00H
$SG3144 DB      'm', 00H, 'o', 00H, 'n', 00H, 't', 00H, 'h', 00H, '<', 00H
        DB      '1', 00H, '2', 00H, 00H, 00H

month$ = 48
get_month1_checked PROC
$LN5:
    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).

This mechanism is probably the same in all compilers. Here is what GCC does:

Listing 19.19: 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"
```

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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” builds¹². 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.

19.6 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:

Offset in memory	array element
0	[0][0]
1	[0][1]
2	[0][2]
3	[0][3]
4	[1][0]
5	[1][1]
6	[1][2]
7	[1][3]
8	[2][0]
9	[2][1]
10	[2][2]
11	[2][3]

Table 19.1: Two-dimensional array represented in memory as one-dimensional

Here is how each cell of 3*4 array are placed in memory:

0	1	2	3
4	5	6	7
8	9	10	11

Table 19.2: 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.

19.6.1 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.

¹²[msdn.microsoft.com/en-us/library/windows/hardware/ff543450\(v=vs.85\).aspx](http://msdn.microsoft.com/en-us/library/windows/hardware/ff543450(v=vs.85).aspx)

Row filling example

Let's fill the second row with these values 0..3:

Listing 19.20: Row filling example

```
#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:

Address	Hex dump
00C33370	00 00 00 00 00 01 02 03 00 00 00 00 00 00 00 00
00C33380	02 00 00 00 C3 66 47 4E 00 00 00 00 00 00 00 00
00C33390	00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00C333A0	00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00C333B0	00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00

Figure 19.7: OllyDbg: array is filled

Column filling example

Let's fill the third column with values: 0..2:

Listing 19.21: Column filling example

```
#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.

Address	Hex dump
01033380	00 00 00 00 00 00 01 00 00 00 02 00 02 00 00 00
01033390	00 00 00 00 1E AA EF 31 1E AA EF 31 00 00 00 00
010333A0	00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
010333B0	00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00

Figure 19.8: OllyDbg: array is filled

19.6.2 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:

```
#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));
}
```

Compile and run it: it shows correct values.

What MSVC 2013 did is fascinating, all three routines are just the same!

Listing 19.22: Optimizing MSVC 2013 x64

```
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
```

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```
array$ = 8
a$ = 16
b$ = 24
get_by_coordinates2 PROC
    movsx rax, r8d
    movsx r9, edx
    add rax, rcx
    movzx eax, BYTE PTR [rax+r9*4]
    ret 0
get_by_coordinates2 ENDP

array$ = 8
a$ = 16
b$ = 24
get_by_coordinates1 PROC
    movsx rax, r8d
    movsx r9, edx
    add rax, rcx
    movzx eax, BYTE PTR [rax+r9*4]
    ret 0
get_by_coordinates1 ENDP
```

GCC also generates equivalent routines, but slightly different:

Listing 19.23: Optimizing GCC 4.9 x64

```
; 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
```

19.6.3 Three-dimensional array example

It's thing in 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 19.24: simple example

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```
#include <stdio.h>

int a[10][20][30];

void insert(int x, int y, int z, int value)
{
    a[x][y][z]=value;
}
```

x86

We get (MSVC 2010):

Listing 19.25: 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$[ebp]
    imul   eax, 2400           ; eax=600*4*x
    mov     ecx, DWORD PTR _y$[ebp]
    imul   ecx, 120            ; ecx=30*4*y
    lea    edx, DWORD PTR _a[eax+ecx] ; edx=a + 600*4*x + 30*4*y
    mov     eax, DWORD PTR _z$[ebp]
    mov     ecx, DWORD PTR _value$[ebp]
    mov     DWORD PTR [edx+eax*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 $address = 600 \cdot 4 \cdot x + 30 \cdot 4 \cdot y + 4z$, 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 19.26: GCC 4.4.1

```
insert      public 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
```

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```

        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.

ARM + Non-optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

Listing 19.27: Non-optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

```

_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]
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 19.28: Optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

```

_insert
MOVW  R9, #0x10FC
MOV.W R12, #2400
MOVT.W R9, #
RSB.W R1, R1, R1, LSL#4 ; R1 - y. R1=y<<4 - y = y*16 - y = y*15
ADD   R9, PC           ; R9 = pointer to a array
LDR.W R9, [R9]
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

```

19.6. MULTIDIMENSIONAL ARRAYS

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.

The `LDR.W R9, [R9]` instruction works like `LEA` ([A.6.2 on page 931](#)) in x86, but it does nothing here, it is redundant. Apparently, the compiler did not optimize it out.

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 19.29: 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
```

19.6.4 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: [86.2 on page 855](#).

Another example in this book is Minesweeper game: its field is also two-dimensional array: [79](#).

19.7 Pack of strings as a two-dimensional array

Let's revisit the function that returns the name of a month: listing 19.8. 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? In fact yes, if you represent the list of strings as a two-dimensional array:

```
#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, 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','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 19.30: Optimizing MSVC 2013 x64

```
month2 DB      04aH
       DB      061H
       DB      06eH
       DB      075H
       DB      061H
       DB      072H
       DB      079H
       DB      00H
       DB      00H
       DB      00H
...
get_month2 PROC
; sign-extend input argument and promote to 64-bit value
    movsxrd 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:

Listing 19.31: 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 19.32: 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 19.33: Non-optimizing MSVC 2013 x64

```
month$ = 8
get_month2 PROC
    mov     DWORD PTR [rsp+8], ecx
    movsxd 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    0
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.

19.7.1 32-bit ARM

Optimizing Keil for Thumb mode uses the multiplication instruction `MULS`:

Listing 19.34: Optimizing Keil 6/2013 (Thumb mode)

```

; R0 = month
    MOVS    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

```

Optimizing Keil for ARM mode uses add and shift operations:

Listing 19.35: 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

```

19.7.2 ARM64

Listing 19.36: 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.

19.7.3 MIPS

Listing 19.37: 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, $a0

month2:      .ascii "January"<0>
              .byte 0, 0
aFebruary:   .ascii "February"<0>

```

19.8. CONCLUSION

```
aMarch:      .byte    0
             .ascii "March"<0>
             .byte 0, 0, 0, 0
aApril:      .ascii "April"<0>
             .byte 0, 0, 0, 0
aMay:        .ascii "May"<0>
             .byte 0, 0, 0, 0, 0
aJune:       .ascii "June"<0>
             .byte 0, 0, 0, 0, 0
aJuly:        .ascii "July"<0>
             .byte 0, 0, 0, 0, 0
aAugust:     .ascii "August"<0>
             .byte 0, 0, 0
aSeptember:  .ascii "September"<0>
aOctober:    .ascii "October"<0>
             .byte 0, 0
aNNovember:  .ascii "November"<0>
             .byte 0
aDecember:   .ascii "December"<0>
             .byte 0, 0, 0, 0, 0, 0, 0, 0, 0
```

19.7.4 Conclusion

This is a bit old-school technique to store text strings. You may find a lot of it in Oracle RDBMS, for example. It's hard to say if it's worth doing on modern computers. Nevertheless, it was a good example of arrays, so it was added to this book.

19.8 Conclusion

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.

19.9 Exercises

- <http://challenges.re/62>
- <http://challenges.re/63>
- <http://challenges.re/64>
- <http://challenges.re/65>
- <http://challenges.re/66>

Chapter 20

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.

20.1 Specific bit checking

20.1.1 x86

Win32 API example:

```
HANDLE fh;  
  
fh=CreateFile ("file", GENERIC_WRITE | GENERIC_READ, FILE_SHARE_READ, NULL, OPEN_ALWAYS,  
             FILE_ATTRIBUTE_NORMAL, NULL);
```

We get (MSVC 2010):

Listing 20.1: MSVC 2010

```
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:

Listing 20.2: WinNT.h

```
#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()`¹ 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`:

¹[msdn.microsoft.com/en-us/library/aa363858\(VS.85\).aspx](http://msdn.microsoft.com/en-us/library/aa363858(VS.85).aspx)

20.1. SPECIFIC BIT CHECKING

Listing 20.3: KERNEL32.DLL (Windows XP SP3 x86)

```
.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 ([8.3.1 on page 86](#))).

The logic of this code fragment is as follows:

```
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:

```
#include <stdio.h>
#include <fcntl.h>

void main()
{
    int handle;

    handle=open ("file", O_RDWR | O_CREAT);
}
```

We get:

Listing 20.4: GCC 4.4.1

```
main          public 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, OFFFFFFFF0h
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 20.5: open() (libc.so.6)

```
.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.

20.1. SPECIFIC BIT CHECKING

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 called `fastcall` ([67.3 on page 691](#)). This works faster since CPU does not need to access the stack in memory to read argument values. GCC has the option `regparm2`, 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 ^{3 4}.

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 20.6: `do_filp_open()` (linux kernel 2.6.31)

```
do_filp_open    proc near
...
    push    ebp
    mov     ebp, esp
    push    edi
    push    esi
    push    ebx
    mov     ebx, ecx
    add     ebx, 1
    sub     esp, 98h
    mov     esi, [ebp+arg_4] ; acc_mode (5th arg)
    test   bl, 3
    mov     [ebp+var_80], eax ; dfd (1th arg)
    mov     [ebp+var_7C], edx ; pathname (2th arg)
    mov     [ebp+var_78], ecx ; open_flag (3th arg)
    jnz    short loc_C01EF684
    mov     ebx, ecx          ; ebx <- open_flag
```

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 20.7: `do_filp_open()` (linux kernel 2.6.31)

```
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 `O_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.

20.1.2 ARM

The `O_CREAT` bit is checked differently in Linux kernel 3.8.0.

Listing 20.8: linux kernel 3.8.0

```
struct file *do_filp_open(int dfd, struct filename *pathname,
                           const struct open_flags *op)
```

²ohse.de/uwe/articles/gcc-attributes.html#func-regparm

³kernelnewbies.org/Linux_2_6_20#head-042c62f290834eb1fe0a1942bbf5bb9a4accbc8f

⁴See also `arch/x86/include/asm/calling.h` file in kernel tree

20.1. SPECIFIC BIT CHECKING

```
{
...
    filp = path_openatdfd, 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 20.9: 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.

20.2 Setting and clearing specific bits

For example:

```
#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);
}
```

20.2.1 x86

Non-optimizing MSVC

We get (MSVC 2010):

Listing 20.10: MSVC 2010

```
_rt$ = -4           ; size = 4
_a$ = 8            ; size = 4
_f PROC
    push  ebp
    mov   ebp, esp
    push  ecx
    mov   eax, DWORD PTR _a$[ebp]
    mov   DWORD PTR _rt$[ebp], eax
    mov   ecx, DWORD PTR _rt$[ebp]
    or    ecx, 16384          ; 00004000H
    mov   DWORD PTR _rt$[ebp], ecx
    mov   edx, DWORD PTR _rt$[ebp]
    and   edx, -513           ; fffffdffH
    mov   DWORD PTR _rt$[ebp], edx
    mov   eax, DWORD PTR _rt$[ebp]
    mov   esp, ebp
    pop   ebp
    ret   0
_f ENDP
```

The **OR** instruction sets one bit to value while ignoring the rest.

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.

OllyDbg

Let's try this example in OllyDbg.

First, let's see the binary form of the constants we are going to use:

0x200 (000000000000000000000000100000000) (i.e., the 10th bit (counting from 1st)).

Inverted **0x200** is **0xFFFFFDFF** (11111111111111110111111111).

0x4000 (00000000000000001000000000000000) (i.e., the 15th bit).

The input value is: **0x12340678** (1001000110100000011001111000). We see how it's loaded:

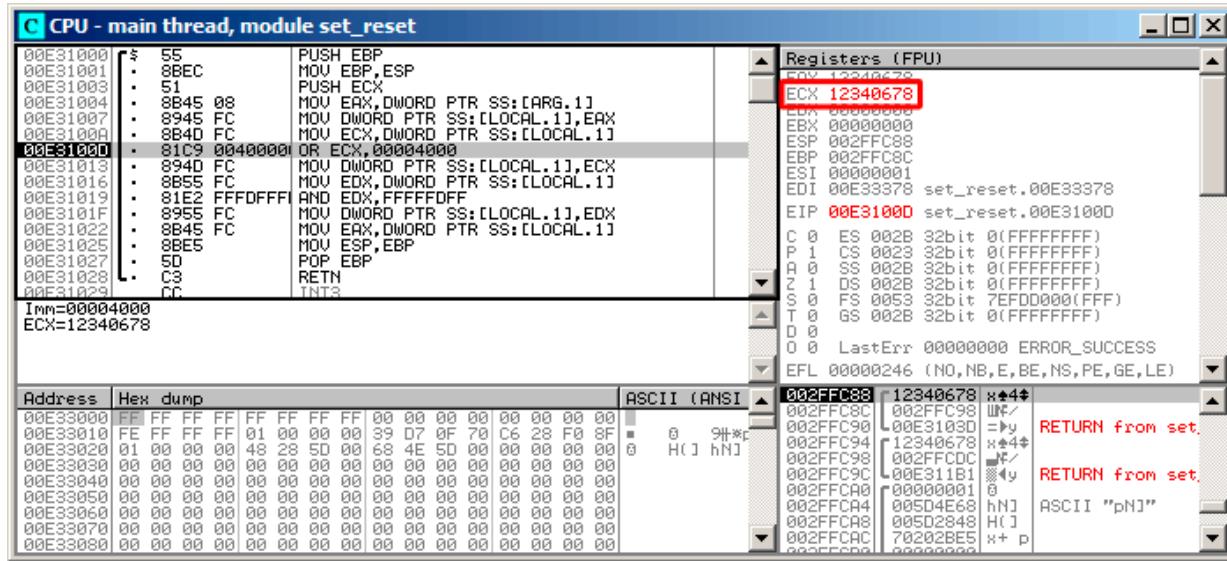


Figure 20.1: OllyDbg: value is loaded into **ECX**

20.2. SETTING AND CLEARING SPECIFIC BITS

OR got executed:

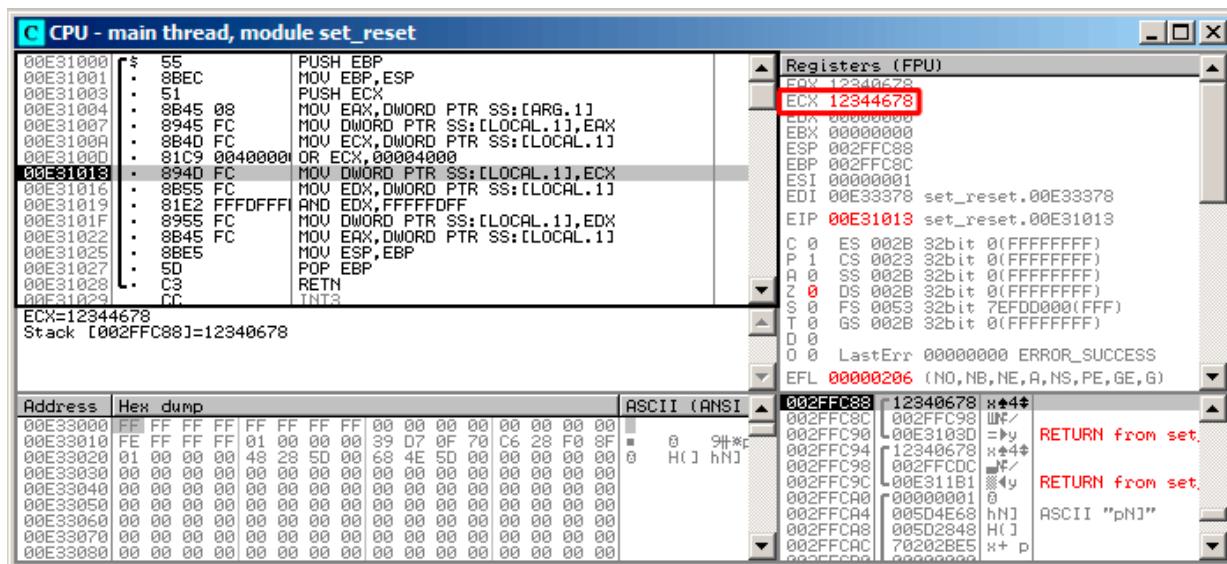


Figure 20.2: OllyDbg: OR executed

15th bit is set: 0x1234**4**678 (10010001101000**1**00011001111000).

20.2. SETTING AND CLEARING SPECIFIC BITS

The value is reloaded again (because the compiler is not in optimizing mode):

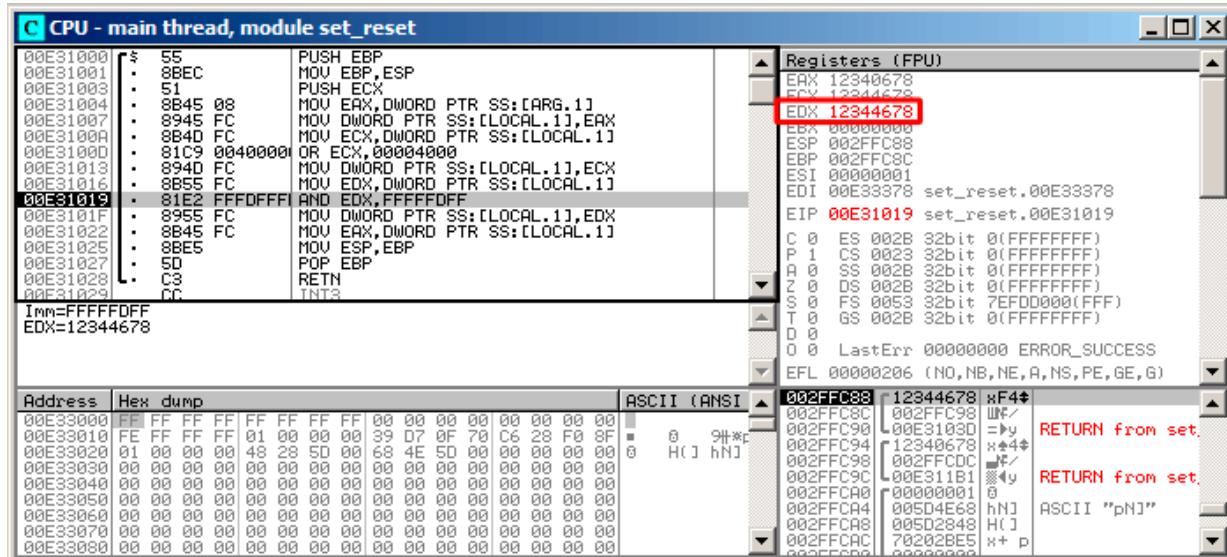


Figure 20.3: OllyDbg: value was reloaded into EDX

20.2. SETTING AND CLEARING SPECIFIC BITS

AND got executed:

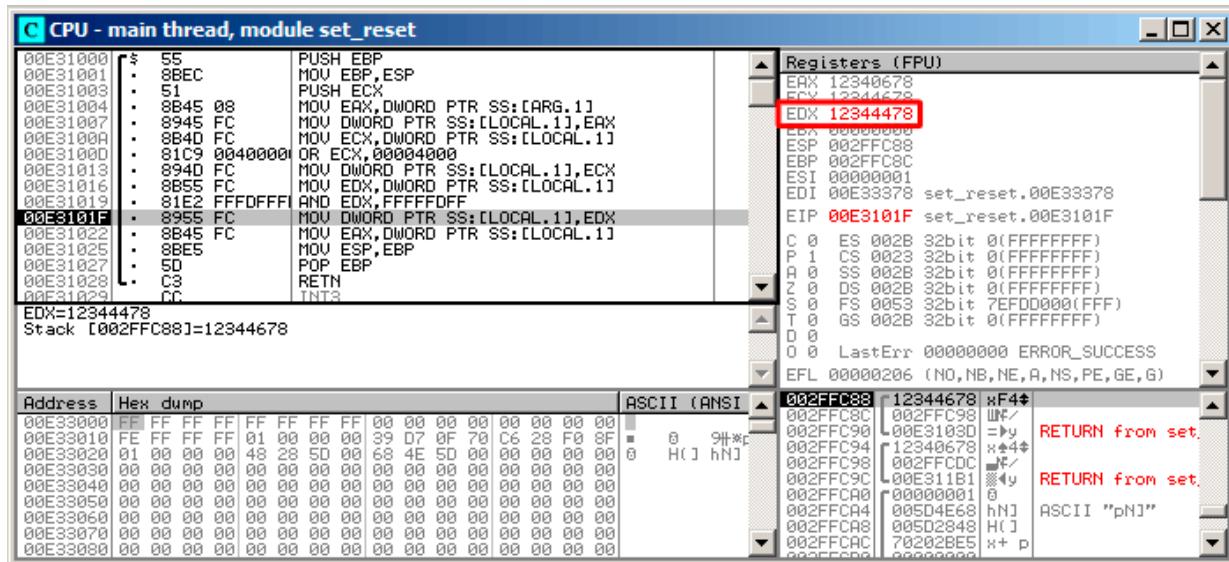


Figure 20.4: OllyDbg: AND executed

The 10th bit was cleared (or, in other words, all bits were left except the 10th) and the final value now is **0x12344478** (10010001101000100010001111000).

Optimizing MSVC

If we compile it in MSVC with optimization turned on (/Ox), the code is even shorter:

Listing 20.11: Optimizing MSVC

```
_a$ = 8           ; size = 4
_f PROC
    mov    eax, DWORD PTR _a$[esp-4]
    and    eax, -513        ; fffffdffH
    or     eax, 16384       ; 00004000H
    ret    0
_f ENDP
```

Non-optimizing GCC

Let's try GCC 4.4.1 without optimization:

Listing 20.12: Non-optimizing GCC

```
public f
proc near

var_4      = dword ptr -4
arg_0      = dword ptr  8

push    ebp
mov     ebp, esp
sub    esp, 10h
mov    eax, [ebp+arg_0]
mov    [ebp+var_4], eax
or     [ebp+var_4], 4000h
and    [ebp+var_4], 0FFFFFDFFh
mov    eax, [ebp+var_4]
leave
retn
endp
```

20.2. SETTING AND CLEARING SPECIFIC BITS

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

Listing 20.13: Optimizing GCC

```
f          public f
          proc near
arg_0      = dword ptr 8
          push    ebp
          mov     ebp, esp
          mov     eax, [ebp+arg_0]
          pop    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.

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RAX ^{x64}							
EAX							
							AX
							AH AL

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`.

Listing 20.14: Optimizing GCC

```
f          public 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* ([45 on page 500](#)).

20.2.2 ARM + Optimizing Keil 6/2013 (ARM mode)

20.2. SETTING AND CLEARING SPECIFIC BITS

Listing 20.15: 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.

20.2.3 ARM + Optimizing Keil 6/2013 (Thumb mode)

Listing 20.16: 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 >> 5**.

20.2.4 ARM + Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 20.17: 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:

```
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 optimizer⁵.

Probably a compiler's optimizer error, but the generated code works correctly anyway.

You can read more about compiler anomalies here ([94 on page 902](#)).

Optimizing Xcode 4.6.3 (LLVM) for Thumb mode generates the same code.

20.2.5 ARM: more about the **BIC** instruction

Let's rework the example slightly:

```
int f(int a)
{
    int rt=a;
    REMOVE_BIT(rt, 0x1234);
    return rt;
};
```

Then the optimizing Keil 5.03 in ARM mode does:

⁵It was LLVM build 2410.2.00 bundled with Apple Xcode 4.6.3

```
f PROC
    BIC      r0,r0,#0x1000
    BIC      r0,r0,#0x234
    BX       lr
ENDP
```

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`.

20.2.6 ARM64: Optimizing GCC (Linaro) 4.9

Optimizing GCC compiling for ARM64 can use the `AND` instruction instead of `BIC`:

Listing 20.18: Optimizing GCC (Linaro) 4.9

```
f:
    and    w0, w0, -513      ; 0xFFFFFFFFFFFFFDFF
    orr    w0, w0, 16384     ; 0x4000
    ret
```

20.2.7 ARM64: Non-optimizing GCC (Linaro) 4.9

Non-optimizing GCC generates more redundant code, but works just like optimized:

Listing 20.19: Non-optimizing GCC (Linaro) 4.9

```
f:
    sub   sp, sp, #32
    str   w0, [sp,12]
    ldr   w0, [sp,12]
    str   w0, [sp,28]
    ldr   w0, [sp,28]
    orr   w0, w0, 16384    ; 0x4000
    str   w0, [sp,28]
    ldr   w0, [sp,28]
    and   w0, w0, -513     ; 0xFFFFFFFFFFFFFDFF
    str   w0, [sp,28]
    ldr   w0, [sp,28]
    add   sp, sp, 32
    ret
```

20.2.8 MIPS

Listing 20.20: Optimizing GCC 4.4.5 (IDA)

```
f:
; $a0=a
; $a0=a|0x4000      ori    $a0, 0x4000
; $a0=a|0x4000      li     $v0, 0xFFFFFDFF
; $a0=a|0x4000      jr     $ra
; $a0=a|0x4000      and    $v0, $a0, $v0
; at finish: $v0 = $a0&$v0 = a|0x4000 & 0xFFFFFDFF
```

`ORI` is, of course, the OR operation. “l” in the instruction name mean that the value is embedded in the machine code.

But after that we have `AND`. There was no way to use `ANDI` because it's not possible to embed the `0xFFFFFDFF` number in a single instruction, so the compiler has to load `0xFFFFFDFF` into register `$V0` first and then generates `AND` which takes all its values from registers.

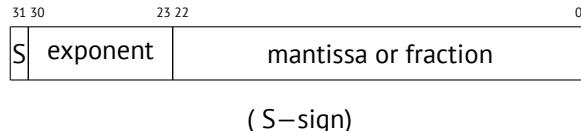
20.3 Shifts

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): [17.1.2 on page 210](#), [17.2.1 on page 215](#).

Shifting operations are also so important because they are often used for specific bit isolation or for constructing a value of several scattered bits.

20.4 Setting and clearing specific bits: FPU example

Here is how bits are located in the *float* type in IEEE 754 form:



The sign of number is in the **MSB**⁶. Will it be possible to change the sign of a floating point number without any FPU instructions?

```
#include <stdio.h>

float my_abs (float i)
{
    unsigned int tmp=(*(unsigned int*)&i) & 0xFFFFFFFF;
    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: [32 on page 450](#).

20.4.1 x86

The code is pretty straightforward:

⁶Most significant bit/byte

Listing 20.21: Optimizing MSVC 2012

```

_tmp$ = 8
_i$ = 8
_my_abs PROC
    and    DWORD PTR _i$[esp-4], 2147483647      ; 7fffffffH
    fld    DWORD PTR _tmp$[esp-4]
    ret    0
_my_abs ENDP

_tmp$ = 8
_i$ = 8
_set_sign PROC
    or     DWORD PTR _i$[esp-4], -2147483648     ; 80000000H
    fld    DWORD PTR _tmp$[esp-4]
    ret    0
_set_sign ENDP

_tmp$ = 8
_i$ = 8
_negate PROC
    xor    DWORD PTR _i$[esp-4], -2147483648     ; 80000000H
    fld    DWORD PTR _tmp$[esp-4]
    ret    0
_negate ENDP

```

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:

Listing 20.22: Optimizing MSVC 2012 x64

```

tmp$ = 8
i$ = 8
my_abs PROC
    movss  DWORD PTR [rsp+8], xmm0
    mov    eax, DWORD PTR i$[rsp]
    btr    eax, 31
    mov    DWORD PTR tmp$[rsp], eax
    movss  xmm0, DWORD PTR tmp$[rsp]
    ret    0
my_abs ENDP
_TEXT ENDS

tmp$ = 8
i$ = 8
set_sign PROC
    movss  DWORD PTR [rsp+8], xmm0
    mov    eax, DWORD PTR i$[rsp]
    bts    eax, 31
    mov    DWORD PTR tmp$[rsp], eax
    movss  xmm0, DWORD PTR tmp$[rsp]
    ret    0
set_sign ENDP

tmp$ = 8
i$ = 8
negate PROC
    movss  DWORD PTR [rsp+8], xmm0
    mov    eax, DWORD PTR i$[rsp]
    btc    eax, 31
    mov    DWORD PTR tmp$[rsp], eax
    movss  xmm0, DWORD PTR tmp$[rsp]
    ret    0
negate ENDP

```

20.4. SETTING AND CLEARING SPECIFIC BITS: FPU EXAMPLE

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`.

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.

20.4.2 MIPS

GCC 4.4.5 for MIPS does mostly the same:

Listing 20.23: Optimizing GCC 4.4.5 (IDA)

```
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    $v0, $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    $v0, $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 zeroes in the constant, so one `LUI` without subsequent `ORI` is enough.

20.4.3 ARM

Optimizing Keil 6/2013 (ARM mode)

Listing 20.24: Optimizing Keil 6/2013 (ARM mode)

```
my_abs PROC  
; clear bit:  
    BIC    r0,r0,#0x80000000  
    BX    lr  
ENDP
```

```

set_sign PROC
; 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)

Listing 20.25: 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 **MOVS / LSLS** 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* $\ll 1$ 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 zeroes. That is how the **LSLS / LSRS** instruction pair clears **MSB**.

Optimizing GCC 4.6.3 (Raspberry Pi, ARM mode)

Listing 20.26: Optimizing GCC 4.6.3 for Raspberry Pi (ARM mode)

```

my_abs
; copy from S0 to R2:
        FMRS      R2, S0
; clear bit:
        BIC      R3, R2, #0x80000000

```

20.5. COUNTING BITS SET TO 1

```
; copy from R3 to S0:
    FMSR    S0, R3
    BX      LR

set_sign
; copy from S0 to R2:
    FMRS    R2, S0
; do OR:
    ORR     R3, R2, #0x80000000
; copy from R3 to S0:
    FMSR    S0, R3
    BX      LR

negate
; copy from S0 to R2:
    FMRS    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 `FMRS` 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 remember 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.

20.5 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"⁷.

```
#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;
};

int main()
```

⁷modern x86 CPUs (supporting SSE4) even have a POPCNT instruction for it

20.5. COUNTING BITS SET TO 1

```
{
    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 $i = 0 \dots 31$:

C/C++ expression	Power of two	Decimal form	Hexadecimal form
$1 \ll 0$	2^0	1	1
$1 \ll 1$	2^1	2	2
$1 \ll 2$	2^2	4	4
$1 \ll 3$	2^3	8	8
$1 \ll 4$	2^4	16	0x10
$1 \ll 5$	2^5	32	0x20
$1 \ll 6$	2^6	64	0x40
$1 \ll 7$	2^7	128	0x80
$1 \ll 8$	2^8	256	0x100
$1 \ll 9$	2^9	512	0x200
$1 \ll 10$	2^{10}	1024	0x400
$1 \ll 11$	2^{11}	2048	0x800
$1 \ll 12$	2^{12}	4096	0x1000
$1 \ll 13$	2^{13}	8192	0x2000
$1 \ll 14$	2^{14}	16384	0x4000
$1 \ll 15$	2^{15}	32768	0x8000
$1 \ll 16$	2^{16}	65536	0x10000
$1 \ll 17$	2^{17}	131072	0x20000
$1 \ll 18$	2^{18}	262144	0x40000
$1 \ll 19$	2^{19}	524288	0x80000
$1 \ll 20$	2^{20}	1048576	0x100000
$1 \ll 21$	2^{21}	2097152	0x200000
$1 \ll 22$	2^{22}	4194304	0x400000
$1 \ll 23$	2^{23}	8388608	0x800000
$1 \ll 24$	2^{24}	16777216	0x1000000
$1 \ll 25$	2^{25}	33554432	0x2000000
$1 \ll 26$	2^{26}	67108864	0x4000000
$1 \ll 27$	2^{27}	134217728	0x8000000
$1 \ll 28$	2^{28}	268435456	0x10000000
$1 \ll 29$	2^{29}	536870912	0x20000000
$1 \ll 30$	2^{30}	1073741824	0x40000000
$1 \ll 31$	2^{31}	2147483648	0x80000000

These constant numbers (bit masks) very often appear in code and a practicing reverse engineer must be able to spot them quickly.

You probably haven't to memorize the decimal numbers, but the hexadecimal ones are very easy to remember.

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:

```
/***
 * Define the SSL options
 */
#define SSL_OPT_NONE          (0)
#define SSL_OPT_RELSET         (1<<0)
#define SSL_OPT_STDENVARS      (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*.

20.5. COUNTING BITS SET TO 1

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.

20.5.1 x86

MSVC

Let's compile (MSVC 2010):

Listing 20.27: MSVC 2010

```
_rt$ = -8           ; size = 4
_i$ = -4           ; size = 4
_a$ = 8            ; size = 4
_f PROC
    push    ebp
    mov     ebp, esp
    sub     esp, 8
    mov     DWORD PTR _rt$[ebp], 0
    mov     DWORD PTR _i$[ebp], 0
    jmp     SHORT $LN4@f
$LN3@f:
    mov     eax, DWORD PTR _i$[ebp]    ; increment of i
    add     eax, 1
    mov     DWORD PTR _i$[ebp], eax
$LN4@f:
    cmp     DWORD PTR _i$[ebp], 32    ; 00000020H
    jge     SHORT $LN2@f             ; loop finished?
    mov     edx, 1
    mov     ecx, DWORD PTR _i$[ebp]
    shl     edx, cl
    and     edx, DWORD PTR _a$[ebp]
    je      SHORT $LN1@f             ; result of AND instruction was 0?
                                            ; then skip next instructions
    mov     eax, DWORD PTR _rt$[ebp]
    add     eax, 1
    mov     DWORD PTR _rt$[ebp], eax
$LN1@f:
    jmp     SHORT $LN3@f
$LN2@f:
    mov     eax, DWORD PTR _rt$[ebp]
    mov     esp, ebp
    pop     ebp
    ret     0
_f    ENDP
```

OllyDbg

Let's load this example into OllyDbg. Let the input value be **0x12345678**.

For $i = 1$, we see how i is loaded into **ECX**:

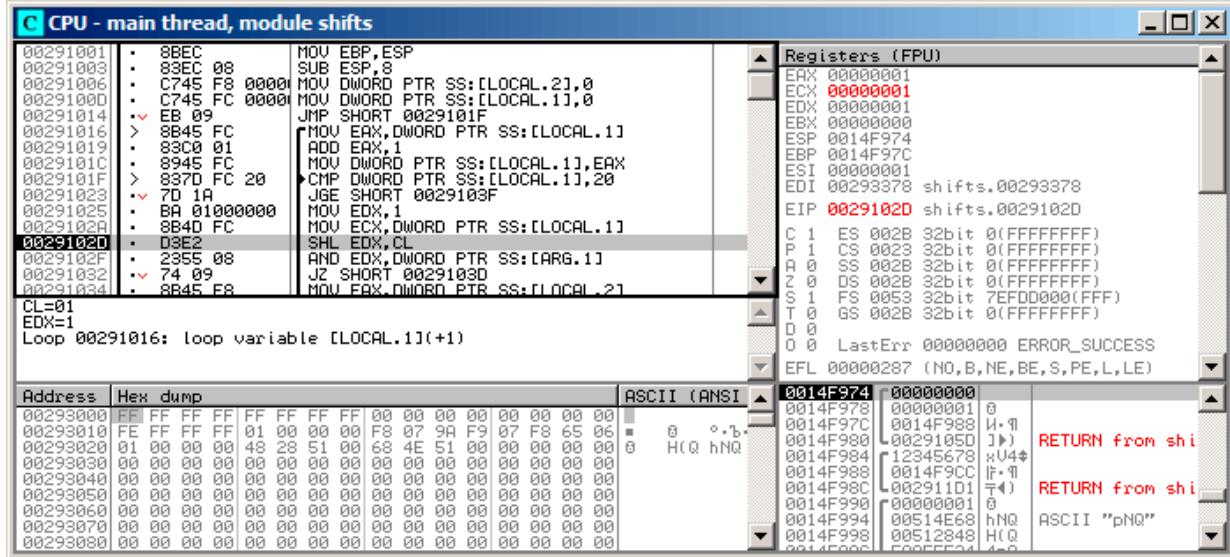


Figure 20.5: OllyDbg: $i = 1$, i is loaded into **ECX**

EDX is 1. **SHL** is to be executed now.

20.5. COUNTING BITS SET TO 1

SHL was executed:

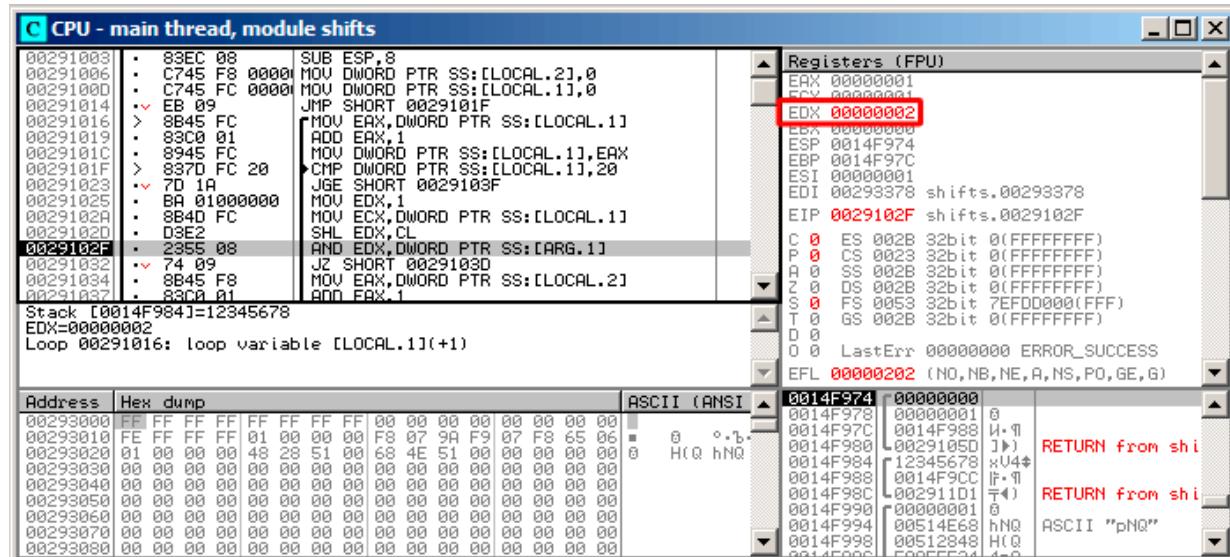


Figure 20.6: OllyDbg: $i = 1$, $\text{EDX} = 1 \ll 1 = 2$

EDX contain $1 \ll 1$ (or 2). This is a bit mask.

20.5. COUNTING BITS SET TO 1

AND sets ZF to 1, which implies that the input value (0x12345678) ANDed with 2 results in 0:

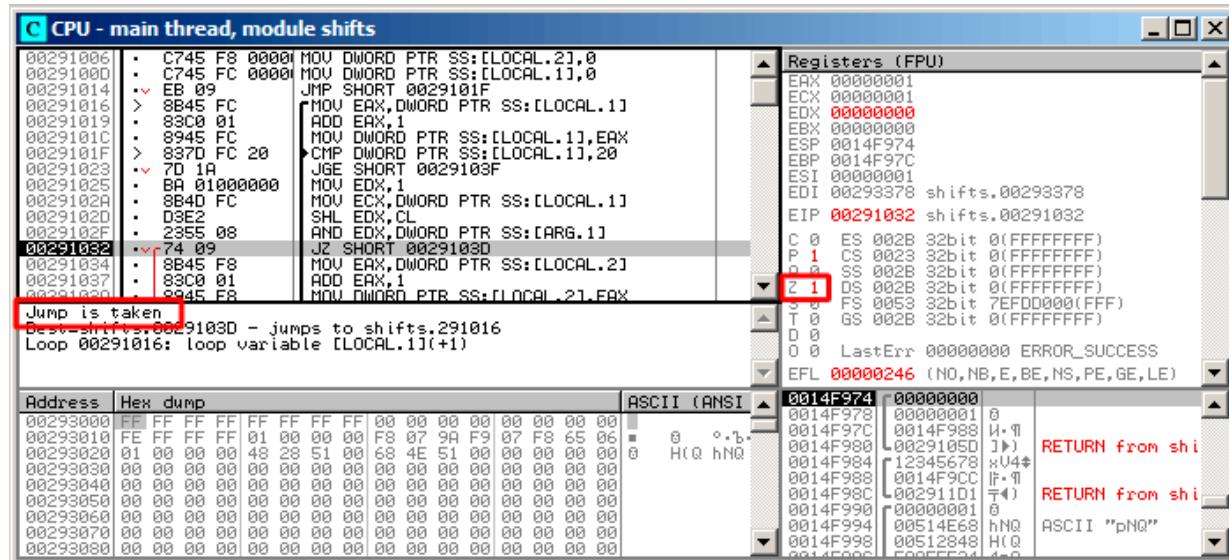


Figure 20.7: OllyDbg: $i = 1$, is there that bit in the input value? No. ($ZF = 1$)

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.

20.5. COUNTING BITS SET TO 1

Let's trace a bit further and i is now 4. `SHL` is to be executed now:

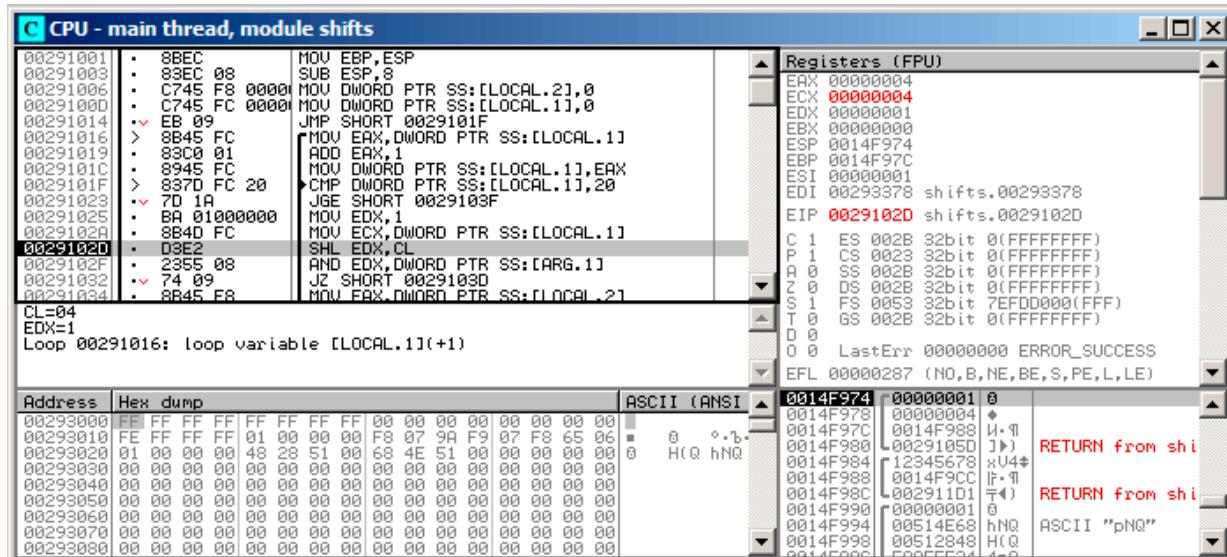


Figure 20.8: OllyDbg: $i = 4$, i is loaded into ECX

20.5. COUNTING BITS SET TO 1

EDX = $1 \ll 4$ (or **0x10** or 16):

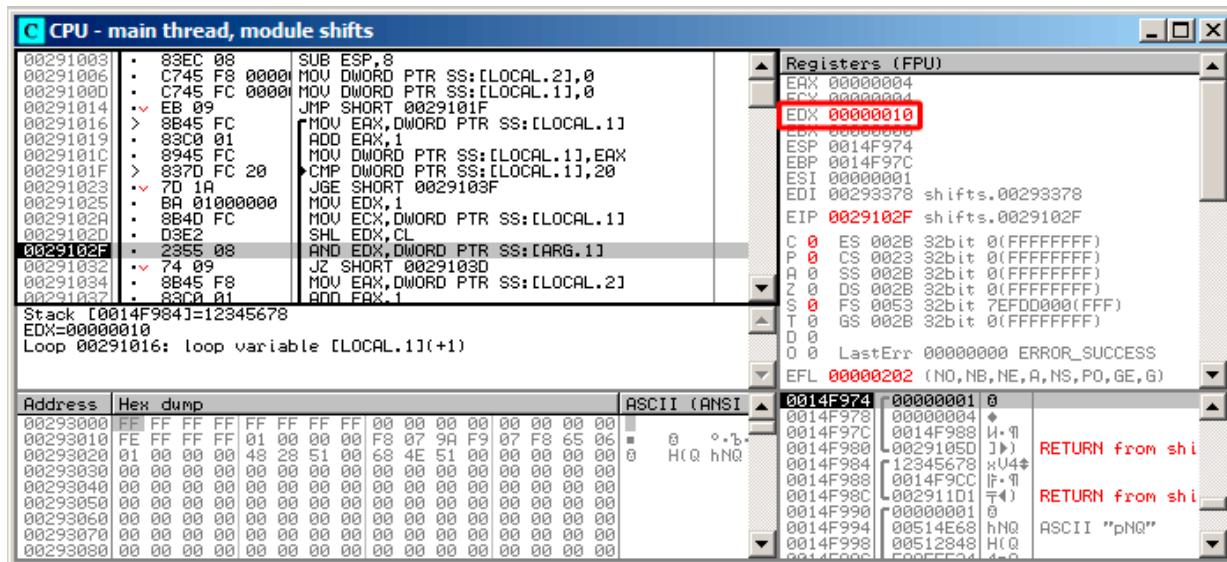


Figure 20.9: OllyDbg: $i = 4$, $\text{EDX } = 1 \ll 4 = 0x10$

This is another bit mask.

20.5. COUNTING BITS SET TO 1

AND is executed:

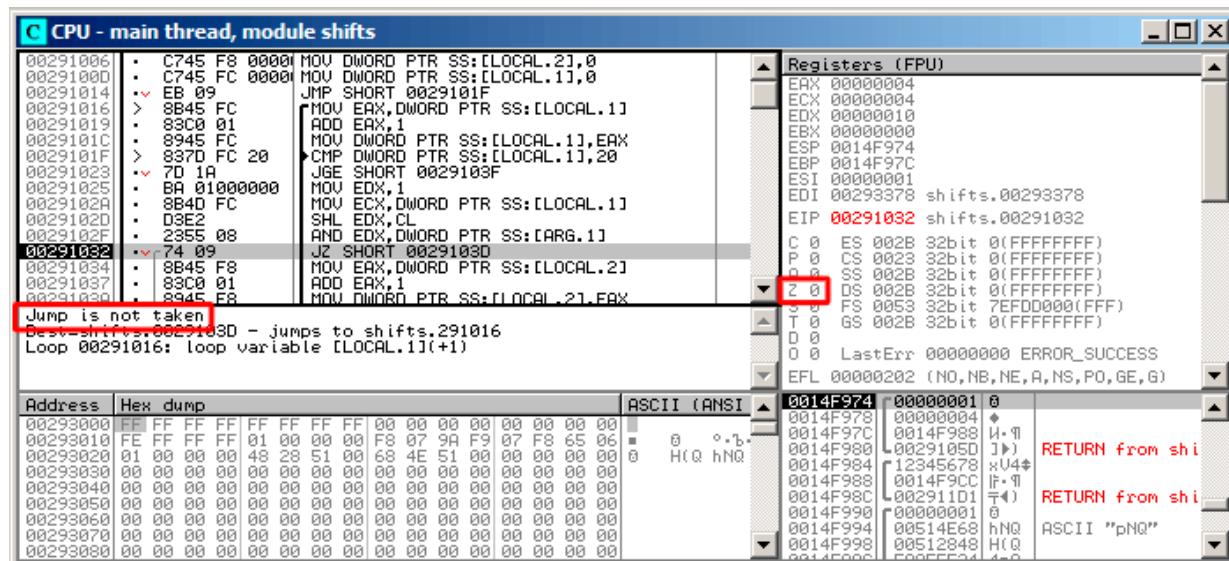


Figure 20.10: OllyDbg: $i = 4$, is there that bit in the input value? Yes. ($ZF = 0$)

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 20.28: GCC 4.4.1

```

public 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:
        cmp    [ebp+i], 1Fh
        jle    short loc_80483D0
        mov    eax, [ebp+rt]
        add    esp, 10h

```

20.5. COUNTING BITS SET TO 1

```
        pop    ebx
        pop    ebp
        retn
f      endp
```

20.5.2 x64

Let's modify the example slightly to extend it to 64-bit:

```
#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.

Listing 20.29: Non-optimizing GCC 4.8.2

```
f:
    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
    pop   rbp
    ret
```

Optimizing GCC 4.8.2

Listing 20.30: 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", which will be written into rt variable, if the last bit is 1
8     shr    rsi, cl        ; RSI=RSI>>CL
9     and    esi, 1         ; ESI=ESI&1
10 ; the last bit is 1? If so, write "new version of rt" into EAX
11     cmovne eax, edx
12     add    rcx, 1         ; RCX++
13     cmp    rcx, 64
14     jne    .L3
15     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`⁸ instruction (which is a synonym for `CMOVNZ`⁹) *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 done 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: [35.1 on page 455](#).

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: [\[AMD13b, p.15\]](#)¹⁰.

Optimizing MSVC 2010

Listing 20.31: 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
    dec   r8       ; R8--
    jne   SHORT $LL4@f
    fatret 0
f      ENDP

```

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`.

⁸Conditional MOVe if Not Equal

⁹Conditional MOVe if Not Zero

¹⁰More information on it: <http://go.yurichev.com/17328>

20.5. COUNTING BITS SET TO 1

You can read more about the rotate instruction here: [A.6.3 on page 937](#).

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:

RDX	R8
0x00000000000000000001	64
0x00000000000000000002	63
0x00000000000000000004	62
0x00000000000000000008	61
...	...
0x40000000000000000000	2
0x80000000000000000000	1

At the end we see the `FATRET` instruction, which was explained here: [20.5.2 on the previous page](#).

Optimizing MSVC 2012

Listing 20.32: MSVC 2012

```
a$ = 8
f      PROC
; RCX = input value
    xor    eax, eax
    mov    edx, 1
    lea    r8d, QWORD PTR [rax+32]
; EDX = 1, R8D = 32
    npad   5
$LL4@f:
; pass 1 -----
    test   rdx, rcx
    je     SHORT $LN3@f
    inc    eax    ; rt++
$LN3@f:
    rol    rdx, 1 ; RDX=RDX<<1
; -----
; pass 2 -----
    test   rdx, rcx
    je     SHORT $LN11@f
    inc    eax    ; rt++
$LN11@f:
    rol    rdx, 1 ; RDX=RDX<<1
; -----
    dec    r8    ; R8--
    jne   SHORT $LL4@f
    fatret 0
f      ENDP
```

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.

20.5.3 ARM + Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 20.33: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
loc_2E54
    MOV    R1, R0
    MOV    R0, #0
    MOV    R2, #1
    MOV    R3, R0
    TST    R1, R2, LSL R3 ; set flags according to R1 & (R2<<R3)
    ADD    R3, R3, #1       ; R3++
```

20.5. COUNTING BITS SET TO 1

ADDNE	R0, R0, #1	; if ZF flag is cleared by TST, then R0++
CMP	R3, #32	
BNE	loc_2E54	
BX	LR	

TST is the same things as **TEST** in x86.

As was noted before ([43.2.1 on page 489](#)), 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**¹¹.

These modicators define how to shift the second operand and by how many bits.

Thus the “**TST R1, R2,LSL R3**” instruction works here as $R1 \wedge (R2 \ll R3)$.

20.5.4 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**.

MOV	R1, R0
MOVS	R0, #0
MOV.W	R9, #1
MOVS	R3, #0
loc_2F7A	
LSL.W	R2, R9, R3
TST	R2, R1
ADD.W	R3, R3, #1
IT NE	
ADDNE	R0, #1
CMP	R3, #32
BNE	loc_2F7A
BX	LR

20.5.5 ARM64 + Optimizing GCC 4.9

Let's take the 64-bit example which has been already used: [20.5.2 on page 328](#).

Listing 20.34: Optimizing GCC (Linaro) 4.8

```
f:
    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?
    bne   .L2              ; yes
    mov    w0, w2          ; return rt
    ret
```

The result is very similar to what GCC generates for x64: [20.30 on page 329](#).

The **CSEL** instruction is “Conditional SELect”. It just chooses one variable of two depending on the flags set by **TST** and copies the value into **W2**, which holds the “rt” variable.

¹¹These instructions are also called “data processing instructions”

20.5.6 ARM64 + Non-optimizing GCC 4.9

And again, we'll work on the 64-bit example which was already used: [20.5.2 on page 328](#). The code is more verbose, as usual.

Listing 20.35: Non-optimizing GCC (Linaro) 4.8

```
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<<1
    ldr    x0, [sp,8]
; X0 = a
    and    x0, x1, x0
; X0 = X1&X0 = (1<<i) & a
; 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    sp, sp, 32
    ret
```

20.5.7 MIPS

Non-optimizing GCC

Listing 20.36: Non-optimizing GCC 4.4.5 (IDA)

```
f:
; IDA is not aware of variable names, we gave them manually:
rt      = -0x10
i       = -0xC
var_4   = -4
a       = 0

        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 than 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: [35.1 on page 455](#).

Listing 20.37: Optimizing GCC 4.4.5 (IDA)

```

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

```

20.6. CONCLUSION

```
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
```

20.6 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").

20.6.1 Check for specific bit (known at compile stage)

Test if the 1000000 bit (0x40) is present in the register's value:

Listing 20.38: C/C++

```
if (input&0x40)
    ...
```

Listing 20.39: x86

```
TEST REG, 40h
JNZ is_set
; bit is not set
```

Listing 20.40: x86

```
TEST REG, 40h
JZ is_cleared
; bit is set
```

Listing 20.41: ARM (ARM mode)

```
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.

20.6.2 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 20.42: C/C++

```
if ((value>>n)&1)
    ....
```

20.6. CONCLUSION

This is usually implemented in x86 code as:

Listing 20.43: x86

```
; REG=input_value  
; CL=n  
SHR REG, CL  
AND REG, 1
```

Or (shift 1 bit n times left, isolate this bit in input value and check if it's not zero):

Listing 20.44: C/C++

```
if (value & (1<<n))  
....
```

This is usually implemented in x86 code as:

Listing 20.45: x86

```
; CL=n  
MOV REG, 1  
SHL REG, CL  
AND input_value, REG
```

20.6.3 Set specific bit (known at compile stage)

Listing 20.46: C/C++

```
value=value|0x40;
```

Listing 20.47: x86

```
OR REG, 40h
```

Listing 20.48: ARM (ARM mode) and ARM64

```
ORR R0, R0, #0x40
```

20.6.4 Set specific bit (specified at runtime)

Listing 20.49: C/C++

```
value=value|(1<<n);
```

This is usually implemented in x86 code as:

Listing 20.50: x86

```
; CL=n  
MOV REG, 1  
SHL REG, CL  
OR input_value, REG
```

20.6.5 Clear specific bit (known at compile stage)

Just apply `AND` operation with the inverted value:

Listing 20.51: C/C++

```
value=value&(~0x40);
```

Listing 20.52: x86

```
AND REG, 0FFFFFFFBh
```

```
AND REG, 0xFFFFFFFFFFFFFFBFh
```

This is actually leaving all bits set except one.

ARM in ARM mode has **BIC** instruction, which works like the **NOT** + **AND** instruction pair:

```
BIC R0, R0, #0x40
```

20.6.6 Clear specific bit (specified at runtime)

```
value=value&(~(1<<n));
```

```
; CL=n
MOV REG, 1
SHL REG, CL
NOT REG
AND input_value, REG
```

20.7 Exercises

- <http://challenges.re/67>
- <http://challenges.re/68>
- <http://challenges.re/69>
- <http://challenges.re/70>

Chapter 21

Linear congruent generator as pseudorandom number generator

The linear congruent generator is probably the simplest possible way to generate random numbers. It's not in favour in modern times¹, but it's so simple (just one multiplication, one addition and one AND operation), we can use it as an example.

```
#include <stdint.h>

// constants from the Numerical Recipes book
#define RNG_a 1664525
#define RNG_c 1013904223

static 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;
}
```

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 [Pre+07]. 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.

21.1 x86

Listing 21.1: Optimizing MSVC 2013

```
_BSS      SEGMENT
_rand_state DD  01H DUP (?)
_BSS      ENDS

_init$ = 8
_srand  PROC
        mov     eax, DWORD PTR _init$[esp-4]
```

¹Mersenne twister is better

21.2. X64

```
        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 21.2: Non-optimizing MSVC 2013

```
_BSS  SEGMENT
_rand_state DD 01H DUP (?)
_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
```

21.2 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:

Listing 21.3: Optimizing MSVC 2013 x64

```
_BSS  SEGMENT
rand_state DD 01H DUP (?)
_BSS  ENDS

init$ = 8
```

21.3. 32-BIT ARM

```
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.

21.3 32-bit ARM

Listing 21.4: Optimizing Keil 6/2013 (ARM mode)

```
my_srand PROC
    LDR    r1, |L0.52| ; load pointer to rand_state
    STR    r0,[r1,#0] ; save rand_state
    BX    lr
    ENDP

my_rand PROC
    LDR    r0, |L0.52| ; load pointer to rand_state
    LDR    r2, |L0.56| ; load RNG_a
    LDR    r1,[r0,#0] ; load rand_state
    MUL    r1,r2,r1
    LDR    r2, |L0.60| ; load RNG_c
    ADD    r1,r1,r2
    STR    r1,[r0,#0] ; save rand_state
; AND with 0x7FFF:
    LSL    r0,r1,#17
    LSR    r0,r0,#17
    BX    lr
    ENDP

|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 `(rand_state << 17) >> 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.

21.4 MIPS

Listing 21.5: Optimizing GCC 4.4.5 (IDA)

```

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, $a0, 3
    addu   $v0, $a0, $v0
    sll      $a0, $v0, 2
    addu   $v0, $a0
; add 1013904223 (RNG_c)
; 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 done by just using shifts and additions! Let's check this assumption:

```
#define RNG_a 1664525

int f (int a)
{
    return a*RNG_a;
}
```

Listing 21.6: 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, $v0, 3
    addu   $a0, $v0, $a0
    sll      $v0, $a0, 2
    jr     $ra
    addu   $v0, $a0, $v0 ; branch delay slot

```

Indeed!

21.4.1 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 21.7: Optimizing GCC 4.4.5 (objdump)

```
# objdump -D rand_03.o

...
00000000 <my_srand>:
 0: 3c020000    lui      v0,0x0
 4: 03e00008    jr      ra
 8: ac440000    sw      a0,0(v0)

0000000c <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: 00022100    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
38: 000420c0    sll     a0,a0,0x3
3c: 00821021    addu   v0,a0,v0
40: 00022080    sll     a0,v0,0x2
44: 00441021    addu   v0,v0,a0
48: 3c043c6e    lui      a0,0x3c6e
4c: 3484f35f    ori      a0,a0,0xf35f
50: 00441021    addu   v0,v0,a0
54: ac620000    sw      v0,0(v1)
58: 03e00008    jr      ra
5c: 30427fff    andi   v0,v0,0x7fff

...
# objdump -r rand_03.o

...
RELOCATION RECORDS FOR [.text]:
OFFSET  TYPE          VALUE
00000000 R_MIPS_HI16 .bss
00000008 R_MIPS_L016 .bss
0000000c R_MIPS_HI16 .bss
00000010 R_MIPS_L016 .bss
00000054 R_MIPS_L016 .bss
...
```

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_L016`. 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 zeroes 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 `$V1`. The `LW` instruction at address `0x10` sums up the high and low parts and loads the value of the `rand_state` variable into `$V1`. 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 ought to remember them.

21.5 Thread-safe version of the example

The thread-safe version of the example is to be demonstrated later: [68.1 on page 698](#).

Chapter 22

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 ¹.

22.1 MSVC: SYSTEMTIME example

Let's take the SYSTEMTIME² win32 structure that describes time.

This is how it's defined:

Listing 22.1: WinBase.h

```
typedef struct _SYSTEMTIME {  
    WORD wYear;  
    WORD wMonth;  
    WORD wDayOfWeek;  
    WORD wDay;  
    WORD wHour;  
    WORD wMinute;  
    WORD wSecond;  
    WORD wMilliseconds;  
} SYSTEMTIME, *PSYSTEMTIME;
```

Let's write a C function to get the current time:

```
#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;  
}
```

We get (MSVC 2010):

Listing 22.2: MSVC 2010 /GS-

```
_t$ = -16 ; size = 16  
_main      PROC  
    push    ebp  
    mov     ebp, esp  
    sub     esp, 16
```

¹AKA "heterogeneous container"

²MSDN: [SYSTEMTIME structure](#)

22.1. MSVC: SYSTEMTIME EXAMPLE

```
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
```

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()`³, 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.

³MSDN: SYSTEMTIME structure

22.1.1 OllyDbg

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:

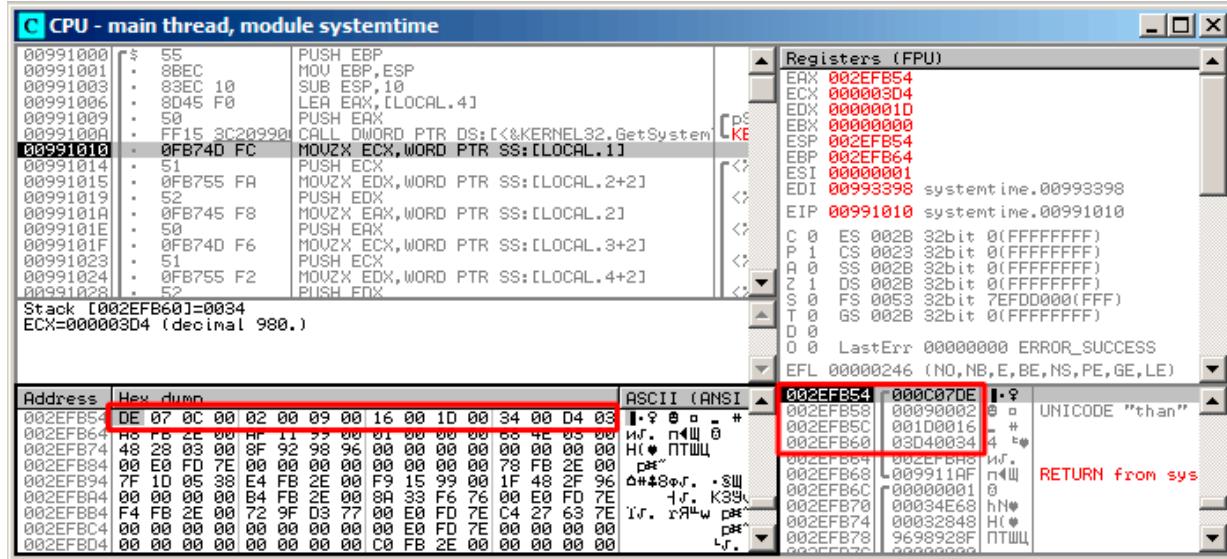


Figure 22.1: OllyDbg: `GetSystemTime()` just executed

The system time of the function execution on my computer is 9 december 2014, 22:29:52:

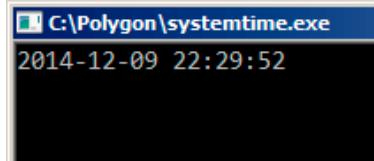


Figure 22.2: OllyDbg: printf() output

So we see these 16 bytes in the data window:

DE 07 0C 00 02 00 09 00 16 00 1D 00 34 00 D4 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:

Hexadecimal number	decimal number	field name
0x07DE	2014	wYear
0x000C	12	wMonth
0x0002	2	wDayOfWeek
0x0009	9	wDay
0x0016	22	wHour
0x001D	29	wMinute
0x0034	52	wSecond
0x03D4	980	wMilliseconds

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.

22.1.2 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 simple example like this:

```
#include <windows.h>
#include <stdio.h>

void main()
{
    WORD array[8];
    GetSystemTime (array);

    printf ("%04d-%02d-%02d %02d:%02d:%02d\n",
            array[0] /* wYear */, array[1] /* wMonth */, array[3] /* wDay */,
            array[4] /* wHour */, array[5] /* wMinute */, array[6] /* wSecond */);

    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 22.3: Non-optimizing MSVC 2010

```
$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] ; wHour
    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, eax
    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.

22.2 Let's allocate space for a structure using malloc()

Sometimes it is simpler to place structures not the in 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 (`/Ox`) so it would be easy see what we need.

Listing 22.4: 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 `MOVSX`, 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).

22.3. UNIX: STRUCT TM

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 */,
        t[4] /* wHour */, t[5] /* wMinute */, t[6] /* wSecond */);

    free (t);

    return;
}
```

We get:

Listing 22.5: Optimizing MSVC

```
$SG78594 DB      '%04d-%02d-%02d %02d:%02d:%02d', 0aH, 00H

_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 cannot be distinguished from the previous one. And again it should be noted, you haven't to do this in practice, unless you really know what you are doing.

22.3 UNIX: struct tm

22.3.1 Linux

Let's take the `tm` structure from `time.h` in Linux for example:

```
#include <stdio.h>
#include <time.h>

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 22.6: 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 ; tm_sec
    mov    [esp], eax
    call   printf
    leave
    ret
```

```
main endp
```

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` ([A.6.2 on page 931](#)).

GDB

Let's try to load the example into GDB ⁴:

Listing 22.7: 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
Copyright (C) 2013 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law. Type "show copying"
and "show warranty" for details.
This GDB was configured as "i686-linux-gnu".
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>...
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 0x00000002 0x00000005 0x00000072
0xbffff10c: 0x00000001 0x00000098 0x00000001 0x00002a30
0xbffff11c: 0x0804b090 0x08048530 0x00000000 0x00000000
(gdb)
```

We can easily find our structure in the stack. First, let's see how it's defined in `time.h`:

Listing 22.8: 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	0x000007de	0x00000000
0xbffff0ec:	0x08048301	0x538c93ed	0x00000025	sec 0x0000000a min
0xbffff0fc:	0x00000012	hour	0x00000002	mday 0x00000005 mon 0x00000072 year

⁴The `date` result is slightly corrected for demonstration purposes. Of course, it's not possible to run GDB that quickly, in the same second.

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0xbfffff10c:	0x00000001	wday	0x00000098	yday	0x00000001	isdst	0x00002a30
0xbfffff11c:	0x0804b090		0x08048530		0x00000000		0x00000000

Or as a table:

Hexadecimal number	decimal number	field name
0x00000025	37	tm_sec
0x0000000a	10	tm_min
0x00000012	18	tm_hour
0x00000002	2	tm_mday
0x00000005	5	tm_mon
0x00000072	114	tm_year
0x00000001	1	tm_wday
0x00000098	152	tm_yday
0x00000001	1	tm_isdst

Just like SYSTEMTIME ([22.1 on page 343](#)), there are also other fields available that are not used, like tm_wday, tm_yday, tm_isdst.

22.3.2 ARM

Optimizing Keil 6/2013 (Thumb mode)

Same example:

Listing 22.9: Optimizing Keil 6/2013 (Thumb mode)

```

var_38 = -0x38
var_34 = -0x34
var_30 = -0x30
var_2C = -0x2C
var_28 = -0x28
var_24 = -0x24
timer = -0xC

PUSH {LR}
MOVS 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()`), so it shows here structure elements accesses and their names.

Listing 22.10: Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)

```

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]
MOV R0, 0xF44 ; "Year: %d\n"
ADD R0, PC ; char *
ADDW R1, R1, #0x76C
BLX _printf
LDR R1, [SP,#0x38+var_34.tm_mon]
MOV R0, 0xF3A ; "Month: %d\n"
ADD R0, PC ; char *
BLX _printf
LDR R1, [SP,#0x38+var_34.tm_mday]
MOV R0, 0xF35 ; "Day: %d\n"
ADD R0, PC ; char *
BLX _printf
LDR R1, [SP,#0x38+var_34.tm_hour]
MOV R0, 0xF2E ; "Hour: %d\n"
ADD R0, PC ; char *
BLX _printf
LDR R1, [SP,#0x38+var_34.tm_min]
MOV R0, 0xF28 ; "Minutes: %d\n"
ADD R0, PC ; char *
BLX _printf
LDR R1, [SP,#0x38+var_34]
MOV R0, 0xF25 ; "Seconds: %d\n"
ADD R0, PC ; char *
BLX _printf
ADD SP, SP, #0x30
POP {R7,PC}

...
00000000 tm      struc ; (sizeof=0x2C, standard type)
00000000 tm_sec  DCD ?
00000004 tm_min  DCD ?
00000008 tm_hour  DCD ?
0000000C tm_mday  DCD ?
00000010 tm_mon   DCD ?
00000014 tm_year  DCD ?
00000018 tm_wday   DCD ?
0000001C tm_yday   DCD ?
00000020 tm_isdst  DCD ?
00000024 tm_gmtoff DCD ?
00000028 tm_zone   DCD ? ; offset
0000002C tm      ends

```

22.3.3 MIPS

Listing 22.11: Optimizing GCC 4.4.5 (IDA)

1 main:

```

2 ; IDA is not aware of structure field names, we named them manually:
3
4
5 var_40      = -0x40
6 var_38      = -0x38
7 seconds     = -0x34
8 minutes    = -0x30
9 hour        = -0x2C
10 day         = -0x28
11 month       = -0x24
12 year        = -0x20
13 var_4      = -4
14
15 lui      $gp, (__gnu_local_gp >> 16)
16 addiu   $sp, -0x50
17 la       $gp, (__gnu_local_gp & 0xFFFF)
18 sw       $ra, 0x50+var_4($sp)
19 sw       $gp, 0x50+var_40($sp)
20 lw       $t9, (time & 0xFFFF)($gp)
21 or       $at, $zero ; load delay slot, NOP
22 jalr    $t9
23 move    $a0, $zero ; branch delay slot, NOP
24 lw       $gp, 0x50+var_40($sp)
25 addiu   $a0, $sp, 0x50+var_38
26 lw       $t9, (localtime_r & 0xFFFF)($gp)
27 addiu   $a1, $sp, 0x50+seconds
28 jalr    $t9
29 sw       $v0, 0x50+var_38($sp) ; branch delay slot
30 lw       $gp, 0x50+var_40($sp)
31 lw       $a1, 0x50+year($sp)
32 lw       $t9, (printf & 0xFFFF)($gp)
33 la       $a0, $LC0      # "Year: %d\n"
34 jalr    $t9
35 addiu   $a1, 1900 ; branch delay slot
36 lw       $gp, 0x50+var_40($sp)
37 lw       $a1, 0x50+month($sp)
38 lw       $t9, (printf & 0xFFFF)($gp)
39 lui     $a0, ($LC1 >> 16) # "Month: %d\n"
40 jalr    $t9
41 la       $a0, ($LC1 & 0xFFFF) # "Month: %d\n" ; branch delay slot
42 lw       $gp, 0x50+var_40($sp)
43 lw       $a1, 0x50+day($sp)
44 lw       $t9, (printf & 0xFFFF)($gp)
45 lui     $a0, ($LC2 >> 16) # "Day: %d\n"
46 jalr    $t9
47 la       $a0, ($LC2 & 0xFFFF) # "Day: %d\n" ; branch delay slot
48 lw       $gp, 0x50+var_40($sp)
49 lw       $a1, 0x50+hour($sp)
50 lw       $t9, (printf & 0xFFFF)($gp)
51 lui     $a0, ($LC3 >> 16) # "Hour: %d\n"
52 jalr    $t9
53 la       $a0, ($LC3 & 0xFFFF) # "Hour: %d\n" ; branch delay slot
54 lw       $gp, 0x50+var_40($sp)
55 lw       $a1, 0x50+minutes($sp)
56 lw       $t9, (printf & 0xFFFF)($gp)
57 lui     $a0, ($LC4 >> 16) # "Minutes: %d\n"
58 jalr    $t9
59 la       $a0, ($LC4 & 0xFFFF) # "Minutes: %d\n" ; branch delay slot
60 lw       $gp, 0x50+var_40($sp)
61 lw       $a1, 0x50+seconds($sp)
62 lw       $t9, (printf & 0xFFFF)($gp)
63 lui     $a0, ($LC5 >> 16) # "Seconds: %d\n"
64 jalr    $t9
65 la       $a0, ($LC5 & 0xFFFF) # "Seconds: %d\n" ; branch delay slot
66 lw       $ra, 0x50+var_4($sp)
67 or       $at, $zero ; load delay slot, NOP
68 jr       $ra
69 addiu   $sp, 0x50
70
71 $LC0: .ascii "Year: %d\n<0>

```

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```

72 $LC1:          .ascii "Month: %d\n"<0>
73 $LC2:          .ascii "Day: %d\n"<0>
74 $LC3:          .ascii "Hour: %d\n"<0>
75 $LC4:          .ascii "Minutes: %d\n"<0>
76 $LC5:          .ascii "Seconds: %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.

22.3.4 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 22.8.

```

#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:

Listing 22.12: GCC 4.7.3

```

GCC_tm2.c: In function 'main':
GCC_tm2.c:11:5: warning: passing argument 2 of 'localtime_r' from incompatible pointer type [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:

Listing 22.13: GCC 4.7.3

```

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
        call    __main
        mov     [esp+30h+var_30], 0 ; arg 0
        call    time
```

22.3. UNIX: STRUCT TM

```
mov    [esp+30h+unix_time], eax
lea    eax, [esp+30h+tm_sec]
mov    [esp+30h+var_2C], eax
lea    eax, [esp+30h+unix_time]
mov    [esp+30h+var_30], eax
call   localtime_r
mov    eax, [esp+30h+tm_year]
add    eax, 1900
mov    [esp+30h+var_2C], eax
mov    [esp+30h+var_30], offset aYearD ; "Year: %d\n"
call   printf
mov    eax, [esp+30h+tm_mon]
mov    [esp+30h+var_2C], eax
mov    [esp+30h+var_30], offset aMonthD ; "Month: %d\n"
call   printf
mov    eax, [esp+30h+tm_mday]
mov    [esp+30h+var_2C], eax
mov    [esp+30h+var_30], offset aDayD ; "Day: %d\n"
call   printf
mov    eax, [esp+30h+tm_hour]
mov    [esp+30h+var_2C], eax
mov    [esp+30h+var_30], offset aHourD ; "Hour: %d\n"
call   printf
mov    eax, [esp+30h+tm_min]
mov    [esp+30h+var_2C], eax
mov    [esp+30h+var_30], offset aMinutesD ; "Minutes: %d\n"
call   printf
mov    eax, [esp+30h+tm_sec]
mov    [esp+30h+var_2C], eax
mov    [esp+30h+var_30], offset aSecondsD ; "Seconds: %d\n"
call   printf
leave
retn
main  endp
```

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” ([22.4 on page 358](#)).

So, a structure is just a pack of variables laying on 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 [[Rit93](#)].

There is no debugger example here: it is just the same as you already saw.

22.3.5 Structure as an array of 32-bit words

```
#include <stdio.h>
#include <time.h>

void main()
{
    struct tm t;
    time_t unix_time;
    int i;

    unix_time=time(NULL);
```

22.3. UNIX: STRUCT TM

```

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.

```

0x00000002D (45)
0x000000033 (51)
0x000000017 (23)
0x00000001A (26)
0x000000006 (6)
0x000000072 (114)
0x000000006 (6)
0x0000000CE (206)
0x000000001 (1)

```

The variables here are in the same order as they are enumerated in the definition of the structure: [22.8 on page 350](#).

Here is how it gets compiled:

Listing 22.14: 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    ebx
    pop    esi
    pop    ebp
    retn
main endp

```

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.

22.3.6 Structure as an array of bytes

We can go even further. Let's *cast* the pointer to an array of bytes and dump it:

```
#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 also at 23:51:45 26-July-2014⁵. The values are just the same as in the previous dump ([22.3.5 on the preceding page](#)), and of course, the lowest byte goes first, because this is a little-endian architecture ([33 on page 452](#)).

Listing 22.15: Optimizing GCC 4.8.1

```
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
    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
```

⁵The time and date are the same for demonstration purposes. Byte values are fixed up.

22.4. FIELDS PACKING IN STRUCTURE

```
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_8048408 ; j=0
    lea    esp, [ebp-0Ch]
    pop    ebx
    pop    esi
    pop    edi
    pop    ebp
    retn
main
endp
```

22.4 Fields packing in structure

One important thing is fields packing in structures⁶.

Let's take a simple example:

```
#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 *char* fields (each is exactly one byte) and two more – *int* (each – 4 bytes).

22.4.1 x86

This compiles to:

Listing 22.16: MSVC 2012 /GS- /Ob0

```
1 _tmp$ = -16
2 _main    PROC
```

⁶See also: [Wikipedia: Data structure alignment](#)

22.4. FIELDS PACKING IN STRUCTURE

```

3  push    ebp
4  mov     ebp, esp
5  sub     esp, 16
6  mov     BYTE PTR _tmp$[ebp], 1      ; set field a
7  mov     DWORD PTR _tmp$[ebp+4], 2   ; set field b
8  mov     BYTE PTR _tmp$[ebp+8], 3   ; set field c
9  mov     DWORD PTR _tmp$[ebp+12], 4 ; set field d
10 sub    esp, 16                  ; allocate place for temporary structure
11 mov    eax, esp
12 mov    ecx, DWORD PTR _tmp$[ebp]  ; copy our structure to the temporary one
13 mov    DWORD PTR [eax], ecx
14 mov    edx, DWORD PTR _tmp$[ebp+4]
15 mov    DWORD PTR [eax+4], edx
16 mov    ecx, DWORD PTR _tmp$[ebp+8]
17 mov    DWORD PTR [eax+8], ecx
18 mov    edx, DWORD PTR _tmp$[ebp+12]
19 mov    DWORD PTR [eax+12], edx
20 call   _f
21 add    esp, 16
22 xor    eax, eax
23 mov    esp, ebp
24 pop    ebp
25 ret    0
26 _main  ENDP
27
28 _s$ = 8 ; size = 16
29 ?f@@YAXUs@@@Z PROC ; f
30 push   ebp
31 mov    ebp, esp
32 mov    eax, DWORD PTR _s$[ebp+12]
33 push   eax
34 movsx  ecx, BYTE PTR _s$[ebp+8]
35 push   ecx
36 mov    edx, DWORD PTR _s$[ebp+4]
37 push   edx
38 movsx  eax, BYTE PTR _s$[ebp]
39 push   eax
40 push   OFFSET $SG3842
41 call   _printf
42 add    esp, 20
43 pop    ebp
44 ret    0
45 ?f@@YAXUs@@@Z ENDP ; f
46 _TEXT   ENDS

```

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 was. 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 22.17: MSVC 2012 /GS- /Zp1

```

1  _main  PROC
2  push   ebp
3  mov    ebp, esp
4  sub    esp, 12
5  mov    BYTE PTR _tmp$[ebp], 1      ; set field a
6  mov    DWORD PTR _tmp$[ebp+1], 2   ; set field b
7  mov    BYTE PTR _tmp$[ebp+5], 3   ; set field c
8  mov    DWORD PTR _tmp$[ebp+6], 4 ; set field d
9  sub    esp, 12                  ; allocate place for temporary structure
10 mov   eax, esp

```

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```

11    mov    ecx, DWORD PTR _tmp$[ebp] ; copy 10 bytes
12    mov    DWORD PTR [eax], ecx
13    mov    edx, DWORD PTR _tmp$[ebp+4]
14    mov    DWORD PTR [eax+4], edx
15    mov    cx, WORD PTR _tmp$[ebp+8]
16    mov    WORD PTR [eax+8], cx
17    call   _f
18    add    esp, 12
19    xor    eax, eax
20    mov    esp, ebp
21    pop    ebp
22    ret    0
23 _main    ENDP
24
25 _TEXT    SEGMENT
26 _s$ = 8 ; size = 10
27 ?f@@YAXUs@@@Z PROC      ; f
28     push   ebp
29     mov    ebp, esp
30     mov    eax, DWORD PTR _s$[ebp+6]
31     push   eax
32     movsx  ecx, BYTE PTR _s$[ebp+5]
33     push   ecx
34     mov    edx, DWORD PTR _s$[ebp+1]
35     push   edx
36     movsx  eax, BYTE PTR _s$[ebp]
37     push   eax
38     push   OFFSET $SG3842
39     call   _printf
40     add    esp, 20
41     pop    ebp
42     ret    0
43 ?f@@YAXUs@@@Z ENDP      ; f

```

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: [45.1.5 on page 505](#).

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 MSVC⁷ and GCC⁸.

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:

Listing 22.18: WinNT.h

```
#include "pshpack1.h"
```

And this:

Listing 22.19: WinNT.h

```
#include "pshpack4.h"          // 4 byte packing is the default
```

The file PshPack1.h looks like:

Listing 22.20: PshPack1.h

⁷MSDN: Working with Packing Structures

⁸Structure-Packing Pragmas

22.4. FIELDS PACKING IN STRUCTURE

```
#if ! (defined(lint) || defined(RC_INVOKED))
#endif (_MSC_VER >= 800 && !_defined(_M_I86)) || defined(_PUSHPOP_SUPPORTED)
#pragma warning(disable:4103)
#ifndef (defined( MIDL_PASS )) || defined( __midl )
#pragma pack(push,1)
#else
#pragma pack(1)
#endif
#ifndef
#pragma pack(1)
#endif
#endif /* ! (defined(lint) || defined(RC_INVOKED)) */
```

This tell the compiler how to pack the structures defined after `#pragma pack`.

22.4. FIELDS PACKING IN STRUCTURE

OllyDbg + fields are packed by default

Let's try our example (where the fields are aligned by default (4 bytes)) in OllyDbg:

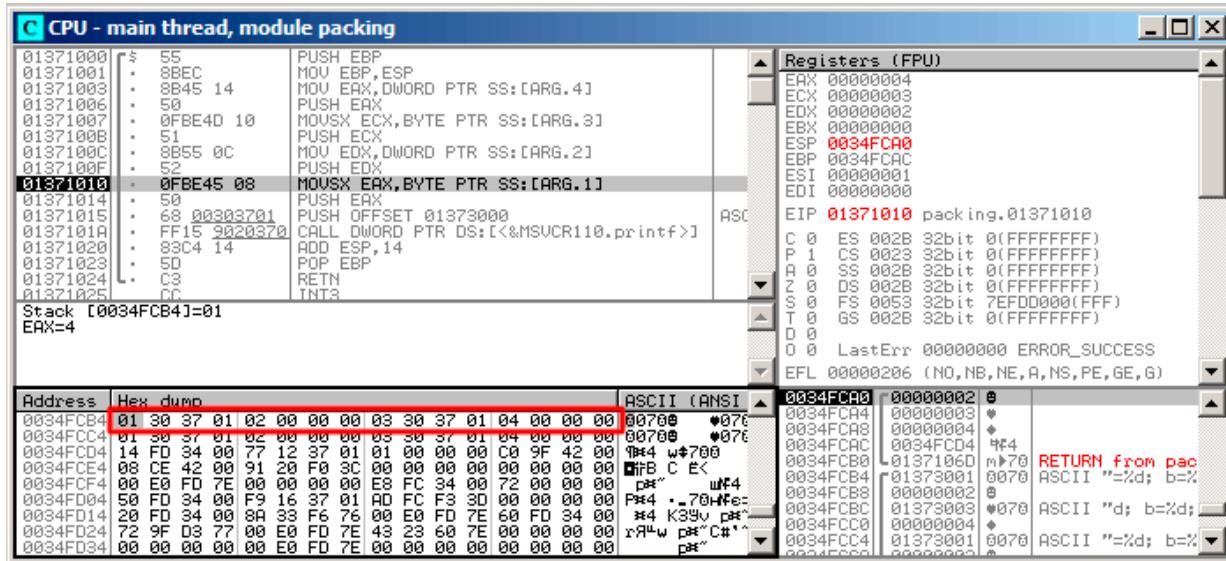


Figure 22.3: OllyDbg: Before `printf()` execution

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 [22.16 on page 358](#), 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 `MOVsx` instruction, which takes bytes, not words: listing [22.16](#) (lines 34 and 38).

By the way, the `MOVsx` (sign-extending) instruction is used here, because `char` is signed by default in MSVC and GCC. If the type `unsigned char` or `uint8_t` was used here, `MOVzx` instruction would have been used instead.

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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

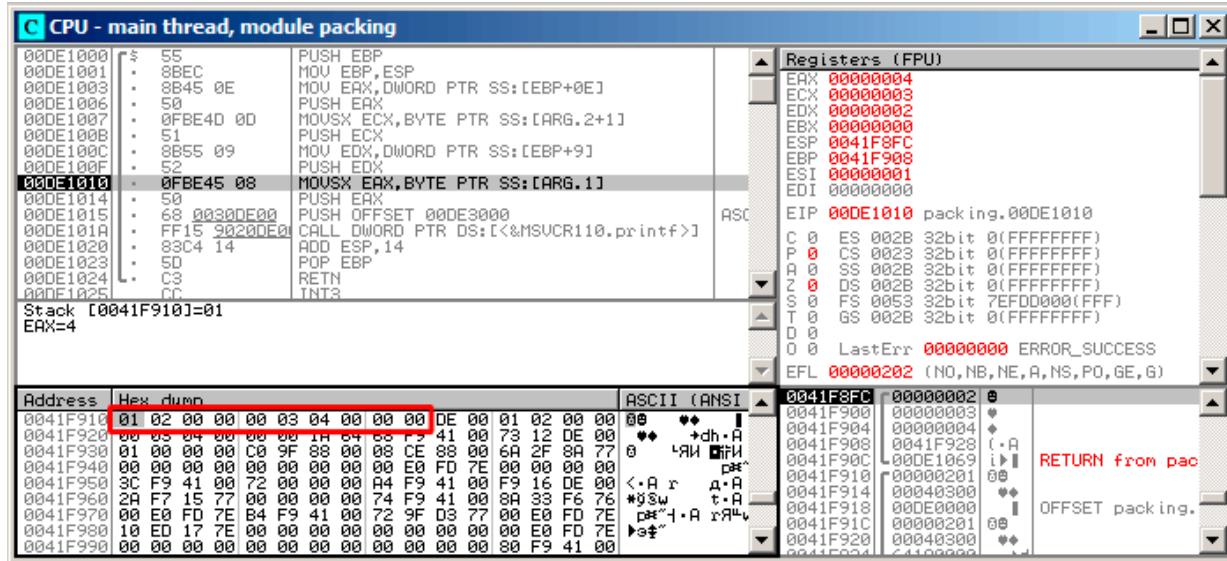


Figure 22.4: OllyDbg: Before `printf()` execution

22.4.2 ARM

Optimizing Keil 6/2013 (Thumb mode)

Listing 22.21: Optimizing Keil 6/2013 (Thumb mode)

```

.text:0000003E          exit ; CODE XREF: f+16
.text:0000003E 05 B0    ADD     SP, SP, #0x14
.text:00000040 00 BD    POP    {PC}

.text:00000280          f
.text:00000280          var_18 = -0x18
.text:00000280          a      = -0x14
.text:00000280          b      = -0x10
.text:00000280          c      = -0xC
.text:00000280          d      = -8
.text:00000280
.text:00000280 0F B5    PUSH   {R0-R3,LR}
.text:00000282 81 B0    SUB    SP, SP, #4
.text:00000284 04 98    LDR    R0, [SP,#16] ; d
.text:00000286 02 9A    LDR    R2, [SP,#8] ; b
.text:00000288 00 90    STR    R0, [SP]
.text:0000028A 68 46    MOV    R0, SP
.text:0000028C 03 7B    LDRB   R3, [R0,#12] ; c
.text:0000028E 01 79    LDRB   R1, [R0,#4] ; a
.text:00000290 59 A0    ADR    R0, aADBCDDD ; "a=%d; b=%d; c=%d; d=%d\n"
.text:00000292 05 F0 AD FF  BL    __2printf
.text:00000296 D2 E6    B     exit

```

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 ($5 * 4 = 0x14$)). Also it is located nearby (take a look at the addresses). Indeed, it doesn't matter

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

```
var_C = -0xC

PUSH {R7, LR}
MOV R7, SP
SUB SP, SP, #4
MOV R9, R1 ; b
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 MOVSX in x86. All the rest –just the same.

22.4.3 MIPS

Listing 22.23: Optimizing GCC 4.4.5 (IDA)

```
1 f:
2
3 var_18      = -0x18
4 var_10      = -0x10
5 var_4       = -4
6 arg_0       = 0
7 arg_4       = 4
8 arg_8       = 8
9 arg_C       = 0xC
10
11 ; $a0=s.a
12 ; $a1=s.b
13 ; $a2=s.c
14 ; $a3=s.d
15     lui    $gp, (__gnu_local_gp >> 16)
16     addiu $sp, -0x28
17     la    $gp, (__gnu_local_gp & 0xFFFF)
18     sw    $ra, 0x28+var_4($sp)
19     sw    $gp, 0x28+var_10($sp)
20 ; prepare byte from 32-bit big-endian integer:
21     sra   $t0, $a0, 24
22     move  $v1, $a1
23 ; prepare byte from 32-bit big-endian integer:
24     sra   $v0, $a2, 24
25     lw    $t9, (printf & 0xFFFF)($gp)
26     sw    $a0, 0x28+arg_0($sp)
27     lui   $a0, ($LC0 >> 16) # "a=%d; b=%d; c=%d; d=%d\n"
28     sw    $a3, 0x28+var_18($sp)
29     sw    $a1, 0x28+arg_4($sp)
30     sw    $a2, 0x28+arg_8($sp)
31     sw    $a3, 0x28+arg_C($sp)
32     la    $a0, ($LC0 & 0xFFFF) # "a=%d; b=%d; c=%d; d=%d\n"
33     move $a1, $t0
34     move $a2, $v1
35     jalr $t9
36     move $a3, $v0 ; branch delay slot
```

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```
37          lw      $ra, 0x28+var_4($sp)
38          or      $at, $zero ; load delay slot, NOP
39          jr      $ra
40          addiu $sp, 0x28 ; branch delay slot
41
42 $LC0:       .ascii "a=%d; b=%d; c=%d; d=%d\n"<0>
```

Structure fields come in registers \$A0..\$A3 and then get reshuffled into \$A1..\$A4 for `printf()`. But there are two SRA (“Shift Word Right Arithmetic”) instructions, which prepare *char* fields. Why? MIPS is a big-endian architecture by default [33 on page 452](#), 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.

22.4.4 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:

```
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.

22.5 Nested structures

Now what about situations when one structure is defined inside another?

```
#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);
}

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);
}
```

22.5. NESTED STRUCTURES

... 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 22.24: Optimizing MSVC 2010 /Ob0

```
$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
    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
    pop    ebx
    add    esp, 24
    ret    0
_main   ENDP
```

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.

22.5.1 OllyDbg

Let's load the example into OllyDbg and take a look at `outer_struct` in memory:

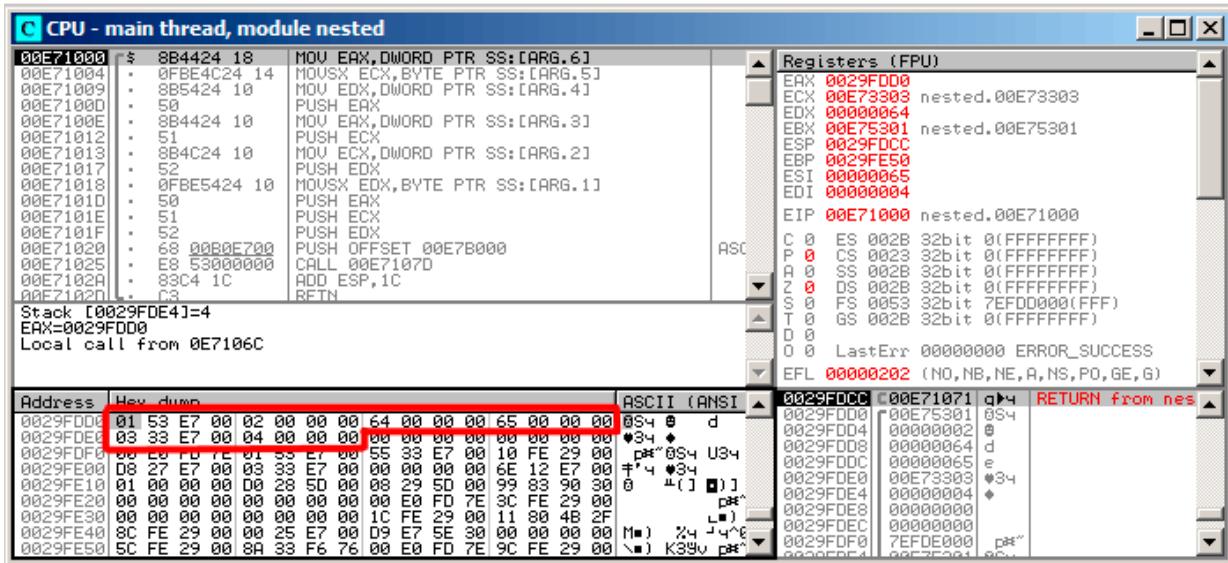


Figure 22.5: OllyDbg: Before `printf()` execution

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.

22.6 Bit fields in a structure

22.6.1 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`⁹ 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:

3:0 (4 bits)	Stepping
7:4 (4 bits)	Model
11:8 (4 bits)	Family
13:12 (2 bits)	Processor Type
19:16 (4 bits)	Extended Model
27:20 (8 bits)	Extended Family

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 assembler¹⁰.

```
#include <stdio.h>

#ifndef __GNUC__
static inline void cpuid(int code, int *a, int *b, int *c, int *d) {
```

⁹wikipedia

¹⁰More about internal GCC assembler

22.6. BIT FIELDS IN A STRUCTURE

```

asm volatile("cpuid": "=a"(*a), "=b"(*b), "=c"(*c), "=d"(*d): "a"(code));
}

#endif

#ifndef _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 22.25: Optimizing MSVC 2008

```

_b$ = -16 ; size = 16
_main PROC
    sub    esp, 16
    push   ebx

    xor    ecx, ecx
    mov    eax, 1
    cpuid
    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

```

22.6. BIT FIELDS IN A STRUCTURE

```

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.

22.6. BIT FIELDS IN A STRUCTURE

MSVC + OllyDbg

Let's load our example into OllyDbg and see, what values are set in EAX/EBX/ECX/EDX after the execution of CPUID:

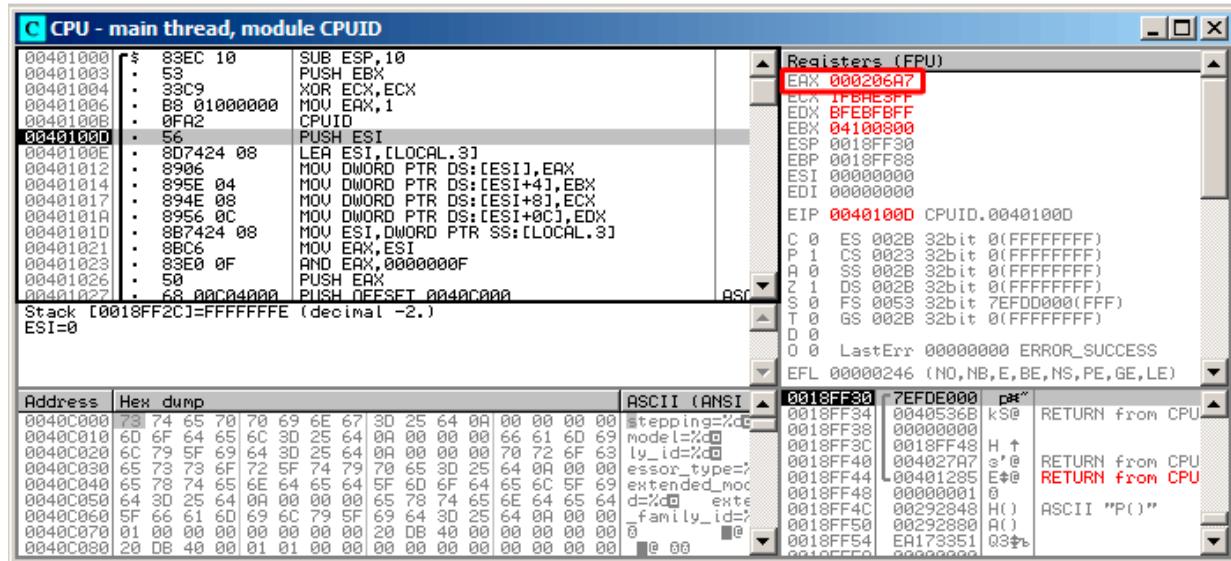


Figure 22.6: OllyDbg: After CPUID execution

EAX has **0x000206A7** (my **CPU** is Intel Xeon E3-1220).
This is 0000000000000000100000011010100111 in binary form.

Here is how the bits are distributed by fields:

field	in binary form	in decimal form
reserved2	0000	0
extended_family_id	00000000	0
extended_model_id	0010	2
reserved1	00	0
processor_id	00	0
family_id	0110	6
model	1010	10
stepping	0111	7

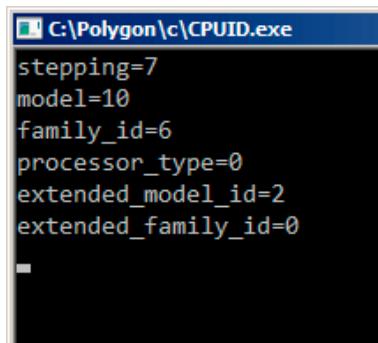


Figure 22.7: OllyDbg: Result

GCC

Let's try GCC 4.4.1 with **-O3** option.

Listing 22.26: Optimizing GCC 4.4.1

```

main          proc near ; DATA XREF: _start+17
    push    ebp
    mov     ebp, esp
    and     esp, 0FFFFFFF0h
    push    esi

```

22.6. BIT FIELDS IN A STRUCTURE

```

mov    esi, 1
push   ebx
mov    eax, esi
sub    esp, 18h
cpuid
mov    esi, eax
and    eax, 0Fh
mov    [esp+8], eax
mov    dword ptr [esp+4], offset aSteppingD ; "stepping=%d\n"
mov    dword ptr [esp], 1
call   __printf_chk
mov    eax, esi
shr    eax, 4
and    eax, 0Fh
mov    [esp+8], eax
mov    dword ptr [esp+4], offset aModelID ; "model=%d\n"
mov    dword ptr [esp], 1
call   __printf_chk
mov    eax, esi
shr    eax, 8
and    eax, 0Fh
mov    [esp+8], eax
mov    dword ptr [esp+4], offset aFamily_idD ; "family_id=%d\n"
mov    dword ptr [esp], 1
call   __printf_chk
mov    eax, esi
shr    eax, 0Ch
and    eax, 3
mov    [esp+8], eax
mov    dword ptr [esp+4], offset aProcessor_type ; "processor_type=%d\n"
mov    dword ptr [esp], 1
call   __printf_chk
mov    eax, esi
shr    eax, 10h
shr    esi, 14h
and    eax, 0Fh
and    esi, 0FFh
mov    [esp+8], eax
mov    dword ptr [esp+4], offset aExtended_model ; "extended_model_id=%d\n"
mov    dword ptr [esp], 1
call   __printf_chk
mov    [esp+8], esi
mov    dword ptr [esp+4], offset unk_80486D0
mov    dword ptr [esp], 1
call   __printf_chk
add    esp, 18h
xor    eax, eax
pop    ebx
pop    esi
mov    esp, ebp
pop    ebp
retn
main          endp

```

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.

22.6.2 Working with the float type as with a structure

As we already noted in the section about FPU ([18 on page 217](#)), both `float` and `double` types consist of a *sign*, a *significand* (or *fraction*) and an *exponent*. But will we be able to work with these fields directly? Let's try this with `float`.



(S-sign)

```
#include <stdio.h>
#include <assert.h>
#include <stdlib.h>
#include <memory.h>

struct float_as_struct
{
    unsigned int fraction : 23; // fractional part
    unsigned int exponent : 8; // exponent + 0x3FF
    unsigned int sign : 1; // sign bit
};

float f(float in)
{
    float f=in;
    struct float_as_struct t;

    assert (sizeof (struct float_as_struct) == sizeof (float));

    memcpy (&t, &f, sizeof (float));

    t.sign=1; // set negative sign
    t.exponent=t.exponent+2; // multiply d by  $2^n$  (n here is 2)

    memcpy (&f, &t, sizeof (float));

    return f;
}

int main()
{
    printf ("%f\n", f(1.234));
}
```

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 2^2 , i.e., by 4.

Let's compile in MSVC 2008 without optimization turned on:

Listing 22.27: Non-optimizing MSVC 2008

```
_t$ = -8 ; size = 4
_f$ = -4 ; size = 4
__in$ = 8 ; size = 4
?f@@YAMM@Z PROC ; f
    push    ebp
    mov     ebp, esp
    sub     esp, 8

    fld     DWORD PTR __in$[ebp]
    fstp   DWORD PTR _f$[ebp]

    push    4
    lea     eax, DWORD PTR _f$[ebp]
    push    eax
    lea     ecx, DWORD PTR _t$[ebp]
    push    ecx
    call    _memcpy
    add     esp, 12

    mov     edx, DWORD PTR _t$[ebp]
    or      edx, -2147483648 ; 80000000H - set minus sign
    mov     DWORD PTR _t$[ebp], edx

    mov     eax, DWORD PTR _t$[ebp]
    shr     eax, 23           ; 00000017H - drop significand
    and     eax, 255          ; 000000ffH - leave here only exponent
    add     eax, 2             ; add 2 to it
```

22.6. BIT FIELDS IN A STRUCTURE

```

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 22.28: 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, 807FFFFh ; leave only significand and exponent 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        ; add new exponent and original value without exponent
    mov    [ebp+var_4], eax
    fld    [ebp+var_4]
    leave
    retn
_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

```

22.7. EXERCISES

```
main    endp
```

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!

22.7 Exercises

- <http://challenges.re/71>
- <http://challenges.re/72>

Chapter 23

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.

23.1 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 get 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 need 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 `01111111` to exponent—this means that the exponent is 1. Then we fill the significand with random bits, set the sign bit to 0 (which means a positive number) and voilà. The generated numbers are to be between 1 and 2, so we must also subtract 1.

A very simple linear congruential random numbers generator is used in my example¹, 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: [21 on page 337](#). So this code in compiled form is omitted.

```
#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()
{
    RNG_state=RNG_state*RNG_a+RNG_c;
    return RNG_state;
};

// FPU PRNG definitions and routines:
```

¹the idea was taken from: <http://go.yurichev.com/17308>

23.1. PSEUDO-RANDOM NUMBER GENERATOR EXAMPLE

```
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

int main()
{
    my_srand(time(NULL)); // PRNG initialization

    for (int i=0; i<100; i++)
        printf ("%f\n", float_rand());

    return 0;
};
```

23.1.1 x86

Listing 23.1: Optimizing MSVC 2010

```
$SG4238 DB      '%f', 0aH, 00H

__real@3ff0000000000000 DQ 03ff0000000000000r ; 1

tv130 = -4
_tmp$ = -4
?float_rand@@YAMXZ PROC
    push    ecx
    call    ?my_rand@@YAIHZ
; 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@3ff0000000000000
; 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
    mov     esi, 100
$LL3@main:
    call    ?float_rand@@YAMXZ
    sub    esp, 8
    fstp   QWORD PTR [esp]
```

23.1. PSEUDO-RANDOM NUMBER GENERATOR EXAMPLE

```

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: [53.1.1 on page 543](#). If we compile this in MSVC 2012, it uses the SIMD instructions for the FPU, read more about it here: [28.5 on page 439](#).

23.1.2 MIPS

Listing 23.2: Optimizing GCC 4.4.5

```

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, 0x7FFFFFFF
; $v1=0x7FFFFFFF
        and   $v1, $v0, $v1
; $v1=pseudorandom value & 0x7FFFFFFF
        lui    $a0, 0x3F80
; $a0=0x3F800000
        or     $v1, $a0
; $v1=pseudorandom value & 0x7FFFFFFF | 0x3F800000
; matter of the following instruction is still hard to get:
        lui    $v0, ($LC0 >> 16)
; 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
        la    $gp, (__gnu_local_gp & 0xFFFF)
        sw    $ra, 0x28+var_4($sp)
        sw    $s2, 0x28+var_8($sp)
        sw    $s1, 0x28+var_C($sp)
        sw    $s0, 0x28+var_10($sp)

```

23.1. PSEUDO-RANDOM NUMBER GENERATOR EXAMPLE

```

        sw      $gp, 0x28+var_18($sp)
        lw      $t9, (time & 0xFFFF)($gp)
        or      $at, $zero ; load delay slot, NOP
        jalr   $t9
        move   $a0, $zero ; branch delay slot
        lui    $s2, ($LC1 >> 16) # "%f\n"
        move   $a0, $v0
        la     $s2, ($LC1 & 0xFFFF) # "%f\n"
        move   $s0, $zero
        jal    my_srand
        li     $s1, 0x64 # 'd' ; branch delay slot

loc_104:
        jal    float_rand
        addiu $s0, 1
        lw     $gp, 0x28+var_18($sp)
; convert value we got from float_rand() to double type (printf() need it):
        cvt.d.s $f2, $f0
        lw     $t9, (printf & 0xFFFF)($gp)
        mfc1  $a3, $f2
        mfc1  $a2, $f3
        jalr   $t9
        move   $a0, $s2
        bne   $s0, $s1, loc_104
        move   $v0, $zero
        lw     $ra, 0x28+var_4($sp)
        lw     $s2, 0x28+var_8($sp)
        lw     $s1, 0x28+var_C($sp)
        lw     $s0, 0x28+var_10($sp)
        jr    $ra
        addiu $sp, 0x28 ; branch delay slot

$LC1:      .ascii "%f\n"<0>
$LC0:      .float 1.0

```

There is also an useless `LUI` instruction added for some weird reason. We considered this artifact earlier: [18.5.6 on page 229](#).

