

Reverse Engineering for Beginners



Dennis Yurichev

Reverse Engineering for Beginners

Dennis Yurichev
<dennis(a)yurichev.com>



©2013-2015, Dennis Yurichev.

This work is licensed under the Creative Commons Attribution-NonCommercial-NoDerivs 3.0 Unported License. To view a copy of this license, visit <http://creativecommons.org/licenses/by-nc-nd/3.0/>.

Text version (October 10, 2015).

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

There is also a LITE-version (introductory short version), intended for those who want a very quick introduction to the basics of reverse engineering: beginners.re

You can also follow me on twitter to get information about updates of this text: @yurichev¹ or to subscribe to the mailing list².

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

¹twitter.com/yurichev

²yurichev.com

Abridged contents

I	Code patterns	1
II	Important fundamentals	462
III	Slightly more advanced examples	471
IV	Java	619
V	Finding important/interesting stuff in the code	657
VI	OS-specific	680
VII	Tools	734
VIII	Examples of real-world RE ³ tasks	740
IX	Examples of reversing proprietary file formats	855
X	Other things	886
XI	Books/blogs worth reading	904
XII	Exercises	908
	Afterword	946
	Appendix	948
	Acronyms used	988

³Reverse Engineering

Contents

I Code patterns	1
1 A short introduction to the CPU	3
1.1 A couple of words about different ISA ⁴ s	3
2 The simplest Function	5
2.1 x86	5
2.2 ARM	5
2.3 MIPS	6
2.3.1 A note about MIPS instruction/register names	6
3 Hello, world!	7
3.1 x86	7
3.1.1 MSVC	7
3.1.2 GCC	8
3.1.3 GCC: AT&T syntax	9
3.2 x86-64	10
3.2.1 MSVC-x86-64	10
3.2.2 GCC-x86-64	11
3.3 GCC—one more thing	12
3.4 ARM	12
3.4.1 Non-optimizing Keil 6/2013 (ARM mode)	13
3.4.2 Non-optimizing Keil 6/2013 (Thumb mode)	14
3.4.3 Optimizing Xcode 4.6.3 (LLVM) (ARM mode)	14
3.4.4 Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)	15
3.4.5 ARM64	17
3.5 MIPS	18
3.5.1 A word about the “global pointer”	18
3.5.2 Optimizing GCC	18
3.5.3 Non-optimizing GCC	20
3.5.4 Role of the stack frame in this example	21
3.5.5 Optimizing GCC: load it into GDB	21
3.6 Conclusion	22
3.7 Exercises	22
3.7.1 Exercise #1	22
3.7.2 Exercise #2	22
4 Function prologue and epilogue	23
4.1 Recursion	23
5 Stack	24
5.1 Why does the stack grow backwards?	24
5.2 What is the stack used for?	25
5.2.1 Save the function’s return address	25
5.2.2 Passing function arguments	26
5.2.3 Local variable storage	27
5.2.4 x86: alloca() function	27
5.2.5 (Windows) SEH	29
5.2.6 Buffer overflow protection	29
5.2.7 Automatic deallocation of data in stack	29

⁴Instruction Set Architecture

5.3 A typical stack layout	29
5.4 Noise in stack	29
5.5 Exercises	33
5.5.1 Exercise #1	33
5.5.2 Exercise #2	33
6 printf() with several arguments	36
6.1 x86	36
6.1.1 x86: 3 arguments	36
6.1.2 x64: 8 arguments	44
6.2 ARM	47
6.2.1 ARM: 3 arguments	47
6.2.2 ARM: 8 arguments	48
6.3 MIPS	52
6.3.1 3 arguments	52
6.3.2 8 arguments	54
6.4 Conclusion	58
6.5 By the way	59
7 scanf()	60
7.1 Simple example	60
7.1.1 About pointers	60
7.1.2 x86	61
7.1.3 MSVC + OllyDbg	63
7.1.4 x64	66
7.1.5 ARM	67
7.1.6 MIPS	68
7.2 Global variables	69
7.2.1 MSVC: x86	69
7.2.2 MSVC: x86 + OllyDbg	71
7.2.3 GCC: x86	72
7.2.4 MSVC: x64	72
7.2.5 ARM: Optimizing Keil 6/2013 (Thumb mode)	73
7.2.6 ARM64	74
7.2.7 MIPS	74
7.3 scanf() result checking	78
7.3.1 MSVC: x86	78
7.3.2 MSVC: x86: IDA	79
7.3.3 MSVC: x86 + OllyDbg	83
7.3.4 MSVC: x86 + Hiew	85
7.3.5 MSVC: x64	86
7.3.6 ARM	87
7.3.7 MIPS	88
7.3.8 Exercise	89
7.4 Exercises	89
7.4.1 Exercise #1	89
8 Accessing passed arguments	90
8.1 x86	90
8.1.1 MSVC	90
8.1.2 MSVC + OllyDbg	91
8.1.3 GCC	91
8.2 x64	92
8.2.1 MSVC	92
8.2.2 GCC	93
8.2.3 GCC: uint64_t instead of int	94
8.3 ARM	95
8.3.1 Non-optimizing Keil 6/2013 (ARM mode)	95
8.3.2 Optimizing Keil 6/2013 (ARM mode)	96
8.3.3 Optimizing Keil 6/2013 (Thumb mode)	96
8.3.4 ARM64	96
8.4 MIPS	98
9 More about results returning	99
9.1 Attempt to use the result of a function returning void	99

9.2 What if we do not use the function result?	100
9.3 Returning a structure	100
10 Pointers	102
10.1 Global variables example	102
10.2 Local variables example	108
10.3 Conclusion	111
11 GOTO operator	112
11.1 Dead code	114
11.2 Exercise	115
12 Conditional jumps	116
12.1 Simple example	116
12.1.1 x86	116
12.1.2 ARM	127
12.1.3 MIPS	130
12.2 Calculating absolute value	133
12.2.1 Optimizing MSVC	133
12.2.2 Optimizing Keil 6/2013: Thumb mode	133
12.2.3 Optimizing Keil 6/2013: ARM mode	133
12.2.4 Non-optimizing GCC 4.9 (ARM64)	134
12.2.5 MIPS	134
12.2.6 Branchless version?	134
12.3 Ternary conditional operator	134
12.3.1 x86	135
12.3.2 ARM	136
12.3.3 ARM64	136
12.3.4 MIPS	137
12.3.5 Let's rewrite it in an <i>if/else</i> way	137
12.3.6 Conclusion	137
12.4 Getting minimal and maximal values	138
12.4.1 32-bit	138
12.4.2 64-bit	140
12.4.3 MIPS	142
12.5 Conclusion	142
12.5.1 x86	142
12.5.2 ARM	142
12.5.3 MIPS	143
12.5.4 Branchless	143
12.6 Exercise	143
13 switch()/case/default	144
13.1 Small number of cases	144
13.1.1 x86	144
13.1.2 ARM: Optimizing Keil 6/2013 (ARM mode)	154
13.1.3 ARM: Optimizing Keil 6/2013 (Thumb mode)	154
13.1.4 ARM64: Non-optimizing GCC (Linaro) 4.9	155
13.1.5 ARM64: Optimizing GCC (Linaro) 4.9	156
13.1.6 MIPS	156
13.1.7 Conclusion	157
13.2 A lot of cases	157
13.2.1 x86	157
13.2.2 ARM: Optimizing Keil 6/2013 (ARM mode)	164
13.2.3 ARM: Optimizing Keil 6/2013 (Thumb mode)	165
13.2.4 MIPS	167
13.2.5 Conclusion	168
13.3 When there are several <i>case</i> statements in one block	169
13.3.1 MSVC	169
13.3.2 GCC	170
13.3.3 ARM64: Optimizing GCC 4.9.1	171
13.4 Fall-through	172
13.4.1 MSVC x86	173
13.4.2 ARM64	174
13.5 Exercises	174

13.5.1 Exercise #1	174
14 Loops	175
14.1 Simple example	175
14.1.1 x86	175
14.1.2 x86: OllyDbg	179
14.1.3 x86: tracer	179
14.1.4 ARM	181
14.1.5 MIPS	184
14.1.6 One more thing	185
14.2 Memory blocks copying routine	185
14.2.1 Straight-forward implementation	185
14.2.2 ARM in ARM mode	186
14.2.3 MIPS	187
14.2.4 Vectorization	187
14.3 Conclusion	188
14.4 Exercises	189
14.4.1 Exercise #1	189
14.4.2 Exercise #2	189
14.4.3 Exercise #3	189
14.4.4 Exercise #4	191
15 Simple C-strings processing	194
15.1 strlen()	194
15.1.1 x86	194
15.1.2 ARM	201
15.1.3 MIPS	204
15.2 Exercises	204
15.2.1 Exercise #1	204
16 Replacing arithmetic instructions to other ones	207
16.1 Multiplication	207
16.1.1 Multiplication using addition	207
16.1.2 Multiplication using shifting	207
16.1.3 Multiplication using shifting, subtracting, and adding	208
16.2 Division	212
16.2.1 Division using shifts	212
16.3 Exercises	212
16.3.1 Exercise #2	212
17 Floating-point unit	214
17.1 IEEE 754	214
17.2 x86	214
17.3 ARM, MIPS, x86/x64 SIMD	214
17.4 C/C++	214
17.5 Simple example	215
17.5.1 x86	215
17.5.2 ARM: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)	222
17.5.3 ARM: Optimizing Keil 6/2013 (Thumb mode)	223
17.5.4 ARM64: Optimizing GCC (Linaro) 4.9	223
17.5.5 ARM64: Non-optimizing GCC (Linaro) 4.9	224
17.5.6 MIPS	225
17.6 Passing floating point numbers via arguments	225
17.6.1 x86	226
17.6.2 ARM + Non-optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)	226
17.6.3 ARM + Non-optimizing Keil 6/2013 (ARM mode)	227
17.6.4 ARM64 + Optimizing GCC (Linaro) 4.9	227
17.6.5 MIPS	228
17.7 Comparison example	229
17.7.1 x86	229
17.7.2 ARM	256
17.7.3 ARM64	259
17.7.4 MIPS	261
17.8 Stack, calculators and reverse Polish notation	261
17.9 x64	261

17.10 Exercises	261
17.10.1 Exercise #1	261
17.10.2 Exercise #2	261
18 Arrays	263
18.1 Simple example	263
18.1.1 x86	263
18.1.2 ARM	266
18.1.3 MIPS	269
18.2 Buffer overflow	270
18.2.1 Reading outside array bounds	270
18.2.2 Writing beyond array bounds	273
18.3 Buffer overflow protection methods	278
18.3.1 Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)	279
18.4 One more word about arrays	281
18.5 Array of pointers to strings	281
18.5.1 x64	282
18.5.2 32-bit ARM	283
18.5.3 ARM64	284
18.5.4 MIPS	285
18.5.5 Array overflow	285
18.6 Multidimensional arrays	288
18.6.1 Two-dimensional array example	288
18.6.2 Access two-dimensional array as one-dimensional	289
18.6.3 Three-dimensional array example	291
18.6.4 More examples	294
18.7 Pack of strings as a two-dimensional array	294
18.7.1 32-bit ARM	296
18.7.2 ARM64	296
18.7.3 MIPS	297
18.7.4 Conclusion	297
18.8 Conclusion	298
18.9 Exercises	298
18.9.1 Exercise #1	298
18.9.2 Exercise #2	301
18.9.3 Exercise #3	305
18.9.4 Exercise #4	306
18.9.5 Exercise #5	307
19 Manipulating specific bit(s)	312
19.1 Specific bit checking	312
19.1.1 x86	312
19.1.2 ARM	314
19.2 Setting and clearing specific bits	315
19.2.1 x86	316
19.2.2 ARM + Optimizing Keil 6/2013 (ARM mode)	321
19.2.3 ARM + Optimizing Keil 6/2013 (Thumb mode)	322
19.2.4 ARM + Optimizing Xcode 4.6.3 (LLVM) (ARM mode)	322
19.2.5 ARM: more about the BIC instruction	322
19.2.6 ARM64: Optimizing GCC (Linaro) 4.9	322
19.2.7 ARM64: Non-optimizing GCC (Linaro) 4.9	323
19.2.8 MIPS	323
19.3 Shifts	323
19.4 Setting and clearing specific bits: FPU ⁵ example	323
19.4.1 A word about the XOR operation	324
19.4.2 x86	324
19.4.3 MIPS	326
19.4.4 ARM	326
19.5 Counting bits set to 1	328
19.5.1 x86	329
19.5.2 x64	337
19.5.3 ARM + Optimizing Xcode 4.6.3 (LLVM) (ARM mode)	339
19.5.4 ARM + Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)	340

⁵Floating-point unit

19.5.5 ARM64 + Optimizing GCC 4.9	340
19.5.6 ARM64 + Non-optimizing GCC 4.9	340
19.5.7 MIPS	341
19.6 Conclusion	343
19.6.1 Check for specific bit (known at compile stage)	343
19.6.2 Check for specific bit (specified at runtime)	343
19.6.3 Set specific bit (known at compile stage)	344
19.6.4 Set specific bit (specified at runtime)	344
19.6.5 Clear specific bit (known at compile stage)	344
19.6.6 Clear specific bit (specified at runtime)	345
19.7 Exercises	345
19.7.1 Exercise #1	345
19.7.2 Exercise #2	346
19.7.3 Exercise #3	349
19.7.4 Exercise #4	349
20 Linear congruential generator	352
20.1 x86	352
20.2 x64	353
20.3 32-bit ARM	354
20.4 MIPS	354
20.4.1 MIPS relocations	355
20.5 Thread-safe version of the example	356
21 Structures	357
21.1 MSVC: SYSTEMTIME example	357
21.1.1 OllyDbg	359
21.1.2 Replacing the structure with array	359
21.2 Let's allocate space for a structure using malloc()	360
21.3 UNIX: struct tm	362
21.3.1 Linux	362
21.3.2 ARM	365
21.3.3 MIPS	366
21.3.4 Structure as a set of values	368
21.3.5 Structure as an array of 32-bit words	369
21.3.6 Structure as an array of bytes	370
21.4 Fields packing in structure	372
21.4.1 x86	372
21.4.2 ARM	376
21.4.3 MIPS	377
21.4.4 One more word	378
21.5 Nested structures	378
21.5.1 OllyDbg	380
21.6 Bit fields in a structure	380
21.6.1 CPUID example	380
21.6.2 Working with the float type as with a structure	384
21.7 Exercises	387
21.7.1 Exercise #1	387
21.7.2 Exercise #2	387
22 Unions	392
22.1 Pseudo-random number generator example	392
22.1.1 x86	393
22.1.2 MIPS	394
22.1.3 ARM (ARM mode)	395
22.2 Calculating machine epsilon	396
22.2.1 x86	397
22.2.2 ARM64	397
22.2.3 MIPS	398
22.2.4 Conclusion	398
22.3 Fast square root calculation	398
23 Pointers to functions	400
23.1 MSVC	401
23.1.1 MSVC + OllyDbg	403

23.1.2 MSVC + tracer	405
23.1.3 MSVC + tracer (code coverage)	407
23.2 GCC	407
23.2.1 GCC + GDB (with source code)	408
23.2.2 GCC + GDB (no source code)	409
24 64-bit values in 32-bit environment	412
24.1 Returning of 64-bit value	412
24.1.1 x86	412
24.1.2 ARM	412
24.1.3 MIPS	413
24.2 Arguments passing, addition, subtraction	413
24.2.1 x86	413
24.2.2 ARM	414
24.2.3 MIPS	415
24.3 Multiplication, division	416
24.3.1 x86	416
24.3.2 ARM	418
24.3.3 MIPS	419
24.4 Shifting right	420
24.4.1 x86	420
24.4.2 ARM	420
24.4.3 MIPS	421
24.5 Converting 32-bit value into 64-bit one	421
24.5.1 x86	421
24.5.2 ARM	421
24.5.3 MIPS	422
25 SIMD	423
25.1 Vectorization	423
25.1.1 Addition example	424
25.1.2 Memory copy example	429
25.2 SIMD strlen() implementation	433
26 64 bits	436
26.1 x86-64	436
26.2 ARM	442
26.3 Float point numbers	443
27 Working with floating point numbers using SIMD	444
27.1 Simple example	444
27.1.1 x64	444
27.1.2 x86	445
27.2 Passing floating point number via arguments	452
27.3 Comparison example	453
27.3.1 x64	453
27.3.2 x86	454
27.4 Calculating machine epsilon: x64 and SIMD	454
27.5 Pseudo-random number generator example revisited	455
27.6 Summary	455
28 ARM-specific details	457
28.1 Number sign (#) before number	457
28.2 Addressing modes	457
28.3 Loading a constant into a register	458
28.3.1 32-bit ARM	458
28.3.2 ARM64	458
28.4 Relocs in ARM64	459
29 MIPS-specific details	461
29.1 Loading constants into register	461
29.2 Further reading about MIPS	461

II Important fundamentals	462
30 Signed number representations	464
31 Endianness	466
31.1 Big-endian	466
31.2 Little-endian	466
31.3 Example	466
31.4 Bi-endian	467
31.5 Converting data	467
32 Memory	468
33 CPU	469
33.1 Branch predictors	469
33.2 Data dependencies	469
34 Hash functions	470
34.1 How one-way function works?	470
III Slightly more advanced examples	471
35 Temperature converting	472
35.1 Integer values	472
35.1.1 Optimizing MSVC 2012 x86	472
35.1.2 Optimizing MSVC 2012 x64	474
35.2 Floating-point values	474
36 Fibonacci numbers	477
36.1 Example #1	477
36.2 Example #2	480
36.3 Summary	483
37 CRC32 calculation example	484
38 Network address calculation example	487
38.1 calc_network_address()	488
38.2 form_IP()	489
38.3 print_as_IP()	490
38.4 form_netmask() and set_bit()	491
38.5 Summary	492
39 Loops: several iterators	493
39.1 Three iterators	493
39.2 Two iterators	494
39.3 Intel C++ 2011 case	495
40 Duff's device	498
41 Division by 9	501
41.1 x86	501
41.2 ARM	502
41.2.1 Optimizing Xcode 4.6.3 (LLVM) (ARM mode)	502
41.2.2 Optimizing Xcode 4.6.3 (LLVM) (Thumb-2 mode)	503
41.2.3 Non-optimizing Xcode 4.6.3 (LLVM) and Keil 6/2013	503
41.3 MIPS	503
41.4 How it works	504
41.4.1 More theory	505
41.5 Getting the divisor	505
41.5.1 Variant #1	505
41.5.2 Variant #2	506
41.6 Exercise #1	506
42 String to number conversion (atoi())	508
42.1 Simple example	508

42.1.1 Optimizing MSVC 2013 x64	508
42.1.2 Optimizing GCC 4.9.1 x64	509
42.1.3 Optimizing Keil 6/2013 (ARM mode)	509
42.1.4 Optimizing Keil 6/2013 (Thumb mode)	510
42.1.5 Optimizing GCC 4.9.1 ARM64	510
42.2 A slightly advanced example	511
42.2.1 Optimizing GCC 4.9.1 x64	512
42.2.2 Optimizing Keil 6/2013 (ARM mode)	513
42.3 Exercise	514
43 Inline functions	515
43.1 Strings and memory functions	516
43.1.1 strcmp()	516
43.1.2 strlen()	518
43.1.3 strcpy()	518
43.1.4 memset()	518
43.1.5 memcpy()	520
43.1.6 memcmp()	522
43.1.7 IDA script	523
44 C99 restrict	524
45 Branchless <i>abs()</i> function	527
45.1 Optimizing GCC 4.9.1 x64	527
45.2 Optimizing GCC 4.9 ARM64	528
46 Variadic functions	529
46.1 Computing arithmetic mean	529
46.1.1 <i>cdecl</i> calling conventions	529
46.1.2 Register-based calling conventions	530
46.2 vprintf() function case	532
47 Strings trimming	534
47.1 x64: Optimizing MSVC 2013	535
47.2 x64: Non-optimizing GCC 4.9.1	536
47.3 x64: Optimizing GCC 4.9.1	537
47.4 ARM64: Non-optimizing GCC (Linaro) 4.9	538
47.5 ARM64: Optimizing GCC (Linaro) 4.9	539
47.6 ARM: Optimizing Keil 6/2013 (ARM mode)	540
47.7 ARM: Optimizing Keil 6/2013 (Thumb mode)	540
47.8 MIPS	541
48 toupper() function	543
48.1 x64	543
48.1.1 Two comparison operations	543
48.1.2 One comparison operation	544
48.2 ARM	545
48.2.1 GCC for ARM64	545
48.3 Summary	546
49 Incorrectly disassembled code	547
49.1 Disassembling from an incorrect start (x86)	547
49.2 How does random noise looks disassembled?	548
50 Obfuscation	552
50.1 Text strings	552
50.2 Executable code	553
50.2.1 Inserting garbage	553
50.2.2 Replacing instructions with bloated equivalents	553
50.2.3 Always executed/never executed code	553
50.2.4 Making a lot of mess	553
50.2.5 Using indirect pointers	554
50.3 Virtual machine / pseudo-code	554
50.4 Other things to mention	554
50.5 Exercises	554

50.5.1 Exercise #1	554
51 C++	555
51.1 Classes	555
51.1.1 A simple example	555
51.1.2 Class inheritance	561
51.1.3 Encapsulation	564
51.1.4 Multiple inheritance	565
51.1.5 Virtual methods	568
51.2 ostream	571
51.3 References	572
51.4 STL	572
51.4.1 std::string	572
51.4.2 std::list	579
51.4.3 std::vector	588
51.4.4 std::map and std::set	595
52 Negative array indices	605
53 Windows 16-bit	608
53.1 Example#1	608
53.2 Example #2	608
53.3 Example #3	609
53.4 Example #4	610
53.5 Example #5	612
53.6 Example #6	616
53.6.1 Global variables	617
IV Java	619
54 Java	620
54.1 Introduction	620
54.2 Returning a value	620
54.3 Simple calculating functions	624
54.4 JVM ⁶ memory model	627
54.5 Simple function calling	627
54.6 Calling beep()	628
54.7 Linear congruential PRNG ⁷	629
54.8 Conditional jumps	630
54.9 Passing arguments	632
54.10 Bitfields	633
54.11 Loops	634
54.12 switch()	636
54.13 Arrays	637
54.13.1 Simple example	637
54.13.2 Summing elements of array	638
54.13.3 main() function sole argument is array too	638
54.13.4 Pre-initialized array of strings	639
54.13.5 Variadic functions	641
54.13.6 Two-dimensional arrays	642
54.13.7 Three-dimensional arrays	643
54.13.8 Summary	644
54.14 Strings	644
54.14.1 First example	644
54.14.2 Second example	645
54.15 Exceptions	646
54.16 Classes	649
54.17 Simple patching	651
54.17.1 First example	651
54.17.2 Second example	653
54.18 Summary	656

⁶Java virtual machine⁷Pseudorandom number generator

V Finding important/interesting stuff in the code	657
55 Identification of executable files	659
55.1 Microsoft Visual C++	659
55.1.1 Name mangling	659
55.2 GCC	659
55.2.1 Name mangling	659
55.2.2 Cygwin	659
55.2.3 MinGW	659
55.3 Intel FORTRAN	660
55.4 Watcom, OpenWatcom	660
55.4.1 Name mangling	660
55.5 Borland	660
55.5.1 Delphi	660
55.6 Other known DLLs	661
56 Communication with the outer world (win32)	662
56.1 Often used functions in the Windows API	662
56.2 tracer: Intercepting all functions in specific module	663
57 Strings	664
57.1 Text strings	664
57.1.1 C/C++	664
57.1.2 Borland Delphi	664
57.1.3 Unicode	665
57.1.4 Base64	667
57.2 Error/debug messages	668
57.3 Suspicious magic strings	668
58 Calls to assert()	669
59 Constants	670
59.1 Magic numbers	670
59.1.1 DHCP	671
59.2 Searching for constants	671
60 Finding the right instructions	672
61 Suspicious code patterns	674
61.1 XOR instructions	674
61.2 Hand-written assembly code	674
62 Using magic numbers while tracing	676
63 Other things	677
63.1 General idea	677
63.2 C++	677
63.3 Some binary file patterns	677
63.4 Memory “snapshots” comparing	678
63.4.1 Windows registry	679
63.4.2 Blink-comparator	679
VI OS-specific	680
64 Arguments passing methods (calling conventions)	681
64.1 cdecl	681
64.2 stdcall	681
64.2.1 Functions with variable number of arguments	682
64.3 fastcall	682
64.3.1 GCC regparm	683
64.3.2 Watcom/OpenWatcom	683
64.4 thiscall	683
64.5 x86-64	683
64.5.1 Windows x64	683
64.5.2 Linux x64	686

64.6 Return values of <i>float</i> and <i>double</i> type	686
64.7 Modifying arguments	686
64.8 Taking a pointer to function argument	687
65 Thread Local Storage	689
65.1 Linear congruential generator revisited	689
65.1.1 Win32	689
65.1.2 Linux	693
66 System calls (syscall-s)	694
66.1 Linux	694
66.2 Windows	695
67 Linux	696
67.1 Position-independent code	696
67.1.1 Windows	698
67.2 <i>LD_PRELOAD</i> hack in Linux	698
68 Windows NT	701
68.1 CRT (win32)	701
68.2 Win32 PE	704
68.2.1 Terminology	704
68.2.2 Base address	705
68.2.3 Subsystem	705
68.2.4 OS version	705
68.2.5 Sections	706
68.2.6 Relocations (relocs)	706
68.2.7 Exports and imports	707
68.2.8 Resources	709
68.2.9 .NET	709
68.2.10 TLS	710
68.2.11 Tools	710
68.2.12 Further reading	710
68.3 Windows SEH	710
68.3.1 Let's forget about MSVC	710
68.3.2 Now let's get back to MSVC	715
68.3.3 Windows x64	728
68.3.4 Read more about SEH	732
68.4 Windows NT: Critical section	732
VII Tools	734
69 Disassembler	735
69.1 IDA	735
70 Debugger	736
70.1 OllyDbg	736
70.2 GDB	736
70.3 tracer	736
71 System calls tracing	737
71.0.1 strace / dtruss	737
72 Decompilers	738
73 Other tools	739
VIII Examples of real-world RE tasks	740
74 Task manager practical joke (Windows Vista)	742
74.1 Using LEA to load values	744
75 Color Lines game practical joke	746

76 Minesweeper (Windows XP)	750
76.1 Exercises	754
77 Hand decompiling + Z3 SMT solver	755
77.1 Hand decompiling	755
77.2 Now let's use the Z3 SMT solver	758
78 Dongles	763
78.1 Example #1: MacOS Classic and PowerPC	763
78.2 Example #2: SCO OpenServer	770
78.2.1 Decrypting error messages	777
78.3 Example #3: MS-DOS	779
79 "QR9": Rubik's cube inspired amateur crypto-algorithm	785
80 SAP	812
80.1 About SAP client network traffic compression	812
80.2 SAP 6.0 password checking functions	822
81 Oracle RDBMS	827
81.1 V\$VERSION table in the Oracle RDBMS	827
81.2 X\$KSMLRU table in Oracle RDBMS	834
81.3 V\$TIMER table in Oracle RDBMS	836
82 Handwritten assembly code	840
82.1 EICAR test file	840
83 Demos	842
83.1 10 PRINT CHR\$(205.5+RND(1)); : GOTO 10	842
83.1.1 Trixter's 42 byte version	842
83.1.2 My attempt to reduce Trixter's version: 27 bytes	843
83.1.3 Taking random memory garbage as a source of randomness	843
83.1.4 Conclusion	844
83.2 Mandelbrot set	845
83.2.1 Theory	846
83.2.2 Let's get back to the demo	851
83.2.3 My "fixed" version	853
IX Examples of reversing proprietary file formats	855
84 Primitive XOR-encryption	856
84.1 Norton Guide: simplest possible 1-byte XOR encryption	857
84.1.1 Entropy	858
84.2 Simplest possible 4-byte XOR encryption	860
84.2.1 Exercise	863
85 Millenium game save file	864
86 Oracle RDBMS: .SYM-files	871
87 Oracle RDBMS: .MSB-files	880
87.1 Summary	885
X Other things	886
88 npad	887
89 Executable files patching	889
89.1 Text strings	889
89.2 x86 code	889
90 Compiler intrinsic	890
91 Compiler's anomalies	891

92 OpenMP	892
92.1 MSVC	894
92.2 GCC	895
93 Itanium	898
94 8086 memory model	901
95 Basic blocks reordering	902
95.1 Profile-guided optimization	902
XI Books/blogs worth reading	904
96 Books	905
96.1 Windows	905
96.2 C/C++	905
96.3 x86 / x86-64	905
96.4 ARM	905
96.5 Cryptography	905
97 Blogs	906
97.1 Windows	906
98 Other	907
XII Exercises	908
99 Level 1	911
99.1 Exercise 1.4	911
100 Level 2	912
100.1 Exercise 2.1	912
100.1.1 Optimizing MSVC 2010 x86	912
100.1.2 Optimizing MSVC 2012 x64	913
100.2 Exercise 2.4	913
100.2.1 Optimizing MSVC 2010	913
100.2.2 GCC 4.4.1	914
100.2.3 Optimizing Keil (ARM mode)	915
100.2.4 Optimizing Keil (Thumb mode)	916
100.2.5 Optimizing GCC 4.9.1 (ARM64)	916
100.2.6 Optimizing GCC 4.4.5 (MIPS)	917
100.3 Exercise 2.6	918
100.3.1 Optimizing MSVC 2010	918
100.3.2 Optimizing Keil (ARM mode)	919
100.3.3 Optimizing Keil (Thumb mode)	919
100.3.4 Optimizing GCC 4.9.1 (ARM64)	920
100.3.5 Optimizing GCC 4.4.5 (MIPS)	921
100.4 Exercise 2.13	921
100.4.1 Optimizing MSVC 2012	921
100.4.2 Keil (ARM mode)	922
100.4.3 Keil (Thumb mode)	922
100.4.4 Optimizing GCC 4.9.1 (ARM64)	922
100.4.5 Optimizing GCC 4.4.5 (MIPS)	922
100.5 Exercise 2.14	923
100.5.1 MSVC 2012	923
100.5.2 Keil (ARM mode)	924
100.5.3 GCC 4.6.3 for Raspberry Pi (ARM mode)	924
100.5.4 Optimizing GCC 4.9.1 (ARM64)	925
100.5.5 Optimizing GCC 4.4.5 (MIPS)	926
100.6 Exercise 2.15	927
100.6.1 Optimizing MSVC 2012 x64	927
100.6.2 Optimizing GCC 4.4.6 x64	930
100.6.3 Optimizing GCC 4.8.1 x86	930
100.6.4 Keil (ARM mode): Cortex-R4F CPU as target	931

100.6.5 Optimizing GCC 4.9.1 (ARM64)	932
100.6.6 Optimizing GCC 4.4.5 (MIPS)	933
100.7 Exercise 2.16	934
100.7.1 Optimizing MSVC 2012 x64	934
100.7.2 Optimizing Keil (ARM mode)	935
100.7.3 Optimizing Keil (Thumb mode)	935
100.7.4 Non-optimizing GCC 4.9.1 (ARM64)	935
100.7.5 Optimizing GCC 4.9.1 (ARM64)	936
100.7.6 Non-optimizing GCC 4.4.5 (MIPS)	939
100.8 Exercise 2.17	940
100.9 Exercise 2.18	940
100.10 Exercise 2.19	940
100.11 Exercise 2.20	940
101 Level 3	942
101.1 Exercise 3.2	942
101.2 Exercise 3.3	942
101.3 Exercise 3.4	942
101.4 Exercise 3.5	942
101.5 Exercise 3.6	943
101.6 Exercise 3.8	943
102 crackme / keygenme	944
Afterword	946
103 Questions?	946
Appendix	948
A x86	948
A.1 Terminology	948
A.2 General purpose registers	948
A.2.1 RAX/EAX/AX/AL	948
A.2.2 RBX/EBX/BX/BL	949
A.2.3 RCX/ECX/CX/CL	949
A.2.4 RDX/EDX/DX/DL	949
A.2.5 RSI/ESI/SI/SIL	949
A.2.6 RDI/EDI/DI/DIL	949
A.2.7 R8/R8D/R8W/R8L	949
A.2.8 R9/R9D/R9W/R9L	950
A.2.9 R10/R10D/R10W/R10L	950
A.2.10 R11/R11D/R11W/R11L	950
A.2.11 R12/R12D/R12W/R12L	950
A.2.12 R13/R13D/R13W/R13L	950
A.2.13 R14/R14D/R14W/R14L	950
A.2.14 R15/R15D/R15W/R15L	950
A.2.15 RSP/ESP/SP/SPL	951
A.2.16 RBP/EBP/BP/BPL	951
A.2.17 RIP/EIP/IP	951
A.2.18 CS/DS/ES/SS/FS/GS	951
A.2.19 Flags register	951
A.3 FPU registers	952
A.3.1 Control Word	952
A.3.2 Status Word	953
A.3.3 Tag Word	953
A.4 SIMD registers	954
A.4.1 MMX registers	954
A.4.2 SSE and AVX registers	954
A.5 Debugging registers	954
A.5.1 DR6	954
A.5.2 DR7	954
A.6 Instructions	955

A.6.1	Prefixes	955
A.6.2	Most frequently used instructions	956
A.6.3	Less frequently used instructions	960
A.6.4	FPU instructions	964
A.6.5	Instructions having printable ASCII opcode	965
B	ARM	967
B.1	Terminology	967
B.2	Versions	967
B.3	32-bit ARM (AArch32)	967
B.3.1	General purpose registers	967
B.3.2	Current Program Status Register (CPSR)	968
B.3.3	VFP (floating point) and NEON registers	968
B.4	64-bit ARM (AArch64)	968
B.4.1	General purpose registers	968
B.5	Instructions	969
B.5.1	Conditional codes table	969
C	MIPS	970
C.1	Registers	970
C.1.1	General purpose registers GPR ⁸	970
C.1.2	Floating-point registers	970
C.2	Instructions	970
C.2.1	Jump instructions	971
D	Some GCC library functions	972
E	Some MSVC library functions	973
F	Cheatsheets	974
F.1	IDA	974
F.2	OllyDbg	974
F.3	MSVC	975
F.4	GCC	975
F.5	GDB	975
G	Exercise solutions	977
G.1	Per chapter	977
G.1.1	“Hello, world!” chapter	977
G.1.2	“Stack” chapter	977
G.1.3	“scanf()” chapter	978
G.1.4	“switch()/case/default” chapter	978
G.1.5	Exercise #1	978
G.1.6	“Loops” chapter	978
G.1.7	Exercise #3	978
G.1.8	Exercise #4	979
G.1.9	“Simple C-strings processing” chapter	979
G.1.10	“Replacing arithmetic instructions to other ones ” chapter	979
G.1.11	“Floating-point unit” chapter	979
G.1.12	“Arrays” chapter	980
G.1.13	“Manipulating specific bit(s)” chapter	981
G.1.14	“Structures” chapter	982
G.1.15	“Obfuscation” chapter	983
G.1.16	“Division by 9” chapter	983
G.2	Level 1	984
G.2.1	Exercise 1.1	984
G.2.2	Exercise 1.4	984
G.3	Level 2	984
G.3.1	Exercise 2.1	984
G.3.2	Exercise 2.4	984
G.3.3	Exercise 2.6	984
G.3.4	Exercise 2.13	985
G.3.5	Exercise 2.14	985
G.3.6	Exercise 2.15	985

⁸General Purpose Registers

G.3.7	Exercise 2.16	985
G.3.8	Exercise 2.17	985
G.3.9	Exercise 2.18	985
G.3.10	Exercise 2.19	985
G.3.11	Exercise 2.20	986
G.4	Level 3	986
G.4.1	Exercise 3.2	986
G.4.2	Exercise 3.3	986
G.4.3	Exercise 3.4	986
G.4.4	Exercise 3.5	986
G.4.5	Exercise 3.6	986
G.4.6	Exercise 3.8	986
G.5	Other	986
G.5.1	"Minesweeper (Windows XP)" example	986

Acronyms used**988****Glossary****992****Index****994****Bibliography****1000**

Preface

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 to duplicate them; 3) recreating [DBMS](#)⁹ structure. This book is about the first meaning.

Topics discussed in-depth

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

Topics touched upon

Oracle RDBMS ([81 on page 827](#)), Itanium ([93 on page 898](#)), copy-protection dongles ([78 on page 763](#)), LD_PRELOAD ([67.2 on page 698](#)), stack overflow, [ELF](#)¹⁰, win32 PE file format ([68.2 on page 704](#)), x86-64 ([26.1 on page 436](#)), critical sections ([68.4 on page 732](#)), syscalls ([66 on page 694](#)), [TLS](#)¹¹, position-independent code ([PIC](#)¹²) ([67.1 on page 696](#)), profile-guided optimization ([95.1 on page 902](#)), C++ STL ([51.4 on page 572](#)), OpenMP ([92 on page 892](#)), SEH ([68.3 on page 710](#)).

About the author



Dennis Yurichev is an experienced reverse engineer and programmer. He can be contacted by email: [dennis\(a\)yurichev.com](mailto:dennis(a)yurichev.com), or on Skype: [dennis.yurichev](#).

Praise for *Reverse Engineering for Beginners*

- “It’s very well done .. and for free .. amazing.”¹³ Daniel Bilar, Siege Technologies, LLC.
- “... excellent and free”¹⁴ 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.
- “... reasonable intro to some of the techniques.”¹⁵ 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.”¹⁶ Sergey Bratus, Research Assistant Professor at the Computer Science Department at Dartmouth College

⁹Database management systems

¹⁰Executable file format widely used in *NIX systems including Linux

¹¹Thread Local Storage

¹²Position Independent Code: [67.1 on page 696](#)

¹³twitter.com/daniel_bilar/status/436578617221742593

¹⁴twitter.com/petefinnigan/status/400551705797869568

¹⁵[reddit](#)

¹⁶twitter.com/sergeybratus/status/505590326560833536

- “Dennis @Yurichev has published an impressive (and free!) book on reverse engineering”¹⁷ Tanel Poder, Oracle RDBMS performance tuning expert.
- “This book is some kind of Wikipedia to beginners...” Archer, Chinese Translator, IT Security Researcher.

Thanks

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

For sending me notes about mistakes and inaccuracies: Stanislav “Beaver” Bobrytskyy, Alexander Lysenko, Shell Rocket, Zhu Ruijin, Changmin Heo.

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

For translating the book into Simplified Chinese: Antiy Labs ([antiy.cn](#)) and Archer.

For translating the book into Korean: Byungho Min.

For proofreading: Alexander “Lstar” Chernenkiy, Vladimir Botov, Andrei Brazhuk, Mark “Logxen” Cooper, Yuan Jochen Kang, Mal Malakov, Lewis Porter, Jarle Thorsen.

Vasil Kolev did a great amount of work in proofreading and correcting many mistakes.

For illustrations and cover art: Andy Nechaevsky.

Thanks also to all the folks on [github.com](#) who have contributed notes and corrections.

Many \LaTeX packages were used: I would like to thank the authors as well.

Donors

Those who supported me during the time when I wrote significant part of the book:

2 * Oleg Vygovsky (50+100 UAH), Daniel Bilar (\$50), James Truscott (\$4.5), Luis Rocha (\$63), Joris van de Vis (\$127), Richard S Shultz (\$20), Jang Minchang (\$20), Shade Atlas (5 AUD), Yao Xiao (\$10), Paweł Szczur (40 CHF), Justin Simms (\$20), Shawn the R0ck (\$27), Ki Chan Ahn (\$50), Triop AB (100 SEK), Ange Albertini (€10+50), Sergey Lukianov (300 RUR), Ludvig Gislason (200 SEK), Gérard Labadie (€40), Sergey Volchkov (10 AUD), Vankayala Vigneswararao (\$50), Philippe Teuwen (\$4), Martin Haeberli (\$10), Victor Cazacov (€5), Tobias Sturzenegger (10 CHF), Sonny Thai (\$15), Bayna AlZaabi (\$75), Redfive B.V. (€25), Joona Oskari Heikkilä (€5), Marshall Bishop (\$50), Nicolas Werner (€12), Jeremy Brown (\$100), Alexandre Borges (\$25), Vladimir Dikovski (€50), Jiarui Hong (100.00 SEK), Jim Di (500 RUR), Tan Vincent (\$30), Sri Harsha Kandrakota (10 AUD), Pillay Harish (10 SGD), Timur Valiev (230 RUR), Carlos Garcia Prado (€10), Salikov Alexander (500 RUR), Oliver Whitehouse (30 GBP), Katy Moe (\$14), Maxim Dyakonov (\$3), Sebastian Aguilera (€20), Hans-Martin Münch (€15), Jarle Thorsen (100 NOK), Vitaly Osipov (\$100), Yuri Romanov (1000 RUR), Aliaksandr Autayeu (€10), Tudor Azoitei (\$40), Z0vsky (€10), Yu Dai (\$10).

Thanks a lot to every donor!

mini-FAQ

Q: Why should one learn assembly language these days?

A: Unless you are an [OS](#)¹⁸ developer, you probably don’t need to code in assembly—modern compilers are much better at performing optimizations than humans¹⁹. Also, modern [CPU](#)²⁰s 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: Your book is huge! Is there anything shorter?

A: There is shortened, lite version found here: <http://beginners.re/#lite>.

Q: I’m not sure if I should try to learn reverse engineering or not.

A: Perhaps, the average time to become familiar with the contents of the shortened LITE-version is 1-2 month(s).

¹⁷ twitter.com/TanelPoder/status/524668104065159169

¹⁸ Operating System

¹⁹ A very good text about this topic: [\[Fog13b\]](#)

²⁰ Central processing unit

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. One might also want to build one's own version of book—read [here](#) to find out more.

Q: I want to translate your book to some other language.

A: Read [my note to translators](#).

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 RE²¹ ([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/andydinka](#).

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.

²¹[reddit.com/r/ReverseEngineering/](#)

Part I

Code patterns

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.²² 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.

²²In fact, he still does it when he can't understand what a particular bit of code does.

Chapter 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 **CPUs** 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 **CPUs** we know of today . In a similar fashion, it is very inconvenient for humans to write in assembly language, due to it being so low-level and difficult to write in without making a huge number of annoying mistakes. The program that converts the high-level **PL** code into assembly is called a *compiler*.

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**² **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 bytes³. 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** instructions⁴ 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,

¹Programming language

²Reduced instruction set computing

³By 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 ([13.2.2 on page 164](#)) section.

⁴These are MOV/PUSH/CALL/lcc

the 64-bit requirements affected the ISA, resulting in us now having three ARM instruction sets: ARM mode, Thumb mode (including Thumb-2) and ARM64. These ISAs intersect partially, but it can be said that they are different ISAs, rather than variations of the same one. Therefore, we 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.

Chapter 2

The simplest Function

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

Here it is:

Listing 2.1: C/C++ Code

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

Lets compile it!

2.1 x86

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

Listing 2.2: 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.

2.2 ARM

There are a few differences on the ARM platform:

Listing 2.3: 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*.

2.3 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 2.4: Optimizing GCC 4.4.5 (assembly output)

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

...while [IDA](#)¹ does it—by their pseudonames:

Listing 2.5: 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 [LR](#)² 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/brunch instruction itself. As a consequence, branch instructions always swap places with the instruction which must be executed beforehand.

2.3.1 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.

¹Interactive Disassembler and debugger developed by [Hex-Rays](#)

²Link Register

Chapter 3

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;
}
```

3.1 x86

3.1.1 MSVC

Let's compile it in MSVC 2010:

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

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

Listing 3.1: 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 [3.1.3 on page 9](#).

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.

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 strings: [57.1.1 on page 664](#).

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 3.2: 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`.

3.1.2 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.

Listing 3.3: 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"

¹You can read more about it in the section about function prologues and epilogues ([4 on page 23](#)).

²CPU flags, however, are modified

³[wikipedia](#)

⁴C runtime library : [68.1 on page 701](#)

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

```

        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, ...`).

3.1.3 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 3.4: let's compile in GCC 4.7.3

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

We get this:

Listing 3.5: 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
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"

```

⁶[Wikipedia: Data structure alignment](#)

```
.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 3.6: 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.

3.2 x86-64

3.2.1 MSVC-x86-64

Let's also try 64-bit MSVC:

Listing 3.7: 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
```

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.

```
        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: [64.3 on page 682](#)). 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:

7th (byte number)	6th	5th	4th	3rd	2nd	1st	0th
RAX ^{x64}							
EAX							
AX							
				AH	AL		

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: [8.2.1 on page 93](#).

3.2.2 GCC–x86-64

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

Listing 3.8: 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 [[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, 01122334h` writes a value into RAX correctly, since the higher bits will be cleared.

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

Listing 3.9: 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 ([\[Mit13\]](#)).

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

3.3 GCC—one more thing

The fact that an *anonymous* C-string has *const* type ([3.1.1 on page 7](#)), 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 3.10: 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
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.

3.4 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 compiler¹⁰).

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

- 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.

3.4.1 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 macros¹¹, but it is more important for us to see the instructions “as is” so let's see the compiled result in [IDA](#).

Listing 3.11: 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`.

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 `PC`¹⁵ 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 __2printf`¹⁷ instruction calls the `printf()` function. Here's how this instruction works:

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

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

That is a difference between “pure” [RISC](#)-processors like ARM and [CISC](#)¹⁸-processors like x86, where the return address is usually stored on the stack¹⁹.

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

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

¹²`STMFD`¹³

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

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

¹⁶Read more about it in relevant section ([6.7.1 on page 696](#))

¹⁷Branch with Link

¹⁸Complex instruction set computing

¹⁹Read more about this in next section ([5 on page 24](#))

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 $\text{current_PC} \pm \approx 32M$.

Next, the `MOV R0, #0`²⁰ instruction just writes 0 into the R0 register. That's because our C-function returns 0 and the return value is to be placed in the R0 register.

The last instruction `LDMFD SP!, R4, PC`²¹ is an inverse instruction of `STMFD`. 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.

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

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

```
armcc.exe --thumb --c90 -00 1.c
```

We are getting (in IDA):

Listing 3.12: 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, #
.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.

3.4.3 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 3.13: 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
```

²⁰MOVE

²¹LDMFD²²

```

__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 (MOVe 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(). *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 different²³.

Why did the compiler replace the printf() with puts()? Probably because puts() is faster²⁴. 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.

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

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

Listing 3.14: 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 0Ex. 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.

²³It 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.

²⁴ciselant.de/projects/gcc_printf/gcc_printf.html

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 RA²⁵ in the LR register and passing control to the puts() function, the processor is also switching from Thumb/Thumb-2 mode to ARM mode (or back). This instruction is placed here since the instruction to which control is passed looks like (it is encoded in ARM mode):

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

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

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

Because it is not very space-efficient.

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

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)

²⁵Return Address

3.4.5 ARM64

GCC

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

Listing 3.15: 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 ...
12 ...
13 Contents of section .rodata:
14 400640 01000200 00000000 48656c6c 6f210a00 .....Hello!...

```

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 968](#). 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: [28.2 on page 457](#).

Hence, in terms of the more familiar x86, the first instruction is just an analogue to a pair of PUSH X29 and PUSH X30. X29 is used as **FP**²⁶ 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: [28.3.1 on page 458](#)). 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: [28.4 on page 459](#).

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: [3.4.3 on page 15](#).

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 3.16: `main()` returning a value of `uint64_t` type

```

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

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

```

²⁶Frame Pointer

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

Listing 3.17: Non-optimizing GCC 4.8.1 + objdump

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

LDP (*Load Pair*) then restores the X29 and X30 registers. There is no exclamation mark after the instruction: this implies that the 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.

3.5 MIPS

3.5.1 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 BSS²⁷”) 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 94 on page 901 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.

3.5.2 Optimizing GCC

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

Listing 3.18: 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

```

²⁷ Block Started by Symbol

```
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 ("Load Word"). Then the address of the text string is loaded to \$4 using LUI ("Load Upper Immediate") and ADDIU ("Add Immediate Unsigned Word") instruction pair. LUI sets the high 16 bits of the register (hence "upper" word in instruction name) and ADDIU adds the lower 16 bits of the address. ADDIU follows JALR (remember *branch delay slots*?). The register \$4 is also called \$A0, which is used for passing the first function argument²⁸.

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 **ALU**²⁹ 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 3.19: 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 error³⁰. The GP value has to be saved indeed, because each function can use its own 64KiB data window.

²⁸The MIPS registers table is available in appendix [C.1 on page 970](#)

²⁹Arithmetic logic unit

³⁰Apparently, functions generating listings are not so critical to GCC users, so some unfixed errors may still exist.

The register containing the `puts()` address is called `$T9`, because registers prefixed with T- are called “temporaries” and their contents may not be preserved.

3.5.3 Non-optimizing GCC

Non-optimizing GCC is more verbose.

Listing 3.20: Non-optimizing GCC 4.4.5 (assembly output)

```

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

```

We see here that register FP is used as a pointer to the stack frame. We also see 3 [NOP³¹](#)s. 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 3.21: 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)

```

³¹No OPeration

```

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
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.

3.5.4 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: [2.3 on page 6](#).

3.5.5 Optimizing GCC: load it into GDB

Listing 3.22: 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
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)

```

3.6 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.

3.7 Exercises

3.7.1 Exercise #1

```

main:
    push 0xFFFFFFFF
    call MessageBeep
    xor  eax,eax
    retn

```

What does this win32-function do?

Answer: [G.1.1 on page 977](#).

3.7.2 Exercise #2

```

main:
    pushq  %rbp
    movq   %rsp, %rbp
    movl   $2, %edi
    call   sleep
    popq   %rbp
    ret

```

What does this Linux-function do? AT&T assembly language syntax is used here.

Answer: [G.1.1 on page 977](#).

Chapter 4

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.

4.1 Recursion

Epilogues and prologues can negatively affect the recursion performance.

More about recursion in this book: [36.3 on page 483](#).

Chapter 5

Stack

The stack is one of the most fundamental data structures in computer science¹.

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.

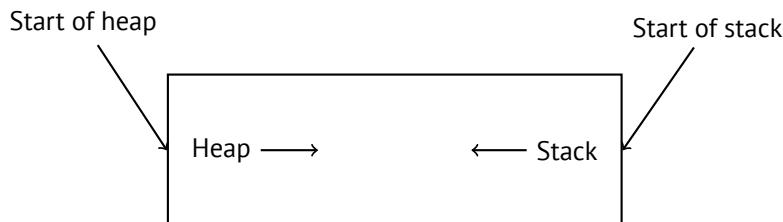
ARM supports both descending and ascending stacks.

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).

5.1 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:

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

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)

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.

5.2 What is the stack used for?

5.2.1 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:
; 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.

⁸irony here

ARM

ARM programs also use the stack for saving return addresses, but differently. As mentioned in “Hello, world!” ([3.4 on page 12](#)), 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: [8.3.2 on page 96](#), [8.3.3 on page 96](#), [19.17 on page 322](#), [19.33 on page 339](#), [19.5.4 on page 340](#), [15.4 on page 202](#), [15.2 on page 201](#), [17.3 on page 222](#).

5.2.2 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 ([64 on page 681](#)). 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);
```

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
...
```

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.

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.

5.2.3 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.

5.2.4 x86: `alloca()` function

It is worth noting the `alloca()` function¹².

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 ([4 on page 23](#)) 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.

MSVC

Let's compile (MSVC 2010):

Listing 5.1: 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
```

¹²In MSVC, the function implementation can be found in `alloca16.asm` and `chkstk.asm` in `C:\Program Files (x86)\Microsoft Visual Studio 10.0\VC\crt\src\intel`

```

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. After the `alloca()` call, `ESP` points to the block of 600 bytes and we can use it as memory for the `buf` array.

GCC + Intel syntax

`GCC 4.4.1` does the same without calling external functions:

Listing 5.2: `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
    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
    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 5.3: `GCC 4.7.3`

```

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

```

¹³It is because `alloca()` is rather a compiler intrinsic ([90 on page 890](#)) 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.

```
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)`.

5.2.5 (Windows) SEH

[SEH¹⁶](#) records are also stored on the stack (if they are present)..

Read more about it: ([68.3 on page 710](#)).

5.2.6 Buffer overflow protection

More about it here ([18.2 on page 270](#)).

5.2.7 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.

5.3 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 var_8
ESP-8	local variable #1, marked in IDA as var_4
ESP-4	saved value of EBP
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
...	...

5.4 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();
```

¹⁶Structured Exception Handling : [68.3 on page 710](#)

```
f2();
};
```

Compiling...

Listing 5.4: 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
    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.

Let's load the example into OllyDbg:

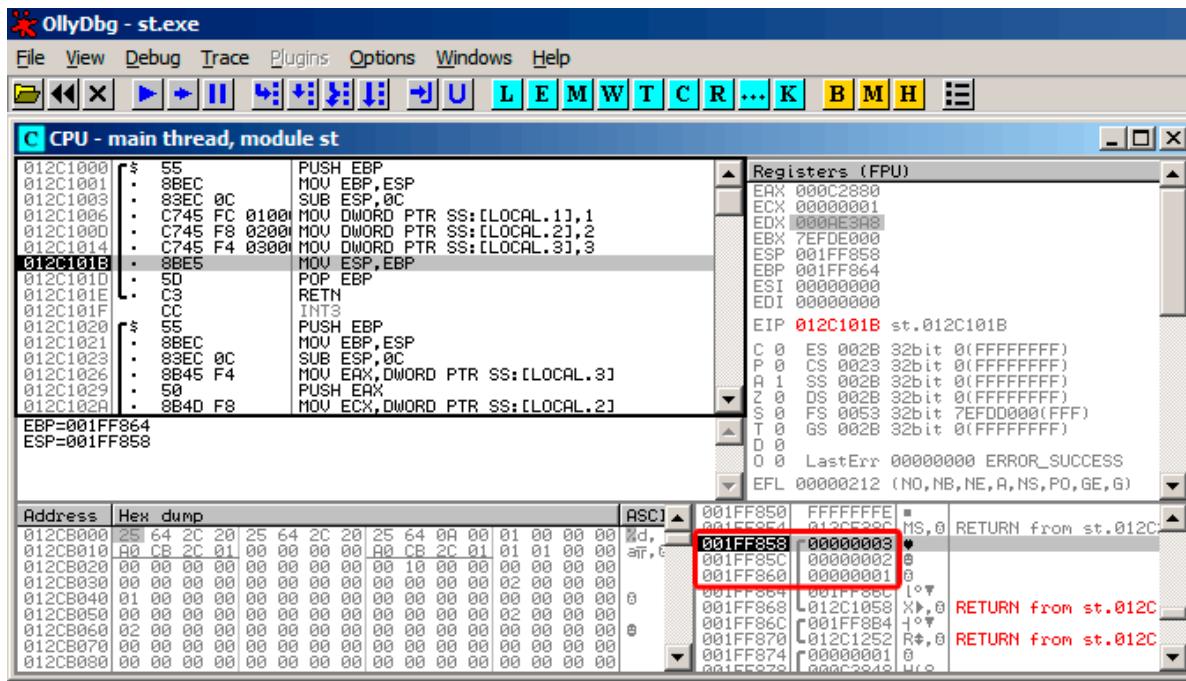


Figure 5.1: OllyDbg: `f1()`

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

And when `f2()` executes:

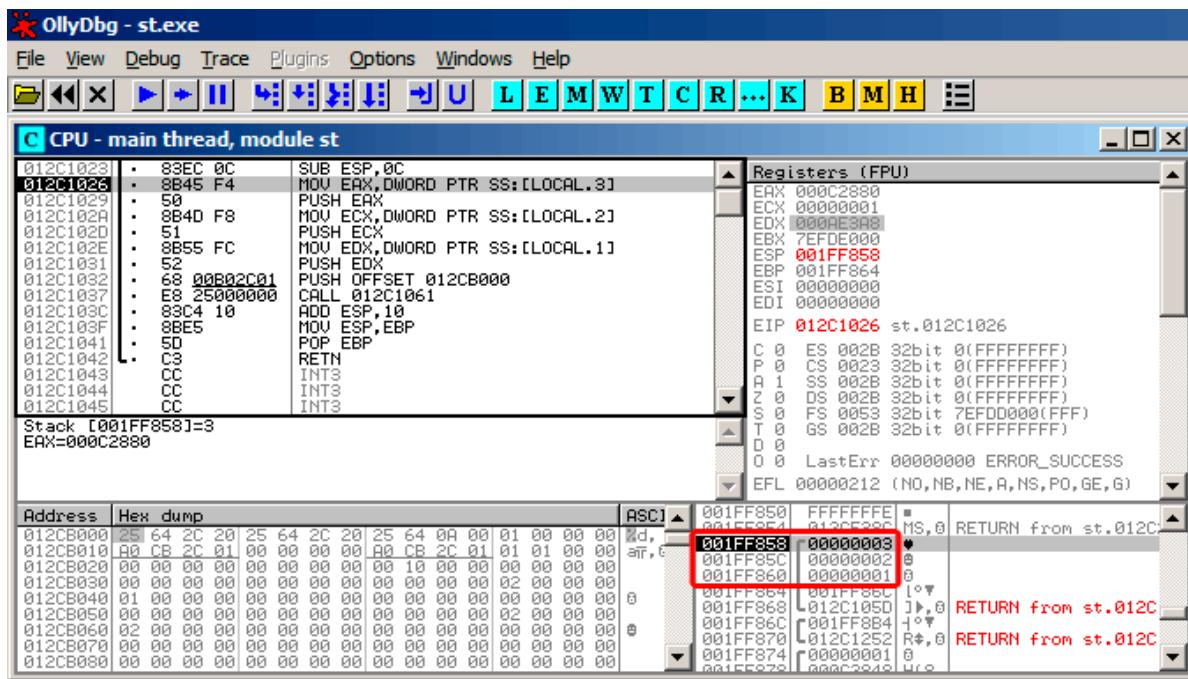


Figure 5.2: OllyDbg: `f2()`

... `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.

5.5 Exercises

5.5.1 Exercise #1

If we compile this piece of code in MSVC and run it, three numbers are printed. Where do they come from? Where do they come from if you compile it in MSVC with optimization (`/Ox`)? Why is the situation completely different if we compile with GCC?

```
#include <stdio.h>

int main()
{
    printf ("%d, %d, %d\n");
    return 0;
}
```

Answer: [G.1.2 on page 977](#).

5.5.2 Exercise #2

What does this code do?

Listing 5.5: Optimizing MSVC 2010

```
$SG3103 DB      '%d', 0aH, 00H

_main PROC
    push    0
    call    DWORD PTR __imp__time64
    push    edx
    push    eax
    push    OFFSET $SG3103 ; '%d'
    call    DWORD PTR __imp__printf
    add     esp, 16
    xor     eax, eax
    ret    0
_main ENDP
```

Listing 5.6: Optimizing Keil 6/2013 (ARM mode)

```
main PROC
    PUSH   {r4,lr}
    MOV    r0,#0
    BL     time
    MOV    r1,r0
    ADR    r0,|L0.32|
    BL     __2printf
    MOV    r0,#0
    POP    {r4,pc}
    ENDP

|L0.32|
    DCB    "%d\n",0
```

Listing 5.7: Optimizing Keil 6/2013 (Thumb mode)

```
main PROC
    PUSH   {r4,lr}
    MOVS  r0,#0
    BL    time
    MOVS  r1,r0
    ADR   r0,|L0.20|
    BL    __2printf
    MOVS  r0,#0
    POP   {r4,pc}
    ENDP

|L0.20|
    DCB    "%d\n",0
```

Listing 5.8: Optimizing GCC 4.9 (ARM64)

```
main:
    stp    x29, x30, [sp, -16]!
    mov    x0, 0
    add    x29, sp, 0
    bl     time
    mov    x1, x0
    ldp    x29, x30, [sp], 16
    adrp   x0, .LC0
    add    x0, x0, :lo12:.LC0
    b      printf
.LC0:
    .string "%d\n"
```

Listing 5.9: Optimizing GCC 4.4.5 (MIPS) (IDA)

```
main:
    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     $t9, (time & 0xFFFF)($gp)
or     $at, $zero
jalr  $t9
move  $a0, $zero
lw     $gp, 0x20+var_10($sp)
lui   $a0, ($LC0 >> 16) # "%d\n"
lw     $t9, (printf & 0xFFFF)($gp)
lw     $ra, 0x20+var_4($sp)
la     $a0, ($LC0 & 0xFFFF) # "%d\n"
move  $a1, $v0
jr    $t9
addiu $sp, 0x20

$LC0: .ascii "%d\n<0>" # DATA XREF: main+28
```

Answer: [G.1.2 on page 977](#).

Chapter 6

printf() with several arguments

Now let's extend the *Hello, world!* ([3 on page 7](#)) 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;
}
```

6.1 x86

6.1.1 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 ([64 on page 681](#)).

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 ...
...
push a1
```

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

Here is a real-world example:

Listing 6.1: 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):

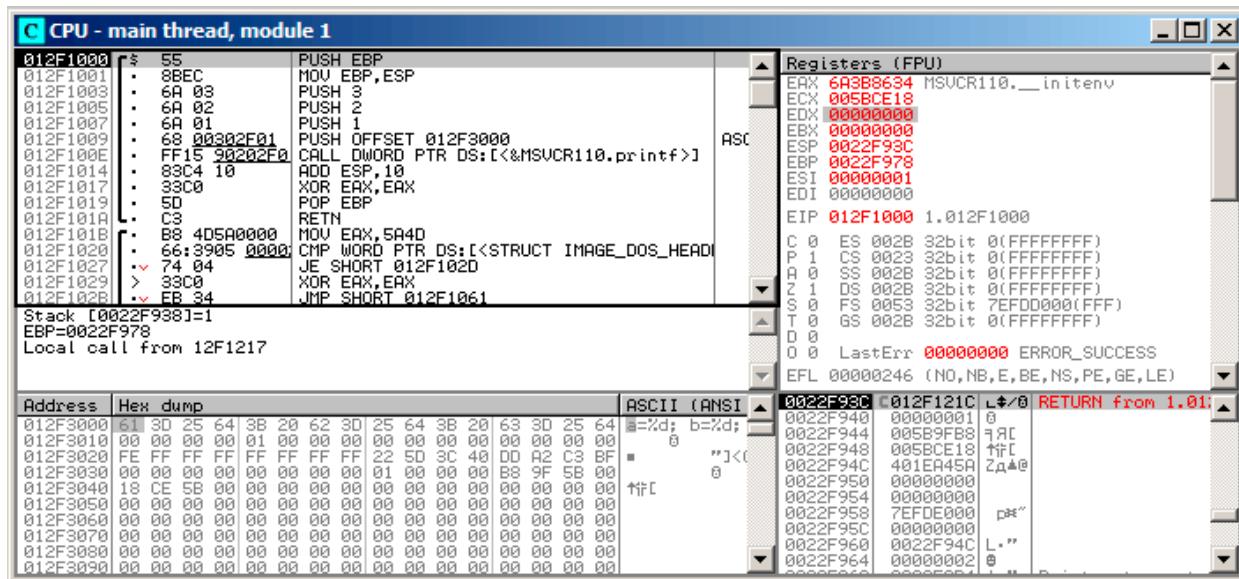


Figure 6.1: OllyDbg: the very start of the main() function

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.

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

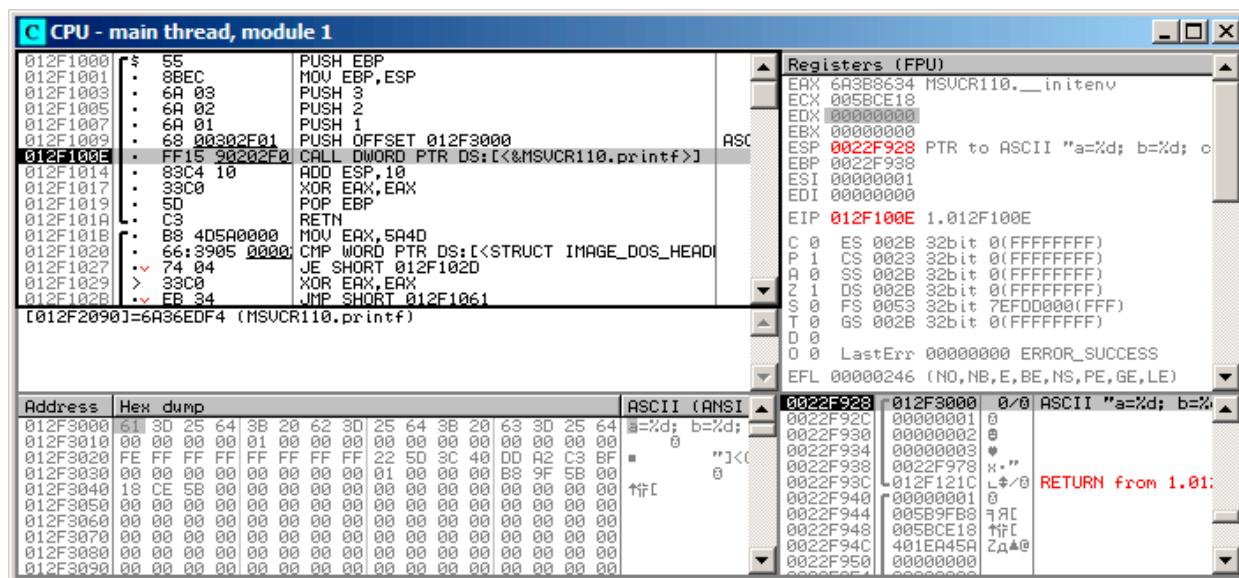


Figure 6.2: OllyDbg: before printf() execution

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:

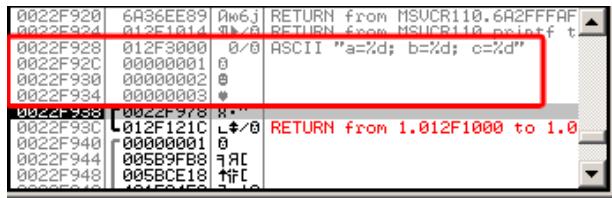


Figure 6.3: OllyDbg: stack after the argument values have been pushed (The red rectangular border was added by me in a graphics editor)

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.

Press F8 (step over).

We see the following output in the console:

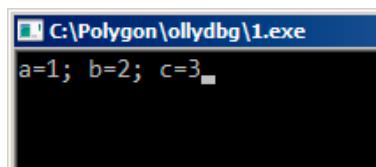


Figure 6.4: `printf()` function executed

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

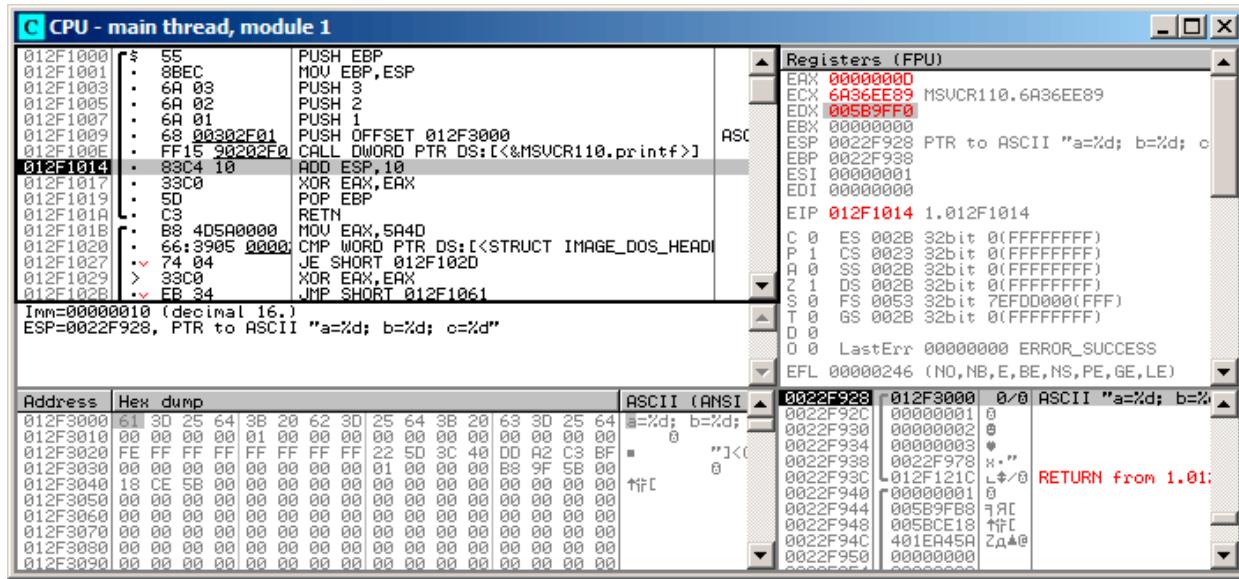


Figure 6.5: OllyDbg after `printf()` execution

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.

Press F8 again to execute ADD ESP, 10 instruction:

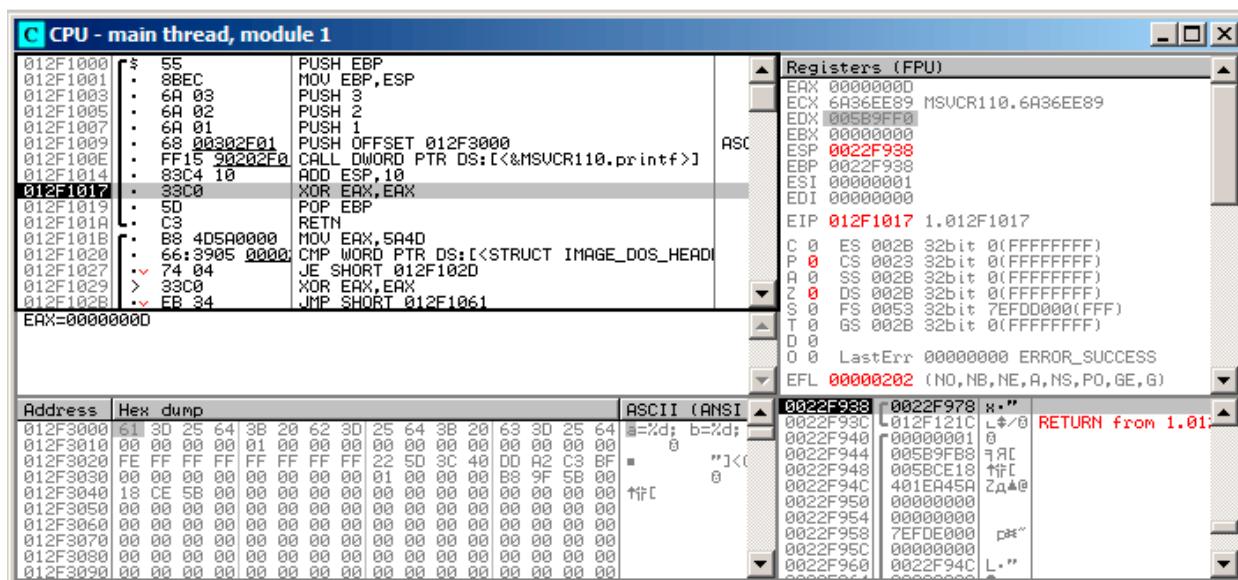


Figure 6.6: OllyDbg: after ADD ESP, 10 instruction execution

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 aADBDCCD ; "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 **GDB**¹ in Linux.

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

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

¹GNU debugger

```
$ 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 6.2: 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
0x080484f0: "a=%d; b=%d; c=%d"
```

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

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

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

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

We also see “`return 0;`” and the information that this expression is in the `1.c` file at the line 6. Indeed, the `1.c` file is located in the current directory, and [GDB](#) finds the string there. How does [GDB](#) know which C-code line is being currently executed? This is due to the fact that the compiler, while generating 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  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. 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
eip          0x804844f  0x804844f <main+50>
...

```

6.1.2 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 6.3: 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: [3.2.2 on page 11](#).

We also noted earlier that the EAX register has been cleared before a `printf()` call: [3.2.2 on page 11](#).

Listing 6.4: 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 6.5: 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
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 6.6: 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      0x0000000000000006
0x7fffffffdf48: 0x0000000000000007      0x00007fff00000008
0x7fffffffdf58: 0x0000000000000000      0x0000000000000000
0x7fffffffdf68: 0x00007ffff7a33de5      0x0000000000000000
0x7fffffffdf78: 0x00007fffffe048       0x0000000100000000
```

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    rs,0x20
0x00000000000400535 <+8>:    mov    DWORD PTR [rs+0x10],0x8
0x0000000000040053d <+16>:   mov    DWORD PTR [rs+0x8],0x7
0x00000000000400545 <+24>:   mov    DWORD PTR [rs],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
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          0x7ffff7dd59f0 140737351866864
rsi          0x7fffffd9 2147483609
rdi          0x0      0
rbp          0x7fffffd60 0x7fffffd60
rsp          0x7fffffd40 0x7fffffd40
r8           0x7ffff7dd26a0 140737351853728
r9           0x7ffff7a60134 140737348239668
r10          0x7fffffd5b0 140737488344496
r11          0x7ffff7a95900 140737348458752
r12          0x400440 4195392
r13          0x7fffffd040 140737488347200
r14          0x0      0
r15          0x0      0
```

```
rip          0x40057b 0x40057b <main+78>
...

```

6.2 ARM

6.2.1 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 ([64.3 on page 682](#)) or win64 ([64.5.1 on page 683](#)).

32-bit ARM

Non-optimizing Keil 6/2013 (ARM mode)

Listing 6.7: 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 6.8: 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, aADBD_CD      ; "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 6.9: 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: [13.1.1 on page 146](#).

ARM64

Non-optimizing GCC (Linaro) 4.9

Listing 6.10: Non-optimizing GCC (Linaro) 4.9

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

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

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.

6.2.2 ARM: 8 arguments

Let's use again the example with 9 arguments from the previous section: [6.1.2 on page 44](#).

```
#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 6E 0F 8F E2  ADR   R0, aADBDCDDDEDFDGD ; "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%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*. 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: [28.2 on page 457](#).

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`.

$(4 + \text{var_4} = 4 + (-4) = 0)$, 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:00000001C          printf_main2
.text:00000001C
.text:00000001C          var_18 = -0x18
.text:00000001C          var_14 = -0x14
.text:00000001C          var_8 = -8
.text:00000001C
.text:00000001C 00 B5    PUSH   {LR}
.text:00000001E 08 23    MOVS   R3, #8
.text:000000020 85 B0    SUB    SP, SP, #0x14
.text:000000022 04 93    STR    R3, [SP, #0x18+var_8]
.text:000000024 07 22    MOVS   R2, #7
.text:000000026 06 21    MOVS   R1, #6
.text:000000028 05 20    MOVS   R0, #5
.text:00000002A 01 AB    ADD    R3, SP, #0x18+var_14
.text:00000002C 07 C3    STMIA  R3!, {R0-R2}
.text:00000002E 04 20    MOVS   R0, #4
.text:000000030 00 90    STR    R0, [SP, #0x18+var_18]
.text:000000032 03 23    MOVS   R3, #3
.text:000000034 02 22    MOVS   R2, #2
.text:000000036 01 21    MOVS   R1, #1
.text:000000038 A0 A0    ADR    R0, aADBDCDDDEDFDGD ; "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d; g=%"...
.text:00000003A 06 F0 D9 F8    BL     __2printf
.text:00000003E
.loc_3E ; CODE XREF: example13_f+16
.text:00000003E 05 B0    ADD    SP, SP, #0x14
.text:000000040 00 BD    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    STMDFD 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
```

²Read more about it: [28.2 on page 457](#).

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

```
_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
_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 6.11: 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.

6.3 MIPS

6.3.1 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 6.12: Optimizing GCC 4.4.5 (assembly output)

```

$LCO:
.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    $4,%hi($LCO)
    addiu $4,$4,%lo($LCO)
; 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 6.13: 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)
; 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 6.14: 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 6.15: Non-optimizing GCC 4.4.5 (IDA)

```

.text:00000000 main:
.text:00000000
.text:00000000 var_10          = -0x10
.text:00000000 var_8           = -8
.text:00000000 var_4           = -4
.text:00000000
; function prologue:
.text:00000000      addiu  $sp, -0x20
.text:00000004      sw     $ra, 0x20+var_4($sp)
.text:00000008      sw     $fp, 0x20+var_8($sp)
.text:0000000C      move   $fp, $sp
.text:00000010      la     $gp, __gnu_local_gp
.text:00000018      sw     $gp, 0x20+var_10($sp)
; load address of the text string:
.text:0000001C      la     $v0, 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

```

6.3.2 8 arguments

Let's use again the example with 9 arguments from the previous section: [6.1.2 on page 44](#).

```
#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 6.16: 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:
    lui      $28,%hi(__gnu_local_gp)
    addiu   $sp,$sp,-56
    addiu   $28,$28,%lo(__gnu_local_gp)
    sw      $31,52($sp)
; pass 5th argument in stack:
    li      $2,4                      # 0x4
    sw      $2,16($sp)
; pass 6th argument in stack:
    li      $2,5                      # 0x5
    sw      $2,20($sp)
; pass 7th argument in stack:
    li      $2,6                      # 0x6
    sw      $2,24($sp)
; pass 8th argument in stack:
    li      $2,7                      # 0x7
    lw      $25,%call16(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 6.17: 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)
; pass 1st argument in $a1:
.text:00000044          la      $a0, ($LC0 & 0xFFFF) # "a=%d; b=%d; c=%d; d=%d; e=%d; f=%d\n"
    ↴ =%d; g=%"...
; 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 6.18: 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,%call116(sprintf)($28)
        nop
        move   $25,$2
        jalr   $25
        nop
; function epilogue:
        lw      $28,40($fp)
; set return value to 0:
        move   $2,$0
        move   $sp,$fp
        lw      $31,52($sp)
        lw      $fp,48($sp)
        addiu $sp,$sp,56
; return
        j      $31
        nop

```

Listing 6.19: 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=%"...
    ↴ =%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
.text:0000008C      or    $at, $zero ; NOP

```

6.4 Conclusion

Here is a rough skeleton of the function call:

Listing 6.20: x86

```

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

```

Listing 6.21: 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 6.22: 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 6.23: 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 6.24: 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 6.25: MIPS (O32 calling convention)

```

LI $4, 1st argument ; AKA $A0
LI $5, 2nd argument ; AKA $A1
LI $6, 3rd argument ; AKA $A2
LI $7, 4th argument ; AKA $A3
; pass 5th, 6th argument, etc, in stack (if needed)
LW temp_reg, address of function
JALR temp_reg

```

6.5 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 7

scanf()

Now let's use `scanf()`.

7.1 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`.

7.1.1 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” place.

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 ([10 on page 102](#))). `scanf()` 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. Internally, in the compiled code there is no information about pointer types at all.

7.1.2 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:

...	...
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 957](#)).

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.

7.1.3 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:

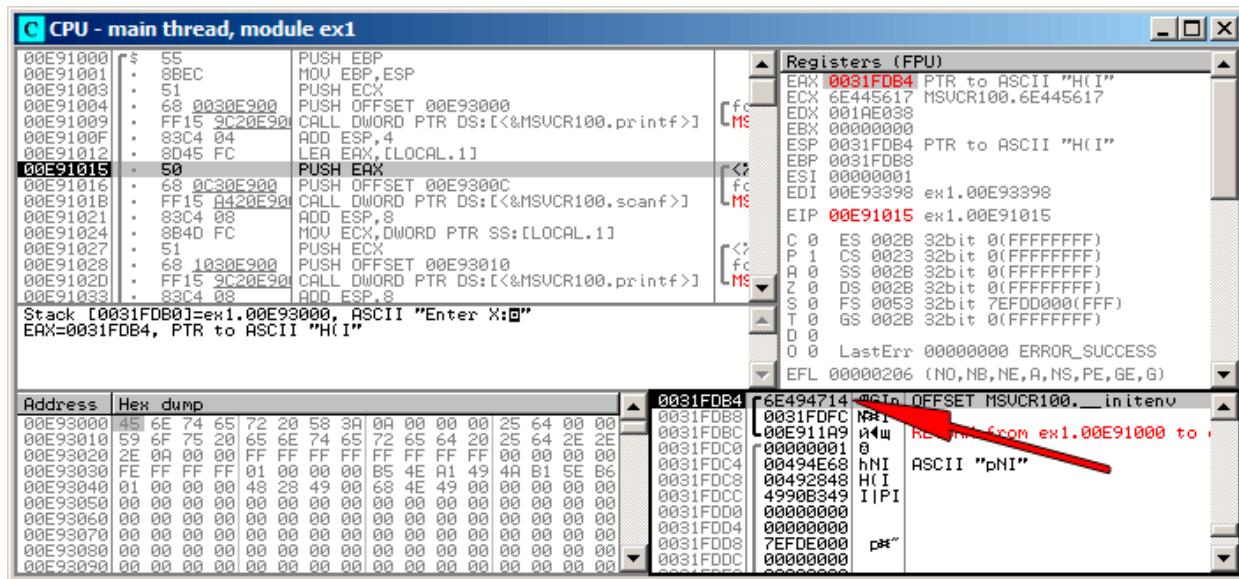


Figure 7.1: OllyDbg: The address of the local variable is calculated

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:

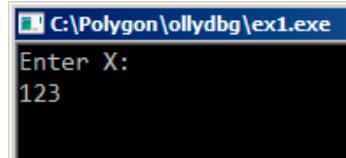


Figure 7.2: User input in the console window

scanf() completed its execution already:

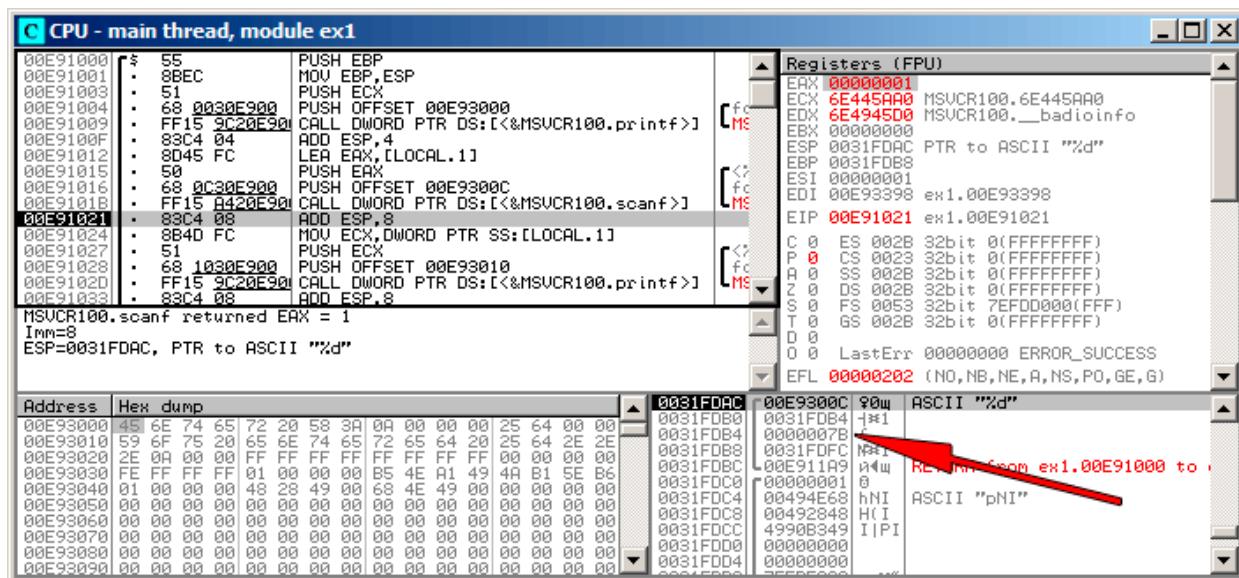


Figure 7.3: OllyDbg: scanf() executed

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).

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

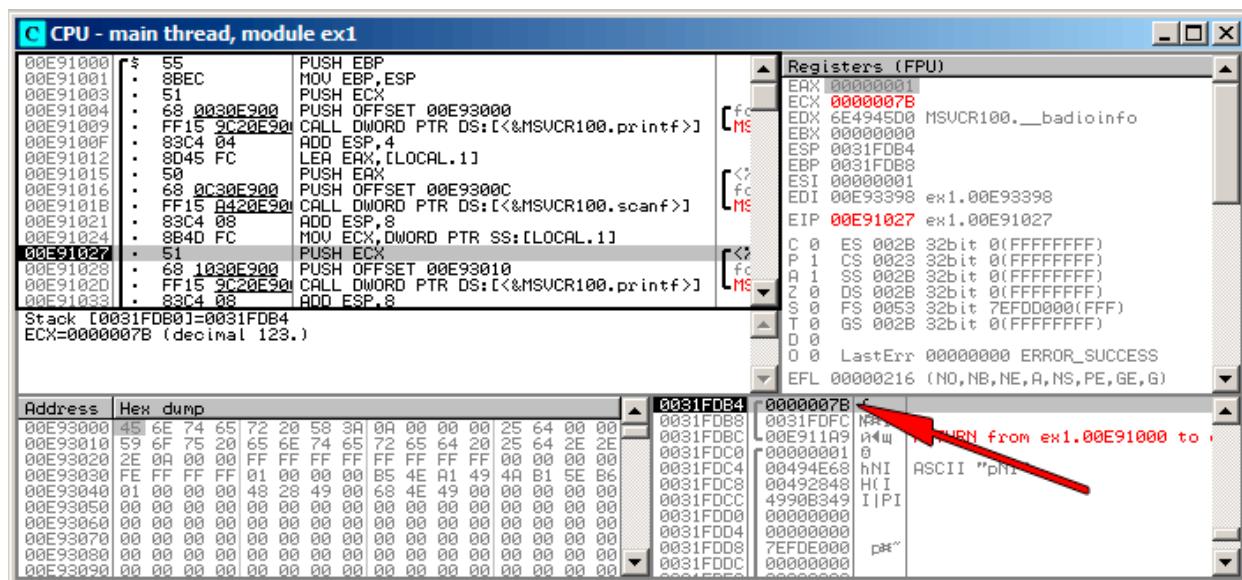


Figure 7.4: OllyDbg: preparing the value for passing to `printf()`

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 puts()`. The reason for this was explained in ([3.4.3 on page 15](#)).

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.

7.1.4 x64

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

MSVC

Listing 7.1: 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 7.2: 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

```

7.1.5 ARM

Optimizing Keil 6/2013 (Thumb mode)

```
.text:00000042          scanf_main
.text:00000042
.text:00000042          var_8      = -8
.text:00000042
.text:00000042 08 B5          PUSH    {R3,LR}
.text:00000044 A9 A0          ADR     R0, aEnterX      ; "Enter X:\n"
.text:00000046 06 F0 D3 F8          BL      __2printf
.text:0000004A 69 46          MOV     R1, SP
.text:0000004C AA A0          ADR     R0, aD           ; "%d"
.text:0000004E 06 F0 CD F8          BL      __Oscanf
.text:00000052 00 99          LDR     R1, [SP,#8+var_8]
.text:00000054 A9 A0          ADR     R0, aYouEnteredD__ ; "You entered %d...\n"
.text:00000056 06 F0 CB F8          BL      __2printf
.text:0000005A 00 20          MOVS   R0, #0
.text:0000005C 08 BD          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 7.3: 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
36 ; restore FP and LR, then add 32 to SP:
37     ldp    x29, x30, [sp], 32
```

ret

There are 32 bytes 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()`.

7.1.6 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 7.4: 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 7.5: Optimizing GCC 4.4.5 (IDA)

```

.text:00000000 main:
.text:00000000
.text:00000000 var_18          = -0x18
.text:00000000 var_10          = -0x10
.text:00000000 var_4           = -4
.text:00000000

```

```
; function prologue:
.text:00000000          lui      $gp, (__gnu_local_gp >> 16)
.text:00000004          addiu   $sp, -0x28
.text:00000008          la      $gp, (__gnu_local_gp & 0xFFFF)
.text: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
```

7.2 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;
}
```

7.2.1 MSVC: x86

```
_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
```

`_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.

¹That is how a [VM](#) behaves

7.2.2 MSVC: x86 + OllyDbg

Things are even simpler here:

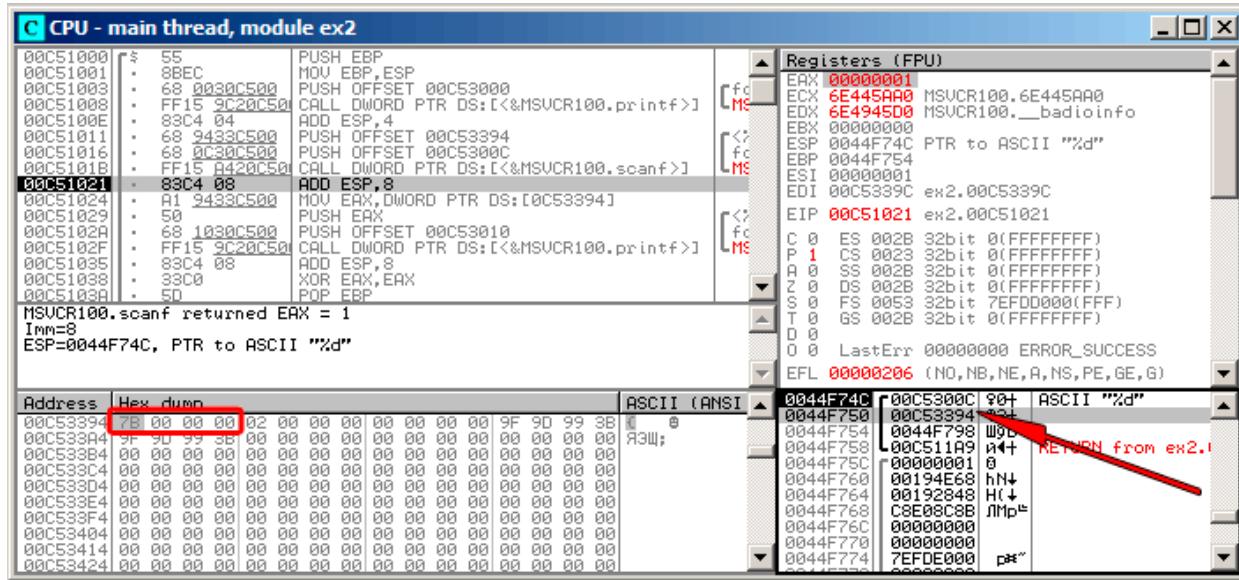


Figure 7.5: OllyDbg: after `scanf()` execution

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 [endianness](#), and x86 uses *little-endian*. This implies that the lowest byte is written first, and the highest written last. Read more about it at: [31 on page 466](#).

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.

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	
0044C000	00001000				Priv	RW	Guar	
0044D000	00003000			Stack of main thread	Priv	RW	Guar	
00590000	00007000				Priv	RW	RW	
00750000	00000000			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	.rdata	Imports	Img	R	RWE	Cop
00C53000	00001000	ex2	.data	Data	Img	RW	RWE	Cop
00C54000	00001000	ex2	.reloc	Relocations	Img	R	RWE	Cop
0E3E0000	00001000	MSVCR100	.text	PE header	Img	R	RWE	Cop
0E3E1000	00082000	MSVCR100	.data	Code, imports, exports	Img	R	RWE	Cop
0E493000	00000000	MSVCR100	.rsrc	Data	Img	RW	Cop	
0E499000	00001000	MSVCR100	.reloc	Resources	Img	R	RWE	Cop
0E49A000	00005000	MSVCR100	.reloc	Relocations	Img	R	RWE	Cop
75500000	00001000	Mod_7550		PE header	Img	R	RWE	Cop
75501000	00003000				Img	R	RWE	Cop
75502000	00001000				Img	RW	RWE	Cop
75503000	00001000	Mod_755E		PE header	Img	R	RWE	Cop
75504000	00004000				Img	R	RWE	Cop
75505000	00005000				Img	RW	Cop	
75633000	00009000				Img	R	RWE	Cop
75640000	00001000	Mod_7564		PE header	Img	R	RWE	Cop
75641000	00038000				Img	R	RWE	Cop
75679000	00002000				Img	RW	RWE	Cop
7567B000	00004000				Img	R	RWE	Cop
76F50000	00001000	kernel32	.text	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	.text	PE header	Img	R	RWE	Cop
77811000	00004000	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	00102000				Img	R	E	RWE
77C23000	00002F000				Img	R	RWE	Cop
77C52000	00000000				Img	RW	Cop	RWE
77C5E000	00006000				Img	R	RWE	Cop
77D00000	00001000	ntdll	.text	PE header	Img	R	RWE	Cop
77D10000	00006000	ntdll	.text	Code, exports	Img	R	E	RWE
77DF0000	00001000	ntdll	RT	Code	Img	R	E	RWE
77E00000	00000000	ntdll	.data	Data	Img	RW	Cop	RWE

Figure 7.6: OllyDbg: process memory map

7.2.3 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
```

7.2.4 MSVC: x64

Listing 7.6: 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:'
    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.

7.2.5 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          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. 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

²Read-only memory

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.

7.2.6 ARM64

Listing 7.7: Non-optimizing GCC 4.9.1 ARM64

```

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

```

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).

7.2.7 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”? [3.5.1 on page 18](#)), since the variable is not initialized at the start.

³Random-access memory

Listing 7.8: 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, 0x418940
.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 7.9: Optimizing GCC 4.4.5 (objdump)

```

1 004006c0 <main>:
2 ; function prologue:
3 4006c0: 3c1c0042          lui    gp,0x42
4 4006c4: 27bdffe0          addiu $sp,sp,-32
5 4006c8: 279c8940          addiu gp,sp,-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: 8fb00010          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 7.10: 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
.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 7.11: Optimizing GCC 4.4.5 (objdump)

```

004006a0 <main>:
 4006a0: 3c1c0042      lui    gp,0x42
 4006a4: 27bdffe0      addiu sp,sp,-32
 4006a8: 279c8930      addiu gp,gp,-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: 8fb00010      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: 8fb00010      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
 4006f4: 0320f809      jalr   t9
 4006f8: 248408e0      addiu a0,a0,2272
 4006fc: 8fb0001c      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.

7.3 scanf() result checking

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?
```

7.3.1 MSVC: x86

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

```
lea    eax, DWORD PTR _x$[ebp]
push   eax
push   OFFSET $SG3833 ; '%d', 00H
call   _scanf
add    esp, 8
cmp    eax, 1
jne    SHORT $LN2@main
mov    ecx, DWORD PTR _x$[ebp]
push   ecx
push   OFFSET $SG3834 ; 'You entered %d...', 0aH, 00H
call   _printf
add    esp, 8
jmp    SHORT $LN1@main
$LN2@main:
push   OFFSET $SG3836 ; 'What you entered? Huh?', 0aH, 00H
call   _printf
add    esp, 4
$LN1@main:
xor    eax, eax
```

The `caller` function (`main()`) needs the `callee` function (`scanf()`) result, so the `callee` returns it in the EAX register.

We check it with the help of the instruction `CMP EAX, 1 (CoMPare)`. In other words, we compare the value in the EAX register with 1.

⁴scanf, wscanf: [MSDN](#)

⁵End of file

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*.

7.3.2 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
.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
```

⁶x86 flags, see also: [wikipedia](#).

```
.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.

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

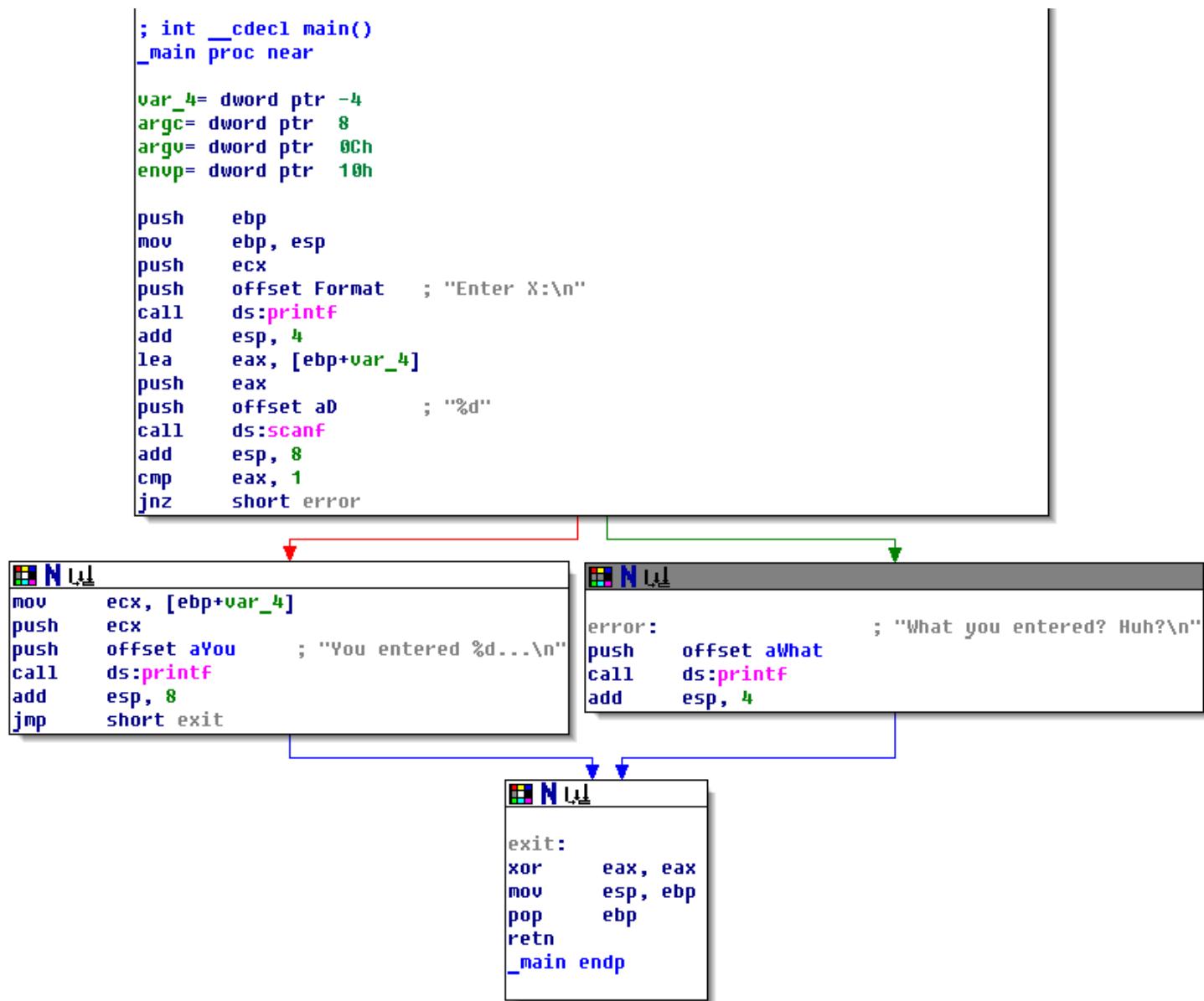


Figure 7.7: Graph mode in IDA

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.

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
```

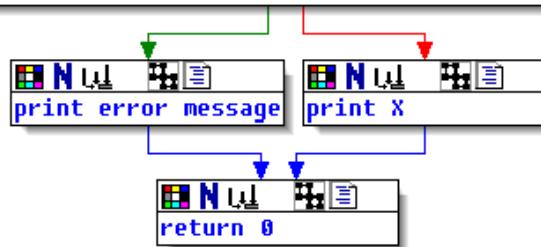


Figure 7.8: Graph mode in IDA with 3 nodes folded

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.

7.3.3 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:

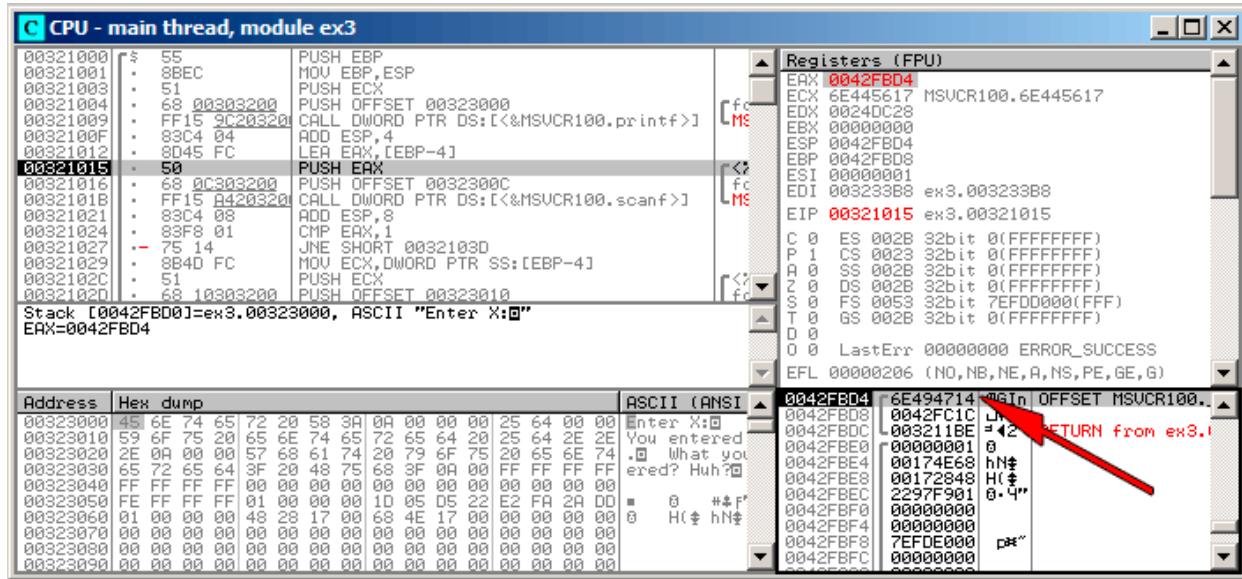


Figure 7.9: OllyDbg: passing variable address into `scanf()`

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:

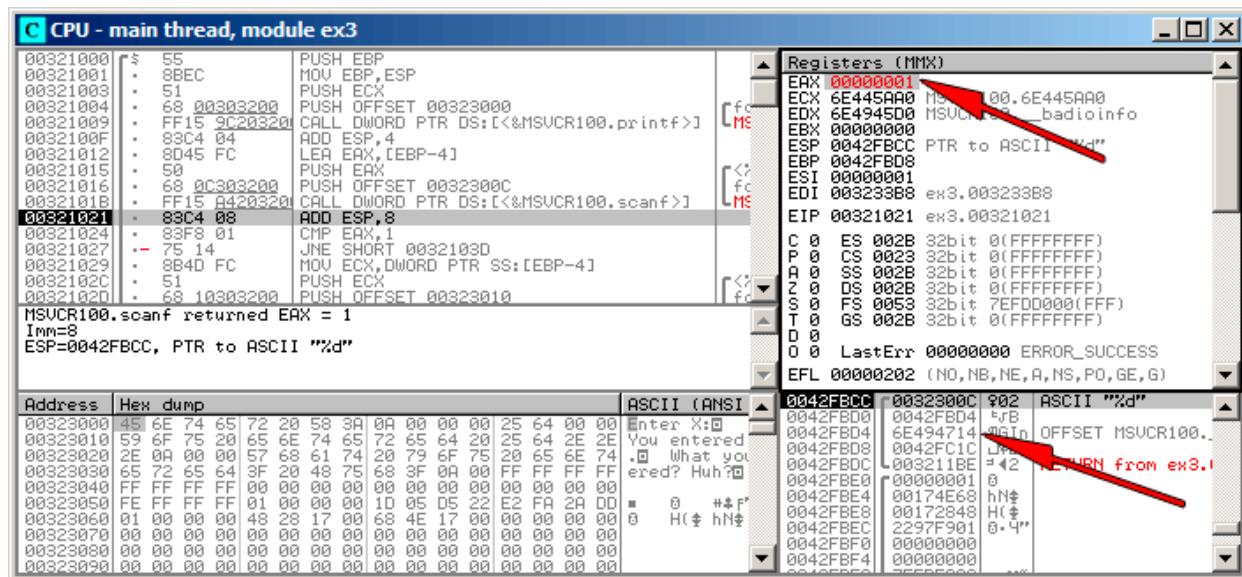


Figure 7.10: OllyDbg: `scanf()` returning error

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:

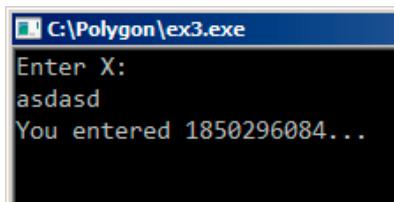


Figure 7.11: console window

Indeed, 1850296084 is a decimal representation of the number in the stack (0x6E494714)!

7.3.4 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 7.12: 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"

⁸ASCII Zero (null-terminated ASCII string)

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):

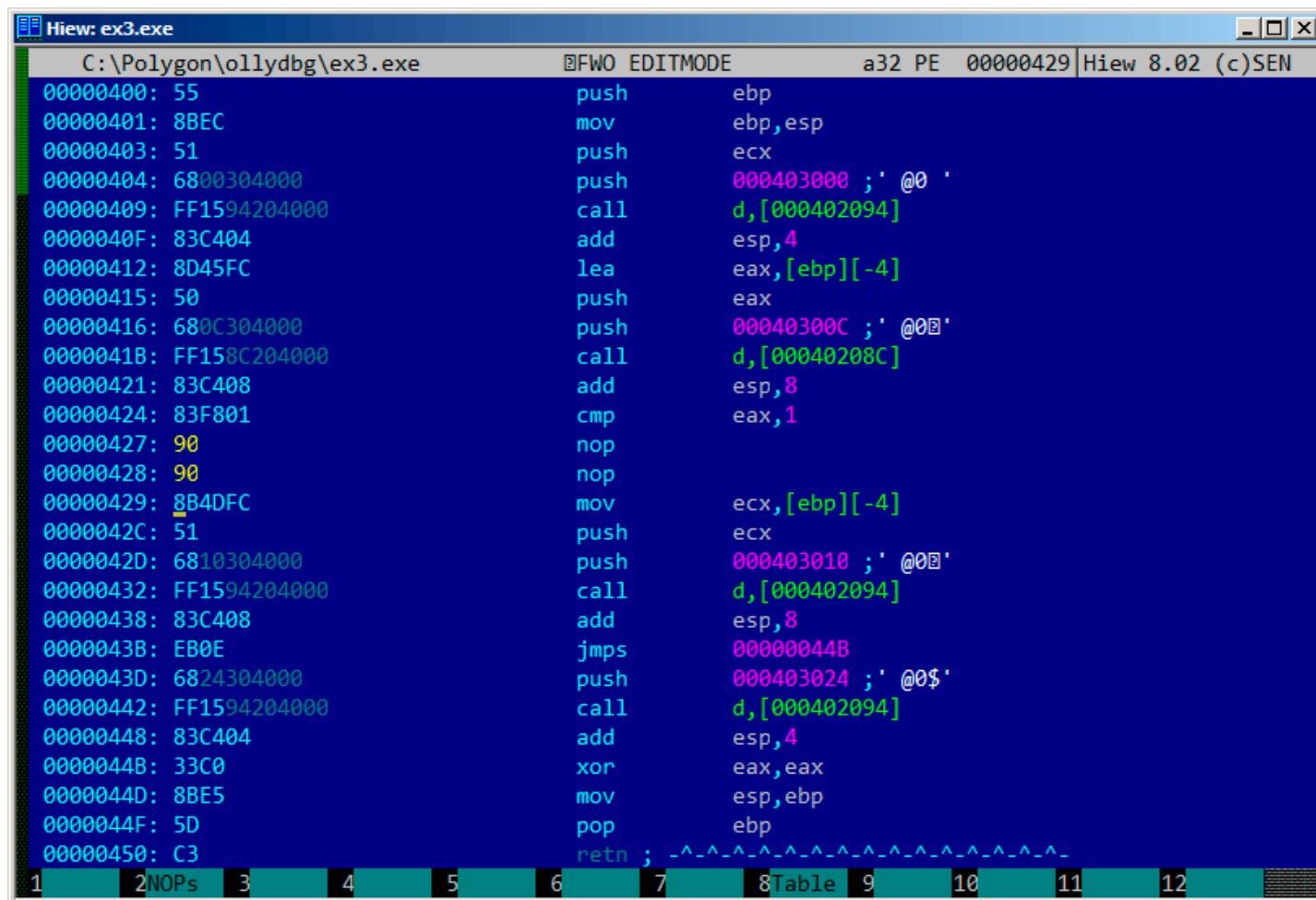


Figure 7.13: Hiew: replacing JNZ with two NOPs

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 aesthetic approach. Another way to patch this instruction is to write just 0 to the second opcode byte ([jump offset](#)), so that JNZ will always jump to the next instruction.

We could also do the opposite: replace first byte with EB while not touching the second byte ([jump offset](#)). We would get an unconditional jump that is always triggered. In this case the error message would be printed every time, no matter the input.

7.3.5 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 7.12: 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
$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

```

7.3.6 ARM

ARM: Optimizing Keil 6/2013 (Thumb mode)

Listing 7.13: 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          ; CODE XREF: main+26
        MOVS R0, #0
        POP {R3,PC}

loc_1E          ; CODE XREF: main+12
        LDR R1, [SP,#8+var_8]
        ADR R0, aYouEnteredD__ ; "You entered %d...\n"
        BL  __2printf
        B   loc_1A

```

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.

ARM64

⁹(PowerPC, ARM) Branch if Equal

Listing 7.14: 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 .LC3:
8     .string "What you entered? Huh?"
9 f6:
10 ; save FP and LR in stack frame:
11     stp    x29, x30, [sp, -32]!
12 ; set stack frame (FP=SP)
13     add    x29, sp, 0
14 ; load pointer to the "Enter X:" string:
15     adrp   x0, .LC0
16     add    x0, x0, :lo12:.LC0
17     bl     puts
18 ; load pointer to the "%d" string:
19     adrp   x0, .LC1
20     add    x0, x0, :lo12:.LC1
21 ; calculate address of x variable in the local stack
22     add    x1, x29, 28
23     bl     __isoc99_scanf
24 ; scanf() returned result in W0.
25 ; check it:
26     cmp    w0, 1
27 ; BNE is Branch if Not Equal
28 ; so if W0<>0, jump to L2 will be occurred
29     bne   .L2
30 ; at this moment W0=1, meaning no error
31 ; load x value from the local stack
32     ldr    w1, [x29,28]
33 ; load pointer to the "You entered %d...\n" string:
34     adrp   x0, .LC2
35     add    x0, x0, :lo12:.LC2
36     bl     printf
37 ; skip the code, which print the "What you entered? Huh?" string:
38     b     .L3
39 .L2:
40 ; load pointer to the "What you entered? Huh?" string:
41     adrp   x0, .LC3
42     add    x0, x0, :lo12:.LC3
43     bl     puts
44 .L3:
45 ; return 0
46     mov    w0, 0
47 ; restore FP and LR:
48     ldp    x29, x30, [sp], 32
49     ret

```

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

7.3.7 MIPS

Listing 7.15: 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
.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`.