23.1.3 ARM (ARM mode)

Listing 23.3: Optimizing GCC 4.6.3 (IDA)

```

float_rand
        STMFD  SP!, {R3,LR}
        BL     my_rand
; R0=pseudorandom value
        FLDS   S0, =1.0
; S0=1.0
        BIC    R3, R0, #0xFF000000
        BIC    R3, R3, #0x800000
        ORR    R3, R3, #0x3F800000
; R3=pseudorandom value & 0x007fffff | 0x3f800000
; copy from R3 to FPU (register S15).
; it behaves like bitwise copy, no conversion done:
        FMSR   S15, R3
; subtract 1.0 and leave result in S0:
        FSUBS  S0, S15, S0
        LDMFD  SP!, {R3,PC}

flt_5C      DCFS 1.0

main
        STMFD  SP!, {R4,LR}
        MOV    R0, #0
        BL    time
        BL    my_srand
        MOV    R4, #0x64 ; 'd'

loc_78

```

23.2. CALCULATING MACHINE EPSILON

```

        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}
aF           DCB "%f",0xA,0

```

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 23.4: Optimizing GCC 4.6.3 (objdump)

```

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

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: eeb77ac0      vcvt.f64.f32 d7, s0
20: ec532b17      vmov   r2, r3, d7
24: ebfffffe      bl     0 <printf>
28: e2544001     subs   r4, r4, #1
2c: 1affffff8     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.

23.2 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:

```

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

union uint_float
{
    uint32_t i;
    float f;
};

float calculate_machine_epsilon(float start)

```

```

{
    union uint_float v;
    v.f=start;
    v.i++;
    return v.f-start;
}

void main()
{
    printf ("%g\n", calculate_machine_epsilon(1.0));
}

```

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 need 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.

23.2.1 x86

Listing 23.5: 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$[esp-4]
    fsubr   DWORD PTR _v$[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 need 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.

23.2.2 ARM64

Let's extend our example to 64-bit:

```

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

typedef union
{
    uint64_t i;
    double d;
} uint_double;

double calculate_machine_epsilon(double start)
{
    uint_double v;
    v.d=start;
    v.i++;
    return v.d-start;
}

void main()
{
    printf ("%g\n", calculate_machine_epsilon(1.0));
}

```

23.3. FAST SQUARE ROOT CALCULATION

```
};
```

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.

Listing 23.6: Optimizing GCC 4.9 ARM64

```
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: [28.4 on page 438](#).

23.2.3 MIPS

The new instruction here is `MTC1` ("Move To Coprocessor 1"), it just transfers data from `GPR` to the FPU's registers.

Listing 23.7: Optimizing GCC 4.4.5 (IDA)

```
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
```

23.2.4 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++.

23.3 Fast square root calculation

Another well-known algorithm where *float* is interpreted as integer is fast calculation of square root.

Listing 23.8: The source code is taken from Wikipedia: <http://go.yurichev.com/17364>

```
/* Assumes that float is in the IEEE 754 single precision floating point format  
 * 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 */  
}
```

23.3. FAST SQUARE ROOT CALCULATION

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 is present in Wikipedia: <http://go.yurichev.com/17360>.

Chapter 24

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 functions¹.

Well-known examples are:

- `qsort()`², `atexit()`³ from the standard C library;
- *NIX OS signals⁴;
- thread starting: `CreateThread()` (win32), `pthread_create()` (POSIX);
- lots of win32 functions, like `EnumChildWindows()`⁵.
- lots of places in the Linux kernel, for example the filesystem driver functions are called via callbacks: <http://go.yurichev.com/17076>
- The GCC plugin functions are also called via callbacks: <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.

The comparison function can be defined as:

```
int (*compare)(const void *, const void *)
```

Let's use a slightly modified example which was found [here](#):

```
1 /* ex3 Sorting ints with qsort */
2
3 #include <stdio.h>
4 #include <stdlib.h>
5
6 int comp(const void * _a, const void * _b)
7 {
8     const int *a=(const int *)_a;
9     const int *b=(const int *)_b;
10
11    if (*a==*b)
12        return 0;
13    else
14        if (*a < *b)
15            return -1;
16        else
17            return 1;
```

¹[wikipedia](#)

²[wikipedia](#)

³<http://go.yurichev.com/17073>

⁴[wikipedia](#)

⁵[MSDN](#)

24.1. MSVC

```
18 }
19
20 int main(int argc, char* argv[])
21 {
22     int numbers[10]={1892,45,200,-98,4087,5,-12345,1087,88,-100000};
23     int i;
24
25     /* Sort the array */
26     qsort(numbers,10,sizeof(int),comp) ;
27     for (i=0;i<9;i++)
28         printf("Number = %d\n",numbers[ i ]) ;
29     return 0;
30 }
```

24.1 MSVC

Let's compile it in MSVC 2010 (some parts were omitted for the sake of brevity) with `/Ox` option:

Listing 24.1: 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
    push  esi
    push  OFFSET _comp
    push  4
    lea   eax, DWORD PTR _numbers$[esp+52]
    push  10                            ; 0000000aH
    push  eax
    mov   DWORD PTR _numbers$[esp+60], 1892   ; 00000764H
    mov   DWORD PTR _numbers$[esp+64], 45      ; 0000002dH
    mov   DWORD PTR _numbers$[esp+68], 200     ; 000000c8H
    mov   DWORD PTR _numbers$[esp+72], -98     ; ffffff9eH
    mov   DWORD PTR _numbers$[esp+76], 4087    ; 00000ff7H
    mov   DWORD PTR _numbers$[esp+80], 5        ; ffffffcfc7H
    mov   DWORD PTR _numbers$[esp+84], -12345   ; 0000043fH
    mov   DWORD PTR _numbers$[esp+88], 1087    ; 00000058H
    mov   DWORD PTR _numbers$[esp+92], 88       ; 00000058H
    mov   DWORD PTR _numbers$[esp+96], -100000  ; fffe7960H
    call  _qsort
    add   esp, 16                         ; 00000010H
...
```

24.1. MSVC

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 24.2: MSVCR80.DLL

```
.text:7816CBF0 ; void __cdecl qsort(void *, unsigned int, unsigned int, int (__cdecl *)(const void *, const void *))  
.text:7816CBF0                 public _qsort  
.text:7816CBF0 _qsort          proc near  
.text:7816CBF0  
.text:7816CBF0 lo              = dword ptr -104h  
.text:7816CBF0 hi              = dword ptr -100h  
.text:7816CBF0 var_FC          = dword ptr -0FCh  
.text:7816CBF0 stkptr          = dword ptr -0F8h  
.text:7816CBF0 lostk           = dword ptr -0F4h  
.text:7816CBF0 histk            = dword ptr -7Ch  
.text:7816CBF0 base             = dword ptr 4  
.text:7816CBF0 num              = dword ptr 8  
.text:7816CBF0 width            = dword ptr 0Ch  
.text:7816CBF0 comp              = dword ptr 10h  
.text:7816CBF0  
.text:7816CBF0                 sub     esp, 100h  
  
....  
  
.text:7816CCE0 loc_7816CCE0:          ; CODE XREF: _qsort+B1  
.text:7816CCE0 shr    eax, 1  
.text:7816CCE2 imul   eax, ebp  
.text:7816CCE5 add    eax, ebx  
.text:7816CCE7 mov    edi, eax  
.text:7816CCE9 push   edi  
.text:7816CCEA push   ebx  
.text:7816CCEB call   [esp+118h+comp]  
.text:7816CCF2 add    esp, 8  
.text:7816CCF5 test   eax, eax  
.text:7816CCF7 jle    short loc_7816CD04
```

`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.

The second reason is that the callback function types must comply strictly, calling the wrong function with wrong arguments or 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.

24.1.1 MSVC + OllyDbg

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:

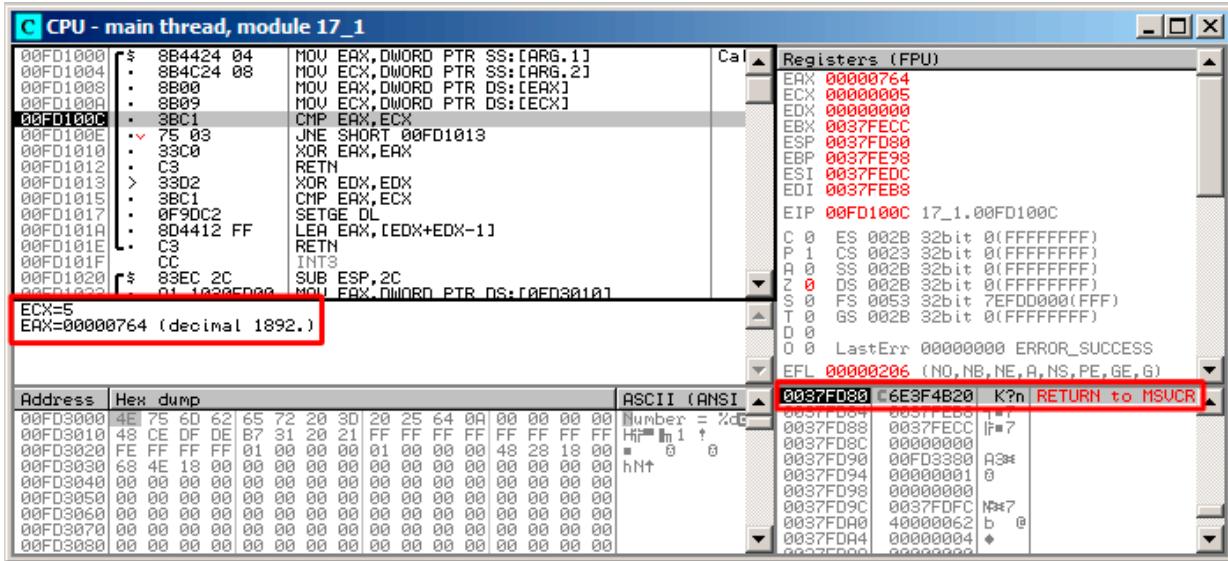


Figure 24.1: OllyDbg: first call of `comp()`

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`).

24.1. MSVC

By tracing (F8) until the RETN instruction and pressing F8 one more time, we return to the `qsort()` function:

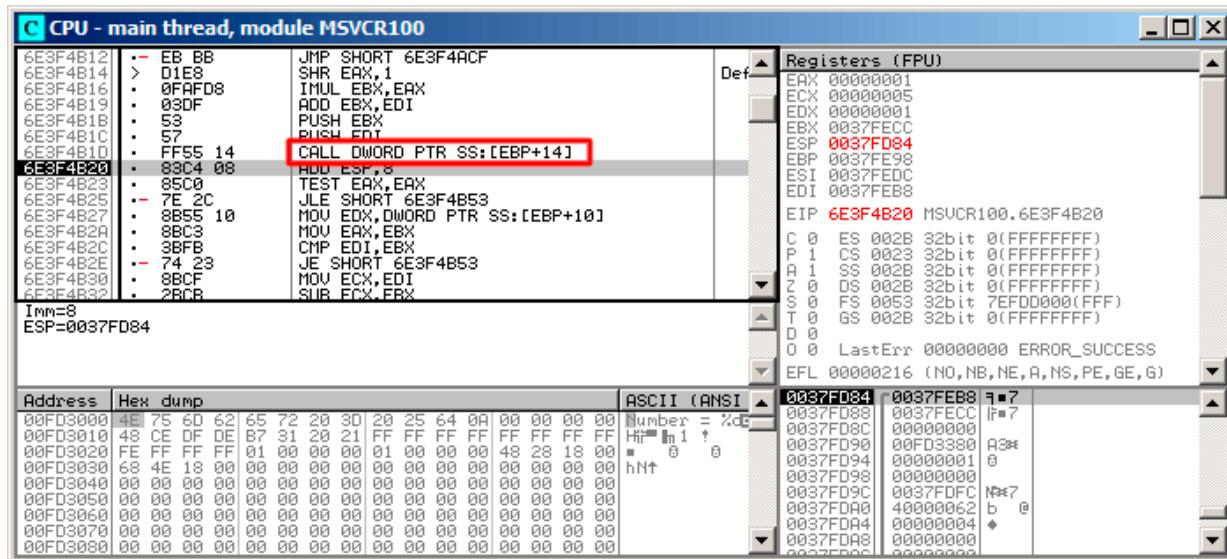


Figure 24.2: OllyDbg: the code in `qsort()` right after `comp()` call

That was a call to the comparison function.

24.1. MSVC

Here is also a screenshot of the moment of the second call of `comp()` – now values that have to be compared are different:

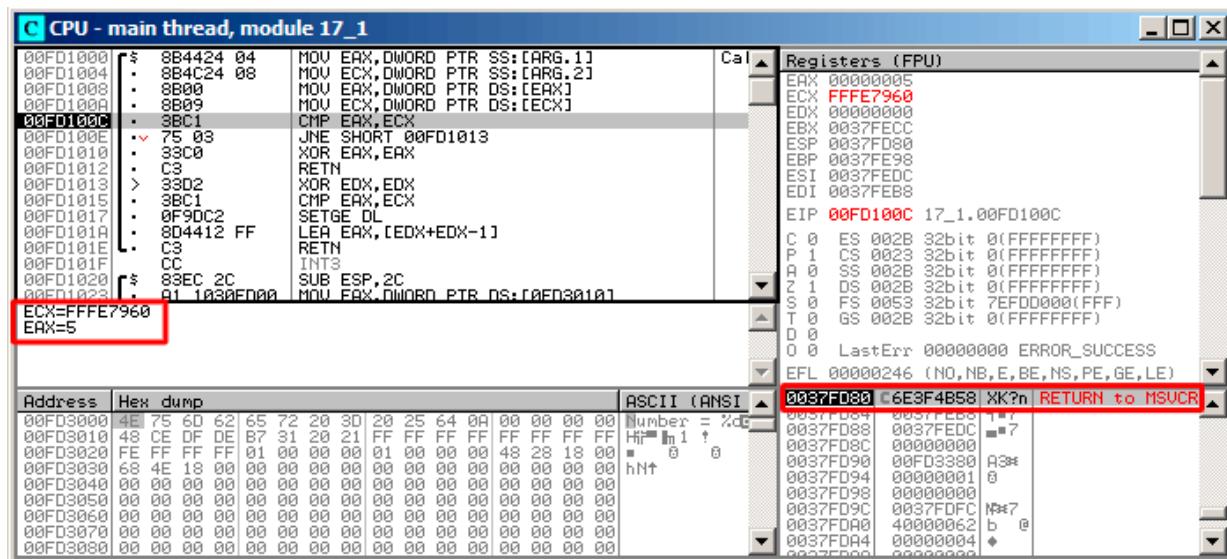


Figure 24.3: OllyDbg: second call of `comp()`

24.1.2 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:

```
PID=4336|New process 17_1.exe
(0) 17_1.exe!0x40100c
EAX=0x00000764 EBX=0x0051f7c8 ECX=0x00000005 EDX=0x00000000
ESI=0x0051f7d8 EDI=0x0051f7b4 EBP=0x0051f794 ESP=0x0051f67c
EIP=0x0028100c
FLAGS=IF
(0) 17_1.exe!0x40100c
EAX=0x00000005 EBX=0x0051f7c8 ECX=0xffffe7960 EDX=0x00000000
ESI=0x0051f7d8 EDI=0x0051f7b4 EBP=0x0051f794 ESP=0x0051f67c
EIP=0x0028100c
FLAGS=PF ZF IF
(0) 17_1.exe!0x40100c
EAX=0x00000764 EBX=0x0051f7c8 ECX=0x00000005 EDX=0x00000000
ESI=0x0051f7d8 EDI=0x0051f7b4 EBP=0x0051f794 ESP=0x0051f67c
EIP=0x0028100c
FLAGS=CF PF ZF IF
...
```

Let's filter out `EAX` and `ECX` and we got:

```
EAX=0x00000764 ECX=0x00000005
EAX=0x00000005 ECX=0xffffe7960
EAX=0x00000764 ECX=0x00000005
EAX=0x0000002d ECX=0x00000005
EAX=0x00000058 ECX=0x00000005
EAX=0x0000043f ECX=0x00000005
EAX=0xfffffcfc7 ECX=0x00000005
EAX=0x000000c8 ECX=0x00000005
EAX=0xfffffff9e ECX=0x00000005
EAX=0x00000ff7 ECX=0x00000005
EAX=0x00000ff7 ECX=0x00000005
EAX=0xfffffff9e ECX=0x00000005
```

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```
EAX=0xffffffff9e ECX=0x00000005
EAX=0xfffffcfc7 ECX=0xffffe7960
EAX=0x00000005 ECX=0xfffffcfc7
EAX=0xffffffff9e ECX=0x00000005
EAX=0xfffffcfc7 ECX=0xffffe7960
EAX=0xffffffff9e ECX=0xfffffcfc7
EAX=0xfffffcfc7 ECX=0xffffe7960
EAX=0x000000c8 ECX=0x00000ff7
EAX=0x0000002d ECX=0x00000ff7
EAX=0x0000043f ECX=0x00000ff7
EAX=0x00000058 ECX=0x00000ff7
EAX=0x00000764 ECX=0x00000ff7
EAX=0x000000c8 ECX=0x00000764
EAX=0x0000002d ECX=0x00000764
EAX=0x0000043f ECX=0x00000764
EAX=0x00000058 ECX=0x00000764
EAX=0x000000c8 ECX=0x00000058
EAX=0x0000002d ECX=0x000000c8
EAX=0x0000043f ECX=0x000000c8
EAX=0x000000c8 ECX=0x00000058
EAX=0x0000002d ECX=0x000000c8
EAX=0x0000002d ECX=0x000000058
```

That's 34 pairs. Therefore, the quick sort algorithm needs 34 comparison operations to sort these 10 numbers.

24.1.3 MSVC + tracer (code coverage)

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:

```
.text:00401000
.text:00401000 ; int __cdecl PtFuncCompare(const void *, const void *)
.text:00401000 PtFuncCompare    proc near             ; DATA XREF: _main+5↓o
.text:00401000
.text:00401000 arg_0          = dword ptr  4
.text:00401000 arg_4          = dword ptr  8
.text:00401000
.text:00401000     mov      eax, [esp+arg_0] ; [ESP+4]=0x45F7ec..0x45F810(step=4), L"?\\x04?
.text:00401004     mov      ecx, [esp+arg_4] ; [ESP+8]=0x45F7ec..0x45F7F4(step=4), 0x45F7Fc
.text:00401008     mov      eax, [eax]       ; [EAX]=5, 0x2d, 0x58, 0xc8, 0x43F, 0x764, 0xFF
.text:0040100A     mov      ecx, [ecx]       ; [ECX]=5, 0x58, 0xc8, 0x764, 0xFF7, 0xFFFFe7960
.text:0040100C     cmp      eax, ecx       ; EAX=5, 0x2d, 0x58, 0xc8, 0x43F, 0x764, 0xFF7,
.text:0040100E     jnz      short loc_401013 ; ZF=False
.text:00401010     xor      eax, eax
.text:00401012     retn
.text:00401013 ;
.text:00401013 loc_401013:           ; CODE XREF: PtFuncCompare+E↑j
.text:00401013     xor      edx, edx
.text:00401015     cmp      eax, ecx       ; EAX=5, 0x2d, 0x58, 0xc8, 0x43F, 0x764, 0xFF7,
.text:00401017     setnl   dl           ; SF=False,true OF=False
.text:0040101A     lea      eax, [edx+edx-1]
.text:0040101E     retn
.text:0040101E PtFuncCompare    endp
.text:0040101F
```

Figure 24.4: tracer and IDA. N.B.: some values are cut at right

[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.

24.2 GCC

Not a big difference:

Listing 24.3: GCC

```
lea    eax, [esp+40h+var_28]
mov   [esp+40h+var_40], eax
mov   [esp+40h+var_28], 764h
mov   [esp+40h+var_24], 2Dh
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], 0FFFFFCFC7h
mov   [esp+40h+var_C], 43Fh
mov   [esp+40h+var_8], 58h
mov   [esp+40h+var_4], 0FFFFE7960h
mov   [esp+40h+var_34], offset comp
mov   [esp+40h+var_38], 4
mov   [esp+40h+var_3C], 0Ah
```

24.2. GCC

```
call    _qsort
```

comp() function:

```
comp          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 wrapper⁶ for `qsort_r()`.

In turn, it is calling `quicksort()`, where our defined function is called via a passed pointer:

Listing 24.4: (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]
...
...
```

24.2.1 GCC + GDB (with source code)

Obviously, we have the C-source code of our example ([24 on page 383](#)), so we can set a breakpoint (`b`) on line number (11—the line where the first comparison occurs). We also need 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 24.5: 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.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law. Type "show copying"
and "show warranty" for details.
This GDB was configured as "i686-linux-gnu".
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>...
```

⁶a concept like `thunk` function

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```
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=0xfffff0f8, _b=_b@entry=0xfffff0fc) at 17_1.c:11
11      if (*a==*b)
(gdb) p *a
$1 = 1892
(gdb) p *b
$2 = 45
(gdb) c
Continuing.

Breakpoint 1, comp (_a=0xfffff104, _b=_b@entry=0xfffff108) at 17_1.c:11
11      if (*a==*b)
(gdb) p *a
$3 = -98
(gdb) p *b
$4 = 4087
(gdb) bt
#0  comp (_a=0xfffff0f8, _b=_b@entry=0xfffff0fc) at 17_1.c:11
#1  0xb7e42872 in msort_with_tmp (p=p@entry=0xfffff07c, b=b@entry=0xfffff0f8, n=n@entry=2)
    at msort.c:65
#2  0xb7e4273e in msort_with_tmp (n=2, b=0xfffff0f8, p=0xfffff07c) at msort.c:45
#3  msort_with_tmp (p=p@entry=0xfffff07c, b=b@entry=0xfffff0f8, n=n@entry=5) at msort.c:53
#4  0xb7e4273e in msort_with_tmp (n=5, b=0xfffff0f8, p=0xfffff07c) at msort.c:45
#5  msort_with_tmp (p=p@entry=0xfffff07c, b=b@entry=0xfffff0f8, n=n@entry=10) at msort.c:53
#6  0xb7e42cef in msort_with_tmp (n=10, b=0xfffff0f8, p=0xfffff07c) at msort.c:45
#7  __GI_qsort_r (b=b@entry=0xfffff0f8, 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=0xfffff0f8, n=10, s=4, cmp=0x804844d <comp>) at msort.c:307
#9  0x0804850d in main (argc=1, argv=0xfffff1c4) at 17_1.c:26
(gdb)
```

24.2.2 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 24.6: 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.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law. Type "show copying"
and "show warranty" for details.
This GDB was configured as "i686-linux-gnu".
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>...
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:
  0x0804844d <+0>:    push   ebp
  0x0804844e <+1>:    mov    ebp,esp
  0x08048450 <+3>:    sub    esp,0x10
  0x08048453 <+6>:    mov    eax,DWORD PTR [ebp+0x8]
```

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```

0x08048456 <+9>:    mov    DWORD PTR [ebp-0x8],eax
0x08048459 <+12>:   mov    eax,DWORD PTR [ebp+0xc]
0x0804845c <+15>:   mov    DWORD PTR [ebp-0x4],eax
0x0804845f <+18>:   mov    eax,DWORD PTR [ebp-0x8]
0x08048462 <+21>:   mov    edx,DWORD PTR [eax]
0x08048464 <+23>:   mov    eax,DWORD PTR [ebp-0x4]
0x08048467 <+26>:   mov    eax,DWORD PTR [eax]
0x08048469 <+28>:   cmp    edx, eax
0x0804846b <+30>:   jne    0x8048474 <comp+39>
0x0804846d <+32>:   mov    eax,0x0
0x08048472 <+37>:   jmp    0x804848e <comp+65>
0x08048474 <+39>:   mov    eax,DWORD PTR [ebp-0x8]
0x08048477 <+42>:   mov    edx,DWORD PTR [eax]
0x08048479 <+44>:   mov    eax,DWORD PTR [ebp-0x4]
0x0804847c <+47>:   mov    eax,DWORD PTR [eax]
0x0804847e <+49>:   cmp    edx, eax
0x08048480 <+51>:   jge    0x8048489 <comp+60>
0x08048482 <+53>:   mov    eax,0xffffffff
0x08048487 <+58>:   jmp    0x804848e <comp+65>
0x08048489 <+60>:   mov    eax,0x1
0x0804848e <+65>:   leave 
0x0804848f <+66>:   ret

End of assembler dump.
(gdb) b *0x08048469
Breakpoint 1 at 0x8048469
(gdb) run
Starting program: /home/dennis/polygon./a.out

Breakpoint 1, 0x08048469 in comp ()
(gdb) info registers
eax          0x2d      45
ecx          0xbffff0f8      -1073745672
edx          0x764     1892
ebx          0xb7fc0000      -1208221696
esp          0xbffffeeb8      0xbffffeeb8
ebp          0xbffffeec8      0xbffffeec8
esi          0xbffff0fc      -1073745668
edi          0xbffff010      -1073745904
eip          0x8048469      0x8048469 <comp+28>
eflags        0x286      [ PF SF IF ]
cs           0x73       115
ss           0x7b       123
ds           0x7b       123
es           0x7b       123
fs           0x0        0
gs           0x33       51
(gdb) c
Continuing.

Breakpoint 1, 0x08048469 in comp ()
(gdb) info registers
eax          0xff7      4087
ecx          0xbffff104      -1073745660
edx          0xfffffff9e      -98
ebx          0xb7fc0000      -1208221696
esp          0xbffffee58      0xbffffee58
ebp          0xbffffee68      0xbffffee68
esi          0xbfffff108      -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           0x33       51
(gdb) c
Continuing.

```

24.2. GCC

```
Breakpoint 1, 0x08048469 in comp ()
(gdb) info registers
eax          0xffffffff9e      -98
ecx          0xbfffff100     -1073745664
edx          0xc8        200
ebx          0xb7fc0000     -1208221696
esp          0xbffffeeb8    0xbffffeeb8
ebp          0xbffffeec8    0xbffffeec8
esi          0xbfffff104     -1073745660
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            0x0        0
gs            0x33       51
(gdb) bt
#0 0x08048469 in comp ()
#1 0xb7e42872 in msort_with_tmp (p=p@entry=0xbfffff07c, b=b@entry=0xbfffff0f8, n=n@entry=2)
at msort.c:65
#2 0xb7e4273e in msort_with_tmp (n=2, b=0xbfffff0f8, p=0xbfffff07c) at msort.c:45
#3 msort_with_tmp (p=p@entry=0xbfffff07c, b=b@entry=0xbfffff0f8, n=n@entry=5) at msort.c:53
#4 0xb7e4273e in msort_with_tmp (n=5, b=0xbfffff0f8, p=0xbfffff07c) at msort.c:45
#5 msort_with_tmp (p=p@entry=0xbfffff07c, b=b@entry=0xbfffff0f8, n=n@entry=10) at msort.c:53
#6 0xb7e42cef in msort_with_tmp (n=10, b=0xbfffff0f8, p=0xbfffff07c) at msort.c:45
#7 __GI_qsort_r (b=b@entry=0xbfffff0f8, 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=0xbfffff0f8, n=10, s=4, cmp=0x804844d <comp>) at msort.c:307
#9 0x0804850d in main ()
```

Chapter 25

64-bit values in 32-bit environment

In a 32-bit environment, GPR's are 32-bit, so 64-bit values are stored and passed as 32-bit value pairs ¹.

25.1 Returning of 64-bit value

```
#include <stdint.h>

uint64_t f ()
{
    return 0x1234567890ABCDEF;
```

25.1.1 x86

In a 32-bit environment, 64-bit values are returned from functions in the EDX : EAX register pair.

Listing 25.1: Optimizing MSVC 2010

```
_f      PROC
        mov     eax, -1867788817      ; 90abcdefH
        mov     edx, 305419896       ; 12345678H
        ret     0
_f      ENDP
```

25.1.2 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):

Listing 25.2: Optimizing Keil 6/2013 (ARM mode)

```
||f|| PROC
    LDR    r0, |L0.12|
    LDR    r1, |L0.16|
    BX    lr
ENDP

|L0.12|
    DCD    0x90abcdef
|L0.16|
    DCD    0x12345678
```

¹By the way, 32-bit values are passed as pairs in 16-bit environment in the same way: [55.4 on page 598](#)

25.1.3 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 25.3: Optimizing GCC 4.4.5 (assembly listing)

```
li      $3,-1867841536          # 0xfffffffff90ab0000
li      $2,305397760           # 0x12340000
ori    $3,$3,0xcdef
j      $31
ori    $2,$2,0x5678
```

Listing 25.4: Optimizing GCC 4.4.5 (IDA)

```
lui    $v1, 0x90AB
lui    $v0, 0x1234
li     $v1, 0x90ABCDEF
jr     $ra
li     $v0, 0x12345678
```

25.2 Arguments passing, addition, subtraction

```
#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, 2345678901234));
#else
    printf ("%I64d\n", f_add(12345678901234, 2345678901234));
#endif
};

uint64_t f_sub (uint64_t a, uint64_t b)
{
    return a-b;
};
```

25.2.1 x86Listing 25.5: Optimizing MSVC 2012 /O_{b1}

```
_a$ = 8          ; size = 8
_b$ = 16         ; size = 8
_f_add PROC
    mov    eax, DWORD PTR _a$[esp-4]
    add    eax, DWORD PTR _b$[esp-4]
    mov    edx, DWORD PTR _a$[esp]
    adc    edx, DWORD PTR _b$[esp]
    ret    0
_f_add ENDP

_f_add_test PROC
    push   5461          ; 00001555H
    push   1972608889    ; 75939f79H
    push   2874          ; 00000b3aH
    push   1942892530    ; 73ce2ff_subH
    call   _f_add
    push   edx
    push   eax
```

25.2. ARGUMENTS PASSING, ADDITION, SUBTRACTION

```

push    OFFSET $SG1436 ; '%I64d', 0aH, 00H
call    _printf
add    esp, 28
ret    0
_f_add_test ENDP

_f_sub PROC
mov    eax, DWORD PTR _a$[esp-4]
sub    eax, DWORD PTR _b$[esp-4]
mov    edx, DWORD PTR _a$[esp]
sbb    edx, DWORD PTR _b$[esp]
ret    0
_f_sub ENDP

```

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 was 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 25.6: 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], 1942892530 ; 73ce2ff_subH
    mov    DWORD PTR [esp+4], 2874      ; 00000b3aH
    call   _f_add
    mov    DWORD PTR [esp+4], eax
    mov    DWORD PTR [esp+8], edx
    mov    DWORD PTR [esp], OFFSET FLAT:LC0 ; "%lld\12\0"
    call   _printf
    add    esp, 28
    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

```

GCC code is the same.

25.2.2 ARM

Listing 25.7: 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`).

25.2.3 MIPS

Listing 25.8: 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
; $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

```

25.3. MULTIPLICATION, DIVISION

```

        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<0>

```

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.

25.3 Multiplication, division

```

#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)
{
    return a % b;
};

```

25.3.1 x86

Listing 25.9: Optimizing MSVC 2013 /Ob1

```

_a$ = 8 ; size = 8
_b$ = 16 ; size = 8

```

25.3. MULTIPLICATION, DIVISION

```

_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: [E on page 947](#).

Listing 25.10: Optimizing GCC 4.8.1 -fno-inline

```

_f_mul:
    push    ebx
    mov     edx, DWORD PTR [esp+8]
    mov     eax, DWORD PTR [esp+16]
    mov     ebx, DWORD PTR [esp+12]
    mov     ecx, DWORD PTR [esp+20]
    imul   ebx, eax
    imul   ecx, edx
    mul    edx
    add    ecx, ebx
    add    edx, ecx
    pop    ebx

```

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```

    ret

_f_div:
    sub    esp, 28
    mov    eax, DWORD PTR [esp+40]
    mov    edx, DWORD PTR [esp+44]
    mov    DWORD PTR [esp+8], eax
    mov    eax, DWORD PTR [esp+32]
    mov    DWORD PTR [esp+12], edx
    mov    edx, DWORD PTR [esp+36]
    mov    DWORD PTR [esp], eax
    mov    DWORD PTR [esp+4], edx
    call   __udivdi3 ; unsigned division
    add    esp, 28
    ret

_f_rem:
    sub    esp, 28
    mov    eax, DWORD PTR [esp+40]
    mov    edx, DWORD PTR [esp+44]
    mov    DWORD PTR [esp+8], eax
    mov    eax, DWORD PTR [esp+32]
    mov    DWORD PTR [esp+12], edx
    mov    edx, DWORD PTR [esp+36]
    mov    DWORD PTR [esp], eax
    mov    DWORD PTR [esp+4], edx
    call   __umoddi3 ; unsigned modulo
    add    esp, 28
    ret

```

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: [D on page 946](#).

25.3.2 ARM

Keil for Thumb mode inserts library subroutine calls:

Listing 25.11: Optimizing Keil 6/2013 (Thumb mode)

```

||f_mul|| PROC
    PUSH    {r4,lr}
    BL      __aeabi_lmul
    POP    {r4,pc}
    ENDP

||f_div|| PROC
    PUSH    {r4,lr}
    BL      __aeabi_ulddivmod
    POP    {r4,pc}
    ENDP

||f_rem|| PROC
    PUSH    {r4,lr}
    BL      __aeabi_ulddivmod
    MOVS   r0,r2
    MOVS   r1,r3
    POP    {r4,pc}
    ENDP

```

Keil for ARM mode, on the other hand, is able to produce 64-bit multiplication code:

Listing 25.12: 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

```

25.3. MULTIPLICATION, DIVISION

```

POP      {r4,pc}
ENDP

||f_div|| PROC
PUSH    {r4,lr}
BL      __aeabi_ulddivmod
POP      {r4,pc}
ENDP

||f_rem|| PROC
PUSH    {r4,lr}
BL      __aeabi_ulddivmod
MOV     r0,r2
MOV     r1,r3
POP      {r4,pc}
ENDP

```

25.3.3 MIPS

Optimizing GCC for MIPS can generate 64-bit multiplication code, but has to call a library routine for 64-bit division:

Listing 25.13: 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:
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      $t9, (__umoddi3 & 0xFFFF)($gp)

```

25.4. SHIFTING RIGHT

```
        or      $at, $zero
        jalr    $t9
        or      $at, $zero
        lw      $ra, 0x20+var_4($sp)
        or      $at, $zero
        jr      $ra
        addiu   $sp, 0x20
```

There are a lot of **NOPs**, probably delay slots filled after the multiplication instruction (it's slower than other instructions, after all).

25.4 Shifting right

```
#include <stdint.h>

uint64_t f (uint64_t a)
{
    return a>>7;
}
```

25.4.1 x86

Listing 25.14: 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 25.15: 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 **EDX** by 7 bits, but pulls new bits from **EAX**, i.e., from the higher part. The higher part is shifted using the more popular **SHR** instruction: indeed, the freed bits in the higher part must be filled with zeroes.

25.4.2 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:

Listing 25.16: 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 25.17: 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
```

25.4.3 MIPS

GCC for MIPS follows the same algorithm as Keil does for Thumb mode:

Listing 25.18: 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
```

25.5 Converting 32-bit value into 64-bit one

```
#include <stdint.h>

int64_t f (int32_t a)
{
    return a;
};
```

25.5.1 x86

Listing 25.19: 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.

25.5.2 ARM

Listing 25.20: Optimizing Keil 6/2013 (ARM mode)

```
||f|| PROC
    ASR    r1,r0,#31
    BX     lr
ENDP
```

25.5. CONVERTING 32-BIT VALUE INTO 64-BIT ONE

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 was 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.

25.5.3 MIPS

GCC for MIPS does the same as Keil did for ARM mode:

Listing 25.21: Optimizing GCC 4.4.5 (IDA)

```
f:  
    sra    $v0, $a0, 31  
    jr    $ra  
    move   $v1, $a0
```

Chapter 26

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.

Bitslice DES¹ –is the idea of processing groups of blocks and keys simultaneously. Let's say, variable of type *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 *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>

26.1 Vectorization

Vectorization² 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.

¹<http://go.yurichev.com/17329>

²Wikipedia: vectorization

26.1. VECTORIZATION

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 EL³.

For example:

```
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 *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 *PMULLD* (*Multiply Packed Signed Dword Integers and Store Low Result*) and *PMULHW* (*Multiply Packed Signed Integers and Store High Result*), it is possible to get 4 64-bit *products* at once.

Thus, loop body execution count is $1024/4$ instead of 1024, that is 4 times less and, of course, faster.

26.1.1 Addition example

Some compilers can do vectorization automatically in simple cases, e.g., Intel C++⁴.

Here is tiny function:

```
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](#)):

```
; int __cdecl f(int, int *, int *, int *)
                public ?f@@YAHHPAH00@Z
?f@@YAHHPAH00@Z proc near

var_10 = dword ptr -10h
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
```

³Remotely. It is installed in the museum of supercomputers: <http://go.yurichev.com/17081>

⁴More about Intel C++ automatic vectorization: [Excerpt: Effective Automatic Vectorization](#)

26.1. VECTORIZATION

```
    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 = ar1
    and    edi, 0Fh          ; is ar1 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, edx
    test   edi, edi
    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!
```

26.1. VECTORIZATION

```

        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
        padd  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      esi, [esp+10h+ar2]

loc_111: ; CODE XREF: f(int,int *,int *,int *)+125
        movdqu xmm0, xmmword ptr [ebx+edi*4]
        padd  xmm0, xmmword ptr [esi+edi*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
        mov   ebx, [esi+ecx*4]
        add   ebx, [edi+ecx*4]
        mov   [eax+ecx*4], ebx
        inc   ecx
        cmp   ecx, edx
        jb    short loc_14D

loc_15B: ; CODE XREF: f(int,int *,int *,int *)+A
        ; f(int,int *,int *,int *)+129 ...
        xor   eax, eax
        pop   ecx
        pop   ebx
        pop   esi
        pop   edi
        retn

loc_162: ; CODE XREF: f(int,int *,int *,int *)+8C
        ; f(int,int *,int *,int *)+9F
        xor   ecx, ecx
        jmp   short loc_127
?f@@YAHHPAH00@Z endp

```

26.1. VECTORIZATION

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 triggered⁵.
- **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:

```
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:

```
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 cases⁶, if the **-O3** option is used and SSE2 support is turned on: **-msse2**.

What we get (GCC 4.4.1):

```
; f(int, int *, int *, int *)
    public _Z1fiPiS_S_
_Z1fiPiS_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
```

⁵More about data alignment: [Wikipedia: Data structure alignment](#)

⁶More about GCC vectorization support: <http://go.yurichev.com/17083>

26.1. VECTORIZATION

```
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_80484C8: ; 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    loc_8048578

loc_80484F8: ; 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
    mov    [ebp+var_18], ecx
    mov    ecx, [ebp+var_14]
    xor    eax, eax
    xor    edx, edx
    nop

loc_8048520: ; CODE XREF: f(int,int *,int *,int *)+9B
    movdqu xmm1, xmmword ptr [edi+eax]
    movdqu xmm0, xmmword ptr [esi+eax]
    add    edx, 1
    paddd xmm0, xmm1
    movdqqa xmmword ptr [ebx+eax], xmm0
    add    eax, 10h
    cmp    edx, ecx
    jb    short loc_8048520
    mov    ecx, [ebp+var_18]
    mov    eax, [ebp+var_10]
    cmp    ecx, eax
    jz     short loc_80484D8

loc_8048547: ; CODE XREF: f(int,int *,int *,int *)+73
    lea    edx, ds:0[eax*4]
```

26.1. VECTORIZATION

```
    add    esi, edx
    add    edi, edx
    add    ebx, edx
    lea    esi, [esi+0]

loc_8048558: ; CODE XREF: f(int,int *,int *,int *)+CC
    mov    edx, [edi]
    add    eax, 1
    add    edi, 4
    add    edx, [esi]
    add    esi, 4
    mov    [ebx], edx
    add    ebx, 4
    cmp    ecx, eax
    jg     short loc_8048558
    add    esp, 0Ch
    xor    eax, eax
    pop    ebx
    pop    esi
    pop    edi
    pop    ebp
    retn

loc_8048578: ; CODE XREF: f(int,int *,int *,int *)+52
    cmp    eax, esi
    jnb    loc_80484C1
    jmp    loc_80484F8
_Z1fiPiS_S_ endp
```

Almost the same, however, not as meticulously as Intel C++.

26.1.2 Memory copy example

Let's revisit the simple `memcpy()` example ([15.2 on page 194](#)):

```
#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 26.1: 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
```

26.1. VECTORIZATION

```
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
je     .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
```

26.1. VECTORIZATION

```

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
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

```

26.1. VECTORIZATION

```
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]
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
jmp    .L4
.L18:
mov    eax,  4
jmp    .L4
.L19:
mov    eax,  5
jmp    .L4
.L20:
mov    eax,  6
jmp    .L4
.L21:
mov    eax,  7
jmp    .L4
.L22:
mov    eax,  8
jmp    .L4
.L23:
mov    eax,  9
jmp    .L4
.L24:
mov    eax,  10
jmp   .L4
```

26.2. SIMD `STRLEN()` IMPLEMENTATION

```
.L25:    mov     eax, 11
        jmp     .L4
.L26:    mov     eax, 12
        jmp     .L4
.L27:    mov     eax, 13
        jmp     .L4
```

26.2 SIMD `strlen()` implementation

It has to be noted that the SIMD instructions can be inserted in C/C++ code via special macros⁷. For MSVC, some of them are located in the `intrin.h` file.

It is possible to implement the `strlen()` function⁸ 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 zero⁹.

```
size_t strlen_sse2(const char *str)
{
    register size_t len = 0;
    const char *s=str;
    bool str_is_aligned=((unsigned int)str)&0xFFFFFFFF0) == (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;

            break;
        }
        s += sizeof(__m128i);
        len += sizeof(__m128i);
    }

    return len;
}
```

Let's compile it in MSVC 2010 with `/Ox` option:

Listing 26.2: Optimizing MSVC 2010

```
_pos$75552 = -4          ; size = 4
_str$ = 8                ; size = 4
?strlen_sse2@@YAIPBD@Z PROC ; strlen_sse2

    push    ebp
    mov     ebp, esp
    and     esp, -16          ; ffffff0H
    mov     eax, DWORD PTR _str$[ebp]
    sub     esp, 12           ; 0000000cH
```

⁷MSDN: MMX, SSE, and SSE2 Intrinsics

⁸strlen() – standard C library function for calculating string length

⁹The example is based on source code from: <http://go.yurichev.com/17330>.

26.2. SIMD `STRLEN()` IMPLEMENTATION

```

push    esi
mov     esi, eax
and    esi, -16           ; ffffffff0H
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 need to 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](#) works¹⁰.

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.

¹⁰[wikipedia](#)

26.2. SIMD `STRLEN()` IMPLEMENTATION

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.

0x008c1ff8	'h'
0x008c1ff9	'e'
0x008c1ffa	'l'
0x008c1ffb	'l'
0x008c1ffc	'o'
0x008c1ffd	'\x00'
0x008c1ffe	random noise
0x008c1fff	random noise

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 byte 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 byte 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 was 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: 1122334455667788000000000000000000

XMM0: 11ab3444007877881111111111111111

After the execution of `pcmpeqb xmm1, xmm0`, the `XMM1` register contains:

XMM1: ff0000ff0000ffff0000000000000000

In our case, this instruction compares each 16-byte block with a block of 16 zero-bytes, which was 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`.

`pmovmskb eax, xmm1`

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` are `0xff`?” 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:

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
"h"	"e"	"l"	"l"	"o"	0	garbage									

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 ¹¹:

XMM1: 0000ff00000000000000ff0000000000

¹¹An order from **MSB** to **LSB**¹² is used here.

26.2. SIMD STRLEN() IMPLEMENTATION

This means that the instruction found two zero bytes, and it is not surprising.

`PMOVMSKB` in our case will set `EAX` to (in binary representation): `001000000100000b`.

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=001000000100000b`

After the execution of `bsf eax, eax`, `EAX` contains 5, meaning 1 was 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 was 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>

Chapter 27

64 bits

27.1 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 :

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RAX ^{x64}							
EAX							
AX							
AH AL							

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).

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R8							
R8D							
R8W							
R8L							

The number of SIMD registers was doubled from 8 to 16: XMM0 - XMM15 .

- In Win64, the function calling convention is slightly different, somewhat resembling fastcall ([67.3 on page 691](#)) . 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)[[Mit13](#)] also somewhat resembles fastcall, 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 ([67 on page 690](#)).

- The C/C++ *int* type is still 32-bit for compatibility.
- All pointers are 64-bit now.

This provokes 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.

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.

27.1. X86-64

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 ([26 on page 406](#))):

```
/*
 * 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
 */

#ifndef _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;
    DES_type    x49, x50, x51, x52, x53, x54, x55, x56;

    x1 = a3 & ~a5;
    x2 = x1 ^ a4;
    x3 = a3 & ~a4;
    x4 = x3 | a5;
    x5 = a6 & x4;
    x6 = x2 ^ x5;
    x7 = a4 & ~a5;
    x8 = a3 ^ a4;
    x9 = a6 & ~x8;
    x10 = x7 ^ x9;
    x11 = a2 | x10;
    x12 = x6 ^ x11;
    x13 = a5 ^ x5;
    x14 = x13 & x8;
    x15 = a5 & ~a4;
    x16 = x3 ^ x14;
    x17 = a6 | x16;
    x18 = x15 ^ x17;
    x19 = a2 | x18;
    x20 = x14 ^ x19;
    x21 = a1 & x20;
    x22 = x12 ^ ~x21;
    *out2 ^= x22;
    x23 = x1 | x5;
    x24 = x23 ^ x8;
    x25 = x18 & ~x2;
    x26 = a2 & ~x25;
    x27 = x24 ^ x26;
    x28 = x6 | x7;
    x29 = x28 ^ x25;
```

27.1. X86-64

```

x30 = x9 ^ x24;
x31 = x18 & ~x30;
x32 = a2 & x31;
x33 = x29 ^ x32;
x34 = a1 & x33;
x35 = x27 ^ x34;
*out4 ^= x35;
x36 = a3 & x28;
x37 = x18 & ~x36;
x38 = a2 | x3;
x39 = x37 ^ x38;
x40 = a3 | x31;
x41 = x24 & ~x37;
x42 = x41 | x3;
x43 = x42 & ~a2;
x44 = x40 ^ x43;
x45 = a1 & ~x44;
x46 = x39 ^ ~x45;
*out1 ^= x46;
x47 = x33 & ~x9;
x48 = x47 ^ x39;
x49 = x4 ^ x36;
x50 = x49 & ~x5;
x51 = x42 | x18;
x52 = x51 ^ a5;
x53 = a2 & ~x52;
x54 = x50 ^ x53;
x55 = a1 | x54;
x56 = x48 ^ ~x55;
*out3 ^= x56;
}

```

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 27.1: Optimizing MSVC 2008

```

PUBLIC _s1
; 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
not    edi
mov    ebp, edi
and    edi, DWORD PTR _a5$[esp+32]
mov    ecx, edx
not    ecx
and    ebp, esi
mov    eax, ecx
and    eax, esi
and    ecx, ebx
mov    DWORD PTR _x1$[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
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    ebx, edi
mov    edi, DWORD PTR _out2$[esp+32]
xor    ebx, DWORD PTR [edi]
not    eax
xor    ebx, DWORD PTR _x6$[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 _x8$[esp+36]
mov    DWORD PTR _x24$[esp+32], edi
xor    edi, ecx
not    edi
and    edi, edx
mov    ebx, edi
and    ebx, ebp
xor    ebx, DWORD PTR _x28$[esp+32]
xor    ebx, eax
not    eax
mov    DWORD PTR _x33$[esp+32], ebx
and    ebx, DWORD PTR _a1$[esp+32]
and    eax, ebp
xor    eax, ebx

```

27.1. X86-64

```

mov    ebx, DWORD PTR _out4$[esp+32]
xor    eax, DWORD PTR [ebx]
xor    eax, DWORD PTR _x24$[esp+32]
mov    DWORD PTR [ebx], eax
mov    eax, DWORD PTR _x28$[esp+32]
and    eax, DWORD PTR _a3$[esp+32]
mov    ebx, DWORD PTR _x3$[esp+36]
or     edi, DWORD PTR _a3$[esp+32]
mov    DWORD PTR _x36$[esp+32], eax
not    eax
and    eax, edx
or     ebx, ebp
xor    ebx, eax
not    eax
and    eax, DWORD PTR _x24$[esp+32]
not    ebp
or     eax, DWORD PTR _x3$[esp+36]
not    esi
and    ebp, eax
or     eax, edx
xor    eax, DWORD PTR _a5$[esp+32]
mov    edx, DWORD PTR _x36$[esp+32]
xor    edx, DWORD PTR _x4$[esp+36]
xor    ebp, edi
mov    edi, DWORD PTR _out1$[esp+32]
not    eax
and    eax, DWORD PTR _a2$[esp+32]
not    ebp
and    ebp, DWORD PTR _a1$[esp+32]
and    edx, esi
xor    eax, edx
or     eax, DWORD PTR _a1$[esp+32]
not    ebp
xor    ebp, DWORD PTR [edi]
not    ecx
and    ecx, DWORD PTR _x33$[esp+32]
xor    ebp, ebx
not    eax
mov    DWORD PTR [edi], ebp
xor    eax, ecx
mov    ecx, DWORD PTR _out3$[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           ; 00000014H
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 27.2: Optimizing MSVC 2008

```

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

```

27.1. X86-64

```
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$[rsp]
xor    r8, r9
not    r9
and    r9, rcx
or     rdx, rbp
mov    rbp, QWORD PTR [rsp+80]
or     r9, rsi
xor    rbx, r12
mov    rcx, r11
not    rcx
not    r14
not    r13
and    rcx, r9
or     r9, rdi
and    rbx, r14
xor    r9, r15
xor    rcx, rdx
mov    rdx, QWORD PTR a1$[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).

64-bit instructions appeared in ARMv8.

27.3 Float point numbers

How floating point numbers are processed in x86-64 is explained here: [28 on the next page](#).

Chapter 28

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: [18 on page 217](#).

28.1 Simple example

```
#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));
}
```

28.1.1 x64

Listing 28.1: Optimizing MSVC 2012 x64

```
_real@4010666666666666 DQ 0401066666666666r ; 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
    ENDP
```

The input floating point values are passed in the XMM0 - XMM3 registers, all the rest—via the stack¹.

a is passed in XMM0, *b*—via XMM1. The XMM-registers are 128-bit (as we know from the section about SIMD: [26 on page 406](#)), but the *double* values are 64 bit, so only lower register half is used.

¹MSDN: Parameter Passing

28.1. SIMPLE EXAMPLE

`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 `XMM0` register.

That is how non-optimizing MSVC works:

Listing 28.2: MSVC 2012 x64

```
_real@4010666666666666 DQ 0401066666666666r ; 4.1
_real@40091eb851eb851f DQ 040091eb851eb851fr ; 3.14

a$ = 8
b$ = 16
_f PROC
    movsd QWORD PTR [rsp+16], xmm1
    movsd QWORD PTR [rsp+8], xmm0
    movsd xmm0, QWORD PTR a$[rsp]
    divsd xmm0, QWORD PTR _real@40091eb851eb851f
    movsd xmm1, QWORD PTR b$[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” ([9.2.1 on page 100](#)), but only their lower register halves, i.e., only 64-bit values of type *double*. GCC produces the same code.

28.1.2 x86

Let's also compile this example for x86. Despite the fact it's generating for x86, MSVC 2012 uses SSE2 instructions:

Listing 28.3: Non-optimizing MSVC 2012 x86

```
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 28.4: Optimizing MSVC 2012 x86

```
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]
```

28.1. SIMPLE EXAMPLE

```
_f      ret     0  
        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 ([18 on page 217](#)); 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)`.

28.1. SIMPLE EXAMPLE

Let's try the optimized example in OllyDbg:

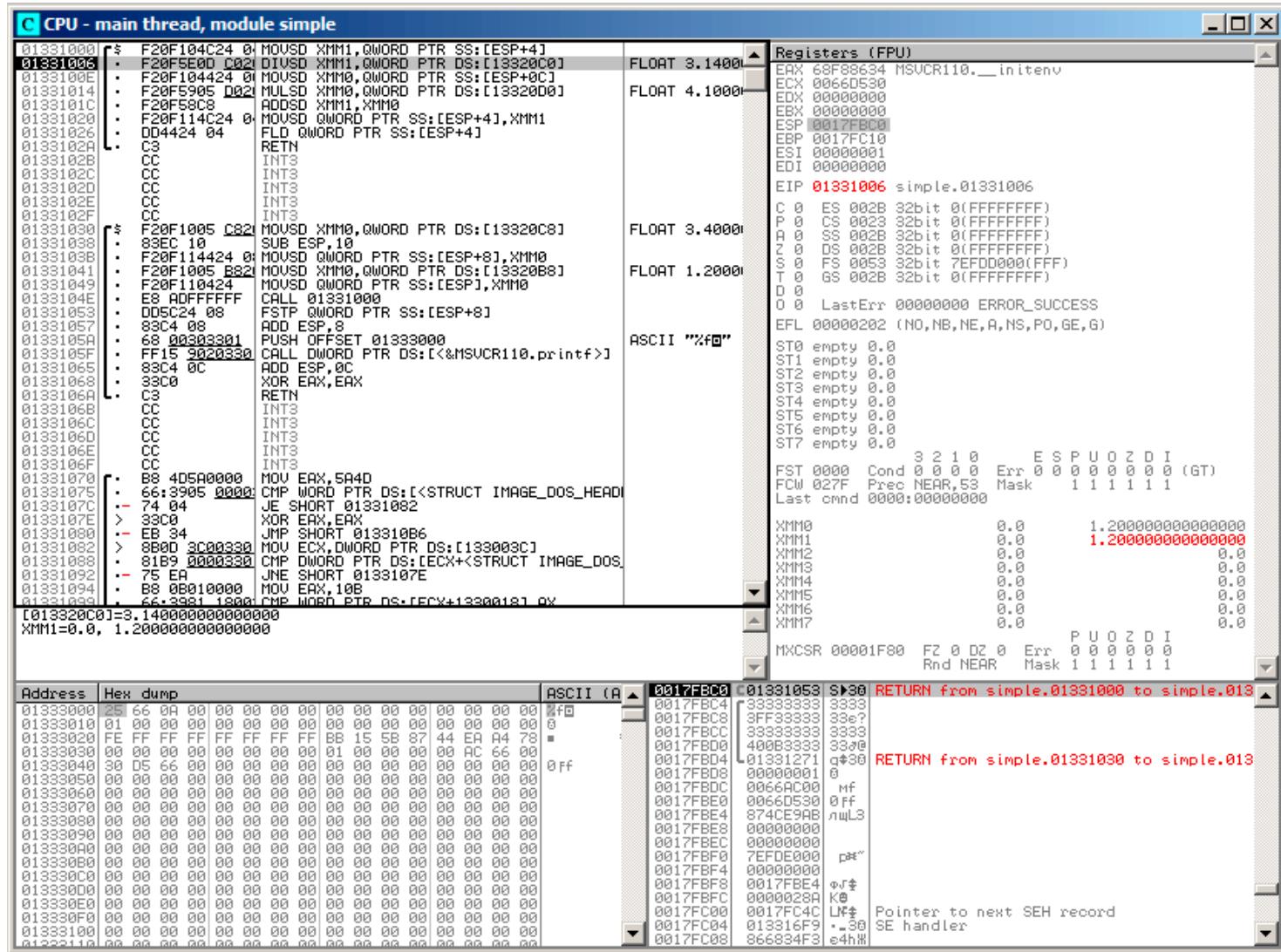


Figure 28.1: OllyDbg: MOVSD loads the value of *a* into XMM1

28.1. SIMPLE EXAMPLE

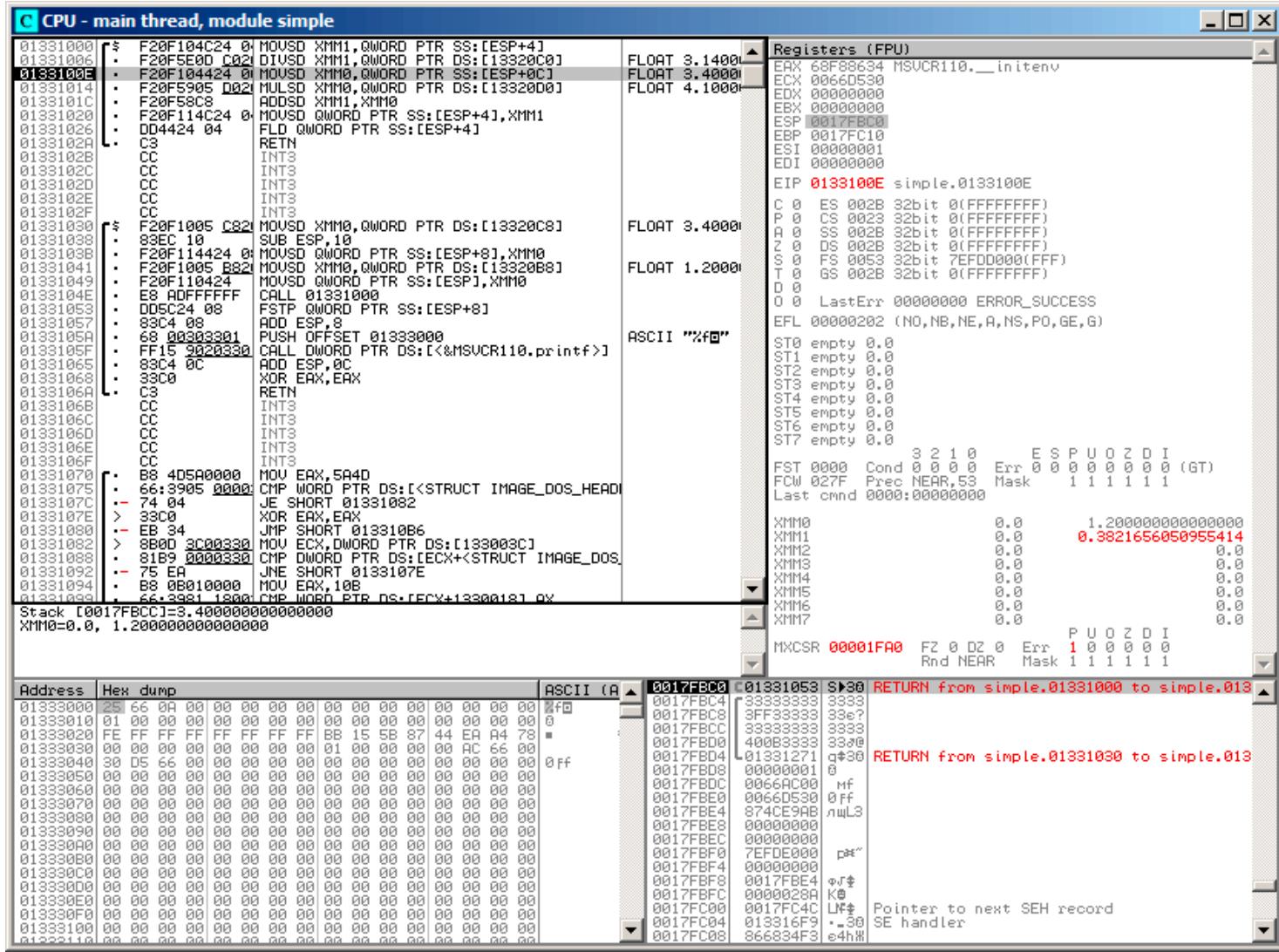


Figure 28.2: OllyDbg: DIVSD calculated quotient and stored it in XMM1

28.1. SIMPLE EXAMPLE

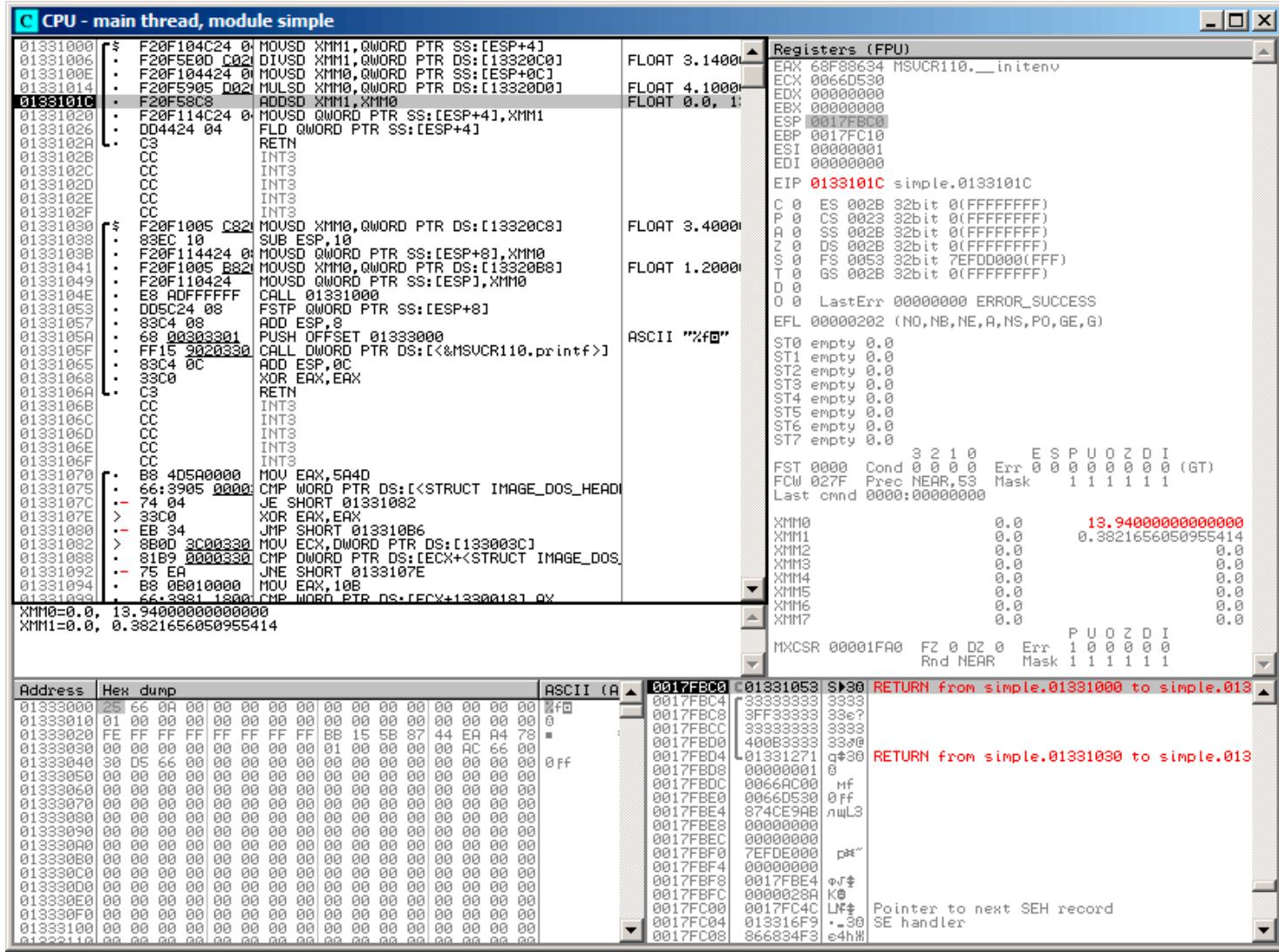
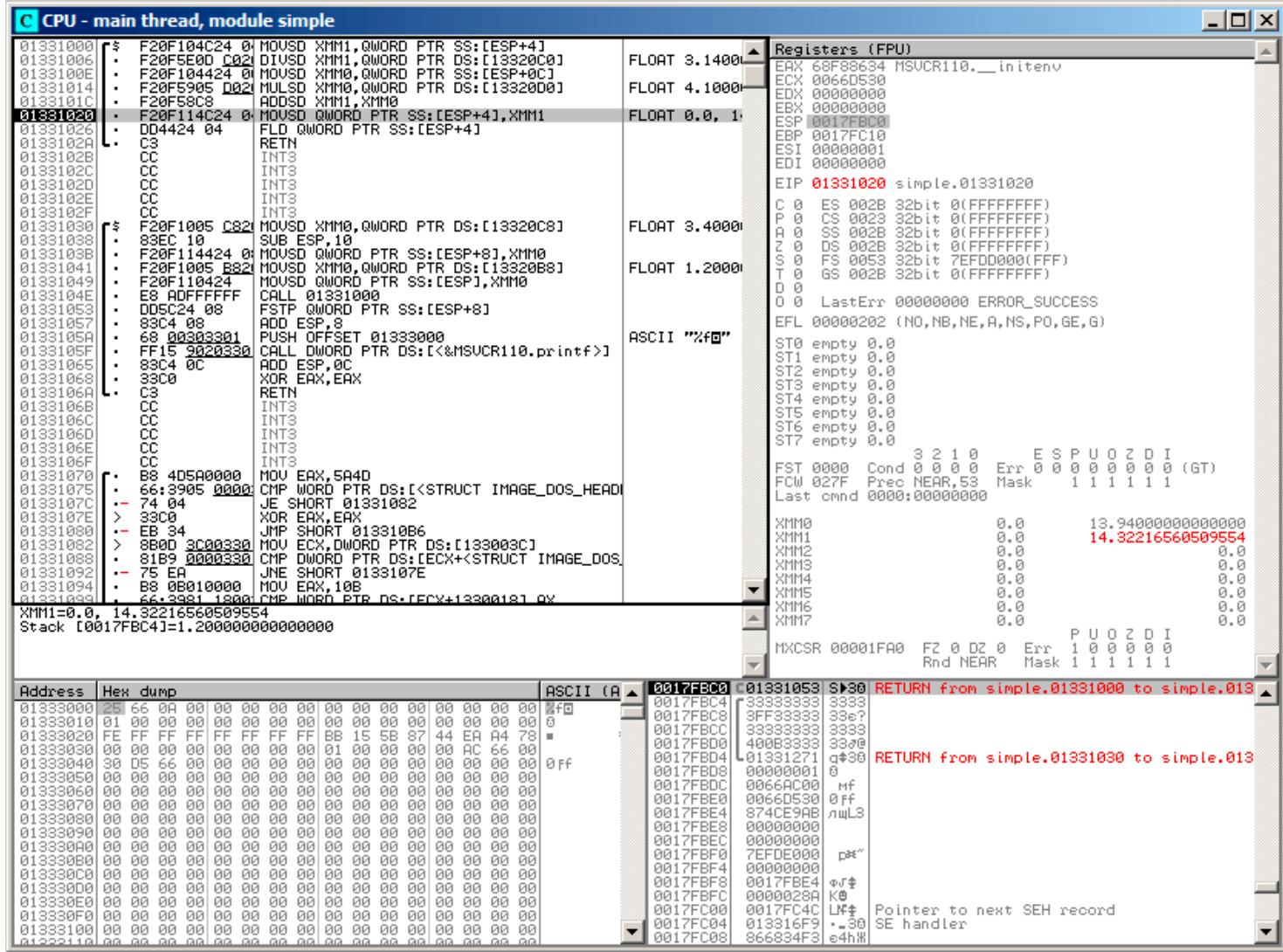


Figure 28.3: OllyDbg: MULSD calculated product and stored it in XMM0

28.1. SIMPLE EXAMPLE



28.1. SIMPLE EXAMPLE

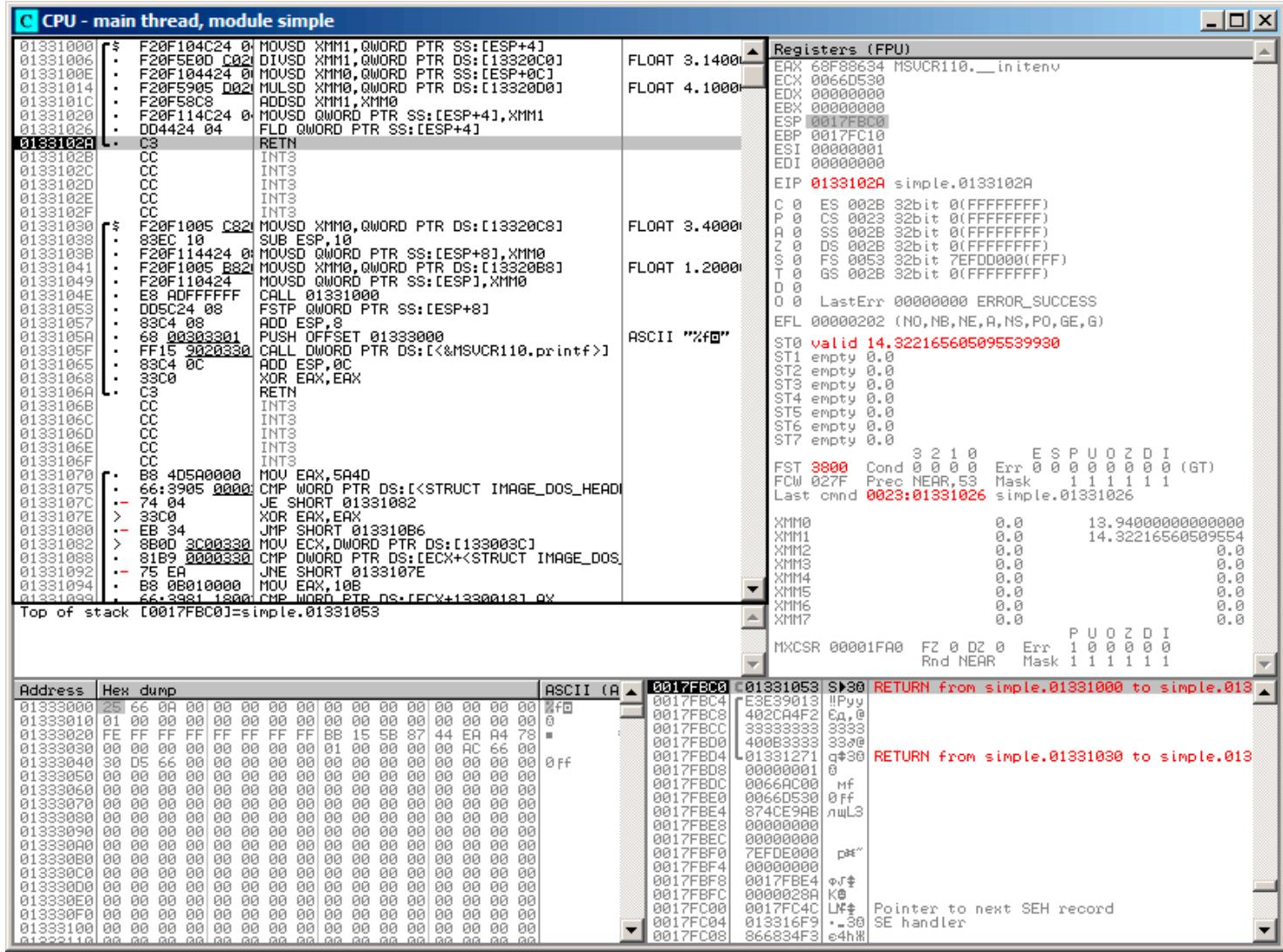


Figure 28.5: OllyDbg: FLD left function result in ST(0)

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.

28.2 Passing floating point number via arguments

```
#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 28.5: Optimizing MSVC 2012 x64

```
$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
    movsd xmm1, QWORD PTR __real@3ff8a3d70a3d70a4
    movsd 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 [Int13] and AMD [AMD13a] manuals, there it is called just `MOVSD`. So there are two instructions sharing the same name in x86 (about the other see: [A.6.2 on page 932](#)). 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 28.6: 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 as the standard requires [[Mit13](#)].

28.3 Comparison example

```
#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));
}
```

28.3.1 x64

Listing 28.7: 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 28.8: 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!

Listing 28.9: Optimizing GCC 4.4.6 x64

```
d_max:
    maxsd xmm0, xmm1
    ret
```

28.3.2 x86

Let's compile this example in MSVC 2012 with optimization turned on:

Listing 28.10: 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:

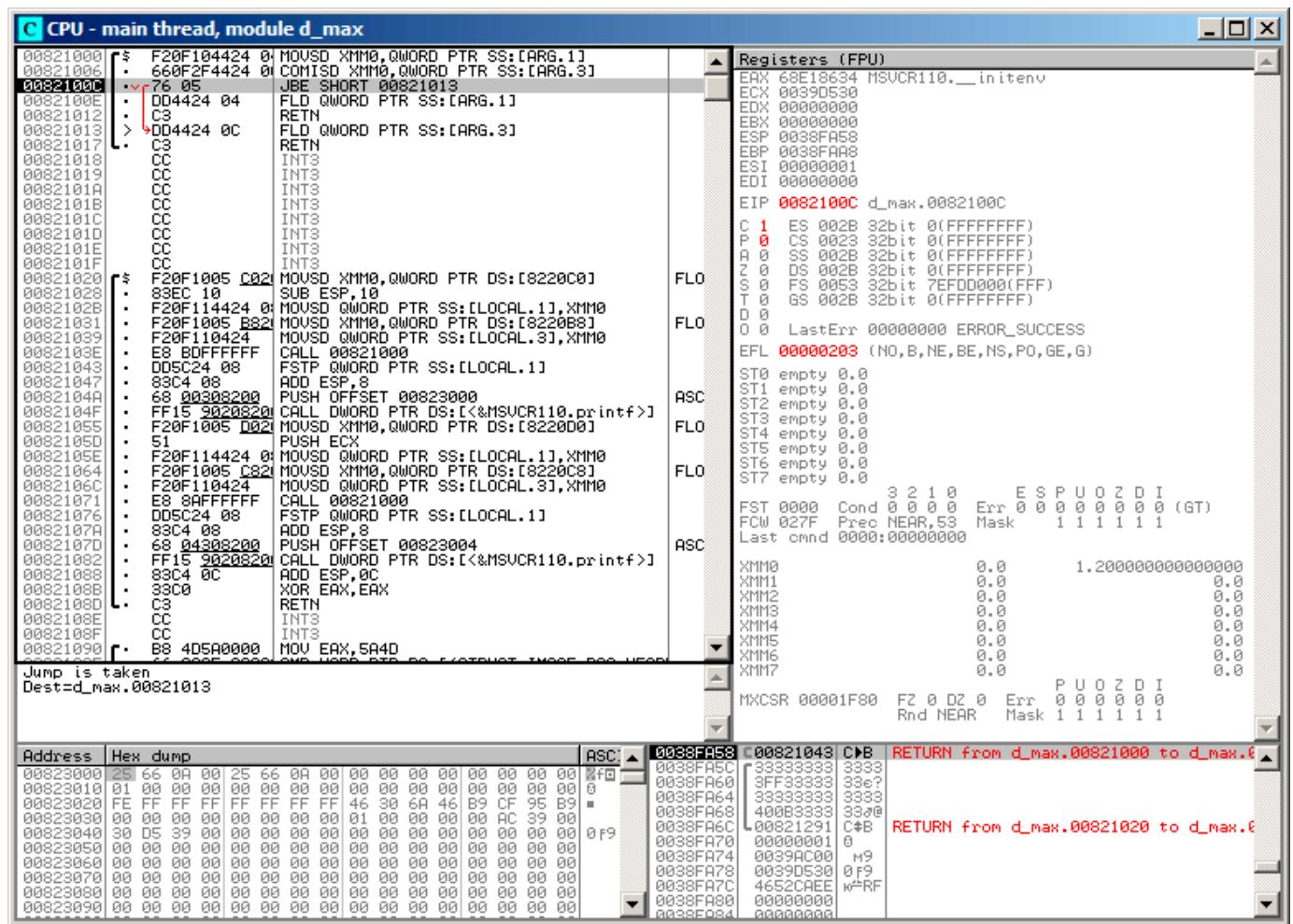


Figure 28.6: OllyDbg: **COMISD** changed **CF** and **PF** flags

28.4 Calculating machine epsilon: x64 and SIMD

Let's revisit the “calculating machine epsilon” example for *double* listing [23.2.2](#).

Now we compile it for x64:

Listing 28.11: Optimizing MSVC 2012 x64

```
v$ = 8
calculate_machine_epsilon PROC
    movsdx QWORD PTR v$[rsp], xmm0
    movaps  xmm1, xmm0
    inc     QWORD PTR v$[rsp]
    movsdx xmm0, QWORD PTR v$[rsp]
    subsd   xmm0, xmm1
    ret     0
calculate_machine_epsilon ENDP
```

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 (*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 yet².

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.

28.5 Pseudo-random number generator example revisited

Let's revisit “pseudo-random number generator example” example listing 23.1.

If we compile this in MSVC 2012, it will use the SIMD instructions for the FPU.

Listing 28.12: Optimizing MSVC 2012

```
_real@3f800000 DD 03f800000r ; 1

tv128 = -4
_tmp$ = -4
?float_rand@@YAMXZ PROC
    push    ecx
    call    ?my_rand@@YAIHZ
; 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$[esp+4], eax
; reload it as float point number:
    movss  xmm0, DWORD PTR _tmp$[esp+4]
; subtract 1.0:
    subss  xmm0, DWORD PTR __real@3f800000
; move value to ST0 by placing it in temporary variable...
    movss  DWORD PTR tv128[esp+4], xmm0
; ... and reloading it into ST0:
    fld    DWORD PTR tv128[esp+4]
    pop    ecx
    ret    0
?float_rand@@YAMXZ ENDP
```

All instructions have the -SS suffix, which stands for “Scalar Single”. “Scalar” implies that only one value is stored in the register. “Single” stands for *float* data type.

28.6 Summary

Only the lower half of XMM registers is used in all examples here, to store number in IEEE 754 format.

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.

²As an exercise, you may try to rework this code to eliminate the usage of the local stack.

28.6. SUMMARY

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.

Chapter 29

ARM-specific details

29.1 Number sign (#) before number

The Keil compiler, IDA and objdump precede all numbers with the “#” number sign, for example: listing.[15.1.4](#). But when GCC 4.9 generates assembly language output, it doesn’t, for example: listing.[41.3](#).

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.

29.2 Addressing modes

This instruction is possible in ARM64:

```
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:

```
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:

C term	ARM term	C statement	how it works
Post-increment	post-indexed addressing	<code>*ptr++</code>	use <code>*ptr</code> value, then increment <code>ptr</code> pointer
Post-decrement	post-indexed addressing	<code>*ptr--</code>	use <code>*ptr</code> value, then decrement <code>ptr</code> pointer
Pre-increment	pre-indexed addressing	<code>++ptr</code>	increment <code>ptr</code> pointer, then use <code>*ptr</code> value
Pre-decrement	pre-indexed addressing	<code>--ptr</code>	decrement <code>ptr</code> pointer, then use <code>*ptr</code> value

Pre-indexing is marked with an exclamation mark in the ARM assembly language. For example, see line 2 in listing.[4.15](#).

Dennis Ritchie (one of the creators of the C language) mentioned that it probably was invented by Ken Thompson (another C creator) because this processor feature was present in PDP-7 [[Rit86](#)][[Rit93](#)]. Thus, C language compilers may use it, if it is present on the target processor.

That’s very convenient for array processing.

29.3 Loading a constant into a register

29.3.1 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:

```
unsigned int f()
{
    return 0x12345678;
};
```

Listing 29.1: GCC 4.6.3 -O3 ARM mode

```
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 29.2: GCC 4.6.3 -O3 -march=armv7-a (ARM mode)

```
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:

```
MOV    R0, 0x12345678
BX     LR
```

29.3.2 ARM64

```
uint64_t f()
{
    return 0x12345678ABCDEF01;
};
```

Listing 29.3: GCC 4.9.1 -O3

```
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:

```
double a()
{
    return 1.5;
};
```

Listing 29.4: GCC 4.9.1 -O3 + objdump

```
0000000000000000 <a>:
0: 1e6f1000 fmov d0, #1.5000000000000000e+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 [ARM13a]. This is also called *minifloat*¹. 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:

```
double a()
{
    return 32;
};
```

Listing 29.5: GCC 4.9.1 -O3

```
a:
    ldr    d0, .LC0
    ret
.LC0:
    .word  0
    .word  1077936128
```

29.4 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 relocs exists. Read more about them (in relation to Win32 PE): [71.2.6 on page 716](#).

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.7) in GCC (Linaro) 4.9 under win32:

Listing 29.6: GCC (Linaro) 4.9 and objdump of object file

```
...>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

¹[wikipedia](#)

29.4. RELOCS IN ARM64

```
...
RELOCATION RECORDS FOR [.text]:
OFFSET      TYPE           VALUE
0000000000000008 R_AARCH64_ADR_PREL_PG_HI21  .rodata
000000000000000c R_AARCH64_ADD_ABS_L012_NC   .rodata
0000000000000010 R_AARCH64_CALL26   printf
```

So there are 3 relocs 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 zeroes in the two lowest bits (because all instructions have a size of 4 bytes), so one need to encode only the highest 26 bits of 28-bit address space ($\pm 128\text{MB}$).

There are no such relocs 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 29.7: objdump of executable file

```
0000000000400590 <main>:
400590:    a9bf7bfd      stp    x29, x30, [sp,#-16]!
400594:    910003fd      mov    x29, sp
400598:    90000000      adrp   x0, 400000 <_init-0x3b8>
40059c:    91192000      add    x0, x0, #0x648
4005a0:    97fffffa0     bl    400420 <puts@plt>
4005a4:    52800000      mov    w0, #0x0          // #0
4005a8:    a8c17bfd      ldp    x29, x30, [sp],#16
4005ac:    d65f03c0      ret

...
Contents of section .rodata:
400640 01000200 00000000 48656c6c 6f210000  .....Hello!..
```

As an example, let's try to disassemble the BL instruction manually.

0x97fffffa0 is 100101111111111111111110100000b. According to [ARM13a, p. C5.6.26], imm26 is the last 26 bits: $imm26 = 1111111111111111111110100000$. It is 0x3FFFFA0, but the MSB is 1, so the number is negative, and we can convert it manually to convenient form for us. By the rules of negation (31 on page 449), just invert all bits: (it is 1011111=0x5F), and add 1 (0x5F+1=0x60). So the number in signed form is -0x60. Let's multiply -0x60 by 4 (because address stored in opcode is divided by 4): it is -0x180. Now let's calculate destination address: 0x4005a0 + (-0x180) = 0x400420 (please note: we consider the address of the BL instruction, not the current value of PC, which may be different!). So the destination address is 0x400420.

More about ARM64-related relocations: [ARM13b].

Chapter 30

MIPS-specific details

30.1 Loading constants into register

```
unsigned int f()
{
    return 0x12345678;
};
```

All instructions in MIPS, just like ARM, have a of 32-bit, so it's not possible to embed a 32-bit constant into one instruction. So this translates to 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 30.1: 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 pseudoinstruction, which allegedly loads a full 32-bit number into the \$V0 register.

Listing 30.2: GCC 4.4.5 -O3 (IDA)

```
lui    $v0, 0x1234
jr     $ra
li     $v0, 0x12345678 ; branch delay slot
```

The GCC assembly output has the LI pseudoinstruction, but in fact, LUI (“Load Upper Immediate”) is there, which stores a 16-bit value into the high part of the register.

30.2 Further reading about MIPS

[[Swe10](#)].

Part II

Important fundamentals



Chapter 31

Signed number representations

There are several methods for representing signed numbers¹, but “two’s complement” is the most popular one in computers.

Here is a table for some byte values:

binary	hexadecimal	unsigned	signed (2's complement)
01111111	0x7f	127	127
01111110	0x7e	126	126
...			
00000110	0x6	6	6
00000101	0x5	5	5
00000100	0x4	4	4
00000011	0x3	3	3
00000010	0x2	2	2
00000001	0x1	1	1
00000000	0x0	0	0
11111111	0xff	255	-1
11111110	0xfe	254	-2
11111101	0xfd	253	-3
11111100	0xfc	252	-4
11111011	0xfb	251	-5
11111010	0xfa	250	-6
...			
10000010	0x82	130	-126
10000001	0x81	129	-127
10000000	0x80	128	-128

The difference between signed and unsigned numbers is that if we represent `0xFFFFFFFF` 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 ([13 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..0x7FFFFFFFFFFFFF`,
 - `int` (-2,147,483,648..2,147,483,647 (- 2.15.. 2.15Gb) or `0x80000000..0x7FFFFFFF`,
 - `char` (-128..127 or `0x80..0x7F`),
 - `ssize_t`.

Unsigned:

- `uint64_t` (0..18,446,744,073,709,551,615 (18 quintillions) or `0..0xFFFFFFFFFFFF`,

¹[wikipedia](#)

31.1. USING IMUL OVER MUL

- `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 most significant bit: 1 mean “minus”, 0 mean “plus”.
- Promoting to a larger data types is simple: [25.5 on page 404](#).
- Negation is simple: just invert all bits and add 1.

We can remember 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` ([A.6.3 on page 934](#)), `MOVSD` ([16.1.1 on page 200](#)), `SAR` ([A.6.3 on page 937](#)).

31.1 Using IMUL over MUL

Example like listing.[56.2](#) where two unsigned values are multiplied compiles into listing.[56.2](#) 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=0xffffffffe0000001`). 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., lower half is the same. 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 *Instruction latencies and throughput for AMD and Intel x86 processors* by Torbjörn Granlund²).

Given than, C/C++ compilers may generate `IMUL` instruction more often than `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`³ and another one: `_umul128`⁴. 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`, then result is shifted by 64-bit right, you'll get higher half of result⁵.

²<http://yurichev.com/mirrors/x86-timing.pdf>

³[https://msdn.microsoft.com/en-us/library/d2s81xt0\(v=vs.80\).aspx](https://msdn.microsoft.com/en-us/library/d2s81xt0(v=vs.80).aspx)

⁴<https://msdn.microsoft.com/library/3dayytw9%28v=vs.100%29.aspx>

⁵Example: <http://stackoverflow.com/a/13187798>

Chapter 32

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:

input A	input B	output
0	0	0
0	1	1
1	0	1
1	1	0

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.

32.1 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>.

32.2 Encryption

XOR is heavily used in both amateur (87) and *real* encryption (at least in *Feistel network*).

XOR is very useful here because: $cipher_text = plain_text \oplus key$ and then: $(plain_text \oplus key) \oplus key = plain_text$.

32.3 RAID4

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:

$$P = D_1 \oplus D_2 \oplus D_3 \quad (32.1)$$

If any of disks is failed, for example, D_2 , it's restored using the very same way:

$$D_2 = D_1 \oplus P \oplus D_3 \quad (32.2)$$

If parity disk failed, it is restored using 32.1 way. If two of any disks are failed, then it wouldn't be possible to restore both.

RAID5 is more complex, 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.

32.4 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:

```
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:

```
X = X XOR Y
Y = Y XOR X
X = X XOR Y
```

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 servers 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:

```
X = X + Y
Y = X - Y
X = X - Y
```

Let's see: X after 1st step has $X + Y$; Y after 2nd step has $X + Y - Y = X$; X after 3rd step has $X + Y - X = Y$.

This trick exploits modulo arithmetic, because overflow will make it impossible.

32.5 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 very easy to traverse list backwards or forward. `std::list` in C++ implements doubly linked list which also is examined in this book: 53.4.2.

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 it $prev \oplus next$ will be stored in this memory cell, often 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 addresss 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.

address	link contents
A_0	A_1
A_1	$A_0 \oplus A_2$
A_2	$A_1 \oplus A_3$
A_3	$A_2 \oplus A_4$
A_4	A_3

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.

Chapter 33

Endianness

The endianness is a way of representing values in memory.

33.1 Big-endian

The `0x12345678` value is represented in memory as:

address in memory	byte value
+0	0x12
+1	0x34
+2	0x56
+3	0x78

Big-endian CPUs include Motorola 68k, IBM POWER.

33.2 Little-endian

The `0x12345678` value is represented in memory as:

address in memory	byte value
+0	0x78
+1	0x56
+2	0x34
+3	0x12

Little-endian CPUs include Intel x86.

33.3 Example

Let's take big-endian MIPS Linux installed and ready in QEMU ¹.

And let's compile this simple example:

```
#include <stdio.h>

int main()
{
    int v, i;
    v=123;

    printf ("%02X %02X %02X %02X\n",
            *(char*)&v,
            *((char*)&v)+1,
            *((char*)&v)+2,
```

¹Available for download here: <http://go.yurichev.com/17008>

33.4. BI-ENDIAN

```
*(((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-endianness in this book: [22.4.3 on page 364](#).

33.4 Bi-endian

CPUs that may switch between endianness are ARM, PowerPC, SPARC, MIPS, [IA64](#)², etc.

33.5 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.

²Intel Architecture 64 (Itanium): [96 on page 909](#)

Chapter 34

Memory

There are 3 main types of memory:

- Global memory **AKA** “static memory allocation”. No need to allocate explicitly, the allocation is done 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: [8.2 on page 75](#).
- Stack **AKA** “allocate on stack”. The allocation is done 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()` ([6.2.4 on page 30](#)) (or a variable-length array) is used. Buffer overflows usually overwrite important stack structures: [19.2 on page 274](#).
- Heap **AKA** “dynamic memory allocation”. Allocation/deallocation is done 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. Another problem is the “use after free”—using a memory block after `free()` was called on it, which is very dangerous. Example in this book: [22.2 on page 347](#).

Chapter 35

CPU

35.1 Branch predictors

Some modern compilers try to get rid of conditional jump instructions. Examples in this book are: [13.1.2 on page 135](#), [13.3 on page 143](#), [20.5.2 on page 328](#).

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.

35.2 Data dependencies

Modern CPUs are able to execute instructions simultaneously ([OOE¹](#)), 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.

¹Out-of-order execution

Chapter 36

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 be aware of your password, 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.

36.1 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:

```
4 6 0 1 3 5 7 8 9 2
```

The algorithm for the simplest possible one-way function is:

- take the number at zeroth position (4 in our case);
- take the number at first position (6 in our case);
- swap numbers at positions of 4 and 6.

Let’s mark the numbers at positions 4 and 6:

```
4 6 0 1 3 5 7 8 9 2  
  ^  ^
```

Let’s swap them and we get this result:

```
4 6 0 1 7 5 3 8 9 2
```

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.

Part III

Slightly more advanced examples

Chapter 37

Temperature converting

Another very popular example in programming books for beginners is a small program that converts Fahrenheit temperature to Celsius or back.

$$C = \frac{5 \cdot (F - 32)}{9}$$

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 remember from school physics lessons).

The `exit()` function terminates the program instantly, without returning to the `caller` function.

37.1 Integer values

```
#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");
        exit(0);
    };
    printf ("Celsius: %d\n", celsius);
}
```

37.1.1 Optimizing MSVC 2012 x86

Listing 37.1: Optimizing MSVC 2012 x86

```
$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
```

37.1. INTEGER VALUES

```

_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                ; 0000000cH
    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:
$LN2@main:
    mov     eax, DWORD PTR _fahr$[esp+8]
    add    eax, -32               ; ffffffe0H
    lea     ecx, DWORD PTR [eax+eax*4]
    mov     eax, 954437177         ; 38e38e39H
    imul   ecx
    sar     edx, 1
    mov     eax, edx
    shr     eax, 31               ; 0000001fH
    add    eax, edx
    cmp     eax, -273              ; ffffffeefH
    jge     SHORT $LN1@main
    push    OFFSET $SG4233          ; 'Error: incorrect temperature!'
    call    esi                   ; call printf()
    add    esp, 4
    push    0
    call    DWORD PTR __imp__exit

$LN10@main:
$LN1@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:

- 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: `lea ecx, DWORD PTR [eax+eax*4]`. Yes, $i + i * 4$ is equivalent to $i * 5$ and `LEA` works faster than `IMUL`. By the way, the `SHL EAX, 2 / ADD EAX, EAX` instruction pair could be also used here instead— some compilers do it like.
- The division by multiplication trick ([43 on page 487](#)) is also used here.
- `main()` returns 0 if we don't have `return 0` at its end. The C99 standard tells us [[ISO07](#), p. 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?

37.1.2 Optimizing MSVC 2012 x64

The code is almost the same, but we can find `INT 3` instructions after each `exit()` call.

```
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 ¹, so if it does, something really odd has happened and it's time to load the debugger.

37.2 Floating-point values

```
#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 37.2: Optimizing MSVC 2010 x86

```
$SG4038 DB      'Enter temperature in Fahrenheit:', 0aH, 00H
$SG4040 DB      '%lf', 00H
$SG4041 DB      'Error while parsing your input', 0aH, 00H
$SG4043 DB      'Error: incorrect temperature!', 0aH, 00H
$SG4044 DB      'Celsius: %lf', 0aH, 00H

__real@c071100000000000 DQ 0c07110000000000r ; -273
__real@402200000000000 DQ 0402200000000000r ; 9
__real@401400000000000 DQ 0401400000000000r ; 5
__real@404000000000000 DQ 0404000000000000r ; 32

_fahr$ = -8                                ; size = 8
_main PROC
    sub esp, 8
    push esi
    mov esi, DWORD PTR __imp_printf
    push OFFSET $SG4038          ; 'Enter temperature in Fahrenheit:'
    call esi                     ; call printf()
    lea eax, DWORD PTR _fahr$[esp+16]
    push eax
    push OFFSET $SG4040          ; '%lf'
    call DWORD PTR __imp_sccanf
    add esp, 12                  ; 0000000cH
```

¹another popular one is `longjmp()`

37.2. FLOATING-POINT VALUES

```

    cmp    eax, 1
    je     SHORT $LN2@main
    push   OFFSET $SG4041          ; 'Error while parsing your input'
    call   esi                   ; call printf()
    add    esp, 4
    push   0
    call   DWORD PTR __imp__exit
$LN2@main:
    fld    QWORD PTR _fahr$[esp+12]
    fsub  QWORD PTR __real@4040000000000000 ; 32
    fmul  QWORD PTR __real@4014000000000000 ; 5
    fdiv  QWORD PTR __real@4022000000000000 ; 9
    fld    QWORD PTR __real@c071100000000000 ; -273
    fcomp ST(1)
    fnstsw ax
    test  ah, 65                ; 00000041H
    jne   SHORT $LN1@main
    push   OFFSET $SG4043          ; 'Error: incorrect temperature!'
    fstp  ST(0)
    call   esi                   ; call printf()
    add    esp, 4
    push   0
    call   DWORD PTR __imp__exit
$LN1@main:
    sub   esp, 8
    fstp QWORD PTR [esp]
    push   OFFSET $SG4044          ; 'Celsius: %lf'
    call   esi
    add   esp, 12                ; 00000000cH
    ; return 0 - by C99 standard
    xor   eax, eax
    pop   esi
    add   esp, 8
    ret   0
$LN10@main:
_main  ENDP

```

...but MSVC 2012 uses [SIMD](#) instructions instead:

Listing 37.3: Optimizing MSVC 2010 x86

```

$SG4228 DB      'Enter temperature in Fahrenheit:', 0aH, 00H
$SG4230 DB      '%lf', 00H
$SG4231 DB      'Error while parsing your input', 0aH, 00H
$SG4233 DB      'Error: incorrect temperature!', 0aH, 00H
$SG4234 DB      'Celsius: %lf', 0aH, 00H
__real@c071100000000000 DQ 0c071100000000000r ; -273
__real@404000000000000 DQ 0404000000000000r ; 32
__real@402200000000000 DQ 0402200000000000r ; 9
__real@401400000000000 DQ 0401400000000000r ; 5

_fahr$ = -8                                ; size = 8
_main  PROC
    sub   esp, 8
    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+16]
    push  eax
    push  OFFSET $SG4230          ; '%lf'
    call  DWORD PTR __imp__scanf
    add   esp, 12                ; 00000000cH
    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:

```

37.2. FLOATING-POINT VALUES

```
$LN2@main:
    movsd  xmm1, QWORD PTR _fahr$[esp+12]
    subsd  xmm1, QWORD PTR __real@4040000000000000 ; 32
    movsd  xmm0, QWORD PTR __real@c071100000000000 ; -273
    mulsd  xmm1, QWORD PTR __real@4014000000000000 ; 5
    divsd  xmm1, QWORD PTR __real@4022000000000000 ; 9
    comisd  xmm0, xmm1
    jbe     SHORT $LN1@main
    push    OFFSET $SG4233           ; 'Error: incorrect temperature!'
    call    esi                     ; call printf()
    add    esp, 4
    push    0
    call    DWORD PTR __imp__exit

$LN10@main:
$LN1@main:
    sub    esp, 8
    movsd QWORD PTR [esp], xmm1
    push   OFFSET $SG4234           ; 'Celsius: %lf'
    call   esi                     ; call printf()
    add    esp, 12                 ; 00000000cH
    ; return 0 - by C99 standard
    xor    eax, eax
    pop    esi
    add    esp, 8
    ret    0

$LN8@main:
_main    ENDP
```

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.

Chapter 38

Fibonacci numbers

Another widespread example used in programming textbooks is a recursive function that generates the Fibonacci numbers¹. The sequence is very simple: each consecutive number is the sum of the previous two. The first two numbers are 1's or 0, 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...

38.1 Example #1

The implementation is simple. This program generates the sequence until 21.

```
#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 38.1: 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]
```

¹<http://go.yurichev.com/17332>

38.1. EXAMPLE #1

```
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
```

We will illustrate the stack frames with this.

38.1. EXAMPLE #1

Let's load the example in OllyDbg and trace to the last call of `f()`:

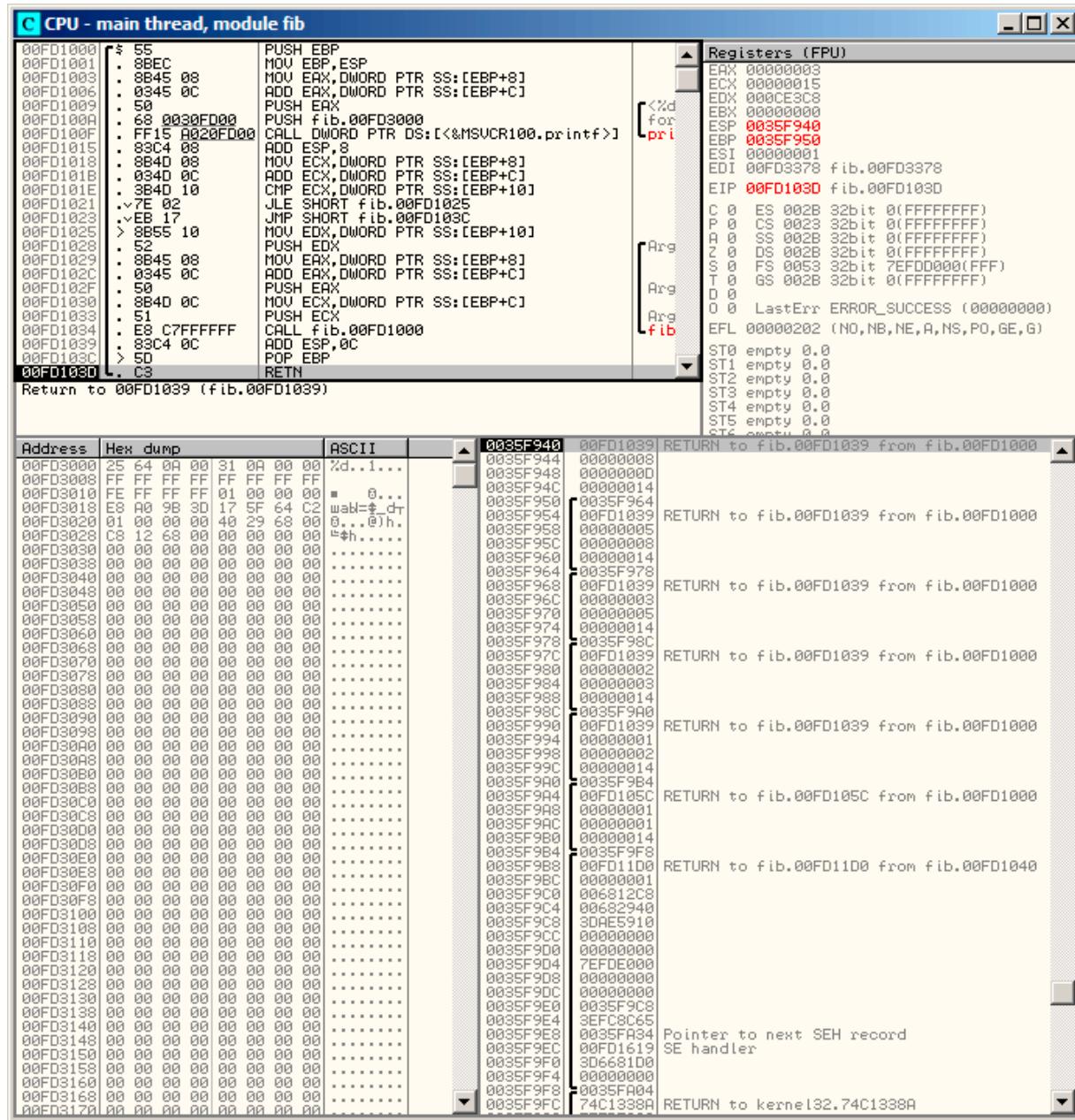


Figure 38.1: OllyDbg: last call of `f()`

38.2. EXAMPLE #2

Let's investigate the stack more closely. Comments were added by the author of this book ²:

```
0035F940 00FD1039 RETURN to fib.00FD1039 from fib.00FD1000
0035F944 00000008 1st argument: a
0035F948 0000000D 2nd argument: b
0035F94C 00000014 3rd argument: limit
0035F950 /0035F964 saved EBP register
0035F954 |00FD1039 RETURN to fib.00FD1039 from fib.00FD1000
0035F958 |00000005 1st argument: a
0035F95C |00000008 2nd argument: b
0035F960 |00000014 3rd argument: limit
0035F964 |0035F978 saved EBP register
0035F968 |00FD1039 RETURN to fib.00FD1039 from fib.00FD1000
0035F96C |00000003 1st argument: a
0035F970 |00000005 2nd argument: b
0035F974 |00000014 3rd argument: limit
0035F978 |0035F98C saved EBP register
0035F97C |00FD1039 RETURN to fib.00FD1039 from fib.00FD1000
0035F980 |00000002 1st argument: a
0035F984 |00000003 2nd argument: b
0035F988 |00000014 3rd argument: limit
0035F98C |0035F9A0 saved EBP register
0035F990 |00FD1039 RETURN to fib.00FD1039 from fib.00FD1000
0035F994 |00000001 1st argument: a
0035F998 |00000002 2nd argument: b
0035F99C |00000014 3rd argument: limit
0035F9A0 |0035F9B4 saved EBP register
0035F9A4 |00FD105C RETURN to fib.00FD105C from fib.00FD1000
0035F9A8 |00000001 1st argument: a \
0035F9AC |00000001 2nd argument: b | prepared in main() for f1()
0035F9B0 |00000014 3rd argument: limit /
0035F9B4 |0035F9F8 saved EBP register
0035F9B8 |00FD11D0 RETURN to fib.00FD11D0 from fib.00FD1040
0035F9BC |00000001 main() 1st argument: argc \
0035F9C0 |006812C8 main() 2nd argument: argv | prepared in CRT for main()
0035F9C4 |00682940 main() 3rd argument: envp /
```

The function is recursive ³, 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 leads to a stack overflow: just remove (or comment out) the limit check and it will crash with exception 0xC00000FD (stack overflow).

38.2 Example #2

My function has some redundancy, so let's add a new local variable *next* and replace all “*a+b*” with it:

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

²By the way, it's possible to select several entries in OllyDbg and copy them to the clipboard (Ctrl-C). That's what was done for this example.