7.3.8 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.

7.4 Exercises

7.4.1 Exercise #1

This code, compiled in Linux x86-64 using GCC is crashing while execution (segmentation fault). However, it works in Windows environment compiled by MSVC 2010 x86. Why?

```

#include <string.h>
#include <stdio.h>

void alter_string(char *s)
{
    strcpy (s, "Goodbye!");
    printf ("Result: %s\n", s);
}

int main()
{
    alter_string ("Hello, world!\n");
}

```

Answer: [G.1.3 on page 978](#).

Chapter 8

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 8.1: 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;
}
```

8.1 x86

8.1.1 MSVC

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

Listing 8.2: 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
```

```

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()`.

8.1.2 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.

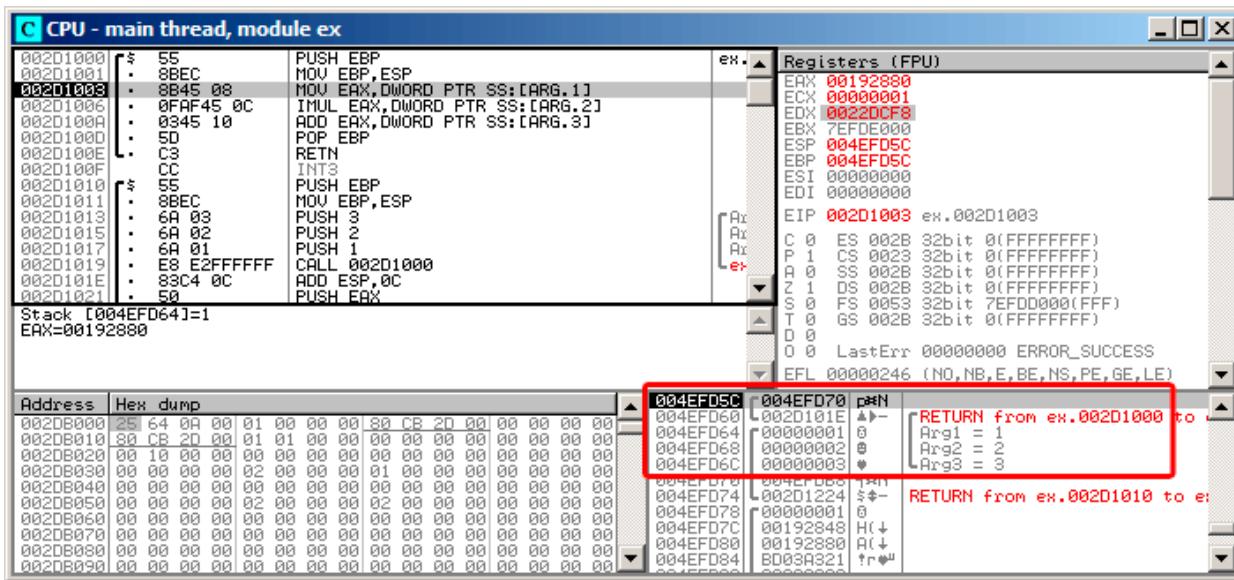


Figure 8.1: OllyDbg: inside of `f()` function

8.1.3 GCC

Let's compile the same in GCC 4.4.1 and see the results in [IDA](#):

Listing 8.3: GCC 4.4.1

```

public f
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
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
ret
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 957](#)) instruction takes care of this at the end.

8.2 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.

8.2.1 MSVC

Optimizing MSVC:

Listing 8.4: 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
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 8.5: 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]
ret
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
ret
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.

8.2.2 GCC

Optimizing GCC generates more or less understandable code:

Listing 8.6: Optimizing GCC 4.4.6 x64

```

f:
; EDI - 1st argument
; ESI - 2nd argument

```

¹[MSDN](#)

²[MSDN](#)

```

; 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 8.7: 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.

8.2.3 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-).

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 8.8: 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.

8.3 ARM

8.3.1 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      STMD   SP!, {R4,LR}
.text:000000B4 03 20 A0 E3      MOV    R2, #3
.text:000000B8 02 10 A0 E3      MOV    R1, #2
.text:000000BC 01 00 A0 E3      MOV    R0, #1
.text:000000C0 F7 FF FF EB      BL     f
.text:000000C4 00 40 A0 E1      MOV    R4, R0
.text:000000C8 04 10 A0 E1      MOV    R1, R4
.text:000000CC 5A 0F 8F E2      ADR    R0, aD_0      ; "%d\n"
.text:000000D0 E3 18 00 EB      BL     __2printf
.text:000000D4 00 00 A0 E3      MOV    R0, #0
.text:000000D8 10 80 BD E8      LDMFD SP!, {R4,PC}

```

The `main()` function simply calls two other functions, with three values passed to the first one –`f()`.

As was noted before, in ARM the first 4 values are usually passed in the first 4 registers (R0-R3).

The `f()` function, as it seems, uses the first 3 registers (R0-R2) as arguments.

The **MLA** (*Multiply Accumulate*) instruction multiplies its first two operands (R3 and R1), adds the third operand (R2) to the product and stores the result into the zeroth register (R0), via which, by standard, functions return values.

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.

³Wikipedia: Multiply–accumulate operation

⁴wikipedia

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].

8.3.2 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.

8.3.3 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 R1. The second instruction (ADDS) adds the result and R2 leaving the result in register R0.

8.3.4 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 8.9: 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
    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: [28.3.1 on page 458](#).

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
    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": [8.2.1 on page 93](#).

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.

8.4 MIPS

Listing 8.10: 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.

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 9

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.

9.1 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: [3.4.3 on page 15](#)), 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 9.1: GCC 4.8.1

```
.LC0:
    .string "Hello, world!"
main:
    push    ebp
    mov     ebp, esp
    and     esp, -16
    sub     esp, 16
```

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

```
mov     DWORD PTR [esp], OFFSET FLAT:.LC0
call    puts
leave
ret
```

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

Listing 9.2: tst.sh

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

And run it:

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

14 is the number of characters printed.

9.2 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 thrown away.

9.3 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;
};

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 9.3: 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 10

Pointers

Pointers are often used to return values from functions (recall `scanf()` case ([7 on page 60](#))). For example, when a function needs to return two values.

10.1 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 10.1: 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
    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
```

Let's see this in OllyDbg:

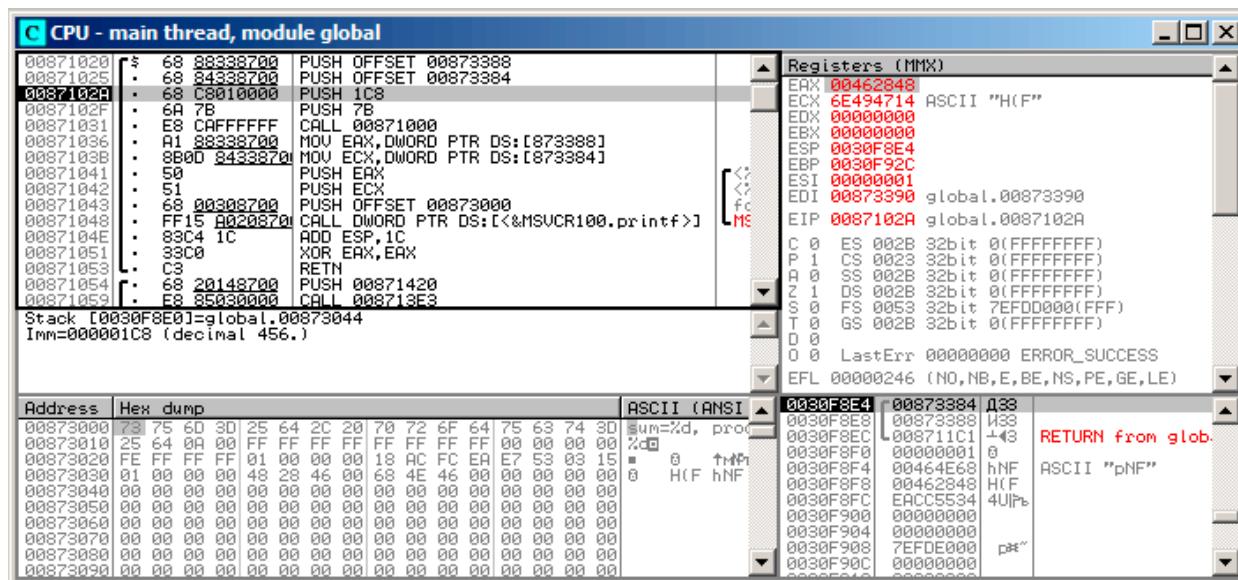


Figure 10.1: OllyDbg: global variables addresses are passed to f1()

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.

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	
00050000	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
00300000	00002000			Heap	Priv	RW	RW	Guar
00460000	00005000				Priv	RW	RW	
004A0000	00007000				Priv	RW	RW	
006B0000	00000000			Default heap	Priv	RW	RW	
00870000	00001000	global		PE header	Img	R	RWE	Cop
00871000	00001000	global	.text	Code	Img	R E	RWE	Cop
00872000	00001000	global	.rdata	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		PE header	Img	R	RWE	Cop
6E3E1000	000082000	MSVCR100	.text	Code, imports, exports	Img	R E	RWE	Cop
6E493000	000066000	MSVCR100	.data	Data	Img	RW	Cop	
6E499000	00001000	MSVCR100	.rsrc	Resources	Img	R	RWE	Cop
6E49A000	00005000	MSVCR100	.reloc	Relocations	Img	R	RWE	Cop
755D0000	00001000	Mod_755D		PE header	Img	R	RWE	Cop
755D1000	000039000				Img	R E	RWE	Cop
755D4000	00001000				Img	RW	RWE	Cop
755D5000	000030000				Img	R	RWE	Cop
755E0000	00001000	Mod_755E		PE header	Img	R	RWE	Cop
755E1000	000040000				Img	R E	RWE	Cop
7562E000	00005000				Img	RW	Cop	RWE
75633000	00009000				Img	R	RWE	Cop

Figure 10.2: OllyDbg: memory map

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

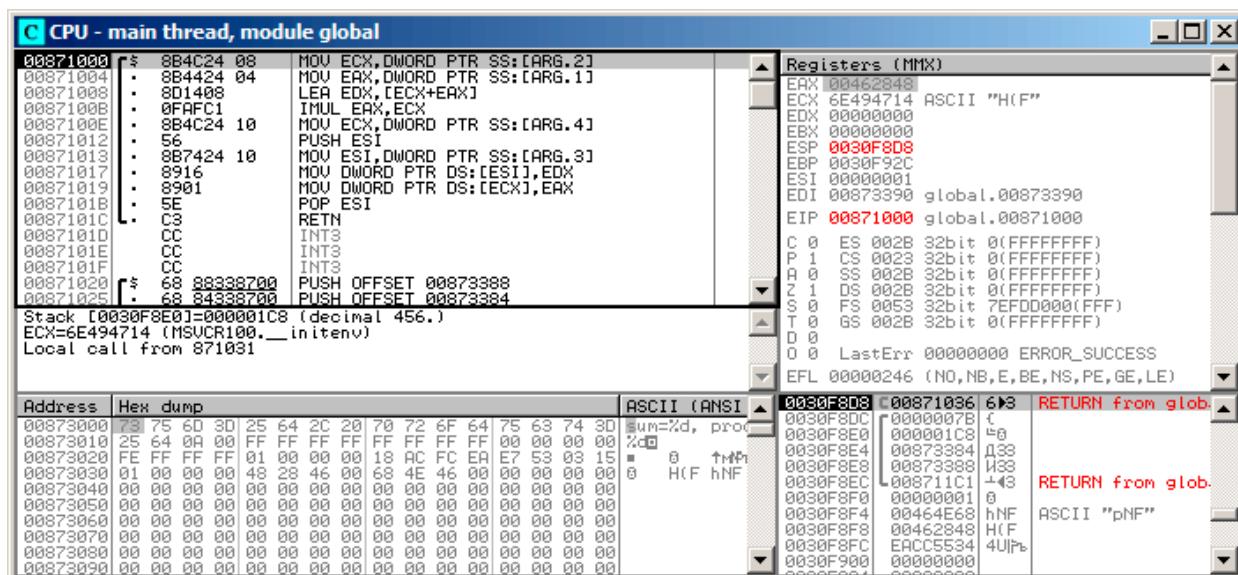


Figure 10.3: OllyDbg: f1() starts

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

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:

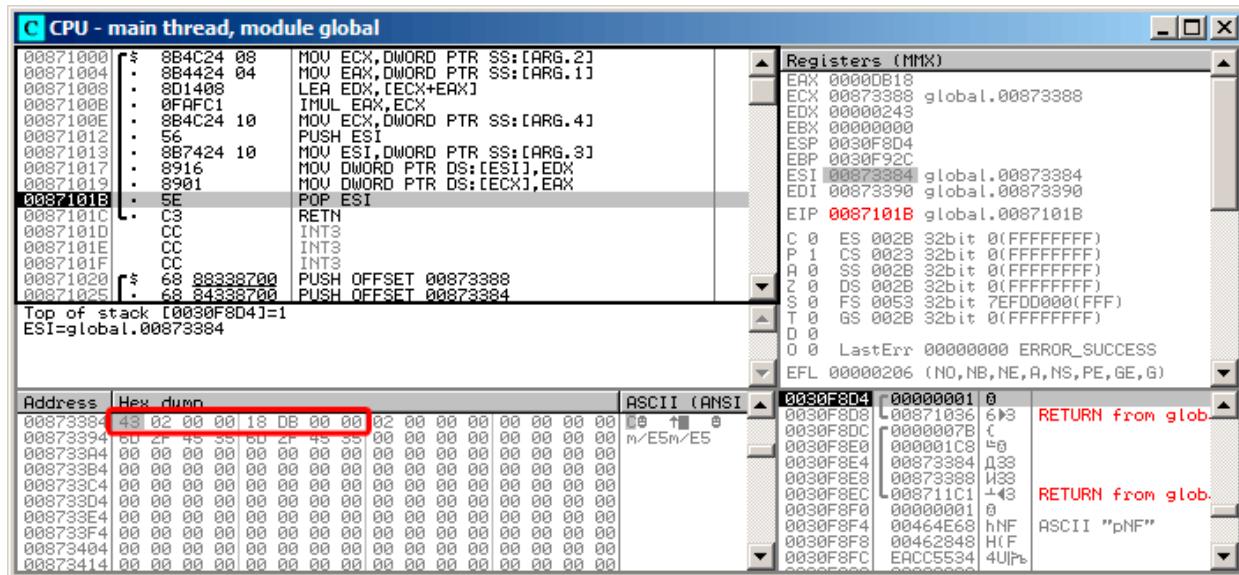


Figure 10.4: OllyDbg: `f1()` execution completed

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

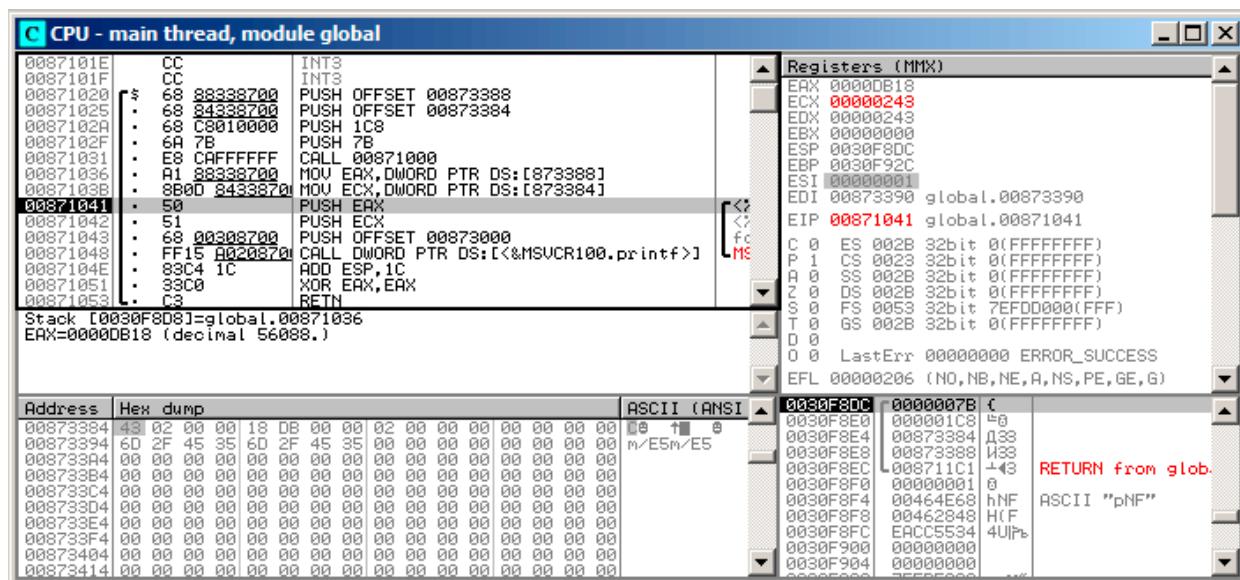


Figure 10.5: OllyDbg: global variables' addresses are passed into `printf()`

10.2 Local variables example

Let's rework our example slightly:

Listing 10.2: 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 10.3: Optimizing MSVC 2010 (/Ob0)

```
_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 0
```

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:

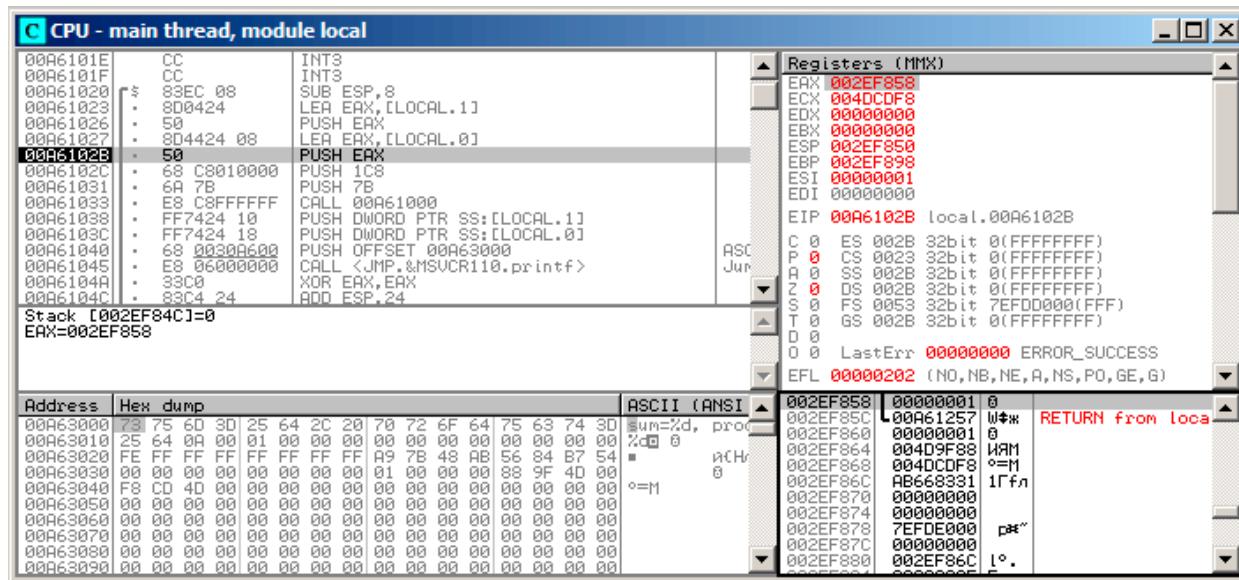


Figure 10.6: OllyDbg: local variables' addresses are pushed into the stack

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

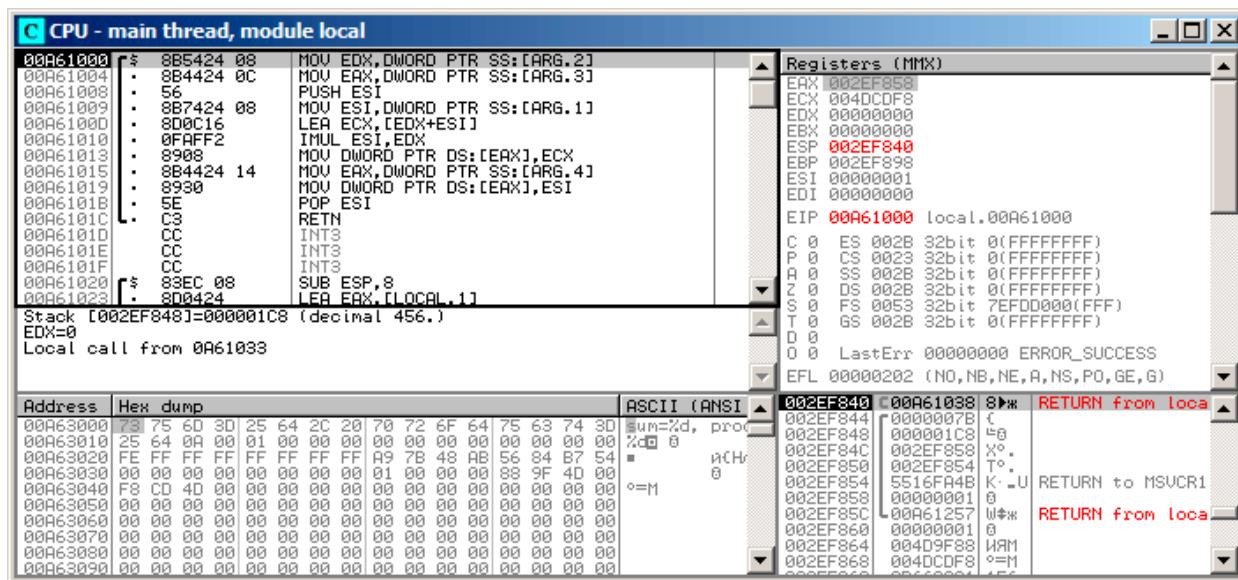


Figure 10.7: OllyDbg: f1() starting

f1() completes:

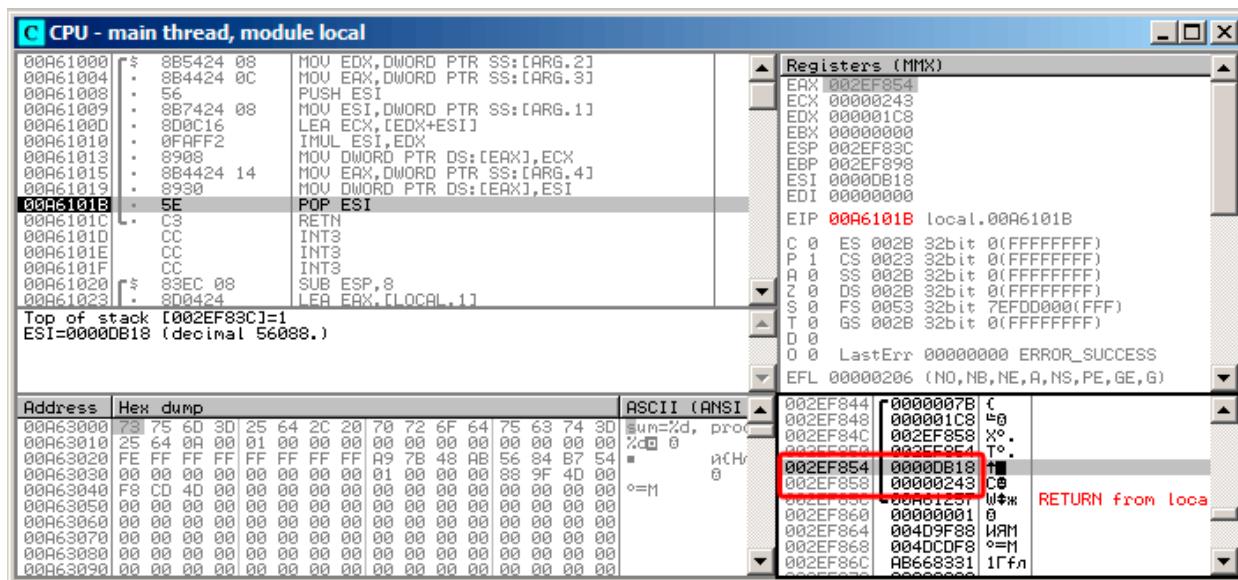


Figure 10.8: OllyDbg: f1() completes execution

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

10.3 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: ([51.3 on page 572](#)).

Chapter 11

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 11.1: 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 11.1: Hiew

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

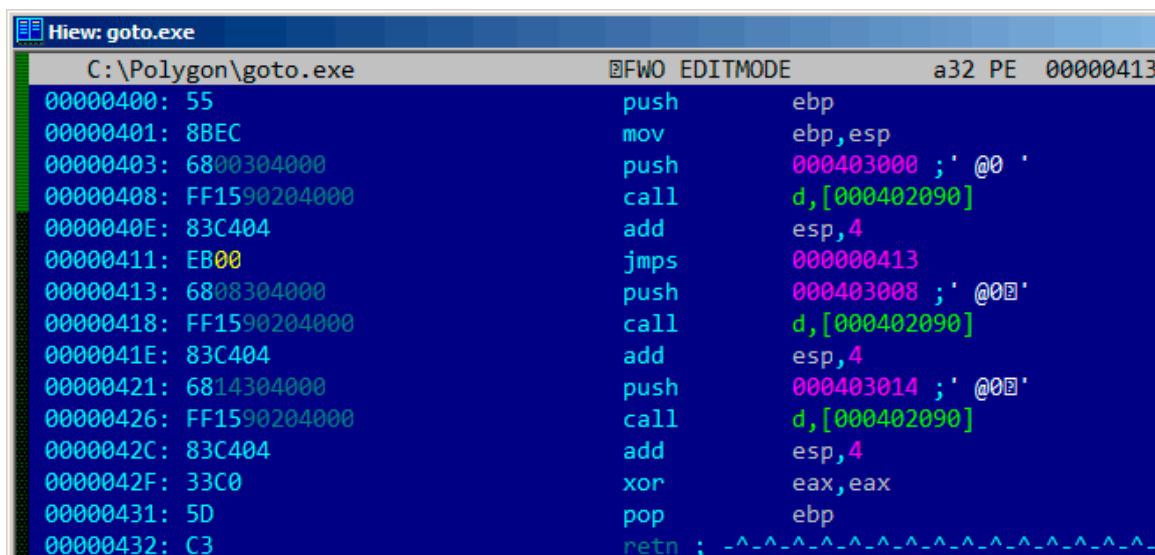


Figure 11.2: Hiew

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:

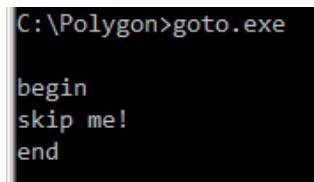


Figure 11.3: Patched executable output

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).

11.1 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 11.2: 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
    ret     0
_main ENDP
```

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

11.2 Exercise

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

Chapter 12

Conditional jumps

12.1 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;
};
```

12.1.1 x86

x86 + MSVC

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

Listing 12.1: 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
    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 12.2: 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.

See also the section about signed number representations ([30 on page 464](#)). 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 12.3: 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
```

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:

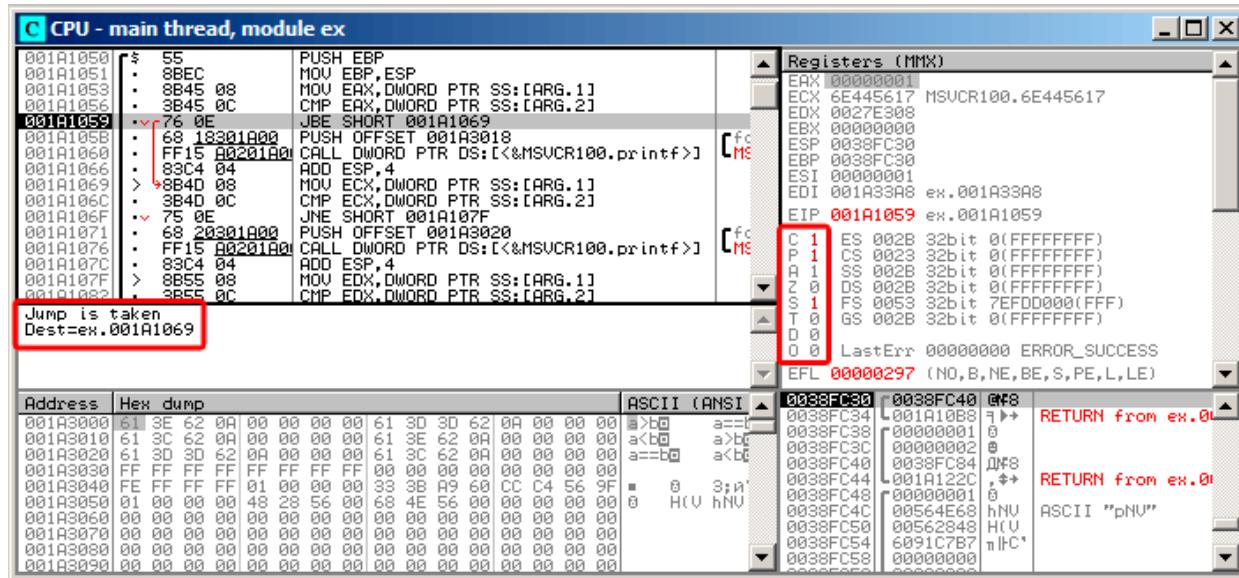


Figure 12.1: OllyDbg: `f_unsigned()`: first conditional jump

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.

The next conditional jump:

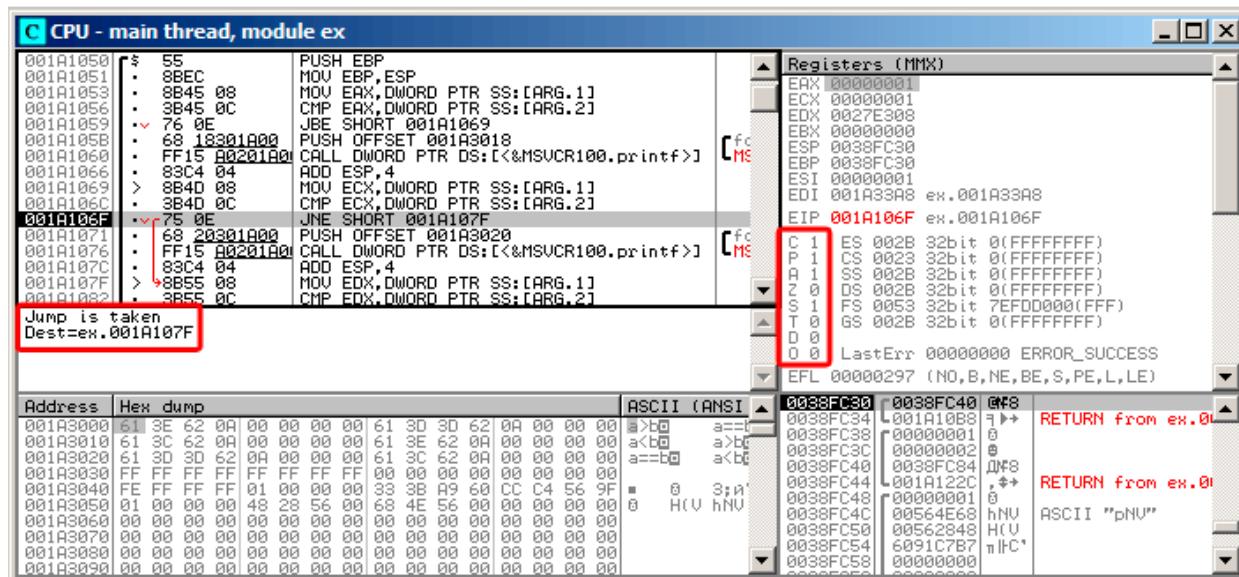


Figure 12.2: OllyDbg: f_unsigned(): second conditional jump

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

The third conditional jump, JNB:

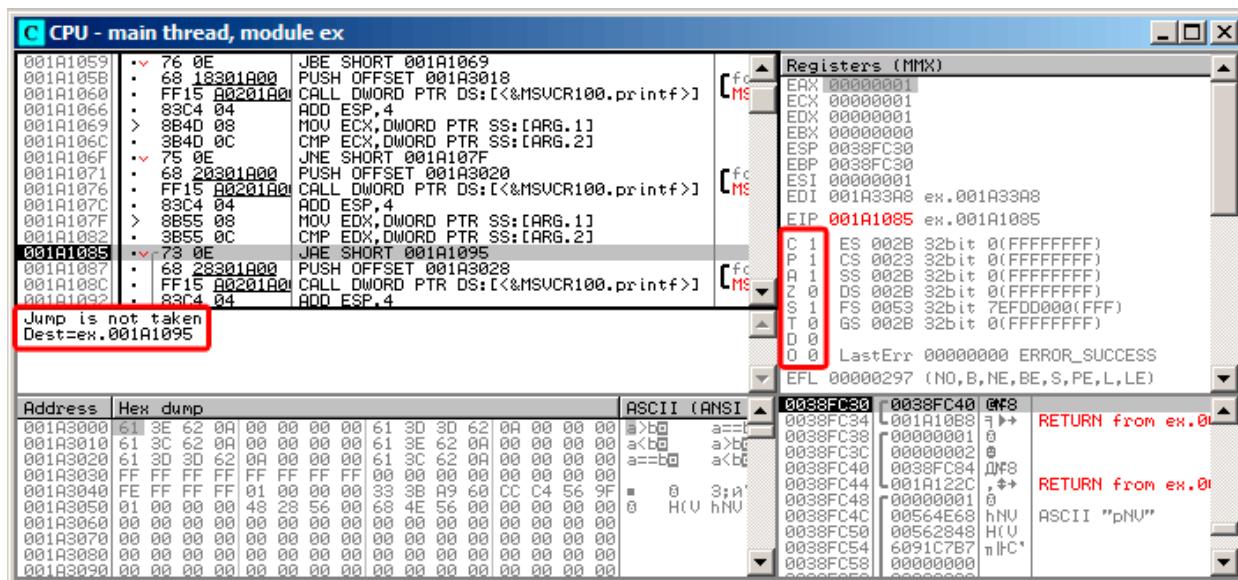


Figure 12.3: OllyDbg: f_unsigned(): third conditional jump

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.

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:

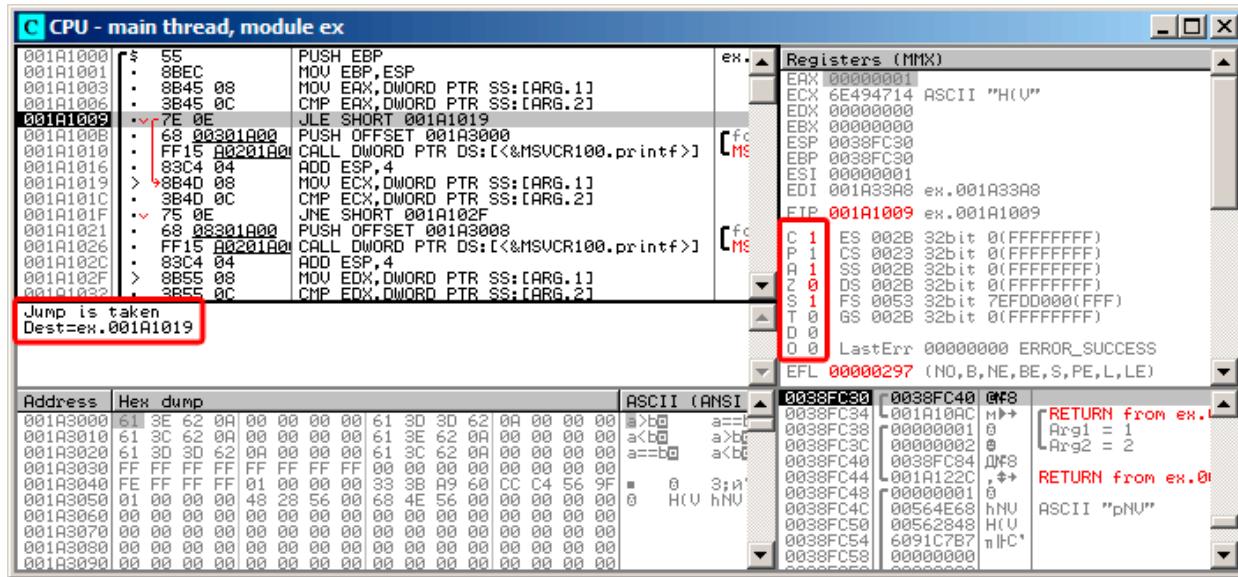


Figure 12.4: OllyDbg: `f_signed()`: first conditional jump

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

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

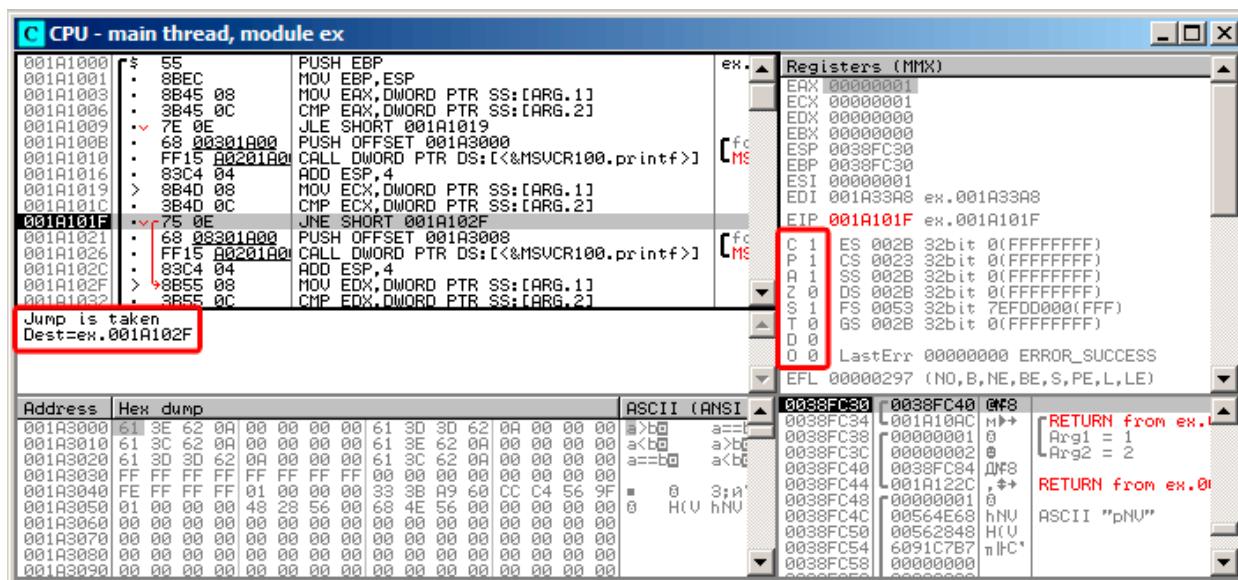


Figure 12.5: OllyDbg: f_signed(): second conditional jump

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:

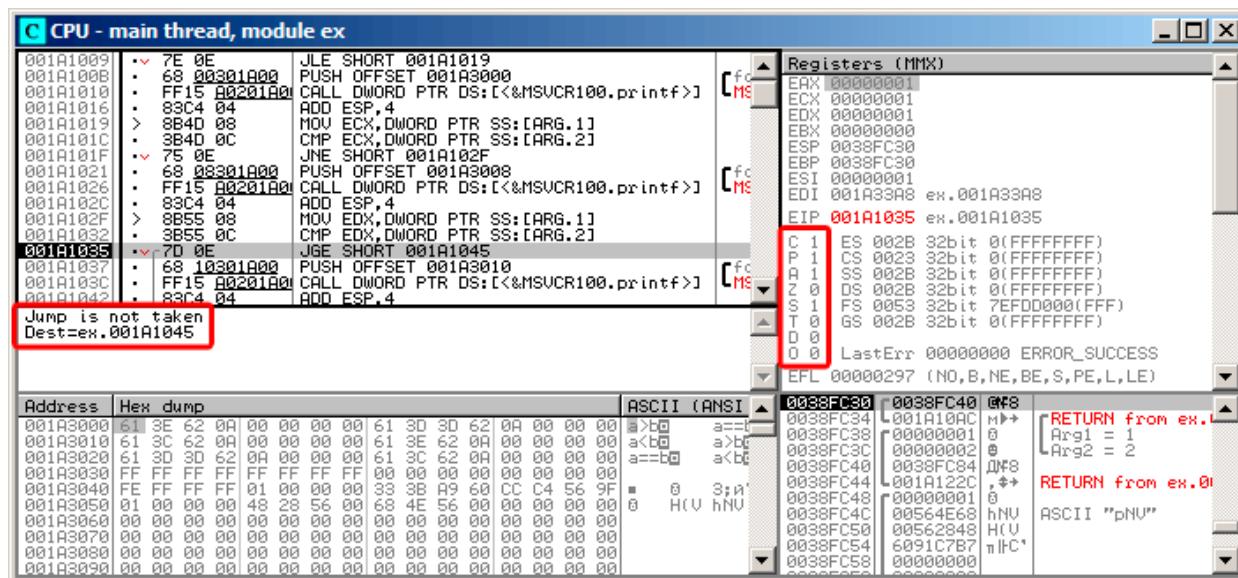


Figure 12.6: OllyDbg: f_signed(): third conditional jump

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             mov    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             mov    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                 pop    ebp
.00401043: C3                 retn  ; -^--^--^--^--^--^--^--^--^--^--^-
.00401044: CC                 int    3
.00401045: CC                 int    3
.00401046: CC                 int    3
.00401047: CC                 int    3
.00401048: CC                 int    3

```

At the bottom of the window, there is a toolbar with various icons: Global, 2FilBlk, 3CryBlk, 4ReLoad, 50rdLdr, 6String, 7Direct, 8Table, 91byte, 10Leave, 11Naked, 12AddNam.

Figure 12.7: 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.

Here is the modified code:

Figure 12.8: 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()` ([3.4.3 on page 15](#)) 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 12.4: 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  
.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: [13.1.1 on page 145](#). 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 12.5: 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.

12.1.2 ARM

32-bit ARM

Optimizing Keil 6/2013 (ARM mode)

Listing 12.6: 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
.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 ADRGT instruction works just like ADR but executes only in case the previous CMP instruction founds one of the numbers greater than the another, while comparing the two (*Greater Than*).

The next BLGT instruction behaves exactly as BL and is triggered only if the result of the comparison was the same (*Greater Than*). ADRGT writes a pointer to the string `a>b\n` into R0 and BLGT calls `printf()`. therefore, these instructions with suffix -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 LDMFD¹, 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 returns 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 ([6.2.1 on page 47](#)).

`f_unsigned` is similar, only the ADRHI, BLHI, and LDMCSFD instructions are used there, these predicates (*HI = Unsigned higher, CS = Carry Set (greater than or equal)*) are analogous to those examined before, but for unsigned values.

There is not much new in the `main()` function for us:

Listing 12.7: `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: [33.1 on page 469](#).

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 12.8: Optimizing Keil 6/2013 (Thumb mode)

```
.text:00000072          f_signed ; CODE XREF: main+6
.text:00000072 70 B5      PUSH    {R4-R6,LR}
```

¹[LDMFD](#)

```
.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 12.9: 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
    addp  x0, .LC11   ; "a<b"
    add   x0, x0, :lo12:.LC11
    b     puts
.L19:
    addp  x0, .LC9     ; "a>b"
    add   x0, x0, :lo12:.LC9
    b     puts
.L15: ; impossible here
    ret
.L20:
    addp  x0, .LC10    ; "a==b"
    add   x0, x0, :lo12:.LC10
    b     puts
```

Listing 12.10: 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.

12.1.3 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 12.11: 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
.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          # 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          # 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          # all 3 conditions were false, so just finish:
.text:000000C8 loc_C8:          # CODE XREF: f_signed+A0
.text:000000C8          move    $sp, $fp
.text:000000CC          lw       $ra, 0x20+var_4($sp)
.text:000000D0          lw       $fp, 0x20+var_8($sp)
.text:000000D4          addiu   $sp, 0x20
.text:000000D8          jr     $ra
.text:000000DC          or       $at, $zero ; branch delay slot, NOP
.text:000000DC # 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 12.12: 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"
.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

```

12.2 Calculating absolute value

A simple function:

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

12.2.1 Optimizing MSVC

This is how the code is usually generated:

Listing 12.13: 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.

12.2.2 Optimizing Keil 6/2013: Thumb mode

Listing 12.14: 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
ENDP
```

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

12.2.3 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 12.15: 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: [33.1 on page 469](#).

12.2.4 Non-optimizing GCC 4.9 (ARM64)

ARM64 has instruction NEG for negating:

Listing 12.16: 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
```

12.2.5 MIPS

Listing 12.17: 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.

12.2.6 Branchless version?

You could have also a branchless version of this code. This we will review later: [45 on page 527](#).

12.3 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";
};
```

12.3.1 x86

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

Listing 12.18: 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 12.19: 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
```

Newer compilers are more concise:

Listing 12.20: 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.

12.3.2 ARM

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

Listing 12.21: 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 12.22: Optimizing Keil 6/2013 (Thumb mode)

```
f PROC
; compare input value with 10
    CMP      r0,#0xa
; jump to |L0.8| if Equal
    BEQ      |L0.8|
    ADR      r0,|L0.12| ; "it is not ten"
    BX      lr
|L0.8|
    ADR      r0,|L0.28| ; "it is ten"
    BX      lr
    ENDP

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

12.3.3 ARM64

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

Listing 12.23: 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 [ARM13a, p390, C5.5]. It has, however, “Conditional SElect” instruction (CSEL), but GCC 4.9 does not seem to be smart enough to use it in such piece of code.

12.3.4 MIPS

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

Listing 12.24: 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)
```

12.3.5 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 12.25: 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 [12.21](#).

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

12.3.6 Conclusion

Why optimizing compilers try to get rid of conditional jumps? Read here about it: [33.1 on page 469](#).

12.4 Getting minimal and maximal values

12.4.1 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 12.26: 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
    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 12.27: 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:

Listing 12.28: 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 12.29: 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

```

12.4.2 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)
{
    if (a<b)
        return a;
    else
        return b;
};

```

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

Listing 12.30: 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 12.31: 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)
    cmovle rax, rdi
    ret

```

MSVC 2013 does almost the same.

ARM64 has the CSEL instruction, which works just as MOVcc in ARM or CMovcc in x86, just the name is different: “Conditional SELect”.

Listing 12.32: 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

```

12.4.3 MIPS

Unfortunately, GCC 4.4.5 for MIPS is not that good:

Listing 12.33: 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.

12.5 Conclusion

12.5.1 x86

Here's the rough skeleton of a conditional jump:

Listing 12.34: 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:

```

12.5.2 ARM

Listing 12.35: 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:

```

12.5.3 MIPS

Listing 12.36: Check for zero

```
BEQZ REG, label
...

```

Listing 12.37: Check for less than zero:

```
BLTZ REG, label
...

```

Listing 12.38: Check for equal values

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

```

Listing 12.39: Check for non-equal values

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

```

Listing 12.40: Check for less than, greater than (signed)

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

```

Listing 12.41: Check for less than, greater than (unsigned)

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

```

12.5.4 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 12.42: 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: [17.7.2 on page 257](#).

Listing 12.43: 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
```

12.6 Exercise

(ARM64) Try rewriting the code in listing [12.23](#) by removing all conditional jump instructions and using the CSEL instruction.

Chapter 13

switch()/case/default

13.1 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
}
```

13.1.1 x86

Non-optimizing MSVC

Result (MSVC 2010):

Listing 13.1: 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:
    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()s.

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 tv64¹.

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 13.2: 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
    _printf
$LN3@f:
    mov   DWORD PTR _a$[esp-4], OFFSET $SG787 ; 'one', 0aH, 00H
    _printf
$LN4@f:
    mov   DWORD PTR _a$[esp-4], OFFSET $SG785 ; 'zero', 0aH, 00H
    _printf
_f    ENDP

```

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

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 ([6.2.1 on page 47](#)).

²wikipedia

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:

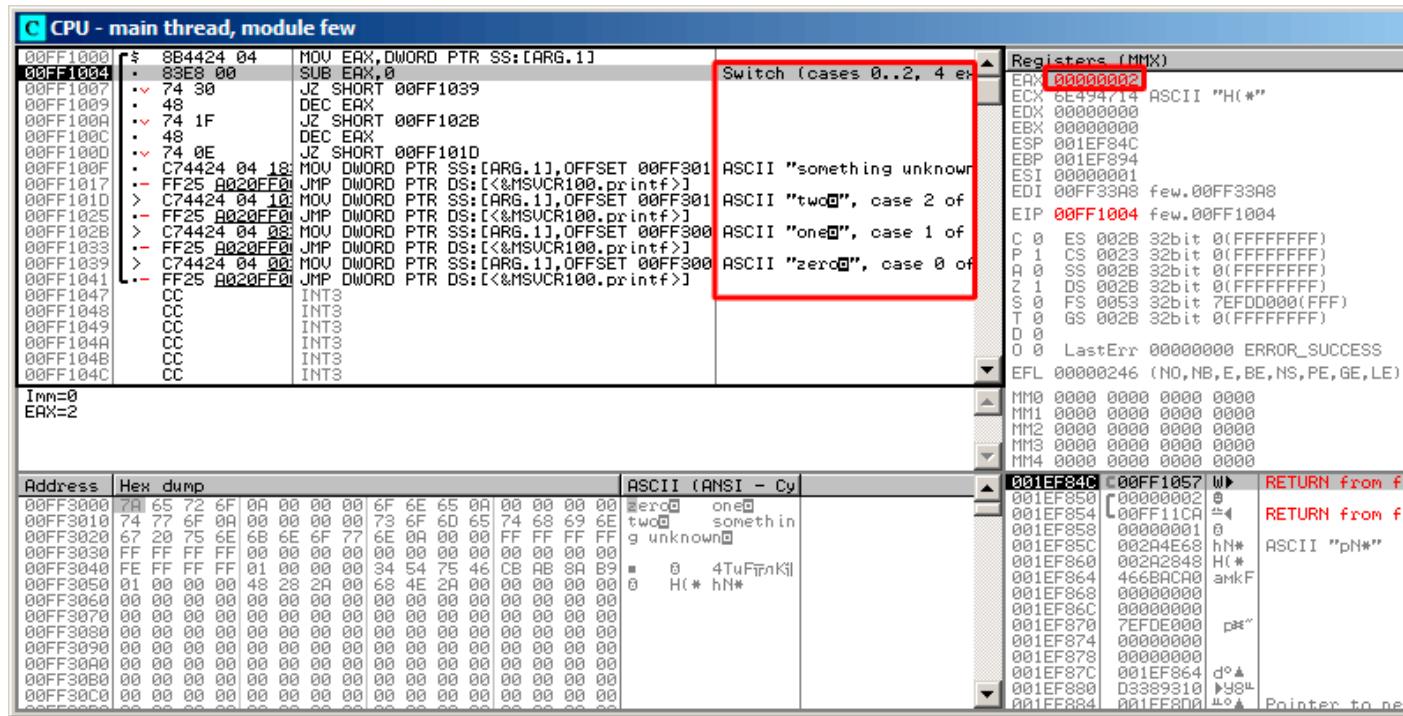


Figure 13.1: OllyDbg: EAX now contain the first (and only) function argument

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:

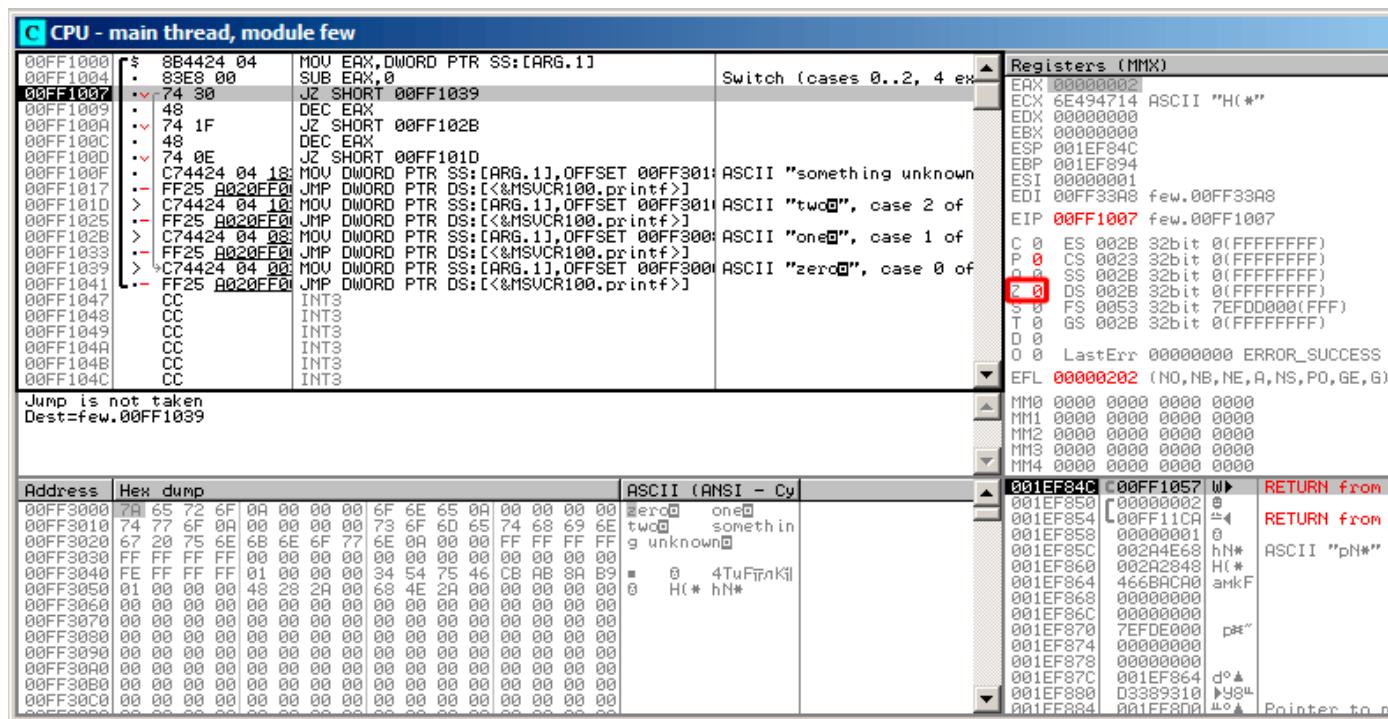


Figure 13.2: OllyDbg: SUB executed

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

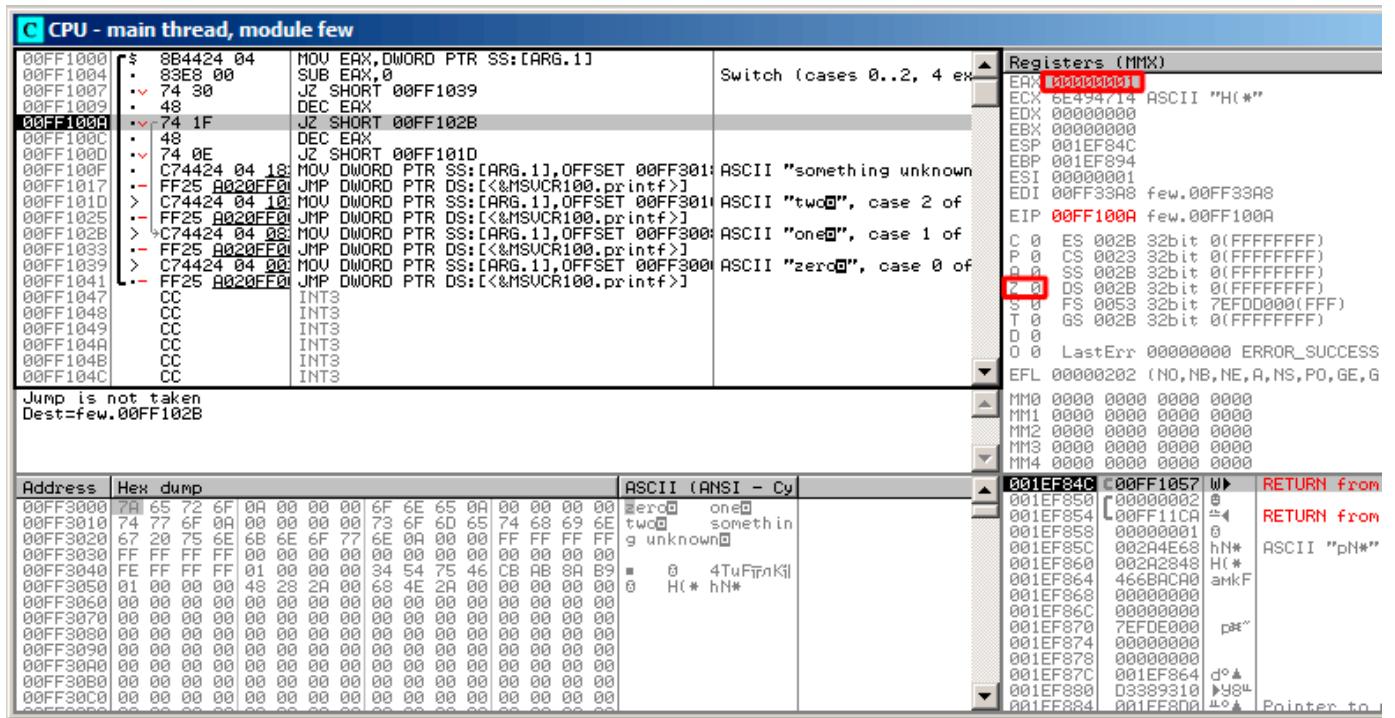


Figure 13.3: OllyDbg: first DEC executed

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

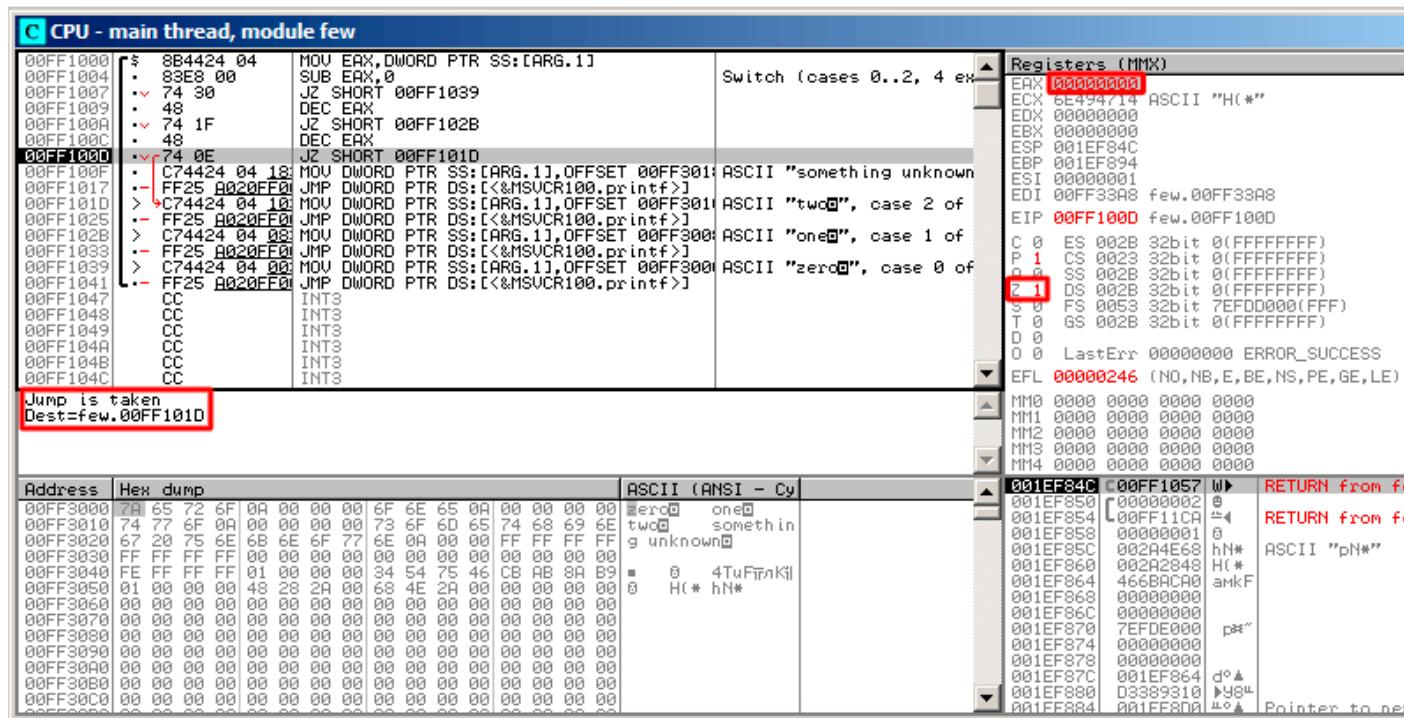


Figure 13.4: OllyDbg: second DEC executed

OllyDbg shows that this jump is to be taken now.

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

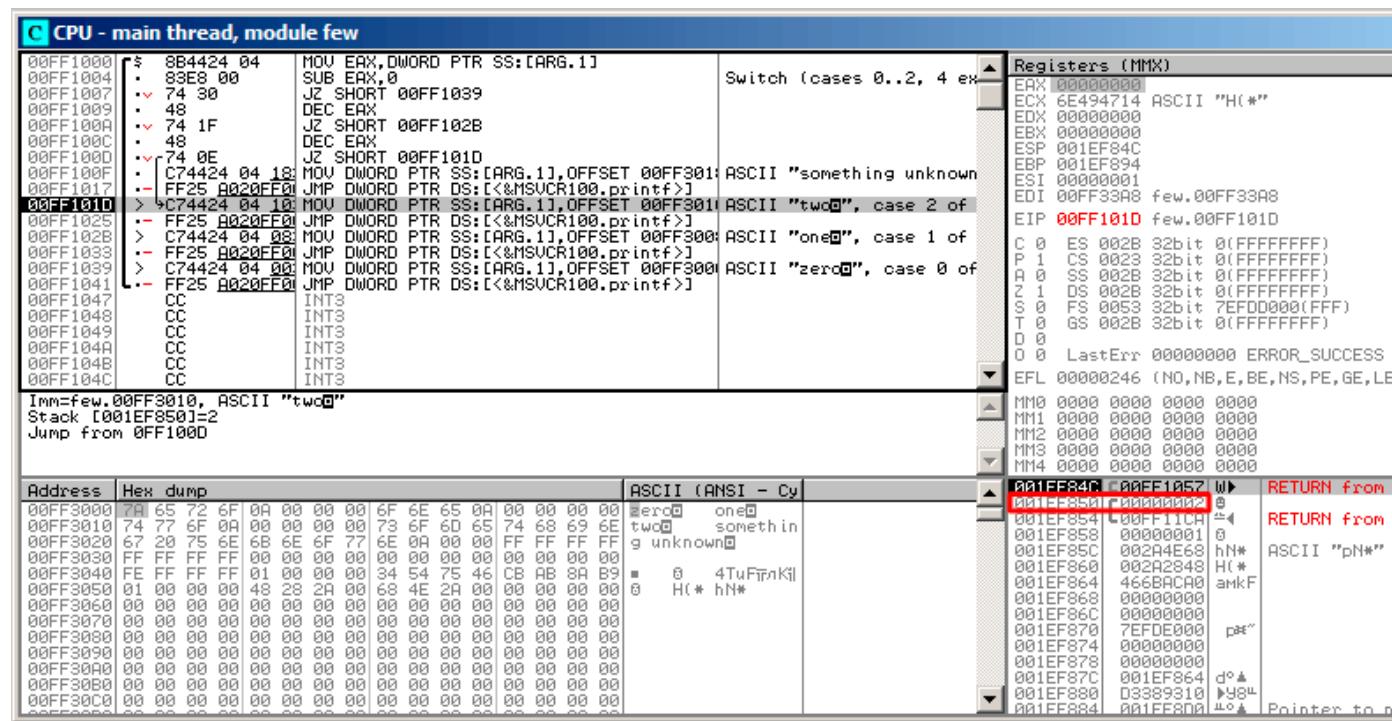


Figure 13.5: OllyDbg: pointer to the string is to be written at the place of the first argument

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

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):

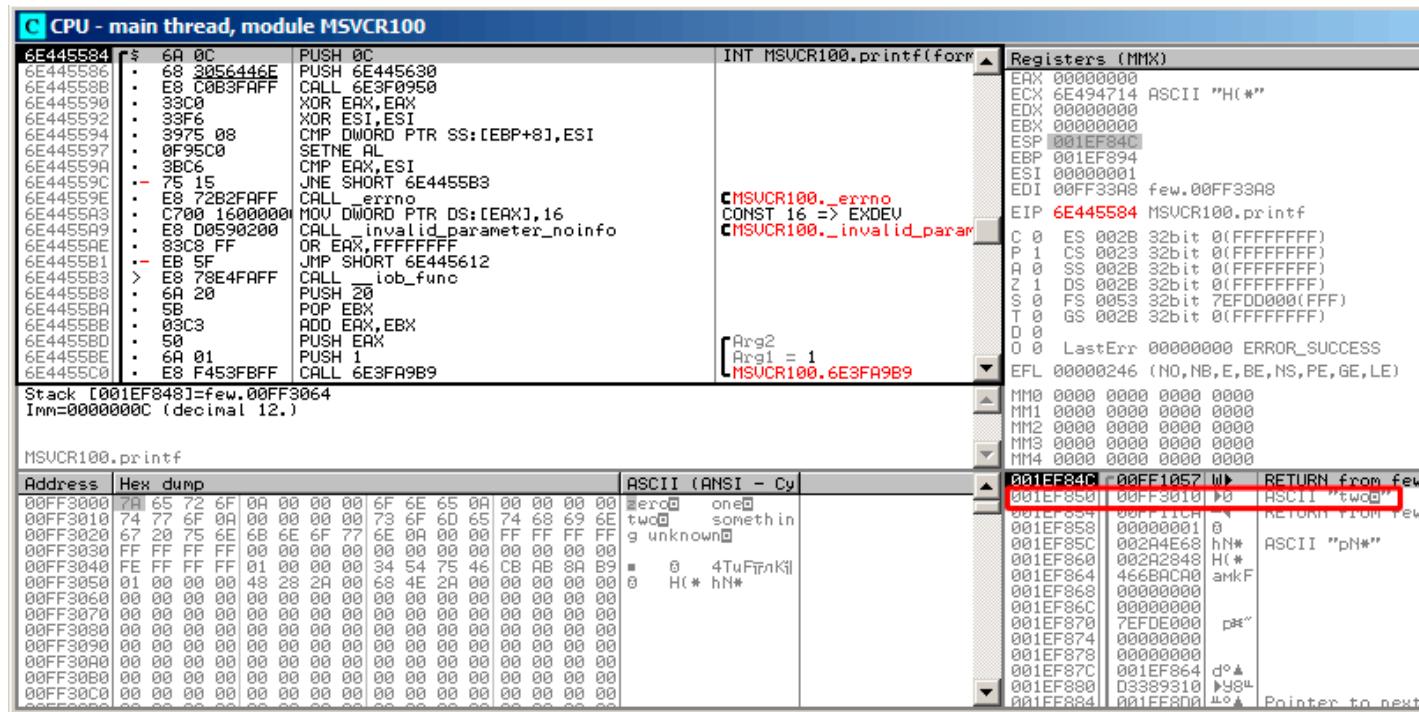


Figure 13.6: OllyDbg: first instruction of printf() in MSVCR100.DLL

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

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

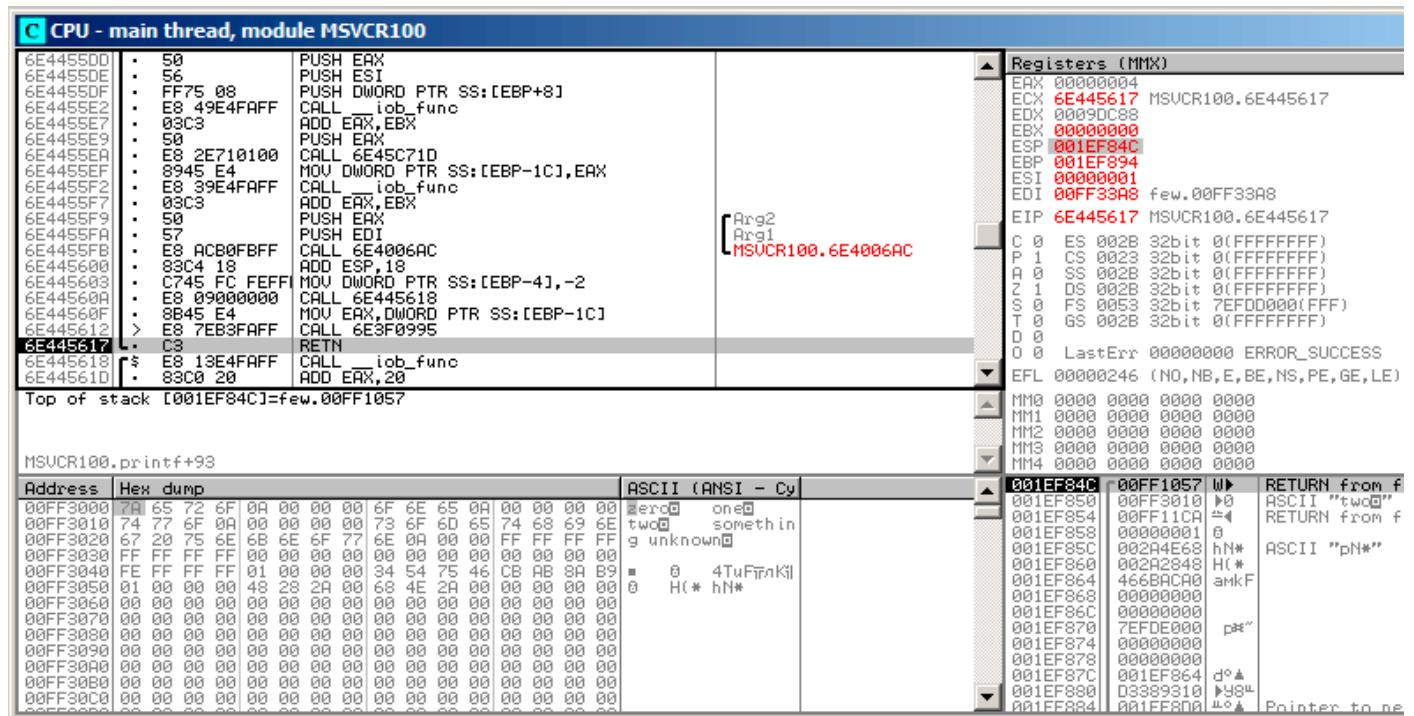


Figure 13.7: OllyDbg: last instruction of `printf()` in MSVCR100.DLL

The string “two” was just printed to the console window.

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

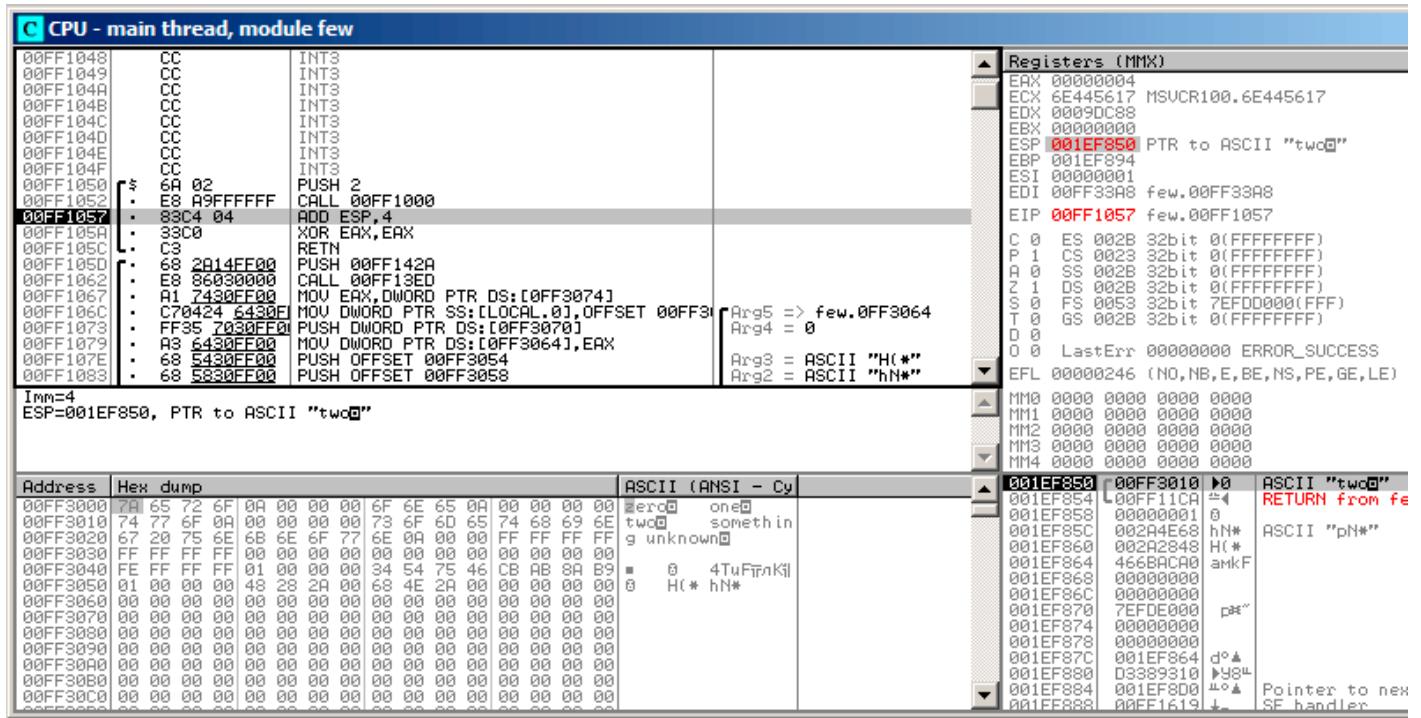


Figure 13.8: OllyDbg: return to main()

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()`.

13.1.2 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, aSomethingUnkn ; "something unknown\n"
.text:0000016C 4E 0F 8F 02    ADREQ  R0, aTwo   ; "two\n"
.text:00000170
.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 ([6.2.1 on page 47](#)). 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 sure that the a variable is not equal to these numbers at this point. And if $R0 = 2$, a pointer to the string «`two\n`» will be loaded by `ADREQ` into $R0$.

13.1.3 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.

13.1.4 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
bl    puts
b     .L32

.L34:
adrp  x0, .LC13      ; "one"
add   x0, x0, :lo12:.LC13
bl    puts
b     .L32

.L35:
adrp  x0, .LC14      ; "two"
add   x0, x0, :lo12:.LC14
bl    puts
b     .L32

.L38:
adrp  x0, .LC15      ; "something unknown"
add   x0, x0, :lo12:.LC15

```

```

    bl      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: [3.4.5 on page 17](#).

13.1.5 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: [13.1.1 on page 145](#).

13.1.6 MIPS

Listing 13.3: Optimizing GCC 4.4.5 (IDA)

```

f:
; is it 1?
    lui    $gp, (__gnu_local_gp >> 16)
    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
    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: [13.1.1 on page 145](#).

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.

13.1.7 Conclusion

A `switch()` with few cases is indistinguishable from an *if/else* construction, for example: listing [13.1.1](#).

13.2 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
}
```

13.2.1 x86

Non-optimizing MSVC

We get (MSVC 2010):

Listing 13.4: 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.

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.

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

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` ([88 on page 887](#)) 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.

OllyDbg

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

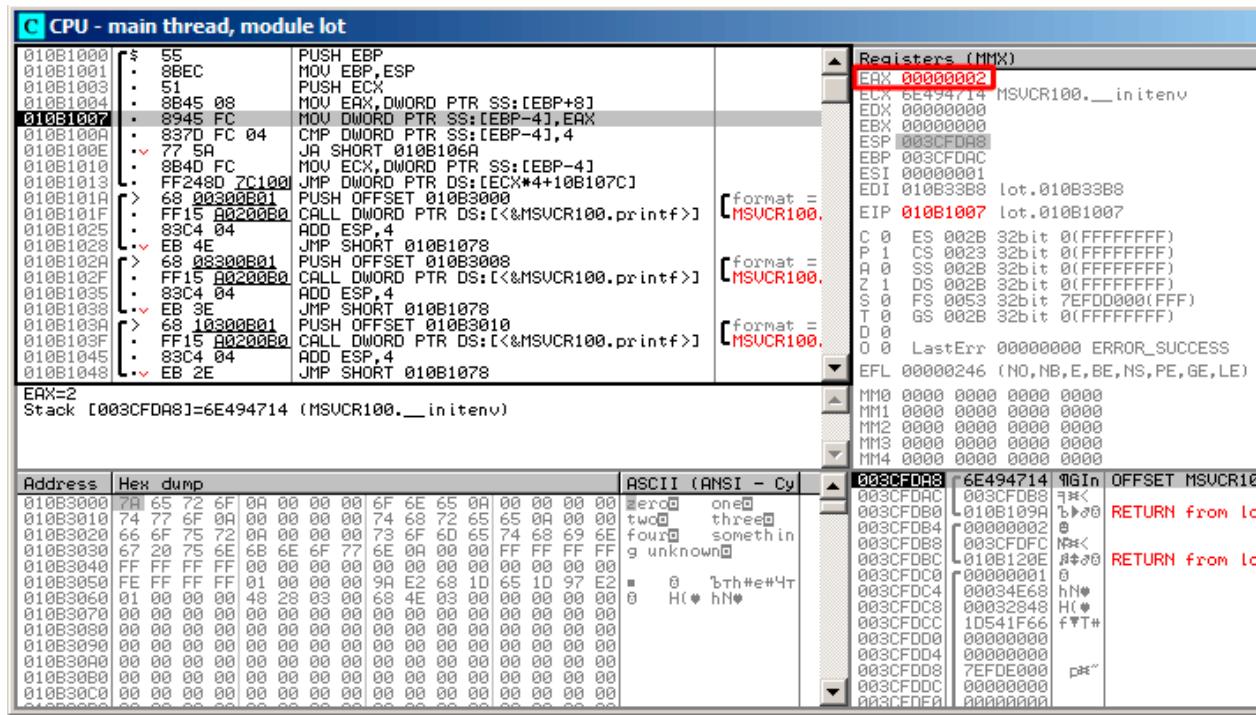


Figure 13.9: OllyDbg: function's input value is loaded in EAX

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

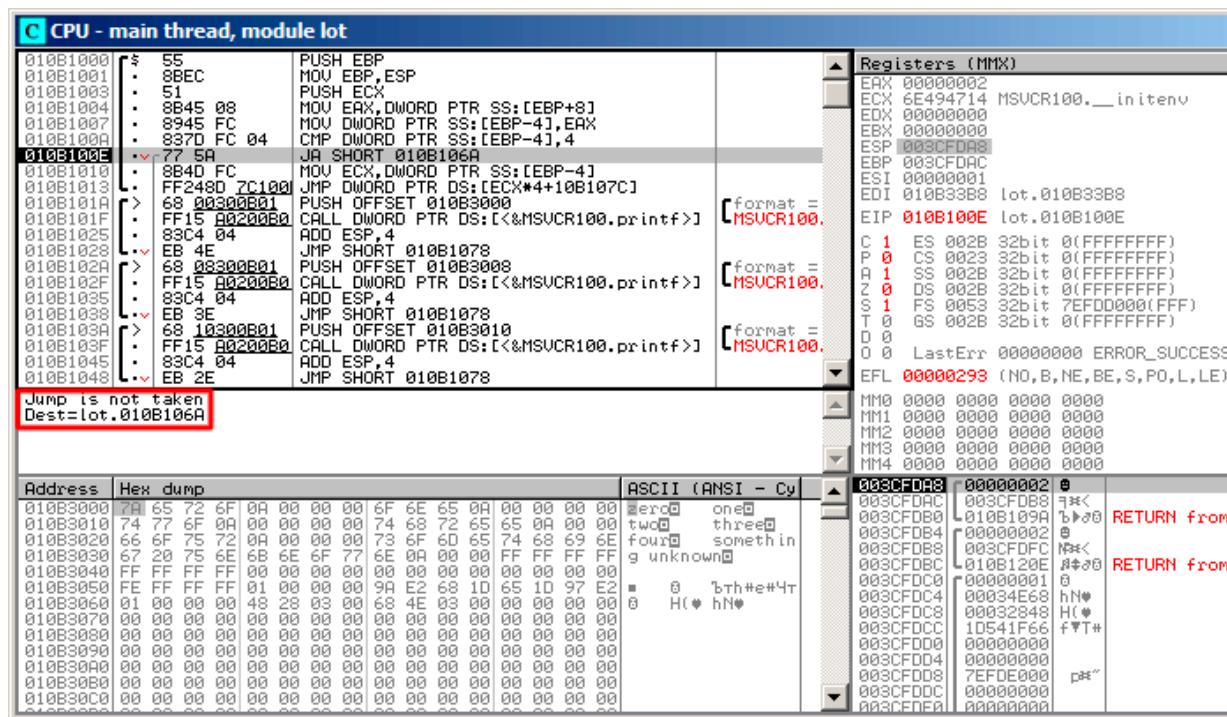


Figure 13.10: OllyDbg: 2 is no bigger than 4: no jump is taken

Here we see a jumtable:

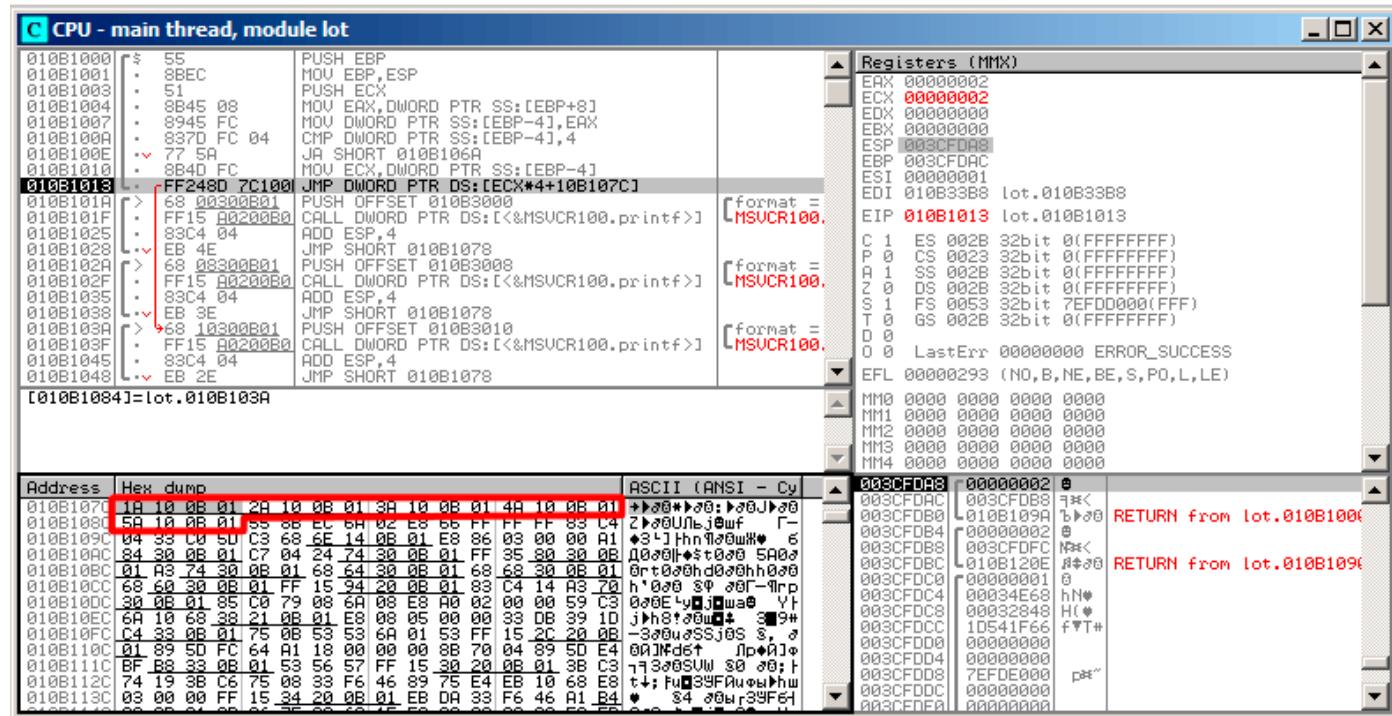


Figure 13.11: OllyDbg: calculating destination address using jumtable

Here we've clicked "Follow in Dump" → "Address constant", so now we see the *jumtable* 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: [68.2.6 on page 706](#), we are going to come back to them later

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

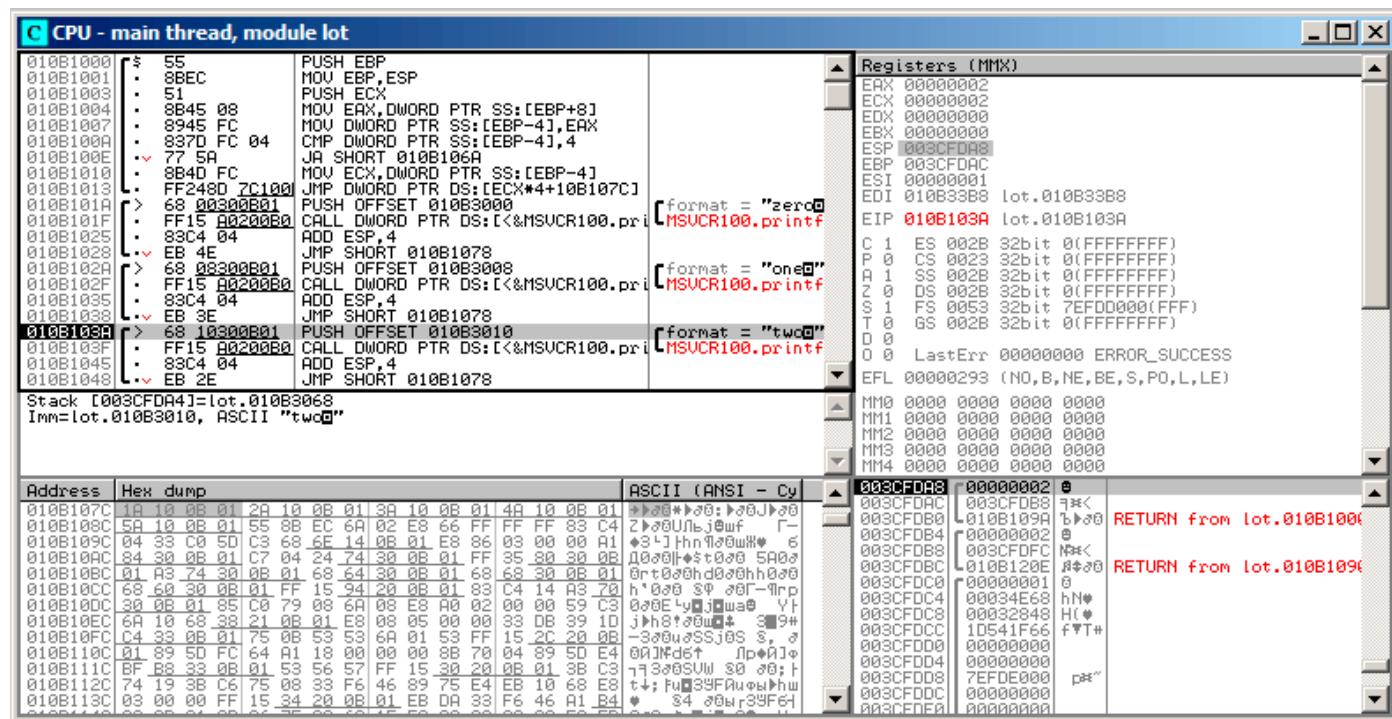


Figure 13.12: OllyDbg: now we at the *case: label*

Non-optimizing GCC

Let's see what GCC 4.4.1 generates:

Listing 13.5: 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

```

```

    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) ([16.2.1 on page 212](#)). Then the address of the label is taken from the `off_804855C` array, stored in EAX, and then `JMP EAX` does the actual jump.

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

Listing 13.6: 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
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 `ADDCC PC, PC, R0, LSL#2`⁵ instruction is being executed only if $R0 < 5$ (*CC=Carry clear/Less than*). Consequently, if ADDCC does not trigger (it is a $R0 \geq 5$ case), a jump to `default_case` label will occur.

But if $R0 < 5$ and ADDCC triggers, the following is to be happen:

The value in $R0$ is multiplied by 4. In fact, `LSL#2` at the instruction's suffix stands for “shift left by 2 bits”. But as we will see later ([16.2.1 on page 212](#)) 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 ADDCC, the value in `PC` is 8 bytes ahead (0x180) than the address at which the ADDCC instruction is located (0x178), or, in other words, 2 instructions ahead.

This is how the pipeline in ARM processors works: when ADDCC is executed, the processor at the moment is beginning to process the instruction after the next one, so that is why `PC` points there. This has to be memorized.

If $a = 0$, then is to be added to the value in `PC`, and the actual value of the `PC` will be written into `PC` (which is 8 bytes ahead) and a jump to the label `loc_180` will happen, which is 8 bytes ahead of the point where the ADDCC instruction is.

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

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

Listing 13.7: Optimizing Keil 6/2013 (Thumb mode)

000000F6	EXPORT f2
000000F6	f2
000000F6 10 B5	PUSH {R4,LR}

⁵ADD—addition

```

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. 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.

13.2.4 MIPS

Listing 13.8: 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
; print "one" and finish
        lui      $a0, ($LC1 >> 16) # "one"
        lw       $t9, (puts & 0xFFFF)($gp)
        or       $at, $zero ; NOP
        jr      $t9
```

```

1a      $a0, ($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.

13.2.5 Conclusion

Rough skeleton of *switch()*:

Listing 13.9: 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
           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 jump table is just array of pointers, like the one described later: [18.5 on page 281](#).

13.3 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.

13.3.1 MSVC

Listing 13.10: 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
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 ([13.2.1 on page 163](#)), 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.

13.3.2 GCC

GCC does the job in the way we already discussed ([13.2.1 on page 163](#)), using just one table of pointers.

13.3.3 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 uses the fact that all offsets in my tiny example are in close proximity to each other. So the jump table consisting of single bytes.

Listing 13.11: 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:
.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 13.12: jumptable in IDA

.rodata:00000000000000064	AREA .rodata, DATA, READONLY
.rodata:00000000000000064	; ORG 0x64
.rodata:00000000000000064 \$d	DCB 9 ; case 1
.rodata:00000000000000065	DCB 9 ; case 2
.rodata:00000000000000066	DCB 6 ; case 3
.rodata:00000000000000067	DCB 6 ; case 4
.rodata:00000000000000068	DCB 6 ; case 5
.rodata:00000000000000069	DCB 6 ; case 6
.rodata:0000000000000006A	DCB 9 ; case 7
.rodata:0000000000000006B	DCB 3 ; case 8
.rodata:0000000000000006C	DCB 3 ; case 9
.rodata:0000000000000006D	DCB 9 ; case 10
.rodata:0000000000000006E	DCB 0xF7 ; case 11
.rodata:0000000000000006F	DCB 0xF7 ; case 12
.rodata:00000000000000070	DCB 0xF7 ; case 13
.rodata:00000000000000071	DCB 0xF7 ; case 14
.rodata:00000000000000072	DCB 0xF7 ; case 15
.rodata:00000000000000073	DCB 0xF7 ; case 16
.rodata:00000000000000074	DCB 0xF7 ; case 17
.rodata:00000000000000075	DCB 0xF7 ; case 18
.rodata:00000000000000076	DCB 0xF7 ; case 19
.rodata:00000000000000077	DCB 3 ; case 20
.rodata:00000000000000078	DCB 3 ; case 21
.rodata:00000000000000079	DCB 0 ; case 22
.rodata:0000000000000007B ; .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).

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

```

If *type* = 1 (R), *read* is to be set to 1, if *type* = 2 (W), *write* is to be set to 2. 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.

13.4.1 MSVC x86

Listing 13.13: 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
    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.

13.4.2 ARM64

Listing 13.14: 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.

13.5 Exercises

13.5.1 Exercise #1

It's possible to rework the C example in [13.2 on page 157](#) in such way that the compiler can produce even smaller code, but will work just the same. Try to achieve it.

Hint: [G.1.5 on page 978](#).

Chapter 14

Loops

14.1 Simple example

14.1.1 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 14.1: MSVC 2010

```
_i$ = -4
_main    PROC
    push    ebp
    mov     ebp, esp
    push    ecx
    mov     DWORD PTR _i$[ebp], 2      ; loop initialization
    jmp    SHORT $LN3@main
```

```

$LN2@main:
    mov    eax, DWORD PTR _i$[ebp] ; here is what we do after each iteration:
    add    eax, 1                 ; add 1 to (i) value
    mov    DWORD PTR _i$[ebp], eax
$LN3@main:
    cmp    DWORD PTR _i$[ebp], 10   ; this condition is checked *before* each iteration
    jge    SHORT $LN1@main        ; if (i) is biggest or equals to 10, lets finish loop'
    mov    ecx, DWORD PTR _i$[ebp]; loop body: call printing_function(i)
    push   ecx
    call   _printing_function
    add    esp, 4
    jmp    SHORT $LN2@main       ; jump to loop begin
$LN1@main:                           ; loop end
    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 14.2: 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 14.3: 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

```

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 14.4: 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 14.5: GCC

```
main          public main
main          proc near
var_20        = dword ptr -20h

    push    ebp
    mov     ebp, esp
    and     esp, 0FFFFFFF0h
    push    ebx
    mov     ebx, 2      ; i=2
    sub     esp, 1Ch

; aligning label loc_80484D0 (loop body begin) by 16-byte border:
    nop

loc_80484D0:
; pass (i) as first argument to printing_function():
    mov     [esp+20h+var_20], ebx
    add     ebx, 1      ; i++
    call   printing_function
```

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

```
    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.

14.1.2 x86: OllyDbg

Let's compile our example in MSVC 2010 with `/Ox` and `/Ob0` options and load it into OllyDbg.

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

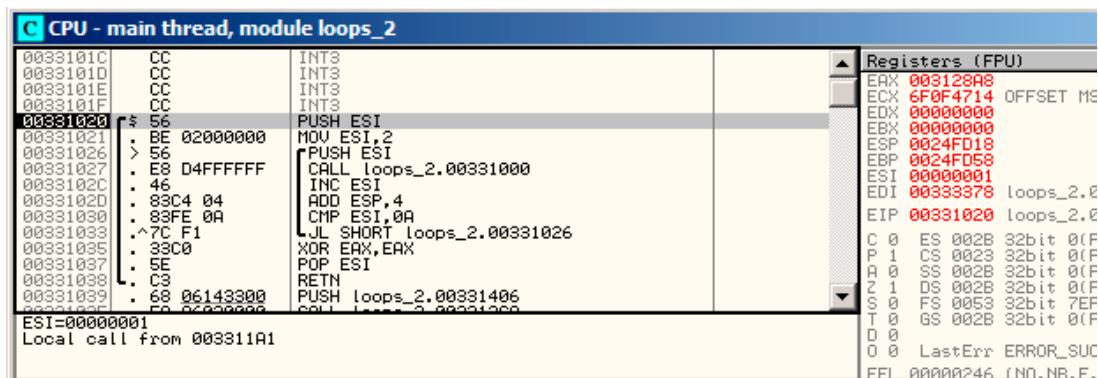


Figure 14.1: OllyDbg: `main()` begin

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

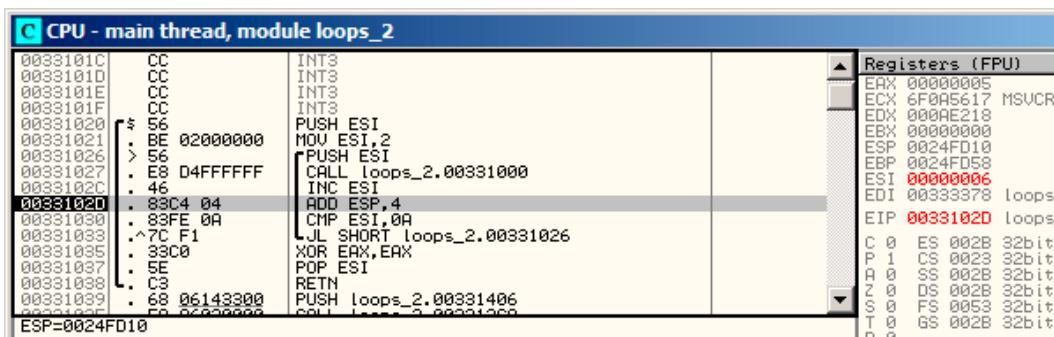


Figure 14.2: OllyDbg: loop body just executed with $i = 6$

9 is the last loop value. That's why JL is not triggering after the [increment](#), and the function will finish:

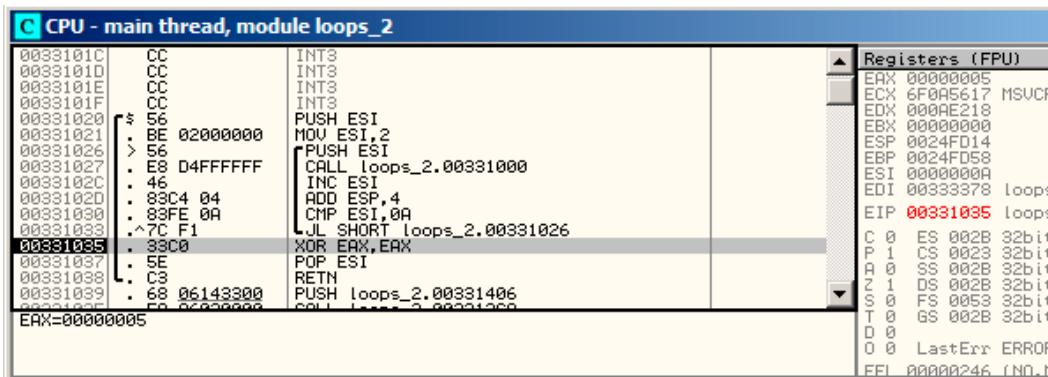


Figure 14.3: OllyDbg: $ESI = 10$, loop end

14.1.3 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
```

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=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.

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
.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=0x38fcfc
.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      ; EAX=0
.text:00401038 _main endp
```

Figure 14.4: [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 14.6: `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=0x38fcfc
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.

14.1.4 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
loc_368 ; CODE XREF: main+8
```

```
CMP    R4, #0xA
BLT    loc_35C
MOV    R0, #0
LDMFD {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           ; CODE XREF: _main+E
    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}
```

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 14.7: 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 14.8: 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
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"

```

14.1.5 MIPS

Listing 14.9: 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
; 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).

14.1.6 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).

14.2 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];
}
```

14.2.1 Straight-forward implementation

Listing 14.10: 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
.L2:
; all bytes copied? exit then:
    cmp    rax, rdx
    je     .L5
; load byte at RSI+i:
    mov    cl, BYTE PTR [rsi+rax]
```

²Single instruction, multiple data

```
; store byte at RDI+i:
    mov     BYTE PTR [rdi+rax], cl
    inc     rax ; i++
    jmp     .L2
.L5:
    ret
```

Listing 14.11: 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 14.12: 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
```

14.2.2 ARM in ARM mode

Keil in ARM mode takes full advantage of conditional suffixes:

Listing 14.13: Optimizing Keil 6/2013 (ARM mode)

```
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.

14.2.3 MIPS

Listing 14.14: 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”). 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.

14.2.4 Vectorization

Optimizing GCC can do much more on this example: [25.1.2 on page 429](#).