³i.e., it calls itself

38.2. EXAMPLE #2

```
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 38.2: 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     ecx, DWORD PTR _next$[ebp]
    push    ecx
    mov     edx, DWORD PTR _b$[ebp]
    push    edx
    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
```

38.2. EXAMPLE #2

Let's load it in OllyDbg once again:

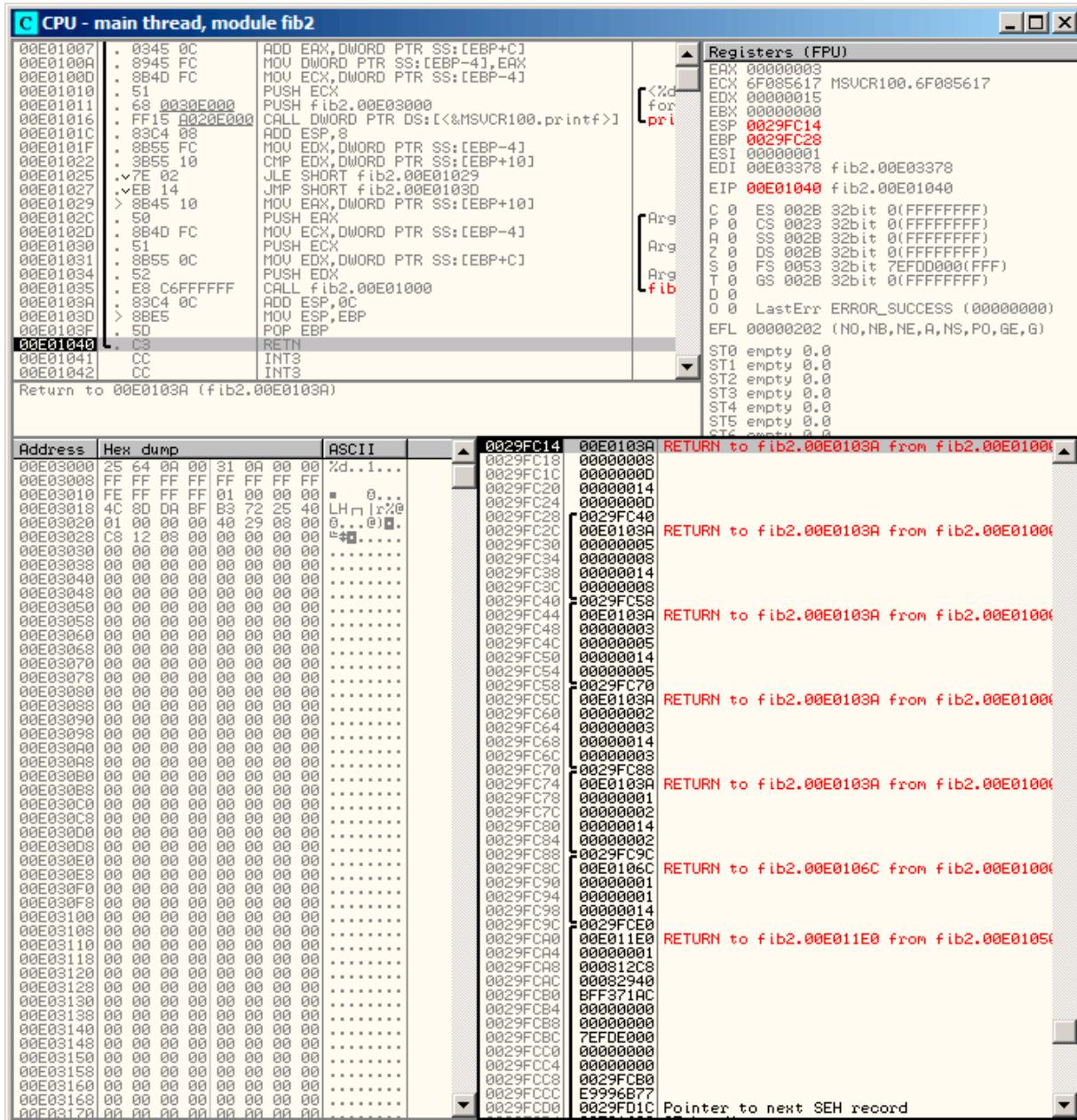


Figure 38.2: OllyDbg: last call of `f()`

Now the `next` variable is present in each frame.

38.3. SUMMARY

Let's investigate the stack more closely. The author has again added his comments:

0029FC14	00E0103A	RETURN to fib2.00E0103A from fib2.00E01000
0029FC18	00000008	1st argument: a
0029FC1C	0000000D	2nd argument: b
0029FC20	00000014	3rd argument: limit
0029FC24	0000000D	"next" variable
0029FC28	/0029FC40	saved EBP register
0029FC2C	00E0103A	RETURN to fib2.00E0103A from fib2.00E01000
0029FC30	00000005	1st argument: a
0029FC34	00000008	2nd argument: b
0029FC38	00000014	3rd argument: limit
0029FC3C	00000008	"next" variable
0029FC40]0029FC58	saved EBP register
0029FC44	00E0103A	RETURN to fib2.00E0103A from fib2.00E01000
0029FC48	00000003	1st argument: a
0029FC4C	00000005	2nd argument: b
0029FC50	00000014	3rd argument: limit
0029FC54	00000005	"next" variable
0029FC58]0029FC70	saved EBP register
0029FC5C	00E0103A	RETURN to fib2.00E0103A from fib2.00E01000
0029FC60	00000002	1st argument: a
0029FC64	00000003	2nd argument: b
0029FC68	00000014	3rd argument: limit
0029FC6C	00000003	"next" variable
0029FC70]0029FC88	saved EBP register
0029FC74	00E0103A	RETURN to fib2.00E0103A from fib2.00E01000
0029FC78	00000001	1st argument: a \
0029FC7C	00000002	2nd argument: b prepared in f1() for next f1() call
0029FC80	00000014	3rd argument: limit /
0029FC84	00000002	"next" variable
0029FC88]0029FC9C	saved EBP register
0029FC8C	00E0106C	RETURN to fib2.00E0106C from fib2.00E01000
0029FC90	00000001	1st argument: a \
0029FC94	00000001	2nd argument: b prepared in main() for f1()
0029FC98	00000014	3rd argument: limit /
0029FC9C]0029FCE0	saved EBP register
0029FCA0	00E011E0	RETURN to fib2.00E011E0 from fib2.00E01050
0029FCA4	00000001	main() 1st argument: argc \
0029FCA8	000812C8	main() 2nd argument: argv prepared in CRT for main()
0029FCAC	00082940	main() 3rd argument: envp /

Here we see it: the *next* value is calculated in each function incarnation, then passed as argument *b* to the next incarnation.

38.3 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 [PL⁴](#) compilers (where recursion is used heavily) use [tail call](#).

⁴LISP, Python, Lua, etc.

Chapter 39

CRC32 calculation example

This is a very popular table-based CRC32 hash calculation technique¹.

```
/* By Bob Jenkins, (c) 2006, Public Domain */

#include <stdio.h>
#include <stddef.h>
#include <string.h>

typedef unsigned long ub4;
typedef unsigned char ub1;

static const ub4 crctab[256] = {
    0x00000000, 0x77073096, 0xee0e612c, 0x990951ba, 0x076dc419, 0x706af48f,
    0xe963a535, 0x9e6495a3, 0x0edb8832, 0x79dc8a4, 0xe0d5e91e, 0x97d2d988,
    0x09b64c2b, 0x7eb17cbd, 0xe7b82d07, 0x90bf1d91, 0x1db71064, 0x6ab020f2,
    0xf3b97148, 0x84be41de, 0x1adad47d, 0x6ddde4eb, 0xf4d4b551, 0x83d385c7,
    0x136c9856, 0x646ba8c0, 0xfd62f97a, 0x8a65c9ec, 0x14015c4f, 0x63066cd9,
    0xfa0f3d63, 0x8d080df5, 0x3b6e20c8, 0x4c69105e, 0xd56041e4, 0xa2677172,
    0x3c03e4d1, 0xb04d447, 0xd20d85fd, 0xa50ab56b, 0x35b5a8fa, 0x42b2986c,
    0xdbbb9d6, 0xacbcf940, 0x32d86ce3, 0x45df5c75, 0xcd60dcf, 0abd13d59,
    0x26d930ac, 0x51de003a, 0xc8d75180, 0xbfd06116, 0x21b4f4b5, 0x56b3c423,
    0xcfba9599, 0xb8bda50f, 0x2802b89e, 0x5f058808, 0xc60cd9b2, 0xb10be924,
    0x2f6f7c87, 0x58684c11, 0xc1611dab, 0xb6662d3d, 0x76dc4190, 0x01db7106,
    0x98d220bc, 0xefd5102a, 0x71b18589, 0x06b6b51f, 0x9fbfe4a5, 0xe8b8d433,
    0x7807c9a2, 0x0f00f934, 0x9609a88e, 0xe10e9818, 0x7f6a0dbb, 0x086d3d2d,
    0x91646c97, 0xe6635c01, 0x6b6b51f4, 0x1c6c6162, 0x856530d8, 0xf262004e,
    0x6c0695ed, 0x1b01a57b, 0x8208f4c1, 0xf50fc457, 0x65b0d9c6, 0x12b7e950,
    0x8bbeb8ea, 0xfc9b9887c, 0x62dd1ddf, 0x15da2d49, 0x8cd37cf3, 0xbd44c65,
    0x4db26158, 0x3ab551ce, 0xa3bc0074, 0xd4bb30e2, 0x4adfa541, 0x3dd895d7,
    0xa4d1c46d, 0xd3d6f4fb, 0x4369e96a, 0x346ed9fc, 0xad678846, 0xda60b8d0,
    0x44042d73, 0x33031de5, 0xaa0a4c5f, 0xdd0d7cc9, 0x5005713c, 0x270241aa,
    0xbe0b1010, 0xc90c2086, 0x5768b525, 0x206f85b3, 0xb966d409, 0xce61e49f,
    0x5edef90e, 0x29d9c998, 0xb0d09822, 0xc7d7a8b4, 0x59b33d17, 0x2eb40d81,
    0xb7bd5c3b, 0xc0ba6cad, 0xedb88320, 0x9abfb3b6, 0x3b6e20c, 0x74b1d29a,
    0xead54739, 0x9dd277af, 0x04db2615, 0x73dc1683, 0x3630b12, 0x94643b84,
    0x0d6d6a3e, 0x7a6a5aa8, 0xe40ecf0b, 0x9309ff9d, 0xa00ae27, 0x7d079eb1,
    0xf00f9344, 0x8708a3d2, 0x1e01f268, 0x6906c2fe, 0xf762575d, 0x806567cb,
    0x196c3671, 0x6e6b06e7, 0xfed41b76, 0x89d32be0, 0x10da7a5a, 0x67dd4acc,
    0xf9b9df6f, 0x8ebeeff9, 0x17b7be43, 0x60b08ed5, 0xd6d6a3e8, 0xa1d1937e,
    0x38d8c2c4, 0x4fdff252, 0xd1bb67f1, 0xa6bc5767, 0x3fb506dd, 0x48b2364b,
    0xd80d2bda, 0xaf0a1b4c, 0x36034af6, 0x41047a60, 0xdf60efc3, 0xa867df55,
    0x316e8eef, 0x4669be79, 0xcb61b38c, 0xbc66831a, 0x256fd2a0, 0x5268e236,
    0xcc0c7795, 0xbb0b4703, 0x220216b9, 0x5505262f, 0xc5ba3bbe, 0xb2bd0b28,
    0x2bb45a92, 0x5cb36a04, 0xc2d7ffa7, 0xb5d0cf31, 0x2cd99e8b, 0x5bdeae1d,
    0x9b64c2b0, 0xec63f226, 0x756aa39c, 0x026d930a, 0x9c0906a9, 0xeb0e363f,
    0x72076785, 0x05005713, 0x95bf4a82, 0xe2b87a14, 0x7bb12bae, 0xcb61b38,
    0x92d28e9b, 0xe5d5be0d, 0x7cdcef7, 0x0bdbdf21, 0x86d3d2d4, 0xf1d4e242,
    0x68ddb3f8, 0x1fd8a36e, 0x81be16cd, 0xf6b9265b, 0x6fb077e1, 0x18b74777,
    0x88085ae6, 0xff0f6a70, 0x66063bca, 0x11010b5c, 0x8f659eff, 0xf862ae69,
    0x616bf7d3, 0x166ccf45, 0xa00ae278, 0xd70dd2ee, 0x4e048354, 0x3903b3c2,
    0xa7672661, 0xd06016f7, 0x4969474d, 0x3e6e77db, 0xae16a4a, 0xd9d65adc,
```

¹The source code was taken from here: <http://go.yurichev.com/17327>

```

0x40df0b66, 0x37d83bf0, 0xa9bcae53, 0xdebb9ec5, 0x47b2cf7f, 0x30b5ffe9,
0xbdbdf21c, 0ocabac28a, 0x53b39330, 0x24b4a3a6, 0xbad03605, 0xcd70693,
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);
        j = (j>>1) ^ ((j&1) ? 0xedb88320 : 0);
        printf("0x%.8lx, ", j);
        if (i%6 == 5) printf("\n");
    }
}

/* the hash function */
ub4 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 -O0 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 interesting 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)
    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:

```

crc      public 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
mov    eax, ebx
jz     short loc_80484D3
nop
lea     esi, [esi+0]    ; padding; works as NOP (ESI does not changing here)

loc_80484B8:
    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_80484B8

loc_80484D3:
    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 ([91 on page 898](#)).

Chapter 40

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 ([CIDR¹](#)), like /8, /16 or similar. This notation just defines the number of bits the mask has, starting at the [MSB](#).

Mask	Hosts	Usable	Netmask	Hex mask	
/30	4	2	255.255.255.252	fffffc	
/29	8	6	255.255.255.248	fffff8	
/28	16	14	255.255.255.240	fffff0	
/27	32	30	255.255.255.224	ffffe0	
/26	64	62	255.255.255.192	fffffc0	
/24	256	254	255.255.255.0	fffff00	class C network
/23	512	510	255.255.254.0	fffffe00	
/22	1024	1022	255.255.252.0	fffffc00	
/21	2048	2046	255.255.248.0	fffff800	
/20	4096	4094	255.255.240.0	fffff000	
/19	8192	8190	255.255.224.0	ffffe000	
/18	16384	16382	255.255.192.0	fffffc000	
/17	32768	32766	255.255.128.0	ffff8000	
/16	65536	65534	255.255.0.0	fffff0000	class B network
/8	16777216	16777214	255.0.0.0	ff000000	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);
```

¹Classless Inter-Domain Routing

40.1. CALC_NETWORK_ADDRESS()

```
};

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 ip5,
                           uint8_t netmask_bits)
{
    uint32_t netmask=form_netmask(netmask_bits);
    uint32_t ip=form_IP(ip1, ip2, ip3, ip4);
    uint32_t netw_addr;

    printf ("netmask=");
    print_as_IP (netmask);

    netw_addr=ip&netmask;

    printf ("network address=");
    print_as_IP (netw_addr);
};

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
};
```

40.1 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.

Listing 40.1: Optimizing MSVC 2012 /Obo

```
1 _ip1$ = 8           ; size = 1
2 _ip2$ = 12          ; size = 1
3 _ip3$ = 16          ; size = 1
4 _ip4$ = 20          ; size = 1
5 _netmask_bits$ = 24 ; size = 1
6 _calc_network_address PROC
7     push    edi
8     push    DWORD PTR _netmask_bits$[esp]
9     call    _form_netmask
10    push   OFFSET $SG3045 ; 'netmask='
11    mov     edi, eax
12    call   DWORD PTR __imp__printf
13    push   edi
14    call   _print_as_IP
15    push   OFFSET $SG3046 ; 'network address='
16    call   DWORD PTR __imp__printf
17    push   DWORD PTR _ip4$[esp+16]
18    push   DWORD PTR _ip3$[esp+20]
19    push   DWORD PTR _ip2$[esp+24]
20    push   DWORD PTR _ip1$[esp+28]
21    call   _form_IP
22    and    eax, edi      ; network address = host address & netmask
23    push   eax
```

40.2. FORM_IP()

```
24     call    _print_as_IP
25     add     esp, 36
26     pop     edi
27     ret     0
28 _calc_network_address ENDP
```

At line 22 we see the most important AND –here the network address is calculated.

40.2 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 it. 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 return it. 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 return it. The return value contain `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 40.2: Non-optimizing MSVC 2012

```
; 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$[ebp]
    ; EAX=000000dd
    shl     eax, 24
    ; EAX=dd000000
    movzx   ecx, BYTE PTR _ip2$[ebp]
    ; ECX=000000cc
    shl     ecx, 16
    ; ECX=00cc0000
    or      eax, ecx
    ; EAX=ddcc0000
    movzx   edx, BYTE PTR _ip3$[ebp]
    ; EDX=000000bb
    shl     edx, 8
    ; EDX=0000bb00
    or      eax, edx
    ; EAX=ddccb00
    movzx   ecx, BYTE PTR _ip4$[ebp]
    ; ECX=000000aa
    or      eax, ecx
    ; EAX=ddccbbaa
    pop    ebp
    ret    0
_form_IP ENDP
```

40.3. PRINT_AS_IP()

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 40.3: Optimizing MSVC 2012 /Obo

```
; 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    ecx, BYTE PTR _ip3$[esp-4]
    ; ECX=000000bb
    shl     eax, 8
    ; EAX=00ddcc00
    or      eax, ecx
    ; EAX=00ddccbb
    movzx    ecx, BYTE PTR _ip4$[esp-4]
    ; ECX=000000aa
    shl     eax, 8
    ; EAX=ddccbb00
    or      eax, ecx
    ; EAX=ddccbbaa
    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.

40.3 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 40.4: Non-optimizing MSVC 2012

```
_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
```

40.4. FORM_NETMASK() AND SET_BIT()

```
; 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
; EAX=000000dd
push   eax
push   OFFSET $SG2973 ; '%d.%d.%d.%d'
call   DWORD PTR __imp_printf
add    esp, 20
pop    ebp
ret    0
_print_as_IP ENDP
```

Optimizing MSVC 2012 does almost the same, but without unnecessary reloading of the input value:

Listing 40.5: Optimizing MSVC 2012 /Ob0

```
_a$ = 8           ; 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
    ; ECX=ddccbbaa
    shr    ecx, 24
    ; ECX=000000dd
    push   ecx
    push   OFFSET $SG3020 ; '%d.%d.%d.%d'
    call   DWORD PTR __imp_printf
    add    esp, 20
    ret    0
/print_as_IP ENDP
```

40.4 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 40.6: Optimizing MSVC 2012 /Ob0

```
_input$ = 8           ; size = 4
_bit$ = 12          ; size = 4
/set_bit PROC
    mov    ecx, DWORD PTR _bit$[esp-4]
    mov    eax, 1
```

40.5. SUMMARY

```
    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
    push   eax
    push   ecx
    call   _set_bit
    inc    bl
    movzx  edx, bl
    add    esp, 8
    mov    ecx, eax
    cmp    edx, esi
    j1    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

40.5 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
```

Chapter 41

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:

```
#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.

41.1 Three iterators

Listing 41.1: Optimizing MSVC 2013 x64

```
f      PROC
; RDX=a1
; RCX=a2
; 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++:

```
#include <stdio.h>

void f(int *a1, int *a2, size_t cnt)
{
    size_t i;
    size_t idx1=0; idx2=0;
```

41.2. TWO ITERATORS

```
// 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.

41.2 Two iterators

GCC 4.9 does even more, leaving only 2 iterators:

Listing 41.2: 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
```

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 has not reached this precalculated value.

You can read more about multiplication using shifts/additions/subtractions here: [17.1.3 on page 211](#).

This code can be rewritten into C/C++ like that:

```
#include <stdio.h>

void f(int *a1, int *a2, size_t cnt)
{
    size_t i;
    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;
    };
}
```

41.3. INTEL C++ 2011 CASE

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 41.3: Optimizing GCC (Linaro) 4.9 ARM64

```
; 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 41.4: Optimizing GCC 4.4.5 for MIPS (IDA)

```
; $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
; 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
```

41.3 Intel C++ 2011 case

Compiler optimizations can also be weird, but nevertheless, still correct. Here is what the Intel C++ compiler 2011 does:

Listing 41.5: Optimizing Intel C++ 2011 x64

```
f      PROC
; parameter 1: rcx = a1
; parameter 2: rdx = a2
; parameter 3: r8  = cnt
.B1.1::           ; Preds .B1.0
```

41.3. INTEL C++ 2011 CASE

```

        test    r8, r8          ;8.14
        jbe     exit           ; Prob 50%      ;8.14
                  ; LOE rdx rcx rbx rbp rsi rdi r8 r12 r13 r14 r15 xmm6 xmm7 xmm8
        ↳ xmm9 xmm10 xmm11 xmm12 xmm13 xmm14 xmm15
.B1.2:::   cmp     r8, 6       ;8.2
        jbe     just_copy     ; Prob 50%      ;8.2
                  ; LOE rdx rcx rbx rbp rsi rdi r8 r12 r13 r14 r15 xmm6 xmm7 xmm8
        ↳ xmm9 xmm10 xmm11 xmm12 xmm13 xmm14 xmm15
.B1.3:::   cmp     rcx, rdx    ;9.11
        jbe     .B1.5         ; Prob 50%      ;9.11
                  ; LOE rdx rcx rbx rbp rsi rdi r8 r12 r13 r14 r15 xmm6 xmm7 xmm8
        ↳ xmm9 xmm10 xmm11 xmm12 xmm13 xmm14 xmm15
.B1.4:::   mov     r10, r8      ;9.11
        mov     r9, rcx        ;9.11
        shl     r10, 5        ;9.11
        lea     rax, QWORD PTR [r8*4] ;9.11
        sub     r9, rdx        ;9.11
        sub     r10, rax        ;9.11
        cmp     r9, r10        ;9.11
        jge     just_copy2    ; Prob 50%      ;9.11
                  ; LOE rdx rcx rbx rbp rsi rdi r8 r12 r13 r14 r15 xmm6 xmm7 xmm8
        ↳ xmm9 xmm10 xmm11 xmm12 xmm13 xmm14 xmm15
.B1.5:::   cmp     rdx, rcx    ;9.11
        jbe     just_copy     ; Prob 50%      ;9.11
                  ; LOE rdx rcx rbx rbp rsi rdi r8 r12 r13 r14 r15 xmm6 xmm7 xmm8
        ↳ xmm9 xmm10 xmm11 xmm12 xmm13 xmm14 xmm15
.B1.6:::   mov     r9, rdx      ;9.11
        lea     rax, QWORD PTR [r8*8] ;9.11
        sub     r9, rcx        ;9.11
        lea     r10, QWORD PTR [rax+r8*4] ;9.11
        cmp     r9, r10        ;9.11
        j1     just_copy      ; Prob 50%      ;9.11
                  ; LOE rdx rcx rbx rbp rsi rdi r8 r12 r13 r14 r15 xmm6 xmm7 xmm8
        ↳ xmm9 xmm10 xmm11 xmm12 xmm13 xmm14 xmm15
just_copy2::: ; Preds .B1.4 .B1.6
; R8 = cnt
; RDX = a2
; RCX = a1
        xor     r10d, r10d    ;8.2
        xor     r9d, r9d      ;
        xor     eax, eax      ;
                  ; LOE rax rdx rcx rbx rbp rsi rdi r8 r9 r10 r12 r13 r14 r15
        ↳ xmm6 xmm7 xmm8 xmm9 xmm10 xmm11 xmm12 xmm13 xmm14 xmm15
.B1.8:::   mov     r11d, DWORD PTR [rax+rdx] ;3.6
        inc     r10          ;8.2
        mov     DWORD PTR [r9+rcx], r11d ;3.6
        add     r9, 12        ;8.2
        add     rax, 28        ;8.2
        cmp     r10, r8        ;8.2
        jb     .B1.8         ; Prob 82%
        jmp     exit          ; Prob 100%      ;8.2
                  ; LOE rax rdx rcx rbx rbp rsi rdi r8 r9 r10 r12 r13 r14 r15
        ↳ xmm6 xmm7 xmm8 xmm9 xmm10 xmm11 xmm12 xmm13 xmm14 xmm15
just_copy::: ; Preds .B1.2 .B1.5 .B1.6
; R8 = cnt
; RDX = a2
; RCX = a1
        xor     r10d, r10d    ;8.2
        xor     r9d, r9d      ;
        xor     eax, eax      ;
                  ; LOE rax rdx rcx rbx rbp rsi rdi r8 r9 r10 r12 r13 r14 r15
        ↳ xmm6 xmm7 xmm8 xmm9 xmm10 xmm11 xmm12 xmm13 xmm14 xmm15
.B1.11:::  mov     r11d, DWORD PTR [rax+rdx] ;3.6

```

41.3. INTEL C++ 2011 CASE

```
inc    r10          ;8.2
mov    DWORD PTR [r9+rcx], r11d   ;3.6
add    r9, 12        ;8.2
add    rax, 28        ;8.2
cmp    r10, r8        ;8.2
jb     .B1.11       ; Prob 82%      ;8.2
                ; LOE rax rdx rcx rbx rbp rsi rdi r8 r9 r10 r12 r13 r14 r15 ↵
        ↵ xmm6 xmm7 xmm8 xmm9 xmm10 xmm11 xmm12 xmm13 xmm14 xmm15
exit::           ; Preds .B1.11 .B1.8 .B1.1
    ret             ;10.1
```

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 probably 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, is passed the tests.

Chapter 42

Duff's device

Duff's device ¹ is an unrolled loop with the possibility to jump inside 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 need 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 byte blocks. Since we are going to work with a 64-bit example here, we are going to clear the memory in 8 byte 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-byte blocks, clear them using 8-byte (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:

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

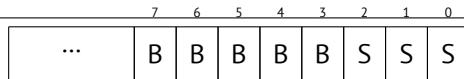
void bzero(uint8_t* dst, size_t count)
{
    int i;

    if (count&(~7))
        // work out 8-byte blocks
        for (i=0; i<count>>3; i++)
        {
            *(uint64_t*)dst=0;
            dst=dst+8;
        };

    // work out the tail
    switch(count & 7)
    {
        case 7: *dst++ = 0;
        case 6: *dst++ = 0;
        case 5: *dst++ = 0;
        case 4: *dst++ = 0;
        case 3: *dst++ = 0;
        case 2: *dst++ = 0;
        case 1: *dst++ = 0;
        case 0: // do nothing
            break;
    }
}
```

Let's first understand how the calculation is done. The memory region size comes as a 64-bit value. And this value can be divided in two parts:

¹wikipedia



(“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 just need to isolate the lowest 3 bits! So the number of 8-byte blocks is calculated as `count >> 3` and remainder as `count & 7`.

We also need to find out if we are going to execute the 8-byte procedure at all, so we need to check if the value of `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 `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 `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, modern CPUs works better for short loops than for unrolled ones). Maybe this is still meaningful on modern low-cost embedded MCU²s.

Let’s see what the optimizing MSVC 2012 does:

```
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
    movsxd rax, r8d
    cmp    rax, r9
    jb     SHORT $LL19@bzero
$LN11@bzero:
; work out the tail
    and   edx, 7
    dec   rdx
    cmp   rdx, 6
    ja    SHORT $LN9@bzero
    lea    r8, OFFSET FLAT:__ImageBase
    mov    eax, DWORD PTR $LN22@bzero[r8+rdx*4]
    add    rax, r8
    jmp    rax
$LN8@bzero:
    mov    BYTE PTR [rcx], 0
    inc    rcx
$LN7@bzero:
    mov    BYTE PTR [rcx], 0
    inc    rcx
$LN6@bzero:
    mov    BYTE PTR [rcx], 0
    inc    rcx
```

²Microcontroller unit

```

$LN5@bzero:
    mov     BYTE PTR [rcx], 0
    inc     rcx
$LN4@bzero:
    mov     BYTE PTR [rcx], 0
    inc     rcx
$LN3@bzero:
    mov     BYTE PTR [rcx], 0
    inc     rcx
$LN2@bzero:
    mov     BYTE PTR [rcx], 0
$LN9@bzero:
    fatret 0
    npad   1
$LN22@bzero:
    DD      $LN2@bzero
    DD      $LN3@bzero
    DD      $LN4@bzero
    DD      $LN5@bzero
    DD      $LN6@bzero
    DD      $LN7@bzero
    DD      $LN8@bzero
bzero  ENDP

```

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 idea³. That is what old-school demomakers did in the past with unrolled loops.

³As 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).

Chapter 43

Division by 9

A very simple function:

```
int f(int a)
{
    return a/9;
};
```

43.1 x86

...is compiled in a very predictable way:

Listing 43.1: 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
    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 `MOVsx` does. If we turn optimization on (`/Ox`), we get:

Listing 43.2: Optimizing MSVC

```
_a$ = 8          ; size = 4
_f    PROC

    mov   ecx, DWORD PTR _a$[esp-4]
    mov   eax, 954437177 ; 38e38e39H
    imul
    sar   edx, 1
    mov   eax, edx
    shr   eax, 31       ; 0000001fH
    add   eax, edx
    ret   0
_f    ENDP
```

43.2. ARM

This is division by multiplication. Multiplication operations work much faster. And it is possible to use this trick¹ 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:

Listing 43.3: Non-optimizing GCC 4.4.1

```
public f
f proc near

arg_0 = dword ptr 8

    push    ebp
    mov     ebp, esp
    mov     ecx, [ebp+arg_0]
    mov     edx, 954437177 ; 38E38E39h
    mov     eax, ecx
    imul   edx
    sar    edx, 1
    mov     eax, ecx
    sar    eax, 1Fh
    mov     ecx, edx
    sub    ecx, eax
    mov     eax, ecx
    pop    ebp
    retn
f endp
```

43.2 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 ([20 on page 303](#)).

Here is an example that divides a 32-bit number by 10, from [[Ltd94](#), 3.3 Division by a Constant]. The output consists of the quotient and the remainder.

```
; 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
```

43.2.1 Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
__text:00002C58 39 1E 08 E3 E3 18 43 E3  MOV    R1, 0x38E38E39
__text:00002C60 10 F1 50 E7  SMMUL  R0, R0, R1
__text:00002C64 C0 10 A0 E1  MOV    R1, R0, ASR#1
__text:00002C68 A0 0F 81 E0  ADD    R0, R1, R0, LSR#31
__text:00002C6C 1E FF 2F E1  BX     LR
```

¹Read more about division by multiplication in [[War02](#), pp. 10-3]

43.3. MIPS

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 `MOVT`, 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 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 $R0 = R1 + R0 \gg 31$

There is no separate shifting instruction in ARM mode. Instead, an instruction like (`MOV`, `ADD`, `SUB`, `RSB`)² 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*.

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

```
MOV      R1, 0x38E38E39
SMMUL.W R0, R0, R1
ASRS    R1, R0, #1
ADD.W   R0, R1, R0, LSR#31
BX      LR
```

There are separate instructions for shifting in Thumb mode, and one of them is used here – `ASRS` (arithmetic shift right).

43.2.3 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.

43.3 MIPS

For some reason, optimizing GCC 4.4.5 generates just a division instruction:

Listing 43.4: 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.

²These instructions are also called “data processing instructions”

43.4. HOW IT WORKS

If we alter the statement to “`a % 9`”, the MFHI instruction is to be used here instead of MFLO.

43.4 How it works

That's how division can be replaced by multiplication and division with 2^n numbers:

$$\text{result} = \frac{\text{input}}{\text{divisor}} = \frac{\text{input} \cdot \frac{2^n}{\text{divisor}}}{2^n} = \frac{\text{input} \cdot M}{2^n}$$

Where M is a *magic* coefficient.

This is how M can be computed:

$$M = \frac{2^n}{\text{divisor}}$$

So these code snippets usually have this form:

$$\text{result} = \frac{\text{input} \cdot M}{2^n}$$

Division by 2^n is usually done by simply shifting to the right.

If $n < 32$, then the low part of the *product* is shifted (in `EAX` or `RAX`).

n is chosen in order to minimize the error.

When doing signed division, the sign of the multiplication result is also added to the output result.

Take a look at the difference:

```
int f3_32_signed(int a)
{
    return a/3;
}

unsigned int f3_32_unsigned(unsigned int a)
{
    return a/3;
}
```

In the unsigned version of the function, the *magic* coefficient is `0xAAAAAAAB` and the multiplication result is divided by 2^{33} .

In the signed version of the function, the *magic* coefficient is `0x55555556` and the multiplication result is divided by 2^{32} . There are no division instruction though: the result is just taken from `EDX`.

The sign is also taken from the multiplication result: the high 32 bits of the result are shifted by 31 (leaving the sign in the least significant bit of `EAX`). 1 is added to the final result if the sign is negative, for result correction.

Listing 43.5: Optimizing MSVC 2012

```
_f3_32_unsigned PROC
    mov     eax, -1431655765          ; aaaaaaabH
    mul     DWORD PTR _a$[esp-4] ; unsigned multiply
; EDX=(input*0xaaaaaaaaab)/2^32
    shr     edx, 1
; EDX=(input*0xaaaaaaaaab)/2^33
    mov     eax, edx
    ret     0
_f3_32_unsigned ENDP

_f3_32_signed PROC
    mov     eax, 1431655766          ; 555555556H
    imul    DWORD PTR _a$[esp-4] ; signed multiply
; take high part of product
; it is just the same as if to shift product by 32 bits right or to divide it by 2^32
    mov     eax, edx              ; EAX=EDX=(input*0x55555556)/2^32
_f3_32_signed ENDP
```

43.5. GETTING THE DIVISOR

```
    shr    eax, 31           ; 0000001fH
    add    eax, edx          ; add 1 if sign is negative
    ret    0
_f3_32_signed ENDP
```

43.4.1 More theory

It works, because that is how it's possible to replace division by multiplication:

$$\frac{x}{c} = x \frac{1}{c}$$

$\frac{1}{c}$ is called *multiplicative inverse* and can be precomputed by compiler.

But this is for real numbers. What about integers? It's possible to find *multiplicative inverse* for integer in the environment of modulo arithmetics³. CPU registers fits nicely: each is limited by 32 or 64 bits, so almost any arithmetic operation on registers are in fact operations on modulo 2^{32} or 2^{64} .

Read more about it in [[War02](#), pp. 10-3].

43.5 Getting the divisor

43.5.1 Variant #1

Often, the code looks like this:

```
    mov    eax, MAGICAL CONSTANT
    imul   input value
    sar    edx, SHIFTING COEFFICIENT ; signed division by  $2^x$  using arithmetic shift right
    mov    eax, edx
    shr    eax, 31
    add    eax, edx
```

Let's denote the 32-bit *magic coefficient* as M , the shifting coefficient as C and the divisor as D .

The divisor we need to get is:

$$D = \frac{2^{32+C}}{M}$$

For example:

Listing 43.6: Optimizing MSVC 2012

```
    mov    eax, 2021161081           ; 78787879H
    imul   DWORD PTR _a$[esp-4]
    sar    edx, 3
    mov    eax, edx
    shr    eax, 31                  ; 0000001fH
    add    eax, edx
```

This is:

$$D = \frac{2^{32+3}}{2021161081}$$

The numbers are larger than 32-bit, so we can use Wolfram Mathematica for convenience:

Listing 43.7: Wolfram Mathematica

```
In[1]:=N[2^(32+3)/2021161081]
Out[1]:=17.
```

³[Wikipedia](#)

43.6. EXERCISE

So the divisor from the code we used as example is 17.

For x64 division, things are the same, but 2^{64} has to be used instead of 2^{32} :

```
uint64_t f1234(uint64_t a)
{
    return a/1234;
};
```

Listing 43.8: Optimizing MSVC 2012 x64

```
f1234 PROC
    mov     rax, 7653754429286296943          ; 6a37991a23aead6fH
    mul     rcx
    shr     rdx, 9
    mov     rax, rdx
    ret     0
f1234 ENDP
```

Listing 43.9: Wolfram Mathematica

```
In[1]:=N[2^(64+9)/16^^6a37991a23aead6f]
Out[1]:=1234.
```

43.5.2 Variant #2

A variant with omitted arithmetic shift also exist:

```
        mov     eax, 55555556h ; 1431655766
        imul   ecx
        mov     eax, edx
        shr     eax, 1Fh
```

The method of getting divisor is simplified:

$$D = \frac{2^{32}}{M}$$

As of my example, this is:

$$D = \frac{2^{32}}{1431655766}$$

And again we use Wolfram Mathematica:

Listing 43.10: Wolfram Mathematica

```
In[1]:=N[2^32/16^^55555556]
Out[1]:=3.
```

The divisor is 3.

43.6 Exercise

- <http://challenges.re/27>

Chapter 44

String to number conversion (atoi())

Let's try to reimplement the standard atoi() C function.

44.1 Simple example

Here is the simplest possible way to read a number represented in ASCII¹ encoding. It's not error-prone: a character other than a digit leads to incorrect result.

```
#include <stdio.h>

int my_atoi (char *s)
{
    int rt=0;

    while (*s)
    {
        rt=rt*10 + (*s-'0');
        s++;
    };

    return rt;
};

int main()
{
    printf ("%d\n", my_atoi ("1234"));
    printf ("%d\n", my_atoi ("1234567890"));
}
```

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 need 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 no shift.

44.1.1 Optimizing MSVC 2013 x64

Listing 44.1: Optimizing MSVC 2013 x64

```
$\$ = 8
my_atoi PROC
; load first character
    movzx    r8d, BYTE PTR [rcx]
; EAX is allocated for "rt" variable
; its 0 at start'
    xor     eax, eax
```

¹American Standard Code for Information Interchange

44.1. SIMPLE EXAMPLE

```
; first character is zero-byte, i.e., string terminator?  
; exit then.  
    test    r8b, r8b  
    je      SHORT $LN9@my_atoi  
$LL2@my_atoi:  
    lea     edx, DWORD PTR [rax+rax*4]  
; EDX=RAX+RAX*4=rt+rt*4=rt*5  
    movsx   eax, r8b  
; EAX=input character  
; load next character to R8D  
    movzx   r8d, BYTE PTR [rcx+1]  
; shift pointer in RCX to the next character:  
    lea     rcx, QWORD PTR [rcx+1]  
    lea     eax, DWORD PTR [rax+rdx*2]  
; EAX=RAX+RDX*2=input character + rt*5*2=input character + rt*10  
; correct digit by subtracting 48 (0x30 or '0')  
    add    eax, -48                                ; ffffffffffffffd0H  
; was last character zero?  
    test   r8b, r8b  
; jump to loop begin, if not  
    jne    SHORT $LL2@my_atoi  
$LN9@my_atoi:  
    ret    0  
my_atoi ENDP
```

A character can be loaded in two places: the first character and all subsequent characters. This is done for loop regrouping. 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 than SUB. But MSVC does this often.

44.1.2 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 44.2: Optimizing GCC 4.9.1 x64

```
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  
    rep    ret  
.L4:  
    rep    ret
```

44.1.3 Optimizing Keil 6/2013 (ARM mode)

Listing 44.3: Optimizing Keil 6/2013 (ARM mode)

```
my_atoi PROC  
; R1 will contain pointer to character
```

44.1. SIMPLE EXAMPLE

```
        MOV      r1,r0
; R0 will contain "rt" variable
        MOV      r0,#0
        B       |L0.28|
|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
```

44.1.4 Optimizing Keil 6/2013 (Thumb mode)

Listing 44.4: Optimizing Keil 6/2013 (Thumb mode)

```
my_atoi PROC
; R1 will be pointer to the input character
        MOVS    r1,r0
; R0 is allocated to "rt" variable
        MOVS    r0,#0
        B      |L0.16|
|L0.6|
        MOVS    r3,#0xa
; R3=10
        MULS    r0,r3,r0
; R0=R3*R0=rt*10
; 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 remember that the order of addition and subtraction operations doesn't matter. That's our case: first, the $rt * 10 - '0'$ expression is computed, then the input character value is added to it. Indeed, the result is the same, but the compiler did some regrouping.

44.1.5 Optimizing GCC 4.9.1 ARM64

The ARM64 compiler can use the pre-increment instruction suffix:

Listing 44.5: Optimizing GCC 4.9.1 ARM64

```

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
; variable to be returned (rt) is in W0, ready to be used in caller function
    ret
.L4:
    mov     w0, w1
    ret

```

44.2 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 was found in the input string:

```

#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'\n", *s);
            exit(0);
        };
        rt=rt*10 + (*s-'0');
        s++;
    };

    if (negative)
        return -rt;
    return rt;
};

int main()
{
    printf ("%d\n", my_atoi ("1234"));
}

```

44.2. A SLIGHTLY ADVANCED EXAMPLE

```
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
};
```

44.2.1 Optimizing GCC 4.9.1 x64

Listing 44.6: Optimizing GCC 4.9.1 x64

```
.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:
; 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 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
```

44.2. A SLIGHTLY ADVANCED EXAMPLE

```
call    exit
```

If the “minus” sign was 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: [50.1.2 on page 529](#).

Optimizing MSVC 2013 x64 does the same tricks.

44.2.2 Optimizing Keil 6/2013 (ARM mode)

Listing 44.7: Optimizing Keil 6/2013 (ARM mode)

```
1 my_atoi PROC  
2     PUSH    {r4-r6,lr}  
3     MOV     r4,r0  
4     LDRB   r0,[r0,#0]  
5     MOV     r6,#0  
6     MOV     r5,r6  
7     CMP     r0,#0x2d '-'  
8 ; R6 will contain 1 if minus was encountered, 0 if otherwise  
9     MOVEQ   r6,#1  
10    ADDEQ   r4,r4,#1  
11    B      |L0.80|  
12 |L0.36|  
13    SUB     r0,r1,#0x30  
14    CMP     r0,#0xa  
15    BCC    |L0.64|  
16    ADR     r0,|L0.220|  
17    BL      __2printf  
18    MOV     r0,#0  
19    BL      exit  
20 |L0.64|  
21    LDRB   r0,[r4],#1  
22    ADD    r1,r5,r5,LSL #2  
23    ADD    r0,r0,r1,LSL #1  
24    SUB    r5,r0,#0x30  
25 |L0.80|  
26    LDRB   r1,[r4,#0]  
27    CMP     r1,#0  
28    BNE    |L0.36|  
29    CMP     r6,#0  
30 ; negate result  
31    RSBNE  r0,r5,#0  
32    MOVEQ   r0,r5  
33    POP    {r4-r6,pc}  
34    ENDP  
35  
36 |L0.220|  
37    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) was “Not Equal” (hence -NE suffix). So what RSBNE does is to subtract the resulting

44.3. EXERCISE

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.

44.3 Exercise

Oh, by the way, security researchers deals often with unpredictable behaviour 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. Try to explain, what happened and why.

Chapter 45

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 45.1: A simple example

```
#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\n", celsius_to_fahrenheit (celsius));
}
```

... is compiled in very predictable way, however, if we turn on GCC optimizations (`-O3`), we'll see:

Listing 45.2: 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 done by multiplication([43 on page 487](#)).)

Yes, our small function `celsius_to_fahrenheit()` was just 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.

45.1 Strings and memory functions

Another very common automatic optimization tactic is the inlining of string functions like `strcpy()`, `strcmp()`, `strlen()`, `memset()`, `memcmp()`, `memcpy()`, 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.

45.1.1 strcmp()

Listing 45.3: strcmp() example

```
bool is_bool (char *s)
{
    if (strcmp (s, "true") == 0)
        return true;
    if (strcmp (s, "false") == 0)
        return false;

    assert(0);
}
```

Listing 45.4: Optimizing GCC 4.8.1

```
.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 45.5: Optimizing MSVC 2010

\$SG3454 DB	'true', 00H
-------------	-------------

45.1. STRINGS AND MEMORY FUNCTIONS

```

$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
$LL6@is_bool:
    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
$LN9@is_bool:
    test   eax, eax
    jne    SHORT $LN2@is_bool

    mov    al, 1
    pop    esi

    ret    0
$LN2@is_bool:

    mov    ecx, OFFSET $SG3456 ; 'false'
    mov    eax, esi
$LL10@is_bool:
    mov    dl, BYTE PTR [eax]
    cmp    dl, BYTE PTR [ecx]
    jne    SHORT $LN11@is_bool
    test   dl, dl
    je     SHORT $LN12@is_bool
    mov    dl, BYTE PTR [eax+1]
    cmp    dl, BYTE PTR [ecx+1]
    jne    SHORT $LN11@is_bool
    add    eax, 2
    add    ecx, 2
    test   dl, dl
    jne    SHORT $LL10@is_bool
$LN12@is_bool:
    xor    eax, eax
    jmp    SHORT $LN13@is_bool
$LN11@is_bool:
    sbb    eax, eax
    sbb    eax, -1
$LN13@is_bool:
    test   eax, eax
    jne    SHORT $LN1@is_bool

    xor    al, al
    pop    esi

    ret    0
$LN1@is_bool:

    push   11

```

45.1. STRINGS AND MEMORY FUNCTIONS

```
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
```

45.1.2 strlen()

Listing 45.6: strlen() example

```
int strlen_test(char *s1)
{
    return strlen(s1);
};
```

Listing 45.7: Optimizing MSVC 2010

```
_s1$ = 8 ; size = 4
_strlen_test PROC
    mov    eax, DWORD PTR _s1$[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
```

45.1.3 strcpy()

Listing 45.8: strcpy() example

```
void strcpy_test(char *s1, char *outbuf)
{
    strcpy(outbuf, s1);
};
```

Listing 45.9: Optimizing MSVC 2010

```
_s1$ = 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
```

45.1.4 memset()

Example#1

Listing 45.10: 32 bytes

```
#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 `MOV`s:

Listing 45.11: Optimizing GCC 4.9.1 x64

```
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: [15.1.4 on page 191](#).

Example#2

Listing 45.12: 67 bytes

```
#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 `MOV`s:

Listing 45.13: Optimizing MSVC 2012 x64

```
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 `MOV`s:

Listing 45.14: Optimizing GCC 4.9.1 x64

```
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
```

45.1.5 memcpy()**Short blocks**

The routine to copy short blocks is often implemented as a sequence of `MOV` instructions.

Listing 45.15: `memcpy()` example

```
void memcpy_7(char *inbuf, char *outbuf)
{
    memcpy(outbuf+10, inbuf, 7);
};
```

Listing 45.16: 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 45.17: 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 : 22.4.1 on page 360](#).

Long blocks

The compilers behave differently in this case.

Listing 45.18: `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 45.19: Optimizing MSVC 2010

```
_inbuf$ = 8           ; size = 4
_outbuf$ = 12          ; size = 4
_memcpy_128 PROC
    push    esi
    mov     esi, DWORD PTR _inbuf$[esp]
    push    edi
    mov     edi, DWORD PTR _outbuf$[esp+4]
    add    edi, 10
    mov    ecx, 32
    rep    movsd
    pop    edi
    pop    esi
    ret    0
_memcpy_128 ENDP
```

When copying 123 bytes, 30 32-byte words are copied first using `MOVSD` (that's 120 bytes), then 2 bytes are copied using `MOVSW`, then one more byte using `MOVSB`.

Listing 45.20: Optimizing MSVC 2010

```
_inbuf$ = 8           ; size = 4
_outbuf$ = 12          ; size = 4
_memcpy_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
_memcpy_123 ENDP
```

GCC uses one big universal functions, that works for any block size:

Listing 45.21: Optimizing GCC 4.8.1

```
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:
```

45.1. STRINGS AND MEMORY FUNCTIONS

```
    pop    esi
    pop    edi
    ret
.L24:
    movzx  eax, BYTE PTR [esi]
    lea    edi, [edx+11]
    add    esi, 1
    test   edi, 2
    mov    BYTE PTR [edx+10], al
    mov    eax, 122
    je     .L7
.L25:
    movzx  edx, WORD PTR [esi]
    add    edi, 2
    add    esi, 2
    sub    eax, 2
    mov    WORD PTR [edi-2], dx
    jmp    .L7
.LFE3:
```

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 complex copy functions use [SIMD](#) instructions and also take the memory alignment in consideration. As an example of SIMD `strlen()` function: [26.2 on page 416](#).

45.1.6 `memcmp()`

Listing 45.22: `memcmp()` example

```
void memcpy_1235(char *inbuf, char *outbuf)
{
    memcpy(outbuf+10, inbuf, 1235);
}
```

For any block size, MSVC 2010 inserts the same universal function:

Listing 45.23: Optimizing MSVC 2010

```
_buf1$ = 8      ; size = 4
_buf2$ = 12     ; size = 4
 memcmp_1235 PROC
    mov    edx, DWORD PTR _buf2$[esp-4]
    mov    ecx, DWORD PTR _buf1$[esp-4]
    push   esi
    push   edi
    mov    esi, 1235
    add    edx, 10
$LL4@memcmp_123:
    mov    eax, DWORD PTR [edx]
    cmp    eax, DWORD PTR [ecx]
    jne    SHORT $LN10@memcmp_123
    sub    esi, 4
    add    ecx, 4
    add    edx, 4
    cmp    esi, 4
    jae    SHORT $LL4@memcmp_123
$LN10@memcmp_123:
    movzx  edi, BYTE PTR [ecx]
    movzx  eax, BYTE PTR [edx]
    sub    eax, edi
    jne    SHORT $LN7@memcmp_123
    movzx  eax, BYTE PTR [edx+1]
    movzx  edi, BYTE PTR [ecx+1]
    sub    eax, edi
    jne    SHORT $LN7@memcmp_123
    movzx  eax, BYTE PTR [edx+2]
    movzx  edi, BYTE PTR [ecx+2]
    sub    eax, edi
```

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```
jne    SHORT $LN7@memcmp_123
cmp    esi, 3
jbe    SHORT $LN6@memcmp_123
movzx  eax, BYTE PTR [edx+3]
movzx  ecx, BYTE PTR [ecx+3]
sub    eax, ecx
$LN7@memcmp_123:
    sar    eax, 31
    pop    edi
    or     eax, 1
    pop    esi
    ret    0
$LN6@memcmp_123:
    pop    edi
    xor    eax, eax
    pop    esi
    ret    0
 memcmp_1235 ENDP
```

45.1.7 strcat()

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 45.24: strcat()

```
lea    edi, [src]
or    ecx, 0FFFFFFFh
repne scasb
not   ecx
sub    edi, ecx
mov    esi, edi
mov    edi, [dst]
mov    edx, ecx
or    ecx, 0FFFFFFFh
repne scasb
mov    ecx, edx
dec    edi
shr    ecx, 2
rep    movsd
mov    ecx, edx
and    ecx, 3
rep    movsb
```

45.1.8 IDA script

There is also a small [IDA](#) script for searching and folding such very frequently seen pieces of inline code:
[GitHub](#).

Chapter 46

C99 restrict

Here is a reason why FORTRAN programs, in some cases, work faster than C/C++ ones.

```
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]`
- 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 was overwritten in 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 was not changed.

`restrict` in the C99 standard[[ISO07](#), pp. 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:

```
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 46.1: GCC x64: f1()

```
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  
    mov     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[]  
    jne    .L6  
.L1:  
    pop    rbx rsi rdi rbp r12 r13 r14 r15  
    ret
```

Listing 46.2: GCC x64: f2()

```
f2:  
    push    r13 r12 rbp rdi rsi rbx  
    mov     r13, QWORD PTR 104[rsp]  
    mov     rbp, QWORD PTR 88[rsp]  
    mov     r12, QWORD PTR 96[rsp]  
    test    r13, r13  
    je      .L7  
    add    r13, 1  
    xor     r10d, r10d  
    mov     edi, 1  
    xor     eax, eax  
    jmp    .L10  
.L11:  
    mov     rax, rdi  
    mov     rdi, r11  
.L10:  
    mov     esi, DWORD PTR [rcx+rax*4]  
    mov     r11d, DWORD PTR [rdx+rax*4]  
    mov     DWORD PTR [r12+rax*4], r10d ; store to update_me[]  
    add    r10d, 123  
    lea     ebx, [rsi+r11]  
    imul   r11d, esi  
    mov     DWORD PTR [r8+rax*4], ebx      ; store to sum[]
```

```

    mov    DWORD PTR [r9+rax*4], r11d ; store to product[]
    add    r11d, ebx
    mov    DWORD PTR 0[rbp+rax*4], r11d ; store to sum_product[]
    lea    r11, 1[rdi]
    cmp    r11, r13
    jne    .L11
.L7:
    pop    rbx rsi rdi rbp r12 r13
    ret

```

The difference between the compiled `f1()` and `f2()` functions is as follows: in `f1()`, `sum[i]` and `product[i]` are reloaded in the middle of the loop, and in `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 `sum[i]` and `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 `restrict` in C, FORTRAN can 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. A lot of linear algebra is done on supercomputers/HPC¹, so probably that is why, traditionally, FORTRAN is still used there [[Loh10](#)].

But when the number of iterations is not very big, certainly, the speed boost may not to be significant.

¹High-Performance Computing

Chapter 47

Branchless *abs()* function

Let's revisit an example we considered earlier [13.2 on page 141](#) and ask ourselves, is it possible to make a branchless version of the function in x86 code?

```
int my_abs (int i)
{
    if (i<0)
        return -i;
    else
        return i;
};
```

And the answer is yes.

47.1 Optimizing GCC 4.9.1 x64

We could see it if we compile it using optimizing GCC 4.9:

Listing 47.1: 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 left 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 was 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: [31 on page 448](#).

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 [[War02](#), pp. 2-4]. It's hard to say, how GCC did it, deduced it by itself or found a suitable pattern among known ones?

47.2 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.

Listing 47.2: Optimizing GCC 4.9 ARM64

```
my_abs:  
; sign-extend input 32-bit value to X0 64-bit register:  
    sxtw    x0, w0  
    eor     x1, x0, x0, asr 63  
; X1=X0^(X0>>63) (shift is arithmetical)  
    sub     x0, x1, x0, asr 63  
; X0=X1-(X0>>63)=X0^(X0>>63)-(X0>>63) (all shifts are arithmetical)  
    ret
```

Chapter 48

Variadic functions

Functions like `printf()` and `scanf()` can have a variable number of arguments. How are these arguments accessed?

48.1 Computing arithmetic mean

Let's imagine that we need to calculate [arithmetic mean](#), and for some weird reason we need 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.

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.

```
#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?

48.1.1 `cdecl` calling conventions

Listing 48.1: 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.

48.1.2 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 48.2: Optimizing MSVC 2012 x64

```

$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

```

48.1. COMPUTING ARITHMETIC MEAN

```

    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
    lea    rcx, QWORD PTR [rcx+8] ; shift pointer to point to the argument after next
    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+5]
    lea    ecx, 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 48.3: Optimizing GCC 4.9.1 x64

```

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]
    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

```

48.2. VPRINTF() FUNCTION CASE

```
    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 : [67.8 on page 696](#).

48.2 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`:

```
#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:

```

_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 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 48.5: Optimizing MSVC 2012 x64

```

fmt$ = 48
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

```

Chapter 49

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 ([CR¹/LF²](#)) from the end of the input string:

```
#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
            break;
    };
    return s;
};

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\r")));
    printf ("%s\n", str_trim (strdup("\r\n")));
    printf ("%s\n", str_trim (strdup("test1\r\n")));
    printf ("%s\n", str_trim (strdup("test2\n\r")));
    printf ("%s\n", str Trim (strdup("test3\n\r\n\r")));
    printf ("%s\n", str Trim (strdup("test4\n")));
    printf ("%s\n", str Trim (strdup("test5\r")));
    printf ("%s\n", str Trim (strdup("test6\r\r\r")));
}
```

The input argument is always returned on exit, this is convenient when you need to chain string processing functions, like it was done here in the `main()` function.

¹Carriage return (13 or '\r' in C/C++)

²Line feed (10 or '\n' in C/C++)

49.1. X64: OPTIMIZING MSVC 2013

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 [Yur13, p. 1.3.8]. 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.

49.1 x64: Optimizing MSVC 2013

Listing 49.1: Optimizing MSVC 2013 x64

```
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 0xFFFFFFFFFFFFFF (-1)
    or      rax, -1
$LL14@str_trim:
    inc     rax
    cmp     BYTE PTR [rcx+rax], 0
    jne     SHORT $LL14@str_trim
; is the input string length zero? exit then:
    test    rax, rax
    je      SHORT $LN15@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
; R8 = 1-s
$LL6@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
    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: [45 on page 500](#).

The first instruction of the inlined `strlen()` is `OR RAX, 0xFFFFFFFFFFFFFF`. It's hard to say why MSVC uses `OR` instead of `MOV RAX, 0xFFFFFFFFFFFFFF`, but it does this often. And of course, it is equivalent: all bits are set, and a number with all bits set is -1 in two's complement arithmetic: [31 on page 448](#).

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 49.2: Inlined `strlen()` by MSVC 2013 x64

```
; 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's try:

Listing 49.3: Our version of `strlen()`

```
; 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 need 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.

49.2 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"
```

49.3. X64: OPTIMIZING GCC 4.9.1

```
    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

49.3 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--
```

49.4. ARM64: NON-OPTIMIZING GCC (LINARO) 4.9

```
; 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 modern CPUs.

The code doesn't use the str_len variable, but str_len-1. So this is more like an index in a buffer. 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).

49.4 ARM64: Non-optimizing GCC (Linaro) 4.9

This implementation is straightforward:

Listing 49.4: 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
    b       .L2
; main loop begin
.L5:
; W0=c
    ldrb    w0, [x29,39]
; W0=c
    cmp     w0, 13      ; is it '\r'?
    beq    .L3
    ldrb    w0, [x29,39]
; W0=c
    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
```

49.5. ARM64: OPTIMIZING GCC (LINARO) 4.9

```

        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
        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
; 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:
; return s
        ldr     x0, [x29,24]
        ldp    x29, x30, [sp], 48
        ret

```

49.5 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 [49.3 on page 522](#) example.

Listing 49.5: 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

```

49.6. ARM: OPTIMIZING KEIL 6/2013 (ARM MODE)

```
; 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
```

49.6 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 49.6: Optimizing Keil 6/2013 (ARM mode)

```
str_trim PROC
    PUSH    {r4,lr}
; 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 '\r'?
    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 R2-1=s+str_len-1
    BEQ    |L0.16|        ; jump to loop begin if loaded byte was '\r' or '\n'
|L0.56|
; return "s"
    MOV     r0,r4
    POP    {r4,pc}
ENDP
```

49.7 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 0x19 offsets. Why did the Keil compiler do so? Honestly, it's hard to say. Probably, this is a quirk of Keil's optimization process. Nevertheless, the code works correctly.

Listing 49.7: Optimizing Keil 6/2013 (Thumb mode)

```
str_trim PROC
    PUSH    {r4,lr}
    MOVS   r4,r0
; R4=s
    BL     strlen      ; strlen() takes "s" value from R0
; R0=str_len
```

49.8. MIPS

```

        MOVS    r3,#0
; R3 will always hold 0
        B      |L0.24|
|L0.12|
        CMP    r1,#0xd      ; is loaded byte '\r'?
        BEQ    |L0.20|
        CMP    r1,#0xa      ; is loaded byte '\n'?
        BNE    |L0.38|      ; jump to exit, if no
|L0.20|
        SUBS   r0,r0,#1      ; R0-- or str_len--
        STRB   r3,[r2,#0x1f] ; store 0 at address R2+0x1F=s+str_len-0x20+0x1F=s+str_len-1
|L0.24|
        CMP    r0,#0      ; str_len==0?
        BEQ    |L0.38|      ; yes? jump to exit
        ADDS   r2,r4,r0      ; R2=R4+R0=s+str_len
        SUBS   r2,r2,#0x20      ; R2=R2-0x20=s+str_len-0x20
        LDRB   r1,[r2,#0x1f] ; load byte at
address R2+0x1F=s+str_len-0x20+0x1F=s+str_len-1 to R1
        CMP    r1,#0      ; is loaded byte 0?
        BNE    |L0.12|      ; jump to loop begin, if its not 0'
|L0.38|
; return "s"
        MOVS   r0,r4
        POP    {r4,pc}
        ENDP

```

49.8 MIPS

Listing 49.8: 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+strlen-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

```

49.8. MIPS

```
; 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)
        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.

Chapter 50

toupper() function

Another very popular function transforms a symbol from lower case to upper case, if needed:

```
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 ¹.

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:

Characters in the coded character set ascii.																
0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	
0x C-@	C-a	C-b	C-c	C-d	C-e	C-f	C-g	C-h	TAB	C-j	C-k	C-l	RET	C-n	C-o	
1x C-p	C-q	C-r	C-s	C-t	C-u	C-v	C-w	C-x	C-y	C-z	ESC	C-\	C-]	C-^	C-_	
2x !	"	#	\$	%	&	'	()	*	+	,	-	.	/			
3x 0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?	
4x @	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	
5x P	Q	R	S	T	U	V	W	X	Y	Z	[\]	^		
6x ^	a	b	c	d	e	f	g	h	i	j	k	l	m	n	o	
7x p	q	r	s	t	u	v	w	x	y	z	{	}	~		DEL	

Figure 50.1: 7-bit [ASCII](#) table in Emacs

50.1 x64

50.1.1 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 artefact:

Listing 50.1: 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     jle    SHORT $LN2@toupper
7     movsx  eax, BYTE PTR c$[rsp]
```

¹However, to be meticulous, there still could be compilers which can't optimize such expressions and will leave them right in the code.

50.1. X64

```
8      cmp    eax, 122
9      jg     SHORT $LN2@toupper
10     movsx  eax, BYTE PTR c$[rsp]
11     sub    eax, 32
12     jmp    SHORT $LN3@toupper
13     jmp    SHORT $LN1@toupper ; compiler artifact
14 $LN2@toupper:
15     movzx  eax, BYTE PTR c$[rsp] ; unnecessary casting
16 $LN1@toupper:
17 $LN3@toupper: ; compiler artifact
18     ret    0
19 toupper ENDP
```

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 50.2: 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
```

50.1.2 One comparison operation

Optimizing MSVC does a better job, it generates only one comparison operation:

Listing 50.3: 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
```

It was explained earlier how to replace the two comparison operations with a single one : [44.2.1 on page 498](#).

We will now rewrite this in C/C++:

```
int tmp=c-97;
if (tmp>25)
    return c;
else
    return c-32;
```

50.2. ARM

The `tmp` variable should 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: [35.1 on page 455](#)) by using the CMOVcc instruction:

Listing 50.4: Optimizing GCC 4.9 (x64)

```
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.

50.2 ARM

Optimizing Keil for ARM mode also generates only one comparison:

Listing 50.5: Optimizing Keil 6/2013 (ARM mode)

```
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 50.6: Optimizing Keil 6/2013 (Thumb mode)

```
toupper PROC  
    MOVS   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.

50.2.1 GCC for ARM64

Listing 50.7: Non-optimizing GCC 4.9 (ARM64)

```
toupper:  
    sub    sp, sp, #16  
    strb  w0, [sp,15]  
    ldrb  w0, [sp,15]  
    cmp    w0, 96  
    bls    .L2  
    ldrb  w0, [sp,15]  
    cmp    w0, 122
```

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```
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 50.8: Optimizing GCC 4.9 (ARM64)

```
toupper:
uxtb   w0, w0
sub    w1, w0, #97
uxtb   w1, w1
cmp    w1, 25
bhi   .L2
sub    w0, w0, #32
uxtb   w0, w0
.L2:
ret
```

50.3 Summary

All these compiler optimizations are very popular nowadays and a practicing reverse engineer usually sees such code patterns often.

Chapter 51

Incorrectly disassembled code

Practicing reverse engineers often have to deal with incorrectly disassembled code.

51.1 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-2D0h], 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]
```

51.2. HOW DOES RANDOM NOISE LOOKS DISASSEMBLED?

```
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.

51.2 How does random noise looks 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 51.1: random noise (x86)

```
mov    b1, 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
```

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```
das
db      64h
pop    ecx
das
hlt

pop    edx
out   0B0h, 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
mov   esi, 659D1985h
```

Listing 51.2: random noise (x86-64)

```
lea    esi, [rax+rdx*4+43558D29h]

loc_AF3: ; CODE XREF: seg000:000000000000000B46
rcl    byte ptr [rsi+rax*8+29BB423Ah], 1
lea    ecx, cs:0FFFFFFFB2A6780Fh
mov    al, 96h
mov    ah, 0CEh
push   rsp
lodsd  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]
stosd
int   87h
db    46h, 4Ch
out   33h, rax
xchg  eax, ebp
test  ecx, ebp
movsd
leave
push   rsp

db 16h

xchg  eax, esi
pop   rdi
```

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```
loc_B3D: ; CODE XREF: seg000:00000000000000B5F
    mov      ds:93CA685DF98A90F9h, eax
    jnz      short near ptr loc_AF3+6
    out     dx, eax
    cwde
    mov      bh, 5Dh ; ']'
    movsb
    pop     rbp
```

Listing 51.3: 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
CMNHIP PC, R10, LSL#22
FLDMIADNV LR!, {D4}
MCR   p5, 2, R2,c15,c6, 4
BLGE 0x1139558
BLGT 0xFF9146E4
STRNEB R5, [R4],#0xCA2
STMNEIB R5, {R0,R4,R6,R7,R9-SP,PC}
STMIA R8, {R0,R2-R4,R7,R8,R10,SP,LR}^
STRB  SP, [R8],PC,ROR#18
LDCCS p9, c13, [R6,#0x1BC]
LDRGE R8, [R9,#0x66E]
STRNEB R5, [R8],#-0x8C3
STCCSL p15, c9, [R7,#-0x84]
RSBLS LR, R2, R11,ASR LR
SVCGT 0x9B0362
SVCGT 0xA73173
STMNEDB R11!, {R0,R1,R4-R6,R8,R10,R11,SP}
STR   R0, [R3],#-0xCE4
LDCGT p15, c8, [R1,#0x2CC]
LDRCCB R1, [R11],-R7,ROR#30
BLLT 0xFED9D58C
BL   0x13E60F4
LDMVSIB R3!, {R1,R4-R7}^
USATNE R10, #7, SP, LSL#11
LDRGEB LR, [R1],#0xE56
STRPLT R9, [LR],#0x567
LDRLT R11, [R1],#-0x29B
SVCNV 0x12DB29
MVNNVS R5, SP, LSL#25
LDCL  p8, c14, [R12,#-0x288]
STCNEL p2, c6, [R6,#-0xBC]!
SVCNV 0x2E5A2F
BLX   0x1A8C97E
TEQGE R3, #0x1100000
STMLSIA R6, {R3,R6,R10,R11,SP}
BICPLS R12, R2, #0x5800
BNE   0x7CC408
TEQGE R2, R4, LSL#20
SUBS  R1, R11, #0x28C
BICVS R3, R12, R7,ASR R0
LDRMI R7, [LR],R3, LSL#21
BLMI  0x1A79234
STMVCDB R6, {R0-R3,R6,R7,R10,R11}
EORMI R12, R6, #0xC5
MCRRCS p1, 0xF, R1,R3,c2
```

Listing 51.4: random noise (ARM (Thumb mode))

```
LSRS  R3, R6, #0x12
LDRH  R1, [R7,#0x2C]
SUBS  R0, #0x55 ; 'U'
ADR   R1, loc_3C
```

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```

LDR    R2, [SP,#0x218]
CMP    R4, #0x86
SXTB   R7, R4
LDR    R4, [R1,#0x4C]
STR    R4, [R4,R2]
STR    R0, [R6,#0x20]
BGT    0xFFFFFFF72
LDRH   R7, [R2,#0x34]
LDRSH  R0, [R2,R4]
LDRB   R2, [R7,R2]

DCB 0x17
DCB 0xED

STRB   R3, [R1,R1]
STR    R5, [R0,#0x6C]
LDMIA  R3, {R0-R5,R7}
ASRS   R3, R2, #3
LDR    R4, [SP,#0x2C4]
SVC    0xB5
LDR    R6, [R1,#0x40]
LDR    R5, =0xB2C5CA32
STMIA  R6, {R1-R4,R6}
LDR    R1, [R3,#0x3C]
STR    R1, [R5,#0x60]
BCC    0xFFFFFFF70
LDR    R4, [SP,#0x1D4]
STR    R5, [R5,#0x40]
ORRS   R5, R7

loc_3C ; DATA XREF: ROM:00000006
B      0xFFFFFFF98

```

Listing 51.5: random noise (MIPS little endian)

```

lw      $t9, 0xCB3($t5)
sb      $t5, 0x3855($t0)
sltiu  $a2, $a0, -0x657A
ldr     $t4, -0x4D99($a2)
daddi  $s0, $s1, 0x50A4
lw      $s7, -0x2353($s4)
bgtzl $a1, 0x17C5C

.byte 0x17
.byte 0xED
.byte 0x4B # K
.byte 0x54 # T

lwc2   $31, 0x66C5($sp)
lwu    $s1, 0x10D3($a1)
ldr     $t6, -0x204B($zero)
lwc1   $f30, 0x4DBE($s2)
daddiu $t1, $s1, 0x6BD9
lwu    $s5, -0x2C64($v1)
cop0   0x13D642D
bne   $gp, $t4, 0xFFFF9EF0
lh    $ra, 0x1819($s1)
sdl   $fp, -0x6474($t8)
jal   0x78C0050
ori   $v0, $s2, 0xC634
blez  $gp, 0xFFFFEA9D4
swl   $t8, -0x2CD4($s2)
sltiu $a1, $k0, 0x685
sdc1   $f15, 0x5964($at)
sw    $s0, -0x19A6($a1)
sltiu $t6, $a3, -0x66AD
lb    $t7, -0x4F6($t3)
sd    $fp, 0x4B02($a1)

```

It is also important to keep in mind that cleverly constructed unpacking and decryption code (including self-modifying) may

51.2. HOW DOES RANDOM NOISE LOOKS DISASSEMBLED?

looks like noise as well, but still execute correctly.

Chapter 52

Obfuscation

The obfuscation is an attempt to hide the code (or its meaning) from reverse engineers.

52.1 Text strings

As we saw in ([60 on page 666](#)) , 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 is also can be compared with another one like this:

```
mov    ebx, offset username
cmp    byte ptr [ebx], 'j'
jnz    fail
cmp    byte ptr [ebx+1], 'o'
jnz    fail
cmp    byte ptr [ebx+2], 'h'
jnz    fail
cmp    byte ptr [ebx+3], 'n'
jnz    fail
jz     it_is_john
```

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](#) or in shellcode.

Another method is to use `sprintf()` for the construction:

```
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: [81.2 on page 779](#).

52.2 Executable code

52.2.1 Inserting garbage

Executable code obfuscation implies inserting random garbage code between real one, which executes but does nothing useful.

A simple example:

Listing 52.1: original code

```
add    eax, ebx
mul    ecx
```

Listing 52.2: obfuscated code

```
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?

52.2.2 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
- PUSH op can also be replaced with the following instructions pair: SUB ESP, 4 (or 8) / MOV [ESP], op .

52.2.3 Always executed/never executed code

If the developer is sure that ESI at always 0 at that point:

```
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):

```
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.
```

52.2.4 Making a lot of mess

```
instruction 1
instruction 2
instruction 3
```

Can be replaced with:

```
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:
```

52.2.5 Using indirect pointers

```
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.

52.3 Virtual machine / pseudo-code

A programmer can construct his/her own PL or ISA and interpreter for it.

(Like the pre-5.0 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. Probably, he/she will also have to write a disassembler/decompiler of some sort.

52.4 Other things to mention

My own (yet weak) attempt to patch the Tiny C compiler to produce obfuscated code: <http://go.yurichev.com/17220>.

Using the `MOV` instruction for really complicated things: [Dol13].

52.5 Exercise

- <http://challenges.re/29>

Chapter 53

C++

53.1 Classes

53.1.1 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:

```
#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);
    };
};

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:

```

_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` ([53.1.1](#))—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 [OOP](#)¹.

The `dump()` function is called two times.

Now let's see the constructors' code:

```

_this$ = -4 ; size = 4
??0c@@QAE@XZ 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 DWORD PTR [eax], 667
    mov ecx, DWORD PTR _this$[ebp]
    mov DWORD PTR [ecx+4], 999
    mov eax, DWORD PTR _this$[ebp]
    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

```

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```
??0c@@QAE@HH@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$[ebp]
    mov  DWORD PTR [edx+4], eax
    mov  eax, DWORD PTR _this$[ebp]
    mov  esp, ebp
    pop  ebp
    ret  8
??0c@@QAE@HH@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 [[ISO13](#), p. 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:

Listing 53.3: MSVC

```
_this$ = -4           ; size = 4
?dump@c@@QAEXXXZ PROC ; c::dump, 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
?dump@c@@QAEXXXZ 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`):

Listing 53.4: MSVC

```
??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
```

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```
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@c@@QAEXXZ PROC ; c::dump, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx+4]
    mov  ecx, DWORD PTR [ecx]
    push eax
    push ecx
    push OFFSET ??_C@_07NJBDCIEC@?$CFd?$DL?5?$CFd?6?$AA@
    call _printf
    add  esp, 12
    ret  0
?dump@c@@QAEXXZ ENDP ; c::dump
```

That's all. The other thing we need to note is that the [stack pointer](#) was not corrected with `add esp, X` after the constructor was called. At the same time, the constructor has `ret 8` instead of `RET` at the end.

This is all because the [thiscall](#) ([53.1.1 on page 543](#)) calling convention is used here, which together with the [stdcall](#) ([67.2 on page 690](#)) 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 ([67 on page 690](#)).

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:

Listing 53.5: Optimizing MSVC 2012 x64

```
; void dump()

?dump@c@@QEAXXZ PROC ; c::dump
    mov    r8d, 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@c@@QEAXXZ ENDP ; c::dump

; c(int a, int b)

??0c@@QEAA@HH@Z PROC ; c::c
    mov    DWORD PTR [rcx], edx ; 1st argument: a
    mov    DWORD PTR [rcx+4], r8d ; 2nd argument: b
    mov    rax, rcx
    ret    0
??0c@@QEAA@HH@Z ENDP ; c::c

; default ctor

??0c@@QEAA@XZ PROC ; c::c
    mov    DWORD PTR [rcx], 667
    mov    DWORD PTR [rcx+4], 999
    mov    rax, rcx
    ret    0
??0c@@QEAA@XZ ENDP ; c::c
```

The *int* data type is still 32-bit in x64², so that is why 32-bit register parts are used here.

² Apparently, for easier porting of 32-bit C/C++ code to x64

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We also see `JMP printf` instead of `RET` in the `dump()` method, that *hack* we already saw earlier: [14.1.1 on page 154](#).

GCC-x86

It is almost the same story in GCC 4.4.1, with a few exceptions.

Listing 53.6: GCC 4.4.1

```
public main
main proc near

var_20 = dword ptr -20h
var_1C = dword ptr -1Ch
var_18 = dword ptr -18h
var_10 = dword ptr -10h
var_8  = dword ptr -8

push ebp
mov  ebp, esp
and  esp, OFFFFFFFF0h
sub  esp, 20h
lea   eax, [esp+20h+var_8]
mov  [esp+20h+var_20], eax
call _ZN1cC1Ev
mov  [esp+20h+var_18], 6
mov  [esp+20h+var_1C], 5
lea   eax, [esp+20h+var_10]
mov  [esp+20h+var_20], eax
call _ZN1cC1Eii
lea   eax, [esp+20h+var_8]
mov  [esp+20h+var_20], eax
call _ZN1c4dumpEv
lea   eax, [esp+20h+var_10]
mov  [esp+20h+var_20], eax
call _ZN1c4dumpEv
mov  eax, 0
leave
retn
main endp
```

Here we see another *name mangling* style, specific to GNU³. 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:

```
_ZN1cC1Ev    public _ZN1cC1Ev ; weak
                proc near           ; CODE XREF: main+10
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:

```
_ZN1cC1Eii   public _ZN1cC1Eii
                proc near
arg_0          = dword ptr  8
```

³There is a good document about the various name mangling conventions in different compilers: [\[Fog14\]](#).

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```
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:

```
void ZN1cC1Eii (int *obj, int a, int b)
{
    *obj=a;
    *(obj+1)=b;
}
```

...and that is completely predictable.

Now the `dump()` function:

```
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:

```
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 `RCX`, `RDX`, `RCX`, `R8` and `R9` [Mit13] registers, and the pointer to *this* via the first one (`RCX`) 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.

```
; default ctor

_ZN1cC2Ev:
    mov  DWORD PTR [rdi], 667
    mov  DWORD PTR [rdi+4], 999
    ret

; c(int a, int b)

_ZN1cC2Ei:
    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
```

53.1.2 Class inheritance

Inherited classes are similar to the simple structures we already discussed, but extended in inheritable classes.

Let's take this simple example:

```
#include <stdio.h>

class object
{
public:
    int color;
    object() { };
    object (int color) { this->color=color; };
    void print_color() { 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;
    };
}
```

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```

        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` options⁴

Listing 53.8: Optimizing MSVC 2008 /Ob0

```

??_C@_09GCEDOLPA@color?$DN?$CFd?6?$AA@ DB 'color=%d', 0aH, 00H ; `string'
?print_color@object@@QAEXXZ PROC ; object::print_color, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx]
    push eax

; 'color=%d', 0aH, 00H
    push OFFSET ??_C@_09GCEDOLPA@color?$DN?$CFd?6?$AA@
    call _printf
    add  esp, 8
    ret  0
?print_color@object@@QAEXXZ ENDP ; object::print_color

```

Listing 53.9: 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@
    call _printf
    add  esp, 20
    ret  0
?dump@box@@QAEXXZ ENDP ; box::dump

```

Listing 53.10: Optimizing MSVC 2008 /Ob0

```

?dump@sphere@@QAEXXZ PROC ; sphere::dump, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx+4]
    mov  ecx, DWORD PTR [ecx]

```

⁴The `/Ob0` option stands for disabling inline expansion since function inlining can make our experiment harder

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```

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*)

offset	description
+0x0	int color

(inherited classes)

box:

offset	description
+0x0	int color
+0x4	int width
+0x8	int height
+0xC	int depth

sphere:

offset	description
+0x0	int color
+0x4	int radius

Let's see `main()` function body:

Listing 53.11: 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
    lea ecx, DWORD PTR _b$[esp+40]
    call ??0box@@QAE@HHHH@Z ; box::box
    push 40
    push 2
    lea ecx, DWORD PTR _s$[esp+32]
    call ??0sphere@@QAE@HH@Z ; sphere::sphere
    lea ecx, DWORD PTR _b$[esp+24]
    call ?print_color@object@@QAEXXZ ; object::print_color
    lea ecx, DWORD PTR _s$[esp+24]
    call ?print_color@object@@QAEXXZ ; object::print_color
    lea ecx, DWORD PTR _b$[esp+24]
    call ?dump@box@@QAEXXZ ; box::dump
    lea ecx, DWORD PTR _s$[esp+24]
    call ?dump@sphere@@QAEXXZ ; sphere::dump
    xor eax, eax
    add esp, 24
    ret 0
_main ENDP

```

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, 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).

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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/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 was explained above, it is passed as the first argument instead of using the `ECX` register).

53.1.3 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 about the fact that some field is private and some other—not?

No, there are no such marks.

Let's try this simple example:

```
#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);
        };
};
```

Let's compile it again in MSVC 2008 with `/Ox` and `/Ob0` options and see the `box::dump()` method code:

```
?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@_0D@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:

offset	description
+0x0	int color
+0x4	int width
+0x8	int height
+0xC	int depth

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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:

```
void hack_oop_encapsulation(class box * o)
{
    o->width=1; // that code cant 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.

```
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`:

```
?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:

```
int main()
{
    box b(1, 10, 20, 30);

    b.dump();

    hack_oop_encapsulation(&b);

    b.dump();

    return 0;
};
```

Let's run:

```
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*.

53.1.4 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:

```
#include <stdio.h>

class box
{
public:
    int width, height, depth;
    box() { };
    box(int width, int height, int depth)
    {
        this->width=width;
```

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```
        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;
        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 53.12: Optimizing MSVC 2008 /Ob0

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```
?dump@box@@QAEXXZ PROC ; box::dump, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx+8]
    mov  edx, DWORD PTR [ecx+4]
    push eax
    mov  eax, DWORD PTR [ecx]
    push edx
    push eax
; 'this is box. width=%d, height=%d, depth=%d', 0aH, 00H
    push OFFSET ??_C@_0CM@DIKPHDFI@this?5is?5box?4?5width?$DN?$CFd?0?5height?$DN?$CFd@
    call _printf
    add  esp, 16
    ret  0
?dump@box@@QAEXXZ ENDP ; box::dump
```

Listing 53.13: Optimizing MSVC 2008 /Ob0

```
?dump@solid_object@@QAEXXZ PROC ; solid_object::dump, COMDAT
; _this$ = ecx
    mov  eax, DWORD PTR [ecx]
    push eax
; 'this is solid_object. density=%d', 0aH
    push OFFSET ??_C@_0CC@KICFJINL@this?5is?5solid_object?4?5density?$DN?$CFd@
    call _printf
    add  esp, 8
    ret  0
?dump@solid_object@@QAEXXZ ENDP ; solid_object::dump
```

Listing 53.14: Optimizing MSVC 2008 /Ob0

```
?dump@solid_box@@QAEXXZ PROC ; solid_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 solid_box. width=%d, height=%d, depth=%d, density=%d', 0aH
    push OFFSET ??_C@_0DO@HNCNIHNN@this?5is?5solid_box?4?5width?$DN?$CFd?0?5hei@
    call _printf
    add  esp, 20
    ret  0
?dump@solid_box@@QAEXXZ ENDP ; solid_box::dump
```

So, the memory layout for all three classes is:

box class:

offset	description
+0x0	width
+0x4	height
+0x8	depth

solid_object class:

offset	description
+0x0	density

It can be said that the *solid_box* class memory layout is *united*:

solid_box class:

offset	description
+0x0	width
+0x4	height
+0x8	depth
+0xC	density

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The code of the `box::get_volume()` and `solid_object::get_density()` methods is trivial:

Listing 53.15: Optimizing MSVC 2008 /Ob0

```
?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 53.16: Optimizing MSVC 2008 /Ob0

```
?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 53.17: Optimizing MSVC 2008 /Ob0

```
?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.

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.

53.1.5 Virtual methods

Yet another simple example:

```
#include <stdio.h>

class object
{
public:
    int color;
    object() { };
    object (int color) { this->color=color; };
    virtual void dump()
    {
        printf ("color=%d\n", color);
    };
}
```

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```

};

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;

    o1->dump();
    o2->dump();
    return 0;
}

```

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()`:

```

_s$ = -32 ; size = 12
_b$ = -20 ; size = 20
_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

```

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```

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.⁵

Let's see the code of the constructor of the `box` class:

```

??_R0?AVbox@@@8 DD FLAT:??_7type_info@@6B@ ; box `RTTI Type Descriptor'
DD 00H
DB '.?AVbox@@', 00H

??_R1A@?0A@EA@box@@8 DD FLAT:??_R0?AVbox@@@8 ; box::`RTTI Base Class Descriptor at (0,-1,0,64)'
DD 01H
DD 00H
DD 0xffffffffH
DD 00H
DD 040H
DD FLAT:??_R3box@@8

??_R2box@@8 DD     FLAT:??_R1A@?0A@EA@box@@8 ; box::`RTTI Base Class Array'
DD     FLAT:??_R1A@?0A@EA@object@@8

??_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
DD FLAT:??_R0?AVbox@@@8
DD FLAT:??_R3box@@8

??_7box@@6B@ DD     FLAT:??_R4box@@6B@ ; box::`vftable'
DD     FLAT:?dump@box@@UAEXXZ

_color$ = 8    ; size = 4
_width$ = 12   ; size = 4
_height$ = 16   ; size = 4
_depth$ = 20   ; size = 4
??0box@@QAE@HHHH@Z PROC ; box::box, COMDAT
; _this$ = ecx
push esi
mov esi, ecx
call ??0object@@QAE@XZ ; object::object
mov eax, DWORD PTR _color$[esp]
mov ecx, DWORD PTR _width$[esp]
mov edx, DWORD PTR _height$[esp]
mov DWORD PTR [esi+4], eax
mov eax, DWORD PTR _depth$[esp]
mov DWORD PTR [esi+16], eax
mov DWORD PTR [esi], OFFSET ??_7box@@6B@
mov DWORD PTR [esi+8], ecx

```

⁵You can read more about pointers to functions in the relevant section([24 on page 383](#))

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```
mov  DWORD PTR [esi+12], edx
mov  eax, esi
pop  esi
ret  16
??0box@@QAE@HHHH@Z ENDP ; box::box
```

Here we see a slightly different memory layout: the first field is a pointer to some table `box::`vftable'` (the name was 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](#)⁶. The table of virtual methods contains 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.

53.2 ostream

Let's start again with a "hello world" example, but now we are going to use ostream:

```
#include <iostream>

int main()
{
    std::cout << "Hello, world!\n";
}
```

Almost any C++ textbook tells us that the `<<` operation can be replaced (overloaded) for other types. That is what is done in ostream. We see that `operator<<` is called for ostream:

Listing 53.18: MSVC 2012 (reduced listing)

```
$SG37112 DB 'Hello, world!', 0aH, 00H

_main PROC
    push OFFSET $SG37112
    push OFFSET ?cout@std@@3V?$basic_ostream@DU?$char_traits@D@std@@@1@A ; std::cout
    call ??$?6U?$char_traits@D@std@@@std@@YAAV?$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
```

Let's modify the example:

```
#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:

Listing 53.19: MSVC 2012

```
$SG37112 DB 'world!', 0aH, 00H
$SG37113 DB 'Hello, ', 00H
```

⁶Run-time type information

53.3. REFERENCES

```
_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

    push OFFSET $SG37112 ; 'world!'
    push eax ; result of previous function execution
    call ??$?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:

```
f(f(std::cout, "Hello, "), "world!");
```

GCC generates almost the same code as MSVC.

53.3 References

In C++, references are pointers ([56 on page 607](#)) as well, but they are called *safe*, because it is harder to make a mistake while dealing with them [[ISO13](#), p. 8.3.2]. For example, reference must always be pointing to an object of the corresponding type and cannot be NULL [[Cli](#), p. 8.6]. Even more than that, references cannot be changed, it is impossible to point them to another object (reseat) [[Cli](#), p. 8.5].

If we are going to try to change the example with pointers ([56 on page 607](#)) to use references instead ...

```
void f2 (int x, int y, int & sum, int & product)
{
    sum=x+y;
    product=x*y;
}
```

...then we can see that the compiled code is just the same as in the pointers example ([56 on page 607](#)):

Listing 53.20: Optimizing MSVC 2010

```
_x$ = 8 ; size = 4
_y$ = 12 ; size = 4
_sum$ = 16 ; size = 4
_product$ = 20 ; size = 4
?f2@YAXHAAHO@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@YAXHAAHO@Z ENDP ; f2
```

(The reason why C++ functions has such strange names is explained here: [53.1.1 on page 543](#).)

Hence, C++ references are as much efficient as usual pointers.

53.4 STL

N.B.: all examples here were checked only in 32-bit environment. x64 wasn't checked.

53.4.1 std::string

Internals

Many string libraries [Yur13, p. 2.2] 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: [Yur13, p. 2.2.1]) 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 **ASCII** strings.

It is not specified in the C++ standard [ISO13] 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 done 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 53.21: example for MSVC

```
#include <string>
#include <stdio.h>

struct std_string
{
    union
    {
        char buf[16];
        char* ptr;
    } u;
    size_t size;      // AKA 'Mysize' in MSVC
    size_t capacity; // AKA 'Myres' in MSVC
};

void dump_std_string(std::string s)
{
    struct std_string *p=(struct std_string*)&s;
    printf ("[%s] size:%d capacity:%d\n", p->size>16 ? p->u.ptr : p->u.buf, p->size, p->capacity);
};

int main()
{
    std::string s1="short string";
    std::string s2="string longer than 16 bytes";

    dump_std_string(s1);
    dump_std_string(s2);

    // that works without using c_str()
    printf ("%s\n", &s1);
    printf ("%s\n", s2);
}
```

Almost everything is clear from the source code.

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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
* string length.)
```

[basic_string.h source code](#)

We consider this in our example:

Listing 53.22: example for GCC

```
#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 than 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 complex example

```
#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 53.23: 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
    push OFFSET $SG39512
    lea ecx, DWORD PTR _s1$[esp+80]
    mov DWORD PTR _s1$[esp+100], 15
    mov DWORD PTR _s1$[esp+96], 0
    mov BYTE PTR _s1$[esp+80], 0
    call ?assign@?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@QAEAAV12@PBDI@Z ; \
        std::basic_string<char, std::char_traits<char>, std::allocator<char> >::assign

    push 7
    push OFFSET $SG39514
    lea ecx, DWORD PTR _s2$[esp+80]
    mov DWORD PTR _s2$[esp+100], 15
    mov DWORD PTR _s2$[esp+96], 0
    mov BYTE PTR _s2$[esp+80], 0
    call ?assign@?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@QAEAAV12@PBDI@Z ; \
        std::basic_string<char, std::char_traits<char>, std::allocator<char> >::assign

    lea eax, DWORD PTR _s2$[esp+72]
    push eax
    lea eax, DWORD PTR _s1$[esp+76]
    push eax
    lea eax, DWORD PTR _s3$[esp+80]
    push eax
    call ??$?HDU?$char_traits@D@std@@V?$allocator@D@1@@std@@YA?AV?$basic_string@DU? \
        $char_traits@D@std@@V?$allocator@D@2@@@ABV10@0@Z ; std::operator+<char, std::char_traits< \
        char>, std::allocator<char> >

    ; inlined c_str() method:
    cmp DWORD PTR _s3$[esp+104], 16
    lea eax, DWORD PTR _s3$[esp+84]
    cmovae eax, DWORD PTR _s3$[esp+84]

    push eax
    push OFFSET $SG39581
    call _printf
    add esp, 20

    cmp DWORD PTR _s3$[esp+92], 16
    jb SHORT $LN119@main
    push DWORD PTR _s3$[esp+72]
    call ??3@YAXPAX@Z ; operator delete
    add esp, 4
$LN119@main:
```

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```

    cmp  DWORD PTR _s2$[esp+92], 16
    mov  DWORD PTR _s3$[esp+92], 15
    mov  DWORD PTR _s3$[esp+88], 0
    mov  BYTE PTR _s3$[esp+72], 0
    jb   SHORT $LN151@main
    push DWORD PTR _s2$[esp+72]
    call ??3@YAXPAX@Z           ; operator delete
    add  esp, 4
$LN151@main:
    cmp  DWORD PTR _s1$[esp+92], 16
    mov  DWORD PTR _s2$[esp+92], 15
    mov  DWORD PTR _s2$[esp+88], 0
    mov  BYTE PTR _s2$[esp+72], 0
    jb   SHORT $LN195@main
    push DWORD PTR _s1$[esp+72]
    call ??3@YAXPAX@Z           ; operator delete
    add  esp, 4
$LN195@main:
    xor  eax, eax
    add  esp, 72
    ret  0
_main ENDP

```

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 53.24: 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  esi, [esp+24]
    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

```

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```
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
mov  eax, DWORD PTR [esp+20]
mov  DWORD PTR [esp+4], ebx
sub  eax, 12
mov  DWORD PTR [esp], eax
call _ZNSs4_Rep10_M_DisposeERKSaIcE
lea  esp, [ebp-12]
xor  eax, eax
pop  ebx
pop  esi
pop  edi
pop  ebp
ret
```

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 [STL⁷](#) types can be defined without problems.

Yes, indeed:

```
#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()` starts.

Listing 53.25: MSVC 2012: here is how a global variable is constructed and also its destructor is registered

```
??__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
```

⁷(C++) Standard Template Library: [53.4 on page 560](#)

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```

call ?assign@$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@QAEAAV12@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 53.26: MSVC 2012: here a global variable is used in `main()`

```

$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
    push eax
    push OFFSET $SG39519 ; '%s'
    call _printf
    add  esp, 8
    xor  eax, eax
    ret  0
_main ENDP

```

Listing 53.27: MSVC 2012: this destructor function is called before exit

```

??__Fs@YAXXZ PROC
    push ecx
    cmp  DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A+20, 16
    jb   SHORT $LN23@dynamic
    push esi
    mov  esi, DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A
    lea  ecx, DWORD PTR $T2[esp+8]
    call ??0$_Wrap_alloc@V?$allocator@D@std@@std@@QAE@XZ
    push OFFSET ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A ; s
    lea  ecx, DWORD PTR $T2[esp+12]
    call ??$destroy@PAD@?$_Wrap_alloc@V?$allocator@D@std@@std@@QAEXPAPAD@Z
    lea  ecx, DWORD PTR $T1[esp+8]
    call ??0$_Wrap_alloc@V?$allocator@D@std@@std@@QAE@XZ
    push esi
    call ??3@YAXPAX@Z ; operator delete
    add  esp, 4
    pop  esi
$LN23@dynamic:
    mov  DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A+20, 15
    mov  DWORD PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A+16, 0
    mov  BYTE PTR ?s@@3V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@A, 0
    pop  ecx
    ret  0
??__Fs@YAXXZ ENDP

```

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:

Listing 53.28: GCC 4.8.1

```

main:
    push ebp
    mov  ebp, esp
    and  esp, -16
    sub  esp, 16
    mov  eax, DWORD PTR s
    mov  DWORD PTR [esp], eax
    call puts
    xor  eax, eax
    leave
    ret

```

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```
.LC0:
    .string "a string"
_GLOBAL__sub_I_s:
    sub esp, 44
    lea eax, [esp+31]
    mov DWORD PTR [esp+8], eax
    mov DWORD PTR [esp+4], OFFSET FLAT:.LC0
    mov DWORD PTR [esp], OFFSET FLAT:s
    call _ZNSsC1EPKcRKSaIcE
    mov DWORD PTR [esp+8], OFFSET FLAT:_dso_handle
    mov DWORD PTR [esp+4], OFFSET FLAT:s
    mov DWORD PTR [esp], OFFSET FLAT:_ZNSsD1Ev
    call __cxa_atexit
    add esp, 44
    ret
.LFE645:
.size _GLOBAL__sub_I_s, .-_GLOBAL__sub_I_s
.section .init_array,"aw"
.align 4
.long _GLOBAL__sub_I_s
.globl s
.bss
.align 4
.type s, @object
.size s, 4
s:
.zero 4
.hidden __dso_handle
```

But it does not create a separate function for this, each destructor is passed to atexit(), one by one.

53.4.2 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 [ISO13] 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:

```
#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, 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\n", a[0], a[1]);
#endif
    dump_List_vals ((struct List_node*)a[0]);
};

int main()
{
    std::list<struct a> l;

    printf ("* empty list:\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");
    dump_List_val((unsigned int*)(void*)&l);

    std::list<struct a>::iterator tmp;
    printf ("node at .begin:\n");
    tmp=l.begin();
    dump_List_node ((struct List_node *)*(void**)&tmp);
    printf ("node at .end:\n");
    tmp=l.end();
    dump_List_node ((struct List_node *)*(void**)&tmp);

    printf ("* let's count from the begin:\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");
    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);
}

```

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```

printf ("removing last element...\n");
l.pop_back();
dump_List_val((unsigned int*)(void*)&l);
};

```

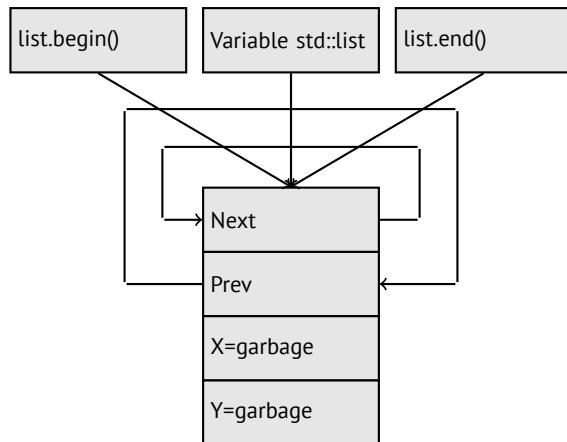
GCC

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:



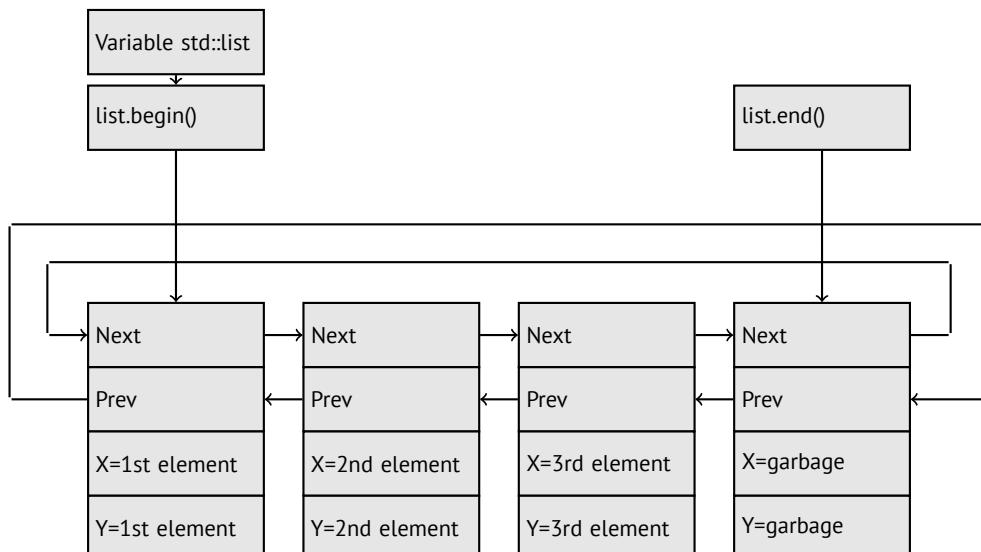
At this moment, the *.begin* and *.end* iterators are equal to each other.

If we push 3 elements, the list internally will be:

```
* 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:



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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.

```
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 circular list.

This is very helpful here: having a pointer to the first list element, i.e., that is in the *l* variable, it is easy to get a pointer to the last one quickly, without the need to traverse the whole list. Inserting an element at the list end is also quick, thanks to this feature.

operator-- and *operator++* just set the current iterator's value to the *current_node->prev* or *current_node->next* values.

The reverse iterators (*.rbegin*, *.rend*) work just as the same, but in reverse.

*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*).

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 was 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 mean that this operation is $O(n)$, i.e., it gets slower steadily as the list grows.

Listing 53.29: Optimizing GCC 4.8.1 -fno-inline-small-functions

```
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+18h]  
    mov [esp+4], esi  
    mov [esp], ebx  
    mov dword ptr [esp+18h], 1 ; X for new element  
    mov dword ptr [esp+1Ch], 2 ; Y for new element  
    call _ZNSt4listI1aSaISO_EE10push_frontERKS0_ ; std::list<a, std::allocator<a>>::push_front(a<  
        const&)  
    mov [esp+4], esi  
    mov [esp], ebx  
    mov dword ptr [esp+18h], 3 ; X for new element  
    mov dword ptr [esp+1Ch], 4 ; Y for new element  
    call _ZNSt4listI1aSaISO_EE10push_frontERKS0_ ; std::list<a, std::allocator<a>>::push_front(a<  
        const&)  
    mov dword ptr [esp], 10h  
    mov dword ptr [esp+18h], 5 ; X for new element  
    mov dword ptr [esp+1Ch], 6 ; Y for new element  
    call _Znwj ; operator new(uint)
```

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```

    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:"
    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 begin:"
    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\n"
    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\n"
    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\n"
    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\n"
    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\n"
    mov  dword ptr [esp], 1
    mov  [esp+0Ch], eax
    mov  eax, [esp+18h]
    mov  [esp+8], eax
    call __printf_chk
    mov  esi, [esp+14h]
    mov  eax, [esi+0Ch]

```

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```

mov [esp+0Ch], eax
mov eax, [esi+8]
mov dword ptr [esp+4], offset a3rdElementDD ; "3rd element: %d %d\n"
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\n"
mov dword ptr [esp], 1
mov [esp+8], eax
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::`v
↳ _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_baseI1aSaISO_EE8_M_clearEv ; std::_List_base<a, std::allocator<a>>::`v
↳ _M_clear(void)
lea esp, [ebp-8]
xor eax, eax
pop ebx
pop esi
pop ebp
retn
main endp

```

Listing 53.30: The whole output

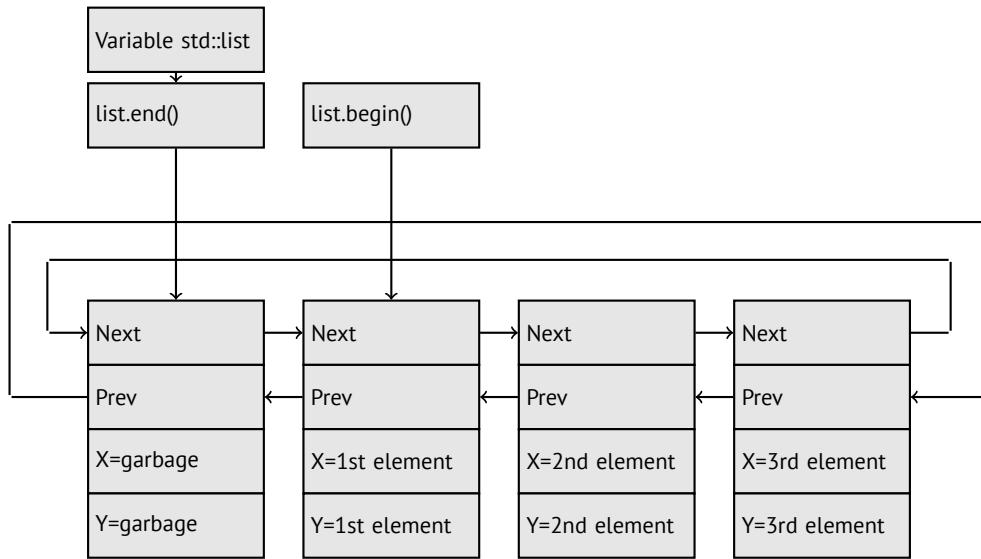
```

* 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 begin:
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=0x000349a0 _Prev=0x00034988 x=5 y=6

```

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:



GCC has its dummy element at the end of the list, while MSVC's is at the beginning.

Listing 53.31: Optimizing MSVC 2012 /Fa2.asm /GS- /Ob1

```

_l$ = -16 ; size = 8
_t1$ = -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<0,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$[esp+32]
    push eax
    call ?dump_List_val@YAXPAI@Z ; dump_List_val
    mov esi, DWORD PTR [ebx]
    add esp, 8
    lea eax, DWORD PTR _t1$[esp+28]
    push eax
    push DWORD PTR [esi+4]
    lea ecx, DWORD PTR _l$[esp+36]
    push esi
    mov DWORD PTR _t1$[esp+40], 1 ; data for a new node
    mov DWORD PTR _t1$[esp+44], 2 ; data for a new node
    ; allocate new node
    call ??$_Buynode@ABUa@@@?$_List_buy@Ua@@V?$allocator@Ua@@@std@@@std@@QAEPAU?_
    ↴ $_List_node@Ua@@PAX@1@PAU21@0ABUa@@@Z ; std::_List_buy<a,std::allocator<a>>::_Buynode<a>
    ↴ const &
    mov DWORD PTR [esi+4], eax
    mov ecx, DWORD PTR [eax+4]
    mov DWORD PTR _t1$[esp+28], 3 ; data for a new node

```

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```

mov    DWORD PTR [ecx], eax
mov    esi, DWORD PTR [ebx]
lea    eax, DWORD PTR _t1$[esp+28]
push   eax
push   DWORD PTR [esi+4]
lea    ecx, DWORD PTR _l$[esp+36]
push   esi
mov    DWORD PTR _t1$[esp+44], 4 ; data for a new node
; allocate new node
call ??$_Buynode@ABuA@@@?$_List_buy@Ua@@V?$allocator@Ua@@@std@@@std@@QAEPAU?_
↳ $_List_node@Ua@@PAX@1@PAU21@0ABuA@@@Z ; std::_List_buy<a, std::allocator<a>>::_Buynode<a>
↳ const &gt;
mov    DWORD PTR [esi+4], eax
mov    ecx, DWORD PTR [eax+4]
mov    DWORD PTR _t1$[esp+28], 5 ; data for a new node
mov    DWORD PTR [ecx], eax
lea    eax, DWORD PTR _t1$[esp+28]
push   eax
push   DWORD PTR [ebx+4]
lea    ecx, DWORD PTR _l$[esp+36]
push   ebx
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?_
↳ $_List_node@Ua@@PAX@1@PAU21@0ABuA@@@Z ; std::_List_buy<a, std::allocator<a>>::_Buynode<a>
↳ const &gt;
mov    DWORD PTR [ebx+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@@@Z ; dump_List_node
push  OFFSET $SG40835 ; 'node at .end:'
call   edi ; printf
push  ebx ; pointer to the node l$ variable points to!
call   ?dump_List_node@@YAXPAUList_node@@@Z ; dump_List_node
push  OFFSET $SG40839 ; '* let's count from the begin:'
call   edi ; printf
mov    esi, DWORD PTR [ebx] ; operator++: get ->next pointer
push  DWORD PTR [esi+12]
push  DWORD PTR [esi+8]
push  OFFSET $SG40846 ; '1st element: %d %d'
call   edi ; printf
mov    esi, DWORD PTR [esi] ; operator++: get ->next pointer
push  DWORD PTR [esi+12]
push  DWORD PTR [esi+8]
push  OFFSET $SG40848 ; '2nd element: %d %d'
call   edi ; printf
mov    esi, DWORD PTR [esi] ; operator++: get ->next pointer
push  DWORD PTR [esi+12]
push  DWORD PTR [esi+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
push  DWORD PTR [ebx+12] ; use x and y fields from the node l variable points to
push  DWORD PTR [ebx+8]

```

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```

push OFFSET $SG40860 ; 'element at .end(): %d %d'
call edi ; printf
mov esi, DWORD PTR [ebx+4] ; operator--: get ->prev pointer
push DWORD PTR [esi+12]
push DWORD PTR [esi+8]
push OFFSET $SG40862 ; '3rd element: %d %d'
call edi ; printf
mov esi, DWORD PTR [esi+4] ; operator--: get ->prev pointer
push DWORD PTR [esi+12]
push DWORD PTR [esi+8]
push OFFSET $SG40864 ; '2nd element: %d %d'
call edi ; printf
mov eax, DWORD PTR [esi+4] ; operator--: get ->prev pointer
push DWORD PTR [eax+12]
push DWORD PTR [eax+8]
push OFFSET $SG40866 ; '1st element: %d %d'
call edi ; printf
add esp, 64
push OFFSET $SG40867 ; 'removing last element...'
call edi ; printf
mov edx, DWORD PTR [ebx+4]
add esp, 4

; prev=next?
; it is the only element, "garbage one"?
; if yes, do not delete it!
cmp edx, ebx
je SHORT $LN349@main
mov ecx, DWORD PTR [edx+4]
mov eax, DWORD PTR [edx]
mov DWORD PTR [ecx], eax
mov ecx, DWORD PTR [edx]
mov eax, DWORD PTR [edx+4]
push edx
mov DWORD PTR [ecx+4], eax
call ??3@YAXPAX@Z ; operator delete
add esp, 4
mov DWORD PTR _l$[esp+32], 2
$LN349@main:
lea eax, DWORD PTR _l$[esp+28]
push eax
call ?dump_List_val@@YAXPAI@Z ; dump_List_val
mov eax, DWORD PTR [ebx]
add esp, 4
mov DWORD PTR [ebx], ebx
mov DWORD PTR [ebx+4], ebx
cmp eax, ebx
je SHORT $LN412@main
$LL414@main:
mov esi, DWORD PTR [eax]
push eax
call ??3@YAXPAX@Z ; operator delete
add esp, 4
mov eax, esi
cmp esi, ebx
jne SHORT $LL414@main
$LN412@main:
push ebx
call ??3@YAXPAX@Z ; operator delete
add esp, 4
xor eax, eax
pop edi
pop esi
pop ebx
add esp, 16
ret 0
_main ENDP

```

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 53.32: The whole output

```
* empty list:
_Myhead=0x003CC258, _Mysize=0
ptr=0x003CC258 _Next=0x003CC258 _Prev=0x003CC258 x=6226002 y=4522072
* 3-elements list:
_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 begin:
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=0x003CC258 _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.

53.4.3 std::vector

We would call `std::vector` a safe wrapper of the PODT⁸ C array. Internally it is somewhat similar to `std::string` (53.4.1 on page 560): 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 (19 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 different⁹, 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
```

⁸(C++) Plain Old Data Type

⁹GCC internals: <http://go.yurichev.com/17086>

```

};

void dump(struct vector_of_ints *in)
{
    printf ("_Myfirst=%p, _Mylast=%p, _Myend=%p\n", in->Myfirst, in->Mylast, in->Myend);
    size_t size=(in->Mylast-in->Myfirst);
    size_t capacity=(in->Myend-in->Myfirst);
    printf ("size=%d, capacity=%d\n", size, capacity);
    for (size_t i=0; i<size; i++)
        printf ("element %d: %d\n", i, in->Myfirst[i]);
};

int main()
{
    std::vector<int> c;
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(1);
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(2);
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(3);
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(4);
    dump ((struct vector_of_ints*)(void*)&c);
    c.reserve (6);
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(5);
    dump ((struct vector_of_ints*)(void*)&c);
    c.push_back(6);
    dump ((struct vector_of_ints*)(void*)&c);
    printf ("%d\n", c.at(5)); // with bounds checking
    printf ("%d\n", c[8]); // operator[], without bounds checking
}

```

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

```

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```
size=6, capacity=6
element 0: 1
element 1: 2
element 2: 3
element 3: 4
element 4: 5
element 5: 6
6
6619158
```

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 if 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:

Listing 53.33: MSVC 2012 /GS- /Ob1

```
$SG52650 DB '%d', 0aH, 00H
$SG52651 DB '%d', 0aH, 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$[ebp]
    mov edx, DWORD PTR [eax+4]
    sub edx, DWORD PTR [ecx]
    sar edx, 2
    cmp edx, DWORD PTR __Pos$[ebp]
    ja SHORT $LN1@at
    push OFFSET ??_C@_0BM@NMJKDPP0@invalid?5vector?$DMT?$D0?5subscript?$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
```

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```

mov  DWORD PTR _c$[ebp+8], 0    ; Myend
lea  eax, DWORD PTR _c$[ebp]
push eax
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
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$$QAH@Z ; std::vector<int, std::v
\ allocator<int> >::push_back
lea  edx, DWORD PTR _c$[ebp]
push edx
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add  esp, 4
mov  DWORD PTR $T5[ebp], 2
lea  eax, DWORD PTR $T5[ebp]
push eax
lea  ecx, DWORD PTR _c$[ebp]
call ?push_back@$vector@HV?$allocator@H@std@@@std@@@QAEX$$QAH@Z ; std::vector<int, std::v
\ 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 $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$$QAH@Z ; std::vector<int, std::v
\ allocator<int> >::push_back
lea  eax, DWORD PTR _c$[ebp]
push eax
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add  esp, 4
mov  DWORD PTR $T3[ebp], 4
lea  ecx, DWORD PTR $T3[ebp]
push ecx
lea  ecx, DWORD PTR _c$[ebp]
call ?push_back@$vector@HV?$allocator@H@std@@@std@@@QAEX$$QAH@Z ; std::vector<int, std::v
\ allocator<int> >::push_back
lea  edx, DWORD PTR _c$[ebp]
push edx
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add  esp, 4
push 6
lea  ecx, DWORD PTR _c$[ebp]
call ?reserve@?$vector@HV?$allocator@H@std@@@std@@@QAEXI@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$$QAH@Z ; std::vector<int, std::v
\ allocator<int> >::push_back
lea  edx, DWORD PTR _c$[ebp]
push edx
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add  esp, 4
mov  DWORD PTR $T1[ebp], 6
lea  eax, DWORD PTR $T1[ebp]
push eax
lea  ecx, DWORD PTR _c$[ebp]
call ?push_back@$vector@HV?$allocator@H@std@@@std@@@QAEX$$QAH@Z ; std::vector<int, std::v
\ allocator<int> >::push_back
lea  ecx, DWORD PTR _c$[ebp]

```

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```

push ecx
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
push 5
lea ecx, DWORD PTR _c$[ebp]
call ?at@?$vector@HV?$allocator@H@std@@@std@@QAEAAHI@Z ; std::vector<int, std::allocator<int>>
↪ > ::at
mov edx, DWORD PTR [eax]
push edx
push OFFSET $SG52650 ; '%d'
call DWORD PTR __imp__printf
add esp, 8
mov eax, 8
shl eax, 2
mov ecx, DWORD PTR _c$[ebp]
mov edx, DWORD PTR [ecx+eax]
push edx
push OFFSET $SG52651 ; '%d'
call DWORD PTR __imp__printf
add esp, 8
lea ecx, DWORD PTR _c$[ebp]
call ?_Tidy@?$vector@HV?$allocator@H@std@@@std@@IAEXXZ ; std::vector<int, std::allocator<int>>
↪ > ::_Tidy
xor eax, eax
mov esp, ebp
pop ebp
ret 0
_main ENDP

```

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 53.34: 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, OFFFFFFFF0h
    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&)

```

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```
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 *)
```

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```

mov dword ptr [esp+10h], 6
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 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, [eax+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, [eax+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

    mov ebx, eax
    mov edx, [esp+14h]
    test edx, edx
    jz short loc_80002A4
    mov [esp], edx ; void *
    call _ZdlPv ; operator delete(void *)

loc_80002A4: ; CODE XREF: main+1FE
    mov [esp], ebx
    call _Unwind_Resume

loc_80002AC: ; CODE XREF: main+1EA
    ; main+1F4
    mov eax, 0
    lea esp, [ebp-0Ch]
    pop ebx
    pop esi
    pop edi
    pop ebp

locret_80002B8: ; DATA XREF: .eh_frame:08000510
    ; .eh_frame:080005BC
    retn
main endp

```

`.reserve()` 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
```

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```
_Myfirst=0x8257008, _Mylast=0x825700c, _Myend=0x825700c
size=1, capacity=1
element 0: 1
_Myfirst=0x8257018, _Mylast=0x8257020, _Myend=0x8257020
size=2, capacity=2
element 0: 1
element 1: 2
_Myfirst=0x8257028, _Mylast=0x8257034, _Myend=0x8257038
size=3, capacity=4
element 0: 1
element 1: 2
element 2: 3
_Myfirst=0x8257028, _Mylast=0x8257038, _Myend=0x8257038
size=4, capacity=4
element 0: 1
element 1: 2
element 2: 3
element 3: 4
_Myfirst=0x8257040, _Mylast=0x8257050, _Myend=0x8257058
size=4, capacity=6
element 0: 1
element 1: 2
element 2: 3
element 3: 4
_Myfirst=0x8257040, _Mylast=0x8257054, _Myend=0x8257058
size=5, capacity=6
element 0: 1
element 1: 2
element 2: 3
element 3: 4
element 4: 5
_Myfirst=0x8257040, _Mylast=0x8257058, _Myend=0x8257058
size=6, capacity=6
element 0: 1
element 1: 2
element 2: 3
element 3: 4
element 4: 5
element 5: 6
6
0
```

We can spot that the buffer size grows in a different way than 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.

53.4.4 std::map and std::set

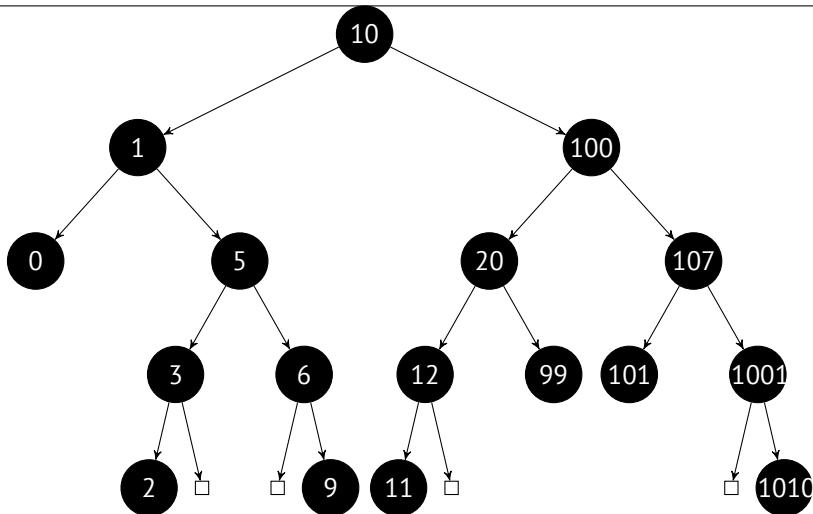
The binary tree is another fundamental data structure. As its name states, this is a tree where each node has at most 2 links to other nodes. Each node has key and/or value.

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 ≈ 10 steps are needed ≈ 1000 keys, or ≈ 13 steps for ≈ 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` contains only keys. `std::map` is the "extended" version of `std::set`: it also has a value at each node.

MSVC

```
#include <map>
#include <set>
#include <string>
#include <iostream>

// structure is not packed!
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;
};

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);
```

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```

m[1001]="one thousand one";
m[1010]="one thousand ten";
m[2]="two";
m[9]="nine";
printf ("dumping m as map:\n");
dump_map_and_set ((struct tree_struct *)(void*)&m, false);

std::map<int, const char*>::iterator it1=m.begin();
printf ("m.begin():\n");
dump_tree_node ((struct tree_node *)*(void**)&it1, false, false);
it1=m.end();
printf ("m.end():\n");
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:\n");
dump_map_and_set ((struct tree_struct *)(void*)&s, true);
std::set<int>::iterator it2=s.begin();
printf ("s.begin():\n");
dump_tree_node ((struct tree_node *)*(void**)&it2, true, false);
it2=s.end();
printf ("s.end():\n");
dump_tree_node ((struct tree_node *)*(void**)&it2, true, false);
};

```

Listing 53.35: MSVC 2012

```

dumping m as map:
ptr=0x0020FE04, Myhead=0x005BB3A0, Mysize=17
ptr=0x005BB3A0 Left=0x005BB4A0 Parent=0x005BB3C0 Right=0x005BB580 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=0x005BB480 Left=0x005BB420 Parent=0x005BB440 Right=0x005BB560 Color=0 Isnil=0
first=107 second=[one hundred seven]
ptr=0x005BB420 Left=0x005BB3A0 Parent=0x005BB480 Right=0x005BB3A0 Color=1 Isnil=0
first=101 second=[one hundred one]
ptr=0x005BB560 Left=0x005BB3A0 Parent=0x005BB480 Right=0x005BB580 Color=1 Isnil=0
first=1001 second=[one thousand one]

```

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```

ptr=0x005BB580 Left=0x005BB3A0 Parent=0x005BB560 Right=0x005BB3A0 Color=0 Isnil=0
first=1010 second=[one thousand ten]
As a tree:
root----10 [ten]
    L-----1 [one]
        L----0 [zero]
        R----5 [five]
            L-----3 [three]
                L-----2 [two]
            R-----6 [six]
                R-----9 [nine]
    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=0x005BB4A0 Left=0x005BB3A0 Parent=0x005BB4C0 Right=0x005BB3A0 Color=1 Isnil=0
first=0 second=[zero]
m.end():

ptr=0x005BB3A0 Left=0x005BB4A0 Parent=0x005BB3C0 Right=0x005BB580 Color=1 Isnil=1

dumping s as set:
ptr=0x0020FDFC, Myhead=0x005BB5E0, Mysize=6
ptr=0x005BB5E0 Left=0x005BB640 Parent=0x005BB600 Right=0x005BB6A0 Color=1 Isnil=1
ptr=0x005BB600 Left=0x005BB660 Parent=0x005BB5E0 Right=0x005BB620 Color=1 Isnil=0
first=123
ptr=0x005BB660 Left=0x005BB640 Parent=0x005BB600 Right=0x005BB680 Color=1 Isnil=0
first=12
ptr=0x005BB640 Left=0x005BB5E0 Parent=0x005BB660 Right=0x005BB5E0 Color=0 Isnil=0
first=11
ptr=0x005BB680 Left=0x005BB5E0 Parent=0x005BB660 Right=0x005BB5E0 Color=0 Isnil=0
first=100
ptr=0x005BB620 Left=0x005BB5E0 Parent=0x005BB600 Right=0x005BB6A0 Color=1 Isnil=0
first=456
ptr=0x005BB6A0 Left=0x005BB5E0 Parent=0x005BB620 Right=0x005BB5E0 Color=0 Isnil=0
first=1001
As a tree:
root----123
    L-----12
        L-----11
        R-----100
    R-----456
        R-----1001

s.begin():
ptr=0x005BB640 Left=0x005BB5E0 Parent=0x005BB660 Right=0x005BB5E0 Color=0 Isnil=0
first=11
s.end():

ptr=0x005BB5E0 Left=0x005BB640 Parent=0x005BB600 Right=0x005BB6A0 Color=1 Isnil=1

```

The structure is not packed, so both `char` values occupy 4 bytes each.

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 ([53.4.2 on page 572](#)).

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. `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 [[Cor+09](#)].

The `.end()` iterator points to the dummy node, it has 1 in `Isnil`, which implies that the node has no key and/or value.

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It can be viewed as a “landing zone” in HDD¹⁰. The “parent” field of the dummy node points to the root node, which serves as a vertex of the tree and contains information.

GCC

¹⁰ Hard disk drive

53.4. STL

```

        printf ("%d\n", *(int*)point_after_struct);
    else
    {
        struct map_pair *p=(struct map_pair *)point_after_struct;
        printf ("%d [%s]\n", p->key, p->value);
    }

    if (n->M_left)
    {
        printf ("%.*sL-----", tabs, ALOT_OF_TABS);
        dump_as_tree (tabs+1, n->M_left, is_set);
    };
    if (n->M_right)
    {
        printf ("%.*sR-----", tabs, ALOT_OF_TABS);
        dump_as_tree (tabs+1, n->M_right, is_set);
    };
};

void dump_map_and_set(struct tree_struct *m, bool is_set)
{
    printf ("ptr=0x%p, M_key_compare=0x%xx, M_header=0x%p, M_node_count=%d\n",
           m, m->M_key_compare, &m->M_header, m->M_node_count);
    dump_tree_node (m->M_header.M_parent, is_set, true, true);
    printf ("As a tree:\n");
    printf ("root----");
    dump_as_tree (1, m->M_header.M_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";
    m[1]="one";
    m[6]="six";
    m[99]="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:\n");
    dump_map_and_set ((struct tree_struct *)(&m), false);

    std::map<int, const char*>::iterator it1=m.begin();
    printf ("m.begin():\n");
    dump_tree_node ((struct tree_node *)*(void**)&it1, false, false, true);
    it1=m.end();
    printf ("m.end():\n");
    dump_tree_node ((struct tree_node *)*(void**)&it1, false, false, false);

    // set

    std::set<int> s;
    s.insert(123);
    s.insert(456);
    s.insert(11);
    s.insert(12);
}

```

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```
s.insert(100);
s.insert(1001);
printf ("dumping s as set:\n");
dump_map_and_set ((struct tree_struct *)(void*)&s, true);
std::set<int>::iterator it2=s.begin();
printf ("s.begin():\n");
dump_tree_node ((struct tree_node **)(void**)&it2, true, false, true);
it2=s.end();
printf ("s.end():\n");
dump_tree_node ((struct tree_node **)(void**)&it2, true, false, false);
};
```

Listing 53.36: GCC 4.8.1

```
dumping m as map:
ptr=0x0028FE3C M_key_compare=0x402b70, M_header=0x0028FE40, M_node_count=17
ptr=0x007A4988 M_left=0x007A4C00 M_parent=0x0028FE40 M_right=0x007A4B80 M_color=1
key=10 value=[ten]
ptr=0x007A4C00 M_left=0x007A4BE0 M_parent=0x007A4988 M_right=0x007A4C60 M_color=1
key=1 value=[one]
ptr=0x007A4BE0 M_left=0x00000000 M_parent=0x007A4C00 M_right=0x00000000 M_color=1
key=0 value=[zero]
ptr=0x007A4C60 M_left=0x007A4B40 M_parent=0x007A4C00 M_right=0x007A4C20 M_color=0
key=5 value=[five]
ptr=0x007A4B40 M_left=0x007A4CE0 M_parent=0x007A4C60 M_right=0x00000000 M_color=1
key=3 value=[three]
ptr=0x007A4CE0 M_left=0x00000000 M_parent=0x007A4B40 M_right=0x00000000 M_color=0
key=2 value=[two]
ptr=0x007A4C20 M_left=0x00000000 M_parent=0x007A4C60 M_right=0x007A4D00 M_color=1
key=6 value=[six]
ptr=0x007A4D00 M_left=0x00000000 M_parent=0x007A4C20 M_right=0x00000000 M_color=0
key=9 value=[nine]
ptr=0x007A4B80 M_left=0x007A49A8 M_parent=0x007A4988 M_right=0x007A4BC0 M_color=1
key=100 value=[one hundred]
ptr=0x007A49A8 M_left=0x007A4BA0 M_parent=0x007A4B80 M_right=0x007A4C40 M_color=0
key=20 value=[twenty]
ptr=0x007A4BA0 M_left=0x007A4C80 M_parent=0x007A49A8 M_right=0x00000000 M_color=1
key=12 value=[twelve]
ptr=0x007A4C80 M_left=0x00000000 M_parent=0x007A4BA0 M_right=0x00000000 M_color=0
key=11 value=[eleven]
ptr=0x007A4C40 M_left=0x00000000 M_parent=0x007A49A8 M_right=0x00000000 M_color=1
key=99 value=[ninety-nine]
ptr=0x007A4BC0 M_left=0x007A4B60 M_parent=0x007A4B80 M_right=0x007A4CA0 M_color=0
key=107 value=[one hundred seven]
ptr=0x007A4B60 M_left=0x00000000 M_parent=0x007A4BC0 M_right=0x00000000 M_color=1
key=101 value=[one hundred one]
ptr=0x007A4CA0 M_left=0x00000000 M_parent=0x007A4BC0 M_right=0x007A4CC0 M_color=1
key=1001 value=[one thousand one]
ptr=0x007A4CC0 M_left=0x00000000 M_parent=0x007A4CA0 M_right=0x00000000 M_color=0
key=1010 value=[one thousand ten]
As a tree:
root----10 [ten]
    -----1 [one]
        -----0 [zero]
        -----5 [five]
            -----3 [three]
                -----2 [two]
            -----6 [six]
                -----9 [nine]
    -----100 [one hundred]
        -----20 [twenty]
            -----12 [twelve]
                -----11 [eleven]
            -----99 [ninety-nine]
        -----107 [one hundred seven]
            -----101 [one hundred one]
            -----1001 [one thousand one]
                -----1010 [one thousand ten]

m.begin():
ptr=0x007A4BE0 M_left=0x00000000 M_parent=0x007A4C00 M_right=0x00000000 M_color=1
```

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```
key=0 value=[zero]
m.end():
ptr=0x0028FE40 M_left=0x007A4BE0 M_parent=0x007A4988 M_right=0x007A4CC0 M_color=0

dumping s as set:
ptr=0x0028FE20, M_key_compare=0x8, M_header=0x0028FE24, M_node_count=6
ptr=0x007A1E80 M_left=0x01D5D890 M_parent=0x0028FE24 M_right=0x01D5D850 M_color=1
key=123
ptr=0x01D5D890 M_left=0x01D5D870 M_parent=0x007A1E80 M_right=0x01D5D8B0 M_color=1
key=12
ptr=0x01D5D870 M_left=0x00000000 M_parent=0x01D5D890 M_right=0x00000000 M_color=0
key=11
ptr=0x01D5D8B0 M_left=0x00000000 M_parent=0x01D5D890 M_right=0x00000000 M_color=0
key=100
ptr=0x01D5D850 M_left=0x00000000 M_parent=0x007A1E80 M_right=0x01D5D8D0 M_color=1
key=456
ptr=0x01D5D8D0 M_left=0x00000000 M_parent=0x01D5D850 M_right=0x00000000 M_color=0
key=1001
As a tree:
root----123
    L-----12
        L-----11
        R-----100
    R-----456
        R-----1001
s.begin():
ptr=0x01D5D870 M_left=0x00000000 M_parent=0x01D5D890 M_right=0x00000000 M_color=0
key=11
s.end():
ptr=0x0028FE24 M_left=0x01D5D870 M_parent=0x007A1E80 M_right=0x01D5D8D0 M_color=0
```

GCC's implementation is very similar ¹¹. 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 53.37: GCC

```
#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;
};
```

¹¹<http://go.yurichev.com/17084>

Listing 53.38: GCC 4.8.1

```
123, 456 are inserted
root----123
        R-----456

11, 12 are inserted
root---123
        L-----11
        R-----12
        R-----456

100, 1001 are inserted
root---123
        L-----12
        L-----11
```

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```
R-----100
R-----456
R-----1001

667, 1, 4, 7 are inserted
root---12
    L-----4
        L-----1
        R-----11
            L-----7
    R-----123
        L-----100
        R-----667
            L-----456
            R-----1001
```

Chapter 54

Negative array indices

It's possible to address the space *before* an array by supplying a negative index, e.g., `array[-1]`.

It's very hard to say why one should use it, there is probably only one known practical application of this technique. C/C++ array elements indices start at 0, but some [PLs](#) have a first index at 1 (at least FORTRAN). Programmers may still have this habit, 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 54.1: Non-optimizing MSVC 2010

```
1 $SG2751 DB      'first element %d', 0aH, 00H
2 $SG2752 DB      'second element %d', 0aH, 00H
3 $SG2753 DB      'last element %d', 0aH, 00H
4 $SG2754 DB      'array[-1]=%02X, array[-2]=%02X, array[-3]=%02X, array[-4]' 
5     DB      ']=%02X', 0aH, 00H
6
7 _fakearray$ = -24          ; size = 4
8 _random_value$ = -20      ; size = 4
9 _array$ = -16            ; size = 10
10 _i$ = -4              ; size = 4
11 _main    PROC
12     push    ebp
13     mov     ebp, esp
14     sub     esp, 24
15     mov     DWORD PTR _random_value$[ebp], 287454020 ; 11223344H
16     ; set fakearray[] one byte earlier before array[]
17     lea     eax, DWORD PTR _array$[ebp]
18     add     eax, -1 ; eax=eax-1
19     mov     DWORD PTR _fakearray$[ebp], eax
20     mov     DWORD PTR _i$[ebp], 0
21     jmp     SHORT $LN3@main
22     ; fill array[] with 0..9
```

```

23 $LN2@main:
24     mov     ecx, DWORD PTR _i$[ebp]
25     add     ecx, 1
26     mov     DWORD PTR _i$[ebp], ecx
27 $LN3@main:
28     cmp     DWORD PTR _i$[ebp], 10
29     jge     SHORT $LN1@main
30     mov     edx, DWORD PTR _i$[ebp]
31     mov     al, BYTE PTR _i$[ebp]
32     mov     BYTE PTR _array$[ebp+edx], al
33     jmp     SHORT $LN2@main
34 $LN1@main:
35     mov     ecx, DWORD PTR _fakearray$[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 $SG2753 ; 'last element %d'
54     call   _printf
55     add    esp, 8
56     ; subtract 4, 3, 2 and 1 from pointer to array[0] in order to find values
before array[]
57     lea     ecx, DWORD PTR _array$[ebp]
58     movzx  edx, BYTE PTR [ecx-4]
59     push   edx
60     lea     eax, DWORD PTR _array$[ebp]
61     movzx  ecx, BYTE PTR [eax-3]
62     push   ecx
63     lea     edx, DWORD PTR _array$[ebp]
64     movzx  eax, BYTE PTR [edx-2]
65     push   eax
66     lea     ecx, DWORD PTR _array$[ebp]
67     movzx  edx, BYTE PTR [ecx-1]
68     push   edx
69     push   OFFSET $SG2754 ; 'array[-1]=%02X, array[-2]=%02X, array[-3]=%02X, array[-4]=%02X'
    ↵ X'
70     call   _printf
71     add    esp, 20
72     xor    eax, eax
73     mov    esp, ebp
74     pop    ebp
75     ret    0
76 _main ENDP

```

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
array[-1]=11, array[-2]=22, array[-3]=33, array[-4]=44

```

Here is the stack fragment we will copypaste from OllyDbg's stack window (with comments added by the author):

Listing 54.2: Non-optimizing MSVC 2010

CPU Stack	
Address	Value
001DFBCC	/001DFBD3 ; fakearray pointer
001DFBD0	11223344 ; random_value
001DFBD4	03020100 ; 4 bytes of array[]
001DFBD8	07060504 ; 4 bytes of array[]
001DFBDC	00CB0908 ; random garbage + 2 last bytes of array[]
001DFBE0	0000000A ; last i value after loop was finished
001DFBE4	001DFC2C ; saved EBP value
001DFBE8	\00CB129D ; Return Address

The pointer to the `fakearray[]` (`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.

Chapter 55

Windows 16-bit

16-bit Windows programs are rare nowadays, but can be used in the cases of retrocomputing or dongle hacking ([81 on page 772](#)).

16-bit Windows versions were up to 3.11. 96/98/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”).

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
```

55.1 Example#1

```
#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.

55.2 Example #2

```
#include <windows.h>

int PASCAL WinMain( HINSTANCE hInstance,
                     HINSTANCE hPrevInstance,
                     LPSTR lpCmdLine,
                     int nCmdShow )
{
```

55.3. EXAMPLE #3

```
    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
    mov     ax, 3        ; MB_YESNOCANCEL
    push    ax
    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
```

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 ([67.2 on page 690](#)), 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.

55.3 Example #3

```
#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;
};
```

```
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"
```

55.4. EXAMPLE #4

```
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
push    ds
mov     ax, offset aCaption ; "caption"
push    ax
xor    ax, ax
push    ax
call   MESSAGEBOX

loc_57:
xor    ax, ax
pop    bp
retn  0Ah
WinMain
endp
```

Somewhat extended example from the previous section.

55.4 Example #4

```
#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);
```

55.4. EXAMPLE #4

```

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

```

55.5. EXAMPLE #5

```
        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
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
mov     ax, 7Bh    ; 123
push    ax
call   func3
xor    ax, ax    ; return 0
pop    bp
ret    0Ah
WinMain    endp
```

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 ([25 on page 395](#)).

`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: [E on page 947](#), [D on page 946](#).

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.

55.5 Example #5

```
#include <windows.h>
```

55.5. EXAMPLE #5

```
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
```

55.5. EXAMPLE #5

```
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    endp

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
        ; string_compare_far+31j
    pop     si
    pop     bp
```

55.5. EXAMPLE #5

```
    retn    8
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

loc_86: ; CODE XREF: remove_digits+Aj
    pop     bp
    retn    2
remove_digits endp

WinMain proc near ; CODE XREF: start+EDp
    push    bp
    mov     bp, sp
    mov     ax, offset aAsd ; "asd"
    push    ax
    mov     ax, offset aDef ; "def"
    push    ax
    call    string_compare
    push    ds
    mov     ax, offset aAsd ; "asd"
    push    ax
    push    ds
    mov     ax, offset aDef ; "def"
    push    ax
    call    string_compare_far
    mov     ax, offset aHello1234World ; "hello 1234 world"
    push    ax
    call    remove_digits
    xor     ax, ax
    push    ax
    push    ds
    mov     ax, offset aHello1234World ; "hello 1234 world"
    push    ax
    push    ds
    mov     ax, offset aCaption ; "caption"
    push    ax
    mov     ax, 3 ; MB_YESNOCANCEL
    push    ax
    call    MESSAGEBOX
    xor     ax, ax
    pop     bp
    retn    0Ah
WinMain endp
```

Here we see a difference between the so-called “near” pointers and the “far” pointers: another weird artefact of segmented memory in 16-bit 8086.

You can read more about it here: [97 on page 912](#).

55.6. EXAMPLE #6

"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: [55.2 on page 596](#). Indeed, the Windows kernel is not aware which data segment to use when accessing text strings, so it needs 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.

55.6 Example #6

```
#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
```

55.6. EXAMPLE #6

```
    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 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
    mov    sp, bp
    pop    bp
    retn  0Ah
WinMain endp
```

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 ([67.1 on page 690](#)).

55.6.1 Global variables

This is the same example, but now these variables are global:

```
#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);
```

55.6. EXAMPLE #6

```
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;
};
```

```
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
    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 56

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.

56.1 Working with addresses instead of pointers

Pointer is just an address in memory. But why 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 able to check bugs in compilation time.

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 sane C/C++ programmer can write:

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

void print_string (char *s)
{
    printf("(address: 0x%llx)\n", s);
    printf ("%s\n", s);
};

int main()
{
    char *s="Hello, world!";
    print_string (s);
}
```

This is what I can write ("Do not try this at home" ("MythBusters")):

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

void print_string (uint64_t address)
{
    printf("(address: 0x%llx)\n", address);
```

56.1. WORKING WITH ADDRESSES INSTEAD OF POINTERS

```
    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. `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)\n"
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
    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:

```
#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()
{
```

56.1. WORKING WITH ADDRESSES INSTEAD OF POINTERS

```
char *s="Hello, world!";
print_string (s);
};
```

It can be rewritten like this:

```
#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 ((uint64_t)s);
};
```

Both source codes resulting in the same assembly output:

```
gcc 1.c -S -masm=intel -O3 -fno-inline
```

```
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).

56.2. PASSING VALUES AS POINTERS; TAGGED UNIONS

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.

56.2 Passing values as pointers; tagged unions

Here is an example on how to pass values in pointers:

```
#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!

```
multiply1:
    mov    rax, rdi
    imul   rax, rsi
    ret

multiply2:
    mov    rax, rdi
    imul   rax, rsi
    ret
```

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: [31.1](#).

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. Read more about it: [\[Yur13, p. 1.3\]](#).

56.3 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:

```
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 should use `MAKEINTRESOURCE` macro, like this:

```
result = FindResource(..., MAKEINTRESOURCE(1234), ...);
```

56.3. POINTERS ABUSE IN WINDOWS KERNEL

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:

```
...
#ifndef !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:

```
HRSRC
FindResourceA(
    HMODULE hModule,
    LPCSTR lpName,
    LPCSTR lpType
)

...
{

    NTSTATUS Status;
    ULONG IdPath[ 3 ];
    PVOID p;

    IdPath[ 0 ] = 0;
    IdPath[ 1 ] = 0;
    try {
        if ((IdPath[ 0 ] = BaseDllMapResourceIdA( lpType )) == -1) {
            Status = STATUS_INVALID_PARAMETER;
        }
        else
            if ((IdPath[ 1 ] = BaseDllMapResourceIdA( lpName )) == -1) {
                Status = STATUS_INVALID_PARAMETER;
    ...
}
```

Let's proceed to *BaseDllMapResourceIdA()* in the same source file:

```
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) {
            if (*lpId == '#') {
                Status = RtlCharToInteger( lpId+1, 10, &Id );
                if (!NT_SUCCESS( Status ) || Id & LDR_RESOURCE_ID_NAME_MASK) {
                    if (NT_SUCCESS( Status )) {
                        Status = STATUS_INVALID_PARAMETER;
                    }
                    BaseSetLastNTError( Status );
                    Id = (ULONG)-1;
                }
            }
            else {
                RtlInitAnsiString( &AnsiString, lpId );
                Status = RtlAnsiStringToUnicodeString( &UnicodeString,
                                                    &AnsiString,
                                                    TRUE
                                            );
            }
        }
    }
}
```

56.3. POINTERS ABUSE IN WINDOWS KERNEL

```

        if (!NT_SUCCESS( Status )){ 
            BaseSetLastNTError( Status );
            Id = (ULONG)-1;
        }
        else {
            s = UnicodeString.Buffer;
            while (*s != UNICODE_NULL) {
                *s = RtlUpcaseUnicodeChar( *s );
                s++;
            }

            Id = (ULONG)UnicodeString.Buffer;
        }
    }
    else {
        Id = (ULONG)lpId;
    }
}
except (EXCEPTION_EXECUTE_HANDLER) {
    BaseSetLastNTError( GetExceptionCode() );
    Id = (ULONG)-1;
}
return Id;
}

```

lpId is ANDed with *LDR_RESOURCE_ID_NAME_MASK*. Which we can find in *public/sdk/inc/ntldr.h*:

```

...
#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 a string). Otherwise - second half (*lpId* is treated as 16-bit value).

Still, this code can be found in Windows 7 kernel32.dll file:

```

.....
.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
.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 ; 
    ↓ -----
.text:0000000078D2452A
.text:0000000078D2452A loc_78D2452A: ; CODE XREF: ↴
    ↓ BaseDllMapResourceIdA+18
.text:0000000078D2452A ; BaseDllMapResourceIdA+1EAD0
.text:0000000078D2452A         jmp     short $+2
.text:0000000078D2452C ; 
    ↓ -----
.text:0000000078D2452C
.text:0000000078D2452C loc_78D2452C: ; CODE XREF: ↴
    ↓ BaseDllMapResourceIdA:loc_78D2452A

```

56.3. POINTERS ABUSE IN WINDOWS KERNEL

```
.text:0000000078D2452C ; BaseDllMapResourceIdA+1EB74
.text:0000000078D2452C     mov     rax, rcx
.text:0000000078D2452F     add     rsp, 50h
.text:0000000078D24533     pop    rbx
.text:0000000078D24534     retn
.text:0000000078D24534 ; 2

    -----
.text:0000000078D24535     align 20h
.text:0000000078D24535 BaseDllMapResourceIdA endp

....
```

....

```
.text:0000000078D42FB4 loc_78D42FB4: ; CODE XREF: ↵
↳ BaseDllMapResourceIdA+D
.text:0000000078D42FB4     cmp     byte ptr [rcx], '#'
.text:0000000078D42FB7     jnz    short loc_78D43005
.text:0000000078D42FB9     inc    rcx
.text:0000000078D42FBC    lea    r8, [rsp+58h+arg_8]
.text:0000000078D42FC1    mov    edx, 0Ah
.text:0000000078D42FC6    call   cs:_imp_RtlCharToInteger
.text:0000000078D42FCC    mov    ecx, [rsp+58h+arg_8]
.text:0000000078D42FD0    mov    [rsp+58h+var_38], rcx
.text:0000000078D42FD5    test   eax, eax
.text:0000000078D42FD7    js    short loc_78D42FE6
.text:0000000078D42FD9    test   rcx, 0xFFFFFFFFFFFF0000h
.text:0000000078D42FE0    jz    loc_78D2452A

....
```

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 there are no pointers below 0x10000 in Windows code, well, 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 you should use it only if you have to. Probably, *FindResource()* function in past had *SHORT* type for its arguments, and then Microsoft has added a way to pass strings there, but older code should also work? I'm not sure, but that's possible.

Now here is my short distilled example:

```
#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!

56.3.1 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:

```
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;

    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:

```
static inline void * __must_check ERR_PTR(long error)
{
    return (void *) error;
}
```

(<https://github.com/torvalds/linux/blob/61d0b5a4b2777dcf5daef245e212b3c1fa8091ca/tools/virtio/linux/err.h>)

This header file also has a macro helper to distinguish error code from pointer:

```
#define IS_ERR_VALUE(x) unlikely((x) >= (unsigned long)-MAX_ERRNO)
```

This mean, errors are the "pointers" which are very close to -1 and, hopefully, there are no valid addresses there in kernel memory area (addresses like 0xFFFFFFFFFFFFFF, 0xFFFFFFFFFFFFFFE, 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:

```
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/aa00edc1287a693eadc7bc67a3d73555d969b35d/drivers/net/ethernet/freescale/fman/fman.c#L826>)

56.4 Null pointers

56.4.1 “Null pointer assignment” error of MS-DOS era

Some oldschoolers may remember a weird error message of MS-DOS era: “Null pointer assignment”. What does it mean?

It's not possible to write a memory at zero 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:

```
#include <stdio.h>

int main()
{
    int *ptr=NULL;
    *ptr=1234;
    printf ("Now let's read at NULL\n");
    printf ("%d\n", *ptr);
}
```

Hard to believe, but it works, with error upon exit, though:

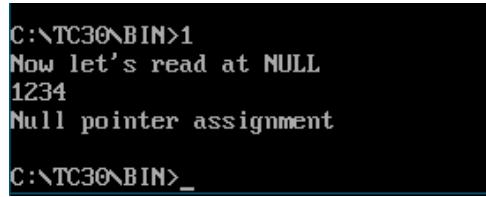


Figure 56.1: Ancient Turbo C 3.0

Let's dig deeper into the source code of CRT (C runtime) of Borland C++ 3.1, file *c0.asm*:

```
;     _checknull()      check for null pointer zapping copyright message
...
;     Check for null pointers before exit

__checknull    PROC    DIST
                PUBLIC   __checknull

IF      LDATA  EQ  false
IFDEF  __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
```

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```
; 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
IFDEF _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 and probably not worth looking into it unless you're fan of retrocomputing or retrogaming. One thing we should know 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 mean, your program at some point has written at address 0.

Our program did so. And this is why 1234 number was correctly read: because it was written at the place of the first 4 zero bytes. Checksum was incorrect upon exit (because the number has left there), so error message has been displayed.

Am I right? I've rewritten the program to check my assumptions:

```
#include <stdio.h>

int main()
{
    int *ptr=NULL;
    *ptr=1234;
    printf ("Now let's read at NULL\n");
    printf ("%d\n", *ptr);
    *ptr=0; // oops, cover our tracks!
};
```

This program works without error message upon exit.

Though method to warn about null pointer assignment is relevant for MS-DOS, it's probably can be still used in low-cost microcontrollers without memory protection and/or [MMU¹](#).

56.4.2 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.

```
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:

¹Memory management unit

56.4. NULL POINTERS

```
int *ptr=malloc(1000);
...
... we forgot to check if memory was really allocated: this is MS-DOS after all and computers ↴
    ↴ had small amount of RAM,
... and RAM shortage was very common.
... malloc() may return NULL, so ptr now is also NULL.

strcpy (ptr, buf); // strcpy() terminates silently because MS-DOS has no memory protection
```

56.4.3 NULL in C/C++

NULL in C/C++ is just a macro which is often defined like this:

```
#define NULL ((void*)0)
```

(libio.h file)

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. You may probably 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 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.

(https://en.wikipedia.org/wiki/Zero_page)

56.4.4 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:

```
#include <windows.h>
#include <stdio.h>

int main()
{
    printf ("0x%llx\n", &MessageBoxA);
}
```

The result is 0x7578feae and doesn't change after several times I run it, because user32.dll (where MessageBoxA function resides) is always loaded at the same address. And also because ASLR² is not enabled (result would be different each time in that case).

Let's call *MessageBoxA()* by address:

```
#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 it is not imported
    LoadLibrary ("user32.dll");
```

²Address Space Layout Randomization

56.5. ARRAY AS FUNCTION ARGUMENT

```
    msgboxaddr(NULL, "Hello, world!", "hello", MB_OK);  
};
```

Weird, but works in Windows 7.

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:

```
int reset()  
{  
    void (*foo)(void) = 0;  
    foo();  
};
```

Who will need to call a function at address 0? This is 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 is portable method.

It even compiles correctly by my GCC 4.8.4 on Linux x64:

```
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>.

56.5 Array as function argument

Someone may ask, what is the difference between declaring function argument type as array instead of pointer?

As it seems, there are no difference at all:

```
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:

```
write_something1:  
    mov    DWORD PTR [rdi+20], 0  
    ret
```

56.5. ARRAY AS FUNCTION ARGUMENT

```
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?

Some people, including Linus Torvalds, criticizes this C/C++ feature: <https://lkml.org/lkml/2015/9/3/428>.

C99 standard also have *static* keyword [C99]:

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.

Part IV

Java

Chapter 57

Java

57.1 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.
- Analysing obfuscated code.
- Building your own obfuscator.
- Building a compiler codegenerator (back-end) targeting **JVM** (like Scala, Clojure, etc³).

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 : [\[Jav13\]](#).

57.2 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.

```
public class ret
{
    public static int main(String[] args)
    {
        return 0;
    }
}
```

Let's compile it:

```
javac ret.java
```

...and decompile it using the standard Java utility:

¹For example, JAD: <http://varaneckas.com/jad/>

²Just-in-time compilation

³Full list: http://en.wikipedia.org/wiki/List_of_JVM_languages

57.2. RETURNING A VALUE

```
javap -c -verbose ret.class
```

And we get:

Listing 57.1: 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 0⁴. 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 returning values. So `iconst_0` pushes 0 into the stack. `ireturn` returns an integer value (*i* in name mean *integer*) from the TOS⁵.

Let's rewrite our example slightly, now we return 1234:

```
public class ret
{
    public static int main(String[] args)
    {
        return 1234;
    }
}
```

...we get:

Listing 57.2: 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;
    }
}
```

Listing 57.3: Constant pool

```
...
  #2 = Integer          12345678
...
```

```
public static int main(java.lang.String[]);
  flags: ACC_PUBLIC, ACC_STATIC
  Code:
    stack=1, locals=1, args_size=1
      0: ldc           #2                  // int 12345678
      2: ireturn
```

⁴Just like in MIPS, where a separate register for zero constant exists : [4.5.2 on page 22](#).

⁵Top Of Stack

57.2. RETURNING A VALUE

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: [29.3 on page 442](#), [30.1 on page 445](#).

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:

```
public class ret
{
    public static boolean main(String[] args)
    {
        return true;
    }
}
```

```
public static boolean main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=1, locals=1, args_size=1
 0:  iconst_1
 1:  ireturn
```

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*:

```
public class ret
{
    public static short main(String[] args)
    {
        return 1234;
    }
}
```

```
public static short main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=1, locals=1, args_size=1
 0:  sipush      1234
 3:  ireturn
```

...and *char*!

```
public class ret
{
    public static char main(String[] args)
    {
        return 'A';
    }
}
```

```
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.

57.2. RETURNING A VALUE

Let's also try a `byte`:

```
public class retc
{
    public static byte main(String[] args)
    {
        return 123;
    }
}
```

```
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:

```
public class ret3
{
    public static long main(String[] args)
    {
        return 1234567890123456789L;
    }
}
```

Listing 57.4: Constant pool

```
...
#2 = Long          12345678901234567891
...
```

```
public static long main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=2, locals=1, args_size=1
0: ldc2_w      #2           // long 12345678901234567891
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:

```
public class ret
{
    public static double main(String[] args)
    {
        return 123.456d;
    }
}
```

Listing 57.5: Constant pool

```
...
#2 = Double       123.456d
...
```

57.3. SIMPLE CALCULATING FUNCTIONS

```
public static double main(java.lang.String[]);
  flags: ACC_PUBLIC, ACC_STATIC
  Code:
    stack=2, locals=1, args_size=1
      0: ldc2_w           #2                  // double 123.456d
      3: dreturn
```

`dreturn` stands for “return double”.

And finally, a single precision floating point number:

```
public class ret
{
    public static float main(String[] args)
    {
        return 123.456f;
    }
}
```

Listing 57.6: Constant pool

```
...
#2 = Float          123.456f
...
```

```
public static float main(java.lang.String[]);
  flags: ACC_PUBLIC, ACC_STATIC
  Code:
    stack=1, locals=1, args_size=1
      0: ldc             #2                  // float 123.456f
      2: freturn
```

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?

```
public 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.

57.3 Simple calculating functions

Let's continue with a simple calculating functions.

```
public class calc
{
    public static int half(int a)
    {
        return a/2;
    }
}
```

57.3. SIMPLE CALCULATING FUNCTIONS

Here's the output when the `iconst_2` instruction is used:

```
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:

```
public class calc
{
    public static double half_double(double a)
    {
        return a/2.0;
    }
}
```

Listing 57.7: Constant pool

```
...
#2 = Double          2.0d
...
```

```
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:

```
public class calc
{
    public static int sum(int a, int b)
    {
        return a+b;
    }
}
```

57.3. SIMPLE CALCULATING FUNCTIONS

```
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_2` –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:

```
public static long lsum(long a, long b)
{
    return a+b;
}
```

...we got:

```
public static long lsum(long, long);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=4, locals=4, args_size=2
0: lload_0
1: lload_2
2: ladd
3: lreturn
```

The second `lload` 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 complex example:

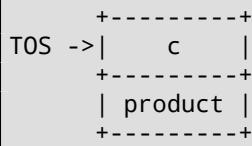
```
public class calc
{
    public static int mult_add(int a, int b, int c)
    {
        return a*b+c;
    }
}
```

```
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](#):



`iload_2` loads the third argument (`c`) in the stack:



Now the `iadd` instruction can add the two values.

57.4 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 (LVA⁶). Used as storage for incoming function arguments and local variables. Instructions like `iload_0` load values from it. `istore` stores values in it. In 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.

57.5 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):

```

public class HalfRandom
{
    public static double f()
    {
        return Math.random()/2;
    }
}

```

Listing 57.8: 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

```

⁶(Java) Local Variable Array

57.5. SIMPLE FUNCTION CALLING

```

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:

```

public class HelloWorld
{
    public static void main(String[] args)
    {
        System.out.println("Hello, World");
    }
}

```

Listing 57.9: Constant pool

```

...
#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
...

```

```

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 in the stack. It's called a *reference* in the Java world, but it's rather a pointer, or an address ⁷.

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.

⁷About difference in pointers and *reference*'s in C++ see: [53.3 on page 559](#).

57.6. CALLING BEEP()

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 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.

57.6 Calling beep()

This is a simple calling of two functions without arguments:

```
public static void main(String[] args)
{
    java.awt.Toolkit.getDefaultToolkit().beep();
};
```

```
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:()V
  ↴ Ljava.awt.Toolkit;
  3: invokevirtual #3                     // Method java.awt.Toolkit.beep:()V
  6: return
```

First `invokestatic` 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.

57.7 Linear congruent PRNG

Let's try a simple pseudorandom numbers generator, which we already considered once in the book ([21 on page 337](#)):

```
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:

```
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
```

57.8. CONDITIONAL JUMPS

```
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`:

```
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()`:

```
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 was 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.

57.8 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
```

57.8. CONDITIONAL JUMPS

```
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:

```
public static int min(int, int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=2, locals=2, args_size=2
0: iload_0
1: iload_1
2: if_icmpge    7
5: iload_1
6: ireturn
7: iload_0
8: ireturn
```

`if_icmpge` 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 ...

```
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:

```
public static int max(int, int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=2, locals=2, args_size=2
0: iload_0
1: iload_1
2: if_icmpge    7
5: iload_0
6: ireturn
7: iload_1
8: ireturn
```

A more complex example:

```
public class cond
{
    public static void f(int i)
    {
        if (i<100)
            System.out.print("<100");
        if (i==100)
```

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```
        System.out.print("==100");
    if (i>100)
        System.out.print(">100");
    if (i==0)
        System.out.print("==0");
}
```

```
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;
   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 `if_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.

57.9 Passing arguments

Let's extend our `min()` / `max()` example:

```
public class minmax
{
    public static int min (int a, int b)
    {
        if (a>b)
            return b;
        return a;
    }
}
```

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```
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:

```
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
  6: istore_2
  7: iload_1
  8: iload_2
  9: invokestatic #2                  // Method max:(II)I
 12: istore_3
 13: iload_1
 14: iload_2
 15: invokestatic #3                  // Method min:(II)I
 18: istore      4
 20: getstatic   #4                  // Field java/lang/System.out:Ljava/io/
↳ PrintStream;
 23: iload      4
 25: invokevirtual #5                // Method java/io/PrintStream.println:(I)V
 28: getstatic   #4                  // Field java/lang/System.out:Ljava/io/
↳ PrintStream;
 31: iload_3
 32: invokevirtual #5                // Method java/io/PrintStream.println:(I)V
 35: return
```

Arguments are passed to the other function in the stack, and the return value is left on [TOS](#).

57.10 Bitfields

All bit-wise operations work just like in any other ISA:

```
public static int set (int a, int b)
{
    return a | 1<<b;
}

public static int clear (int a, int b)
{
    return a & (~(1<<b));
}
```

```
public static int set(int, int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=3, locals=2, args_size=2
  0: iload_0
```

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```
1:  iconst_1
2:  iload_1
3:  ishl
4:  ior
5:  ireturn

public static int clear(int, int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=3, locals=2, args_size=2
0: iload_0
1: iconst_1
2: iload_1
3: ishl
4: iconst_m1
5: ixor
6: iand
7: ireturn
```

`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 ([32 on page 450](#)).

Let's extend all data types to 64-bit `long`:

```
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: i2l
5: lor
6: lreturn

public static long lclear(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: iconst_m1
5: ixor
6: i2l
7: land
8: lreturn
```

The code is the same, but instructions with `l` prefix are used, which operate on 64-bit values. Also, the second argument of the function still is of type `int`, and when the 32-bit value in it needs to be promoted to 64-bit value the `i2l` instruction is used, which essentially extend the value of an `integer` type to a `long` one.

57.11 Loops

57.11. 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
 8:  getstatic    #2           // Field java/lang/System.out:Ljava/io/
↳ PrintStream;
 11: iload_1
 12: invokevirtual #3          // Method java/io/PrintStream.println:(I)V
 15: iinc         1, 1
 18: goto         2
 21: return
```

`iconst_1` loads 1 into `TOS`, `istore_1` stores it in the `LVA` at slot 1. 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* mean *integer* and *V* mean 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:

```
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);
        }
    }
}
```

```
public static void main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=2, locals=5, args_size=1
 0: bipush      20
 2: istore_1
 3: iconst_0
 4: istore_2
 5: iconst_1
```

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```
6: istore_3
7: iconst_1
8: istore      4
10: iload       4
12: iload_1
13: if_icmpgt   37
16: iload_2
17: iload_3
18: iadd
19: istore_2
20: iload_2
21: iload_3
22: isub
23: istore_3
24: getstatic    #2           // Field java/lang/System.out:Ljava/io/
↳ PrintStream;
27: iload_2
28: invokevirtual #3          // Method java/io/PrintStream.println:(I)V
31: iinc        4, 1
34: goto         10
37: return
```

Here is a map of the LVA slots:

- 0 – the sole argument of `main()`
- 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.

57.12 switch()

The `switch()` statement is implemented with the `tableswitch` instruction:

```
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:

```
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
```

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```
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
80: getstatic    #2           // Field java/lang/System.out:Ljava/io/
↳ PrintStream;
83: ldc         #8           // String four\n
85: 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\n
96: invokevirtual #4           // Method java/io/PrintStream.println:(Ljava/lang/
↳ /String;)V
99: return
```

57.13 Arrays

57.13.1 Simple example

Let's first create an array of 10 integers and fill it:

```
public static void main(String[] args)
{
    int a[]={new int[10];
    for (int i=0; i<10; i++)
        a[i]=i;
    dump (a);
}
```

```
public static void main(java.lang.String[]);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=3, locals=3, args_size=1
0: bipush      10
2: newarray     int
4: astore_1
5: iconst_0
6: istore_2
```

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```
7: iload_2
8: bipush      10
10: if_icmpge   23
13: aload_1
14: iload_2
15: iload_2
16: iastore
17: iinc        2, 1
20: goto        7
23: aload_1
24: invokestatic #4           // Method dump:([I)V
27: return
```

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. `iastore` 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:

```
public static void dump(int a[])
{
    for (int i=0; i<a.length; i++)
        System.out.println(a[i]);
}
```

```
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:  aload_0
4:  arraylength
5:  if_icmpge   23
8:  getstatic   #2           // Field java/lang/System.out:Ljava/io/PrintStream;
↳ PrintStream;
11:  aload_0
12:  iload_1
13:  iaload
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.

57.13.2 Summing elements of array

Another example:

```
public class ArraySum
{
```

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```
public static int f (int[] a)
{
    int sum=0;
    for (int i=0; i<a.length; i++)
        sum=sum+a[i];
    return sum;
}
```

```
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:  aload_0
 6:  arraylength
 7:  if_icmpge      22
10:  iload_1
11:  aload_0
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*.

57.13.3 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:

```
public 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.

```
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;
```

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```
20: ldc          #5           // String . How are you?
22: invokevirtual #6           // Method java/io/PrintStream.println:(Ljava/lang/V
↳ /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.

57.13.4 Pre-initialized array of strings

```
class Month
{
    public static String[] months =
    {
        "January",
        "February",
        "March",
        "April",
        "May",
        "June",
        "July",
        "August",
        "September",
        "October",
        "November",
        "December"
    };

    public String get_month (int i)
    {
        return months[i];
    }
}
```

The `get_month()` function is simple: Функция `get_month()` проста:

```
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
```

`aaload` operates on an array of *references*. 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?

```
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
```

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```
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
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 very well-known instruction in stack computers (including the Forth programming language) which just duplicates the value at [TOS](#). 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.

57.13.5 Variadic functions

Variadic functions actually use arrays:

```
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);
```

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```
}
```

```
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: aload_0  
    4: arraylength  
    5: if_icmpge      23  
    8: getstatic      #2           // Field java/lang/System.out:Ljava/io/PrintStream;  
    ↳ PrintStream;  
    11: aload_0  
    12: iload_1  
    13: iaload  
    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.

```
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:

```
public PrintStream format(String format, Object... args)
```

(<http://docs.oracle.com/javase/tutorial/java/data/numberformat.html>)

Let's see:

```
public static void main(String[] args)  
{  
    int i=123;
```

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```
        double d=123.456;
        System.out.format("int: %d double: %f.%n", i, d);
    }
```

```
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;
  ↳ PrintStream;
  10: ldc         #5          // String int: %d double: %f.%n
  12: iconst_2
  13: anewarray    #6          // class java/lang/Object
  16: dup
  17: iconst_0
  18: iload_1
  19: invokestatic #7          // Method java/lang/Integer.valueOf:(I)Ljava/lang/Object;
  ↳ /Integer;
  22: aastore
  23: dup
  24: iconst_1
  25: dload_2
  26: invokestatic #8          // Method java/lang/Double.valueOf:(D)Ljava/lang/Object;
  ↳ Double;
  29: aastore
  30: invokevirtual #9          // Method java/io/PrintStream.format:(Ljava/lang/String;Ljava/lang/Object;)V;
  ↳ String;[Ljava/lang/Object;)Ljava/io/PrintStream;
  33: pop
  34: return
```

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 contain 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).

57.13.6 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:

```
public static void main(String[] args)
{
    int[][] a = new int[5][10];
    a[1][2]=3;
}
```

```
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
  3: multianewarray #2, 2          // class "[[I"
  7: astore_1
```

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```
8: aload_1
9: iconst_1
10: aaload
11: iconst_2
12: iconst_3
13: iastore
14: return
```

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. The value to be written is set at offset 12. `iastore` at 13 writes the array's element.

How it is an element accessed?

```
public static int get12 (int[][][] in)
{
    return in[1][2];
}
```

```
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.

57.13.7 Three-dimensional arrays

Three-dimensional arrays are just one-dimensional arrays of *references* to one-dimensional arrays of *references*.

```
public static void main(String[] args)
{
    int[][][] a = new int[5][10][15];
    a[1][2][3]=4;
    get_elem(a);
}
```

```
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
3: bipush      15
5: multianewarray #2,  3           // class "[][][I"
9: astore_1
10: aload_1
11: iconst_1
12: aaload
13: iconst_2
14: aaload
15: iconst_3
16: iconst_4
17: iastore
18: aload_1
19: invokestatic #3                // Method get_elem:([[[I])
```

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```
22: pop  
23: return
```

Now it takes two `aaload` instructions to find right reference:

```
public static int get_elem (int[][][] a)  
{  
    return a[1][2][3];  
}
```

```
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
```

57.13.8 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.

57.14 Strings

57.14.1 First example

Strings are objects and are constructed in the same way as other objects (and arrays).

```
public static void main(String[] args)  
{  
    System.out.println("What is your name?");  
    String input = System.console().readLine();  
    System.out.println("Hello, "+input);  
}
```

```
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;  
↳ PrintStream;  
    3: ldc #3 // String What is your name?  
    5: invokevirtual #4 // Method java/io/PrintStream.println:(Ljava/lang/String)V  
↳ /String; )V  
    8: invokespecial #5 // Method java/lang/System.console:()Ljava/io/Console;  
↳ Console;  
    11: invokevirtual #6 // Method java/io/Console.readLine:()Ljava/lang/String;  
↳ String;  
    14: astore_1  
    15: getstatic #2 // Field java/lang/System.out:Ljava/io/PrintStream;  
↳ PrintStream;  
    18: new #7 // class java/lang/StringBuilder  
    21: dup  
    22: invokespecial #8 // Method java/lang/StringBuilder."<init>":()V  
    25: ldc #9 // String Hello,
```

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```
27: invokevirtual #10           // Method java/lang/StringBuilder.append:(Ljava/<
↳ lang/String;)Ljava/lang/StringBuilder;
  30: aload_1
  31: invokevirtual #10           // Method java/lang/StringBuilder.append:(Ljava/<
↳ lang/String;)Ljava/lang/StringBuilder;
  34: invokevirtual #11           // Method java/lang/StringBuilder.toString:()<
↳ Ljava/lang/String;
  37: invokevirtual #4           // Method java/io/PrintStream.println:(Ljava/lang/<
↳ /String;)V
  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`. 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.

57.14.2 Second example

Another example:

```
public class strings
{
    public static char test (String a)
    {
        return a.charAt(3);
    }

    public static String concat (String a, String b)
    {
        return a+b;
    }
}
```

```
public static char test(java.lang.String);
  flags: ACC_PUBLIC, ACC_STATIC
  Code:
    stack=2, locals=1, args_size=1
      0: aload_0
      1: iconst_3
      2: invokevirtual #2           // Method java/lang/String.charAt:(I)C
      5: ireturn
```

The string concatenation is done using `StringBuilder`:

```
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:

```
public static void main(String[] args)
{
    String s="Hello!";
```

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```
        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`:

```
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
    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
      22: invokevirtual #7               // Method java/lang/StringBuilder.append:(Ljava/
    ↳ lang/String;)Ljava/lang/StringBuilder;
      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:()V
    ↳ Ljava/lang/String;
      37: invokevirtual #11              // Method java/io/PrintStream.println:(Ljava/lang/
    ↳ /String;)V
      40: return
```

57.15 Exceptions

Let's rework our *Month* example ([57.13.4 on page 641](#)) a bit:

Listing 57.10: IncorrectMonthException.java

```
public class IncorrectMonthException extends Exception
{
    private int index;

    public IncorrectMonthException(int index)
    {
        this.index = index;
    }
    public int getIndex()
    {
        return index;
    }
}
```

Listing 57.11: Month2.java

```
class Month2
{
    public static String[] months =
    {
        "January",
        "February",
        "March",
```

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```
"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:

```
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.

```
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`:

Listing 57.12: Month2.class

```
public static java.lang.String get_month(int) throws IncorrectMonthException;
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=3, locals=1, args_size=1
```

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```

0: iload_0
1: iflt      10
4: iload_0
5: bipush    11
7: if_icmple 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. 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`:

Listing 57.13: Month2.class

```

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
    27: invokevirtual #11      // Method java/lang/StringBuilder.append:(Ljava/
  ↵ lang/String;)Ljava/lang/StringBuilder;
    30: aload_1
    31: invokevirtual #12      // Method IncorrectMonthException.getIndex:()I
    34: invokevirtual #13      // Method java/lang/StringBuilder.append:(I)Ljava/
  ↴ lang/StringBuilder;
    37: invokevirtual #14      // Method java/lang/StringBuilder.toString:()V
  ↴ 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:
  from   to   target type
    0    11    14  Class IncorrectMonthException

```

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*

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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:

Listing 57.14: from some random .class file found on the author’s computer

```
.catch java/io/FileNotFoundException from met001_335 to met001_360\
using met001_360
.catch java/io/FileNotFoundException from met001_185 to met001_214\
using met001_214
.catch java/io/FileNotFoundException from met001_181 to met001_192\
using met001_195
.catch java/io/FileNotFoundException from met001_155 to met001_176\
using met001_176
.catch java/io/FileNotFoundException from met001_83 to met001_129 using \
met001_129
.catch java/io/FileNotFoundException from met001_42 to met001_66 using \
met001_69
.catch java/io/FileNotFoundException from met001_begin to met001_37\
using met001_37
```

57.16 Classes

Simple class:

Listing 57.15: test.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:

```
public test();
flags: ACC_PUBLIC
Code:
```

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```
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**:

```
public static void set_a(int);
flags: ACC_PUBLIC, ACC_STATIC
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
```

Getter of **b**:

```
public static int get_b();
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=1, locals=0, args_size=0
 0: getstatic      #3                // Field b:I
 3: ireturn
```

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 57.16: 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
Code:
stack=2, locals=2, args_size=1
 0: new           #2                // class test
```

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```
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
```

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.

57.17 Simple patching

57.17.1 First example

Let's proceed with a simple code patching task.

```
public 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:

57.17. SIMPLE PATCHING

```

; Segment type: Pure code
.method public static nag_screen()V
.limit stack 2
.line 4
• 178 000 002 |    getstatic java/lang/System.out Ljava/io/PrintStream; ; CODE XREF: main+8↑P
• 018 003       ldc "This program is not registered"
• 182 000 004     invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
                 .line 5
• 177           return
• ??? ??? ???+   .end method
• ??? ??? ???+
???
;
```



```

; Segment type: Pure code
.method public static main([Ljava/lang/String;)V
.limit stack 2
.limit locals 1
.line 8
• 178 000 002     getstatic java/lang/System.out Ljava/io/PrintStream;
• 018 005       ldc "Greetings from the mega-software"
• 182 000 004     invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
                 .line 9
• 184 000 006     invokestatic nag.nag_screen()V
                 .line 10
• 177           return
;
```

Figure 57.1: IDA

Let's patch the first byte of the function to 177 (which is the `return` instruction's opcode):

```

; Segment type: Pure code
.method public static nag_screen()V
.limit stack 2
.line 4
| nag_screen:                                     ; CODE XREF: main+8↑P
• 177         return
• 000         0 ; 0x00
• 002         2 ; 0x02
• 018 003     ldc "This program is not registered"
• 182 000 004     invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
                 .line 5
• 177         return
• ??? ??? ???+   .end method
• ??? ??? ???+
???
;
```

Figure 57.2: IDA

But that doesn't work (JRE 1.7):

```

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)
;
```

57.17. SIMPLE PATCHING

Perhaps JVM has some other checks related to the stack maps.

OK, let's patch it differently by removing the call to `nag()`:

```
; Segment type: Pure code
.method public static main([Ljava/lang/String;)V
.limit stack 2
.limit locals 1
.line 8
• 178 000 002    getstatic java/lang/System.out Ljava/io/PrintStream;
• 018 005        ldc "Greetings from the mega-software"
• 182 000 004    invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
.line 9
• 000            nop
• 000            nop
• 000            nop
• 177            return
.
,
=====
```

Figure 57.3: IDA

0 is the opcode for [NOP](#).

Now that works!

57.17.2 Second example

Another simple crackme example:

```
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:

57.17. SIMPLE PATCHING

The screenshot shows the Java bytecode for a simple password verification program. The code is annotated with assembly-like comments and line numbers. It prompts for input, reads it, compares it to a secret, and prints a message based on the result. A specific instruction at address 178 000 002 is highlighted in yellow, labeled 'ifeq met002_35'. A dashed rectangle highlights the entire conditional block starting from this instruction.

```
; Segment type: Pure code
.method public static main([Ljava/lang/String;)V
.limit stack 2
.limit locals 2
.line 3
• 178 000 002    getstatic java/lang/System.out Ljava/io/PrintStream;
• 018 003        ldc "Please enter the password"
• 182 000 004    invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
.line 4
• 184 000 005    invokestatic java/lang/System.console()Ljava/io/Console;
• 182 000 006    invokevirtual java/io/Console.readLine()Ljava/lang/String;
• 076            astore_1 ; met002_slot001
.line 5
• 043            aload_1 ; met002_slot001
• 018 007        ldc "Secret"
• 182 000 008    invokevirtual java/lang/String.equals(Ljava/lang/Object;)Z
• 153 000 014    ifeq met002_35
.line 6
• 178 000 002    getstatic java/lang/System.out Ljava/io/PrintStream;
• 018 009        ldc "password is correct"
• 182 000 004    invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
• 167 000 011    goto met002_43
.line 8

met002_35:                                ; CODE XREF: main+21↑j
178 000 002    .stack use locals
              locals Object java/lang/String
              .end stack
              getstatic java/lang/System.out Ljava/io/PrintStream;
              ldc "password is not correct"
              invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
.line 9
```

Figure 57.4: 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):

57.17. SIMPLE PATCHING

```

; Segment type: Pure code
.method public static main([Ljava/lang/String;)V
.limit stack 2
.limit locals 2
.line 3
• 178 000 002      getstatic java/lang/System.out Ljava/io/PrintStream;
• 018 003          ldc "Please enter the password"
• 182 000 004      invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
.line 4
• 184 000 005      invokestatic java/lang/System.console()Ljava/io/Console;
• 182 000 006      invokevirtual java/io/Console.readLine()Ljava/lang/String;
• 076              astore_1 ; met002_slot001
.line 5
• 043              aload_1 ; met002_slot001
• 018 007          ldc "secret"
• 182 000 008      invokevirtual java/lang/String.equals(Ljava/lang/Object;)Z
• 153 000 003      ifeq met002_24
.line 6

met002_24:                                ; CODE XREF: main+21↑j
• 178 000 002      getstatic java/lang/System.out Ljava/io/PrintStream;
• 018 009          ldc "password is correct"
• 182 000 004      invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
• 167 000 011      goto met002_43
.line 8
178 000 002      .stack use locals
                  locals Object java/lang/String
                  .end stack
• 018 010          getstatic java/lang/System.out Ljava/io/PrintStream;
• 018 010          ldc "password is not correct"
• 182 000 004      invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
.line 9

```

Figure 57.5: IDA

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)

  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)

```

But it should be mentioned that it worked in JRE 1.6.

We can also try to replace 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 `iconst_1` instruction plus a pack of `NOPs`:

```

; Segment type: Pure code
.method public static main([Ljava/lang/String;)V
.limit stack 2
.limit locals 2
.line 3
• 178 000 002    getstatic java/lang/System.out Ljava/io/PrintStream;
• 018 003        ldc "Please enter the password"
• 182 000 004    invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
.line 4
• 184 000 005    invokestatic java/lang/System.console()Ljava/io/Console;
• 182 000 006    invokevirtual java/io/Console.readLine()Ljava/lang/String;
• 076             astore_1 ; met002_slot001
.line 5
• 004             iconst_1
• 000             nop
• 153 000 014    ifeq met002_35
.line 6
• 178 000 002    getstatic java/lang/System.out Ljava/io/PrintStream;
• 018 009        ldc "password is correct"
• 182 000 004    invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
• 167 000 011    goto met002_43
.line 8

met002_35:          ; CODE XREF: main+21↑j
178 000 002    .stack use locals
                  locals Object java/lang/String
                  .end stack

```

Figure 57.6: IDA

1 needs always to be in the TOS when the `ifeq` instruction is executed, so `ifeq` would never jump.

This works.

57.18 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.

Part V

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 Boost⁸, libpng⁹), 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)¹⁰.

<http://www.google.com/search?q=CsDecomprLZC>

Astoundingly, MaxDB and SAP 6.0 software shared likewise code for the compression/decompression of network packets.

⁸<http://go.yurichev.com/17036>

⁹<http://go.yurichev.com/17037>

¹⁰More about it in relevant section ([83.1 on page 822](#))

Chapter 58

Identification of executable files

58.1 Microsoft Visual C++

MSVC versions and DLLs that can be imported:

Marketing version	Internal version	CL.EXE version	DLLs that can be imported	Release date
6	6.0	12.00	msvcrt.dll, msncpy60.dll	June 1998
.NET (2002)	7.0	13.00	msvcr70.dll, msncpy70.dll	February 13, 2002
.NET 2003	7.1	13.10	msvcr71.dll, msncpy71.dll	April 24, 2003
2005	8.0	14.00	msvcr80.dll, msncpy80.dll	November 7, 2005
2008	9.0	15.00	msvcr90.dll, msncpy90.dll	November 19, 2007
2010	10.0	16.00	msvcr100.dll, msncpy100.dll	April 12, 2010
2012	11.0	17.00	msvcr110.dll, msncpy110.dll	September 12, 2012
2013	12.0	18.00	msvcr120.dll, msncpy120.dll	October 17, 2013

msncpy*.dll contain C++-related functions, so if it is imported, this is probably a C++ program.

58.1.1 Name mangling

The names usually start with the `?` symbol.

You can read more about MSVC's name mangling here: [53.1.1 on page 543](#).

58.2 GCC

Aside from *NIX targets, GCC is also present in the win32 environment, in the form of Cygwin and MinGW.

58.2.1 Name mangling

Names usually start with the `_Z` symbols.

You can read more about GCC's name mangling here: [53.1.1 on page 543](#).

58.2.2 Cygwin

cygwin1.dll is often imported.

58.2.3 MinGW

msvcrt.dll may be imported.

58.3 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.

58.4 Watcom, OpenWatcom

58.4.1 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:

```
W?method$class$n__v
```

58.5 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$qp14TWindowsObject
@TrueColorTo8BitN$qpviiiiit1iiiiii
@TrueColorTo16BitN$qpviiiiit1iiiiii
@DIB24BitTo8BitBitmap$qpviiiiit1iiiiii
@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.

58.5.1 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	2c 10 40 00 09 08 57 69	.True.@.,@...Wi
00000430	64 65 43 68 61 72 03 00	00 00 00 ff ff 00 00 90	deChar.....
00000440	44 10 40 00 02 04 43 68	61 72 01 00 00 00 00 ff	D@...Char.....
00000450	00 00 00 90 58 10 40 00	01 08 53 6d 61 6c 6c 69X@...Smalli
00000460	6e 74 02 00 80 ff ff ff	7f 00 00 90 70 10 40 00	nt.....p@.
00000470	01 07 49 6e 74 65 67 65	72 04 00 00 00 80 ff ff	..Integer.....
00000480	ff 7f 8b c0 88 10 40 00	01 04 42 79 74 65 01 00@...Byte..
00000490	00 00 00 ff 00 00 00 90	9c 10 40 00 01 04 57 6f@...Wo
000004a0	72 64 03 00 00 00 00 ff	ff 00 00 90 b0 10 40 00	rd.....@.
000004b0	01 08 43 61 72 64 69 6e	61 6c 05 00 00 00 00 ff	..Cardinal.....
000004c0	ff ff ff 90 c8 10 40 00	10 05 49 6e 74 36 34 00@...Int64.

58.6. OTHER KNOWN DLLS

000004d0	00 00 00 00 00 00 80 ff	ff ff ff ff ff ff ff 7f 90
000004e0	e4 10 40 00 04 08 45 78	74 65 6e 64 65 64 02 90	..@...Extended..
000004f0	f4 10 40 00 04 06 44 6f	75 62 6c 65 01 8d 40 00	..@...Double..@..
00000500	04 11 40 00 04 08 43 75	72 72 65 6e 63 79 04 90	..@...Currency..
00000510	14 11 40 00 0a 06 73 74	72 69 6e 67 20 11 40 00	..@...string ..@..
00000520	0b 0a 57 69 64 65 53 74	72 69 6e 67 30 11 40 00	..WideString0..@..
00000530	0c 07 56 61 72 69 61 6e	74 8d 40 00 40 11 40 00	..Variant..@..@..
00000540	0c 0a 4f 6c 65 56 61 72	69 61 6e 74 98 11 40 00	..OleVariant..@..
00000550	00 00 00 00 00 00 00 00	00 00 00 00 00 00 00 00
00000560	00 00 00 00 00 00 00 00	00 00 00 00 98 11 40 00@..
00000570	04 00 00 00 00 00 00 00	18 4d 40 00 24 4d 40 00M@..\$M@..
00000580	28 4d 40 00 2c 4d 40 00	20 4d 40 00 68 4a 40 00	(M@..,M@.. M@..hJ@..
00000590	84 4a 40 00 c0 4a 40 00	07 54 4f 62 6a 65 63 74	.J@..J@..TObject
000005a0	a4 11 40 00 07 07 54 4f	62 6a 65 63 74 98 11 40	..@...TObject..@..
000005b0	00 00 00 00 00 00 06 06	53 79 73 74 65 6d 00 00System..
000005c0	c4 11 40 00 0f 0a 49 49	6e 74 65 72 66 61 63 65	..@...IInterface
000005d0	00 00 00 00 01 00 00 00	00 00 00 00 00 c0 00 00
000005e0	00 00 00 00 46 06 53 79	73 74 65 6d 03 00 ff ffF.System....
000005f0	f4 11 40 00 0f 09 49 44	69 73 70 61 74 63 68 c0	..@...IDispatch..
00000600	11 40 00 01 00 04 02 00	00 00 00 00 c0 00 00 00	..@.....
00000610	00 00 00 46 06 53 79 73	74 65 6d 04 00 ff ff 90F.System....
00000620	cc 83 44 24 04 f8 e9 51	6c 00 00 83 44 24 04 f8	..D\$...Ql...D\$..
00000630	e9 6f 6c 00 00 83 44 24	04 f8 e9 79 6c 00 00 cc	.o1...D\$...yl...
00000640	cc 21 12 40 00 2b 12 40	00 35 12 40 00 01 00 00	!.!..@..+.@..5..@..
00000650	00 00 00 00 00 00 00 00	00 c0 00 00 00 00 00 00
00000660	46 41 12 40 00 08 00 00	00 00 00 00 00 8d 40 00	FA..@.....@..
00000670	bc 12 40 00 4d 12 40 00	00 00 00 00 00 00 00 00	..@..M..@.....
00000680	00 00 00 00 00 00 00 00	00 00 00 00 00 00 00 00
00000690	bc 12 40 00 0c 00 00 00	4c 11 40 00 18 4d 40 00	..@.....L..@..M@..
000006a0	50 7e 40 00 5c 7e 40 00	2c 4d 40 00 20 4d 40 00	P~@..`~@..,M@.. M@..
000006b0	6c 7e 40 00 84 4a 40 00	c0 4a 40 00 11 54 49 6e	l~@..J@..J@..TIn
000006c0	74 65 72 66 61 63 65 64	4f 62 6a 65 63 74 8b c0	terfacedObject..
000006d0	d4 12 40 00 07 11 54 49	6e 74 65 72 66 61 63 65	..@...TInterface
000006e0	64 4f 62 6a 65 63 74 bc	12 40 00 a0 11 40 00 00	dObject..@...@..
000006f0	00 06 53 79 73 74 65 6d	00 00 8b c0 00 13 40 00	..System.....@..
00000700	11 0b 54 42 6f 75 6e 64	41 72 72 61 79 04 00 00	..TBoundArray...
00000710	00 00 00 00 00 03 00 00	00 6c 10 40 00 06 53 79l..@..Sy
00000720	73 74 65 6d 28 13 40 00	04 09 54 44 61 74 65 54	stem(..@...TDateT
00000730	69 6d 65 01 ff 25 48 e0	c4 00 8b c0 ff 25 44 e0	ime..%H.....%D..

The first 4 bytes of the data segment (DATA) can be 00 00 00 00 , 32 13 8B C0 or FF FF FF FF . This information can be useful when dealing with packed/encrypted Delphi executables.

58.6 Other known DLLs

- vcomp*.dll – Microsoft's implementation of OpenMP.

Chapter 59

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 Monitor¹ utility from SysInternals can help.

For the basic analysis of network accesses, Wireshark² 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 API³s 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.

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: [78](#).

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.

59.1 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.

- Registry access (advapi32.dll): `RegEnumKeyEx`^{4 5}, `RegEnumValue`^{6 5}, `RegGetValue`^{7 5}, `RegOpenKeyEx`^{8 5}, `RegQueryValueEx`^{9 5}.
- Access to text .ini-files (kernel32.dll): `GetPrivateProfileString` ^{10 5}.
- Dialog boxes (user32.dll): `MessageBox` ^{11 5}, `MessageBoxEx` ^{12 5}, `SetDlgItemText` ^{13 5}, `GetDlgItemText` ^{14 5}.

¹<http://go.yurichev.com/17301>

²<http://go.yurichev.com/17303>

³Application programming interface

⁴[MSDN](#)

⁵May have the -A suffix for the ASCII version and -W for the Unicode version

⁶[MSDN](#)

⁷[MSDN](#)

⁸[MSDN](#)

⁹[MSDN](#)

¹⁰[MSDN](#)

¹¹[MSDN](#)

¹²[MSDN](#)

¹³[MSDN](#)

¹⁴[MSDN](#)

59.2. TRACER: INTERCEPTING ALL FUNCTIONS IN SPECIFIC MODULE

- Resources access ([71.2.8 on page 718](#)): (user32.dll): LoadMenu ^{15 5}.
- TCP/IP networking (ws2_32.dll): WSARRecv ¹⁶, WSASend ¹⁷.
- File access (kernel32.dll): CreateFile ^{18 5}, ReadFile ¹⁹, ReadFileEx ²⁰, WriteFile ²¹, WriteFileEx ²².
- High-level access to the Internet (wininet.dll): WinHttpOpen ²³.
- Checking the digital signature of an executable file (wintrust.dll): WinVerifyTrust ²⁴.
- 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.

59.2 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.

For example, let's see, what does the `uptime` utility from cygwin use:

```
tracer -l:uptime.exe --one-time-INT3-bp:cygwin1.dll!.*
```

Thus we may see all that `cygwin1.dll` library functions that were called at least once, and where from:

```
One-time INT3 breakpoint: cygwin1.dll!__main (called from uptime.exe!OEP+0x6d (0x40106d))
One-time INT3 breakpoint: cygwin1.dll!_geteuid32 (called from uptime.exe!OEP+0xba3 (0x401ba3))
One-time INT3 breakpoint: cygwin1.dll!_getuid32 (called from uptime.exe!OEP+0xbba (0x401baa))
One-time INT3 breakpoint: cygwin1.dll!_getegid32 (called from uptime.exe!OEP+0xcb7 (0x401cb7))
One-time INT3 breakpoint: cygwin1.dll!_getgid32 (called from uptime.exe!OEP+0xcbe (0x401cbe))
One-time INT3 breakpoint: cygwin1.dll!sysconf (called from uptime.exe!OEP+0x735 (0x401735))
One-time INT3 breakpoint: cygwin1.dll!setlocale (called from uptime.exe!OEP+0x7b2 (0x4017b2))
One-time INT3 breakpoint: cygwin1.dll!_open64 (called from uptime.exe!OEP+0x994 (0x401994))
One-time INT3 breakpoint: cygwin1.dll!_lseek64 (called from uptime.exe!OEP+0x7ea (0x4017ea))
One-time INT3 breakpoint: cygwin1.dll!read (called from uptime.exe!OEP+0x809 (0x401809))
One-time INT3 breakpoint: cygwin1.dll!sscanf (called from uptime.exe!OEP+0x839 (0x401839))
One-time INT3 breakpoint: cygwin1.dll!uname (called from uptime.exe!OEP+0x139 (0x401139))
One-time INT3 breakpoint: cygwin1.dll!time (called from uptime.exe!OEP+0x22e (0x40122e))
One-time INT3 breakpoint: cygwin1.dll!localtime (called from uptime.exe!OEP+0x236 (0x401236))
One-time INT3 breakpoint: cygwin1.dll!sprintf (called from uptime.exe!OEP+0x25a (0x40125a))
One-time INT3 breakpoint: cygwin1.dll!setutent (called from uptime.exe!OEP+0x3b1 (0x4013b1))
One-time INT3 breakpoint: cygwin1.dll!getutent (called from uptime.exe!OEP+0x3c5 (0x4013c5))
One-time INT3 breakpoint: cygwin1.dll!endutent (called from uptime.exe!OEP+0x3e6 (0x4013e6))
One-time INT3 breakpoint: cygwin1.dll!puts (called from uptime.exe!OEP+0x4c3 (0x4014c3))
```

¹⁵[MSDN](#)

¹⁶[MSDN](#)

¹⁷[MSDN](#)

¹⁸[MSDN](#)

¹⁹[MSDN](#)

²⁰[MSDN](#)

²¹[MSDN](#)

²²[MSDN](#)

²³[MSDN](#)

²⁴[MSDN](#)

Chapter 60

Strings

60.1 Text strings

60.1.1 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 [Rit79] 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 looks like this:

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

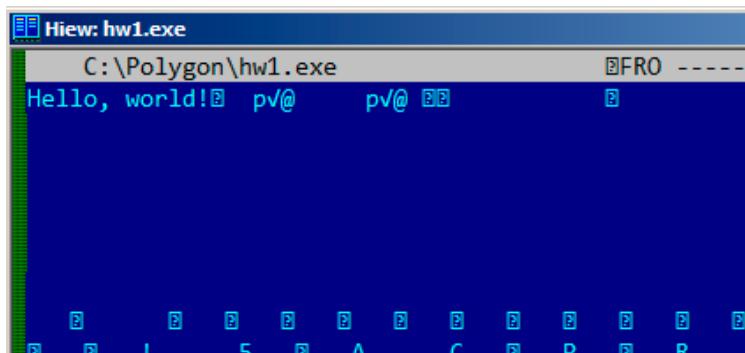


Figure 60.1: Hiew

60.1.2 Borland Delphi

The string in Pascal and Borland Delphi is preceded by an 8-bit or 32-bit string length.

For example:

Listing 60.1: Delphi

```
CODE:00518AC8          dd 19h
CODE:00518ACC aLoading__Plea db 'Loading... , please wait.',0
...
CODE:00518AFC          dd 10h
```

60.1. TEXT STRINGS

CODE:00518B00 aPreparingRun__ db 'Preparing run...',0

60.1.3 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.

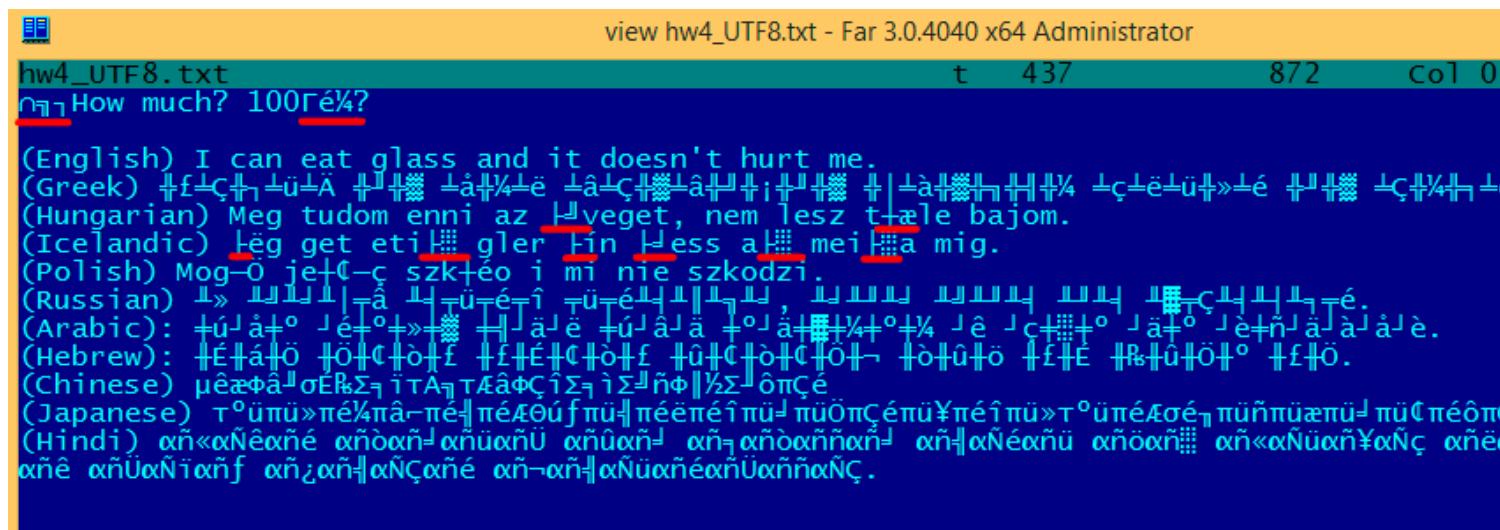
The most popular encoding methods are: UTF-8 (is widespread in Internet and *NIX systems) and UTF-16LE (is used in Windows).

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 codepage¹:

```
How much? 100€?  
  
(English) I can eat glass and it doesn't hurt me.  
(Greek) Μπορώ να φάω σπασμένα γυαλιά χωρίς να πάθω τίποτα.  
(Hungarian) Meg tudom enni az üveget, nem lesz tőle bajom.  
(Icelandic) Ég get etið gler án þess að meiða mig.  
(Polish) Mogę jeść szkło i mi nie szkodzi.  
(Russian) Я могу есть стекло, оно мне не вредит.  
(Arabic) أَنْ قَادِرُ عَلَى أَكْل الزَّجاج وَ مَنْ لَا يَزْلِمْنِي .  
(Hebrew) יָכֹל אֶאָכְל זְבַבִּית וְהַלֵּא מִזְמַרְתִּי .  
(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 काँच खा सकता हूँ और मुझे उससे कोई चोट नहीं पहुंचती.
```



view hw4_UTF8.txt - Far 3.0.4040 x64 Administrator
hw4_UTF8.txt t 437 872 Col 0
How much? 100€?
(English) I can eat glass and it doesn't hurt me.
(Greek) Μπορώ να φάω σπασμένα γυαλιά χωρίς να πάθω τίποτα.
(Hungarian) Meg tudom enni az üveget, nem lesz tőle bajom.
(Icelandic) Ég get etið gler án þess að meiða mig.
(Polish) Mogę jeść szkło i mi nie szkodzi.
(Russian) Я могу есть стекло, оно мне не вредит.
(Arabic) أَنْ قَادِرُ عَلَى أَكْل الزَّجاج وَ مَنْ لَا يَزْلِمْنِي .
(Hebrew) יָכֹל אֶאָכְל זְבַבִּית וְהַלֵּא מִזְמַרְתִּי .
(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 काँच खा सकता हूँ और मुझे उससे कोई चोट नहीं पहुंचती.

Figure 60.2: FAR: UTF-8

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.

¹The example and translations was taken from here: <http://go.yurichev.com/17304>

60.1. TEXT STRINGS

At the beginning, before the “How much?” string we see 3 bytes, which are in fact the [BOM²](#). 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:

```
int wmain()
{
    wprintf(L"Hello, world!\n");
};
```

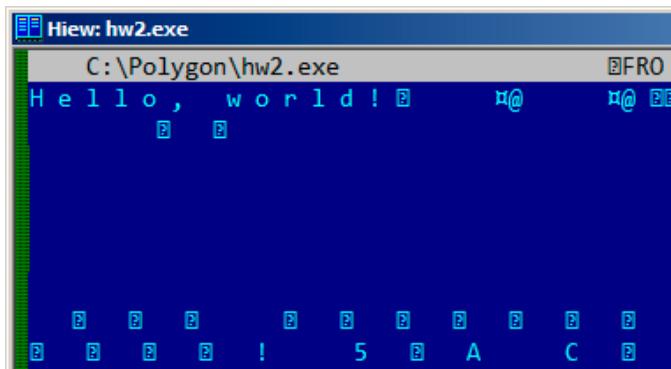


Figure 60.3: Hiew

We can see this often in Windows NT system files:

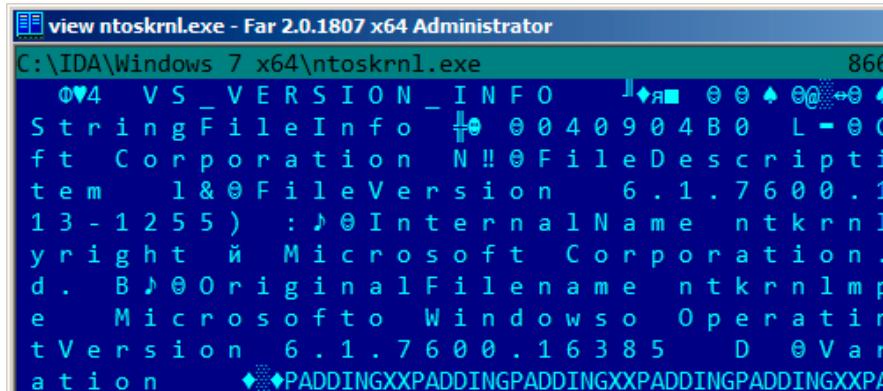


Figure 60.4: Hiew

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:

²Byte order mark

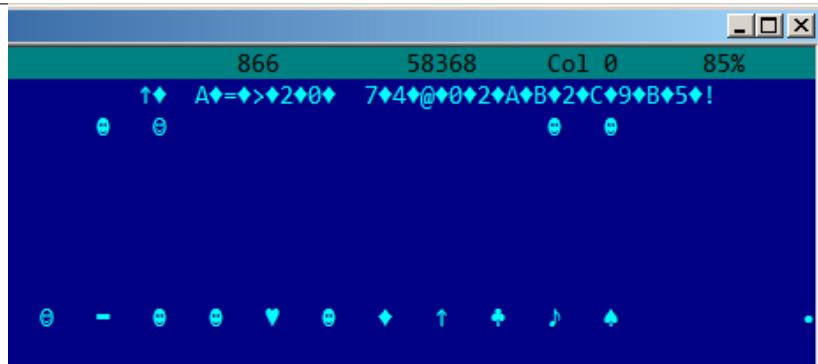


Figure 60.5: Hiew: UTF-16LE

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 plane³. 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.

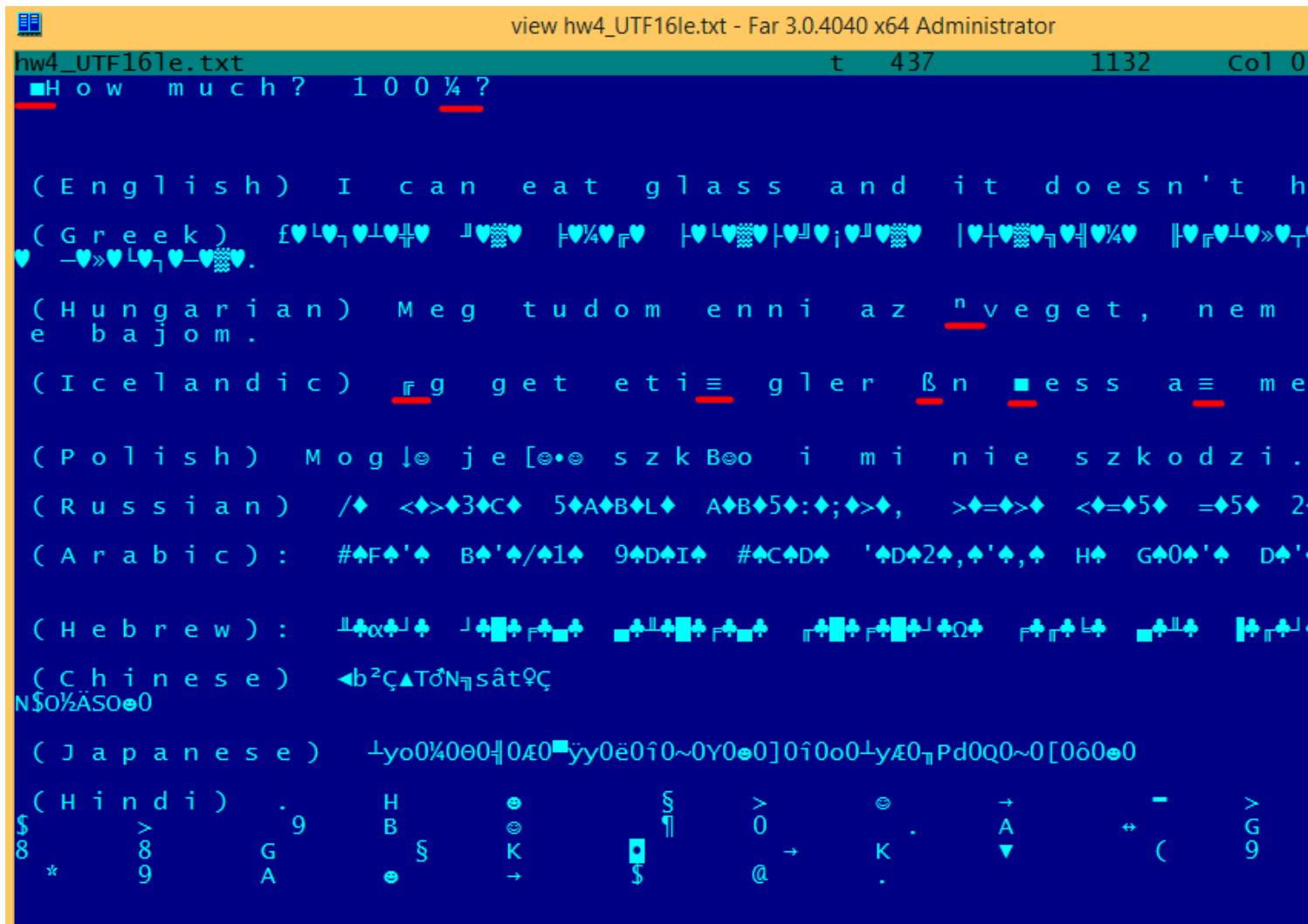


Figure 60.6: FAR: UTF-16LE

Here we can also see the **BOM** in 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.

³wikipedia

60.1.4 Base64

The base64 encoding is highly popular for the cases when you need 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) ends with 1 or 2 padding equality symbol(s) ("="), for example:

```
AVjbbVSVfcUMu1xvjaMgjNtueRwBbxnyJw8dpGnLW8ZW8aKG3v4Y0icuQT+qEJAp91AOuWs=
```

```
WjbbVSVfcUMu1xvjaMgjNtueRwBbxnyJw8dpGnLW8ZW8aKG3v4Y0icuQT+qEJAp91AOuQ=
```

The equality sign ("=") is never encounter in the middle of base64-encoded strings.

60.2 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 `ksdwrt()`.

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 happen⁴.

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: [81.2 on page 779](#).

60.3 Suspicious magic strings

Some magic strings which are usually used in backdoors looks pretty suspicious. For example, there was a backdoor in the TP-Link WR740 home router⁵. The backdoor was 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](#)⁶. 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.

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".

⁴blog.yurichev.com

⁵<http://sekurak.pl/tp-link-httptftp-backdoor/>

⁶Request for Comments

Chapter 61

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 61.1: 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_nbisBit ; "sp->lzw_nbisBit <= 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_nbisBit <= BITS_MAX`”, this predictably gives us some open-source code that’s related to the LZW compression.

Chapter 62

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 `0xFFFFFFFF` (1010101010101010101010101010) and `0xFFFF55AA` (0101010101010101010101010101) are also popular—those are composed of alternating bits. That may help to distinguish some signal from a signal where all bits are turned on (1111 ...) or off (0000 ...). For example, the `0x55AA` constant is used at least in the boot sector, [MBR¹](#), 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 MD5² algorithm initializes its own internal variables like this:

```
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:

Listing 62.1: linux/lib/crc16.c

```
/** CRC table for the CRC-16. The poly is 0x8005 (x^16 + x^15 + x^2 + 1) */
u16 const crc16_table[256] = {
    0x0000, 0xC0C1, 0xC181, 0x0140, 0xC301, 0x03C0, 0x0280, 0xC241,
    0xC601, 0x06C0, 0x0780, 0xC741, 0x0500, 0xC5C1, 0xC481, 0x0440,
    0xCC01, 0x0CC0, 0xD80, 0xCD41, 0xF00, 0xCFC1, 0xCE81, 0xE40,
    ...
```

See also the precomputed table for CRC32: [39 on page 470](#).

62.1 Magic numbers

A lot of file formats define a standard file header where a *magic number(s)*³ is used, single one or even several.

For example, all Win32 and MS-DOS executables start with the two characters “MZ”⁴.

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)

```
cmp [buf], 0x6468544D ; "MThd"
jnz _error_not_a_MIDI_file
```

¹Master Boot Record

²[wikipedia](#)

³[wikipedia](#)

⁴[wikipedia](#)

62.1. MAGIC NUMBERS

...or by calling a function for comparing memory blocks like `memcmp()` or any other equivalent code up to a `CMPSB` ([A.6.3 on page 934](#)) 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.

62.1.1 Dates

Often, one may encounter number like `0x19861115`, which is clearly looks like a date (year 1986, 11th month (November), 15th 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 `0x15111986`.

Well-known example is `0x19540119` (magic number used in UFS2 superblock structure), which is a birthday of Marshall Kirk McKusick, prominent FreeBSD contributor.

Also, numbers like those are very popular in amateur-grade cryptography, for example, excerpt from the *secret function* internals from HASP3 dongle ⁵:

```
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);
        }
    }
}
```

62.1.2 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 like `DhcpExtractOptionsForValidation()` and `DhcpExtractFullOptions()`:

Listing 62.2: `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:

⁵<https://web.archive.org/web/20160311231616/http://www.woodmann.com/fravia/bayu3.htm>

Listing 62.3: dhcpcore.dll (Windows 7 x64)

```
.text:000007FF6480875F  mov     eax, [rsi]
.text:000007FF64808761  cmp     eax, cs:dword_7FF6483CBE8
.text:000007FF64808767  jnz    loc_7FF64817179
```

And:

Listing 62.4: dhcpcore.dll (Windows 7 x64)

```
.text:000007FF648082C7  mov     eax, [r12]
.text:000007FF648082CB  cmp     eax, cs:dword_7FF6483CBEC
.text:000007FF648082D1  jnz    loc_7FF648173AF
```

62.2 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*⁶.

⁶[GitHub](#)

Chapter 63

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]
----------------------	----------------------

PID=13944 TID=28744 (0) 0x2f64e919 (Excel.exe!BASE+0x11e919) EAX=0x02088006 EBX=0x02088018 ECX=0x00000001 EDX=0x00000001 ESI=0x02088000 EDI=0x00544804 EBP=0x0274FA3C ESP=0x0274F9F8 EIP=0x2F64E919 FLAGS=PF IF FPU ControlWord=IC RC=NEAR PC=64bits PM UM OM ZM DM IM FPU StatusWord= FPU ST(0): 1.000000

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:

PID=32852 TID=36488 (0) 0x2f40e91b (Excel.exe!BASE+0x11e91b) EAX=0x00598006 EBX=0x00598018 ECX=0x00000001 EDX=0x00000001 ESI=0x00598000 EDI=0x00294804 EBP=0x026CF93C ESP=0x026CF8F8 EIP=0x2F40E91B FLAGS=PF IF FPU ControlWord=IC RC=NEAR PC=64bits PM UM OM ZM DM IM FPU StatusWord=C1 P FPU ST(0): 0.333333

Also as a practical joke, we can modify it on the fly:

tracer -l:excel.exe bpx=excel.exe!BASE+0x11E91B, set(st0,666)

```

PID=36540|TID=24056|(0) 0x2f40e91b (Excel.exe!BASE+0x11e91b)
EAX=0x00680006 EBX=0x00680018 ECX=0x00000001 EDX=0x00000001
ESI=0x00680000 EDI=0x00395404 EBP=0x0290FD9C ESP=0x0290FD58
EIP=0x2F40E91B
FLAGS=PF IF
FPU ControlWord=IC RC=NEAR PC=64bits PM UM OM ZM DM IM
FPU StatusWord=C1 P
FPU ST(0): 0.333333
Set ST0 register to 666.000000

```

Excel shows 666 in the cell, finally convincing us that we have found the right point.

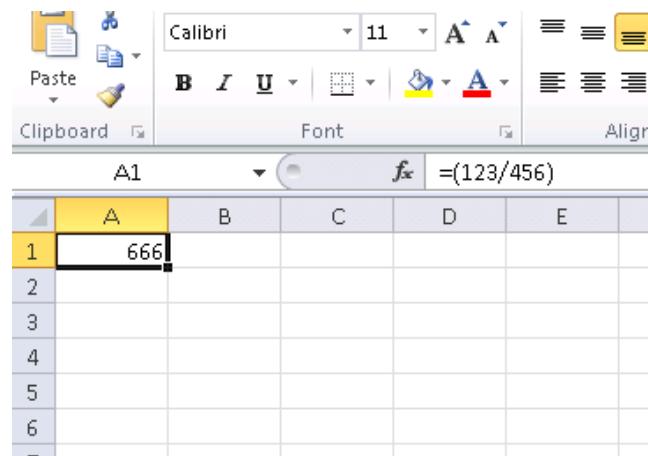


Figure 63.1: The practical joke worked

If we try the same Excel version, but in x64, we will find only 12 `FDIV` instructions there, and the one we looking for is the third one.

```
tracer.exe -l:excel.exe bpx=excel.exe!BASE+0x1B7FCC, set(st0,666)
```

It seems that a lot of division operations of *float* and *double* types, were replaced by the compiler with SSE instructions like `DIVSD` (`DIVSD` is present 268 times in total).

Chapter 64

Suspicious code patterns

64.1 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” ([19.3 on page 282](#)). Its generation and checking are often done using the `XOR` instruction.

This AWK script can be used for processing [IDA](#) listing (.lst) files:

```
gawk -e '$2=="xor" { tmp=substr($3, 0, length($3)-1); if (tmp!=$4) if($4!="esp") if ($4!="ebp") { print $1, $2, tmp, ",", $4 } }' filename.lst
```

It is also worth noting that this kind of script can also match incorrectly disassembled code ([51 on page 532](#)).

64.2 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: [A.6 on page 929](#).

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):

```
MultiplyTest proc near ; CODE XREF: Get386Stepping
    xor    cx, cx
loc_620555:           ; CODE XREF: MultiplyTest+E
    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
```

64.2. HAND-WRITTEN ASSEMBLY CODE

```
    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
```

Indeed, if we look in the [WRK¹](#) v1.2 source code, this code can be found easily in file *WRK-v1.2\base\ntos\ke\i386\cpu.asm*.

¹Windows Research Kernel

Chapter 65

Using magic numbers while tracing

Often, our main goal is to understand how the program uses a value that was either read from file or received via network. The manual tracing of a value is often a very labour-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 was 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 file¹, so this technique may be useful for DOS programs as well.

¹See also my blog post about this DosBox feature: blog.yurichev.com

Chapter 66

Other things

66.1 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.

66.2 C++

RTTI ([53.1.5 on page 558](#))-data may be also useful for C++ class identification.

66.3 Some binary file patterns

All examples here were prepared on the Windows with active code page 437 ¹ in console. Binary files internally may look visually different if another code page is set.