14.3 Conclusion

Rough skeleton of loop from 2 to 9 inclusive:

Listing 14.15: 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 14.16: 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 14.17: 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 14.18: x86

```
MOV [counter], 2 ; initialization
JMP label_check
label_increment:
ADD [counter], 1 ; increment
label_check:
CMP [counter], 10
JGE exit
; loop body
; do something here
; use counter variable in local stack
JMP label_increment
exit:
```

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 14.19: 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 14.20: 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 14.21: 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

```

14.4 Exercises

14.4.1 Exercise #1

Why isn't the LOOP instruction used by modern compilers anymore?

14.4.2 Exercise #2

Take a loop example from this section ([14.1.1 on page 175](#)), compile it in your favorite OS and compiler and modify (patch) the executable file so the loop range will be [6..20].

14.4.3 Exercise #3

What does this code do?

Listing 14.22: Optimizing MSVC 2010

```

$SG2795 DB      '%d', 0aH, 00H
_main    PROC
        push    esi
        push    edi
        mov     edi, DWORD PTR __imp__printf
        mov     esi, 100
        npad   3 ; align next label
$LL3@main:
        push    esi

```

```

push    OFFSET $SG2795 ; '%d'
call    edi
dec    esi
add    esp, 8
test   esi, esi
jg     SHORT $LL3@main
pop    edi
xor    eax, eax
pop    esi
ret    0
_main  ENDP

```

Listing 14.23: Non-optimizing Keil 6/2013 (ARM mode)

```

main PROC
    PUSH    {r4,lr}
    MOV     r4,#0x64
|L0.8|
    MOV     r1,r4
    ADR     r0,|L0.40|
    BL      __2printf
    SUB    r4,r4,#1
    CMP    r4,#0
    MOVLE  r0,#0
    BGT    |L0.8|
    POP    {r4,pc}
    ENDP

|L0.40|
    DCB    "%d\n",0

```

Listing 14.24: Non-optimizing Keil 6/2013 (Thumb mode)

```

main PROC
    PUSH    {r4,lr}
    MOVS   r4,#0x64
|L0.4|
    MOVS   r1,r4
    ADR    r0,|L0.24|
    BL     __2printf
    SUBS  r4,r4,#1
    CMP   r4,#0
    BGT   |L0.4|
    MOVS   r0,#0
    POP    {r4,pc}
    ENDP

    DCW    0x0000
|L0.24|
    DCB    "%d\n",0

```

Listing 14.25: Optimizing GCC 4.9 (ARM64)

```

main:
    stp    x29, x30, [sp, -32]!
    add    x29, sp, 0
    stp    x19, x20, [sp,16]
    adrp   x20, .LC0
    mov    w19, 100
    add    x20, x20, :lo12:.LC0
.L2:
    mov    w1, w19
    mov    x0, x20
    bl     printf
    subs   w19, w19, #1
    bne   .L2
    ldp    x19, x20, [sp,16]
    ldp    x29, x30, [sp], 32
    ret
.LC0:

```

```
.string "%d\n"
```

Listing 14.26: Optimizing GCC 4.4.5 (MIPS) (IDA)

```
main:
var_18      = -0x18
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      $s1, 0x28+var_8($sp)
        sw      $s0, 0x28+var_C($sp)
        sw      $gp, 0x28+var_18($sp)
        la      $s1, $LC0      # "%d\n"
        li      $s0, 0x64      # 'd'

loc_28:           # CODE XREF: main+40
        lw      $t9, (printf & 0xFFFF)($gp)
        move   $a1, $s0
        move   $a0, $s1
        jalr   $t9
        addiu $s0, -1
        lw      $gp, 0x28+var_18($sp)
        bnez   $s0, loc_28
        or     $at, $zero
        lw      $ra, 0x28+var_4($sp)
        lw      $s1, 0x28+var_8($sp)
        lw      $s0, 0x28+var_C($sp)
        jr     $ra
        addiu $sp, 0x28

$LC0:          .ascii "%d\n"<0>           # DATA XREF: main+1C
```

Answer: [G.1.7 on page 978](#).

14.4.4 Exercise #4

What does this code do?

Listing 14.27: Optimizing MSVC 2010

```
$SG2795 DB      '%d', 0aH, 00H

_main PROC
    push  esi
    push  edi
    mov   edi, DWORD PTR __imp__printf
    mov   esi, 1
    npad 3 ; align next label
$LL3@main:
    push  esi
    push  OFFSET $SG2795 ; '%d'
    call  edi
    add   esi, 3
    add   esp, 8
    cmp   esi, 100
    jl    SHORT $LL3@main
    pop   edi
    xor   eax, eax
    pop   esi
    ret   0
_main ENDP
```

Listing 14.28: Non-optimizing Keil 6/2013 (ARM mode)

```

main PROC
    PUSH    {r4,lr}
    MOV     r4,#1
|L0.8|
    MOV     r1,r4
    ADR     r0,|L0.40|
    BL      __2printf
    ADD     r4,r4,#3
    CMP     r4,#0x64
    MOVGE  r0,#0
    BLT    |L0.8|
    POP    {r4,pc}
    ENDP

|L0.40|
    DCB    "%d\n",0

```

Listing 14.29: Non-optimizing Keil 6/2013 (Thumb mode)

```

main PROC
    PUSH    {r4,lr}
    MOVS   r4,#1
|L0.4|
    MOVS   r1,r4
    ADR    r0,|L0.24|
    BL     __2printf
    ADDS  r4,r4,#3
    CMP   r4,#0x64
    BLT   |L0.4|
    MOVS  r0,#0
    POP   {r4,pc}
    ENDP

    DCW   0x0000
|L0.24|
    DCB   "%d\n",0

```

Listing 14.30: Optimizing GCC 4.9 (ARM64)

```

main:
    stp    x29, x30, [sp, -32]!
    add    x29, sp, 0
    stp    x19, x20, [sp,16]
    adrp   x20, .LC0
    mov    w19, 1
    add    x20, x20, :lo12:.LC0
.L2:
    mov    w1, w19
    mov    x0, x20
    add    w19, w19, 3
    bl     printf
    cmp    w19, 100
    bne   .L2
    ldp    x19, x20, [sp,16]
    ldp    x29, x30, [sp], 32
    ret
.LC0:
    .string "%d\n"

```

Listing 14.31: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

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)
sw       $gp, 0x28+var_18($sp)
la       $s2, $LC0          # "%d\n"
li       $s0, 1
li       $s1, 0x64  # 'd'

loc_30:                                # CODE XREF: main+48
lw       $t9, (printf & 0xFFFF)($gp)
move   $a1, $s0
move   $a0, $s2
jalr   $t9
addiu $s0, 3
lw       $gp, 0x28+var_18($sp)
bne   $s0, $s1, loc_30
or     $at, $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

$LC0:        .ascii "%d\n<0>"           # DATA XREF: main+20

```

Answer: [G.1.8 on page 979](#).

Chapter 15

Simple C-strings processing

15.1 `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!");
}
```

15.1.1 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

```
; here we calculate the difference between two pointers

mov    eax, DWORD PTR _eos$[ebp]
sub    eax, DWORD PTR _str$[ebp]
sub    eax, 1           ; subtract 1 and return result
mov    esp, ebp
pop    ebp
ret    0
_strlen_ ENDP
```

We get two new instructions here: MOVSX and TEST.

The first one—MOVsx—takes a byte from an address in memory and stores the value in a 32-bit register. MOVsx stands for *MOV with Sign-Extend*. MOVsx sets the rest of the bits, from the 8th to the 31th, to 1 if the source byte is *negative* or to 0 if is *positive*.

And here is why.

By default, the *char* type is signed in MSVC and GCC. If we have two values of which one is *char* and the other is *int*, (*int* is signed too), and if the first value contain -2 (coded as 0xFE) and we just copy this byte into the *int* container, it makes 0x000000FE, and this from the point of signed *int* view is 254, but not -2. In signed *int*, -2 is coded as 0xFFFFFFFF. So if we 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 ([30 on page 464](#)).

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 ([19 on page 312](#)). 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
```

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 15.1: 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 subtract 1 to/from a variable.

Optimizing MSVC + OllyDbg

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

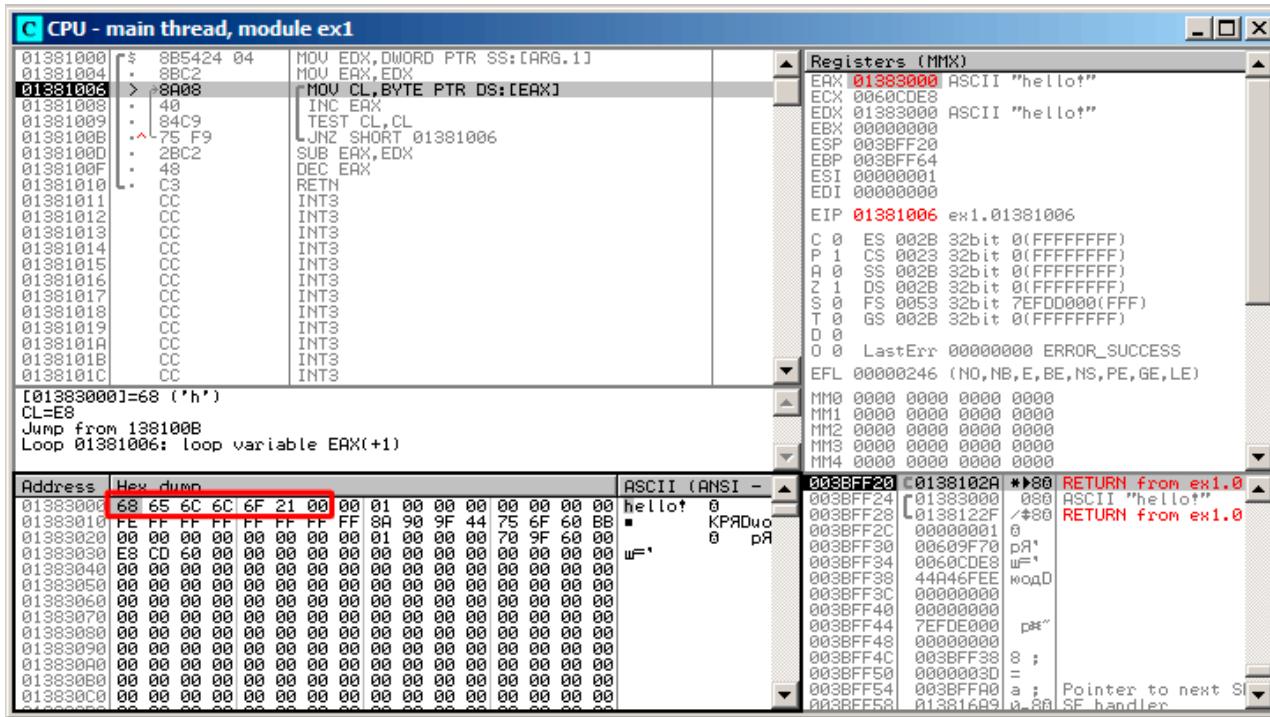


Figure 15.1: OllyDbg: first iteration start

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.

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

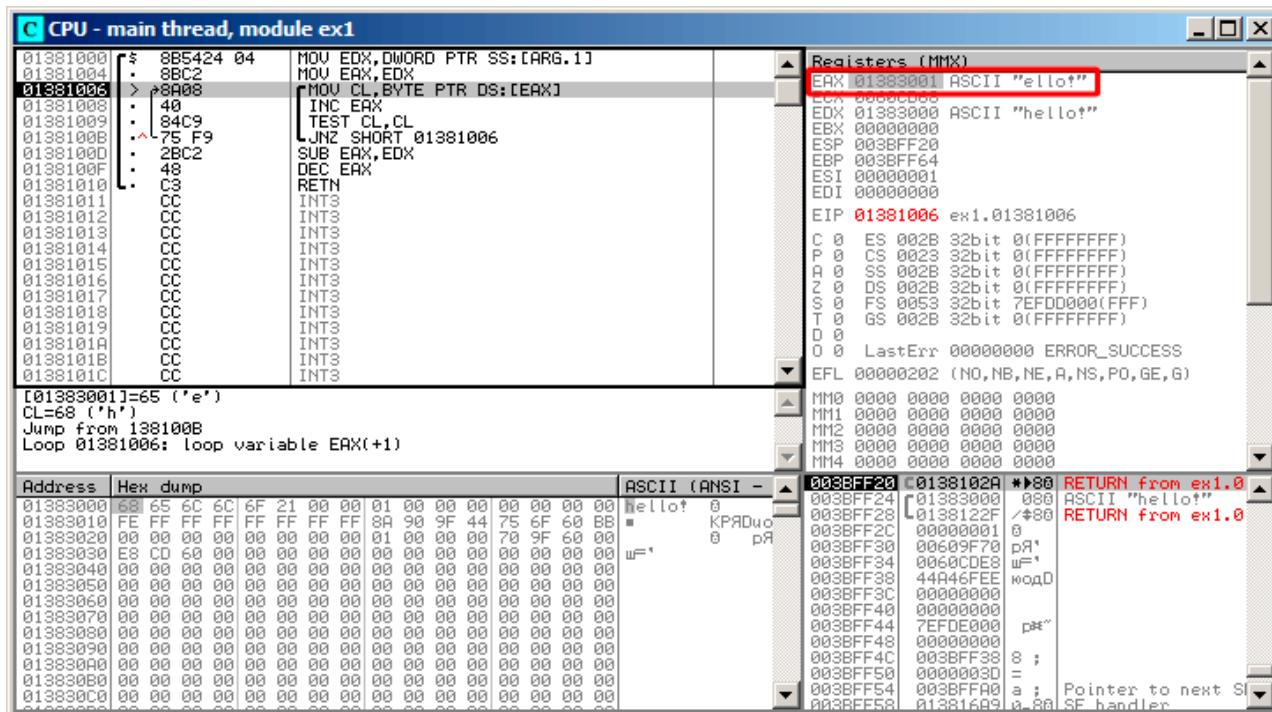


Figure 15.2: OllyDbg: second iteration start

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

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

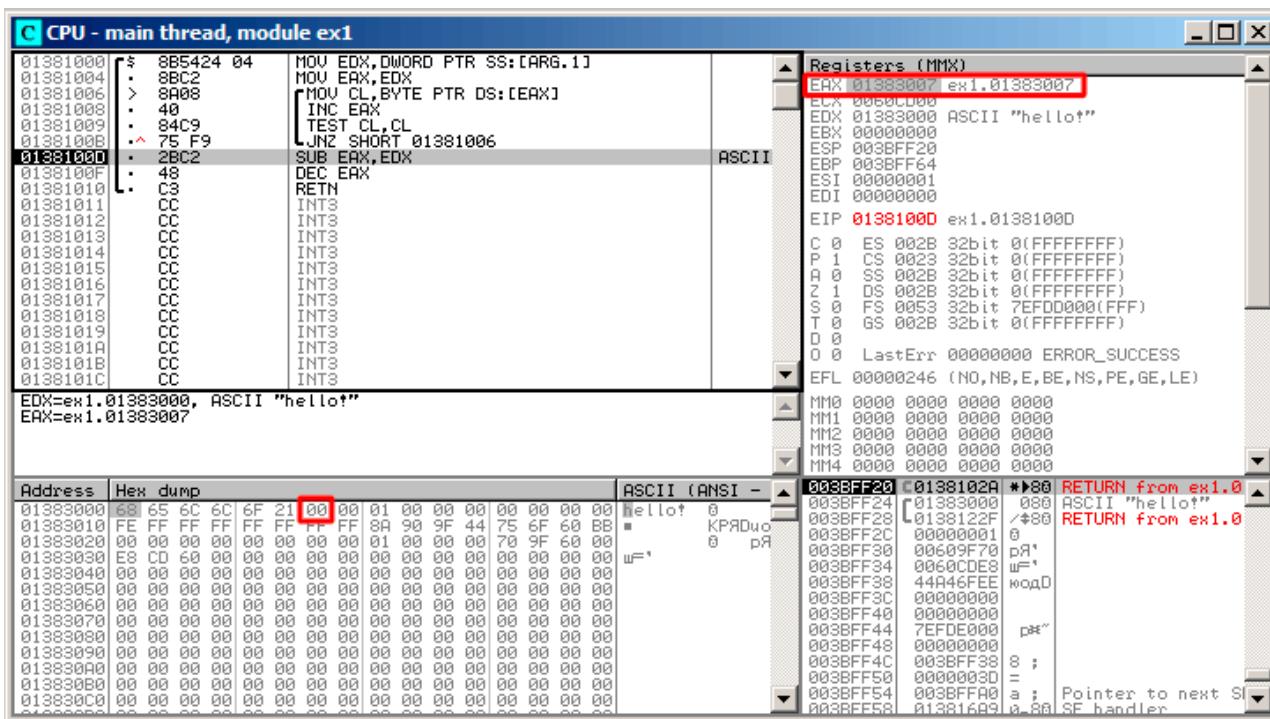


Figure 15.3: OllyDbg: pointers difference to be calculated now

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.

The SUB instruction just got executed:

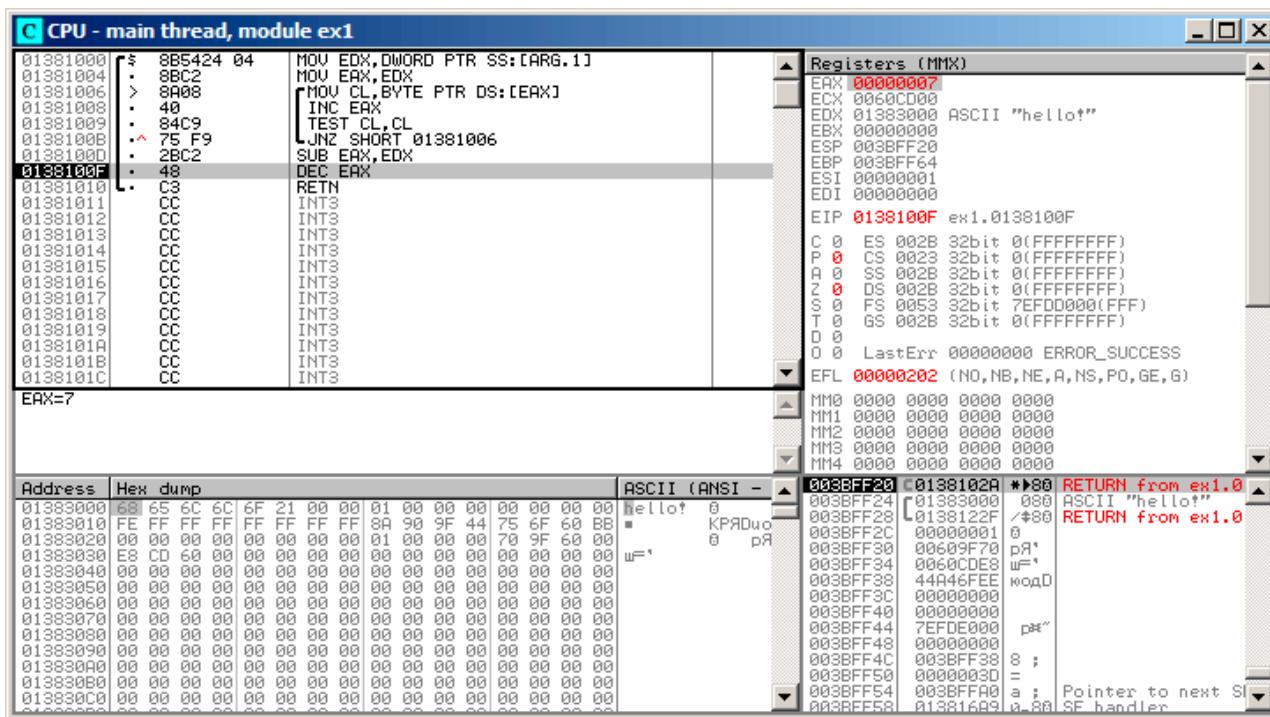


Figure 15.4: OllyDbg: EAX to be decremented now

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 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" ([30 on page 464](#)).

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.

15.1.2 ARM

32-bit ARM

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

Listing 15.2: 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.

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

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

since the `char` type is signed according to the C standard. It was already written about it ([15.1.1 on page 195](#)) 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 15.3: 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: [28.2 on page 457](#).

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 ([15.1.1 on page 200](#)).

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

Optimizing Keil 6/2013 (ARM mode)

Listing 15.4: Optimizing Keil 6/2013 (ARM mode)

```
_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
```

³(PowerPC, ARM) Branch if Not Equal

⁴MoVe Not

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 [15.1.1 on page 196](#): 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
    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.

15.1.3 MIPS

Listing 15.5: 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:
    bnez   $a1, loc_4
; increment "eos" anyway:
    addiu  $v1, 1 ; branch delay slot
; loop finished. invert "str" variable:
    nor    $v0, $zero, $a0
; $v0=-str-1
    jr     $ra
; return value = $v1 + $v0 = eos + ( -str-1 ) = eos - str - 1
    addu   $v0, $v1, $v0 ; branch delay slot
```

MIPS lacks a NOT instruction, but has NOR which is OR + NOT operation. This operation is widely used in digital electronics⁵, but isn't very popular in computer programming. So, the NOT operation is implemented here as NOR DST, \$ZERO, SRC.

From fundamentals [30 on page 464](#) 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.

15.2 Exercises

15.2.1 Exercise #1

What does this code do?

Listing 15.6: Optimizing MSVC 2010

```
_s$ = 8
_f PROC
    mov    edx, DWORD PTR _s$[esp-4]
    mov    cl, BYTE PTR [edx]
    xor    eax, eax
    test   cl, cl
    je     SHORT $LN2@f
    npad  4 ; align next label
$LL4@f:
    cmp    cl, 32
    jne    SHORT $LN3@f
    inc    eax
$LN3@f:
    mov    cl, BYTE PTR [edx+1]
    inc    edx
    test   cl, cl
    jne    SHORT $LL4@f
$LN2@f:
    ret    0
_f ENDP
```

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

Listing 15.7: GCC 4.8.1 -O3

```
f:
.LFB24:
    push    ebx
    mov     ecx, DWORD PTR [esp+8]
    xor     eax, eax
    movzx  edx, BYTE PTR [ecx]
    test   dl, dl
    je     .L2
.L3:
    cmp    dl, 32
    lea    ebx, [eax+1]
    cmove  eax, ebx
    add    ecx, 1
    movzx  edx, BYTE PTR [ecx]
    test   dl, dl
    jne   .L3
.L2:
    pop    ebx
    ret
```

Listing 15.8: Optimizing Keil 6/2013 (ARM mode)

```
f PROC
    MOV    r1,#0
|L0.4|
    LDRB   r2,[r0,#0]
    CMP    r2,#0
    MOVEQ  r0,r1
    BXEQ   lr
    CMP    r2,#0x20
    ADDEQ  r1,r1,#1
    ADD    r0,r0,#1
    B     |L0.4|
    ENDP
```

Listing 15.9: Optimizing Keil 6/2013 (Thumb mode)

```
f PROC
    MOVS   r1,#0
    B     |L0.12|
|L0.4|
    CMP    r2,#0x20
    BNE   |L0.10|
    ADDS  r1,r1,#1
|L0.10|
    ADDS  r0,r0,#1
|L0.12|
    LDRB   r2,[r0,#0]
    CMP    r2,#0
    BNE   |L0.4|
    MOVS   r0,r1
    BX    lr
    ENDP
```

Listing 15.10: Optimizing GCC 4.9 (ARM64)

```
f:
    ldrb  w1, [x0]
    cbz   w1, .L4
    mov   w2, 0
.L3:
    cmp   w1, 32
    ldrb  w1, [x0,1]!
    csinc w2, w2, w2, ne
    cbnz  w1, .L3
.L2:
    mov   w0, w2
    ret
.L4:
```

mov	w2, w1
b	.L2

Listing 15.11: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

f:
    lb      $v1, 0($a0)
    or      $at, $zero
    beqz   $v1, locret_48
    li      $a1, 0x20 # ' '
    b       loc_28
    move   $v0, $zero
loc_18:                      # CODE XREF: f:loc_28
    lb      $v1, 0($a0)
    or      $at, $zero
    beqz   $v1, locret_40
    or      $at, $zero

loc_28:                      # CODE XREF: f+10
    # f+38
    bne   $v1, $a1, loc_18
    addiu $a0, 1
    lb     $v1, 0($a0)
    or     $at, $zero
    bnez  $v1, loc_28
    addiu $v0, 1

locret_40:                   # CODE XREF: f+20
    jr    $ra
    or     $at, $zero
locret_48:                   # CODE XREF: f+8
    jr    $ra
    move  $v0, $zero

```

Answer [G.1.9 on page 979](#).

Chapter 16

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 52.1.

For example, the LEA instruction is often used for simple arithmetic calculations: [A.6.2 on page 957](#).

16.1 Multiplication

16.1.1 Multiplication using addition

Here is a simple example:

Listing 16.1: 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
```

16.1.2 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 16.2: Non-optimizing MSVC 2010

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

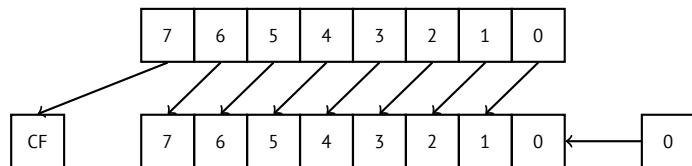
```

    mov     eax, DWORD PTR _a$[ebp]
    shl     eax, 2
    pop    ebp
    ret    0
_f      ENDP

```

Multiplication by 4 is just shifting the number to the left by 2 bits and inserting 2 zero bits at the right (as the last two bits). It is just like multiplying 3 by 100 – we 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 16.3: Non-optimizing Keil 6/2013 (ARM mode)

```

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

```

Multiplication by 4 in MIPS:

Listing 16.4: Optimizing GCC 4.4.5 (IDA)

```

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

```

SLL is “Shift Left Logical”.

16.1.3 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;
}

```

x86

Listing 16.5: 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 16.6: 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      lr
    ENDP

; a*28
||f2|| PROC
    RSB     r0,r0,r0,LSL #3
; R0=R0<<3-R0=R0*8-R0=a*8-a=a*7
    LSL     r0,r0,#2
; R0=R0<<2=R0*4=a*7*4=a*28
    BX      lr
    ENDP

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

```

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

Listing 16.7: 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 16.8: 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)
{
    return a*7;
};
```

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

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

x64

Listing 16.9: 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 16.10: 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=X0*32=a*32
    sub     x0, x1, x0, lsl 2
; X0=X1-X0<<2=a*32-a<<2=a*32-a*4=a*28
    ret

; a*17
```

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

16.2 Division

16.2.1 Division using shifts

Example of division by 4:

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

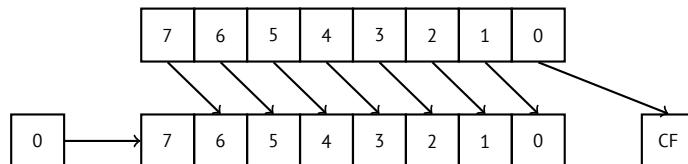
We get (MSVC 2010):

Listing 16.11: 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 16.12: Non-optimizing Keil 6/2013 (ARM mode)

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

Division by 4 in MIPS:

Listing 16.13: Optimizing GCC 4.4.5 (IDA)

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

The SRL instruction is “Shift Right Logical”.

16.3 Exercises

16.3.1 Exercise #2

What does this code do?

Listing 16.14: Optimizing MSVC 2010

```
_a$ = 8
_f PROC
    mov    ecx, DWORD PTR _a$[esp-4]
    lea    eax, DWORD PTR [ecx*8]
    sub    eax, ecx
    ret    0
_f ENDP
```

Listing 16.15: Non-optimizing Keil 6/2013 (ARM mode)

```
f PROC
    RSB    r0,r0,r0,LSL #3
    BX     lr
    ENDP
```

Listing 16.16: Non-optimizing Keil 6/2013 (Thumb mode)

```
f PROC
    LSLS   r1,r0,#3
    SUBS   r0,r1,r0
    BX     lr
    ENDP
```

Listing 16.17: Optimizing GCC 4.9 (ARM64)

```
f:
    lsl    w1, w0, 3
    sub    w0, w1, w0
    ret
```

Listing 16.18: Optimizing GCC 4.4.5 (MIPS) (IDA)

```
f:
    sll    $v0, $a0, 3
    jr    $ra
    subu   $v0, $a0
```

Answer [G.1.10 on page 979](#).

Chapter 17

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](#).

17.1 IEEE 754

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

17.2 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”.

17.3 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.

17.4 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.

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)

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* ([21.6.2 on page 384](#)) 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)

The *float* type requires the same number of bits as the *int* type in 32-bit environments, but the number representation is completely different.

17.5 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));
}
```

17.5.1 x86

MSVC

Compile it in MSVC 2010:

Listing 17.1: 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:
; 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 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)

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):

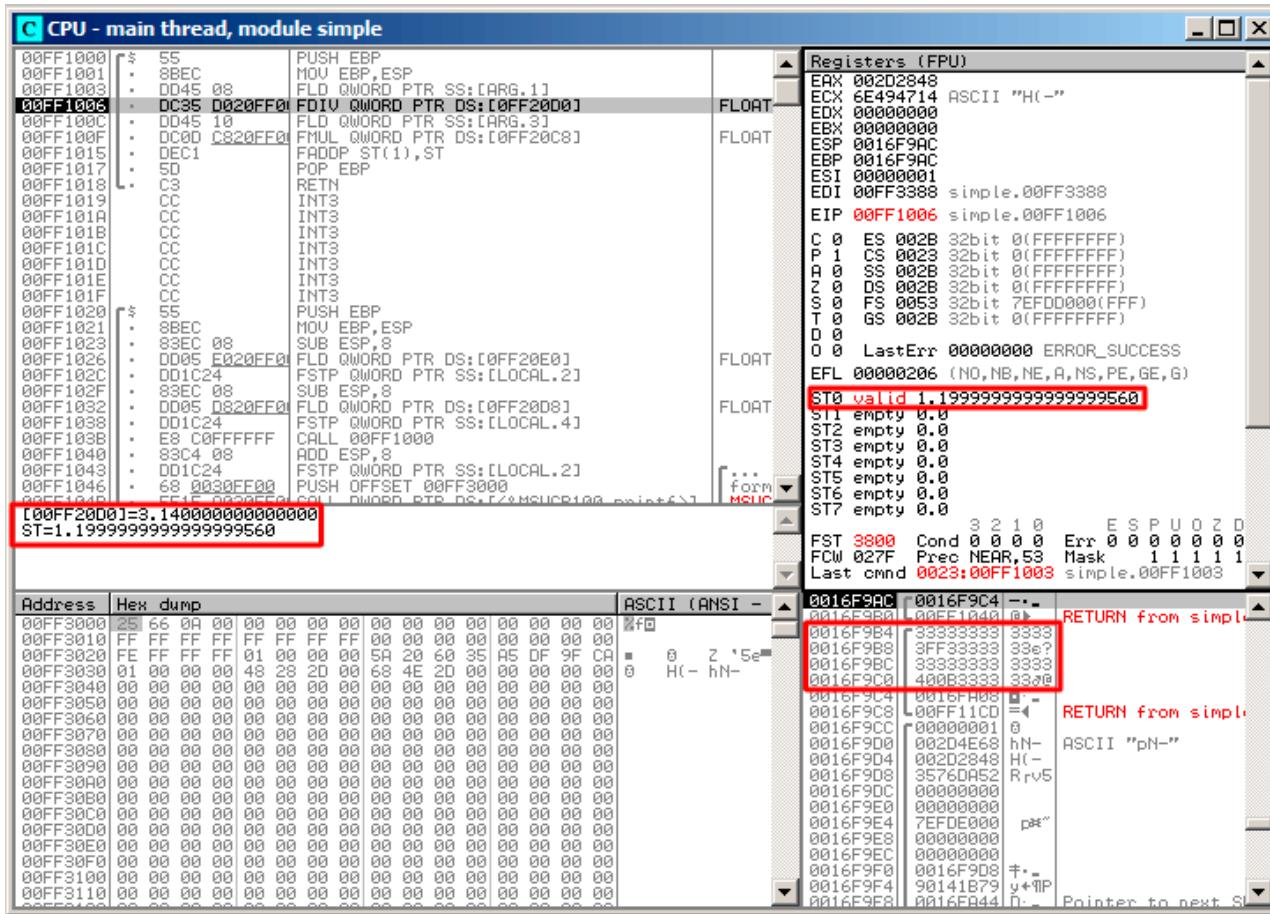


Figure 17.1: OllyDbg: first FLD executed

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

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

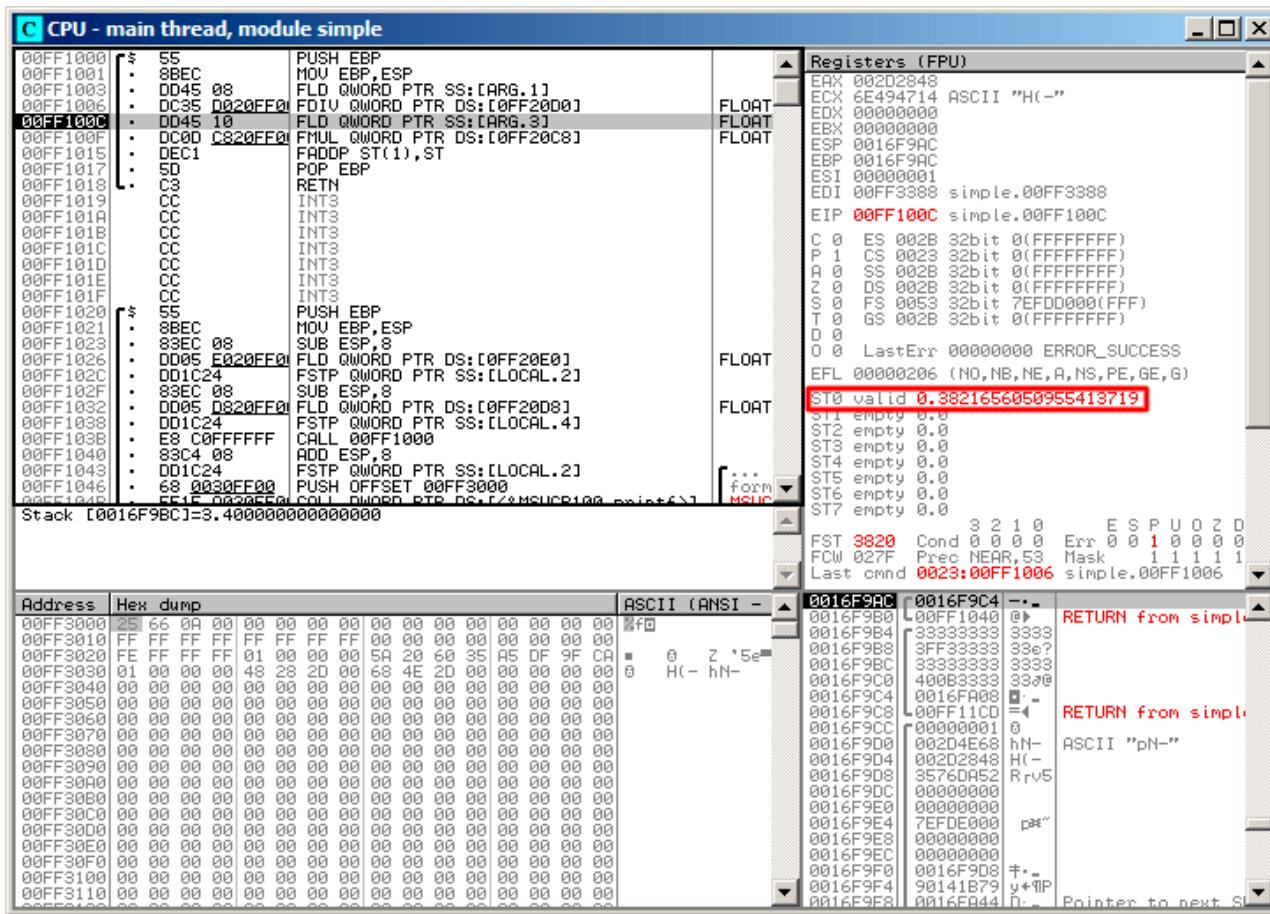


Figure 17.2: OllyDbg: FDIV executed

Third step: the next FLD was executed, loading 3.4 into ST(0) (here we see the approximate value 3.39999...):

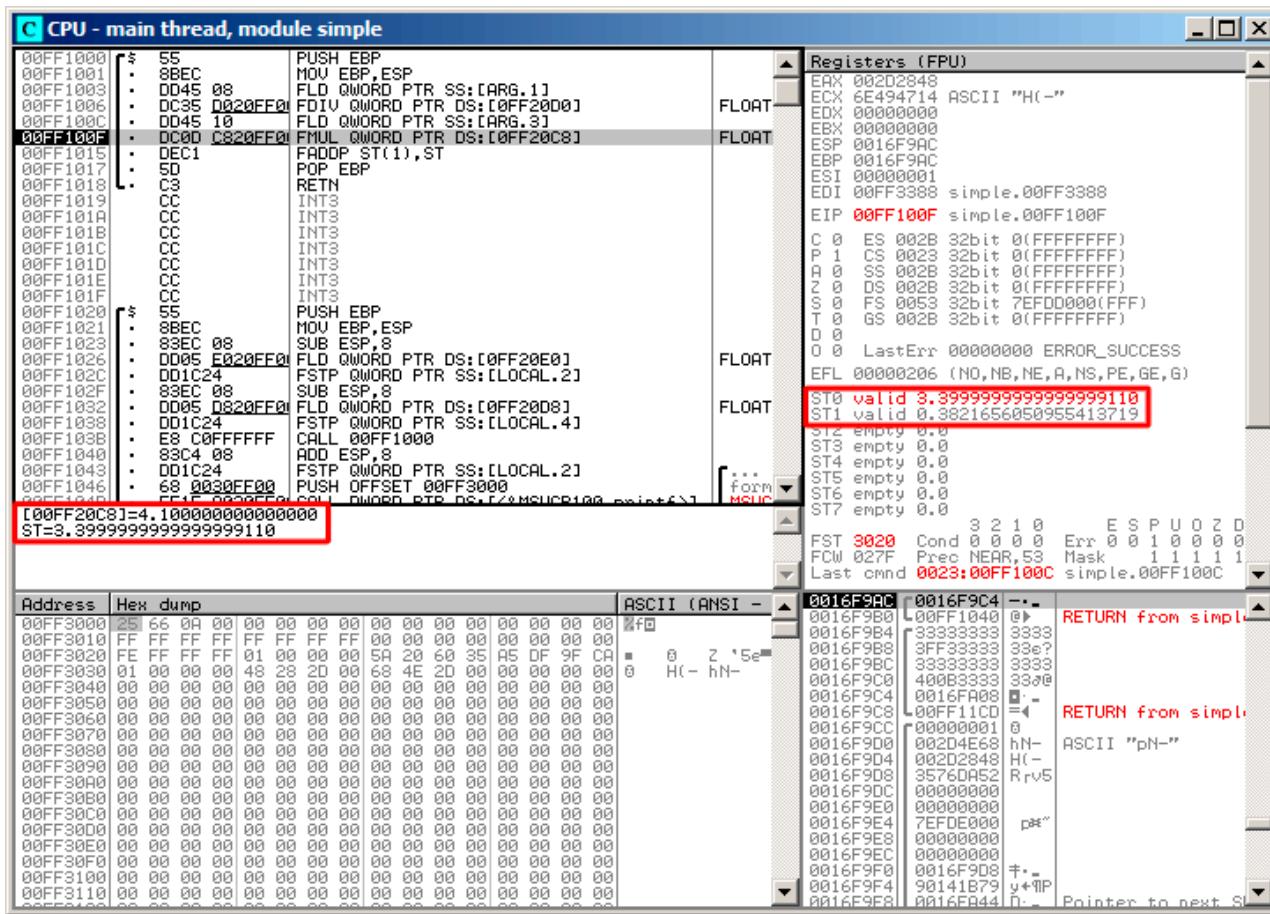


Figure 17.3: OllyDbg: second FLD executed

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.

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

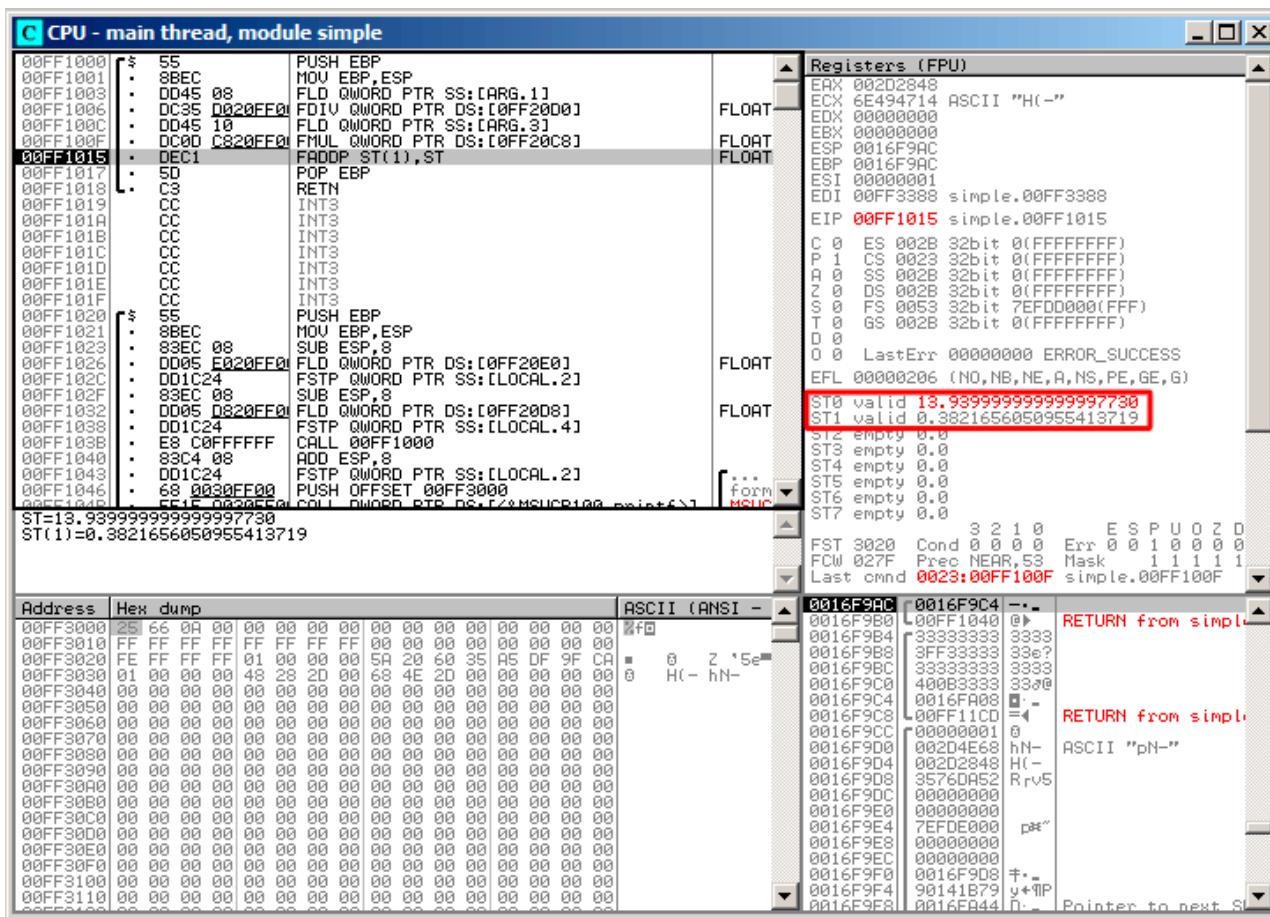


Figure 17.4: OllyDbg: FMUL executed

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

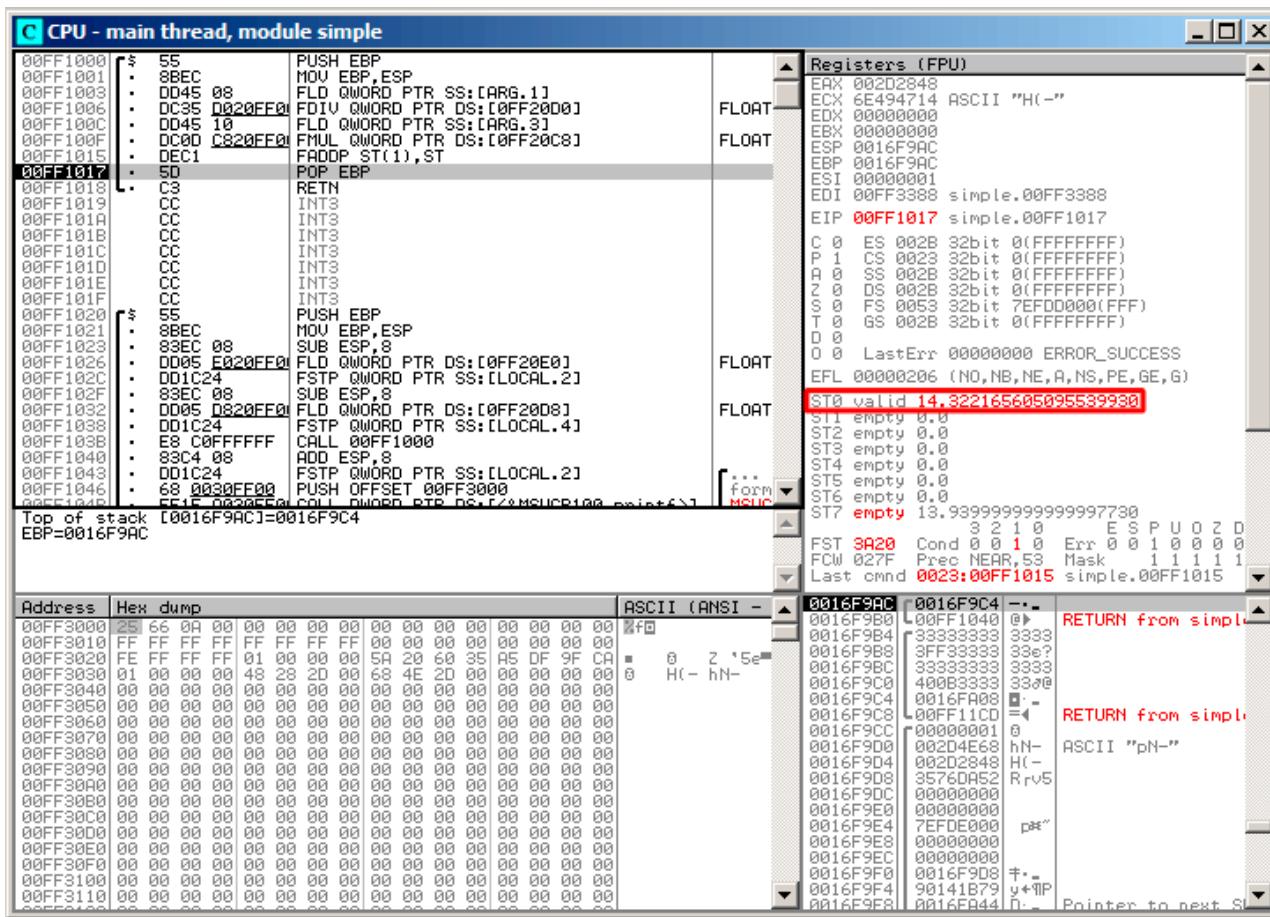


Figure 17.5: OllyDbg: FADDP executed

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: [17.2 on page 214](#). 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 17.2: Optimizing GCC 4.4.1

```

public f
proc near

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.

17.5.2 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 17.3: 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 968](#).

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.

17.5.3 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*.

17.5.4 ARM64: Optimizing GCC (Linaro) 4.9

Very compact code:

Listing 17.4: 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
```

17.5.5 ARM64: Non-optimizing GCC (Linaro) 4.9

Listing 17.5: 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 ; /
    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.

17.5.6 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 970](#). When one needs to work with 64-bit *double* values, a pair of 32-bit F-registers is used.

Listing 17.6: 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)

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 instruction have no effect. If someone knows more about it, please drop an email to author¹¹.

17.6 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;
}
```

¹¹dennis(a)yurichev.com

17.6.1 x86

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

Listing 17.7: 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: 17.6.2.

17.6.2 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}

```

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

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.

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

```

_main
    STMFD   SP!, {R4-R6,LR}
    LDR     R2, =0xA3D70A4 ; y
    LDR     R3, =0x3FF8A3D7
    LDR     R0, =0xAE147AE1 ; x
    LDR     R1, =0x40400147
    BL      pow
    MOV     R4, R0
    MOV     R2, R4
    MOV     R3, R1
    ADR     R0, a32_011_54Lf ; "32.01 ^ 1.54 = %lf\n"
    BL      __2printf
    MOV     R0, #0
    LDMFD  SP!, {R4-R6,PC}

y          DCD 0xA3D70A4      ; DATA XREF: _main+4
dword_520  DCD 0x3FF8A3D7    ; DATA XREF: _main+8
; double x
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.

17.6.4 ARM64 + Optimizing GCC (Linaro) 4.9

Listing 17.8: 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
    bl     pow
; result of pow() in D0
    adrp   x0, .LC2
    add    x0, x0, :lo12:.LC2
    bl     printf
    mov    w0, 0
    ldp    x29, x30, [sp], 16
    ret
.LC0:
; 32.01 in IEEE 754 format
    .word   -1374389535
    .word   1077936455
.LC1:
; 1.54 in IEEE 754 format
    .word   171798692
    .word   1073259479
.LC2:
    .string "32.01 ^ 1.54 = %lf\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.

17.6.5 MIPS

Listing 17.9: 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"
    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:                  # main+18
; 1.54:
.rodata.cst8:000000A0 $LC1:           .word 0x3FF8A3D7      # DATA XREF: main+24
.rodata.cst8:000000A0:                  # main+30
.rodata.cst8:000000A4 dword_A4:        .word 0xA3D70A4      # DATA XREF: main+14
```

And again, we see here LUI loading a 32-bit part of a *double* number into \$V0. And again, it's hard to comprehend why.

The new instruction for us here is MFC1 ("Move From Coprocessor 1"). The FPU is coprocessor number 1, hence "1" in the instruction name. This instruction transfers values from the coprocessor's registers to the registers of the CPU ([GPR](#)). So 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.

17.7 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.

17.7.1 x86

Non-optimizing MSVC

MSVC 2010 generates the following:

Listing 17.10: 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]

; 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.

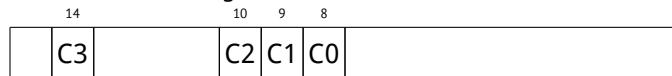
Unfortunately, CPUs before Intel P6¹³ don't have any conditional jumps instructions which check the C3/C2/C0 bits. Probably, it is a matter of history (remember: FPU was separate chip in past).

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, 5`¹⁴, 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:

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.

¹³Intel P6 is Pentium Pro, Pentium II, etc

¹⁴5=101b

¹⁵[wikipedia.org/wiki/Parity_flag](https://en.wikipedia.org/wiki/Parity_flag)

First OllyDbg example: $a=1.2$ and $b=3.4$

Let's load the example into OllyDbg:

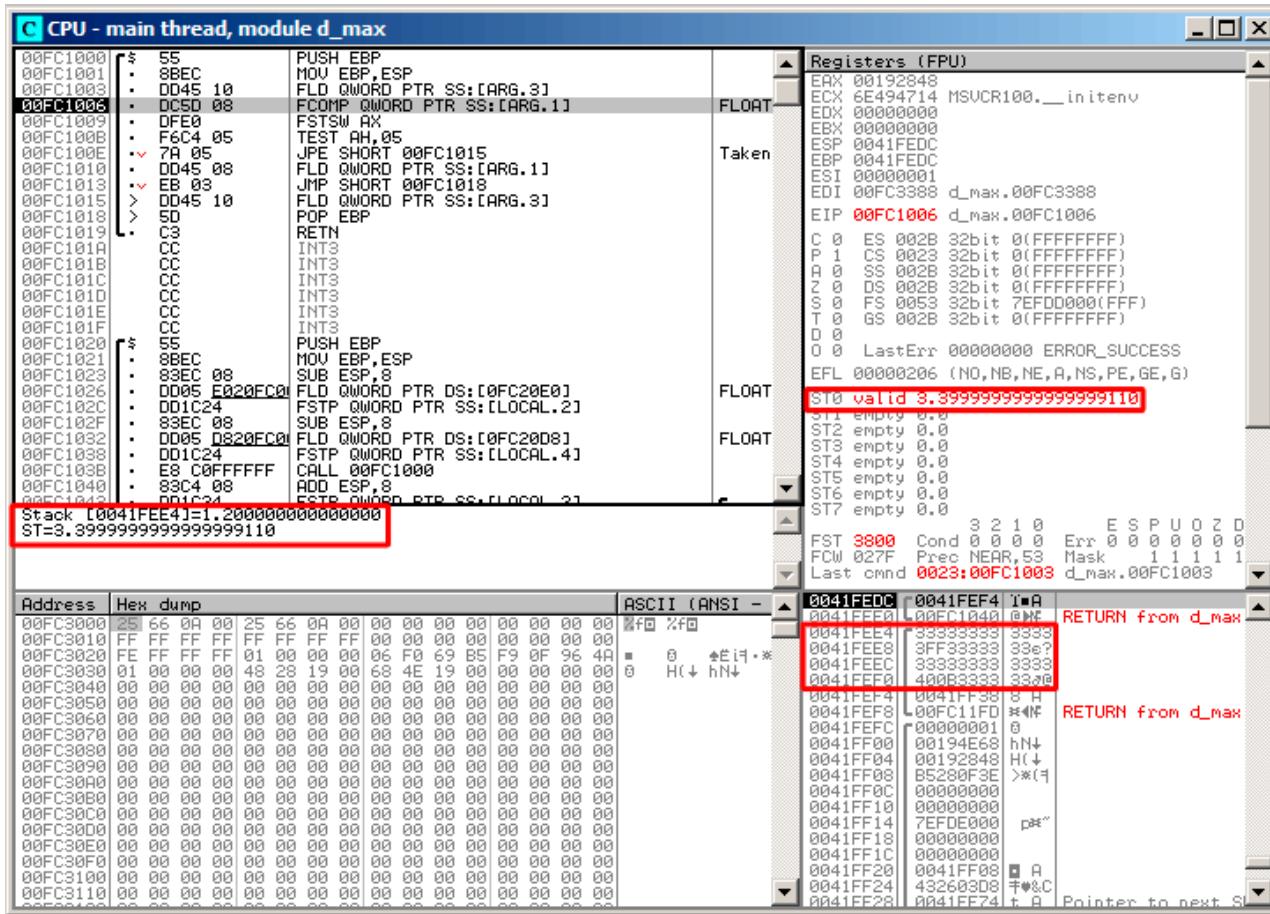


Figure 17.6: OllyDbg: first FLD is executed

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 FCMP is being executed. OllyDbg shows the second FCMP argument, which is in stack right now.

FCOMP is executed:

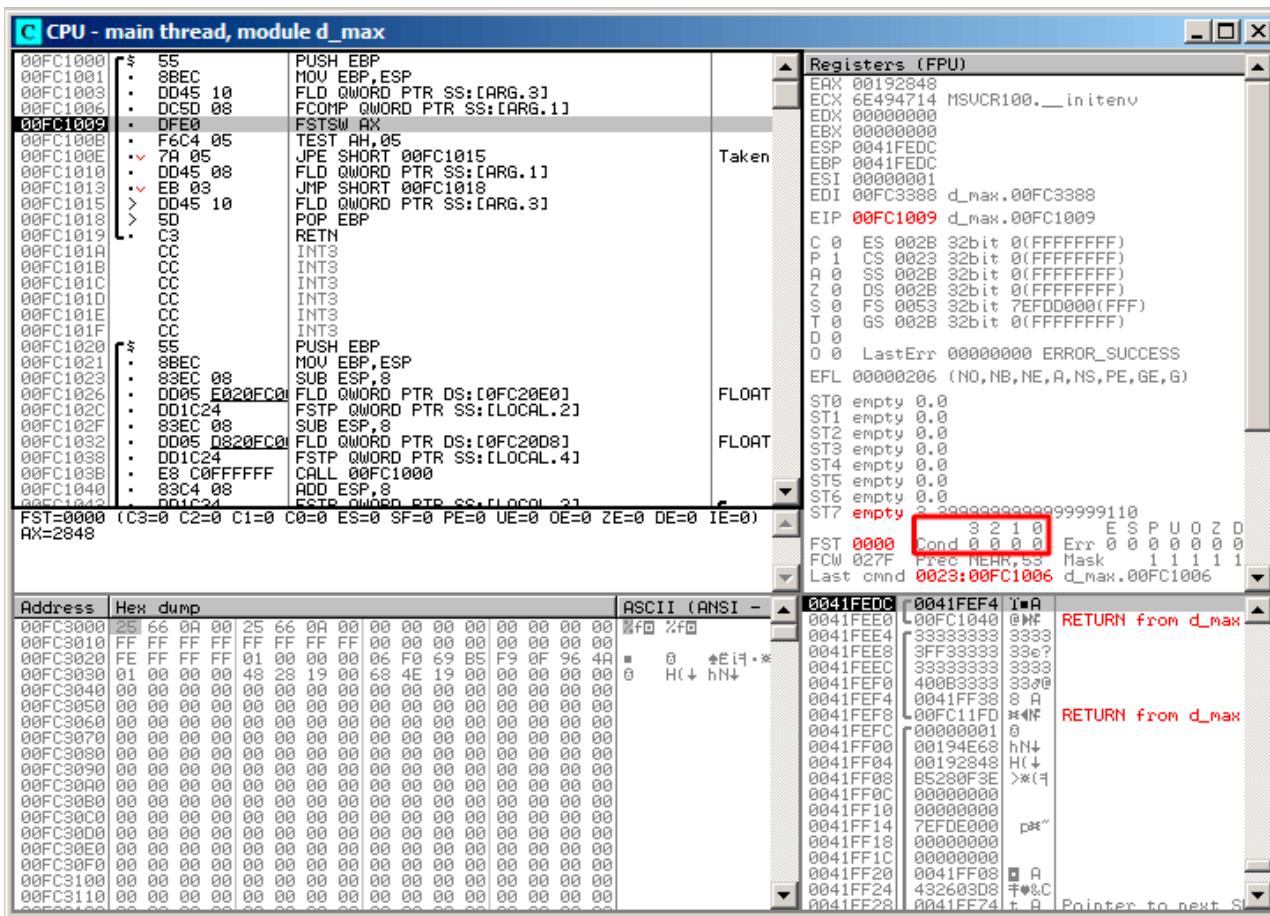


Figure 17.7: OllyDbg: FCOMP is executed

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: [17.5.1 on page 221](#).

FNSTSW is executed:

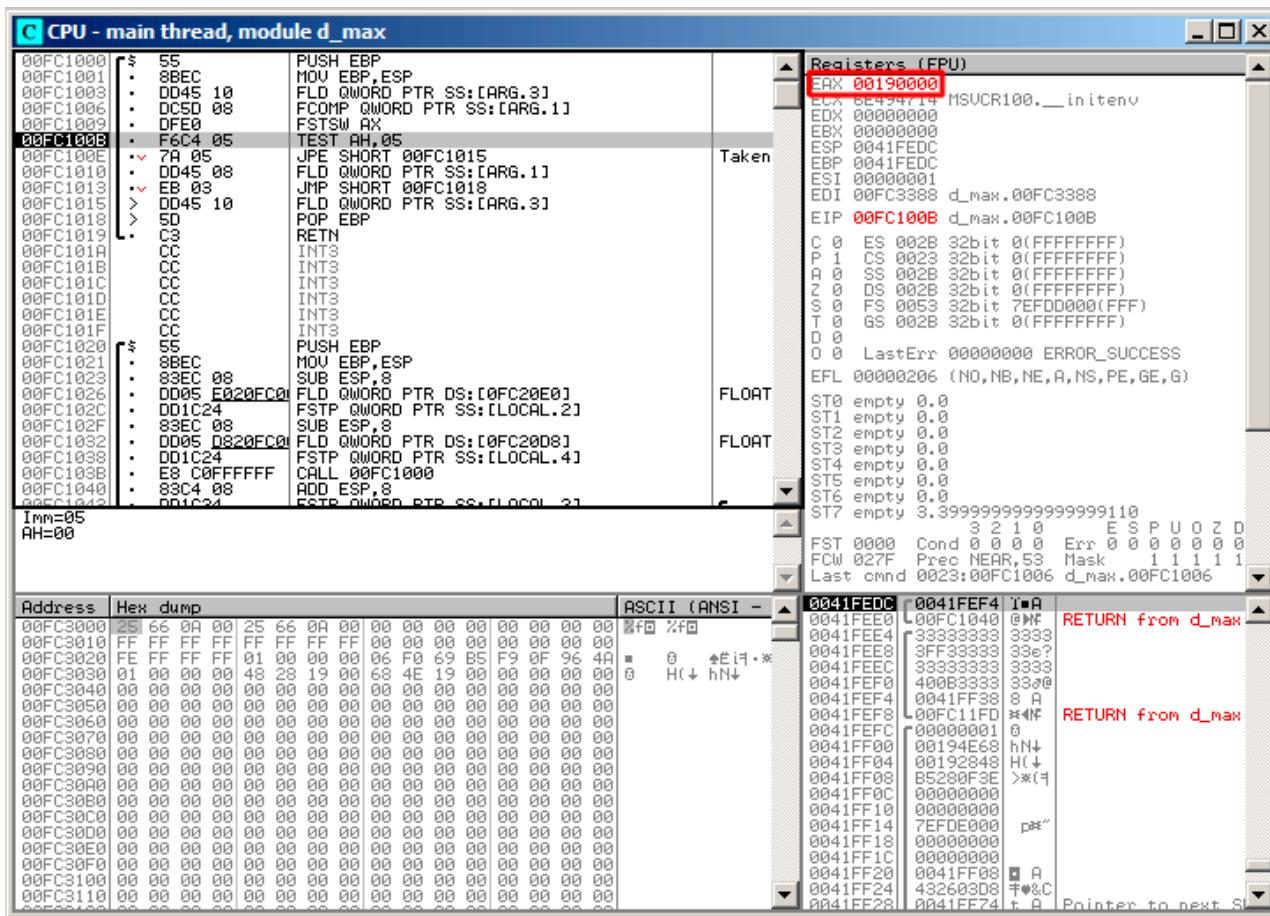


Figure 17.8: OllyDbg: FNSTSW is executed

We see that the AX register contain zeroes: indeed, all condition flags are zero. (OllyDbg disassembles the FNSTSW instruction as FSTSW—they are synonyms).

TEST is executed:

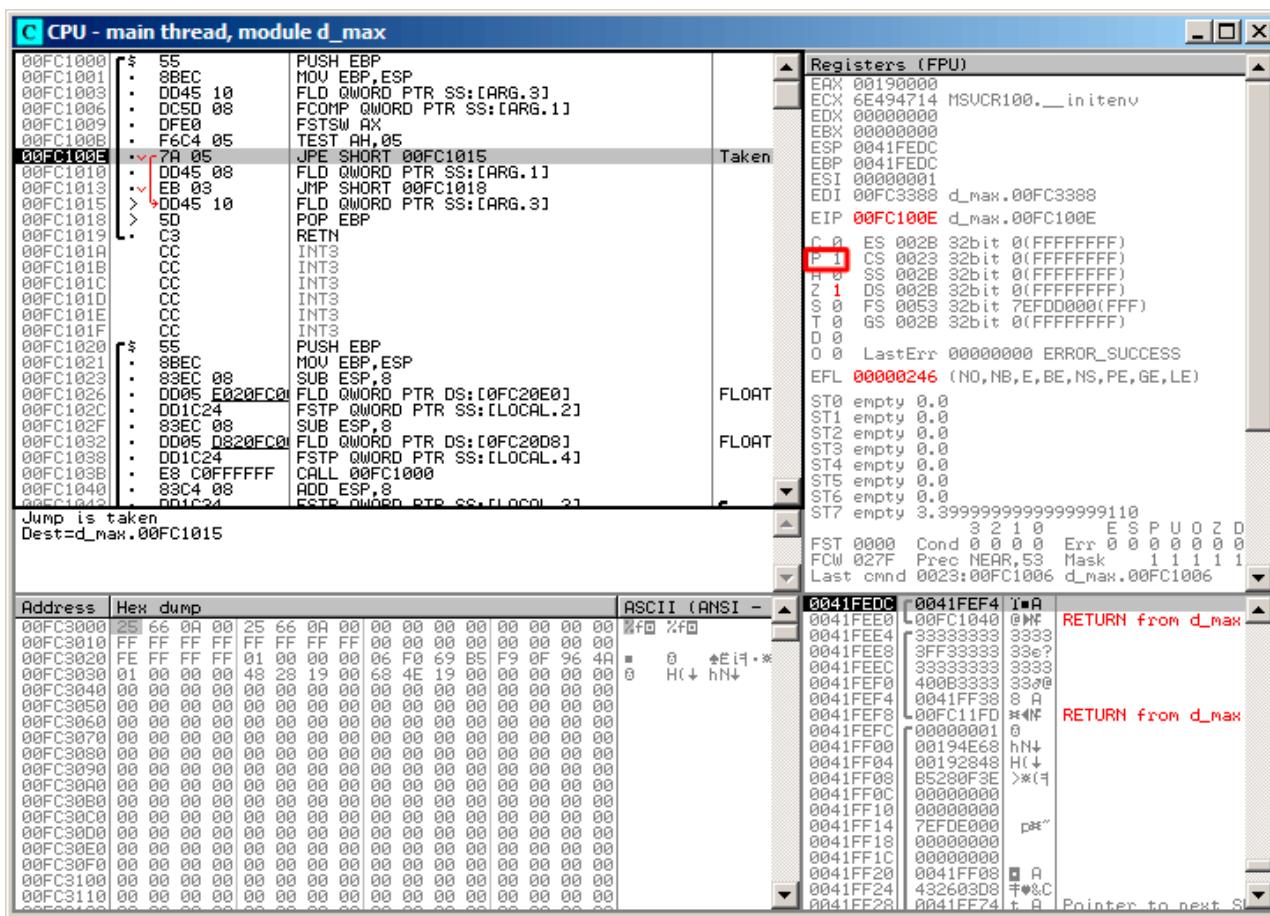


Figure 17.9: OllyDbg: TEST is executed

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)

JPE triggered, FLD loads the value of b (3.4) in ST(0):

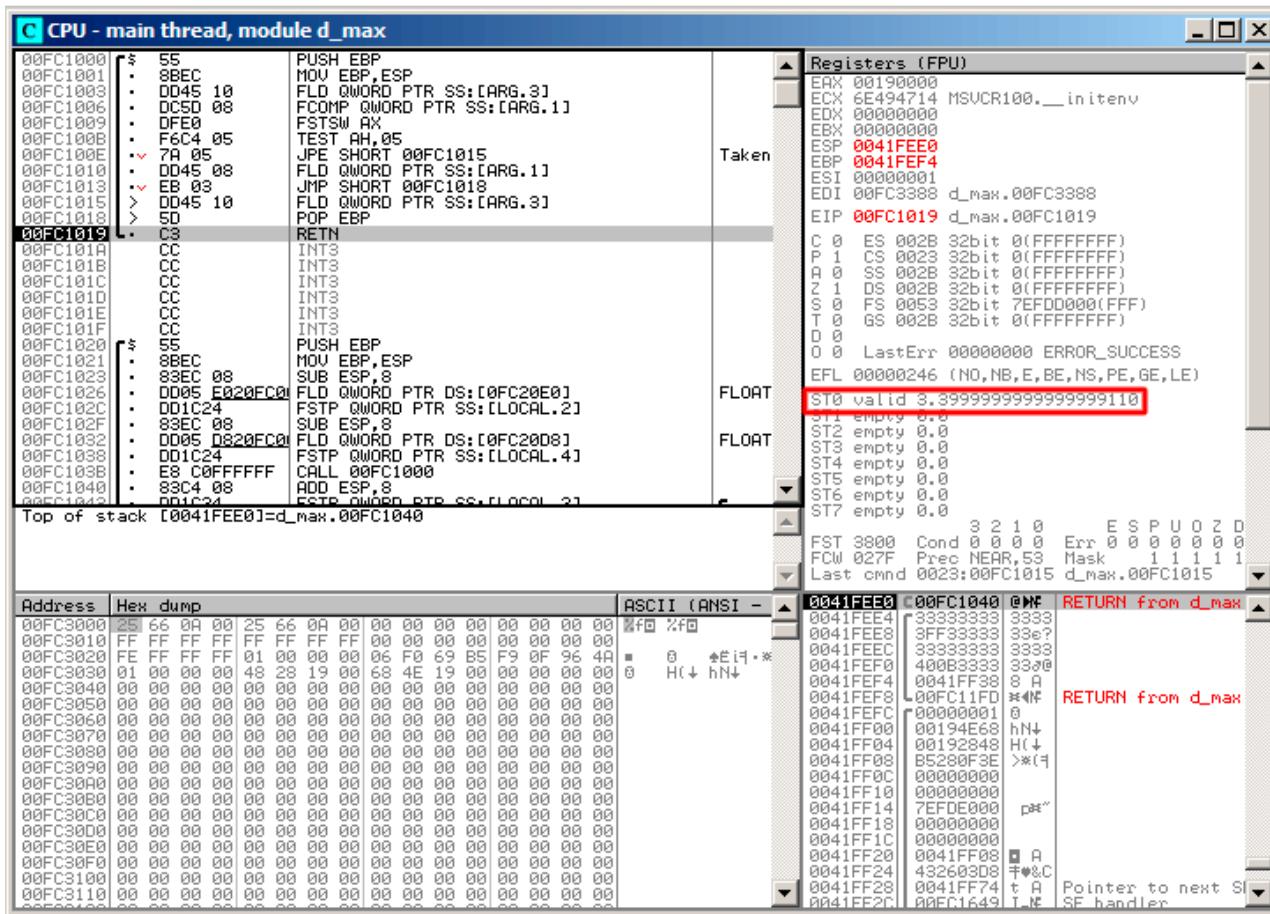


Figure 17.10: OllyDbg: second FLD is executed

The function finishes its work.

Second OllyDbg example: a=5.6 and b=-4

Let's load example into OllyDbg:

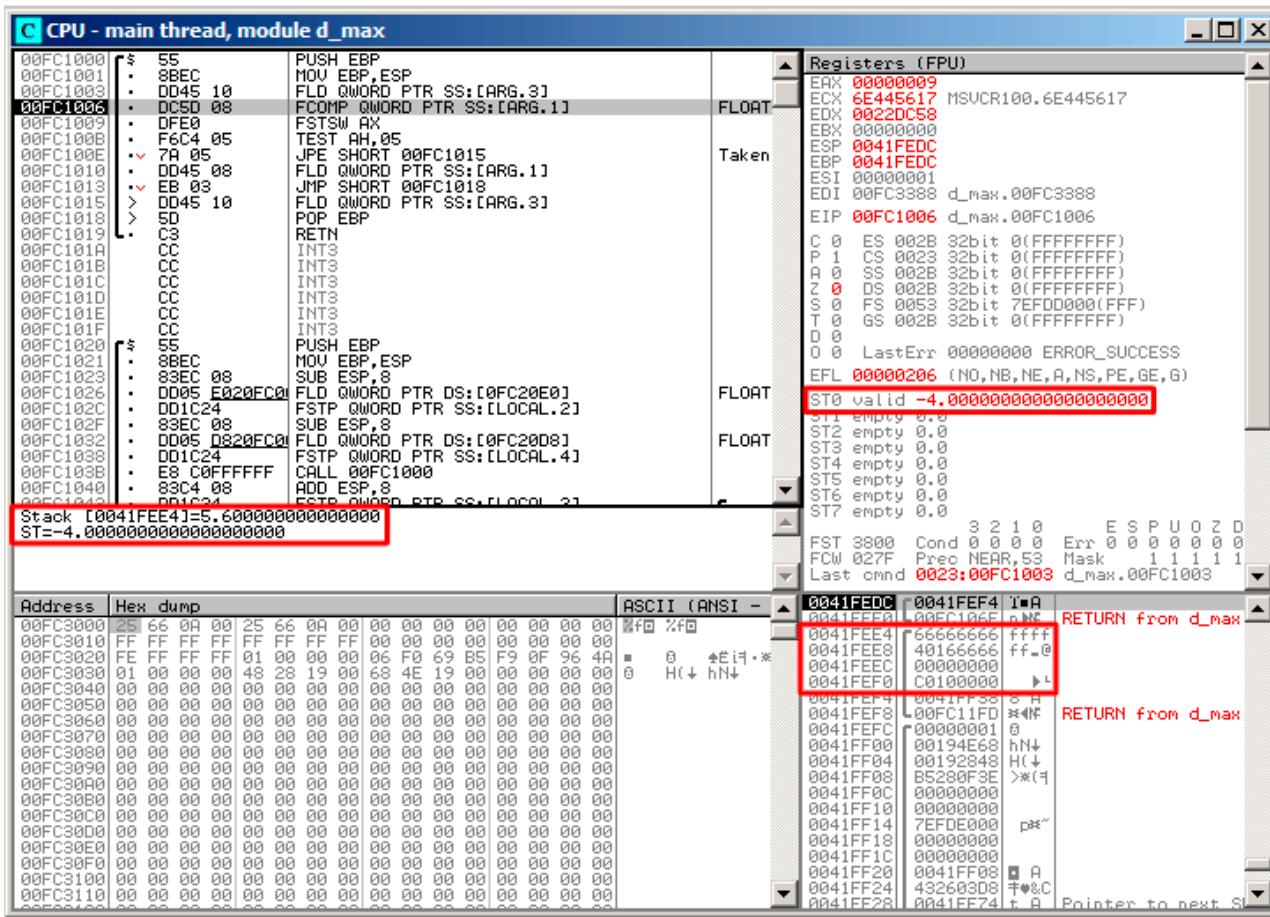


Figure 17.11: OllyDbg: first FLD executed

Current function arguments: $a = 5.6$ and $b = -4$. $b (-4)$ is already loaded in ST(0). FCMP about to execute now. OllyDbg shows the second FCMP argument, which is in stack right now.

FCOMP executed:

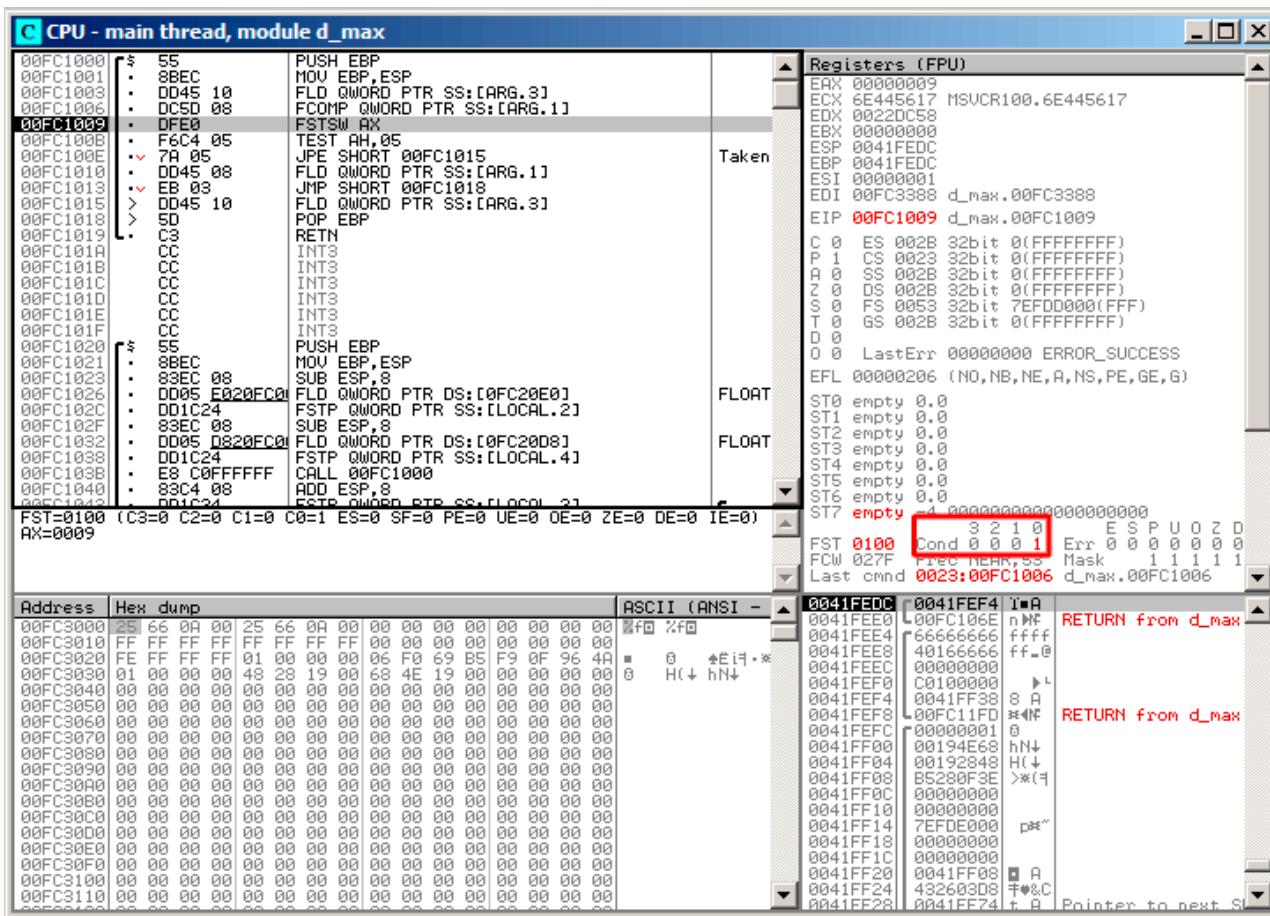


Figure 17.12: OllyDbg: FCOMP executed

We see the state of the FPU's condition flags: all zeroes except C0.

FNSTSW executed:

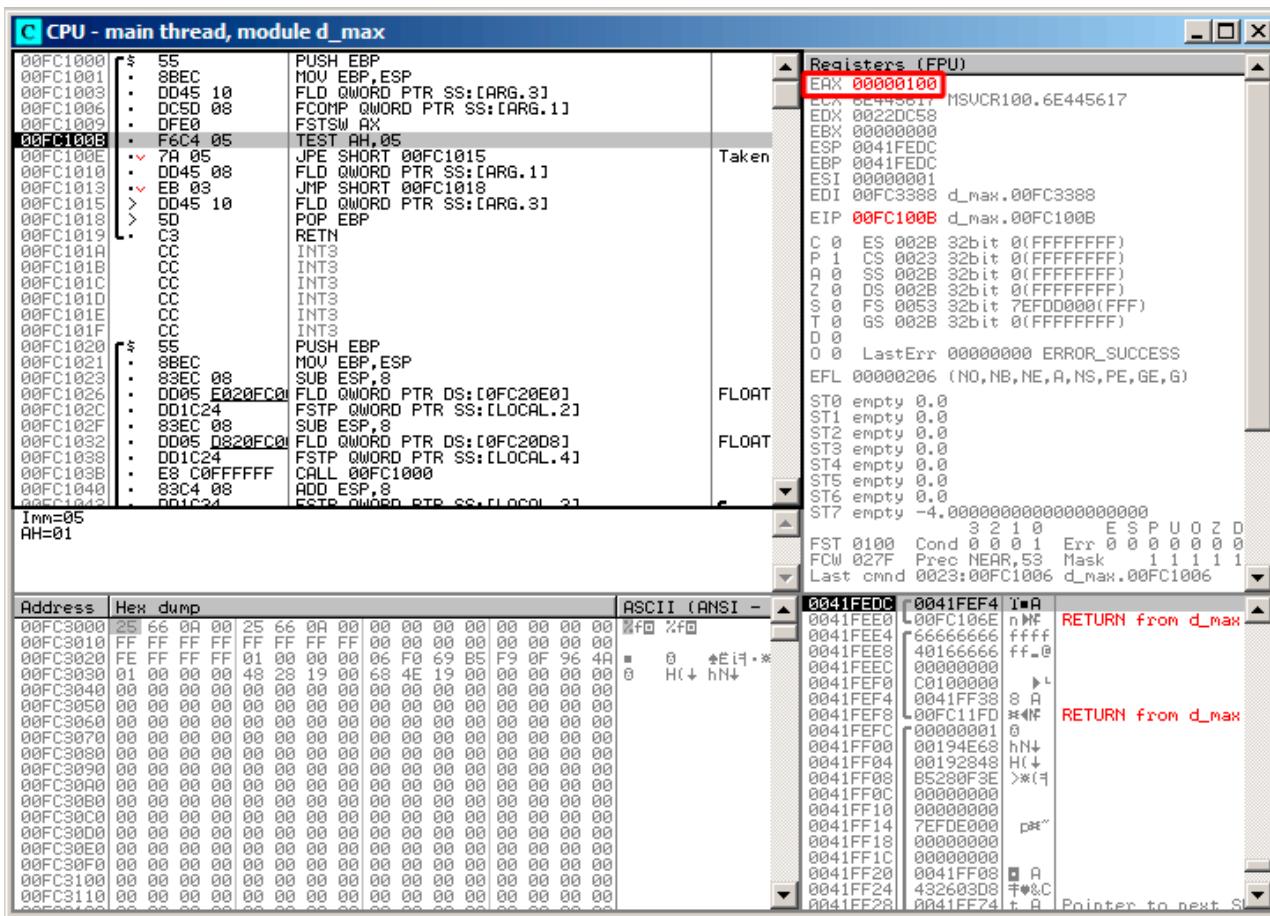


Figure 17.13: OllyDbg: FNSTSW executed

We see that the AX register contains 0x100: the C0 flag is at the 16th bit.

TEST executed:

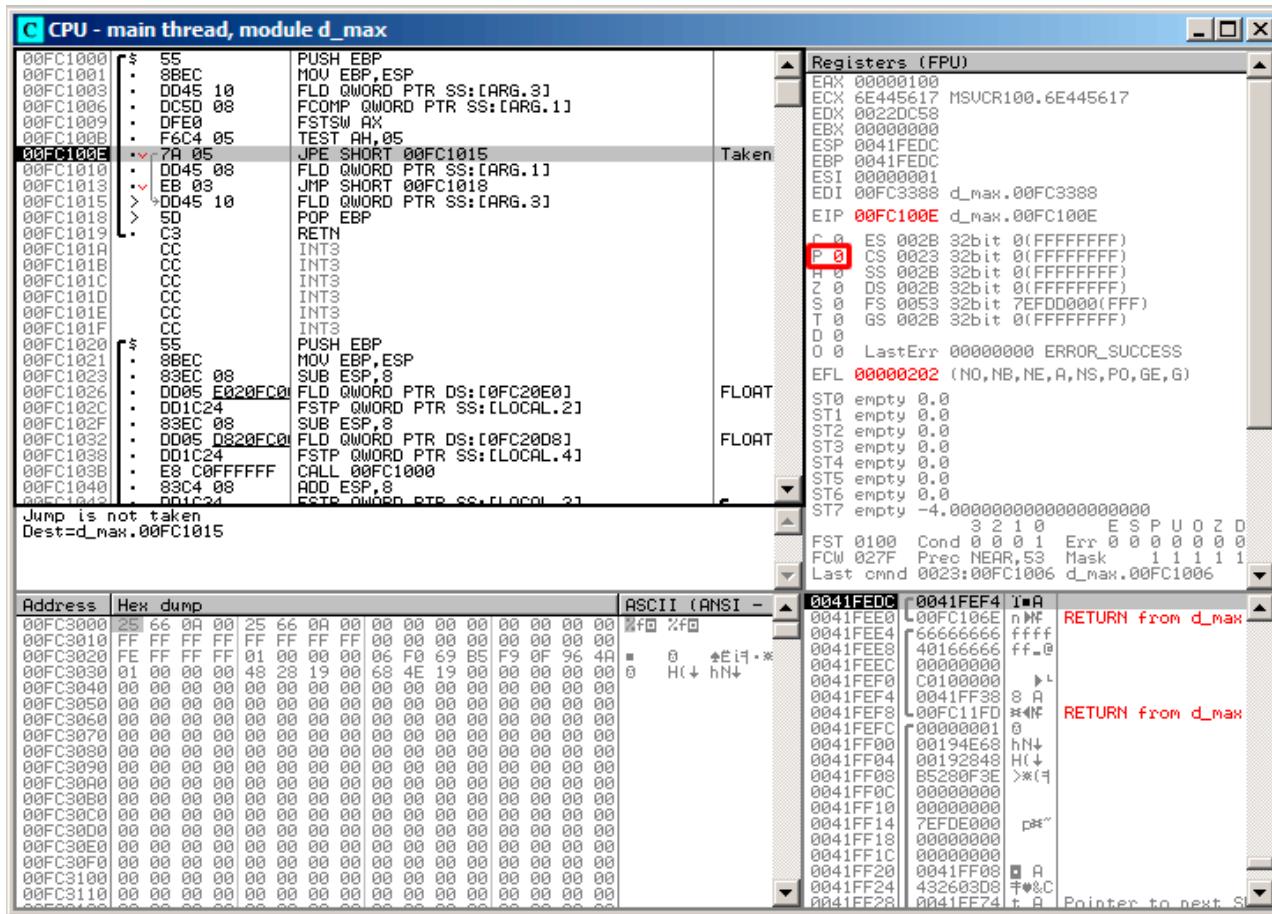


Figure 17.14: OllyDbg: TEST executed

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.

JPE wasn't triggered, so FLD loads the value of a (5.6) in ST(0):

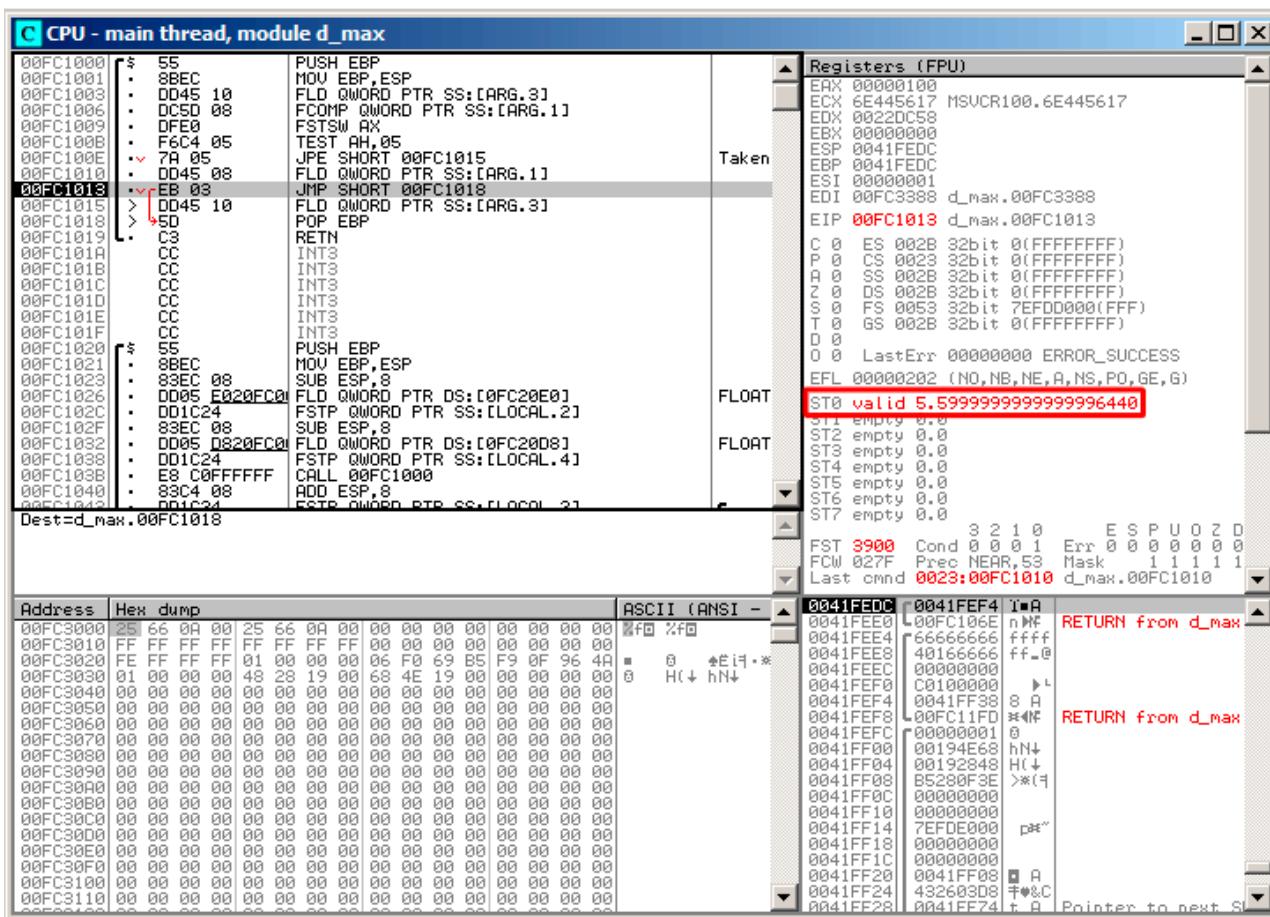


Figure 17.15: OllyDbg: second FLD executed

The function finishes its work.

Optimizing MSVC 2010

Listing 17.11: 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

```

```

    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.

First OllyDbg example: a=1.2 and b=3.4

Both FLD are executed:

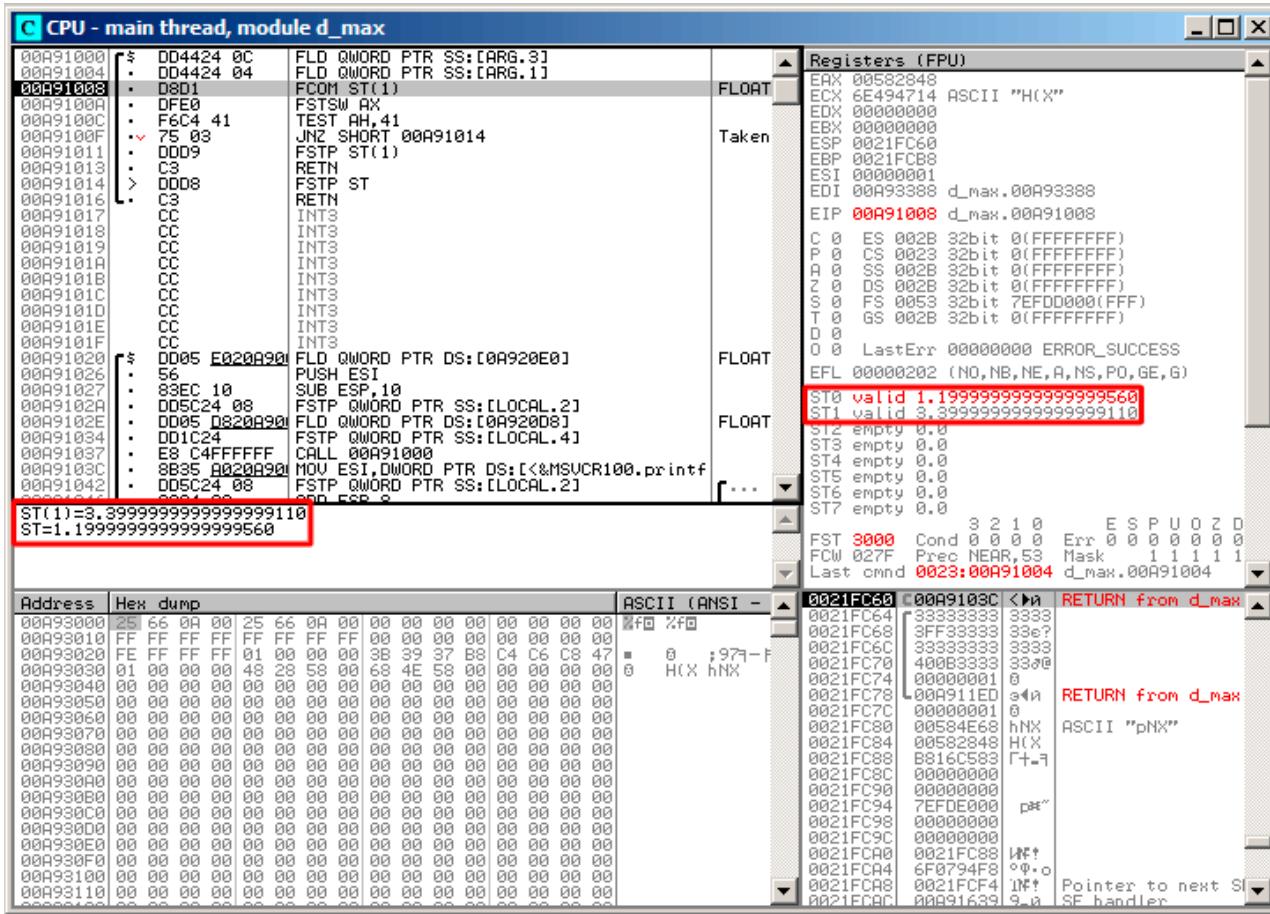


Figure 17.16: OllyDbg: both FLD are executed

FCOM being executed: OllyDbg shows the contents of ST(0) and ST(1) for convenience.

FCOM is done:

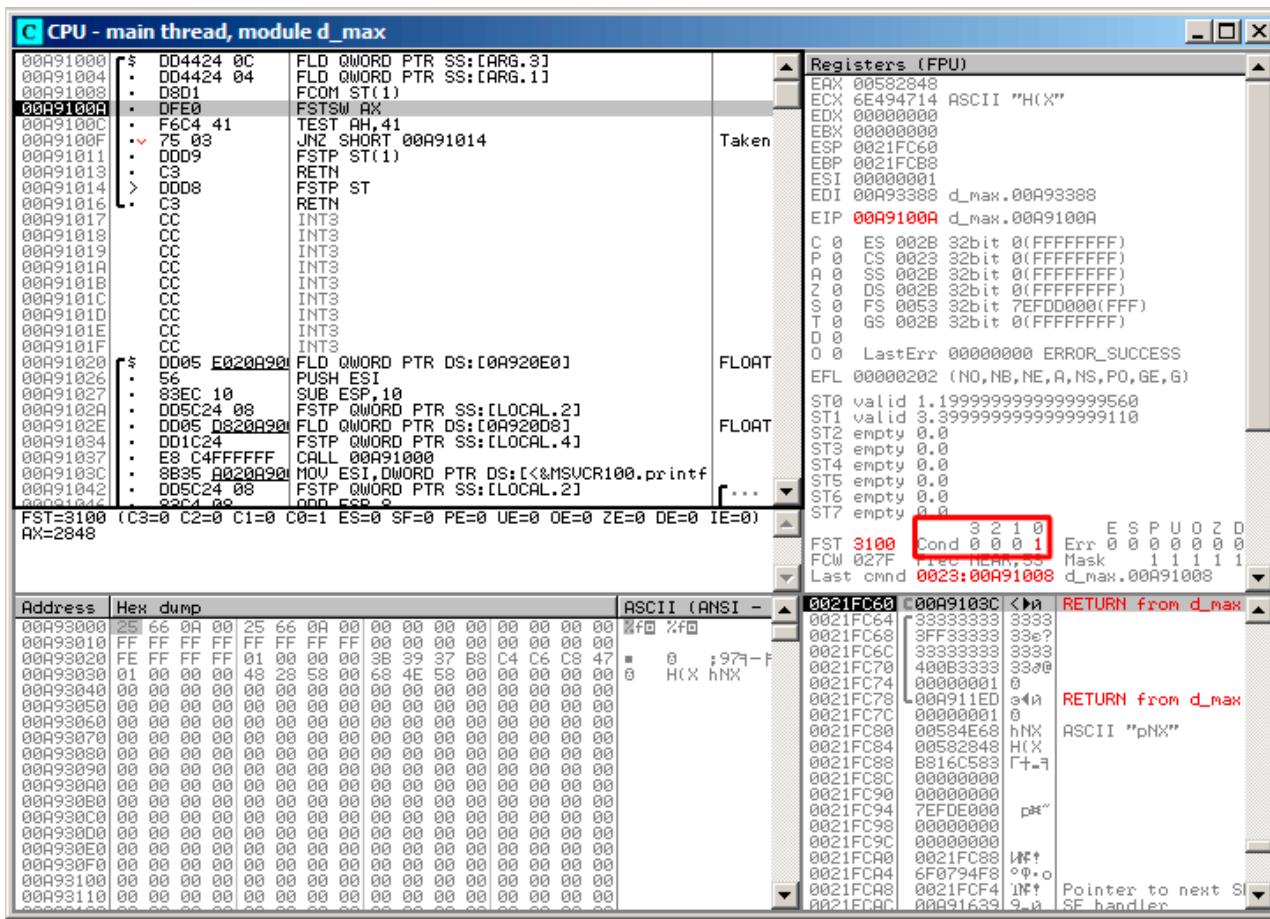


Figure 17.17: OllyDbg: FCOM is done

C0 is set, all other condition flags are cleared.

FNSTSW is done, AX=0x3100:

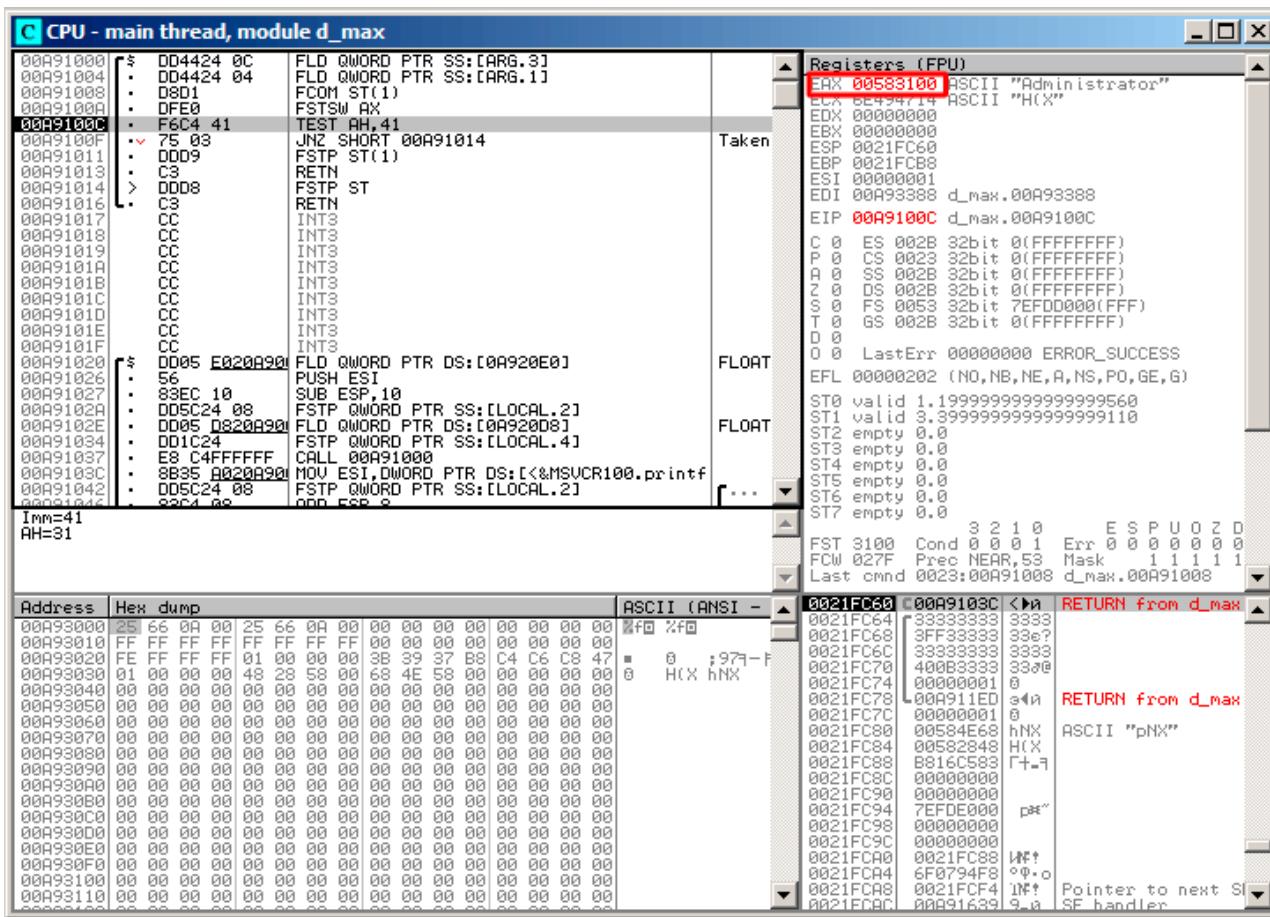


Figure 17.18: OllyDbg: FNSTSW is executed

TEST is executed:

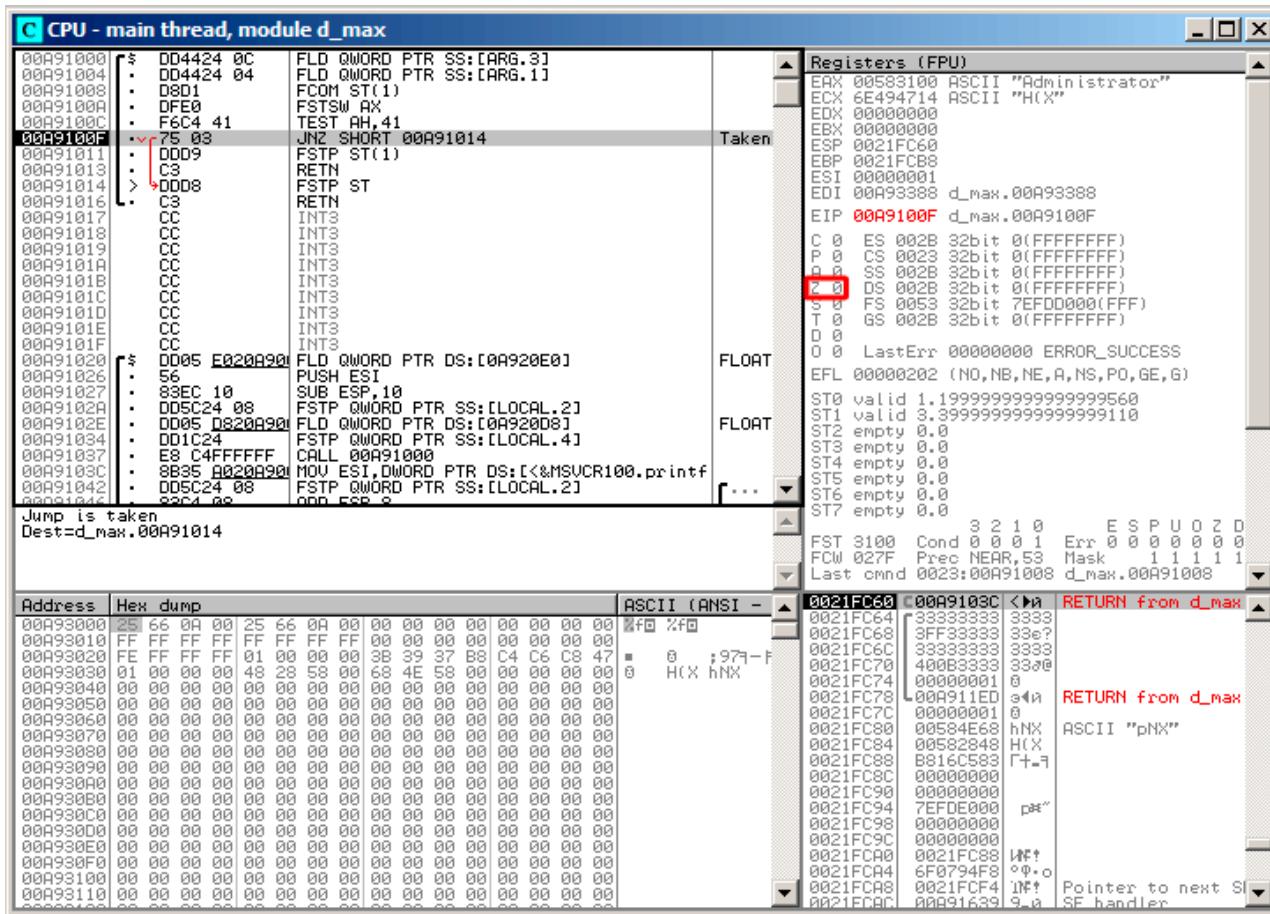


Figure 17.19: OllyDbg: TEST is executed

ZF=0, conditional jump is about to trigger now.

FSTP ST (or FSTP ST(0)) was executed –1.2 was popped from the stack, and 3.4 was left on top:

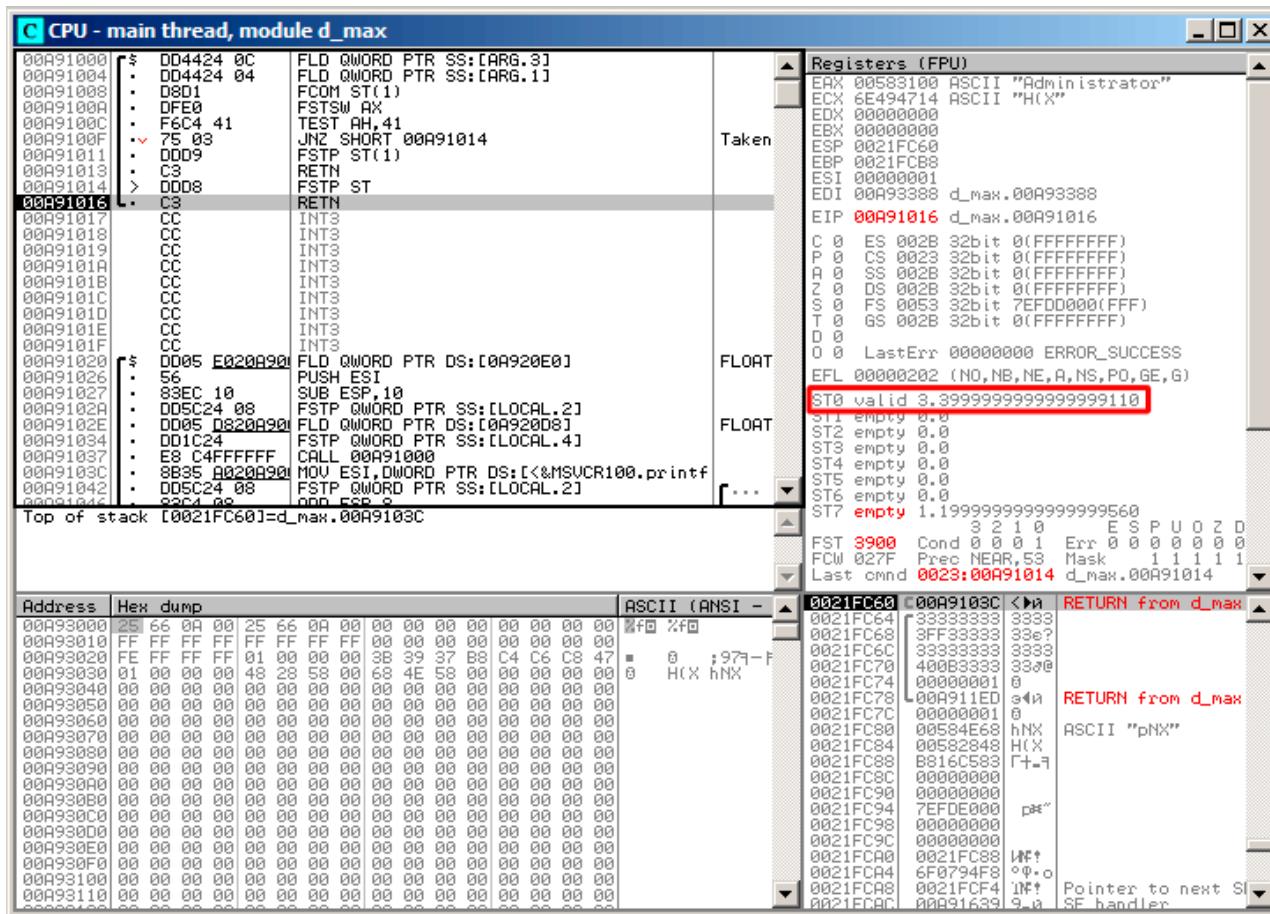


Figure 17.20: OllyDbg: FSTP is executed

We see that the FSTP ST instruction works just like popping one value from the FPU stack.

Second OllyDbg example: a=5.6 and b=-4

Both FLD are executed:

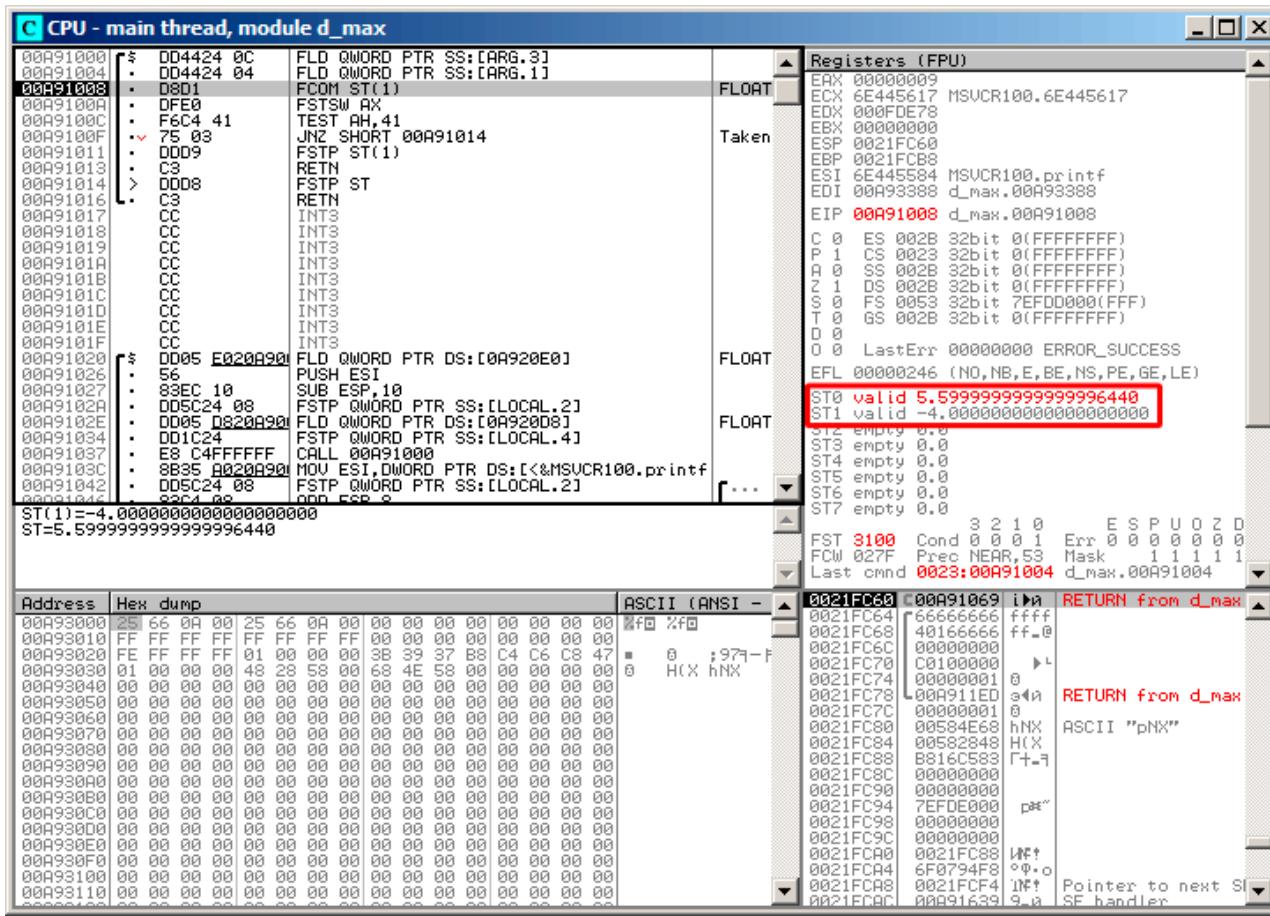


Figure 17.21: OllyDbg: both FLD are executed

FCOM is about to execute.

FCOM is done:

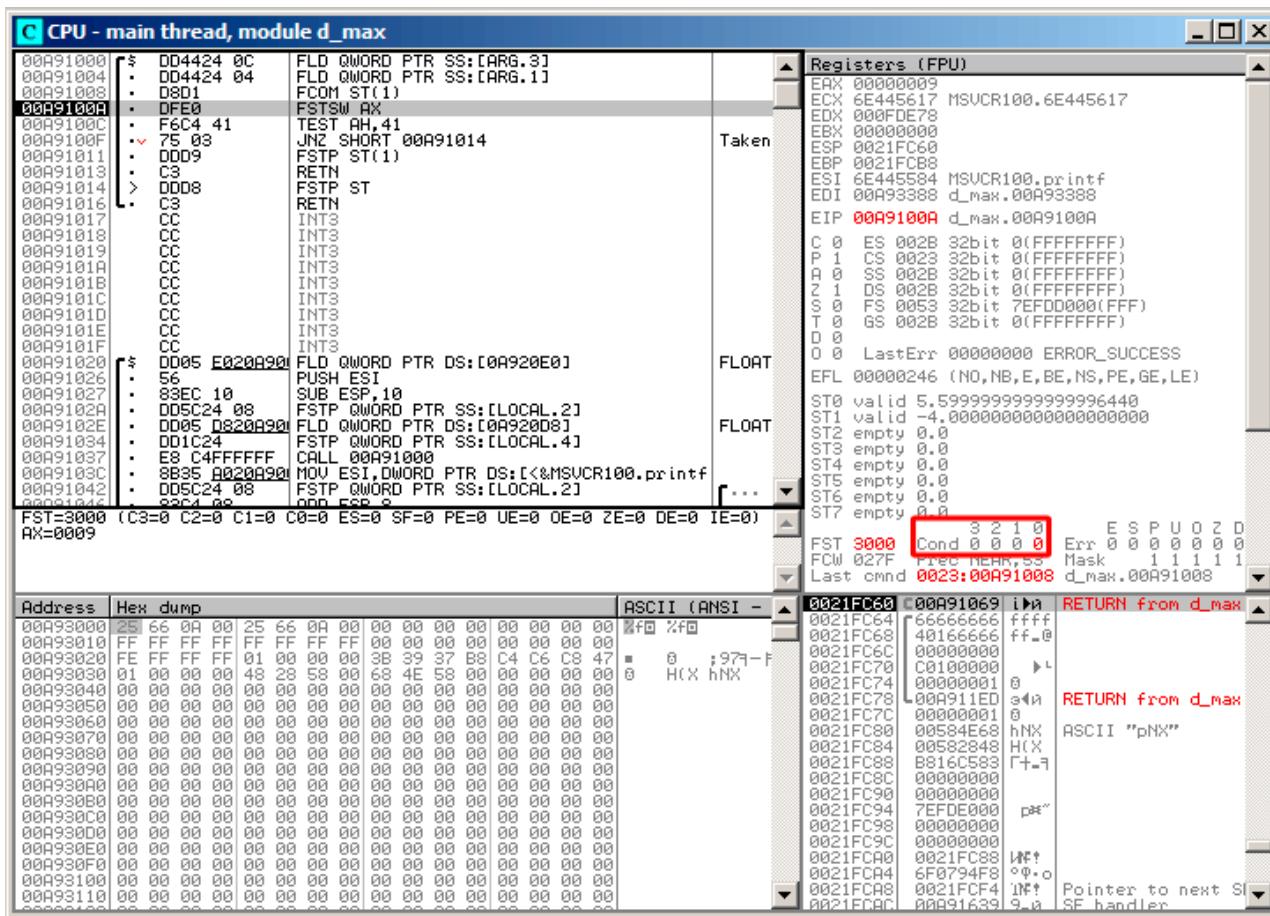


Figure 17.22: OllyDbg: FCOM is finished

All conditional flags are cleared.

FNSTSW done, AX=0x3000:

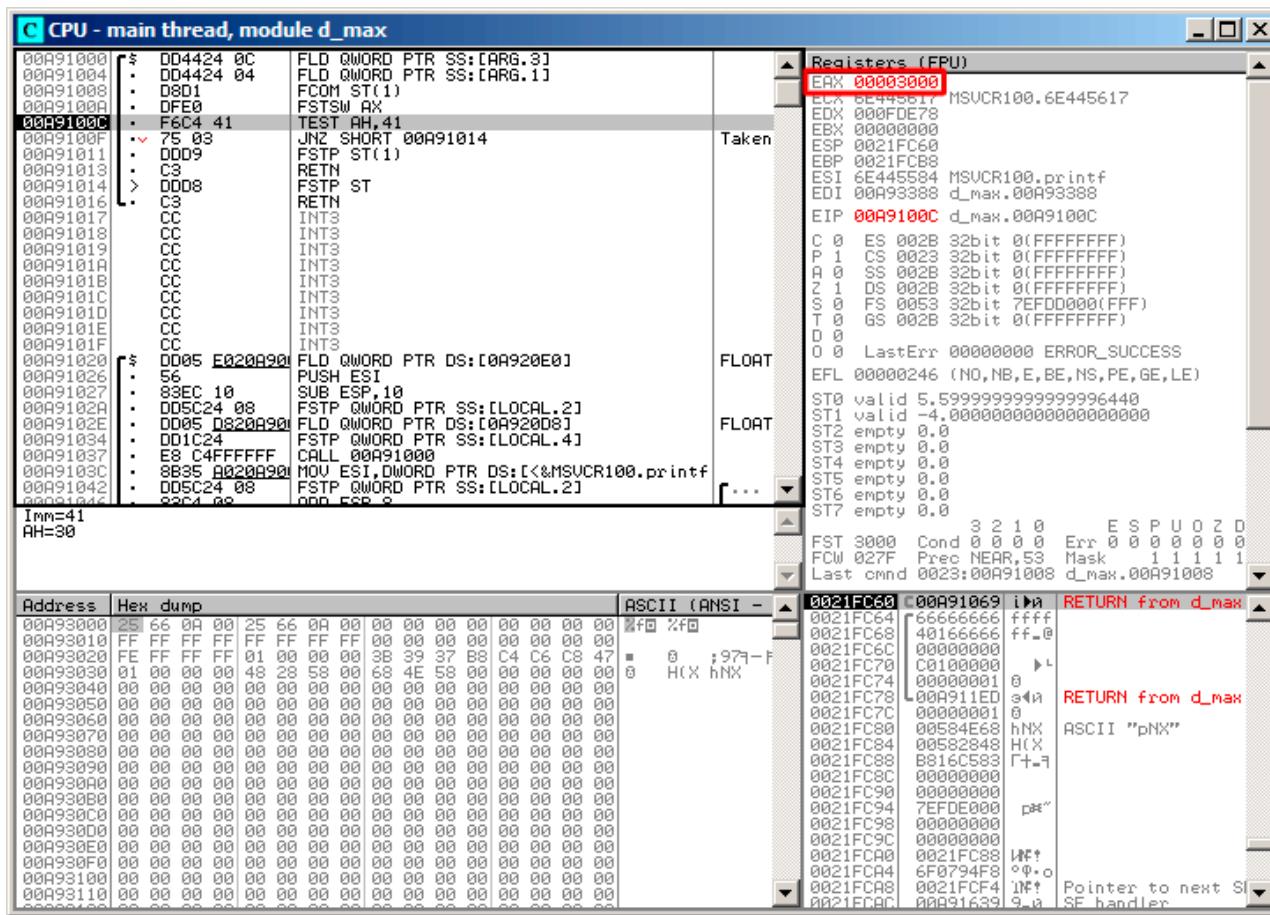


Figure 17.23: OllyDbg: FNSTSW was executed

TEST is done:

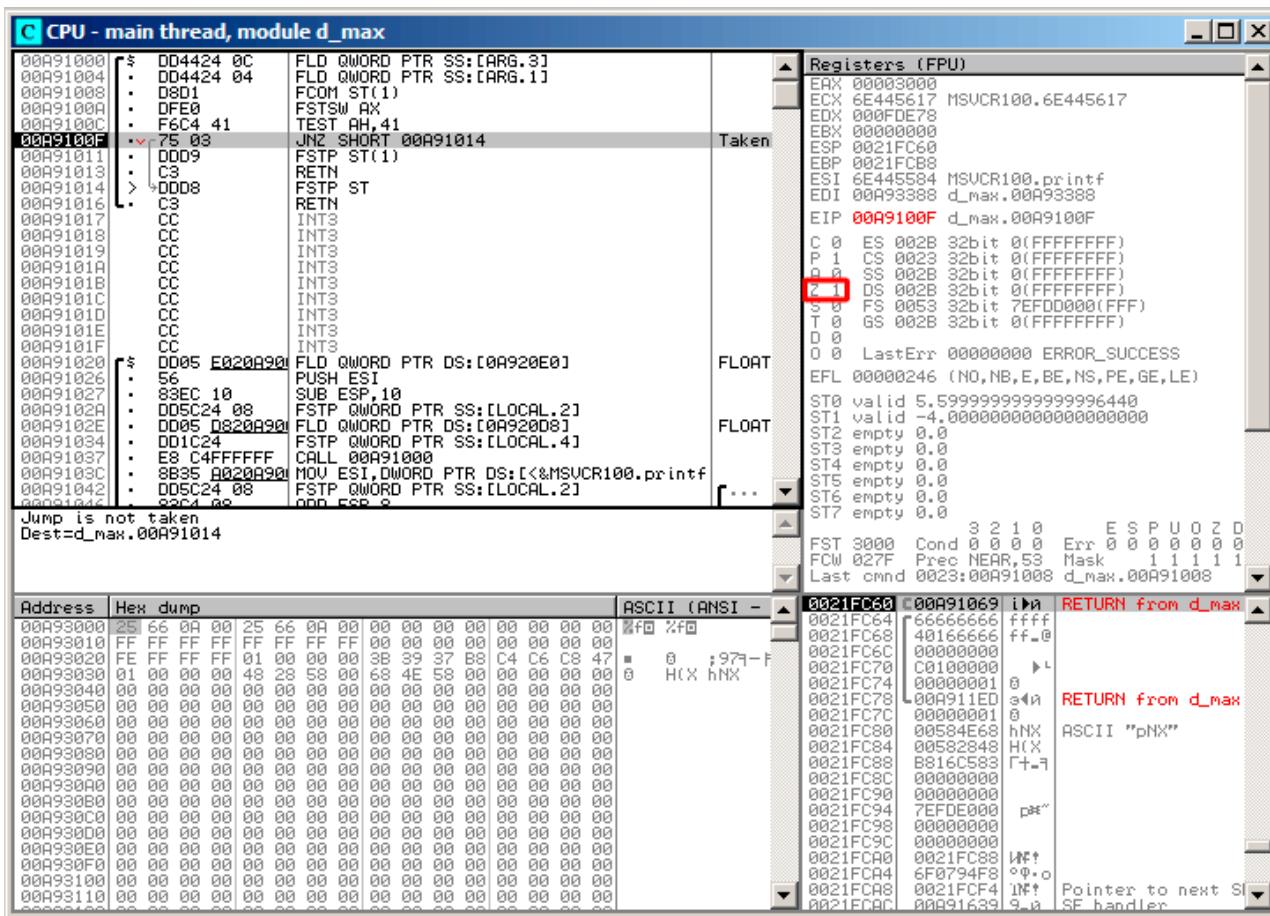


Figure 17.24: OllyDbg: TEST was executed

ZF=1, jump will not happen now.

FSTP ST(1) was executed: a value of 5.6 is now at the top of the FPU stack.

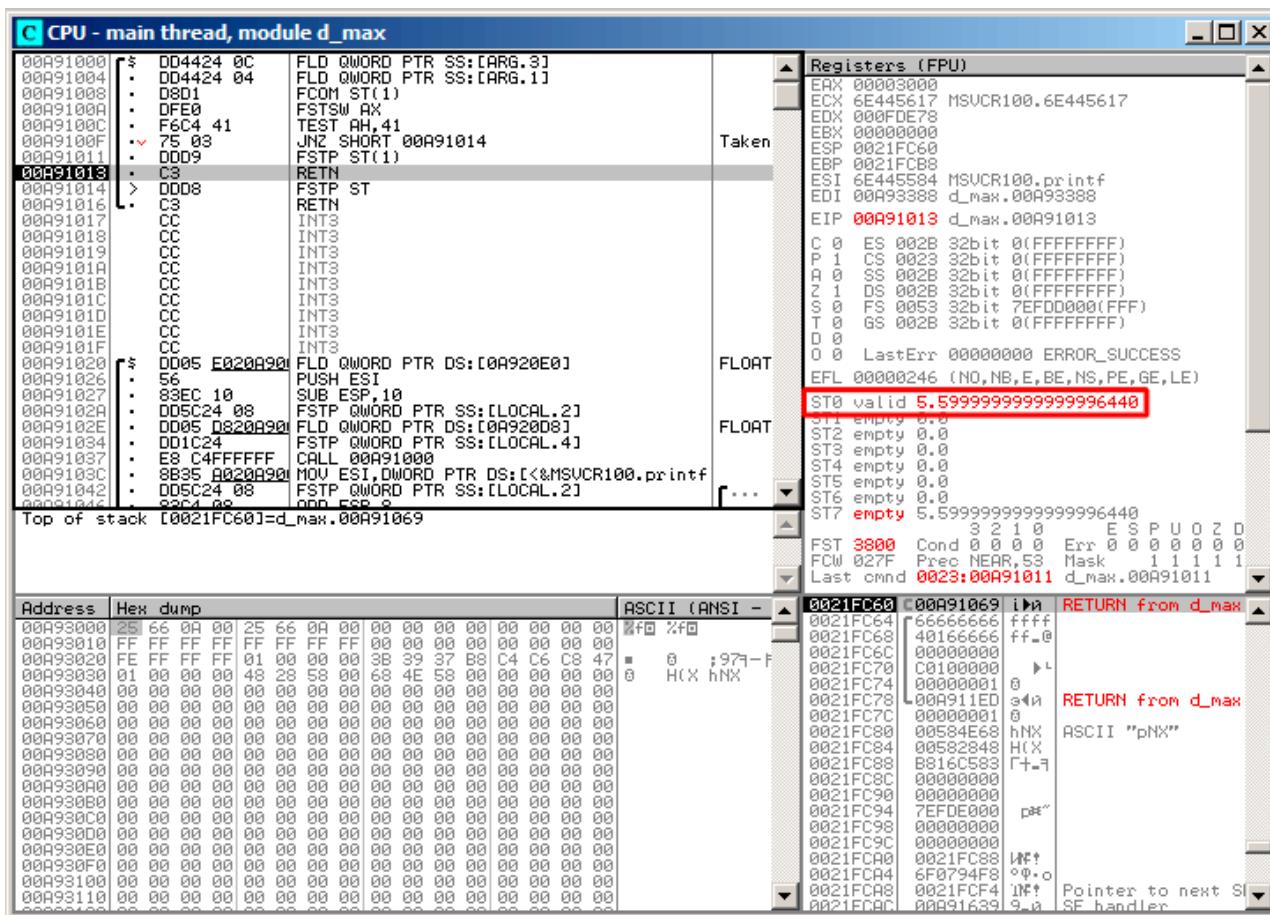


Figure 17.25: OllyDbg: FSTP was executed

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 17.12: 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

; 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

```

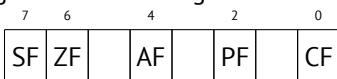
FUCOMPP is almost like FCOM, but pops both values from the stack and handles “not-a-numbers” differently.

A bit about *not-a-numbers*.

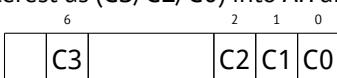
The FPU is able to deal with special values which are *not-a-numbers* or NaNs¹⁷. These are infinity, result of division by 0, etc. Not-a-numbers can be “quiet” and “signaling”. It is possible to continue to work with “quiet” NaNs, but if one tries to do any operation with “signaling” NaNs, an exception 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.

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 SETcc¹⁸ 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.

¹⁷[wikipedia.org/wiki/NaN](https://en.wikipedia.org/wiki/NaN)

¹⁸cc is condition code

Optimizing GCC 4.4.1

Listing 17.13: 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

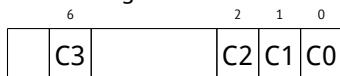
loc_8048448:
; store _a to ST(0), pop value at top of stack, leave _a at top
                fstp   st(1)

loc_804844A:
                pop    ebp
                retn
d_max          endp

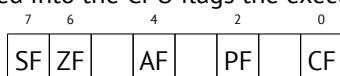
```

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.

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.

¹⁹Starting at Pentium Pro, Pentium-II, etc.

So what we get is:

Listing 17.14: 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 $ST0(a) \leq ST1(b)$. Otherwise ($a > b$), it leaves *a* in ST(0).

The last FSTP leaves ST(0) on top of the stack, discarding the contents of ST(1).

Let's trace this function in GDB:

Listing 17.15: 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
22 Dump of assembler code for function d_max:
23 0x080484a0 <+0>: fildl 0x4(%esp)
24 => 0x080484a4 <+4>: fildl 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    0x4000d9999999999999800 +3.39999999999999911
56 =>R6: Valid    0x3fff99999999999999800 +1.19999999999999956
57   R5: Empty    0x000000000000000000000000
58   R4: Empty    0x000000000000000000000000
59   R3: Empty    0x000000000000000000000000
60   R2: Empty    0x000000000000000000000000
61   R1: Empty    0x000000000000000000000000
62   R0: Empty    0x000000000000000000000000
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            0xbfffff10c 0xbfffff10c
91 ebp            0xbfffff128 0xbfffff128
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 +3.39999999999999911
106 =>R6: Valid    0x4000d9999999999999800 +3.39999999999999911
107   R5: Empty    0x000000000000000000000000
108   R4: Empty    0x000000000000000000000000
109   R3: Empty    0x000000000000000000000000
110   R2: Empty    0x000000000000000000000000
111   R1: Empty    0x000000000000000000000000
112   R0: Empty    0x000000000000000000000000

```

```

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 $eip
124 Dump of assembler code for function d_max:
125 0x080484a0 <+0>:    fldl  0x4(%esp)
126 0x080484a4 <+4>:    fldl  0xc(%esp)
127 0x080484a8 <+8>:    fxch  %st(1)
128 0x080484aa <+10>:   fucomi %st(1),%st
129 0x080484ac <+12>:   fcmovbe %st(1),%st
130 => 0x080484ae <+14>:  fstp   %st(1)
131 0x080484b0 <+16>:   ret
132 End of assembler dump.
133 (gdb) ni
134 0x080484b0 in d_max ()
135 (gdb) info float
136 =>R7: Valid 0x4000d999999999999800 +3.39999999999999911
137 R6: Empty 0x4000d99999999999800
138 R5: Empty 0x00000000000000000000000000000000
139 R4: Empty 0x00000000000000000000000000000000
140 R3: Empty 0x00000000000000000000000000000000
141 R2: Empty 0x00000000000000000000000000000000
142 R1: Empty 0x00000000000000000000000000000000
143 R0: Empty 0x00000000000000000000000000000000
144
145 Status Word:      0x3800
146          TOP: 7
147 Control Word:     0x037f  IM DM ZM OM UM PM
148          PC: Extended Precision (64-bits)
149          RC: Round to nearest
150 Tag Word:         0xffff
151 Instruction Pointer: 0x73:0x080484ae
152 Operand Pointer:   0x7b:0xbfffff118
153 Opcode:          0x0000
154 (gdb) quit
155 A debugging session is active.
156
157 Inferior 1 [process 30194] will be killed.
158
159 Quit anyway? (y or n) y
160 dennis@ubuntuvm:~/polygon$
```

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 ([17.5.1 on page 221](#)). And GDB doesn’t show ST_x 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.

17.7.2 ARM

Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 17.16: 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
VMOVT.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 ([FPSCR²⁰](#)), 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 ([APSR²¹](#)).

VMOVT is the analog of the MOVT, 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 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 17.17: 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
VMOVT.F64   D16, D17
VMOV        R0, R1, D16
BX          LR

```

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 VMOVT 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 17.18: Angry Birds Classic

```

...
ITE NE
VMOVNE      R2, R3, D16
VMOVEQ      R2, R3, D17
BLX         _objc_msgSend ; not prefixed
...

```

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 prefixed (BLX).

²⁰(ARM) Floating-Point Status and Control Register

²¹(ARM) Application Program Status Register

One more that's slightly harder, which is also from Angry Birds:

Listing 17.19: 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 prefixed
...
```

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, ITEEE EQ (*if-then-else-else-else*), then the suffixes would have been set as follows:

```
-EQ
-NE
-NE
-NE
```

Another fragment from Angry Birds:

Listing 17.20: Angry Birds Classic

```
...
CMP.W      R0, #0xFFFFFFFF
ITTE LE
SUBLE.W    R10, R0, #1
NEGLE      R0, R0
MOVGT      R10, R0
MOVS       R6, #0          ; not prefixed
CBZ       R0, loc_1E7E32 ; not prefixed
...
```

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, ITT, ITTT. 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 17.21: 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 17.22: Optimizing Keil 6/2013 (Thumb mode)

PUSH	{R3-R7,LR}
MOVS	R4, R2
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.

17.7.3 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:
; 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).

17.7.4 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 17.23: 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.

17.8 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.

17.9 x64

On how floating point numbers are processed in x86-64, read more here: [27 on page 444](#).

17.10 Exercises

17.10.1 Exercise #1

Eliminate the FXCH instruction in the example [17.7.1 on page 253](#) and test it.

17.10.2 Exercise #2

What does this code do?

Listing 17.24: Optimizing MSVC 2010

```
__real@4014000000000000 DQ 0401400000000000r ; 5

_a1$ = 8          ; size = 8
_a2$ = 16         ; size = 8
_a3$ = 24         ; size = 8
_a4$ = 32         ; size = 8
_a5$ = 40         ; size = 8
```

²²[wikipedia.org/wiki/Reverse_Polish_notation](https://en.wikipedia.org/wiki/Reverse_Polish_notation)

```

_f      PROC
    fld    QWORD PTR _a1$[esp-4]
    fadd  QWORD PTR _a2$[esp-4]
    fadd  QWORD PTR _a3$[esp-4]
    fadd  QWORD PTR _a4$[esp-4]
    fadd  QWORD PTR _a5$[esp-4]
    fdiv  QWORD PTR __real@4014000000000000
    ret   0
_f      ENDP

```

Listing 17.25: Non-optimizing Keil 6/2013 (Thumb mode / compiled for Cortex-R4F CPU)

```

f PROC
    VADD.F64 d0,d0,d1
    VMOV.F64 d1,#5.00000000
    VADD.F64 d0,d0,d2
    VADD.F64 d0,d0,d3
    VADD.F64 d2,d0,d4
    VDIV.F64 d0,d2,d1
    BX     lr
ENDP

```

Listing 17.26: Optimizing GCC 4.9 (ARM64)

```

f:
    fadd  d0, d0, d1
    fmov  d1, 5.0e+0
    fadd  d2, d0, d2
    fadd  d3, d2, d3
    fadd  d0, d3, d4
    fdiv  d0, d0, d1
    ret

```

Listing 17.27: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

f:
arg_10      = 0x10
arg_14      = 0x14
arg_18      = 0x18
arg_1C      = 0x1C
arg_20      = 0x20
arg_24      = 0x24

    lwc1    $f0, arg_14($sp)
    add.d   $f2, $f12, $f14
    lwc1    $f1, arg_10($sp)
    lui     $v0, ($LC0 >> 16)
    add.d   $f0, $f2, $f0
    lwc1    $f2, arg_1C($sp)
    or      $at, $zero
    lwc1    $f3, arg_18($sp)
    or      $at, $zero
    add.d   $f0, $f2
    lwc1    $f2, arg_24($sp)
    or      $at, $zero
    lwc1    $f3, arg_20($sp)
    or      $at, $zero
    add.d   $f0, $f2
    lwc1    $f2, dword_6C
    or      $at, $zero
    lwc1    $f3, $LC0
    jr     $ra
    div.d   $f0, $f2

$LC0:      .word 0x40140000      # DATA XREF: f+C
                                # f+44
dword_6C:  .word 0                  # DATA XREF: f+3C

```

Answer [G.1.11 on page 979](#).

Chapter 18

Arrays

An array is just a set of variables in memory that lie next to each other and that have the same type¹.

18.1 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;
};
```

18.1.1 x86

MSVC

Let's compile:

Listing 18.1: 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
```

¹AKA² “homogeneous container”

```

    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 [16.2.1 on page 212](#).

80 bytes are allocated on the stack for the array, 20 elements of 4 bytes.

Let's try this example in OllyDbg.

We see how the array gets filled: each element is 32-bit word of *int* type and its value is the index multiplied by 2:

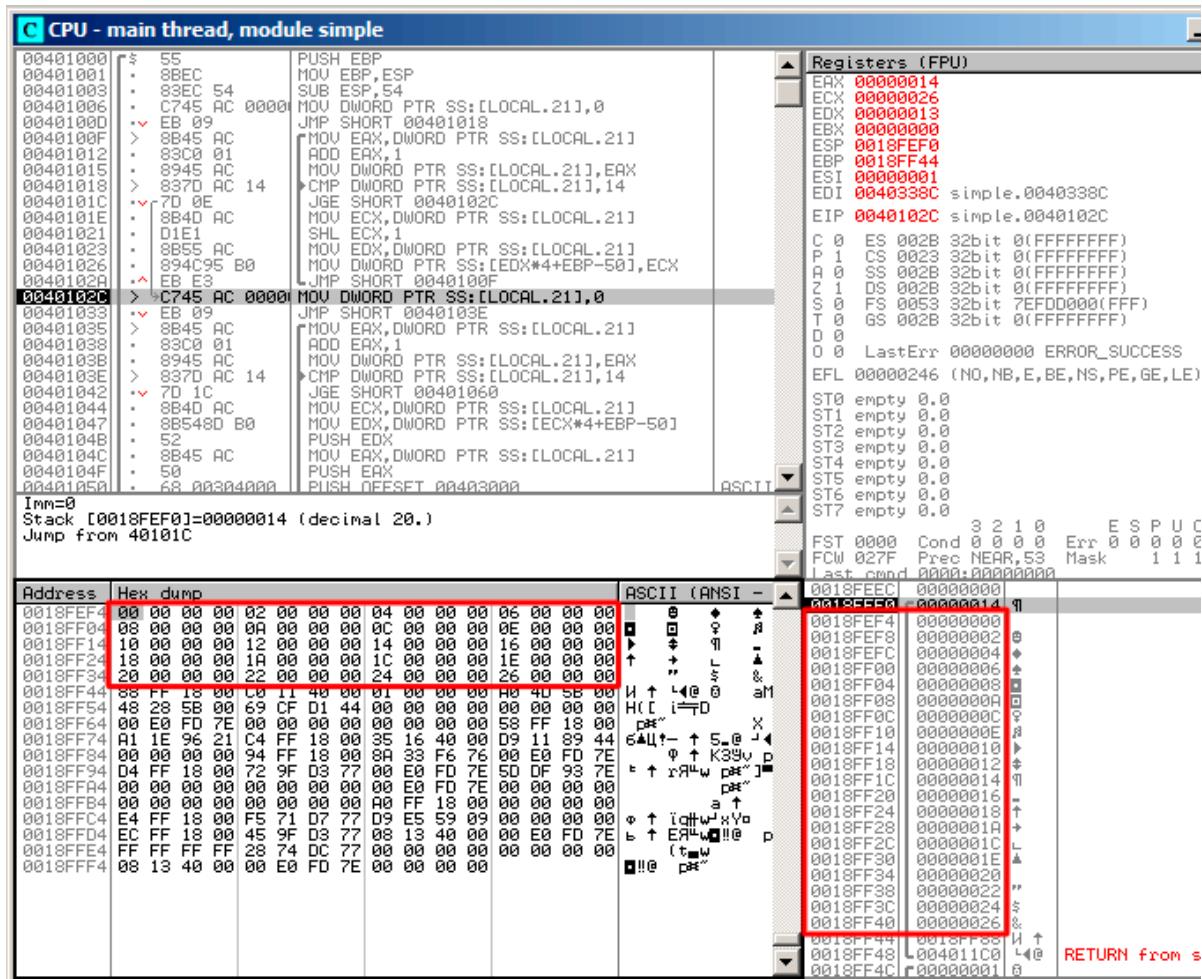


Figure 18.1: OllyDbg: after array filling

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 18.2: 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

```

```

        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!

18.1.2 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
        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.

Non-optimizing GCC 4.9.1 (ARM64)

Listing 18.3: 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:
    ldp    x29, x30, [sp], 112
    ret

```

18.1.3 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 18.4: 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)
        move $v0, $zero
        lw    $s3, 0x80+var_8($sp)
        lw    $s2, 0x80+var_C($sp)
        lw    $s1, 0x80+var_10($sp)
        lw    $s0, 0x80+var_14($sp)
        jr    $ra

```

```

        addiu    $sp, 0x80
$LC0:      .ascii  "a[%d]=%d\n<0>    # DATA XREF: main+44

```

Something interesting: there are two loops and the first one doesn't need 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: [39 on page 493](#). Their goal is to get rid of of multiplications.

18.2 Buffer overflow

18.2.1 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 18.5: 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$[ebp]
    mov    DWORD PTR _a$[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:

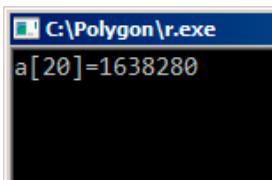


Figure 18.2: OllyDbg: console output

It is just *something* that was lying in the stack near to the array, 80 bytes away from its first element.

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:

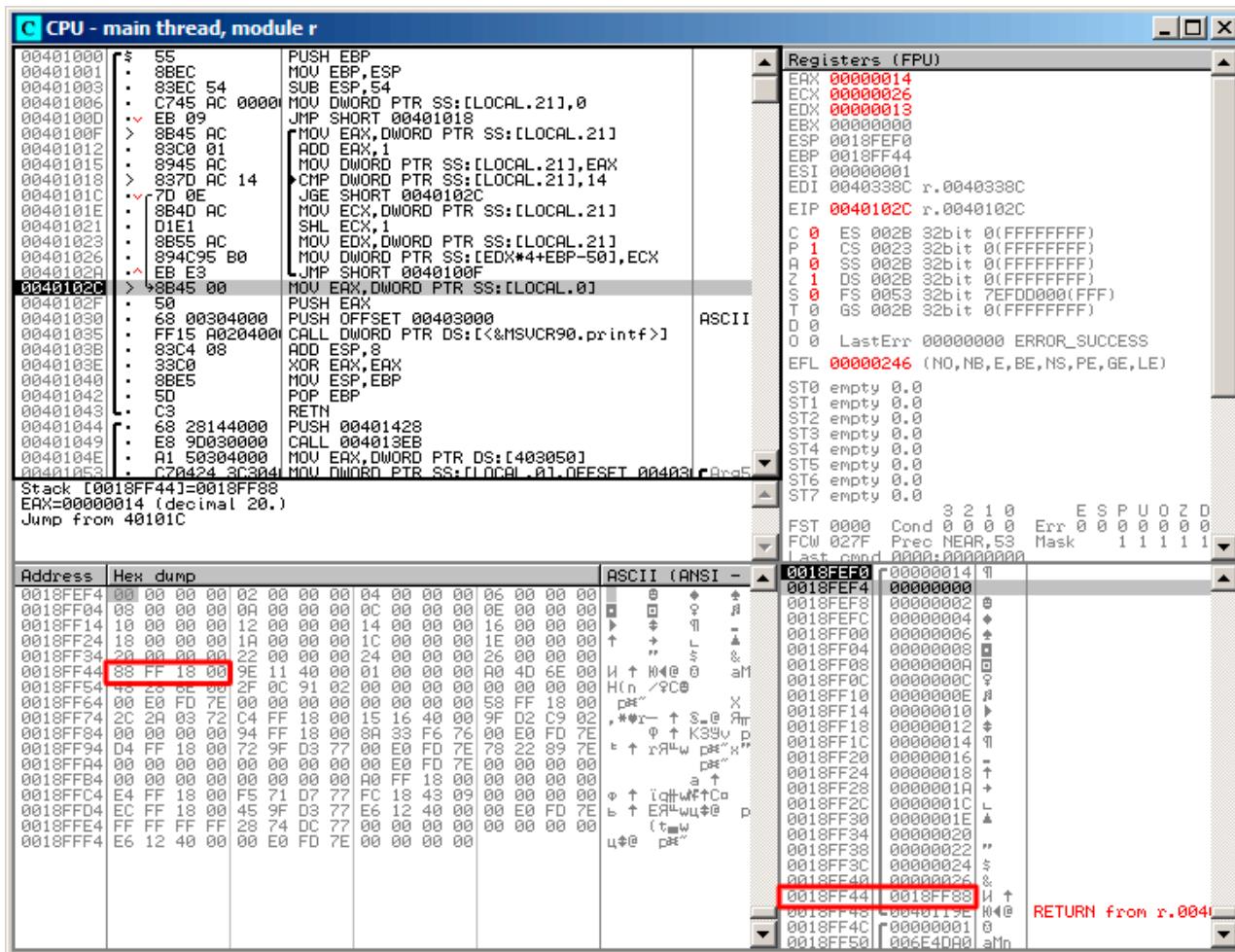


Figure 18.3: OllyDbg: reading of the 20th element and execution of `printf()`

What is this? Judging by the stack layout, this is the saved value of the EBP register.

Let's trace further and see how it gets restored:

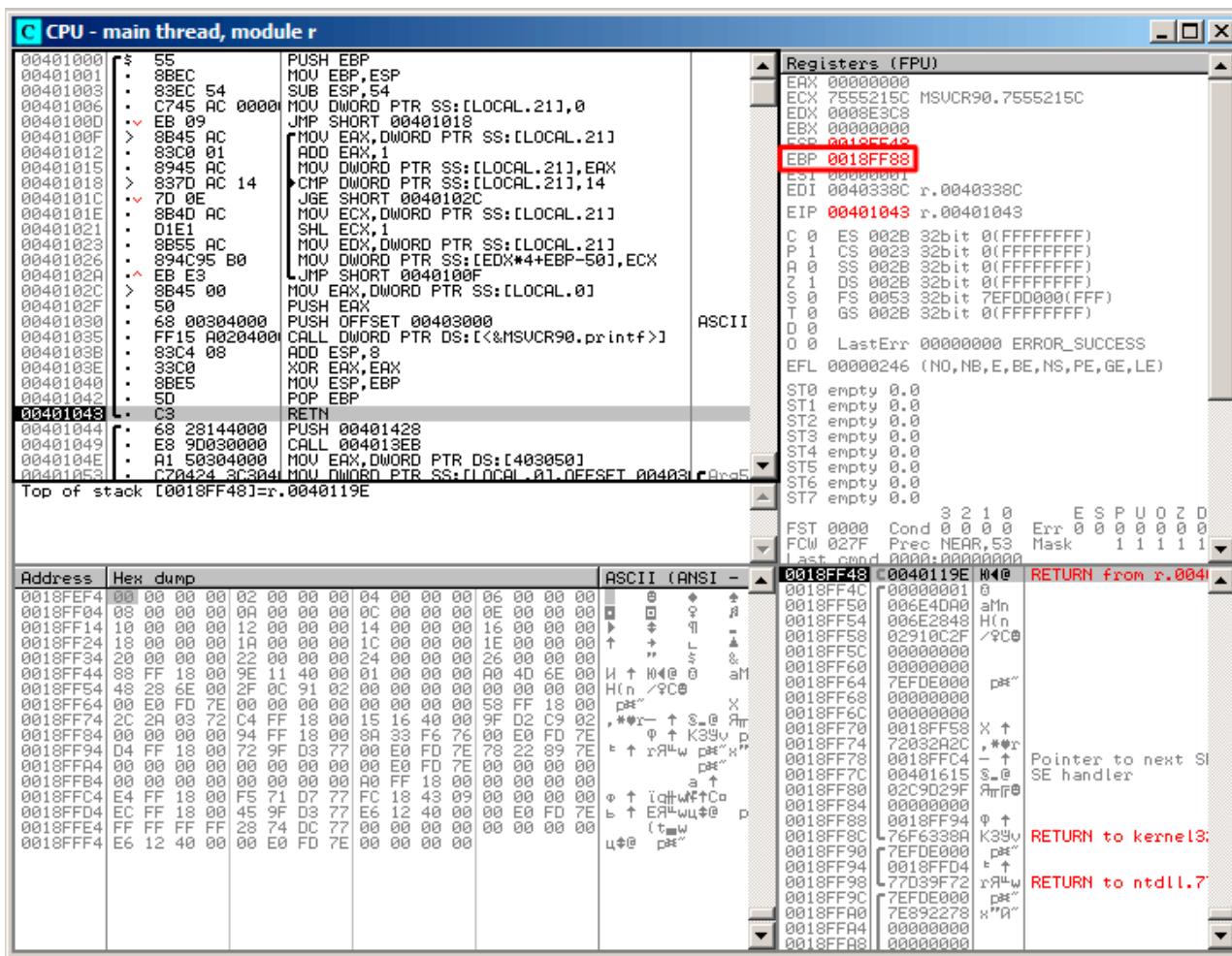


Figure 18.4: OllyDbg: restoring value of EBP

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.

18.2.2 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

Listing 18.6: Non-optimizing MSVC 2008

```
_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.

Let's load it into OllyDbg, and trace until all 30 elements are written:

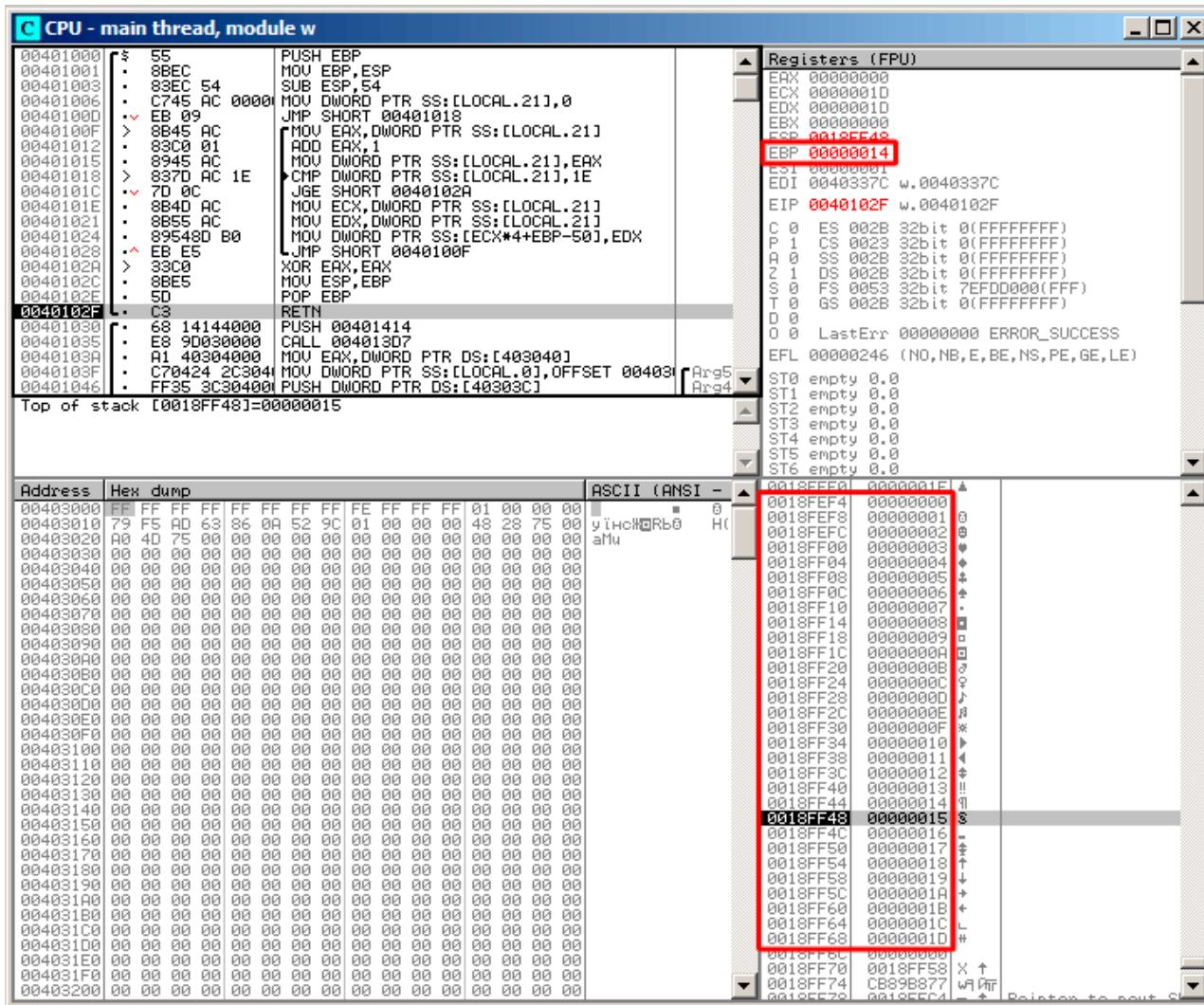


Figure 18.5: OllyDbg: after restoring the value of EBP

Trace until the function end:

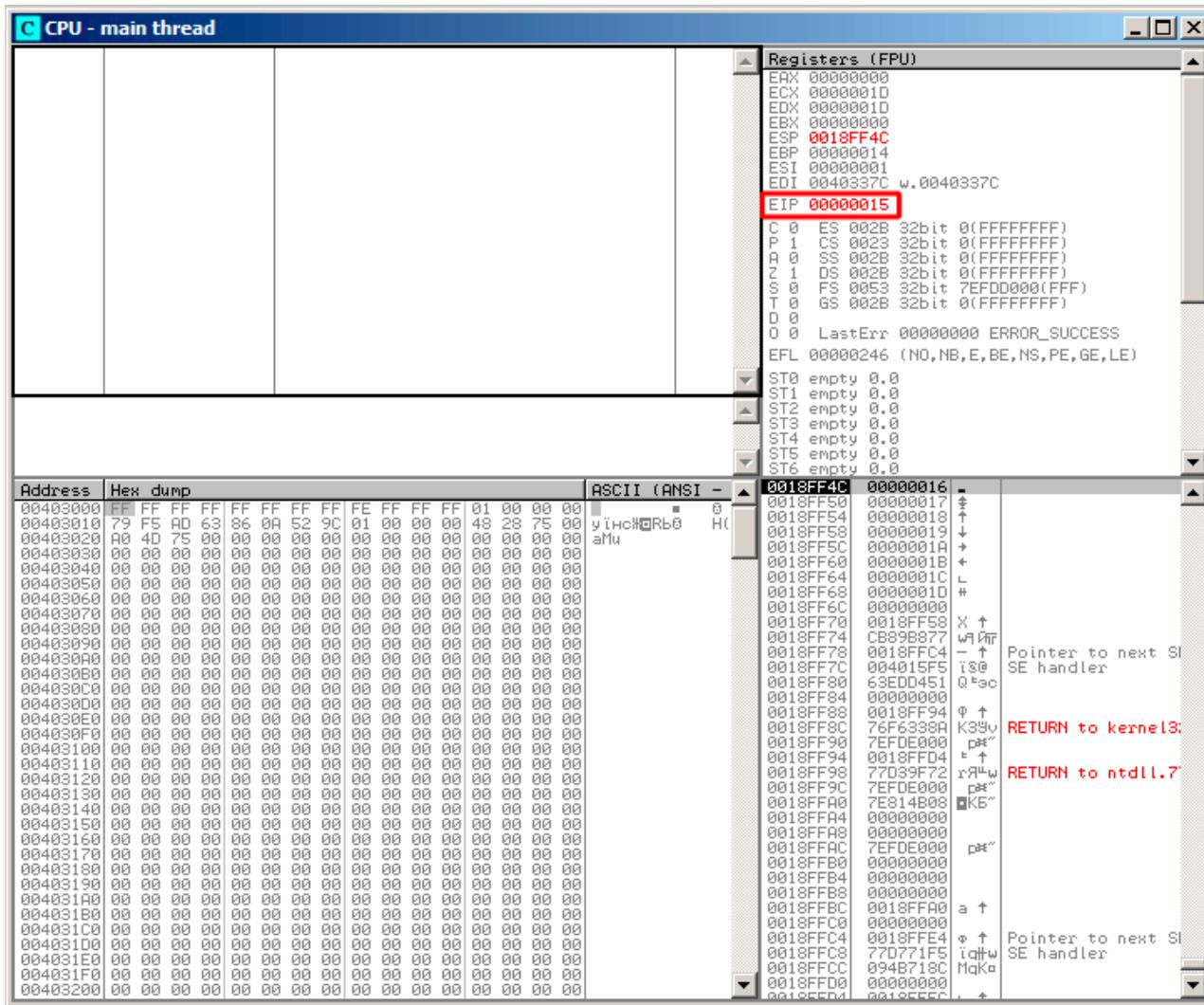


Figure 18.6: OllyDbg: EIP was restored, but OllyDbg can't disassemble at 0x15

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—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 $(20+1)*\text{sizeof}(\text{int})$. 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 <code>i</code> variable
ESP+4	80 bytes allocated for <code>a[20]</code> 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.

The RET instruction takes the return address from the stack (that is the address in `CRT`), which was called `main()`, and 21 is stored there (0x15 in hexadecimal). The CPU traps at address 0x15, but there is no executable code there, so exception gets raised.

Welcome! It is called a *buffer overflow*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 be 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)

```

The register values are slightly different than in win32 example, since the stack layout is slightly different too.

⁴[wikipedia](#)

⁵Classic article about it: [[One96](#)].

18.3 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 ([18.1 on page 263](#)) 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()` ([5.2.4 on page 27](#)) 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 18.7: 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
    mov     DWORD PTR [esp], ebx
    call    puts
    mov     eax, DWORD PTR [ebp-12]
    xor     eax, DWORD PTR gs:20           ; check canary
    jne    .L5
```

⁶compiler-side buffer overflow protection methods: wikipedia.org/wiki/Buffer_overflow_protection

⁷wikipedia.org/wiki/Domestic_canary#Miner.27s_canary

```

    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](#) ([65 on page 689](#))—some information specific to thread is stored there. By the way, in win32 the `fs` register plays the same role, pointing to [TIB](#)⁸ ⁹.

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.

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

Let's get back to our simple array example ([18.1 on page 263](#)), again, now we can see how LLVM checks the correctness of the “canary”:

```

_main

var_64      = -0x64
var_60      = -0x60
var_5C      = -0x5C
var_58      = -0x58
var_54      = -0x54
var_50      = -0x50
var_4C      = -0x4C
var_48      = -0x48
var_44      = -0x44
var_40      = -0x40

```

⁸Thread Information Block

⁹[wikipedia.org/wiki/Win32_Thread_Information_Block](http://en.wikipedia.org/wiki/Win32_Thread_Information_Block)

```

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, #a0bjc_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
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.

18.4 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()` ([5.2.4 on page 27](#)) internally.

It's also possible to use garbage collecting libraries for C. And there are also libraries supporting smart pointers for C++.

18.5 Array of pointers to strings

Here is an example for an array of pointers.

Listing 18.8: 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];
}

```

18.5.1 x64

Listing 18.9: 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
    movsxrd rax, ecx
    lea     rcx, OFFSET FLAT:month1
    mov     rax, QWORD PTR [rcx+rax*8]
    ret     0
get_month1 ENDP

```

The code is very simple:

- The first MOVSXD 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.

¹⁰It is somewhat weird, but negative array index could be passed here as *month* (negative array indices will have been explained later: [52 on page 605](#)). 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.

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 18.10: 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 18.11: 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.

18.5.2 32-bit ARM

ARM in ARM mode

Listing 18.12: 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

    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
```

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.

```

    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

```

18.5.3 ARM64

Listing 18.13: 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:
    .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.

18.5.4 MIPS

Listing 18.14: 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>
```

18.5.5 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 18.15: 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
                           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 18.16: Executable file in IDA

```

off_140011000 dq offset qword_140011060
                  ; DATA XREF: .text:0000000140001003
                  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"
qword_140011060 dq 797261756E614Ah
                  ; DATA XREF: sub_140001020+4
                  ; .data:off_140011000
aFebruary_1      db 'February',0
                  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

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 18.17: 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 18.18: 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 18.19: 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"
```

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).

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)

18.6 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 18.1: 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 18.2: 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.

18.6.1 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.

Row filling example

Let's fill the second row with these values 0..3:

Listing 18.20: 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;
}
```

```

        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 18.7: OllyDbg: array is filled

Column filling example

Let's fill the third column with values: 0..2:

Listing 18.21: 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 18.8: OllyDbg: array is filled

18.6.2 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 18.22: Optimizing MSVC 2013 x64

```

array$ = 8
a$ = 16
b$ = 24
get_by_coordinates3 PROC
; RCX=address of array
; RDX=a
; R8=b
    movsx rax, r8d
; EAX=b
    movsx r9, edx
; R9=a
    add    rax, rcx
; RAX=b+address of array
    movzx eax, BYTE PTR [rax+r9*4]
; AL=load byte at address RAX+R9*4=b+address of array+a*4=address of array+a*4+b
    ret    0
get_by_coordinates3 ENDP

array$ = 8
a$ = 16
b$ = 24
get_by_coordinates2 PROC
    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 18.23: 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
```

18.6.3 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 18.24: simple example

```
#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 18.25: 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+x*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 18.26: 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
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 18.27: 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 18.28: Optimizing Xcode 4.6.3 (LLVM) (Thumb mode)

```
_insert
MOVW  R9, #0x10FC
MOV.W R12, #2400
MOVT.W R9, #0
RSB.W R1, R1, R1, LSL#4 ; R1 - y. R1=y<<4 - y = y*16 - y = y*15
ADD   R9, PC           ; 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
```

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 957](#)) 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 18.29: 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

```

18.6.4 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: [83.2 on page 845](#).

18.7 Pack of strings as a two-dimensional array

Let's revisit the function that returns the name of a month: listing [18.8](#). 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 },
    { 'J','u','n','e', 0, 0, 0, 0, 0, 0 },
    { 'J','u','l','y', 0, 0, 0, 0, 0, 0 },
    { 'A','u','g','u','s','t', 0, 0, 0, 0 },
    { 'S','e','p','t','e','m','b','e','r', 0 },
    { 'O','c','t','o','b','e','r', 0, 0, 0 },
    { 'N','o','v','e','m','b','e','r', 0, 0 },
    { 'D','e','c','e','m','b','e','r', 0, 0 }
};

// in 0..11 range
const char* get_month2 (int month)

```

```
{
    return &month2[month][0];
};
```

Here is what we've get:

Listing 18.30: 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
    movsx 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 18.31: 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 18.32: 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 18.33: 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.

18.7.1 32-bit ARM

Optimizing Keil for Thumb mode uses the multiplication instruction MULS:

Listing 18.34: 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 18.35: 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
```

18.7.2 ARM64

Listing 18.36: 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.

18.7.3 MIPS

Listing 18.37: 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>
              .byte 0
aMarch:      .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
aNovember:   .ascii "November"<0>
              .byte 0
aDecember:   .ascii "December"<0>
              .byte 0, 0, 0, 0, 0, 0, 0, 0, 0

```

18.7.4 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.

18.8 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.

18.9 Exercises

18.9.1 Exercise #1

What does this code do?

Listing 18.38: MSVC 2010 + /O1

```
_a$ = 8          ; size = 4
_b$ = 12         ; size = 4
_c$ = 16         ; size = 4
?s@YAXPAN00@Z PROC      ; s, COMDAT
    mov    eax, DWORD PTR _b$[esp-4]
    mov    ecx, DWORD PTR _a$[esp-4]
    mov    edx, DWORD PTR _c$[esp-4]
    push   esi
    push   edi
    sub    ecx, eax
    sub    edx, eax
    mov    edi, 200      ; 000000c8H
$LL6@s:
    push   100        ; 00000064H
    pop    esi
$LL3@s:
    fld    QWORD PTR [ecx+eax]
    fadd  QWORD PTR [eax]
    fstp  QWORD PTR [edx+eax]
    add    eax, 8
    dec    esi
    jne    SHORT $LL3@s
    dec    edi
    jne    SHORT $LL6@s
    pop    edi
    pop    esi
    ret    0
?s@@YAXPAN00@Z ENDP      ; s
```

(/O1: minimize space).

Listing 18.39: Optimizing Keil 6/2013 (ARM mode)

```
PUSH   {r4-r12,lr}
MOV    r9,r2
MOV    r10,r1
MOV    r11,r0
MOV    r5,#0
|L0.20|
    ADD   r0,r5,r5,LSL #3
    ADD   r0,r0,r5,LSL #4
    MOV   r4,#0
    ADD   r8,r10,r0,LSL #5
    ADD   r7,r11,r0,LSL #5
    ADD   r6,r9,r0,LSL #5
|L0.44|
    ADD   r0,r8,r4,LSL #3
    LDM   r0,{r2,r3}
    ADD   r1,r7,r4,LSL #3
    LDM   r1,{r0,r1}
    BL    __aeabi_dadd
    ADD   r2,r6,r4,LSL #3
    ADD   r4,r4,#1
    STM   r2,{r0,r1}
    CMP   r4,#0x64
```

```

BLT    |L0.44|
ADD    r5,r5,#1
CMP    r5,#0xc8
BLT    |L0.20|
POP    {r4-r12,pc}

```

Listing 18.40: Optimizing Keil 6/2013 (Thumb mode)

```

PUSH   {r0-r2,r4-r7,lr}
MOVS   r4,#0
SUB    sp,sp,#8
|L0.6|
MOVS   r1,#0x19
MOVS   r0,r4
LSLS   r1,r1,#5
MULS   r0,r1,r0
LDR    r2,[sp,#8]
LDR    r1,[sp,#0xc]
ADDS   r2,r0,r2
STR    r2,[sp,#0]
LDR    r2,[sp,#0x10]
MOVS   r5,#0
ADDS   r7,r0,r2
ADDS   r0,r0,r1
STR    r0,[sp,#4]
|L0.32|
LSLS   r6,r5,#3
ADDS   r0,r0,r6
LDM    r0!,{r2,r3}
LDR    r0,[sp,#0]
ADDS   r1,r0,r6
LDM    r1,{r0,r1}
BL     __aeabi_dadd
ADDS   r2,r7,r6
ADDS   r5,r5,#1
STM    r2!,{r0,r1}
CMP    r5,#0x64
BGE   |L0.62|
LDR    r0,[sp,#4]
B     |L0.32|
|L0.62|
ADDS   r4,r4,#1
CMP    r4,#0xc8
BLT    |L0.6|
ADD    sp,sp,#0x14
POP    {r4-r7,pc}

```

Listing 18.41: Non-optimizing GCC 4.9 (ARM64)

```

s:
    sub    sp, sp, #48
    str    x0, [sp,24]
    str    x1, [sp,16]
    str    x2, [sp,8]
    str    wzr, [sp,44]
    b     .L2
.L5:
    str    wzr, [sp,40]
    b     .L3
.L4:
    ldr    w1, [sp,44]
    mov    w0, 100
    mul    w0, w1, w0
    sxtw  x1, w0
    ldrsw x0, [sp,40]
    add    x0, x1, x0
    lsl    x0, x0, 3
    ldr    x1, [sp,8]
    add    x0, x1, x0
    ldr    w2, [sp,44]

```

```

    mov    w1, 100
    mul    w1, w2, w1
    sxtw   x2, w1
    ldrsw  x1, [sp,40]
    add    x1, x2, x1
    lsl    x1, x1, 3
    ldr    x2, [sp,24]
    add    x1, x2, x1
    ldr    x2, [x1]
    ldr    w3, [sp,44]
    mov    w1, 100
    mul    w1, w3, w1
    sxtw   x3, w1
    ldrsw  x1, [sp,40]
    add    x1, x3, x1
    lsl    x1, x1, 3
    ldr    x3, [sp,16]
    add    x1, x3, x1
    ldr    x1, [x1]
    fmov   d0, x2
    fmov   d1, x1
    fadd   d0, d0, d1
    fmov   x1, d0
    str    x1, [x0]
    ldr    w0, [sp,40]
    add    w0, w0, 1
    str    w0, [sp,40]
.L3:
    ldr    w0, [sp,40]
    cmp    w0, 99
    ble   .L4
    ldr    w0, [sp,44]
    add    w0, w0, 1
    str    w0, [sp,44]
.L2:
    ldr    w0, [sp,44]
    cmp    w0, 199
    ble   .L5
    add    sp, sp, 48
    ret

```

Listing 18.42: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

sub_0:
    li     $t3, 0x27100
    move   $t2, $zero
    li     $t1, 0x64 # 'd'

loc_10:                      # CODE XREF: sub_0+54
    addu  $t0, $a1, $t2
    addu  $a3, $a2, $t2
    move   $v1, $a0
    move   $v0, $zero

loc_20:                      # CODE XREF: sub_0+48
    lwc1  $f2, 4($v1)
    lwc1  $f0, 4($t0)
    lwc1  $f3, 0($v1)
    lwc1  $f1, 0($t0)
    addiu $v0, 1
    add.d $f0, $f2, $f0
    addiu $v1, 8
    swc1  $f0, 4($a3)
    swc1  $f1, 0($a3)
    addiu $t0, 8
    bne   $v0, $t1, loc_20
    addiu $a3, 8
    addiu $t2, 0x320
    bne   $t2, $t3, loc_10
    addiu $a0, 0x320

```

jr	\$ra
or	\$at, \$zero

Answer [G.1.12 on page 980](#).

18.9.2 Exercise #2

What does this code do?

Listing 18.43: MSVC 2010 + /O1

```

tv315 = -8           ; size = 4
tv291 = -4           ; size = 4
_a$ = 8              ; size = 4
_b$ = 12             ; size = 4
_c$ = 16             ; size = 4
?m@@YAXPAN00@Z PROC    ; m, COMDAT
    push    ebp
    mov     ebp, esp
    push    ecx
    push    ecx
    mov     edx, DWORD PTR _a$[ebp]
    push    ebx
    mov     ebx, DWORD PTR _c$[ebp]
    push    esi
    mov     esi, DWORD PTR _b$[ebp]
    sub    edx, esi
    push    edi
    sub    esi, ebx
    mov    DWORD PTR tv315[ebp], 100   ; 00000064H
$LL9@m:
    mov    eax, ebx
    mov    DWORD PTR tv291[ebp], 300   ; 0000012cH
$LL6@m:
    fldz
    lea    ecx, DWORD PTR [esi+eax]
    fstp   QWORD PTR [eax]
    mov    edi, 200                 ; 000000c8H
$LL3@m:
    dec    edi
    fld    QWORD PTR [ecx+edx]
    fmul   QWORD PTR [ecx]
    fadd   QWORD PTR [eax]
    fstp   QWORD PTR [eax]
    jne    HORT $LL3@m
    add    eax, 8
    dec    DWORD PTR tv291[ebp]
    jne    SHORT $LL6@m
    add    ebx, 800                 ; 00000320H
    dec    DWORD PTR tv315[ebp]
    jne    SHORT $LL9@m
    pop    edi
    pop    esi
    pop    ebx
    leave
    ret    0
?m@@YAXPAN00@Z ENDP      ; m

```

(/O1: minimize space).

Listing 18.44: Optimizing Keil 6/2013 (ARM mode)

PUSH	{r0-r2,r4-r11,lr}
SUB	sp,sp,#8
MOV	r5,#0
L0.12	
LDR	r1,[sp,#0xc]
ADD	r0,r5,r5,LSL #3
ADD	r0,r0,r5,LSL #4

```

ADD    r1,r1,r0,LSL #5
STR    r1,[sp,#0]
LDR    r1,[sp,#8]
MOV    r4,#0
ADD    r11,r1,r0,LSL #5
LDR    r1,[sp,#0x10]
ADD    r10,r1,r0,LSL #5
|L0.52|
MOV    r0,#0
MOV    r1,r0
ADD    r7,r10,r4,LSL #3
STM    r7,{r0,r1}
MOV    r6,r0
LDR    r0,[sp,#0]
ADD    r8,r11,r4,LSL #3
ADD    r9,r0,r4,LSL #3
|L0.84|
LDM    r9,{r2,r3}
LDM    r8,{r0,r1}
BL     __aeabi_dmul
LDM    r7,{r2,r3}
BL     __aeabi_dadd
ADD    r6,r6,#1
STM    r7,{r0,r1}
CMP    r6,#0xc8
BLT   |L0.84|
ADD    r4,r4,#1
CMP    r4,#0x12c
BLT   |L0.52|
ADD    r5,r5,#1
CMP    r5,#0x64
BLT   |L0.12|
ADD    sp,sp,#0x14
POP   {r4-r11,pc}

```

Listing 18.45: Optimizing Keil 6/2013 (Thumb mode)

```

PUSH   {r0-r2,r4-r7,lr}
MOVS   r0,#0
SUB    sp,sp,#0x10
STR    r0,[sp,#0]
|L0.8|
MOVS   r1,#0x19
LSLS   r1,r1,#5
MULS   r0,r1,r0
LDR    r2,[sp,#0x10]
LDR    r1,[sp,#0x14]
ADDS   r2,r0,r2
STR    r2,[sp,#4]
LDR    r2,[sp,#0x18]
MOVS   r5,#0
ADDS   r7,r0,r2
ADDS   r0,r0,r1
STR    r0,[sp,#8]
|L0.32|
LSLS   r4,r5,#3
MOVS   r0,#0
ADDS   r2,r7,r4
STR    r0,[r2,#0]
MOVS   r6,r0
STR    r0,[r2,#4]
|L0.44|
LDR    r0,[sp,#8]
ADDS   r0,r0,r4
LDM    r0!,{r2,r3}
LDR    r0,[sp,#4]
ADDS   r1,r0,r4
LDM    r1,{r0,r1}
BL     __aeabi_dmul
ADDS   r3,r7,r4

```

```

LDM      r3,{r2,r3}
BL       __aeabi_dadd
ADDS    r2,r7,r4
ADDS    r6,r6,#1
STM     r2!,{r0,r1}
CMP     r6,#0xc8
BLT    |L0.44|
MOVS   r0,#0xff
ADDS   r5,r5,#1
ADDS   r0,r0,#0x2d
CMP     r5,r0
BLT    |L0.32|
LDR     r0,[sp,#0]
ADDS   r0,r0,#1
CMP     r0,#0x64
STR     r0,[sp,#0]
BLT    |L0.8|
ADD    sp,sp,#0x1c
POP    {r4-r7,pc}

```

Listing 18.46: Non-optimizing GCC 4.9 (ARM64)

```

m:
    sub    sp, sp, #48
    str    x0, [sp,24]
    str    x1, [sp,16]
    str    x2, [sp,8]
    str    wzr, [sp,44]
    b     .L2

.L7:
    str    wzr, [sp,40]
    b     .L3

.L6:
    ldr    w1, [sp,44]
    mov    w0, 100
    mul    w0, w1, w0
    sxtw  x1, w0
    ldrsw x0, [sp,40]
    add    x0, x1, x0
    lsl    x0, x0, 3
    ldr    x1, [sp,8]
    add    x0, x1, x0
    ldr    x1, .LC0
    str    x1, [x0]
    str    wzr, [sp,36]
    b     .L4

.L5:
    ldr    w1, [sp,44]
    mov    w0, 100
    mul    w0, w1, w0
    sxtw  x1, w0
    ldrsw x0, [sp,40]
    add    x0, x1, x0
    lsl    x0, x0, 3
    ldr    x1, [sp,8]
    add    x0, x1, x0
    ldr    w2, [sp,44]
    mov    w1, 100
    mul    w1, w2, w1
    sxtw  x2, w1
    ldrsw x1, [sp,40]
    add    x1, x2, x1
    lsl    x1, x1, 3
    ldr    x2, [sp,8]
    add    x1, x2, x1
    ldr    x2, [x1]
    ldr    w3, [sp,44]
    mov    w1, 100
    mul    w1, w3, w1
    sxtw  x3, w1

```

```

ldrsw  x1, [sp,40]
add   x1, x3, x1
lsl   x1, x1, 3
ldr   x3, [sp,24]
add   x1, x3, x1
ldr   x3, [x1]
ldr   w4, [sp,44]
mov   w1, 100
mul   w1, w4, w1
sxtw  x4, w1
ldrsw  x1, [sp,40]
add   x1, x4, x1
lsl   x1, x1, 3
ldr   x4, [sp,16]
add   x1, x4, x1
ldr   x1, [x1]
fmov  d0, x3
fmov  d1, x1
fmul  d0, d0, d1
fmov  x1, d0
fmov  d0, x2
fmov  d1, x1
fadd  d0, d0, d1
fmov  x1, d0
str   x1, [x0]
ldr   w0, [sp,36]
add   w0, w0, 1
str   w0, [sp,36]
.L4:
ldr   w0, [sp,36]
cmp   w0, 199
ble   .L5
ldr   w0, [sp,40]
add   w0, w0, 1
str   w0, [sp,40]
.L3:
ldr   w0, [sp,40]
cmp   w0, 299
ble   .L6
ldr   w0, [sp,44]
add   w0, w0, 1
str   w0, [sp,44]
.L2:
ldr   w0, [sp,44]
cmp   w0, 99
ble   .L7
add   sp, sp, 48
ret

```

Listing 18.47: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

m:
    li      $t5, 0x13880
    move   $t4, $zero
    li      $t1, 0xC8
    li      $t3, 0x12C

loc_14:                                # CODE XREF: m+7C
    addu  $t0, $a0, $t4
    addu  $a3, $a1, $t4
    move   $v1, $a2
    move   $t2, $zero

loc_24:                                # CODE XREF: m+70
    mtc1  $zero, $f0
    move   $v0, $zero
    mtc1  $zero, $f1
    or     $at, $zero
    swc1  $f0, 4($v1)
    swc1  $f1, 0($v1)

```

```

loc_3C:                                # CODE XREF: m+5C
    lwc1    $f4, 4($t0)
    lwc1    $f2, 4($a3)
    lwc1    $f5, 0($t0)
    lwc1    $f3, 0($a3)
    addiu   $v0, 1
    mul.d   $f2, $f4, $f2
    add.d   $f0, $f2
    swc1    $f0, 4($v1)
    bne    $v0, $t1, loc_3C
    swc1    $f1, 0($v1)
    addiu   $t2, 1
    addiu   $v1, 8
    addiu   $t0, 8
    bne    $t2, $t3, loc_24
    addiu   $a3, 8
    addiu   $t4, 0x320
    bne    $t4, $t5, loc_14
    addiu   $a2, 0x320
    jr     $ra
    or     $at, $zero

```

Answer [G.1.12](#) on page 980.

18.9.3 Exercise #3

What does this code do?

Try to determine the dimensions of the array, at least partially.

Listing 18.48: Optimizing MSVC 2010

```

_array$ = 8
_x$ = 12
_y$ = 16
_f PROC
    mov    eax, DWORD PTR _x$[esp-4]
    mov    edx, DWORD PTR _y$[esp-4]
    mov    ecx, eax
    shl    ecx, 4
    sub    ecx, eax
    lea    eax, DWORD PTR [edx+ecx*8]
    mov    ecx, DWORD PTR _array$[esp-4]
    fld    QWORD PTR [ecx+eax*8]
    ret    0
_f ENDP

```

Listing 18.49: Non-optimizing Keil 6/2013 (ARM mode)

```

f PROC
    RSB    r1,r1,r1,LSL #4
    ADD    r0,r0,r1,LSL #6
    ADD    r1,r0,r2,LSL #3
    LDM    r1,{r0,r1}
    BX    lr
    ENDP

```

Listing 18.50: Non-optimizing Keil 6/2013 (Thumb mode)

```

f PROC
    MOVS   r3,#0xf
    LSLS   r3,r3,#6
    MULS   r1,r3,r1
    ADDS   r0,r1,r0
    LSLS   r1,r2,#3
    ADDS   r1,r0,r1
    LDM    r1,{r0,r1}
    BX    lr
    ENDP

```

Listing 18.51: Optimizing GCC 4.9 (ARM64)

```
f:
    sxtw    x1, w1
    add     x0, x0, x2, sxtw 3
    lsl     x2, x1, 10
    sub     x1, x2, x1, lsl 6
    ldr     d0, [x0,x1]
    ret
```

Listing 18.52: Optimizing GCC 4.4.5 (MIPS) (IDA)

```
f:
    sll     $v0, $a1, 10
    sll     $a1, 6
    subu   $a1, $v0, $a1
    addu   $a1, $a0, $a1
    sll     $a2, 3
    addu   $a1, $a2
    lwc1   $f0, 4($a1)
    or      $at, $zero
    lwc1   $f1, 0($a1)
    jr     $ra
    or      $at, $zero
```

Answer [G.1.12 on page 980](#)

18.9.4 Exercise #4

What does this code do?

Try to determine the dimensions of the array, at least partially.

Listing 18.53: Optimizing MSVC 2010

```
_array$ = 8
_x$ = 12
_y$ = 16
_z$ = 20
_f PROC
    mov    eax, DWORD PTR _x$[esp-4]
    mov    edx, DWORD PTR _y$[esp-4]
    mov    ecx, eax
    shl    ecx, 4
    sub    ecx, eax
    lea    eax, DWORD PTR [edx+ecx*4]
    mov    ecx, DWORD PTR _array$[esp-4]
    lea    eax, DWORD PTR [eax+eax*4]
    shl    eax, 4
    add    eax, DWORD PTR _z$[esp-4]
    mov    eax, DWORD PTR [ecx+eax*4]
    ret    0
_f ENDP
```

Listing 18.54: Non-optimizing Keil 6/2013 (ARM mode)

```
f PROC
    RSB    r1,r1,r1,LSL #4
    ADD    r1,r1,r1,LSL #2
    ADD    r0,r0,r1,LSL #8
    ADD    r1,r2,r2,LSL #2
    ADD    r0,r0,r1,LSL #6
    LDR    r0,[r0,r3,LSL #2]
    BX    lr
    ENDP
```

Listing 18.55: Non-optimizing Keil 6/2013 (Thumb mode)

```
f PROC
    PUSH   {r4,lr}
```

```

MOVS    r4,#0x4b
LSLS    r4,r4,#8
MULS    r1,r4,r1
ADDS    r0,r1,r0
MOVS    r1,#0xff
ADDS    r1,r1,#0x41
MULS    r2,r1,r2
ADDS    r0,r0,r2
LSLS    r1,r3,#2
LDR     r0,[r0,r1]
POP    {r4,pc}
ENDP

```

Listing 18.56: Optimizing GCC 4.9 (ARM64)

```

f:
sxtw  x2, w2
mov   w4, 19200
add   x2, x2, x2, lsl 2
smull x1, w1, w4
lsl   x2, x2, 4
add   x3, x2, x3, sxtw
add   x0, x0, x3, lsl 2
ldr   w0, [x0,x1]
ret

```

Listing 18.57: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

f:
sll   $v0, $a1, 10
sll   $a1, 8
addu $a1, $v0
sll   $v0, $a2, 6
sll   $a2, 4
addu $a2, $v0
sll   $v0, $a1, 4
subu $a1, $v0, $a1
addu $a2, $a3
addu $a1, $a0, $a1
sll   $a2, 2
addu $a1, $a2
lw    $v0, 0($a1)
jr   $ra
or   $at, $zero

```

Answer [G.1.12 on page 980](#)

18.9.5 Exercise #5

What does this code do?

Listing 18.58: Optimizing MSVC 2012 /GS-

```

COMM  _tbl:DWORD:064H

tv759 = -4      ; size = 4
_main PROC
    push  ecx
    push  ebx
    push  ebp
    push  esi
    xor   edx, edx
    push  edi
    xor   esi, esi
    xor   edi, edi
    xor   ebx, ebx
    xor   ebp, ebp
    mov   DWORD PTR tv759[esp+20], edx
    mov   eax, OFFSET _tbl+4

```

```

npad    8 ; align next label
$LL6@main:
    lea      ecx, DWORD PTR [edx+edx]
    mov      DWORD PTR [eax+4], ecx
    mov      ecx, DWORD PTR tv759[esp+20]
    add      DWORD PTR tv759[esp+20], 3
    mov      DWORD PTR [eax+8], ecx
    lea      ecx, DWORD PTR [edx*4]
    mov      DWORD PTR [eax+12], ecx
    lea      ecx, DWORD PTR [edx*8]
    mov      DWORD PTR [eax], edx
    mov      DWORD PTR [eax+16], ebp
    mov      DWORD PTR [eax+20], ebx
    mov      DWORD PTR [eax+24], edi
    mov      DWORD PTR [eax+32], esi
    mov      DWORD PTR [eax-4], 0
    mov      DWORD PTR [eax+28], ecx
    add      eax, 40
    inc      edx
    add      ebp, 5
    add      ebx, 6
    add      edi, 7
    add      esi, 9
    cmp      eax, OFFSET _tbl+404
    jl      SHORT $LL6@main
    pop     edi
    pop     esi
    pop     ebp
    xor     eax, eax
    pop     ebx
    pop     ecx
    ret     0
_main    ENDP

```

Listing 18.59: Non-optimizing Keil 6/2013 (ARM mode)

```

main PROC
    LDR      r12, |L0.60|
    MOV      r1,#0
|L0.8|
    ADD      r2,r1,r1,LSL #2
    MOV      r0,#0
    ADD      r2,r12,r2,LSL #3
|L0.20|
    MUL      r3,r1,r0
    STR      r3,[r2,r0,LSL #2]
    ADD      r0,r0,#1
    CMP      r0,#0xa
    BLT      |L0.20|
    ADD      r1,r1,#1
    CMP      r1,#0xa
    MOVGE   r0,#0
    BLT      |L0.8|
    BX      lr
    ENDP

|L0.60|
    DCD      |||.bss||

    AREA |||.bss||, DATA, NOINIT, ALIGN=2

tbl
    %      400

```

Listing 18.60: Non-optimizing Keil 6/2013 (Thumb mode)

```

main PROC
    PUSH    {r4,r5,lr}
    LDR     r4, |L0.40|
    MOVS   r1,#0

```

```

|L0.6|
    MOVS    r2,#0x28
    MULS    r2,r1,r2
    MOVS    r0,#0
    ADDS    r3,r2,r4

|L0.14|
    MOVS    r2,r1
    MULS    r2,r0,r2
    LSLS    r5,r0,#2
    ADDS    r0,r0,#1
    CMP     r0,#0xa
    STR     r2,[r3,r5]
    BLT     |L0.14|
    ADDS    r1,r1,#1
    CMP     r1,#0xa
    BLT     |L0.6|
    MOVS    r0,#0
    POP    {r4,r5,pc}
    ENDP

    DCW    0x0000
|L0.40|
    DCD    || .bss ||

    AREA || .bss ||, DATA, NOINIT, ALIGN=2

tbl
%        400

```

Listing 18.61: Non-optimizing GCC 4.9 (ARM64)

```

.comm  tbl,400,8
main:
    sub    sp, sp, #16
    str    wzr, [sp,12]
    b     .L2
.L5:
    str    wzr, [sp,8]
    b     .L3
.L4:
    ldr    w1, [sp,12]
    ldr    w0, [sp,8]
    mul    w3, w1, w0
    adrp   x0, tbl
    add    x2, x0, :lo12:tbl
    ldrsw  x4, [sp,8]
    ldrsw  x1, [sp,12]
    mov    x0, x1
    lsl    x0, x0, 2
    add    x0, x0, x1
    lsl    x0, x0, 1
    add    x0, x0, x4
    str    w3, [x2,x0,lsl 2]
    ldr    w0, [sp,8]
    add    w0, w0, 1
    str    w0, [sp,8]
.L3:
    ldr    w0, [sp,8]
    cmp    w0, 9
    ble    .L4
    ldr    w0, [sp,12]
    add    w0, w0, 1
    str    w0, [sp,12]
.L2:
    ldr    w0, [sp,12]
    cmp    w0, 9
    ble    .L5
    mov    w0, 0
    add    sp, sp, 16
    ret

```

Listing 18.62: Non-optimizing GCC 4.4.5 (MIPS) (IDA)

```

main:

var_18      = -0x18
var_10      = -0x10
var_C       = -0xC
var_4       = -4

        addiu   $sp, -0x18
        sw      $fp, 0x18+var_4($sp)
        move    $fp, $sp
        la      $gp, __gnu_local_gp
        sw      $gp, 0x18+var_18($sp)
        sw      $zero, 0x18+var_C($fp)
        b      loc_A0
        or      $at, $zero

loc_24:           # CODE XREF: main+AC
        sw      $zero, 0x18+var_10($fp)
        b      loc_7C
        or      $at, $zero

loc_30:           # CODE XREF: main+88
        lw      $v0, 0x18+var_C($fp)
        lw      $a0, 0x18+var_10($fp)
        lw      $a1, 0x18+var_C($fp)
        lw      $v1, 0x18+var_10($fp)
        or      $at, $zero
        mult   $a1, $v1
        mflo   $a2
        lw      $v1, (tbl & 0xFFFF)($gp)
        sll   $v0, 1
        sll   $a1, $v0, 2
        addu  $v0, $a1
        addu  $v0, $a0
        sll   $v0, 2
        addu  $v0, $v1, $v0
        sw      $a2, 0($v0)
        lw      $v0, 0x18+var_10($fp)
        or      $at, $zero
        addiu $v0, 1
        sw      $v0, 0x18+var_10($fp)

loc_7C:           # CODE XREF: main+28
        lw      $v0, 0x18+var_10($fp)
        or      $at, $zero
        slti  $v0, 0xA
        bnez  $v0, loc_30
        or      $at, $zero
        lw      $v0, 0x18+var_C($fp)
        or      $at, $zero
        addiu $v0, 1
        sw      $v0, 0x18+var_C($fp)

loc_A0:           # CODE XREF: main+1C
        lw      $v0, 0x18+var_C($fp)
        or      $at, $zero
        slti  $v0, 0xA
        bnez  $v0, loc_24
        or      $at, $zero
        move   $v0, $zero
        move   $sp, $fp
        lw      $fp, 0x18+var_4($sp)
        addiu $sp, 0x18
        jr      $ra
        or      $at, $zero

.comm  tbl:0x64          # DATA XREF: main+4C

```

Answer [G.1.12 on page 981](#)

Chapter 19

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.

19.1 Specific bit checking

19.1.1 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 19.1: MSVC 2010

```
push    0
push    128
push    4
push    0
push    1
push    -1073741824
push    OFFSET $SG78813
call    DWORD PTR __imp__CreateFileA@28
mov     DWORD PTR _fh$[ebp], eax
```

Let's take a look in WinNT.h:

Listing 19.2: 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`:

Listing 19.3: 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
```

¹[msdn.microsoft.com/en-us/library/aa363858\(VS.85\).aspx](http://msdn.microsoft.com/en-us/library/aa363858(VS.85).aspx)

Here we see the TEST instruction, however it doesn't take the whole second argument, but only the most significant byte ($\text{ebp} + \text{dwDesiredAccess} + 3$) 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 ([7.3.1 on page 79](#))).

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 19.4: 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, 0FFFFFFF0h
sub    esp, 20h
mov    [esp+20h+var_1C], 42h
mov    [esp+20h+var_20], offset aFile ; "file"
call   _open
mov    [esp+20h+var_4], eax
leave
retn
main          endp
```

If we take a look in the open() function in the libc.so.6 library, it is only a syscall:

Listing 19.5: 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.

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 ([64.3 on page 682](#)). This works faster since CPU does not need to access the stack in memory to read argument values. GCC has the option *regparm*², through which it's possible to set the number of arguments that can be passed via registers.

²ohse.de/uwe/articles/gcc-attributes.html#func-regparm

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 19.6: `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 19.7: `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.

19.1.2 ARM

The `O_CREAT` bit is checked differently in Linux kernel 3.8.0.

Listing 19.8: linux kernel 3.8.0

```
struct file *do_filp_open(int dfd, struct filename *pathname,
                         const struct open_flags *op)
{
...
    filp = path_openat(dfd, pathname, &nd, op, flags | LOOKUP_RCU);
...
}

static struct file *path_openat(int dfd, struct filename *pathname,
                               struct nameidata *nd, const struct open_flags *op, int flags)
{
...
    error = do_last(nd, &path, file, op, &opened, pathname);
...
```

³kernelnewbies.org/Linux_2_6_20#head-042c62f290834eb1fe0a1942bbf5bb9a4accbc8f

⁴See also `arch/x86/include/asm/calling.h` file in kernel tree

```

}

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 19.9: do_last() (vmlinux)

```

...
.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.

19.2 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);
}
```

19.2.1 x86

Non-optimizing MSVC

We get (MSVC 2010):

Listing 19.10: 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 (00000000000000000000000000000000) (i.e., the 10th bit (counting from 1st)).

Inverted 0x200 is 0xFFFFFDFF (111111111111111111111111).

0x4000 (00000000000000001000000000000000) (i.e., the 15th bit).

The input value is: 0x12340678 (1001000110100000011001111000). We see how it's loaded:

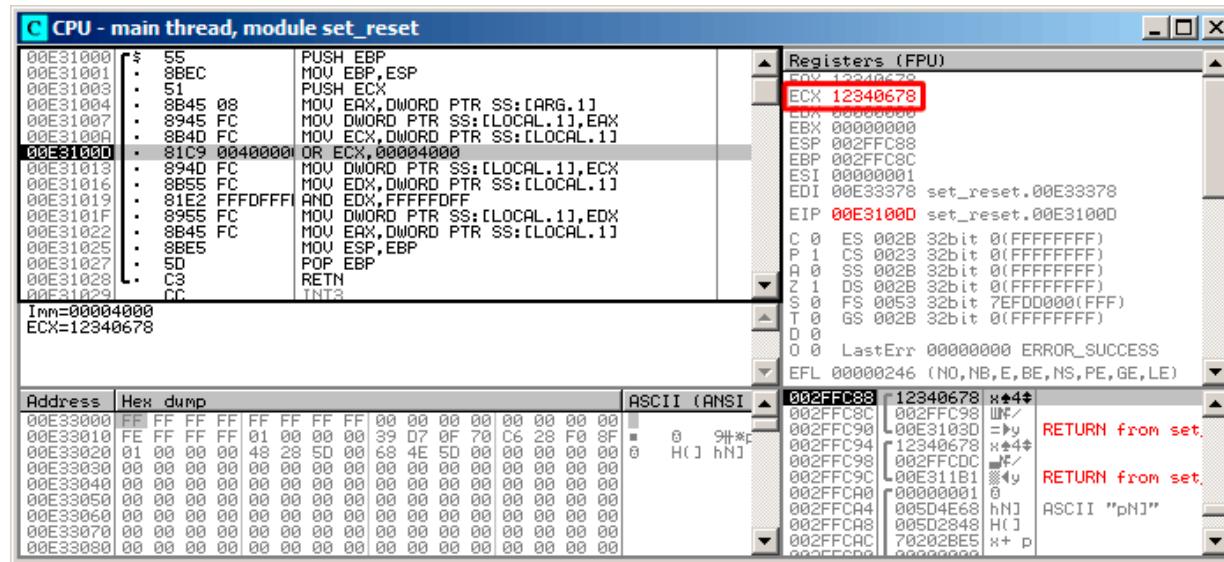


Figure 19.1: OllyDbg: value is loaded into ECX

OR got executed:

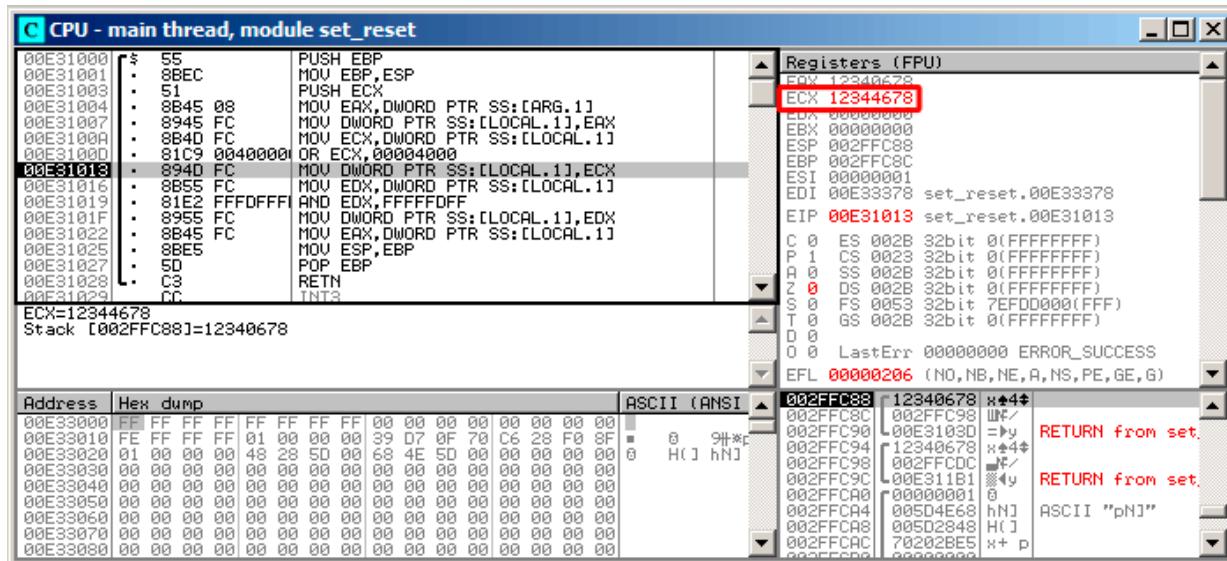


Figure 19.2: OllyDbg: OR executed

15th bit is set: 0x12344678 (10010001101000100011001111000).

The value is reloaded again (because the compiler is not in optimizing mode):

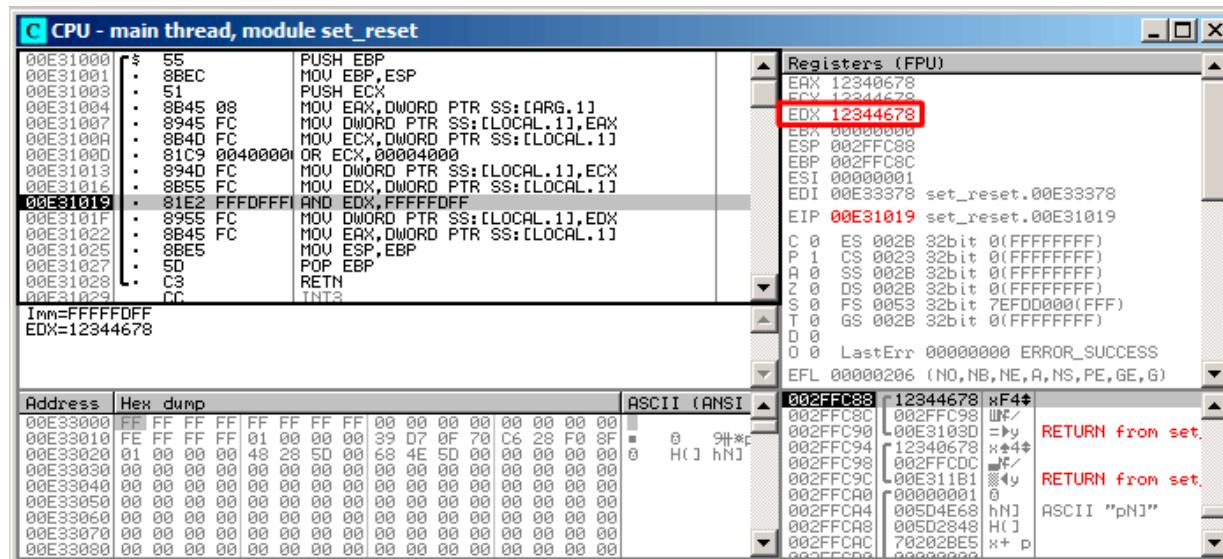


Figure 19.3: OllyDbg: value was reloaded into EDX

AND got executed:

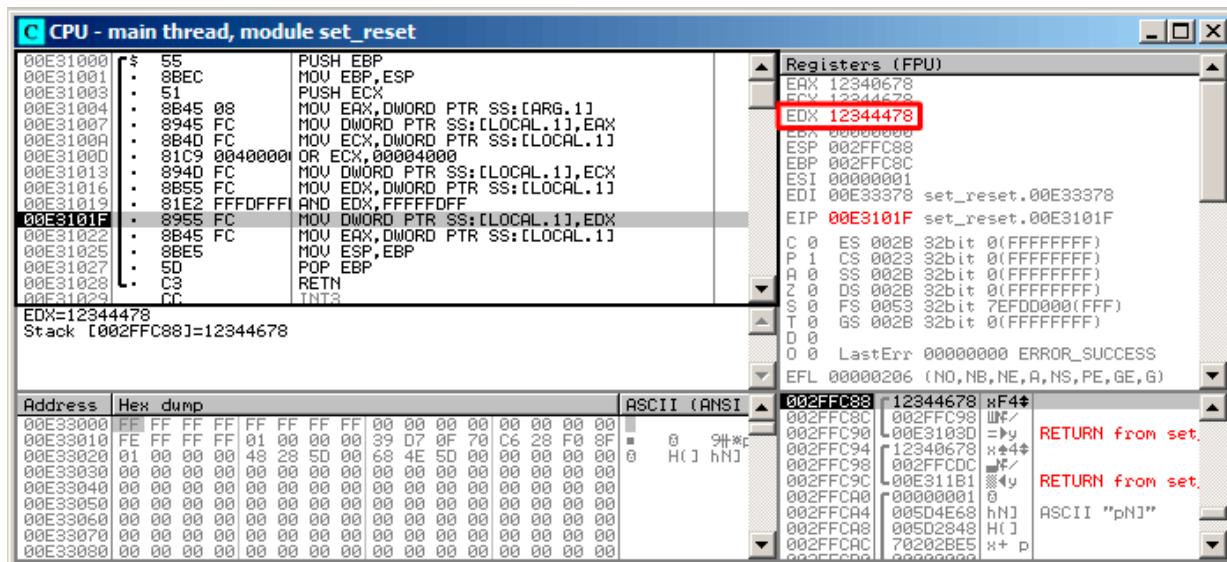


Figure 19.4: OllyDbg: AND executed

The 10th bit was cleared (or, in other words, all bits were left except the 10th) and the final value now is 0x12344478 (1001000110100010001111000).

Optimizing MSVC

If we compile it in MSVC with optimization turned on (/Ox), the code is even shorter:

Listing 19.11: 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 19.12: Non-optimizing GCC

```
public f
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
f endp
```

There is a redundant code present, however, it is shorter than the MSVC version without optimization.

Now let's try GCC with optimization turned on -O3:

Optimizing GCC

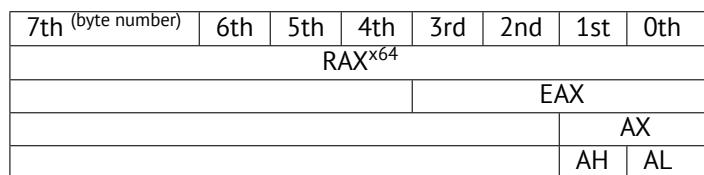
Listing 19.13: Optimizing GCC

```

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.



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 19.14: 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* ([43 on page 515](#)).

19.2.2 ARM + Optimizing Keil 6/2013 (ARM mode)

Listing 19.15: 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` (*Bltwise 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.

19.2.3 ARM + Optimizing Keil 6/2013 (Thumb mode)

Listing 19.16: 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 $0x4000 \gg 5$.

19.2.4 ARM + Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 19.17: 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 ([91 on page 891](#)).

Optimizing Xcode 4.6.3 (LLVM) for Thumb mode generates the same code.

19.2.5 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:

```

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.

19.2.6 ARM64: Optimizing GCC (Linaro) 4.9

Optimizing GCCcompiling for ARM64 can use the AND instruction instead of BIC:

⁵It was LLVM build 2410.2.00 bundled with Apple Xcode 4.6.3

Listing 19.18: Optimizing GCC (Linaro) 4.9

```
f:
    and    w0, w0, -513      ; 0xFFFFFFFFFFFFFDFF
    orr    w0, w0, 16384     ; 0x4000
    ret
```

19.2.7 ARM64: Non-optimizing GCC (Linaro) 4.9

Non-optimizing GCC generates more redundant code, but works just like optimized:

Listing 19.19: 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
```

19.2.8 MIPS

Listing 19.20: Optimizing GCC 4.4.5 (IDA)

```
f:
; $a0=a
; $a0=a|0x4000
        ori    $a0, 0x4000
        li     $v0, 0xFFFFFDFF
        jr     $ra
        and   $v0, $a0, $v0
; at finish: $v0 = $a0&$v0 = a|0x4000 & 0xFFFFFDFF
```

ORI is, of course, the OR operation. “I” 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.

19.3 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): [16.1.2 on page 207](#), [16.2.1 on page 212](#).

Shifting operations are also so important because they are often used for specific bit isolation or for constructing a value of several scattered bits.

19.4 Setting and clearing specific bits: FPU example

Here is how bits are located in the *float* type in IEEE 754 form:

S	exponent	mantissa or fraction
---	----------	----------------------

(S-sign)

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.

19.4.1 A word about the XOR operation

XOR is widely used when one need just to flip specific bit(s). Indeed, the XOR operation applied with 1 is effectively inverting a bit:

input A	input B	output
0	0	0
0	1	1
1	0	1
1	1	0

And on the contrary, 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.

19.4.2 x86

The code is pretty straightforward:

Listing 19.21: Optimizing MSVC 2012

```
_tmp$ = 8
_i$ = 8
_my_abs PROC
```

⁶Most significant bit/byte

```

        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 19.22: 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

```

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.

19.4.3 MIPS

GCC 4.4.5 for MIPS does mostly the same:

Listing 19.23: 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.

19.4.4 ARM

Optimizing Keil 6/2013 (ARM mode)

Listing 19.24: 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 19.25: 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: $1 << 31 = 0x80000000$.

The code of my_abs is weird and it effectively works like this expression: $(i << 1) >> 1$. This statement looks meaningless. But nevertheless, when *input* $<< 1$ is executed, the **MSB** (sign bit) is just dropped. When the subsequent *result* $>> 1$ 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 19.26: 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
; 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 `10000000000000000000000000000000`, 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 10 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.

19.5 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()
{
    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 $i = 0 \dots 31$:

⁷modern x86 CPUs (supporting SSE4) even have a POPCNT instruction for it

C/C++ expression	Power of two	Decimal form	Hexadecimal form
$1 \ll 0$	1	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_STDENVVARS    (1<<1)
#define SSL_OPT_EXPORTCERTDATA (1<<3)
#define SSL_OPT_FAKEBASICAUTH (1<<4)
#define SSL_OPT_STRICTREQUIRE (1<<5)
#define SSL_OPT_OPTRENEGOTIATE (1<<6)
#define SSL_OPT_LEGACYDNFORMAT (1<<7)
```

Let's get back to our example.

The `IS_SET` macro checks bit presence in `a`. 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.

19.5.1 x86

MSVC

Let's compile (MSVC 2010):

Listing 19.27: 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              ; EDX=EDX<<CL
    and   edx, DWORD PTR _a$[ebp]
    je    SHORT $LN1@f          ; result of AND instruction was 0?
                                ; then skip next instructions
    mov   eax, DWORD PTR _rt$[ebp]
    add   eax, 1                ; no, not zero
    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:

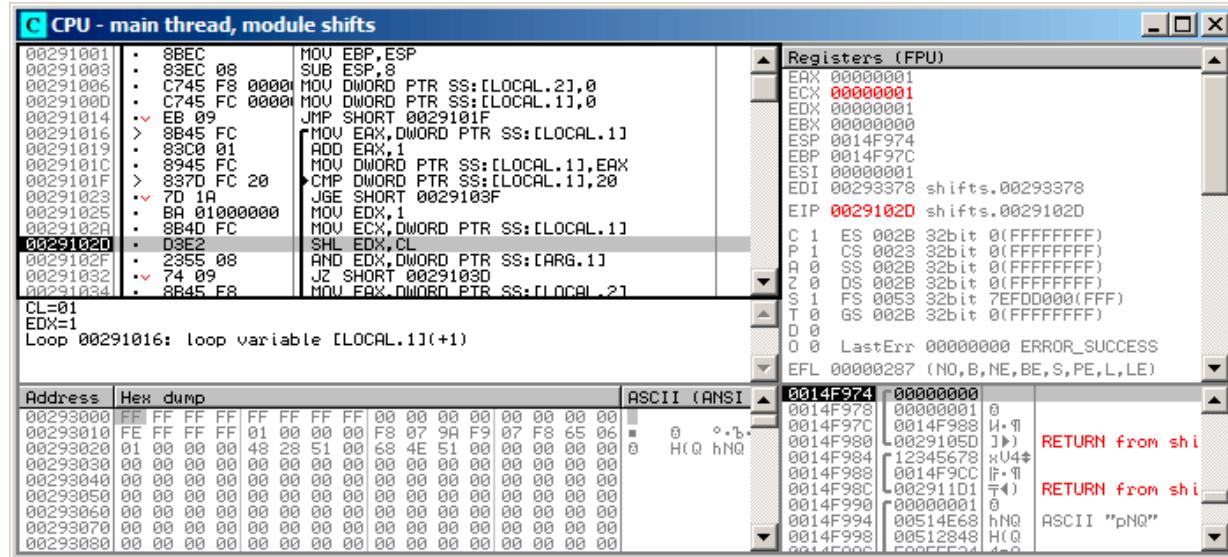


Figure 19.5: OllyDbg: $i = 1$, i is loaded into ECX

EDX is 1. SHL is to be executed now.

SHL was executed:

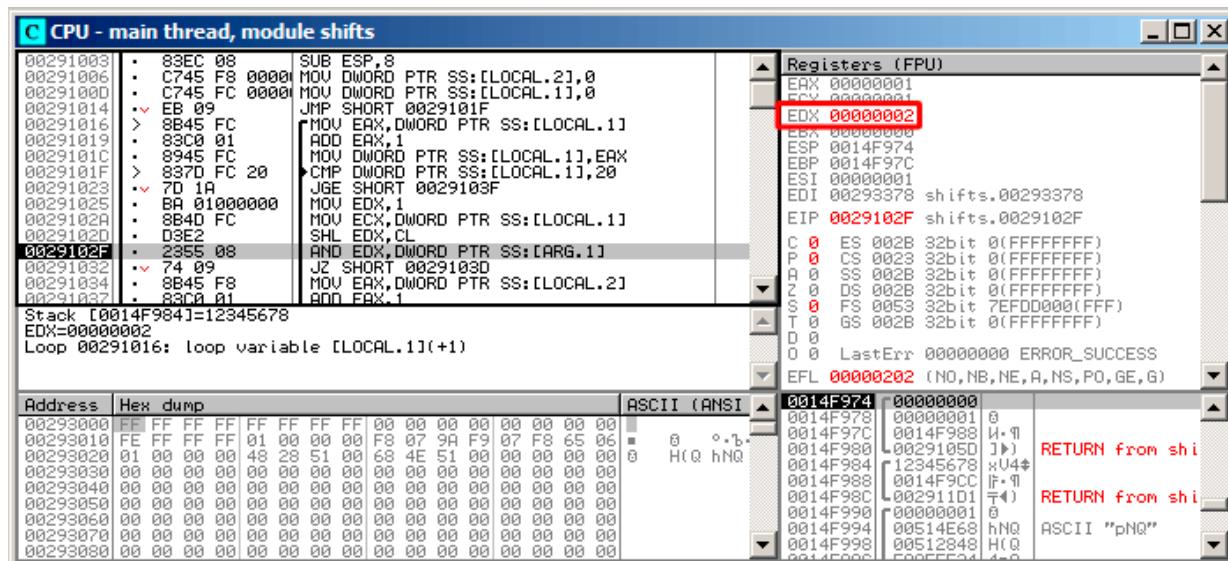


Figure 19.6: OllyDbg: $i = 1$, EDX = 1 << 1 = 2

EDX contain $1 \ll 1$ (or 2). This is a bit mask.

AND sets ZF to 1, which implies that the input value (0x12345678) ANDed with 2 results in 0:

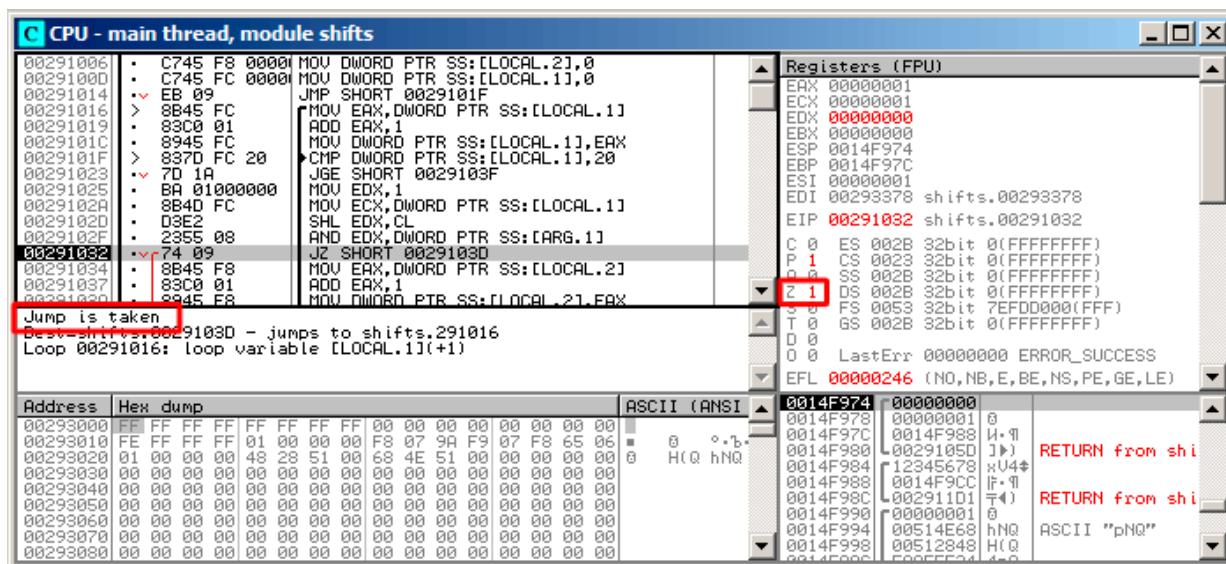


Figure 19.7: OllyDbg: $i = 1$, is there that bit in the input value? No. (ZF =1)

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.

Let's trace a bit further and i is now 4. SHL is to be executed now:

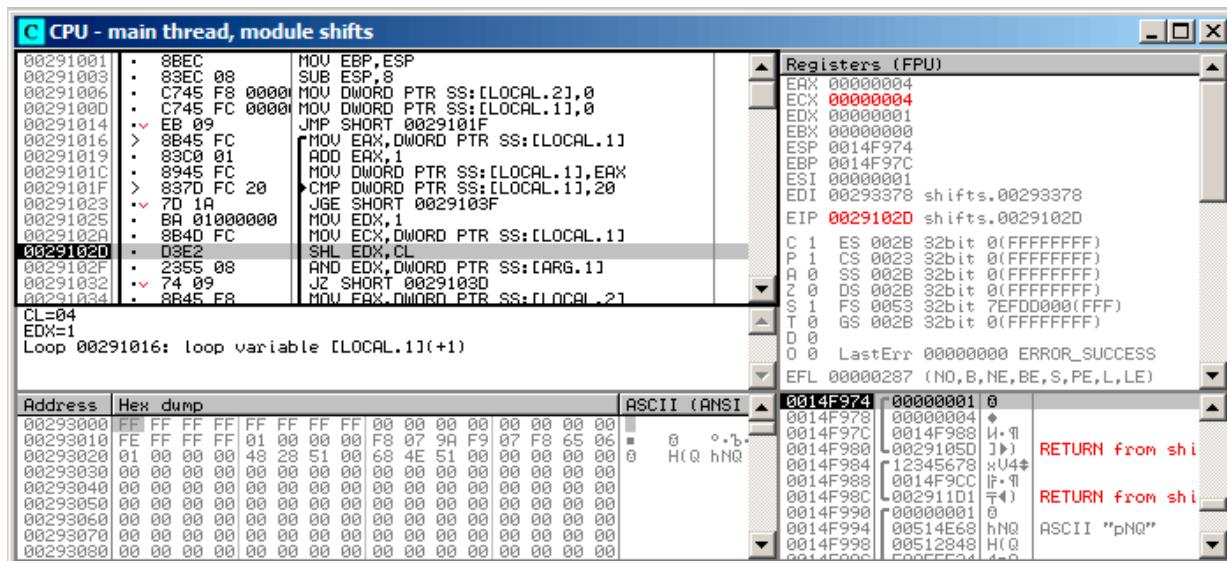


Figure 19.8: OllyDbg: $i = 4$, i is loaded into ECX

EDX =1 << 4 (or 0x10 or 16):

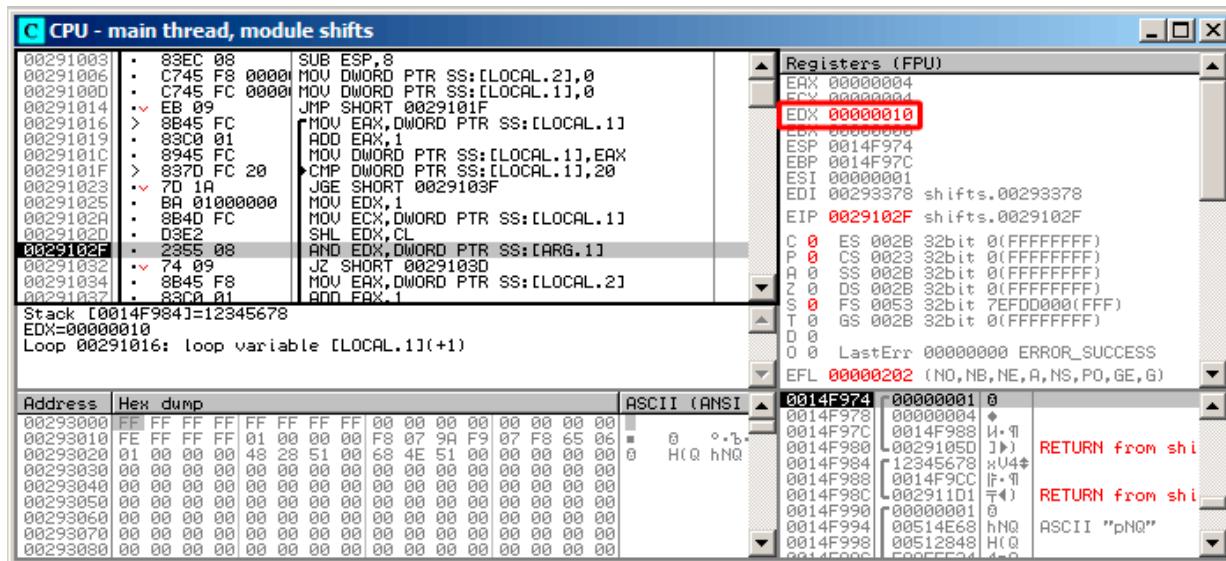


Figure 19.9: OllyDbg: $i = 4$, EDX = 1 << 4 = 0x10

This is another bit mask.

AND is executed:

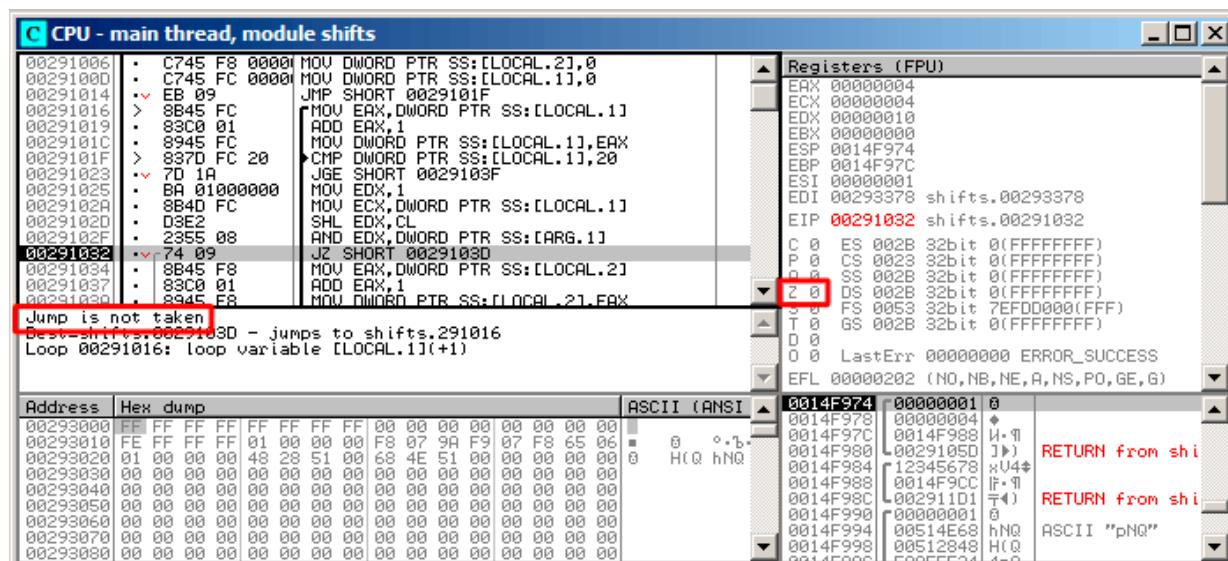


Figure 19.10: OllyDbg: $i = 4$, is there that bit in the input value? Yes. ($ZF = 0$)

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 19.28: GCC 4.4.1

```

f          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
          pop    ebx

```

```

        pop      ebp
        retn
f         endp

```

19.5.2 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 19.29: 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 19.30: 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 CMOVNE⁸ instruction (which is a synonym for CMOVNZ⁹) *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: [33.1 on page 469](#).

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 19.31: 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
$L14@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 $L14@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.

You can read more about the rotate instruction here: [A.6.3 on page 963](#).

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:

⁸Conditional MOVe if Not Equal

⁹Conditional MOVe if Not Zero

¹⁰More information on it: <http://go.yurichev.com/17328>

RDX	R8
0x0000000000000001	64
0x0000000000000002	63
0x0000000000000004	62
0x0000000000000008	61
...	...
0x4000000000000000	2
0x8000000000000000	1

At the end we see the FATRET instruction, which was explained here: [19.5.2 on the preceding page](#).

Optimizing MSVC 2012

Listing 19.32: 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.

19.5.3 ARM + Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

Listing 19.33: Optimizing Xcode 4.6.3 (LLVM) (ARM mode)

```
MOV      R1, R0
MOV      R0, #0
MOV      R2, #1
MOV      R3, R0
loc_2E54
TST      R1, R2,LSL R3 ; set flags according to R1 & (R2<<R3)
ADD      R3, R3, #1      ; R3++
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 ([41.2.1 on page 503](#)), 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, RSB¹¹.