¹https://en.wikipedia.org/wiki/Code_page_437

66.3.1 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:

		h	1252	2175000	Col 0	23%	21:25
000007CA70:	EF 07 C6 07 D6 07 26 08	0C 08 CE 07 24 07 60 07	i•À•Ö•&•?	í•`•			
000007CA80:	CC 07 AA 07 A2 07 AC 07	E9 07 BF 07 D6 07 2C 08	ł•ä•đ•-•é•ż•Ö•,	ł			
000007CA90:	09 08 CA 07 31 07 5E 07	BC 07 9A 07 93 07 9E 07	o•È•1•^•%•ś•“•ż•	o			
000007CAA0:	E6 07 BD 07 D8 07 2F 08	06 08 CB 07 3E 07 5E 07	a•%•ø•/•↑•È•>•^•	a			
000007CAB0:	B3 07 91 07 8B 07 97 07	E1 07 BB 07 DB 07 32 08	³•‘•<•—•á•»•Û•2•	³			
000007CAC0:	03 08 CB 07 4C 07 61 07	AA 07 89 07 84 07 91 07	♥•Ë•L•a•æ•‰•,,•‘•	♥			
000007CAD0:	E0 07 BB 07 DC 07 33 08	01 08 CC 07 57 07 64 07	à•»•Ü•3•Ø•ł•W•d•	à			
000007CAE0:	A4 07 84 07 81 07 90 07	DE 07 BB 07 DE 07 34 08	¤•„•ø•ø•ø•»•ø•4•	¤			
000007CAF0:	FF 07 CD 07 65 07 69 07	A0 07 81 07 7F 07 90 07	ÿ•Í•e•i••ø•ø•ø•	ÿ			
000007CB00:	DE 07 BC 07 DF 07 33 08	FF 07 CE 07 70 07 6F 07	þ•%•ß•3•ÿ•Î•p•o•	þ			
000007CB10:	9F 07 82 07 81 07 93 07	DD 07 BC 07 E0 07 34 08	ÿ•,•ø•“•ÿ•%•à•4•	ÿ			
000007CB20:	FE 07 CE 07 7E 07 78 07	9F 07 84 07 84 07 96 07	þ•Î•~•x•ÿ•,,•—•	þ			
000007CB30:	DE 07 BD 07 DF 07 32 08	FF 07 CE 07 87 07 7F 07	þ•%•ß•2•ÿ•Î•†•ø•	þ			
000007CB40:	A1 07 87 07 88 07 9B 07	E2 07 BF 07 DE 07 2F 08	i•‡•^•»•â•ż•ø•/•	i			
000007CB50:	02 08 CF 07 93 07 89 07	A4 07 8C 07 8D 07 9F 07	ø•ł•“•‰•ø•€•ø•ÿ•	ø			
000007CB60:	E4 07 C0 07 DD 07 2D 08	03 08 CF 07 9C 07 92 07	ä•À•ÿ•-•ø•ł•ø•æ•’•	ä			
000007CB70:	A9 07 90 07 91 07 A3 07	E6 07 C3 07 DD 07 2B 08	ø•ø•‘•ø•æ•À•ÿ•+•	ø			
000007CB80:	04 08 D0 07 A7 07 9C 07	AE 07 96 07 96 07 A7 07	♦•Đ•§•æ•®•—•—•§•	♦			
000007CB90:	E8 07 C7 07 DF 07 29 08	04 08 D3 07 B1 07 A7 07	è•ç•ß•)•♦•ø•±•§•	è			
000007CBA0:	B4 07 9B 07 9B 07 AB 07	E8 07 CA 07 E1 07 27 08	‘•»•»•«•è•È•á•'•	‘			
000007CBB0:	03 08 D5 07 BB 07 B3 07	BB 07 A1 07 A0 07 AF 07	♥•õ•»•³•»•j••-	♥			
000007CBC0:	EA 07 CD 07 E3 07 25 08	03 08 D8 07 C4 07 BD 07	ê•Í•ã•%•ø•ø•Ä•%	ê			
000007CBD0:	C1 07 A6 07 A5 07 B3 07	EA 07 D1 07 E6 07 22 08	Á•!•¥•³•é•Ñ•æ•"•	Á			
000007CBE0:	01 08 DC 07 CE 07 C8 07	C8 07 AD 07 AA 07 B7 07	ø•Ü•ł•È•È•-•ø•...	ø			

1Help 2Wrap 3Quit 4Text 5 6Edit 7Search 80EM 9 10Quit

Figure 66.1: FAR: array of 16-bit values

I used a file containing 12-channel signal digitized using 16-bit ADC².

²Analog-to-digital converter

66.3. SOME BINARY FILE PATTERNS

And here is an example of very typical MIPS code. As we may remember, 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:

```

Hiew: FW96650A.bin
FW96650A.bin          FRO ----- 00005000 Hiew 8.02 (c)SEN
00005000: A0 B0 02 3C-04 00 BE AF-40 00 43 8C-21 F0 A0 03 a<@ !n@ CM!Ёa@
00005010: FF 1F 02 3C-21 E8 C0 03-FF FF 42 34-24 10 62 00 B4$@b
00005020: 00 A0 03 3C-25 10 43 00-04 00 BE 8F-08 00 E0 03 a<%@C @ !P@ r@
00005030: 08 00 BD 27-F8 FF BD 27-A0 B0 02 3C-04 00 BE AF @ J@. J@. a<@ !n@
00005040: 48 00 43 8C-21 F0 A0 03-FF 1F 02 3C-21 E8 C0 03 H CM!Ёa@ B4$@b
00005050: FF FF 42 34-24 10 62 00-00 A0 03 3C-25 10 43 00 a<%@C
00005060: 04 00 BE 8F-08 00 E0 03-08 00 BD 27-F8 FF BD 27 @ !P@ r@ J@. J@.
00005070: 21 10 00 00-04 00 BE AF-08 00 80 14-21 F0 A0 03 !@ @ !n@ A@!Ёa@
00005080: A0 B0 03 3C-21 E8 C0 03-44 29 02 7C-3C 00 62 AC a<@ !sh@D )@|< b@
00005090: 04 00 BE 8F-08 00 E0 03-08 00 BD 27-01 00 03 24 @ !P@ r@ J@. @$
000050A0: 44 29 62 7C-A0 B0 03 3C-21 E8 C0 03-3C 00 62 AC D)b|a<@ !sh@C
000050B0: 04 00 BE 8F-08 00 E0 03-08 00 BD 27-F8 FF BD 27 @ !P@ r@ J@. J@.
000050C0: A0 B0 02 3C-04 00 BE AF-84 00 43 8C-21 F0 A0 03 a<@ !n@ CM!Ёa@
000050D0: 21 E8 C0 03-C4 FF 03 7C-84 00 43 AC-04 00 BE 8F !sh@- @|D CM@ !P
000050E0: 08 00 E0 03-08 00 BD 27-F8 FF BD 27-A0 B0 02 3C @ r@ J@. a<@C
000050F0: 04 00 BE AF-20 00 43 8C-21 F0 A0 03-01 00 04 24 @ !n@ CM!Ёa@ @$
00005100: 21 E8 C0 03-44 08 83 7C-20 00 43 AC-04 00 BE 8F !sh@D@G | CM@ !P
00005110: 08 00 E0 03-08 00 BD 27-F8 FF BD 27-A0 B0 02 3C @ r@ J@. a<@C
00005120: 04 00 BE AF-20 00 43 8C-21 F0 A0 03-21 E8 C0 03 @ !n@ CM!Ёa@ !sh@C
00005130: 44 08 03 7C-20 00 43 AC-04 00 BE 8F-08 00 E0 03 D@B | CM@ !P@ r@B
00005140: 08 00 BD 27-F8 FF BD 27-A0 B0 03 3C-04 00 BE AF @ J@. J@. a<@ !n@P
00005150: 10 00 62 8C-01 00 08 24-04 A5 02 7D-08 00 09 24 @ bM@ @$@e@ }@ @$
00005160: 10 00 62 AC-04 7B 22 7D-04 48 02 7C-04 84 02 7D @ bM@ {"}@H@ | @D@}
00005170: 10 00 62 AC-21 F0 A0 03-21 18 00 00-A0 B0 0B 3C @ bM@ CM!Ёa@ !@ a<@C
00005180: 51 00 0A 24-02 00 88 94-00 00 89 94-00 44 08 00 Q @$@ ИФ ЙФ D@B
00005190: 25 40 09 01-01 00 63 24-14 00 68 AD-F9 FF 6A 14 %@@@@ c$@ h@. j@B
000051A0: 04 00 84 24-21 18 00 00-A0 B0 0A 3C-07 00 09 24 @ D$!@ a<@ !@ @$
000051B0: 02 00 A4 94-00 00 A8 94-00 24 04 00-25 20 88 00 @ д@ ИФ $@ % И

```

1Global 2FilBlk 3CryBlk 4ReLoad 5 6String 7Direct 8Table 9 10Leave 11 12AddNam

Figure 66.2: Hiew: very typical MIPS code

Another example of such pattern here is book: [89 on page 881](#).

66.3.2 Sparse files

This is sparse file with data scattered among almost empty file. Each space character here is in fact zero byte (which 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.

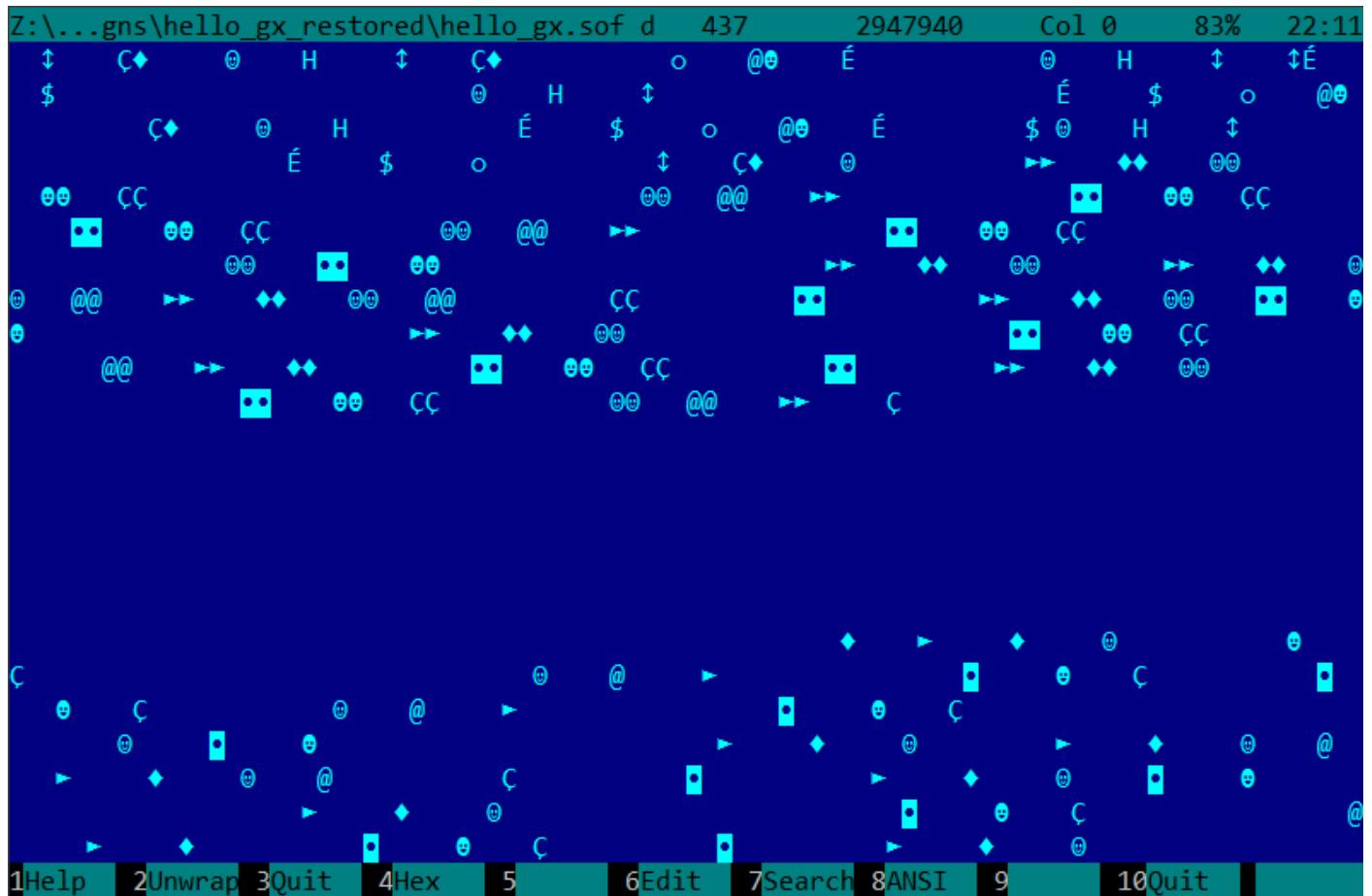


Figure 66.3: FAR: Sparse file

66.3.3 Compressed 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.

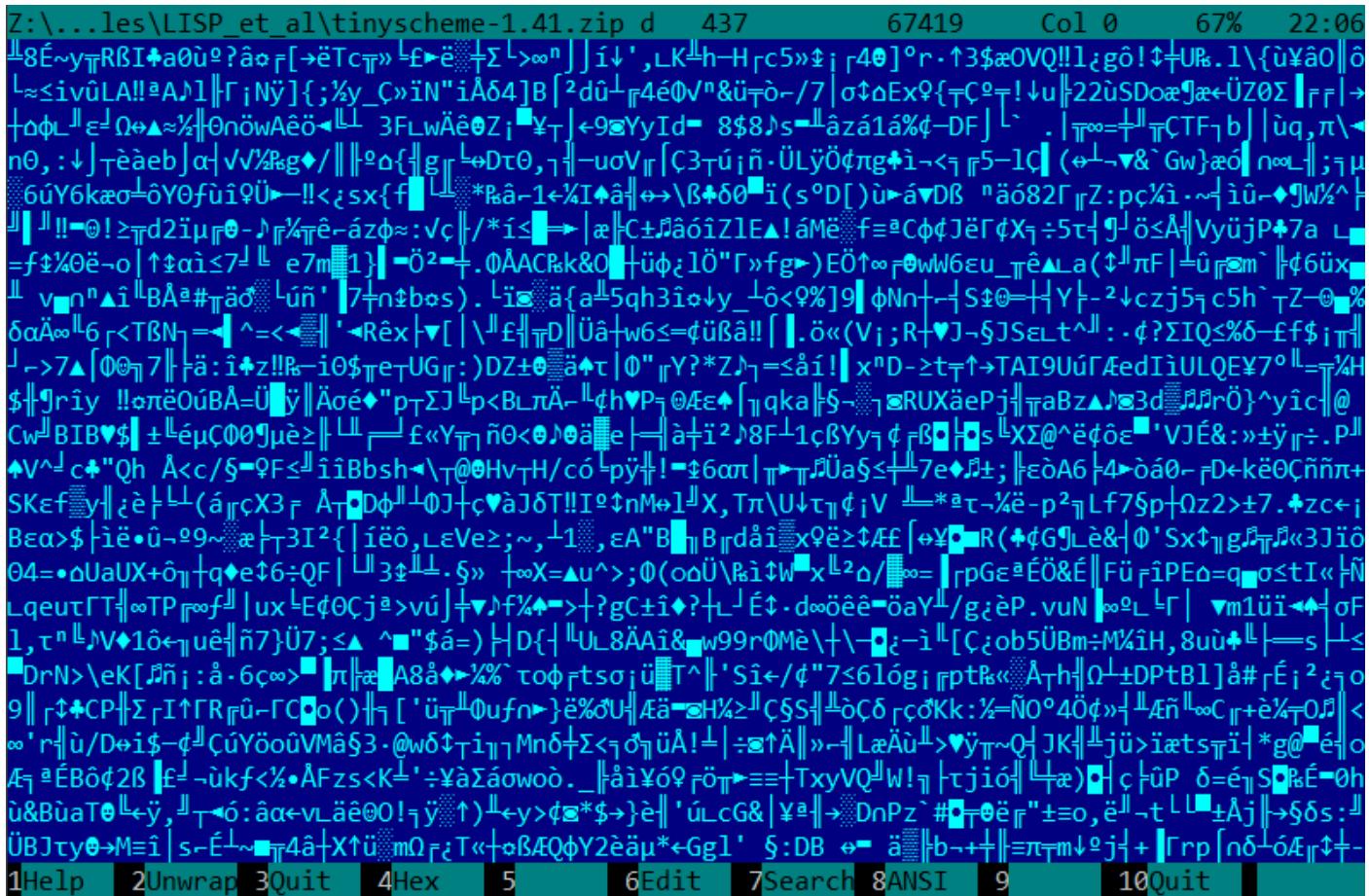


Figure 66.4: FAR: Compressed file

66.3.4 CDFS

OS installations are usually distributed as ISO files which are copies of CD/DVD discs. Filesystem used is named **CDFS**, here is 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 66.5: FAR: ISO file: Ubuntu 15 installation CD³

66.3.5 32-bit x86 executable code

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 66.6: FAR: Executable 32-bit x86 code

66.3.6 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:



Figure 66.7: Example picture

You see that this picture has some pixels which probably cannot 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:

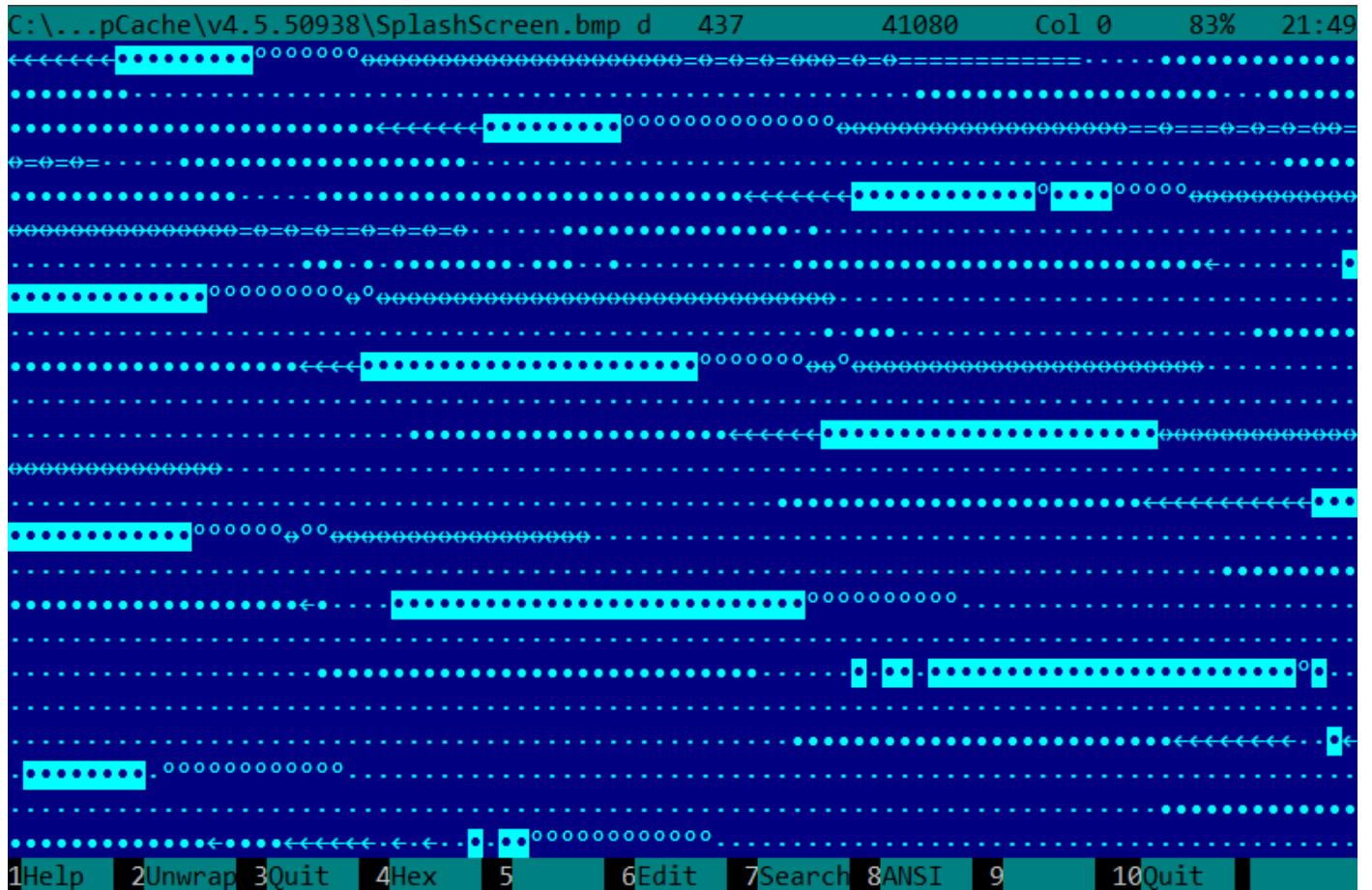


Figure 66.8: BMP file fragment

66.4 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.

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

66.4. MEMORY “SNAPSHOTS” COMPARING

and back it up to some place. Then shoot once, the bullet count goes to 99, do a second “snapshot” and then compare both: the must be must be a byte somewhere which was 100 in 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 was 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 **FC⁴** (“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: [88 on page 874](#).

66.4.1 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. Probably, this is the reason why the “windows registry cleaner” shareware is so popular.

66.4.2 Blink-comparator

Comparison of files or memory snapshots remind us blink-comparator ⁵: 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.

⁴MS-DOS utility for comparing binary files

⁵<http://go.yurichev.com/17348>

Part VI

OS-specific

Chapter 67

Arguments passing methods (calling conventions)

67.1 cdecl

This is the most popular method for passing arguments to functions in the C/C++ languages.

The caller also must return the value of the `stack pointer (ESP)` to its initial state after the `callee` function exits.

Listing 67.1: cdecl

```
push arg3  
push arg2  
push arg1  
call function  
add esp, 12 ; returns ESP
```

67.2 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)`¹. The `caller` is not adjusting the `stack pointer`, there are no `add esp, x` instruction.

Listing 67.2: 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 [9.1 on page 97](#) and change it slightly by adding the `__stdcall` modifier:

```
int __stdcall f2 (int a, int b, int c)  
{  
    return a*b+c;  
};
```

It is to be compiled in almost the same way as [9.2 on page 97](#), but you will see `RET 12` instead of `RET`. `SP` is not update in the `caller`.

As a consequence, the number of function arguments can be easily deduced from the `RETN n` instruction: just divide `n` by 4.

Listing 67.3: MSVC 2010

```

_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           ; 0000000cH
_f2@12 ENDP

; ...
    push    3
    push    2
    push    1
    call    _f2@12
    push    eax
    push    OFFSET $SG81369
    call    _printf
    add    esp, 8

```

67.2.1 Functions 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.

67.3 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 modern (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 67.4: fastcall

```

push arg3
mov edx, arg2
mov ecx, arg1
call function

function:
.. do something ..
ret 4

```

For example, we may take the function from [9.1 on page 97](#) and change it slightly by adding a `__fastcall` modifier:

```

int __fastcall f3 (int a, int b, int c)
{

```

67.4. THISCALL

```
    return a*b+c;  
};
```

Here is how it is to be compiled:

Listing 67.5: 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.

67.3.1 GCC regparm

It is the evolution of *fastcall*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 ([20.1.1 on page 305](#)).

67.3.2 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 has an underscore appended to the function name in order to distinguish them from those having a different calling convention.

67.4 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 very visible that internally: all function-methods have an extra argument.

For an example, see ([53.1.1 on page 543](#)).

²<http://go.yurichev.com/17040>

67.5.1 Windows x64

The method of passing arguments in Win64 somewhat resembles **fastcall**. 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:

```
#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\n", a, b, c, d, e, f, g);
}

int main()
{
    f1(1,2,3,4,5,6,7);
}
```

Listing 67.6: MSVC 2012 /0b

```
$SG2937 DB      '%d %d %d %d %d %d', 0aH, 00H

main PROC
    sub    rsp, 72          ; 00000048H

    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          ; 00000048H
    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          ; 00000048H

    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]
```

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```

    mov    DWORD PTR [rsp+32], eax
    mov    r9d, DWORD PTR c$[rsp]
    mov    r8d, DWORD PTR b$[rsp]
    mov    edx, DWORD PTR a$[rsp]
    lea    rcx, OFFSET FLAT:$SG2937
    call   printf

    add    rsp, 72
    ret    0
f1    ENDP

```

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 done because the compiler can not 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.

Listing 67.7: Optimizing MSVC 2012 /O**b**

```

$SG2777 DB      '%d %d %d %d %d %d', 0aH, 00H

a$ = 80
b$ = 88
c$ = 96
d$ = 104
e$ = 112
f$ = 120
g$ = 128
f1    PROC
$LN3:
    sub   rsp, 72          ; 00000048H

    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$[rsp]
    mov   DWORD PTR [rsp+40], eax
    mov   DWORD PTR [rsp+32], r9d
    mov   r9d, r8d
    mov   r8d, edx
    mov   edx, ecx
    lea   rcx, OFFSET FLAT:$SG2777
    call  printf

    add   rsp, 72          ; 00000048H
    ret   0
f1    ENDP

main  PROC
    sub   rsp, 72          ; 00000048H

    mov   edx, 2
    mov   DWORD PTR [rsp+48], 7
    mov   DWORD PTR [rsp+40], 6
    lea   r9d, QWORD PTR [rdx+2]
    lea   r8d, QWORD PTR [rdx+1]
    lea   ecx, QWORD PTR [rdx-1]
    mov   DWORD PTR [rsp+32], 5
    call  f1

    xor   eax, eax
    add   rsp, 72          ; 00000048H
    ret   0
main  ENDP

```

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 ([A.6.2 on page 931](#)).

67.6. RETURN VALUES OF FLOAT AND DOUBLE TYPE

`MOV` would be 1 byte longer here (5 instead of 4).

Another example of such thing is: [77.1 on page 753](#).

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: [53.1.1 on page 545](#).

67.5.2 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 67.8: Optimizing GCC 4.7.3

```
.LC0:
    .string "%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
    mov    edi, 1
    mov    DWORD PTR [rsp+16], eax
    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.

67.6 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.

67.7 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 (author of these lines have never seen any such case in his practice).

```
#include <stdio.h>

void f(int a, int b)
{
    a=a+b;
    printf ("%d\n", a);
}
```

Listing 67.9: MSVC 2012

```
_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++ ([53.3 on page 559](#)), and if you not 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. But the C/C++ languages standards don't offer any way to access them.

67.8 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 67.10: 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
```

67.8. TAKING A POINTER TO FUNCTION ARGUMENT

The address of the place in the stack where *a* was 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 67.11: 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     rdx, OFFSET FLAT:$SG2994 ; '%d'
    call    printf
    add     rsp, 40
    ret     0
f
ENDP
```

GCC also stores the input value in the local stack:

Listing 67.12: 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
    mov    edx, DWORD PTR [rsp+12] ; reload value from the local stack and pass it to printf()
    ↳ printf()
    mov    esi, OFFSET FLAT:.LC0   ; '%d'
    mov    edi, 1
    xor    eax, eax
    call   __printf_chk
    add    rsp, 24
    ret
```

GCC for ARM64 does the same, but this space is called *Register Save Area* here:

Listing 67.13: Optimizing GCC 4.9.1 ARM64

```
f:
    stp    x29, x30, [sp, -32]!
    add    x29, sp, 0             ; setup FP
    add    x1, x29, 32            ; calculate address of variable in Register Save Area
    str    w0, [x1, -4]!          ; store input value there
    mov    x0, x1                ; pass address of variable to the modify_a()
    bl     modify_a
    ldr    w1, [x29, 28]          ; load value from the variable and pass it to printf()
    adrp   x0, .LC0 ; '%d'
    add    x0, x0, :lo12:.LC0
    bl     printf                ; call printf()
    ldp    x29, x30, [sp], 32
    ret
.LC0:
    .string "%d\n"
```

By the way, a similar usage of the *Shadow Space* is also considered here : [48.1.2 on page 515](#).

Chapter 68

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](#)¹:

Listing 68.1: C++11

```
#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](#).

68.1 Linear congruent generator revisited

The pseudorandom number generator we considered earlier [21 on page 337](#) 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.

68.1.1 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):

```
1 #include <stdint.h>
2 #include <windows.h>
3 #include <winnt.h>
4
5 // from the Numerical Recipes book:
6 #define RNG_a 1664525
7 #define RNG_c 1013904223
8
9 __declspec( thread ) uint32_t rand_state;
```

¹ C11 also has thread support, optional though

68.1. LINEAR CONGRUENTIAL GENERATOR REVISITED

```

11 void my_srand (uint32_t init)
12 {
13     rand_state=init;
14 }
15
16 int my_rand ()
17 {
18     rand_state=rand_state*RNG_a;
19     rand_state=rand_state+RNG_c;
20     return rand_state & 0x7fff;
21 }
22
23 int main()
24 {
25     my_srand(0x12345678);
26     printf ("%d\n", my_rand());
27 }

```

Hiew shows us that there is a new PE section in the executable file: `.tls`.

Listing 68.2: 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
    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.

68.1. LINEAR CONGRUENTIAL GENERATOR REVISITED

The `GS:` selector is used in Win64 and the address of the `TLS` is 0x58:

Listing 68.3: 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+r8d*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 [rcx+rax*8]
    imul   eax, DWORD PTR [rcx+rax], 1664525      ; 0019660dH
    add    eax, 1013904223                      ; 3c6ef35fH
    mov    DWORD PTR [rcx+rax], 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):

```
1 #include <stdint.h>
2 #include <windows.h>
3 #include <winnt.h>
4
5 // from the Numerical Recipes book:
6 #define RNG_a 1664525
7 #define RNG_c 1013904223
8
9 __declspec( thread ) uint32_t rand_state=1234;
10
11 void my_srand (uint32_t init)
12 {
13     rand_state = init;
14 }
15
16 int my_rand ()
17 {
18     rand_state = rand_state * RNG_a;
19     rand_state = rand_state + RNG_c;
20     return rand_state & 0x7fff;
21 }
22
23 int main()
24 {
25     printf ("%d\n", my_rand());
26 }
```

68.1. LINEAR CONGRUENTIAL GENERATOR REVISITED

The code is no differ from what we already saw, but in IDA we see:

```
.tls:00404000 ; Segment type: Pure data
.tls:00404000 ; Segment permissions: Read/Write
.tls:00404000 _tls          segment para public 'DATA' use32
.tls:00404000             assume cs:_tls
.tls:00404000             ;org 404000h
.tls:00404000 TlsStart      db    0           ; DATA XREF: .rdata:TlsDirectory
.tls:00404001             db    0
.tls:00404002             db    0
.tls:00404003             db    0
.tls:00404004             dd    1234
.tls:00404008 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

__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 68.4: 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 [OEP²](#).

68.1.2 Linux

Here is how a thread-local global variable is declared in GCC:

```
_thread uint32_t rand_state=1234;
```

This is not the standard C/C++ modifier, but a rather GCC-specific one [3](#).

The `GS:` selector is also used to access the [TLS](#), but in a somewhat different way:

Listing 68.5: Optimizing GCC 4.8.1 x86

```
.text:08048460 my_srand        proc near
.text:08048460
.text:08048460 arg_0          = dword ptr 4
.text:08048460
.text:08048460                 mov     eax, [esp+arg_0]
.text:08048464                 mov     gs:0FFFFFFFCh, eax
.text:0804846A                 retn
.text:0804846A my_srand       endp

.text:08048470 my_rand         proc near
.text:08048470                 imul   eax, gs:0FFFFFFFCh, 19660Dh
.text:0804847B                 add    eax, 3C6EF35Fh
.text:08048480                 mov    gs:0FFFFFFFCh, eax
.text:08048486                 and    eax, 7FFFh
.text:0804848B                 retn
.text:0804848B my_rand       endp
```

More about it: [\[Dre13\]](#).

²Original Entry Point

³<http://go.yurichev.com/17062>

Chapter 69

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](#)¹.

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](#)².

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.

69.1 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 69.1: A simple example of the usage of two syscalls

```
section .text
global _start

_start:
    mov    edx,len ; buffer len
    mov    ecx,msg ; buffer
    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
```

¹Blue Screen of Death

²System Service Dispatch Table

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([74](#) on page [746](#)) can be used.

69.2 Windows

Here they are called via `int 0x2e` or using the special x86 instruction `SYSENTER`.

The full list of syscalls in Windows: <http://go.yurichev.com/17320>.

Further reading:

“Windows Syscall Shellcode” by Piotr Bania:

<http://go.yurichev.com/17321>.

Chapter 70

Linux

70.1 Position-independent code

While analyzing Linux shared (.so) libraries, one may frequently spot this code pattern:

Listing 70.1: libc-2.17.so x86

```
.text:0012D5E3 __x86_get_pc_thunk_bx proc near ; CODE XREF: sub_17350+3
.text:0012D5E3
.text:0012D5E3         mov     ebx, [esp+0] ; sub_173CC+4 ...
.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] ; "__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
.text:00057A04         lea    eax, (aInvalidKindIn_ - 1AF000h)[ebx] ; "! \"invalid ↳
    ↳ KIND in __gen_tempname\""
.text:00057A0A         mov    [esp+0ACh+var_A4], 14Ah
.text:00057A12         mov    [esp+0ACh+var_AC], eax
.text:00057A15         call   __assert_fail
```

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 crucial now 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:

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

70.1. POSITION-INDEPENDENT CODE

```
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
```

Listing 70.2: GCC 4.7.3

```
.text:00000440          public __x86_get_pc_thunk_bx
.text:00000440 __x86_get_pc_thunk_bx proc near           ; CODE XREF: _init_proc+4
.text:00000440                                     ; deregister_tm_clones+4 ...
.text:00000440         mov     ebx, [esp+0]
.text:00000443         retn
.text:00000443 __x86_get_pc_thunk_bx endp

.text:00000570          public f1
.text:00000570 f1      proc near
.text:00000570
.text:00000570 var_1C      = dword ptr -1Ch
.text:00000570 var_18      = dword ptr -18h
.text:00000570 var_14      = dword ptr -14h
.text:00000570 var_8       = dword ptr -8
.text:00000570 var_4       = dword ptr -4
.text:00000570 arg_0       = dword ptr 4
.text:00000570
.text:00000570         sub     esp, 1Ch
.text:00000573         mov     [esp+1Ch+var_8], ebx
.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, ds:(global_variable_ptr - 2000h)[ebx]
.text:0000058C         mov     esi, [eax]
.text:0000058E         lea     eax, (aReturningD - 2000h)[ebx] ; "returning %d\n"
.text:00000594         add     esi, [esp+1Ch+arg_0]
.text:00000598         mov     [esp+1Ch+var_18], eax
.text:0000059C         mov     [esp+1Ch+var_1C], 1
.text:000005A3         mov     [esp+1Ch+var_14], esi
.text:000005A7         call    __printf_chk
.text:000005AC         mov     eax, esi
.text:000005AE         mov     ebx, [esp+1Ch+var_8]
.text:000005B2         mov     esi, [esp+1Ch+var_4]
.text:000005B6         add     esp, 1Ch
.text:000005B9         retn
.text:000005B9 f1      endp
```

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]
```

70.2. LD_PRELOAD HACK IN LINUX

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 RIP¹-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 the everything:

```
00000000000000720 <f1>:
720: 48 8b 05 b9 08 20 00    mov    rax,QWORD PTR [rip+0x2008b9]      # 200fe0 <_DYNAMIC+0x2008b9>
    ↳ x1d0>
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 fe ff ff          call   620 <__printf_chk@plt>
741: 89 d8                  mov    eax,ebx
743: 5b                      pop    rbx
744: c3                      ret
```

0x2008b9 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 [Fog13a].

70.1.1 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 process’ memory blocks—since each instance that’s loaded in memory is *fixed* to work only at these addresses..

70.2 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(74 on page 746), 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 Wikipedia²:

¹program counter in AMD64

²wikipedia

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 a strcmp(), and not use the original function ³.

```
#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 init = false;

_Noreturn void die (const char * fmt, ...)
{
    va_list va;
    va_start (va, fmt);

    vprintf (fmt, va);
    exit(0);
};

static void find_original_functions ()
{
    if (init)
        return;

    libc_handle = dlopen ("libc.so.6", RTLD_LAZY);
    if (libc_handle==NULL)
        die ("can't open libc.so.6\n");

    open_ptr = dlsym (libc_handle, "open");
    if (open_ptr==NULL)
        die ("can't find open()\n");

    close_ptr = dlsym (libc_handle, "close");
    if (close_ptr==NULL)
        die ("can't find close()\n");

    read_ptr = dlsym (libc_handle, "read");
    if (read_ptr==NULL)
        die ("can't find read()\n");

    init = true;
}

static int opened_fd=0;
```

³For example, here is how simple strcmp() interception works in this article ⁴ written by Yong Huang

70.2. LD_PRELOAD HACK IN LINUX

```
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
```

Let's run *uptime* while loading our library before the others:

```
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>
- Kevin Pulo—Fun with *LD_PRELOAD*. A lot of examples and ideas. yurichev.com
- File functions interception for compression/decompression files on fly (zlibc). <http://go.yurichev.com/17146>

Chapter 71

Windows NT

71.1 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 GUI¹ win32 applications, `WinMain` is used instead of `main()`, having its own arguments:

```
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.

```
1 __tmainCRTStartup proc near
2
3 var_24 = dword ptr -24h
4 var_20 = dword ptr -20h
5 var_1C = dword ptr -1Ch
6 ms_exc = CPPEH_RECORD ptr -18h
7
8     push    14h
9     push    offset stru_4092D0
10    call    __SEH_prolog4
11    mov     eax, 5A4Dh
12    cmp     ds:400000h, ax
13    jnz    short loc_401096
14    mov     eax, ds:40003Ch
15    cmp     dword ptr [eax+400000h], 4550h
16    jnz    short loc_401096
17    mov     ecx, 10Bh
18    cmp     [eax+400018h], cx
19    jnz    short loc_401096
20    cmp     dword ptr [eax+400074h], 0Eh
21    jbe    short loc_401096
```

¹Graphical user interface

71.1. CRT (WIN32)

```
22 xor    ecx, ecx
23 cmp    [eax+4000E8h], ecx
24 setnz cl
25 mov    [ebp+var_1C], ecx
26 jmp    short loc_40109A
27
28
29 loc_401096: ; CODE XREF: __tmainCRTStartup+18
30     ; __tmainCRTStartup+29 ...
31     and    [ebp+var_1C], 0
32
33 loc_40109A: ; CODE XREF: __tmainCRTStartup+50
34     push   1
35     call   __heap_init
36     pop    ecx
37     test   eax, eax
38     jnz    short loc_4010AE
39     push   1Ch
40     call   _fast_error_exit
41     pop    ecx
42
43 loc_4010AE: ; CODE XREF: __tmainCRTStartup+60
44     call   __mtinit
45     test   eax, eax
46     jnz    short loc_4010BF
47     push   10h
48     call   _fast_error_exit
49     pop    ecx
50
51 loc_4010BF: ; CODE XREF: __tmainCRTStartup+71
52     call   sub_401F2B
53     and    [ebp+ms_exc.disabled], 0
54     call   __ioinit
55     test   eax, eax
56     jge    short loc_4010D9
57     push   1Bh
58     call   __amsg_exit
59     pop    ecx
60
61 loc_4010D9: ; CODE XREF: __tmainCRTStartup+8B
62     call   ds:GetCommandLineA
63     mov    dword_40B7F8, eax
64     call   __crtGetEnvironmentStringsA
65     mov    dword_40AC60, eax
66     call   __setargv
67     test   eax, eax
68     jge    short loc_4010FF
69     push   8
70     call   __amsg_exit
71     pop    ecx
72
73 loc_4010FF: ; CODE XREF: __tmainCRTStartup+B1
74     call   __setenvp
75     test   eax, eax
76     jge    short loc_401110
77     push   9
78     call   __amsg_exit
79     pop    ecx
80
81 loc_401110: ; CODE XREF: __tmainCRTStartup+C2
82     push   1
83     call   __cinit
84     pop    ecx
85     test   eax, eax
86     jz    short loc_401123
87     push   eax
88     call   __amsg_exit
89     pop    ecx
90
91 loc_401123: ; CODE XREF: __tmainCRTStartup+D6
```

71.1. CRT (WIN32)

```

92      mov    eax, envp
93      mov    dword_40AC80, eax
94      push   eax          ; envp
95      push   argv          ; argv
96      push   argc          ; argc
97      call   _main
98      add    esp, 0Ch
99      mov    [ebp+var_20], eax
100     cmp   [ebp+var_1C], 0
101     jnz   short $LN28
102     push  eax          ; uExitCode
103     call  $LN32
104
$LN28:    ; CODE XREF: __tmainCRTStartup+105
105     call  __cexit
106     jmp   short loc_401186
107
108
$LN27:    ; DATA XREF: .rdata:stru_4092D0
109     mov   eax, [ebp+ms_exc.exc_ptr] ; Exception filter 0 for function 401044
110     mov   ecx, [eax]
111     mov   ecx, [ecx]
112     mov   [ebp+var_24], ecx
113     push  eax
114     push  ecx
115     call  __XcptFilter
116     pop   ecx
117     pop   ecx
118
119
$LN24:
120     retn
121
122
123
124
$LN14:    ; DATA XREF: .rdata:stru_4092D0
125     mov   esp, [ebp+ms_exc.old_esp] ; Exception handler 0 for function 401044
126     mov   eax, [ebp+var_24]
127     mov   [ebp+var_20], eax
128     cmp   [ebp+var_1C], 0
129     jnz   short $LN29
130     push  eax          ; int
131     call  __exit
132
133
134
$LN29:    ; CODE XREF: __tmainCRTStartup+135
135     call  __c_exit
136
137
loc_401186: ; CODE XREF: __tmainCRTStartup+112
138     mov   [ebp+ms_exc.disabled], 0FFFFFFFEh
139     mov   eax, [ebp+var_20]
140     call  __SEH_epilog4
141     retn
142

```

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 abnormally with the following error:

```
runtime error R6030
- CRT not initialized
```

Global object initializations in C++ is also occur in the [CRT](#) before the execution of `main()`: [53.4.1 on page 564](#).

The value that `main()` returns is passed to `cexit()`, or in `$LN32`, which in turn calls `doexit()`.

71.2. WIN32 PE

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.

```
#include <windows.h>

int main()
{
    MessageBox (NULL, "hello, world", "caption", MB_OK);
}
```

Let's compile it in MSVC 2008.

```
cl no_crt.c user32.lib /link /entry:main
```

We are getting a runnable .exe with size 2560 bytes, that has a PE header in it, instructions calling **MessageBox**, two strings in the data segment, the **MessageBox** function imported from **user32.dll** and nothing else.

This works, but you cannot write **WinMain** with its 4 arguments instead of **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.

```
cl no_crt.c user32.lib /link /entry:main /align:16
```

Linker says:

```
LINK : warning LNK4108: /ALIGN specified without /DRIVER; image may not run
```

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.

71.2 Win32 PE

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**², 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 ³.

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.

71.2.1 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**⁴— 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.

²Dynamic-link library

³For example, Hiew([76 on page 748](#)) can calculate it

⁴Virtual Address

71.2. WIN32 PE

- **RVA**⁵—the VA-address minus the base address. Many addresses in PE-file tables use RVA-addresses.
- **IAT**⁶—an array of addresses of imported symbols⁷. 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**⁸— an array of names of symbols to be imported⁹.

71.2.2 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.

Often, **MSVC** the linker generates the .exe files with a base address of `0x400000`¹⁰, and with the code section starting at `0x401000`. This mean 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`¹¹.

There is also another reason to load modules at various base addresses, in this case random ones.

It is **ASLR**¹².

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` [RA09].

71.2.3 Subsystem

There is also a *Subsystem* field, usually it is:

- native¹³ (.sys-driver),
- console (console application) or
- **GUI** (non-console).

71.2.4 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 here¹⁴.

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 options¹⁵, it is possible to force it to compile for Windows XP.

⁵Relative Virtual Address

⁶Import Address Table

⁷[Pie02]

⁸Import Name Table

⁹[Pie02]

¹⁰The origin of this address choice is described here: [MSDN](#)

¹¹This can be changed by the /BASE linker option

¹²wikipedia

¹³Meaning, the module use Native API instead of Win32

¹⁴wikipedia

¹⁵MSDN

71.2.5 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 *IMAGE_SCN_CNT_CODE* or *IMAGE_SCN_MEM_EXECUTE* flags will be set on the code section—this is executable code.
- On data section—*IMAGE_SCN_CNT_INITIALIZED_DATA*, *IMAGE_SCN_MEM_READ* and *IMAGE_SCN_MEM_WRITE* flags.
- On an empty section with uninitialized data—*IMAGE_SCN_CNT_UNINITIALIZED_DATA*, *IMAGE_SCN_MEM_READ* and *IMAGE_SCN_MEM_WRITE*.
- On a constant data section (one that's protected from writing), the flags *IMAGE_SCN_CNT_INITIALIZED_DATA* and *IMAGE_SCN_MEM_READ* can be set, but not *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: [71.2.1 on the previous page](#).
- `.edata` – exports section (rare)
- `.pdata` – section containing all information about exceptions in Windows NT for MIPS, IA64 and x64: [71.3.3 on page 737](#)
- `.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 ¹⁶.

Some compilers and linkers can add a section with debugging symbols and other debugging information (MinGW for instance). However it is not so in modern versions of [MSVC](#) (separate [PDB](#) files are used there for this purpose).

That is how a PE section is described in the file:

```
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;
```

¹⁷

A word about terminology: *PointerToRawData* it called “Offset” in Hiew and *VirtualAddress* is called “RVA” there.

¹⁶[MSDN](#)

¹⁷[MSDN](#)

71.2.6 Relocations (relocs)

AKA FIXUP-s (at least in Hiew).

They are also present in almost all executable file formats¹⁸. 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 ([70.1 on page 705](#)). But it is not always convenient.

That is why a relocations table is present. There the addresses of points that need to 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:

A1 00 00 41 00	mov	eax, [00041000]
----------------	-----	-----------------

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 relocations 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, relocations are darkened in Hiew, for example: [fig.8.12](#).

OllyDbg underlines the places in memory to which relocations are to be applied, for example: [fig.14.11](#).

71.2.7 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 MFC¹⁹ 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.

¹⁸Even in .exe files for MS-DOS

¹⁹Microsoft Foundation Classes

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.

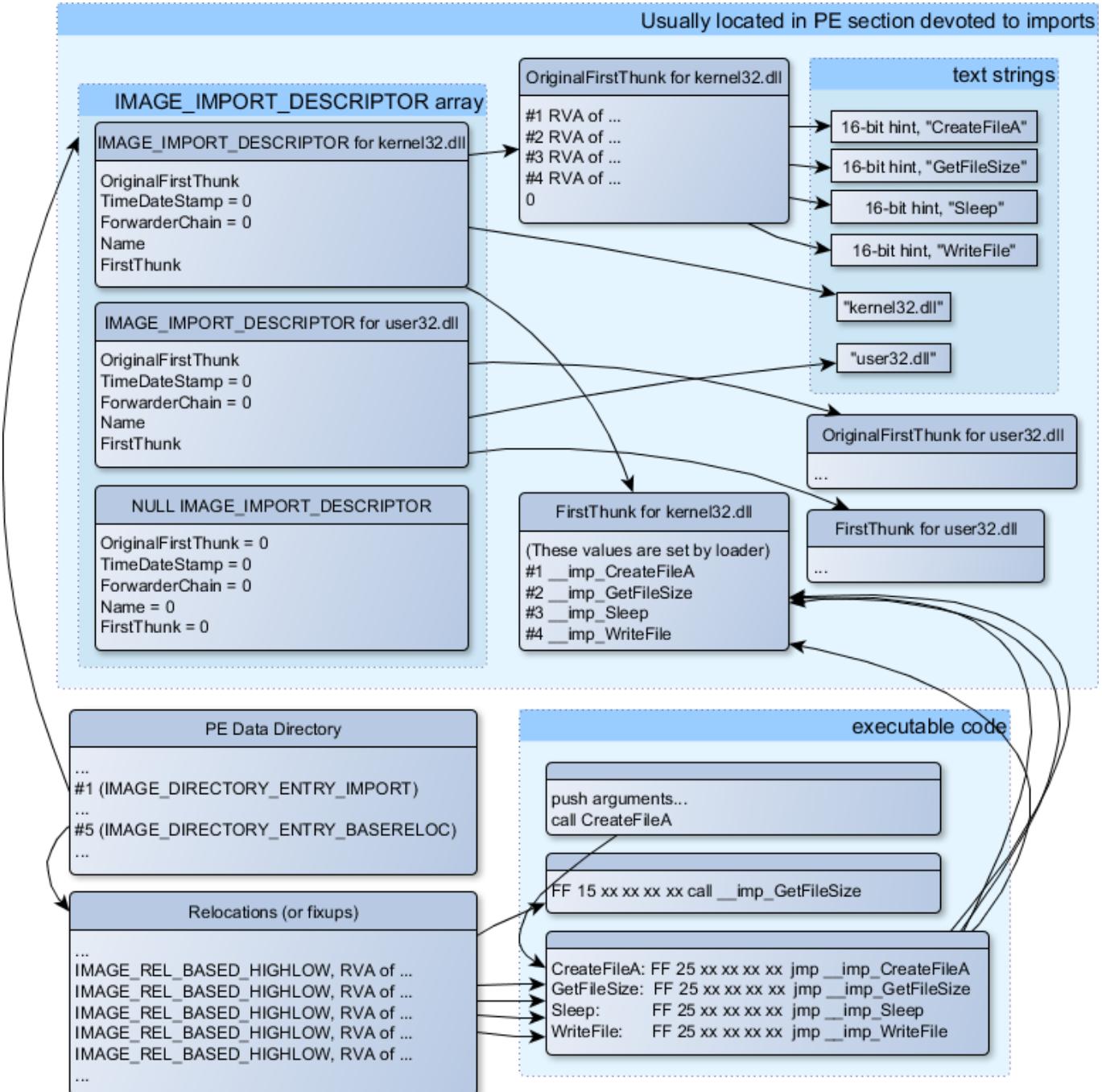


Figure 71.1: A scheme that unites all PE-file structures related to imports

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.

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- 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 `relocs` table, for the case when the module is loaded at a different base address.

But, obviously, this may enlarge `relocs` table significantly. Because there are might be a lot of calls to imported functions in the module. Furthermore, large `relocs` 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 `relocs` 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, author of these lines once wrote the `PE_add_import20` 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` 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” ²¹. The `BIND.EXE` utility in Windows SDK is for for this. For speeding up the loading of your program, Matt Pietrek in [Pie02], 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 in the beginning of the PE file. Supposedly, it is done 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.

71.2.8 Resources

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 ([71.2.11 on the following page](#)).

71.2.9 .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:

²⁰yurichev.com

²¹[MSDN](#). There is also the “new-style binding”.

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 ²².

71.2.10 TLS

This section holds initialized data for the TLS(68 on page 698) (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.

71.2.11 Tools

- objdump (present in cygwin) for dumping all PE-file structures.
- Hiew(76 on page 748) as editor.
- pefile—Python-library for PE-file processing ²³.
- ResHack AKA Resource Hacker—resources editor ²⁴.
- PE_add_import²⁵ – simple tool for adding symbol(s) to PE executable import table.
- PE_patcher²⁶ – simple tool for patching PE executables.
- PE_search_str_refs²⁷ – simple tool for searching for a function in PE executables which use some text string.

71.2.12 Further reading

- Daniel Pistelli—The .NET File Format ²⁸

71.3 Windows SEH

71.3.1 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, TIB has the address of the last 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 all information about the CPU state (register values, etc) at the moment of the exception. The exception handler considering the exception, was it made for it? 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 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.

²²MSDN

²³<http://go.yurichev.com/17052>

²⁴<http://go.yurichev.com/17052>

²⁵<http://go.yurichev.com/17049>

²⁶yurichev.com

²⁷yurichev.com

²⁸<http://go.yurichev.com/17056>

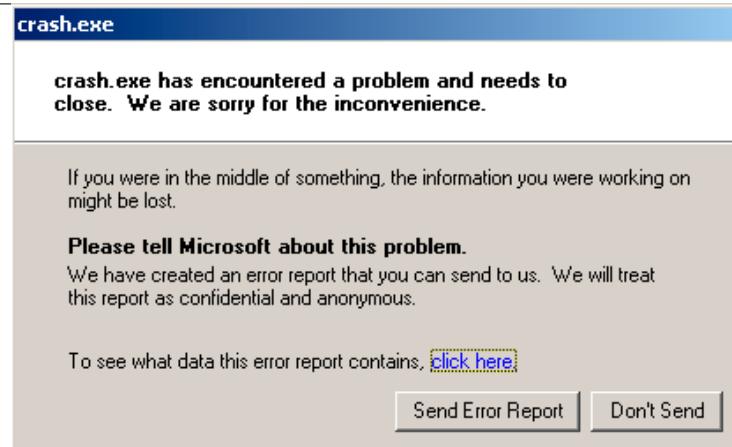


Figure 71.2: Windows XP

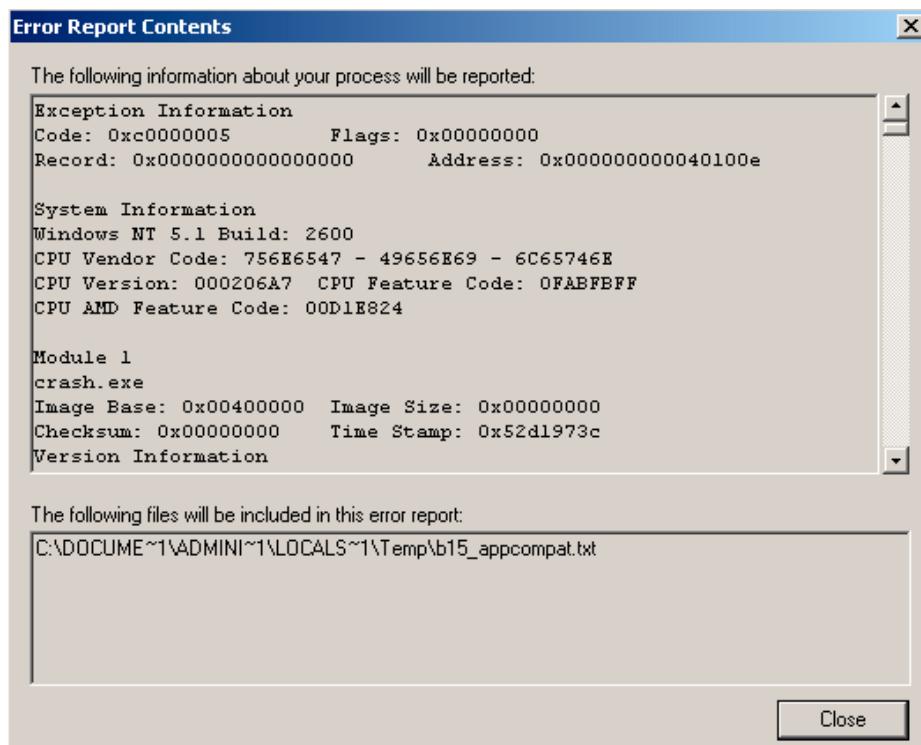


Figure 71.3: Windows XP

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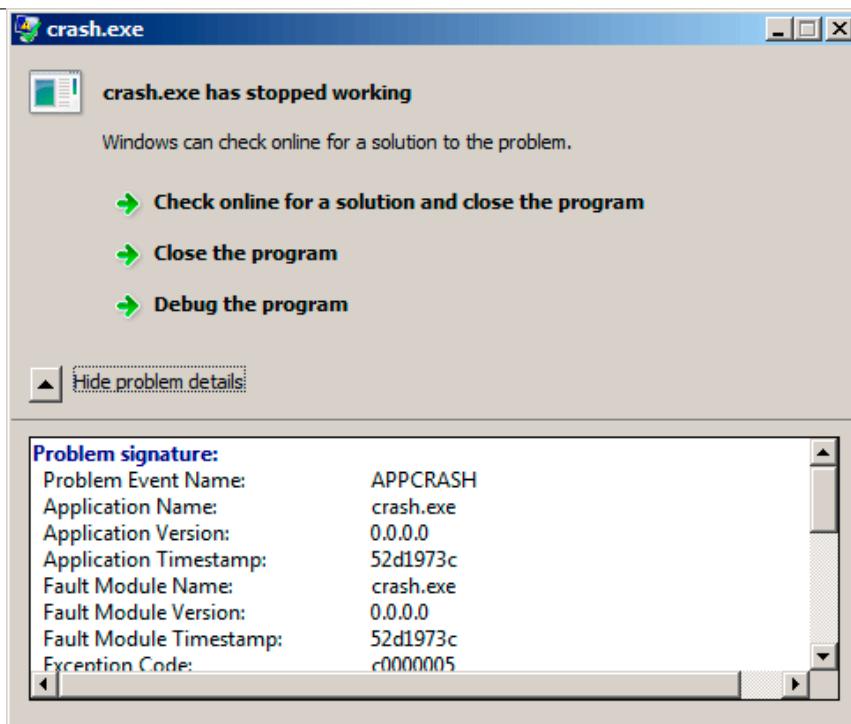


Figure 71.4: Windows 7

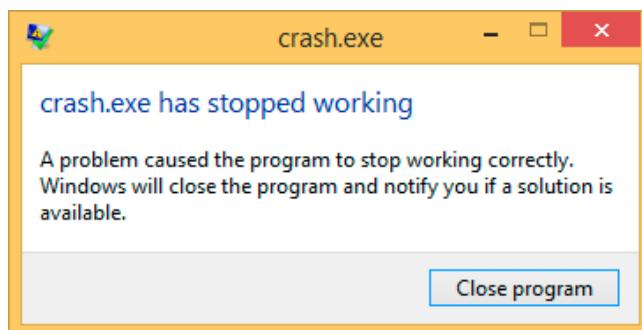


Figure 71.5: Windows 8.1

Earlier, this handler was called Dr. Watson ²⁹.

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 containing all possible information about the CPU and memory state.

Let's write our own primitive exception handler ³⁰:

```
#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;
```

²⁹wikipedia

³⁰This example is based on the example from [Pie]

It must be compiled with the SAFESEH option: `cl seh1.cpp /link /safeseh:no`

More about SAFESEH here:

MSDN

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```

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;
};

int main()
{
    DWORD handler = (DWORD)except_handler; // take a pointer to our handler

    // install exception handler
    __asm
    {
        push    handler          // make EXCEPTION_REGISTRATION record:
        push    FS:[0]           // address of handler function
        mov     FS:[0],ESP       // address of previous handler
    }

    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
    {
        mov     eax,[ESP]         // remove our EXCEPTION_REGISTRATION record
        mov     FS:[0], EAX        // get pointer to previous record
        add     esp, 8             // install previous record
        // 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 71.1: MSVC/VC/crt/src/exsup.inc

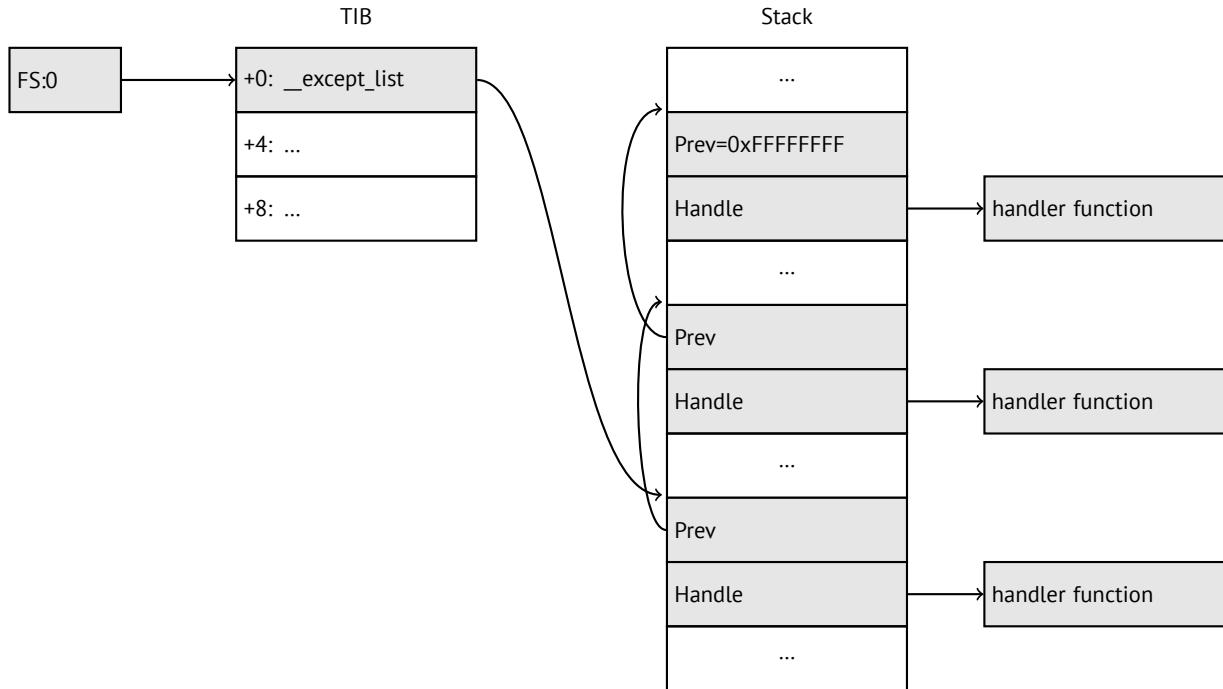
```

\_EXCEPTION\_REGISTRATION struct
    prev   dd    ?
    handler dd    ?
\_EXCEPTION\_REGISTRATION ends

```

7.1.3. WINDOWS SEH

So each “handler” field points to a handler and an each “prev” field points to the previous record in the stack. The last record has `0xFFFFFFFF` (-1) in the “prev” field.



After our handler is installed, we call `RaiseException()`³¹. 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. 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:

as defined in WinBase.h	as defined in ntstatus.h	numerical value
EXCEPTION_ACCESS_VIOLATION	STATUS_ACCESS_VIOLATION	0xC0000005
EXCEPTION_DATATYPE_MISALIGNMENT	STATUS_DATATYPE_MISALIGNMENT	0x80000002
EXCEPTION_BREAKPOINT	STATUS_BREAKPOINT	0x80000003
EXCEPTION_SINGLE_STEP	STATUS_SINGLE_STEP	0x80000004
EXCEPTION_ARRAY_BOUNDS_EXCEEDED	STATUS_ARRAY_BOUNDS_EXCEEDED	0xC000008C
EXCEPTION_FLT_DENORMAL_OPERAND	STATUS_FLOAT_DENORMAL_OPERAND	0xC000008D
EXCEPTION_FLT_DIVIDE_BY_ZERO	STATUS_FLOAT_DIVIDE_BY_ZERO	0xC000008E
EXCEPTION_FLT_INEXACT_RESULT	STATUS_FLOAT_INEXACT_RESULT	0xC000008F
EXCEPTION_FLT_INVALID_OPERATION	STATUS_FLOAT_INVALID_OPERATION	0xC0000090
EXCEPTION_FLT_OVERFLOW	STATUS_FLOAT_OVERFLOW	0xC0000091
EXCEPTION_FLT_STACK_CHECK	STATUS_FLOAT_STACK_CHECK	0xC0000092
EXCEPTION_FLT_UNDERFLOW	STATUS_FLOAT_UNDERFLOW	0xC0000093
EXCEPTION_INT_DIVIDE_BY_ZERO	STATUS_INTEGER_DIVIDE_BY_ZERO	0xC0000094
EXCEPTION_INT_OVERFLOW	STATUS_INTEGER_OVERFLOW	0xC0000095
EXCEPTION_PRIV_INSTRUCTION	STATUS_PRIVILEGED_INSTRUCTION	0xC0000096
EXCEPTION_IN_PAGE_ERROR	STATUS_IN_PAGE_ERROR	0xC0000006
EXCEPTION_ILLEGAL_INSTRUCTION	STATUS_ILLEGAL_INSTRUCTION	0xC000001D
EXCEPTION_NONCONTINUABLE_EXCEPTION	STATUS_NONCONTINUABLE_EXCEPTION	0xC0000025
EXCEPTION_STACK_OVERFLOW	STATUS_STACK_OVERFLOW	0xC00000FD
EXCEPTION_INVALID_DISPOSITION	STATUS_INVALID_DISPOSITION	0xC0000026
EXCEPTION_GUARD_PAGE	STATUS_GUARD_PAGE_VIOLATION	0x80000001
EXCEPTION_INVALID_HANDLE	STATUS_INVALID_HANDLE	0xC0000008
EXCEPTION_POSSIBLE_DEADLOCK	STATUS_POSSIBLE_DEADLOCK	0xC0000194
CONTROL_C_EXIT	STATUS_CONTROL_C_EXIT	0xC000013A

That is how the code is defined:

³¹[MSDN](#)

S	U	0	Facility code	Error code
---	---	---	---------------	------------

S is a basic status code: 11—error; 10—warning; 01—informational; 00—success. U—whether the code is user code.

That is why we chose 0xE1223344— 0xE (1110b) mean this 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 71.2: 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 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()`: ([6.2.4 on page 30](#)).

71.3.2 Now let's get back to MSVC

Supposedly, Microsoft programmers needed exceptions in C, but not in C++, so they added a non-standard C extension to MSVC³². It is not related to C++ PL exceptions.

```
__try
{
    ...
}
__except(filter code)
{
    handler code
}
```

“Finally” block may be instead of handler code:

```
__try
{
    ...
}
__finally
{
    ...
}
```

³²[MSDN](#)

7.1.3. WINDOWS SEH

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 71.3: WRK-v1.2/base/ntos/ob/obwait.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 71.4: WRK-v1.2/base/ntos/cache/cachesub.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 71.5: WRK-v1.2/base/ntos/cache/copysup.c

```
LONG
CcCopyReadExceptionFilter(
    IN PEXCEPTION_POINTERS ExceptionPointer,
    IN PNTSTATUS ErrorCode
)

/*++
```

Routine Description:

This routine serves as a 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.

ErrorCode - A pointer to an NTSTATUS that is to receive the real status.

Return Value:

EXCEPTION_EXECUTE_HANDLER

--*/

```
{
    *ErrorCode = ExceptionPointer->ExceptionRecord->ExceptionCode;
```

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```

if ( (*ExceptionCode == STATUS_IN_PAGE_ERROR) &&
    (ExceptionPointer->ExceptionRecord->NumberParameters >= 3) ) {

    *ExceptionCode = (NTSTATUS) ExceptionPointer->ExceptionRecord->ExceptionInformation[2];
}

ASSERT( !NT_SUCCESS(*ExceptionCode) );

return EXCEPTION_EXECUTE_HANDLER;
}

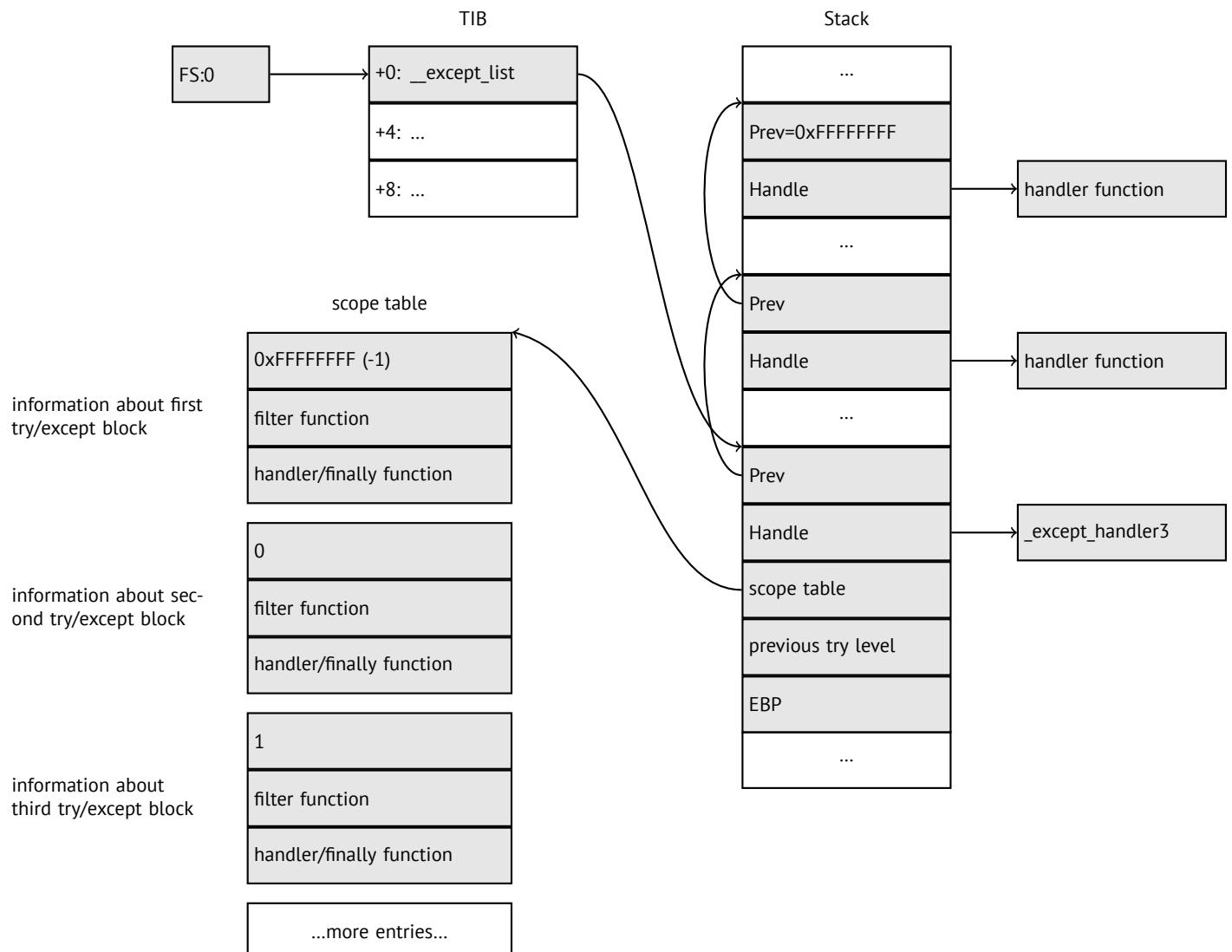
```

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 Windows³³. Another reimplementation is present in Wine³⁴ and ReactOS³⁵.

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

```
#include <stdio.h>
#include <windows.h>
#include <excpt.h>

int main()
{
    int* p = NULL;
    __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 71.6: 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
$T74622  DD      0fffffffH    ; previous try level
           DD      FLAT:$L74617  ; filter
           DD      FLAT:$L74618  ; handler

CONST    ENDS
_TEXT    SEGMENT
$T74621 = -32 ; size = 4
_p$ = -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
```

³³<http://go.yurichev.com/17058>

³⁴[GitHub](#)

³⁵<http://go.yurichev.com/17060>

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```

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
    inc    eax
$L74619:
$L74626:
    ret    0

; handler code:
$L74618:
    mov    esp, DWORD PTR __$SEHRec$[ebp]
    push  OFFSET FLAT:$SG74608 ; 'access violation, can''t recover'
    call   _printf
    add    esp, 4
    mov    DWORD PTR __$SEHRec$[ebp+20], -1 ; setting previous try level back to -1
$L74616:
    xor    eax, eax
    mov    ecx, DWORD PTR __$SEHRec$[ebp+8]
    mov    DWORD PTR fs:_except_list, ecx
    pop    edi
    pop    esi
    pop    ebx
    mov    esp, ebp
    pop    ebp
    ret    0
_main  ENDP
_TEXT  ENDS
END

```

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
```

Listing 71.7: tracer.exe output

```
EXCEPTION_ACCESS_VIOLATION at 2.exe!main+0x44 (0x401054) ExceptionInformation[0]=1
```

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```
EAX=0x00000000 EBX=0x7efde000 ECX=0x0040cbc8 EDX=0x0008e3c8
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=0x18ffc4 handler=0x401204 (2.exe!_except_handler3)
SEH3 frame. previous trylevel=0
scopetable entry[0]. previous try level=-1, filter=0x401531 (2.exe!mainCRTStartup+0x18d) ↴
    ↴ handler=0x401545 (2.exe!mainCRTStartup+0x1a1)
* SEH frame at 0x18ffc4 prev=0x18ffe4 handler=0x771f71f5 (ntdll.dll!__except_handler4)
SEH4 frame. previous trylevel=0
SEH4 header:   GSCookieOffset=0xffffffff GSCookieXOROffset=0x0
                EHCookieOffset=0xffffffffcc EHCookieXOROffset=0x0
scopetable entry[0]. previous try level=-2, filter=0x771f74d0 (ntdll.dll!__safe_se_handler_table+0x20) handler=0x771f90eb (ntdll.dll!_TppTerminateProcess@4+0x43)
* SEH frame at 0x18ffe4 prev=0xffffffff handler=0x77247428 (ntdll.dll!_FinalExceptionHandler@16) ↴
    ↴ )
```

We see that the SEH chain consists of 4 handlers.

The first two are located in our example. Two? But we made only one? Yes, another one was 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 ntdll.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

```
#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)
    }
```

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```

    {
        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 71.8: 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
$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
$T74644  DD      0xffffffffH ; previous try level for outer block
            DD      FLAT:$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

```

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```

push    -1 ; previous try level
push    OFFSET FLAT:$T74644
push    OFFSET FLAT:__except_handler3
mov     eax, DWORD PTR fs:_except_list
push    eax
mov     DWORD PTR fs:_except_list, esp
add    esp, -20
push    ebx
push    esi
push    edi
mov     DWORD PTR __$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
↓ 0
mov     DWORD PTR __$SEHRec$[ebp+20], 1 ; inner try block entered. set previous try level to 1
↓ 1
push    OFFSET FLAT:$SG74617 ; 'hello!'
call    _printf
add    esp, 4
push    0
push    0
push    0
push    1122867 ; 00112233H
call    DWORD PTR __imp_RaiseException@16
push    OFFSET FLAT:$SG74619 ; '0x112233 raised. now let's crash'
call    _printf
add    esp, 4
mov     eax, DWORD PTR _p$[ebp]
mov     DWORD PTR [eax], 13
mov     DWORD PTR __$SEHRec$[ebp+20], 0 ; inner try block exited. set previous try level back to 0
↓ 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:
$L74639:
    mov    esp, DWORD PTR __$SEHRec$[ebp]
    push   OFFSET FLAT:$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
↓ back to 0

$L74615:
    mov    DWORD PTR __$SEHRec$[ebp+20], -1 ; outer try block exited, set previous try level back to -1
↓ 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

```

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```
    mov    ecx, DWORD PTR __$SEHRec$[ebp+4]
    push   ecx
    mov    edx, DWORD PTR $T74642[ebp]
    push   edx
    call   _filter_user_exceptions
    add    esp, 8
$L74636:
$L74649:
    ret    0

; outer block handler:
$L74635:
    mov    esp, DWORD PTR __$SEHRec$[ebp]
    push   OFFSET FLAT:$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
    pop    esi
    pop    ebx
    mov    esp, ebp
    pop    ebp
    ret    0
_main    ENDP
```

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 71.9: tracer.exe output

```
(0) 3.exe!printf
EAX=0x00000001b EBX=0x000000000 ECX=0x0040cc58 EDX=0x0008e3c8
ESI=0x000000000 EDI=0x000000000 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
scopetable entry[0]. previous try level=-1, filter=0x401120 (3.exe!main+0xb0) handler=0x40113b ↴
    ↴ (3.exe!main+0xcb)
scopetable entry[1]. previous try level=0, filter=0x4010e8 (3.exe!main+0x78) handler=0x401100 ↴
    ↴ (3.exe!main+0x90)
* SEH frame at 0x18ff78 prev=0x18ffc4 handler=0x4012e0 (3.exe!_except_handler3)
SEH3 frame. previous trylevel=0
scopetable entry[0]. previous try level=-1, filter=0x40160d (3.exe!mainCRTStartup+0x18d) ↴
    ↴ handler=0x401621 (3.exe!mainCRTStartup+0x1a1)
* SEH frame at 0x18ffc4 prev=0x18ffe4 handler=0x771f71f5 (ntdll.dll!__except_handler4)
SEH4 frame. previous trylevel=0
SEH4 header:   GSCookieOffset=0xffffffff GSCookieXOROffset=0x0
                EHCookieOffset=0xfffffffcc EHCookieXOROffset=0x0
scopetable entry[0]. previous try level=-2, filter=0x771f74d0 (ntdll.dll! ↴
    ↴ __safe_se_handler_table+0x20) handler=0x771f90eb (ntdll.dll!_TppTerminateProcess@4+0x43)
* SEH frame at 0x18ffe4 prev=0xffffffff handler=0x77247428 (ntdll.dll!_FinalExceptionHandler@16 ↴
    ↴ )
```

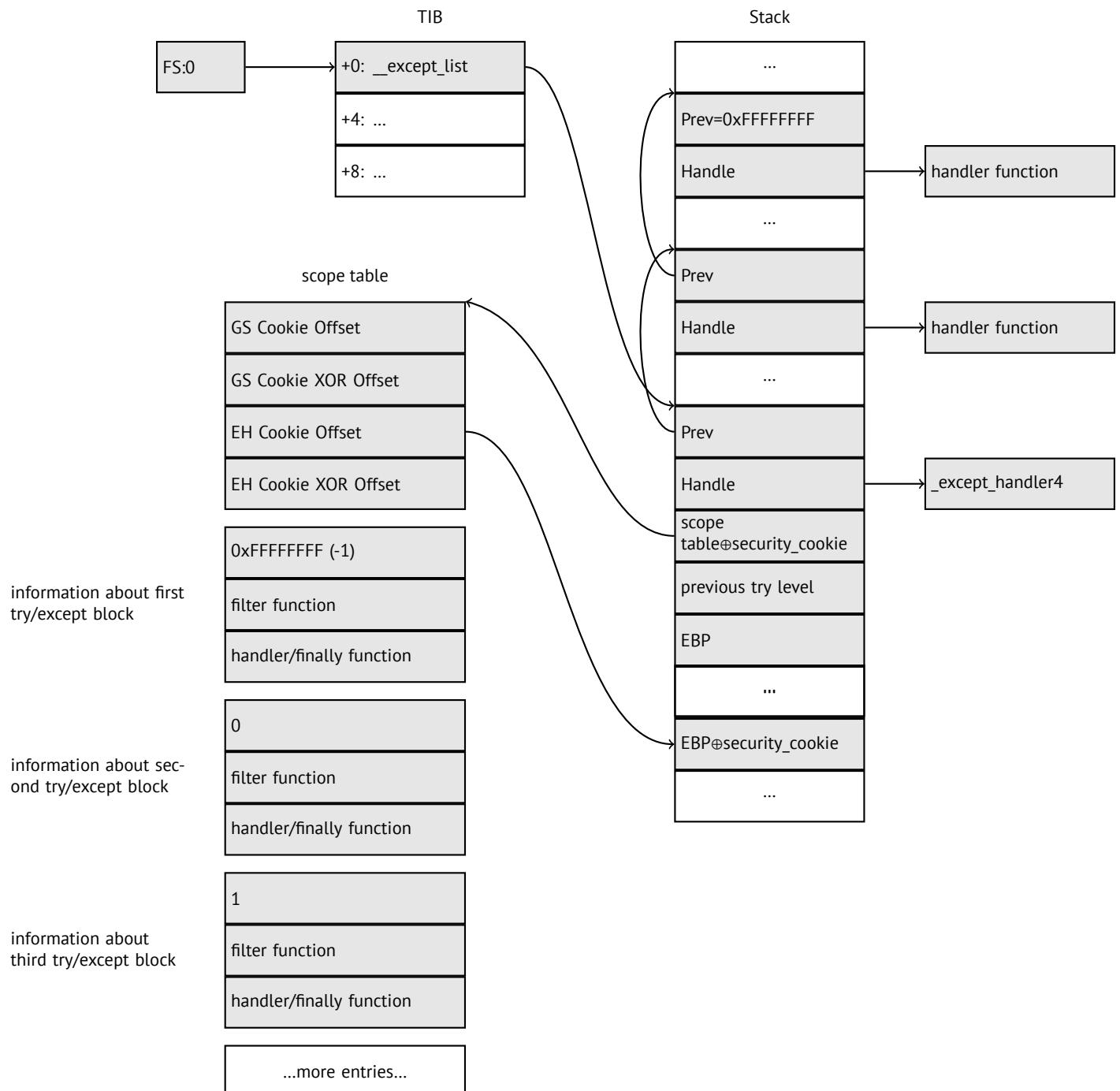
SEH4

During a buffer overflow ([19.2 on page 274](#)) 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

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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 71.10: MSVC 2012: one try block example

```
$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 0ffffffeH    ; GS Cookie Offset
                   00H           ; GS Cookie XOR Offset
                   0fffffcch     ; EH Cookie Offset
                   00H           ; EH Cookie XOR Offset
```

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```

    DD          0fffffffefH      ; 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:
    mov     DWORD PTR tv68[ebp], 0
$LN5@main:
    mov     eax, DWORD PTR tv68[ebp]
$LN9@main:
$LN11@main:
    ret    0

; handler:
$LN8@main:
    mov     esp, DWORD PTR __$SEHRec$[ebp]
    push    OFFSET $SG85488 ; 'access violation, can''t recover'
    call    _printf
    add     esp, 4
    mov     DWORD PTR __$SEHRec$[ebp+20], -2 ; previous try level
$LN6@main:
    xor     eax, eax
    mov     ecx, DWORD PTR __$SEHRec$[ebp+8]

```

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```

    mov    DWORD PTR fs:0, ecx
    pop    ecx
    pop    edi
    pop    esi
    pop    ebx
    mov    esp, ebp
    pop    ebp
    ret    0
_main    ENDP

```

Listing 71.11: MSVC 2012: two try blocks example

```

$SG85486 DB      'in filter. code=0x%08X', 0aH, 00H
$SG85488 DB      'yes, that is our exception', 0aH, 00H
$SG85490 DB      'not our exception', 0aH, 00H
$SG85497 DB      'hello!', 0aH, 00H
$SG85499 DB      '0x112233 raised. now let's crash', 0aH, 00H
$SG85501 DB      'access violation, can't recover', 0aH, 00H
$SG85503 DB      'user exception caught', 0aH, 00H

xdata$x      SEGMENT
__sehtable$_main DD 0fffffeH           ; GS Cookie Offset
                  DD 00H                 ; GS Cookie XOR Offset
                  DD 0fffffc8H          ; EH Cookie Offset
                  DD 00H                 ; EH Cookie Offset
                  DD 0fffffeH           ; 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 ↴
    ↳ level=0
    mov     DWORD PTR __$SEHRec$[ebp+20], 1 ; entering inner try block, setting previous try ↴
    ↳ level=1
    push    OFFSET $SG85497 ; '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 $SG85499 ; '0x112233 raised. now let's crash'
call    _printf
add    esp, 4
mov    eax, DWORD PTR _p$[ebp]
mov    DWORD PTR [eax], 13
mov    DWORD PTR __$SEHRec$[ebp+20], 0 ; exiting inner try block, set previous try level ↴
↳ back to 0
jmp    SHORT $LN2@main

; inner block filter:
$LN12@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:
$LN13@main:
    mov    esp, DWORD PTR __$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:
$LN8@main:
$LN19@main:
    mov    ecx, DWORD PTR __$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
$LN10@main:
$LN17@main:
    ret    0

; outer block handler:
$LN9@main:
    mov    esp, DWORD PTR __$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
$LN7@main:
    xor    eax, eax
    mov    ecx, DWORD PTR __$SEHRec$[ebp+8]

```

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```
    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
_ep$ = 12 ; size = 4
_filter_user_exceptions PROC
    push   ebp
    mov    ebp, esp
    mov    eax, DWORD PTR _code$[ebp]
    push   eax
    push   OFFSET $SG85486 ; 'in filter. code=0x%08X'
    call   _printf
    add    esp, 8
    cmp    DWORD PTR _code$[ebp], 1122867 ; 00112233H
    jne    SHORT $LN2@filter_use
    push   OFFSET $SG85488 ; 'yes, that is our exception'
    call   _printf
    add    esp, 4
    mov    eax, 1
    jmp    SHORT $LN3@filter_use
    jmp    SHORT $LN3@filter_use
$LN2@filter_use:
    push   OFFSET $SG85490 ; 'not our exception'
    call   _printf
    add    esp, 4
    xor    eax, eax
$LN3@filter_use:
    pop    ebp
    ret    0
_filter_user_exceptions ENDP
```

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* \oplus *security_cookie* value in the stack. **Cookie XOR Offset** is an additional difference between the *EBP* \oplus *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:

security_cookie \oplus (*CookieXOROffset* + *address_of_saved_EBP*) == *stack*[*address_of_saved_EBP* + *CookieOffset*]

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.

71.3.3 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 71.12: 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
```

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```
$pdata$main DD imagerel $LN9
    DD imagerel $LN9+61
    DD imagerel $unwind$main
pdata ENDS
pdata SEGMENT
$pdata$main$filt$0 DD imagerel main$filter$0
    DD imagerel main$filter$0+32
    DD imagerel $unwind$main$filter$0
pdata ENDS
xdata SEGMENT
$unwind$main DD 020609H
    DD 030023206H
    DD imagerel __C_specific_handler
    DD 01H
    DD imagerel $LN9+8
    DD imagerel $LN9+40
    DD imagerel main$filter$0
    DD imagerel $LN9+40
$unwind$main$filter$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$x SEGMENT
main$filter$0 PROC
    push rbp
    sub rsp, 32
    mov rbp, rdx
$LN5@main$filter$0:
    mov rax, QWORD PTR [rcx]
    xor ecx, ecx
    cmp DWORD PTR [rax], -1073741819; c0000005H
    sete cl
    mov eax, ecx
$LN7@main$filter$0:
    add rsp, 32
    pop rbp
    ret 0
    int 3
main$filter$0 ENDP
text$x ENDS
```

Listing 71.13: 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

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```

$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
    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

```

7.1.3. WINDOWS SEH

```
$LN9@main:
    xor    eax, eax
    add    rsp, 32
    pop    rbx
    ret    0
main    ENDP

text$x SEGMENT
main$filter$0 PROC
    push   rbp
    sub    rsp, 32
    mov    rbp, rdx
$LN10@main$filter$:
    mov    rax, QWORD PTR [rcx]
    xor    ecx, ecx
    cmp    DWORD PTR [rax], -1073741819; c0000005H
    sete   cl
    mov    eax, ecx
$LN12@main$filter$:
    add    rsp, 32
    pop    rbp
    ret    0
    int    3
main$filter$0 ENDP

main$filter$1 PROC
    push   rbp
    sub    rsp, 32
    mov    rbp, rdx
$LN6@main$filter$:
    mov    rax, QWORD PTR [rcx]
    mov    rdx, rcx
    mov    ecx, DWORD PTR [rax]
    call   filter_user_exceptions
    npad   1 ; align next label
$LN8@main$filter$:
    add    rsp, 32
    pop    rbp
    ret    0
    int    3
main$filter$1 ENDP
text$x ENDS

_TEXT  SEGMENT
code$ = 48
ep$ = 56
filter_user_exceptions PROC
$LN6:
    push   rbx
    sub    rsp, 32
    mov    ebx, ecx
    mov    edx, ecx
    lea    rcx, OFFSET FLAT:$SG86277 ; 'in filter. code=0x%08X'
    call   printf
    cmp    ebx, 1122867; 00112233H
    jne    SHORT $LN2@filter_use
    lea    rcx, OFFSET FLAT:$SG86279 ; 'yes, that is our exception'
    call   printf
    mov    eax, 1
    add    rsp, 32
    pop    rbx
    ret    0
$LN2@filter_use:
    lea    rcx, OFFSET FLAT:$SG86281 ; 'not our exception'
    call   printf
    xor    eax, eax
    add    rsp, 32
    pop    rbx
    ret    0
filter_user_exceptions ENDP
```

```
_TEXT ENDS
```

Read [[Sko12](#)] 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 tools targeted at automated analysis.

71.3.4 Read more about SEH

[[Pie](#)], [[Sko12](#)].

71.4 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:

Listing 71.14: (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:

Listing 71.15: 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
```

71.4. WINDOWS NT: CRITICAL SECTION

```
pop    ebp  
retn   4  
  
... skipped
```

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 done there using `WaitForSingleObject()`.

And here is how the `LeaveCriticalSection()` function works:

Listing 71.16: Windows 2008/ntdll.dll/x86 (begin)

```
_RtlLeaveCriticalSection@4 proc near  
  
arg_0      = dword ptr  8  
  
    mov     edi, edi  
    push    ebp  
    mov     ebp, esp  
    push    esi  
    mov     esi, [ebp+arg_0]  
    add     dword ptr [esi+8], 0FFFFFFFh ; RecursionCount  
    jnz     short loc_7DE922B2  
    push    ebx  
    push    edi  
    lea     edi, [esi+4]    ; LockCount  
    mov     dword ptr [esi+0Ch], 0  
    mov     ebx, 1  
    mov     eax, edi  
    lock xadd [eax], ebx  
    inc     ebx  
    cmp     ebx, 0FFFFFFFh  
    jnz     loc_7DEA8EB7  
  
loc_7DE922B0:  
    pop     edi  
    pop     ebx  
  
loc_7DE922B2:  
    xor     eax, eax  
    pop     esi  
    pop     ebp  
    retn   4  
  
... skipped
```

`XADD` is “exchange and add”. In this case, it adds 1 to `LockCount` and stores the result in the `EBX` register, and at the same time 1 goes to `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 behaviour.

Part VII

Tools

Chapter 72

Disassembler

72.1 IDA

An older freeware version is available for download ¹.

Hot-keys cheatsheet: [F.1 on page 948](#)

¹hex-rays.com/products/ida/support/download_freeware.shtml

Chapter 73

Debugger

73.1 OllyDbg

Very popular user-mode win32 debugger:

ollydbg.de.

Hot-keys cheatsheet: [F.2 on page 948](#)

73.2 GDB

Not very popular debugger among reverse engineers, but very comfortable nevertheless.

Some commands: [F.5 on page 949](#).

73.3 tracer

The author often uses *tracer*¹ 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.

However, for learning purposes it is highly advisable to trace code in a debugger manually, watch how the registers state changes (e.g. classic SoftICE, OllyDbg, WinDbg highlight changed registers), flags, data, change them manually, watch the reaction, etc.

¹yurichev.com

Chapter 74

System calls tracing

74.0.1 strace / dtruss

It shows which system calls (syscalls([69](#) on page [703](#))) are called by a process right now.

For example: Por ejemplo:

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.

Chapter 75

Decompilers

There is only one known, publicly available, high-quality decompiler to C code: Hex-Rays:

hex-rays.com/products/decompiler/

Chapter 76

Other tools

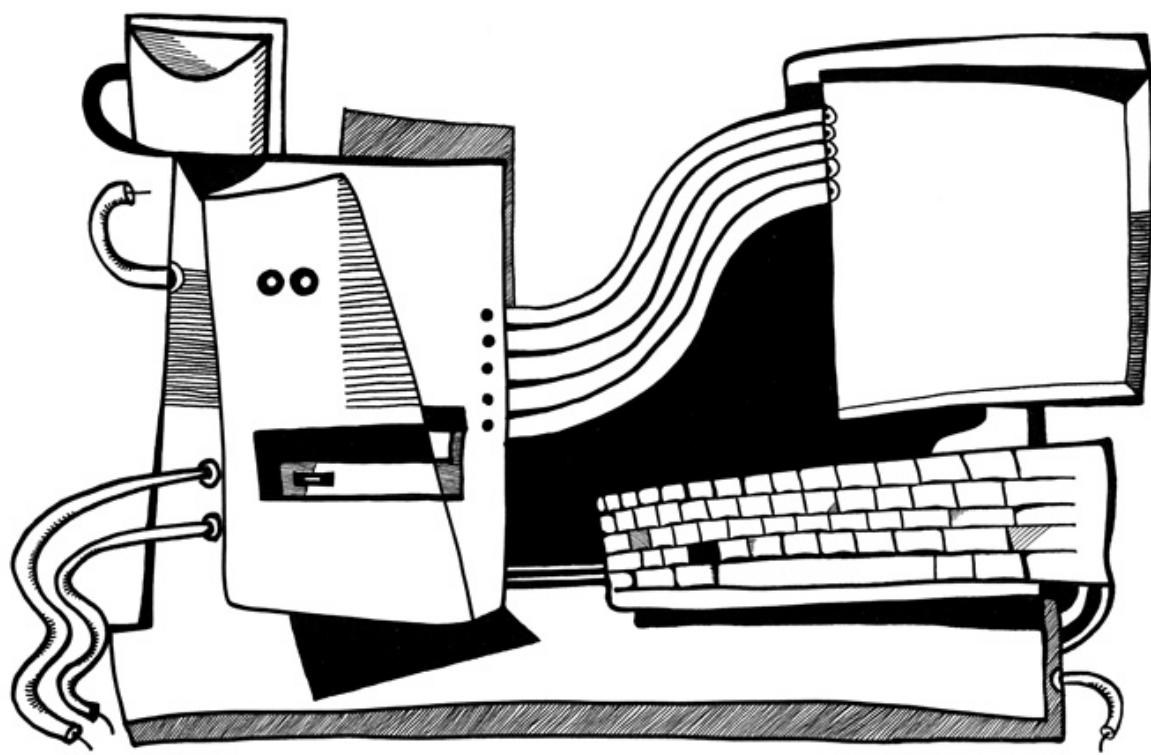
- Microsoft Visual Studio Express¹: Stripped-down free version of Visual Studio, convenient for simple experiments. Some useful options: [F.3 on page 949](#).
- Hiew²: for small modifications of code in binary files.
- binary grep: a small utility for searching any byte sequence in a big pile of files, including non-executable ones: [GitHub](#).

¹visualstudio.com/en-US/products/visual-studio-express-vs

²hiew.ru

Part VIII

Examples from practice



Chapter 77

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 zero¹).

The second argument has to point to the buffer which is getting all the information.

So we need 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.

Uxrefs to __imp_NtQuerySystemInformation		
Dire...	T.	Address
Up	p	wWinMain+50E
Up	p	wWinMain+542
Up	p	CPerfPage::TimerEvent(void)+200
	p	InitPerfInfo(void)+2C
	p	InitPerfInfo(void)+F0
	p	CalcCpuTime(int)+5F
	p	CalcCpuTime(int)+248
	p	CPerfPage::CalcPhysicalMem(unsigned ...)
	p	CPerfPage::CalcPhysicalMem(unsigned ...)
	p	CProcPage::GetProcessInfo(void)+2B
	p	CProcPage::UpdateProcInfoArray(void)+...
	p	CProcPage::UpdateProcInfoArray(void)+...
	p	CProcPage::Initialize(HWND__ *)+201
	p	CProcPage::GetTaskListEx(void)+3C

Figure 77.1: 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 77.1: taskmgr.exe (Windows Vista)

```
.text:10000B4B3 xor    r9d, r9d
.text:10000B4B6 lea     rdx, [rsp+0C78h+var_C58] ; buffer
```

¹MSDN

```

.text:10000B4BB xor    ecx, ecx
.text:10000B4BD lea    ebp, [r9+40h]
.text:10000B4C1 mov    r8d, ebp
.text:10000B4C4 call   cs:_imp_NtQuerySystemInformation ; 0
.text:10000B4CA xor    ebx, ebx
.text:10000B4CC cmp    eax, ebx
.text:10000B4CE jge    short loc_10000B4D7
.text:10000B4D0
.text:10000B4D0 loc_10000B4D0: ; CODE XREF: InitPerfInfo(void)+97
                               ; InitPerfInfo(void)+AF
.text:10000B4D0 xor    al, al
.text:10000B4D2 jmp    loc_10000B5EA
.text:10000B4D7 ; -----
.text:10000B4D7 loc_10000B4D7: ; CODE XREF: InitPerfInfo(void)+36
.text:10000B4D7 mov    eax, [rsp+0C78h+var_C50]
.text:10000B4DB mov    esi, ebx
.text:10000B4DD mov    r12d, 3E80h
.text:10000B4E3 mov    cs:?g_PageSize@@3KA, eax ; ulong g_PageSize
.text:10000B4E9 shr    eax, 0Ah
.text:10000B4EC lea    r13, __ImageBase
.text:10000B4F3 imul   eax, [rsp+0C78h+var_C4C]
.text:10000B4F8 cmp    [rsp+0C78h+var_C20], bp1
.text:10000B4FD mov    cs:?g_MEMMax@@3_JA, rax ; __int64 g_MEMMax
.text:10000B504 movzx  eax, [rsp+0C78h+var_C20] ; number of CPUs
.text:10000B509 cmova eax, ebp
.text:10000B50C cmp    al, bl
.text:10000B50E mov    cs:?g_cProcessors@@3EA, al ; uchar g_cProcessors

```

`g_cProcessors` is a global variable, and this name was 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:

```

typedef struct _SYSTEM_BASIC_INFORMATION {
    BYTE Reserved1[24];
    PVOID Reserved2[4];
    CCHAR NumberOfProcessors;
} SYSTEM_BASIC_INFORMATION;

```

This is a x64 system, so each `PVOID` takes 8 byte. 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:

01`0000B4F8: 40386C2458	cmp	[rsp][058],bp1
01`0000B4FD: 48890544A00100	mov	[00000001 00025548],rax
01`0000B504: 0FB6442458	movzx	eax,b,[rsp][058]
01`0000B509: 0F47C5	cmova	eax,ebp
01`0000B50C: 3AC3	cmp	al,bl
01`0000B50E: 880574950100	mov	[00000001 00024A88],al
01`0000B514: 7645	jbe	.00000001 0000B55B --D3
01`0000B516: 488BFB	mov	rdi,rbx
01`0000B519: 498BD4	5mov	rdx,r12
01`0000B51C: 8BCD	mov	ecx,ebp

Figure 77.2: Hiew: find the place to be patched

Let's replace the `MOVZX` 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):

77.1. USING LEA TO LOAD VALUES

00`0000A8F8: 40386C2458	cmp [rsp][058], bp
00`0000A8FD: 48890544A00100	mov [000024948], rax
00`0000A904: 66B84000	mov ax, 00040 ; '@'
00`0000A908: 90	nop
00`0000A909: 0F47C5	cmova eax, ebp
00`0000A90C: 3AC3	cmp al, bl
00`0000A90E: 880574950100	mov [000023E88], al
00`0000A914: 7645	jbe 00000A95B
00`0000A916: 488BFB	mov rdi, rbx
00`0000A919: 498BD4	mov rdx, r12
00`0000A91C: 8BCD	mov ecx, ebp

Figure 77.3: Hiew: patch it

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%.

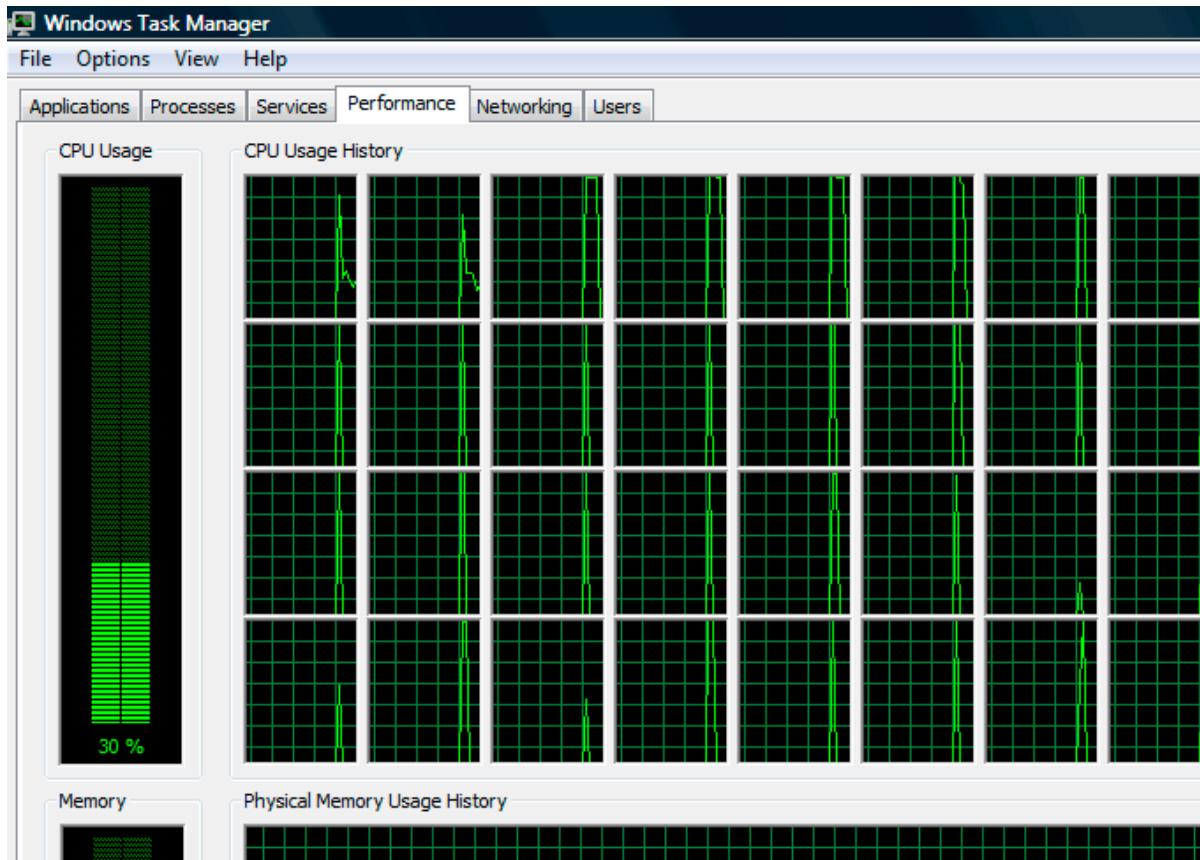


Figure 77.4: Fooled Windows Task Manager

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 structures inside it limited to 64 cores.

77.1 Using LEA to load values

Sometimes, `LEA` is used in `taskmgr.exe` instead of `MOV` to set the first argument of `NtQuerySystemInformation()`:

Listing 77.2: taskmgr.exe (Windows Vista)

```
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
```

77.1. USING LEA TO LOAD VALUES

```
...
    mov    r8d, 30h
    lea    r9, [rsp+298h+var_268]
    lea    rdx, [rsp+298h+var_258]
    lea    ecx, [r8-2Dh] ; 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: [67.5.1 on page 694](#).

Chapter 78

Color Lines game practical joke

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>¹. Here is how it looks:

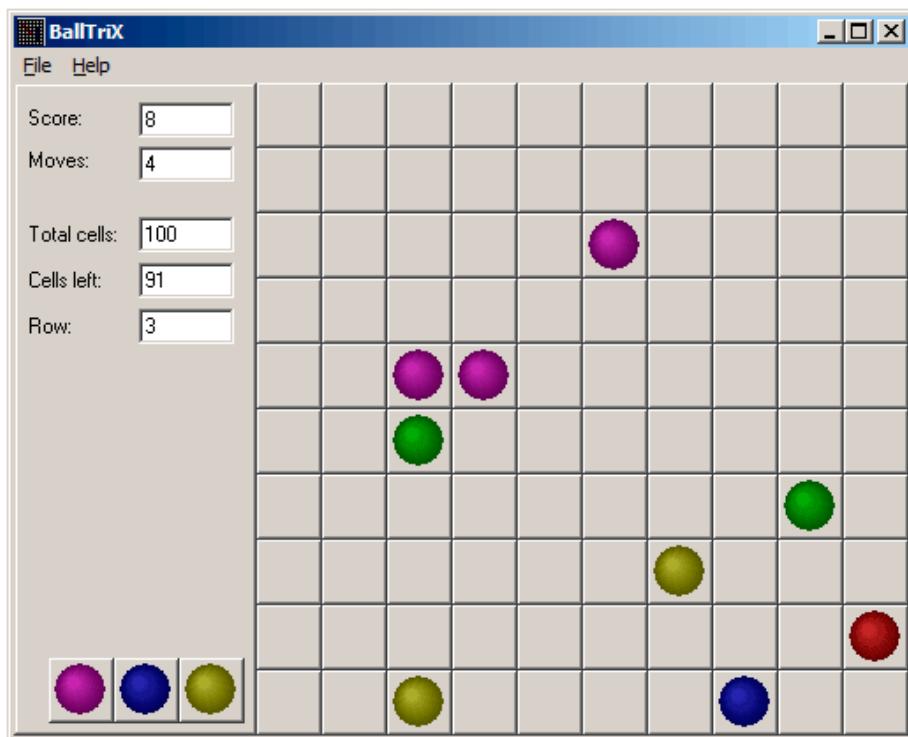


Figure 78.1: How this game looks usually

¹Or at <http://go.yurichev.com/17365> or <http://go.yurichev.com/17366>.

So let's see, is it be 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
.text:00402C9C arg_0      = dword ptr 8
.text:00402C9C
.text:00402C9C push    ebp
.text:00402C9D mov     ebp, esp
.text:00402C9F push    ebx
.text:00402CA0 push    esi
.text:00402CA1 push    edi
.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_40D430, edx
.text:00402CD1 mov     eax, dword_40D430
.text:00402CD6 jmp    $+5
.text:00402CDB pop    edi
.text:00402CDC pop    esi
.text:00402CDD pop    ebx
.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:00402BBB          mov    eax, dword_40C058 ; 5 here
.text:00402BC0          push   eax
.text:00402BC1          call   random
.text:00402BC6          add    esp, 4
.text:00402BC9          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.

```
.00402BB8: 83C410    add    esp,010
.00402BBB: A158C04000  mov    eax,[00040C058]
.00402BC0: 31C0      xor    eax,eax
```

```
.00402BC2: 90          nop
.00402BC3: 90          nop
.00402BC4: 90          nop
.00402BC5: 90          nop
.00402BC6: 90          nop
.00402BC7: 90          nop
.00402BC8: 90          nop
.00402BC9: 40          inc      eax
.00402BCA: 8B4DF8      mov      ecx,[ebp][-8]
.00402BCD: 8D0C49      lea      ecx,[ecx][ecx]*2
.00402BD0: 8B15F4D54000 mov      edx,[00040D5F4]
```

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:

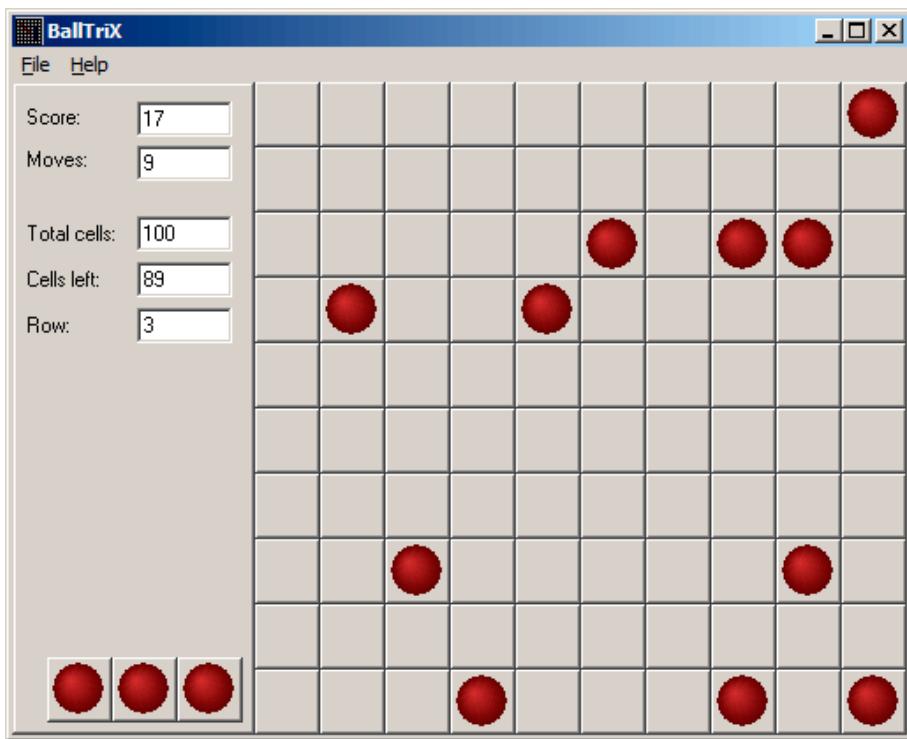


Figure 78.2: Practical joke works

Oh yes, it works².

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.

²Author of this book once did this as a joke for his coworkers with the hope that they would stop playing. They didn't.

Chapter 79

Minesweeper (Windows XP)

For those who is 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:

```
.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
.text:01003940                 call    ds:_imp__rand
.text:01003946                 cdq
.text:01003947                 idiv   [esp+arg_0]
.text:0100394B                 mov    eax, edx
.text:0100394D                 retn   4
.text:0100394D _Rnd@4          endp
```

[IDA](#) named it so, and it was the name given to it by Minesweeper's developers.

The function is very simple:

```
int Rnd(int limit)
{
    return rand() % limit;
};
```

(There was 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:

```
.text:010036C7          push   _xBoxMac
.text:010036CD          call   _Rnd@4          ; Rnd(x)
.text:010036D2          push   _yBoxMac
.text:010036D8          mov    esi, eax
.text:010036DA          inc    esi
.text:010036DB          call   _Rnd@4          ; Rnd(x)
.text:010036E0          inc    eax
.text:010036E1          mov    ecx, eax
.text:010036E3          shl    ecx, 5           ; ECX=ECX*32
.text:010036E6          test   _rgBlk[ecx+esi], 80h
.text:010036EE          jnz   short loc_10036C7
.text:010036F0          shl    eax, 5           ; EAX=EAX*32
.text:010036F3          lea    eax, _rgBlk[eax+esi]
.text:010036FA          or    byte ptr [eax], 80h
.text:010036FD          dec    _cBombStart
```

```
.text:01003703          jnz      short loc_10036C7
```

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 was placed before (it's possible if the pair of `Rnd()` generates a coordinates pair which was 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):

```
.data:01005340 _rgBlk           db 360h dup(?)           ; DATA XREF: MainWndProc(x,x,x,x)+574
.data:01005340                 ; DisplayBlk(x,x)+23
.data:010056A0 _Preferences     dd ?                   ; DATA XREF: FixMenus()+2
...
```

$864/32 = 27$.

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`)¹.

So we got this memory dump of the array:

Address	Hex dump
01005340	10 10 10 10 10 10 10 10 10 10 10 OF OF OF OF OF
01005350	OF
01005360	10 OF 10 OF OF OF OF OF
01005370	OF
01005380	10 OF 10 OF OF OF OF OF
01005390	OF
010053A0	10 OF OF OF OF OF OF OF 8F OF 10 OF OF OF OF OF
010053B0	OF
010053C0	10 OF 10 OF OF OF OF OF
010053D0	OF
010053E0	10 OF 10 OF OF OF OF OF
010053F0	OF
01005400	10 OF OF 8F OF OF 8F OF OF 10 OF OF OF OF OF
01005410	OF
01005420	10 8F OF OF 8F OF OF OF OF OF 10 OF OF OF OF OF
01005430	OF
01005440	10 8F OF OF OF OF 8F OF 8F 10 OF OF OF OF OF
01005450	OF
01005460	10 OF OF OF OF 8F OF OF 8F 10 OF OF OF OF OF
01005470	OF
01005480	10 10 10 10 10 10 10 10 10 10 10 OF OF OF OF OF
01005490	OF
010054A0	OF
010054B0	OF
010054C0	OF

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:

¹All addresses here are for Minesweeper for Windows XP SP3 English. They may differ for other service packs.



Figure 79.1: Mines

By comparing the mine places and the dump, we can conclude that 0x10 stands for border, 0x0F – empty block, 0x8F – mine.

Now we'll add comments and also enclose all 0x8F bytes into square brackets:

```

border:
01005340 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 OF OF OF OF OF
01005350 OF OF
line #1:
01005360 10 OF OF OF OF OF OF OF OF 10 OF OF OF OF OF OF OF OF OF OF
01005370 OF OF
line #2:
01005380 10 OF OF OF OF OF OF OF OF 10 OF OF OF OF OF OF OF OF OF
01005390 OF OF
line #3:
010053A0 10 OF OF OF OF OF OF OF [8F]OF 10 OF OF OF OF OF OF OF OF
010053B0 OF OF
line #4:
010053C0 10 OF OF OF OF OF OF OF 10 OF OF OF OF OF OF OF OF OF OF
010053D0 OF OF
line #5:
010053E0 10 OF OF OF OF OF OF OF 10 OF OF OF OF OF OF OF OF OF OF
010053F0 OF OF
line #6:
01005400 10 OF OF [8F]OF [8F]OF 10 OF OF OF OF OF OF OF OF OF OF
01005410 OF OF
line #7:
01005420 10[8F]OF OF[8F]OF OF OF OF 10 OF OF OF OF OF OF OF OF OF
01005430 OF OF
line #8:
01005440 10[8F]OF OF OF OF [8F]OF OF [8F]10 OF OF OF OF OF OF
01005450 OF OF
line #9:
01005460 10 OF OF OF OF [8F]OF OF OF OF [8F]10 OF OF OF OF OF OF
01005470 OF OF
border:
01005480 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 OF OF OF OF
01005490 OF OF

```

Now we'll remove all *border bytes* (0x10) and what's beyond those:

```

OF OF OF OF OF OF OF OF
OF OF OF OF OF OF OF OF
OF OF OF OF OF OF [8F]OF
OF OF OF OF OF OF OF OF
OF OF OF OF OF OF OF OF
OF OF [8F]OF OF [8F]OF OF OF
[8F]OF OF [8F]OF OF OF OF
[8F]OF OF OF OF [8F]OF OF [8F]
OF OF OF OF [8F]OF OF OF [8F]

```

Yes, these are mines, now it can be clearly seen and compared with the screenshot.

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:

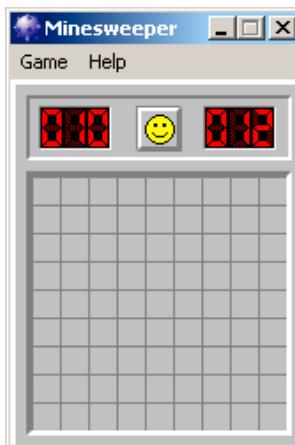


Figure 79.2: All mines are removed in debugger

We can also move all of them to the first line:

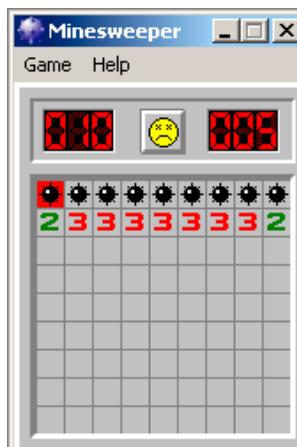


Figure 79.3: Mines set in debugger

Well, the debugger is not very convenient for eavesdropping (which was our goal anyway), so we'll write a small utility to dump the contents of the board:

```
// 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);
```

79.1. EXERCISES

```
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 [PID²](#) ³ and the address of the array (`0x01005340` for Windows XP SP3 English) and it will dump it ⁴.

It attaches itself to a win32 process by [PID](#) and just reads process memory at the address.

79.1 Exercises

- Why do the *border bytes* (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.
- Modify my utility so it can work without the array address specified and without a [PDB](#) file. Yes, it's possible to find board information in the data segment of Minesweeper's running process automatically.

²Program/process ID

³PID it can be seen in Task Manager (enable it in "View → Select Columns")

⁴The compiled executable is here: [beginners.re](#)

Chapter 80

Hand decompiling + Z3 SMT solver

Amateur cryptography is usually (unintentionally) very weak and can be broken easily—for cryptographers, of course.

But let's pretend we are not among these crypto-professionals.

Here is one-way hash function (read more about them: [36 on page 456](#)), that converted a 64-bit value to another and we need to try to reverse its flow back.

80.1 Hand decompiling

Here its assembly language listing in [IDA](#):

```
sub_401510    proc near
; ECX = input
    mov     rdx, 5D7E0D1F2E0F1F84h
    mov     rax, rcx          ; input
    imul   rax, rdx
    mov     rdx, 388D76AEE8CB1500h
    mov     ecx, eax
    and    ecx, 0Fh
    ror    rax, cl
    xor    rax, rdx
    mov     rdx, 0D2E9EE7E83C4285Bh
    mov     ecx, eax
    and    ecx, 0Fh
    rol    rax, cl
    lea    r8, [rax+rdx]
    mov     rdx, 888888888888889h
    mov     rax, r8
    mul    rdx
    shr    rdx, 5
    mov     rax, rdx
    lea    rcx, [r8+rdx*4]
    shl    rax, 6
    sub    rcx, rax
    mov     rax, r8
    rol    rax, cl
; EAX = output
    retn
sub_401510    endp
```

The example was compiled by GCC, so the first argument is passed in `ECX`.

If you don't have Hex-Rays or if you distrust to it, you can try to reverse this code manually. One method is to represent the [CPU](#) registers as local C variables and replace each instruction by a one-line equivalent expression, like:

```
uint64_t f(uint64_t input)
{
    uint64_t rax, rbx, rcx, rdx, r8;
    ecx=input;
```

80.1. HAND DECOMPILING

```
rdx=0x5D7E0D1F2E0F1F84;
rax=rcx;
rax*=rdx;
rdx=0x388D76AEE8CB1500;
rax=_lrotr(rax, rax&0xF); // rotate right
rax^=rdx;
rdx=0xD2E9EE7E83C4285B;
rax=_lrotl(rax, rax&0xF); // rotate left
r8=rax+rdx;
rdx=0x8888888888888889;
rax=r8;
rax*=rdx;
rdx=rdx>>5;
rax=rdx;
rcx=r8+rdx*4;
rax=rax<<6;
rcx=rcx-rax;
rax=r8
rax=_lrotl (rax, rcx&0xFF); // rotate left
return rax;
};
```

If you are careful enough, this code can be compiled and will even work in the same way as the original.

Then, we are going to rewrite it gradually, keeping in mind all registers usage. Attention and focus is very important here—any tiny typo may ruin all your work!

Here is the first step:

```
uint64_t f(uint64_t input)
{
    uint64_t rax, rbx, rcx, rdx, r8;

    ecx=input;

    rdx=0x5D7E0D1F2E0F1F84;
    rax=rcx;
    rax*=rdx;
    rdx=0x388D76AEE8CB1500;
    rax=_lrotr(rax, rax&0xF); // rotate right
    rax^=rdx;
    rdx=0xD2E9EE7E83C4285B;
    rax=_lrotl(rax, rax&0xF); // rotate left
    r8=rax+rdx;

    rdx=0x8888888888888889;
    rax=r8;
    rax*=rdx;
    // RDX here is a high part of multiplication result
    rdx=rdx>>5;
    // RDX here is division result!
    rax=rdx;

    rcx=r8+rdx*4;
    rax=rax<<6;
    rcx=rcx-rax;
    rax=r8
    rax=_lrotl (rax, rcx&0xFF); // rotate left
    return rax;
};
```

Next step:

```
uint64_t f(uint64_t input)
{
    uint64_t rax, rbx, rcx, rdx, r8;

    ecx=input;

    rdx=0x5D7E0D1F2E0F1F84;
    rax=rcx;
```

80.1. HAND DECOMPILING

```
rax*=rdx;
rdx=0x388D76AEE8CB1500;
rax=_lrotr(rax, rax&0xF); // rotate right
rax^=rdx;
rdx=0xD2E9EE7E83C4285B;
rax=_lrotl(rax, rax&0xF); // rotate left
r8=rax+rdx;

rdx=0x8888888888888889;
rax=r8;
rax*=rdx;
// RDX here is a high part of multiplication result
rdx=rdx>>5;
// RDX here is division result!
rax=rdx;

rcx=(r8+rdx*4)-(rax<<6);
rax=r8
rax=_lrotl (rax, rcx&0xFF); // rotate left
return rax;
};
```

We can spot the division using multiplication ([43 on page 487](#)). Indeed, let's calculate the divider in Wolfram Mathematica:

Listing 80.1: Wolfram Mathematica

```
In[1]:=N[2^(64 + 5)/16^^8888888888888889]
Out[1]:=60.
```

We get this:

```
uint64_t f(uint64_t input)
{
    uint64_t rax, rbx, rcx, rdx, r8;

    ecx=input;

    rdx=0x5D7E0D1F2E0F1F84;
    rax=rcx;
    rax*=rdx;
    rdx=0x388D76AEE8CB1500;
    rax=_lrotr(rax, rax&0xF); // rotate right
    rax^=rdx;
    rdx=0xD2E9EE7E83C4285B;
    rax=_lrotl(rax, rax&0xF); // rotate left
    r8=rax+rdx;

    rax=rdx=r8/60;

    rcx=(r8+rax*4)-(rax*64);
    rax=r8
    rax=_lrotl (rax, rcx&0xFF); // rotate left
    return rax;
};
```

One more step:

```
uint64_t f(uint64_t input)
{
    uint64_t rax, rbx, rcx, rdx, r8;

    rax=input;
    rax*=0x5D7E0D1F2E0F1F84;
    rax=_lrotr(rax, rax&0xF); // rotate right
    rax^=0x388D76AEE8CB1500;
    rax=_lrotl(rax, rax&0xF); // rotate left
    r8=rax+0xD2E9EE7E83C4285B;

    rcx=r8-(r8/60)*60;
    rax=r8
```

80.2. NOW LET'S USE THE Z3 SMT SOLVER

```
    rax=_lrotl (rax, rcx&0xFF); // rotate left
    return rax;
};
```

By simple reducing, we finally see that it's calculating the remainder, not the quotient:

```
uint64_t f(uint64_t input)
{
    uint64_t rax, rbx, rcx, rdx, r8;

    rax=input;
    rax*=0x5D7E0D1F2E0F1F84;
    rax=_lrotr(rax, rax&0xF); // rotate right
    rax^=0x388D76AEE8CB1500;
    rax=_lrotl(rax, rax&0xF); // rotate left
    r8=rax+0xD2E9EE7E83C4285B;

    return _lrotl (r8, r8 % 60); // rotate left
};
```

We end up with this fancy formatted source-code:

```
#include <stdio.h>
#include <stdint.h>
#include <stdbool.h>
#include <string.h>
#include <intrin.h>

#define C1 0x5D7E0D1F2E0F1F84
#define C2 0x388D76AEE8CB1500
#define C3 0xD2E9EE7E83C4285B

uint64_t hash(uint64_t v)
{
    v*=C1;
    v=_lrotr(v, v&0xF); // rotate right
    v^=C2;
    v=_lrotl(v, v&0xF); // rotate left
    v+=C3;
    v=_lrotl(v, v % 60); // rotate left
    return v;
};

int main()
{
    printf ("%llu\n", hash(...));
};
```

Since we are not cryptoanalysts we can't find an easy way to generate the input value for some specific output value. The rotate instruction's coefficients look frightening—it's a warranty that the function is not bijective, it has collisions, or, speaking more simply, many inputs may be possible for one output.

Brute-force is not solution because values are 64-bit ones, that's beyond reality.

80.2 Now let's use the Z3 SMT solver

Still, without any special cryptographic knowledge, we may try to break this algorithm using the excellent SMT solver from Microsoft Research named Z3¹. It is in fact theorem prover, but we are going to use it as SMT solver. Simply said, we can think about it as a system capable of solving huge equation systems.

Here is the Python source code:

```
1 from z3 import *
2
3 C1=0x5D7E0D1F2E0F1F84
4 C2=0x388D76AEE8CB1500
```

¹<http://go.yurichev.com/17314>

80.2. NOW LET'S USE THE Z3 SMT SOLVER

```

5 C3=0xD2E9EE7E83C4285B
6
7 inp, i1, i2, i3, i4, i5, i6, outp = BitVecs('inp i1 i2 i3 i4 i5 i6 outp', 64)
8
9 s = Solver()
10 s.add(i1==inp*C1)
11 s.add(i2==RotateRight (i1, i1 & 0xF))
12 s.add(i3==i2 ^ C2)
13 s.add(i4==RotateLeft(i3, i3 & 0xF))
14 s.add(i5==i4 + C3)
15 s.add(outp==RotateLeft (i5, URem(i5, 60)))
16
17 s.add(outp==10816636949158156260)
18
19 print s.check()
20 m=s.model()
21 print m
22 print (" inp=0x%X" % m[inp].as_long())
23 print ("outp=0x%X" % m[outp].as_long())

```

This is going to be our first solver.

We see the variable definitions on line 7. These are just 64-bit variables. `i1..i6` are intermediate variables, representing the values in the registers between instruction executions.

Then we add the so-called constraints on lines 10..15. The last constraint at 17 is the most important one: we are going to try to find an input value for which our algorithm will produce 10816636949158156260.

Essentially, the SMT-solver searches for (any) values that satisfies all constraints.

`RotateRight`, `RotateLeft`, `URem` – are functions from the Z3 Python [API](#), not related to Python [PL](#).

Then we run it:

```

...>python.exe 1.py
sat
[i1 = 3959740824832824396,
 i3 = 8957124831728646493,
 i5 = 10816636949158156260,
 inp = 1364123924608584563,
 outp = 10816636949158156260,
 i4 = 14065440378185297801,
 i2 = 4954926323707358301]
inp=0x12EE577B63E80B73
outp=0x961C69FF0AEFD7E4

```

“sat” mean “satisfiable”, i.e., the solver was able to found at least one solution. The solution is printed in the square brackets. The last two lines are the input/output pair in hexadecimal form. Yes, indeed, if we run our function with `0x12EE577B63E80B73` as input, the algorithm will produce the value we were looking for.

But, as we noticed before, the function we work with is not bijective, so there may be other correct input values. The Z3 SMT solver is not capable of producing more than one result, but let's hack our example slightly, by adding line 19, which implies “look for any other results than this”:

```

1 from z3 import *
2
3 C1=0x5D7E0D1F2E0F1F84
4 C2=0x388D76AEE8CB1500
5 C3=0xD2E9EE7E83C4285B
6
7 inp, i1, i2, i3, i4, i5, i6, outp = BitVecs('inp i1 i2 i3 i4 i5 i6 outp', 64)
8
9 s = Solver()
10 s.add(i1==inp*C1)
11 s.add(i2==RotateRight (i1, i1 & 0xF))
12 s.add(i3==i2 ^ C2)
13 s.add(i4==RotateLeft(i3, i3 & 0xF))
14 s.add(i5==i4 + C3)
15 s.add(outp==RotateLeft (i5, URem(i5, 60)))
16
17 s.add(outp==10816636949158156260)

```

80.2. NOW LET'S USE THE Z3 SMT SOLVER

```

18 s.add(inp!=0x12EE577B63E80B73)
19
20 print s.check()
21 m=s.model()
22 print m
23 print (" inp=%0X" % m[inp].as_long())
24 print ("outp=%0X" % m[outp].as_long())
25

```

Indeed, it finds another correct result:

```

...>python.exe 2.py
sat
[i1 = 3959740824832824396,
 i3 = 8957124831728646493,
 i5 = 10816636949158156260,
 inp = 10587495961463360371,
 outp = 10816636949158156260,
 i4 = 14065440378185297801,
 i2 = 4954926323707358301]
inp=0x92EE577B63E80B73
outp=0x961C69FF0AEFD7E4

```

This can be automated. Each found result can be added as a constraint and then the next result will be searched for. Here is a slightly more sophisticated example:

```

1 from z3 import *
2
3 C1=0x5D7E0D1F2E0F1F84
4 C2=0x388D76AEE8CB1500
5 C3=0xD2E9EE7E83C4285B
6
7 inp, i1, i2, i3, i4, i5, i6, outp = BitVecs('inp i1 i2 i3 i4 i5 i6 outp', 64)
8
9 s = Solver()
10 s.add(i1==inp*C1)
11 s.add(i2==RotateRight (i1, i1 & 0xF))
12 s.add(i3==i2 ^ C2)
13 s.add(i4==RotateLeft(i3, i3 & 0xF))
14 s.add(i5==i4 + C3)
15 s.add(outp==RotateLeft (i5, URem(i5, 60)))
16
17 s.add(outp==10816636949158156260)
18
19 # copypasted from http://stackoverflow.com/questions/11867611/z3py-checking-all-solutions-for-a-
   ↴ equation
20 result=[]
21 while True:
22     if s.check() == sat:
23         m = s.model()
24         print m[inp]
25         result.append(m)
26         # Create a new constraint the blocks the current model
27         block = []
28         for d in m:
29             # d is a declaration
30             if d.arity() > 0:
31                 raise Z3Exception("uninterpreted functions are not supported")
32             # create a constant from declaration
33             c=d()
34             if is_array(c) or c.sort().kind() == Z3_UNINTERPRETED_SORT:
35                 raise Z3Exception("arrays and uninterpreted sorts are not supported")
36             block.append(c != m[d])
37         s.add(Or(block))
38     else:
39         print "results total=",len(result)
40         break

```

We got:

80.2. NOW LET'S USE THE Z3 SMT SOLVER

```
1364123924608584563
1234567890
9223372038089343698
4611686019661955794
13835058056516731602
3096040143925676201
12319412180780452009
7707726162353064105
16931098199207839913
1906652839273745429
11130024876128521237
15741710894555909141
651833885770113333
5975809943035972467
15199181979890748275
10587495961463360371
results total= 16
```

So there are 16 correct input values for `0x92EE577B63E80B73` as a result.

The second is 1234567890—it is indeed the value which was used originally while preparing this example.

Let's also try to research our algorithm a bit more. Acting on a sadistic whim, let's find if there are any possible input/output pairs in which the lower 32-bit parts are equal to each other?

Let's remove the `outp` constraint and add another, at line 17:

```
1 from z3 import *
2
3 C1=0x5D7E0D1F2E0F1F84
4 C2=0x388D76AEE8CB1500
5 C3=0xD2E9EE7E83C4285B
6
7 inp, i1, i2, i3, i4, i5, i6, outp = BitVecs('inp i1 i2 i3 i4 i5 i6 outp', 64)
8
9 s = Solver()
10 s.add(i1==inp*C1)
11 s.add(i2==RotateRight (i1, i1 & 0xF))
12 s.add(i3==i2 ^ C2)
13 s.add(i4==RotateLeft(i3, i3 & 0xF))
14 s.add(i5==i4 + C3)
15 s.add(outp==RotateLeft (i5, URem(i5, 60)))
16
17 s.add(outp & 0xFFFFFFFF == inp & 0xFFFFFFFF)
18
19 print s.check()
20 m=s.model()
21 print m
22 print (" inp=0x%X" % m[inp].as_long())
23 print ("outp=0x%X" % m[outp].as_long())
```

It is indeed so:

```
sat
[i1 = 14869545517796235860,
 i3 = 8388171335828825253,
 i5 = 6918262285561543945,
 inp = 1370377541658871093,
 outp = 14543180351754208565,
 i4 = 10167065714588685486,
 i2 = 5541032613289652645]
inp=0x13048F1D12C00535
outp=0xC9D3C17A12C00535
```

Let's be more sadistic and add another constraint: last the 16 bits must be `0x1234`:

```
1 from z3 import *
2
3 C1=0x5D7E0D1F2E0F1F84
4 C2=0x388D76AEE8CB1500
```

80.2. NOW LET'S USE THE Z3 SMT SOLVER

```
5 C3=0xD2E9EE7E83C4285B
6
7 inp, i1, i2, i3, i4, i5, i6, outp = BitVecs('inp i1 i2 i3 i4 i5 i6 outp', 64)
8
9 s = Solver()
10 s.add(i1==inp*C1)
11 s.add(i2==RotateRight (i1, i1 & 0xF))
12 s.add(i3==i2 ^ C2)
13 s.add(i4==RotateLeft(i3, i3 & 0xF))
14 s.add(i5==i4 + C3)
15 s.add(outp==RotateLeft (i5, URem(i5, 60)))
16
17 s.add(outp & 0xFFFFFFFF == inp & 0xFFFFFFFF)
18 s.add(outp & 0xFFFF == 0x1234)
19
20 print s.check()
21 m=s.model()
22 print m
23 print (" inp=0x%X" % m[inp].as_long())
24 print ("outp=0x%X" % m[outp].as_long())
```

Oh yes, this possible as well:

```
sat
[i1 = 2834222860503985872,
 i3 = 2294680776671411152,
 i5 = 17492621421353821227,
 inp = 461881484695179828,
 outp = 419247225543463476,
 i4 = 2294680776671411152,
 i2 = 2834222860503985872]
inp=0x668EEC35F961234
outp=0x5D177215F961234
```

Z3 works very fast and it implies that the algorithm is weak, it is not cryptographic at all (like the most of the amateur cryptography).

Is it possible to tackle real cryptography by these methods? Real algorithms like AES, RSA, etc, can also be represented as huge system of equations, but these are so huge that they are impossible to work with on computers, now or in the near future. Of course, cryptographers are aware of this.

Summarizing, when dealing with amateur crypto, it's a very good idea to try a SMT/SAT solver (like Z3).

Another article about Z3 is [[Yur12](#)].

Chapter 81

Dongles

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 that is not present here, you can read here: [[Yur12](#)].

81.1 Example #1: MacOS Classic and PowerPC

Here is an example of a program for MacOS Classic ¹, 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:

```
...
seg000:000C87FC 38 60 00 01      li      %r3, 1
seg000:000C8800 48 03 93 41      bl      check1
seg000:000C8804 60 00 00 00      nop
seg000:000C8808 54 60 06 3F      clrlwi. %r0, %r3, 24
seg000:000C880C 40 82 00 40      bne    OK
seg000:000C8810 80 62 9F D8      lwz    %r3, TC_aInvalidSecurityDevice
...
...
```

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 [[SK95](#)] we will find 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 [[IBM00](#)] 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 ([16.1.1 on page 201](#)), but it also sets the flags, so `BNE` can check them afterwards.

Let’s take a look into the `check1()` function:

```
seg000:00101B40          check1: # CODE XREF: seg000:00063E7Cp
seg000:00101B40          # sub_64070+160p ...
seg000:00101B40
seg000:00101B40          .set arg_8, 8
```

¹pre-UNIX MacOS

81.1. EXAMPLE #1: MACOS CLASSIC AND POWERPC

```

seg000:00101B40      mflr    %r0
seg000:00101B40 7C 08 02 A6      stw     %r0, arg_8(%sp)
seg000:00101B44 90 01 00 08      stwu   %sp, -0x40(%sp)
seg000:00101B48 94 21 FF C0      bl     check2
seg000:00101B4C 48 01 6B 39      nop
seg000:00101B50 60 00 00 00      lwz     %r0, 0x40+arg_8(%sp)
seg000:00101B54 80 01 00 48      addi   %sp, %sp, 0x40
seg000:00101B58 38 21 00 40      mtlr   %r0
seg000:00101B5C 7C 08 03 A6      blr
seg000:00101B60 4E 80 00 20      # End of function check1

```

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.

[BLR](#)² 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:

```

seg000:00118684          check2: # CODE XREF: check1+Cp
seg000:00118684
seg000:00118684          .set var_18, -0x18
seg000:00118684          .set var_C, -0xC
seg000:00118684          .set var_8, -8
seg000:00118684          .set var_4, -4
seg000:00118684          .set arg_8, 8
seg000:00118684
seg000:00118684 93 E1 FF FC  stw     %r31, var_4(%sp)
seg000:00118688 7C 08 02 A6  mflr   %r0
seg000:0011868C 83 E2 95 A8  lwz     %r31, off_1485E8 # dword_24B704
seg000:00118690          .using dword_24B704, %r31
seg000:00118690 93 C1 FF F8  stw     %r30, var_8(%sp)
seg000:00118694 93 A1 FF F4  stw     %r29, var_C(%sp)
seg000:00118698 7C 7D 1B 78  mr      %r29, %r3
seg000:0011869C 90 01 00 08  stw     %r0, arg_8(%sp)
seg000:001186A0 54 60 06 3E  clrlwi %r0, %r3, 24
seg000:001186A4 28 00 00 01  cmplwi %r0, 1
seg000:001186A8 94 21 FF B0  stwu   %sp, -0x50(%sp)
seg000:001186AC 40 82 00 0C  bne    loc_1186B8
seg000:001186B0 38 60 00 01  li     %r3, 1
seg000:001186B4 48 00 00 6C  b     exit
seg000:001186B8
seg000:001186B8          loc_1186B8: # CODE XREF: check2+28j
seg000:001186B8 48 00 03 D5  bl     sub_118A8C
seg000:001186BC 60 00 00 00  nop
seg000:001186C0 3B C0 00 00  li     %r30, 0
seg000:001186C4
seg000:001186C4          skip:    # CODE XREF: check2+94j
seg000:001186C4 57 C0 06 3F  clrlwi %r0, %r30, 24
seg000:001186C8 41 82 00 18  beq    loc_1186E0
seg000:001186CC 38 61 00 38  addi   %r3, %sp, 0x50+var_18
seg000:001186D0 80 9F 00 00  lwz    %r4, dword_24B704
seg000:001186D4 48 00 C0 55  bl     .RBETHODNEXT
seg000:001186D8 60 00 00 00  nop
seg000:001186DC 48 00 00 1C  b     loc_1186F8
seg000:001186E0
seg000:001186E0          loc_1186E0: # CODE XREF: check2+44j
seg000:001186E0 80 BF 00 00  lwz    %r5, dword_24B704
seg000:001186E4 38 81 00 38  addi   %r4, %sp, 0x50+var_18
seg000:001186E8 38 60 08 C2  li     %r3, 0x1234
seg000:001186EC 48 00 BF 99  bl     .RBETHODFIRST
seg000:001186F0 60 00 00 00  nop
seg000:001186F4 3B C0 00 01  li     %r30, 1
seg000:001186F8
seg000:001186F8          loc_1186F8: # CODE XREF: check2+58j
seg000:001186F8 54 60 04 3F  clrlwi %r0, %r3, 16

```

²(PowerPC) Branch to Link Register

81.1. EXAMPLE #1: MACOS CLASSIC AND POWERPC

```

seg000:001186FC 41 82 00 0C    beq      must_jump
seg000:00118700 38 60 00 00    li       %r3, 0          # error
seg000:00118704 48 00 00 1C    b        exit
seg000:00118708
seg000:00118708           must_jump: # CODE XREF: check2+78j
seg000:00118708 7F A3 EB 78    mr       %r3, %r29
seg000:0011870C 48 00 00 31    bl       check3
seg000:00118710 60 00 00 00    nop
seg000:00118714 54 60 06 3F    clrlwi. %r0, %r3, 24
seg000:00118718 41 82 FF AC    beq      skip
seg000:0011871C 38 60 00 01    li       %r3, 1
seg000:00118720
seg000:00118720           exit:   # CODE XREF: check2+30j
seg000:00118720           # check2+80j
seg000:00118720 80 01 00 58    lwz     %r0, 0x50+arg_8(%sp)
seg000:00118724 38 21 00 50    addi    %sp, %sp, 0x50
seg000:00118728 83 E1 FF FC    lwz     %r31, var_4(%sp)
seg000:0011872C 7C 08 03 A6    mtlr    %r0
seg000:00118730 83 C1 FF F8    lwz     %r30, var_8(%sp)
seg000:00118734 83 A1 FF F4    lwz     %r29, var_C(%sp)
seg000:00118738 4E 80 00 20    blr
seg000:00118738           # End of function check2

```

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? ([71.2.7 on page 716](#))), 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., 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()`:

```

seg000:0011873C           check3: # CODE XREF: check2+88p
seg000:0011873C
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
seg000:0011873C 93 E1 FF FC    stw     %r31, var_4(%sp)
seg000:00118740 7C 08 02 A6    mflr    %r0
seg000:00118744 38 A0 00 00    li      %r5, 0
seg000:00118748 93 C1 FF F8    stw     %r30, var_8(%sp)
seg000:0011874C 83 C2 95 A8    lwz     %r30, off_1485E8 # dword_24B704
seg000:00118750
seg000:00118750           .using dword_24B704, %r30
seg000:00118750           stw     %r29, var_C(%sp)
seg000:00118754 3B A3 00 00    addi    %r29, %r3, 0
seg000:00118758 38 60 00 00    li      %r3, 0
seg000:0011875C 90 01 00 08    stw     %r0, arg_8(%sp)
seg000:00118760 94 21 FF B0    stwu   %sp, -0x50(%sp)

```

81.1. EXAMPLE #1: MACOS CLASSIC AND POWERPC

```

seg000:00118764 80 DE 00 00    lwz      %r6, dword_24B704
seg000:00118768 38 81 00 38    addi     %r4, %sp, 0x50+var_18
seg000:0011876C 48 00 C0 5D    bl       .RBEREAD
seg000:00118770 60 00 00 00    nop
seg000:00118774 54 60 04 3F    clrlwi. %r0, %r3, 16
seg000:00118778 41 82 00 0C    beq     loc_118784
seg000:0011877C 38 60 00 00    li      %r3, 0
seg000:00118780 48 00 02 F0    b       exit
seg000:00118784
seg000:00118784          loc_118784: # CODE XREF: check3+3Cj
seg000:00118784 A0 01 00 38    lhz      %r0, 0x50+var_18(%sp)
seg000:00118788 28 00 04 B2    cmplwi  %r0, 0x1100
seg000:0011878C 41 82 00 0C    beq     loc_118798
seg000:00118790 38 60 00 00    li      %r3, 0
seg000:00118794 48 00 02 DC    b       exit
seg000:00118798
seg000:00118798          loc_118798: # CODE XREF: check3+50j
seg000:00118798 80 DE 00 00    lwz      %r6, dword_24B704
seg000:0011879C 38 81 00 38    addi     %r4, %sp, 0x50+var_18
seg000:001187A0 38 60 00 01    li      %r3, 1
seg000:001187A4 38 A0 00 00    li      %r5, 0
seg000:001187A8 48 00 C0 21    bl       .RBEREAD
seg000:001187AC 60 00 00 00    nop
seg000:001187B0 54 60 04 3F    clrlwi. %r0, %r3, 16
seg000:001187B4 41 82 00 0C    beq     loc_1187C0
seg000:001187B8 38 60 00 00    li      %r3, 0
seg000:001187BC 48 00 02 B4    b       exit
seg000:001187C0
seg000:001187C0          loc_1187C0: # CODE XREF: check3+78j
seg000:001187C0 A0 01 00 38    lhz      %r0, 0x50+var_18(%sp)
seg000:001187C4 28 00 06 4B    cmplwi  %r0, 0x09AB
seg000:001187C8 41 82 00 0C    beq     loc_1187D4
seg000:001187CC 38 60 00 00    li      %r3, 0
seg000:001187D0 48 00 02 A0    b       exit
seg000:001187D4
seg000:001187D4          loc_1187D4: # CODE XREF: check3+8Cj
seg000:001187D4 4B F9 F3 D9    bl       sub_B7BAC
seg000:001187D8 60 00 00 00    nop
seg000:001187DC 54 60 06 3E    clrlwi  %r0, %r3, 24
seg000:001187E0 2C 00 00 05    cmpwi   %r0, 5
seg000:001187E4 41 82 01 00    beq     loc_1188E4
seg000:001187E8 40 80 00 10    bge     loc_1187F8
seg000:001187EC 2C 00 00 04    cmpwi   %r0, 4
seg000:001187F0 40 80 00 58    bge     loc_118848
seg000:001187F4 48 00 01 8C    b       loc_118980
seg000:001187F8
seg000:001187F8          loc_1187F8: # CODE XREF: check3+ACj
seg000:001187F8 2C 00 00 0B    cmpwi   %r0, 0xB
seg000:001187FC 41 82 00 08    beq     loc_118804
seg000:00118800 48 00 01 80    b       loc_118980
seg000:00118804
seg000:00118804          loc_118804: # CODE XREF: check3+C0j
seg000:00118804 80 DE 00 00    lwz      %r6, dword_24B704
seg000:00118808 38 81 00 38    addi     %r4, %sp, 0x50+var_18
seg000:0011880C 38 60 00 08    li      %r3, 8
seg000:00118810 38 A0 00 00    li      %r5, 0
seg000:00118814 48 00 BF B5    bl       .RBEREAD
seg000:00118818 60 00 00 00    nop
seg000:0011881C 54 60 04 3F    clrlwi. %r0, %r3, 16
seg000:00118820 41 82 00 0C    beq     loc_11882C
seg000:00118824 38 60 00 00    li      %r3, 0
seg000:00118828 48 00 02 48    b       exit
seg000:0011882C
seg000:0011882C          loc_11882C: # CODE XREF: check3+E4j
seg000:0011882C A0 01 00 38    lhz      %r0, 0x50+var_18(%sp)
seg000:00118830 28 00 11 30    cmplwi  %r0, 0xFEAO
seg000:00118834 41 82 00 0C    beq     loc_118840
seg000:00118838 38 60 00 00    li      %r3, 0
seg000:0011883C 48 00 02 34    b       exit
seg000:00118840

```

81.1. EXAMPLE #1: MACOS CLASSIC AND POWERPC

```

seg000:00118840          loc_118840: # CODE XREF: check3+F8j
seg000:00118840 38 60 00 01    li      %r3, 1
seg000:00118844 48 00 02 2C    b       exit
seg000:00118848          loc_118848: # CODE XREF: check3+B4j
seg000:00118848 80 DE 00 00    lwz      %r6, dword_24B704
seg000:0011884C 38 81 00 38    addi     %r4, %sp, 0x50+var_18
seg000:00118850 38 60 00 0A    li      %r3, 0xA
seg000:00118854 38 A0 00 00    li      %r5, 0
seg000:00118858 48 00 BF 71    bl      .RBEREAD
seg000:0011885C 60 00 00 00    nop
seg000:00118860 54 60 04 3F    clrlwi. %r0, %r3, 16
seg000:00118864 41 82 00 0C    beq     loc_118870
seg000:00118868 38 60 00 00    li      %r3, 0
seg000:0011886C 48 00 02 04    b       exit
seg000:00118870          loc_118870: # CODE XREF: check3+128j
seg000:00118870 A0 01 00 38    lhz      %r0, 0x50+var_18(%sp)
seg000:00118874 28 00 03 F3    cmplwi  %r0, 0xA6E1
seg000:00118878 41 82 00 0C    beq     loc_118884
seg000:0011887C 38 60 00 00    li      %r3, 0
seg000:00118880 48 00 01 F0    b       exit
seg000:00118884          loc_118884: # CODE XREF: check3+13Cj
seg000:00118884 57 BF 06 3E    clrlwi  %r31, %r29, 24
seg000:00118888 28 1F 00 02    cmplwi  %r31, 2
seg000:0011888C 40 82 00 0C    bne     loc_118898
seg000:00118890 38 60 00 01    li      %r3, 1
seg000:00118894 48 00 01 DC    b       exit
seg000:00118898          loc_118898: # CODE XREF: check3+150j
seg000:00118898 80 DE 00 00    lwz      %r6, dword_24B704
seg000:0011889C 38 81 00 38    addi     %r4, %sp, 0x50+var_18
seg000:001188A0 38 60 00 0B    li      %r3, 0xB
seg000:001188A4 38 A0 00 00    li      %r5, 0
seg000:001188A8 48 00 BF 21    bl      .RBEREAD
seg000:001188AC 60 00 00 00    nop
seg000:001188B0 54 60 04 3F    clrlwi. %r0, %r3, 16
seg000:001188B4 41 82 00 0C    beq     loc_1188C0
seg000:001188B8 38 60 00 00    li      %r3, 0
seg000:001188BC 48 00 01 B4    b       exit
seg000:001188C0          loc_1188C0: # CODE XREF: check3+178j
seg000:001188C0 A0 01 00 38    lhz      %r0, 0x50+var_18(%sp)
seg000:001188C4 28 00 23 1C    cmplwi  %r0, 0x1C20
seg000:001188C8 41 82 00 0C    beq     loc_1188D4
seg000:001188CC 38 60 00 00    li      %r3, 0
seg000:001188D0 48 00 01 A0    b       exit
seg000:001188D4          loc_1188D4: # CODE XREF: check3+18Cj
seg000:001188D4 28 1F 00 03    cmplwi  %r31, 3
seg000:001188D8 40 82 01 94    bne     error
seg000:001188DC 38 60 00 01    li      %r3, 1
seg000:001188E0 48 00 01 90    b       exit
seg000:001188E4          loc_1188E4: # CODE XREF: check3+A8j
seg000:001188E4 80 DE 00 00    lwz      %r6, dword_24B704
seg000:001188E8 38 81 00 38    addi     %r4, %sp, 0x50+var_18
seg000:001188EC 38 60 00 0C    li      %r3, 0xC
seg000:001188F0 38 A0 00 00    li      %r5, 0
seg000:001188F4 48 00 BE D5    bl      .RBEREAD
seg000:001188F8 60 00 00 00    nop
seg000:001188FC 54 60 04 3F    clrlwi. %r0, %r3, 16
seg000:00118900 41 82 00 0C    beq     loc_11890C
seg000:00118904 38 60 00 00    li      %r3, 0
seg000:00118908 48 00 01 68    b       exit
seg000:0011890C          loc_11890C: # CODE XREF: check3+1C4j
seg000:0011890C A0 01 00 38    lhz      %r0, 0x50+var_18(%sp)
seg000:00118910 28 00 1F 40    cmplwi  %r0, 0x40FF

```

81.1. EXAMPLE #1: MACOS CLASSIC AND POWERPC

```

seg000:00118914 41 82 00 0C    beq      loc_118920
seg000:00118918 38 60 00 00    li       %r3, 0
seg000:0011891C 48 00 01 54    b        exit
seg000:00118920
seg000:00118920          loc_118920: # CODE XREF: check3+1D8j
seg000:00118920 57 BF 06 3E    clrlwi   %r31, %r29, 24
seg000:00118924 28 1F 00 02    cmplwi   %r31, 2
seg000:00118928 40 82 00 0C    bne     loc_118934
seg000:0011892C 38 60 00 01    li       %r3, 1
seg000:00118930 48 00 01 40    b        exit
seg000:00118934
seg000:00118934          loc_118934: # CODE XREF: check3+1ECj
seg000:00118934 80 DE 00 00    lwz      %r6, dword_24B704
seg000:00118938 38 81 00 38    addi    %r4, %sp, 0x50+var_18
seg000:0011893C 38 60 00 0D    li       %r3, 0xD
seg000:00118940 38 A0 00 00    li       %r5, 0
seg000:00118944 48 00 BE 85    bl      .RBEREAD
seg000:00118948 60 00 00 00    nop
seg000:0011894C 54 60 04 3F    clrlwi. %r0, %r3, 16
seg000:00118950 41 82 00 0C    beq     loc_11895C
seg000:00118954 38 60 00 00    li       %r3, 0
seg000:00118958 48 00 01 18    b        exit
seg000:0011895C
seg000:0011895C          loc_11895C: # CODE XREF: check3+214j
seg000:0011895C A0 01 00 38    lhz      %r0, 0x50+var_18(%sp)
seg000:00118960 28 00 07 CF    cmplwi   %r0, 0xFC7
seg000:00118964 41 82 00 0C    beq     loc_118970
seg000:00118968 38 60 00 00    li       %r3, 0
seg000:0011896C 48 00 01 04    b        exit
seg000:00118970
seg000:00118970          loc_118970: # CODE XREF: check3+228j
seg000:00118970 28 1F 00 03    cmplwi   %r31, 3
seg000:00118974 40 82 00 F8    bne     error
seg000:00118978 38 60 00 01    li       %r3, 1
seg000:0011897C 48 00 00 F4    b        exit
seg000:00118980
seg000:00118980          loc_118980: # CODE XREF: check3+B8j
seg000:00118980          # check3+C4j
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 60 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 C8    b        exit
seg000:001189AC
seg000:001189AC          loc_1189AC: # CODE XREF: check3+264j
seg000:001189AC A0 01 00 38    lhz      %r0, 0x50+var_18(%sp)
seg000:001189B0 28 00 1D 6A    cmplwi   %r0, 0xAED0
seg000:001189B4 40 82 00 0C    bne     loc_1189C0
seg000:001189B8 3B E0 00 01    li       %r31, 1
seg000:001189BC 48 00 00 14    b        loc_1189D0
seg000:001189C0
seg000:001189C0          loc_1189C0: # CODE XREF: check3+278j
seg000:001189C0 28 00 18 28    cmplwi   %r0, 0x2818
seg000:001189C4 41 82 00 0C    beq     loc_1189D0
seg000:001189C8 38 60 00 00    li       %r3, 0
seg000:001189CC 48 00 00 A4    b        exit
seg000:001189D0
seg000:001189D0          loc_1189D0: # CODE XREF: check3+280j
seg000:001189D0          # check3+288j
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 57 E0 06 3F    clrlwi. %r0, %r31, 24
seg000:001189E0 41 82 00 10    beq     good2

```

81.1. EXAMPLE #1: MACOS CLASSIC AND POWERPC

```

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:   # CODE XREF: check3+2A4j
seg000:001189F0 38 60 00 01    li      %r3, 1
seg000:001189F4 48 00 00 7C    b       exit
seg000:001189F8
seg000:001189F8          loc_1189F8: # CODE XREF: check3+29Cj
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: # CODE XREF: check3+2D8j
seg000:00118A20 A0 01 00 38    lhz     %r0, 0x50+var_18(%sp)
seg000:00118A24 28 00 11 D3    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: # CODE XREF: check3+2ECj
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:   # CODE XREF: check3+2F4j
seg000:00118A44          # check3+2FCj
seg000:00118A44 57 A0 06 3E    clrlwi %r0, %r29, 24
seg000:00118A48 28 00 00 03    cmplwi %r0, 3
seg000:00118A4C 40 82 00 20    bne    error
seg000:00118A50 57 E0 06 3F    clrlwi. %r0, %r31, 24
seg000:00118A54 41 82 00 10    beq    good
seg000:00118A58 48 00 4B F5    bl      sub_11D64C
seg000:00118A5C 60 00 00 00    nop
seg000:00118A60 48 00 00 10    b       exit
seg000:00118A64
seg000:00118A64          good:   # CODE XREF: check3+318j
seg000:00118A64 38 60 00 01    li      %r3, 1
seg000:00118A68 48 00 00 08    b       exit
seg000:00118A6C
seg000:00118A6C          error:   # CODE XREF: check3+19Cj
seg000:00118A6C          # check3+238j ...
seg000:00118A6C 38 60 00 00    li      %r3, 0
seg000:00118A70
seg000:00118A70          exit:   # CODE XREF: check3+44j
seg000:00118A70          # check3+58j ...
seg000:00118A70 80 01 00 58    lwz     %r0, 0x50+arg_8(%sp)
seg000:00118A74 38 21 00 50    addi   %sp, %sp, 0x50
seg000:00118A78 83 E1 FF FC    lwz     %r31, var_4(%sp)
seg000:00118A7C 7C 08 03 A6    mtlr   %r0
seg000:00118A80 83 C1 FF F8    lwz     %r30, var_8(%sp)
seg000:00118A84 83 A1 FF F4    lwz     %r29, var_C(%sp)
seg000:00118A88 4E 80 00 20    blr
seg000:00118A88          # End of function check3

```

There are a lot of calls to `.RBEREAD()`. The function probably 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?

81.2. EXAMPLE #2: SCO OPENSERVER

Yes, indeed, by googling these function names it is easy to find the Sentinel Eve3 dongle manual!

Perhaps we don't even need 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 [IBM00].

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.

81.2 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
```

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:00022AE1      movsx  eax, al  
.text:00022AE4      cmp    eax, '3'  
.text:00022AE9      jz    loc_22B84  
.text:00022AEF      cmp    eax, '4'  
.text:00022AF4      jz    loc_22B94  
.text:00022AFA      cmp    eax, '5'  
.text:00022AFF      jnz   short loc_22B6B  
.text:00022B01      movsx  ebx, byte ptr [esi]  
.text:00022B04      sub    ebx, '0'  
.text:00022B07      mov    eax, 7
```

81.2. EXAMPLE #2: SCO OPENSERVER

```

.text:00022B0C      add    eax, ebx
.text:00022B0E      push   eax
.text:00022B0F      lea    eax, [ebp+var_44]
.text:00022B12      push   offset aDevS1D ; "/dev/s1%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, 0FFFFFFFh
.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
.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
.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 *
.text:00022B5D      call   _open
.text:00022B62      add    esp, 8
.text:00022B65      test  eax, eax
.text:00022B67      mov    [edi], eax
.text:00022B69      jge   short loc_22B78
.text:00022B6B
.text:00022B6B loc_22B6B: ; CODE XREF: SSQC+47j
.text:00022B6B      mov    eax, 0FFFFFFFh
.text:00022B70      pop    ebx
.text:00022B71      pop    esi
.text:00022B72      pop    edi
.text:00022B73      mov    esp, ebp
.text:00022B75      pop    ebp
.text:00022B76      retn
.text:00022B78
.text:00022B78 loc_22B78: ; CODE XREF: SSQC+B1j
.text:00022B78      pop    ebx
.text:00022B79      pop    esi
.text:00022B7A      pop    edi
.text:00022B7B      xor   eax, eax
.text:00022B7D      mov    esp, ebp
.text:00022B7F      pop    ebp
.text:00022B80      retn
.text:00022B84
.text:00022B84 loc_22B84: ; CODE XREF: SSQC+31j
.text:00022B84      mov    al, [esi]
.text:00022B86      pop    ebx
.text:00022B87      pop    esi
.text:00022B88      pop    edi
.text:00022B89      mov    ds:byte_407224, al
.text:00022B8E      mov    esp, ebp
.text:00022B90      xor   eax, eax
.text:00022B92      pop    ebp
.text:00022B93      retn
.text:00022B94
.text:00022B94 loc_22B94: ; CODE XREF: SSQC+3Cj
.text:00022B94      mov    al, [esi]
.text:00022B96      pop    ebx

```

81.2. EXAMPLE #2: SCO OPENSERVER

```
.text:00022B97      pop    esi
.text:00022B98      pop    edi
.text:00022B99      mov    ds:byte_407225, al
.text:00022B9E      mov    esp, ebp
.text:00022BA0      xor    eax, eax
.text:00022BA2      pop    ebp
.text:00022BA3      retn
.text:00022BA4
.loc_22BA4: ; CODE XREF: SSQC+1Fj
.text:00022BA4      movsx  eax, ds:byte_407225
.text:00022BAB      push   esi
.text:00022BAC      push   eax
.text:00022BAD      movsx  eax, ds:byte_407224
.text:00022BB4      push   eax
.text:00022BB5      lea    eax, [ebp+var_44]
.text:00022BB8      push   offset a46CCS    ; "46%c%c%s"
.text:00022BBD      push   eax
.text:00022BBE      call   nl_sprintf
.text:00022BC3      lea    eax, [ebp+var_44]
.text:00022BC6      push   eax
.text:00022BC7      call   strlen
.text:00022BCC      add    esp, 18h
.text:00022BCF      cmp    eax, 1Bh
.text:00022BD4      jle   short loc_22BDA
.text:00022BD6      mov    [ebp+var_29], 0
.text:00022BDA
.loc_22BDA: ; CODE XREF: SSQC+11Cj
.text:00022BDA      lea    eax, [ebp+var_44]
.text:00022BDD      push   eax
.text:00022BDE      call   strlen
.text:00022BE3      push   eax          ; unsigned int
.text:00022BE4      lea    eax, [ebp+var_44]
.text:00022BE7      push   eax          ; void *
.text:00022BE8      mov    eax, [edi]
.text:00022BEA      push   eax          ; int
.text:00022BEB      call   _write
.text:00022BF0      add    esp, 10h
.text:00022BF3      pop    ebx
.text:00022BF4      pop    esi
.text:00022BF5      pop    edi
.text:00022BF6      mov    esp, ebp
.text:00022BF8      pop    ebp
.text:00022BF9      retn
.text:00022BFA      db    0Eh dup(90h)
.text:00022BFA  SSQC  endp
```

Yes, indeed, the program needs to communicate with the driver somehow.

The only place where the `SSQC()` function is called is the [thunk function](#):

```
.text:0000DBE8      public SSQ
.text:0000DBE8  SSQ  proc near ; CODE XREF: sys_info+A9p
.text:0000DBE8          ; sys_info+CBp ...
.text:0000DBE8
.text:0000DBE8  arg_0 = dword ptr 8
.text:0000DBE8
.text:0000DBE8      push   ebp
.text:0000DBE9      mov    ebp, esp
.text:0000DBEB      mov    edx, [ebp+arg_0]
.text:0000DBEE      push   edx
.text:0000DBEF      call   SSQC
.text:0000DBF4      add    esp, 4
.text:0000DBF7      mov    esp, ebp
.text:0000DBF9      pop    ebp
.text:0000DBFA      retn
.text:0000DBFB  SSQ  endp
```

`SSQ()` is called from at least 2 functions.

One of these is:

81.2. EXAMPLE #2: SCO OPENSERVER

```

.data:0040169C _51_52_53      dd offset aPressAnyKeyT_0 ; DATA XREF: init_sys+392r
.data:0040169C                 ; sys_info+A1r
.data:0040169C                 ; "PRESS ANY KEY TO CONTINUE: "
.data:004016A0      dd offset a51      ; "51"
.data:004016A4      dd offset a52      ; "52"
.data:004016A8      dd offset a53      ; "53"

...
.data:004016B8 _3C_or_3E      dd offset a3c      ; DATA XREF: sys_info:loc_D67Br
.data:004016B8                 ; "3C"
.data:004016BC      dd offset a3e      ; "3E"

; these names we gave to the labels:
.data:004016C0 answers1      dd 6B05h      ; DATA XREF: sys_info+E7r
.data:004016C4                 dd 3D87h
.data:004016C8 answers2      dd 3Ch       ; DATA XREF: sys_info+F2r
.data:004016CC                 dd 832h
.data:004016D0 _C_and_B      db 0Ch       ; DATA XREF: sys_info+BAr
.data:004016D0                 ; sys_info:OKr
.data:004016D1 byte_4016D1    db 0Bh       ; DATA XREF: sys_info+FD
.data:004016D2                 db 0

...
.text:0000D652          xor     eax, eax
.text:0000D654          mov     al, ds:ctl_port
.text:0000D659          mov     ecx, _51_52_53[eax*4]
.text:0000D660          push    ecx
.text:0000D661          call    SSQ
.text:0000D666          add    esp, 4
.text:0000D669          cmp    eax, 0FFFFFFFh
.text:0000D66E          jz     short loc_D6D1
.text:0000D670          xor    ebx, ebx
.text:0000D672          mov    al, _C_and_B
.text:0000D677          test   al, al
.text:0000D679          jz     short loc_D6C0

.text:0000D67B loc_D67B: ; CODE XREF: sys_info+106j
.text:0000D67B          mov    eax, _3C_or_3E[ebx*4]
.text:0000D682          push   eax
.text:0000D683          call   SSQ
.text:0000D688          push   offset a4g      ; "4G"
.text:0000D68D          call   SSQ
.text:0000D692          push   offset a0123456789 ; "0123456789"
.text:0000D697          call   SSQ
.text:0000D69C          add    esp, 0Ch
.text:0000D69F          mov    edx, answers1[ebx*4]
.text:0000D6A6          cmp    eax, edx
.text:0000D6A8          jz     short OK
.text:0000D6AA          mov    ecx, answers2[ebx*4]
.text:0000D6B1          cmp    eax, ecx
.text:0000D6B3          jz     short OK
.text:0000D6B5          mov    al, byte_4016D1[ebx]
.text:0000D6BB          inc    ebx
.text:0000D6BC          test   al, al
.text:0000D6BE          jnz    short loc_D67B

.text:0000D6C0 loc_D6C0: ; CODE XREF: sys_info+C1j
.text:0000D6C0          inc    ds:ctl_port
.text:0000D6C6          xor    eax, eax
.text:0000D6C8          mov    al, ds:ctl_port
.text:0000D6CD          cmp    eax, edi
.text:0000D6CF          jle    short loc_D652
.text:0000D6D1 loc_D6D1: ; CODE XREF: sys_info+98j
.text:0000D6D1          ; sys_info+B6j
.text:0000D6D1          mov    edx, [ebp+var_8]
.text:0000D6D4          inc    edx

```

81.2. EXAMPLE #2: SCO OPENSERVER

```
.text:0000D6D5          mov     [ebp+var_8], edx
.text:0000D6D8          cmp     edx, 3
.text:0000D6DB          jle     loc_D641
.text:0000D6E1
.text:0000D6E1 loc_D6E1: ; CODE XREF: sys_info+16j
.text:0000D6E1           ; sys_info+51j ...
.text:0000D6E1           pop    ebx
.text:0000D6E2           pop    edi
.text:0000D6E3           mov    esp, ebp
.text:0000D6E5           pop    ebp
.text:0000D6E6           retn
.text:0000D6E8 OK:      ; CODE XREF: sys_info+F0j
.text:0000D6E8           ; sys_info+FBj
.text:0000D6E8           mov    al, _C_and_B[ebx]
.text:0000D6EE           pop    ebx
.text:0000D6EF           pop    edi
.text:0000D6F0           mov    ds:ctl_model, al
.text:0000D6F5           mov    esp, ebp
.text:0000D6F7           pop    ebp
.text:0000D6F8           retn
.text:0000D6F8 sys_info  endp
```

“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: [36 on page 456](#).

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 mistake³.

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 var_10  = byte ptr -10h
.text:0000D708 var_8   = dword ptr -8
.text:0000D708 var_2   = word ptr -2
.text:0000D708
.text:0000D708         push    ebp
.text:0000D709         mov     eax, ds:net_env
.text:0000D70E         mov     ebp, esp
.text:0000D710         sub    esp, 1Ch
.text:0000D713         test   eax, eax
.text:0000D715         jnz    short loc_D734
.text:0000D717         mov    al, ds:ctl_model
.text:0000D71C         test   al, al
.text:0000D71E         jnz    short loc_D77E
.text:0000D720         mov    [ebp+var_8], offset aIeCvulnvv0kgT_ ; "Ie-cvulnvV\\b0KG]T_"
.text:0000D727         mov    edx, 7
```

³What a strange feeling: to find bugs in such ancient software.

81.2. EXAMPLE #2: SCO OPENSERVER

```
.text:0000D72C        jmp     loc_D7E7
...
.text:0000D7E7 loc_D7E7: ; CODE XREF: prep_sys+24j
.text:0000D7E7          ; prep_sys+33j
.text:0000D7E7          push    edx
.text:0000D7E8          mov     edx, [ebp+var_8]
.text:0000D7EB          push    20h
.text:0000D7ED          push    edx
.text:0000D7EE          push    16h
.text:0000D7F0          call    err_warn
.text:0000D7F5          push    offset station_sem
.text:0000D7FA          call    ClosSem
.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 [xor-ing](#):

```
.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 var_54         = byte ptr -54h
.text:0000A43C arg_0          = dword ptr 8
.text:0000A43C arg_4          = dword ptr 0Ch
.text:0000A43C arg_8          = dword ptr 10h
.text:0000A43C arg_C          = dword ptr 14h
.text:0000A43C
.text:0000A43C              push    ebp
.text:0000A43D              mov     ebp, esp
.text:0000A43F              sub     esp, 54h
.text:0000A442              push    edi
.text:0000A443              mov     ecx, [ebp+arg_8]
.text:0000A446              xor     edi, edi
.text:0000A448              test   ecx, ecx
.text:0000A44A              push   esi
.text:0000A44B              jle    short loc_A466
.text:0000A44D              mov     esi, [ebp+arg_C] ; key
.text:0000A450              mov     edx, [ebp+arg_4] ; string
.text:0000A453
.text:0000A453 loc_A453:      ; CODE XREF: err_warn+28j
.text:0000A453              xor     eax, eax
.text:0000A455              mov     al, [edx+edi]
.text:0000A458              xor     eax, esi
.text:0000A45A              add     esi, 3
.text:0000A45D              inc     edi
.text:0000A45E              cmp     edi, ecx
.text:0000A460              mov     [ebp+edi+var_55], al
.text:0000A464              jl    short loc_A453
.text:0000A466
.text:0000A466 loc_A466:      ; CODE XREF: err_warn+Fj
.text:0000A466              mov     [ebp+edi+var_54], 0
.text:0000A46B              mov     eax, [ebp+arg_0]
.text:0000A46E              cmp     eax, 18h
.text:0000A473              jnz    short loc_A49C
.text:0000A475              lea     eax, [ebp+var_54]
.text:0000A478              push   eax
.text:0000A479              call   status_line
.text:0000A47E              add    esp, 4
.text:0000A481
.text:0000A481 loc_A481:      ; CODE XREF: err_warn+72j
.text:0000A481              push   50h
.text:0000A483              push   0
.text:0000A485              lea     eax, [ebp+var_54]
.text:0000A488              push   eax
.text:0000A489              call   memset
.text:0000A48E              call   pcv_refresh
.text:0000A493              add    esp, 0Ch
```

81.2. EXAMPLE #2: SCO OPENSERVER

```
.text:0000A496          pop    esi
.text:0000A497          pop    edi
.text:0000A498          mov    esp, ebp
.text:0000A49A          pop    ebp
.text:0000A49B          retn
.text:0000A49C loc_A49C:           ; CODE XREF: err_warn+37j
.text:0000A49C          push   0
.text:0000A49E          lea    eax, [ebp+var_54]
.text:0000A4A1          mov    edx, [ebp+arg_0]
.text:0000A4A4          push   edx
.text:0000A4A5          push   eax
.text:0000A4A6          call   pcv_lputs
.text:0000A4AB          add    esp, 0Ch
.text:0000A4AE          jmp    short loc_A481
.text:0000A4AE err_warn    endp
```

That's why we were unable to find the error messages in the executable files, because they are encrypted (which 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.

```
.text:0000DA55 loc_DA55:           ; CODE XREF: sync_sys+24Cj
.text:0000DA55          push   offset aOffln  ; "offln"
.text:0000DA5A          call   SSQ
.text:0000DA5F          add    esp, 4
.text:0000DA62          mov    dl, [ebx]
.text:0000DA64          mov    esi, eax
.text:0000DA66          cmp    dl, 0Bh
.text:0000DA69          jnz   short loc_DA83
.text:0000DA6B          cmp    esi, 0FE81h
.text:0000DA71          jz    OK
.text:0000DA77          cmp    esi, 0FFFFF8EFh
.text:0000DA7D          jz    OK
.text:0000DA83
.text:0000DA83 loc_DA83:           ; CODE XREF: sync_sys+201j
.text:0000DA83          mov    cl, [ebx]
.text:0000DA85          cmp    cl, 0Ch
.text:0000DA88          jnz   short loc_DA9F
.text:0000DA8A          cmp    esi, 12A9h
.text:0000DA90          jz    OK
.text:0000DA96          cmp    esi, 0FFFFFF5h
.text:0000DA99          jz    OK
.text:0000DA9F loc_DA9F:           ; CODE XREF: sync_sys+220j
.text:0000DA9F          mov    eax, [ebp+var_18]
.text:0000DAA2          test  eax, eax
.text:0000DAA4          jz    short loc_DAB0
.text:0000DAA6          push  24h
.text:0000DAA8          call   timer
.text:0000DAAD          add    esp, 4
.text:0000DAB0 loc_DAB0:           ; CODE XREF: sync_sys+23Cj
.text:0000DAB0          inc    edi
.text:0000DAB1          cmp    edi, 3
.text:0000DAB4          jle   short loc_DA55
.text:0000DAB6          mov    eax, ds:net_env
.text:0000DABB          test  eax, eax
.text:0000DABD          jz    short error
...
.text:0000DAF7 error:            ; CODE XREF: sync_sys+255j
.text:0000DAF7          ; sync_sys+274j ...
.text:0000DAF7          mov    [ebp+var_8], offset encrypted_error_message2
.text:0000DAFE          mov    [ebp+var_C], 17h ; decrypting key
.text:0000DB05          jmp    decrypt_end_print_message
```

81.2. EXAMPLE #2: SCO OPENSERVER

```
...
; this name we gave to label:
.text:0000D9B6 decrypt_end_print_message:           ; CODE XREF: sync_sys+29Dj
.text:0000D9B6                                         ; sync_sys+2ABj
.text:0000D9B6             mov     eax, [ebp+var_18]
.text:0000D9B9             test    eax, eax
.text:0000D9BB             jnz    short loc_D9FB
.text:0000D9BD             mov     edx, [ebp+var_C] ; key
.text:0000D9C0             mov     ecx, [ebp+var_8] ; string
.text:0000D9C3             push    edx
.text:0000D9C4             push    20h
.text:0000D9C6             push    ecx
.text:0000D9C7             push    18h
.text:0000D9C9             call    err_warn
.text:0000D9CE             push    0Fh
.text:0000D9D0             push    190h
.text:0000D9D5             call    sound
.text:0000D9DA             mov     [ebp+var_18], 1
.text:0000D9E1             add    esp, 18h
.text:0000D9E4             call    pcv_kbhit
.text:0000D9E9             test   eax, eax
.text:0000D9EB             jz    short loc_D9FB

...
; this name we gave to label:
.data:00401736 encrypted_error_message2 db 74h, 72h, 78h, 43h, 48h, 6, 5Ah, 49h, 4Ch, 2 dup(47h
    )
.data:00401736                                         db 51h, 4Fh, 47h, 61h, 20h, 22h, 3Ch, 24h, 33h, 36h, 76h
.data:00401736                                         db 3Ah, 33h, 31h, 0Ch, 0, 0Bh, 1Fh, 7, 1Eh, 1Ah
```

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.

81.2.1 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 81.1: Decryption function

```
.text:0000A44D             mov     esi, [ebp+arg_C] ; key
.text:0000A450             mov     edx, [ebp+arg_4] ; string
.text:0000A453 loc_A453:      xor    eax, eax
.text:0000A453             mov     al, [edx+edi] ; load encrypted byte
.text:0000A455             xor    eax, esi      ; decrypt it
.text:0000A458             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:

```
.text:0000DAF7 error:          ; CODE XREF: sync_sys+255j
.text:0000DAF7                 ; sync_sys+274j ...
.text:0000DAF7             mov    [ebp+var_8], offset encrypted_error_message2
.text:0000DAFE             mov    [ebp+var_C], 17h ; decrypting key
.text:0000DB05             jmp    decrypt_end_print_message

...
; this name we gave to label manually:
.text:0000D9B6 decrypt_end_print_message:           ; CODE XREF: sync_sys+29Dj
```

81.2. EXAMPLE #2: SCO OPENSERVER

```
.text:0000D9B6 ; sync_sys+2ABj
.text:0000D9B6     mov    eax, [ebp+var_18]
.text:0000D9B9     test   eax, eax
.text:0000D9BB     jnz    short loc_D9FB
.text:0000D9BD     mov    edx, [ebp+var_C] ; key
.text:0000D9C0     mov    ecx, [ebp+var_8] ; string
.text:0000D9C3     push   edx
.text:0000D9C4     push   20h
.text:0000D9C6     push   ecx
.text:0000D9C7     push   18h
.text:0000D9C9     call   err_warn
```

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:

Listing 81.2: 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]

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 contain unprintable characters.

Listing 81.3: Python 3.x

```
#!/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, 0x33, 0x36, 0x76,
0x3A, 0x33, 0x31, 0x0C, 0x0, 0x0B, 0x1F, 0x7, 0x1E, 0x1A], 

[0x49, 0x65, 0x2D, 0x63, 0x76, 0x75, 0x6C, 0x6E, 0x76, 0x56, 0x5C,
8, 0x4F, 0x4B, 0x47, 0x5D, 0x54, 0x5F, 0x1D, 0x26, 0x2C, 0x33,
0x27, 0x28, 0x6F, 0x72, 0x75, 0x78, 0x7B, 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, 0x7F, 0x6F, 0x0, 0x4C, 0x40, 0x9, 0x4D, 0x5A,
0x46, 0x5D, 0x57, 0x49, 0x57, 0x3B, 0x21, 0x23, 0x6A, 0x38, 0x23,
0x36, 0x24, 0x2A, 0x7C, 0x3A, 0x1A, 0x6, 0x0D, 0x0E, 0x0A, 0x14,
0x10], 

[0x72, 0x7C, 0x72, 0x79, 0x76, 0x0,
0x50, 0x43, 0x4A, 0x59, 0x5D, 0x5B, 0x41, 0x41, 0x1B, 0x5A,
0x24, 0x32, 0x2E, 0x29, 0x28, 0x70, 0x20, 0x22, 0x38, 0x28, 0x36,
0x0D, 0x0B, 0x48, 0x4B, 0x4E]]
```

81.3. EXAMPLE #3: MS-DOS

```
def is_string_printable(s):
    return all(list(map(lambda x: curses.ascii.isprint(x), s)))

cnt=1
for msg in msgs:
    print ("message #%d" % 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 81.4: Results

```
message #1
key= 20 value= `eb^h%| ``hudw|_af{n~f%ljmSbnwlpk
key= 21 value= ajc]i"}cawtgv{^bgto}g"millcmvkqh
key= 22 value= bkd\j#rbbvsfuz!cduh|d#bhomdlujni
key= 23 value= check security device connection
key= 24 value= lifbl!pd|tqhsx#ejwjbb!`nQofbshlo
message #2
key= 7 value= No security device found
key= 8 value= An#rbbvsVuz!cduhld#ghtme?#!'!#!
message #3
key= 7 value= Bk<waoqNUpu$`yreoa\wpmpusj,bkIjh
key= 8 value= Mj?vfnr0jqv%gxqd`_vwlstlk/clHii
key= 9 value= Lm>ugasLkvw&fgpgag^uvcrwml.`mwhj
key= 10 value= O1!td`tMhwx'efwfbf!tubuvnm!anvok
key= 11 value= No security device station found
key= 12 value= In#rjbvsnuz!{duhdd#r{`whho#gPtme
message #4
key= 14 value= Number of authorized users exceeded
key= 15 value= Ovlmdq!hg#`juknuhydk!vrbsp!Zy`dbe
message #5
key= 17 value= check security device station
key= 18 value= `ijbh!td`tmhwx'efwfbf!tubuVnm!'!
```

There is some garbage, but we can quickly find the English-language messages!

By the way, since the algorithm is a simple xor-ing 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.

81.3 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 en masse the code was 16-bit. 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
```

81.3. EXAMPLE #3: MS-DOS

```

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
seg030:0046 57          push    di
seg030:0047 8B 16 82 E7  mov     dx, _in_port_1 ; 0x37A
seg030:004B EC          in     al, dx
seg030:004C 8A D8        mov     bl, al
seg030:004E 80 E3 FE    and    bl, 0FEh
seg030:0051 80 CB 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
seg030:005E EE          out    dx, al
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
seg030:0073      loc_359D3: ; CODE XREF: sent_pro+37j
seg030:0073 46          inc    si
seg030:0074
seg030:0074      loc_359D4: ; CODE XREF: sent_pro+30j
seg030:0074 81 FE 96 00  cmp    si, 96h
seg030:0078 7C F9        jl     short loc_359D3
seg030:007A 68 C3 00    push    0C3h
seg030:007D 0E          push    cs
seg030:007E E8 B3 FF    call    near ptr out_port
seg030:0081 59          pop    cx
seg030:0082 68 C7 00    push    0C7h
seg030:0085 0E          push    cs
seg030:0086 E8 AB FF    call    near ptr out_port
seg030:0089 59          pop    cx
seg030:008A 68 D3 00    push    0D3h
seg030:008D 0E          push    cs
seg030:008E E8 A3 FF    call    near ptr out_port
seg030:0091 59          pop    cx
seg030:0092 68 C3 00    push    0C3h
seg030:0095 0E          push    cs
seg030:0096 E8 9B FF    call    near ptr out_port
seg030:0099 59          pop    cx
seg030:009A 68 C7 00    push    0C7h
seg030:009D 0E          push    cs
seg030:009E E8 93 FF    call    near ptr out_port
seg030:00A1 59          pop    cx
seg030:00A2 68 D3 00    push    0D3h

```

81.3. EXAMPLE #3: MS-DOS

```

seg030:00A5 0E          push    cs
seg030:00A6 E8 8B FF    call    near ptr out_port
seg030:00A9 59          pop     cx
seg030:00AA BF FF FF    mov     di, 0FFFFh
seg030:00AD EB 40        jmp    short loc_35A4F
seg030:00AF
seg030:00AF loc_35A0F: ; CODE XREF: sent_pro+BDj
seg030:00AF BE 04 00    mov     si, 4
seg030:00B2
seg030:00B2 loc_35A12: ; CODE XREF: sent_pro+ACj
seg030:00B2 D1 E7        shl     di, 1
seg030:00B4 8B 16 80 E7    mov     dx, _in_port_2 ; 0x379
seg030:00B8 EC          in      al, dx
seg030:00B9 A8 80        test   al, 80h
seg030:00BB 75 03        jnz    short loc_35A20
seg030:00BD 83 CF 01    or     di, 1
seg030:00C0
seg030:00C0 loc_35A20: ; CODE XREF: sent_pro+7Aj
seg030:00C0 F7 46 FE 08+  test   [bp+var_2], 8
seg030:00C5 74 05        jz     short loc_35A2C
seg030:00C7 68 D7 00    push   0D7h ; '+'
seg030:00CA EB 0B        jmp    short loc_35A37
seg030:00CC
seg030:00CC loc_35A2C: ; CODE XREF: sent_pro+84j
seg030:00CC 68 C3 00    push   0C3h
seg030:00CF 0E          push   cs
seg030:00D0 E8 61 FF    call   near ptr out_port
seg030:00D3 59          pop    cx
seg030:00D4 68 C7 00    push   0C7h
seg030:00D7
seg030:00D7 loc_35A37: ; CODE XREF: sent_pro+89j
seg030:00D7 0E          push   cs
seg030:00D8 E8 59 FF    call   near ptr out_port
seg030:00DB 59          pop    cx
seg030:00DC 68 D3 00    push   0D3h
seg030:00DF 0E          push   cs
seg030:00E0 E8 51 FF    call   near ptr out_port
seg030:00E3 59          pop    cx
seg030:00E4 8B 46 FE    mov    ax, [bp+var_2]
seg030:00E7 D1 E0        shl    ax, 1
seg030:00E9 89 46 FE    mov    [bp+var_2], ax
seg030:00EC 4E          dec    si
seg030:00ED 75 C3        jnz   short loc_35A12
seg030:00EF
seg030:00EF loc_35A4F: ; CODE XREF: sent_pro+6Cj
seg030:00EF C4 5E 06    les    bx, [bp+arg_0]
seg030:00F2 FF 46 06    inc    word ptr [bp+arg_0]
seg030:00F5 26 8A 07    mov    al, es:[bx]
seg030:00F8 98          cbw
seg030:00F9 89 46 FE    mov    [bp+var_2], ax
seg030:00FC 0B C0        or     ax, ax
seg030:00FE 75 AF        jnz   short loc_35A0F
seg030:0100 68 FF 00    push   0FFh
seg030:0103 0E          push   cs
seg030:0104 E8 2D FF    call   near ptr out_port
seg030:0107 59          pop    cx
seg030:0108 8B 16 82 E7    mov     dx, _in_port_1 ; 0x37A
seg030:010C EC          in      al, dx
seg030:010D 8A C8        mov     cl, al
seg030:010F 80 E1 5F    and    cl, 5Fh
seg030:0112 8A C1        mov     al, cl
seg030:0114 EE          out    dx, al
seg030:0115 EC          in      al, dx
seg030:0116 8A C8        mov     cl, al
seg030:0118 F6 C1 20    test   cl, 20h
seg030:011B 74 08        jz    short loc_35A85
seg030:011D 8A 5E FD    mov    bl, [bp+var_3]
seg030:0120 80 E3 DF    and    bl, 0DFh
seg030:0123 EB 03        jmp    short loc_35A88
seg030:0125

```

81.3. EXAMPLE #3: MS-DOS

```

seg030:0125          loc_35A85: ; CODE XREF: sent_pro+DAj
seg030:0125 8A 5E FD    mov     bl, [bp+var_3]
seg030:0128
seg030:0128          loc_35A88: ; CODE XREF: sent_pro+E2j
seg030:0128 F6 C1 80    test    cl, 80h
seg030:012B 74 03      jz     short loc_35A90
seg030:012D 80 E3 7F    and    bl, 7Fh
seg030:0130
seg030:0130          loc_35A90: ; CODE XREF: sent_pro+EAj
seg030:0130 8B 16 82 E7    mov     dx, _in_port_1 ; 0x37A
seg030:0134 8A C3      mov     al, bl
seg030:0136 EE         out    dx, al
seg030:0137 8B C7      mov     ax, di
seg030:0139 5F         pop    di
seg030:013A 5E         pop    si
seg030:013B C9         leave
seg030:013C CB         retf
seg030:013C          sent_pro endp

```

This is again a Sentinel Pro “hashing” dongle as in the previous example. It is noticeably because text 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 printer⁴. 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. Probably 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', 0FF5Fh>
dseg:3E51 70 61 70 65+    struct_0 <'paper', 0FFDFh>
dseg:3E6C 63 6F 6B 65+    struct_0 <'coke', 0F568h>
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            var_2 = word ptr -2
seg030:0145
seg030:0145 C8 06 00 00    enter   6, 0
seg030:0149 56            push    si
seg030:014A 66 6A 00      push    large 0      ; newtime
seg030:014D 6A 00          push    0           ; cmd

```

⁴If we consider Centronics only. The following IEEE 1284 standard allows the transfer of information from the printer.

81.3. EXAMPLE #3: MS-DOS

```

seg030:014F 9A C1 18 00+    call    _biostime
seg030:0154 52                push    dx
seg030:0155 50                push    ax
seg030:0156 66 58                pop    eax
seg030:0158 83 C4 06                add    sp, 6
seg030:015B 66 89 46 FA                mov    [bp+var_6], eax
seg030:015F 66 3B 06 D8+                cmp    eax, _expiration
seg030:0164 7E 44                jle    short loc_35B0A
seg030:0166 6A 14                push   14h
seg030:0168 90                nop
seg030:0169 0E                push   cs
seg030:016A E8 52 00                call   near ptr get_rand
seg030:016D 59                pop    cx
seg030:016E 8B F0                mov    si, ax
seg030:0170 6B C0 1B                imul  ax, 1Bh
seg030:0173 05 BC 3C                add   ax, offset _Q
seg030:0176 1E                push   ds
seg030:0177 50                push   ax
seg030:0178 0E                push   cs
seg030:0179 E8 C5 FE                call   near ptr sent_pro
seg030:017C 83 C4 04                add   sp, 4
seg030:017F 89 46 FE                mov   [bp+var_2], ax
seg030:0182 8B C6                mov   ax, si
seg030:0184 6B C0 12                imul  ax, 18
seg030:0187 66 0F BF C0                movsx eax, ax
seg030:018B 66 8B 56 FA                mov   edx, [bp+var_6]
seg030:018F 66 03 D0                add   edx, eax
seg030:0192 66 89 16 D8+                mov   _expiration, edx
seg030:0197 8B DE                mov   bx, si
seg030:0199 6B DB 1B                imul  bx, 27
seg030:019C 8B 87 D5 3C                mov   ax, _Q._A[bx]
seg030:01A0 3B 46 FE                cmp   ax, [bp+var_2]
seg030:01A3 74 05                jz    short loc_35B0A
seg030:01A5 B8 01 00                mov   ax, 1
seg030:01A8 EB 02                jmp   short loc_35B0C
seg030:01AA
seg030:01AA      loc_35B0A: ; CODE XREF: check_dongle+1Fj
seg030:01AA          ; check_dongle+5Ej
seg030:01AA 33 C0                xor   ax, ax
seg030:01AC
seg030:01AC      loc_35B0C: ; CODE XREF: check_dongle+63j
seg030:01AC 5E                pop   si
seg030:01AD C9                leave
seg030:01AE CB                retf
seg030:01AE      check_dongle endp

```

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:

```

seg030:01BF      get_rand proc far ; CODE XREF: check_dongle+25p
seg030:01BF
seg030:01BF      arg_0     = word ptr 6
seg030:01BF
seg030:01BF 55                push   bp
seg030:01C0 8B EC                mov    bp, sp
seg030:01C2 9A 3D 21 00+            call   _rand
seg030:01C7 66 0F BF C0                movsx eax, ax
seg030:01CB 66 0F BF 56+            movsx edx, [bp+arg_0]
seg030:01D0 66 0F AF C2                imul  eax, edx
seg030:01D4 66 BB 00 80+            mov    ebx, 8000h
seg030:01DA 66 99                cdq
seg030:01DC 66 F7 FB                idiv  ebx
seg030:01DF 5D                pop   bp
seg030:01E0 CB                retf
seg030:01E0      get_rand endp

```

81.3. EXAMPLE #3: MS-DOS

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:

```
seg033:087B 9A 45 01 96+  call    check_dongle
seg033:0880 0B C0          or      ax, ax
seg033:0882 74 62          jz      short OK
seg033:0884 83 3E 60 42+  cmp     word_620E0, 0
seg033:0889 75 5B          jnz     short OK
seg033:088B FF 06 60 42  inc     word_620E0
seg033:088F 1E             push    ds
seg033:0890 68 22 44        push   offset aTrupcRequiresA ; "This Software ↴
                                ↴ Lock\n"
seg033:0893 1E             push    ds
seg033:0894 68 60 E9        push   offset byte_6C7E0 ; dest
seg033:0897 9A 79 65 00+    call    _strcpy
seg033:089C 83 C4 08        add    sp, 8
seg033:089F 1E             push    ds
seg033:08A0 68 42 44        push   offset aPleaseContactA ; "Please Contact ..."
seg033:08A3 1E             push    ds
seg033:08A4 68 60 E9        push   offset byte_6C7E0 ; dest
seg033:08A7 9A CD 64 00+    call    _strcat
```

Bypassing the dongle is easy, just force the `check_dongle()` function to always return 0.

For example, by inserting this code at its beginning:

```
mov ax,0
retf
```

The observant reader might recall that the `strcpy()` C function usually requires two pointers in its arguments, but we see that 4 values are passed:

```
seg033:088F 1E             push    ds
seg033:0890 68 22 44        push   offset aTrupcRequiresA ; "This Software ↴
                                ↴ Requires a Software Lock\n"
seg033:0893 1E             push    ds
seg033:0894 68 60 E9        push   offset byte_6C7E0 ; dest
seg033:0897 9A 79 65 00+    call    _strcpy
seg033:089C 83 C4 08        add    sp, 8
```

This is related to MS-DOS' memory model. You can read more about it here: [97 on page 912](#).

So as you may see, `strcpy()` and any other function that take pointer(s) in arguments work with 16-bit pairs.

Let's get back to our example. `DS` is currently set to the data segment located in the executable, that is where the text string is stored.

In the `sent_pro()` function, each byte of the string is loaded at `seg030:00EF`: the `LES` instruction loads the `ES:BX` pair simultaneously from the passed argument. The `MOV` at `seg030:00F5` loads the byte from the memory at which the `ES:BX` pair points.

Chapter 82

“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 lost¹.

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
.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
.text:0054102B loc_54102B:          ; CODE XREF: set_bit+15
.text:0054102B         shl     dl, cl
.text:0054102D         mov     cl, cube64[eax+esi*8]
.text:00541034         not    dl
.text:00541036         and    cl, dl
.text:00541038         mov     cube64[eax+esi*8], cl
.text:0054103F         pop    esi
.text:00541040         retn
.text:00541040 set_bit          endp
.text:00541040
.text:00541041         align 10h
.text:00541050
.text:00541050 ; ===== S U B R O U T I N E =====
.text:00541050
.text:00541050
.text:00541050 get_bit          proc near           ; CODE XREF: rotate1+16
.text:00541050                           ; rotate2+16 ...
.text:00541050 arg_0              = dword ptr  4
```

¹He also got permission from the customer to publish the algorithm's details

```

.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
.text:00541067 get_bit         endp
.text:00541067
.text:00541068                 align 10h
.text:00541070
.text:00541070 ; ===== S U B R O U T I N E =====
.text:00541070
.text:00541070
.text:00541070 rotate1         proc near             ; CODE XREF: rotate_all_with_password+8E
.text:00541070
.text:00541070 internal_array_64= byte ptr -40h
.text:00541070 arg_0           = dword ptr  4
.text:00541070
.text:00541070                 sub    esp, 40h
.text:00541073                 push   ebx
.text:00541074                 push   ebp
.text:00541075                 mov    ebp, [esp+48h+arg_0]
.text:00541079                 push   esi
.text:0054107A                 push   edi
.text:0054107B                 xor    edi, edi      ; EDI is loop1 counter
.text:0054107D                 lea    ebx, [esp+50h+internal_array_64]
.text:00541081
.text:00541081 first_loop1_begin:        ; CODE XREF: rotate1+2E
.text:00541081                 xor    esi, esi      ; ESI is loop2 counter
.text:00541083
.text:00541083 first_loop2_begin:        ; CODE XREF: rotate1+25
.text:00541083                 push   ebp             ; arg_0
.text:00541084                 push   esi
.text:00541085                 push   edi
.text:00541086                 call   get_bit
.text:0054108B                 add    esp, 0Ch
.text:0054108E                 mov    [ebx+esi], al  ; store to internal array
.text:00541091                 inc    esi
.text:00541092                 cmp    esi, 8
.text:00541095                 jl    short first_loop2_begin
.text:00541097                 inc    edi
.text:00541098                 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
.text:005410AB second_loop2_begin:        ; CODE XREF: rotate1+4E
.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, OFFFFFFFFh
.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
.text:005410D0
.text:005410D1          align 10h
.text:005410E0
.text:005410E0 ; ===== S U B R O U T I N E =====
.text:005410E0
.text:005410E0
.text:005410E0 rotate2      proc near           ; CODE XREF: rotate_all_with_password+7A
.text:005410E0
.text:005410E0 internal_array_64= byte ptr -40h
.text:005410E0 arg_0        = dword ptr 4
.text:005410E0
.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
.text:005410F1 loc_5410F1:    ; CODE XREF: rotate2+2E
.text:005410F1          xor    esi, esi      ; loop2 counter
.text:005410F3
.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
.text:00541119
.text:00541119 loc_541119:    ; CODE XREF: rotate2+57
.text:00541119          xor    esi, esi      ; loop2 counter
.text:0054111B
.text:0054111B loc_54111B:    ; CODE XREF: rotate2+4E
.text:0054111B          mov    al, [ebx+esi]  ; get byte from internal array
.text:0054111E          push  eax
.text:0054111F          push  edi          ; loop1 counter
.text:00541120          push  esi          ; loop2 counter
.text:00541121          push  ebp          ; arg_0
.text:00541122          call  set_bit
.text:00541127          add   esp, 10h
.text:0054112A          inc   esi          ; increment loop2 counter
.text:0054112B          cmp   esi, 8
.text:0054112E          jl    short loc_54111B
.text:00541130          dec   edi          ; decrement loop2 counter
.text:00541131          add   ebx, 8
.text:00541134          cmp   edi, 0FFFFFFFh
.text:00541137          jg    short loc_541119
.text:00541139          pop   edi
.text:0054113A          pop   esi
.text:0054113B          pop   ebp
.text:0054113C          pop   ebx
.text:0054113D          add   esp, 40h

```

```

.text:00541140          retn
.text:00541140 rotate2    endp
.text:00541140
.text:00541141          align 10h
.text:00541150
.text:00541150 ; ===== S U B R O U T I N E =====
.text:00541150
.text:00541150
.text:00541150 rotate3     proc near           ; CODE XREF: rotate_all_with_password+66
.text:00541150
.text:00541150 var_40      = byte ptr -40h
.text:00541150 arg_0       = dword ptr 4
.text:00541150
.text:00541150 sub esp, 40h
.text:00541153 push ebx
.text:00541154 push ebp
.text:00541155 mov ebp, [esp+48h+arg_0]
.text:00541159 push esi
.text:0054115A push edi
.text:0054115B xor edi, edi
.text:0054115D lea ebx, [esp+50h+var_40]
.text:00541161
.text:00541161 loc_541161: xor esi, esi           ; CODE XREF: rotate3+2E
.text:00541161
.text:00541163 loc_541163:                   ; CODE XREF: rotate3+25
.text:00541163 push esi
.text:00541164 push ebp
.text:00541165 push edi
.text:00541166 call get_bit
.text:0054116B add esp, 0Ch
.text:0054116E mov [ebx+esi], al
.text:00541171 inc esi
.text:00541172 cmp esi, 8
.text:00541175 jl short loc_541163
.text:00541177 inc edi
.text:00541178 add ebx, 8
.text:0054117B cmp edi, 8
.text:0054117E jl short loc_541161
.text:00541180 xor ebx, ebx
.text:00541182 lea edi, [esp+50h+var_40]
.text:00541186
.text:00541186 loc_541186:                   ; CODE XREF: rotate3+54
.text:00541186 mov esi, 7
.text:0054118B loc_54118B:                   ; CODE XREF: rotate3+4E
.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, 0FFFFFFFh
.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:005411AD
.text:005411AE align 10h

```

```

.text:005411B0 ; ===== S U B R O U T I N E =====
.text:005411B0
.text:005411B0
.text:005411B0 rotate_all_with_password proc near      ; CODE XREF: crypt+1F
.text:005411B0                                         ; decrypt+36
.text:005411B0
.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
.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
.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
.text:00541215 call_rotate3:           ; CODE XREF: rotate_all_with_password+6F
.text:00541215             push   esi
.text:00541216             call   rotate3
.text:0054121B             add    esp, 4
.text:0054121E             dec    edi
.text:0054121F             jnz   short call_rotate3
.text:00541221             jmp   short next_character_in_password
.text:00541223
.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
.text:00541229 loc_541229:           ; CODE XREF: rotate_all_with_password+83
.text:00541229             push   esi

```

```

.text:0054122A          call   rotate2
.text:0054122F          add    esp, 4
.text:00541232          dec    edi
.text:00541233          jnz   short loc_541229
.text:00541235          jmp   short next_character_in_password
.text:00541237
.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
.text:0054123D loc_54123D:           ; CODE XREF: rotate_all_with_password+97
.text:0054123D          push   esi
.text:0054123E          call   rotate1
.text:00541243          add    esp, 4
.text:00541246          dec    edi
.text:00541247          jnz   short loc_54123D
.text:00541249
.text:00541249 next_character_in_password: ; CODE XREF: rotate_all_with_password+26
.text:00541249          ; rotate_all_with_password+2A ...
.text:00541249          mov    al, [ebp+1]
.text:0054124C          inc    ebp
.text:0054124D          test   al, al
.text:0054124F          jnz   loop_begin
.text:00541255          pop    edi
.text:00541256          pop    esi
.text:00541257          pop    ebx
.text:00541258
.text:00541258 exit:                ; CODE XREF: rotate_all_with_password+A
.text:00541258          pop    ebp
.text:00541259          retn
.text:00541259 rotate_all_with_password endp
.text:00541259
.text:0054125A          align 10h
.text:00541260
.text:00541260 ; ===== S U B R O U T I N E =====
.text:00541260
.text:00541260
.text:00541260 crypt     proc near           ; CODE XREF: crypt_file+8A
.text:00541260
.text:00541260 arg_0      = dword ptr 4
.text:00541260 arg_4      = dword ptr 8
.text:00541260 arg_8      = dword ptr 0Ch
.text:00541260
.text:00541260          push   ebx
.text:00541261          mov    ebx, [esp+4+arg_0]
.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          retn
.text:005412A7 crypt    endp
.text:005412A7
.text:005412A8          align   10h
.text:005412B0
.text:005412B0 ; ===== S U B R O U T I N E =====
.text:005412B0
.text:005412B0
.text:005412B0 ; int __cdecl decrypt(int, int, void *Src)
.text:005412B0 decrypt      proc near             ; CODE XREF: decrypt_file+99
.text:005412B0
.text:005412B0 arg_0        = dword ptr  4
.text:005412B0 arg_4        = dword ptr  8
.text:005412B0 Src         = dword ptr  0Ch
.text:005412B0
.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    __strupd
.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
.text:005412D1 loc_5412D1:          ; CODE XREF: decrypt+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
.text:005412F7             mov     ecx, 10h
.text:005412FC             mov     esi, offset cube64
.text:00541301             add    ebx, 40h
.text:00541304             cmp    ebp, eax
.text:00541306             rep    movsd
.text:00541308             j1    short loc_5412D1
.text:0054130A             mov     edx, [esp+10h+Src]
.text:0054130E             push   edx           ; Memory
.text:0054130F             call    _free
.text:00541314             add    esp, 4
.text:00541317             pop    edi
.text:00541318             pop    esi
.text:00541319             pop    ebp
.text:0054131A             pop    ebx
.text:0054131B             retn
.text:0054131B decrypt    endp
.text:0054131B
.text:0054131C             align   10h
.text:00541320
.text:00541320 ; ===== S U B R O U T I N E =====
.text:00541320
.text:00541320 ; int __cdecl crypt_file(int Str, char *Filename, int password)
.text:00541320 crypt_file    proc near             ; CODE XREF: _main+42

```

```

.text:00541320          = dword ptr  4
.text:00541320 Str       = dword ptr  8
.text:00541320 Filename  = dword ptr  0Ch
.text:00541320
.text:00541320          mov     eax, [esp+Str]
.text:00541324          push    ebp
.text:00541325          push    offset Mode      ; "rb"
.text:0054132A          push    eax           ; Filename
.text:0054132B          call    _fopen         ; open file
.text:00541330          mov     ebp, eax
.text:00541332          add    esp, 8
.text:00541335          test   ebp, ebp
.text:00541337          jnz    short loc_541348
.text:00541339          push    offset Format    ; "Cannot open input file!\n"
.text:0054133E          call    _printf
.text:00541343          add    esp, 4
.text:00541346          pop    ebp
.text:00541347          retn
.text:00541348          ; CODE XREF: crypt_file+17
.text:00541348          push    ebx
.text:00541349          push    esi
.text:0054134A          push    edi
.text:0054134B          push    2             ; Origin
.text:0054134D          push    0             ; Offset
.text:0054134F          push    ebp            ; File
.text:00541350          call    _fseek
.text:00541355          push    ebp            ; File
.text:00541356          call    _ftell          ; get file size
.text:0054135B          push    0             ; Origin
.text:0054135D          push    0             ; Offset
.text:0054135F          push    ebp            ; File
.text:00541360          mov    [esp+2Ch+Str], eax
.text:00541364          call    _fseek          ; rewind to start
.text:00541369          mov    esi, [esp+2Ch+Str]
.text:0054136D          and    esi, 0FFFFFFC0h ; reset all lowest 6 bits
.text:00541370          add    esi, 40h        ; align size to 64-byte border
.text:00541373          push    esi            ; Size
.text:00541374          call    _malloc
.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          mov    edi, ebx
.text:00541383          push    ebp            ; File
.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:005413BB          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:005413EB      push    edi        ; File
.text:005413EC      call    _fclose   ; Memory
.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      retn
.text:005413FE crypt_file    endp
.text:005413FF      align 10h
.text:00541400
.text:00541400 ; ===== S U B R O U T I N E =====
.text:00541400
.text:00541400
.text:00541400 ; int __cdecl decrypt_file(char *Filename, int, void *Src)
.text:00541400 decrypt_file proc near           ; CODE XREF: _main+6E
.text:00541400
.text:00541400 Filename      = dword ptr 4
.text:00541400 arg_4        = dword ptr 8
.text:00541400 Src          = dword ptr 0Ch
.text:00541400
.text:00541404      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:00541429      pop    edi
.text:0054142A      pop    esi
.text:0054142B      pop    ebp
.text:0054142C      pop    ebx
.text:0054142D      retn
.text:0054142E
.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: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
.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, OFFFFFFF9h
.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:005414A2          push   offset awb_0    ; "wb"
.text:005414A7          push   ecx           ; Filename
.text:005414A8          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
.text:005414B4          call   _fwrite
.text:005414B9          push   ebp           ; File
.text:005414BA          call   _fclose
.text:005414BF          push   ebx           ; Memory
.text:005414C0          call   _free
.text:005414C5          add    esp, 2Ch
.text:005414C8          pop    edi
.text:005414C9          pop    esi
.text:005414CA          pop    ebp
.text:005414CB          pop    ebx
.text:005414CC          retn
.text:005414CC  decrypt_file    endp

```

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.

```

.text:00541320 ; int __cdecl crypt_file(int Str, char *Filename, int password)
.text:00541320 crypt_file      proc near
.text:00541320
.text:00541320 Str           = dword ptr 4
.text:00541320 Filename       = dword ptr 8
.text:00541320 password      = dword ptr 0Ch
.text:00541320

```

Open the file and report if an error occurs:

```
.text:00541320          mov    eax, [esp+Str]
.text:00541324          push   ebp
.text:00541325          push   offset Mode      ; "rb"
.text:0054132A          push   eax       ; Filename
.text:0054132B          call   _fopen      ; open file
.text:00541330          mov    ebp, eax
.text:00541332          add    esp, 8
.text:00541335          test   ebp, ebp
.text:00541337          jnz   short loc_541348
.text:00541339          push   offset Format   ; "Cannot open input file!\n"
.text:0054133E          call   _printf
.text:00541343          add    esp, 4
.text:00541346          pop    ebp
.text:00541347          retn
.text:00541348 loc_541348:
```

Get the file size via `fseek()`/`ftell()`:

```
.text:00541348 push  ebx
.text:00541349 push  esi
.text:0054134A push  edi
.text:0054134B push  2          ; Origin
.text:0054134D push  0          ; Offset
.text:0054134F push  ebp        ; File

; move current file position to the end
.text:00541350 call  _fseek
.text:00541355 push  ebp        ; File
.text:00541356 call  _ftell      ; get current file position
.text:0054135B push  0          ; Origin
.text:0054135D push  0          ; Offset
.text:0054135F push  ebp        ; File
.text:00541360 mov   [esp+2Ch+Str], eax

; move current file position to the start
.text:00541364 call  _fseek
```

This fragment of code calculates the file size aligned on a 64-byte boundary. This is because this cryptographic algorithm works with only 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 was already divided by 64 and adds 64. It is almost the same.

```
.text:00541369 mov    esi, [esp+2Ch+Str]
; reset all lowest 6 bits
.text:0054136D and   esi, 0FFFFFFC0h
; align size to 64-byte border
.text:00541370 add   esi, 40h
```

Allocate buffer with aligned size:

```
.text:00541373          push   esi        ; Size
.text:00541374          call   _malloc
```

Call `memset()`, e.g., clear the allocated buffer².

```
.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 mov    edi, ebx
.text:00541383 push   ebp        ; File
.text:00541384 shr    ecx, 2
.text:00541387 rep stosd
.text:00541389 mov    ecx, edx
.text:0054138B push   1          ; Count
```

²`malloc()` + `memset()` could be replaced by `calloc()`

```
.text:0054138D and    ecx, 3
.text:00541390 rep stosb           ; memset (buffer, 0, aligned_size)
```

Read file via the standard C function `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 `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:005413A9          push   ebx           ; buffer
.text:005413AA          call   crypt          ; do crypt
```

Create the output file. By the way, the developer forgot to check if it was 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 `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
.text:005413DB          push   eax           ; Str
.text:005413DC          call   _fwrite        ; write original file size
```

Write the encrypted 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
```

Close the file and free the allocated buffer:

```
.text:005413EB          push   edi           ; File
.text:005413EC          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          retn
.text:005413FE crypt_file endp
```

Here is the reconstructed C code:

```
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=f.tell (f);
    fseek (f, 0, SEEK_SET);

    flen_aligned=(flen&0xFFFFFC0)+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:

```
.text:00541400 ; int __cdecl decrypt_file(char *Filename, int, void *Src)
.text:00541400 decrypt_file    proc near
.text:00541400
.text:00541400 Filename        = dword ptr  4
.text:00541400 arg_4          = dword ptr  8
.text:00541400 Src            = dword ptr  0Ch
.text:00541400
.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:00541429             pop    edi
.text:0054142A             pop    esi
.text:0054142B             pop    ebp
.text:0054142C             pop    ebx
.text:0054142D             retn
```

```

.text:0054142E
.text:0054142E loc_54142E:
.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

```

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:00541485          pop    esi
.text:00541486          pop    ebp
.text:00541487          pop    ebx
.text:00541488          retn
.text:00541489          loc_541489:

```

Call decrypt().

```

.text:00541489          mov    eax, [esp+10h+Src]
.text:0054148D          mov    edi, [ebx+3]
.text:00541490          add    ebp, 0FFFFFF9h
.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:005414A2          push   offset awb_0    ; "wb"
.text:005414A7          push   ecx         ; Filename
.text:005414A8          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
.text:005414B4          call   _fwrite
.text:005414B9          push   ebp         ; File
.text:005414BA          call   _fclose
.text:005414BF          push   ebx         ; Memory

```

```

.text:005414C0          call    _free
.text:005414C5          add    esp, 2Ch
.text:005414C8          pop    edi
.text:005414C9          pop    esi
.text:005414CA          pop    ebp
.text:005414CB          pop    ebx
.text:005414CC          retn
.text:005414CC decrypt_file    endp

```

Here is the reconstructed C code:

```

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=f.tell (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");

    fwrite (buf+(3+4), real_flen, 1, f);

    fclose (f);

    free (buf);
}

```

OK, now let's go deeper.

Function `crypt()`:

```

.text:00541260 crypt          proc near
.text:00541260
.text:00541260 arg_0          = dword ptr 4
.text:00541260 arg_4          = dword ptr 8
.text:00541260 arg_8          = dword ptr 0Ch
.text:00541260
.text:00541260          push    ebx
.text:00541261          mov     ebx, [esp+4+arg_0]
.text:00541265          push    ebp
.text:00541266          push    esi
.text:00541267          push    edi
.text:00541268          xor    ebp, ebp

```

```
.text:0054126A  
.text:0054126A loc_54126A:
```

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.