These modifiers define how to shift the second operand and by how many bits.

Thus the “TST R1, R2, LSL R3” instruction works here as $R1 \wedge (R2 \ll R3)$.

19.5.4 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

```

19.5.5 ARM64 + Optimizing GCC 4.9

Let's take the 64-bit example which has been already used: [19.5.2 on page 337](#).

Listing 19.34: 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: [19.30 on page 338](#).

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.

19.5.6 ARM64 + Non-optimizing GCC 4.9

And again, we'll work on the 64-bit example which was already used: [19.5.2 on page 337](#).

The code is more verbose, as usual.

Listing 19.35: Non-optimizing GCC (Linaro) 4.8

```

f:
    sub    sp, sp, #32

```

¹¹These instructions are also called “data processing instructions”

```

    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

```

19.5.7 MIPS

Non-optimizing GCC

Listing 19.36: 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: [3.1 on page 469](#).

Listing 19.37: 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

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

```

19.6 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").

19.6.1 Check for specific bit (known at compile stage)

Test if the 1000000 bit (0x40) is present in the register's value:

Listing 19.38: C/C++

```

if (input&0x40)
...

```

Listing 19.39: x86

```

TEST REG, 40h
JNZ is_set
; bit is not set

```

Listing 19.40: x86

```

TEST REG, 40h
JZ is_cleared
; bit is set

```

Listing 19.41: 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.

19.6.2 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 19.42: C/C++

```

if ((value>>n)&1)
...

```

This is usually implemented in x86 code as:

Listing 19.43: 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 19.44: C/C++

```
if (value & (1<<n))
    ....
```

This is usually implemented in x86 code as:

Listing 19.45: x86

```
; CL=n
MOV REG, 1
SHL REG, CL
AND input_value, REG
```

19.6.3 Set specific bit (known at compile stage)

Listing 19.46: C/C++

```
value=value|0x40;
```

Listing 19.47: x86

```
OR REG, 40h
```

Listing 19.48: ARM (ARM mode) and ARM64

```
ORR R0, R0, #0x40
```

19.6.4 Set specific bit (specified at runtime)

Listing 19.49: C/C++

```
value=value|(1<<n);
```

This is usually implemented in x86 code as:

Listing 19.50: x86

```
; CL=n
MOV REG, 1
SHL REG, CL
OR input_value, REG
```

19.6.5 Clear specific bit (known at compile stage)

Just apply AND operation with the inverted value:

Listing 19.51: C/C++

```
value=value&(~0x40);
```

Listing 19.52: x86

```
AND REG, 0FFFFFFFBFh
```

Listing 19.53: x64

```
AND REG, 0xFFFFFFFFFFFFFFFBFh
```

This is actually leaving all bits set except one.

ARM in ARM mode has BIC instruction, which works like the NOT +AND instruction pair:

Listing 19.54: ARM (ARM mode)

```
BIC R0, R0, #0x40
```

19.6.6 Clear specific bit (specified at runtime)

Listing 19.55: C/C++

```
value=value&(~(1<<n));
```

Listing 19.56: x86

```
; CL=n
MOV REG, 1
SHL REG, CL
NOT REG
AND input_value, REG
```

19.7 Exercises

19.7.1 Exercise #1

What does this code do?

Listing 19.57: Optimizing MSVC 2010

```
_a$ = 8
_f PROC
    mov     ecx, DWORD PTR _a$[esp-4]
    mov     eax, ecx
    mov     edx, ecx
    shl     edx, 16          ; 00000010H
    and    eax, 65280        ; 0000ff00H
    or      eax, edx
    mov     edx, ecx
    and    edx, 16711680     ; 00ff0000H
    shr     ecx, 16          ; 00000010H
    or      edx, ecx
    shl     eax, 8
    shr     edx, 8
    or      eax, edx
    ret    0
_f ENDP
```

Listing 19.58: Optimizing Keil 6/2013 (ARM mode)

```
f PROC
    MOV    r1,#0xff0000
    AND    r1,r1,r0,LSL #8
    MOV    r2,#0xff00
    ORR    r1,r1,r0,LSR #24
    AND    r2,r2,r0,LSR #8
    ORR    r1,r1,r2
    ORR    r0,r1,r0,LSL #24
    BX    lr
ENDP
```

Listing 19.59: Optimizing Keil 6/2013 (Thumb mode)

```
f PROC
    MOVS   r3,#0xff
    LSLS   r2,r0,#8
    LSLS   r3,r3,#16
    ANDS   r2,r2,r3
    LSRS   r1,r0,#24
    ORRS   r1,r1,r2
    LSRS   r2,r0,#8
    ASRS   r3,r3,#8
    ANDS   r2,r2,r3
    ORRS   r1,r1,r2
    LSLS   r0,r0,#24
```

```
ORRS      r0,r0,r1
BX       lr
ENDP
```

Listing 19.60: Optimizing GCC 4.9 (ARM64)

```
f:
    rev    w0, w0
    ret
```

Listing 19.61: Optimizing GCC 4.4.5 (MIPS) (IDA)

```
f:
    srl    $v0, $a0, 24
    sll    $v1, $a0, 24
    sll    $a1, $a0, 8
    or     $v1, $v0
    lui    $v0, 0xFF
    and   $v0, $a1, $v0
    srl    $a0, 8
    or     $v0, $v1, $v0
    andi  $a0, 0xFF00
    jr    $ra
    or     $v0, $a0
```

Answer: [G.1.13 on page 981.](#)

19.7.2 Exercise #2

What does this code do?

Listing 19.62: Optimizing MSVC 2010

```
_a$ = 8                                ; size = 4
_f PROC
    push    esi
    mov     esi, DWORD PTR _a$[esp]
    xor     ecx, ecx
    push    edi
    lea     edx, DWORD PTR [ecx+1]
    xor     eax, eax
    npad   3 ; align next label
$LL3@f:
    mov     edi, esi
    shr     edi, cl
    add     ecx, 4
    and     edi, 15
    imul   edi, edx
    lea     edx, DWORD PTR [edx+edx*4]
    add     eax, edi
    add     edx, edx
    cmp     ecx, 28
    jle     SHORT $LL3@f
    pop     edi
    pop     esi
    ret     0
_f ENDP
```

Listing 19.63: Optimizing Keil 6/2013 (ARM mode)

```
f PROC
    MOV    r3,r0
    MOV    r1,#0
    MOV    r2,#1
    MOV    r0,r1
|L0.16|
    LSR    r12,r3,r1
    AND    r12,r12,#0xf
    MLA    r0,r12,r2,r0
```

```

ADD      r1,r1,#4
ADD      r2,r2,r2,LSL #2
CMP      r1,#0x1c
LSL      r2,r2,#1
BLE      |L0.16|
BX       lr
ENDP

```

Listing 19.64: Optimizing Keil 6/2013 (Thumb mode)

```

f PROC
    PUSH   {r4,lr}
    MOVS   r3,r0
    MOVS   r1,#0
    MOVS   r2,#1
    MOVS   r0,r1
|L0.10|
    MOVS   r4,r3
    LSRS   r4,r4,r1
    LSLS   r4,r4,#28
    LSRS   r4,r4,#28
    MULS   r4,r2,r4
    ADDS   r0,r4,r0
    MOVS   r4,#0xa
    MULS   r2,r4,r2
    ADDS   r1,r1,#4
    CMP    r1,#0x1c
    BLE    |L0.10|
    POP    {r4,pc}
ENDP

```

Listing 19.65: Non-optimizing GCC 4.9 (ARM64)

```

f:
    sub   sp, sp, #32
    str   w0, [sp,12]
    str   wzr, [sp,28]
    mov   w0, 1
    str   w0, [sp,24]
    str   wzr, [sp,20]
    b     .L2
.L3:
    ldr   w0, [sp,28]
    ldr   w1, [sp,12]
    lsr   w0, w1, w0
    and  w1, w0, 15
    ldr   w0, [sp,24]
    mul   w0, w1, w0
    ldr   w1, [sp,20]
    add   w0, w1, w0
    str   w0, [sp,20]
    ldr   w0, [sp,28]
    add   w0, w0, 4
    str   w0, [sp,28]
    ldr   w1, [sp,24]
    mov   w0, w1
    lsl   w0, w0, 2
    add   w0, w0, w1
    lsl   w0, w0, 1
    str   w0, [sp,24]
.L2:
    ldr   w0, [sp,28]
    cmp   w0, 28
    ble   .L3
    ldr   w0, [sp,20]
    add   sp, sp, 32
    ret

```

Listing 19.66: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

f:
    srl    $v0, $a0, 8
    srl    $a3, $a0, 20
    andi   $a3, 0xF
    andi   $v0, 0xF
    srl    $a1, $a0, 12
    srl    $a2, $a0, 16
    andi   $a1, 0xF
    andi   $a2, 0xF
    sll    $t2, $v0, 4
    sll    $v1, $a3, 2
    sll    $t0, $v0, 2
    srl    $t1, $a0, 4
    sll    $t5, $a3, 7
    addu   $t0, $t2
    subu   $t5, $v1
    andi   $t1, 0xF
    srl    $v1, $a0, 28
    sll    $t4, $a1, 7
    sll    $t2, $a2, 2
    sll    $t3, $a1, 2
    sll    $t7, $a2, 7
    srl    $v0, $a0, 24
    addu   $a3, $t5, $a3
    subu   $t3, $t4, $t3
    subu   $t7, $t2
    andi   $v0, 0xF
    sll    $t5, $t1, 3
    sll    $t6, $v1, 8
    sll    $t2, $t0, 2
    sll    $t4, $t1, 1
    sll    $t1, $v1, 3
    addu   $a2, $t7, $a2
    subu   $t1, $t6, $t1
    addu   $t2, $t0, $t2
    addu   $t4, $t5
    addu   $a1, $t3, $a1
    sll    $t5, $a3, 2
    sll    $t3, $v0, 8
    sll    $t0, $v0, 3
    addu   $a3, $t5
    subu   $t0, $t3, $t0
    addu   $t4, $t2, $t4
    sll    $t3, $a2, 2
    sll    $t2, $t1, 6
    sll    $a1, 3
    addu   $a1, $t4, $a1
    subu   $t1, $t2, $t1
    addu   $a2, $t3
    sll    $t2, $t0, 6
    sll    $t3, $a3, 2
    andi   $a0, 0xF
    addu   $v1, $t1, $v1
    addu   $a0, $a1
    addu   $a3, $t3
    subu   $t0, $t2, $t0
    sll    $a2, 4
    addu   $a2, $a0, $a2
    addu   $v0, $t0, $v0
    sll    $a1, $v1, 2
    sll    $a3, 5
    addu   $a3, $a2, $a3
    addu   $v1, $a1
    sll    $v0, 6
    addu   $v0, $a3, $v0
    sll    $v1, 7
    jr    $ra
    addu   $v0, $v1, $v0

```

Answer: G.1.13 on page 981.

19.7.3 Exercise #3

Using the [MSDN¹²](#) documentation, find out which flags were used in the `MessageBox()` win32 function call.

Listing 19.67: Optimizing MSVC 2010

```
_main PROC
    push    278595          ; 00044043H
    push    OFFSET $SG79792 ; 'caption'
    push    OFFSET $SG79793 ; 'hello, world!'
    push    0
    call    DWORD PTR __imp__MessageBoxA@16
    xor     eax, eax
    ret    0
_main ENDP
```

Answer: [G.1.13 on page 981](#).

19.7.4 Exercise #4

What does this code do?

Listing 19.68: Optimizing MSVC 2010

```
_m$ = 8           ; size = 4
_n$ = 12          ; size = 4
_f    PROC
    mov     ecx, DWORD PTR _n$[esp-4]
    xor     eax, eax
    xor     edx, edx
    test   ecx, ecx
    je      SHORT $LN2@f
    push   esi
    mov     esi, DWORD PTR _m$[esp]
$LL3@f:
    test   cl, 1
    je      SHORT $LN1@f
    add    eax, esi
    adc    edx, 0
$LN1@f:
    add    esi, esi
    shr    ecx, 1
    jne   SHORT $LL3@f
    pop    esi
$LN2@f:
    ret    0
_f    ENDP
```

Listing 19.69: Optimizing Keil 6/2013 (ARM mode)

```
f PROC
    PUSH   {r4,lr}
    MOV    r3,r0
    MOV    r0,#0
    MOV    r2,r0
    MOV    r12,r0
    B     |L0.48|
|L0.24|
    TST    r1,#1
    BEQ   |L0.40|
    ADDS  r0,r0,r3
    ADC   r2,r2,r12
|L0.40|
    LSL    r3,r3,#1
    LSR    r1,r1,#1
|L0.48|
    CMP    r1,#0
    MOVEQ r1,r2
```

¹²Microsoft Developer Network

```

BNE      |L0.24|
POP      {r4,pc}
ENDP

```

Listing 19.70: Optimizing Keil 6/2013 (Thumb mode)

```

f PROC
    PUSH   {r4,r5,lr}
    MOVS   r3,r0
    MOVS   r0,#0
    MOVS   r2,r0
    MOVS   r4,r0
    B      |L0.24|
|L0.12|
    LSLS   r5,r1,#31
    BEQ    |L0.20|
    ADDS   r0,r0,r3
    ADCS   r2,r2,r4
|L0.20|
    LSLS   r3,r3,#1
    LSRS   r1,r1,#1
|L0.24|
    CMP    r1,#0
    BNE    |L0.12|
    MOVS   r1,r2
    POP    {r4,r5,pc}
    ENDP

```

Listing 19.71: Optimizing GCC 4.9 (ARM64)

```

f:
    mov    w2, w0
    mov    x0, 0
    cbz    w1, .L2
.L3:
    and    w3, w1, 1
    lsr    w1, w1, 1
    cmp    w3, wzr
    add    x3, x0, x2, uxtw
    lsl    w2, w2, 1
    csel   x0, x3, x0, ne
    cbnz   w1, .L3
.L2:
    ret

```

Listing 19.72: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

mult:
    beqz   $a1, loc_40
    move   $a3, $zero
    move   $a2, $zero
    addu   $t0, $a3, $a0

loc_10:                                # CODE XREF: mult+38
    sltu   $t1, $t0, $a3
    move   $v1, $t0
    andi   $t0, $a1, 1
    addu   $t1, $a2
    beqz   $t0, loc_30
    srl   $a1, 1
    move   $a3, $v1
    move   $a2, $t1

loc_30:                                # CODE XREF: mult+20
    beqz   $a1, loc_44
    sll   $a0, 1
    b     loc_10
    addu   $t0, $a3, $a0
loc_40:                                # CODE XREF: mult
    move   $a2, $zero

```

```
loc_44:          # CODE XREF: mult:loc_30
    move    $v0, $a2
    jr     $ra
    move    $v1, $a3
```

Answer: [G.1.13 on page 982](#).

Chapter 20

Linear congruential generator as pseudorandom number generator

The linear congruential 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.

20.1 x86

Listing 20.1: Optimizing MSVC 2013

```
_BSS      SEGMENT
_rand_state DD 01H DUP (?)
_BSS      ENDS

_init$ = 8
_srand  PROC
        mov     eax, DWORD PTR _init$[esp-4]
        mov     DWORD PTR _rand_state, eax
```

¹Mersenne twister is better

```

    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 20.2: 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

```

20.2 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 20.3: Optimizing MSVC 2013 x64

```

_BSS  SEGMENT
rand_state DD 01H DUP (?)
_BSS  ENDS

init$ = 8
my_srand PROC
; ECX = input argument
    mov    DWORD PTR rand_state, ecx

```

```

        ret    0
my_srand ENDP

_TEXT  SEGMENT
my_rand PROC
    imul    eax, DWORD PTR rand_state, 1664525      ; 0019660dH
    add     eax, 1013904223                          ; 3c6ef35fH
    mov     DWORD PTR rand_state, eax
    and     eax, 32767                                ; 00007fffH
    ret    0
my_rand ENDP

_TEXT  ENDS

```

GCC compiler generates mostly the same code.

20.3 32-bit ARM

Listing 20.4: 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.

20.4 MIPS

Listing 20.5: 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 20.6: 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!

20.4.1 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 20.7: 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.

20.5 Thread-safe version of the example

The thread-safe version of the example is to be demonstrated later: [65.1 on page 689](#).

Chapter 21

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.

21.1 MSVC: SYSTEMTIME example

Let's take the SYSTEMTIME² win32 structure that describes time.

This is how it's defined:

Listing 21.1: 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 21.2: MSVC 2010 /GS-

```
_t$ = -16 ; size = 16
_main      PROC
    push    ebp
    mov     ebp, esp
    sub     esp, 16
    lea     eax, DWORD PTR _t$[ebp]
```

¹AKA “heterogeneous container”

²MSDN: SYSTEMTIME structure

```

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

21.1.1 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:

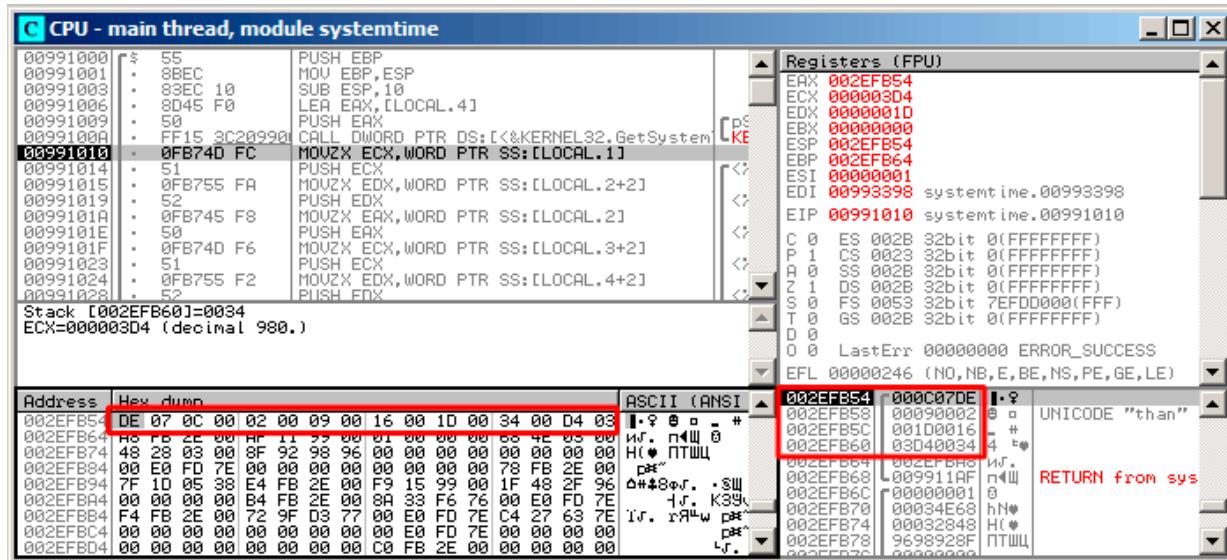


Figure 21.1: OllyDbg: `GetSystemTime()` just executed

The system time of the function execution on my computer is 9 december 2014, 22:29:52:

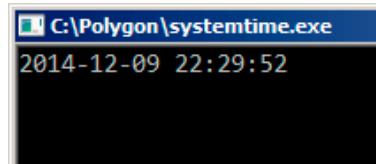


Figure 21.2: OllyDbg: `printf()` output

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.

21.1.2 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 21.3: 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.

21.2 Let's allocate space for a structure using malloc()

Sometimes it is simpler to place structures not 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 21.4: 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).

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 21.5: 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.

21.3 UNIX: struct tm

21.3.1 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 21.6: 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
    retn
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 957](#)).

GDB

Let's try to load the example into GDB ⁴:

Listing 21.7: 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 21.8: 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
0xbffff10c:	0x00000001	wday	0x00000098	yday 0x00000001 isdst 0x00002a30
0xbffff11c:	0x0804b090		0x08048530	0x00000000 0x00000000

Or as a table:

⁴The *date* result is slightly corrected for demonstration purposes. Of course, it's not possible to run GDB that quickly, in the same second.

	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 ([21.1 on page 357](#)), there are also other fields available that are not used, like tm_wday, tm_yday, tm_isdst.

21.3.2 ARM

Optimizing Keil 6/2013 (Thumb mode)

Same example:

Listing 21.9: 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 21.10: 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

```

21.3.3 MIPS

Listing 21.11: Optimizing GCC 4.4.5 (IDA)

```

1 main:
2
3 ; IDA is not aware of structure field names, we named them manually:
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>"
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.

21.3.4 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 21.8.

```
#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 21.12: 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 21.13: 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
        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” ([21.4 on page 372](#)).

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.

21.3.5 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);

    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: [21.8 on page 364](#).

Here is how it gets compiled:

Listing 21.14: 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.

21.3.6 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 ([21.3.5 on the previous page](#)), and of course, the lowest byte goes first, because this is a little-endian architecture ([31 on page 466](#)).

Listing 21.15: 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
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
```

⁵The time and date are the same for demonstration purposes. Byte values are fixed up.

```
; 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
```

21.4 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).

21.4.1 x86

This compiles to:

Listing 21.16: MSVC 2012 /GS- /Ob0

```
1 _tmp$ = -16
2 _main    PROC
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
```

⁶See also: [Wikipedia: Data structure alignment](#)

```

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 21.17: 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
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: [43.1.5 on page 520](#).

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 21.18: WinNT.h

```
#include "pshpack1.h"
```

And this:

Listing 21.19: WinNT.h

```
#include "pshpack4.h"           // 4 byte packing is the default
```

The file *PshPack1.h* looks like:

Listing 21.20: PshPack1.h

```

#ifndef ! (defined(lint) || defined(RC_INVOKED))
#ifndef (_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
#else
#pragma pack(1)
#endif
#endif /* ! (defined(lint) || defined(RC_INVOKED)) */

```

This tell the compiler how to pack the structures defined after *#pragma pack*.

⁷[MSDN: Working with Packing Structures](#)

⁸[Structure-Packing Pragmas](#)

OllyDbg + fields are packed by default

Let's try our example (where the fields are aligned by default (4 bytes)) in OllyDbg:

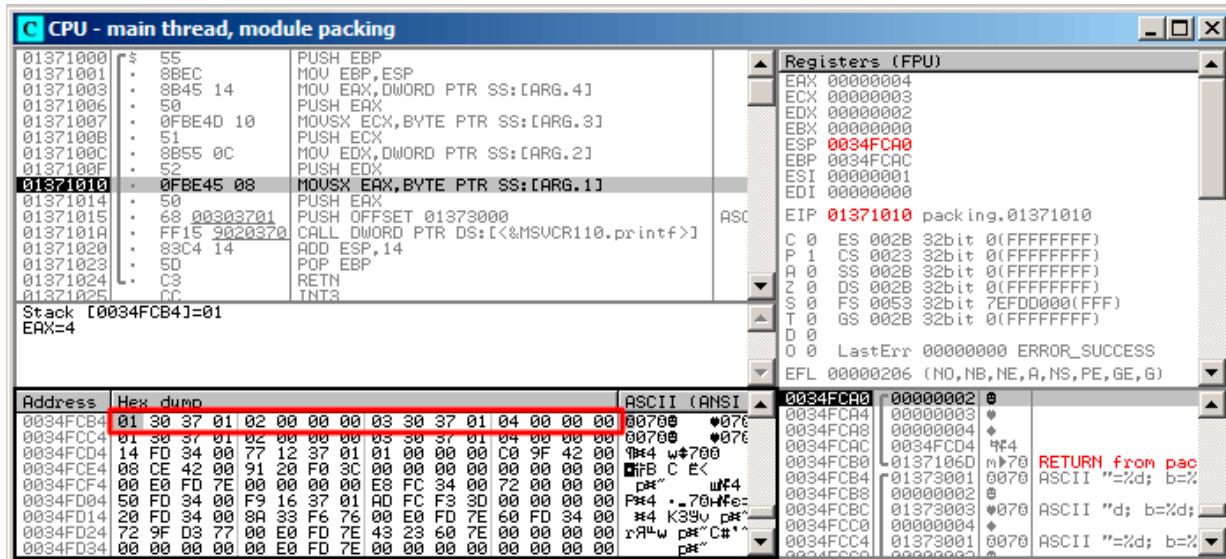


Figure 21.3: OllyDbg: Before printf() execution

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 [21.16 on page 372](#), 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 [21.16](#) (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.

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

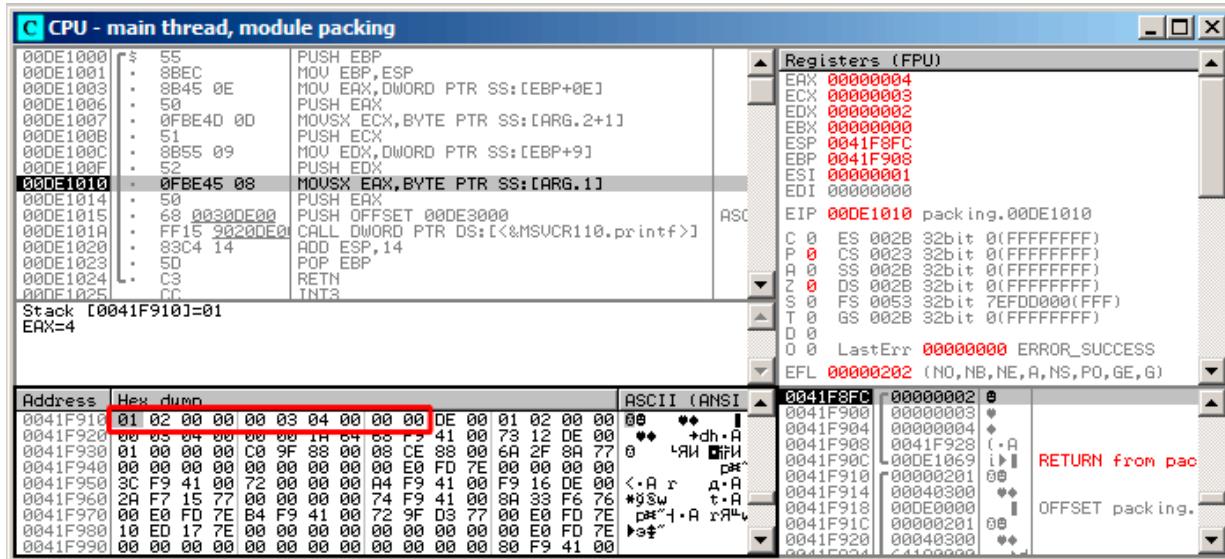


Figure 21.4: OllyDbg: Before `printf()` execution

21.4.2 ARM

Optimizing Keil 6/2013 (Thumb mode)

Listing 21.21: 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
.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, aADBDCDDD ; "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 holds 5 local variables too ($5 * 4 = 0x14$)). Also it is located nearby (take a look at the addresses). Indeed, it doesn't matter which epilogue gets executed, if it works just as we need. Apparently, Keil decides to reuse a part of another function to economize. The epilogue takes 4 bytes while jump –only 2.

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

Listing 21.22: 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.

21.4.3 MIPS

Listing 21.23: 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
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 [31 on page 466](#), 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.

21.4.4 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.

21.5 Nested structures

Now what about situations when one structure is defined inside of 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);
}
```

... 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 21.24: 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.

21.5.1 OllyDbg

Let's load the example into OllyDbg and take a look at `outer_struct` in memory:

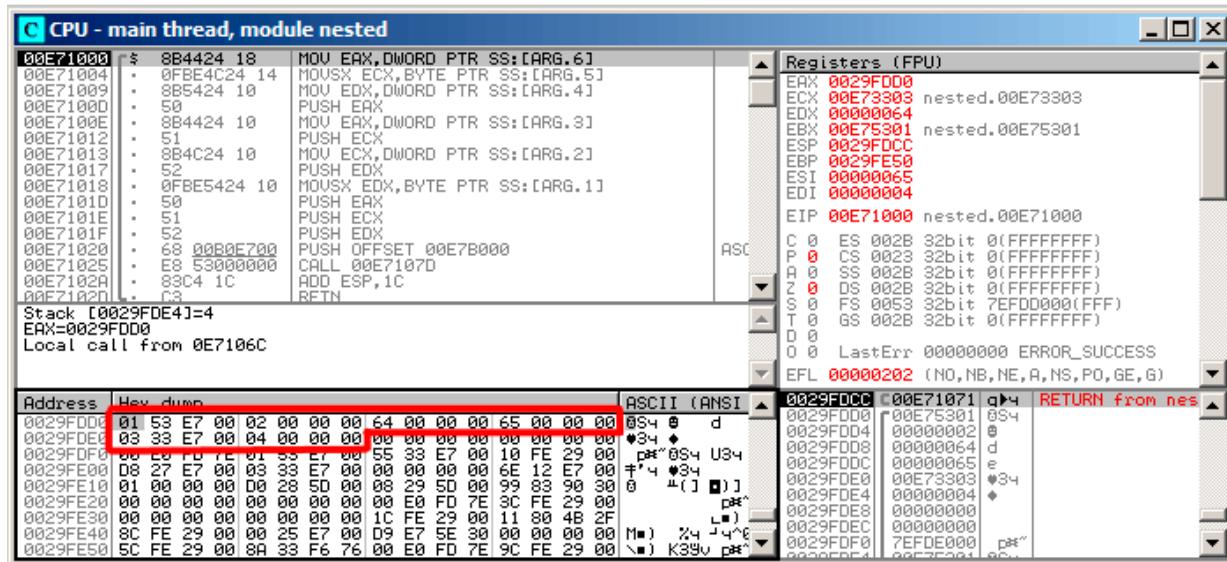


Figure 21.5: OllyDbg: Before `printf()` execution

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.

21.6 Bit fields in a structure

21.6.1 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) {
    asm volatile("cpuid": "=a"( *a), "=b"( *b), "=c"( *c), "=d"( *d): "a"(code));
}

```

⁹wikipedia

¹⁰More about internal GCC assembler

```
#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];

#ifndef _MSC_VER
    __cpuid(b,1);
#endif

#ifndef __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 21.25: 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
    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.

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:

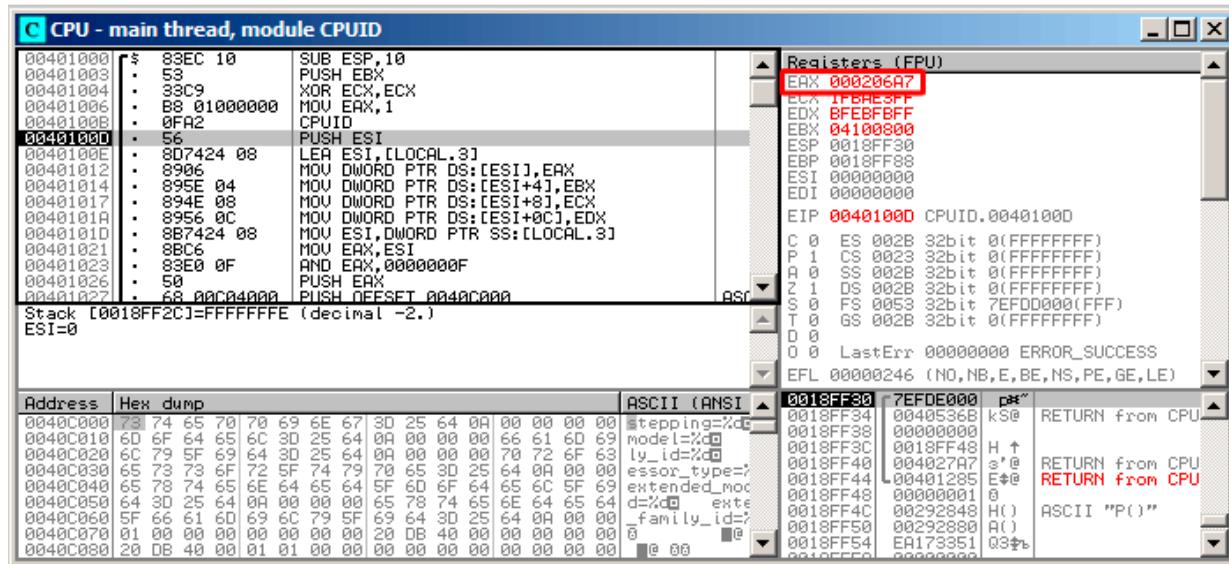


Figure 21.6: OllyDbg: After CPUID execution

EAX has 0x000206A7 (my CPU is Intel Xeon E3-1220).
This is 00000000000000100000011010100111 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

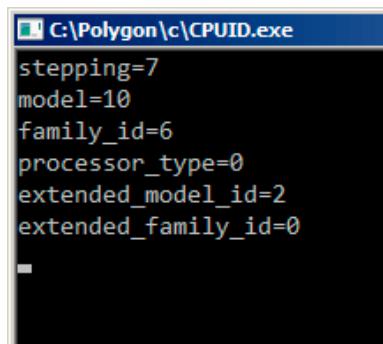


Figure 21.7: OllyDbg: Result

GCC

Let's try GCC 4.4.1 with -O3 option.

Listing 21.26: Optimizing GCC 4.4.1

```
main proc near ; DATA XREF: _start+17
push    ebp
mov     ebp, esp
and    esp, 0FFFFFFF0h
push    esi
```

```

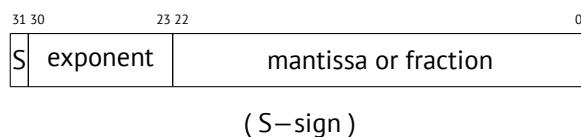
mov    esi, 1
push   ebx
mov    eax, esi
sub    esp, 18h
cpuid
mov    esi, eax
and    eax, 0Fh
mov    [esp+8], eax
mov    dword ptr [esp+4], offset aSteppingD ; "stepping=%d\n"
mov    dword ptr [esp], 1
call   __printf_chk
mov    eax, esi
shr    eax, 4
and    eax, 0Fh
mov    [esp+8], eax
mov    dword 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.

21.6.2 Working with the float type as with a structure

As we already noted in the section about FPU ([17 on page 214](#)), 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`.



```
#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 21.27: 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
    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 21.28: 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, 807FFFFFh ; 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
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!

21.7 Exercises

21.7.1 Exercise #1

[Linux x86 \(beginners.re\)¹¹](#)

[Linux MIPS \(beginners.re\)¹²](#)

This program for Linux x86 and Linux MIPS opens a file and prints a number. What is this number?

Answer: [G.1.14 on page 982.](#)

21.7.2 Exercise #2

This function takes some structure on input and does something. Try to reverse engineer structure field types. Function contents may be ignored for the moment.

Listing 21.29: Optimizing MSVC 2010

```
$SG2802 DB      '%f', 0aH, 00H
$SG2803 DB      '%c, %d', 0aH, 00H
$SG2805 DB      'error #2', 0aH, 00H
$SG2807 DB      'error #1', 0aH, 00H

__real@405ec000000000000 DQ 0405ec000000000000r ; 123
__real@407bc000000000000 DQ 0407bc000000000000r ; 444

_s$ = 8
_f PROC
    push    esi
    mov     esi, DWORD PTR _s$[esp]
    cmp     DWORD PTR [esi], 1000
    jle     SHORT $LN4@f
    cmp     DWORD PTR [esi+4], 10
    jbe     SHORT $LN3@f
    fld     DWORD PTR [esi+8]
    sub     esp, 8
    fmul   QWORD PTR __real@407bc000000000000
    fld     QWORD PTR [esi+16]
    fmul   QWORD PTR __real@405ec000000000000
    faddp  ST(1), ST(0)
    fstp   QWORD PTR [esp]
    push    OFFSET $SG2802 ; '%f'
    call    _printf
    movzx  eax, BYTE PTR [esi+25]
    movsx  ecx, BYTE PTR [esi+24]
    push    eax
    push    ecx
    push    OFFSET $SG2803 ; '%c, %d'
    call    _printf
    add    esp, 24
    pop    esi
    ret    0

$LN3@f:
    pop    esi
    mov    DWORD PTR _s$[esp-4], OFFSET $SG2805 ; 'error #2'
    jmp    _printf

$LN4@f:
    pop    esi
    mov    DWORD PTR _s$[esp-4], OFFSET $SG2807 ; 'error #1'
    jmp    _printf
_f ENDP
```

¹¹GCC 4.8.1 -O3

¹²GCC 4.4.5 -O3

Listing 21.30: Non-optimizing Keil 6/2013 (ARM mode)

```
f PROC
    PUSH {r4-r6,lr}
    MOV r4,r0
    LDR r0,[r0,#0]
    CMP r0,#0x3e8
ADRLE r0,|L0.140|
BLE |L0.132|
LDR r0,[r4,#4]
CMP r0,#0xa
ADRLS r0,|L0.152|
BLS |L0.132|
ADD r0,r4,#0x10
LDM r0,{r0,r1}
LDR r3,|L0.164|
MOV r2,#0
BL __aeabi_dmul
MOV r5,r0
MOV r6,r1
LDR r0,[r4,#8]
LDR r1,|L0.168|
BL __aeabi_fmul
BL __aeabi_f2d
MOV r2,r5
MOV r3,r6
BL __aeabi_dadd
MOV r2,r0
MOV r3,r1
ADR r0,|L0.172|
BL __2printf
LDRB r2,[r4,#0x19]
LDRB r1,[r4,#0x18]
POP {r4-r6,lr}
ADR r0,|L0.176|
B __2printf
|L0.132|
POP {r4-r6,lr}
B __2printf
ENDP

|L0.140|
DCB "error #1\n",0
DCB 0
DCB 0
|L0.152|
DCB "error #2\n",0
DCB 0
DCB 0
|L0.164|
DCD 0x405ec000
|L0.168|
DCD 0x43de0000
|L0.172|
DCB "%f\n",0
|L0.176|
DCB "%c, %d\n",0
```

Listing 21.31: Non-optimizing Keil 6/2013 (Thumb mode)

```
f PROC
    PUSH {r4-r6,lr}
    MOV r4,r0
    LDR r0,[r0,#0]
    CMP r0,#0x3e8
ADRLE r0,|L0.140|
BLE |L0.132|
LDR r0,[r4,#4]
CMP r0,#0xa
ADRLS r0,|L0.152|
BLS |L0.132|
```

```

ADD    r0,r4,#0x10
LDM    r0,{r0,r1}
LDR    r3,|L0.164|
MOV    r2,#0
BL     __aeabi_dmul
MOV    r5,r0
MOV    r6,r1
LDR    r0,[r4,#8]
LDR    r1,|L0.168|
BL     __aeabi_fmul
BL     __aeabi_f2d
MOV    r2,r5
MOV    r3,r6
BL     __aeabi_dadd
MOV    r2,r0
MOV    r3,r1
ADR    r0,|L0.172|
BL     __2printf
LDRB   r2,[r4,#0x19]
LDRB   r1,[r4,#0x18]
POP    {r4-r6,lr}
ADR    r0,|L0.176|
B      __2printf
|L0.132|
POP    {r4-r6,lr}
B      __2printf
ENDP

|L0.140|
DCB    "error #1\n",0
DCB    0
DCB    0
|L0.152|
DCB    "error #2\n",0
DCB    0
DCB    0
|L0.164|
DCD    0x405ec000
|L0.168|
DCD    0x43de0000
|L0.172|
DCB    "%f\n",0
|L0.176|
DCB    "%c, %d\n",0

```

Listing 21.32: Optimizing GCC 4.9 (ARM64)

```

f:
stp    x29, x30, [sp, -32]!
add    x29, sp, 0
ldr    w1, [x0]
str    x19, [sp,16]
cmp    w1, 1000
ble    .L2
ldr    w1, [x0,4]
cmp    w1, 10
bls    .L3
ldr    s1, [x0,8]
mov    x19, x0
ldr    s0, .LC1
adrp   x0, .LC0
ldr    d2, [x19,16]
add    x0, x0, :lo12:.LC0
fmul   s1, s1, s0
ldr    d0, .LC2
fmul   d0, d2, d0
fcvt   d1, s1
fadd   d0, d1, d0
bl     printf
ldrb   w1, [x19,24]

```

```

    adrp    x0, .LC3
    ldrb    w2, [x19,25]
    add    x0, x0, :lo12:.LC3
    ldr    x19, [sp,16]
    ldp    x29, x30, [sp], 32
    b     printf
.L3:
    ldr    x19, [sp,16]
    adrp    x0, .LC4
    ldp    x29, x30, [sp], 32
    add    x0, x0, :lo12:.LC4
    b     puts
.L2:
    ldr    x19, [sp,16]
    adrp    x0, .LC5
    ldp    x29, x30, [sp], 32
    add    x0, x0, :lo12:.LC5
    b     puts
.size   f, .-f
.LC1:
    .word   1138622464
.LC2:
    .word   0
    .word   1079951360
.LC0:
    .string "%f\n"
.LC3:
    .string "%c, %d\n"
.LC4:
    .string "error #2"
.LC5:
    .string "error #1"

```

Listing 21.33: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

f:

var_10      = -0x10
var_8       = -8
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      $s0, 0x20+var_8($sp)
        sw      $gp, 0x20+var_10($sp)
        lw      $v0, 0($a0)
        or      $at, $zero
        slti   $v0, 0x3E9
        bnez   $v0, loc_C8
        move   $s0, $a0
        lw      $v0, 4($a0)
        or      $at, $zero
        sltiu $v0, 0xB
        bnez   $v0, loc_AC
        lui      $v0, (dword_134 >> 16)
        lwc1   $f4, $LC1
        lwc1   $f2, 8($a0)
        lui      $v0, ($LC2 >> 16)
        lwc1   $f0, 0x14($a0)
        mul.s   $f2, $f4, $f2
        lwc1   $f4, dword_134
        lwc1   $f1, 0x10($a0)
        lwc1   $f5, $LC2
        cvt.d.s $f2, $f2
        mul.d   $f0, $f4, $f0
        lw      $t9, (printf & 0xFFFF)($gp)
        lui      $a0, ($LC0 >> 16) # "%f\n"
        add.d   $f4, $f2, $f0

```

```

mfc1    $a2, $f5
mfc1    $a3, $f4
jalr    $t9
la      $a0, ($LC0 & 0xFFFF) # "%f\n"
lw      $gp, 0x20+var_10($sp)
lbu    $a2, 0x19($s0)
lb      $a1, 0x18($s0)
lui    $a0, ($LC3 >> 16) # "%c, %d\n"
lw      $t9, (printf & 0xFFFF)($gp)
lw      $ra, 0x20+var_4($sp)
lw      $s0, 0x20+var_8($sp)
la      $a0, ($LC3 & 0xFFFF) # "%c, %d\n"
jr      $t9
addiu   $sp, 0x20
loc_AC:
lui    $a0, ($LC4 >> 16) # "error #2"
lw      $t9, (puts & 0xFFFF)($gp)
lw      $ra, 0x20+var_4($sp)
lw      $s0, 0x20+var_8($sp)
la      $a0, ($LC4 & 0xFFFF) # "error #2"
jr      $t9
addiu   $sp, 0x20
loc_C8:
lui    $a0, ($LC5 >> 16) # "error #1"
lw      $t9, (puts & 0xFFFF)($gp)
lw      $ra, 0x20+var_4($sp)
lw      $s0, 0x20+var_8($sp)
la      $a0, ($LC5 & 0xFFFF) # "error #1"
jr      $t9
addiu   $sp, 0x20
$LC0:   .ascii "%f\n"<0>
$LC3:   .ascii "%c, %d\n"<0>
$LC4:   .ascii "error #2"<0>
$LC5:   .ascii "error #1"<0>
$LC1:   .data # .rodata.cst4
        .word 0x43DE0000
$LC2:   .data # .rodata.cst8
        .word 0x405EC000
dword_134: .word 0

```

Answer: [G.1.14 on page 983.](#)

Chapter 22

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.

22.1 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 32-bit values in DWORD form. Then we can transform this value to *float* and then divide it by RAND_MAX (0xFFFFFFFF in our case)— we getting a value in the 0..1 interval.

But as we know, division is slow. Also, we would like to issue as few FPU operations as possible. Can we get rid of the division?

Let's recall what a floating point number consists of: sign bit, significand bits and exponent bits. We just 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 filling the significand with random bits, set the sign bit to 0 (which means a positive number) and voilà. The generated numbers is to be between 1 and 2, so we must also subtract 1.

A very simple linear congruential random numbers generator is used in my 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: [20 on page 352](#). 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>

```

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;
};

```

22.1.1 x86

Listing 22.1: Optimizing MSVC 2010

```

$SG4238 DB      '%f', 0aH, 00H

__real@3ff0000000000000 DQ 03ff000000000000r ; 1

tv130 = -4
_tmp$ = -4
?float_rand@@YAMXZ PROC
    push    ecx
    call    ?my_rand@@YAIXZ
; 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]
    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: [51.1.1 on page 556](#).

If we compile this in MSVC 2012, it uses the SIMD instructions for the FPU, read more about it here: [27.5 on page 455](#).

22.1.2 MIPS

Listing 22.2: 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)
        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: [17.5.6 on page 225](#).

22.1.3 ARM (ARM mode)

Listing 22.3: Optimizing GCC 4.6.3 (IDA)

```

float_rand
    STMF D 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
    STMF D SP!, {R4,LR}
    MOV   R0, #0
    BL    time
    BL    my_srand
    MOV   R4, #0x64 ; 'd'

loc_78
    BL    float_rand
; S0=pseudorandom value

```

```

        LDR    R0, =aF      ; "%f"
; convert float type value into double type value (printf() will need it):
        FCVTDS D7, S0
; bitwise copy from D7 into R2/R3 pair of registers (for printf()):
        FMRRD R2, R3, D7
        BL    printf
        SUBS R4, R4, #1
        BNE   loc_78
        MOV   R0, R4
        LDMFD SP!, {R4,PC}

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 22.4: 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 random noise.

22.2 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`.

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.

22.2.1 x86

Listing 22.5: 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.

22.2.2 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));
}

```

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 22.6: 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: [27.4 on page 454](#).

22.2.3 MIPS

The new instruction here is MTC1 (“Move To Coprocessor 1”), it just transfers data from [GPR](#) to the FPU’s registers.

Listing 22.7: 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
```

22.2.4 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++.

22.3 Fast square root calculation

Another well-known algorithm where *float* is interpreted as integer is fast calculation of square root.

Listing 22.8: 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 */
}
```

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 23

Pointers to functions

A pointer to a function, as any other pointer, is just the address of the function's start in its code segment.

They are often used for calling callback functions ¹.

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 functions 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;
18 }
19
20 int main(int argc, char* argv[])
```

¹[wikipedia](#)

²[wikipedia](#)

³<http://go.yurichev.com/17073>

⁴[wikipedia](#)

⁵MSDN

```

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  }

```

23.1 MSVC

Let's compile it in MSVC 2010 (some parts were omitted for the sake of brevity) with /Ox option:

Listing 23.1: 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                          ; 000000028H
    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$[esp+80], 5    ; 
    mov   DWORD PTR _numbers$[esp+84], -12345 ; fffffcfc7H
    mov   DWORD PTR _numbers$[esp+88], 1087  ; 0000043fH
    mov   DWORD PTR _numbers$[esp+92], 88   ; 00000058H
    mov   DWORD PTR _numbers$[esp+96], -100000 ; fffe7960H
    call  _qsort
    add   esp, 16                          ; 00000010H
...

```

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 23.2: MSVCR80.DLL

```
.text:7816CBF0 ; void __cdecl qsort(void *, unsigned int, unsigned int, int (__cdecl *)(const void *, 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 of wrong types may lead to serious problems, however, the crashing of the process is not a problem here – the problem is how to determine the reason for the crash – because the compiler may be silent about the potential problems while compiling.

23.1.1 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:

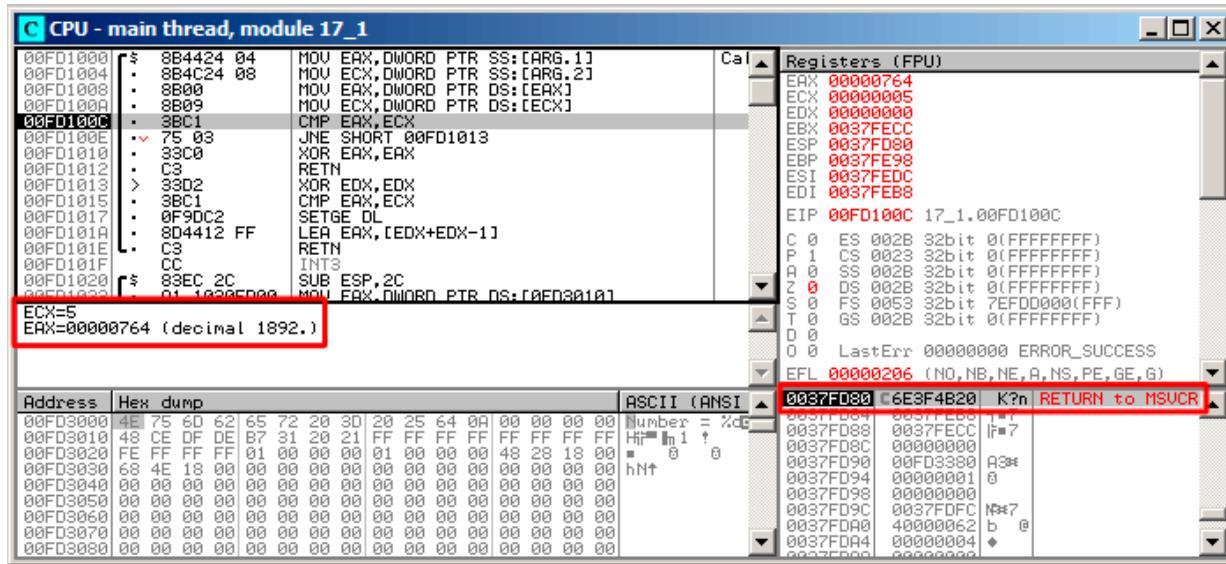


Figure 23.1: OllyDbg: first call of `comp()`

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`).

By tracing (F8) until the RETN instruction and pressing F8 one more time, we return to the `qsort()` function:

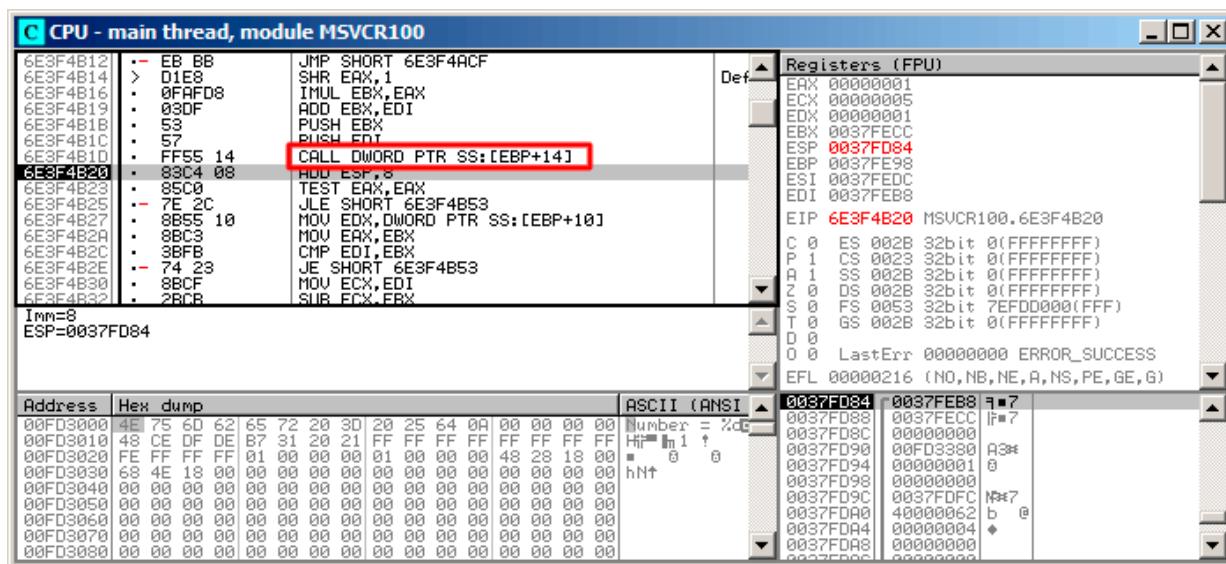


Figure 23.2: OllyDbg: the code in `qsort()` right after `comp()` call

That was a call to the comparison function.

Here is also a screenshot of the moment of the second call of `comp()` – now values that have to be compared are different:

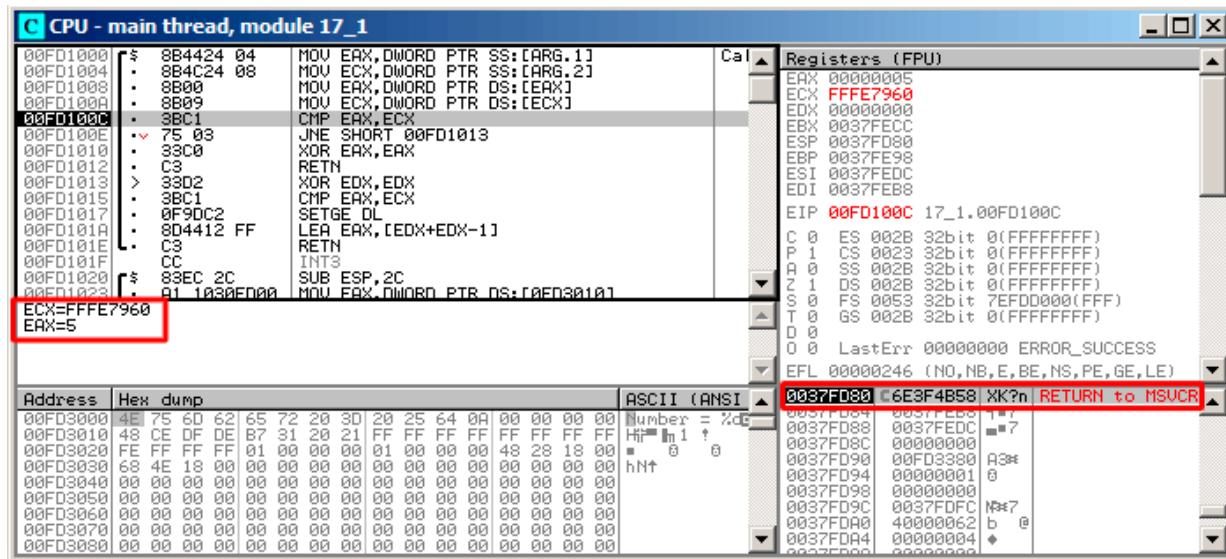


Figure 23.3: OllyDbg: second call of `comp()`

23.1.2 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
EAX=0xfffffff9e ECX=0x00000005
EAX=0xfffffcfc7 ECX=0xffffe7960
```

```
EAX=0x00000005 ECX=0xfffffcfc7
EAX=0xfffffff9e ECX=0x00000005
EAX=0xfffffcfc7 ECX=0xffffe7960
EAX=0xfffffff9e 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=0x00000058
```

That's 34 pairs. Therefore, the quick sort algorithm needs 34 comparison operations to sort these 10 numbers.

23.1.3 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
.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          ; EAX=1, 0xFFFFFFFF
.text:0040101E PtFuncCompare endp
.text:0040101F
```

Figure 23.4: 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.

23.2 GCC

Not a big difference:

Listing 23.3: 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], 0FFE7960h
mov   [esp+40h+var_34], offset comp
mov   [esp+40h+var_38], 4
mov   [esp+40h+var_3C], 0Ah
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 23.4: (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]
...

```

23.2.1 GCC + GDB (with source code)

Obviously, we have the C-source code of our example ([23 on page 400](#)), 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 23.5: 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/>...
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

```

⁶a concept like [thunk function](#)

```

Breakpoint 1, comp (_a=0xbffff0f8, _b=_b@entry=0xbffff0fc) 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=0xbffff104, _b=_b@entry=0xbffff108) at 17_1.c:11
11      if (*a==*b)
(gdb) p *a
$3 = -98
(gdb) p *b
$4 = 4087
(gdb) bt
#0  comp (_a=0xbffff0f8, _b=_b@entry=0xbffff0fc) at 17_1.c:11
#1  0xb7e42872 in msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=2)
    at msort.c:65
#2  0xb7e4273e in msort_with_tmp (n=2, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#3  msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=5) at msort.c:53
#4  0xb7e4273e in msort_with_tmp (n=5, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#5  msort_with_tmp (p=p@entry=0xbffff07c, b=b@entry=0xbffff0f8, n=n@entry=10) at msort.c:53
#6  0xb7e42cef in msort_with_tmp (n=10, b=0xbffff0f8, p=0xbffff07c) at msort.c:45
#7  __GI_qsort_r (b=b@entry=0xbffff0f8, n=n@entry=10, s=s@entry=4, cmp=cmp@entry=0x804844d <comp>,
    arg=arg@entry=0x0) at msort.c:297
#8  0xb7e42dcf in __GI_qsort (b=0xbffff0f8, n=10, s=4, cmp=0x804844d <comp>) at msort.c:307
#9  0x0804850d in main (argc=1, argv=0xbffff1c4) at 17_1.c:26
(gdb)

```

23.2.2 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 23.6: 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]
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          0xbfffff0f8      -1073745672
edx          0x764      1892
ebx          0xb7fc0000      -1208221696
esp          0xbfffffeeb8      0xbfffffeeb8
ebp          0xbfffffec8      0xbfffffec8
esi          0xbfffff0fc      -1073745668
edi          0xbfffff010      -1073745904
eip          0x8048469      0x8048469 <comp+28>
eflags        0x286      [ PF SF IF ]
cs           0x73       115
ss           0x7b       123
ds           0x7b       123
es           0x7b       123
fs           0x0        0
gs           0x33       51

```

```

(gdb) c
Continuing.

```

```

Breakpoint 1, 0x08048469 in comp ()
(gdb) info registers
eax          0xffff7      4087
ecx          0xbfffff104      -1073745660
edx          0xffffffff9e      -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.

```

```

Breakpoint 1, 0x08048469 in comp ()
(gdb) info registers
eax          0xffffffff9e      -98
ecx          0xbfffff100      -1073745664
edx          0xc8       200
ebx          0xb7fc0000      -1208221696
esp          0xbfffffeeb8      0xbfffffeeb8
ebp          0xbfffffec8      0xbfffffec8
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 24

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.

24.1 Returning of 64-bit value

```
#include <stdint.h>

uint64_t f ()
{
    return 0x1234567890ABCDEF;
}
```

24.1.1 x86

In a 32-bit environment, 64-bit values are returned from functions in the EDX:EAX register pair.

Listing 24.1: Optimizing MSVC 2010

```
_f      PROC
        mov     eax, -1867788817      ; 90abcdefH
        mov     edx, 305419896       ; 12345678H
        ret     0
_f      ENDP
```

24.1.2 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 24.2: 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: [53.4 on page 610](#)

24.1.3 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 24.3: Optimizing GCC 4.4.5 (assembly listing)

```
li      $3,-1867841536          # 0xffffffff90ab0000
li      $2,305397760           # 0x12340000
ori    $3,$3,0xcdef
j      $31
ori    $2,$2,0x5678
```

Listing 24.4: Optimizing GCC 4.4.5 (IDA)

```
lui    $v1, 0x90AB
lui    $v0, 0x1234
li     $v1, 0x90ABCDEF
jr     $ra
li     $v0, 0x12345678
```

24.2 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;
};
```

24.2.1 x86

Listing 24.5: Optimizing MSVC 2012 /Ob1

```
_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
```

```

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 24.6: 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.

24.2.2 ARM

Listing 24.7: 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).

24.2.3 MIPS

Listing 24.8: 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

```

```

        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.

24.3 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;
};
```

24.3.1 x86

Listing 24.9: Optimizing MSVC 2013 /Ob1

```
_a$ = 8 ; size = 8
_b$ = 16 ; size = 8
```

```

_f_mul PROC
    push    ebp
    mov     ebp,  esp
    mov     eax,  DWORD PTR _b$[ebp+4]
    push    eax
    mov     ecx,  DWORD PTR _b$[ebp]
    push    ecx
    mov     edx,  DWORD PTR _a$[ebp+4]
    push    edx
    mov     eax,  DWORD PTR _a$[ebp]
    push    eax
    call    __allmul ; long long multiplication
    pop    ebp
    ret    0
_f_mul ENDP

_a$ = 8 ; size = 8
_b$ = 16 ; size = 8
_f_div PROC
    push    ebp
    mov     ebp,  esp
    mov     eax,  DWORD PTR _b$[ebp+4]
    push    eax
    mov     ecx,  DWORD PTR _b$[ebp]
    push    ecx
    mov     edx,  DWORD PTR _a$[ebp+4]
    push    edx
    mov     eax,  DWORD PTR _a$[ebp]
    push    eax
    call    __aulldiv ; unsigned long long division
    pop    ebp
    ret    0
_f_div ENDP

_a$ = 8 ; size = 8
_b$ = 16 ; size = 8
_f_rem PROC
    push    ebp
    mov     ebp,  esp
    mov     eax,  DWORD PTR _b$[ebp+4]
    push    eax
    mov     ecx,  DWORD PTR _b$[ebp]
    push    ecx
    mov     edx,  DWORD PTR _a$[ebp+4]
    push    edx
    mov     eax,  DWORD PTR _a$[ebp]
    push    eax
    call    __aullrem ; unsigned long long remainder
    pop    ebp
    ret    0
_f_rem ENDP

```

Multiplication and division are more complex operations, so usually the compiler embeds calls to a library functions doing that.

These functions are described here: [E on page 973](#).

Listing 24.10: 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

```

```

    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 972](#).

24.3.2 ARM

Keil for Thumb mode inserts library subroutine calls:

Listing 24.11: 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_uldmod
    POP    {r4,pc}
    ENDP

||f_rem|| PROC
    PUSH   {r4,lr}
    BL     __aeabi_uldmod
    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 24.12: 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

```

```

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

```

24.3.3 MIPS

Optimizing GCC for MIPS can generate 64-bit multiplication code, but has to call a library routine for 64-bit division:

Listing 24.13: 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)
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).

24.4 Shifting right

```
#include <stdint.h>

uint64_t f (uint64_t a)
{
    return a>>7;
}
```

24.4.1 x86

Listing 24.14: Optimizing MSVC 2012 /O_{b1}

```

_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 24.15: 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.

24.4.2 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 24.16: 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 24.17: 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

```

24.4.3 MIPS

GCC for MIPS follows the same algorithm as Keil does for Thumb mode:

Listing 24.18: 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

```

24.5 Converting 32-bit value into 64-bit one

```

#include <stdint.h>

int64_t f (int32_t a)
{
    return a;
}

```

24.5.1 x86

Listing 24.19: 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.

24.5.2 ARM

Listing 24.20: Optimizing Keil 6/2013 (ARM mode)

```

||f|| PROC
    ASR    r1,r0,#31
    BX     lr
    ENDP

```

Keil for ARM is different: it just arithmetically shifts right the input value by 31 bits. As we know, the sign bit is **MSB**, and the arithmetical shift copies the sign bit into the “emerged” bits. So after “ASR r1,r0,#31”, R1 containing 0xFFFFFFFF if the input value 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.

24.5.3 MIPS

GCC for MIPS does the same as Keil did for ARM mode:

Listing 24.21: Optimizing GCC 4.4.5 (IDA)

```
f:  
    sra    $v0, $a0, 31  
    jr    $ra  
    move   $v1, $a0
```

Chapter 25

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>

25.1 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.

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:

¹<http://go.yurichev.com/17329>

²Wikipedia: vectorization

³Remotely. It is installed in the museum of supercomputers: <http://go.yurichev.com/17081>

```
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.

25.1.1 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
    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
```

⁴More about Intel C++ automatic vectorization: [Excerpt: Effective Automatic Vectorization](#)

```

    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!
    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 XMMO

```

```

padddd  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]
    padddd 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

```

The SSE2-related instructions are:

- **MOVDQU** (*Move Unaligned Double Quadword*) – just loads 16 bytes from memory into a XMM-register.
- **PADD_D** (*Add Packed Integers*) – adds 4 pairs of 32-bit numbers and leaves the result in the first operand. By the way, no exception is raised in case of overflow and no flags are to be set, just the low 32 bits of the result are to be stored. If

one of PADDD's operands is the address of a value in memory, then the address must be aligned on a 16-byte boundary. If it is not aligned, an exception will be triggered ⁵.

- 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

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]
```

⁵More about data alignment: [Wikipedia: Data structure alignment](#)

⁶More about GCC vectorization support: <http://go.yurichev.com/17083>

```

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
padddd xmm0, xmm1
movdqa 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]
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++.

25.1.2 Memory copy example

Let's revisit the simple `memcpy()` example ([14.2 on page 185](#)):

```
#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 25.1: 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
    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
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
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
.L25:
    mov    eax, 11
    jmp   .L4
.L26:
    mov    eax, 12
    jmp   .L4
.L27:
    mov    eax, 13

```

```
jmp     .L4
```

25.2 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 25.2: 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
push    esi
mov     esi, eax
and    esi, -16           ; ffffff0H
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
```

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>.

```

$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

```

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.

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

¹⁰[wikipedia](#)

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: 11223344556677880000000000000000

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						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: 0000ff000000000000ff0000000000

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>

¹¹An order from **MSB** to **LSB**¹² is used here.

Chapter 26

64 bits

26.1 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:

7th (byte number)	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).

7th (byte number)	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 ([64.3 on page 682](#)). 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 ([64 on page 681](#)).

- 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.

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 ([25 on page 423](#))):

```
/*
 * 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
*/
#endif _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;
    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 26.1: 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
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 26.2: 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
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).

26.2 ARM

64-bit instructions appeared in ARMv8.

26.3 Float point numbers

How floating point numbers are processed in x86-64 is explained here: [27 on the following page.](#)

Chapter 27

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: [17 on page 214](#).

27.1 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));
}
```

27.1.1 x64

Listing 27.1: 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
f
    ENDP
```

The input floating point values are passed in the XMM0-XMM3 registers, all the rest—via the stack ¹.

a is passed in XMM0, *b*—via XMM1. The XMM-registers are 128-bit (as we know from the section about [SIMD: 25 on page 423](#)), but the *double* values are 64 bit, so only lower register half is used.

DIVSD is an SSE-instruction that stands for “Divide Scalar Double-Precision Floating-Point Values”, it just divides one value of type *double* by another, stored in the lower halves of operands.

¹[MSDN: Parameter Passing](#)

The constants are encoded by compiler in IEEE 754 format.

MULSD and ADDSD work just as the same, but do multiplication and addition.

The result of the function's execution in type *double* is left in the in XMMO register.

That is how non-optimizing MSVC works:

Listing 27.2: 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” ([8.2.1 on page 93](#)), but only their lower register halves, i.e., only 64-bit values of type *double*. GCC produces the same code.

27.1.2 x86

Let's also compile this example for x86. Despite the fact it's generating for x86, MSVC 2012 uses SSE2 instructions:

Listing 27.3: 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 27.4: 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]
    ret 0
_f ENDP
```

It's almost the same code, however, there are some differences related to calling conventions: 1) the arguments are passed not in XMM registers, but in the stack, like in the FPU examples ([17 on page 214](#)); 2) the result of the function is returned in ST(0) – in order to do so, it's copied (through local variable tv) from one of the XMM registers to ST(0).

Let's try the optimized example in OllyDbg:

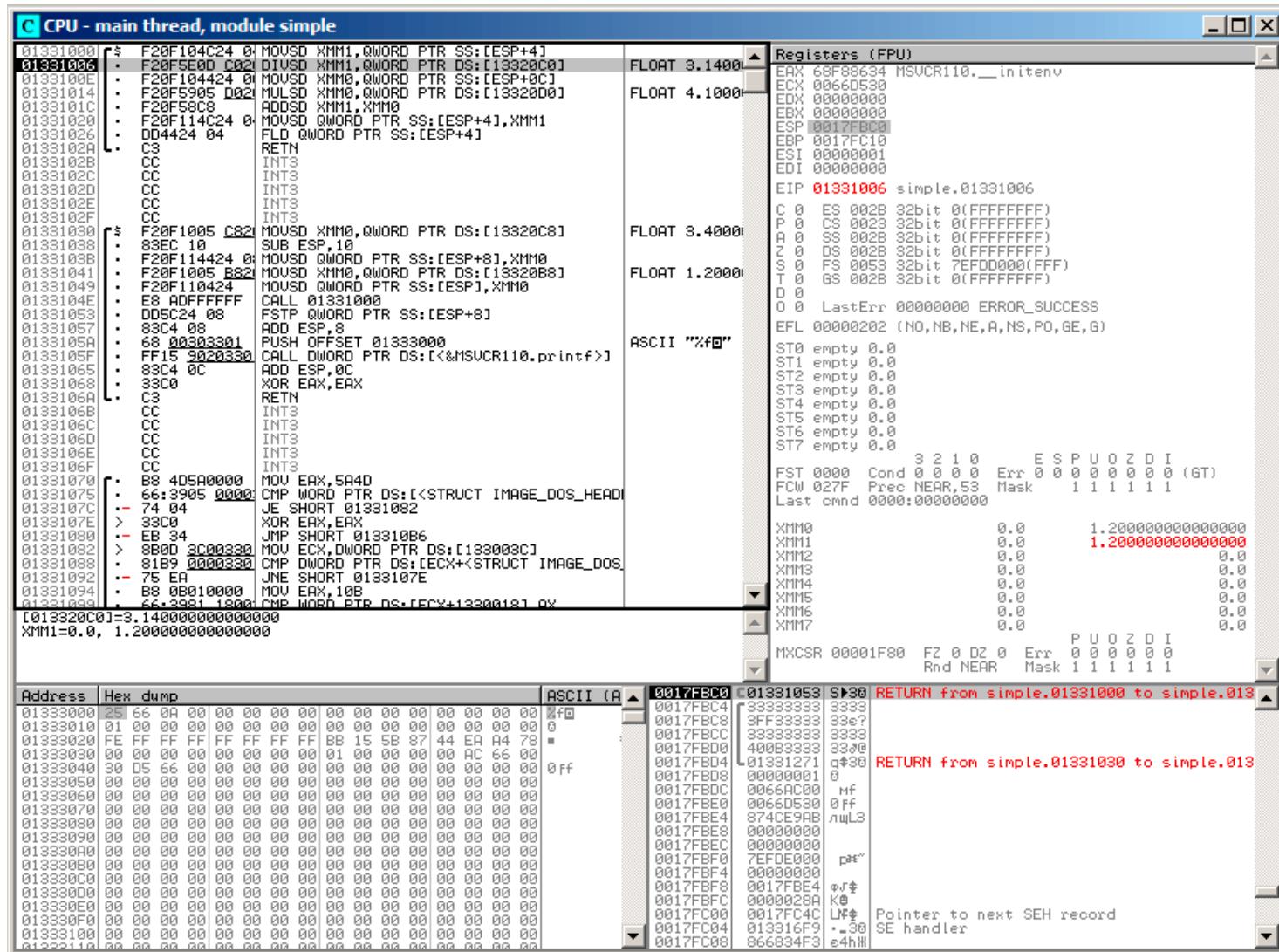


Figure 27.1: OllyDbg: MOVSD loads the value of *a* into XMM1

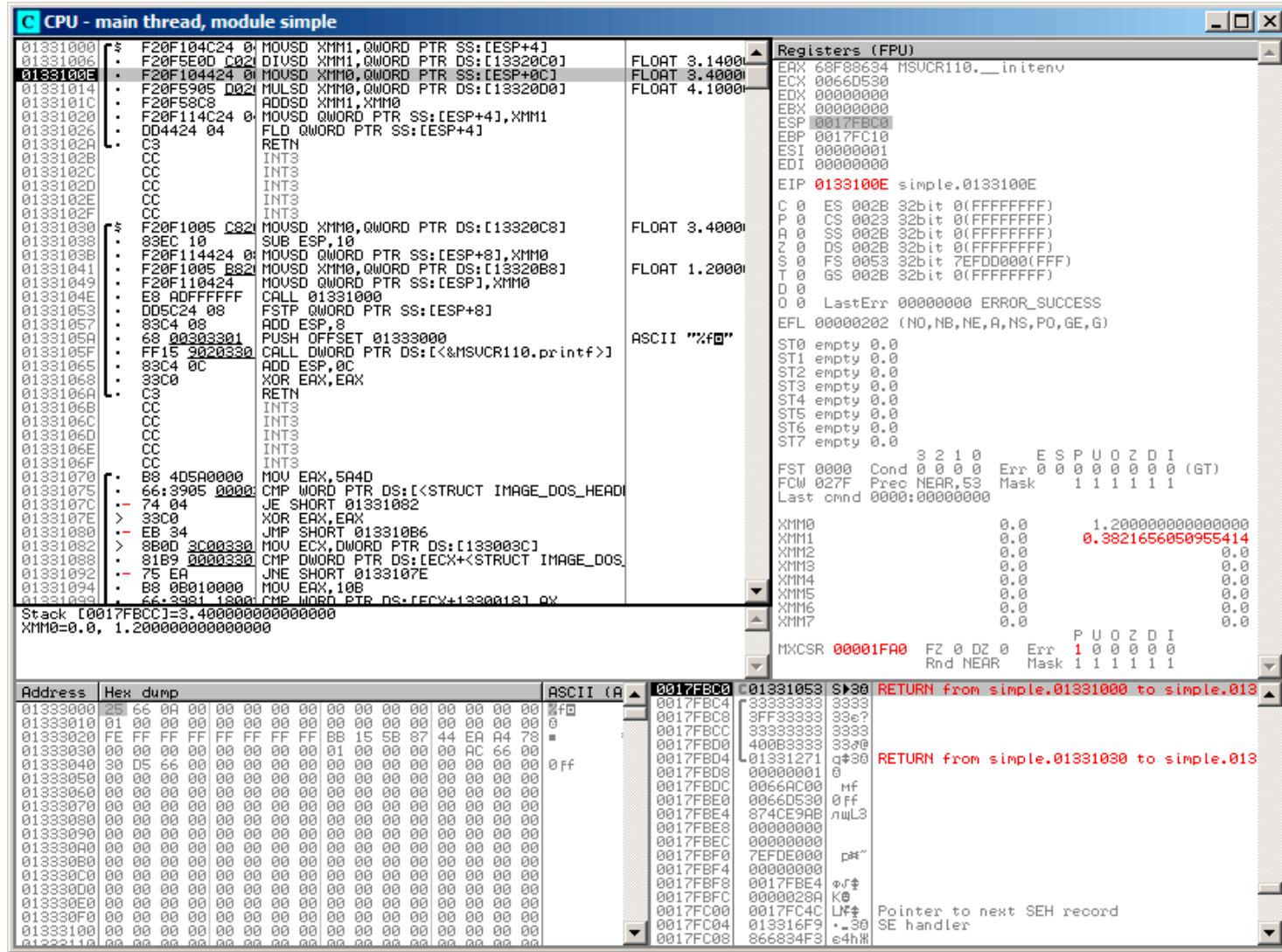


Figure 27.2: OllyDbg: DIVSD calculated quotient and stored it in XMM1

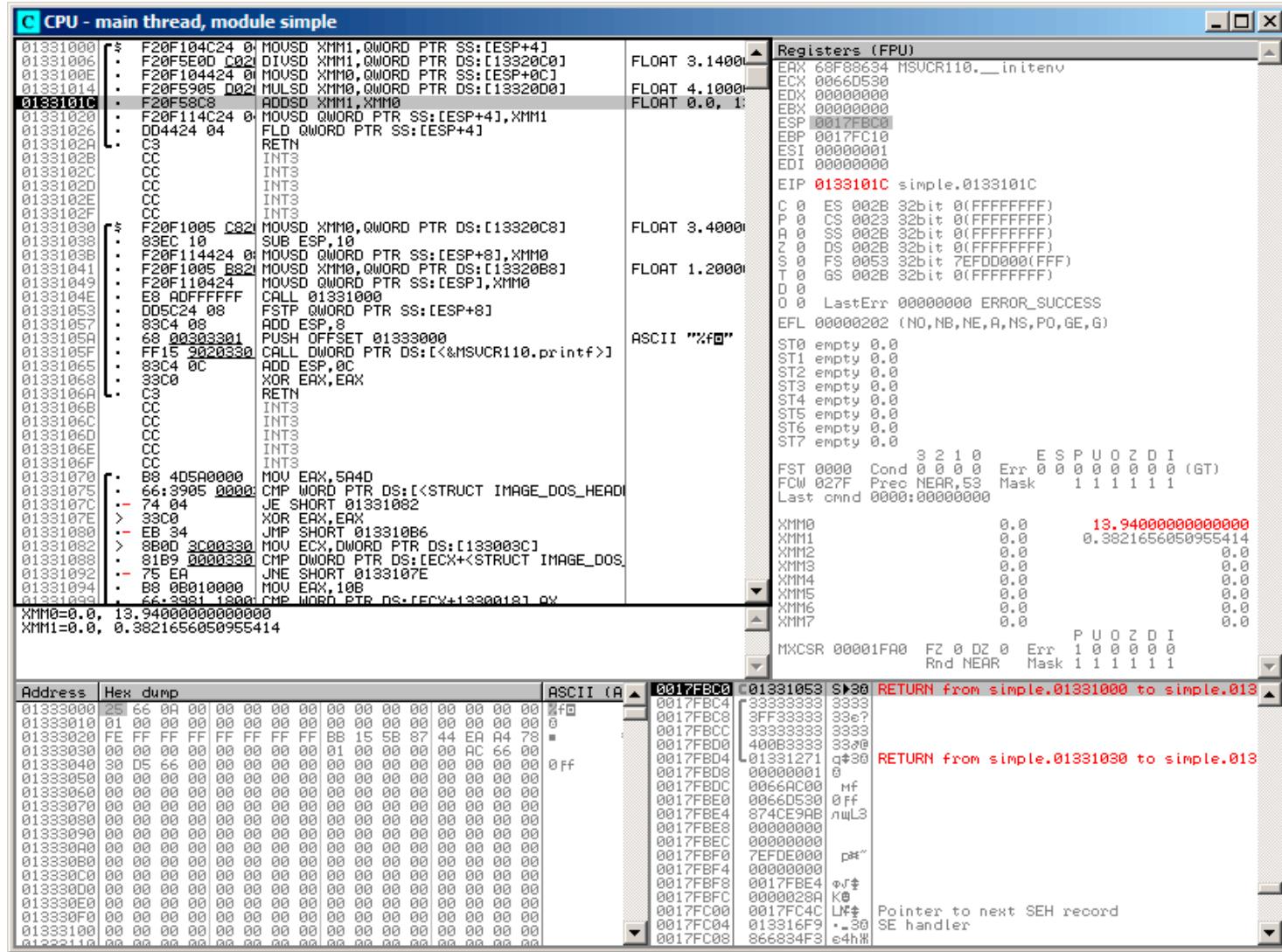


Figure 27.3: OllyDbg: MULSD calculated product and stored it in XMMO

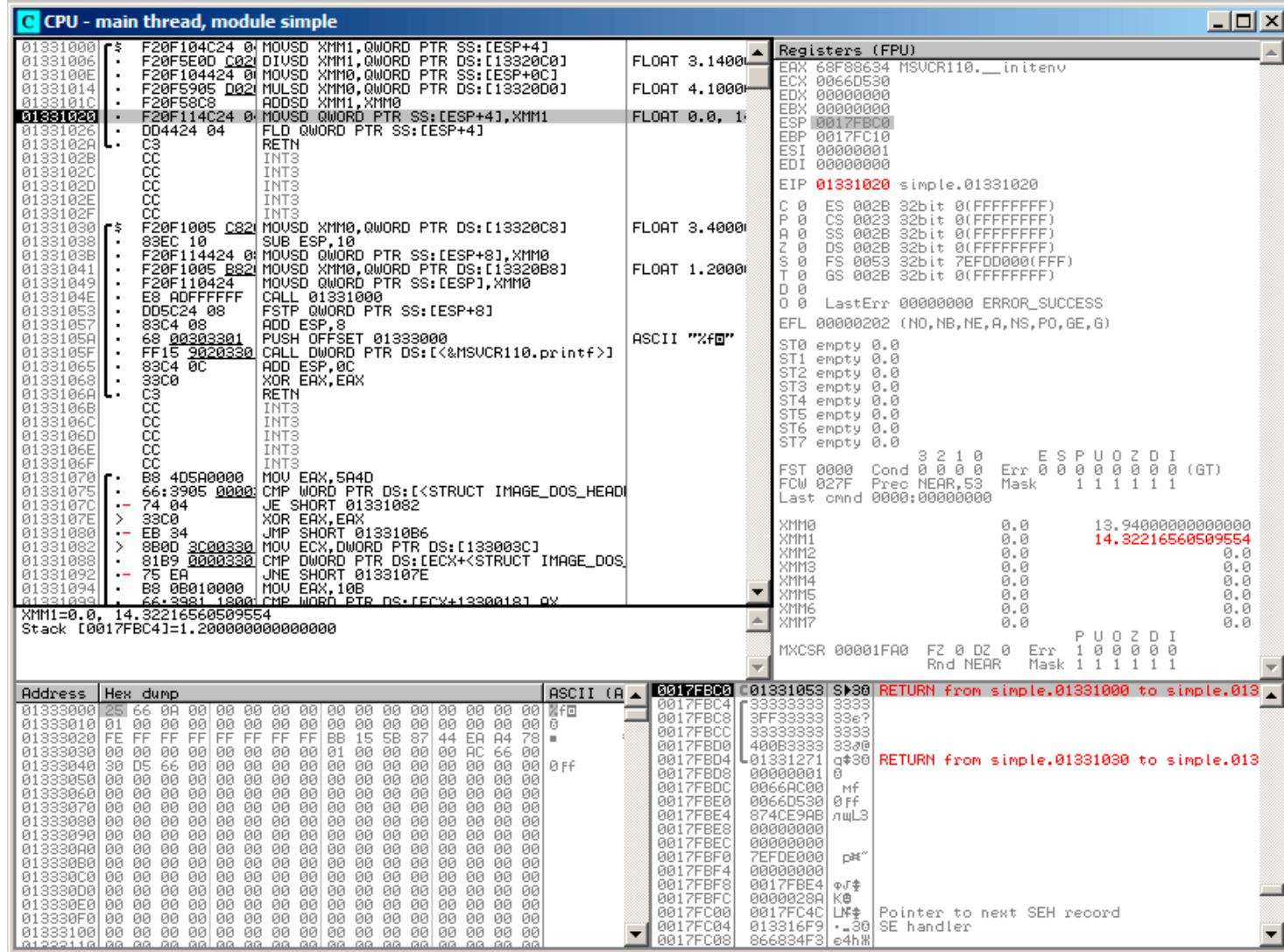


Figure 27.4: OllyDbg: ADDSD adds value in XMM0 to XMM1

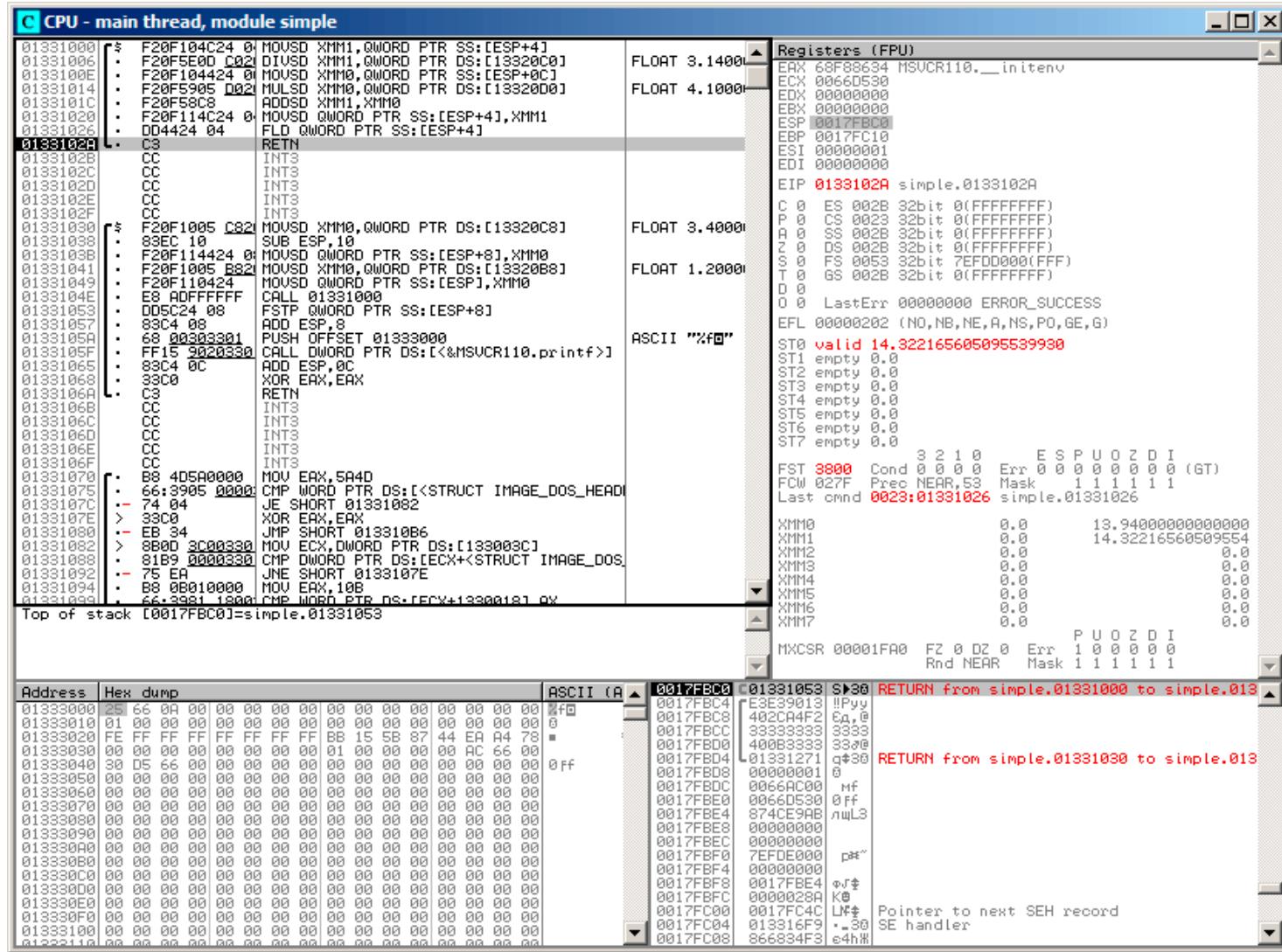


Figure 27.5: OllyDbg: FLD left function result in ST(0)

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.

27.2 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 27.5: 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 957](#)). 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 27.6: 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](#)].

27.3 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));
}
```

27.3.1 x64

Listing 27.7: 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 27.8: MSVC 2012 x64

```
a$ = 8
b$ = 16
d_max PROC
    movsd QWORD PTR [rsp+16], xmm1
    movsd QWORD PTR [rsp+8], xmm0
    movsd xmm0, QWORD PTR a$[rsp]
    comisd xmm0, QWORD PTR b$[rsp]
    jbe SHORT $LN1@d_max
    movsd xmm0, QWORD PTR a$[rsp]
    jmp SHORT $LN2@d_max
$LN1@d_max:
    movsd xmm0, QWORD PTR b$[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 27.9: Optimizing GCC 4.4.6 x64

```
d_max:
    maxsd xmm0, xmm1
    ret
```

27.3.2 x86

Let's compile this example in MSVC 2012 with optimization turned on:

Listing 27.10: 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:

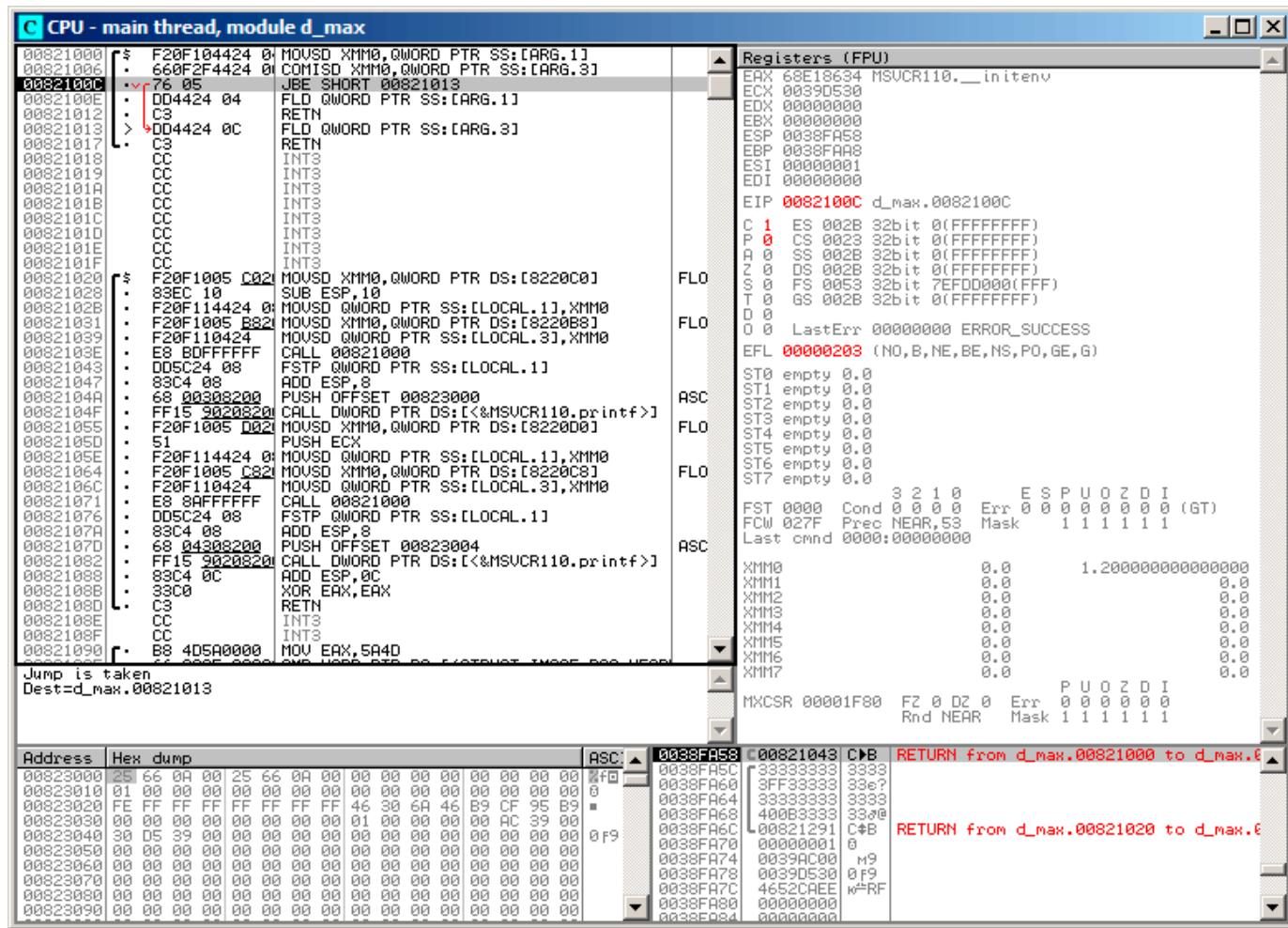


Figure 27.6: OllyDbg: COMISD changed CF and PF flags

27.4 Calculating machine epsilon: x64 and SIMD

Let's revisit the "calculating machine epsilon" example for *double* listing 22.2.2.

Now we compile it for x64:

Listing 27.11: 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 yet ².

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.

27.5 Pseudo-random number generator example revisited

Let's revisit “pseudo-random number generator example” example listing 22.1.

If we compile this in MSVC 2012, it will use the SIMD instructions for the FPU.

Listing 27.12: 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.

27.6 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.

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.

²As an exercise, you may try to rework this code to eliminate the usage of the local stack.

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 28

ARM-specific details

28.1 Number sign (#) before number

The Keil compiler, [IDA](#) and objdump precede all numbers with the “#” number sign, for example: listing.[14.1.4](#). But when GCC 4.9 generates assembly language output, it doesn’t, for example: listing.[39.3](#).

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.

28.2 Addressing modes

This instruction is possible in ARM64:

```
1dr    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:

```
1dr    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.[3.15](#).

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.

28.3 Loading a constant into a register

28.3.1 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 28.1: 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 28.2: 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
```

28.3.2 ARM64

```
uint64_t f()
{
    return 0x12345678ABCDEF01;
};
```

Listing 28.3: 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 28.4: 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 VFPEExpandImm() 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 28.5: GCC 4.9.1 -O3

```
a:
 1dr      d0, .LC0
 ret
.LC0:
 .word    0
 .word    1077936128
```

28.4 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): [68.2.6 on page 706](#).

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.6) in GCC (Linaro) 4.9 under win32:

Listing 28.6: 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
18: a8c17bfd      ldp    x29, x30, [sp],#16
1c: d65f03c0      ret
```

...>aarch64-linux-gnu-objdump.exe -r hw.o
...

¹wikipedia

```
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 relocations in this object file.

- The first one takes the page address, cuts the lowest 12 bits and writes the remaining high 21 bits to the ADRP instruction's bit fields. This is because we don't need to encode the low 12 bits, and the ADRP instruction has space only for 21 bits.
- The second one puts the 12 bits of the address relative to the page start into the ADD instruction's bit fields.
- The last, 26-bit one, is applied to the instruction at address 0x10 where the jump to the `printf()` function is. All ARM64 (and in ARM in ARM mode) instruction addresses have zeroes in the two lowest bits (because all instructions have a size of 4 bytes), so one needs to encode only the highest 26 bits of 28-bit address space ($\pm 128\text{MB}$).

There are no such relocations in the executable file: because it's known where the "Hello!" string is located, in which page, and the address of `puts()` is also known. So there are values set already in the ADRP, ADD and BL instructions (the linker has written them while linking):

Listing 28.7: 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 `1001011111111111111110100000b`. According to [ARM13a, p.C5.6.26], `imm26` is the last 26 bits: $imm26 = 1111111111111111111110100000$. It is `0x3FFFA0`, 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 (30 on page 465), 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 29

MIPS-specific details

29.1 Loading constants into register

```
unsigned int f()
{
    return 0x12345678;
};
```

All instructions in MIPS, just like ARM, have a 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 29.1: 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 29.2: 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.

29.2 Further reading about MIPS

[[Swe10](#)].

Part II

Important fundamentals



Chapter 30

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 0xFFFFFFF and 0x0000002 as unsigned, then the first number (4294967294) is bigger than the second one (2). If we represent them both as signed, the first one is to be -2, and it is smaller than the second (2). That is the reason why conditional jumps ([12 on page 116](#)) are present both for signed (e.g. JG, JL) and unsigned (JA, JB) operations.

For the sake of simplicity, that is what one need 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..0x7FFFFFF`,
 - `char` (-128..127 or `0x80..0x7F`),
 - `ssize_t`.

Unsigned:

- `uint64_t` (0..18,446,744,073,709,551,615 (18 quintillions) or `0..0xFFFFFFFFFFFFFF`),
- `unsigned int` (0..4,294,967,295 (4.3Gb) or `0..0xFFFFFFFF`),
- `unsigned char` (0..255 or `0..0xFF`),

¹[wikipedia](#)

- 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: [24.5 on page 421](#).
- 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 960](#)), MOVSX ([15.1.1 on page 195](#)), SAR ([A.6.3 on page 963](#)).

Chapter 31

Endianness

The endianness is a way of representing values in memory.

31.1 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.

31.2 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.

31.3 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,
           *((char*)&v)+3);
}
```

¹Available for download here: <http://go.yurichev.com/17008>

And 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: [21.4.3 on page 377](#).

31.4 Bi-endian

CPUs that may switch between endianness are ARM, PowerPC, SPARC, MIPS, [IA64](#)², etc.

31.5 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() are not shuffle any bytes on latter.

²Intel Architecture 64 (Itanium): [93 on page 898](#)

Chapter 32

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 reside next to them in memory. There’s an example in this book: [7.2 on page 69](#).
- 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’s 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\(\)](#) ([5.2.4 on page 27](#)) (or a variable-length array) is used. Buffer overflows usually overwrite important stack structures: [18.2 on page 270](#).
- Heap. AKA “dynamic memory allocation”. Allocation 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: [21.2 on page 360](#).

Chapter 33

CPU

33.1 Branch predictors

Some modern compilers try to get rid of conditional jump instructions. Examples in this book are: [12.1.2 on page 127](#), [12.3 on page 134](#), [19.5.2 on page 337](#).

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.

33.2 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 to 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 34

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: the input can be long, but CRC32’s result is always limited to 32 bits. 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.

Such functions are MD5, SHA1, etc, 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 user’s passwords) but only hashes (a cracker can’t reveal passwords). Besides, an internet forum engine is not aware of your password, it has 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 is matching the resulting value that we need. Other methods are much more complex.

34.1 How one-way function works?

One-way function is a function which is able to transform one value into another, while it is impossible (or very hard) to do reverse it back. Some people have difficulties while understanding how it’s possible at all. Let’s consider simple demonstration.

We’ve got vector of 10 numbers in range 0..9, each encounters only once, for example:

4	6	0	1	3	5	7	8	9	2
---	---	---	---	---	---	---	---	---	---

Algorithm of simplest possible one-way function is:

- take a number at zeroth position (4 in our case);
- take a number at first position (6 in our case);
- swap numbers at positions of 4 and 6.

Let’s mark numbers on positions of 4 and 6:

4	6	0	1	3	5	7	8	9	2
		^		^					

Let’s swap them and we’ve got a result:

4	6	0	1	7	5	3	8	9	2
---	---	---	---	---	---	---	---	---	---

While looking at the result and even if we know algorithm, we can’t say unambiguously initial numbers set. Because first two numbers could be 0 and/or 1, and then they could be participate in swapping procedure.

This is utterly simplified example for demonstration, real one-way functions may be much more complex.

Part III

Slightly more advanced examples

Chapter 35

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.