```
.text:0054126A          mov    eax, [esp+10h+arg_8]  
.text:0054126E          mov    ecx, 10h  
.text:00541273          mov    esi, ebx ; EBX is pointer within input buffer  
.text:00541275          mov    edi, offset cube64  
.text:0054127A          push   1  
.text:0054127C          push   eax  
.text:0054127D          rep    movsd
```

Call **rotate_all_with_password()**:

```
.text:0054127F          call   rotate_all_with_password
```

Copy encrypted contents back from “cube64” to buffer:

```
.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 ; add 64 to input buffer pointer  
.text:0054129D          cmp    ebp, eax ; EBP contain amount of encrypted data.  
.text:0054129F          rep    movsd
```

If **EBP** is not bigger than the size input argument, then continue to the next block.

```
.text:005412A1          jl    short loc_54126A  
.text:005412A3          pop   edi  
.text:005412A4          pop   esi  
.text:005412A5          pop   ebp  
.text:005412A6          pop   ebx  
.text:005412A7          retn  
.text:005412A7 crypt    endp
```

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.

```
.text:005411B0 rotate_all_with_password proc near  
.text:005411B0  
.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
```

Check the current character in the password. If it is zero, exit:

```
.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          loop_begin:
```

Call `tolower()`, a standard C function.

```
.text:005411C7          movsx  eax, byte ptr [ebp+0]
.text:005411CB          push   eax      ; C
.text:005411CC          call   _tolower
.text:005411D1          add    esp, 4
```

Hmm, if the password contains 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.

```
.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
```

Subtract the value of “a” (97) from the character.

```
.text:005411DF          sub    ecx, 'a' ; 97
```

After subtracting, we’ll get 0 for “a” here, 1 for “b”, etc. And 25 for “z”.

```
.text:005411E2          cmp    ecx, 24
.text:005411E5          jle   short skip_subtracting
.text:005411E7          sub    ecx, 24
```

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).

```
.text:005411EA          ; CODE XREF: rotate_all_with_password+35
.text:005411EA skip_subtracting:
```

This is actually division via multiplication. You can read more about it in the “Division by 9” section ([43 on page 487](#)).

The code actually divides the password character’s value by 3.

```
.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
```

`EDX` is the remainder of the division.

```
.text:00541204 sub    edx, 0
.text:00541207 jz    short call_rotate1 ; if remainder is zero, go to rotate1
.text:00541209 dec   edx
.text:0054120A jz    short call_rotate2 ; .. if it is 1, go to 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
```

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.

```
.text:00541215 call_rotate3:  
.text:00541215          push    esi  
.text:00541216          call    rotate3  
.text:0054121B          add    esp, 4  
.text:0054121E          dec    edi  
.text:0054121F          jnz    short call_rotate3  
.text:00541221          jmp    short next_character_in_password  
.text:00541223  
.text:00541223 call_rotate2:  
.text:00541223          test   ebx, ebx  
.text:00541225          jle    short next_character_in_password  
.text:00541227          mov    edi, ebx  
.text:00541229  
.text:00541229 loc_541229:  
.text:00541229          push    esi  
.text:0054122A          call    rotate2  
.text:0054122F          add    esp, 4  
.text:00541232          dec    edi  
.text:00541233          jnz    short loc_541229  
.text:00541235          jmp    short next_character_in_password  
.text:00541237  
.text:00541237 call_rotate1:  
.text:00541237          test   ebx, ebx  
.text:00541239          jle    short next_character_in_password  
.text:0054123B          mov    edi, ebx  
.text:0054123D  
.text:0054123D loc_54123D:  
.text:0054123D          push    esi  
.text:0054123E          call    rotate1  
.text:00541243          add    esp, 4  
.text:00541246          dec    edi  
.text:00541247          jnz    short loc_54123D  
.text:00541249
```

Fetch the next character from the password string.

```
.text:00541249 next_character_in_password:  
.text:00541249          mov    al, [ebp+1]
```

[Increment](#) the character pointer in the password string:

```
.text:0054124C          inc    ebp  
.text:0054124D          test   al, al  
.text:0054124F          jnz    loop_begin  
.text:00541255          pop    edi  
.text:00541256          pop    esi  
.text:00541257          pop    ebx  
.text:00541258 exit:  
.text:00541258          pop    ebp  
.text:00541259          retn  
.text:00541259 rotate_all_with_password endp
```

Here is the reconstructed C code:

```
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()`:

```

.text:00541050 get_bit          proc near
.text:00541050
.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
.text:00541067 get_bit          endp

```

...in other words: calculate an index in the `cube64` array: `arg_4 + arg_0 * 8`. Then shift a byte from the array by `arg_8` bits right. Isolate the lowest bit and return it.

Let's see another function, `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

```

The value in the `DL` is 1 here. It gets shifted left by `arg_8`. For example, if `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
.text:0054102B
.text:0054102B loc_54102B:
.text:0054102B          shl    dl, cl
```

If arg_C is not zero...

```
.text:0054102D          mov     cl, cube64[eax+esi*8]
```

...invert DL. For example, if DL's state after the shift was 0x10 or 1000b in binary form, there is 0xEF to be after the NOT instruction (or 11101111b in binary form).

```
.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
.text:00541040 set_bit    endp
```

It is almost the same as get_bit(), except, if 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 set_bit() and 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:

```
#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.

```
.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             sub    esp, 40h
.text:00541073             push   ebx
.text:00541074             push   ebp
.text:00541075             mov    ebp, [esp+48h+arg_0]
.text:00541079             push   esi
.text:0054107A             push   edi
.text:0054107B             xor    edi, edi      ; EDI is loop1 counter

```

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 xor    esi, esi      ; ESI is loop 2 counter
.text:00541083
.text:00541083 first_loop2_begin:
.text:00541083 push   ebp          ; arg_0
.text:00541084 push   esi          ; loop 1 counter
.text:00541085 push   edi          ; loop 2 counter
.text:00541086 call   get_bit
.text:0054108B add    esp, 0Ch
.text:0054108E mov    [ebx+esi], al  ; store to internal array
.text:00541091 inc    esi          ; increment loop 1 counter
.text:00541092 cmp    esi, 8
.text:00541095 jl    short first_loop2_begin
.text:00541097 inc    edi          ; increment loop 2 counter

; increment internal array pointer by 8 at each loop 1 iteration
.text:00541098 add    ebx, 8
.text:0054109B cmp    edi, 8
.text:0054109E jl    short first_loop1_begin

```

...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.

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]  ; EN(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 2 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:

```
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:

```
.text:005410E0 rotate2 proc near
.text:005410E0
.text:005410E0 internal_array_64 = byte ptr -40h
.text:005410E0 arg_0 = dword ptr 4
.text:005410E0
.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      ; loop 1 counter
.text:005410ED    lea     ebx, [esp+50h+internal_array_64]
.text:005410F1
.text:005410F1 loc_5410F1:
.text:005410F1    xor     esi, esi      ; loop 2 counter
.text:005410F3
.text:005410F3 loc_5410F3:
.text:005410F3    push    esi      ; loop 2 counter
.text:005410F4    push    edi      ; loop 1 counter
.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 loop 1 counter
.text:00541102    cmp     esi, 8
.text:00541105    jl     short loc_5410F3
.text:00541107    inc     edi      ; increment loop 2 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      ; loop 1 counter is initial state 7
.text:00541119
.text:00541119 loc_541119:
.text:00541119    xor     esi, esi      ; loop 2 counter
.text:0054111B
.text:0054111B loc_54111B:
.text:0054111B    mov     al, [ebx+esi]  ; get byte from internal array
.text:0054111E    push    eax
.text:0054111F    push    edi      ; loop 1 counter
.text:00541120    push    esi      ; loop 2 counter
.text:00541121    push    ebp      ; arg_0
.text:00541122    call    set_bit
```

```

.text:00541127    add    esp, 10h
.text:0054112A    inc    esi          ; increment loop 2 counter
.text:0054112B    cmp    esi, 8
.text:0054112E    jl     short loc_54111B
.text:00541130    dec    edi          ; decrement loop 2 counter
.text:00541131    add    ebx, 8
.text:00541134    cmp    edi, 0FFFFFFFh
.text:00541137    jg    short loc_541119
.text:00541139    pop    edi
.text:0054113A    pop    esi
.text:0054113B    pop    ebp
.text:0054113C    pop    ebx
.text:0054113D    add    esp, 40h
.text:00541140    retn
.text:00541140 rotate2 endp

```

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:

```

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:

```

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);

    for (i=0; i<8; i++)
        for (j=0; j<8; j++)
            set_bit (7-j, v, i, tmp[i][j]);
}

```

Well, now things are simpler. If we consider cube64 as a 3D cube of size $8 \times 8 \times 8$, 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 $8 \times 8 \times 8$ Rubik's cube ³?

Yes, indeed.

Let's look closer into the `decrypt()` function, here is its rewritten version:

```

void decrypt (BYTE *buf, int sz, char *pw)
{
    char *p=strdup (pw);
    strrev (p);
    int i=0;

    do

```

³wikipedia

```

    {
        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()`⁴ 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's cube! If you want to get back, do the same in reverse order and direction! If you need 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:

```

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). $3 \times 8 = 24$, 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.

Here is the whole source code reconstructed:

```

#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)

```

⁴MSDN

```

        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;
            }
        }
        p++;
    }
};

```

```

        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;

    f=fopen(fin, "rb");

    if (f==NULL)
    {
        printf ("Cannot open input file!\n");
        return;
    };

    fseek (f, 0, SEEK_END);
    flen=f.tell (f);
    fseek (f, 0, SEEK_SET);

    flen_aligned=(flen&0xFFFFFC0)+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=f.tell (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");

    fwrite (buf+(3+4), real_flen, 1, f);

    fclose (f);

    free (buf);
};

// run: input output 0/1 password
// 0 for encrypt, 1 for decrypt

int main(int argc, char *argv[])
{
    if (argc!=5)
    {
        printf ("Incorrect parameters!\n");
        return 1;
    };

    if (strcmp (argv[3], "0")==0)
        crypt_file (argv[1], argv[2], argv[4]);
    else
        if (strcmp (argv[3], "1")==0)
            decrypt_file (argv[1], argv[2], argv[4]);
}

```

```
    else
        printf ("Wrong param %s\n", argv[3]);
    return 0;
};
```

Chapter 83

SAP

83.1 About SAP client network traffic compression

(Tracing the connection between the TDW_NOCOMPRESS SAPGUI¹ 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 here² and here³).

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 a annoying pop-up window that cannot be closed:

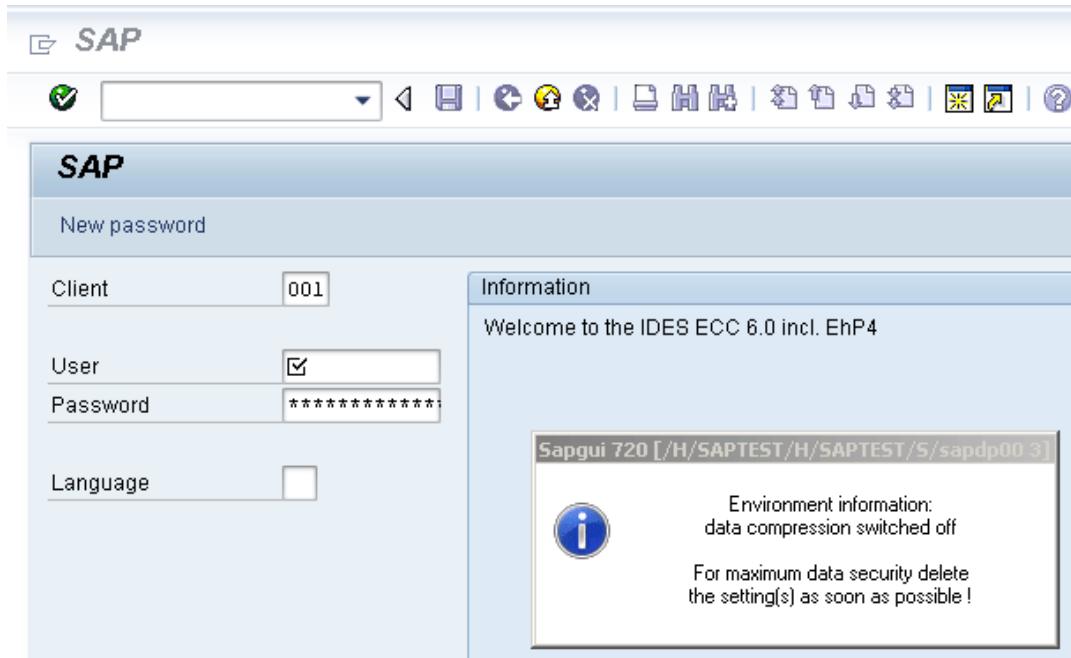


Figure 83.1: Screenshot

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 manager⁴ 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.

¹SAP GUI client

²<http://go.yurichev.com/17221>

³blog.yurichev.com

⁴<http://go.yurichev.com/17347>

83.1. ABOUT SAP CLIENT NETWORK TRAFFIC COMPRESSION

We see the following fragment of code (all file offsets are valid for SAPGUI 720 win32, SAPguilib.dll file version 7200,1,0,9009):

```
.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:6440D52F          push    offset byte_64443AF8
.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:6440D54A          push    eax      ; Str
.text:6440D54B          call    ds:atoi
.text:6440D551          test   eax, eax
.text:6440D553          setnz  al
.text:6440D556          pop    ecx
.text:6440D557          mov     [edi+15h], al
```

The string returned by `chk_env()` via its second argument is then handled by the MFC string functions and then `atoi()`⁵ 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):

```
.text:64413F20 ; int __cdecl chk_env(char *VarName, int)
.text:64413F20 chk_env      proc near
.text:64413F20
.text:64413F20 DstSize      = dword ptr -0Ch
.text:64413F20 var_8        = dword ptr -8
.text:64413F20 DstBuf       = dword ptr -4
.text:64413F20 VarName      = dword ptr 8
.text:64413F20 arg_4        = dword ptr 0Ch
.text:64413F20
.text:64413F20          push    ebp
.text:64413F21          mov     ebp, esp
.text:64413F23          sub    esp, 0Ch
.text:64413F26          mov     [ebp+DstSize], 0
.text:64413F2D          mov     [ebp+DstBuf], 0
.text:64413F34          push    offset unk_6444C88C
.text:64413F39          mov     ecx, [ebp+arg_4]

; (demangled name) ATL::CStringT::operator=(char const *)
.text:64413F3C          call    ds:mfc90_820
.text:64413F42          mov     eax, [ebp+VarName]
.text:64413F45          push    eax      ; VarName
.text:64413F46          mov     ecx, [ebp+DstSize]
.text:64413F49          push    ecx      ; DstSize
.text:64413F4A          mov     edx, [ebp+DstBuf]
.text:64413F4D          push    edx      ; DstBuf
.text:64413F4E          lea     eax, [ebp+DstSize]
.text:64413F51          push    eax      ; ReturnSize
.text:64413F52          call    ds:getenv_s
.text:64413F58          add    esp, 10h
.text:64413F5B          mov     [ebp+var_8], eax
.text:64413F5E          cmp     [ebp+var_8], 0
.text:64413F62          jz    short loc_64413F68
.text:64413F64          xor     eax, eax
.text:64413F66          jmp     short loc_64413FBC
.text:64413F68 loc_64413F68:
```

⁵standard C library function that converts the digits in a string to a number

83.1. ABOUT SAP CLIENT NETWORK TRAFFIC COMPRESSION

```
.text:64413F68          cmp    [ebp+DstSize], 0
.text:64413F6C          jnz    short loc_64413F72
.text:64413F6E          xor    eax, eax
.text:64413F70          jmp    short loc_64413FBC
.text:64413F72          mov    ecx, [ebp+DstSize]
.text:64413F75          push   ecx
.text:64413F76          mov    ecx, [ebp+arg_4]

; demangled name: ATL::CSimpleStringT<char, 1>::Preallocate(int)
.text:64413F79          call   ds:mfc90_2691
.text:64413F7F          mov    [ebp+DstBuf], eax
.text:64413F82          mov    edx, [ebp+VarName]
.text:64413F85          push   edx           ; VarName
.text:64413F86          mov    eax, [ebp+DstSize]
.text:64413F89          push   eax           ; DstSize
.text:64413F8A          mov    ecx, [ebp+DstBuf]
.text:64413F8D          push   ecx           ; DstBuf
.text:64413F8E          lea    edx, [ebp+DstSize]
.text:64413F91          push   edx           ; ReturnSize
.text:64413F92          call   ds:getenv_s
.text:64413F98          add    esp, 10h
.text:64413F9B          mov    [ebp+var_8], eax
.text:64413F9E          push   0xFFFFFFFFh
.text:64413FA0          mov    ecx, [ebp+arg_4]

; demangled name: ATL::CSimpleStringT::ReleaseBuffer(int)
.text:64413FA3          call   ds:mfc90_5835
.text:64413FA9          cmp    [ebp+var_8], 0
.text:64413FAD          jz    short loc_64413FB3
.text:64413FAF          xor    eax, eax
.text:64413FB1          jmp    short loc_64413FBC
.text:64413FB3          mov    ecx, [ebp+arg_4]

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
.text:64413FB6          call   ds:mfc90_910
.text:64413FBC          loc_64413FBC:
.text:64413FBC          mov    esp, ebp
.text:64413FBE          pop    ebp
.text:64413FBF          retn
.text:64413FBF  chk_env  endp
```

Yes. The `getenv_s()`⁶ function is a Microsoft security-enhanced version of `getenv()`⁷.

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:

⁶[MSDN](#)

⁷Standard C library returning environment variable

83.1. ABOUT SAP CLIENT NETWORK TRAFFIC COMPRESSION

DPTRACE	"GUI-OPTION: Trace set to %d"
TDW_HEXDUMP	"GUI-OPTION: Hexdump enabled"
TDW_WORKDIR	"GUI-OPTION: working directory '%s'"
TDW_SPLASHSRCEENOFF	"GUI-OPTION: Splash Screen Off" / "GUI-OPTION: Splash Screen On"
TDW_REPLYTIMEOUT	"GUI-OPTION: reply timeout %d milliseconds"
TDW_PLAYBACKTIMEOUT	"GUI-OPTION: PlaybackTimeout set to %d milliseconds"
TDW_NOCOMPRESS	"GUI-OPTION: no compression read"
TDW_EXPERT	"GUI-OPTION: expert mode"
TDW_PLAYBACKPROGRESS	"GUI-OPTION: PlaybackProgress"
TDW_PLAYBACKNETTRAFFIC	"GUI-OPTION: PlaybackNetTraffic"
TDW_PLAYLOG	"GUI-OPTION: /PlayLog is YES, file %s"
TDW_PLAYTIME	"GUI-OPTION: /PlayTime set to %d milliseconds"
TDW_LOGFILE	"GUI-OPTION: TDW_LOGFILE '%s'"
TDW_WAN	"GUI-OPTION: WAN - low speed connection enabled"
TDW_FULLSCREEN	"GUI-OPTION: FullMenu enabled"
SAP_CP / SAP_CODEPAGE	"GUI-OPTION: SAP_CODEPAGE '%d'"
UPDOWNLOAD_CP	"GUI-OPTION: UPDOWNLOAD_CP '%d'"
SNC_PARTNERNAME	"GUI-OPTION: SNC name '%s'"
SNC_QOP	"GUI-OPTION: SNC_QOP '%s'"
SNC_LIB	"GUI-OPTION: SNC is set to: %s"
SAPGUI_INPLACE	"GUI-OPTION: environment variable SAPGUI_INPLACE is on"

The settings for each variable are written in the array via a pointer in the `EDI` register. `EDI` is set before the function call:

```
.text:6440EE00          lea     edi, [ebp+2884h+var_2884] ; options here like +0x15...
.text:6440EE03          lea     ecx, [esi+24h]
.text:6440EE06          call    load_command_line
.text:6440EE0B          mov     edi, eax
.text:6440EE0D          xor     ebx, ebx
.text:6440EE0F          cmp     edi, ebx
.text:6440EE11          jz    short loc_6440EE42
.text:6440EE13          push    edi
.text:6440EE14          push    offset aSapguiStoppedA ; "Sapgui stopped after ↴
    ↴ commandline interp"...
.text:6440EE19          push    dword_644F93E8
.text:6440EE1F          call    FEWTraceError
```

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:

```
.text:64405160          push    dword ptr [esi+2854h]
.text:64405166          push    offset aCdwsguiPrepare ; "\nCDwsGui::PrepareInfoWindow: ↴
    ↴ sapgui env"...
.text:6440516B          push    dword ptr [esi+2848h]
.text:64405171          call    dbg
.text:64405176          add     esp, 0Ch
```

...or:

```
.text:6440237A          push    eax
.text:6440237B          push    offset aCclientStart_6 ; "CClient::Start: set shortcut ↴
    ↴ user to '\%'"...
.text:64402380          push    dword ptr [edi+4]
.text:64402383          call    dbg
.text:64402388          add     esp, 0Ch
```

It is very useful.

So let's see the contents of this pesky annoying pop-up window's function:

```
.text:64404F4F CDwsGui__PrepareInfoWindow proc near
.text:64404F4F
.text:64404F4F pvParam      = byte ptr -3Ch
.text:64404F4F var_38       = dword ptr -38h
.text:64404F4F var_34       = dword ptr -34h
.text:64404F4F rc           = tagRECT ptr -2Ch
.text:64404F4F cy           = dword ptr -1Ch
```

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```

.text:64404F4F h          = dword ptr -18h
.text:64404F4F var_14     = dword ptr -14h
.text:64404F4F var_10     = dword ptr -10h
.text:64404F4F var_4      = dword ptr -4
.text:64404F4F
.text:64404F4F push      30h
.text:64404F51 mov       eax, offset loc_64438E00
.text:64404F56 call      __EH_prolog3
.text:64404F5B mov       esi, ecx      ; ECX is pointer to object
.text:64404F5D xor       ebx, ebx
.text:64404F5F lea       ecx, [ebp+var_14]
.text:64404F62 mov       [ebp+var_10], ebx

; demangled name: ATL::CStringT(void)
.text:64404F65 call      ds:mfc90_316
.text:64404F6B mov       [ebp+var_4], ebx
.text:64404F6E lea       edi, [esi+2854h]
.text:64404F74 push     offset aEnvironmentInf ; "Environment information:\n"
.text:64404F79 mov       ecx, edi

; demangled name: ATL::CStringT::operator=(char const *)
.text:64404F7B call      ds:mfc90_820
.text:64404F81 cmp       [esi+38h], ebx
.text:64404F84 mov       ebx, ds:mfc90_2539
.text:64404F8A jbe      short loc_64404FA9
.text:64404F8C push    dword ptr [esi+34h]
.text:64404F8F lea       eax, [ebp+var_14]
.text:64404F92 push    offset aWorkingDirecto ; "working directory: '\%s'\n"
.text:64404F97 push    eax

; 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:64404FBF lea       eax, [ebp+var_14]
.text:64404FC2 push    eax
.text:64404FC3 mov       ecx, edi

; demangled name: ATL::CStringT::operator+=(class ATL::CSimpleStringT<char, 1> const &)
.text:64404FC5 call      ds:mfc90_941
.text:64404FCB xor       ebx, ebx
.text:64404FCD inc      ebx
.text:64404FCE 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 loc_64404FD6:
.text:64404FD6 cmp       [esi+38h], ebx
.text:64404FD9 jbe      short loc_64404FF1

```

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```

.text:64404FDB          cmp    dword ptr [esi+2978h], 0
.text:64404FE2          jz     short loc_64404FF1
.text:64404FE4          push   offset aHexdumpInTrace ; "hexdump in trace activated\n"
.text:64404FE9          mov    ecx, edi

; demangled name: ATL::CStringT::operator+=(char const *)
.text:64404FEB          call   ds:mfc90_945
.text:64404FF1

.text:64404FF1 loc_64404FF1:
.text:64404FF1
.text:64404FF1          cmp    byte ptr [esi+78h], 0
.text:64404FF5          jz     short loc_64405007
.text:64404FF7          push   offset aLoggingActivat ; "logging activated\n"
.text:64404FFC          mov    ecx, edi

; demangled name: ATL::CStringT::operator+=(char const *)
.text:64404FFE          call   ds:mfc90_945
.text:64405004          mov    [ebp+var_10], ebx
.text:64405007

.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"
.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:
.text:6440501D          mov    eax, [esi+20h]
.text:64405020          test   eax, eax
.text:64405022          jz     short loc_6440503A
.text:64405024          cmp    dword ptr [eax+28h], 0
.text:64405028          jz     short loc_6440503A
.text:6440502A          push   offset aDataRecordMode ; "data record mode switched on\n"
    ↴ "
.text:6440502F          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

.text:6440503A loc_6440503A:
.text: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"...

; demangled name: ATL::CStringT::operator+=(char const *)
.text:6440504A          call   ds:mfc90_945
.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
.text:6440506B          cdq
.text:6440506B          sub    eax, edx
.text:6440506D          sar    eax, 1
.text:6440506F          mov    [ebp+var_34], eax
.text:64405072

.text:64405072 loc_64405072:

```

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```

.text:64405072          push    edi           ; hWnd
.text:64405073          mov     [ebp+cy], 0A0h
.text:6440507A          call    ds:GetDC
.text:64405080          mov     [ebp+var_10], eax
.text:64405083          mov     ebx, 12Ch
.text:64405088          cmp     eax, edi
.text:6440508A          jz    loc_64405113
.text:64405090          push    11h           ; i
.text:64405092          call    ds:GetStockObject
.text:64405098          mov     edi, ds:SelectObject
.text:6440509E          push    eax           ; h
.text:6440509F          push    [ebp+var_10] ; hdc
.text:644050A2          call    edi ; SelectObject
.text:644050A4          and    [ebp+rc.left], 0
.text:644050A8          and    [ebp+rc.top], 0
.text:644050AC          mov     [ebp+h], eax
.text:644050AF          push    401h           ; format
.text:644050B4          lea     eax, [ebp+rc]
.text:644050B7          push    eax           ; lprc
.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
.text:644050DB          push    eax           ; lpchText
.text:644050DC          push    [ebp+var_10] ; hdc
.text:644050DF          call    ds:DrawTextA
.text:644050E5          push    4            ; nIndex
.text:644050E7          call    ds:GetSystemMetrics
.text:644050ED          mov     ecx, [ebp+rc.bottom]
.text:644050F0          sub     ecx, [ebp+rc.top]
.text:644050F3          cmp     [ebp+h], 0
.text:644050F7          lea     eax, [eax+ecx+28h]
.text:644050FB          mov     [ebp+cy], eax
.text:644050FE          jz    short loc_64405108
.text:64405100          push    [ebp+h]       ; h
.text:64405103          push    [ebp+var_10] ; hdc
.text:64405106          call    edi ; SelectObject
.text:64405108          loc_64405108:
.text:64405108          push    [ebp+var_10] ; hDC
.text:6440510B          push    0             ; hWnd
.text:6440510D          call    ds:ReleaseDC
.text:64405113          loc_64405113:
.text:64405113          mov     eax, [ebp+var_38]
.text:64405116          push    80h           ; uFlags
.text:6440511B          push    [ebp+cy]      ; cy
.text:6440511E          inc    eax
.text:6440511F          push    ebx           ; cx
.text:64405120          push    eax           ; Y
.text:64405121          mov     eax, [ebp+var_34]
.text:64405124          add    eax, 0FFFFFED4h
.text:64405129          cdq
.text:6440512A          sub    eax, edx
.text:6440512C          sar    eax, 1
.text:6440512E          push    eax           ; X
.text:6440512F          push    0             ; hWndInsertAfter
.text:64405131          push    dword ptr [esi+285Ch] ; hWnd
.text:64405137          call    ds:SetWindowPos
.text:6440513D          xor    ebx, ebx
.text:6440513F          inc    ebx
.text:64405140          jmp    short loc_6440514D
.text:64405142

```

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```
.text:64405142 loc_64405142:
.text:64405142          push    offset byte_64443AF8

; demangled name: ATL::CStringT::operator=(char const *)
.text:64405147          call    ds:mfc90_820
.text:6440514D loc_6440514D:
.text:6440514D          cmp     dword_6450B970, ebx
.text:64405153          jl      short loc_64405188
.text:64405155          call    sub_6441C910
.text:6440515A          mov     dword_644F858C, ebx
.text:64405160          push   dword ptr [esi+2854h]
.text:64405166          push   offset aCdwsGuiPrepare ; "\nCDwsGui::PrepareInfoWindow: ↴
    ↳ sapgui env"...
.text:6440516B          push   dword ptr [esi+2848h]
.text:64405171          call   dbg
.text:64405176          add    esp, 0Ch
.text:64405179          mov    dword_644F858C, 2
.text:64405183          call   sub_6441C920
.text:64405188          or     [ebp+var_4], 0FFFFFFFh
.text:6440518C          lea    ecx, [ebp+var_14]

; demangled name: ATL::CStringT::~CStringT()
.text:6440518F          call   ds:mfc90_601
.text:64405195          call   __EH_epilog3
.text:6440519A          retn
.text:6440519A CDwsGui__PrepareInfoWindow endp
```

At the start of the function **ECX** contains a pointer to the object (since it is a `thiscall` ([53.1.1 on page 543](#))-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 aDataCompression ; "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
.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" ↴
    ↳ delete\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
```

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```
.text:6440506B          sub    eax, edx
.text:6440506D          sar    eax, 1
.text:6440506F          mov    [ebp+var_34], eax
.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
.text:64404C19
.text:64404C19 arg_0           = dword ptr 4
.text:64404C19
.text:64404C19 push   ebx
.text:64404C1A push   ebp
.text:64404C1B push   esi
.text:64404C1C push   edi
.text:64404C1D mov    edi, [esp+10h+arg_0]
.text:64404C21 mov    eax, [edi]
.text:64404C23 mov    esi, ecx ; ESI/ECX are pointers to some unknown object.
.text:64404C25 mov    [esi], eax
.text:64404C27 mov    eax, [edi+4]
.text:64404C2A mov    [esi+4], eax
.text:64404C2D mov    eax, [edi+8]
.text:64404C30 mov    [esi+8], eax
.text:64404C33 lea    eax, [edi+0Ch]
.text:64404C36 push   eax
.text:64404C37 lea    ecx, [esi+0Ch]

; demangled name: ATL::CStringT::operator=(class ATL::CStringT ... &)
.text:64404C3A call   ds:mfc90_817
.text:64404C40 mov    eax, [edi+10h]
.text:64404C43 mov    [esi+10h], eax
.text:64404C46 mov    al, [edi+14h]
.text:64404C49 mov    [esi+14h], al
.text:64404C4C mov    al, [edi+15h] ; copy byte from 0x15 offset
.text:64404C4F mov    [esi+15h], al ; to 0x15 offset in CDwsGui object
```

The function was called from the function named **CDwsGui::CopyOptions!** And thanks again for debugging information.

But the real answer is in **CDwsGui::Init()**:

```
.text:6440B0BF loc_6440B0BF:
.text:6440B0BF          mov    eax, [ebp+arg_0]
.text:6440B0C2          push  [ebp+arg_4]
.text:6440B0C5          mov    [esi+2844h], eax
.text:6440B0CB          lea    eax, [esi+28h] ; ESI is pointer to CDwsGui object
.text:6440B0CE          push  eax
.text:6440B0CF          call  CDwsGui__CopyOptions
```

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.

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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):

```
.text:64409D58      cmp    [esi+3Dh], bl ; ESI is pointer to CDwsGui object
.text:64409D5B      lea    ecx, [esi+2B8h]
.text:64409D61      setz   al
.text:64409D64      push   eax           ; arg_10 of CConnectionContext::CreateNetwork
.text:64409D65      push   dword ptr [esi+64h]

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
.text:64409D68      call   ds:mfc90_910
.text:64409D68          ; no arguments
.text:64409D6E      push   eax
.text:64409D6F      lea    ecx, [esi+2BCh]

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
.text:64409D75      call   ds:mfc90_910
.text:64409D75          ; no arguments
.text:64409D7B      push   eax
.text:64409D7C      push   esi
.text:64409D7D      lea    ecx, [esi+8]
.text:64409D80      call   CConnectionContext__CreateNetwork
```

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:

```
...
.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.

```
.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      set_EAX_to_1:
.text:64411E04      xor    eax, eax
.text:64411E06      inc    eax           ; EAX -> 1
.text:64411E07      jmp    short loc_64411E0B
.text:64411E09      set_EAX_to_0:
.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):

```
.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
.text:64406F99 loc_64406F99:
.text:64406F99          push    dword ptr [edi+2868h] ; int
.text:64406F9F          lea     edx, [ebp+7728h+var_77A4]
.text:64406FA2          push    edx      ; int
.text:64406FA3          push    30000   ; int
.text:64406FA8          lea     edx, [ebp+7728h+Dst]
.text:64406FAB          push    edx      ; Dst
.text:64406FAC          push    ecx      ; int
.text:64406FAD          push    eax      ; Src
.text:64406FAE          push    dword ptr [edi+28C0h] ; int
.text:64406FB4          call    sub_644055C5      ; actual compression routine
.text:64406FB9          add    esp, 1Ch
.text:64406FBC          cmp     eax, 0FFFFFFF6h
.text:64406FBF          jz    short loc_64407004
.text:64406FC1          cmp     eax, 1
.text:64406FC4          jz    loc_6440708C
.text:64406FCA          cmp     eax, 2
.text:64406FCD          jz    short loc_64407004
.text:64406FCF          push    eax
.text:64406FD0          push    offset aCompressionErr ; "compression error [rc = %d]- ↴
    ↳ program wi"...
.text:64406FD5          push    offset aGui_err_compre ; "GUI_ERR_COMPRESS"
.text:64406FDA          push    dword ptr [edi+28D0h]
.text:64406FE0          call    SapPcTxtRead
```

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 ; "\nERROR: 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 past⁸, 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.

83.2 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 remembered it, but then we got this error message «*Password logon no longer possible - too many failed attempts*», since he've made all these attempts in trying to recall it.

⁸<http://go.yurichev.com/17312>

83.2. SAP 6.0 PASSWORD CHECKING FUNCTIONS

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 TYPEINFODUMP⁹ utility for converting PDB files into something readable and grepable.

Here is an example of a function information + its arguments + its local variables:

```
FUNCTION ThVmcsEvent
    Address: 10143190 Size: 675 bytes Index: 60483 TypeIndex: 60484
    Type: int NEAR_C ThVmcsEvent (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
Flags: d0
PARAMETER serverName
    Address: Reg335+304 Size: 8 bytes Index: 60492 TypeIndex: 60493
    Type: unsigned short*
Flags: d0
STATIC_LOCAL_VAR func
    Address: 12274af0 Size: 8 bytes Index: 60495 TypeIndex: 60496
    Type: wchar_t*
Flags: 80
LOCAL_VAR admhead
    Address: Reg335+304 Size: 8 bytes Index: 60498 TypeIndex: 60499
    Type: unsigned char*
Flags: 90
LOCAL_VAR record
    Address: Reg335+64 Size: 204 bytes Index: 60501 TypeIndex: 60502
    Type: AD_RECORD
Flags: 90
LOCAL_VAR adlen
    Address: Reg335+296 Size: 4 bytes Index: 60508 TypeIndex: 60509
    Type: int
Flags: 90
```

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 variable¹⁰, that reflects the current trace level.

There are a lot of debugging inserts in the *disp+work.exe* file:

```
cmp    cs:ct_level, 1
jl    short loc_1400375DA
call   DpLock
lea     rcx, aDpxxtool4_c ; "dpxxtool4.c"
```

⁹<http://go.yurichev.com/17038>

¹⁰More about trace level: <http://go.yurichev.com/17039>

83.2. SAP 6.0 PASSWORD CHECKING FUNCTIONS

```
mov    edx, 4Eh          ; line
call   CTrcSaveLocation
mov    r8, cs:func_48
mov    rcx, cs:hd1        ; hd1
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:

```
FUNCTION rcui::AgiPassword::DiagISelection
FUNCTION ssf_password_encrypt
FUNCTION ssf_password_decrypt
FUNCTION password_logon_disabled
FUNCTION dySignSkipUserPassword
FUNCTION migrate_password_history
FUNCTION password_is_initial
FUNCTION rcui::AgiPassword::IsVisible
FUNCTION password_distance_ok
FUNCTION get_password_downwards_compatibility
FUNCTION dySignUnSkipUserPassword
FUNCTION rcui::AgiPassword::GetTypeName
FUNCTION `rcui::AgiPassword::AgiPassword'::`1'::dtor$2
FUNCTION `rcui::AgiPassword::AgiPassword'::`1'::dtor$0
FUNCTION `rcui::AgiPassword::AgiPassword'::`1'::dtor$1
FUNCTION usm_set_password
FUNCTION rcui::AgiPassword::TraceTo
FUNCTION days_since_last_password_change
FUNCTION rsecgrp_generate_random_password
FUNCTION rcui::AgiPassword::`scalar deleting destructor'
FUNCTION password_attempt_limit_exceeded
FUNCTION handle_incorrect_password
FUNCTION `rcui::AgiPassword::`scalar deleting destructor'':`1'::dtor$1
FUNCTION calculate_new_password_hash
FUNCTION shift_password_to_history
FUNCTION rcui::AgiPassword::GetType
FUNCTION found_password_in_history
FUNCTION `rcui::AgiPassword::`scalar deleting destructor'':`1'::dtor$0
FUNCTION rcui::AgiObj::IsaPassword
FUNCTION password_idle_check
FUNCTION SlicHwPasswordForDay
FUNCTION rcui::AgiPassword::IsaPassword
FUNCTION rcui::AgiPassword::AgiPassword
FUNCTION delete_user_password
FUNCTION usm_set_user_password
FUNCTION Password_API
FUNCTION get_password_change_for_SSO
FUNCTION password_in_USR40
FUNCTION rsec_agrp_abap_generate_random_password
```

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 *chkpass()* function –one of the password checking functions.

First, we would like to make sure that we are at the correct point:

83.2. SAP 6.0 PASSWORD CHECKING FUNCTIONS

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
    ↴      ", 0x41) (called from 0x1402f1060 (disp+work.exe!usrexist+0x3c0))
PID=2236|TID=2248|(0) disp+work.exe!chckpass -> 0x35
```

The call path is: *syssigni()* -> *DyISigni()* -> *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:00000001402ED56A      call    password_idle_check
.text:00000001402ED56F      cmp     eax, 33h
.text:00000001402ED572      jz      loc_1402EDB4E
.text:00000001402ED578      cmp     eax, 36h
.text:00000001402ED57B      jz      loc_1402EDB3D
.text:00000001402ED581      xor     edx, edx      ; usr02_READONLY
.text:00000001402ED583      mov     rcx, rbx      ; usr02
.text:00000001402ED586      call    password_attempt_limit_exceeded
.text:00000001402ED58B      test   al, al
.text:00000001402ED58D      jz      short loc_1402ED5A0
.text:00000001402ED58F      mov     eax, 35h
.text:00000001402ED594      add    rsp, 60h
.text:00000001402ED598      pop    r14
.text:00000001402ED59A      pop    r12
.text:00000001402ED59C      pop    rdi
.text:00000001402ED59D      pop    rsi
.text:00000001402ED59E      pop    rbx
.text:00000001402ED59F      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) disp+work.exe!password_attempt_limit_exceeded -> 1
PID=2744|TID=360|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) disp+work.exe!password_attempt_limit_exceeded -> 1
PID=2744|TID=360|We modify return value (EAX/RAX) of this function to 0
```

Excellent! We can successfully login now.

By the way, we can pretend we forgot the password, fixing the *chckpass()* function to return a value of 0 is enough to bypass the check:

```
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]
cmp   ax, 'N'
jz    short loc_1402E19D4
```

83.2. SAP 6.0 PASSWORD CHECKING FUNCTIONS

```
cmp    ax, 'n'
jz     short loc_1402E19D4
cmp    ax, '0'
jnz    short loc_1402E19DE
```

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++. It was apparently rewritten some time ago?

Chapter 84

Oracle RDBMS

84.1 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 84.1: `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$WAITSTAT"
.rodata:0800C4A8          dd 4
.rodata:0800C4AC          dd offset _2__STRING_10103_0 ; "NULL"
.rodata:0800C4B0          dd 3
.rodata:0800C4B4          dd 0
.rodata:0800C4B8          dd 195h
.rodata:0800C4BC          dd 4
.rodata:0800C4C0          dd 0
.rodata:0800C4C4          dd 0FFFEC1CBh
.rodata:0800C4C8          dd 3
.rodata:0800C4CC          dd 0
.rodata:0800C4D0          dd 0Ah
.rodata:0800C4D4          dd offset _2__STRING_10104_0 ; "V$WAITSTAT"
.rodata:0800C4D8          dd 4
.rodata:0800C4DC          dd offset _2__STRING_10103_0 ; "NULL"
```

84.1. V\$VERSION TABLE IN THE ORACLE RDBMS

```
.rodata:0800C4E0          dd 3
.rodata:0800C4E4          dd 0
.rodata:0800C4E8          dd 4Eh
.rodata:0800C4EC          dd 3
.rodata:0800C4F0          dd 0
.rodata:0800C4F4          dd 0FFFC003h
.rodata:0800C4F8          dd 4
.rodata:0800C4FC          dd 0
.rodata:0800C500          dd 5
.rodata:0800C504          dd offset _2__STRING_10105_0 ; "GV$BH"
.rodata:0800C508          dd 4
.rodata:0800C50C          dd offset _2__STRING_10103_0 ; "NULL"
.rodata:0800C510          dd 3
.rodata:0800C514          dd 0
.rodata:0800C518          dd 269h
.rodata:0800C51C          dd 15h
.rodata:0800C520          dd 0
.rodata:0800C524          dd 0FFFC1EDh
.rodata:0800C528          dd 8
.rodata:0800C52C          dd 0
.rodata:0800C530          dd 4
.rodata:0800C534          dd offset _2__STRING_10106_0 ; "V$BH"
.rodata:0800C538          dd 4
.rodata:0800C53C          dd offset _2__STRING_10103_0 ; "NULL"
.rodata:0800C540          dd 3
.rodata:0800C544          dd 0
.rodata:0800C548          dd 0F5h
.rodata:0800C54C          dd 14h
.rodata:0800C550          dd 0
.rodata:0800C554          dd 0FFFC1EEh
.rodata:0800C558          dd 5
.rodata:0800C55C          dd 0
```

By the way, often, while analysing 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»¹

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
-----
VIEW_DEFINITION
-----

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
-----
```

¹Draft ANSI C Standard (ANSI X3J11/88-090) (May 13, 1988) (yurichev.com)

84.1. V\$VERSION TABLE IN THE ORACLE RDBMS

VIEW_DEFINITION

```
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')` in the `kqf.o` file, we find it in the `kqfvip` table:

Listing 84.2: kqf.o

```
rodata:080185A0 kqfvip          dd offset _2__STRING_11126_0 ; DATA XREF: kqfgvcn+18
.rodata:080185A0                  ; kqfgvt+F
.rodata:080185A0                  ; "select inst_id,decode(indx,1,'data ↴
    ↴ bloc"...
.rodata:080185A4          dd offset kqfv459_c_0
.rodata:080185A8          dd 0
.rodata:080185AC          dd 0

...
.rodata:08019570          dd offset _2__STRING_11378_0 ; "select BANNER from GV$VERSION
    ↴ where in"...
.rodata:08019574          dd offset kqfv133_c_0
.rodata:08019578          dd 0
.rodata:0801957C          dd 0
.rodata:08019580          dd offset _2__STRING_11379_0 ; "select inst_id,decode(bitand((
    ↴ cfflg,1),0"...
.rodata:08019584          dd offset kqfv403_c_0
.rodata:08019588          dd 0
.rodata:0801958C          dd 0
.rodata:08019590          dd offset _2__STRING_11380_0 ; "select STATUS , NAME,
    ↴ IS_RECOVERY_DEST"...
.rodata:08019594          dd offset kqfv199_c_0
```

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 *fixed view*. As for `V$VERSION`, this table contains 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:

Listing 84.3: kqf.o

```
.rodata:080BBAC4 kqfv133_c_0      dd 6           ; DATA XREF: .rodata:08019574
.rodata:080BBAC8          dd offset _2__STRING_5017_0 ; "BANNER"
.rodata:080BBACC          dd 0
.rodata:080BBAD0          dd offset _2__STRING_0_0
```

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 tables² program, to gather all this information from Oracle RDBMS for Linux's object files. For `V$VERSION`, we find this:

Listing 84.4: Result of oracle tables

```
kqfviw_element.viewname: [V$VERSION] ?: 0x3 0x43 0x1 0xfffffc085 0x4
kqfvip_element.statement: [select BANNER from GV$VERSION where inst_id = USERENV('Instance')]
kqfvip_element.params:
[BANNER]
```

and:

Listing 84.5: Result of oracle tables

```
kqfviw_element.viewname: [GV$VERSION] ?: 0x3 0x26 0x2 0xfffffc192 0x1
```

²yurichev.com

84.1. V\$VERSION TABLE IN THE ORACLE RDBMS

```
kqfvip_element.statement: [select inst_id, banner from x$version]
kqfvip_element.params:
[INST_ID] [BANNER]
```

The `GV$VERSION` fixed view is different from `V$VERSION` only in that it contains 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:

```
SQL> select * from x$version;
ADDR          INDX      INST_ID
-----
BANNER
-----
ODBAF574      0          1
Oracle Database 11g Enterprise Edition Release 11.2.0.1.0 - Production
...
...
```

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 84.6: kqf.o

```
.rodata:0803CAC0          dd 9           ; element number 0x1f6
.rodata:0803CAC4          dd offset _2__STRING_13113_0 ; "X$VERSION"
.rodata:0803CAC8          dd 4
.rodata:0803CACC          dd offset _2__STRING_13114_0 ; "kqvt"
.rodata:0803CAD0          dd 4
.rodata:0803CAD4          dd 4
.rodata:0803CAD8          dd 0
.rodata:0803CADC          dd 4
.rodata:0803CAE0          dd 0Ch
.rodata:0803CAE4          dd 0FFFC075h
.rodata:0803CAE8          dd 3
.rodata:0803CAEC          dd 0
.rodata:0803CAF0          dd 7
.rodata:0803CAF4          dd offset _2__STRING_13115_0 ; "X$KQFSZ"
.rodata:0803CAF8          dd 5
.rodata:0803CAFC          dd offset _2__STRING_13116_0 ; "kqfsz"
.rodata:0803CB00          dd 1
.rodata:0803CB04          dd 38h
.rodata:0803CB08          dd 0
.rodata:0803CB0C          dd 7
.rodata:0803CB10          dd 0
.rodata:0803CB14          dd 0FFFC09Dh
.rodata:0803CB18          dd 2
.rodata:0803CB1C          dd 0
```

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 84.7: kqf.o

```
.rodata:0808C360 kqvt_c_0      kqftap_param <4, offset _2__STRING_19_0, 917h, 0, 0, 0, 4, 0, ↵
    ↴ 0>                                         ; DATA XREF: .rodata:08042680
.rodata:0808C360
.rodata:0808C360
.rodata:0808C384          kqftap_param <4, offset _2__STRING_20_0, 0B02h, 0, 0, 0, 4, 0, ↵
    ↴ 0> ; "INDX"                                ; "ADDR"
.rodata:0808C3A8          kqftap_param <7, offset _2__STRING_21_0, 0B02h, 0, 0, 0, 4, 0, ↵
    ↴ 0> ; "INST_ID"                            kqftap_param <6, offset _2__STRING_5017_0, 601h, 0, 0, 0, 50h, ↵
    ↴ 0, 0> ; "BANNER"
```

84.1. V\$VERSION TABLE IN THE ORACLE RDBMS

```
.rodata:0808C3F0          kqftap_param <0, offset _2__STRING_0_0, 0, 0, 0, 0, 0, 0, 0>
```

It contains information about all fields in the `X$VERSION` table. The only reference to this table is in the `kqftap` table:

Listing 84.8: `kqftap`

```
.rodata:08042680          kqftap_element <0, offset kqvt_c_0, offset kqvrow, 0> ; ↵
    ↴ element 0x1f6
```

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 tables³ utility too. For `X$VERSION` we get:

Listing 84.9: Result of oracle tables

```
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 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
```

```
_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
```

³yurichev.com

84.1. V\$VERSION TABLE IN THE ORACLE RDBMS

```

    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

loc_2CE110D: ; CODE XREF: _kqvrow_+29E00E6
    mov    edx, ds:off_628B09C[ecx*4] ; [ECX*4+628B09Ch]=0x2ce1116, 0x2ce11ac, 0x2ce11db, 0x2ce11f6, 0x2ce1236, 0x2ce127a
    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]=0xc98c938
    push   edx ; EDX=0
    push   edx ; EDX=0
    push   50h
    push   ecx ; ECX=0x8a172b4
    push   dword ptr [esi+10494h] ; [ESI+10494h]=0xc98cd58
    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=0xb2001
    and   edi, 0FFh ; 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"
    ↳ 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]=0xcdfe554
    push   eax ; EAX=0x65852100, "Oracle Database 11g Enterprise Edition Release %d.%d.%d.%d %s"
    ↳ Release %d.%d.%d.%d %s"
    mov    eax, [ebp+Dest] ; [EBP-10h]=0xce2ffb0
    push   eax ; EAX=0xce2ffb0
    call   ds:_imp_sprintf ; op1=MSVCR80.dll!sprintf tracing nested maximum level (1)
    ↳ reached, skipping this CALL
    add    esp, 38h
    mov    dword ptr [ebx], 1

loc_2CE1192: ; CODE XREF: _kqvrow_+FB
    ; _kqvrow_+128 ...
    test   edi, edi ; EDI=0
    jnz    __VInfreq_kqvrow
    mov    esi, [ebp+var_C] ; [EBP-0Ch]=0xcdfe248
    mov    edi, [ebp+var_4] ; [EBP-4]=0xc98c938
    mov    eax, ebx ; EBX=0xcdfe554
    mov    ebx, [ebp+var_8] ; [EBP-8]=0
    lea    eax, [eax+4] ; [EAX+4]=0xce2ffb0, "NLSRTL Version 11.2.0.1.0 - Production"
    ↳ ", "Oracle Database 11g Enterprise Edition Release 11.2.0.1.0 - Production", "PL/SQL "

```

84.1. V\$VERSION TABLE IN THE ORACLE RDBMS

```

↳ Release 11.2.0.1.0 - Production", "TNS for 32-bit Windows: Version 11.2.0.1.0 - ↳
↳ Production"

loc_2CE11A8: ; CODE XREF: _kqvrow_+29E00F6
    mov     esp, ebp
    pop     ebp
    retn            ; 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 ↵

```

84.2. X\$KSMLRU TABLE IN ORACLE RDBMS

```

    ↳ 11.2.0.1.0 - Production"
        mov      [ebx+4], esi      ; ESI=0xce2ffb0, "TNS for 32-bit Windows: Version 11.2.0.1.0 ↵
    ↳ - Production"
        mov      ecx, 50h
        mov      [ebp+var_18], ecx ; ECX=0x50
        push     ecx              ; ECX=0x50
        push     esi              ; ESI=0xce2ffb0, "TNS for 32-bit Windows: Version 11.2.0.1.0 ↵
    ↳ - Production"
        call    _lxvers          ; tracing nested maximum level (1) reached, skipping this ↵
    ↳ CALL
        add    esp, 10h
        mov    edx, [ebp+var_18] ; [EBP-18h]=0x50
        mov    dword ptr [ebx], 5
        test   edx, edx          ; EDX=0x50
        jnz    loc_2CE1192
        mov    edx, [ebp+var_14]
        mov    esi, [ebp+var_C]
        mov    eax, ebx
        mov    ebx, [ebp+var_8]
        mov    ecx, 5
        jmp    loc_2CE10F6

loc_2CE127A: ; DATA XREF: .rdata:0628B0B0
    mov    edx, [ebp+var_14] ; [EBP-14h]=0xc98c938
    mov    esi, [ebp+var_C] ; [EBP-0Ch]=0xcdfe248
    mov    edi, [ebp+var_4] ; [EBP-4]=0xc98c938
    mov    eax, ebx          ; EBX=0xcdfe554
    mov    ebx, [ebp+var_8] ; [EBP-8]=0

loc_2CE1288: ; CODE XREF: _kqvrow_+1F
    mov    eax, [eax+8]      ; [EAX+8]=0xce2ffb0, "NLSRTL Version 11.2.0.1.0 - Production"
    test   eax, eax          ; EAX=0xce2ffb0, "NLSRTL Version 11.2.0.1.0 - Production"
    jz    short loc_2CE12A7
    push   offset aXKqvvsnBuffer ; "x$kqvvsn buffer"
    push   eax                ; EAX=0xce2ffb0, "NLSRTL Version 11.2.0.1.0 - Production"
    mov    eax, [ebp+arg_C] ; [EBP+14h]=0x8a172b4
    push   eax                ; EAX=0x8a172b4
    push   dword ptr [edx+10494h] ; [EDX+10494h]=0xc98cd58
    call   _kgfrf             ; tracing nested maximum level (1) reached, skipping this ↵
    ↳ CALL
        add    esp, 10h

loc_2CE12A7: ; CODE XREF: _kqvrow_+1C1
    xor    eax, eax
    mov    esp, ebp
    pop    ebp
    retn   ; EAX=0
_kqvrow_ endp

```

Now it is easy to see that the row number is passed from outside. The function returns the string, constructing it as follows:

String 1	Using <code>vsnstr</code> , <code>vsnnnum</code> , <code>vsnban</code> global variables. Calling <code>sprintf()</code> .
String 2	Calling <code>kkxvsn()</code> .
String 3	Calling <code>lmxver()</code> .
String 4	Calling <code>npinli()</code> , <code>nrtnsvrs()</code> .
String 5	Calling <code>lxvers()</code> .

That's how the corresponding functions are called for determining each module's version.

84.2 X\$KSMLRU table in 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 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 tables⁴'s help, that contain all information about the X\$-tables. We can see here that the `ksmlrs()` function is called to prepare this table's elements:

Listing 84.10: Result of oracle tables

```

kqftab_element.name: [X$KSMLRU] ?: [ksmlr] 0x4 0x64 0x11 0xc 0xfffffc0bb 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=[KSMLRIDX] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[KSMLRDUR] ?: 0xb02 0x0 0x0 0x0 0x4 0x4 0x0
kqftap_param.name=[KSMLRSHRPOOL] ?: 0xb02 0x0 0x0 0x0 0x4 0x8 0x0
kqftap_param.name=[KSMLRCOM] ?: 0x501 0x0 0x0 0x0 0x14 0xc 0x0
kqftap_param.name=[KSMLRSIZ] ?: 0x2 0x0 0x0 0x0 0x4 0x20 0x0
kqftap_param.name=[KSMLRNUM] ?: 0x2 0x0 0x0 0x0 0x4 0x24 0x0
kqftap_param.name=[KSMLRHON] ?: 0x501 0x0 0x0 0x0 0x20 0x28 0x0
kqftap_param.name=[KSMLROHV] ?: 0xb02 0x0 0x0 0x0 0x4 0x48 0x0
kqftap_param.name=[KSMLRSES] ?: 0x17 0x0 0x0 0x0 0x4 0x4c 0x0
kqftap_param.name=[KSMLRADU] ?: 0x2 0x0 0x0 0x0 0x4 0x50 0x0
kqftap_param.name=[KSMLRNID] ?: 0x2 0x0 0x0 0x0 0x4 0x54 0x0
kqftap_param.name=[KSMLRNSD] ?: 0x2 0x0 0x0 0x0 0x4 0x58 0x0
kqftap_param.name=[KSMLRNCD] ?: 0x2 0x0 0x0 0x0 0x4 0x5c 0x0
kqftap_param.name=[KSMLRNED] ?: 0x2 0x0 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()` in the end. At the end of the `ksmsplu()` function we see a call to `memset()`:

Listing 84.11: 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

```

⁴yurichev.com

84.3. V\$TIMER TABLE IN ORACLE RDBMS

```
.text:00434C81      push    eax          ; Dst
.text:00434C82      call    __intel_fast_memset
.text:00434C87      add     esp, 0Ch
.text:00434C8A      mov     esp, ebp
.text:00434C8C      pop    ebp
.text:00434C8D      retn
.text:00434C8D _ksmsplu endp
```

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 behaviour, but as an experiment for locating a piece of code that we need, it perfectly suits our needs!

84.3 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 ⁵)

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

VIEW_DEFINITION

V\$TIMER

```
select HSECS from GV$TIMER where inst_id = USERENV('Instance')
```

```
SQL> select * from V$FIXED_VIEW_DEFINITION where view_name='GV$TIMER';
```

VIEW_NAME

VIEW_DEFINITION

GV\$TIMER

```
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`:

⁵<http://go.yurichev.com/17088>

Listing 84.12: Result of oracle tables

```
kqftab_element.name: [X$KSUTM] ?: [ksutm] 0x1 0x4 0x4 0x0 0xfffffc09b 0x3
kqftap_param.name=[ADDR] ?: 0x10917 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INDX] ?: 0x20b02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INST_ID] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[KSUTMTIM] ?: 0x1302 0x0 0x0 0x0 0x4 0x0 0x1e
kqftap_element.fn1=NULL
kqftap_element.fn2=NULL
```

When we try to find the string `KSUTMTIM`, we see it in this function:

```
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
ret
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):

Listing 84.13: ksu.o

```
ksugtm    proc near
var_1C      = byte ptr -1Ch
arg_4       = dword ptr  0Ch

push    ebp
mov     ebp, esp
sub    esp, 1Ch
lea     eax, [ebp+var_1C]
push    eax
call    slgcs
pop     ecx
mov     edx, [ebp+arg_4]
mov     [edx], eax
mov     eax, 4
mov     esp, ebp
pop     ebp
ret
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
```

84.3. V\$TIMER TABLE IN ORACLE RDBMS

Let's try again:

```
SQL> select * from V$TIMER;

HSECS
-----
27294929

SQL> select * from V$TIMER;

HSECS
-----
27295006

SQL> select * from V$TIMER;

HSECS
-----
27295167
```

Listing 84.14: tracer output

```
TID=2428|(0) oracle.exe!_ksugtm (0x0, 0xd76c5f0) (called from oracle.exe!__VInfreq_qerfxFetch)
  ↳ +0xfad (0x56bb6d5))
Argument 2/2
0D76C5F0: 38 C9                      "8.          "
TID=2428|(0) oracle.exe!_ksugtm () -> 0x4 (0x4)
Argument 2/2 difference
00000000: D1 7C A0 01                  ".|..        "
TID=2428|(0) oracle.exe!_ksugtm (0x0, 0xd76c5f0) (called from oracle.exe!__VInfreq_qerfxFetch)
  ↳ +0xfad (0x56bb6d5))
Argument 2/2
0D76C5F0: 38 C9                      "8.          "
TID=2428|(0) oracle.exe!_ksugtm () -> 0x4 (0x4)
Argument 2/2 difference
00000000: 1E 7D A0 01                  ".}..        "
TID=2428|(0) oracle.exe!_ksugtm (0x0, 0xd76c5f0) (called from oracle.exe!__VInfreq_qerfxFetch)
  ↳ +0xfad (0x56bb6d5))
Argument 2/2
0D76C5F0: 38 C9                      "8.          "
TID=2428|(0) oracle.exe!_ksugtm () -> 0x4 (0x4)
Argument 2/2 difference
00000000: BF 7D A0 01                  ".}..        "
```

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):

```
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
```

84.3. V\$TIMER TABLE IN ORACLE RDBMS

```

        mov    esp, ebp
        pop    ebp
        retn
slgcs    endp

```

(it is just a call to `sltrgatime64()` and division of its result by 10 ([43 on page 487](#)))

And win32-version:

```

_slgcs    proc near             ; CODE XREF: _dbgefgHtElResetCount+15
          ; _dbgerRunActions+1528
          db      66h
          nop
          push   ebp
          mov    ebp, esp
          mov    eax, [ebp+8]
          mov    dword ptr [eax], 0
          call   ds:_imp__GetTickCount@0 ; GetTickCount()
          mov    edx, eax
          mov    eax, 0CCCCCCCCDh
          mul    edx
          shr    edx, 3
          mov    eax, edx
          mov    esp, ebp
          pop    ebp
          retn
_slgcs    endp

```

It is just the result of `GetTickCount()`⁶ divided by 10 ([43 on page 487](#)).

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_tab_registry_0` to oracle tables⁷, now we can see how the table column's variables are *connected* to a specific functions:

```
[X$KSUTM] [kqfd_OPN_ksutm_c] [kqfd_tabl_fetch] [NULL] [NULL] [kqfd_DRN_ksutm_c]
[X$KSUSGIF] [kqfd_OPN_ksusg_c] [kqfd_tabl_fetch] [NULL] [NULL] [kqfd_DRN_ksusg_c]
```

OPN, apparently stands for *open*, and *DRN*, apparently, for *drain*.

Chapter 85

Handwritten assembly code

85.1 EICAR test file

This .COM-file is intended for testing antivirus software, it is possible to run in MS-DOS and it prints this string: "EICAR-STANDARD-ANTIVIRUS-TEST-FILE!"¹.

Its important property is that it's consists entirely of printable ASCII-symbols, which, in turn, makes it possible to create it in any text editor:

```
X50!P%@AP[4\PZX54(P^)7CC)7}EICAR-STANDARD-ANTIVIRUS-TEST-FILE!$H+H*
```

Let's decompile it:

```
; initial conditions: SP=0FFF Eh, SS:[SP]=0
0100 58          pop     ax
; AX=0, SP=0
0101 35 4F 21    xor     ax, 214Fh
; AX = 214Fh and SP = 0
0104 50          push    ax
; 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, SP = FFFCh, SS:[FFFC] = 140h 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
010E 58          pop     ax
; AX = 214Fh, BX = 140h, DX = 11Ch and SP = 0
010F 35 34 28    xor     ax, 2834h
; AX = 97Bh, BX = 140h, DX = 11Ch and SP = 0
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 7D 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.

¹[wikipedia](#)

85.1. EICAR TEST FILE

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 need to pass x86 code in string form.

Here is also a list of all x86 instructions which have printable opcodes: [A.6.5 on page 939](#).

Chapter 86

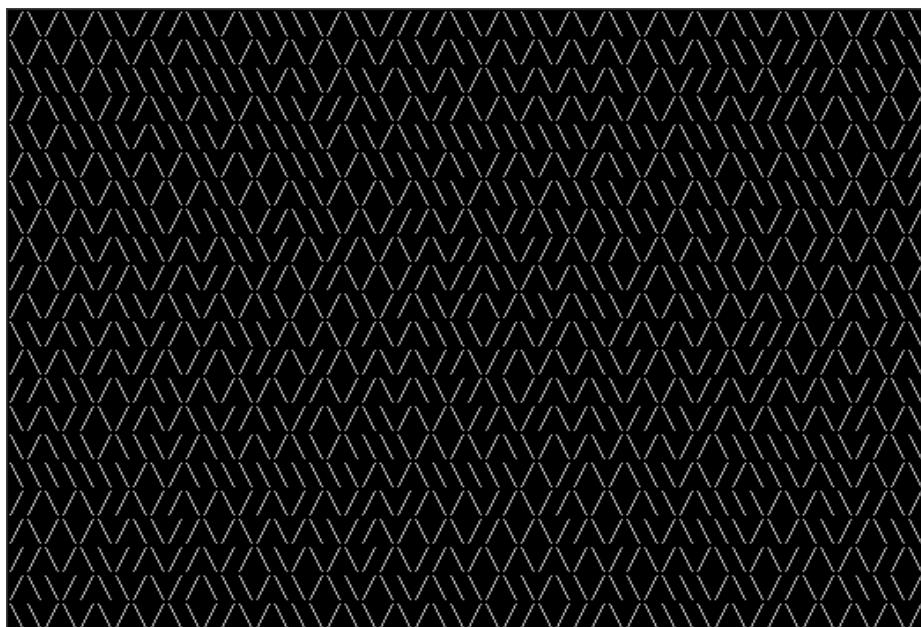
Demos

Demos (or demomaking) were an excellent exercise in mathematics, computer graphics programming and very tight x86 hand coding.

86.1 10 PRINT CHR\$(205.5+RND(1)); : GOTO 10

All examples here are MS-DOS .COM files.

In [al12] 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:



There are a few known implementations for 16-bit x86.

86.1.1 Trixter's 42 byte version

The listing was taken from his website¹, but the comments are mine.

```
00000000: B001      mov       al,1      ; set 40x25 video mode
00000002: CD10      int       010
00000004: 30FF      xor       bh,bh    ; set video page for int 10h call
00000006: B9D007    mov       cx,007D0  ; 2000 characters to output
00000009: 31C0      xor       ax,ax
0000000B: 9C        pushf
; get random value from timer chip
0000000C: FA        cli       ; disable interrupts
```

¹<http://go.yurichev.com/17305>

86.1. 10 PRINT CHR\$(205.5+RND(1)); : GOTO 10

```
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
```

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 BCD² value).

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.

86.1.2 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: B40E      mov     ah,00E
00000015: CD10      int     010
00000017: E2EA      loop    000000003
; exit to DOS
00000019: CD20      int     020
```

86.1.3 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 webpage³ 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.

²Binary-coded decimal

³<http://go.yurichev.com/17305>

86.1. 10 PRINT CHR\$(205.5+RND(1)); : GOTO 10

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 “herm1t” Baranovich did (11 and 10 bytes)⁴:

Listing 86.1: Andrey “herm1t” Baranovich: 11 bytes

```
00000000: B05C      mov     al,05C    ; '\'  
; read AL byte from random place of memory  
00000002: AE        scasd  
; 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: EBF5      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.

Listing 86.2: Peter Ferrie: 10 bytes

```
; AL is random at this point  
00000000: AE        scasd  
; CF is set according subtracting random memory byte from AL.  
; so it is somewhat random at this point  
00000001: D6        setalc  
; AL is set to 0xFF if CF=1 or to 0 if otherwise  
00000002: 242D      and     al,02D    ; '-'  
; AL here is 0x2D or 0  
00000004: 042F      add     al,02F    ; '/'  
; AL here is 0x5C or 0x2F  
00000006: CD29      int     029      ; output AL to screen  
00000008: EBF6      jmps    00000000 ; loop endlessly
```

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 need 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.

86.1.4 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.

⁴<http://go.yurichev.com/17087>

86.2 Mandelbrot set

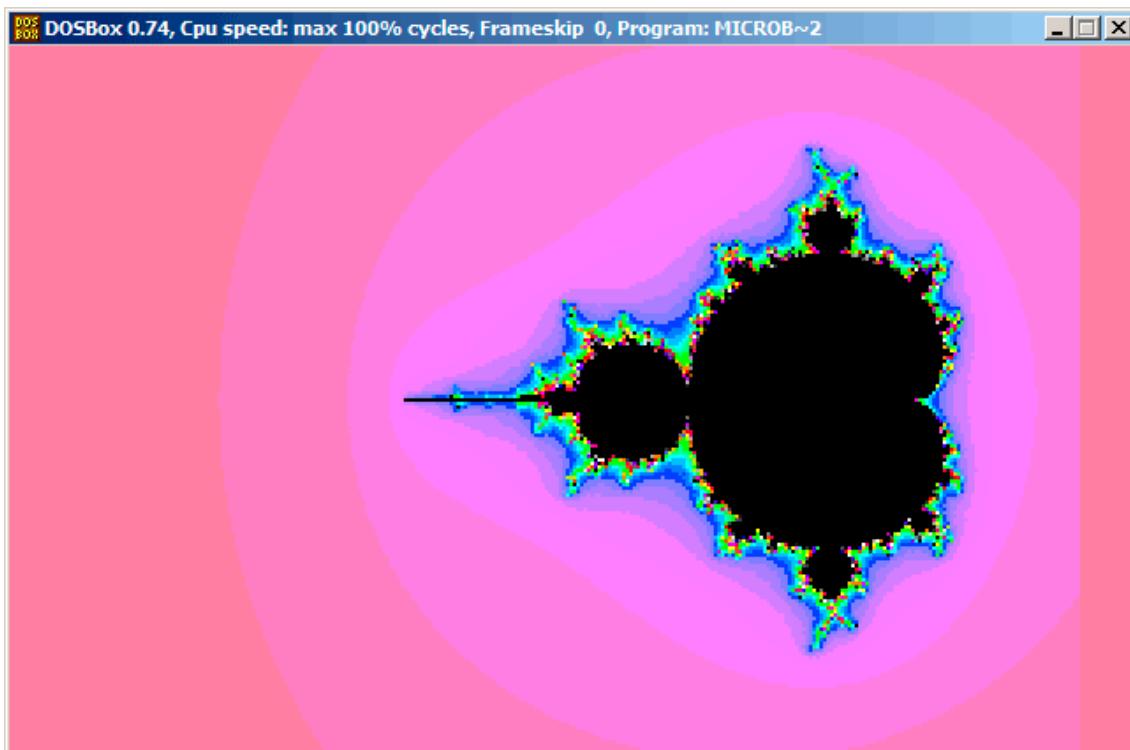
You know, if you magnify the coastline, it still looks like a coastline, and a lot of other things have this property. Nature has recursive algorithms that it uses to generate clouds and Swiss cheese and things like that.

Donald Knuth, interview 1993

Mandelbrot set is a fractal, which exhibits self-similarity. When you increase scale, you see that this characteristic pattern repeating infinitely.

Here is a demo⁵ 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.

⁵Download it [here](#),

86.2.1 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 need to know:

- Addition: $(a + bi) + (c + di) = (a + c) + (b + d)i$

In other words:

$$\text{Re}(\text{sum}) = \text{Re}(a) + \text{Re}(b)$$

$$\text{Im}(\text{sum}) = \text{Im}(a) + \text{Im}(b)$$

- Multiplication: $(a + bi)(c + di) = (ac - bd) + (bc + ad)i$

In other words:

$$\text{Re}(\text{product}) = \text{Re}(a) \cdot \text{Re}(c) - \text{Re}(b) \cdot \text{Re}(d)$$

$$\text{Im}(\text{product}) = \text{Im}(b) \cdot \text{Im}(c) + \text{Im}(a) \cdot \text{Im}(d)$$

- Square: $(a + bi)^2 = (a + bi)(a + bi) = (a^2 - b^2) + (2ab)i$

In other words:

$$\text{Re}(\text{square}) = \text{Re}(a)^2 - \text{Im}(a)^2$$

$$\text{Im}(\text{square}) = 2 \cdot \text{Re}(a) \cdot \text{Im}(a)$$

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 86.3: For complex numbers

```
def check_if_is_in_set(P):
    P_start=P
    iterations=0

    while True:
```

86.2. MANDELBROT SET

```
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

# 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 86.4: For integer numbers

```
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 article⁶, but we'll modify it so it will print the iteration numbers instead of some symbol ⁷:

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;

namespace Mnoj
{
    class Program
    {
        static void Main(string[] args)
```

⁶[wikipedia](#)

⁷Here is also the executable file: [beginners.re](#)

86.2. MANDELBROT SET

```
    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.WriteLine("{0,2:D} ", iterations);
        }
        Console.WriteLine("\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 mean that this point was wandering for 40 iterations but never got off limits. A number n less then 40 mean that point remained inside the bounds only for n iterations, then it went outside them.

86.2. MANDELBROT SET

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:

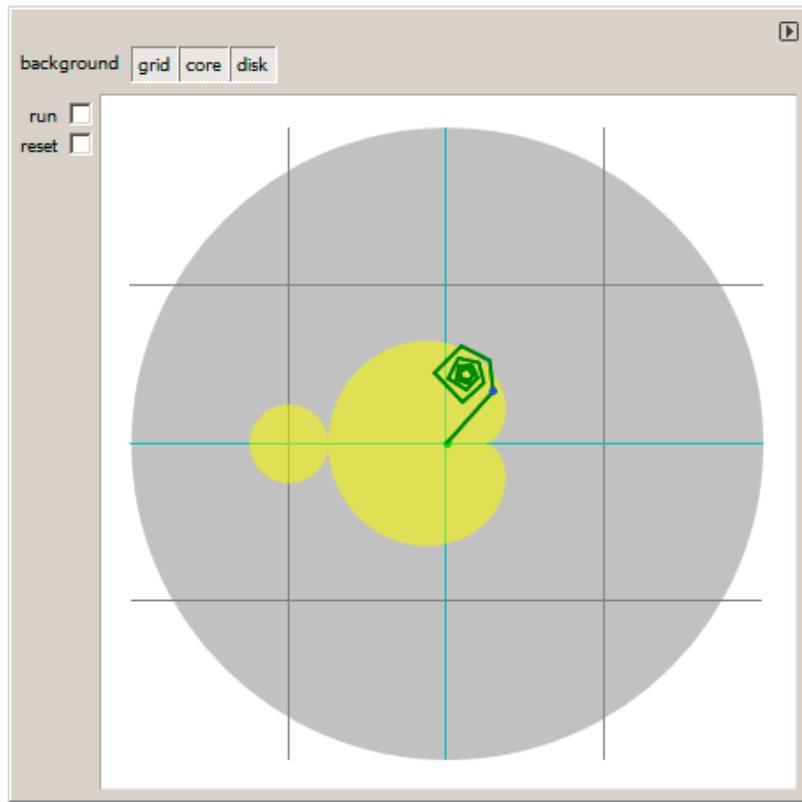


Figure 86.1: Click inside yellow area

This implies that the point we've clicked belongs to the Mandelbrot set.

86.2. MANDELBROT SET

Then we've clicked outside the yellow area and saw a much more chaotic point movement, which quickly went off bounds:

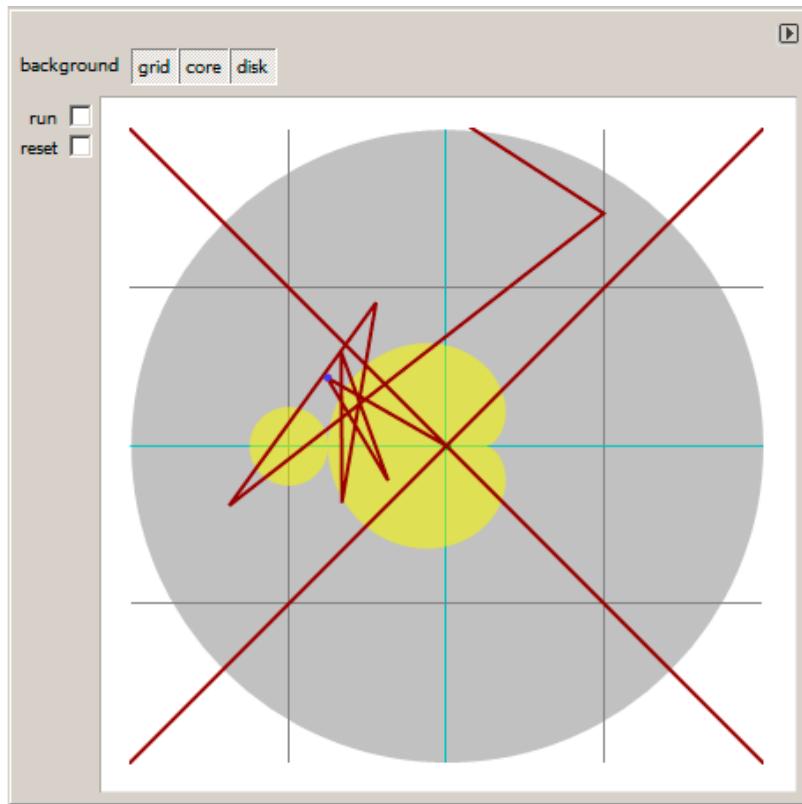


Figure 86.2: Click outside yellow area

This mean the point not belongs to Mandelbrot set.

Another good demo is available here: <http://go.yurichev.com/17310>.

86.2.2 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 is it, but let's also add comments:

Listing 86.5: Commented source code

```

1 ; X is column on screen
2 ; Y is row on screen
3
4
5 ; X=0, Y=0           X=319, Y=0
6 ; +----->
7 ;
8 ;
9 ;
10 ;
11 ;
12 ;
13 ; v
14 ; X=0, Y=199       X=319, Y=199
15
16
17 ; switch to VGA 320*200*256 graphics mode
18 mov al,13h
19 int 10h
20 ; initial BX is 0
21 ; initial DI is 0xFFFF
22 ; DS:BX (or DS:0) is pointing to Program Segment Prefix at this moment
23 ; ... first 4 bytes of which are CD 20 FF 9F
24 les ax,[bx]
25 ; ES:AX=9FFF:20CD
26
27 FillLoop:
28 ; set DX to 0. CWD works as: DX:AX = sign_extend(AX).
29 ; AX here 0x20CD (at startup) or less then 320 (when getting back after loop),
30 ; so DX will always be 0.
31 cwd
32 mov ax,di
33 ; AX is current pointer within VGA buffer
34 ; divide current pointer by 320
35 mov cx,320
36 div cx
37 ; DX (start_X) - remainder (column: 0..319); AX - result (row: 0..199)
38 sub ax,100
39 ; AX=AX-100, so AX (start_Y) now is in range -100..99
40 ; DX is in range 0..319 or 0x0000..0x013F
41 dec dh
42 ; DX now is in range 0xFF00..0x003F (-256..63)
43
44 xor bx,bx
45 xor si,si
46 ; BX (temp_X)=0; SI (temp_Y)=0
47
48 ; get maximal number of iterations
49 ; CX is still 320 here, so this is also maximal number of iteration
50 MandelLoop:
51 mov bp,si      ; BP = temp_Y
52 imul si,bx    ; SI = temp_X*temp_Y
53 add si,si     ; SI = SI*2 = (temp_X*temp_Y)*2
54 imul bx,bx    ; BX = BX^2 = temp_X^2
55 jo MandelBreak ; overflow?
56 imul bp,bp    ; BP = BP^2 = temp_Y^2
57 jo MandelBreak ; overflow?
58 add bx,bp     ; BX = BX+BP = temp_X^2 + temp_Y^2
59 jo MandelBreak ; overflow?
60 sub bx,bp     ; BX = BX-BP = temp_X^2 + temp_Y^2 - temp_Y^2 = temp_X^2
61 sub bx,bp     ; BX = BX-BP = temp_X^2 - temp_Y^2
62

```

86.2. MANDELBROT SET

```

63 ; correct scale:
64 sar bx,6      ; BX=BX/64
65 add bx,dx     ; BX=BX+start_X
66 ; now temp_X = temp_X^2 - temp_Y^2 + start_X
67 sar si,6      ; SI=SI/64
68 add si,ax     ; SI=SI+start_Y
69 ; now temp_Y = (temp_X*temp_Y)*2 + start_Y
70
71 loop MandelLoop
72
73 MandelBreak:
74 ; CX=iterations
75 xchg ax,cx
76 ; AX=iterations. store AL to VGA buffer at ES:[DI]
77 stosb
78 ; stosb also increments DI, so DI now points to the next point in VGA buffer
79 ; jump always, so this is eternal loop here
80 jmp FillLoop

```

Algorithm:

- Switch to 320×200 VGA video mode, 256 colors. $320 \times 200 = 64000$ (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: [97 on page 912](#).

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 0xFFFF 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.

- A 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 (was 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: remember 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 need to 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

86.2. MANDELBROT SET

places where the points are in the Mandelbrot set. The palette can be initialized at the program's start, but remember, 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 0xFFFF at the start⁸. That's OK, because the program works for all DI in the range of 0..0xFFFF 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.

86.2.3 My “fixed” version

Listing 86.6: My “fixed” version

```
1 org 100h
2 mov al,13h
3 int 10h
4
5 ; set palette
6 mov dx, 3c8h
7 mov al, 0
8 out dx, al
9 mov cx, 100h
10 inc dx
11 l00:
12 mov al, cl
13 shl ax, 2
14 out dx, al ; red
15 out dx, al ; green
16 out dx, al ; blue
17 loop l00
18
19 push 0a000h
20 pop es
21
22 xor di, di
23
24 FillLoop:
25 cwd
26 mov ax,di
27 mov cx,320
28 div cx
29 sub ax,100
30 sub dx,160
31
32 xor bx,bx
33 xor si,si
34
35 MandelLoop:
36 mov bp,si
37 imul si,bx
38 add si,si
39 imul bx,bx
40 jo MandelBreak
41 imul bp,bp
42 jo MandelBreak
43 add bx,bp
44 jo MandelBreak
45 sub bx,bp
46 sub bx,bp
```

⁸More information about initial register values: <http://go.yurichev.com/17004>

86.2. MANDELBROT SET

```
47
48    sar bx,6
49    add bx,dx
50    sar si,6
51    add si,ax
52
53    loop MandelLoop
54
55    MandelBreak:
56    xchg ax,cx
57    stosb
58    cmp di, OFA00h
59    jb FillLoop
60
61    ; wait for keypress
62    xor ax,ax
63    int 16h
64    ; set text video mode
65    mov ax, 3
66    int 10h
67    ; exit
68    int 20h
```

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)⁹.

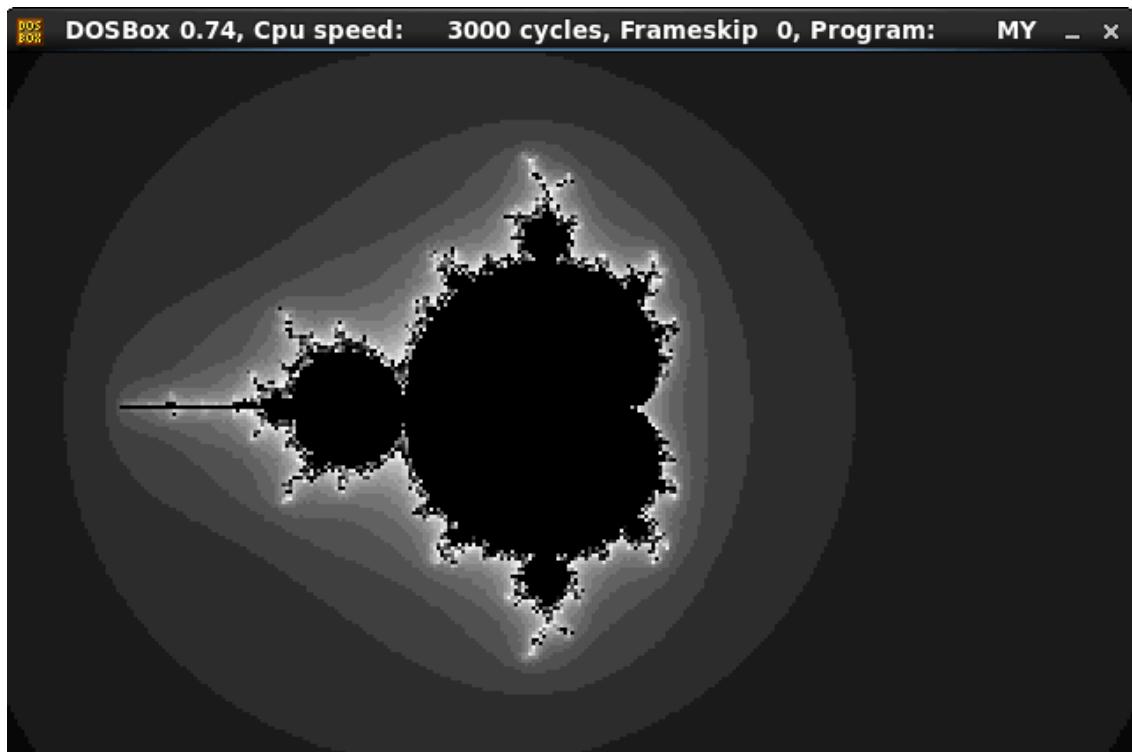


Figure 86.3: My “fixed” version

⁹You can experiment by yourself: get DosBox and NASM and compile it as: `nasm fiole.asm -fbin -o file.com`

Part IX

Examples of reversing proprietary file formats

Chapter 87

Primitive XOR-encryption

87.1 Norton Guide: simplest possible 1-byte XOR encryption

Norton Guide¹ 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:

The screenshot shows a hex editor window titled "view X86.NG - Far 2.0.1807 x64 Administrator". The file path is "U:\retrocomputing\MS-DOS\norton guide\X86.NG". The table has columns for address, hex, ASCII, and comments. The data consists of many 1A bytes (ASCII →) and other characters like 1B, 1C, 1D, etc., followed by strings of letters and symbols.

					866	372131	Col 0	0%
00000000170:	00 00 00 00 00 00 00 00 00	00 00 18 1A B3 1A 1D 1A				↑→ →→→		
00000000180:	02 1A 1A 1A 1A 1A 1A 1A 1A	1A 1A 1A 1A 1A 1A 1A 1A	0-----					
00000000190:	1A 1A 1A 1A FF 18 1A 1A	31 B5 18 1A E9 F2 18 1A	→→→↑→→1↓↑→Щ€↑→					
000000001A0:	69 77 19 1A B9 6B 19 1A	55 9A 19 1A 4E 1A 1A 1A	iw↓→k↓→Ub↓→N→→					
000000001B0:	1A 1A 1A 1A 7E 1A 1A 1A	1A 1A 1A 1A 74 1A 1A 1A	→→→~→→→→t→→					
000000001C0:	1A 1A 1A 1A 9E 1A 1A 1A	1A 1A 1A 1A 95 1A 1A 1A	→→→Ю→→→→X→→					
000000001D0:	1A 1A 1A 1A BA 1A 1A 1A	1A 1A 1A 1A B2 1A 1A 1A	→→→ →→→→■→→					
000000001E0:	1A 1A 1A 1A 59 4A 4F 1A	53 74 69 6E 68 6F 79 6E	→→→YJ0→Stinhoyn					
000000001F0:	73 75 74 3A 69 7F 6E 1A	48 7F 7D 73 69 6E 7F 68	sut:iан→Ha}sinoh					
00000000200:	69 1A 4A 68 75 6E 7F 79	6E 73 75 74 36 3A 6A 68	i→Jhunоynsut6:jh					
00000000210:	73 6C 73 76 7F 7D 7F 1A	5F 62 79 7F 6A 6E 73 75	slsvo}o→_byajnsu					
00000000220:	74 69 1A 5B 7E 7E 68 7F	69 69 73 74 7D 3A 77 75	ti→[~~haiist]:wu					
00000000230:	7E 7F 69 1A 55 6A 79 75	7E 7F 69 1A 1A 18 1A 51	~oi→Ujyu~oi→→↑Q					
00000000240:	1A 19 1A 12 1A 1A 1A 1A	1A 1A 1A 1A 1A 1A 1A	→↓→‡→→→→→→					
00000000250:	1A 1A 1A 1A 1A 1A 21	A4 19 1A 99 A8 1E 1A 3E	→→→→!д↓→Щи▲→→					
00000000260:	1A 1A 1A 1A 1A 1A 2E	1A 1A 1A 1A 1A 1A 50	→→→→.→→→→P					
00000000270:	1A 1A 1A 1A 1A 1A 5C	4A 4F 1A 53 74 69 6E 68	→→→→\J0→Stinh					
00000000280:	6F 79 6E 73 75 74 3A 69	7F 6E 1A 48 7F 7D 73 69	оynsut:iан→Ha}si					
00000000290:	6E 7F 68 69 36 3A 7E 7B	6E 7B 3A 6E 63 6A 7F 69	nahi6:~{n{:ncjoi					
000000002A0:	1A 1A 18 1A 33 1A 18 1A	1E 1A 1A 1A 1A 1A 1A	→→↑3→↑▲→→→→					
000000002B0:	1A 1A 1A 1A 1A 1A 1A	1A 1A 1A 1A AC C6 1E 1A	→→→→→→→→M ▲→					
000000002C0:	02 1A 1A 1A 1A 1A 1A 1A	32 1A 1A 1A 1A 1A 1A	0-----2→→→→					
000000002D0:	57 57 42 1A 53 74 69 6E	68 6F 79 6E 73 75 74 3A	MWB→Stinhoynsut:					
000000002E0:	69 7F 6E 1A 1A 1A 1A 8B	09 99 1A 1A 1A E5 E5 E5	iан→→→ЛоЩ→→xxx					
000000002F0:	E5 E5 E5 1A 1A 1A 1A 1A	1A 1A 1A 1A 1A 1A 08	xxx→→→→→→→→•					
00000000300:	19 8A 0C 1A 1A 2E 19 62	01 1A 1A 4D 19 CC 07 1A	↓K♀→→.↓b0→→M↓•→					
00000000310:	1A 63 19 72 3A 1A 1A 84	19 39 3E 1A 1A A9 19 1A	→с↓r:→→Д↓9→→й↓→					
00000000320:	33 1A 1A A7 19 7F 37 1A	1A CB 19 67 28 1A 1A 18	3→→з↓δ7→→T↓g(→→↑					

Figure 87.1: 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.

¹wikipedia

87.1. NORTON GUIDE: SIMPLEST POSSIBLE 1-BYTE XOR ENCRYPTION

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:

```

X86.NG          FUO EDITMODE      0000032F | Hiew 8.02 (c)SEN
00000170: 00 00 00 00-00 00 00 00-00 00 02 00-A9 00 07 00  й
00000180: 18 00 00 00-00 00 00 00-00 00 00 00-00 00 00 00  0
00000190: 00 00 00 00-E5 02 00 00-2B AF 02 00-F3 E8 02 00  х +н єш
000001A0: 73 6D 03 00-A3 71 03 00-4F 80 03 00-54 00 00 00  sm гq ОА Т
000001B0: 00 00 00 00-64 00 00 00-00 00 00 00-6E 00 00 00  d  н
000001C0: 00 00 00 00-84 00 00 00-00 00 00 00-8F 00 00 00  А  П
000001D0: 00 00 00 00-A0 00 00 00-00 00 00 00-A8 00 00 00  а  и
000001E0: 00 00 00 00-43 50 55 00-49 6E 73 74-72 75 63 74  CPU Instruct
000001F0: 69 6F 6E 20-73 65 74 00-52 65 67 69-73 74 65 72  ion set Register
00000200: 73 00 50 72-6F 74 65 63-74 69 6F 6E-2C 20 70 72  s Protection, pr
00000210: 69 76 69 6C-65 67 65 00-45 78 63 65-70 74 69 6F  ivilege Exceptio
00000220: 6E 73 00 41-64 64 72 65-73 73 69 6E-67 20 6D 6F  ns Addressing mo
00000230: 64 65 73 00-4F 70 63 6F-64 65 73 00-00 02 00 4B  des Opcodes  К
00000240: 00 03 00 08-00 00 00 00-00 00 00 00-00 00 00 00 00  0  0
00000250: 00 00 00 00-00 00 00 3B-BE 03 00 83-B2 04 00 24  ;= Г $ 4 J
00000260: 00 00 00 00-00 00 00 34-00 00 00 00-00 00 00 00 4A  FPU Instr
00000270: 00 00 00 00-00 00 00 46-50 55 00 49-6E 73 74 72  uction set Regis
00000280: 75 63 74 69-6F 6E 20 73-65 74 00 52-65 67 69 73  ter, data types
00000290: 74 65 72 73-2C 20 64 61-74 61 20 74-79 70 65 73
000002A0: 00 00 02 00-29 00 02 00-04 00 00 00-00 00 00 00 00  ) 0 0
000002B0: 00 00 00 00-00 00 00 00-00 00 00 00-B6 DC 04 00  ||#
000002C0: 18 00 00 00-00 00 00 00-28 00 00 00-00 00 00 00 00  0  ( 
000002D0: 4D 4D 58 00-49 6E 73 74-72 75 63 74-69 6F 6E 20  MMX Instruction
000002E0: 73 65 74 00-00 00 00 91-13 83 00 00-00 FF FF FF  set C#Г
000002F0: FF FF FF 00-00 00 00 00-00 00 00 00-00 00 00 12  0
00000300: 03 90 16 00-00 34 03 78-1B 00 00 57-03 D6 1D 00  БР 40x0 W 0
00000310: 00 79 03 68-20 00 00 9E-03 23 24 00-00 B3 03 00  yh 10#$ 0
00000320: 29 00 00 BD-03 65 2D 00-00 D1 03 7D-32 00 00 02  ) JBe- =}2 0

```

Figure 87.2: Hiew XORing with 0x1A

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 was 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.

More about Norton Guide's file format: <http://go.yurichev.com/17317>.

87.1.1 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.

Listing 87.1: Wolfram Mathematica 10

```

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"];

```

87.1. NORTON GUIDE: SIMPLEST POSSIBLE 1-BYTE XOR ENCRYPTION

```
In[5]:= Entropy[2, decrypted] // N
Out[5]= 5.62724

In[6]:= Entropy[2, ExampleData[{"Text", "ShakespearesSonnets"}]] // N
Out[6]= 4.42366
```

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>.

One more word about base of entropy

Wolfram Mathematica calculates entropy with base of e (base of the natural logarithm), and the UNIX *ent* utility² 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/>

87.2 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):

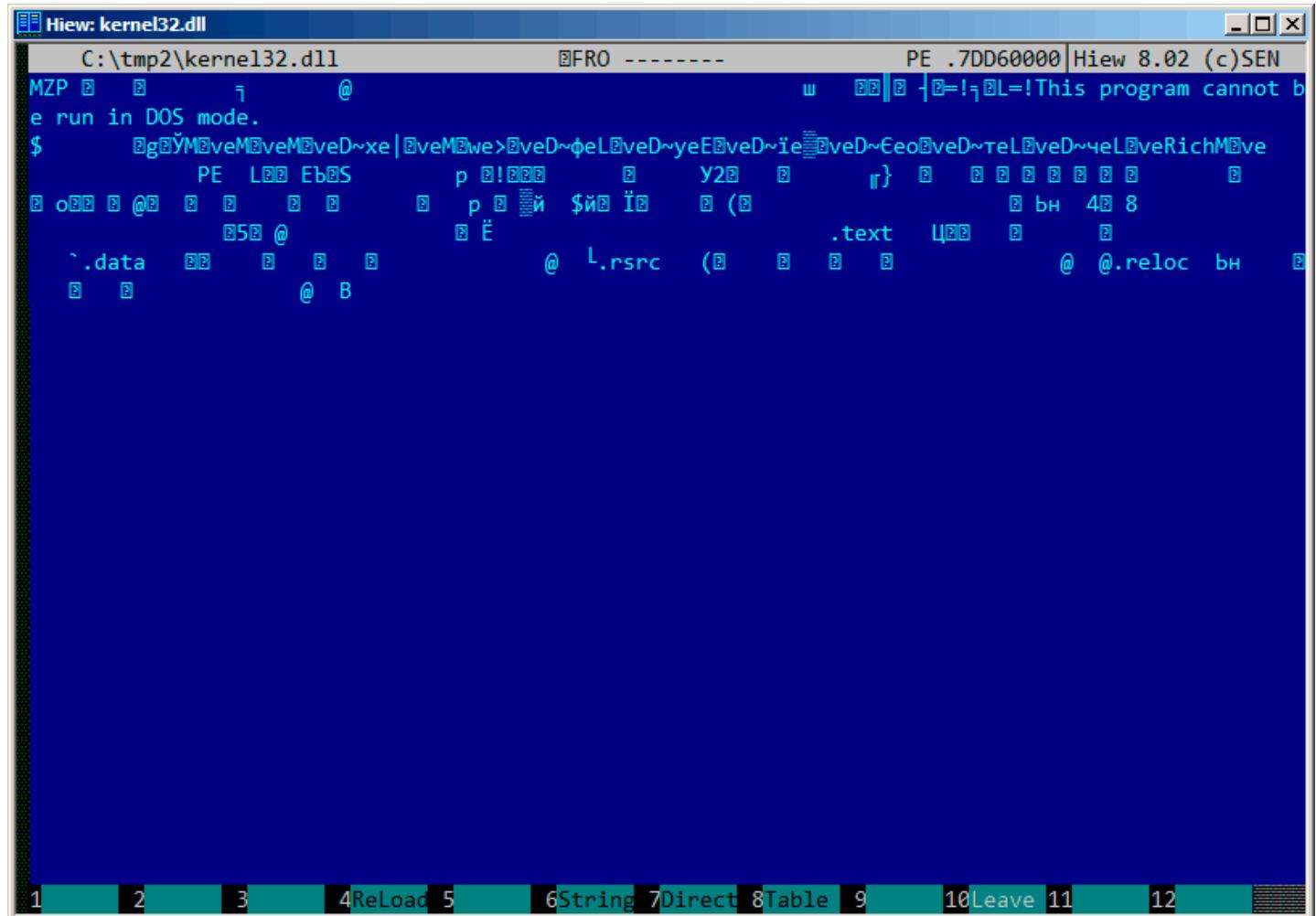


Figure 87.3: Original file

87.2. SIMPLEST POSSIBLE 4-BYTE XOR ENCRYPTION

Here it is “encrypted” with a 4-byte key:

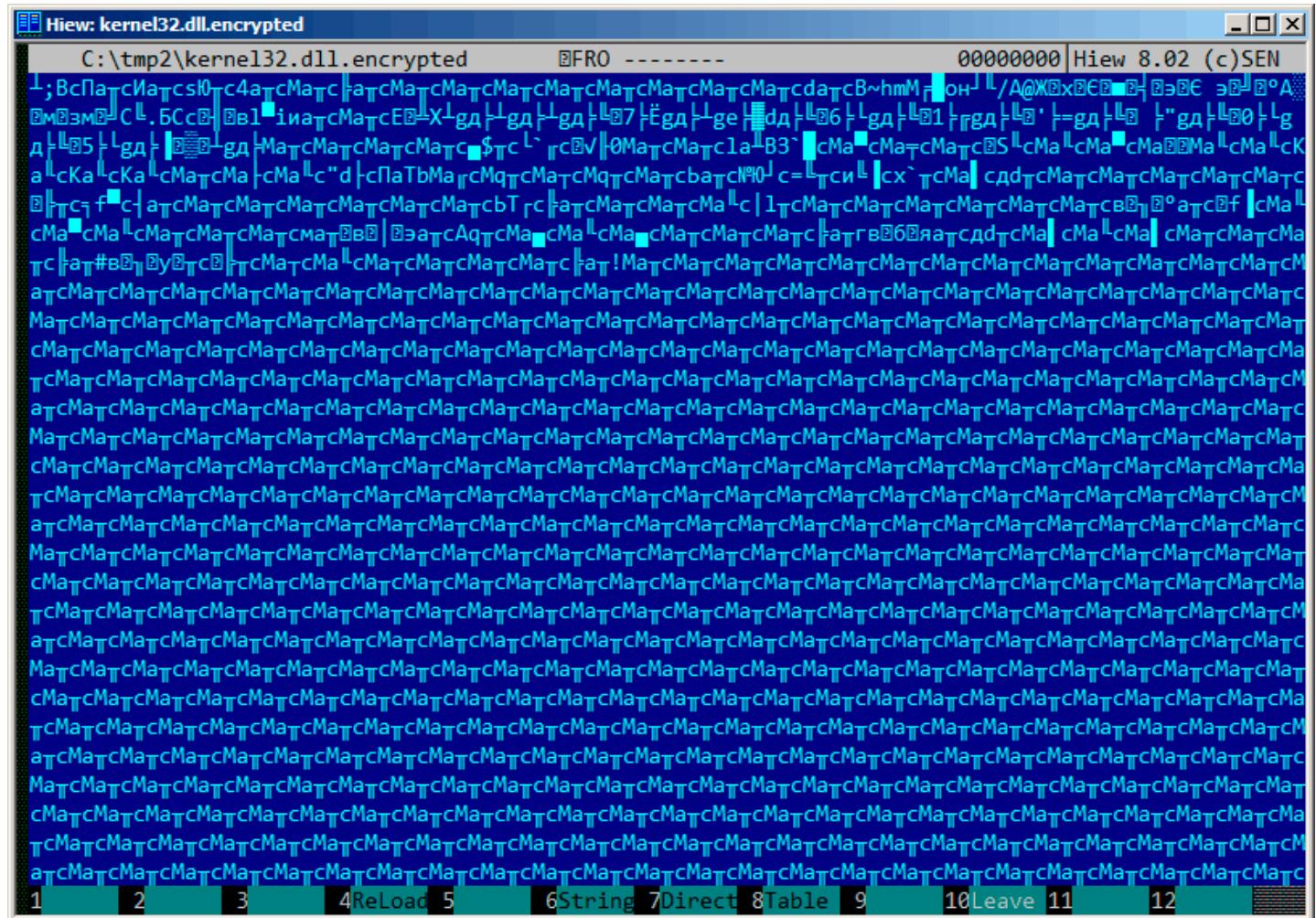


Figure 87.4: “Encrypted” file

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.

87.2. SIMPLEST POSSIBLE 4-BYTE XOR ENCRYPTION

Here is the beginning of a PE-header in hexadecimal form:

```

Hiew: kernel32.dll
C:\tmp2\kernel32.dll          FRO ----- PE .7DD60290|Hiew 8.02 (c)SEN
.7DD600E0: 00 00 00 00-00 00 00 00-50 45 00 00-4C 01 04 00      PE L@@
.7DD600F0: 85 9A 15 53-00 00 00 00-00 00 00 00-E0 00 02 21 E@@S      p @!
.7DD60100: 0B 01 09 00-00 00 0D 00-00 00 03 00-00 00 00 00 @@S      @@
.7DD60110: 93 32 01 00-00 00 01 00-00 00 0D 00-00 00 D6 7D Y2@      @     @}
.7DD60120: 00 00 01 00-00 00 01 00-06 00 01 00-06 00 01 00 @@S      @ @ @ @ @
.7DD60130: 06 00 01 00-00 00 00 00-00 00 11 00-00 00 01 00 @@S      @ @     @
.7DD60140: AE 05 11 00-03 00 40 01-00 00 04 00-00 10 00 00 o@@S @@@@ @ @
.7DD60150: 00 00 10 00-00 10 00 00-00 00 00 00-10 00 00 00 @@S      @ @     @
.7DD60160: 70 FF 0B 00-B1 A9 00 00-24 A9 0C 00-F4 01 00 00 p @@@ $й@ й@
.7DD60170: 00 00 0F 00-28 05 00 00-00 00 00 00-00 00 00 00 @@S      @ (@
.7DD60180: 00 00 00 00-00 00 00 00-00 00 10 00-9C AD 00 00 @@S      @ бн
.7DD60190: 34 07 0D 00-38 00 00 00-00 00 00 00-00 00 00 00 4@ 8
.7DD601A0: 00 00 00 00-00 00 00 00-00 00 00 00-00 00 00 00 @@S      @
.7DD601B0: 10 35 08 00-40 00 00 00-00 00 00 00-00 00 00 00 @@S      @
.7DD601C0: 00 00 01 00-F0 0D 00 00-00 00 00 00-00 00 00 00 @@S      @
.7DD601D0: 00 00 00 00-00 00 00 00-00 00 00 00-00 00 00 00 @@S      @
.7DD601E0: 2E 74 65 78-74 00 00 00-96 07 0C 00-00 00 01 00 .text    Ц@@@     @
.7DD601F0: 00 00 0D 00-00 00 01 00-00 00 00 00-00 00 00 00 @@S      @
.7DD60200: 00 00 00 00-20 00 00 60-2E 64 61 74-61 00 00 00 ` .data
.7DD60210: 0C 10 00 00-00 00 0E 00-00 00 01 00-00 00 0E 00 @@S      @ @ @ @
.7DD60220: 00 00 00 00-00 00 00 00-00 00 00 00-40 00 00 C0 @@S      @ L
.7DD60230: 2E 72 73 72-63 00 00 00-28 05 00 00-00 00 0F 00 .rsrc    (@ @
.7DD60240: 00 00 01 00-00 00 0F 00-00 00 00 00-00 00 00 00 @@S      @ @
.7DD60250: 00 00 00 00-40 00 00 40-2E 72 65 6C-6F 63 00 00 @@S      @ @.reloc
.7DD60260: 9C AD 00 00-00 00 10 00-00 00 01 00-00 00 10 00 бн      @ @ @
.7DD60270: 00 00 00 00-00 00 00 00-00 00 00 00-40 00 00 42 @@S      @ B
.7DD60280: 00 00 00 00-00 00 00 00-00 00 00 00-00 00 00 00 @@S      @
.7DD60290: 00 00 00 00-00 00 00 00-00 00 00 00-00 00 00 00 @@S      @

```

1Global 2FilBlk 3CryBlk 4ReLoad 5 6String 7Direct 8Table | 9 10Leave 11 12AddNam

Figure 87.5: PE-header

87.2. SIMPLEST POSSIBLE 4-BYTE XOR ENCRYPTION

Here it is “encrypted”:

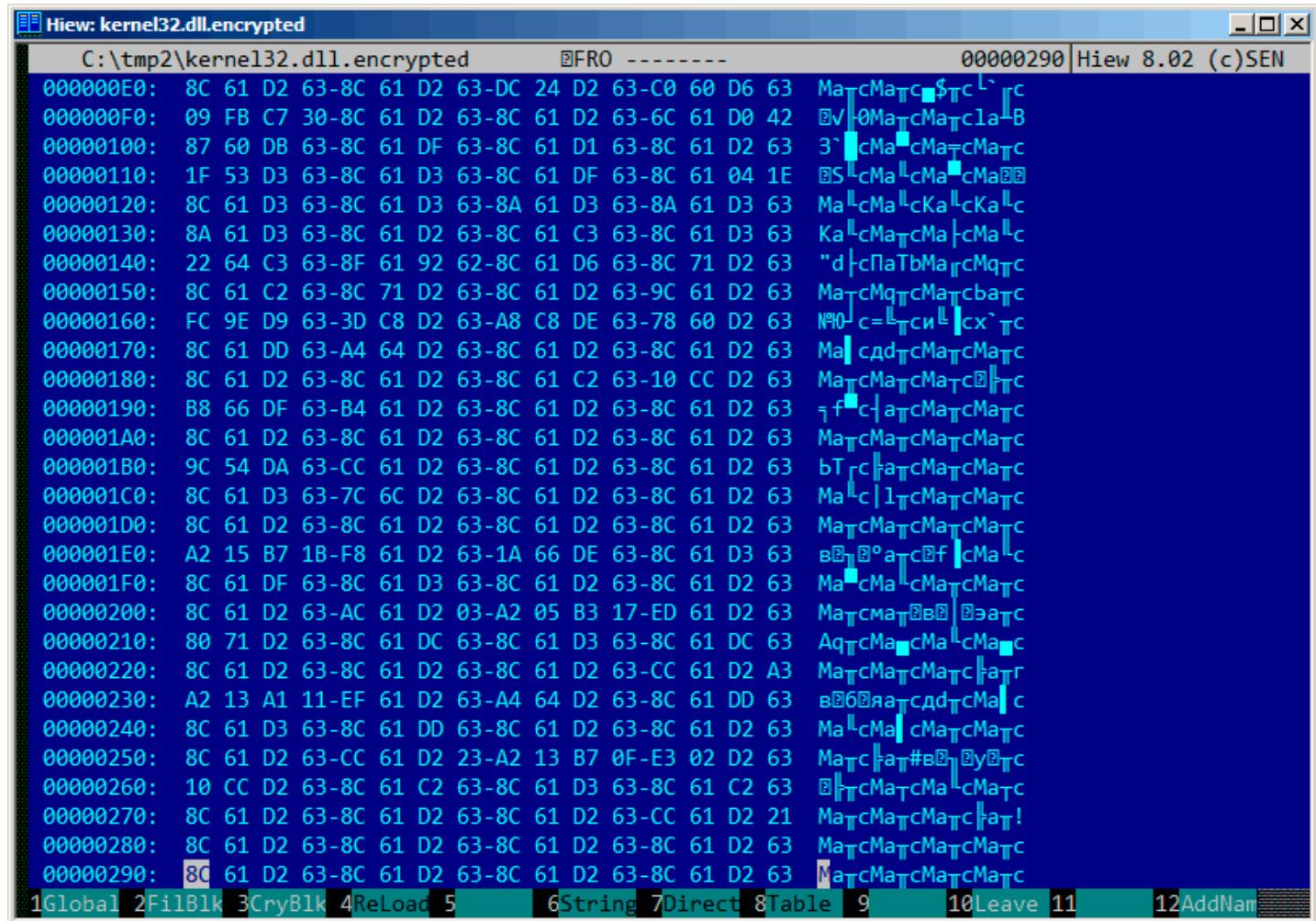


Figure 87.6: “Encrypted” PE-header

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 remember these properties of PE-files: 1) PE-header has many zero-filled areas; 2) all PE-sections are padded with zeroes 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>.

87.2.1 Exercise

- <http://challenges.re/50>

Chapter 88

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 on other planets, and so on¹.

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.

¹It 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 88.1: Mine: state 1

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:



Figure 88.2: Mine: state 2

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:

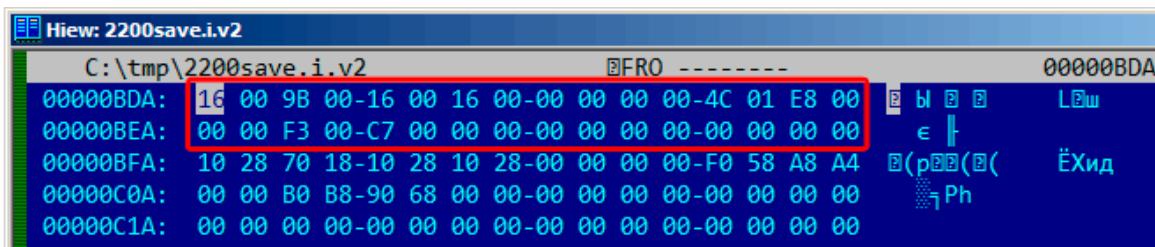
```
...> FC /b 2200save.i.v1 2200SAVE.I.V2  
Comparing files 2200save.i.v1 and 2200SAVE.I.V2  
00000016: 0D 04  
00000017: 03 04  
0000001C: 1F 1E  
00000146: 27 3B  
00000BDA: 0E 16  
00000BDC: 66 9B  
00000BDE: 0E 16  
00000BE0: 0E 16  
00000BE6: DB 4C  
00000BE7: 00 01  
00000BE8: 99 E8  
00000BEC: A1 F3  
00000BEE: 83 C7  
00000BFB: A8 28  
00000BFD: 98 18  
00000BFF: A8 28  
00000C01: A8 28  
00000C07: D8 58  
00000C09: E4 A4  
00000C0D: 38 B8  
00000C0F: E8 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. 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](#).