35.1 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);
}
```

35.1.1 Optimizing MSVC 2012 x86

Listing 35.1: 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
_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 ([41 on page 501](#)) 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 supports it partially?

35.1.2 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.

35.2 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 35.2: 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@0711000000000000 DQ 0c07110000000000r ; -273
__real@4022000000000000 DQ 0402200000000000r ; 9
__real@4014000000000000 DQ 0401400000000000r ; 5
__real@4040000000000000 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_scantf
    add    esp, 12                 ; 00000000cH
    cmp    eax, 1
    je    SHORT $LN2@main
```

¹another popular one is `longjmp()`

```

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 35.3: 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@c0711000000000000 DQ 0c071100000000000r ; -273
__real@4040000000000000 DQ 0404000000000000r ; 32
__real@4022000000000000 DQ 0402200000000000r ; 9
__real@4014000000000000 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:
$LN2@main:
movsd  xmm1, QWORD PTR _fahr$[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                  ; 0000000cH
; 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 36

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...

36.1 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 36.1: MSVC 2010 x86

```
_TEXT SEGMENT
_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 $SG2750 ; "%d"
    call DWORD PTR __imp__printf
    add  esp, 8
    mov  ecx, DWORD PTR _limit$[ebp]
    push ecx
    mov  edx, DWORD PTR _a$[ebp]
    add  edx, DWORD PTR _b$[ebp]
    push edx
    mov  eax, DWORD PTR _b$[ebp]
    push eax
```

¹<http://go.yurichev.com/17332>

```
call    _fib
add    esp, 12
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
```

We will illustrate the stack frames with this.

Let's load the example in OllyDbg and trace to the last call of `f()`:

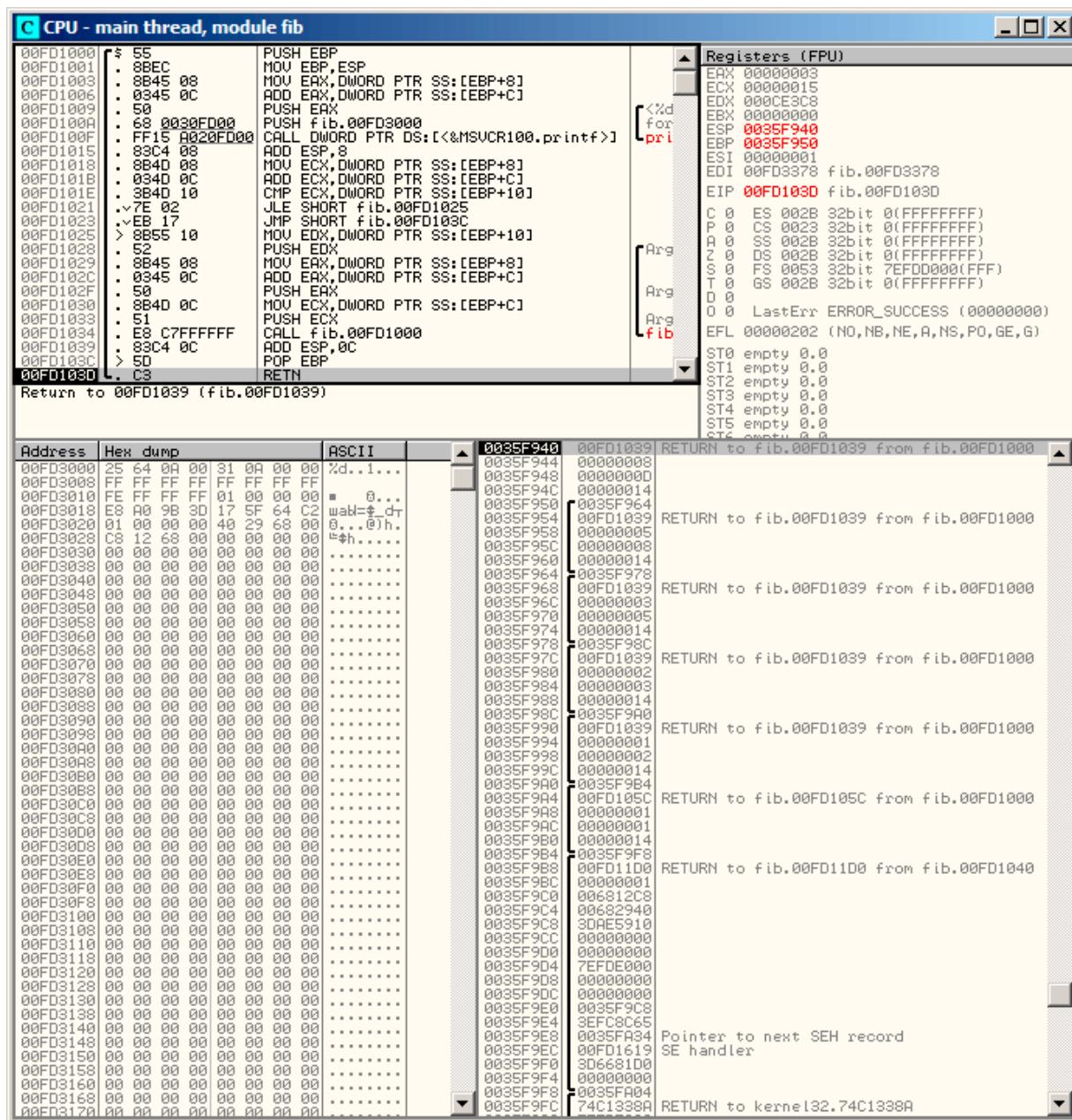


Figure 36.1: OllyDbg: last call of `f()`

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 very end we see the 3 arguments for `main()`. `argc` is 1 (yes, indeed, we have ran the program without command-line arguments).

It's easy to lead to a stack overflow: just remove (or comment) the limit check and it will crash with exception 0xC00000FD (stack overflow.)

36.2 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>

void fib (int a, int b, int limit)
{
    int next=a+b;
    printf ("%d\n", next);
    if (next > limit)
        return;
    fib (b, next, limit);
}

```

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

```

};

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 36.2: 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

```

Let's load OllyDbg once again:

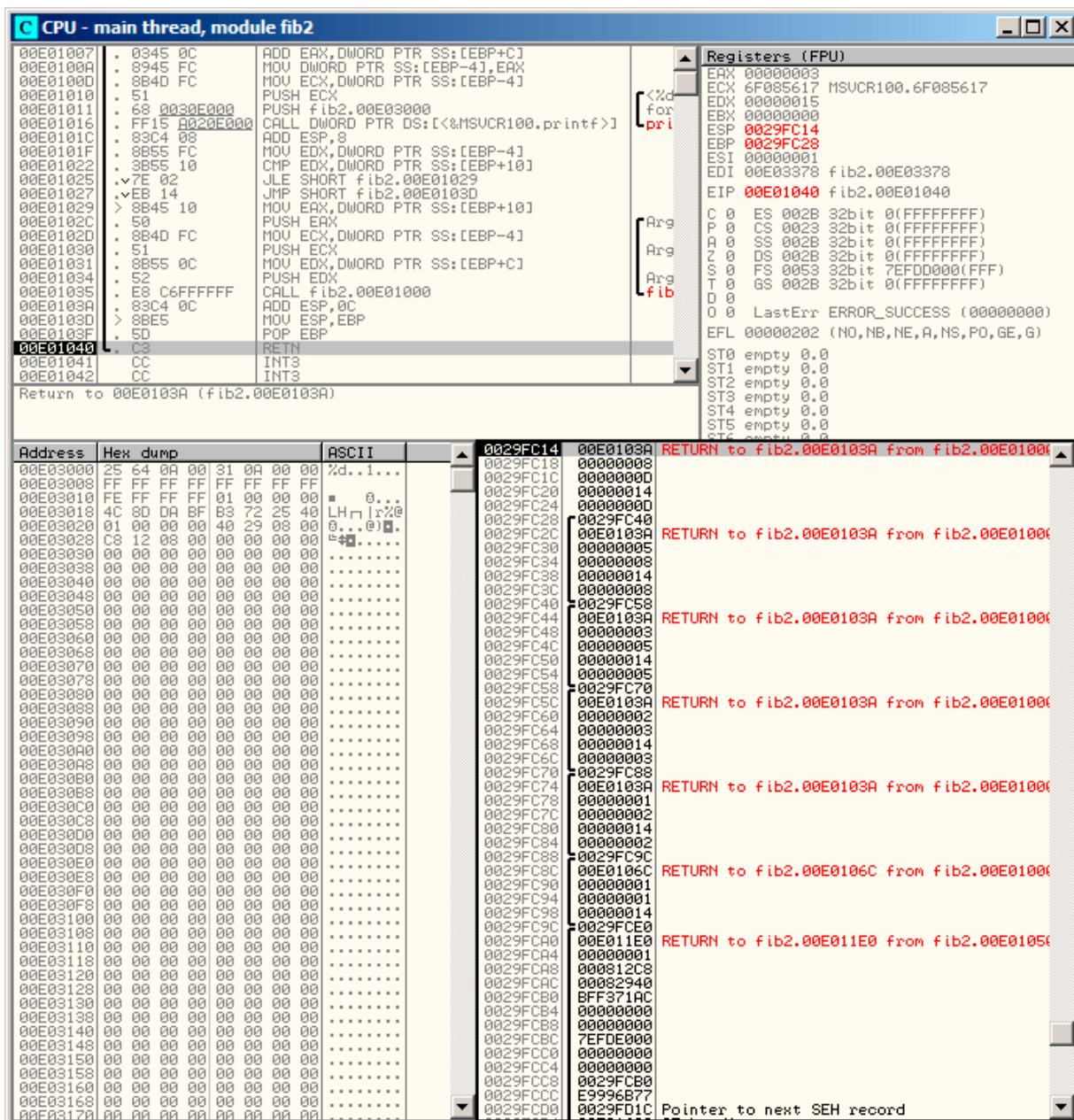


Figure 36.2: OllyDbg: last call of f()

Now the *next* variable is present in each frame.

Let's investigate the stack more closely. Author have also added his comments again:

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()
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.

36.3 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, 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 to be 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 some functional [PL⁴](#) compilers (where recursion is used heavily) use [tail call](#).

⁴LISP, Python, Lua, etc.

Chapter 37

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, 0x79dcb8a4, 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, 0x4b04d447, 0xd20d85fd, 0xa50ab56b, 0x35b5a8fa, 0x42b2986c,
    0xdbbbc9d6, 0xacbcf940, 0x32d86ce3, 0x45df5c75, 0xcdcd60dcf, 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, 0xb01a57b, 0x8208f4c1, 0xf50fc457, 0x65b0d9c6, 0x12b7e950,
    0x8bbeb8ea, 0xfc9887c, 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, 0xeb40d81,
    0xb7bd5c3b, 0xc0ba6cad, 0xedb88320, 0x9abfb3b6, 0x03b6e20c, 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, 0x0cb61b38,
    0x92d28e9b, 0xe5d5be0d, 0x7cdcef7, 0x0bdbdf21, 0x86d3d2d4, 0xf1d4e242,
    0x68ddb3f8, 0x1fda836e, 0x81be16cd, 0xf6b9265b, 0x6fb077e1, 0x18b74777,
    0x88085ae6, 0xff0f6a70, 0x66063bca, 0x11010b5c, 0x8f659eff, 0xf862ae69,
    0x616bffd3, 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 = 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:

```

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          ; padding
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 ([88 on page 887](#)).

Chapter 38

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 ([CIDR](#)¹), 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	ffffffffffc	
/29	8	6	255.255.255.248	ffffffff8	
/28	16	14	255.255.255.240	ffffffff0	
/27	32	30	255.255.255.224	ffffffe0	
/26	64	62	255.255.255.192	ffffffc0	
/24	256	254	255.255.255.0	ffffff00	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	fffffe000	
/18	16384	16382	255.255.192.0	fffffc000	
/17	32768	32766	255.255.128.0	fffff8000	
/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);
};

uint32_t form_netmask (uint8_t netmask_bits)
```

¹Classless Inter-Domain Routing

```

{
    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 ↴
    ↴ netmask_bits)
{
    uint32_t netmask=form_netmask(netmask_bits);
    uint32_t ip=form_IP(ip1, ip2, ip3, ip4);
    uint32_t netw_adr;

    printf ("netmask=");
    print_as_IP (netmask);

    netw_adr=ip&netmask;

    printf ("network address=");
    print_as_IP (netw_adr);
};

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
}

```

38.1 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 38.1: Optimizing MSVC 2012 /Ob0

```

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
24    call    _print_as_IP
25    add    esp, 36
26    pop    edi
27    ret    0

```

```
_calc_network_address ENDP
```

At line 22 we see the most important AND—here the network address is calculated.

38.2 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 38.2: 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
```

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 38.3: Optimizing MSVC 2012 /Ob0

```
; 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$[esp-4]
    ; ECX=000000bb
    shl     eax, 8
    ; EAX=00ddcc00
    or      eax, ecx
    ; EAX=00ddccb0
    movzx    ecx, BYTE PTR _ip4$[esp-4]
    ; ECX=000000aa
    shl     eax, 8
    ; EAX=ddccb00
    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.

38.3 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 38.4: 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=00ddccb0
    and    ecx, 255
    ; ECX=000000bb
    push    ecx
    mov     edx, DWORD PTR _a$[ebp]
    ; EDX=ddccbbaa
    shr     edx, 16
    ; EDX=0000ddcc
    and    edx, 255
    ; EDX=000000cc
    push    edx
    mov     eax, DWORD PTR _a$[ebp]
    ; EAX=ddccbbaa
    shr     eax, 24
    ; EAX=000000dd
```

```

and    eax, 255 ; probably redundant instruction
; 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 38.5: 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=00ddccb
    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

```

38.4 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 38.6: Optimizing MSVC 2012 /Ob0

```

_input$ = 8      ; size = 4
_bit$ = 12       ; size = 4
/set_bit PROC
    mov    ecx, DWORD PTR _bit$[esp-4]
    mov    eax, 1
    shl    eax, cl
    or     eax, DWORD PTR _input$[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
    jl    SHORT $LL3@form_netma
$LN9@form_netma:
    pop   esi
    mov   eax, ecx
    pop   ebx
    ret   0
_form_netmask ENDP

```

`set_bit()` is primitive: it just shift left 1 to number of bits we need and then ORs it with the “input” value. `form_netmask()` has a loop: it will set as many bits (starting from the [MSB](#)) as passed in the `netmask_bits` argument

38.5 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 39

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.

39.1 Three iterators

Listing 39.1: 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;

    // 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.

39.2 Two iterators

GCC 4.9 does even more, leaving only 2 iterators:

Listing 39.2: 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: [16.1.3 on page 208](#).

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;
    };
}

```

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 39.3: 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 39.4: 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
```

39.3 Intel C++ 2011 case

Compiler optimizations can also be weird, but nevertheless, still correct. Here is what the Intel C++ compiler 2011 does:

Listing 39.5: Optimizing Intel C++ 2011 x64

```
f      PROC
; parameter 1: rcx = a1
; parameter 2: rdx = a2
; parameter 3: r8  = cnt
.B1.1::           ; Preds .B1.0
```

```

    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::: ; Preds .B1.1
    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::: ; Preds .B1.2
    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::: ; Preds .B1.3
    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::: ; Preds .B1.3 .B1.4
    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::: ; Preds .B1.5
    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
    jl    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::: ; Preds .B1.8 just_copy2
    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%      ;8.2
    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::: ; Preds .B1.11 just_copy
    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     .B1.11       ;8.2
      ; Prob 82%
      ; 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 40

Duff's device

Duff's device¹ 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>

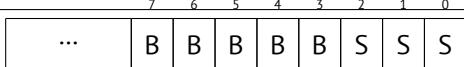
void bzero(uint8_t* dst, size_t count)
{
    int i;

    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 41

Division by 9

A very simple function:

```
int f(int a)
{
    return a/9;
};
```

41.1 x86

...is compiled in a very predictable way:

Listing 41.1: 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   ecx
    pop   ebp
    ret   0
_f    ENDP
```

IDIV divides the 64-bit number stored in the EDX: EAX register pair by the value in the ECX. As a result, EAX will contain the [quotient](#), and EDX—the remainder. The result is returned from the `f()` function in the EAX register, so the value is not moved after the division operation, it is in right place already. Since IDIV uses the value in the EDX: EAX register pair, the CDQ instruction (before IDIV) extends the value in EAX to a 64-bit value taking its sign into account, just as MOVSX does. If we turn optimization on (/Ox), we get:

Listing 41.2: Optimizing MSVC

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

    mov   ecx, DWORD PTR _a$[esp-4]
    mov   eax, 954437177 ; 38e38e39H
    imul  ecx
    sar   edx, 1
    mov   eax, edx
    shr   eax, 31       ; 0000001fH
    add   eax, edx
    ret   0
_f    ENDP
```

This is division by multiplication. Multiplication operations work much faster. And it is possible to use this trick ¹ to produce code which is effectively equivalent and faster.

¹Read more about division by multiplication in [War02, pp. 10-3]

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 41.3: 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

```

41.2 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 ([19 on page 312](#)).

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

```

41.2.1 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

```

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 two multiplies numbers, treating them as signed numbers and leaving the high 32-bit part of result in the R0 register, dropping the low 32-bit part of the result.

The “MOV R1, R0, ASR#1” instruction is an arithmetic shift right by one bit.

“ADD R0, R1, R0, LSR#31” is $R0 = R1 + R0 \gg 31$

There is no separate shifting instruction in ARM mode. Instead, an instructions 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*.

41.2.2 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).

41.2.3 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.

41.3 MIPS

For some reason, optimizing GCC 4.4.5 generate just a division instruction:

Listing 41.4: 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.

If we alter the statement to “a % 9”, the MFHI instruction is to be used here instead of MFLO.

²These instructions are also called “data processing instructions”

41.4 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). If $n \geq 32$, then the high part of the [product](#) is shifted (in EDX or RDX).

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 41.5: Optimizing MSVC 2012

```
_f3_32_unsigned PROC
    mov     eax, -1431655765      ; aaaaaaaabH
    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      ; 55555556H
    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
    shr     eax, 31             ; 0000001fH
    add     eax, edx            ; add 1 if sign is negative
    ret     0
_f3_32_signed ENDP
```

41.4.1 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].

41.5 Getting the divisor

41.5.1 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 41.6: Optimizing MSVC 2012

```
mov    eax, 2021161081           ; 78787879H
imul   DWORD PTR _a$[esp-4]
sar    edx, 3
mov    eax, edx
shr    eax, 31                  ; 00000001fH
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 41.7: Wolfram Mathematica

```
In[1]:=N[2^(32+3)/2021161081]
Out[1]:=17.
```

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;
};
```

³Wikipedia

Listing 41.8: Optimizing MSVC 2012 x64

```
f1234 PROC
    mov    rax, 7653754429286296943          ; 6a37991a23aead6fH
    mul    rcx
    shr    rdx, 9
    mov    rax, rdx
    ret    0
f1234 ENDP
```

Listing 41.9: Wolfram Mathematica

```
In[1]:=N[2^(64+9)/16^6a37991a23aead6f]
Out[1]:=1234.
```

41.5.2 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 41.10: Wolfram Mathematica

```
In[1]:=N[2^32/16^55555556]
Out[1]:=3.
```

The divisor is 3.

41.6 Exercise #1

What does this code do?

Listing 41.11: Optimizing MSVC 2010

```
_a$ = 8
_f PROC
    mov    ecx, DWORD PTR _a$[esp-4]
    mov    eax, -968154503 ; c64b2279H
    imul   ecx
    add    edx, ecx
    sar    edx, 9
    mov    eax, edx
    shr    eax, 31          ; 00000001FH
    add    eax, edx
    ret    0
_f ENDP
```

Listing 41.12: Optimizing GCC 4.9 (ARM64)

```
f:  
    mov      w1, 8825  
    movk    w1, 0xc64b, lsl 16  
    smull   x1, w0, w1  
    lsr     x1, x1, 32  
    add     w1, w0, w1  
    asr     w1, w1, 9  
    sub     w0, w1, w0, asr 31  
    ret
```

Answer [G.1.16 on page 983](#).

Chapter 42

String to number conversion (atoi())

Let's try to reimplement the standard atoi() C function.

42.1 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 shift.

42.1.1 Optimizing MSVC 2013 x64

Listing 42.1: Optimizing MSVC 2013 x64

```
s$ = 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
; first character is zero-byte, i.e., string terminator?
```

¹American Standard Code for Information Interchange

```

; 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.

42.1.2 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 42.2: 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

```

42.1.3 Optimizing Keil 6/2013 (ARM mode)

Listing 42.3: Optimizing Keil 6/2013 (ARM mode)

```

my_atoi PROC
; R1 will contain pointer to character
    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

```

42.1.4 Optimizing Keil 6/2013 (Thumb mode)

Listing 42.4: 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.

42.1.5 Optimizing GCC 4.9.1 ARM64

The ARM64 compiler can use the pre-increment instruction suffix:

Listing 42.5: 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

```

42.2 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"));
    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
};
```

42.2.1 Optimizing GCC 4.9.1 x64

Listing 42.6: 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
    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: [48.1.2 on page 544](#).

Optimizing MSVC 2013 x64 does the same tricks.

42.2.2 Optimizing Keil 6/2013 (ARM mode)

Listing 42.7: 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 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.

42.3 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 43

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 43.1: 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 43.2: 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([41 on page 501](#))).

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.

43.1 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.

43.1.1 strcmp()

Listing 43.3: strcmp() example

```
bool is_bool (char *s)
{
    if (strcmp (s, "true")==0)
        return true;
    if (strcmp (s, "false")==0)
        return false;

    assert(0);
}
```

Listing 43.4: 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 43.5: Optimizing MSVC 2010

\$SG3454 DB	'true', 00H
-------------	-------------

```

$SG3456 DB      'false', 00H

_s$ = 8          ; size = 4
?is_bool@@YA_NPAD@Z PROC ; is_bool
    push    esi
    mov     esi, DWORD PTR _s$[esp]
    mov     ecx, OFFSET $SG3454 ; 'true'
    mov     eax, esi
    npad   4 ; align next label
$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

```

```

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

```

43.1.2 strlen()

Listing 43.6: strlen() example

```

int strlen_test(char *s1)
{
    return strlen(s1);
}

```

Listing 43.7: 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

```

43.1.3 strcpy()

Listing 43.8: strcpy() example

```

void strcpy_test(char *s1, char *outbuf)
{
    strcpy(outbuf, s1);
}

```

Listing 43.9: 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

```

43.1.4 memset()

Example#1

Listing 43.10: 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 43.11: 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: [14.1.4 on page 182](#).

Example#2

Listing 43.12: 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 43.13: 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 43.14: 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
```

43.1.5 memcpy()

Short blocks

The routine to copy short blocks is often implemented as a sequence of MOV instructions.

Listing 43.15: memcpy() example

```
void memcpy_7(char *inbuf, char *outbuf)
{
    memcpy(outbuf+10, inbuf, 7);
};
```

Listing 43.16: 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 43.17: 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: [21.4.1 on page 374](#).

Long blocks

The compilers behave differently in this case.

Listing 43.18: 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 MOVS instruction (because 128 divides evenly by 4):

Listing 43.19: 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 MOVSZ.

Listing 43.20: 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 43.21: 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:
    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: [25.2 on page 433](#).

43.1.6 memcmp()

Listing 43.22: 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 43.23: 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
    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
```

43.1.7 IDA script

There is also a small [IDA](#) script for searching and folding such very frequently seen pieces of inline code: [GitHub](#).

Chapter 44

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 44.1: 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 44.2: 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 45

Branchless *abs()* function

Let's revisit an example we considered earlier [12.2 on page 133](#) 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.

45.1 Optimizing GCC 4.9.1 x64

We could see it if we compile it using optimizing GCC 4.9:

Listing 45.1: 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: [30 on page 464](#).

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?

45.2 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 45.2: 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 46

Variadic functions

Functions like `printf()` and `scanf()` can have a variable number of arguments. How are these arguments accessed?

46.1 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?

46.1.1 *cdecl* calling conventions

Listing 46.1: 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.

46.1.2 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 46.2: 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
    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 46.3: 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
    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 : [64.8 on page 687](#).

46.2 *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:

Listing 46.4: Optimizing MSVC 2010

```

_fmt$ = 8
_die  PROC
; load 1st argument (format-string)
mov    ecx, DWORD PTR _fmt$[esp-4]

```

```

; get pointer to the 2nd argument
lea    eax, DWORD PTR _fmt$[esp]
push   eax           ; pass 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 46.5: 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 47

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++)

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.

47.1 x64: Optimizing MSVC 2013

Listing 47.1: Optimizing MSVC 2013 x64

```
s$ = 8
str_trim PROC

; RCX is the first function argument and it always holds pointer to the string

; 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 string length zero? exit then
    test    eax, eax
$LN18@str_trim:
    je     SHORT $LN15@str_trim
; RAX holds string length
; here is probably disassembler (or assembler printing routine) error,
; LEA RDX... should be here instead of LEA EDX...
    lea     edx, DWORD PTR [rax-1]
; idle instruction: EAX will be reset at the next instructions execution'
    mov     eax, edx
; load character at address s[str_len-1]
    movzx   eax, BYTE PTR [rdx+rcx]
; save also pointer to the last character to R8
    lea     r8, QWORD PTR [rdx+rcx]
    cmp     al, 13 ; is it '\r'?
    je     SHORT $LN2@str_trim
    cmp     al, 10 ; is it '\n'?
    jne     SHORT $LN15@str_trim
$LN2@str_trim:
; store 0 to that place
    mov     BYTE PTR [r8], 0
    mov     eax, edx
; check character for 0, but conditional jump is above...
    test    edx, edx
    jmp     SHORT $LN18@str_trim
$LN15@str_trim:
; return "s"
    mov     rax, rcx
    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: [43 on page 515](#).

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: [30 on page 464](#).

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 47.2: 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 47.3: 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. There is another trick at the end. If we do not count `strlen()`'s inlined code, there are only 3 conditional jumps in the function. There should be 4: the 4th has to be located at the function end, to check if the character is zero. But there is an unconditional jump to the "\$LN18@str_trim" label, where we see `JE`, which was first used to check if the input string is empty, right after `strlen()` finishes. So the code uses the `JE` instruction at this place for two purposes! This may be overkill, but nevertheless, MSVC did it.

You can read more on why it's important to do the job without conditional jumps, if possible: [33.1 on page 469](#).

47.2 x64: Non-optimizing GCC 4.9.1

```
str_trim:
    push   rbp
    mov    rbp, rsp
    sub    rsp, 32
    mov    QWORD PTR [rbp-24], rdi
; for() first part begins here
    mov    rax, QWORD PTR [rbp-24]
    mov    rdi, rax
    call   strlen
    mov    QWORD PTR [rbp-8], rax ; str_len
; for() first part ends here
    jmp   .L2
; for() body begins here
.L5:
    cmp   BYTE PTR [rbp-9], 13 ; c=='\r'?
    je    .L3
    cmp   BYTE PTR [rbp-9], 10 ; c=='\n'?
    jne   .L4
.L3:
    mov   rax, QWORD PTR [rbp-8] ; str_len
    lea   rdx, [rax-1] ; EDX=str_len-1
    mov   rax, QWORD PTR [rbp-24] ; s
    add   rax, rdx ; RAX=s+str_len-1
    mov   BYTE PTR [rax], 0 ; s[str_len-1]=0
; for() body ends here
; for() third part begins here
    sub   QWORD PTR [rbp-8], 1 ; str_len--
; for() third part ends here
.L2:
; for() second part begins here
    cmp   QWORD PTR [rbp-8], 0 ; str_len==0?
    je    .L4 ; exit then
; check second clause, and load "c"
    mov   rax, QWORD PTR [rbp-8] ; RAX=str_len
    lea   rdx, [rax-1] ; RDX=str_len-1
    mov   rax, QWORD PTR [rbp-24] ; RAX=s
```

```

    add    rax, rdx          ; RAX=s+str_len-1
    movzx eax, BYTE PTR [rax] ; AL=s[str_len-1]
    mov    BYTE PTR [rbp-9], al ; store loaded char into "c"
    cmp    BYTE PTR [rbp-9], 0 ; is it zero?
    jne    .L5                ; yes? exit then
; for() second part ends here
.L4:
; return "s"
    mov    rax, QWORD PTR [rbp-24]
    leave
    ret

```

Comments are added by the author of the book. After the execution of `strlen()`, the control is passed to the L2 label, and there two clauses are checked, one after another. The second will never be checked, if the first one (`str_len==0`) is false (this is “short-circuit”).

Now let's see this function in short form:

- First for() part (call to `strlen()`)
- goto L2
- L5: for() body. goto exit, if needed
- for() third part (decrement of `str_len`)
- L2: for() second part: check first clause, then second. goto loop body begin or exit.
- L4: // exit
- return s

47.3 x64: Optimizing GCC 4.9.1

```

str_trim:
    push    rbx
    mov     rbx, rdi
; RBX will always be "s"
    call    strlen
; check for str_len==0 and exit if its so'
    test   rax, rax
    je     .L9
    lea    rdx, [rax-1]
; RDX will always contain str_len-1 value, not str_len
; so RDX is more like buffer index variable
    lea    rsi, [rbx+rdx]      ; RSI=s+str_len-1
    movzx ecx, BYTE PTR [rsi] ; load character
    test   cl, cl
    je     .L9                 ; exit if its zero'
    cmp    cl, 10
    je     .L4
    cmp    cl, 13               ; exit if its not' '\n' and not '\r'
    jne    .L9
.L4:
; this is weird instruction. we need RSI=s-1 here.
; its possible to get it by' MOV RSI, EBX / DEC RSI
; but this is two instructions instead of one
    sub    rsi, rax
; RSI = s+str_len-1-str_len = s-1
; main loop begin
.L12:
    test   rdx, rdx
; store zero at address s-1+str_len-1+1 = s-1+str_len = s+str_len-1
    mov    BYTE PTR [rsi+1+rdx], 0
; check for str_len-1==0. exit if so.
    je     .L9
    sub    rdx, 1               ; equivalent to str_len--
; load next character at address s+str_len-1
    movzx ecx, BYTE PTR [rbx+rdx]
    test   cl, cl               ; is it zero? exit then
    je     .L9

```

```

        cmp    cl, 10          ; is it '\n'?
        je     .L12
        cmp    cl, 13          ; is it '\r'?
        je     .L12
.L9:
; return "s"
        mov    rax, rbx
        pop   rbx
        ret

```

Now this is more complex. The code before the loop's body start is executed only once, but it has the CR/LF characters check too! What is this code duplication for?

The common way to implement the main loop is probably this:

- (loop start) check for CR/LF characters, make decisions
- store zero character

But GCC has decided to reverse these two steps. Of course, *store zero character* cannot be first step, so another check is needed:

- workout first character. match it to CR/LF, exit if character is not CR/LF
- (loop begin) store zero character
- check for CR/LF characters, make decisions

Now the main loop is very short, which is good for 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).

47.4 ARM64: Non-optimizing GCC (Linaro) 4.9

This implementation is straightforward:

Listing 47.4: 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:
        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
        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

```

47.5 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 [47.3 on page 537](#) example.

Listing 47.5: 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
; 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

```

47.6 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 47.6: 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

```

47.7 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 47.7: 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
    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

```

47.8 MIPS

Listing 47.8: 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
; 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 48

toupper() function

Another very popular function transforms 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;
}
```

'a'+'A' expression is left in source code for better readability, it is to be optimized by compiler, of course ¹.

The [ASCII](#) code of "a" symbol is 97 (or 0x61), and 65 (or 0x41) for "A" symbol. The difference (or distance) between them in [ASCII](#) table is 32 (or 0x20).

For better understanding, reader may take a look at 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 48.1: 7-bit [ASCII](#) table in Emacs

48.1 x64

48.1.1 Two comparison operations

Non-optimizing MSVC is straightforward: the code checks if input symbol is in [97..122] range (or in ['a'..'z'] range) and subtracts 32 in this case. There are also minor compiler artefact:

Listing 48.1: 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]
8     cmp    eax, 122
```

¹However, if to be meticulous, there are still could be a compilers which can't optimize such expressions and leaving them right in the code.

```

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 artefact
14 $LN2@toupper:
15     movzx  eax, BYTE PTR c$[rsp] ; unnecessary casting
16 $LN1@toupper:
17 $LN3@toupper: ; compiler artefact
18     ret    0
19 toupper ENDP

```

It's important to notice that input byte is loaded into 64-bit local stack slot at line 3. All the rest bits ([8..63]) are untouched, i.e., contains some random noise (you'll see it in debugger). All instructions operates only on byte-level, so it's fine. The last MOVZX instruction at line 15 takes byte from local stack slot and zero-extends it into *int* 32-bit data type.

Non-optimizing GCC does mostly the same:

Listing 48.2: 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

```

48.1.2 One comparison operation

Optimizing MSVC does its job better, it generates only one comparison operation:

Listing 48.3: 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 two comparison operations by one : [42.2.1 on page 513](#).

We would rewrite this into C/C++:

```

int tmp=c-97;
if (tmp>25)
    return c;
else
    return c-32;

```

tmp variable should be signed. This makes two subtracting operations in case of transformation plus one comparison operation. While original algorithm uses two comparison operations plus one subtracting operation.

Optimizing GCC is even better, it got rid of jumps (which is good: [33.1 on page 469](#)) by using CMovcc instruction:

Listing 48.4: Optimizing GCC 4.9 (x64)

```

1 toupper:
2     lea    edx, [rdi-97] ; 0x61
3     lea    eax, [rdi-32] ; 0x20
4     cmp    d1, 25
5     cmova eax, edi
6     ret

```

At line 3 the code prepares the subtracted value in advance, as if conversion will happen always. At line 5 subtracted value in EAX is replaced by untouched input value if conversion is not needed. And then this value (of course incorrect) is dropped. Advance subtracting is a price compiler paying for the absence of conditional jumps.

48.2 ARM

Optimizing Keil for ARM mode also generates only one comparison:

Listing 48.5: 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

```

SUBLS and ANDLS instructions are executing only if R1 value is less than 0x19 (or equal). They do actual conversion.

Optimizing Keil for Thumb mode generates only one comparison operation as well:

Listing 48.6: 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

```

Last two LSLS and LSRS instructions works like `AND reg, 0xFF`: they are analogous to C/C++-expression `(i << 24) >> 24`. Apparently, Keil for Thumb mode deduced that two 2-byte instructions is shorter then the code loading 0xFF constant into register plus AND instruction.

48.2.1 GCC for ARM64

Listing 48.7: 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
    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 48.8: 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
```

48.3 Summary

All these compiler optimizations are very popular nowadays and practicing reverse engineer usually sees such code patterns often.

Chapter 49

Incorrectly disassembled code

Practicing reverse engineers often have to deal with incorrectly disassembled code.

49.1 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]
push

```

```

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.

49.2 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 49.1: 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
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 49.2: random noise (x86-64)

```

lea    esi, [rax+rdx*4+43558D29h]

loc_AF3: ; CODE XREF: seg000:00000000000000B46
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

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 49.3: 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 49.4: random noise (ARM (Thumb mode))

```

LSRS    R3, R6, #0x12
LDRH    R1, [R7, #0x2C]
SUBS    R0, #0x55 ; 'U'
ADR     R1, loc_3C
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 49.5: 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 look like noise as well, but still execute correctly.

Chapter 50

Obfuscation

The obfuscation is an attempt to hide the code (or its meaning) from reverse engineers.

50.1 Text strings

As we saw in ([57 on page 664](#)) , 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: [78.2 on page 770](#).

50.2 Executable code

50.2.1 Inserting garbage

Executable code obfuscation implies inserting random garbage code between real one, which executes but does nothing useful.

A simple example:

Listing 50.1: original code

```
add    eax, ebx
mul    ecx
```

Listing 50.2: 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?

50.2.2 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 label / RET.
- PUSH op can also be replaced with the following instructions pair: SUB ESP, 4 (or 8) / MOV [ESP], op.

50.2.3 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.
```

50.2.4 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:
```

50.2.5 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.

50.3 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.

50.4 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: [\[Dol13\]](#).

50.5 Exercises

50.5.1 Exercise #1

This is a very short program, compiled using the patched Tiny C compiler ¹. Try to find out what it does.
[beginners.re](#).

Answer: [G.1.15 on page 983](#).

¹blog.yurichev.com

Chapter 51

C++

51.1 Classes

51.1.1 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:

Listing 51.1: MSVC

```

_c2$ = -16 ; size = 8
_c1$ = -8 ; size = 8
_main PROC
    push ebp
    mov esp, ebp
    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* ([51.1.1](#))—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:

Listing 51.2: MSVC

```

_this$ = -4 ; size = 4
??0c@@QAE@XZ PROC ; c::c, COMDAT
; _this$ = ecx
    push ebp
    mov esp, ebp
    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
??0c@@QAE@HH@Z PROC ; c::c, COMDAT

```

¹Object-Oriented Programming

```
; _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 51.3: 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 51.4: 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$[esp-4]
  mov  eax, ecx
  mov  ecx, DWORD PTR _a$[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` ([51.1.1 on page 556](#)) calling convention is used here, which together with the `stdcall` ([64.2 on page 681](#)) 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 ([64 on page 681](#)).

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 51.5: 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.

We also see `JMP printf` instead of `RET` in the `dump()` method, that *hack* we already saw earlier: [13.1.1 on page 145](#).

²Apparently, for easier porting of 32-bit C/C++ code to x64

GCC-x86

It is almost the same story in GCC 4.4.1, with a few exceptions.

Listing 51.6: 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, 0FFFFFFF0h
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:

```

public _ZN1cC1Ev ; weak
_ZN1cC1Ev    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:

```

public _ZN1cC1Eii
_ZN1cC1Eii  proc near

arg_0        = dword ptr  8
arg_4        = dword ptr  0Ch
arg_8        = dword ptr  10h

push    ebp

```

³There is a good document about the various name mangling conventions in different compilers: [\[Fog14\]](#).

```

    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 RDI, RSI, RDX, RCX, R8 and R9 [Mit13] registers, and the pointer to *this* via the first one (RDI) and that is what we see here. The *int* data type is also 32-bit here. The JMP instead of RET *hack* is also used here.

Listing 51.7: GCC 4.4.6 x64

```

; 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

```

51.1.2 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;
        this->radius=radius;
    };
    void dump()
    {
        printf ("this is sphere. color=%d, radius=%d\n", color, radius);
    };
};

```

```

};

int main()
{
    box b(1, 10, 20, 30);
    sphere s(2, 40);

    b.print_color();
    s.print_color();

    b.dump();
    s.dump();

    return 0;
}

```

Let's investigate the generated code of the dump() functions/methods and also object::print_color(), and see the memory layout for the structures-objects (for 32-bit code).

So, here are the dump() methods for several classes, generated by MSVC 2008 with /Ox and /Ob0 options ⁴

Listing 51.8: 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 51.9: 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 51.10: Optimizing MSVC 2008 /Ob0

```

?dump@sphere@@QAEXXZ PROC ; sphere::dump, COMDAT
; _this$ = ecx
    mov eax, DWORD PTR [ecx+4]
    mov ecx, DWORD PTR [ecx]
    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

```

⁴The /Ob0 option stands for disabling inline expansion since function inlining can make our experiment harder

```

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 51.11: Optimizing MSVC 2008 /Obo

```

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$[esp+40]
    call ??0box@@QAE@HHH@Z ; box::box
    push 40
    push 2
    lea ecx, DWORD PTR _s$[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, a pointers to both the *box* and *sphere* objects are passed as `this`, and it can work with these objects easily since the *color* field in these objects is always at the pinned address (at offset +0x0).

It can be said that the `object::print_color()` method is agnostic in relation to the input object type as long as the fields are *pinned* at the same addresses, and this condition is always true.

And if you create inherited class of the *box* class, the compiler will add the new fields after the *depth* field, leaving the *box* class fields at the pinned addresses.

Thus, the `box::dump()` method will work fine for accessing the *color/width/height/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).

51.1.3 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@_0DG@NCNGAADL@this?5is?5box?4?5color?$DN?$CFd?0?5width?$DN?$CFd?0@
    call _printf
    add  esp, 20
    ret  0
?dump@box@@QAEXXZ ENDP ; box::dump
```

Here is a memory layout of the class:

offset	description
+0x0	int color
+0x4	int width
+0x8	int height
+0xC	int depth

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*.

51.1.4 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;
        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 51.12: Optimizing MSVC 2008 /Ob0

```
?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 51.13: 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 51.14: 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

The code of the *box::get_volume()* and *solid_object::get_density()* methods is trivial:

Listing 51.15: 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 51.16: 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 51.17: 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.

51.1.5 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);
    };
};

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$[esp+48]
    call ??0box@@QAE@HHHH@Z ; box::box
    push 40
    push 2
    lea ecx, DWORD PTR _s$[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:_type_info@@6B@ ; box `RTTI Type Descriptor'
    DD 00H
    DB '.?AVbox@@', 00H

??_R1A@?OA@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@?OA@EA@box@@8 ; box::`RTTI Base Class Array'
    DD FLAT:_R1A@?OA@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
    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.

⁵You can read more about pointers to functions in the relevant section: ([23 on page 400](#))

⁶Run-time type information

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.

51.2 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 51.18: 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 51.19: MSVC 2012

```
$SG37112 DB 'world!', 0aH, 00H
$SG37113 DB 'Hello, ', 00H

_main PROC
    push OFFSET $SG37113 ; 'Hello, '
    push OFFSET ?cout@std@@3V?$basic_ostream@DU?$char_traits@D@std@@@1@A ; std::cout
    call ??$?6U?$char_traits@D@std@@@std@@YAAV?$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?$char_traits@D@std@@@std@@YAAV?$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
```

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.

51.3 References

In C++, references are pointers ([10 on page 102](#)) 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 ([10 on page 102](#)) 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 ([10 on page 102](#)):

Listing 51.20: Optimizing MSVC 2010

```
_x$ = 8                                ; size = 4
_y$ = 12                               ; size = 4
_sum$ = 16                             ; size = 4
_product$ = 20                          ; size = 4
?f2@@YAXHAAH0@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@@YAXHAAH0@Z ENDP                  ; f2
```

(The reason why C++ functions has such strange names is explained here: [51.1.1 on page 556](#).)

51.4 STL

N.B.: all examples here were checked only in 32-bit environment. x64 wasn't checked.

51.4.1 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 51.21: 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.

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 51.22: 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-offsetof(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 51.23: 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$[esp+80]
    push eax
    call ??$?HDI?$char_traits@D@std@@V?$allocator@D@1@@std@@YA?AV?$basic_string@DU? \
        $char_traits@D@std@@V?$allocator@D@2@@0@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

$LN119@main:
    cmp DWORD PTR _s2$[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 51.24: 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

    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 51.25: 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
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 51.26: 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

```

⁷(C++) Standard Template Library: [51.4 on page 572](#)

Listing 51.27: 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 51.28: 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
.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.

51.4.2 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();
printf ("node at .end:\n");
tmp=l.end();
printf ("node at .end():\n");

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);

printf ("removing last element...\n");
l.pop_back();
dump_List_val((unsigned int*)(void*)&l);
};

```

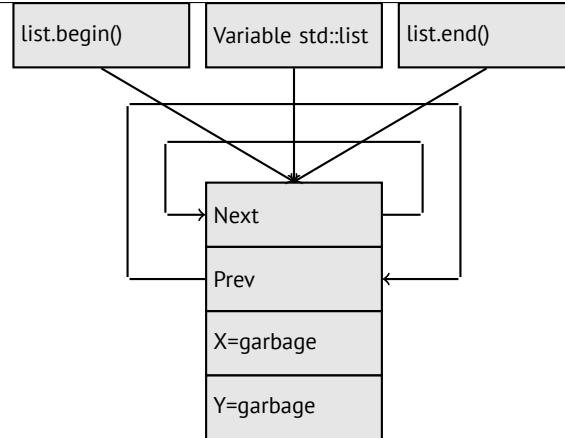
GCC

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:



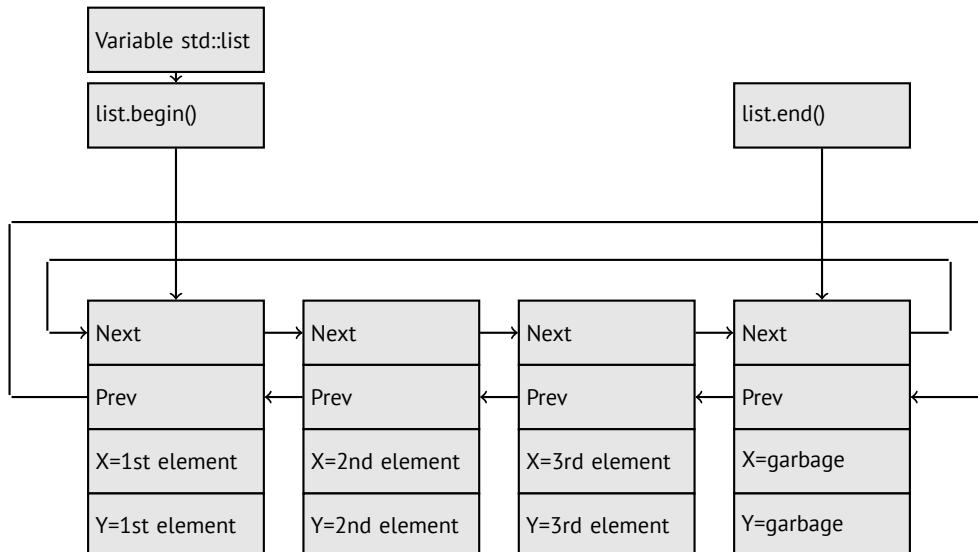
At this moment, the .begin and .end iterators are equal to each other.

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:



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 51.29: 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 _ZNSt4listI1aSaIS0_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 _ZNSt4listI1aSaIS0_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)
    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(
        const 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]
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 51.30: The whole output

```

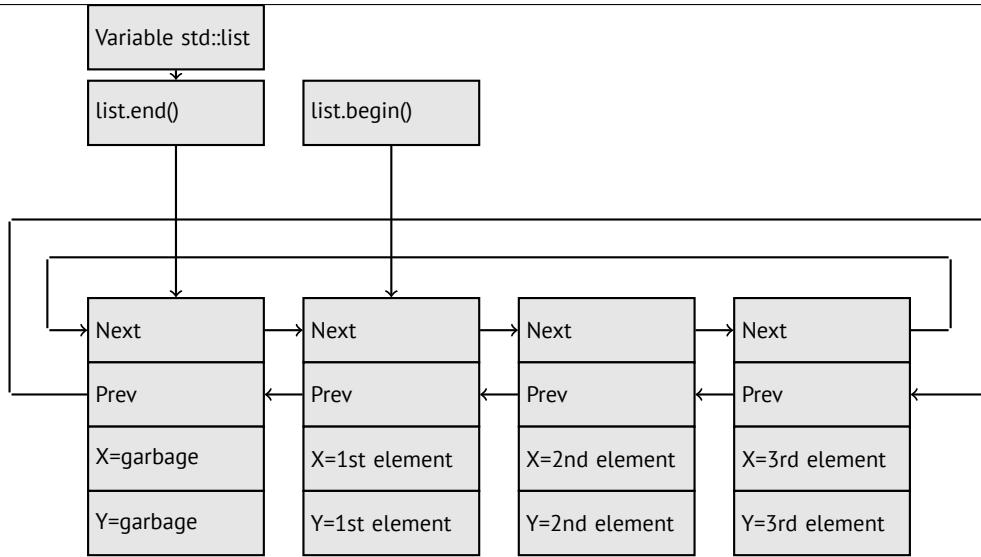
* empty list:
ptr=0x0028fe90 _Next=0x0028fe90 _Prev=0x0028fe90 x=3 y=0
* 3-elements list:
ptr=0x000349a0 _Next=0x00034988 _Prev=0x0028fe90 x=3 y=4
ptr=0x00034988 _Next=0x00034b40 _Prev=0x000349a0 x=1 y=2
ptr=0x00034b40 _Next=0x0028fe90 _Prev=0x00034988 x=5 y=6
ptr=0x0028fe90 _Next=0x000349a0 _Prev=0x00034b40 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

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 51.31: 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 ?_Buynode@?$_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<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?_
    ↳ $List_node@Ua@@PAX@1@PAU21@0ABUa@@@Z ; std::List_buy<a, std::allocator<a>>::_Buynode<a>
    ↳ const &gt;
    mov DWORD PTR [esi+4], eax
    mov ecx, DWORD PTR [eax+4]
    mov DWORD PTR _t1$[esp+28], 3 ; data for a new node
    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 ??$_Buynode@ABu@@@@?$_List_buy@Ua@@V?$allocator@Ua@@@std@@@std@@QAEPAU?_
↳ $_List_node@Ua@@PAX@1@PAU21@0ABu@@@Z ; std::_List_buy<a, std::allocator<a>>::_Buynode<a>
↳ const &gt;
mov  DWORD PTR [esi+4], eax
mov  ecx, DWORD PTR [eax+4]
mov  DWORD PTR _t1$[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@ABu@@@@?$_List_buy@Ua@@V?$allocator@Ua@@@std@@@std@@QAEPAU?_
↳ $_List_node@Ua@@PAX@1@PAU21@0ABu@@@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]
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 51.32: 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.

51.4.3 std::vector

We would call std::vector a safe wrapper of the POD⁸ C array. Internally it is somewhat similar to std::string (51.4.1 on page 572): 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 (18 on page 263). 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
};

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]);
}

```

⁸(C++) Plain Old Data Type

⁹GCC internals: <http://go.yurichev.com/17086>

```

};

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
element 4: 5
_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
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 51.33: 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 $LN1@at
    push OFFSET ??_C@_0BM@NMJKDPO@invalid?5vector?$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$[ebp+4], 0    ; Mylast
    mov DWORD PTR _c$[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@@QAE$QAH@Z ; std::vector<int, std::allocator<int> <
        >::push_back
    lea edx, DWORD PTR _c$[ebp]
    push edx
```

```

call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
mov DWORD PTR $T5[ebp], 2
lea eax, DWORD PTR $T5[ebp]
push eax
lea ecx, DWORD PTR _c$[ebp]
call ?push_back@?$vector@HV?$allocator@H@std@@@std@@@QAEX$$QAH@Z ; std::vector<int, std::allocator<
allocator<int> >::push_back
lea ecx, DWORD PTR _c$[ebp]
push ecx
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
mov DWORD PTR $T4[ebp], 3
lea edx, DWORD PTR $T4[ebp]
push edx
lea ecx, DWORD PTR _c$[ebp]
call ?push_back@?$vector@HV?$allocator@H@std@@@std@@@QAEX$$QAH@Z ; std::vector<int, std::allocator<
allocator<int> >::push_back
lea eax, DWORD PTR _c$[ebp]
push eax
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
mov DWORD PTR $T3[ebp], 4
lea ecx, DWORD PTR $T3[ebp]
push ecx
lea ecx, DWORD PTR _c$[ebp]
call ?push_back@?$vector@HV?$allocator@H@std@@@std@@@QAEX$$QAH@Z ; std::vector<int, std::allocator<
allocator<int> >::push_back
lea edx, DWORD PTR _c$[ebp]
push edx
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
push 6
lea ecx, DWORD PTR _c$[ebp]
call ?reserve@?$vector@HV?$allocator@H@std@@@std@@@QAEXI@Z ; std::vector<int, std::allocator<
int> >::reserve
lea eax, DWORD PTR _c$[ebp]
push eax
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
mov DWORD PTR $T2[ebp], 5
lea ecx, DWORD PTR $T2[ebp]
push ecx
lea ecx, DWORD PTR _c$[ebp]
call ?push_back@?$vector@HV?$allocator@H@std@@@std@@@QAEX$$QAH@Z ; std::vector<int, std::allocator<
allocator<int> >::push_back
lea edx, DWORD PTR _c$[ebp]
push edx
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
mov DWORD PTR $T1[ebp], 6
lea eax, DWORD PTR $T1[ebp]
push eax
lea ecx, DWORD PTR _c$[ebp]
call ?push_back@?$vector@HV?$allocator@H@std@@@std@@@QAEX$$QAH@Z ; std::vector<int, std::allocator<
allocator<int> >::push_back
lea ecx, DWORD PTR _c$[ebp]
push ecx
call ?dump@@YAXPAUvector_of_ints@@@Z ; dump
add esp, 4
push 5
lea ecx, DWORD PTR _c$[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 51.34: 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, 0FFFFFFF0h
    sub  esp, 20h
    mov  dword ptr [esp+14h], 0
    mov  dword ptr [esp+18h], 0
    mov  dword ptr [esp+1Ch], 0
    lea   eax, [esp+14h]
    mov  [esp], eax
    call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
    mov  dword ptr [esp+10h], 1
    lea   eax, [esp+10h]
    mov  [esp+4], eax
    lea   eax, [esp+14h]
    mov  [esp], eax
    call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int, std::allocator<int>>::push_back(
    ↳ int const&
    lea   eax, [esp+14h]
    mov  [esp], eax
    call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
    mov  dword ptr [esp+10h], 2
    lea   eax, [esp+10h]
    mov  [esp+4], eax
    lea   eax, [esp+14h]
    mov  [esp], eax
    call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int, std::allocator<int>>::push_back(
    ↳ int const&
    lea   eax, [esp+14h]
    mov  [esp], eax
    call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
    mov  dword ptr [esp+10h], 3
    lea   eax, [esp+10h]
    mov  [esp+4], eax
    lea   eax, [esp+14h]
    mov  [esp], eax
    call _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int, std::allocator<int>>::push_back(
    ↳ int const&
    lea   eax, [esp+14h]
    mov  [esp], eax
    call _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
    mov  dword ptr [esp+10h], 4

```

```

    lea    eax, [esp+10h]
    mov    [esp+4], eax
    lea    eax, [esp+14h]
    mov    [esp], eax
    call   _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int, std::allocator<int>>::push_back(
        ↴ int const&
    lea    eax, [esp+14h]
    mov    [esp], eax
    call   _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
    mov    ebx, [esp+14h]
    mov    eax, [esp+1Ch]
    sub    eax, ebx
    cmp    eax, 17h
    ja    short loc_80001CF
    mov    edi, [esp+18h]
    sub    edi, ebx
    sar    edi, 2
    mov    dword ptr [esp], 18h
    call   _Znwj           ; operator new(uint)
    mov    esi, eax
    test   edi, edi
    jz    short loc_80001AD
    lea    eax, ds:0[edi*4]
    mov    [esp+8], eax      ; n
    mov    [esp+4], ebx      ; src
    mov    [esp], esi        ; dest
    call   memmove

loc_80001AD: ; CODE XREF: main+F8
    mov    eax, [esp+14h]
    test   eax, eax
    jz    short loc_80001BD
    mov    [esp], eax      ; void *
    call   _ZdlPv          ; operator delete(void *)

loc_80001BD: ; CODE XREF: main+117
    mov    [esp+14h], esi
    lea    eax, [esi+edi*4]
    mov    [esp+18h], eax
    add    esi, 18h
    mov    [esp+1Ch], esi

loc_80001CF: ; CODE XREF: main+DD
    lea    eax, [esp+14h]
    mov    [esp], eax
    call   _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
    mov    dword ptr [esp+10h], 5
    lea    eax, [esp+10h]
    mov    [esp+4], eax
    lea    eax, [esp+14h]
    mov    [esp], eax
    call   _ZNSt6vectorIiSaIiEE9push_backERKi ; std::vector<int, std::allocator<int>>::push_back(
        ↴ int const&
    lea    eax, [esp+14h]
    mov    [esp], eax
    call   _Z4dumpP14vector_of_ints ; dump(vector_of_ints *)
    mov    dword ptr [esp+10h], 6
    lea    eax, [esp+10h]
    mov    [esp+4], eax
    lea    eax, [esp+14h]
    mov    [esp], eax
    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
_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.

51.4.4 std::map and std::set

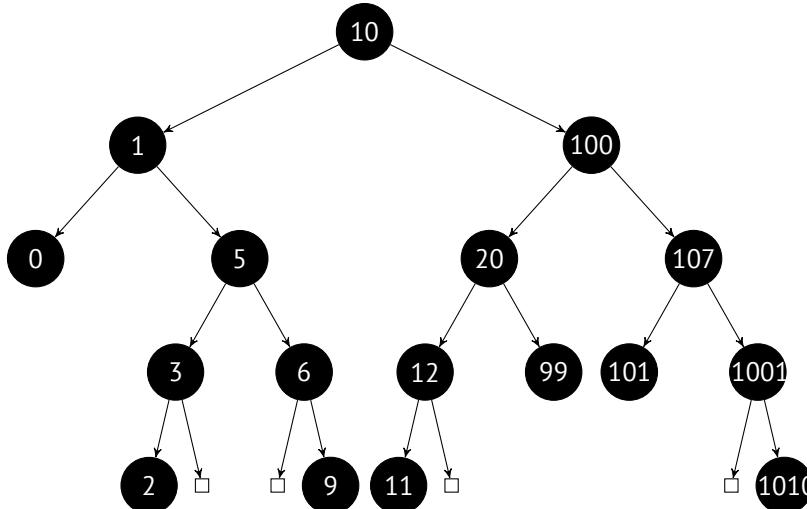
The binary tree is another fundamental data structure. As its name states, this is a tree where each node has at most 2 links to other nodes. Each node has key and/or value.

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);
    if (n->Isnil==0)
    {
        if (is_set)
            printf ("first=%d\n", n->first);
        else
            printf ("first=%d second=[%s]\n", n->first, n->second);
    }

    if (traverse)
    {
        if (n->Isnil==1)
            dump_tree_node (n->Parent, is_set, true);
        else
        {
            if (n->Left->Isnil==0)
                dump_tree_node (n->Left, is_set, true);
            if (n->Right->Isnil==0)
                dump_tree_node (n->Right, is_set, true);
        };
    };
}
```



```
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 51.35: 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]
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 ([51.4.2 on page 584](#)).

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. 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

```

#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;
}

```

¹⁰Hard disk drive


```

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 *) (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, 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);
    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 51.36: 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
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
    -----12
        -----11
        -----100
    -----456
        -----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 similar¹¹. 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 51.37: GCC

¹¹<http://go.yurichev.com/17084>

```

};

int main()
{
    std::set<int> s;
    s.insert(123);
    s.insert(456);
    printf ("123, 456 are inserted\n");
    dump_map_and_set ((struct tree_struct *)(void*)&s);
    s.insert(11);
    s.insert(12);
    printf ("\n");
    printf ("11, 12 are inserted\n");
    dump_map_and_set ((struct tree_struct *)(void*)&s);
    s.insert(100);
    s.insert(1001);
    printf ("\n");
    printf ("100, 1001 are inserted\n");
    dump_map_and_set ((struct tree_struct *)(void*)&s);
    s.insert(667);
    s.insert(1);
    s.insert(4);
    s.insert(7);
    printf ("\n");
    printf ("667, 1, 4, 7 are inserted\n");
    dump_map_and_set ((struct tree_struct *)(void*)&s);
    printf ("\n");
}

```

Listing 51.38: 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
        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 52

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 52.1: 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'
70     ↳ X'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 52.2: 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 53

Windows 16-bit

16-bit Windows programs are rare nowadays, but can be used in the cases of retrocomputing or dongle hacking ([78 on page 763](#)).

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

53.1 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 endp
---------	---

Seems to be easy, so far.

53.2 Example #2

```
#include <windows.h>

int PASCAL WinMain( HINSTANCE hInstance,
                     HINSTANCE hPrevInstance,
                     LPSTR lpCmdLine,
                     int nCmdShow )
{
    MessageBox (NULL, "hello, world", "caption", MB_YESNOCANCEL);
```

```
    return 0;
};
```

```
WinMain proc near
push bp
mov bp, sp
xor ax, ax      ; NULL
push ax
push ds
mov ax, offset aHelloWorld ; 0x18. "hello, world"
push ax
push ds
mov ax, offset aCaption ; 0x10. "caption"
push ax
mov ax, 3        ; MB_YESNOCANCEL
push ax
call MESSAGEBOX
xor ax, ax      ; return 0
pop bp
ret 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 ([64.2 on page 681](#)), 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.

53.3 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"
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.

53.4 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);
    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           ; AX=low part d, DX=high part d
        sub    cx, ax
        mov     ax, cx
        sbb    bx, dx
        mov     dx, bx
        pop    bp
        retn   14
func3    endp

```

```

WinMain    proc near
    push    bp
    mov     bp, sp
    mov     ax, 123
    push    ax
    mov     ax, 456
    push    ax
    mov     ax, 789
    push    ax
    call    func1
    mov     ax, 9      ; high part of 600000
    push    ax
    mov     ax, 27C0h ; low part of 600000
    push    ax
    mov     ax, 0Ah    ; high part of 700000
    push    ax
    mov     ax, 0AE60h ; low part of 700000
    push    ax
    mov     ax, 0Ch    ; high part of 800000
    push    ax
    mov     ax, 3500h ; low part of 800000
    push    ax
    call    func2
    mov     ax, 9      ; high part of 600000
    push    ax
    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
    retn  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 ([24 on page 412](#)).

`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 973](#), [D on page 972](#).

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.

53.5 Example #5

```

#include <windows.h>

int PASCAL string_compare (char *s1, char *s2)
{
    while (1)
    {
        if (*s1!=*s2)
            return 0;

```

```

        if (*s1==0 || *s2==0)
            return 1; // end of string
        s1++;
        s2++;
    };
};

int PASCAL string_compare_far (char far *s1, char far *s2)
{
    while (1)
    {
        if (*s1!=*s2)
            return 0;
        if (*s1==0 || *s2==0)
            return 1; // end of string
        s1++;
        s2++;
    };
};

void PASCAL remove_digits (char *s)
{
    while (*s)
    {
        if (*s>='0' && *s<='9')
            *s='-';
        s++;
    };
};

char str[]="hello 1234 world";

int PASCAL WinMain( HINSTANCE hInstance,
                    HINSTANCE hPrevInstance,
                    LPSTR lpCmdLine,
                    int nCmdShow )
{
    string_compare ("asd", "def");
    string_compare_far ("asd", "def");
    remove_digits (str);
    MessageBox (NULL, str, "caption", MB_YESNOCANCEL);
    return 0;
};

```

```

string_compare proc near

arg_0 = word ptr 4
arg_2 = word ptr 6

    push    bp
    mov     bp, sp
    push    si
    mov     si, [bp+arg_0]
    mov     bx, [bp+arg_2]

loc_12: ; CODE XREF: string_compare+21j
    mov     al, [bx]
    cmp     al, [si]
    jz     short loc_1C
    xor     ax, ax
    jmp     short loc_2B

loc_1C: ; CODE XREF: string_compare+Ej
    test    al, al
    jz     short loc_22
    jnz     short loc_27

```

```

loc_22: ; CODE XREF: string_compare+16j
    mov     ax, 1
    jmp     short loc_2B

loc_27: ; CODE XREF: string_compare+18j
    inc     bx
    inc     si
    jmp     short loc_12

loc_2B: ; CODE XREF: string_compare+12j
    ; string_compare+1Dj
    pop     si
    pop     bp
    retn    4
string_compare 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
    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: [94 on page 901](#).

“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: [53.2 on page 608](#). Indeed, the Windows kernel is not aware which data segment to use when accessing text strings, so it need the complete information.

The reason for this distinction is that a compact program may use just one 64kb data segment, so it doesn’t need to pass the high part of the address, which is always the same. A bigger program may use several 64kb data segments, so it needs to specify the segment of the data each time.

It’s the same story for code segments. A compact program may have all executable code within one 64kb-segment, then all functions in it will be called using the `CALL NEAR` instruction, and the code flow will be returned using `RETN`. But if there are several code segments, then the address of the function is to be specified by a pair, it is to be called using the `CALL FAR` instruction, and the code flow is to be returned using `RETF`.

This is what is set in the compiler by specifying “memory model”.

The compilers targeting MS-DOS and Win16 have specific libraries for each memory model: they differ by pointer types for code and data.

53.6 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
        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 ([64.1 on page 681](#)).

53.6.1 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);

    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.

Part IV

Java

Chapter 54

Java

54.1 Introduction

There are some well-known decompilers for Java (or [JVM](#) bytecode in general)¹.

The reason of this is because [JVM](#)-bytecode decompiling is somewhat easier than for lower level x86 code:

- There are much more information about data types.
- [JVM](#) memory model is much more rigorous and outlined.
- Java compiler don't do any optimization job ([JVM JIT](#)² does at runtime), so bytecode in class files is usually pretty readable.

When [JVM](#) bytecode knowledge may be useful?

- Quick-and-dirty patching tasks of class files without need to recompile decompiler's results.
- Analysing obfuscated code.
- Build your own obfuscator.
- Build compiler codegenerator (back-end) targetting [JVM](#) (like Scala, Clojure, etc ³).

Let's start with simple pieces of code. JDK 1.7 is used everywhere, unless mentioned otherwise.

This command to decompile class files was used everywhere : `javap -c -verbose`

This book was used by me while preparing all examples : [\[Jav13\]](#).

54.2 Returning a value

Probably the simplest Java function is 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 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 standard Java utility:

```
javap -c -verbose ret.class
```

¹For example, JAD: <http://varaneckas.com/jad/>

²Just-in-time compilation

³Full list: http://en.wikipedia.org/wiki/List_of_JVM_languages

And what we've got:

Listing 54.1: 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
```

Java developers decide that 0 is one of the busiest constants in programming, so there are separate short one-byte `iconst_0` instruction which pushes 0 ⁴. There are also `iconst_1` (which pushes 1), `iconst_2`, etc, up to `iconst_5`. There are also `iconst_m1` which pushes -1.

Stack is used in JVM for data passing into functions to be called and also returning values. So `iconst_0` pushed 0 into stack. `ireturn` returns integer value (*i* in name mean *integer*) from the [TOS](#)⁵.

Let's rewrite our example slightly, now we return 1234:

```
public class ret
{
    public static int main(String[] args)
    {
        return 1234;
    }
}
```

...we got:

Listing 54.2: 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 value into stack. *short* in name implies a 16-bit value is to be pushed. 1234 number is indeed well fit in 16-bit value.

What about larger values?

```
public class ret
{
    public static int main(String[] args)
    {
        return 12345678;
    }
}
```

Listing 54.3: 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
```

It's not possible to encode a 32-bit number in a JVM instruction opcode, developers didn't left such possibility. So 32-bit number 12345678 is stored in so called "constant pool" which is, let's say, library of most used constants (including strings, objects, etc).

⁴Just like in MIPS, where a separate register for zero constant exists : [3.5.2 on page 19](#).

⁵Top Of Stack

This way of passing constants is not unique to JVM. MIPS, ARM and other RISC CPUs also can't encode 32-bit numbers in 32-bit opcode, so RISC CPU code (including MIPS and ARM) has to construct values in several steps, or to keep them in data segment: [28.3 on page 458](#), [29.1 on page 461](#).

MIPS code is also traditionally has constant pool, named “literal pool”, these are segments called “.lit4” (for 32-bit single precision floating point number constants storage) and “.lit8” (for 64-bit double precision floating point number constants storage).

Let's also 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 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 a class file and checked at runtime.

The same story about 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 mean “push byte”. Needless to say that *char* in Java is 16-bit UTF-16 character, and it's equivalent to *short*, but ASCII code of “A” character is 65, and it's possible to use instruction for passing byte into stack.

Let's also try *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 to bother with 16-bit *short* date type which is internally works as 32-bit integer? Why use *char* data type if it is the same as *short* data type?

The answer is simple: for data type control and source code readability. *char* may essentially be the same as *short* but we quickly grasp that it's placeholder for UTF-16 character, and not for some other integer value. When using *short* we may show to everyone that a variable range is limited by 16 bits. It's a very good idea to use *boolean* type where it needs to, instead of C-style *int* for the same purpose.

There are also 64-bit integer data type in Java:

```
public class ret3
{
    public static long main(String[] args)
    {
        return 1234567890123456789L;
    }
}
```

Listing 54.4: Constant pool

```
...
#2 = Long          1234567890123456789L
...
```

```
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 1234567890123456789L
3: lreturn
```

The 64-bit number is also stored in constant pool, *ldc2_w* loads it and *lreturn* (*long return*) returns it.

ldc2_w instruction is also used to load double precision floating point numbers (which also occupies 64 bits) from constant pool:

```
public class ret
{
    public static double main(String[] args)
    {
        return 123.456d;
    }
}
```

Listing 54.5: Constant pool

```
...
#2 = Double      123.456d
...
```

```
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, single precision floating point number:

```
public class ret
{
    public static float main(String[] args)
    {
        return 123.456f;
    }
}
```

Listing 54.6: 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
```

`ldc` instruction used here is the same as used for 32-bit integer numbers loading from constant pool. `freturn` stands for “return float”.

Now what about function returning 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 implies, `return` instruction is used to return control without returning actual value. Knowing all this, it's very easy to deduce function (or method) returning type from the last instruction.

54.3 Simple calculating functions

Let's continue with simple calculating functions.

```
public class calc
{
    public static int half(int a)
    {
        return a/2;
    }
}
```

This is the case when `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 zeroth function argument and pushes it to stack. `iconst_2` pushes 2 into stack. After these two instructions execution, this is how stack looks like:

```

+---+
TOS ->| 2 |
+---+
| a |
+---+

```

`idiv` just takes two values at the `TOS`, divides one by another and leave result at `TOS`:

```

+-----+
TOS ->| result |
+-----+

```

`ireturn` takes it and returns.

Let's proceed to double precision floating point numbers:

```

public class calc
{
    public static double half_double(double a)
    {
        return a/2.0;
    }
}

```

Listing 54.7: 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 very same, but `ldc2_w` instruction is used to load constant of 2.0 from constant pool. Also, all other three instructions has `d` prefix, meaning they work with *double* data type values.

Let's now use two arguments function:

```

public class calc
{
    public static int sum(int a, int b)
    {
        return a+b;
    }
}

```

```

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 first function argument (a), `iload_2`—second (b). Here is a stack after both instruction executed:

```
+---+
TOS ->| b |
+---+
| a |
+---+
```

iadd adds two values and leave result at TOS:

```
+-----+
TOS ->| result |
+-----+
```

Let's extend this example to *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 second argument from 2nd slot. That's because 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
```

First step is multiplication. Product is left at the TOS:

```
+-----+
TOS ->| product |
+-----+
```

iload_2 loads third argument (c) into stack:

```
+-----+
TOS ->|   c   |
+-----+
| product |
+-----+
```

Now iadd instruction can add two values.

54.4 JVM memory model

x86 and other low-level environments uses stack for arguments passing and as local variables storage. JVM is slightly different.

It has:

- Local variable array (LVA⁶). It is used as storage for incoming function arguments and local variables. Instructions like `iload_0` loads values from it. `istore` stores values to it. First, function arguments are came: starting at 0 or at 1 (if zeroth argument is occupied by `this` pointer). Then local variables are allocated.
- 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.

54.5 Simple function calling

`Math.random()` returns a pseudorandom number in range of [0.0 ...1.0), but let's say, by some reason, we need to devise a function returning number in range of [0.0 ...0.5):

```
public class HalfRandom
{
    public static double f()
    {
        return Math.random()/2;
    }
}
```

Listing 54.8: Constant pool

```
...
#2 = Methodref          #18.#19      //  java/lang/Math.random:()D
#3 = Double              2.0d
...
#12 = Utf8                ()D
...
#18 = Class               #22         //  java/lang/Math
#19 = NameAndType         #23:#12     //  random:()D
#22 = Utf8                java/lang/Math
#23 = Utf8                random
```

```
public static double f();
  flags: ACC_PUBLIC, ACC_STATIC
  Code:
    stack=4, locals=0, args_size=0
      0: invokestatic  #2           // Method java/lang/Math.random:()D
      3: ldc2_w       #3           // double 2.0d
      6: ddiv
      7: dreturn
```

`invokestatic` calls for the `Math.random()` function and left result at the [TOS](#). Then the result is divided by 2.0 and returned. But how function name is encoded? It's encoded in the constant pool using `Methodref` expression. It defines class and method names. First field of `Methodref` is points to the `Class` expression which is, in turn, points to the usual text string (“java/lang/Math”). Second `Methodref` expression points to `NameAndType` expression which also has two links to the strings. First string is “random” which is the name of method. The second string is “()D” which encodes function type. It implies it returns `double` value (hence `D` in the string). This is the way 1) JVM can check data type correctness; 2) Java decompilers can restore data types from a compiled class file.

Now let's finally try “Hello, world!” example:

⁶(Java) Local Variable Array

```
public class HelloWorld
{
    public static void main(String[] args)
    {
        System.out.println("Hello, World");
    }
}
```

Listing 54.9: 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 is taking pointer to the “Hello, World” string in constant pool and pushes into stack. It’s called *reference* in the Java world, but it’s rather pointer, or address ⁷.

The familiar `invokevirtual` instruction takes information about `println` function (or method) from the constant pool and call it. As we may know, there are several `println` methods, dedicated for each data type. Our case is `println` function version, which is intended for `String` data type.

But what about the first `getstatic` instruction? This instruction takes a *reference* (or address of) field of object `System.out` and pushes it into the stack. This value is acting like *this* pointer for `println` method. Thus, internally, `println` method takes two arguments at input: 1) *this*, i.e., pointer to object; 2) address of “Hello, World” string.

Indeed, `println()` is called as a method within initialized `System.out` object.

For convenience, `javap` utility writes all this information in comments.

54.6 Calling `beep()`

This is also simplest possible calling of two functions without arguments:

```
public static void main(String[] args)
{
    java.awt.Toolkit.getDefaultToolkit().beep();
}
```

⁷About difference in pointers and *reference's* in C++: [51.3 on page 572](#).

```

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 reference to the object of `Toolkit` class. The `invokevirtual` instruction at offset 3 calls `beep()` method of this class.

54.7 Linear congruent PRNG

Let's try simple pseudorandom numbers generator, which we already considered it once in the book ([20 on page 352](#)):

```

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 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
      7: putstatic     #4                  // Field RNG_c:I
     10: return

```

That's the way variables are initialized. `RNG_a` occupies 3rd slot in class and `RNG_c` – 4th, and `putstatic` puts constants there.

`my_srand()` function just stores input value into `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 input value and pushes it into stack. But why not `iload_0`? It's because this function may use class fields, and so `this` variable is also passed to the function as zeroth argument. Field `rand_state` occupied 2nd slot in class, so `putstatic` copies value from the [TOS](#) into 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 object fields, do operations and updates `rand_state` value using `putstatic` instruction. At offset 20, `rand_state` value is reloaded again (it's because it was dropped from the stack before, by `putstatic`). This seems as non-efficient code, but be sure, [JVM](#) is usually good enough to optimize such things really well.

54.8 Conditional jumps

Now let's proceed to conditional jumps.

```

public class abs
{
    public static int abs(int a)
    {
        if (a<0)
            return -a;
        return a;
    }
}

```

```

public static int abs(int);
flags: ACC_PUBLIC, ACC_STATIC
Code:
stack=1, locals=1, args_size=1
 0: iload_0
 1: ifge      7
 4: iload_0
 5: ineg
 6: ireturn
 7: iload_0
 8: ireturn

```

`ifge` jumps to offset 7 if value at [TOS](#) is greater or equal to 0. Don't forget, any `ifXX` instruction pops the value (to be compared) from stack.

`ineg` just negates value at [TOS](#).

Another example:

```

public static int min (int a, int b)
{
    if (a>b)
        return b;
    return a;
}

```

What we've got:

```

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_icmple    7
5: iload_1
6: ireturn
7: iload_0
8: ireturn

```

`if_icmple` pops two values and compares them. If the second one is lesser (or equal) than first, jump to offset 7 is occurred.

When we define `max()` function ...

```

public static int max (int a, int b)
{
    if (a>b)
        return a;
    return b;
}

```

...resulting code is just the same, but two last `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_icmple    7
5: iload_0
6: ireturn
7: iload_1
8: ireturn

```

More complex example:

```

public class cond
{
    public static void f(int i)
    {
        if (i<100)
            System.out.print("<100");
        if (i==100)
            System.out.print("==100");
        if (i>100)
            System.out.print(">100");
        if (i==0)
            System.out.print("==0");
    }
}

```

```

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 first, jump to offset 14 is occurred. `if_icmpne` and `if_icmple` works just as the same, but different conditions are used.

There are also `ifne` instruction at offset 43. Its name is misnomer, it would be better to name it as `ifnz` (jump if value at [TOS](#) is not zero). And that is what it does: it jumps to offset 54 if input value is not zero. If zero, execution flow is proceeded to offset 46, where the “`==0`” string is printed.

N.B.: [JVM](#) has no unsigned data types, so comparison instructions operates only on signed integer values.

54.9 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;
    }

    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;
↳ 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;
↳ PrintStream;
31: iload_3
32: invokevirtual #5                  // Method java/io/PrintStream.println:(I)V
35: return

```

Arguments are passed to other function in stack, and the returning value is left on [TOS](#).

54.10 Bitfields

All bit-wise operations works 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
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 into stack, this is the same as `0xFFFFFFFF` number. XORing with `0xFFFFFFFF` as one of operand, is the same effect as inverting all bits ([A.6.2 on page 959](#)).

Let's also extended 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 is used, which operates on 64-bit values. Also, second functions argument still has *int* type, and when a 32-bit value in it needs to be promoted to 64-bit value *i2l* instruction is used, which essentially extend value of *integer* type to *long* one.

54.11 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 to *LVA* at slot 1. Why not zeroth slot? Because *main()* function has one argument (array of *String*) and pointer to it (or *reference*) is now in zeroth slot.

So, *i* local variable is always to be in 1st slot.

Instructions at offsets 3 and 5 compares *i* with 10. If *i* is larger, execution flow has passed to offset 21, where function is finished. If it's not, `println` is called. *i* is then reloaded at offset 11, for `println`. By the way, we call `println` method for *integer* data type, and we see this in comments: "(I)V" (*I* mean *integer* and *V* mean returning type is *void*).

When `println` is finished, *i* is incremented at offset 15. First operand of the instruction is a number of slot (1), second is a number (1) to add to variable.

`goto` is just GOTO, it jumps to the loop body begin at offset 2.

Let's proceed to 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
 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 LVA slots map:

- 0 – the sole `main()` argument
- 1 – *limit*, always holding 20
- 2 – *f*
- 3 – *g*
- 4 – *i*

We can see that Java compiler allocated variables in LVA slots just in the same sequence, as variables were declared in the source code.

There are separate `istore` instructions for accessing slots by number 0, 1, 2, 3, but not 4 and larger, so there `istore` with additional operand at offset 8 which takes slot number as operand. The same story about `iload` at offset 10.

But is not it's dubious to allocate another slot for `limit` variable which always holding 20 (so it's constant in essence), and reload its value so often? [JVM JIT](#) compiler is usually good enough to optimize such things. Manual intervention into the code is probably not worth it.

54.12 switch()

`switch()` statement is implemented by `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
        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

```

54.13 Arrays

54.13.1 Simple example

Let's first create 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
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

```

`newarray` instruction creates an array object of 10 `int` elements. Array size is set by `bipush` and left at [TOS](#). Array type is set in `newarray` instruction operand. After `newarray` execution, a *reference* (or pointer) to the newly created array in heap is left at the [TOS](#). `astore_1` stores the *reference* to the 1st slot in [LVA](#). Second part of `main()` function is the loop which stores *i* value into corresponding array element. `aload_1` gets *reference* of array and places it into stack. `iastore` then stores integer value from stack to the array, *reference* of which is currently at [TOS](#). Third part of `main()` function calls `dump()` function. An argument for it is prepared by `aload_1` instruction (offset 23).

Now let's proceed to `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;
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

```

Incoming reference to array is in the zeroth slot. `a.length` expression in the source code is converted into `arraylength` instruction: it takes *reference* to array and leave array size at [TOS](#). `iaload` at offset 13 is used to load array elements, it requires to array *reference* be present in stack (prepared by `aload_0` at 11), and also 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.

54.13.2 Summing elements of array

Another example:

```

public class ArraySum
{
    public static int f (int[] a)
    {
        int sum=0;
        for (int i=0; i<a.length; i++)
            sum=sum+a[i];
        return sum;
    }
}

```

```

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 has *reference* to input array. [LVA](#) slot 1 has local variable *sum*.

54.13.3 main() function sole argument is array too

Let's use the sole `main()` function argument, which is 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?");
}

```

Zeroth argument is a program name (like in C/C++, etc), so the 1st argument supplied by 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: istruct_1
  13: aaload
  14: invokevirtual #4           // Method java/io/PrintStream.print:(Ljava/lang/
  ↴ String;)V
  17: getstatic      #2           // Field java/lang/System.out:Ljava/io/
  ↴ PrintStream;
  20: ldc            #5           // String . How are you?
  22: invokevirtual #6           // Method java/io/PrintStream.println:(Ljava/lang/
  ↴ /String;)V
  25: return

```

`aload_0` at 11 loads *reference* of the zeroth [LVA](#) slot (1st and only `main()` argument). `istruct_1` and `aaload` at 12 and 13 takes *reference* to the first (counting at 0) element of array. The *reference* to string object is at [TOS](#) at offset 14, and it is taken from there by `println` method.

54.13.4 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];
    }
}

```

`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 array of *references*. Java String is object, so *a*-instructions are used to operate on them. areturn returns *reference* to String object.

How months[] array is 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
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 new array of *references* (hence *a* in prefix). Object type is defined in anewarray operand, it is "java/lang/String" text string here. bipush 12 before anewarray sets array size. We see here new instruction for

us: dup. It's very well-known stack computers (including Forth programming language) instruction which just duplicates value at [TOS](#). It is used here to duplicate *reference* to array, because `aastore` instruction pops *reference* to array from stack, but subsequent `aastore` is needing it again. Java compiler concluded that it's better to generate `dup` instead of generating `getstatic` instruction before each array store operation (i.e., 11 times).

`aastore` puts *reference* (to string) into array at 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.

54.13.5 Variadic functions

Variadic functions are in fact 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);
}
```

```
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 array of integers using `aload_0` at offset 3. Then it getting array 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

```

Array is constructed in `main()` using `newarray` instruction, then it's filled, and `f()` is called.

Oh, by the way, array object is not destroyed upon `main()` end. There are no destructors in Java at all, because JVM has garbage collector which does this automatically, when it feels it needs to.

What about `format()` method? It takes two arguments at input: string and 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;
    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/Integer;
  ↳ /Integer;
  22: aastore
  23: dup
  24: iconst_1
  25: dload_2
  26: invokestatic #8          // Method java/lang/Double.valueOf:(D)Ljava/lang/Double;
  ↳ 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 `int` and `double` types are first promoted to `Integer` and `Double` objects using `valueOf` methods. `format()` method needs objects of `Object` type at input, and since `Integer` and `Double` classes are inherited from root `Object` class, they suitable as elements in input array. On the other hand, array is always homogeneous, i.e., it can't contain elements of the different types, which makes impossible to push values of `int` and `double` types to it.

Array of `Object` objects is created at offset 13, `Integer` objects is added into array at offset 22, `Double` object is added into array at offset 29.

The penultimate `pop` instruction discards element at `TOS`, so at the moment of `return` execution, stack is to be empty (or balanced).

54.13.6 Two-dimensional arrays

Two-dimensional arrays in Java are just one-dimensional arrays of *references* to another one-dimensional arrays.

Let's create 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
8:  aload_1
9:  iconst_1
10: aaload
11: iconst_2
12: iconst_3
13: iastore
14: return
```

It's created using `multianewarray` instruction: object type and dimensionality are passed as operands. Array size (10^5) is left in stack (using instructions `iconst_5` and `bipush`).

Reference to row #1 is loaded at offset 10 (`iconst_1` and `aaload`). Column is chosen using `iconst_2` instruction at offset 11. Value to be written is set at offset 12. `iastore` at 13 writes array element there.

How it is 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
```

Reference to array row is loaded at offset 2, column is set at offset 3, `iaload` loads array element.

54.13.7 Three-dimensional arrays

Three-dimensional arrays are just one-dimensional arrays of *references* of 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)I
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

```

54.13.8 Summary

It's possible to do a buffer overflow in Java? No, because array length is always present in array object, array bounds are controlled, and exception is to be raised in case of out-of-bounds access.

There are no multi-dimensional arrays in Java in a C/C++ sense, so Java is not very suited for fast scientific computations.

54.14 Strings

54.14.1 First example

Strings are objects and 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;
3: ldc          #3           // String What is your name?

```

```

5: invokevirtual #4           // Method java/io/PrintStream.println:(Ljava/lang/V
↳ /String;)V
  8: invokestatic  #5         // Method java/lang/System.console:()Ljava/io/(
↳ Console;
  11: invokevirtual #6        // Method java/io/Console.readLine:()Ljava/lang/V
↳ String;
  14: astore_1
  15: getstatic   #2         // Field java/lang/System.out:Ljava/io/
↳ PrintStream;
  18: new          #7         // class java/lang/StringBuilder
  21: dup
  22: invokespecial #8        // Method java/lang/StringBuilder."<init>":()V
  25: ldc          #9         // String Hello,
  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:()V
↳ Ljava/lang/String;
  37: invokevirtual #4        // Method java/io/PrintStream.println:(Ljava/lang/V
↳ /String;)V
  40: return

```

`readLine()` method is called at offset 11, *reference* to string (which supplied by user) is then stored at [TOS](#). At offset 14 *reference* to string is stored to slot 1 of [LVA](#). The string user entered is reloaded at offset 30 and concatenated with the "Hello," string using `StringBuilder` class. Constructed string is then printed using `println` method at offset 37.

54.14.2 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

```

String concatenation is done using `StringBuilder` class:

```

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:()V
↳ Ljava/lang/String;
18: areturn

```

Another example:

```

public static void main(String[] args)
{
    String s="Hello!";
    int n=123;
    System.out.println("s=" + s + " n=" + n);
}

```

And again, strings are constructed using `StringBuilder` class and its `append` method, then constructed string is passed to `println` method:

```

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

```

54.15 Exceptions

Let's rework our `Month` example ([54.13.4 on page 639](#)) slightly:

Listing 54.10: `IncorrectMonthException.java`

```

public class IncorrectMonthException extends Exception
{
    private int index;

    public IncorrectMonthException(int index)
    {
        this.index = index;
    }
    public int getIndex()
    {
        return index;
    }
}

```

Listing 54.11: Month2.java

```

class Month2
{
    public static String[] months =
    {
        "January",
        "February",
        "March",
        "April",
        "May",
        "June",
        "July",
        "August",
        "September",
        "October",
        "November",
        "December"
    };

    public static String get_month (int i) throws IncorrectMonthException
    {
        if (i<0 || i>11)
            throw new IncorrectMonthException(i);
        return months[i];
    }

    public static void main (String[] args)
    {
        try
        {
            System.out.println(get_month(100));
        }
        catch(IncorrectMonthException e)
        {
            System.out.println("incorrect month index: "+ e.getIndex());
            e.printStackTrace();
        }
    }
}

```

Essentially, `IncorrectMonthException.class` has just object constructor and one accessor method.

`IncorrectMonthException` class is inherited from `Exception`, so `IncorrectMonthException` constructor first calls constructor of `Exception` class, then it put 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 accessor. Reference to `IncorrectMonthException` is passed in zeroth [LVA](#) slot (`this`), `aload_0` takes it, `getfield` loads integer value from 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 on `get_month()` in `Month2.class`:

Listing 54.12: 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
  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 new instruction at offset 10. Object type is passed as operand to the instruction (and this is `IncorrectMonthException`). Then its constructor is called with index integer is passed via **TOS** (offset 15). At the time of control flow being at offset 18, object is already constructed, now `athrow` instruction takes *reference* to newly constructed object and signalling to **JVM** to find appropriate exception handler.

`athrow` instruction don't return control flow to here, so at offset 19 is another **basic block**, not related to exceptions business, we can get here from offset 7.

How handler works? `main()` in `Month2.class`:

Listing 54.13: 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 `Exception_table`, which defines that from offset 0 to 11 (inclusive) an exception `IncorrectMonthException` may happen, and if it will, control flow is to be passed to offset 14. Indeed, the main program is ended at offset 11. At the offset 14 handler started, it's not possible to get here, there are no conditional/unconditional jumps to this area. But JVM will transfer execution flow here in case of exception. The very first `astore_1` (at 14) takes incoming `reference` to exception object and stores it to LVA slot 1. Later, `getIndex()` method (of this exception object) will be called for it at offset 31. `Reference` to current exception object is passed right before (offset 30). All the rest of the code is string manipulating code: first integer value returned by `getIndex()` is converted into string by `toString()` method, then it concatenates with "incorrect month index:" text string (like we already considered before), then `println()` and `printStackTrace()` are called. After `printStackTrace()` finishes, exception is handled, we can proceed to normal functioning. At offset 47 there are `return` which finishes `main()` function, but there could be any other code which executes as if no exceptions raised.

Here is an example, how IDA shows exception ranges:

Listing 54.14: 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
```

54.16 Classes

Simple class:

Listing 54.15: 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;
    }
}
```

Constructor just sets both fields to zeroes:

```

public test();
flags: ACC_PUBLIC
Code:
  stack=1, locals=1, args_size=1
    0: aload_0
    1: invokespecial #1           // Method java/lang/Object."<init>":()V
    4: iconst_0
    5: putstatic      #2         // Field a:I
    8: iconst_0
    9: putstatic      #3         // Field b:I
   12: return

```

Setter of a:

```

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 are no difference in the code which works with public and private fields. But this type information is present in .class file, and it's not possible to access private fields anyway.

Let's create object and call method:

Listing 54.16: 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
 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

```

new instruction creates object, but don't call constructor (it is called at offset 4). set_a() method is called at offset 16. a field is accessed using getstatic instruction at offset 21.

54.17 Simple patching

54.17.1 First example

Let's proceed to simple 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 we would remove printing of "This program is not registered" string?

Let's finally load the .class file into IDA:

```

; Segment type: Pure code
.method public static nag_screen()V
.limit stack 2
.line 4
• 178 000 002 | ldc "This program is not registered"
• 018 003       invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
• 182 000 004   .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 | ldc "Greetings from the mega-software"
• 018 005       invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
• 182 000 004   .line 9
• 184 000 006   invokestatic nag.nag_screen()V
• 177           .line 10
• 177           return
;

```

Figure 54.1: IDA

Let's patch first byte of the function to 177 (which is return instruction opcode):

```

; Segment type: Pure code
.method public static nag_screen()V
.limit stack 2
.line 4
| nag_screen:                                     ; CODE XREF: main+8jP
• 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
• 177         .line 5
• ??? ??? ???+ .end method
• ??? ??? ???+
• ???
;
```

Figure 54.2: 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)

```

Perhaps, JVM has some other checks related to stack maps.

OK, let's patch it differently by removing 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 54.3: IDA

0 is opcode for NOP.

Now that works!

54.17.2 Second example

Now 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 to IDA:

```

; 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 54.4: IDA

We see here `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 password is not correct (`equals` method return `False`, which is 0). The very first idea is to patch this instruction. There are two bytes in `ifeq` opcode, which encodes jump offset. To make this instruction idle, we must set byte 3 at 3rd byte (because 3 is to be added to the current address resulting always jump to the next instruction, since `ifeq` instruction length is 3 bytes):

```

; 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;
                 ldc "password is not correct"
• 182 000 004    invokevirtual java/io/PrintStream.println(Ljava/lang/String;)V
.line 9

```

Figure 54.5: 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 needless to say, it was worked in JRE 1.6.

We can also try to replace all 3 `ifeq` opcode bytes by zero bytes (`NOP`), and it's still doesn't work. Well, probably there are more stack map checks appeared in JRE 1.7.

OK, we'll replace the whole call to `equals` method by `iconst_1` instruction plus 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 54.6: IDA

1 is always to be at the TOS when `ifeq` instruction is executed, so `ifeq` will never jump.
This works.

54.18 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 cryptographical 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, author of these lines once tried to understand how the compression/decompression of network packets worked 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 ([80.1 on page 812](#))

Chapter 55

Identification of executable files

55.1 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, msdp60.dll	June 1998
.NET (2002)	7.0	13.00	msvcr70.dll, msdp70.dll	February 13, 2002
.NET 2003	7.1	13.10	msvcr71.dll, msdp71.dll	April 24, 2003
2005	8.0	14.00	msvcr80.dll, msdp80.dll	November 7, 2005
2008	9.0	15.00	msvcr90.dll, msdp90.dll	November 19, 2007
2010	10.0	16.00	msvcr100.dll, msdp100.dll	April 12, 2010
2012	11.0	17.00	msvcr110.dll, msdp110.dll	September 12, 2012
2013	12.0	18.00	msvcr120.dll, msdp120.dll	October 17, 2013

msvcp*.dll contain C++-related functions, so if it is imported, this is probably a C++ program.

55.1.1 Name mangling

The names usually start with the ? symbol.

You can read more about MSVC's name mangling here: [51.1.1 on page 556](#).

55.2 GCC

Aside from *NIX targets, GCC is also present in the win32 environment, in the form of Cygwin and MinGW.

55.2.1 Name mangling

Names usually start with the _Z symbols.

You can read more about GCC's name mangling here: [51.1.1 on page 556](#).

55.2.2 Cygwin

cygwin1.dll is often imported.

55.2.3 MinGW

msvcrt.dll may be imported.

55.3 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.

55.4 Watcom, OpenWatcom

55.4.1 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
```

55.5 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.

55.5.1 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..
000004d0	00 00 00 00 00 00 80 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 00 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	.ol..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.

55.6 Other known DLLs

- vcomp*.dll—Microsoft's implementation of OpenMP.

Chapter 56

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: [75](#).

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.

56.1 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): RegEnumKeyEx⁴ [5](#), RegEnumValue⁶ [5](#), RegGetValue⁷ [5](#), RegOpenKeyEx⁸ [5](#), RegQueryValueEx⁹ [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](#).
- Resources access ([68.2.8 on page 709](#)) : (user32.dll): LoadMenu [15](#) [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](#)

¹⁵[MSDN](#)

- TCP/IP networking (ws2_32.dll): WSARecv ¹⁶, WSARecv 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.

56.2 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))
```

¹⁶[MSDN](#)

¹⁷[MSDN](#)

¹⁸[MSDN](#)

¹⁹[MSDN](#)

²⁰[MSDN](#)

²¹[MSDN](#)

²²[MSDN](#)

²³[MSDN](#)

²⁴[MSDN](#)

Chapter 57

Strings

57.1 Text strings

57.1.1 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");
}
```

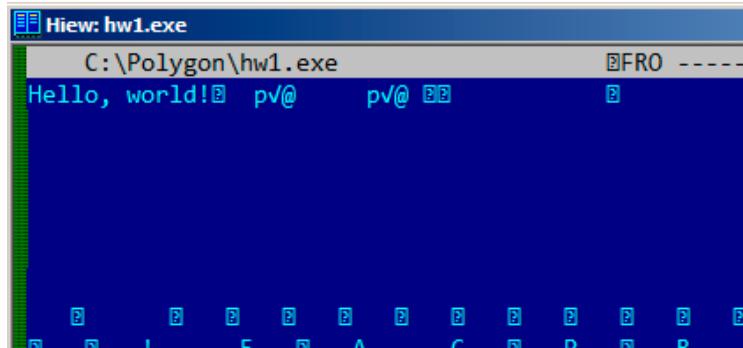


Figure 57.1: Hiew

57.1.2 Borland Delphi

The string in Pascal and Borland Delphi is preceded by an 8-bit or 32-bit string length.

For example:

Listing 57.1: Delphi

```
CODE:00518AC8          dd 19h
CODE:00518ACC aLoading__Plea db 'Loading... , please wait.',0
...
CODE:00518AFC          dd 10h
CODE:00518B00 aPreparingRun__ db 'Preparing run...',0
```

57.1.3 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): أَنَا قَادِرٌ عَلَى أَكْلِ الزَّجاجِ وَهُنَّ لَا يَؤْلِمُنِي.
(Hebrew): אָנוּ בָּכוֹל זְכַרְיוֹן דִּכְרֵי תְּזִקָּה לֹא.
(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.
```

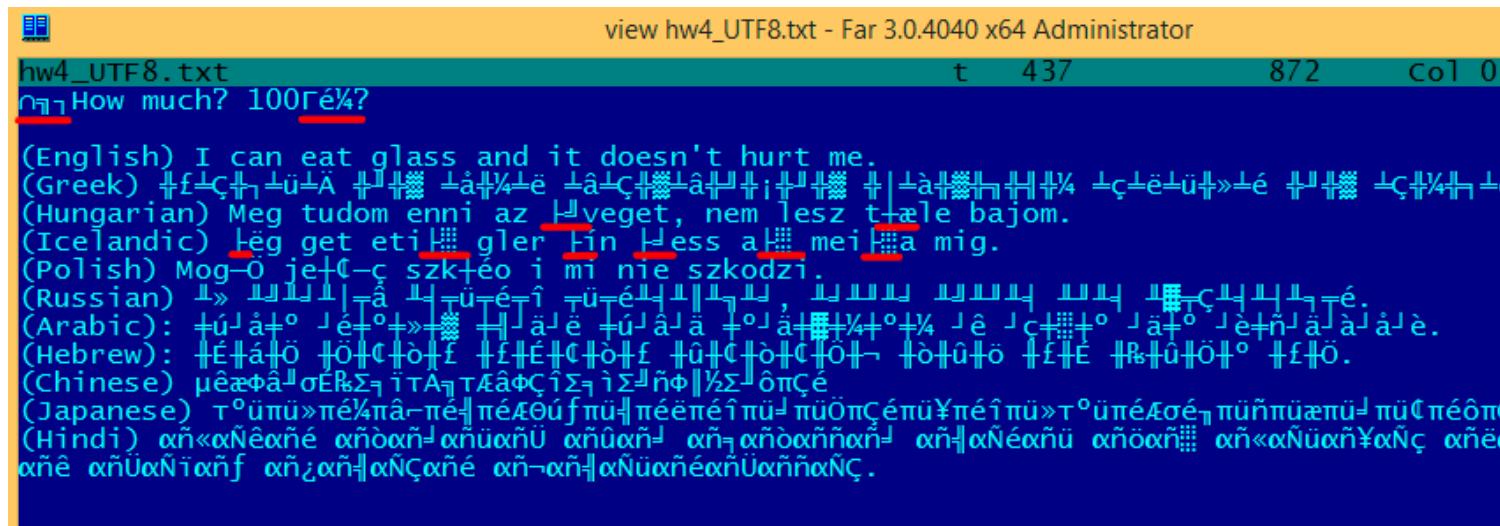


Figure 57.2: FAR: UTF-8

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.

At the beginning, before the "How much?" string we see 3 bytes, which are in fact the **BOM**². The **BOM** defines the encoding system to be used.

¹The example and translations was taken from here: <http://go.yurichev.com/17304>

²Byte order mark

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");
}
```

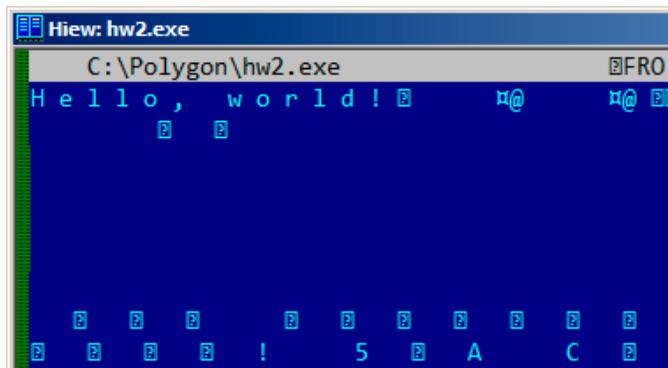


Figure 57.3: Hiew

We can see this often in [Windows NT](#) system files:

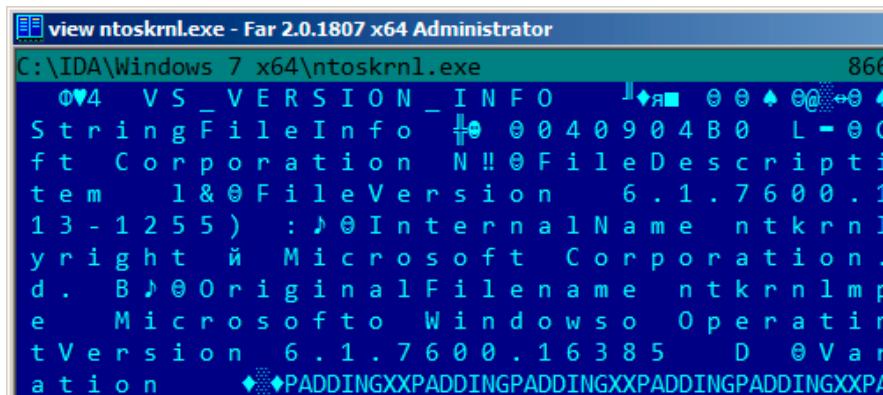


Figure 57.4: Hiew

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:

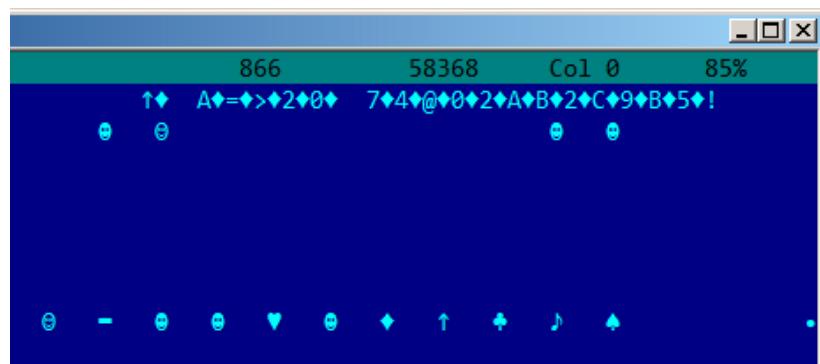


Figure 57.5: Hiew: UTF-16LE

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 plane ³. 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 57.6: 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.

57.1.4 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) end with 1 or 2 padding equality symbol(s) ("="), for example:

AVjbVSVfcUMu1xvjaMgjNtueRwBbxnyJw8dpGnLW8ZW8aKG3v4Y0icu0T+qEJA91A0uWs=

WVibbVSfCUMu1xyjaMgiNtueRwBbxnyJw8dpGnLW8ZW8aKG3v4Y0icuOT+qEJAp9IA0u0==

The equality sign ("=") is never encountered in the middle of base64-encoded strings.

³ wikipedia

57.2 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: [78.2 on page 770](#).

57.3 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 58

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 58.1: 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_nbitsBit ; "sp->lzw_nbits <= BITS_MAX"
.text:107D6771 call ds:_assert
```

It is advisable to “google” both the conditions and file names, which can lead us to an open-source library. For example, if we “google” `“sp->lzw_nbits <= BITS_MAX”`, this predictably gives us some open-source code that’s related to the LZW compression.

Chapter 59

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 0xAAAAAAA (10101010101010101010101010101010) and 0x5555555 (01010101010101010101010101010101) are also popular—those are composed of alternating bits. That may help to distinguish some signal from the signal where all bits are turned on (1111 ...) or off (0000 ...). For example, the 0x55AA constant is used at least in the boot sector, [MBR](#)¹, 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 very 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 59.1: 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, 0x0D80, 0xCD41, 0x0F00, 0xCFC1, 0xCE81, 0x0E40,
    ...
}
```

See also the precomputed table for CRC32: [37 on page 484](#).

59.1 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](#)

...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 960](#)) 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.

59.1.1 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 59.2: `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:

Listing 59.3: `dhcpcore.dll` (Windows 7 x64)

```
.text:000007FF6480875F mov     eax, [rsi]
.text:000007FF64808761 cmp     eax, cs:dword_7FF6483CBE8
.text:000007FF64808767 jnz     loc_7FF64817179
```

And:

Listing 59.4: `dhcpcore.dll` (Windows 7 x64)

```
.text:000007FF648082C7 mov     eax, [r12]
.text:000007FF648082CB cmp     eax, cs:dword_7FF6483CBEC
.text:000007FF648082D1 jnz     loc_7FF648173AF
```

59.2 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*⁵.

⁵[GitHub](#)

Chapter 60

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.

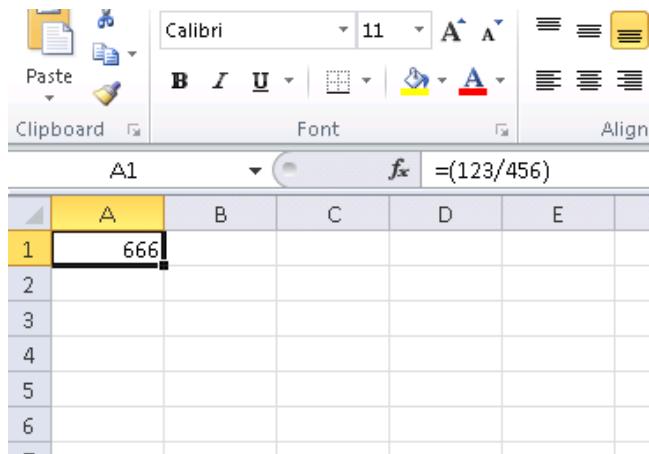


Figure 60.1: The practical joke worked

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 61

Suspicious code patterns

61.1 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” ([18.3 on page 278](#)). 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 ([49 on page 547](#)).

61.2 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 955](#).

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
    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 62

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 63

Other things

63.1 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.

63.2 C++

RTTI ([51.1.5 on page 570](#))-data may be also useful for C++ class identification.

63.3 Some binary file patterns

Sometimes, we can clearly spot an array of 16/32/64-bit values visually, in hex editor. 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:

The screenshot shows the Hiew binary editor displaying assembly code for the file FW96650A.bin. The code is written in a standard assembly language, likely MIPS, with various instructions such as BE, AF, F0, etc. The editor has a blue background with white text. At the top, there's a menu bar with options like File, View, Tools, Options, Help, and a status bar indicating 'Hiew 8.02 (c)SEN'. Below the menu is a toolbar with icons for opening files, saving, and other functions. The main window contains the assembly code, which is heavily annotated with Russian comments. The bottom of the window features a series of tabs labeled 1Global, 2FillBlk, 3CryBlk, 4Reload, 5, 6String, 7Direct, 8Table, 9, 10Leave, 11, and 12AddNan.

Figure 63.1: Hiew: very typical MIPS code

Another example of such pattern here is book: [86 on page 871](#).

63.4 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 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 [FC](#)¹ (“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: [85 on page 864](#).

¹MS-DOS utility for comparing binary files

63.4.1 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.

63.4.2 Blink-comparator

Comparison of files or memory snapshots remind us blink-comparator²: 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.

²<http://go.yurichev.com/17348>

Part VI

OS-specific

Chapter 64

Arguments passing methods (calling conventions)

64.1 cdecl

This is the most popular method for passing arguments to functions in the C/C++ languages.

The **glscaller** also must return the value of the **stack pointer** (ESP) to its initial state after the **callee** function exits.

Listing 64.1: cdecl

```
push arg3
push arg2
push arg1
call function
add esp, 12 ; returns ESP
```

64.2 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 $x = \text{arguments number} * \text{sizeof(int)}$ ¹. The **caller** is not adjusting the **stack pointer**, there are no add esp, x instruction.

Listing 64.2: 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 [8.1 on page 90](#) 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 [8.2 on page 90](#), 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 64.3: MSVC 2010

```
_a$ = 8                                ; size = 4
_b$ = 12                                ; size = 4
```

¹The size of an *int* type variable is 4 in x86 systems and 8 in x64 systems

```

_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

```

64.2.1 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.

64.3 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 64.4: fastcall

```

push arg3
mov edx, arg2
mov ecx, arg1
call function

function:
.. do something ..
ret 4

```

For example, we may take the function from [8.1 on page 90](#) and change it slightly by adding a `__fastcall` modifier:

```

int __fastcall f3 (int a, int b, int c)
{
    return a*b+c;
}

```

Here is how it is to be compiled:

Listing 64.5: 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.

64.3.1 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 ([19.1.1 on page 313](#)).

64.3.2 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.

64.4 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 ([51.1.1 on page 556](#)).

64.5 x86-64

64.5.1 Windows x64

The method of for 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.

²<http://go.yurichev.com/17040>

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\n", a, b, c, d, e, f, g);
}

int main()
{
    f1(1,2,3,4,5,6,7);
}
```

Listing 64.6: 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]
    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          ; 00000048H
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 64.7: Optimizing MSVC 2012 /0b

```
$SG2777 DB      '%d %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 957](#)). It's hard to say if it worth doing so, but maybe.

Another example of such thing is: [74.1 on page 744](#).

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: [51.1.1 on page 558](#).

64.5.2 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 64.8: 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.

64.6 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.

64.7 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 64.9: MSVC 2012

<code>_a\$ = 8</code>	<code>; size = 4</code>
-----------------------	-------------------------

```
_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++ ([51.3 on page 572](#)), 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.

64.8 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 64.10: Optimizing MSVC 2010

```
$SG2796 DB      '%d', 0aH, 00H

_a$ = 8
_f PROC
    lea     eax, DWORD PTR _a$[esp-4] ; just get the address of value in local stack
    push    eax                      ; and pass it to modify_a()
    call    _modify_a
    mov     ecx, DWORD PTR _a$[esp]   ; reload it from the local stack
    push    ecx                      ; and pass it to printf()
    push    OFFSET $SG2796 ; '%d'
    call    _printf
    add     esp, 12
    ret     0
_f ENDP
```

The address of the place in the stack where *a* 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 64.11: Optimizing MSVC 2012 x64

```
$SG2994 DB      '%d', 0aH, 00H
a$ = 48
```

```

f PROC
    mov     DWORD PTR [rsp+8], ecx ; save input value in Shadow Space
    sub     rsp, 40
    lea     rcx, QWORD PTR a$[rsp] ; get address of value and pass it to modify_a()
    call    modify_a
    mov     edx, DWORD PTR a$[rsp] ; reload value from Shadow Space and pass it to printf()
    ↳ ()
        lea     rcx, OFFSET FLAT:$SG2994 ; '%d'
        call   printf
        add    rsp, 40
        ret    0
f ENDP

```

GCC also stores the input value in the local stack:

Listing 64.12: 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 64.13: 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()
    b1    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
    b1    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 : [46.1.2 on page 530](#).

Chapter 65

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 65.1: 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](#).

65.1 Linear congruent generator revisited

The pseudorandom number generator we considered earlier [20 on page 352](#) 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.

65.1.1 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;
10
11 void my_srand (uint32_t init)
```

¹ C11 also has thread support, optional though

```

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 65.2: 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.

The `GS:` selector is used in Win64 and the address of the [TLS](#) is `0x58`:

Listing 65.3: 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 }

```

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_srand()` 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 & 0xffff;
}

int main()
{
    // rand_state is already initialized at the moment (using GetTickCount())
}
```

```
printf ("%d\n", my_rand());
};
```

Let's see it in IDA:

Listing 65.4: 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 [OEP](#)².

65.1.2 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 65.5: 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 66

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.

66.1 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 66.1: 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. 4 is for sys_exit
    int    0x80

section .data

msg    db  'Hello, world!',0xa
len    equ $ - msg
```

¹Black 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([71](#) on page [737](#)) can be used.

66.2 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 67

Linux

67.1 Position-independent code

While analyzing Linux shared (.so) libraries, one may frequently spot this code pattern:

Listing 67.1: libc-2.17.so x86

```
.text:0012D5E3 __x86_get_pc_thunk_bx proc near ; CODE XREF: sub_17350+3
.text:0012D5E3                                     ; sub_173CC+4 ...
.text:0012D5E3         mov     ebx, [esp+0]
.text:0012D5E6         retn
.text:0012D5E6 __x86_get_pc_thunk_bx endp

...
.text:000576C0 sub_576C0      proc near ; CODE XREF: tmpfile+73
...
.text:000576C0         push    ebp
.text:000576C1         mov     ecx, large gs:0
.text:000576C8         push    edi
.text:000576C9         push    esi
.text:000576CA         push    ebx
.text:000576CB         call    __x86_get_pc_thunk_bx
.text:000576D0         add    ebx, 157930h
.text:000576D6         sub    esp, 9Ch

...
.text:000579F0         lea    eax, (a__gen_tempname - 1AF000h)[ebx] ; "__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>
```

```

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 67.2: 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]

```

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+0x2
     ↳ 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](#)].

67.1.1 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..

67.2 *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* ([71 on page 737](#)), it is possible to see that the utility takes this information the */proc/uptime* file:

```
$ strace uptime
...
open("/proc/uptime", O_RDONLY)      = 3
lseek(3, 0, SEEK_SET)              = 0
read(3, "416166.86 414629.38\n", 2047) = 20
...
```

It is not a real file on disk, it is a virtual one and its contents are generated on fly in the Linux kernel. There are just two numbers:

```
$ cat /proc/uptime
416690.91 415152.03
```

What we can learn from Wikipedia ²:

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.

¹program counter in AMD64

²wikipedia

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;

int open(const char *pathname, int flags)
{
    find_original_functions();

    int fd=(*open_ptr)(pathname, flags);
    if (strcmp(pathname, "/proc/uptime")==0)
```

³For example, here is how simple strcmp() interception works in this article ⁴ written by Yong Huang

```

        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/17043>
- 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 68

Windows NT

68.1 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
22     xor     ecx, ecx
```

¹Graphical user interface

```

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
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
105 $LN28:    ; CODE XREF: __tmainCRTStartup+105
106     call  __cexit
107     jmp   short loc_401186
108
109 $LN27:    ; DATA XREF: .rdata:stru_4092D0
110     mov   eax, [ebp+ms_exc.exc_ptr] ; Exception filter 0 for function 401044
111     mov   ecx, [eax]
112     mov   ecx, [ecx]
113     mov   [ebp+var_24], ecx
114     push  eax
115     push  ecx
116     call  __XcptFilter
117     pop   ecx
118     pop   ecx
119
120 $LN24:
121     retn
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
142     retn

```

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()`: [51.4.1 on page 577](#).

The value that `main()` returns is passed to `cexit()`, or in `$LN32`, which in turn calls `doexit()`.

Is it possible to get rid of the [CRT](#)? Yes, if you know what you are doing.

The [MSVC](#)'s linker has the `/ENTRY` option for setting an entry point.

```
#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 PE² 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.

68.2 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 DLL³, 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 ⁴.

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.

68.2.1 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.
- VA⁵— 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.
- RVA⁶—the VA-address minus the base address. Many addresses in PE-file tables use RVA-addresses.

²Portable Executable: 68.2

³Dynamic-link library

⁴For example, Hiew(73 on page 739) can calculate it

⁵Virtual Address

⁶Relative Virtual Address

- **IAT**⁷ – an array of addresses of imported symbols⁸. 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**⁹ – an array of names of symbols to be imported¹⁰.

68.2.2 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 0x400000¹¹, 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 0x10000000¹².

There is also another reason to load modules at various base addresses, in this case random ones.

It is **ASLR**¹³¹⁴.

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].

68.2.3 Subsystem

There is also a *Subsystem* field, usually it is:

- native¹⁵ (.sys-driver),
- console (console application) or
- GUI (non-console).

68.2.4 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 here¹⁶.

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 options¹⁷, it is possible to force it to compile for Windows XP.

⁷Import Address Table

⁸[Pie02]

⁹Import Name Table

¹⁰[Pie02]

¹¹The origin of this address choice is described here: [MSDN](#)

¹²This can be changed by the /BASE linker option

¹³Address Space Layout Randomization

¹⁴wikipedia

¹⁵Meaning, the module use Native API instead of Win32

¹⁶wikipedia

¹⁷MSDN

68.2.5 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: [68.2.1 on the preceding page](#).
- `.edata`—exports section (rare)
- `.pdata`— section containing all information about exceptions in Windows NT for MIPS, [IA64](#) and x64: [68.3.3 on page 728](#)
- `.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/encoders often garble section names or replace the names with their own.

[MSVC](#) allows you to declare data in arbitrarily named section ¹⁸.

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;
```

¹⁹

A word about terminology: *PointerToRawData* it called “Offset” in Hiew and *VirtualAddress* is called “RVA” there.

68.2.6 Relocations (relocs)

[AKA FIXUP-s](#) (at least in Hiew).

They are also present in almost all executable file formats ²⁰. Exceptions are shared dynamic libraries compiled with [PIC](#), or any other [PIC](#)-code.

¹⁸[MSDN](#)

¹⁹[MSDN](#)

²⁰Even in .exe files for MS-DOS

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 ([67.1 on page 696](#)). 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, [000410000]
----------------	-----	------------------

The base address of the module is 0x400000, the [RVA](#) of the global variable is 0x10000.

If the module is loaded at base address 0x500000, the real address of the global variable must be 0x510000.

As we can see, the address of variable is encoded in the instruction MOV, after the byte 0xA1.

That is why the address of the 4 bytes after 0xA1, is written in the relocs table.

If the module is loaded at a different base address, the [OS](#) loader enumerates all addresses in the table, finds each 32-bit word the address points to, subtracts the original base address from it (we get the [RVA](#) here), and adds the new base address to it.

If a module is loaded at its original base address, nothing happens.

All global variables can be treated like that.

Relocs may have various types, however, in Windows for x86 processors, the type is usually [IMAGE_REL_BASED_HIGHLOW](#).

By the way, relocs are darkened in Hiew, for example: [fig.7.12](#).

OllyDbg underlines the places in memory to which relocs are to be applied, for example: [fig.13.11](#).

68.2.7 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 [MFC²¹](#) library usually loads mfc.dll by ordinals, and in such programs there are no [MFC](#) function names in [INT](#).

When loading such programs in [IDA](#), it will ask for a path to the mfc.dll files in order to determine the function names. If you don't tell [IDA](#) the path to these DLLs, there will be *mfc80_123* instead of function names.

Imports section

Often a separate section is allocated for the imports table and everything related to it (with name like .idata), however, this is not a strict rule.

Imports are also a confusing subject because of the terminological mess. Let's try to collect all information in one place.

²¹Microsoft Foundation Classes

Usually located in PE section devoted to imports

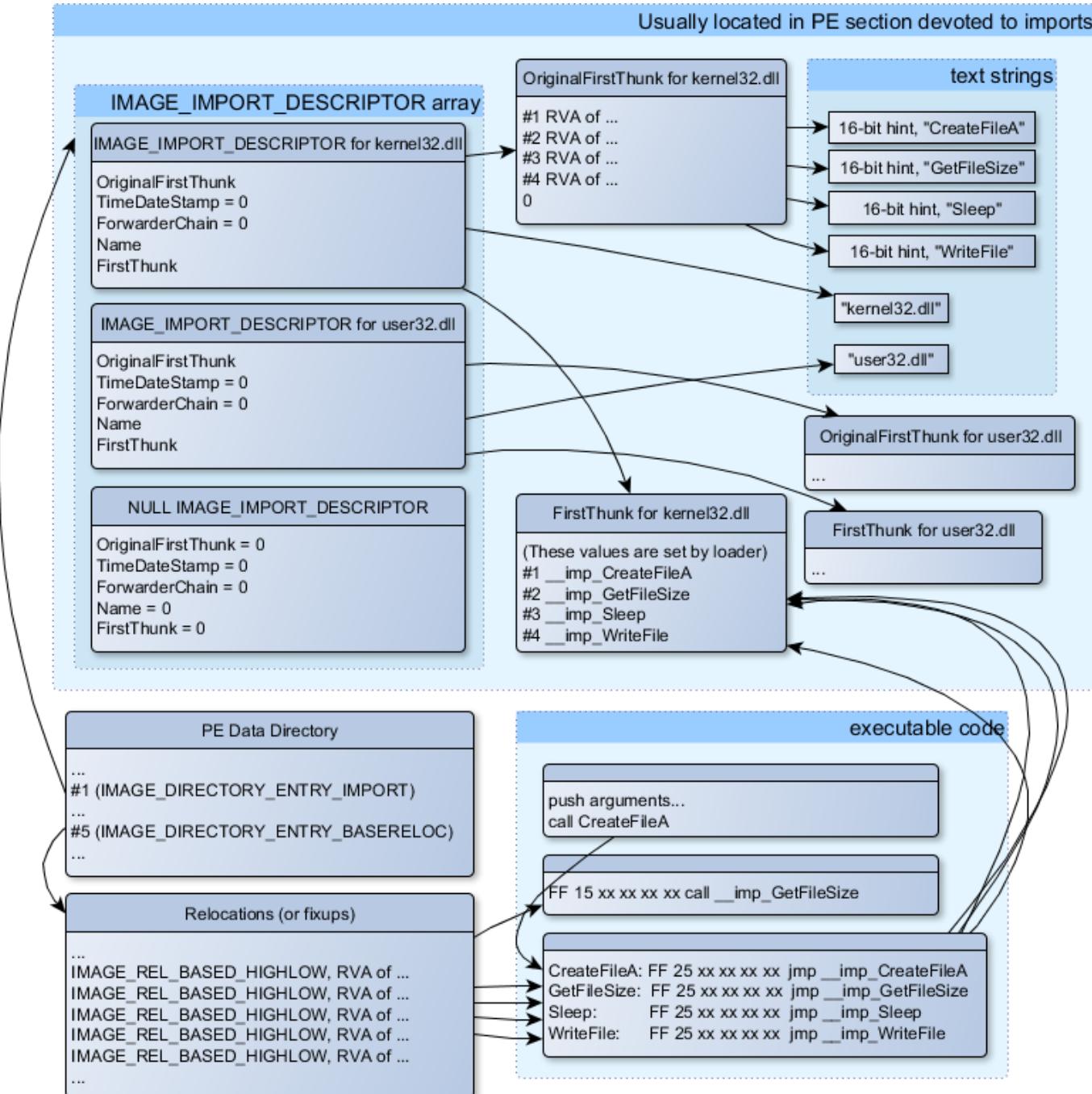


Figure 68.1: A scheme that unites all PE-file structures related to imports

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 `IAT` table. This is an array of [RVA](#) addresses, each of which points to a text string with a function name. Each string is prefixed by a 16-bit integer ("hint")—"ordinal" of function.

While loading, if it is possible to find a function by ordinal, then the strings comparison will not occur. The array is terminated by zero. There is also a pointer to the `IAT` table named `FirstThunk`, it is just the [RVA](#) address of the place where the loader writes the addresses of the resolved functions.

The points where the loader writes addresses are marked by [IDA](#) like this: `__imp_CreateFileA`, etc.

There are at least two ways to use the addresses written by the loader.

- The code will have instructions like `call __imp_CreateFileA`, and since the field with the address of the imported function is a global variable in some sense, the address of the `call` instruction (plus 1 or 2) is to be added to the `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 relocations are not necessary because these CALL-s have relative addresses and do not need to be corrected.

These two methods can be combined. Possible, the linker creates individual “thunk”s if there are too many calls to the function, but not done by default.

By the way, the array of function addresses to which FirstThunk is pointing is not necessary to be located in the IAT section. For example, author of these lines once wrote the PE_add_import²² 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”²³. The BIND.EXE utility in Windows SDK is 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.

68.2.8 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 ([68.2.11 on the next page](#)).

68.2.9 .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:

```
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 instruction²⁴.

²²yurichev.com

²³[MSDN](#). There is also the “new-style binding”.

²⁴[MSDN](#)

68.2.10 TLS

This section holds initialized data for the [TLS](#)([65 on page 689](#)) (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.

68.2.11 Tools

- objdump (present in cygwin) for dumping all PE-file structures.
- Hiew([73 on page 739](#)) as editor.
- pefile—Python-library for PE-file processing ^{[25](#)}.
- ResHack [AKA](#) Resource Hacker—resources editor ^{[26](#)}.
- PE_add_import^{[27](#)} – simple tool for adding symbol(s) to PE executable import table.
- PE_patcher^{[28](#)} – simple tool for patching PE executables.
- PE_search_str_refs^{[29](#)} – simple tool for searching for a function in PE executables which use some text string.

68.2.12 Further reading

- Daniel Pistelli—The .NET File Format ^{[30](#)}

68.3 Windows SEH

68.3.1 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 be found.

At the very end of the chain there a standard handler that shows the well-known dialog box, informing the user about a process crash, some technical information about the [CPU](#) state at the time of the crash, and offering to collect all information and send it to developers in Microsoft.

²⁵<http://go.yurichev.com/17052>

²⁶<http://go.yurichev.com/17052>

²⁷<http://go.yurichev.com/17049>

²⁸yurichev.com

²⁹yurichev.com

³⁰<http://go.yurichev.com/17056>

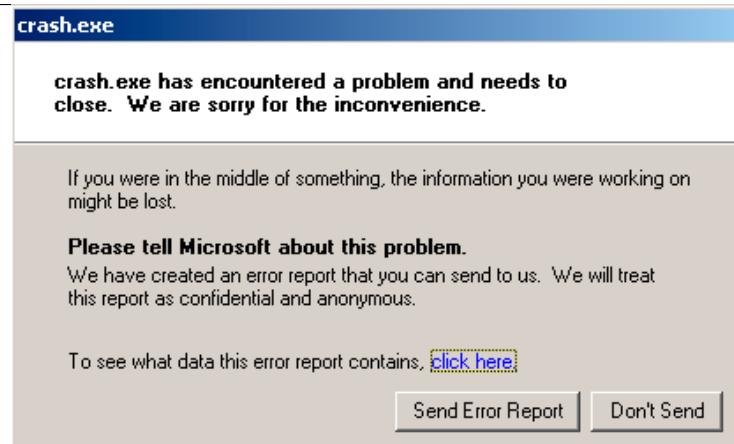


Figure 68.2: Windows XP

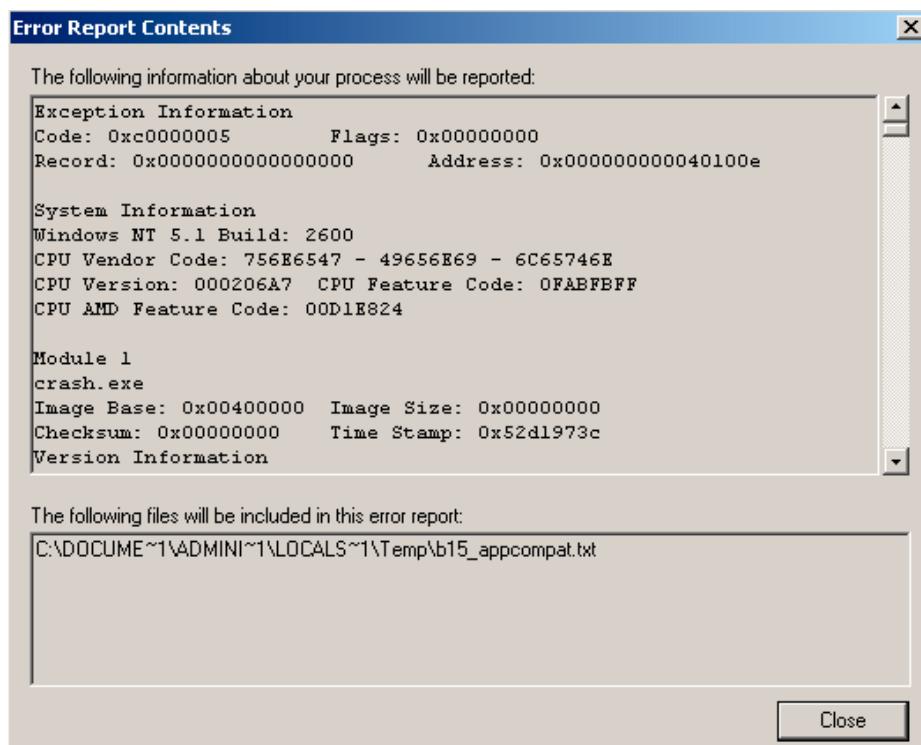


Figure 68.3: Windows XP

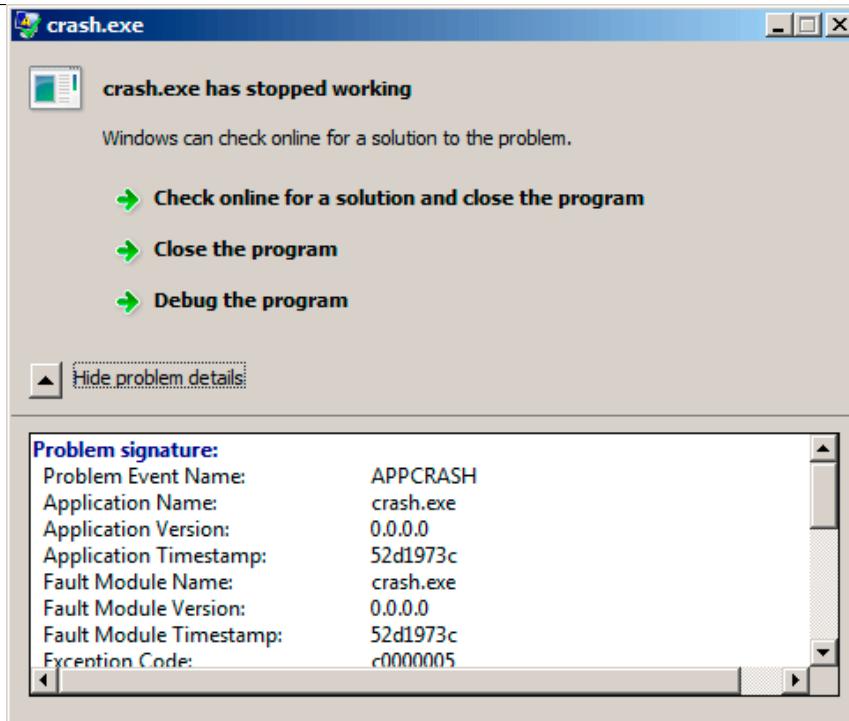


Figure 68.4: Windows 7

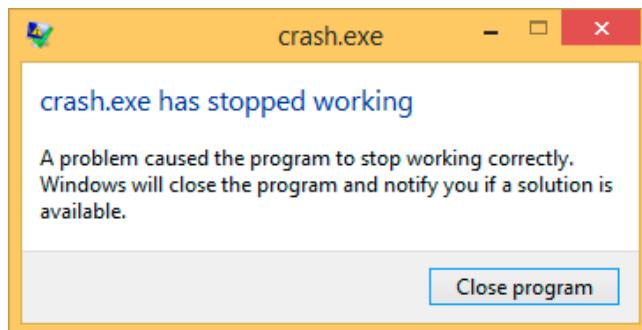


Figure 68.5: Windows 8.1

Earlier, this handler was called Dr. Watson ³¹.

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 ³²:

```
#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;
```

³¹[wikipedia](#)

³²This example is based on the example from [Pie]

It must be compiled with the SAFESEH option: `cl seh1.cpp /link /safe seh: no`

More about SAFESEH here:

[MSDN](#)

```

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
        mov     FS:[0],ESP        // add new EXCEPTION_REGISTRATION
    }

    RaiseException (0xE1223344, 0, 0, NULL);

    // now do something very bad
    int* ptr=NULL;
    int val=0;
    val=*ptr;
    printf ("val=%d\n", val);

    // deinstall exception handler
    __asm
    {
        mov     eax,[ESP]         // remove our EXCEPTION_REGISTRATION record
        mov     FS:[0], EAX        // get pointer to previous record
        add     esp, 8             // install previous record
        add     esp, 8             // clean our EXCEPTION_REGISTRATION off stack
    }

    return 0;
}

```

The FS:segment register is pointing to the [TIB](#) in win32. The very first element in the TIB is a pointer to the last handler in the chain. We save it in the stack and store the address of our handler there. The structure is named `_EXCEPTION_REGISTRATION`, it is a simple singly-linked list and its elements are stored right in the stack.

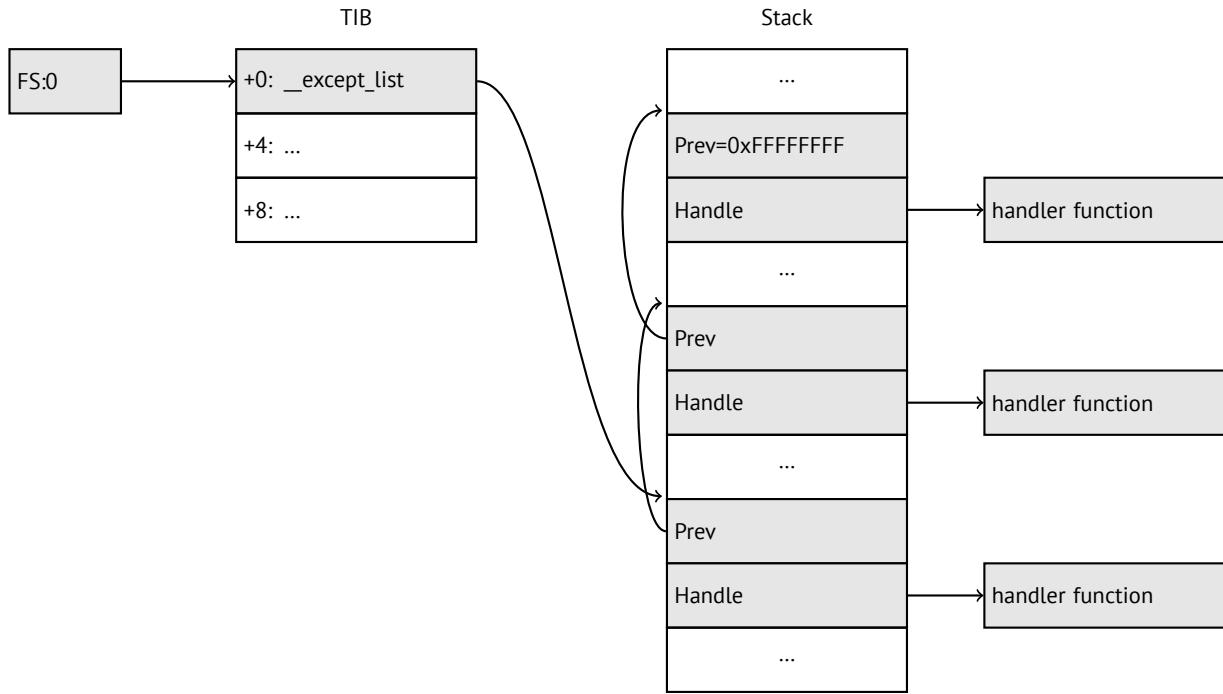
Listing 68.1: MSVC/VC/crt/src/exsup.inc

```

\_EXCEPTION\REGISTRATION struc
    prev    dd      ?
    handler dd      ?
\_EXCEPTION\REGISTRATION ends

```

So each “handler” field points to a handler and an each “prev” field points to the previous record in the stack. The last record has 0xFFFFFFFF (-1) in the “prev” field.



After our handler is installed, we call `RaiseException()`³³. This is an user exception. The handler checks the code. If the code is 0xE123344, 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	29	28	27	16	15	0
S	U	0		Facility code		Error code

³³MSDN

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 68.2: 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()`: ([5.2.4 on page 27](#)).

68.3.2 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 MSVC³⁴. It is not related to C++ PL exceptions.

```
_try
{
    ...
}
__except(filter code)
{
    handler code
}
```

“Finally” block may be instead of handler code:

```
_try
{
    ...
}
__finally
{
    ...
}
```

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](#)):

³⁴[MSDN](#)

Listing 68.3: 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 68.4: 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 68.5: 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

--*/
{
    *ExceptionCode = ExceptionPointer->ExceptionRecord->ExceptionCode;

    if ( (*ExceptionCode == STATUS_IN_PAGE_ERROR) &&
        (ExceptionPointer->ExceptionRecord->NumberParameters >= 3) ) {

        *ExceptionCode = (NTSTATUS) ExceptionPointer->ExceptionRecord->ExceptionInformation[2];
    }
}

```

```

    ASSERT( !NT_SUCCESS(*ExceptionCode) );
    return EXCEPTION_EXECUTE_HANDLER;
}

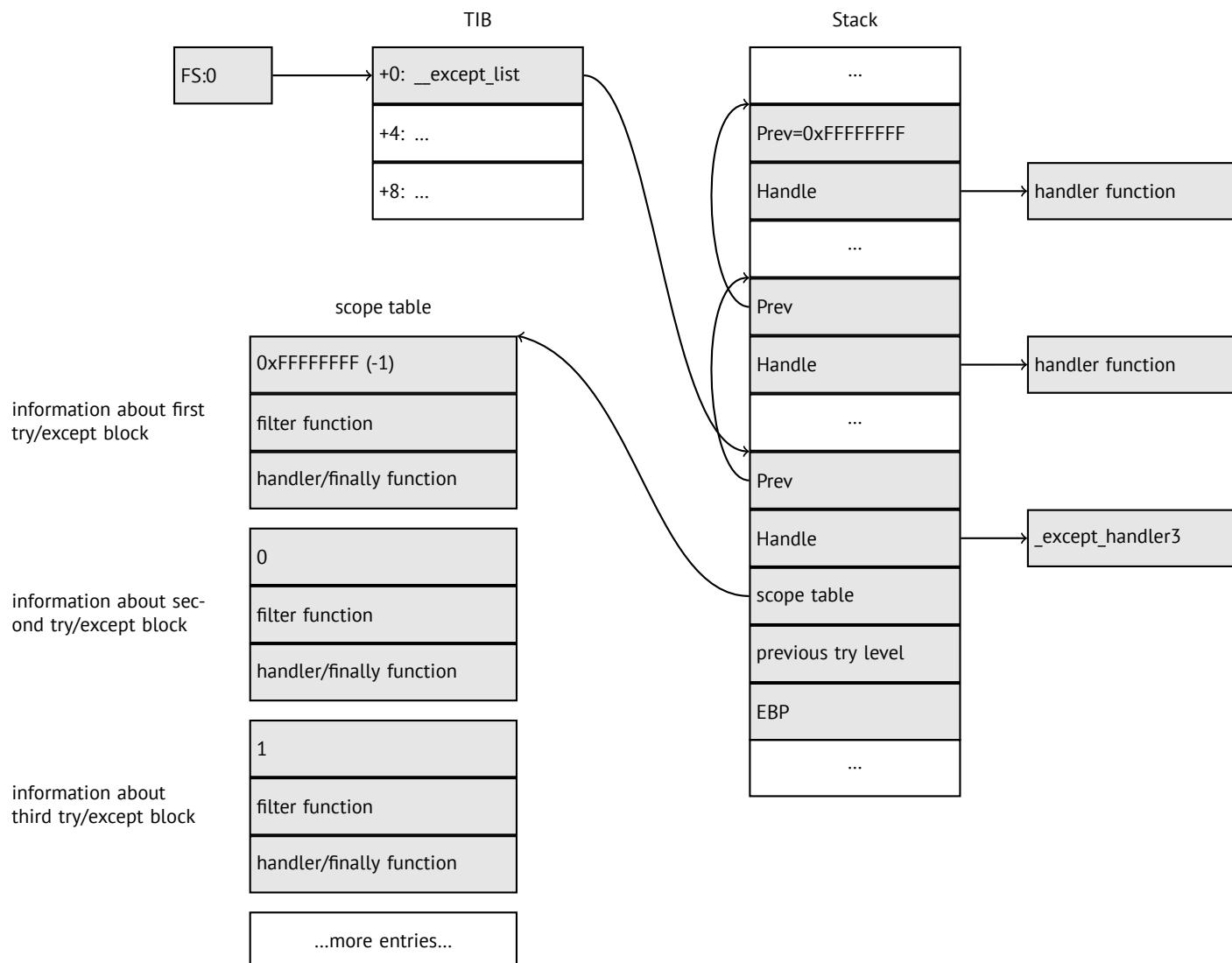
```

Internally, SEH is an extension of the OS-supported exceptions. But the handler function is `_except_handler3` (for SEH3) or `_except_handler4` (for SEH4). The code of this handler is MSVC-related, it is located in its libraries, or in `msvcr*.dll`. It is very important to know that SEH is a MSVC thing. Other win32-compilers may offer something completely different.

SEH3

SEH3 has `_except_handler3` as a handler function, and extends the `_EXCEPTION_REGISTRATION` table, adding a pointer to the *scope table* and *previous try level* variable. SEH4 extends the *scope table* by 4 values for buffer overflow protection.

The *scope table* is a table that consists of pointers to the filter and handler code blocks, for each nested level of *try/except*.



Again, it is very important to understand that the `OS` takes care only of the `prev/handle` fields, and nothing more. It is the job of the `_except_handler3` function to read the other fields and *scope table*, and decide which handler to execute and when.

The source code of the `_except_handler3` function is closed. However, Sanos OS, which has a win32 compatibility layer, has the same functions reimplemented, which are somewhat equivalent to those in Windows³⁵. Another reimplementation is present in Wine³⁶ and ReactOS³⁷.

³⁵<http://go.yurichev.com/17058>

³⁶[GitHub](#)

³⁷<http://go.yurichev.com/17060>

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 68.6: 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
$T74622  DD      0xffffffffH ; previous try level
          DD      FLAT:$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:$T74622    ; scope table
    push    OFFSET FLAT:_except_handler3 ; handler
    mov     eax, DWORD PTR fs:_except_list
    push    eax                      ; prev
    mov     DWORD PTR fs:_except_list, esp
    add    esp, -16
; 3 registers to be saved:
    push    ebx
    push    esi
    push    edi
    mov     DWORD PTR __$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 68.7: tracer.exe output

```

EXCEPTION_ACCESS_VIOLATION at 2.exe!main+0x44 (0x401054) ExceptionInformation[0]=1
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=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 ↴
    ↳ )

```

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)
        {
            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 68.8: 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
    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$[ebp+20], 0 ; outer try block entered. set previous try level to
↳ 0
mov    DWORD PTR __$SEHRec$[ebp+20], 1 ; inner try block entered. set previous try level to
↳ 1
push   OFFSET FLAT:$SG74617 ; 'hello!'
call   _printf
add    esp, 4
push   0
push   0
push   0
push   1122867    ; 00112233H
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
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

$L74615:
    mov    DWORD PTR __$SEHRec$[ebp+20], -1 ; outer try block exited, set previous try level ↳
    ↳ back to -1
    jmp   SHORT $L74633

; outer block filter:
$L74634:
$L74651:
    mov    ecx, DWORD PTR __$SEHRec$[ebp+4]
    mov    edx, DWORD PTR [ecx]
    mov    eax, DWORD PTR [edx]
    mov    DWORD PTR $T74642[ebp], eax
    mov    ecx, DWORD PTR __$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 68.9: tracer.exe output

```

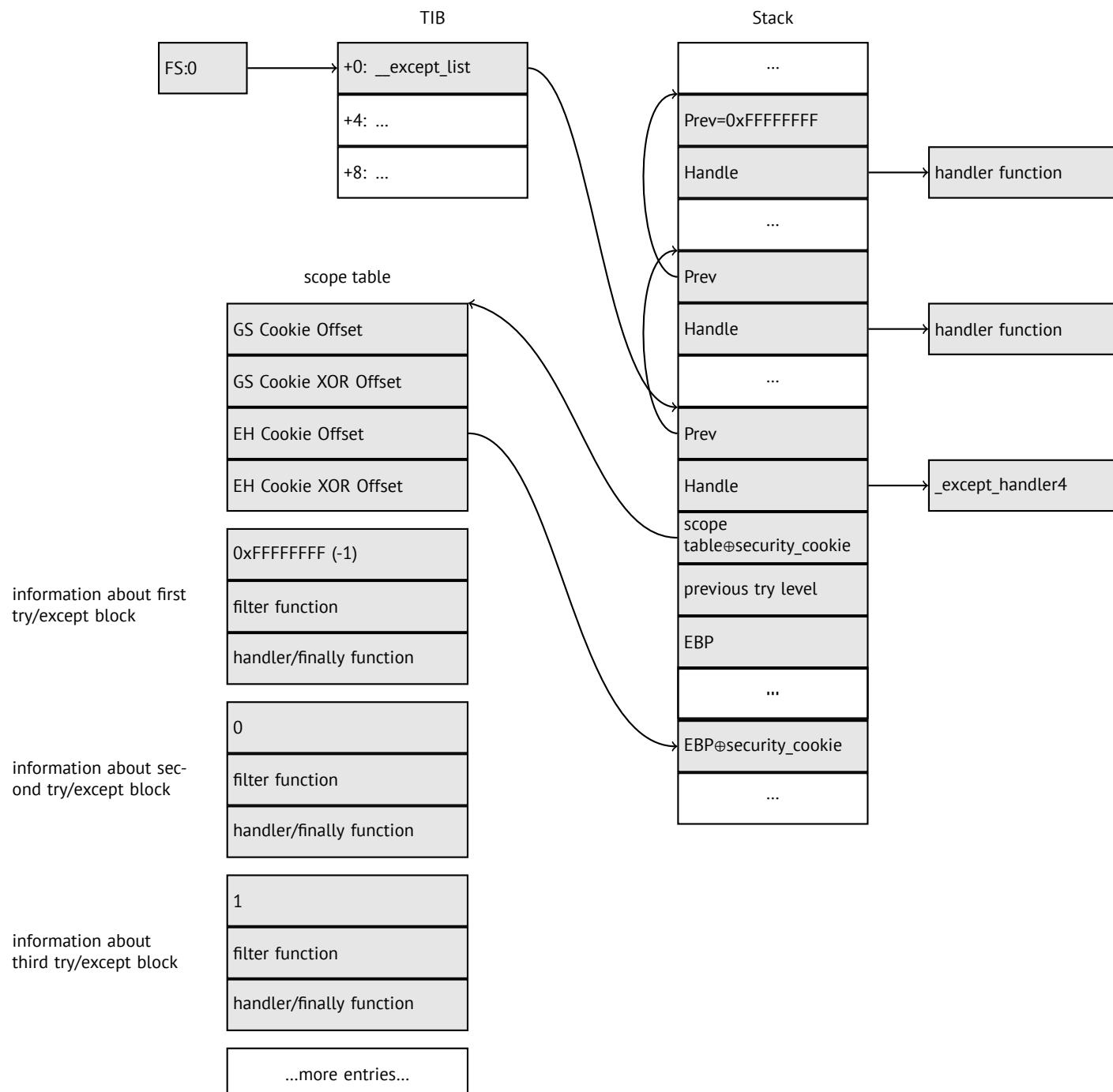
(0) 3.exe!printf
EAX=0x00000001b EBX=0x000000000 ECX=0x0040cc58 EDX=0x0008e3c8
ESI=0x000000000 EDI=0x000000000 EBP=0x0018f840 ESP=0x0018f838
EIP=0x004011b6
FLAGS=PF ZF IF
* SEH frame at 0x18f88c prev=0x18fe9c handler=0x771db4ad (ntdll.dll!ExecuteHandler2@20+0x3a)
* SEH frame at 0x18fe9c prev=0x18ff78 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 ([18.2 on page 270](#)) attack, the address of the *scope table* can be rewritten, so starting from MSVC 2005, SEH3 was upgraded to SEH4 in order to have buffer overflow protection. The pointer to the *scope table* is now **xored** with a **security cookie**. The *scope table* was extended to have a header consisting of two pointers to *security cookies*. Each element has an offset inside the stack of another value: the address of the **stack frame** (EBP) **xored** with the **security_cookie**, placed in the stack. This value will be read during exception handling and checked for correctness. The *security cookie* in the stack is random each time, so hopefully a remote attacker can't predict it.

The initial *previous try level* is -2 in SEH4 instead of -1.



Here are both examples compiled in MSVC 2012 with SEH4:

Listing 68.10: 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
                  0ffffffeH    ; previous try level
                  FLAT:$LN12@main ; filter
                  FLAT:$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]
    mov    DWORD PTR fs:0, ecx
    pop    ecx
    pop    edi
    pop    esi
    pop    ebx
    mov    esp, ebp
    pop    ebp
    ret    0

```

_main ENDP

Listing 68.11: 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
    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]
    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.

68.3.3 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 68.12: 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
$pdata$main DD  imagerel $LN9
            DD  imagerel $LN9+61
            DD  imagerel $unwind$main
pdata   ENDS
pdata   SEGMENT
$pdata$main$filter$0 DD imagerel main$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 68.13: 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
\$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$filter$0 DD imagerel main$filter$0
        DD      imagerel main$filter$0+32
        DD      imagerel $unwind$main$filter$0
$pdata$main$filter$1 DD imagerel main$filter$1
        DD      imagerel main$filter$1+30
        DD      imagerel $unwind$main$filter$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 $LN14+59
        DD      imagerel main$filter$0
        DD      imagerel $LN14+59
        DD      imagerel $LN14+8
        DD      imagerel $LN14+74
        DD      imagerel main$filter$1
        DD      imagerel $LN14+74
$unwind$main$filter$0 DD 020601H
        DD      050023206H
$unwind$main$filter$1 DD 020601H
        DD      050023206H
xdata   ENDS

_TEXT  SEGMENT
main   PROC
$LN14:
    push   rbx
    sub    rsp, 32
    xor    ebx, ebx
    lea    rcx, OFFSET FLAT:$SG86288 ; 'hello!'
    call   printf
    xor    r9d, r9d
    xor    r8d, r8d
    xor    edx, edx
    mov    ecx, 1122867 ; 00112233H
    call   QWORD PTR __imp_RaiseException
    lea    rcx, OFFSET FLAT:$SG86290 ; '0x112233 raised. now let's crash'
    call   printf
    mov    DWORD PTR [rbx], 13
    jmp   SHORT $LN13@main
$LN11@main:
    lea    rcx, OFFSET FLAT:$SG86292 ; 'access violation, can't recover'
    call   printf
    npad  1 ; align next label
$LN13@main:
    jmp   SHORT $LN9@main
$LN7@main:
    lea    rcx, OFFSET FLAT:$SG86294 ; 'user exception caught'
    call   printf
    npad  1 ; align next label
$LN9@main:
    xor    eax, eax
    add    rsp, 32
    pop    rbx
    ret   0
main   ENDP

text$x  SEGMENT
main$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   $LN2@filter_use
    lea    rcx, OFFSET FLAT:$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 a tools targeted at automated analysis.

68.3.4 Read more about SEH

[Pie], [Sko12].

68.4 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 68.14: (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 68.15: 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
        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 68.16: 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 69

Disassembler

69.1 IDA

An older freeware version is available for download ¹.

Hot-keys cheatsheet: [F.1 on page 974](#)

¹hex-rays.com/products/ida/support/download_freeware.shtml

Chapter 70

Debugger

70.1 OllyDbg

Very popular user-mode win32 debugger:
ollydbg.de.

Hot-keys cheatsheet: [F.2 on page 974](#)

70.2 GDB

Not very popular debugger among reverse engineers, but very comfortable nevertheless. Some commands: [F.5 on page 975](#).

70.3 tracer

The author often use *tracer*¹ instead of a debugger.

The author of these lines stopped using a debugger eventually, since all he need 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 71

System calls tracing

71.0.1 strace / dtruss

It shows which system calls (syscalls([66 on page 694](#))) are called by a process right now. For example:

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 72

Decompilers

There is only one known, publicly available, high-quality decompiler to C code: Hex-Rays:

hex-rays.com/products/decompiler/

Chapter 73

Other tools

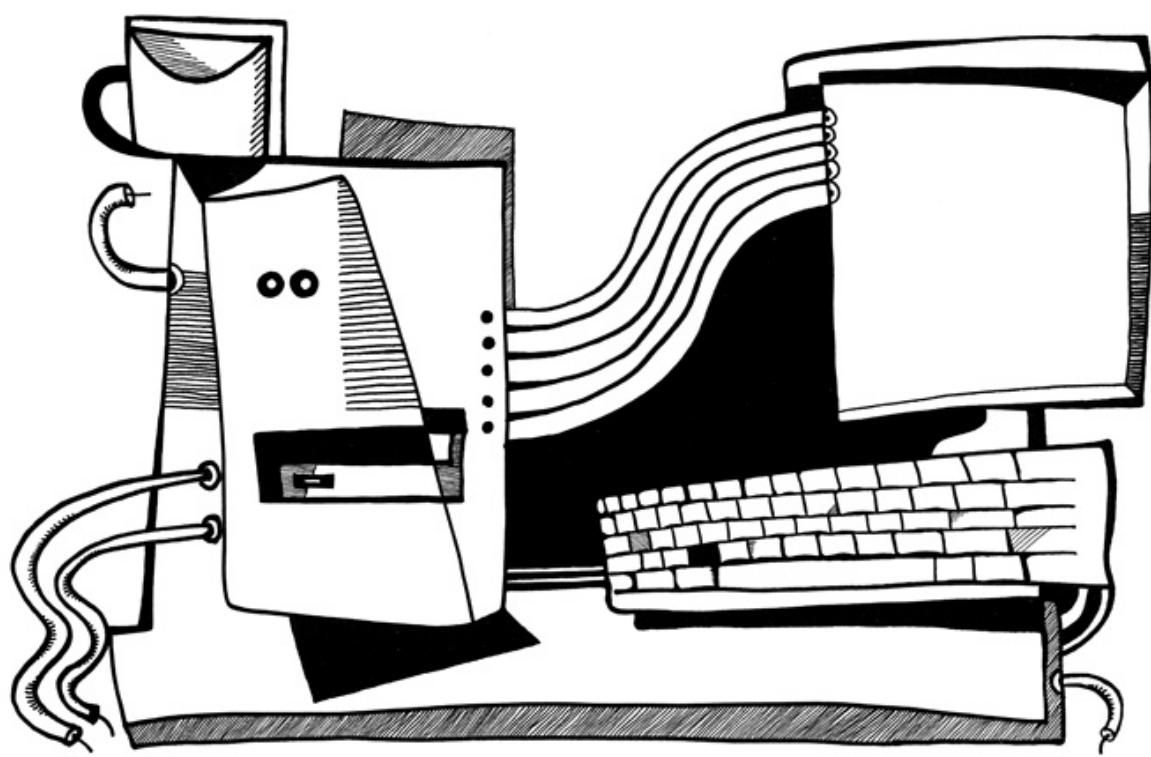
- Microsoft Visual Studio Express¹: Stripped-down free version of Visual Studio, convenient for simple experiments. Some useful options: [F.3 on page 975](#).
- Hiew² for small modifications of code in binary files.
- binary grep: a small utility for searching any byte sequence in a big pile of files, including non-executable ones: [GitHub](#).

¹visualstudio.com/en-US/products/visual-studio-express-vs

²hiew.ru

Part VIII

Examples of real-world RE tasks



Chapter 74

Task manager practical joke (Windows Vista)

Let's see if it's possible to hack Task Manager slightly so it would detect more [CPU](#) cores.

Let us first think, how does the Task Manager know the number of cores? There is the `GetSystemInfo()` [win32](#) function present in `win32` userspace which can tell us this. But it's not imported in `taskmgr.exe`. There is, however, another one in [NTAPI](#), `NtQuerySystemInformation()`, which is used in `taskmgr.exe` in several places. To get the number of cores, one has to call this function with the `SystemBasicInformation` constant as a first argument (which is zero ¹).

The second argument has to point to the buffer which is getting all the information.

So we 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.

xrefs to __imp_NtQuerySystemInformation			
Dire...	T.	Address	Text
Up	p	wWinMain+50E	call cs:__imp_NtQuerySystemInformation; 0
Up	p	wWinMain+542	call cs:__imp_NtQuerySystemInformation; 2
Up	p	CPerfPage::TimerEvent(void)+200	call cs:__imp_NtQuerySystemInformation; not zero
	p	InitPerfInfo(void)+2C	call cs:__imp_NtQuerySystemInformation; 0
D...	p	InitPerfInfo(void)+F0	call cs:__imp_NtQuerySystemInformation; 8
D...	p	CalcCpuTime(int)+5F	call cs:__imp_NtQuerySystemInformation; 8
D...	p	CalcCpuTime(int)+248	call cs:__imp_NtQuerySystemInformation; 2
D...	p	CPerfPage::CalcPhysicalMem(unsigned ...)	call cs:__imp_NtQuerySystemInformation; not zero
D...	p	CPerfPage::CalcPhysicalMem(unsigned ...)	call cs:__imp_NtQuerySystemInformation; not zero
D...	p	CProcPage::GetProcessInfo(void)+2B	call cs:__imp_NtQuerySystemInformation; 5
D...	p	CProcPage::UpdateProcInfoArray(void)+...	call cs:__imp_NtQuerySystemInformation; 0
D...	p	CProcPage::UpdateProcInfoArray(void)+...	call cs:__imp_NtQuerySystemInformation; 2
D...	p	CProcPage::Initialize(HWND __ *)+201	call cs:__imp_NtQuerySystemInformation; 0
D...	p	CProcPage::GetTaskListEx(void)+3C	call cs:__imp_NtQuerySystemInformation; 5

Figure 74.1: 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 74.1: taskmgr.exe (Windows Vista)

```
.text:10000B4B3 xor    r9d, r9d
.text:10000B4B6 lea     rdx, [rsp+0C78h+var_C58] ; buffer
.text:10000B4BB xor    ecx, ecx
.text:10000B4BD lea     ebp, [r9+40h]
.text:10000B4C1 mov    r8d, ebp
.text:10000B4C4 call   cs:__imp_NtQuerySystemInformation ; 0
```

¹MSDN

```

.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
.text:10000B4D0          ; 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 $24 + 4 * 8 = 56$ 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,b1
01`0000B50E: 880574950100	mov	[00000001 00024A88],al
01`0000B514: 7645	jbe	.00000001`0000B55B -->3
01`0000B516: 488BFB	mov	rdi,rbx
01`0000B519: 498BD4	5mov	rdx,r12
01`0000B51C: 8BCD	mov	ecx,ebp

Figure 74.2: 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):

00`0000A8F8:	40386C2458	cmp [rsp][058], bp1
00`0000A8FD:	48890544A00100	mov [000024948], rax
00`0000A904:	66B84000	mov ax, 00040 ; '@'
00`0000A908:	90	nop
00`0000A909:	0F47C5	cmovea 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 74.3: 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%.

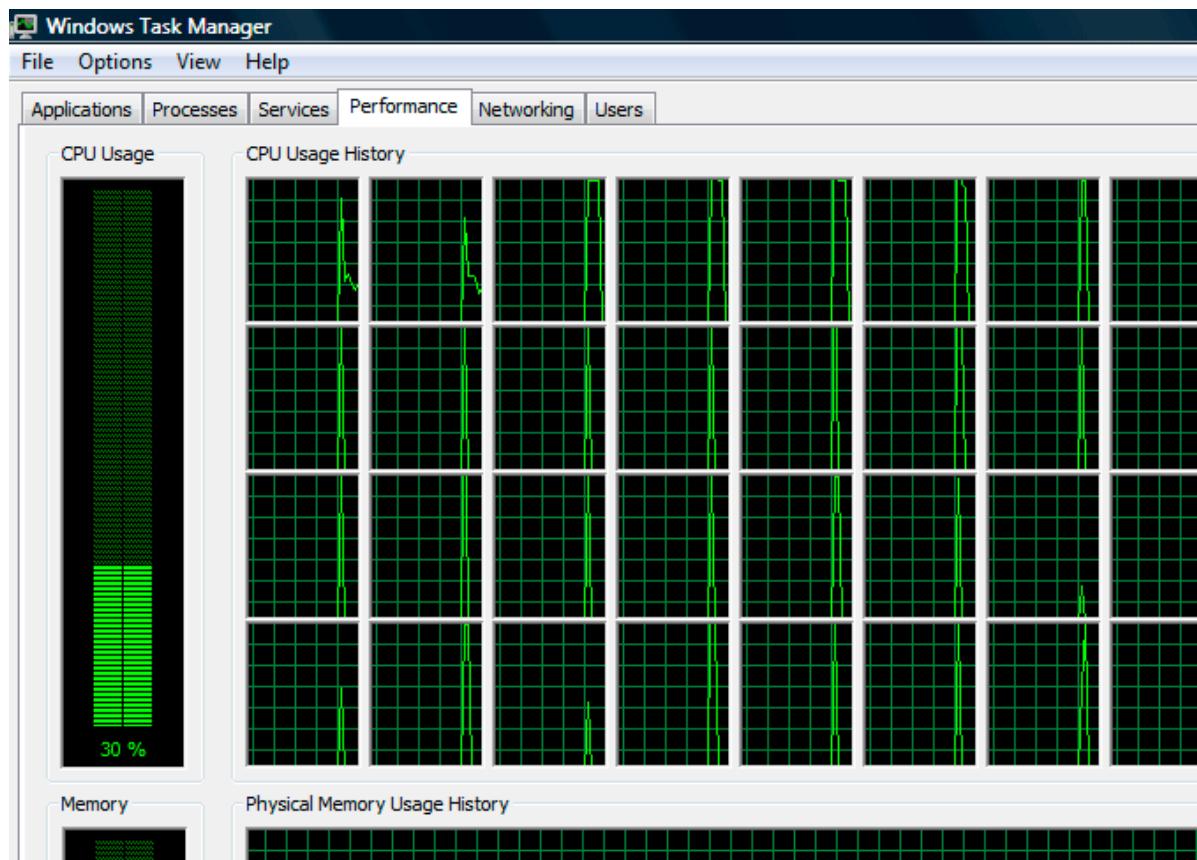


Figure 74.4: Fooled Windows Task Manager

The biggest number Task Manager is not crashes 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.

74.1 Using LEA to load values

Sometimes, LEA is used in taskmgr.exe instead of MOV to set the first argument of NtQuerySystemInformation():

Listing 74.2: 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

```

```
...
    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
```

It's hard to say why, but it is what [MSVC](#) often does. Maybe this is some kind of optimization and LEA works faster or better than loading values using MOV?

Another example of such thing is: [64.5.1 on page 685](#).

Chapter 75

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>. Here is how it looks:

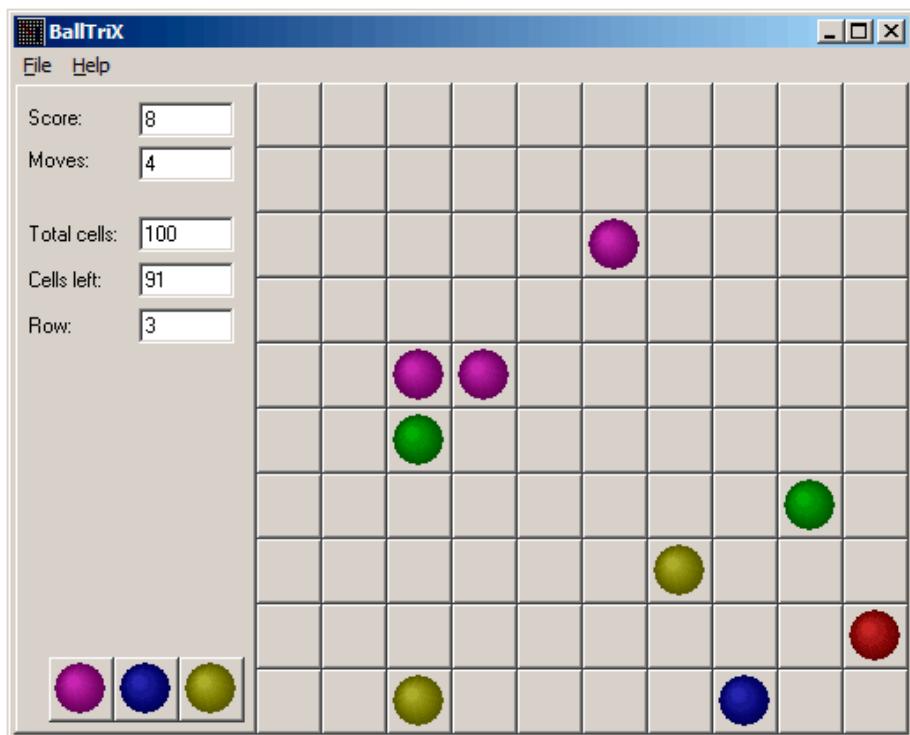


Figure 75.1: How this game looks usually

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:

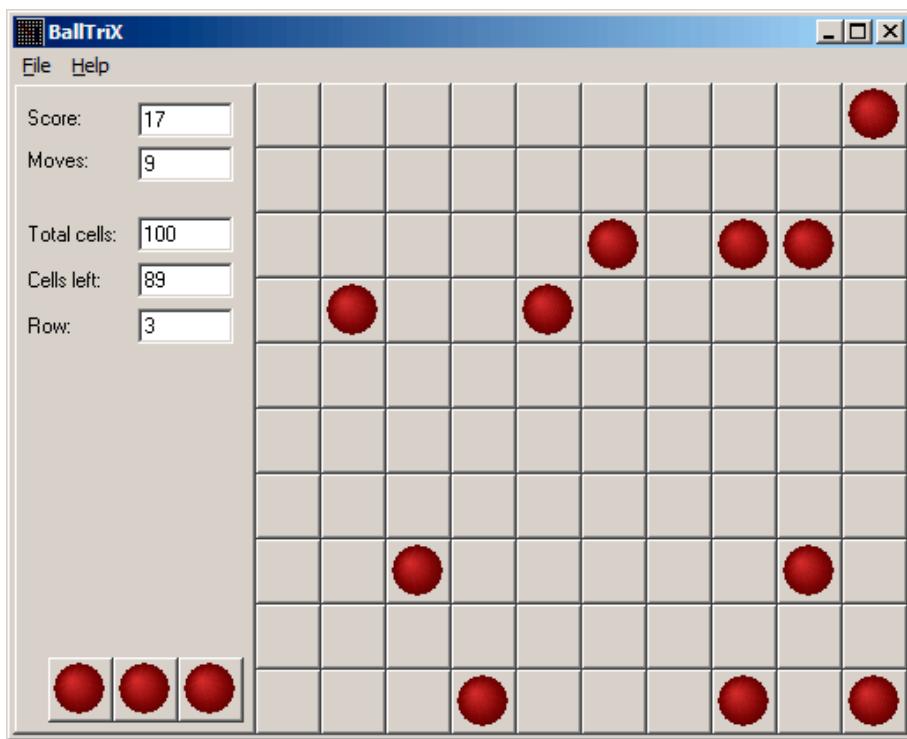


Figure 75.2: Practical joke works

Oh yes, it works¹.

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.

¹Author of this book once did this as a joke for his coworkers with the hope that they would stop playing. They didn't.

Chapter 76

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                   proc near             ; StartGame()+61
.text:01003940 arg_0           = dword ptr  4
.text:01003940                   call    ds:_imp__rand
.text:01003940 cdq
.text:01003946 idiv   [esp+arg_0]
.text:01003947 mov    eax, edx
.text:0100394B retn   4
.text:0100394D endp
.text:0100394D _Rnd@4
```

[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 run 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 10 0F 0F 0F 0F 0F
01005350	0F
01005360	10 0F 10 0F 0F 0F 0F 0F
01005370	0F
01005380	10 0F 10 0F 0F 0F 0F 0F
01005390	0F
010053A0	10 0F 0F 0F 0F 0F 0F 0F 8F 0F 10 0F 0F 0F 0F 0F 0F
010053B0	0F
010053C0	10 0F 10 0F 0F 0F 0F 0F
010053D0	0F
010053E0	10 0F 10 0F 0F 0F 0F 0F
010053F0	0F
01005400	10 0F 0F 8F 0F 0F 8F 0F 0F 0F 10 0F 0F 0F 0F 0F 0F
01005410	0F
01005420	10 8F 0F 0F 8F 0F 0F 0F 0F 0F 10 0F 0F 0F 0F 0F 0F
01005430	0F
01005440	10 8F 0F 0F 0F 0F 8F 0F 0F 8F 10 0F 0F 0F 0F 0F 0F
01005450	0F
01005460	10 0F 0F 0F 0F 8F 0F 0F 0F 8F 10 0F 0F 0F 0F 0F 0F
01005470	0F
01005480	10 10 10 10 10 10 10 10 10 10 10 10 0F 0F 0F 0F 0F
01005490	0F
010054A0	0F
010054B0	0F
010054C0	0F

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 click 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 76.1: 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 OF OF OF OF OF
01005350 OF OF
line #1:
01005360 10 OF OF OF OF OF OF OF 10 OF OF OF OF OF OF OF
01005370 OF OF
line #2:
01005380 10 OF OF OF OF OF OF OF 10 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
010053B0 OF OF
line #4:
010053C0 10 OF OF OF OF OF OF OF 10 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
010053F0 OF OF
line #6:
01005400 10 OF OF[8F]OF OF OF[8F]OF 10 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
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[8F]10 OF OF OF OF OF OF
01005470 OF OF
border:
01005480 10 10 10 10 10 10 10 10 10 10 10 OF OF 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 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:

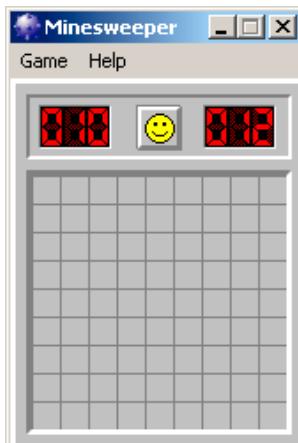


Figure 76.2: All mines are removed in debugger

We can also move all of them to the first line:

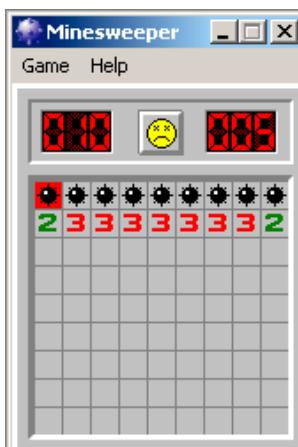


Figure 76.3: Mines set in debugger

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);
```

```

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.

76.1 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. Hint: [G.5.1 on page 986](#).

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 77

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: [34 on page 470](#)), that converted a 64-bit value to another and we need to try to reverse its flow back.

77.1 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;
    rdx=0x5D7E0D1F2E0F1F84;
```

```

    rax=rax;
    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;
    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 ([41 on page 501](#)). Indeed, let's calculate the divider in Wolfram Mathematica:

Listing 77.1: 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=_lrotl(rax, rax&0xF); // rotate right
    rax^=0x388D76AEE8CB1500;
    rax=_lrotl(rax, rax&0xF); // rotate left
    r8=rax+0xD2E9EE7E83C4285B;

    rcx=r8-(r8/60)*60;
    rax=r8
    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=_lrol(rax, rax&0xF); // rotate left
    r8=rax+0xD2E9EE7E83C4285B;

    return _lrol (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=_lrol(v, v&0xF); // rotate left
    v+=C3;
    v=_lrol(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.

77.2 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
5 C3=0xD2E9EE7E83C4285B
6
7 inp, i1, i2, i3, i4, i5, i6, outp = BitVecs('inp i1 i2 i3 i4 i5 i6 outp', 64)
```

¹<http://go.yurichev.com/17314>

```

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)
18
19 s.add(inp!=0x12EE577B63E80B73)
20
21 print s.check()

```

```

22 m=s.model()
23 print m
24 print (" inp=0x%X" % m[inp].as_long())
25 print ("outp=0x%X" % m[outp].as_long())

```

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:

```

1364123924608584563
1234567890
9223372038089343698
4611686019661955794

```

```

13835058056516731602
3096040143925676201
12319412180780452009
7707726162353064105
16931098199207839913
1906652839273745429
11130024876128521237
15741710894555909141
6518338857701133333
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
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 78

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](#)].

78.1 Example #1: MacOS Classic and PowerPC

Here is an example of a program for MacOS Classic¹, 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 ([15.1.1 on page 195](#)), 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
seg000:00101B40
seg000:00101B40 7C 08 02 A6      mflr    %r0
```

¹pre-UNIX MacOS

```

seg000:00101B44 90 01 00 08      stw    %r0, arg_8(%sp)
seg000:00101B48 94 21 FF C0      stwu   %sp, -0x40(%sp)
seg000:00101B4C 48 01 6B 39      bl     check2
seg000:00101B50 60 00 00 00      nop
seg000:00101B54 80 01 00 48      lwz    %r0, 0x40+arg_8(%sp)
seg000:00101B58 38 21 00 40      addi   %sp, %sp, 0x40
seg000:00101B5C 7C 08 03 A6      mtlr   %r0
seg000:00101B60 4E 80 00 20      blr
seg000:00101B60                 # 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     .RBEGINNEXT
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     .RBEGINFIRST
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
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

```

²(PowerPC) Branch to Link Register

```

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? ([68.2.7 on page 707](#))), 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           .using dword_24B704, %r30
seg000:00118750 93 A1 FF F4   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)
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      .RBREAD
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
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
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      .RBERREAD
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
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
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
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      .RBERREAD
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
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
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
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      .RBERREAD
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
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
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
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          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     .RBREAD
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 `.RBREAD()`. 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 `.RBREAD()` with one of these values: 0, 1, 8, 0xA, 0xB, 0xC, 0xD, 4, 5. Probably a memory address or something like that?

Yes, indeed, by googling these function names it is easy to find the Sentinel Eve3 dongle manual!

Perhaps, we don't even need to learn any other PowerPC instructions: all this function does is just call `.RBREAD()`, 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 [[IBMOO](#)].

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.

78.2 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
.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      loc_22B48: ; CODE XREF: SSQC+79j
.text:00022B48          mov    edx, [edi]
.text:00022B4A      test   edx, edx
.text:00022B4C      jle    short loc_22B57
.text:00022B4E      push   edx           ; int
.text:00022B4F      call   _close
.text:00022B54      add    esp, 4
.text:00022B57      loc_22B57: ; CODE XREF: SSQC+94j
.text:00022B57          push   2             ; int
.text:00022B59      lea    eax, [ebp+var_44]
.text:00022B5C      push   eax           ; char *
.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      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      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      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      loc_22B94: ; CODE XREF: SSQC+3Cj
.text:00022B94          mov    al, [esi]
.text:00022B96      pop    ebx
.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
.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:

```
.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 db 0Kr ; 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
.text:0000D67B loc_D67B: ; CODE XREF: sys_info+106j
    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
.text:0000D6C0 loc_D6C0: ; CODE XREF: sys_info+C1j
    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
.text:0000D6D1 loc_D6D1: ; CODE XREF: sys_info+98j
    ; sys_info+B6j
    mov edx, [ebp+var_8]
.text:0000D6D4 inc edx
.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
    ; 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: [34 on page 470](#).

But let's get back to the program. So the program can only check the presence or absence of a connected dongle. No other information can be written to such dongle, as it has no memory. The two-character codes are commands (we can see how the commands are handled in the SSQC() function) and all other strings are hashed inside the dongle, being transformed into a 16-bit number. The algorithm was secret, so it was not possible to write a driver replacement or to remake the dongle hardware that would emulate it perfectly. However, it is always possible to intercept all accesses to it and to find what constants the hash function results are compared to. But we need to say that it is possible to build a robust software copy protection scheme based on secret cryptographic hash-function: let it encrypt/decrypt the data files your software uses.

But let's get back to the code.

Codes 51/52/53 are used for LPT printer port selection. 3x/4x are used for “family” selection (that's how Sentinel Pro dongles are differentiated from each other: more than one dongle can be connected to a LPT port).

The only non-2-character string passed to the hashing function is "0123456789". Then, the result is compared against the set of valid results. If it is correct, 0xC or 0xB is to be written into the global variable `ctl_model`.

Another text string that gets passed is "PRESS ANY KEY TO CONTINUE:", but the result is not checked. Hard to say why, probably by mistake ³.

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
.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
```

³What a strange feeling: to find bugs in such ancient software.

.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:    xor    eax, eax           ; CODE XREF: err_warn+28j
.text:0000A453             mov    al, [edx+edi]
.text:0000A455             xor    eax, esi
.text:0000A458             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:    xor    eax, eax           ; 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:    xor    eax, eax           ; 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
.text:0000A496             pop    esi
.text:0000A497             pop    edi
.text:0000A498             mov    esp, ebp
.text:0000A49A             pop    ebp
.text:0000A49B             retn
.text:0000A49C
.text:0000A49C loc_A49C:    xor    eax, eax           ; 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:0000A4A8             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 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, 0FFFFFFF5h
.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
...
; 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.

78.2.1 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 78.1: Decryption function

```

.text:0000A44D          mov     esi, [ebp+arg_C] ; key
.text:0000A450          mov     edx, [ebp+arg_4] ; string
.text:0000A453 loc_A453:
.text:0000A453          xor     eax, eax
.text:0000A455          mov     al, [edx+edi] ; load encrypted byte
.text:0000A458          xor     eax, esi      ; decrypt it
.text:0000A45A          add     esi, 3       ; change key for the next byte
.text:0000A45D          inc     edi
.text:0000A45E          cmp     edi, ecx
.text:0000A460          mov     [ebp+edi+var_55], al
.text:0000A464          jl    short loc_A453

```

As we can see, not just string is supplied to the decryption function, but also the key:

```

.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
.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 [xor](#)ing: 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 78.2: 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 78.3: 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]]]

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 78.4: 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/c1Hii
key= 9 value= Lm>ugasLkvw&fgpgag^uvcrwml.`mwhj
key= 10 value= 01!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 xoring encryption, the very same function can be used to encrypt messages. If needed, we can encrypt our own messages, and patch the program by inserting them.

78.3 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
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
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 68 C3 00      loc_35A2C: ; CODE XREF: sent_pro+84j
                            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 0E              loc_35A37: ; CODE XREF: sent_pro+89j
                            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  C4 5E 06      loc_35A4F: ; CODE XREF: sent_pro+6Cj
                            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
seg030:0125 8A 5E FD      loc_35A85: ; CODE XREF: sent_pro+DAj
                            mov    bl, [bp+var_3]
seg030:0128
seg030:0128  F6 C1 80      loc_35A88: ; CODE XREF: sent_pro+E2j
                            test  cl, 80h
seg030:012B 74 03          jz    short loc_35A90
seg030:012D 80 E3 7F      and    bl, 7Fh
seg030:0130
seg030:0130 8B 16 82 E7      loc_35A90: ; CODE XREF: sent_pro+EAj
                            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      struct ; (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', OFFADh>
dseg:3E36 63 61 74 00+  struct_0 <'cat', OFF5Fh>
dseg:3E51 70 61 70 65+  struct_0 <'paper', OFFDFh>
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', OFFAEh>
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
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

```

⁴If we consider Centronics only. The following IEEE 1284 standard allows the transfer of information from the printer.

```

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

```

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 aTrpcRequiresA ; "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
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: [94 on page 901](#).

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 79

“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
.text:00541000
.text:00541000 arg_0        = dword ptr  4
.text:00541000 arg_4        = dword ptr  8
.text:00541000 arg_8        = dword ptr  0Ch
.text:00541000 arg_C        = byte ptr  10h
.text:00541000
.text:00541000             mov    al, [esp+arg_C]
.text:00541004             mov    ecx, [esp+arg_8]
.text:00541008             push   esi
.text:00541009             mov    esi, [esp+4+arg_0]
.text:0054100D             test   al, al
.text:0054100F             mov    eax, [esp+4+arg_4]
.text:00541013             mov    dl, 1
.text:00541015             jz    short loc_54102B
.text:00541017             shl    dl, cl
.text:00541019             mov    cl, cube64[eax+esi*8]
.text:00541020             or     cl, dl
.text:00541022             mov    cube64[eax+esi*8], cl
.text:00541029             pop   esi
.text:0054102A             retn 
.text:0054102B loc_54102B:          ; 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
.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 rotate1         proc near           ; CODE XREF: rotate_all_with_password+8E
.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 first_loop1_begin:      ; CODE XREF: rotate1+2E
.text:00541081             xor    esi, esi      ; ESI is loop2 counter
.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:    xor    esi, esi      ; CODE XREF: rotate2+2E
.text:005410F1
.text:005410F3 loc_5410F3:    xor    esi, esi      ; 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:    xor    esi, esi      ; CODE XREF: rotate2+57
.text:00541119
.text:0054111B loc_54111B:    xor    esi, esi      ; 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: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    __strup
.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         jl    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 loc_541348:          ; 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: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
.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, 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

```

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
```

²malloc() + memset() could be replaced by calloc()

```
.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)
```

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, 0FFFFFFF9h
.text:00541493     lea    esi, [ebx+7]
.text:00541496     push   eax          ; Src
.text:00541497     push   ebp          ; int
.text:00541498     push   esi          ; int
.text:00541499     call   decrypt
.text:0054149E     mov    ecx, [esp+1Ch+arg_4]
.text: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 dwds 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
.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
.text:005411EA skip_subtracting: ; CODE XREF: rotate_all_with_password+35
```

This is actually division via multiplication. You can read more about it in the “Division by 9” section ([41 on page 501](#)).

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
.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.

<code>.text:00541020</code>	<code>or</code>	<code>cl, dl</code>
-----------------------------	-----------------	---------------------

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*8*8, where each element is a bit, `get_bit()` and `set_bit()` take just the coordinates of a bit as input.

The `rotate1/2/3` functions are in fact rotating all bits in a specific plane. These three functions are one for each cube side and the `v` argument sets the plane in the range of 0..7.

Maybe, the algorithm's author was thinking of a 8*8*8 Rubik's cube 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
    {
        memcpy (cube, buf+i, 8*8);
        rotate_all (p, 3);
        memcpy (buf+i, cube, 8*8);
        i+=64;
    }
    while (i<sz);
```

³[wikipedia](#)

```
    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)
        return true;
    return false;
};

void rotate_f (int row)
{
    bool tmp[8][8];
    int x, y;
```

⁴MSDN

```

for (x=0; x<8; x++)
    for (y=0; y<8; y++)
        tmp[x][y]=get_bit (x, y, row);

    for (x=0; x<8; x++)
        for (y=0; y<8; y++)
            set_bit (y, 7-x, row, tmp[x][y]);
};

void rotate_t (int row)
{
    bool tmp[8][8];
    int y, z;

    for (y=0; y<8; y++)
        for (z=0; z<8; z++)
            tmp[y][z]=get_bit (row, y, z);

    for (y=0; y<8; y++)
        for (z=0; z<8; z++)
            set_bit (row, z, 7-y, tmp[y][z]);
};

void rotate_l (int row)
{
    bool tmp[8][8];
    int x, z;

    for (x=0; x<8; x++)
        for (z=0; z<8; z++)
            tmp[x][z]=get_bit (x, row, z);

    for (x=0; x<8; x++)
        for (z=0; z<8; z++)
            set_bit (7-z, row, x, tmp[x][z]);
};

void rotate_all (char *pwd, int v)
{
    char *p=pwd;

    while (*p)
    {
        char c=*p;
        int q;

        c=tolower (c);

        if (c>='a' && c<='z')
        {
            q=c-'a';
            if (q>24)
                q-=24;

            int quotient=q/3;
            int remainder=q % 3;

            switch (remainder)
            {
                case 0: for (int i=0; i<v; i++) rotate_f (quotient); break;
                case 1: for (int i=0; i<v; i++) rotate_t (quotient); break;
                case 2: for (int i=0; i<v; i++) rotate_l (quotient); break;
            };
        };

        p++;
    };
}

```

```

void crypt (BYTE *buf, int sz, char *pw)
{
    int i=0;

    do
    {
        memcpy (cube, buf+i, 8*8);
        rotate_all (pw, 1);
        memcpy (buf+i, cube, 8*8);
        i+=64;
    }
    while (i<sz);
};

void decrypt (BYTE *buf, int sz, char *pw)
{
    char *p=strdup (pw);
    strrev (p);
    int i=0;

    do
    {
        memcpy (cube, buf+i, 8*8);
        rotate_all (p, 3);
        memcpy (buf+i, cube, 8*8);
        i+=64;
    }
    while (i<sz);

    free (p);
};

void crypt_file(char *fin, char* fout, char *pw)
{
    FILE *f;
    int flen, flen_aligned;
    BYTE *buf;

    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&0xFFFFFFFFC0)+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 80

SAP

80.1 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:

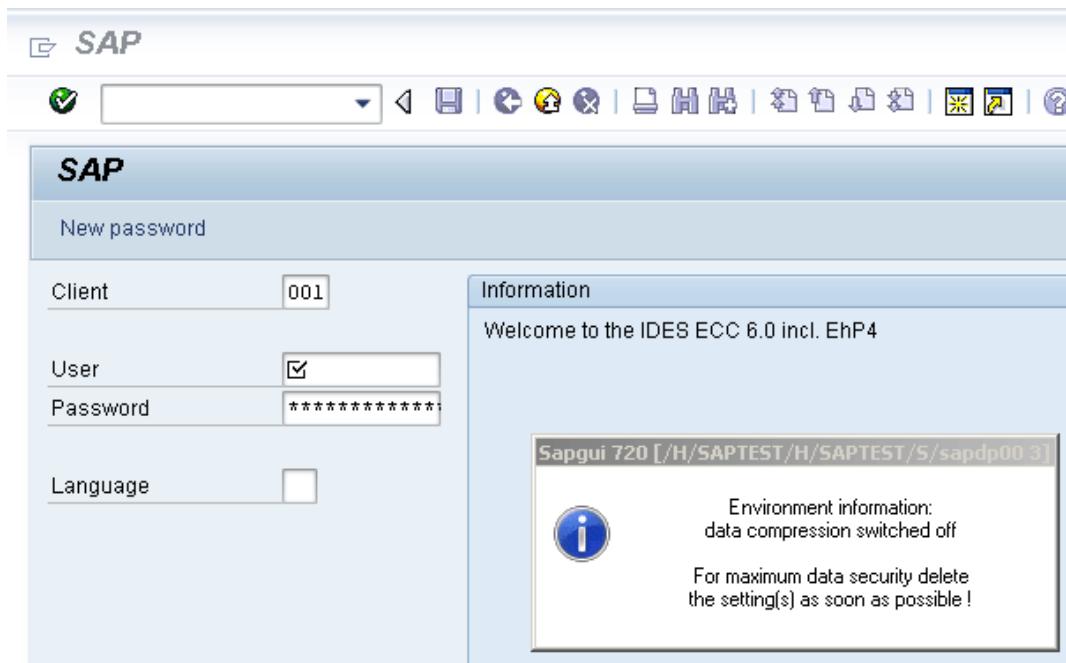


Figure 80.1: Screenshot

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.

We see the following fragment of code (all file offsets are valid for SAPGUI 720 win32, SAPguilib.dll file version 7200,1,0,9009):

¹SAP GUI client

²<http://go.yurichev.com/17221>

³blog.yurichev.com

⁴<http://go.yurichev.com/17347>

```

.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:
.text:64413F68         cmp    [ebp+DstSize], 0
.text:64413F6C         jnz    short loc_64413F72

```

⁵standard C library function that converts the digits in a string to a number

```

.text:64413F6E          xor    eax, eax
.text:64413F70          jmp    short loc_64413FBC
.text:64413F72
.text:64413F72 loc_64413F72:
.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
.text:64413FB3 loc_64413FB3:
.text:64413FB3          mov    ecx, [ebp+arg_4]

; demangled name: const char* ATL::CSimpleStringT::operator PCXSTR
.text:64413FB6          call   ds:mfc90_910
.text:64413FBC
.text:64413FBC loc_64413FBC:
.text: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:

⁶MSDN

⁷Standard C library returning environment variable

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
.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
.text:64404FD6 loc_64404FD6:
.text:64404FD6                 cmp    [esi+38h], ebx
.text:64404FD9                 jbe    short loc_64404FF1
.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          cdq
.text:6440506B          sub    eax, edx
.text:6440506D          sar    eax, 1
.text:6440506F          mov    [ebp+var_34], eax
.text:64405072
.text:64405072 loc_64405072:
.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
.text:64405108 loc_64405108:
.text:64405108          push   [ebp+var_10]     ; hDC
.text:6440510B          push   0              ; hWnd
.text:6440510D          call   ds:ReleaseDC
.text:64405113
.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 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          add    esp, 4Ch
.text:64405188 loc_64405188:
.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` ([51.1.1 on page 556](#))-type of function). In our case, the object obviously has class type of `CDwsGui`. Depending on the option turned on in the object, a specific message part is to be concatenated with the resulting message.

If the value at address `this+0x3D` is not zero, the compression is off:

```
.text:64405007 loc_64405007:
.text:64405007          cmp     byte ptr [esi+3Dh], 0
.text:6440500B          jz      short bypass
.text:6440500D          push   offset aDataCompressio ; "data compression switched off\n"
    ↳ n"
.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:
.text:6440501D
```

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
```

```
.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.

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.

80.2 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.

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!

⁸<http://go.yurichev.com/17312>

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 stmntnum
  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
j1    short loc_1400375DA
call   DpLock
lea     rcx, aDpxxtool4_c ; "dpxxtool4.c"
mov     edx, 4Eh           ; line
call   CTrcSaveLocation
mov     r8, cs:func_48
mov     rcx, cs:hd1         ; hd1
```

⁹<http://go.yurichev.com/17038>

¹⁰More about trace level: <http://go.yurichev.com/17039>

```

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 *chckpass()* function – one of the password checking functions.

First, we would like to make sure that we are at the correct point:

Run [tracer](#):

```
tracer64.exe -a:disp+work.exe bpf=disp+work.exe!chckpass, args:3, unicode
```

```
PID=2236|TID=2248|(0) disp+work.exe!chckpass (0x202c770, L"Brewered1
↳      ", 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()* -> *dchkusr()* -> *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
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 81

Oracle RDBMS

81.1 V\$VERSION table in the Oracle RDBMS

Oracle RDBMS 11.2 is a huge program, its main module `oracle.exe` contains 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 be found in the `kqfviw` table stored in the same file, `kqf.o`:

Listing 81.1: `kqf.o`

.rodata:0800C4A0 kqfviw	dd 0Bh	; DATA XREF: kqfchk:loc_8003A6D
		; 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 0FFF1CBh	
.rodata:0800C4C8	dd 3	
.rodata:0800C4CC	dd 0	
.rodata:0800C4D0	dd 0Ah	
.rodata:0800C4D4	dd offset _2__STRING_10104_0	; "V\$WAITSTAT"
.rodata:0800C4D8	dd 4	
.rodata:0800C4DC	dd offset _2__STRING_10103_0	; "NULL"
.rodata:0800C4E0	dd 3	
.rodata:0800C4E4	dd 0	
.rodata:0800C4E8	dd 4Eh	

```
.rodata:0800C4EC      dd 3
.rodata:0800C4F0      dd 0
.rodata:0800C4F4      dd 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 `kqfviv` 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 `kqfviv` 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 `kqfviv` 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
-----
VIEW_DEFINITION
-----

GV$VERSION
select inst_id, banner from x$version
```

¹Draft ANSI C Standard (ANSI X3J11/88-090) (May 13, 1988) (yurichev.com)

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 81.2: `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 81.3: `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 81.4: 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 81.5: Result of oracle tables

```
kqfviw_element.viewname: [GV$VERSION] ?: 0x3 0x26 0x2 0xfffffc192 0x1
kqfvip_element.statement: [select inst_id, banner from x$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:

²yurichev.com

```
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 81.6: kqf.o

```
.rodata:0803CAC0      dd 9           ; element number 0x1f6
.rodata:0803CAC4      dd offset _2__STRING_13113_0 ; "X$VERSION"
.rodata:0803CAC8      dd 4
.rodata:0803CACC      dd offset _2__STRING_13114_0 ; "kqvt"
.rodata:0803CAD0      dd 4
.rodata:0803CAD4      dd 4
.rodata:0803CAD8      dd 0
.rodata:0803CADC      dd 4
.rodata:0803CAE0      dd 0Ch
.rodata:0803CAE4      dd 0FFFFC075h
.rodata:0803CAE8      dd 3
.rodata:0803CAEC      dd 0
.rodata:0803CAF0      dd 7
.rodata:0803CAF4      dd offset _2__STRING_13115_0 ; "X$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 0FFFFC09Dh
.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 81.7: kqf.o

```
.rodata:0808C360 kqvt_c_0      kqftap_param <4, offset _2__STRING_19_0, 917h, 0, 0, 0, 0, 4, 0, ↵
    ↴ 0>
.rodata:0808C360                      ; DATA XREF: .rodata:08042680
.rodata:0808C360                      ; "ADDR"
.rodata:0808C384      kqftap_param <4, offset _2__STRING_20_0, 0B02h, 0, 0, 0, 4, 0, ↵
    ↴ 0> ; "INDX"
.rodata:0808C3A8      kqftap_param <7, offset _2__STRING_21_0, 0B02h, 0, 0, 0, 4, 0, ↵
    ↴ 0> ; "INST_ID"
.rodata:0808C3CC      kqftap_param <6, offset _2__STRING_5017_0, 601h, 0, 0, 0, 50h, ↵
    ↴ 0, 0> ; "BANNER"
.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 81.8: kqf.o

```
.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 81.9: 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
    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
```

³yurichev.com

```

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, OFFh ; EDI=0xb200100
    push   edi          ; EDI=0
    mov    edi, [ebp+arg_18] ; [EBP+20h]=0
    push   eax          ; EAX=1
    mov    eax, ds:_imp_vsnban ; [597D6D8h]=0x65852100, "Oracle Database 11g" ↵
↳ Enterprise Edition Release %d.%d.%d.%d.%d %s"
    push   edx          ; EDX=0
    push   ecx          ; ECX=2
    push   ebx          ; EBX=0xb
    mov    ebx, [ebp+arg_8] ; [EBP+10h]=0xcdfe554
    push   eax          ; EAX=0x65852100, "Oracle Database 11g Enterprise Edition" ↵
↳ 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    __VIfreq_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" ↵
    "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
    ↳ 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   _kghfrf          ; 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 vsnstr, vsnnum, vsnban global variables. Calling sprintf().
String 2	Calling kkxvsn().
String 3	Calling lmxver().
String 4	Calling npinli(), nrtnsvrs().
String 5	Calling lxvers().

That's how the corresponding functions are called for determining each module's version.

81.2 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 81.10: Result of oracle tables

```
kqftab_element.name: [X$KSMLRU] ?: [ksmlr] 0x4 0x64 0x11 0xc 0xffffc0bb 0x5
kqftap_param.name=[ADDR] ?: 0x917 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INDX] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[INST_ID] ?: 0xb02 0x0 0x0 0x0 0x4 0x0 0x0
kqftap_param.name=[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=[KSMLRSSES] ?: 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 81.11: 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
.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)

⁴yurichev.com

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!

81.3 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
```

```
-----
```

```
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:

Listing 81.12: 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"
```

⁵<http://go.yurichev.com/17088>

```

push    [ebp+arg_8]
push    [ebp+arg_0]
call    kqfd_cfui_drain
add    esp, 14h
mov    esp, ebp
pop    ebp
retn
kqfd_DRN_ksutm_c endp

```

The `kqfd_DRN_ksutm_c()` function is mentioned in the `kqfd_tab_registry_0` table:

```

dd offset _2__STRING_62_0 ; "X$KSUTM"
dd offset kqfd_OPN_ksutm_c
dd offset kqfd_tabl_fetch
dd 0
dd 0
dd offset kqfd_DRN_ksutm_c

```

There is a function `ksugtm()` referenced here. Let's see what's in it (Linux x86):

Listing 81.13: `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
retn
ksugtm      endp

```

The code in the win32 version is almost the same.

Is this the function we are looking for? Let's see:

```
tracer -a:oracle.exe bpf=oracle.exe!_ksugtm,args:2,dump_args:0x4
```

Let's try again:

```

SQL> select * from V$TIMER;
HSECS
-----
27294929

SQL> select * from V$TIMER;
HSECS
-----
27295006

SQL> select * from V$TIMER;
HSECS
-----
27295167

```

Listing 81.14: `tracer` output

```

TID=2428|(0) oracle.exe!_ksugtm (0x0, 0xd76c5f0) (called from oracle.exe!__VInfreq_qerfxFetch\2
    ↳ +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\2
    ↳ +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\2
    ↳ +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
    mov     esp, ebp
    pop    ebp
    retn
slgcs      endp

```

(it is just a call to sltrgatime64() and division of its result by 10 ([41 on page 501](#)))

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 ([41 on page 501](#)).

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*.

⁶[MSDN](#)

⁷[yurichev.com](#)

Chapter 82

Handwritten assembly code

82.1 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=0FFEh, 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.

Essentially, all these instructions are here only to execute this code:

¹wikipedia

```
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 965](#).

Chapter 83

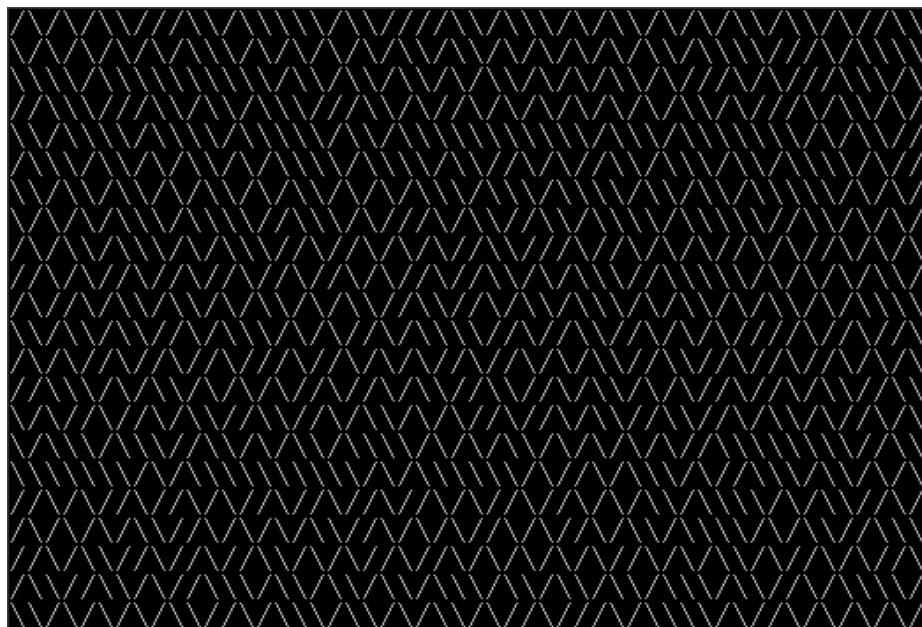
Demos

Demos (or demomaking) were an excellent exercise in mathematics, computer graphics programming and very tight x86 hand coding.

83.1 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.

83.1.1 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    ; push flags
; get random value from timer chip
0000000C: FA        cli       ; disable interrupts
0000000D: E643      out      043,al   ; write 0 to port 43h

```

¹<http://go.yurichev.com/17305>

```
; 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     00000022
; 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 [BCD](#)² 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.

83.1.2 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    00000013
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
```

83.1.3 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.

Another idea to minimize the code is to use the INT 29h DOS syscall, which just prints the character stored in the AL register.

²Binary-coded decimal

³<http://go.yurichev.com/17305>

That is what Peter Ferrie and Andrey “herm1t” Baranovich did (11 and 10 bytes)⁴:

Listing 83.1: Andrey “herm1t” Baranovich: 11 bytes

```
00000000: B05C      mov     al,05C    ; '\'
; read AL byte from random place of memory
00000002: AE        scasb
; PF = parity(AL - random_memory_byte) = parity(5Ch - random_memory_byte)
00000003: 7A02      jp      00000007
00000005: B02F      mov     al,02F    ; '/'
00000007: CD29      int     029      ; output AL to screen
00000009: EBF5      jmp     00000000 ; loop endlessly
```

SCASB also uses the value in the AL register, it subtracts a random memory byte's value from the 5Ch value in AL. JP is a rare instruction, here it is 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 83.2: Peter Ferrie: 10 bytes

```
; AL is random at this point
00000000: AE        scasb
; CF is set according to 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.

83.1.4 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.

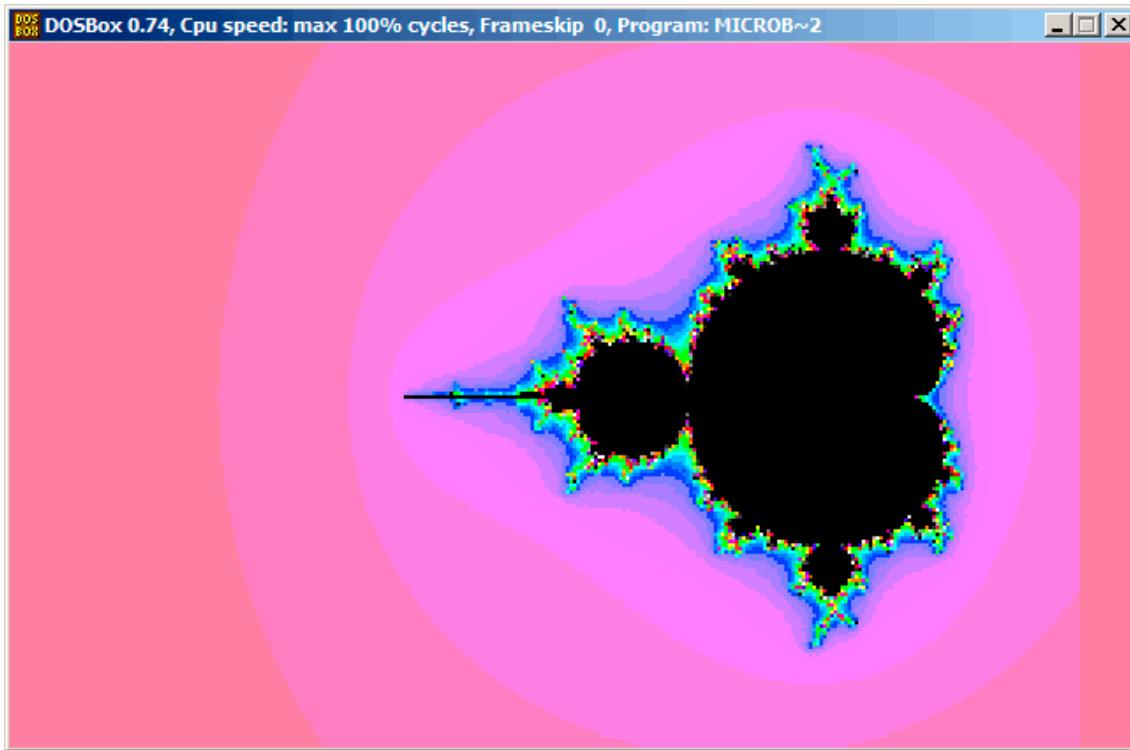
⁴<http://go.yurichev.com/17087>

83.2 Mandelbrot set

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](#),

83.2.1 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 83.3: For complex numbers

```
def check_if_is_in_set(P):
    P_start=P
    iterations=0

    while True:
        if (P>bounds):
            break
        P=P^2+P_start
```

```

        if iterations > max_iterations:
            break
        iterations++

    return iterations

# black-white
for each point on screen P:
    if check_if_is_in_set (P) < max_iterations:
        draw point

# 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 83.4: 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 symbol⁷:

```

using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;

namespace Mnoj
{
    class Program
    {
        static void Main(string[] args)
        {
            double realCoord, imagCoord;
            double realTemp, imagTemp, realTemp2, arg;
            int iterations;

```

⁶wikipedia

⁷Here is also the executable file: [beginners.re](#)

```
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 means that this point was wandering for 40 iterations but never got off limits. A number n less than 40 means that point remained inside the bounds only for n iterations, then it went outside them.

There is a cool demo available at <http://go.yurichev.com/17309>, which shows visually how the point moves on the plane at each iteration for some specific point. Here are two screenshots.

First, we've clicked inside the yellow area and saw that the trajectory (green line) eventually swirls at some point inside:

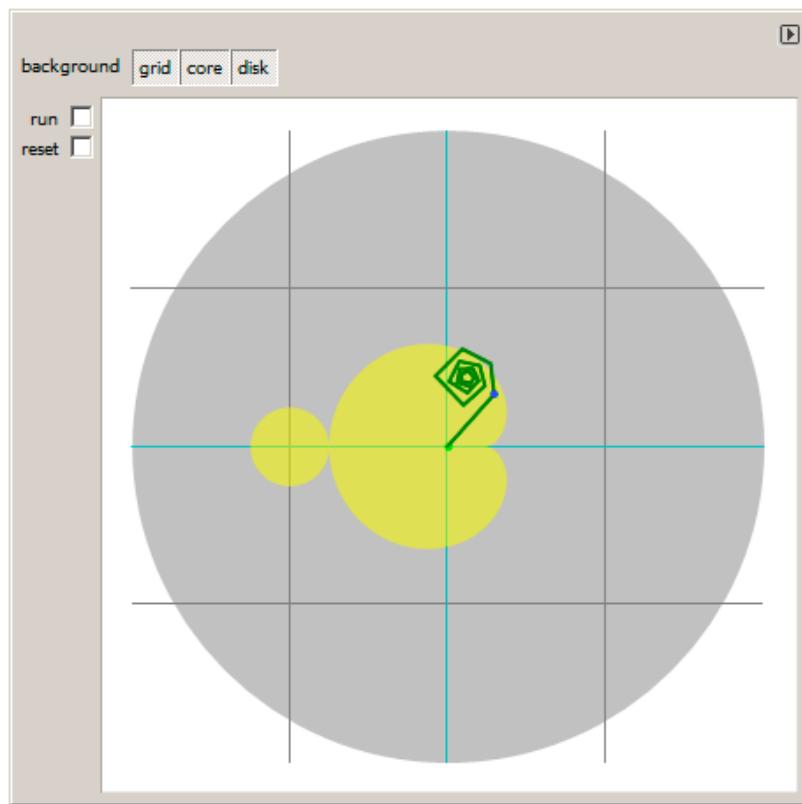


Figure 83.1: Click inside yellow area

This implies that the point we've clicked belongs to the Mandelbrot set.

Then we've clicked outside the yellow area and saw a much more chaotic point movement, which quickly went off bounds:

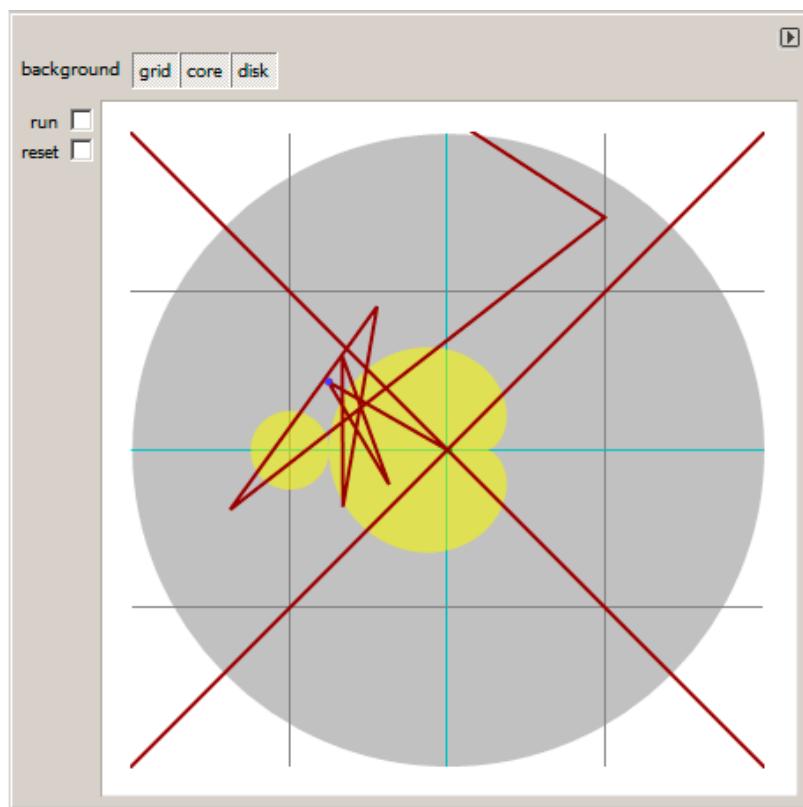


Figure 83.2: Click outside yellow area

This mean the point not belongs to Mandelbrot set.

Another good demo is available here: <http://go.yurichev.com/17310>.

83.2.2 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 83.5: 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 0xFFFFE
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 than 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

```

```

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: [94 on page 901](#).

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 no crash can happen. 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 places where the points are in the Mandelbrot set. The palette can be initialized at th 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.

83.2.3 My “fixed” version

Listing 83.6: 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
47
48 sar bx,6
49 add bx,dx
50 sar si,6
51 add si,ax
52

```

⁸More information about initial register values: <http://go.yurichev.com/17004>

```

53    loop MandelLoop
54
55    MandelBreak:
56    xchg ax,cx
57    stosb
58    cmp di, 0FA00h
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.

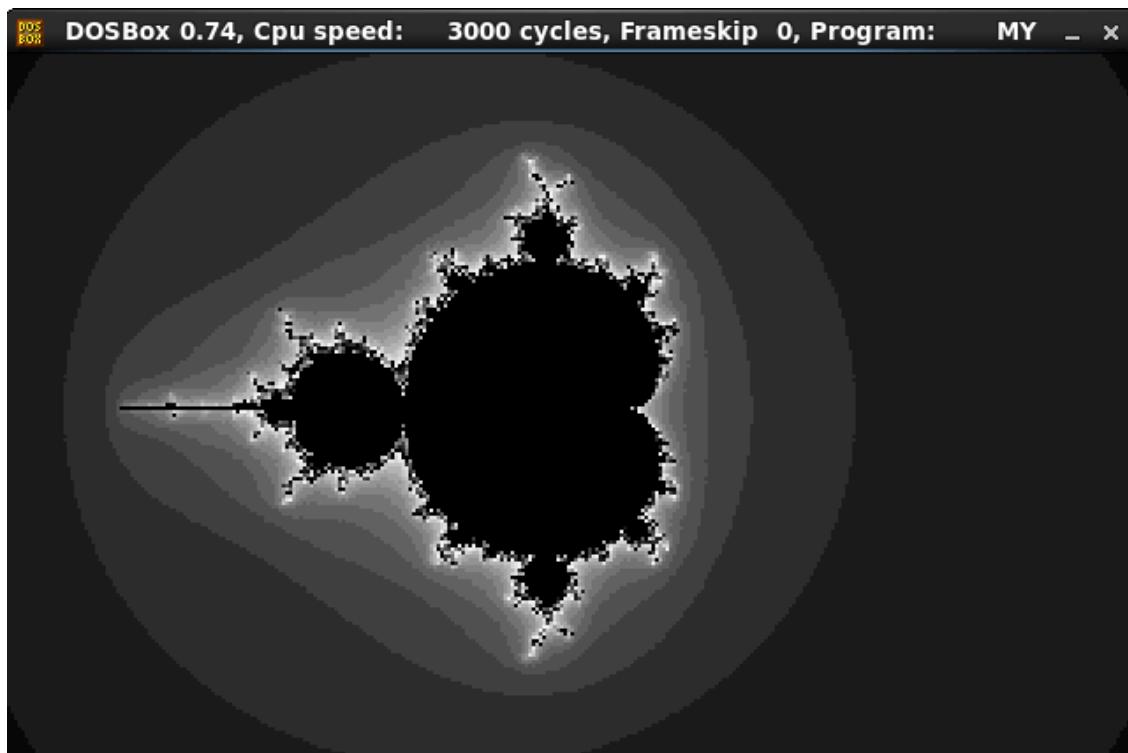


Figure 83.3: My “fixed” version

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 84

Primitive XOR-encryption

84.1 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 terminal window titled "view X86.NG - Far 2.0.1807 x64 Administrator". The file path is "U:\retrocomputing\MS-DOS\norton guide\X86.NG". The file size is 866 and the number of lines is 372131. The content is displayed in two columns. The left column shows memory addresses starting from 0000000170. The right column shows the hex dump of the file. A large number of '1A' bytes are present, each represented by an arrow pointing to the right, indicating they are encrypted. Some other characters like 'E9', 'F2', '9A', etc., are also visible.

Address	Hex Dump
0000000170:	00 00 00 00 00 00 00 00
0000000180:	02 1A 1A 1A 1A 1A 1A 1A
0000000190:	1A 1A 1A 1A FF 18 1A 1A
00000001A0:	69 77 19 1A B9 6B 19 1A
00000001B0:	1A 1A 1A 1A 7E 1A 1A 1A
00000001C0:	1A 1A 1A 1A 9E 1A 1A 1A
00000001D0:	1A 1A 1A 1A BA 1A 1A 1A
00000001E0:	1A 1A 1A 1A 59 4A 4F 1A
00000001F0:	73 75 74 3A 69 7F 6E 1A
0000000200:	69 1A 4A 68 75 6E 7F 79
0000000210:	73 6C 73 76 7F 7D 7F 1A
0000000220:	74 69 1A 5B 7E 7E 68 7F
0000000230:	7E 7F 69 1A 55 6A 79 75
0000000240:	1A 19 1A 12 1A 1A 1A 1A
0000000250:	1A 1A 1A 1A 1A 1A 1A 21
0000000260:	1A 1A 1A 1A 1A 1A 1A 2E
0000000270:	1A 1A 1A 1A 1A 1A 1A 5C
0000000280:	6F 79 6E 73 75 74 3A 69
0000000290:	6E 7F 68 69 36 3A 7E 7B
00000002A0:	1A 1A 18 1A 33 1A 18 1A
00000002B0:	1A 1A 1A 1A 1A 1A 1A 1A
00000002C0:	02 1A 1A 1A 1A 1A 1A 1A
00000002D0:	57 57 42 1A 53 74 69 6E
00000002E0:	69 7F 6E 1A 1A 1A 1A 8B
00000002F0:	E5 E5 E5 1A 1A 1A 1A 1A
0000000300:	19 8A 0C 1A 1A 2E 19 62
0000000310:	1A 63 19 72 3A 1A 1A 84
0000000320:	33 1A 1A A7 19 7F 37 1A

Figure 84.1: 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

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:

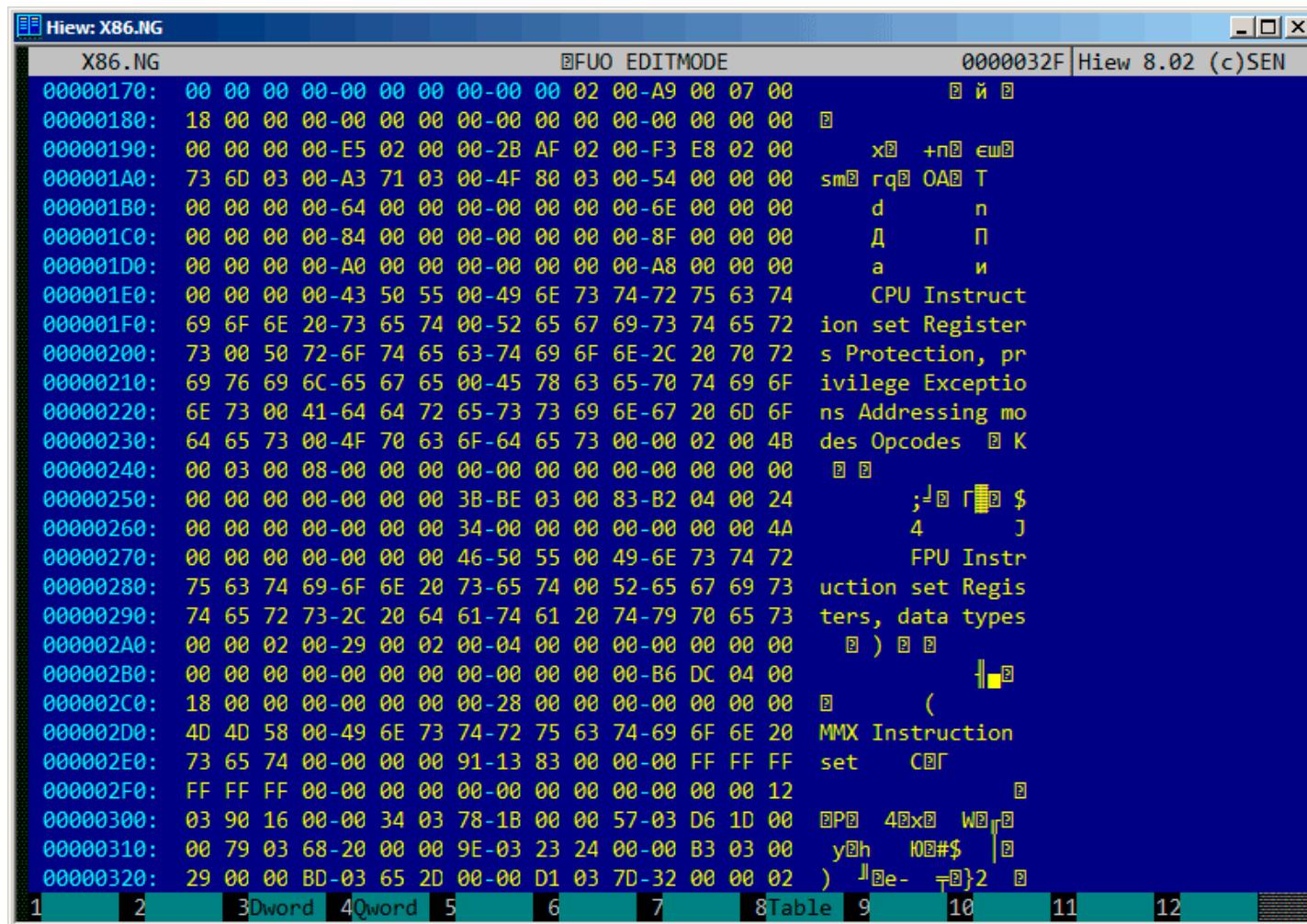


Figure 84.2: Hiew XORing with 0x1A

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>.