Here is the new version of file opened in Hiew, we marked the values related to the resources mined in the game:



Hiew: 2200save.i.v2

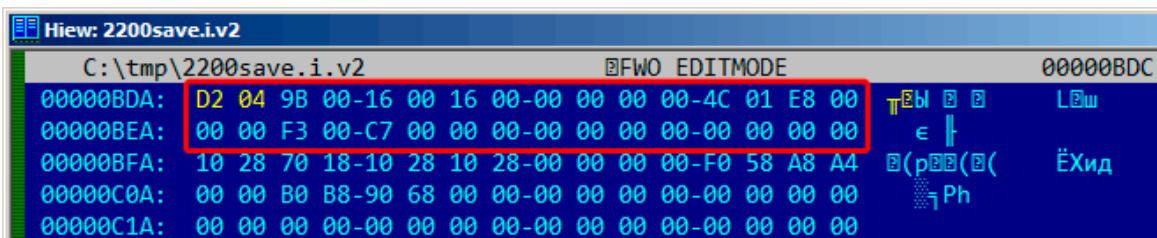
C:\tmp\2200save.i.v2

	00000BDA	00000BEA	00000BFA	00000C0A	00000C1A
00000BDA:	16 00 9B 00-16 00 16 00-00 00 00 00-4C 01 E8 00	00 00 F3 00-C7 00 00 00-00 00 00 00-00 00 00 00	10 28 70 18-10 28 10 28-00 00 00 00-F0 58 A8 A4	00 00 B0 B8-90 68 00 00-00 00 00 00-00 00 00 00	00 00 00 00-00 00 00 00-00 00 00 00-00 00 00 00
00000BEA:	16 00 9B 00-16 00 16 00-00 00 00 00-4C 01 E8 00	00 00 F3 00-C7 00 00 00-00 00 00 00-00 00 00 00	10 28 70 18-10 28 10 28-00 00 00 00-F0 58 A8 A4	00 00 B0 B8-90 68 00 00-00 00 00 00-00 00 00 00	00 00 00 00-00 00 00 00-00 00 00 00-00 00 00 00

Figure 88.3: Hiew: state 1

Let's check each, and these are. 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):



Hiew: 2200save.i.v2							
C:\tmp\2200save.i.v2	FWD	EDITMODE	00000BDC	Текущий	Левый	Слева	Справа
00000BDA:	D2	04	9B	00-16	00 16	00-00	00 00 00-4C 01 E8 00
00000BEA:	00	00	F3	00-C7	00 00	00-00	00 00 00-00 00 00 00
00000BFA:	10	28	70	18-10	28 10	28-00	00 00 00-F0 58 A8 A4
00000C0A:	00	00	B0	B8-90	68 00	00-00	00 00 00-00 00 00 00
00000C1A:	00	00	00	00-00	00 00	00-00	00 00 00-00 00 00 00

Figure 88.4: Hiew: let's write 1234 (0x4D2) there

Then we will load the changed file in the game and took a look at mine statistics:



Figure 88.5: Let's check for hydrogen value

So yes, this is it.

Now let's try to finish the game as soon as possible, set the maximal values everywhere:

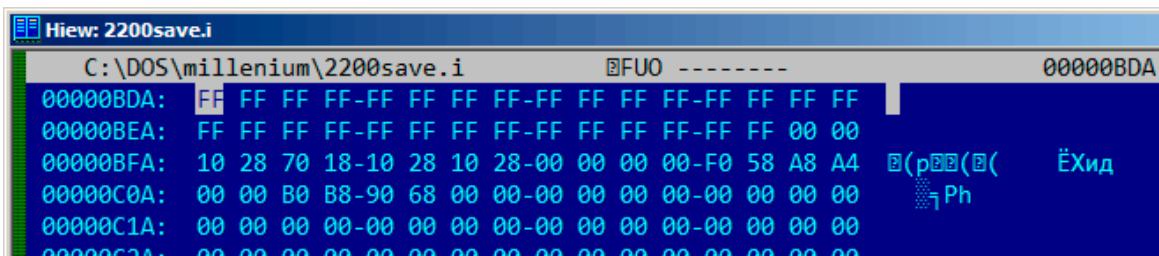


Figure 88.6: Hiew: let's set maximal values

0xFFFF is 65535, so yes, we now have a lot of resources:

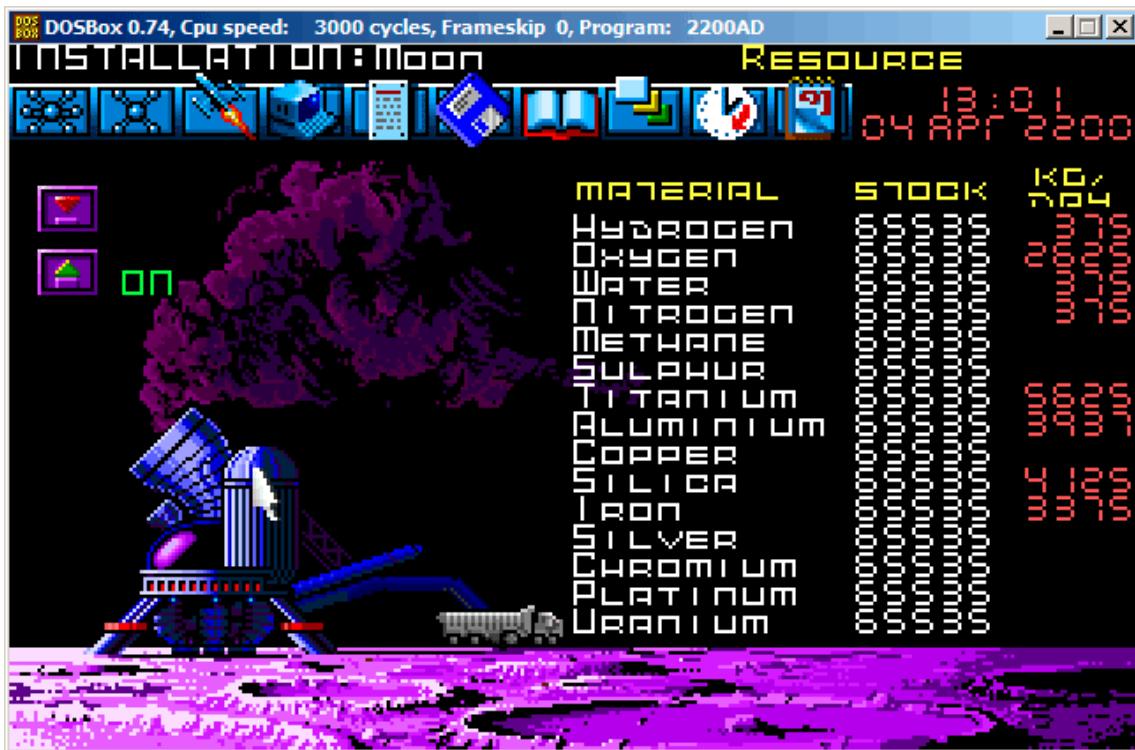


Figure 88.7: All resources are 65535 (0xFFFF) indeed

Let's skip some "days" in the game and oops! We have a lower amount of some resources:



Figure 88.8: Resource variables overflow

That's just overflow. The game's developer probably 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 was 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: [66.4 on page 687](#).

Chapter 89

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 location	call type	entry point	argument values in hex (? means dubious value)
_kqvrow()		00000000	
_opifch2() +2729	CALLptr	00000000	23D4B914 E47F264 1F19AE2 EB1C8A8 1
_kpoal8() +2832	CALLrel	_opifch2()	89 5 EB1CC74
_opiopr() +1248	CALLreg	00000000	5E 1C EB1F0A0
_ttcpip() +1051	CALLreg	00000000	5E 1C EB1F0A0 0
_opitsk() +1404	CALL???	00000000	C96C040 5E EB1F0A0 0 EB1ED30 EB1F1CC 53E52E 0 EB1F1F8
_opiino() +980	CALLrel	_opitsk()	0 0
_opiopr() +1248	CALLreg	00000000	3C 4 EB1FBF4
_opidrv() +1201	CALLrel	_opiopr()	3C 4 EB1FBF4 0
_sou2o() +55	CALLrel	_opidrv()	3C 4 EB1FBF4
_opimai_real() +124	CALLrel	_sou2o()	EB1FC04 3C 4 EB1FBF4
_opimai() +125	CALLrel	_opimai_real()	2 EB1FC2C
_OracleThreadStart@ 4() +830	CALLrel	_opimai()	2 EB1FF6C 7C88A7F4 EB1FC34 0 EB1FD04
77E6481C	CALLreg	00000000	E41FF9C 0 0 E41FF9C 0 EB1FFC4
00000000	CALL???	00000000	

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 `orawtc8.sym` file that comes with the `orawtc8.dll` file in Oracle 8.1.7 ¹.

¹We can choose an ancient Oracle RDBMS version intentionally due to the smaller size of its modules

Here is the file opened in Hiew:

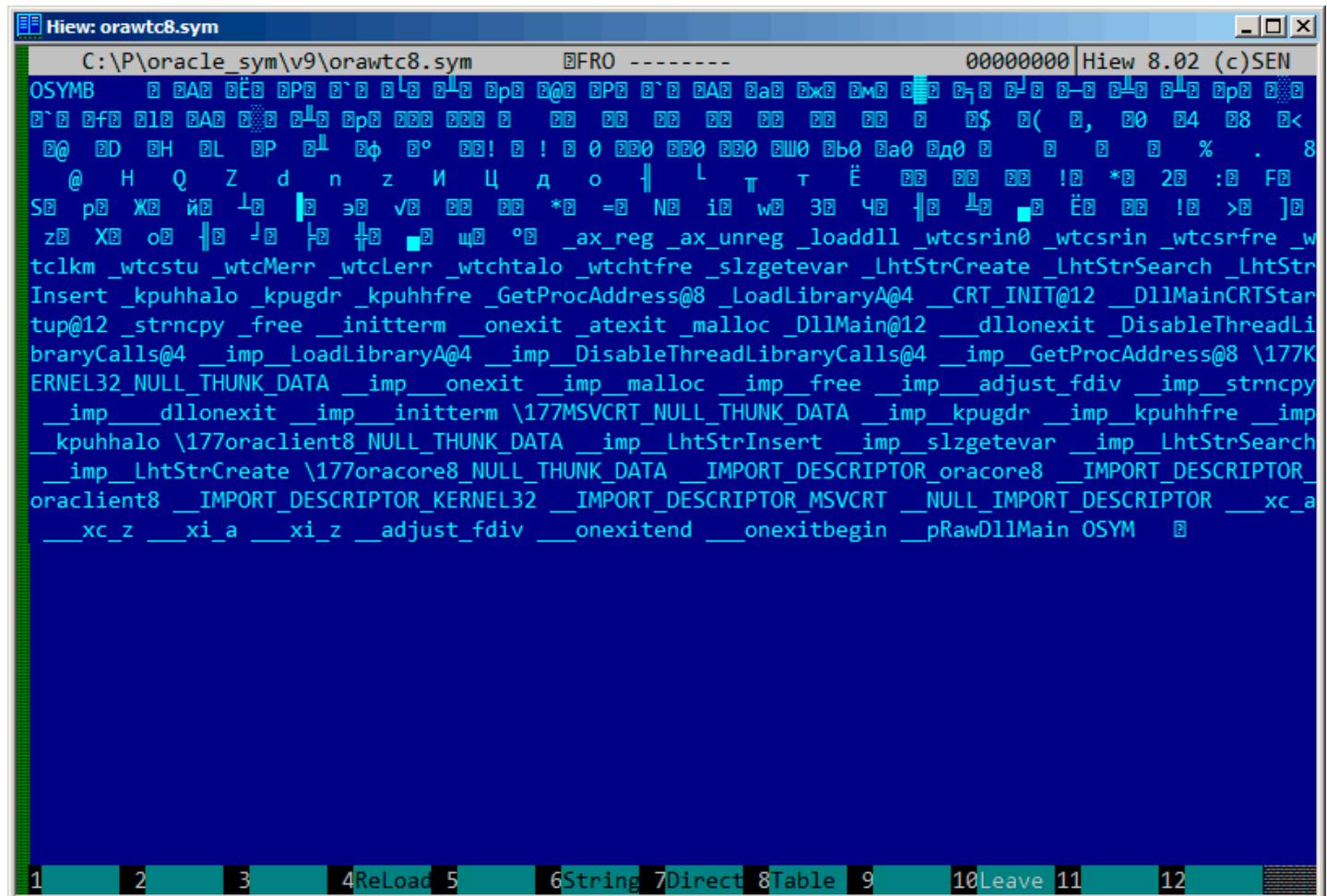


Figure 89.1: The whole file in Hiew

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:

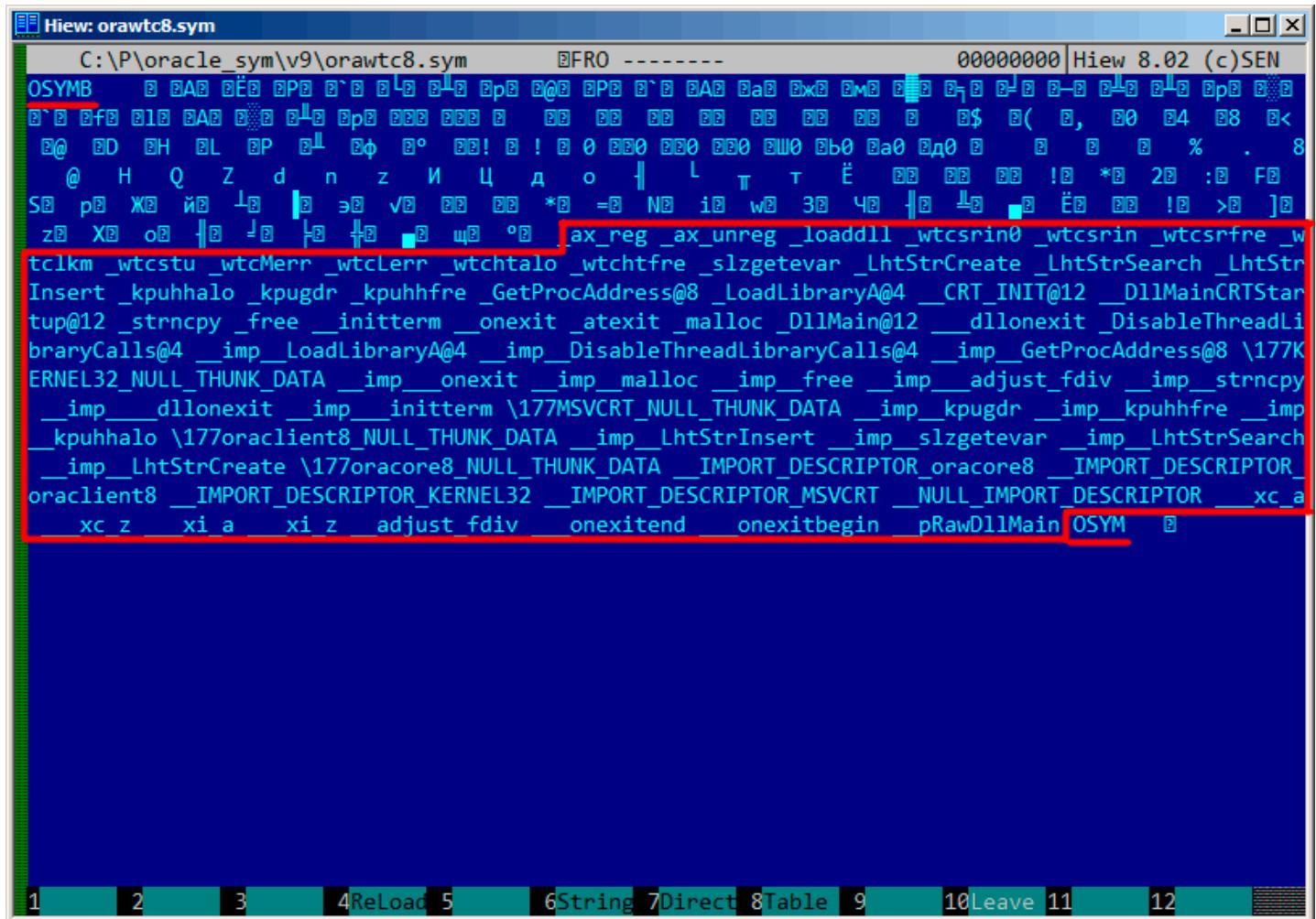


Figure 89.2: OSYM signature and text strings

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 42 00 00 00  00 10 00 10 80 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:

The screenshot shows the Hiew 8.02 debugger interface with the title "Hiew: asd2". The file path is "C:\P\oracle_sym\v9\asd2". The memory dump starts at address 00000000. The data is presented in two columns: hex values on the left and ASCII characters on the right. A vertical selection bar is positioned on the right side of the hex dump area. The bottom of the screen features a toolbar with various icons and labels, including "1Global", "2FilBlk", "3CryBlk", "4ReLoad", "5", "6String", "7Direct", "8Table", "9", "10Leave", "11", and "12AddNam".

Address	Hex	ASCII
00000000:	00 10 00 10-80 10 00 10-F0 10 00 10-50 11 00 10	0 0A 0E 0P0 0
00000010:	60 11 00 10-C0 11 00 10-D0 11 00 10-70 13 00 10	~ 0L0 0L0 0P0 0
00000020:	40 15 00 10-50 15 00 10-60 15 00 10-80 15 00 10	@0 0P0 0~0 0A0 0
00000030:	A0 15 00 10-A6 15 00 10-AC 15 00 10-B2 15 00 10	a0 0x0 0M0 0P0 0
00000040:	B8 15 00 10-BE 15 00 10-C4 15 00 10-CA 15 00 10	1B 0L0 0~0 0P0 0
00000050:	D0 15 00 10-E0 15 00 10-B0 16 00 10-60 17 00 10	1B 0P0 0X0 0~0 0
00000060:	66 17 00 10-6C 17 00 10-80 17 00 10-B0 17 00 10	f0 010 0A0 0X0 0
00000070:	D0 17 00 10-E0 17 00 10-10 18 00 10-16 18 00 10	1B 0P0 000 000 0
00000080:	00 20 00 10-04 20 00 10-08 20 00 10-0C 20 00 10	00 00 00 00 0
00000090:	10 20 00 10-14 20 00 10-18 20 00 10-1C 20 00 10	0 00 00 00 0
000000A0:	20 20 00 10-24 20 00 10-28 20 00 10-2C 20 00 10	0\$ 0(0, 0
000000B0:	30 20 00 10-34 20 00 10-38 20 00 10-3C 20 00 10	0 04 08 0< 0
000000C0:	40 20 00 10-44 20 00 10-48 20 00 10-4C 20 00 10	@ 0D 0H 0L 0
000000D0:	50 20 00 10-D0 20 00 10-E4 20 00 10-F8 20 00 10	P 0L 0f 0o 0
000000E0:	0C 21 00 10-20 21 00 10-00 30 00 10-04 30 00 10	0! 0 ! 0 0 00 0
000000F0:	08 30 00 10-0C 30 00 10-98 30 00 10-9C 30 00 10	00 000 0W0 0b0 0
00000100:	A0 30 00 10-A4 30 00 10-00 00 00 00-08 00 00 00	a0 0d0 0 0
00000110:	12 00 00 00-1B 00 00 00-25 00 00 00-2E 00 00 00	0 0 % .
00000120:	38 00 00 00-40 00 00 00-48 00 00 00-51 00 00 00	8 @ H Q
00000130:	5A 00 00 00-64 00 00 00-6E 00 00 00-7A 00 00 00	Z d n z
00000140:	88 00 00 00-96 00 00 00-A4 00 00 00-AE 00 00 00	И Ц д о
00000150:	B6 00 00 00-C0 00 00 00-D2 00 00 00-E2 00 00 00	L T T
00000160:	F0 00 00 00-07 01 00 00-10 01 00 00-16 01 00 00	E 00 00 00
00000170:	21 01 00 00-2A 01 00 00-32 01 00 00-3A 01 00 00	!0 *0 20 :0
00000180:	46 01 00 00-53 01 00 00-70 01 00 00-86 01 00 00	F0 S0 p0 X0
00000190:	A9 01 00 00-C1 01 00 00-DE 01 00 00-ED 01 00 00	й0 10 0 30
000001A0:	FB 01 00 00-07 02 00 00-1B 02 00 00-2A 02 00 00	v0 00 00 *0

Figure 89.3: Binary block

There is a clear pattern in it.

We will add red lines to divide the block:

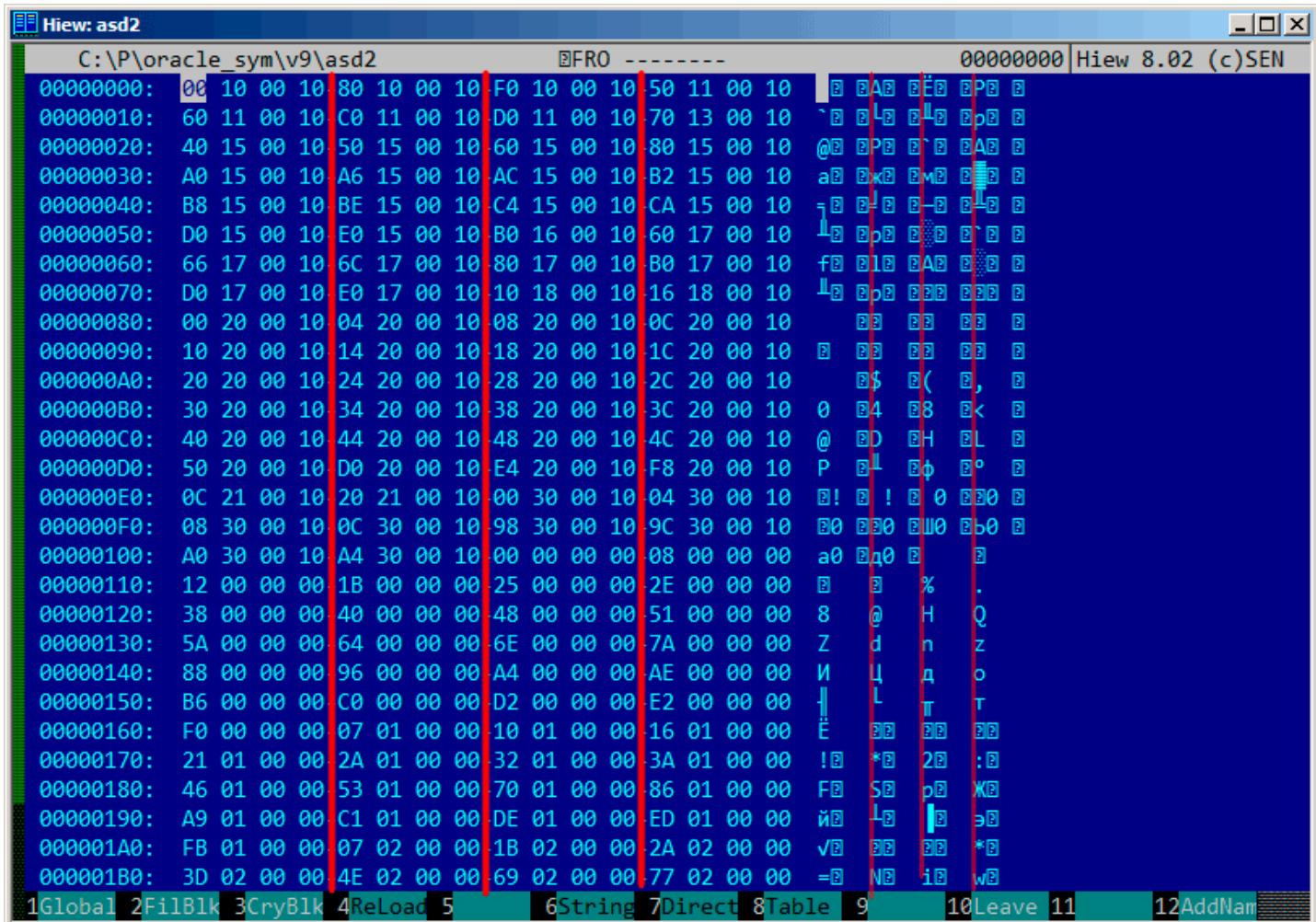


Figure 89.4: Binary block patterns

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 89.1: first column is address

```
$ od -v -t x4 binary_block
00000000 10001000 10001080 100010f0 10001150
00000020 10001160 100011c0 100011d0 10001370
00000040 10001540 10001550 10001560 10001580
00000060 100015a0 100015a6 100015ac 100015b2
00000100 100015b8 100015be 100015c4 100015ca
00000120 100015d0 100015e0 100016b0 10001760
00000140 10001766 1000176c 10001780 100017b0
00000160 100017d0 100017e0 10001810 10001816
00000200 10002000 10002004 10002008 1000200c
00000220 10002010 10002014 10002018 1000201c
00000240 10002020 10002024 10002028 1000202c
00000260 10002030 10002034 10002038 1000203c
00000300 10002040 10002044 10002048 1000204c
00000320 10002050 100020d0 100020e4 100020f8
00000340 1000210c 10002120 10003000 10003004
00000360 10003008 1000300c 10003098 1000309c
00000400 100030a0 100030a4 00000000 00000008
```

```

0000420 00000012 0000001b 00000025 0000002e
0000440 00000038 00000040 00000048 00000051
0000460 0000005a 00000064 0000006e 0000007a
0000500 00000088 00000096 000000a4 000000ae
0000520 000000b6 000000c0 000000d2 000000e2
0000540 000000f0 00000107 00000110 00000116
0000560 00000121 0000012a 00000132 0000013a
0000600 00000146 00000153 00000170 00000186
0000620 000001a9 000001c1 000001de 000001ed
0000640 000001fb 00000207 0000021b 0000022a
0000660 0000023d 0000024e 00000269 00000277
0000700 00000287 00000297 000002b6 000002ca
0000720 000002dc 000002f0 00000304 00000321
0000740 0000033e 0000035d 0000037a 00000395
0000760 000003ae 000003b6 000003be 000003c6
0001000 000003ce 000003dc 000003e9 000003f8
0001020

```

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
.text:60351000 arg_0          = dword ptr  8
.text:60351000 arg_4          = dword ptr  0Ch
.text:60351000 arg_8          = dword ptr  10h
.text:60351000
.text:60351000                 push   ebp
.text:60351001                 mov    ebp, esp
.text:60351003                 mov    eax, dword_60353014
.text:60351008                 cmp    eax, OFFFFFFFFh
.text:6035100B                 jnz    short loc_6035104F
.text:6035100D                 mov    ecx, hModule
.text:60351013                 xor    eax, eax
.text:60351015                 cmp    ecx, OFFFFFFFFh
.text:60351018                 mov    dword_60353014, eax
.text:6035101D                 jnz    short loc_60351031
.text:6035101F                 call   sub_603510F0
.text:60351024                 mov    ecx, eax
.text:60351026                 mov    eax, dword_60353014
.text:6035102B                 mov    hModule, ecx
.text:60351031
.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:

```

.text:60351080 sub_60351080    proc near
.text:60351080
.text:60351080 arg_0          = dword ptr  8
.text:60351080 arg_4          = dword ptr  0Ch
.text:60351080
.text:60351080                 push   ebp
.text:60351081                 mov    ebp, esp
.text:60351083                 mov    eax, dword_60353018
.text:60351088                 cmp    eax, OFFFFFFFFh
.text:6035108B                 jnz    short loc_603510CF
.text:6035108D                 mov    ecx, hModule

```

```

.text:60351093          xor    eax, eax
.text:60351095          cmp    ecx, 0FFFFFFFh
.text:60351098          mov    dword_60353018, eax
.text:6035109D          jnz    short loc_603510B1
.text:6035109F          call   sub_603510F0
.text:603510A4          mov    ecx, eax
.text:603510A6          mov    eax, dword_60353018
.text:603510AB          mov    hModule, ecx
.text:603510B1
.text:603510B1 loc_603510B1:           ; CODE XREF: sub_60351080+1D
.text:603510B1          test   ecx, ecx
.text:603510B3          jbe    short loc_603510CF
.text:603510B5          push   offset aAx_unreg ; "ax_unreg"
.text:603510BA          push   ecx             ; hModule
.text:603510BB          call   ds:GetProcAddress
...

```

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:

```

#include <stdio.h>
#include <stdint.h>
#include <io.h>
#include <assert.h>
#include <malloc.h>
#include <fcntl.h>
#include <string.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 (argc>1); // file name
    assert (argc>2); // additional offset (if needed)

    // 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>\n\n");
printf ("static main() {\n");

for (i=0; i<cnt; i++)
    printf ("\tMakeName(0x%08X, \"%s\");\n", offset + d1[i], &d3[d2[i]]);

printf ("}\n");

close (h);
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(0x603511C0, "_wtcsrfre");
    MakeName(0x603511D0, "_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:

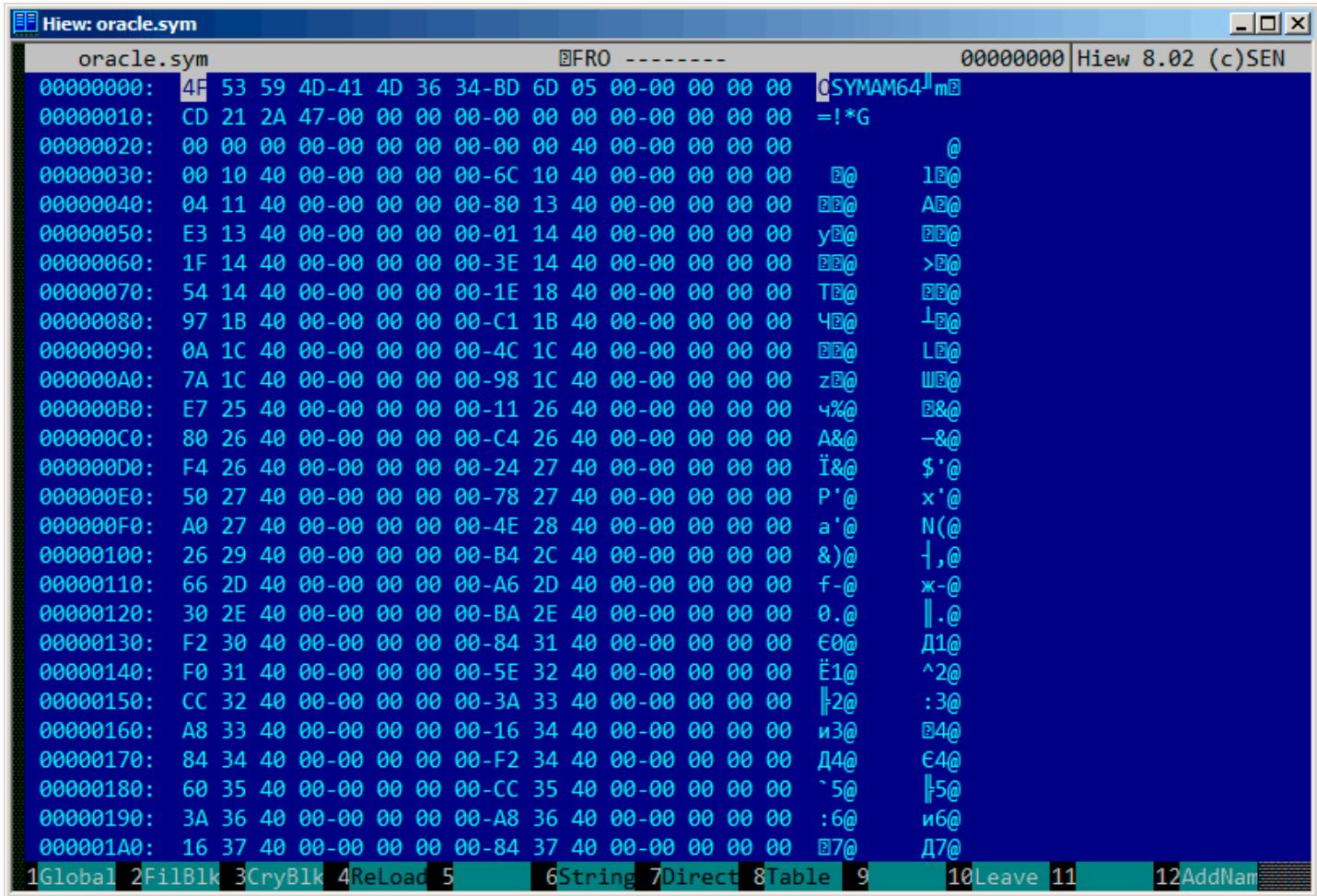


Figure 89.5: .SYM-file example from Oracle RDBMS for win64

So yes, all tables now have 64-bit elements, even string offsets! The signature is now `OSYMA64`, to distinguish the target platform, apparently.

This is it! Here is also library which has functions to access Oracle RDBMS.SYM-files: [GitHub](#).

Chapter 90

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 ¹.

This is the beginning of the ORAUS.MSG text file with some irrelevant comments stripped:

Listing 90.1: Beginning of ORAUS.MSG file without comments

```
00000, 00000, "normal, successful completion"
00001, 00000, "unique constraint (%s.%s) violated"
00017, 00000, "session requested to set trace event"
00018, 00000, "maximum number of sessions exceeded"
00019, 00000, "maximum number of session licenses exceeded"
00020, 00000, "maximum number of processes (%s) exceeded"
00021, 00000, "session attached to some other process; cannot switch session"
00022, 00000, "invalid session ID; access denied"
00023, 00000, "session references process private memory; cannot detach session"
00024, 00000, "logins from more than one process not allowed in single-process mode"
00025, 00000, "failed to allocate %s"
00026, 00000, "missing or invalid session ID"
00027, 00000, "cannot kill current session"
00028, 00000, "your session has been killed"
00029, 00000, "session is not a user session"
00030, 00000, "User session ID does not exist."
00031, 00000, "session marked for kill"
...
...
```

The first number is the error code. The second is perhaps maybe some additional flags.

¹Open-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:

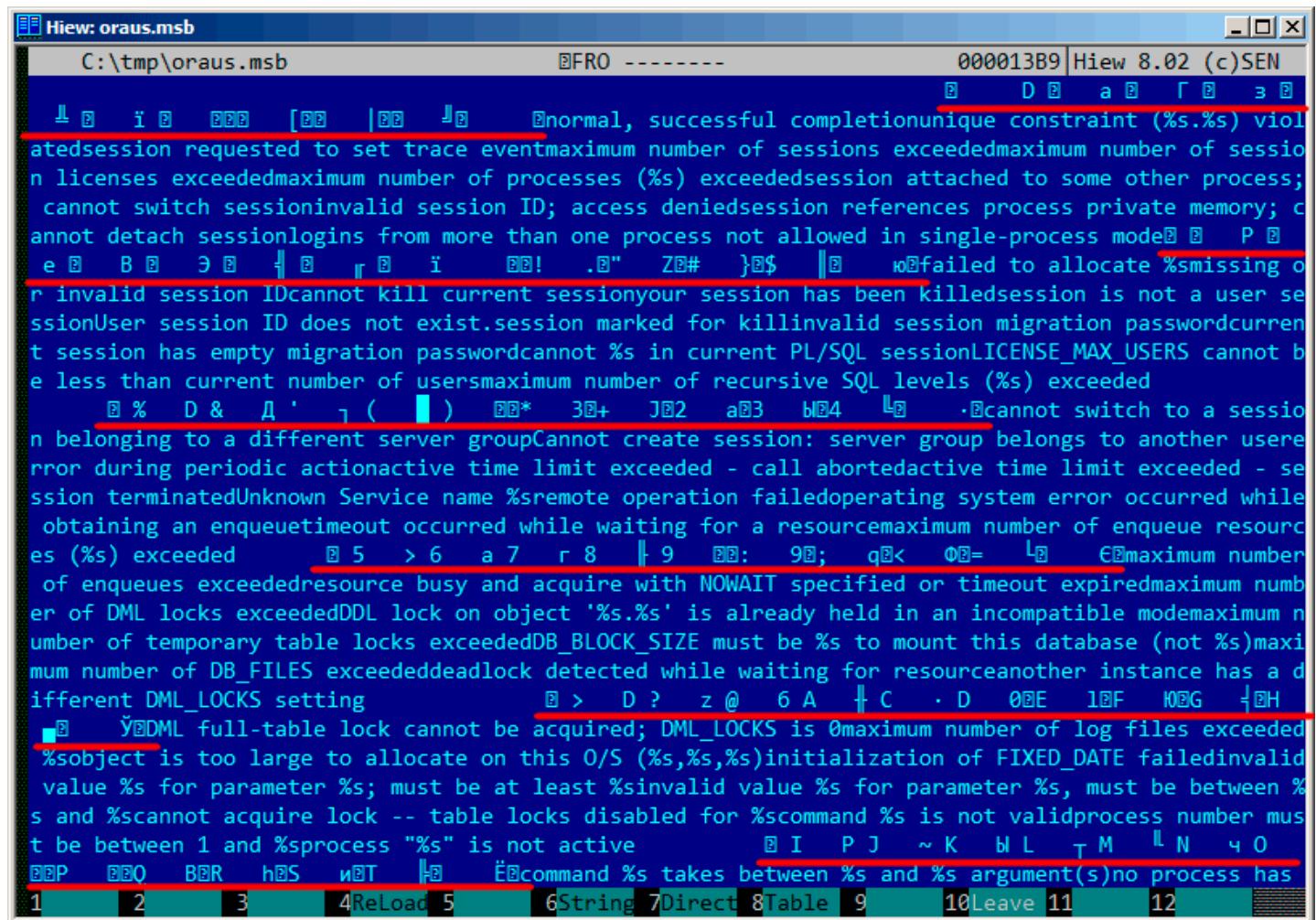


Figure 90.1: Hiew: first block

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.

Let's see the contents of the first block:

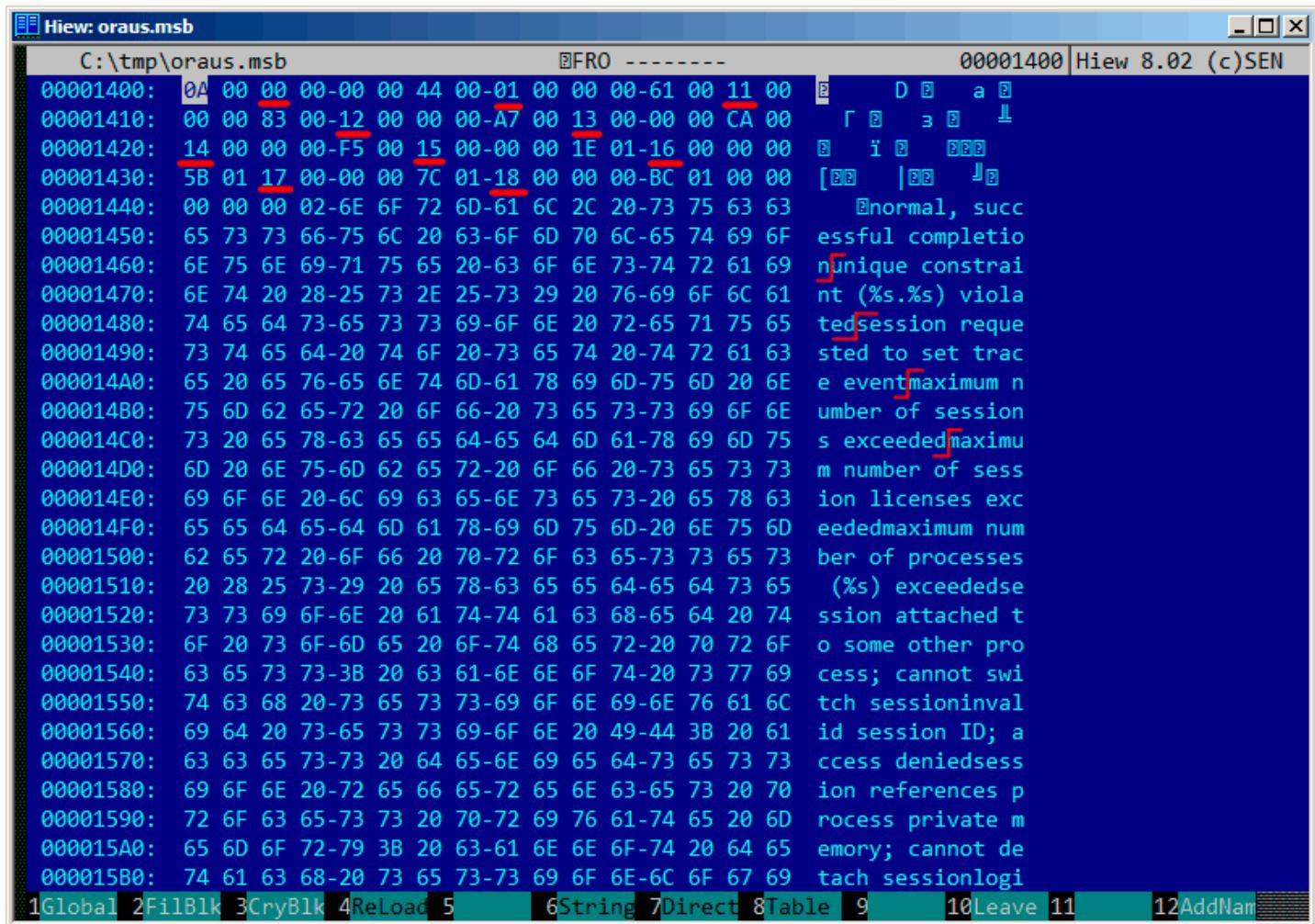


Figure 90.2: Hiew: first block

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 in 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) mean 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-terminating 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 (%s.%s) violated" starts at position 0x1461 (from the file's start) or at 0x61 (from the start of the block). These numbers (0x44 and 0x61) are familiar somehow! We can clearly see them at the start of the block.

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:

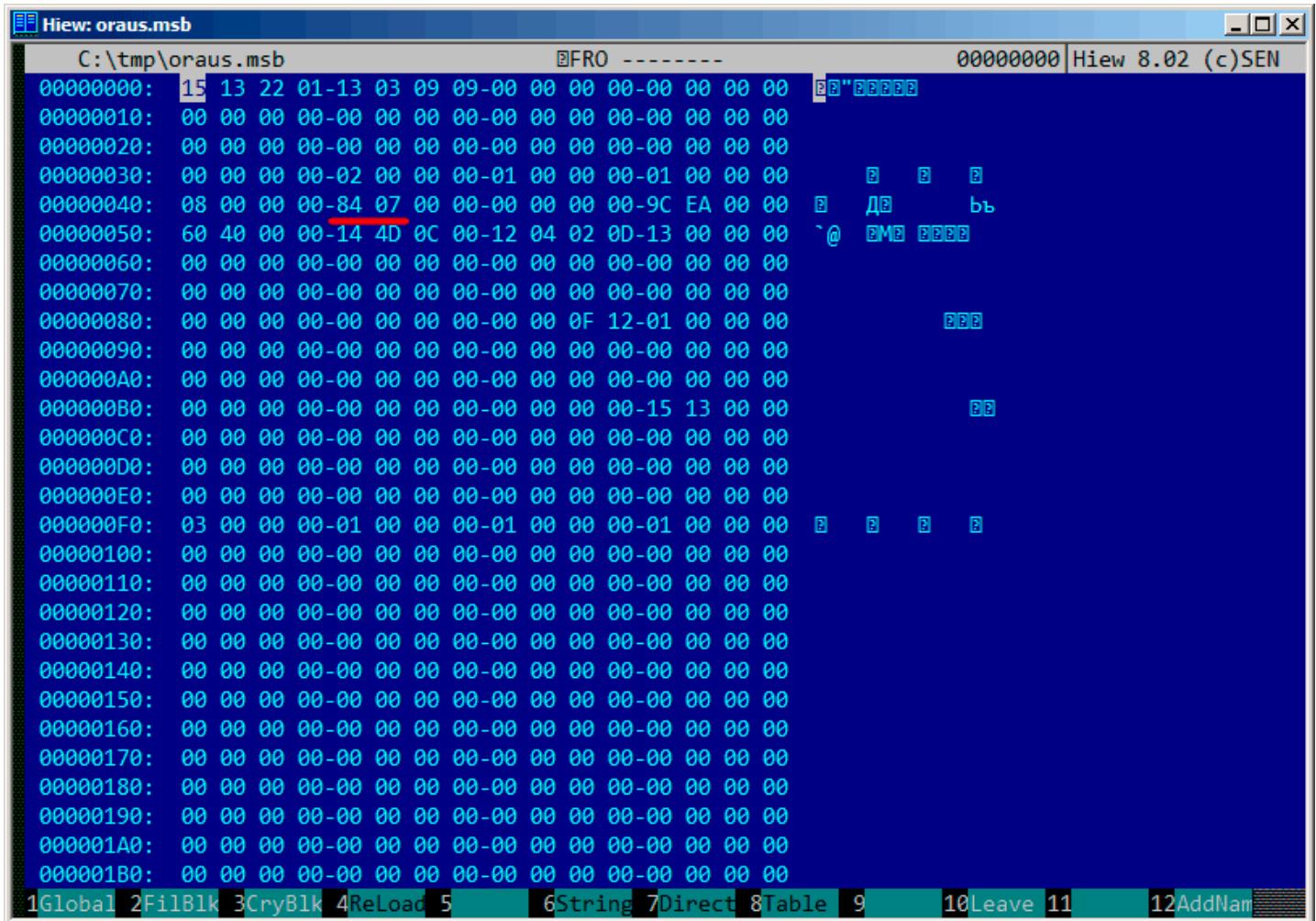


Figure 90.3: Hiew: file header

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) was done. If we have to write a .MSB file packer, we would probably need to understand the meaning of the other values.

90.1. SUMMARY

There is also a table that came after the header which probably contains 16-bit values:

Figure 90.4: Hiew: last_errnos table

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](#).

90.1 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 was an interesting and yet easy task to understand a proprietary file format without looking into Oracle RDBMS's code.

Part X

Other things

Chapter 91

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.

```
; ; 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
                            if size eq 8
                                ; jmp .+8; .npad 6
                                DB 0EBH, 06H, 8DH, 9BH, 00H, 00H, 00H, 00H
                            else
                                if size eq 9
                                    ; jmp .+9; .npad 7
```


Chapter 92

Executable files patching

92.1 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.

92.2 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` ([67.2 on page 690](#)). 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 function 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 relocations ([71.2.6 on page 716](#)) must not be touched while patching, because the Windows loader may overwrite your new code. (They are grayed in Hiew, for example: [fig.8.12](#)). As a last resort, it is possible to write jumps that circumvent the relocations, or you will need to edit the relocations table.

Chapter 93

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](#). For programmer's convenience, at least MSVC has pseudofunctions `_rotl()` and `_rotr1` 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](#).

¹[MSDN](#)

Chapter 94

Compiler's anomalies

Intel C++ 10.1, which was used for Oracle RDBMS 11.2 Linux86 compilation, may emit two `JZ` in row, and there are no references to the second `JZ`. The second `JZ` is thus meaningless.

Listing 94.1: kdli.o from libserver11.a

```
.text:08114CF1          loc_8114CF1: ; CODE XREF: __PGOSF539_kdlimemSer+89A
.text:08114CF1          ; __PGOSF539_kdlimemSer+3994
.text:08114CF1 8B 45 08    mov     eax, [ebp+arg_0]
.text:08114CF4 0F B6 50 14    movzx  edx, byte ptr [eax+14h]
.text:08114CF8 F6 C2 01    test    dl, 1
.text:08114CFB 0F 85 17 08 00 00   jnz    loc_8115518
.text:08114D01 85 C9        test    ecx, ecx
.text:08114D03 0F 84 8A 00 00 00   jz     loc_8114D93
.text:08114D09 0F 84 09 08 00 00   jz     loc_8115518
.text:08114D0F 8B 53 08        mov     edx, [ebx+8]
.text:08114D12 89 55 FC        mov     [ebp+var_4], edx
.text:08114D15 31 C0        xor    eax, eax
.text:08114D17 89 45 F4        mov     [ebp+var_C], eax
.text:08114D1A 50            push   eax
.text:08114D1B 52            push   edx
.text:08114D1C E8 03 54 00 00    call   len2nbytes
.text:08114D21 83 C4 08        add    esp, 8
```

Listing 94.2: from the same code

```
.text:0811A2A5          loc_811A2A5: ; CODE XREF: kdliSerLengths+11C
.text:0811A2A5          ; kdliSerLengths+1C1
.text:0811A2A5 8B 7D 08    mov     edi, [ebp+arg_0]
.text:0811A2A8 8B 7F 10    mov     edi, [edi+10h]
.text:0811A2AB 0F B6 57 14    movzx  edx, byte ptr [edi+14h]
.text:0811A2AF F6 C2 01    test    dl, 1
.text:0811A2B2 75 3E        jnz    short loc_811A2F2
.text:0811A2B4 83 E0 01    and    eax, 1
.text:0811A2B7 74 1F        jz     short loc_811A2D8
.text:0811A2B9 74 37        jz     short loc_811A2F2
.text:0811A2BB 6A 00        push   0
.text:0811A2BD FF 71 08    push   dword ptr [ecx+8]
.text:0811A2C0 E8 5F FE FF FF  call   len2nbytes
```

It is probably a code generator bug that was not found by tests, because resulting code works correctly anyway.

Other compiler anomalies here in this book: [20.2.4 on page 313](#), [41.3 on page 481](#), [49.7 on page 525](#), [19.7 on page 300](#), [13.4.1 on page 147](#), [20.5.2 on page 330](#).

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.

Chapter 95

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 zeroes. This is also called “proof of work”¹ (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:

```
#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;
int32_t* __max;

time_t start;

#ifndef __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
```

¹wikipedia

```

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]);
    free(__min); free(__max);
}

```

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:

```

#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 ².

The example can be compiled ³ 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
```

²N.B.: This is intentionally simplest possible example, but in practice, the usage of OpenMP can be harder and more complex

³sha512.c(h) and u64.h files can be taken from the OpenSSL library: <http://go.yurichev.com/17324>

95.1 MSVC

Now this is how MSVC 2012 generates the main loop:

Listing 95.1: MSVC 2012

```
push    OFFSET _main$omp$1
push    0
push    1
call    __vcomp_fork
add    esp, 16
; 00000010H
```

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 `_mainomp1`:

Listing 95.2: MSVC 2012

```
$T1 = -8
$T2 = -4
_main$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
    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
    pop     ecx
    inc     esi
$LN6@main$omp$1:
    cmp     esi, DWORD PTR $T2[ebp]
    jle    SHORT $LL2@main$omp$1
    call    __vcomp_for_static_end
    pop     esi
    leave
    ret    0
_main$omp$1 ENDP
```

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 in the beginning of the `check_nonce()` function to gather statistics about the arguments with which the function was called.

This is what we see when we run it:

```
threads=4
...
checked=2800000
```

95.1. MSVC

```
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
```

Yes, the result is correct, the first 3 bytes are zeroes:

```
C:\...\sha512sum test
000000f4a8fac5a4ed38794da4c1e39f54279ad5d9bb3c5465cdf57adaf60403
df6e3fe6019f5764fc9975e505a7395fed780fee50eb38dd4c0279cb114672e2 *test
```

The running time is $\approx 2..3$ seconds on 4-core Intel Xeon E3-1220 3.10 GHz. In the task manager we see 5 threads: 1 main thread + 4 more. No further optimizations are done to keep this example as small and clear as possible. But probably it can be done much faster. My CPU has 4 cores, that is why OpenMP started exactly 4 threads.

By looking at the statistics table we can clearly see how the loop was sliced in 4 even parts. Oh well, almost even, if we don't consider the last bit.

There are also pragmas for [atomic operations](#).

Let's see how this code is compiled:

```
#pragma omp atomic
checked++;

#pragma omp critical
if ((checked % 100000)==0)
    printf ("checked=%d\n", checked);
```

Listing 95.3: MSVC 2012

```
push    edi
push    OFFSET _checked
call    __vcomp_atomic_add_i4
; Line 55
push    OFFSET _$vcomp$critsect$
call    __vcomp_enter_critsect
add    esp, 12           ; 0000000cH
; Line 56
mov     ecx, DWORD PTR _checked
mov     eax, ecx
cdq
mov     esi, 100000       ; 000186a0H
idiv
esi
test   edx, edx
jne    SHORT $LN1@check_nonc
; Line 57
push    ecx
push    OFFSET ??_C@_0M@NPNHLI00@checked?$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` instruction⁴ in it.

`vcomp_enter_critsect()` eventually calling win32 API function `EnterCriticalSection()`⁵.

⁴Read more about LOCK prefix: [A.6.1 on page 929](#)

⁵You can read more about critical sections here: [71.4 on page 741](#)

95.2 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 95.4: 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 95.5: 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 ; 0xFFFFFFFF
    cdq
    idiv   ebx
    mov    ecx, eax
    mov    eax, 2147483647 ; 0xFFFFFFFF
    cdq
    idiv   ebx
    mov    eax, edx
    cmp    esi, eax
    jl     .L15
.L18:
    imul   esi, ecx
    mov    edx, esi
    add    eax, edx
    lea    ebx, [rax+rcx]
    cmp    eax, ebx
    jge    .L14
    mov    DWORD PTR [rbp-20], eax
.L17:
    mov    eax, DWORD PTR [rbp-20]
    mov    edi, eax
    call   check_nonce
    add    DWORD PTR [rbp-20], 1
    cmp    DWORD PTR [rbp-20], ebx
    jl     .L17
    jmp   .L14
.L15:
    mov    eax, 0
    add    ecx, 1
    jmp   .L18
.L14:
    add    rsp, 40
    pop    rbx
    pop    rbp
    ret
```

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()`.

95.2. GCC

GCC also inserted the `LOCK ADD` instruction right in the code, unlike MSVC, which generated a call to a separate DLL function:

Listing 95.6: GCC 4.8.1

```
lock add      DWORD PTR checked[rip], 1
call  GOMP_critical_start
mov   ecx, DWORD PTR checked[rip]
mov   edx, 351843721
mov   eax, ecx
imul  edx
sar   edx, 13
mov   eax, ecx
sar   eax, 31
sub   edx, eax
mov   eax, edx
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](#).

Chapter 96

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, [EPIC](#)¹ 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:

Listing 96.1: Linux kernel 3.2.0.4

```
#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:

Listing 96.2: Linux Kernel 3.2.0.4 for Itanium 2 (McKinley)

0090	tea_encrypt:	
0090 08 80 80 41 00 21	adds r16 = 96, r32	// ptr to ctx->KEY[2]
↳ [2]		
0096 80 C0 82 00 42 00	adds r8 = 88, r32	// ptr to ctx->KEY[0]
↳ [0]		
009C 00 00 04 00	nop.i 0	
00A0 09 18 70 41 00 21	adds r3 = 92, r32	// ptr to ctx->KEY[1]
↳ [1]		

¹Explicitly parallel instruction computing

00A6 F0 20 88 20 28 00	ld4 r15 = [r34], 4	// load z
00AC 44 06 01 84	adds r32 = 100, r32;;	// ptr to ctx->KEY
↳ [3]		
00B0 08 98 00 20 10 10	ld4 r19 = [r16]	// r19=k2
00B6 00 01 00 00 42 40	mov r16 = r0	// r0 always contains zero
↳ zero		
00BC 00 08 CA 00	mov.i r2 = ar.lc	// save lc register
00C0 05 70 00 44 10 10 9E FF FF FF 7F 20	ld4 r14 = [r34]	// load y
00CC 92 F3 CE 6B	movl r17 = 0xFFFFFFFF9E3779B9;;	// TEA_DELTA
00D0 08 00 00 00 01 00	nop.m 0	
00D6 50 01 20 20 20 00	ld4 r21 = [r8]	// r21=k0
00DC F0 09 2A 00	mov.i ar.lc = 31	// TEA_ROUNDS is 32
00E0 0A A0 00 06 10 10	ld4 r20 = [r3];;	// r20=k1
00E6 20 01 80 20 20 00	ld4 r18 = [r32]	// r18=k3
00EC 00 00 04 00	nop.i 0	
00F0		
00F0	loc_F0:	
00F0 09 80 40 22 00 20	add r16 = r16, r17	// r16=sum, r17=z
↳ TEA_DELTA		
00F6 D0 71 54 26 40 80	shladd r29 = r14, 4, r21	// r14=y, r21=k0
00FC A3 70 68 52	extr.u r28 = r14, 5, 27;;	
0100 03 F0 40 1C 00 20	add r30 = r16, r14	
0106 B0 E1 50 00 40 40	add r27 = r28, r20;;	// r20=k1
010C D3 F1 3C 80	xor r26 = r29, r30;;	
0110 0B C8 6C 34 0F 20	xor r25 = r27, r26;;	
0116 F0 78 64 00 40 00	add r15 = r15, r25	// r15=z
011C 00 00 04 00	nop.i 0;;	
0120 00 00 00 00 01 00	nop.m 0	
0126 80 51 3C 34 29 60	extr.u r24 = r15, 5, 27	
012C F1 98 4C 80	shladd r11 = r15, 4, r19	// r19=k2
0130 0B B8 3C 20 00 20	add r23 = r15, r16;;	
0136 A0 C0 48 00 40 00	add r10 = r24, r18	// r18=k3
013C 00 00 04 00	nop.i 0;;	
0140 0B 48 28 16 0F 20	xor r9 = r10, r11;;	
0146 60 B9 24 1E 40 00	xor r22 = r23, r9	
014C 00 00 04 00	nop.i 0;;	
0150 11 00 00 00 01 00	nop.m 0	
0156 E0 70 58 00 40 A0	add r14 = r14, r22	
015C A0 FF FF 48	br.cloop.sptk.few loc_F0;;	
0160 09 20 3C 42 90 15	st4 [r33] = r15, 4	// store z
0166 00 00 00 02 00 00	nop.m 0	
016C 20 08 AA 00	mov.i ar.lc = r2;;	// restore lc
↳ register		
0170 11 00 38 42 90 11	st4 [r33] = r14	// store y
0176 00 00 00 02 00 80	nop.i 0	
017C 08 00 84 00	br.ret.sptk.many b0;;	

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 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:

<http://go.yurichev.com/17322>.

Another introductory paper on Itanium assembly: [Bur], [haq].

Another very interesting Itanium feature is the *speculative execution* and the NaT (“not a thing”) bit, somewhat resembling NaN numbers:

MSDN.

Chapter 97

8086 memory model

When dealing with 16-bit programs for MS-DOS or Win16 ([81.3 on page 788](#) or [55.5 on page 600](#)), 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 artefact.

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 old software porting reason¹, 8086 can support many 64KB windows simultaneously, placed within the 1MB address space. This is some kind of a toy-level virtualization. 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](#)², [VGA](#)³) 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 0xFFFF.

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.

¹The author is not 100% sure here

²Enhanced Graphics Adapter

³Video Graphics Array

Chapter 98

Basic blocks reordering

98.1 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++:

Listing 98.1: orageneric11.dll (win32)

```
public _skgfsync
proc near

; address 0x6030D86A

        db      66h
        nop
        push   ebp
        mov    ebp, esp
        mov    edx, [ebp+0Ch]
        test   edx, edx
        jz     short loc_6030D884
        mov    eax, [edx+30h]
        test   eax, 400h
        jnz    __VInfreq_skgfsync ; write to log
continue:
        mov    eax, [ebp+8]
        mov    edx, [ebp+10h]
        mov    dword ptr [eax], 0
        lea    eax, [edx+0Fh]
        and    eax, 0FFFFFFFCh
        mov    ecx, [eax]
        cmp    ecx, 45726963h
        jnz    error           ; exit with error
        mov    esp, ebp
        pop    ebp
        retn
_skgfsync endp

...
; address 0x60B953F0

__VInfreq_skgfsync:
        mov    eax, [edx]
```

98.1. PROFILE-GUIDED OPTIMIZATION

```
test    eax, eax
jz     continue
mov    ecx, [ebp+10h]
push   ecx
mov    ecx, [ebp+8]
push   edx
push   ecx
push   offset ...
push   dword ptr [edx+4]
call   dword ptr [eax] ; write to log
add    esp, 14h
jmp    continue

error:
    mov    edx, [ebp+8]
    mov    dword ptr [edx], 69AAh ; 27050 "function called with invalid FIB/IOV ↵
    ↳ structure"
        mov    eax, [eax]
        mov    [edx+4], eax
        mov    dword ptr [edx+8], 0FA4h ; 4004
        mov    esp, ebp
        pop    ebp
        retn

; END OF FUNCTION CHUNK FOR _skgfsync
```

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.

Part XI

Books/blogs worth reading

Chapter 99

Books

99.1 Windows

[RA09].

99.2 C/C++

[ISO13].

99.3 x86 / x86-64

[Int13], [AMD13a]

99.4 ARM

ARM manuals: <http://go.yurichev.com/17024>

99.5 Cryptography

[Sch94]

Chapter 100

Blogs

100.1 Windows

- Microsoft: Raymond Chen
- nynaeve.net

Chapter 101

Other

There are two excellent RE¹-related subreddits on reddit.com: [reddit.com/r/ReverseEngineering/](https://www.reddit.com/r/ReverseEngineering/) and [reddit.com/r/remath](https://www.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 onFreeNode².

¹Reverse Engineering

²freenode.net

Afterword

Chapter 102

Questions?

Do not hesitate to mail any questions to the author: `<dennis(a)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 me. 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

Appendix A

x86

A.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.

A.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. Probably, 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.: R8L, but IDA names these registers by adding the B suffix, e.g.: R8B.

A.2.1 RAX/EAX/AX/AL

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RAX ^{x64}							
				EAX			
							AX
							AH AL

AKA accumulator. The result of a function is usually returned via this register.

A.2.2 RBX/EBX/BX/BL

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RBX ^{x64}							
EBX							
BX							
BH							BL

A.2.3 RCX/ECX/CX/CL

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RCX ^{x64}							
ECX							
CX							
CH							CL

AKA counter: in this role it is used in REP prefixed instructions and also in shift instructions (SHL/SHR/RxL/RxR).

A.2.4 RDX/EDX/DX/DL

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RDX ^{x64}							
EDX							
DX							
DH							DL

A.2.5 RSI/ESI/SI/SIL

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RSI ^{x64}							
ESI							
SI							
SIL ^{x64}							

AKA “source index”. Used as source in the instructions REP MOVSx, REP CMPSx.

A.2.6 RDI/EDI/DI/DIL

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RDI ^{x64}							
EDI							
DI							
DIL ^{x64}							

AKA “destination index”. Used as a pointer to the destination in the instructions REP MOVSx, REP STOSx.

A.2.7 R8/R8D/R8W/R8L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R8							
R8D							
R8W							
R8L							

A.2.8 R9/R9D/R9W/R9L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R9							
R9D							
R9W							
R9L							

A.2.9 R10/R10D/R10W/R10L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R10							
R10D							
R10W							
R10L							

A.2.10 R11/R11D/R11W/R11L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R11							
R11D							
R11W							
R11L							

A.2.11 R12/R12D/R12W/R12L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R12							
R12D							
R12W							
R12L							

A.2.12 R13/R13D/R13W/R13L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R13							
R13D							
R13W							
R13L							

A.2.13 R14/R14D/R14W/R14L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R14							
R14D							
R14W							
R14L							

A.2.14 R15/R15D/R15W/R15L

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
R15							
R15D							
R15W							
R15L							

A.2.15 RSP/ESP/SP/SPL

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RSP							
ESP							
SP							
SPL							

AKA stack pointer. Usually points to the current stack except in those cases when it is not yet initialized.

A.2.16 RBP/EBP/BP/BPL

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RBP							
EBP							
BP							
BPL							

AKA frame pointer. Usually used for local variables and accessing the arguments of the function. More about it: ([8.1.2 on page 67](#)).

A.2.17 RIP/EIP/IP

Byte number:							
7th	6th	5th	4th	3rd	2nd	1st	0th
RIP ^{x64}							
EIP							
IP							

AKA “instruction pointer”¹. 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
```

A.2.18 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 done for faster access to the [TLS](#) and other structures like the [TIB](#).

In the past, these registers were used as segment registers ([97 on page 912](#)).

¹Sometimes also called “program counter”

A.2.19 Flags register

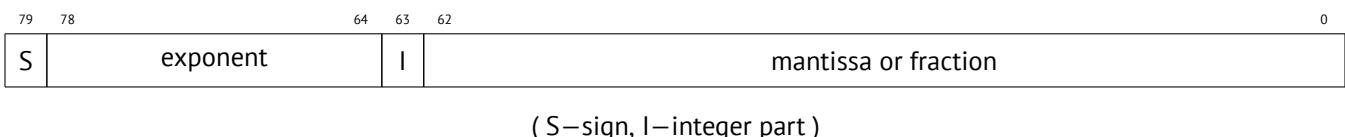
AKA EFLAGS.

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)	(18.7.1 on page 233).
4 (0x10)	AF (Adjust)	
6 (0x40)	ZF (Zero)	Setting to 0 if the last operation's result was 0.
7 (0x80)	SF (Sign)	
8 (0x100)	TF (Trap)	Used for debugging. If turned on, an exception is to be generated after each instruction's execution.
9 (0x200)	IF (Interrupt enable)	Are interrupts enabled. The CLI/STI instructions are used for setting/resetting the flag
10 (0x400)	DF (Direction)	A directions is set for the REP MOVSx, REP CMPSx, REP LODSx, REP SCASx instructions. The CLD/STD instructions are used for setting/resetting the flag
11 (0x800)	OF (Overflow)	
12, 13 (0x3000)	IOPL (I/O privilege level) ⁸⁰²⁸⁶	
14 (0x4000)	NT (Nested task) ⁸⁰²⁸⁶	
16 (0x10000)	RF (Resume) ⁸⁰³⁸⁶	Used for debugging. The CPU ignores the hardware breakpoint in DRx if the flag is set.
17 (0x20000)	VM (Virtual 8086 mode) ⁸⁰³⁸⁶	
18 (0x40000)	AC (Alignment check) ⁸⁰⁴⁸⁶	
19 (0x80000)	VIF (Virtual interrupt) ^{Pentium}	
20 (0x100000)	VIP (Virtual interrupt pending) ^{Pentium}	
21 (0x200000)	ID (Identification) ^{Pentium}	

All the rest flags are reserved.

A.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:



(S—sign, I—integer part)

A.3.1 Control Word

Register controlling the behaviour of the FPU.

A.3. FPU REGISTERS

Bit	Abbreviation (meaning)	Description
0	IM (Invalid operation Mask)	
1	DM (Denormalized operand Mask)	
2	ZM (Zero divide Mask)	
3	OM (Overflow Mask)	
4	UM (Underflow Mask)	
5	PM (Precision Mask)	
7	IEM (Interrupt Enable Mask)	Exceptions enabling, 1 by default (disabled)
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.

A.3.2 Status Word

Read-only register.

Bit	Abbreviation (meaning)	Description
15	B (Busy)	Is FPU do something (1) or results are ready (0)
14	C3	
13, 12, 11	TOP	points to the currently zeroth register
10	C2	
9	C1	
8	C0	
7	IR (Interrupt Request)	
6	SF (Stack Fault)	
5	P (Precision)	
4	U (Underflow)	
3	O (Overflow)	
2	Z (Zero)	
1	D (Denormalized)	
0	I (Invalid operation)	

The SF, P, U, O, Z, D, I bits signal about exceptions.

About the C3, C2, C1, C0 you can read more here: ([18.7.1 on page 233](#)).

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.

A.3.3 Tag Word

The register has current information about the usage of numbers registers.

Bit	Abbreviation (meaning)
15, 14	Tag(7)
13, 12	Tag(6)
11, 10	Tag(5)
9, 8	Tag(4)
7, 6	Tag(3)
5, 4	Tag(2)
3, 2	Tag(1)
1, 0	Tag(0)

Each tag contains information about a physical FPU register (R(x)), not logical (ST(x)).

For each tag:

A.4. SIMD REGISTERS

- 00 – The register contains a non-zero value
- 01 – The register contains 0
- 10 – The register contains a special value ([NAN²](#), ∞ , or denormal)
- 11 – The register is empty

A.4 SIMD registers

A.4.1 MMX registers

8 64-bit registers: MM0..MM7.

A.4.2 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.

A.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

A.5.1 DR6

Bit (mask)	Description
0 (1)	B0 – breakpoint #1 was triggered
1 (2)	B1 – breakpoint #2 was triggered
2 (4)	B2 – breakpoint #3 was triggered
3 (8)	B3 – breakpoint #4 was triggered
13 (0x2000)	BD – modification attempt of one of the DRx registers. may be raised if GD is enabled
14 (0x4000)	BS – single step breakpoint (TF flag was set in EFLAGS). Highest priority. Other bits may also be set.
15 (0x8000)	BT (task switch flag)

N.B. A single step breakpoint is a breakpoint which occurs after each instruction. It can be enabled by setting TF in EFLAGS ([A.2.19 on page 926](#)).

A.5.2 DR7

Breakpoint types are set here.

²Not a Number

Bit (mask)	Description
0 (1)	L0 – enable breakpoint #1 for the current task
1 (2)	G0 – enable breakpoint #1 for all tasks
2 (4)	L1 – enable breakpoint #2 for the current task
3 (8)	G1 – enable breakpoint #2 for all tasks
4 (0x10)	L2 – enable breakpoint #3 for the current task
5 (0x20)	G2 – enable breakpoint #3 for all tasks
6 (0x40)	L3 – enable breakpoint #4 for the current task
7 (0x80)	G3 – enable breakpoint #4 for all tasks
8 (0x100)	LE – not supported since P6
9 (0x200)	GE – not supported since P6
13 (0x2000)	GD – exception is to be raised if any MOV instruction tries to modify one of the DRx registers
16,17 (0x30000)	breakpoint #1: R/W – type
18,19 (0xC0000)	breakpoint #1: LEN – length
20,21 (0x300000)	breakpoint #2: R/W – type
22,23 (0xC00000)	breakpoint #2: LEN – length
24,25 (0x3000000)	breakpoint #3: R/W – type
26,27 (0xC000000)	breakpoint #3: LEN – length
28,29 (0x30000000)	breakpoint #4: R/W – type
30,31 (0xC0000000)	breakpoint #4: LEN – length

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

A.6 Instructions

Instructions marked as (M) are not usually generated by the compiler: if you see one of them, it was probably a hand-written piece of assembly code, or is a compiler intrinsic ([93 on page 901](#)).

Only the most frequently used instructions are listed here. You can read [[Int13](#)] or [[AMD13a](#)] for a full documentation.

Instruction's opcodes has to be memorized? No, only those which are used for code patching ([92.2 on page 900](#)). All the rest of the opcodes don't need to be memorized.

A.6.1 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 ([71.4 on page 741](#)).

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 ([A.6.2 on page 932](#)) and STOSx ([A.6.2 on page 933](#)) instructions.

The instructions prefixed by REP are sensitive to the DF flag, which is used to set the direction.

A.6. INSTRUCTIONS

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 ([A.6.3 on page 934](#)) and SCASx ([A.6.2 on page 933](#)) instructions.

Instructions prefixed by REPE/REPNE are sensitive to the DF flag, which is used to set the direction.

A.6.2 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 mean 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: [25 on page 395](#).

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, **INC** doesn't modify CF flag.

IMUL signed multiply **IMUL** often used instead of **MUL**, read more about it: [31.1](#).

INC **increment**.Unlike other arithmetic instructions, **INC** doesn't modify CF flag.

JCXZ, 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

A.6. INSTRUCTIONS

JNG jump if not greater (signed): ZF=1 or SF≠OF

JNLE jump if not lesser (signed): ZF=0 and 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

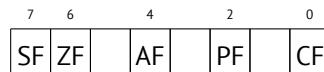
JPO jump if PF flag is cleared (Jump Parity Odd)

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:



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 size³.

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).

```
int f(int a, int b)
{
    return a*8+b;
};
```

Listing A.1: Optimizing MSVC 2010

```
_a$ = 8                                ; size = 4
_b$ = 12                               ; size = 4
_f PROC
    mov    eax, DWORD PTR _b$[esp-4]
    mov    ecx, DWORD PTR _a$[esp-4]
    lea    eax, DWORD PTR [eax+ecx*8]
    ret    0
_f ENDP
```

Intel C++ uses LEA even more:

```
int f1(int a)
{
    return a*13;
};
```

Listing A.2: Intel C++ 2011

```
_f1 PROC NEAR
    mov    ecx, DWORD PTR [4+esp]      ; ecx = a
    lea    edx, DWORD PTR [ecx+ecx*8]  ; edx = a*9
    lea    eax, DWORD PTR [edx+ecx*4]  ; eax = a*9 + a*4 = a*13
    ret
```

³See also: [wikipedia](#)

A.6. INSTRUCTIONS

These two instructions performs faster than one IMUL.

MOVSB/MOVSW/MOVSD/MOVSQ 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 MOVSw, 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
MOVS     ; copy remaining byte
```

(Supposedly, it works faster than copying 15 bytes using just one REP MOVSB).

MOVSX load with sign extension see also: ([16.1.1 on page 200](#))

MOVZX load and clear all other bits see also: ([16.1.1 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: [31.1](#).

NEG negation: $op = -op$

NOP **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: [7.1.1 on page 44](#).

More examples of such operations: ([91 on page 898](#)).

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 $op1: op1 = \neg op1$. logical inversion 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)`

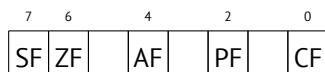
PUSH push a value into the stack: `ESP=ESP-4 (or 8); SS:[ESP]=value`

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 ([97 on page 912](#)), into RETF (“return far”).

RET can have an operand. Then it works like this: `POP tmp; ADD ESP op1; JMP tmp`. **RET** with an operand usually ends functions in the `stdcall` calling convention, see also: [67.2 on page 690](#).

SAHF copy bits from AH to CPU flags:



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:

```
; work with 64-bit values: subtract val2 from val1.
; .lo mean 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
```

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One more example: [25 on page 395](#).

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 **ASCIIIZ** string's length:

Example:

```
lea    edi, string
mov    ecx, 0FFFFFFFh ; scan  $2^{32}-1$  bytes, i.e., almost "infinitely"
xor    eax, eax        ; 0 is the terminator
repne scasb
add    edi, 0FFFFFFFh ; correct it

; now EDI points to the last character of the ASCIIIZ string.

; lets determine string length'
; current ECX = -1-strlen

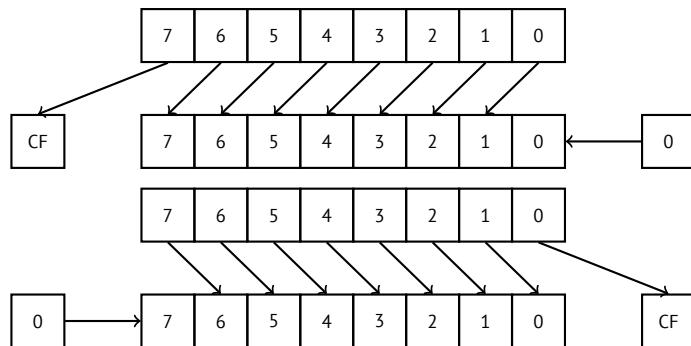
not    ecx
dec    ecx

; 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:



These instructions are frequently used for multiplication and division by 2^n . Another very frequent application is processing bit fields: [20 on page 303](#).

SHRD op1, op2, op3: shift value in op2 right by op3 bits, taking bits from op1.

Example: [25 on page 395](#).

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/RDI.

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:

```
; 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).

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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: [20 on page 303](#)

XCHG exchange the values in the operands

XOR op1, op2: **XOR⁴** values. $op1 = op1 \oplus op2$. A frequently occurring pattern is **XOR reg,reg**, which implies zeroing of *reg*. See also: [32 on page 450](#).

A.6.3 Less frequently used instructions

BSF bit scan forward, see also: [26.2 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: [25.5 on page 404](#).

Interestingly to know these instructions was initially named as **SEX** (*Sign EXtend*), as Stephen P. Morse (one of Intel 8086 CPU designers) wrote in [[Mor80](#)]:

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 ([A.6.2 on page 930](#)).

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 A.3: base\ntos\rtl\i386\movemem.asm

```
; ULONG
; RtlCompareMemory (
;     IN PVOID Source1,
;     IN PVOID Source2,
;     IN ULONG Length
```

⁴eXclusive OR

A.6. INSTRUCTIONS

```
; )

; 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
cPublicFpo 3,0

    push    esi          ; save registers
    push    edi
    cld
    mov     esi,RcmSource1
    mov     edi,RcmSource2
    ; (esi) -> first block to compare
    ; (edi) -> second block to compare

;
; Compare dwords, if any.
;

rcm10:  mov     ecx,RcmLength      ; (ecx) = length in bytes
        shr     ecx,2          ; (ecx) = length in dwords
        jz      rcm20          ; no dwords, try bytes
        repe   cmpsd           ; compare dwords
        jnz    rcm40          ; mismatch, go find byte

;
; Compare residual bytes, if any.
;

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
;
```

A.6. INSTRUCTIONS

```
; 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: ([22.6.1 on page 367](#)).

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: [[Bro](#)] 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 ([69 on page 703](#)), but was later replaced by the SYSENTER or SYSCALL instructions.

INT 3 (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 loaded. If it is not loaded, Windows offers to run one of the registered system debuggers. If [MSVS⁵](#) 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()`⁶.

There is also a win32 function in kernel32.dll named `DebugBreak()`⁷, 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 ([81.3 on page 788](#)).

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.

⁵Microsoft Visual Studio

⁶[MSDN](#)

⁷[MSDN](#)

A.6. INSTRUCTIONS

OUT (M) output data to port. The instruction usually can be seen in OS drivers or in old MS-DOS code, for example ([81.3 on page 788](#)).

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. AKA “hamming weight”. AKA “NSA instruction” due to some 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.

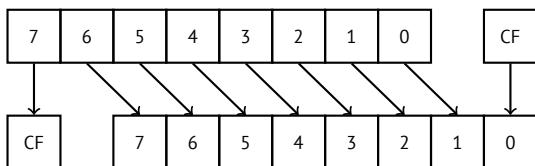
[Sch94]

POPF restore flags from the stack (AKA EFLAGS register)

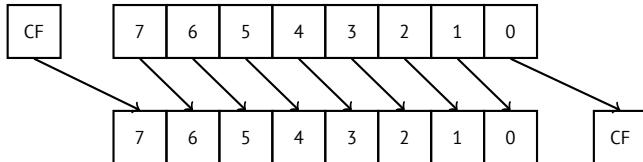
PUSHA (M) pushes the values of the (R|E)AX, (R|E)CX, (R|E)DX, (R|E)BX, (R|E)BP, (R|E)SI, (R|E)DI registers to the stack.

PUSHF push flags (AKA EFLAGS register)

RCL (M) rotate left via CF flag:

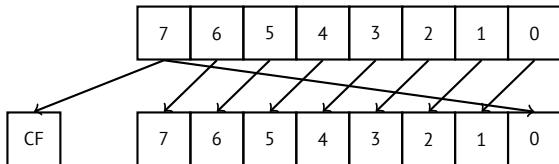


RCR (M) rotate right via CF flag:

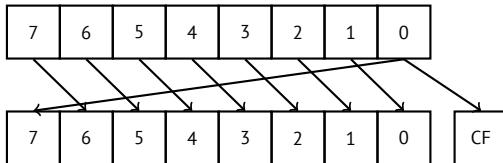


ROL/ROR (M) cyclic shift

ROL: rotate left:



ROR: rotate right:



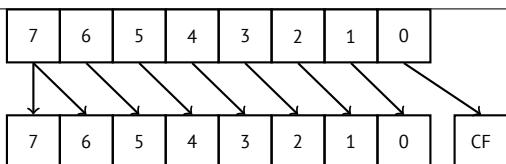
Despite the fact that almost all CPUs have these instructions, there are no corresponding operations in C/C++, so the compilers of these PLs usually do not generate these instructions.

For the programmer’s convenience, at least **MSVC** has the pseudofunctions (compiler intrinsics) `_rotl()` and `_rotr()`⁸, which are translated by the compiler directly to these instructions.

SAL Arithmetic shift left, synonymous to **SHL**

SAR Arithmetic shift right

⁸[MSDN](#)



Hence, the sign bit always stays at the place of the [MSB](#).

SETcc 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 ([A.6.2 on page 930](#)).

STC (M) set CF flag

STD (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 (M) set IF flag

SYSCALL (AMD) call syscall ([69 on page 703](#))

SYSENTER (Intel) call syscall ([69 on page 703](#))

UD2 (M) undefined instruction, raises exception. Used for testing.

A.6.4 FPU instructions

-R in the mnemonic usually implies that the operands are reversed, -P implies that one element is popped from the stack after the instruction's execution, -PP 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 op: ST(0)=op+ST(0)

FADD ST(0), ST(i): ST(0)=ST(0)+ST(i)

FADDP 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 ST(0)=-ST(0)

FCOM compare ST(0) with ST(1)

FCOM op: compare ST(0) with op

FCOMP compare ST(0) with ST(1); pop one element from the stack

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 ([A.3 on page 926](#)) from 16-bit op.

FLDZ push zero to stack

FLD op: push op to the stack.

FMUL op: ST(0)=ST(0)*op

A.6. INSTRUCTIONS

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 ([A.3 on page 926](#)) into 16-bit op after checking for pending exceptions.

FNSTCW op: store FPU control word ([A.3 on page 926](#)) into 16-bit op.

FSTSW op: store FPU status word ([A.3.2 on page 927](#)) into 16-bit op after checking for pending exceptions.

FNSTSW op: store FPU status word ([A.3.2 on page 927](#)) 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)

FXCH exchange values in ST(0) and ST(1)

A.6.5 Instructions having printable ASCII opcode

(In 32-bit mode).

These can be suitable for shellcode construction. See also: [85.1 on page 850](#).

ASCII character	hexadecimal code	x86 instruction
0	30	XOR
1	31	XOR
2	32	XOR
3	33	XOR
4	34	XOR
5	35	XOR
7	37	AAA
8	38	CMP
9	39	CMP
:	3a	CMP
;	3b	CMP
<	3c	CMP
=	3d	CMP
?	3f	AAS
@	40	INC
A	41	INC
B	42	INC
C	43	INC
D	44	INC

E	45	INC
F	46	INC
G	47	INC
H	48	DEC
I	49	DEC
J	4a	DEC
K	4b	DEC
L	4c	DEC
M	4d	DEC
N	4e	DEC
O	4f	DEC
P	50	PUSH
Q	51	PUSH
R	52	PUSH
S	53	PUSH
T	54	PUSH
U	55	PUSH
V	56	PUSH
W	57	PUSH
X	58	POP
Y	59	POP
Z	5a	POP
[5b	POP
\	5c	POP
]	5d	POP
^	5e	POP
-	5f	POP
`	60	PUSHA
a	61	POPA
f	66	(in 32-bit mode) switch to 16-bit operand size (in 32-bit mode) switch to 16-bit address size
g	67	
h	68	PUSH
i	69	IMUL
j	6a	PUSH
k	6b	IMUL
p	70	JO
q	71	JNO
r	72	JB
s	73	JAE
t	74	JE
u	75	JNE
v	76	JBE
w	77	JA
x	78	JS
y	79	JNS
z	7a	JP

In summary: AAA, AAS, CMP, DEC, IMUL, INC, JA, JAE, JB, JBE, JE, JNE, JNO, JNS, JO, JP, JS, POP, POPA, PUSH, PUSHA, XOR.

Appendix B

ARM

B.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.

B.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).

B.3 32-bit ARM (AArch32)

B.3.1 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.

B.3.2 Current Program Status Register (CPSR)

Bit	Description
0..4	M—processor mode
5	T—Thumb state
6	F—FIQ disable
7	I—IRQ disable
8	A—imprecise data abort disable
9	E—data endianness
10..15, 25, 26	IT—if-then state
16..19	GE—greater-than-or-equal-to
20..23	DNM—do not modify
24	J—Java state
27	Q—sticky overflow
28	V—overflow
29	C—carry/borrow/extend
30	Z—zero bit
31	N—negative/less than

B.3.3 VFP (floating point) and NEON registers

0..31 ^{bits}	32..64	65..96	97..127
Q0 ^{128 bits}			
D0 ^{64 bits}		D1	
S0 ^{32 bits}	S1	S2	S3

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.

B.4 64-bit ARM (AArch64)

B.4.1 General purpose registers

The register count 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)

B.5. INSTRUCTIONS

- 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: [ARM13c].

The 32-bit part of each X-register is also accessible via W-registers (W0, W1, etc).

High 32-bit part	low 32-bit part
	X0
	W0

B.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 lack this suffix do 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).

B.5.1 Conditional codes table

Code	Description	Flags
EQ	Equal	Z == 1
NE	Not equal	Z == 0
CS AKA HS (Higher or Same)	Carry set / Unsigned, Greater than, equal	C == 1
CC AKA LO (LOwer)	Carry clear / Unsigned, Less than	C == 0
MI	Minus, negative / Less than	N == 1
PL	Plus, positive or zero / Greater than, equal	N == 0
VS	Overflow	V == 1
VC	No overflow	V == 0
HI	Unsigned higher / Greater than	C == 1 and Z == 0
LS	Unsigned lower or same / Less than or equal	C == 0 or Z == 1
GE	Signed greater than or equal / Greater than or equal	N == V
LT	Signed less than / Less than	N != V
GT	Signed greater than / Greater than	Z == 0 and N == V
LE	Signed less than or equal / Less than, equal	Z == 1 or N != V
None / AL	Always	Any

Appendix C

MIPS

C.1 Registers

(O32 calling convention)

C.1.1 General purpose registers GPR

Number	Pseudoname	Description
\$0	\$ZERO	Always zero. Writing to this register is effectively an idle instruction (NOP).
\$1	\$AT	Used as a temporary register for assembly macros and pseudoinstructions.
\$2 ...\$3	\$V0 ...\$V1	Function result is returned here.
\$4 ...\$7	\$A0 ...\$A3	Function arguments.
\$8 ...\$15	\$T0 ...\$T7	Used for temporary data.
\$16 ...\$23	\$S0 ...\$S7	Used for temporary data*.
\$24 ...\$25	\$T8 ...\$T9	Used for temporary data.
\$26 ...\$27	\$K0 ...\$K1	Reserved for OS kernel.
\$28	\$GP	Global Pointer**.
\$29	\$SP	SP *.
\$30	\$FP	FP *
\$31	\$RA	RA .
n/a	PC	PC .
n/a	HI	high 32 bit of multiplication or division remainder***.
n/a	LO	low 32 bit of multiplication and division remainder***.

C.1.2 Floating-point registers

Name	Description
\$F0..\$F1	Function result returned here.
\$F2..\$F3	Not used.
\$F4..\$F11	Used for temporary data.
\$F12..\$F15	First two function arguments.
\$F16..\$F19	Used for temporary data.
\$F20..\$F31	Used for temporary data*.

* – [Callee](#) must preserve the value.

** – [Callee](#) must preserve the value (except in [PIC](#) code).

*** – accessible using the [MFHI](#) and [MFLO](#) instructions.

C.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 remember 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.

C.2.1 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 pseudoinstruction for `BEQ $ZERO, $ZERO, LABEL`), while J-instructions can't.

Appendix D

Some GCC library functions

name	meaning
<code>__divdi3</code>	signed division
<code>__moddi3</code>	getting remainder (modulo) of signed division
<code>__udivdi3</code>	unsigned division
<code>__umoddi3</code>	getting remainder (modulo) of unsigned division

Appendix E

Some MSVC library functions

11 in function name stands for “long long”, e.g., a 64-bit data type.

name	meaning
<code>__alldiv</code>	signed division
<code>__allmul</code>	multiplication
<code>__allrem</code>	remainder of signed division
<code>__allshl</code>	shift left
<code>__allshr</code>	signed shift right
<code>__aulldiv</code>	unsigned division
<code>__aullrem</code>	remainder of unsigned division
<code>__aullshr</code>	unsigned shift right

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`.

Appendix F

Cheatsheets

F.1 IDA

Hot-keys cheatsheet:

key	meaning
Space	switch listing and graph view
C	convert to code
D	convert to data
A	convert to string
*	convert to array
U	undefine
O	make offset of operand
H	make decimal number
R	make char
B	make binary number
Q	make hexadecimal number
N	rename identifier
?	calculator
G	jump to address
:	add comment
Ctrl-X	show references to the current function, label, variable (incl. in local stack)
X	show references to the function, label, variable,etc.
Alt-I	search for constant
Ctrl-I	search for the next occurrence of constant
Alt-B	search for byte sequence
Ctrl-B	search for the next occurrence of byte sequence
Alt-T	search for text (including instructions, etc)
Ctrl-T	search for the next occurrence of text
Alt-P	edit current function
Enter	jump to function, variable, etc
Esc	get back
Num -	fold function or selected area
Num +	unhide function or area

Function/area folding may be useful for hiding function parts when you realize what they do. this is used in my [script¹](#) for hiding some often used patterns of inline code.

F.2 OllyDbg

Hot-keys cheatsheet:

¹[GitHub](#)

hot-key	meaning
F7	trace into
F8	step over
F9	run
Ctrl-F2	restart

F.3 MSVC

Some useful options which were used through this book.

option	meaning
/O1	minimize space
/Ob0	no inline expansion
/Ox	maximum optimizations
/GS-	disable security checks (buffer overflows)
/Fa(file)	generate assembly listing
/Zi	enable debugging information
/Zp(n)	pack structs on <i>n</i> -byte boundary
/MD	produced executable will use <code>MSVCR*.DLL</code>

Some information about MSVC versions: [58.1 on page 661](#).

F.4 GCC

Some useful options which were used through this book.

option	meaning
-Os	code size optimization
-O3	maximum optimization
-regparm=	how many arguments are to be passed in registers
-o file	set name of output file
-g	produce debugging information in resulting executable
-S	generate assembly listing file
-masm=intel	produce listing in Intel syntax
-fno-inline	do not inline functions

F.5 GDB

Some of commands we used in this book:

option	meaning
break filename.c:number	set a breakpoint on line number in source code
break function	set a breakpoint on function
break *address	set a breakpoint on address
b	—
p variable	print value of variable
run	run
r	—
cont	continue execution
c	—
bt	print stack
set disassembly-flavor intel	set Intel syntax
disas	disassemble current function
disas function	disassemble function
disas function,+50	disassemble portion
disas \$eip,+0x10	—
disas/r	disassemble with opcodes
info registers	print all registers
info float	print FPU-registers
info locals	dump local variables (if known)
x/w ...	dump memory as 32-bit word
x/w \$rdi	dump memory as 32-bit word at address stored in RDI
x/10w ...	dump 10 memory words
x/s ...	dump memory as string
x/i ...	dump memory as code
x/10c ...	dump 10 characters
x/b ...	dump bytes
x/h ...	dump 16-bit halfwords
x/g ...	dump giant (64-bit) words
finish	execute till the end of function
next	next instruction (don't dive into functions)
step	next instruction (dive into functions)
set step-mode on	do not use line number information while stepping
frame n	switch stack frame
info break	list of breakpoints
del n	delete breakpoint
set args ...	set command-line arguments

Acronyms used

OS Operating System	xxi
OOP Object-Oriented Programming	543
PL Programming language	4
PRNG Pseudorandom number generator	xiii
ROM Read-only memory	81
ALU Arithmetic logic unit	22
PID Program/process ID	763
LF Line feed (10 or '\n' in C/C++)	519
CR Carriage return (13 or '\r' in C/C++)	519
RA Return Address	18
PE Portable Executable	6
SP stack pointer. SP/ESP/RSP in x86/x64. SP in ARM	15
DLL Dynamic-link library	713
PC Program Counter. IP/EIP/RIP in x86/64. PC in ARM	16
LR Link Register	8
IDA Interactive Disassembler and debugger developed by Hex-Rays	8
IAT Import Address Table	714
INT Import Name Table	714
RVA Relative Virtual Address	714
VA Virtual Address	713
OEP Original Entry Point	702
MSVC Microsoft Visual C++	936
MSVS Microsoft Visual Studio	936
ASLR Address Space Layout Randomization	617
MFC Microsoft Foundation Classes	716
TLS Thread Local Storage	xix

CRT C runtime library	10
CPU Central processing unit	xxi
FPU Floating-point unit.....	viii
CISC Complex instruction set computing	16
RISC Reduced instruction set computing	4
GUI Graphical user interface.....	710
RTTI Run-time type information.....	558
BSS Block Started by Symbol.....	21
SIMD Single instruction, multiple data.....	194
BSOD Blue Screen of Death	703
DBMS Database management systems	xix
ISA Instruction Set Architecture	iv
HPC High-Performance Computing	511
SEH Structured Exception Handling.....	32
ELF Executable file format widely used in *NIX systems including Linux	xix
TIB Thread Information Block	283
PIC Position Independent Code: 70.1 on page 705	xix
NAN Not a Number	928
NOP No OPeration	23
BEQ (PowerPC, ARM) Branch if Equal	94
BNE (PowerPC, ARM) Branch if Not Equal	207
BLR (PowerPC) Branch to Link Register	773
XOR eXclusive OR	934
MCU Microcontroller unit	485
RAM Random-access memory	81

F.5. GDB

GCC GNU Compiler Collection	5
EGA Enhanced Graphics Adapter	912
VGA Video Graphics Array	912
API Application programming interface	664
ASCII American Standard Code for Information Interchange	493
ASCIIZ ASCII Zero (null-terminated ASCII string)	92
IA64 Intel Architecture 64 (Itanium): 96 on page 909	453
EPIC Explicitly parallel instruction computing	909
OOE Out-of-order execution	455
MSB Most significant bit/byte	315
LSB Least significant bit/byte	
STL (C++) Standard Template Library: 53.4 on page 560	564
PODT (C++) Plain Old Data Type	575
HDD Hard disk drive	587
VM Virtual Memory	
WRK Windows Research Kernel	678
GPR General Purpose Registers	xviii
SSDT System Service Dispatch Table	703
RE Reverse Engineering	918
RAID Redundant Array of Independent Disks	x
BCD Binary-coded decimal	853
BOM Byte order mark	668
GDB GNU debugger	43
FP Frame Pointer	20
MBR Master Boot Record	672
JPE Jump Parity Even (x86 instruction)	238

CIDR Classless Inter-Domain Routing	473
STMFD Store Multiple Full Descending (ARM instruction)	
LDMFD Load Multiple Full Descending (ARM instruction)	
STMED Store Multiple Empty Descending (ARM instruction)	27
LDMED Load Multiple Empty Descending (ARM instruction)	27
STMFA Store Multiple Full Ascending (ARM instruction)	27
LDMFA Load Multiple Full Ascending (ARM instruction)	27
STMEA Store Multiple Empty Ascending (ARM instruction)	27
LDMEA Load Multiple Empty Ascending (ARM instruction)	27
APSR (ARM) Application Program Status Register	261
FPSCR (ARM) Floating-Point Status and Control Register	261
RFC Request for Comments	670
TOS Top Of Stack	622
LVA (Java) Local Variable Array	628
JVM Java virtual machine	xiii
JIT Just-in-time compilation	621
CDFS Compact Disc File System	xiv
CD Compact Disc	
ADC Analog-to-digital converter	681
EOF End of file	85
MMU Memory management unit	616

Glossary

real number numbers which may contain a dot. this is *float* and *double* in C/C++. [215](#)

decrement Decrease by 1. [15](#), [184](#), [201](#), [441](#), [688](#), [815](#), [930](#), [932](#), [936](#)

increment Increase by 1. [16](#), [184](#), [188](#), [201](#), [206](#), [324](#), [327](#), [441](#), [811](#), [930](#)

integral data type usual numbers, but not a real ones. may be used for passing variables of boolean data type and enumerations. [231](#)

product Multiplication result. [98](#), [223](#), [226](#), [407](#), [433](#), [449](#), [490](#)

arithmetic mean a sum of all values divided by their count . [514](#)

stack pointer A register pointing to a place in the stack. [10](#), [11](#), [16](#), [27](#), [30](#), [38](#), [53](#), [55](#), [73](#), [99](#), [545](#), [597](#), [690–693](#), [925](#), [931](#), [941](#), [952](#)

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](#). [469](#)

quotient Division result. [215](#), [219](#), [221](#), [222](#), [226](#), [432](#), [487](#), [515](#), [767](#)

anti-pattern Generally considered as bad practice. [29](#), [75](#), [454](#)

atomic operation “*ατομός*” stands for “indivisible” in Greek, so an atomic operation is guaranteed not to be interrupted by other threads. [742](#), [906](#)

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 . [650](#), [913](#), [914](#)

callee A function being called by another. [26](#), [29](#), [42](#), [66](#), [86](#), [97](#), [99](#), [101](#), [155](#), [420](#), [454](#), [545](#), [597](#), [690–693](#), [695](#), [696](#), [944](#)

caller A function calling another. [7](#), [8](#), [10](#), [42](#), [86](#), [97](#), [98](#), [100](#), [108](#), [155](#), [420](#), [458](#), [545](#), [690](#), [692](#), [693](#), [696](#)

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: ([93](#) on page [901](#)). [936](#)

CP/M Control Program for Microcomputers: a very basic disk [OS](#) used before MS-DOS. [851](#)

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. [772](#)

endianness Byte order: [33](#) on page [452](#). [18](#), [78](#), [345](#), [934](#)

GiB Gibibyte: 2^{30} or 1024 mebibytes or 1073741824 bytes. [14](#)

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. [27](#), [29](#), [347](#), [561](#), [563](#), [575](#), [577](#), [712](#), [713](#)

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](#), [930](#)

leaf function A function which does not call any other function. [24](#), [29](#)

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. [29](#), [773](#), [941](#), [943](#)

Glossary

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: [53.1.1 on page 543](#), [543](#), [661](#), [662](#)

NaN not a number: a special cases for floating point numbers, usually signaling about errors . [234](#), [256](#), [911](#)

NEON AKA “Advanced SIMD”—SIMD from ARM. [942](#)

NOP “no operation”, idle instruction. [688](#)

NTAPI API available only in the Windows NT line. Largely not documented by Microsoft. [751](#)

PDB (Win32) Debugging information file, usually just function names, but sometimes also function arguments and local variables names. [660](#), [715](#), [751](#), [752](#), [759](#), [763](#), [833](#)

POKE BASIC language instruction for writing a byte at a specific address. [688](#)

register allocator The part of the compiler that assigns CPU registers to local variables. [200](#), [305](#), [420](#)

reverse engineering act of understanding how the thing works, sometimes in order to clone it. [v](#), [936](#)

security cookie A random value, different at each execution. You can read more about it here: [19.3 on page 282](#). [732](#)

stack frame A part of the stack that contains information specific to the current function: local variables, function arguments, RA, etc. [67](#), [98](#), [466](#), [733](#)

stdout standard output. [18](#), [30](#), [155](#)

thunk function Tiny function with a single role: call another function. [19](#), [391](#), [773](#), [781](#)

tracer My own simple debugging tool. You can read more about it here: [73.3 on page 745](#). [188–190](#), [665](#), [675](#), [679](#), [728](#), [737](#), [835](#), [841](#), [845](#), [846](#), [848](#), [900](#)

user mode A restricted CPU mode in which all application software code is executed. cf. [kernel mode](#). [788](#)

Windows NT Windows NT, 2000, XP, Vista, 7, 8. [292](#), [417](#), [596](#), [668](#), [703](#), [714](#), [741](#), [854](#), [936](#)

word data type fitting in [GPR](#). In the computers older than PCs, the memory size was often measured in words rather than bytes. [566](#)

xoring often used in the English language, which implying applying the [XOR](#) operation. [732](#), [733](#), [784](#), [787](#)

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