84.1.1 Entropy

A very important property of such primitive encryption systems is that information entropy of the encrypted/decrypted block is the same. Here is my analyze in Wolfram Mathematica 10.

Listing 84.1: 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"];
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 file, get entropy of it, decrypt it, save it, get entropy again (the same!). Mathematica also offers some well-known English language texts for analyze. So we also get entropy of Shakespeare's sonnets, and it is close to entropy of file we analyzed. The file we analyzed consting of English language sentences, which are close to language of Shakespeare. And XOR-ed bytewise English language text has the same entropy.

However, this is not to be true when the file is XOR-ed by 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 UNIX *ent* utility² uses base of 2. So we set base of 2 explicitly in Entropy command, so Mathematica gives the same results as *ent* utility.

²<http://www.fourmilab.ch/random/>

84.2 Simplest possible 4-byte XOR encryption

If longer pattern was used while XOR-encryption, for example, 4 byte pattern, it's easy to spot it as well. As example, here is beginning of kernel32.dll file (32-bit version from Windows Server 2008):

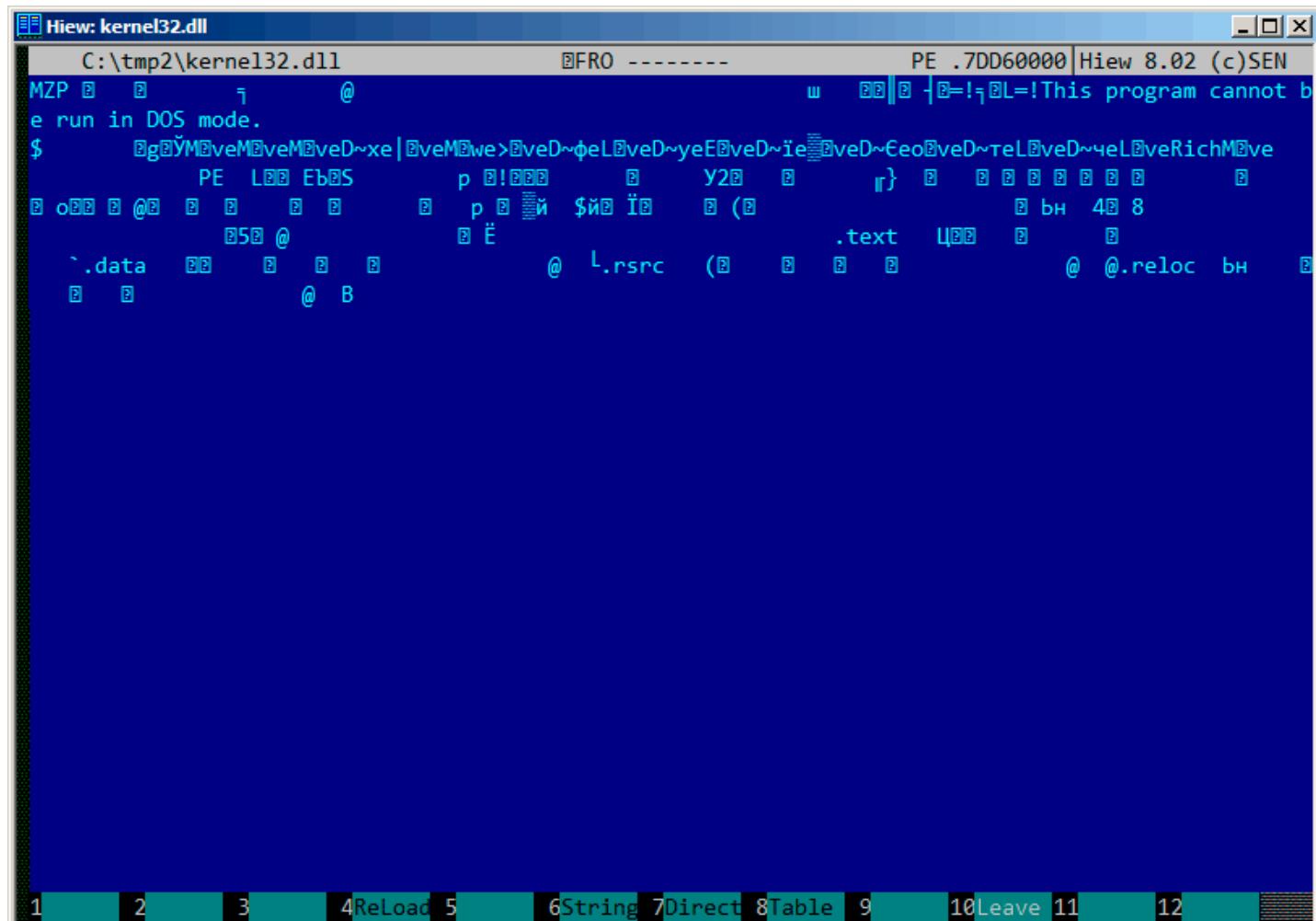


Figure 84.3: Original file

Here is it “encrypted” by 4-byte key:

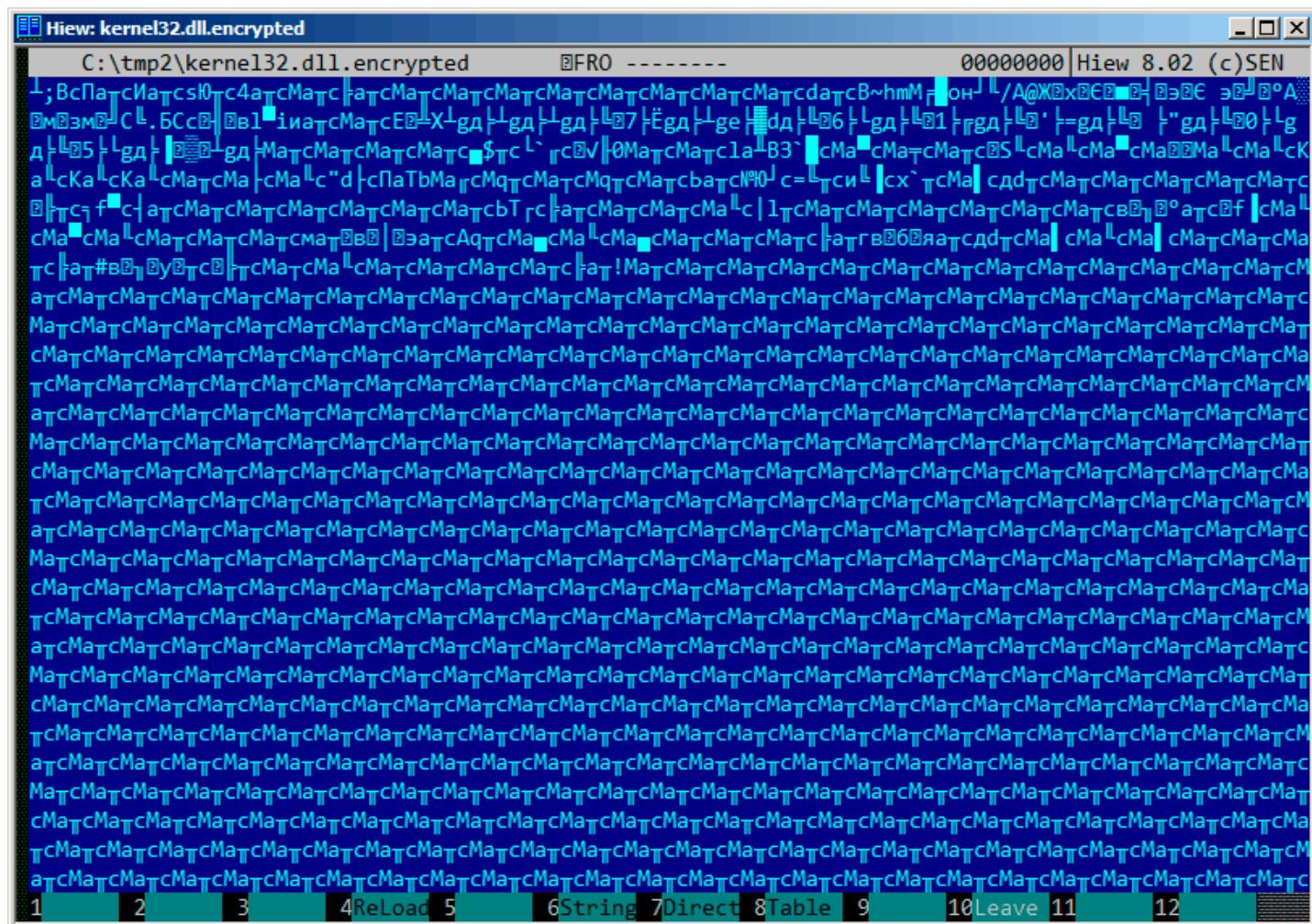


Figure 84.4: “Encrypted” file

It's very easy to spot recurring 4 symbols. Indeed, PE-file header has a lot of long zero lacunes, which is the reason why key became visible.

Here is beginning of PE-header in hexadecimal form:

```

Hiew: kernel32.dll
C:\tmp2\kernel32.dll
.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 Eb@S p @!
.7DD60100: 0B 01 09 00-00 00 0D 00-00 00 03 00-00 00 00 00 @@ @
.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 @ @ @ @ @
.7DD60130: 06 00 01 00-00 00 00 00-00 00 11 00-00 00 01 00 @ @ @ @
.7DD60140: AE 05 11 00-03 00 40 01-00 00 04 00-00 10 00 00 o@@ @ @ @ @
.7DD60150: 00 00 10 00-00 10 00 00-00 00 00 00-10 00 00 00 @ @ @
.7DD60160: 70 FF 0B 00-B1 A9 00 00-24 A9 0C 00-F4 01 00 00 p @ $й @
.7DD60170: 00 00 0F 00-28 05 00 00-00 00 00 00-00 00 00 00 @ (@
.7DD60180: 00 00 00 00-00 00 00 00-00 00 10 00-9C AD 00 00 @ 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
.7DD601B0: 10 35 08 00-40 00 00 00-00 00 00 00-00 00 00 00 @@ @
.7DD601C0: 00 00 01 00-F0 0D 00 00-00 00 00 00-00 00 00 00 @ E
.7DD601D0: 00 00 00 00-00 00 00 00-00 00 00 00-00 00 00 00
.7DD601E0: 2E 74 65 78-74 00 00 00-96 07 0C 00-00 00 01 00 .text @@@ @
.7DD601F0: 00 00 0D 00-00 00 01 00-00 00 00 00-00 00 00 00 @
.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 @@ @ @ @
.7DD60220: 00 00 00 00-00 00 00 00-00 00 00 00-40 00 00 C0 @ 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 @ @
.7DD60250: 00 00 00 00-40 00 00 40-2E 72 65 6C-6F 63 00 00 @ @.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 @ B
.7DD60280: 00 00 00 00-00 00 00 00-00 00 00 00-00 00 00 00
.7DD60290: 00 00 00 00-00 00 00 00-00 00 00 00-00 00 00 00

```

1Global 2FilBlk 3CryBlk 4ReLoad 5String 6Direct 7Table 8Leave 9AddNam 10Leave 11 12AddNam

Figure 84.5: PE-header

Here is it “encrypted”:

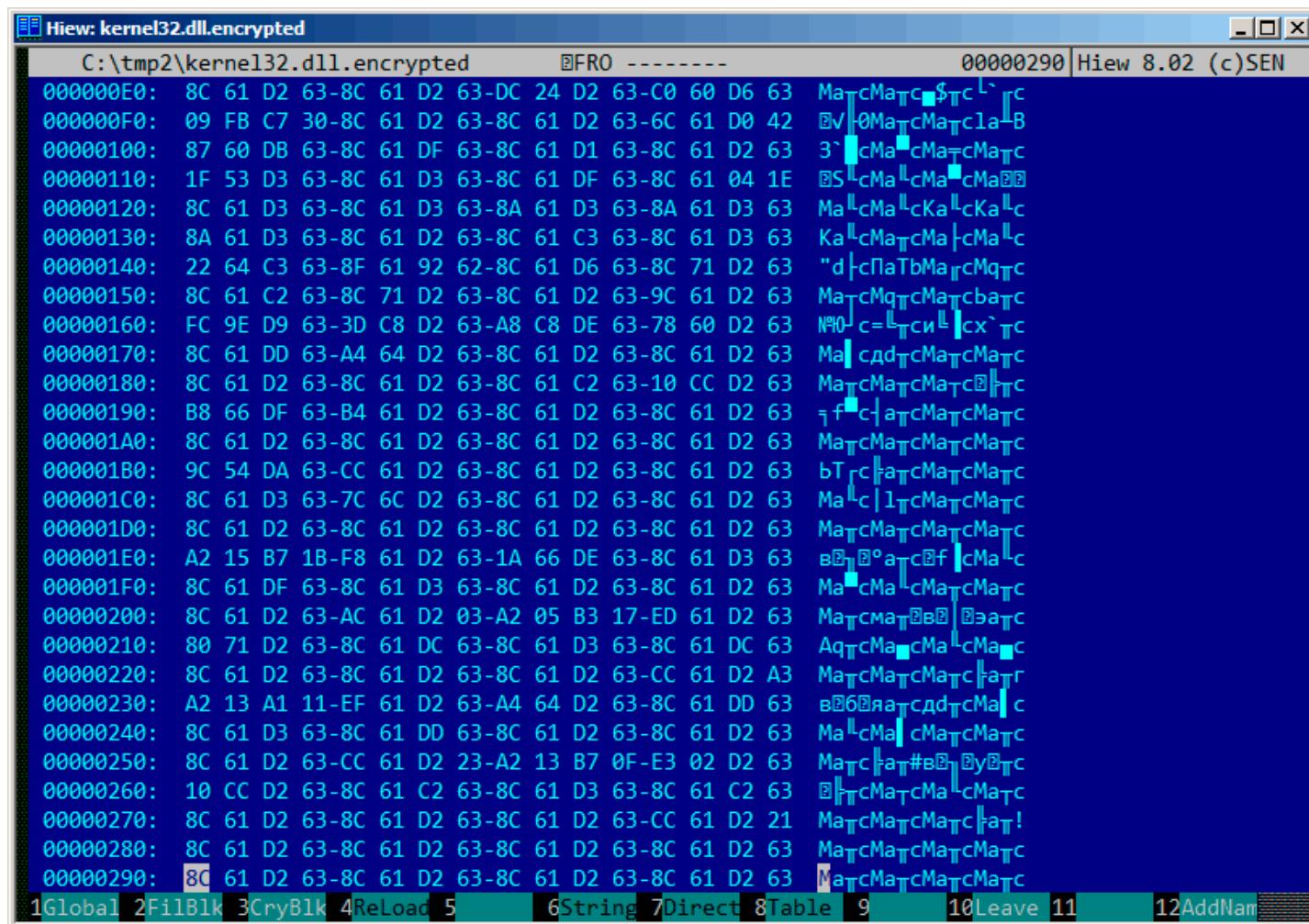


Figure 84.6: “Encrypted” PE-header

It's easy to spot that key is the following 4 bytes: 8C 61 D2 63. It's easy to decrypt the whole file using this information.

So this is important to remember these property of PE-files: 1) PE-header has many zero lacunas; 2) all PE-sections padded with zeroes by page border (4096 bytes), so long zero lacunas usually present after all sections.

Some other file formats may contain long zero lacunas. It's very typical for files used by scientific and engineering software.

For those who wants to inspect these files on one's own, they are downloadable there: <http://go.yurichev.com/17352>.

84.2.1 Exercise

As an exercise, try to decrypt the following file. Key is different, of course. <http://go.yurichev.com/17353>.

Chapter 85

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 85.1: 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 85.2: 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:

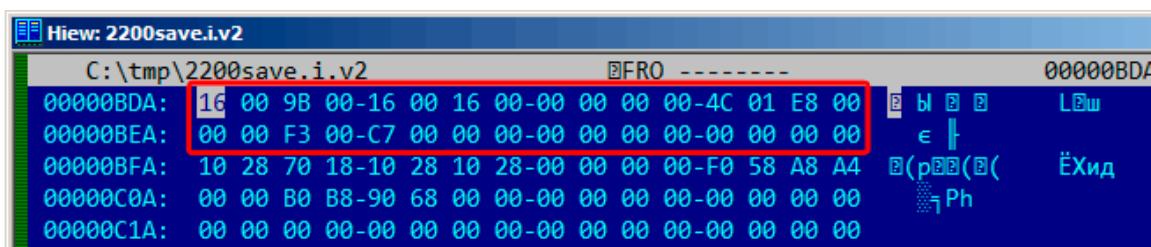
```
...> FC /b 2200save.i.v1 2200SAVE.I.V2
Comparing files 2200save.i.v1 and 2200SAVE.I.V2
00000016: 0D 04
00000017: 03 04
0000001C: 1F 1E
00000146: 27 3B
00000BDA: 0E 16
00000BDC: 66 9B
00000BDE: 0E 16
00000BEO: 0E 16
00000BE6: DB 4C
00000BE7: 00 01
00000BE8: 99 E8
00000BEC: A1 F3
00000BEE: 83 C7
00000BFB: A8 28
00000BFD: 98 18
00000BFF: A8 28
00000C01: A8 28
00000C07: D8 58
00000C09: E4 A4
00000COD: 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 0xE (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:



Address	Value	Label
00000BDA	16 00	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 85.3: 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):

```
C:\tmp\2200save.i.v2 FWD EDITMODE 00000BDC
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 85.4: Hiew: let's write 1234 (0x4D2) there

Then we will load the changed file in the game and took a look at mine statistics:

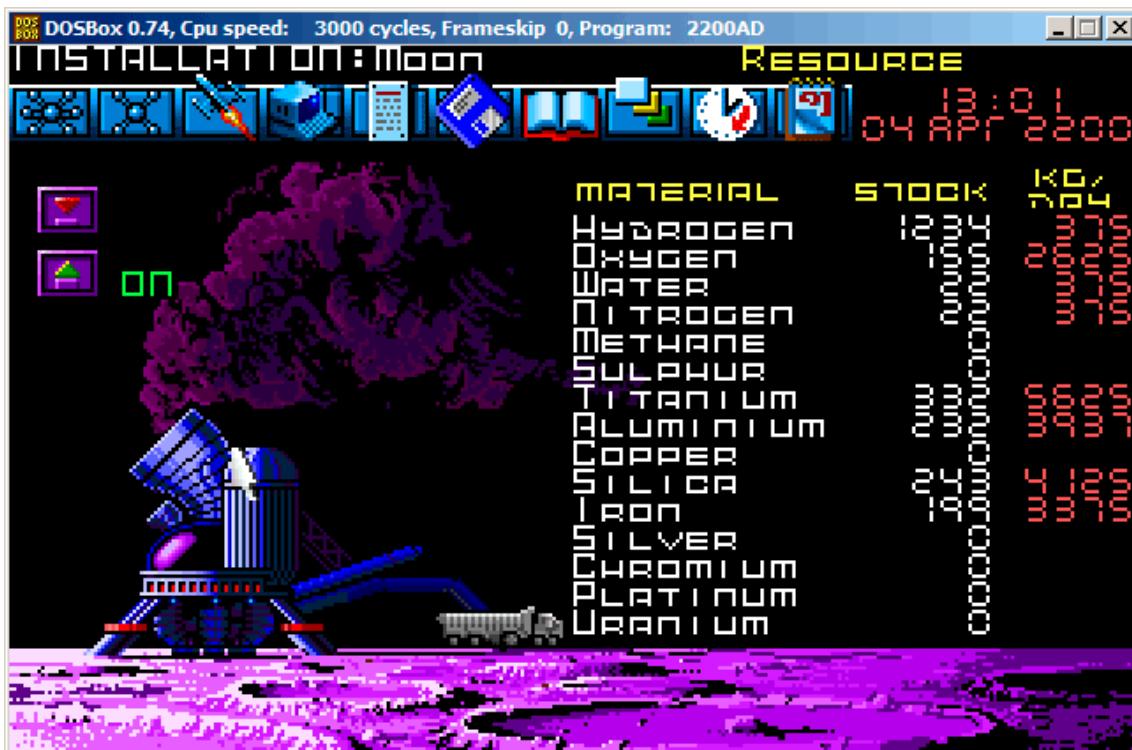


Figure 85.5: Let's check for hydrogen value

So yes, this is it.

Now let's try to finish the game as soon as possible, set the maximal values everywhere:

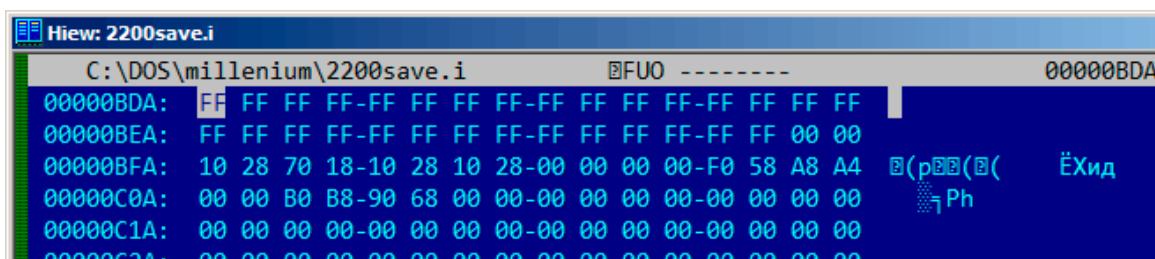


Figure 85.6: Hiew: let's set maximal values

0xFFFF is 65535, so yes, we now have a lot of resources:



Figure 85.7: 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 85.8: 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: [63.4 on page 678](#).

Chapter 86

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 chose an ancient Oracle RDBMS version intentionally due to the smaller size of its modules

Here is the file opened in Hiew:

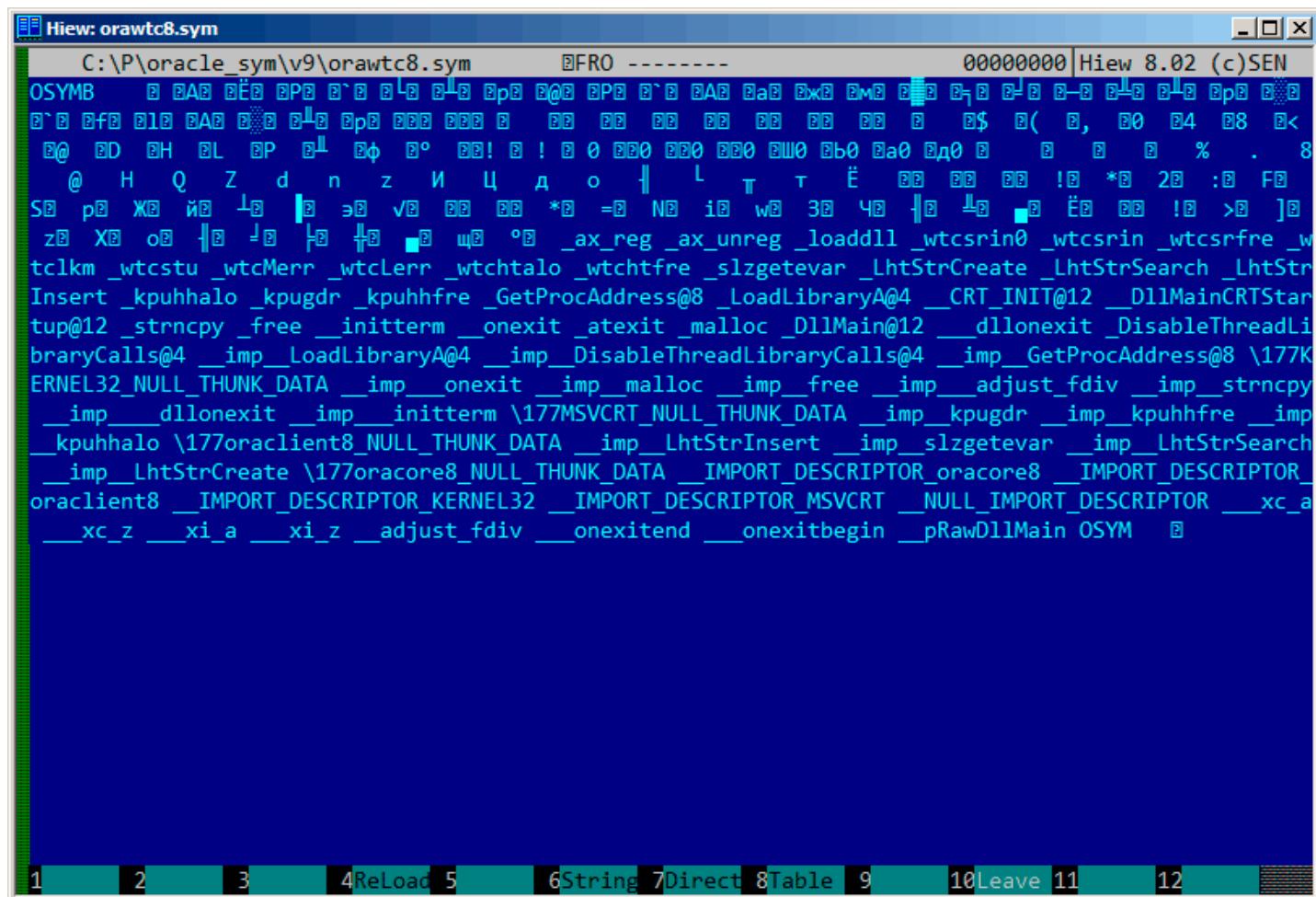


Figure 86.1: The whole file in Hiew

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:

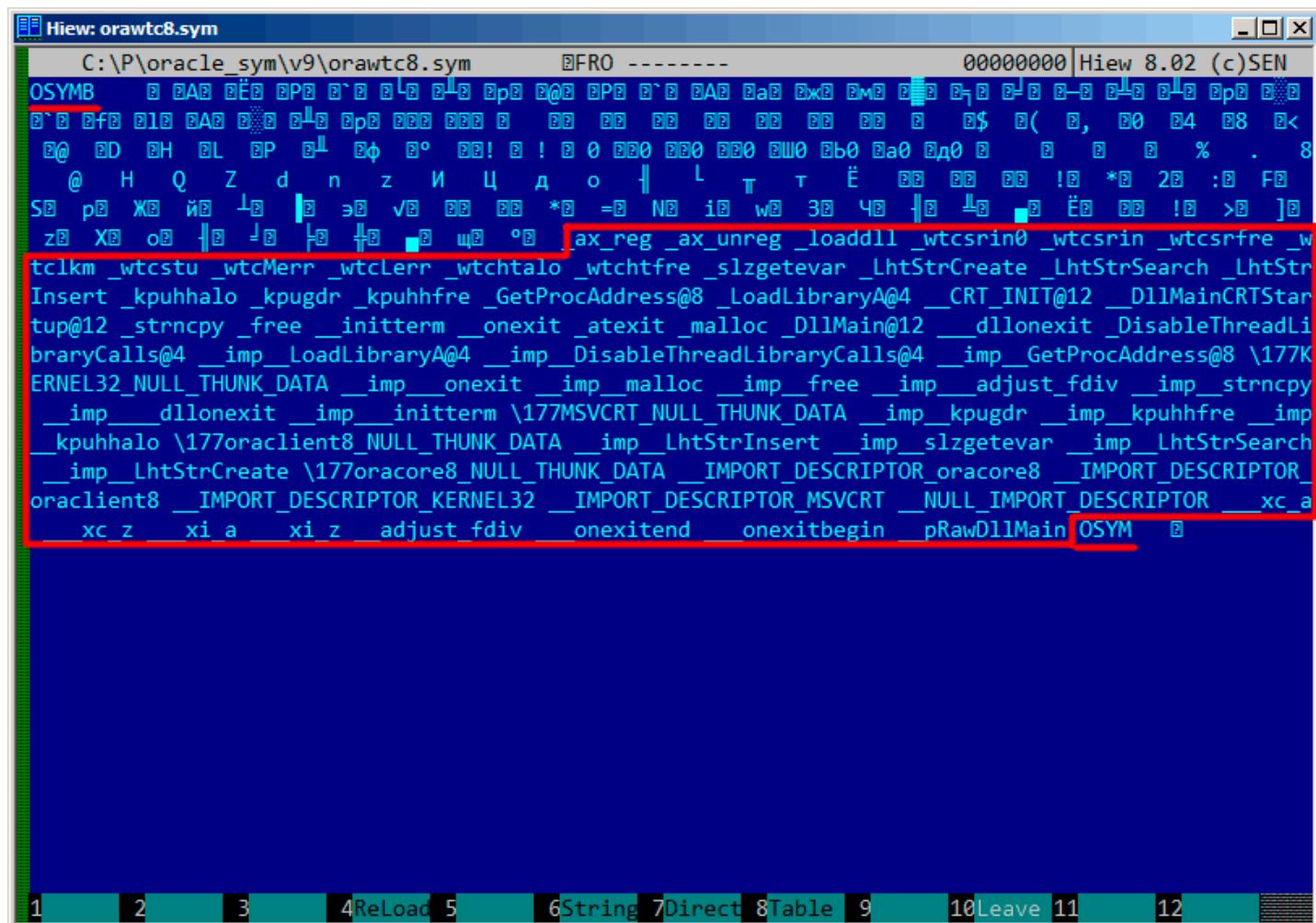


Figure 86.2: OSYM signature and text strings

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:

```

C:\P\oracle_sym\v9\asd2      FRO -----
00000000: 00 10 00 10-80 10 00 10-F0 10 00 10-50 11 00 10 00 00000000|Hiew 8.02 (c)SEN
00000010: 60 11 00 10-C0 11 00 10-D0 11 00 10-70 13 00 10 00 00000010|`0 010 010 0p0 0
00000020: 40 15 00 10-50 15 00 10-60 15 00 10-80 15 00 10 00 00000020|@0 0p0 010 0A0 0
00000030: A0 15 00 10-A6 15 00 10-AC 15 00 10-B2 15 00 10 00 00000030|a0 0x0 0M0 010 0
00000040: B8 15 00 10-BE 15 00 10-C4 15 00 10-CA 15 00 10 00 00000040|`0 010 0-0 000 0
00000050: D0 15 00 10-E0 15 00 10-B0 16 00 10-60 17 00 10 00 00000050|10 0p0 010 010 0
00000060: 66 17 00 10-6C 17 00 10-80 17 00 10-B0 17 00 10 00 00000060|f0 010 0A0 010 0
00000070: D0 17 00 10-E0 17 00 10-10 18 00 10-16 18 00 10 00 00000070|`0 0p0 000 000 0
00000080: 00 20 00 10-04 20 00 10-08 20 00 10-0C 20 00 10 00 00000080|00 00 00 00 0
00000090: 10 20 00 10-14 20 00 10-18 20 00 10-1C 20 00 10 00 00000090|00 00 00 00 0
000000A0: 20 20 00 10-24 20 00 10-28 20 00 10-2C 20 00 10 00 000000A0|0$ 0( 0, 0
000000B0: 30 20 00 10-34 20 00 10-38 20 00 10-3C 20 00 10 00 000000B0|0 04 08 0< 0
000000C0: 40 20 00 10-44 20 00 10-48 20 00 10-4C 20 00 10 00 000000C0|@ 0D 0H 0L 0
000000D0: 50 20 00 10-D0 20 00 10-E4 20 00 10-F8 20 00 10 00 000000D0|R 01 0ф 0° 0
000000E0: 0C 21 00 10-20 21 00 10-00 30 00 10-04 30 00 10 00 000000E0|0! 0 ! 0 0 000 0
000000F0: 08 30 00 10-0C 30 00 10-98 30 00 10-9C 30 00 10 00 000000F0|00 000 0ш0 0б0 0
00000100: A0 30 00 10-A4 30 00 10-00 00 00 00-08 00 00 00 00 00000100|a0 0д0 0 0
00000110: 12 00 00 00-1B 00 00 00-25 00 00 00-2E 00 00 00 00 00000110|0 0 % .
00000120: 38 00 00 00-40 00 00 00-48 00 00 00-51 00 00 00 00 00000120|8 @ H Q
00000130: 5A 00 00 00-64 00 00 00-6E 00 00 00-7A 00 00 00 00 00000130|Z d n z
00000140: 88 00 00 00-96 00 00 00-A4 00 00 00-AE 00 00 00 00 00000140|И Ц д о
00000150: B6 00 00 00-C0 00 00 00-D2 00 00 00-E2 00 00 00 00 00000150|I L T T
00000160: F0 00 00 00-07 01 00 00-10 01 00 00-16 01 00 00 00 00000160|E 00 00 00
00000170: 21 01 00 00-2A 01 00 00-32 01 00 00-3A 01 00 00 00 00000170|!0 *0 20 :0
00000180: 46 01 00 00-53 01 00 00-70 01 00 00-86 01 00 00 00 00000180|F0 S0 p0 X0
00000190: A9 01 00 00-C1 01 00 00-DE 01 00 00-ED 01 00 00 00 00 00000190|й0 10 |0 30
000001A0: FB 01 00 00-07 02 00 00-1B 02 00 00-2A 02 00 00 00 000001A0|v0 00 00 *0

```

Figure 86.3: Binary block

There is a clear pattern in it.

We will add red lines to divide the block:

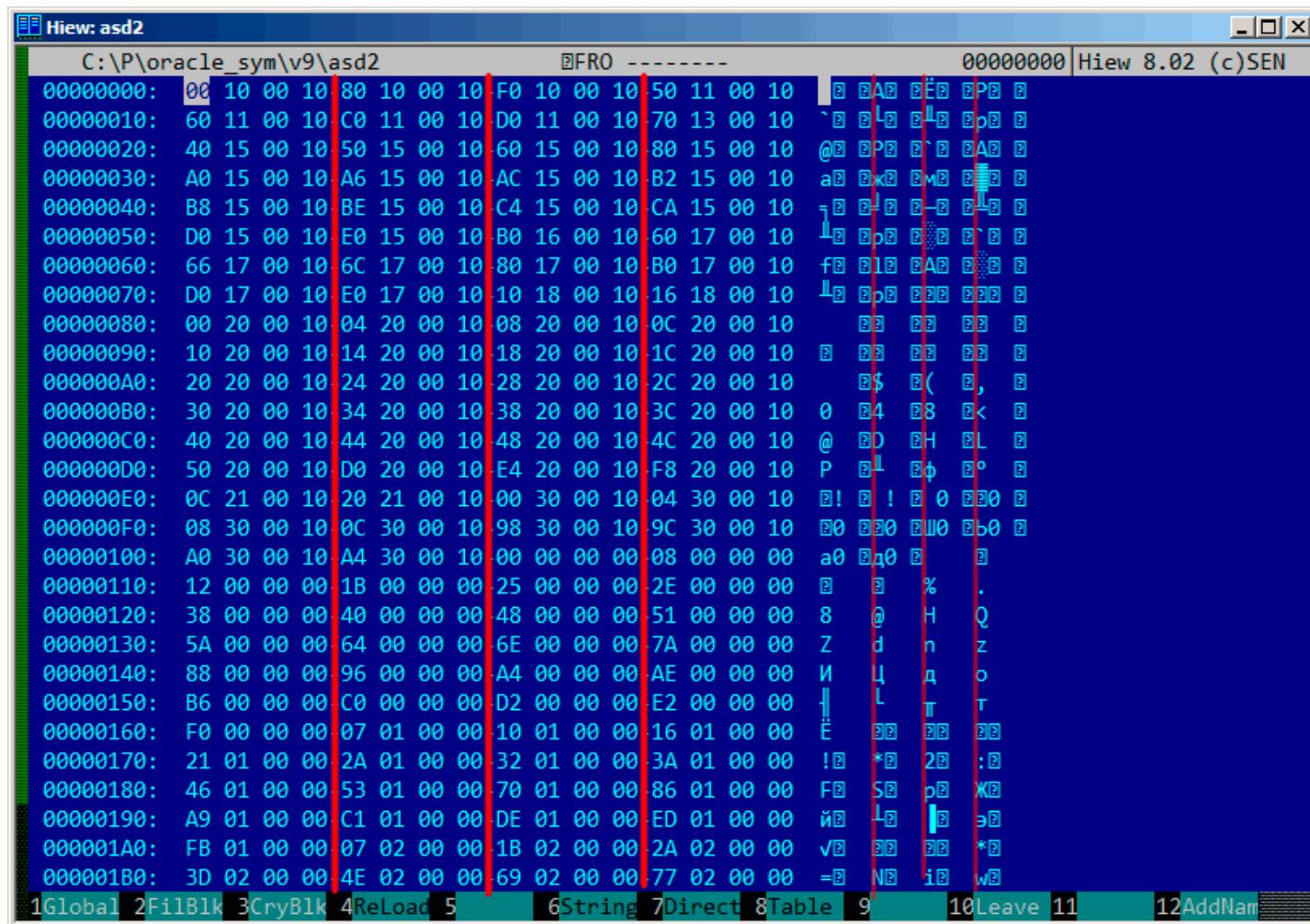


Figure 86.4: Binary block patterns

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 86.1: 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
00000420 00000012 0000001b 00000025 0000002e
00000440 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, OFFFFFFFFh

```

```

.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 timestamp (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:

Address	Hex	ASCII	Description
00000000:	4F 53 59 4D-41 4D 36 34-BD	OSYMAM64	Signature
00000010:	6D 05 00-00 00 00 00	=!*G	
00000020:	00 00 00 00-00 00 00 00	@	
00000030:	00 10 40 00-00 00 00 00	1@	
00000040:	00 10 40 00-00 00 00 00	A@	
00000050:	00 10 40 00-00 00 00 00	B@	
00000060:	00 10 40 00-00 00 00 00	C@	
00000070:	00 10 40 00-00 00 00 00	D@	
00000080:	00 10 40 00-00 00 00 00	E@	
00000090:	00 10 40 00-00 00 00 00	F@	
000000A0:	00 10 40 00-00 00 00 00	G@	
000000B0:	00 10 40 00-00 00 00 00	H@	
000000C0:	00 10 40 00-00 00 00 00	I@	
000000D0:	00 10 40 00-00 00 00 00	J@	
000000E0:	00 10 40 00-00 00 00 00	K@	
000000F0:	00 10 40 00-00 00 00 00	L@	
00000100:	00 10 40 00-00 00 00 00	M@	
00000110:	00 10 40 00-00 00 00 00	N@	
00000120:	00 10 40 00-00 00 00 00	O@	
00000130:	00 10 40 00-00 00 00 00	P@	
00000140:	00 10 40 00-00 00 00 00	Q@	
00000150:	00 10 40 00-00 00 00 00	R@	
00000160:	00 10 40 00-00 00 00 00	S@	
00000170:	00 10 40 00-00 00 00 00	T@	
00000180:	00 10 40 00-00 00 00 00	U@	
00000190:	00 10 40 00-00 00 00 00	V@	
000001A0:	00 10 40 00-00 00 00 00	W@	

Figure 86.5: .SYM-file example from Oracle RDBMS for win64

So yes, all tables now have 64-bit elements, even string offsets! The signature is now OSYMAM64, to distinguish the target platform, apparently.

This is it! Here is also library which has functions to access Oracle RDBMS.SYM-files: [GitHub](#).

Chapter 87

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 87.1: 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:

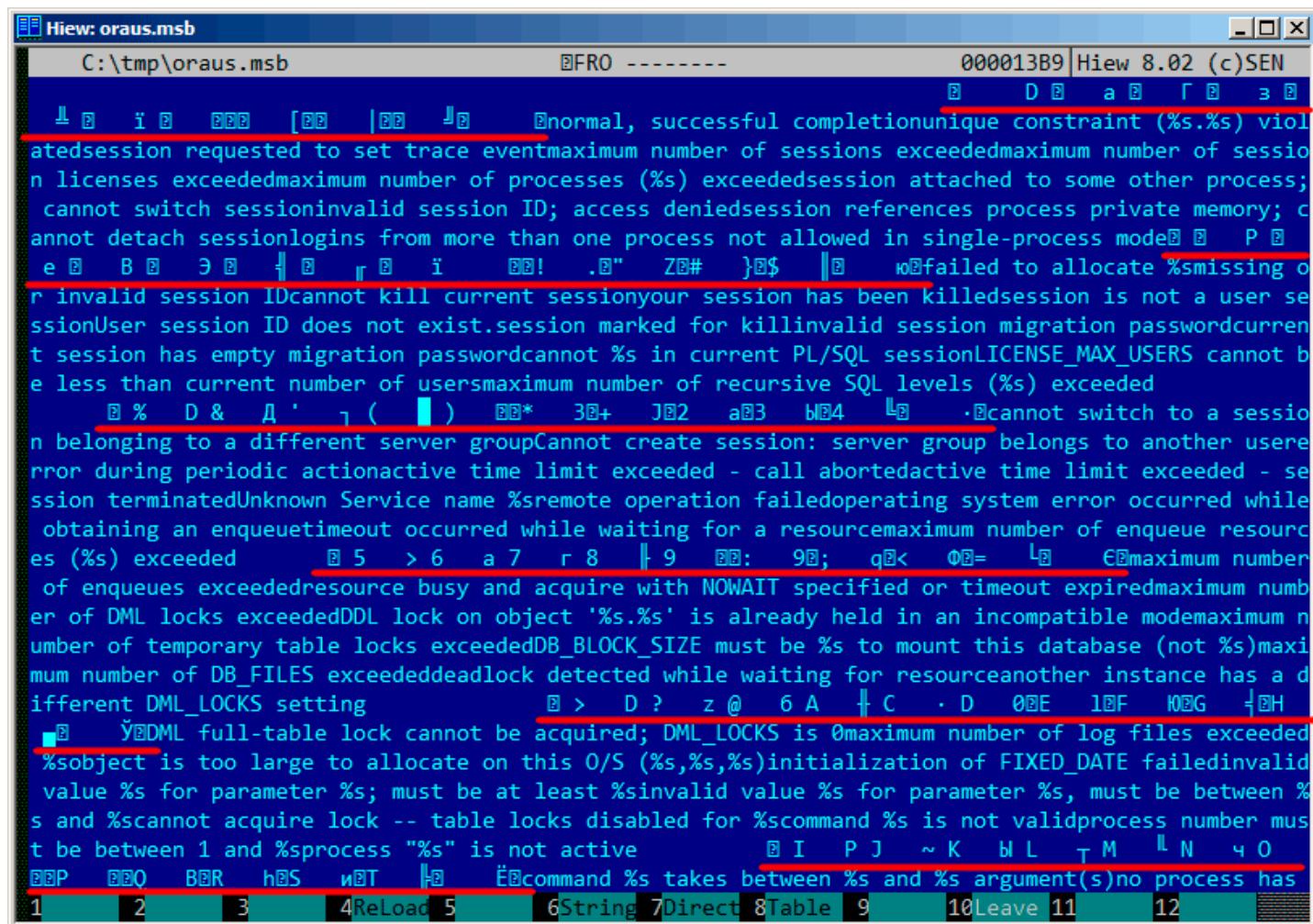


Figure 87.1: Hiew: first block

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:

The screenshot shows the Hiew 8.02 debugger interface. The left pane displays memory dump in hex and ASCII. The right pane shows the ASCII representation of the messages. Red lines highlight specific bytes in the hex dump, corresponding to error codes in the ASCII text. The ASCII text contains various Oracle error messages.

Hex Address	Hex Value	ASCII Value	Message Content
00001400	0A 00 00 00-00 00 44 00-01 00 00 00-61 00 11 00	E D a	
00001410	00 00 83 00-12 00 00 00-A7 00 13 00-00 00 CA 00	Г з ы	
00001420	14 00 00 00-F5 00 15 00-00 00 1E 01-16 00 00 00	и ѿ	
00001430	5B 01 17 00-00 00 7C 01-18 00 00 00-BC 01 00 00	[]	
00001440	00 00 00 02-6E 6F 72 6D-61 6C 2C 20-73 75 63 63	Normal, succ	
00001450	65 73 73 66-75 6C 20 63-6F 6D 70 6C-65 74 69 6F	essful completio	
00001460	6E 75 6E 69-71 75 65 20-63 6F 6E 73-74 72 61 69	nique constrai	
00001470	6E 74 20 28-25 73 2E 25-73 29 20 76-69 6F 6C 61	nt (%s.%s) viola	
00001480	74 65 64 73-65 73 73 69-6F 6E 20 72-65 71 75 65	ted session reque	
00001490	73 74 65 64-20 74 6F 20-73 65 74 20-74 72 61 63	sted to set trac	
000014A0	65 20 65 76-65 6E 74 6D-61 78 69 6D-75 6D 20 6E	e eventmaximum n	
000014B0	75 6D 62 65-72 20 6F 66-20 73 65 73-73 69 6F 6E	umber of session	
000014C0	73 20 65 78-63 65 65 64-65 64 6D 61-78 69 6D 75	s exceededmaximu	
000014D0	6D 20 6E 75-6D 62 65 72-20 6F 66 20-73 65 73 73	m number of sess	
000014E0	69 6F 6E 20-6C 69 63 65-6E 73 65 73-20 65 78 63	ion licenses exc	
000014F0	65 65 64 65-64 6D 61 78-69 6D 75 6D-20 6E 75 6D	eededmaximum num	
00001500	62 65 72 20-6F 66 20 70-72 6F 63 65-73 73 65 73	ber of processes	
00001510	20 28 25 73-29 20 65 78-63 65 65 64-65 64 73 65	(%s) exceededse	
00001520	73 73 69 6F-6E 20 61 74-74 61 63 68-65 64 20 74	ssion attached t	
00001530	6F 20 73 6F-6D 65 20 6F-74 68 65 72-20 70 72 6F	o some other pro	
00001540	63 65 73 73-3B 20 63 61-6E 6E 6F 74-20 73 77 69	cess; cannot swi	
00001550	74 63 68 20-73 65 73 73-69 6F 6E 69-6E 76 61 6C	tch sessioninval	
00001560	69 64 20 73-65 73 73 69-6F 6E 20 49-44 3B 20 61	id session ID; a	
00001570	63 63 65 73-73 20 64 65-6E 69 65 64-73 65 73 73	ccess deniedsess	
00001580	69 6F 6E 20-72 65 66 65-72 65 6E 63-65 73 20 70	ion references p	
00001590	72 6F 63 65-73 73 20 70-72 69 76 61-74 65 20 6D	rocess private m	
000015A0	65 6D 6F 72-79 3B 20 63-61 6E 6E 6F-74 20 64 65	emory; cannot de	
000015B0	74 61 63 68-20 73 65 73-73 69 6F 6E-6C 6F 67 69	tach sessionlogi	

Figure 87.2: 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-terminated C strings, their size must be encoded somewhere. The size of the first string "normal, successful completion" is 29 (0x1D) bytes. The size of the second string "unique constraint (%s.%s) violated" is 34 (0x22) bytes. We can't find these values (0x1D or/and 0x22) in the block.

There is also another thing. Oracle RDBMS has to determine the position of the string it needs to load in the block, right? The first string "normal, successful completion" starts at position 0x1444 (if we count starting at the beginning of the file) or at 0x44 (from the block's start). The second string "unique constraint (%s.%s) violated" starts at position 0x1461 (from the file's start) or at 0x61 (from the at the block's start). 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:

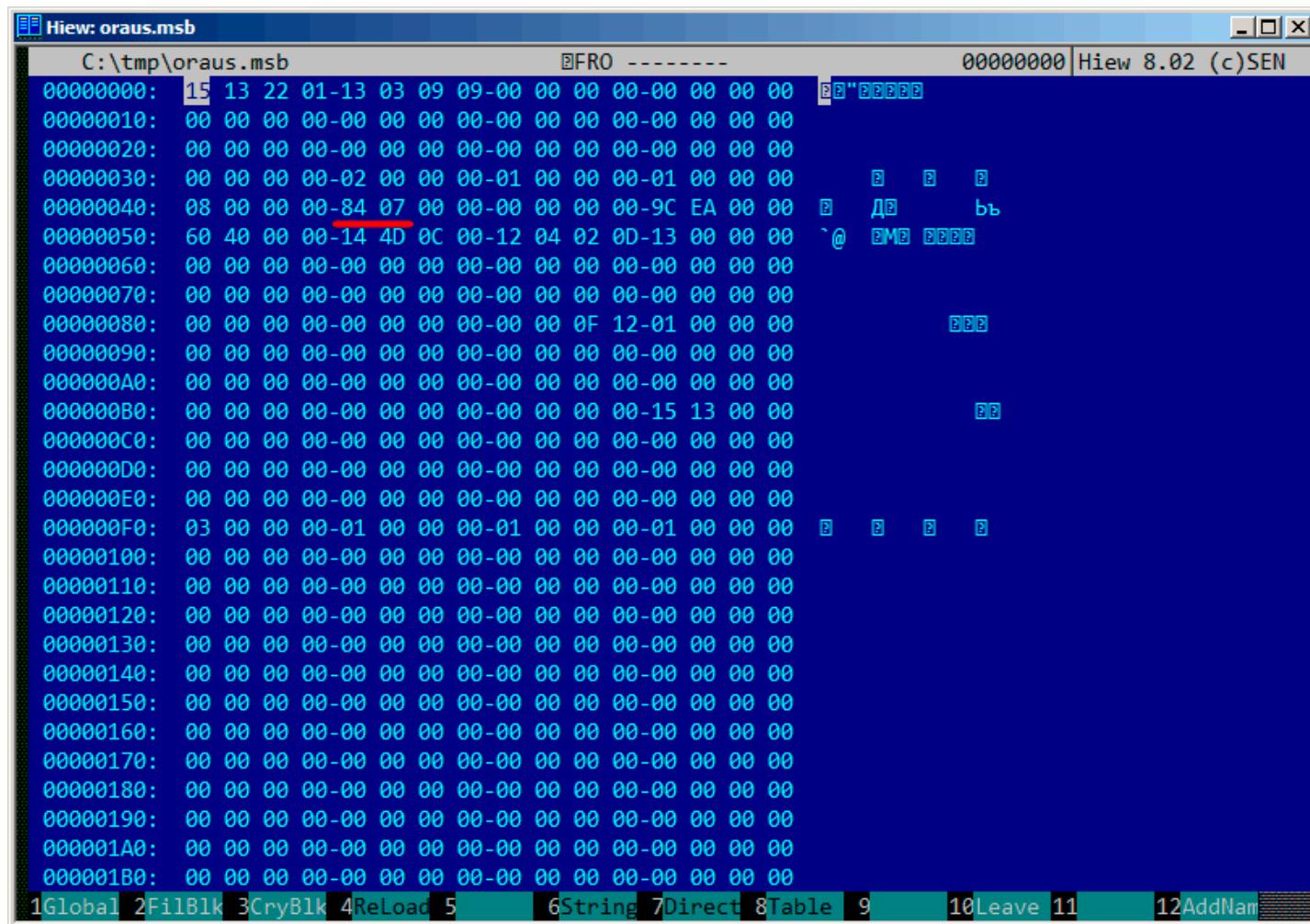


Figure 87.3: Hiew: file header

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.

There is also a table that came after the header which probably contains 16-bit values:

Figure 87.4: 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](#).

87.1 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 88

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
                            else
                                if size eq 9
                                    ; jmp .+9; .npad 7
                                    DB 0EBH, 07H, 8DH, 0A4H, 24H, 00H, 00H, 00H
```


Chapter 89

Executable files patching

89.1 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.

89.2 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 ([64.2 on page 681](#)). 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 relocs ([68.2.6 on page 706](#)) must not to be touched while patching, because the Windows loader may overwrite your new code. (They are grayed in Hiew, for example: fig.[7.12](#)). As a last resort, it is possible to write jumps that circumvent the relocs, or you will need to edit the relocs table.

Chapter 90

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 91

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 91.1: 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 91.2: 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: [19.2.4 on page 322](#), [39.3 on page 495](#), [47.7 on page 540](#), [18.7 on page 296](#), [12.4.1 on page 138](#), [19.5.2 on page 339](#).

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 92

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>

92.1 MSVC

Now this is how MSVC 2012 generates the main loop:

Listing 92.1: 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 92.2: MSVC 2012

```
$T1 = -8                                ; size = 4
$T2 = -4                                ; size = 4
_main$omp$1 PROC                          ; COMDAT
    push    ebp
    mov     ebp, esp
    push    ecx
    push    ecx
    push    esi
    lea     eax, DWORD PTR $T2[ebp]
    push    eax
    lea     eax, DWORD PTR $T1[ebp]
    push    eax
    push    1
    push    1
    push    2147483646                      ; 7fffffffH
    push    0
    call    __vcomp_for_static_simple_init
    mov     esi, DWORD PTR $T1[ebp]
    add    esp, 24                           ; 00000018H
    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
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 92.3: 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           ; 00000000cH
; 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.

92.2 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.

⁴Read more about LOCK prefix: [A.6.1 on page 955](#)

⁵You can read more about critical sections here: [68.4 on page 732](#)

Listing 92.4: 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 92.5: 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()`.

GCC also inserted the `LOCK ADD` instruction right in the code, unlike MSVC, which generated a call to a separate DLL function:

Listing 92.6: 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 93

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 93.1: 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 93.2: 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		
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 OB 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 OB 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 94

8086 memory model

When dealing with 16-bit programs for MS-DOS or Win16 ([78.3 on page 779](#) or [53.5 on page 612](#)), 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 95

Basic blocks reordering

95.1 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 95.1: 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]
        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 96

Books

96.1 Windows

[RA09].

96.2 C/C++

[ISO13].

96.3 x86 / x86-64

[Int13], [AMD13a]

96.4 ARM

ARM manuals: <http://go.yurichev.com/17024>

96.5 Cryptography

[Sch94]

Chapter 97

Blogs

97.1 Windows

- Microsoft: Raymond Chen
- nynaeve.net

Chapter 98

Other

There are two excellent RE-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 a ##re channel on FreeNode¹.

¹freenode.net

Part XII

Exercises



There are two questions almost for every exercise, if otherwise not specified:

1) What does this function do? Answer in one sentence.

2) Rewrite this function into C/C++.

It is allowed to use Google to search for any leads. However, if you like to make your task harder, you may try to solve it without using Google.

Some hints and the solutions can be found in the appendix of this book.

Chapter 99

Level 1

Level 1 exercises are ones you may try to solve in your mind.

99.1 Exercise 1.4

This program requires a password. Find it.

As an additional exercise, try to change the password by patching the executable file. Also try using one with a different length. What is the shortest possible password here?

Try also to crash the program using only string input.

- [win32 \(beginners.re\)](#)
- [Linux x86 \(beginners.re\)](#)
- [Mac OS X \(beginners.re\)](#)
- [MIPS \(beginners.re\)](#)

Chapter 100

Level 2

For solving exercises of level 2, you may need a text editor or paper and pencil.

100.1 Exercise 2.1

100.1.1 Optimizing MSVC 2010 x86

```

__real@3fe00000000000000 DQ 03fe00000000000000r
__real@3f50624dd2f1a9fc DQ 03f50624dd2f1a9fcr

_g$ = 8
tv132 = 16
_x$ = 16
f1 PROC
    fld    QWORD PTR _x$[esp-4]
    fld    QWORD PTR __real@3f50624dd2f1a9fc
    fld    QWORD PTR __real@3fe00000000000000
    fld    QWORD PTR _g$[esp-4]
$LN2@f1:
    fld    ST(0)
    fmul  ST(0), ST(1)
    fsub  ST(0), ST(4)
    call   __ftol2_sse
    cdq
    xor    eax, edx
    sub    eax, edx
    mov    DWORD PTR tv132[esp-4], eax
    fild  DWORD PTR tv132[esp-4]
    fcomp ST(3)
    fnstsw ax
    test   ah, 5
    jnp   SHORT $LN19@f1
    fld    ST(3)
    fdiv  ST(0), ST(1)
    faddp ST(1), ST(0)
    fmul  ST(0), ST(1)
    jmp   SHORT $LN2@f1
$LN19@f1:
    fstp  ST(3)
    fstp  ST(1)
    fstp  ST(0)
    ret   0
f1 ENDP

__real@3ff00000000000000 DQ 03ff00000000000000r

_x$ = 8
f2 PROC
    fld    QWORD PTR _x$[esp-4]
    sub    esp, 16
    fstp  QWORD PTR [esp+8]

```

```

fld1
fstp    QWORD PTR [esp]
call    f1
add    esp, 16
ret    0
f2 ENDP

```

100.1.2 Optimizing MSVC 2012 x64

```

__real@3fe00000000000000 DQ 03fe00000000000000r
__real@3f50624dd2f1a9fc DQ 03f50624dd2f1a9fc
__real@3ff00000000000000 DQ 03ff00000000000000r

x$ = 8
f PROC
    movsd xmm2, QWORD PTR __real@3ff00000000000000
    movsd xmm5, QWORD PTR __real@3f50624dd2f1a9fc
    movsd xmm4, QWORD PTR __real@3fe00000000000000
    movapd xmm3, xmm0
    npad 4
$LL4@f:
    movapd xmm1, xmm2
    mulsd xmm1, xmm2
    subsd xmm1, xmm3
    cvttsd2si eax, xmm1
    cdq
    xor    eax, edx
    sub    eax, edx
    movd   xmm0, eax
    cvtdq2pd xmm0, xmm0
    comisd xmm5, xmm0
    ja     SHORT $LN18@f
    movapd xmm0, xmm3
    divsd xmm0, xmm2
    addsd xmm0, xmm2
    movapd xmm2, xmm0
    mulsd xmm2, xmm4
    jmp    SHORT $LL4@f
$LN18@f:
    movapd xmm0, xmm2
    ret    0
f ENDP

```

100.2 Exercise 2.4

This is a standard C library function. The source code is taken from MSVC 2010.

100.2.1 Optimizing MSVC 2010

```

PUBLIC _f
_TEXT SEGMENT
_arg1$ = 8           ; size = 4
_arg2$ = 12          ; size = 4
_f PROC
    push  esi
    mov   esi, DWORD PTR _arg1$[esp]
    push  edi
    mov   edi, DWORD PTR _arg2$[esp+4]
    cmp   BYTE PTR [edi], 0
    mov   eax, esi
    je    SHORT $LN7@f
    mov   dl, BYTE PTR [esi]
    push  ebx

```

```

test    dl, dl
je     SHORT $LN4@f
sub    esi, edi
npad   6 ; align next label
$LL5@f:
    mov    ecx, edi
    test   dl, dl
    je     SHORT $LN2@f
$LL3@f:
    mov    dl, BYTE PTR [ecx]
    test   dl, dl
    je     SHORT $LN14@f
    movsx ebx, BYTE PTR [esi+ecx]
    movsx edx, dl
    sub    ebx, edx
    jne    SHORT $LN2@f
    inc    ecx
    cmp    BYTE PTR [esi+ecx], bl
    jne    SHORT $LL3@f
$LN2@f:
    cmp    BYTE PTR [ecx], 0
    je     SHORT $LN14@f
    mov    dl, BYTE PTR [eax+1]
    inc    eax
    inc    esi
    test   dl, dl
    jne    SHORT $LL5@f
    xor    eax, eax
    pop    ebx
    pop    edi
    pop    esi
    ret    0
_f    ENDP
_TEXT  ENDS
END

```

100.2.2 GCC 4.4.1

```

public f
proc near

var_C      = dword ptr -0Ch
var_8       = dword ptr -8
var_4       = dword ptr -4
arg_0       = dword ptr  8
arg_4       = dword ptr  0Ch

        push    ebp
        mov     ebp, esp
        sub    esp, 10h
        mov     eax, [ebp+arg_0]
        mov     [ebp+var_4], eax
        mov     eax, [ebp+arg_4]
        movzx  eax, byte ptr [eax]
        test   al, al
        jnz    short loc_8048443
        mov     eax, [ebp+arg_0]
        jmp    short locret_8048453

loc_80483F4:
        mov     eax, [ebp+var_4]
        mov     [ebp+var_8], eax
        mov     eax, [ebp+arg_4]
        mov     [ebp+var_C], eax
        jmp    short loc_804840A

loc_8048402:
        add    [ebp+var_8], 1

```

```

add    [ebp+var_C], 1

loc_804840A:
    mov    eax, [ebp+var_8]
    movzx eax, byte ptr [eax]
    test   al, al
    jz     short loc_804842E
    mov    eax, [ebp+var_C]
    movzx eax, byte ptr [eax]
    test   al, al
    jz     short loc_804842E
    mov    eax, [ebp+var_8]
    movzx edx, byte ptr [eax]
    mov    eax, [ebp+var_C]
    movzx eax, byte ptr [eax]
    cmp    dl, al
    jz     short loc_8048402

loc_804842E:
    mov    eax, [ebp+var_C]
    movzx eax, byte ptr [eax]
    test   al, al
    jnz   short loc_804843D
    mov    eax, [ebp+var_4]
    jmp   short locret_8048453

loc_804843D:
    add    [ebp+var_4], 1
    jmp   short loc_8048444

loc_8048443:
    nop

loc_8048444:
    mov    eax, [ebp+var_4]
    movzx eax, byte ptr [eax]
    test   al, al
    jnz   short loc_80483F4
    mov    eax, 0

locret_8048453:
    leave
    retn
f
    endp

```

100.2.3 Optimizing Keil (ARM mode)

PUSH	{r4,lr}
LDRB	r2,[r1,#0]
CMP	r2,#0
POPEQ	{r4,pc}
B	L0.80

|L0.20|

LDRB	r12,[r3,#0]
CMP	r12,#0
BEQ	L0.64
LDRB	r4,[r2,#0]
CMP	r4,#0
POPEQ	{r4,pc}
CMP	r12,r4
ADDEQ	r3,r3,#1
ADDEQ	r2,r2,#1
BEQ	L0.20
B	L0.76

|L0.64|

LDRB	r2,[r2,#0]
CMP	r2,#0

```

|L0.76|    POPEQ   {r4,pc}
ADD      r0,r0,#1
|L0.80|    LDRB    r2,[r0,#0]
CMP      r2,#0
MOVNE   r3,r0
MOVNE   r2,r1
MOVEQ   r0,#0
BNE     |L0.20|
POP     {r4,pc}

```

100.2.4 Optimizing Keil (Thumb mode)

```

PUSH    {r4,r5,lr}
LDRB    r2,[r1,#0]
CMP     r2,#0
BEQ    |L0.54|
B      |L0.46|
|L0.10|   MOVS    r3,r0
MOVS    r2,r1
B       |L0.20|
|L0.16|   ADDS    r3,r3,#1
ADDS    r2,r2,#1
|L0.20|   LDRB    r4,[r3,#0]
CMP     r4,#0
BEQ    |L0.38|
LDRB    r5,[r2,#0]
CMP     r5,#0
BEQ    |L0.54|
CMP     r4,r5
BEQ    |L0.16|
B      |L0.44|
|L0.38|   LDRB    r2,[r2,#0]
CMP     r2,#0
BEQ    |L0.54|
|L0.44|   ADDS    r0,r0,#1
|L0.46|   LDRB    r2,[r0,#0]
CMP     r2,#0
BNE    |L0.10|
MOVS    r0,#0
|L0.54|   POP     {r4,r5,pc}

```

100.2.5 Optimizing GCC 4.9.1 (ARM64)

Listing 100.1: Optimizing GCC 4.9.1 (ARM64)

```

func:
    ldrb    w6, [x1]
    mov     x2, x0
    cbz    w6, .L2
    ldrb    w2, [x0]
    cbz    w2, .L24
.L17:
    ldrb    w2, [x0]
    cbz    w2, .L5
    cmp     w6, w2
    mov     x5, x0
    mov     x2, x1

```

```

    beq    .L18
    b     .L5
.L4:
    ldrb   w4, [x2]
    cmp    w3, w4
    cbz    w4, .L8
    bne    .L8
.L18:
    ldrb   w3, [x5,1]!
    add    x2, x2, 1
    cbnz   w3, .L4
.L8:
    ldrb   w2, [x2]
    cbz    w2, .L27
.L5:
    ldrb   w2, [x0,1]!
    cbnz   w2, .L17
.L24:
    mov    x2, 0
.L2:
    mov    x0, x2
    ret
.L27:
    mov    x2, x0
    mov    x0, x2
    ret

```

100.2.6 Optimizing GCC 4.4.5 (MIPS)

Listing 100.2: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

f:
    lb      $v1, 0($a1)
    or      $at, $zero
    bnez   $v1, loc_18
    move   $v0, $a0

locret_10:                      # CODE XREF: f+50
                                # f+78
    jr      $ra
    or      $at, $zero

loc_18:                          # CODE XREF: f+8
    lb      $a0, 0($a0)
    or      $at, $zero
    beqz   $a0, locret_94
    move   $a2, $v0

loc_28:                          # CODE XREF: f+8C
    lb      $a0, 0($a2)
    or      $at, $zero
    beqz   $a0, loc_80
    or      $at, $zero
    bne    $v1, $a0, loc_80
    move   $a3, $a1
    b     loc_60
    addiu  $a2, 1

loc_48:                          # CODE XREF: f+68
    lb      $t1, 0($a3)
    or      $at, $zero
    beqz   $t1, locret_10
    or      $at, $zero
    bne    $t0, $t1, loc_80
    addiu  $a2, 1

loc_60:                          # CODE XREF: f+40
    lb      $t0, 0($a2)

```

```

        or      $at, $zero
        bnez    $t0, loc_48
        addiu   $a3, 1
        lb      $a0, 0($a3)
        or      $at, $zero
        beqz    $a0, locret_10
        or      $at, $zero

loc_80:                                # CODE XREF: f+30
                                         # f+38 ...
        addiu   $v0, 1
        lb      $a0, 0($v0)
        or      $at, $zero
        bnez    $a0, loc_28
        move    $a2, $v0

locret_94:                               # CODE XREF: f+20
        jr      $ra
        move    $v0, $zero

```

100.3 Exercise 2.6

100.3.1 Optimizing MSVC 2010

```

PUBLIC _f
; Function compile flags: /Ogtpy
_TEXT SEGMENT
_k0$ = -12           ; size = 4
_k3$ = -8            ; size = 4
_k2$ = -4            ; size = 4
_v$ = 8              ; size = 4
_k1$ = 12             ; size = 4
_k$ = 12              ; size = 4
_f PROC
    sub    esp, 12    ; 0000000cH
    mov    ecx, DWORD PTR _v$[esp+8]
    mov    eax, DWORD PTR [ecx]
    mov    ecx, DWORD PTR [ecx+4]
    push   ebx
    push   esi
    mov    esi, DWORD PTR _k$[esp+16]
    push   edi
    mov    edi, DWORD PTR [esi]
    mov    DWORD PTR _k0$[esp+24], edi
    mov    edi, DWORD PTR [esi+4]
    mov    DWORD PTR _k1$[esp+20], edi
    mov    edi, DWORD PTR [esi+8]
    mov    esi, DWORD PTR [esi+12]
    xor    edx, edx
    mov    DWORD PTR _k2$[esp+24], edi
    mov    DWORD PTR _k3$[esp+24], esi
    lea    edi, DWORD PTR [edx+32]
$LL8@f:
    mov    esi, ecx
    shr    esi, 5
    add    esi, DWORD PTR _k1$[esp+20]
    mov    ebx, ecx
    shl    ebx, 4
    add    ebx, DWORD PTR _k0$[esp+24]
    sub    edx, 1640531527    ; 61c88647H
    xor    esi, ebx
    lea    ebx, DWORD PTR [edx+ecx]
    xor    esi, ebx
    add    eax, esi
    mov    esi, eax
    shr    esi, 5

```

```

add    esi, DWORD PTR _k3$[esp+24]
mov    ebx, eax
shl    ebx, 4
add    ebx, DWORD PTR _k2$[esp+24]
xor    esi, ebx
lea    ebx, DWORD PTR [edx+eax]
xor    esi, ebx
add    ecx, esi
dec    edi
jne    SHORT $LL8@f
mov    edx, DWORD PTR _v$[esp+20]
pop    edi
pop    esi
mov    DWORD PTR [edx], eax
mov    DWORD PTR [edx+4], ecx
pop    ebx
add    esp, 12           ; 0000000cH
ret    0
_f    ENDP

```

100.3.2 Optimizing Keil (ARM mode)

```

PUSH   {r4-r10,lr}
ADD    r5,r1,#8
LDM    r5,{r5,r7}
LDR    r2,[r0,#4]
LDR    r3,[r0,#0]
LDR    r4,|L0.116|
LDR    r6,[r1,#4]
LDR    r8,[r1,#0]
MOV    r12,#0
MOV    r1,r12
|L0.40|
ADD    r12,r12,r4
ADD    r9,r8,r2,LSL #4
ADD    r10,r2,r12
EOR    r9,r9,r10
ADD    r10,r6,r2,LSR #5
EOR    r9,r9,r10
ADD    r3,r3,r9
ADD    r9,r5,r3,LSL #4
ADD    r10,r3,r12
EOR    r9,r9,r10
ADD    r10,r7,r3,LSR #5
EOR    r9,r9,r10
ADD    r1,r1,#1
CMP    r1,#0x20
ADD    r2,r2,r9
STRCS r2,[r0,#4]
STRCS r3,[r0,#0]
BCC    |L0.40|
POP    {r4-r10,pc}

|L0.116|
DCD    0x9e3779b9

```

100.3.3 Optimizing Keil (Thumb mode)

```

PUSH   {r1-r7,lr}
LDR    r5,|L0.84|
LDR    r3,[r0,#0]
LDR    r2,[r0,#4]
STR    r5,[sp,#8]
MOVS  r6,r1
LDM    r6,{r6,r7}

```

```

LDR    r5,[r1,#8]
STR    r6,[sp,#4]
LDR    r6,[r1,#0xc]
MOVS   r4,#0
MOVS   r1,r4
MOV    lr,r5
MOV    r12,r6
STR    r7,[sp,#0]

|L0.30|
LDR    r5,[sp,#8]
LSLS   r6,r2,#4
ADDS   r4,r4,r5
LDR    r5,[sp,#4]
LSRS   r7,r2,#5
ADDS   r5,r6,r5
ADDS   r6,r2,r4
EORS   r5,r5,r6
LDR    r6,[sp,#0]
ADDS   r1,r1,#1
ADDS   r6,r7,r6
EORS   r5,r5,r6
ADDS   r3,r5,r3
LSLS   r5,r3,#4
ADDS   r6,r3,r4
ADD    r5,r5,lr
EORS   r5,r5,r6
LSRS   r6,r3,#5
ADD    r6,r6,r12
EORS   r5,r5,r6
ADDS   r2,r5,r2
CMP    r1,#0x20
BCC    |L0.30|
STR    r3,[r0,#0]
STR    r2,[r0,#4]
POP    {r1-r7,pc}

```

```
|L0.84|
DCD    0x9e3779b9
```

100.3.4 Optimizing GCC 4.9.1 (ARM64)

Listing 100.3: Optimizing GCC 4.9.1 (ARM64)

```

f:
ldr    w3, [x0]
mov    w4, 0
ldr    w2, [x0,4]
ldr    w10, [x1]
ldr    w9, [x1,4]
ldr    w8, [x1,8]
ldr    w7, [x1,12]
.L2:
mov    w5, 31161
add    w6, w10, w2, lsl 4
movk   w5, 0x9e37, lsl 16
add    w1, w9, w2, lsr 5
add    w4, w4, w5
eor    w1, w6, w1
add    w5, w2, w4
mov    w6, 14112
eor    w1, w1, w5
movk   w6, 0xc6ef, lsl 16
add    w3, w3, w1
cmp    w4, w6
add    w5, w3, w4
add    w6, w8, w3, lsl 4
add    w1, w7, w3, lsr 5
eor    w1, w6, w1

```

```

    eor    w1, w1, w5
    add    w2, w2, w1
    bne    .L2
    str    w3, [x0]
    str    w2, [x0,4]
    ret

```

100.3.5 Optimizing GCC 4.4.5 (MIPS)

Listing 100.4: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

f:
    lui    $t2, 0x9E37
    lui    $t1, 0xC6EF
    lw     $v0, 0($a0)
    lw     $v1, 4($a0)
    lw     $t6, 0xC($a1)
    lw     $t5, 0($a1)
    lw     $t4, 4($a1)
    lw     $t3, 8($a1)
    li     $t2, 0x9E3779B9
    li     $t1, 0xC6EF3720
    move   $a1, $zero

loc_2C:                      # CODE XREF: f+6C
    addu  $a1, $t2
    sll   $a2, $v1, 4
    addu  $t0, $a1, $v1
    srl   $a3, $v1, 5
    addu  $a2, $t5
    addu  $a3, $t4
    xor   $a2, $t0, $a2
    xor   $a2, $a3
    addu  $v0, $a2
    sll   $a3, $v0, 4
    srl   $a2, $v0, 5
    addu  $a3, $t3
    addu  $a2, $t6
    xor   $a2, $a3, $a2
    addu  $a3, $v0, $a1
    xor   $a2, $a3
    bne   $a1, $t1, loc_2C
    addu  $v1, $a2
    sw    $v1, 4($a0)
    jr    $ra
    sw    $v0, 0($a0)

```

100.4 Exercise 2.13

This is a well-known cryptographic algorithm from the past. How is it called?

100.4.1 Optimizing MSVC 2012

```

_in$ = 8                                ; size = 2
_f PROC
    movzx  ecx, WORD PTR _in$[esp-4]
    lea    eax, DWORD PTR [ecx*4]
    xor   eax, ecx
    add   eax, eax
    xor   eax, ecx
    shl   eax, 2
    xor   eax, ecx
    and   eax, 32                         ; 00000020H

```

```

shl    eax, 10          ; 0000000aH
shr    ecx, 1
or     eax, ecx
ret    0
_f      ENDP

```

100.4.2 Keil (ARM mode)

```

f PROC
    EOR    r1,r0,r0,LSR #2
    EOR    r1,r1,r0,LSR #3
    EOR    r1,r1,r0,LSR #5
    AND    r1,r1,#1
    LSR    r0,r0,#1
    ORR    r0,r0,r1,LSL #15
    BX    lr
    ENDP

```

100.4.3 Keil (Thumb mode)

```

f PROC
    LSRS   r1,r0,#2
    EORS   r1,r1,r0
    LSRS   r2,r0,#3
    EORS   r1,r1,r2
    LSRS   r2,r0,#5
    EORS   r1,r1,r2
    LSLS   r1,r1,#31
    LSRS   r0,r0,#1
    LSRS   r1,r1,#16
    ORRS   r0,r0,r1
    BX    lr
    ENDP

```

100.4.4 Optimizing GCC 4.9.1 (ARM64)

```

f:
    uxth   w1, w0
    lsr    w2, w1, 3
    lsr    w0, w1, 1
    eor    w2, w2, w1, lsr 2
    eor    w2, w1, w2
    eor    w1, w2, w1, lsr 5
    and   w1, w1, 1
    orr   w0, w0, w1, lsl 15
    ret

```

100.4.5 Optimizing GCC 4.4.5 (MIPS)

Listing 100.5: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

f:
    andi   $a0, 0xFFFF
    srl    $v1, $a0, 2
    srl    $v0, $a0, 3
    xor   $v0, $v1, $v0
    xor   $v0, $a0, $v0
    srl    $v1, $a0, 5
    xor   $v0, $v1
    andi   $v0, 1
    srl    $a0, 1

```

sll	\$v0, 15
jr	\$ra
or	\$v0, \$a0

100.5 Exercise 2.14

Another well-known algorithm. The function takes two variables and returns one.

100.5.1 MSVC 2012

```

_rt$1 = -4                                ; size = 4
_rt$2 = 8                                ; size = 4
_x$ = 8                                 ; size = 4
_y$ = 12                                ; size = 4
?f@@YAIID@Z PROC                          ; f
    push    ecx
    push    esi
    mov     esi, DWORD PTR _x$[esp+4]
    test   esi, esi
    jne    SHORT $LN7@f
    mov     eax, DWORD PTR _y$[esp+4]
    pop    esi
    pop    ecx
    ret    0

$LN7@f:
    mov     edx, DWORD PTR _y$[esp+4]
    mov     eax, esi
    test   edx, edx
    je     SHORT $LN8@f
    or    eax, edx
    push   edi
    bsf   edi, eax
    bsf   eax, esi
    mov    ecx, eax
    mov    DWORD PTR _rt$1[esp+12], eax
    bsf   eax, edx
    shr   esi, cl
    mov    ecx, eax
    shr   edx, cl
    mov    DWORD PTR _rt$2[esp+8], eax
    cmp   esi, edx
    je     SHORT $LN22@f

$LN23@f:
    jbe   SHORT $LN2@f
    xor   esi, edx
    xor   edx, esi
    xor   esi, edx

$LN2@f:
    cmp   esi, 1
    je    SHORT $LN22@f
    sub   edx, esi
    bsf   eax, edx
    mov    ecx, eax
    shr   edx, cl
    mov    DWORD PTR _rt$2[esp+8], eax
    cmp   esi, edx
    jne   SHORT $LN23@f

$LN22@f:
    mov    ecx, edi
    shl   esi, cl
    pop    edi
    mov    eax, esi

$LN8@f:
    pop    esi
    pop    ecx

```

```
    ret    0
?f@YAIIIZ ENDP
```

100.5.2 Keil (ARM mode)

```
||f1|| PROC
    CMP    r0,#0
    RSB    r1,r0,#0
    AND    r0,r0,r1
    CLZ    r0,r0
    RSBNE r0,r0,#0x1f
    BX    lr
    ENDP

f PROC
    MOVS   r2,r0
    MOV    r3,r1
    MOVEQ  r0,r1
    CMPNE r3,#0
    PUSH   {lr}
    POPEQ  {pc}
    ORR    r0,r2,r3
    BL    ||f1||
    MOV    r12,r0
    MOV    r0,r2
    BL    ||f1||
    LSR    r2,r2,r0
|L0.196|
    MOV    r0,r3
    BL    ||f1||
    LSR    r0,r3,r0
    CMP    r2,r0
    EORHI r1,r2,r0
    EORHI r0,r0,r1
    EORHI r2,r1,r0
    BEQ   |L0.240|
    CMP    r2,#1
    SUBNE r3,r0,r2
    BNE   |L0.196|
|L0.240|
    LSL    r0,r2,r12
    POP   {pc}
    ENDP
```

100.5.3 GCC 4.6.3 for Raspberry Pi (ARM mode)

```
f:
    subs   r3, r0, #0
    beq   .L162
    cmp   r1, #0
    moveq r1, r3
    beq   .L162
    orr   r2, r1, r3
    rsb   ip, r2, #0
    and   ip, ip, r2
    cmp   r2, #0
    rsb   r2, r3, #0
    and   r2, r2, r3
    clz   r2, r2
    rsb   r2, r2, #31
    clz   ip, ip
    rsbne ip, ip, #31
    mov   r3, r3, lsr r2
    b    .L169
.L171:
```

```

    eorhi    r1, r1, r2
    eorhi    r3, r1, r2
    cmp      r3, #1
    rsb      r1, r3, r1
    beq      .L167

.L169:
    rsb      r0, r1, #0
    and     r0, r0, r1
    cmp      r1, #0
    clz      r0, r0
    mov      r2, r0
    rsbne   r2, r0, #31
    mov      r1, r1, lsr r2
    cmp      r3, r1
    eor      r2, r1, r3
    bne      .L171

.L167:
    mov      r1, r3, asl ip
.L162:
    mov      r0, r1
    bx      lr

```

100.5.4 Optimizing GCC 4.9.1 (ARM64)

Listing 100.6: Optimizing GCC 4.9.1 (ARM64)

```

f:
    mov      w3, w0
    mov      w0, w1
    cbz      w3, .L8
    mov      w0, w3
    cbz      w1, .L8
    mov      w6, 31
    orr      w5, w3, w1
    neg      w2, w3
    neg      w7, w5
    and     w2, w2, w3
    clz      w2, w2
    sub      w2, w6, w2
    and     w5, w7, w5
    mov      w4, w6
    clz      w5, w5
    lsr      w0, w3, w2
    sub      w5, w6, w5
    b       .L13

.L22:
    bls      .L12
    eor      w1, w1, w2
    eor      w0, w1, w2

.L12:
    cmp      w0, 1
    sub      w1, w1, w0
    beq      .L11

.L13:
    neg      w2, w1
    cmp      w1, wzr
    and     w2, w2, w1
    clz      w2, w2
    sub      w3, w4, w2
    csel    w2, w3, w2, ne
    lsr      w1, w1, w2
    cmp      w0, w1
    eor      w2, w1, w0
    bne      .L22

.L11:
    lsl      w0, w0, w5

.L8:
    ret

```

100.5.5 Optimizing GCC 4.4.5 (MIPS)

Listing 100.7: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

f:

var_20      = -0x20
var_18      = -0x18
var_14      = -0x14
var_10      = -0x10
var_C       = -0xC
var_8       = -8
var_4       = -4

        lui      $gp, (__gnu_local_gp >> 16)
        addiu   $sp, -0x30
        la      $gp, (__gnu_local_gp & 0xFFFF)
        sw      $ra, 0x30+var_4($sp)
        sw      $s4, 0x30+var_8($sp)
        sw      $s3, 0x30+var_C($sp)
        sw      $s2, 0x30+var_10($sp)
        sw      $s1, 0x30+var_14($sp)
        sw      $s0, 0x30+var_18($sp)
        sw      $gp, 0x30+var_20($sp)
        move   $s0, $a0
        beqz   $a0, loc_154
        move   $s1, $a1
        bnez   $a1, loc_178
        or     $s2, $a1, $a0
        move   $s1, $a0

loc_154:          # CODE XREF: f+2C
        lw      $ra, 0x30+var_4($sp)
        move   $v0, $s1
        lw      $s4, 0x30+var_8($sp)
        lw      $s3, 0x30+var_C($sp)
        lw      $s2, 0x30+var_10($sp)
        lw      $s1, 0x30+var_14($sp)
        lw      $s0, 0x30+var_18($sp)
        jr      $ra
        addiu $sp, 0x30

loc_178:          # CODE XREF: f+34
        lw      $t9, (__clzsi2 & 0xFFFF)($gp)
        negu   $a0, $s2
        jalr   $t9
        and    $a0, $s2
        lw      $gp, 0x30+var_20($sp)
        bnez   $s2, loc_20C
        li     $s4, 0x1F
        move   $s4, $v0

loc_198:          # CODE XREF: f:loc_20C
        lw      $t9, (__clzsi2 & 0xFFFF)($gp)
        negu   $a0, $s0
        jalr   $t9
        and    $a0, $s0
        nor    $v0, $zero, $v0
        lw      $gp, 0x30+var_20($sp)
        srlv   $s0, $v0
        li     $s3, 0x1F
        li     $s2, 1

loc_1BC:          # CODE XREF: f+F0
        lw      $t9, (__clzsi2 & 0xFFFF)($gp)
        negu   $a0, $s1
        jalr   $t9
        and    $a0, $s1
        lw      $gp, 0x30+var_20($sp)
        beqz   $s1, loc_1DC

```

```

        or      $at, $zero
        subu   $v0, $s3, $v0

loc_1DC:                                # CODE XREF: f+BC
        srlv   $s1, $v0
        xor    $v1, $s1, $s0
        beq    $s0, $s1, loc_214
        sltu   $v0, $s1, $s0
        beqz   $v0, loc_1FC
        or     $at, $zero
        xor    $s1, $v1
        xor    $s0, $s1, $v1

loc_1FC:                                # CODE XREF: f+D8
        beq    $s0, $s2, loc_214
        subu   $s1, $s0
        b      loc_1BC
        or     $at, $zero

loc_20C:                                # CODE XREF: f+78
        b      loc_198
        subu   $s4, $v0

loc_214:                                # CODE XREF: f+D0
                                         # f:loc_1FC
        lw     $ra, 0x30+var_4($sp)
        sllv   $s1, $s0, $s4
        move   $v0, $s1
        lw     $s4, 0x30+var_8($sp)
        lw     $s3, 0x30+var_C($sp)
        lw     $s2, 0x30+var_10($sp)
        lw     $s1, 0x30+var_14($sp)
        lw     $s0, 0x30+var_18($sp)
        jr     $ra
        addiu  $sp, 0x30

```

100.6 Exercise 2.15

A well-known algorithm again. What does it do?

Take also notice that the code for x86 uses FPU, but SIMD instructions are used instead in x64 code. That's OK: [27 on page 444](#).

100.6.1 Optimizing MSVC 2012 x64

```

__real@412e848000000000 DQ 0412e848000000000r ; 1e+006
__real@4010000000000000 DQ 0401000000000000r ; 4
__real@4008000000000000 DQ 0400800000000000r ; 3
__real@3f800000 DD 03f80000r ; 1

tmp$1 = 8
tmp$2 = 8
f      PROC
        movsd  xmm3, QWORD PTR __real@4008000000000000
        movss  xmm4, DWORD PTR __real@3f800000
        mov    edx, DWORD PTR ?RNG_state@?1??get_rand@@9@9
        xor    ecx, ecx
        mov    r8d, 200000 ; 00030d40H
        npad   2 ; align next label
$LL4@f:
        imul   edx, 1664525 ; 0019660dH
        add    edx, 1013904223 ; 3c6ef35fH
        mov    eax, edx
        and    eax, 8388607 ; 007fffffH
        imul   edx, 1664525 ; 0019660dH
        bts    eax, 30

```

```

add    edx, 1013904223 ; 3c6ef35fH
mov    DWORD PTR tmp$2[rsp], eax
mov    eax, edx
and    eax, 8388607 ; 007fffffH
bts    eax, 30
movss  xmm0, DWORD PTR tmp$2[rsp]
mov    DWORD PTR tmp$1[rsp], eax
cvtps2pd xmm0, xmm0
subsd  xmm0, xmm3
cvtpd2ps xmm2, xmm0
movss  xmm0, DWORD PTR tmp$1[rsp]
cvtps2pd xmm0, xmm0
mulss  xmm2, xmm2
subsd  xmm0, xmm3
cvtpd2ps xmm1, xmm0
mulss  xmm1, xmm1
addss  xmm1, xmm2
comiss xmm4, xmm1
jbe    SHORT $LN3@f
inc    ecx

$LN3@f:
imul   edx, 1664525 ; 0019660dH
add    edx, 1013904223 ; 3c6ef35fH
mov    eax, edx
and    eax, 8388607 ; 007fffffH
imul   edx, 1664525 ; 0019660dH
bts    eax, 30
add    edx, 1013904223 ; 3c6ef35fH
mov    DWORD PTR tmp$2[rsp], eax
mov    eax, edx
and    eax, 8388607 ; 007fffffH
bts    eax, 30
movss  xmm0, DWORD PTR tmp$2[rsp]
mov    DWORD PTR tmp$1[rsp], eax
cvtps2pd xmm0, xmm0
subsd  xmm0, xmm3
cvtpd2ps xmm2, xmm0
movss  xmm0, DWORD PTR tmp$1[rsp]
cvtps2pd xmm0, xmm0
mulss  xmm2, xmm2
subsd  xmm0, xmm3
cvtpd2ps xmm1, xmm0
mulss  xmm1, xmm1
addss  xmm1, xmm2
comiss xmm4, xmm1
jbe    SHORT $LN15@f
inc    ecx

$LN15@f:
imul   edx, 1664525 ; 0019660dH
add    edx, 1013904223 ; 3c6ef35fH
mov    eax, edx
and    eax, 8388607 ; 007fffffH
imul   edx, 1664525 ; 0019660dH
bts    eax, 30
add    edx, 1013904223 ; 3c6ef35fH
mov    DWORD PTR tmp$2[rsp], eax
mov    eax, edx
and    eax, 8388607 ; 007fffffH
bts    eax, 30
movss  xmm0, DWORD PTR tmp$2[rsp]
mov    DWORD PTR tmp$1[rsp], eax
cvtps2pd xmm0, xmm0
subsd  xmm0, xmm3
cvtpd2ps xmm2, xmm0
movss  xmm0, DWORD PTR tmp$1[rsp]
cvtps2pd xmm0, xmm0
mulss  xmm2, xmm2
subsd  xmm0, xmm3
cvtpd2ps xmm1, xmm0
mulss  xmm1, xmm1

```

```

addss  xmm1,  xmm2
comiss xmm4,  xmm1
jbe    SHORT $LN16@f
inc    ecx

$LN16@f:
imul   edx,  1664525          ; 0019660dH
add    edx,  1013904223       ; 3c6ef35fH
mov    eax,  edx
and    eax,  8388607          ; 007fffffH
imul   edx,  1664525          ; 0019660dH
bts   eax,  30
add    edx,  1013904223       ; 3c6ef35fH
mov    DWORD PTR tmp$2[rsp], eax
mov    eax,  edx
and    eax,  8388607          ; 007fffffH
bts   eax,  30
movss  xmm0,  DWORD PTR tmp$2[rsp]
mov    DWORD PTR tmp$1[rsp], eax
cvtps2pd xmm0,  xmm0
subsd  xmm0,  xmm3
cvtpd2ps xmm2,  xmm0
movss  xmm0,  DWORD PTR tmp$1[rsp]
cvtps2pd xmm0,  xmm0
mulss  xmm2,  xmm2
subsd  xmm0,  xmm3
cvtpd2ps xmm1,  xmm0
mulss  xmm1,  xmm1
addss  xmm1,  xmm2
comiss xmm4,  xmm1
jbe    SHORT $LN17@f
inc    ecx

$LN17@f:
imul   edx,  1664525          ; 0019660dH
add    edx,  1013904223       ; 3c6ef35fH
mov    eax,  edx
and    eax,  8388607          ; 007fffffH
imul   edx,  1664525          ; 0019660dH
bts   eax,  30
add    edx,  1013904223       ; 3c6ef35fH
mov    DWORD PTR tmp$2[rsp], eax
mov    eax,  edx
and    eax,  8388607          ; 007fffffH
bts   eax,  30
movss  xmm0,  DWORD PTR tmp$2[rsp]
mov    DWORD PTR tmp$1[rsp], eax
cvtps2pd xmm0,  xmm0
subsd  xmm0,  xmm3
cvtpd2ps xmm2,  xmm0
movss  xmm0,  DWORD PTR tmp$1[rsp]
cvtps2pd xmm0,  xmm0
mulss  xmm2,  xmm2
subsd  xmm0,  xmm3
cvtpd2ps xmm1,  xmm0
mulss  xmm1,  xmm1
addss  xmm1,  xmm2
comiss xmm4,  xmm1
jbe    SHORT $LN18@f
inc    ecx

$LN18@f:
dec    r8
jne    $LL4@f
movd   xmm0,  ecx
mov    DWORD PTR ?RNG_state@?1??get_rand@@9@9,  edx
cvtdq2ps xmm0,  xmm0
cvtps2pd xmm1,  xmm0
mulsd  xmm1,  QWORD PTR __real@4010000000000000
divsd  xmm1,  QWORD PTR __real@412e848000000000
cvtpd2ps xmm0,  xmm1
ret    0
ENDP
f

```

100.6.2 Optimizing GCC 4.4.6 x64

```

f1:
    mov    eax, DWORD PTR v1.2084[rip]
    imul   eax, eax, 1664525
    add    eax, 1013904223
    mov    DWORD PTR v1.2084[rip], eax
    and    eax, 8388607
    or     eax, 1073741824
    mov    DWORD PTR [rsp-4], eax
    movss  xmm0, DWORD PTR [rsp-4]
    subss  xmm0, DWORD PTR .LC0[rip]
    ret

f:
    push   rbp
    xor    ebp, ebp
    push   rbx
    xor    ebx, ebx
    sub    rsp, 16

.L6:
    xor    eax, eax
    call   f1
    xor    eax, eax
    movss  DWORD PTR [rsp], xmm0
    call   f1
    movss  xmm1, DWORD PTR [rsp]
    mulss  xmm0, xmm0
    mulss  xmm1, xmm1
    lea    eax, [rbx+1]
    addss  xmm1, xmm0
    movss  xmm0, DWORD PTR .LC1[rip]
    ucomiss xmm0, xmm1
    cmova  ebx, eax
    add    ebp, 1
    cmp    ebp, 1000000
    jne   .L6
    cvtsi2ss      xmm0, ebx
    unpcklps      xmm0, xmm0
    cvtps2pd      xmm0, xmm0
    mulsd  xmm0, QWORD PTR .LC2[rip]
    divsd  xmm0, QWORD PTR .LC3[rip]
    add    rsp, 16
    pop    rbx
    pop    rbp
    unpcklpd      xmm0, xmm0
    cvtpd2ps      xmm0, xmm0
    ret

v1.2084:
    .long  305419896
.LC0:
    .long  1077936128
.LC1:
    .long  1065353216
.LC2:
    .long  0
    .long  1074790400
.LC3:
    .long  0
    .long  1093567616

```

100.6.3 Optimizing GCC 4.8.1 x86

```

f1:
    sub    esp, 4
    imul   eax, DWORD PTR v1.2023, 1664525
    add    eax, 1013904223
    mov    DWORD PTR v1.2023, eax

```

```

and    eax, 8388607
or     eax, 1073741824
mov    DWORD PTR [esp], eax
fld    DWORD PTR [esp]
fsub   DWORD PTR .LC0
add    esp, 4
ret
f:
push   esi
mov    esi, 1000000
push   ebx
xor    ebx, ebx
sub    esp, 16
.L7:
call   f1
fstp   DWORD PTR [esp]
call   f1
lea    eax, [ebx+1]
fld    DWORD PTR [esp]
fmul   st, st(0)
fxch   st(1)
fmul   st, st(0)
faddp  st(1), st
fld1
fucomip st, st(1)
fstp   st(0)
cmova  ebx, eax
sub    esi, 1
jne   .L7
mov    DWORD PTR [esp+4], ebx
fild   DWORD PTR [esp+4]
fmul   DWORD PTR .LC3
fdiv   DWORD PTR .LC4
fstp   DWORD PTR [esp+8]
fld    DWORD PTR [esp+8]
add    esp, 16
pop    ebx
pop    esi
ret
v1.2023:
.long  305419896
.LC0:
.long  1077936128
.LC3:
.long  1082130432
.LC4:
.long  1232348160

```

100.6.4 Keil (ARM mode): Cortex-R4F CPU as target

```

f1    PROC
      LDR   r1, |L0.184|
      LDR   r0,[r1,#0] ; v1
      LDR   r2,|L0.188|
      VMOV.F32 s1,#3.00000000
      MUL   r0,r0,r2
      LDR   r2,|L0.192|
      ADD   r0,r0,r2
      STR   r0,[r1,#0] ; v1
      BFC   r0,#23,#9
      ORR   r0,r0,#0x40000000
      VMOV   s0,r0
      VSUB.F32 s0,s0,s1
      BX    lr
      ENDP

f    PROC

```

```

PUSH    {r4,r5,lr}
MOV     r4,#0
LDR     r5, |L0.196|
MOV     r3,r4
|L0.68|
BL      f1
VMOV.F32 s2,s0
BL      f1
VMOV.F32 s1,s2
ADD    r3,r3,#1
VMUL.F32 s1,s1,s1
VMLA.F32 s1,s0,s0
VMOV    r0,s1
CMP     r0,#0x3f800000
ADDLT   r4,r4,#1
CMP     r3,r5
BLT    |L0.68|
VMOV    s0,r4
VMOV.F64 d1,#4.00000000
VCVT.F32.S32 s0,s0
VCVT.F64.F32 d0,s0
VMUL.F64 d0,d0,d1
VLDR    d1, |L0.200|
VDIV.F64 d2,d0,d1
VCVT.F32.F64 s0,d2
POP    {r4,r5,pc}
ENDP

|L0.184|
DCD    |||.data||

|L0.188|
DCD    0x0019660d

|L0.192|
DCD    0x3c6ef35f

|L0.196|
DCD    0x000f4240

|L0.200|
DCFD   0x412e848000000000 ; 1000000
DCD    0x00000000
AREA  |||.data||, DATA, ALIGN=2
v1
DCD    0x12345678

```

100.6.5 Optimizing GCC 4.9.1 (ARM64)

Listing 100.8: Optimizing GCC 4.9.1 (ARM64)

```

f1:
    adrp    x2, .LANCHOR0
    mov     w3, 26125
    mov     w0, 62303
    movk   w3, 0x19, lsl 16
    movk   w0, 0x3c6e, lsl 16
    ldr    w1, [x2,:lo12:.LANCHOR0]
    fmov   s0, 3.0e+0
    madd   w0, w1, w3, w0
    str    w0, [x2,:lo12:.LANCHOR0]
    and    w0, w0, 8388607
    orr    w0, w0, 1073741824
    fmov   s1, w0
    fsub   s0, s1, s0
    ret

main_function:
    adrp    x7, .LANCHOR0
    mov     w3, 16960
    movk   w3, 0xf, lsl 16
    mov     w2, 0

```

```

fmov    s2, 3.0e+0
ldr     w1, [x7,#:lo12:.LANCHOR0]
fmov    s3, 1.0e+0
.L5:
    mov     w6, 26125
    mov     w0, 62303
    movk   w6, 0x19, lsl 16
    movk   w0, 0x3c6e, lsl 16
    mov     w5, 26125
    mov     w4, 62303
    madd   w1, w1, w6, w0
    movk   w5, 0x19, lsl 16
    movk   w4, 0x3c6e, lsl 16
    and    w0, w1, 8388607
    add    w6, w2, 1
    orr    w0, w0, 1073741824
    madd   w1, w1, w5, w4
    fmov   s0, w0
    and    w0, w1, 8388607
    orr    w0, w0, 1073741824
    fmov   s1, w0
    fsub   s0, s0, s2
    fsub   s1, s1, s2
    fmul   s1, s1, s1
    fmadd  s0, s0, s0, s1
    fcmp   s0, s3
    csel   w2, w2, w6, pl
    subs   w3, w3, #1
    bne    .L5
    scvtf  s0, w2
    str    w1, [x7,#:lo12:.LANCHOR0]
    fmov   d1, 4.0e+0
    fcvt   d0, s0
    fmul   d0, d0, d1
    ldr    d1, .LC0
    fdiv   d0, d0, d1
    fcvt   s0, d0
    ret
.LC0:
    .word   0
    .word   1093567616
v1:
    .word   1013904223
v2:
    .word   1664525
.LANCHOR0 = . + 0
v3.3095:
    .word   305419896

```

100.6.6 Optimizing GCC 4.4.5 (MIPS)

Listing 100.9: Optimizing GCC 4.4.5 (MIPS) (IDA)

```

f1:
    mov    eax, DWORD PTR v1.2084[rip]
    imul   eax, eax, 1664525
    add    eax, 1013904223
    mov    DWORD PTR v1.2084[rip], eax
    and    eax, 8388607
    or     eax, 1073741824
    mov    DWORD PTR [rsp-4], eax
    movss  xmm0, DWORD PTR [rsp-4]
    subss  xmm0, DWORD PTR .LC0[rip]
    ret
f:
    push   rbp
    xor    ebp, ebp
    push   rbx

```

```

        xor    ebx, ebx
        sub    rsp, 16
.L6:
        xor    eax, eax
        call   f1
        xor    eax, eax
        movss  DWORD PTR [rsp], xmm0
        call   f1
        movss  xmm1, DWORD PTR [rsp]
        mulss  xmm0, xmm0
        mulss  xmm1, xmm1
        lea    eax, [rbx+1]
        addss  xmm1, xmm0
        movss  xmm0, DWORD PTR .LC1[rip]
        ucomiss xmm0, xmm1
        cmova eax, eax
        add    ebp, 1
        cmp    ebp, 1000000
        jne    .L6
        cvtsi2ss      xmm0, ebx
        unpcklps      xmm0, xmm0
        cvtps2pd      xmm0, xmm0
        mulsd  xmm0, QWORD PTR .LC2[rip]
        divsd  xmm0, QWORD PTR .LC3[rip]
        add    rsp, 16
        pop    rbp
        pop    rbp
        unpcklpd      xmm0, xmm0
        cvtpd2ps      xmm0, xmm0
        ret
v1.2084:
        .long  305419896
.LC0:
        .long  1077936128
.LC1:
        .long  1065353216
.LC2:
        .long  0
        .long  1074790400
.LC3:
        .long  0
        .long  1093567616

```

100.7 Exercise 2.16

Well-known function. What does it compute? Why does the stack overflow if 4 and 2 are supplied at input? Is there any error?

100.7.1 Optimizing MSVC 2012 x64

```

m$ = 48
n$ = 56
f     PROC
$LN14:
        push   rbx
        sub    rsp, 32
        mov    eax, edx
        mov    ebx, ecx
        test   ecx, ecx
        je    SHORT $LN11@f
$LL5@f:
        test   eax, eax
        jne    SHORT $LN1@f
        mov    eax, 1
        jmp    SHORT $LN12@f

```

```

$LN1@f:
    lea      edx, DWORD PTR [rax-1]
    mov      ecx, ebx
    call     f
$LN12@f:
    dec      ebx
    test    ebx, ebx
    jne     SHORT $LL5@f
$LN11@f:
    inc      eax
    add      rsp, 32
    pop      rbx
    ret     0
f      ENDP

```

100.7.2 Optimizing Keil (ARM mode)

```

f PROC
    PUSH    {r4,lr}
    MOVS   r4,r0
    ADDEQ  r0,r1,#1
    POPEQ  {r4,pc}
    CMP    r1,#0
    MOVEQ  r1,#1
    SUBEQ  r0,r0,#1
    BEQ    |L0.48|
    SUB    r1,r1,#1
    BL     f
    MOV    r1,r0
    SUB    r0,r4,#1
|L0.48|
    POP    {r4,lr}
    B      f
    ENDP

```

100.7.3 Optimizing Keil (Thumb mode)

```

f PROC
    PUSH    {r4,lr}
    MOVS   r4,r0
    BEQ    |L0.26|
    CMP    r1,#0
    BEQ    |L0.30|
    SUBS  r1,r1,#1
    BL     f
    MOVS  r1,r0
|L0.18|
    SUBS  r0,r4,#1
    BL     f
    POP    {r4,pc}
|L0.26|
    ADDS  r0,r1,#1
    POP    {r4,pc}
|L0.30|
    MOVS  r1,#1
    B      |L0.18|
    ENDP

```

100.7.4 Non-optimizing GCC 4.9.1 (ARM64)

Listing 100.10: Non-optimizing GCC 4.9.1 (ARM64)

```
f:
```

```

    stp    x29, x30, [sp, -48]!
    add    x29, sp, 0
    str    x19, [sp,16]
    str    w0, [x29,44]
    str    w1, [x29,40]
    ldr    w0, [x29,44]
    cmp    w0, wzr
    bne   .L2
    ldr    w0, [x29,40]
    add    w0, w0, 1
    b     .L3
.L2:
    ldr    w0, [x29,40]
    cmp    w0, wzr
    bne   .L4
    ldr    w0, [x29,44]
    sub   w0, w0, #1
    mov    w1, 1
    bl    ack
    b     .L3
.L4:
    ldr    w0, [x29,44]
    sub   w19, w0, #1
    ldr    w0, [x29,40]
    sub   w1, w0, #1
    ldr    w0, [x29,44]
    bl    ack
    mov    w1, w0
    mov    w0, w19
    bl    ack
.L3:
    ldr    x19, [sp,16]
    ldp    x29, x30, [sp], 48
    ret

```

100.7.5 Optimizing GCC 4.9.1 (ARM64)

Optimizing GCC generates a lot more code. Why?

Listing 100.11: Optimizing GCC 4.9.1 (ARM64)

```

ack:
    stp    x29, x30, [sp, -160]!
    add    x29, sp, 0
    stp    d8, d9, [sp,96]
    stp    x19, x20, [sp,16]
    stp    d10, d11, [sp,112]
    stp    x21, x22, [sp,32]
    stp    d12, d13, [sp,128]
    stp    x23, x24, [sp,48]
    stp    d14, d15, [sp,144]
    stp    x25, x26, [sp,64]
    stp    x27, x28, [sp,80]
    cbz   w0, .L2
    sub   w0, w0, #1
    fmov  s10, w0
    b     .L4
.L46:
    fmov  w0, s10
    mov   w1, 1
    sub   w0, w0, #1
    fmov  s10, w0
    fmov  w0, s13
    cbz   w0, .L2
.L4:
    fmov  s13, s10
    cbz   w1, .L46
    sub   w1, w1, #1
    fmov  s11, s10

```

```

        b      .L7
.L48:
    fmov  w0, s11
    mov   w1, 1
    sub   w0, w0, #1
    fmov  s11, w0
    fmov  w0, s14
    cbz   w0, .L47
.L7:
    fmov  s14, s11
    cbz   w1, .L48
    sub   w1, w1, #1
    fmov  s12, s11
    b     .L10
.L50:
    fmov  w0, s12
    mov   w1, 1
    sub   w0, w0, #1
    fmov  s12, w0
    fmov  w0, s15
    cbz   w0, .L49
.L10:
    fmov  s15, s12
    cbz   w1, .L50
    sub   w1, w1, #1
    fmov  s8, s12
    b     .L13
.L52:
    fmov  w0, s8
    mov   w1, 1
    sub   w0, w0, #1
    fmov  s8, w0
    fmov  w0, s9
    cbz   w0, .L51
.L13:
    fmov  s9, s8
    cbz   w1, .L52
    sub   w1, w1, #1
    fmov  w22, s8
    b     .L16
.L54:
    mov   w1, 1
    sub   w22, w22, #1
    cbz   w28, .L53
.L16:
    mov   w28, w22
    cbz   w1, .L54
    sub   w1, w1, #1
    mov   w21, w22
    b     .L19
.L56:
    mov   w1, 1
    sub   w21, w21, #1
    cbz   w24, .L55
.L19:
    mov   w24, w21
    cbz   w1, .L56
    sub   w1, w1, #1
    mov   w20, w21
    b     .L22
.L58:
    mov   w1, 1
    sub   w20, w20, #1
    cbz   w25, .L57
.L22:
    mov   w25, w20
    cbz   w1, .L58
    sub   w1, w1, #1
    mov   w26, w20
    b     .L25

```

```

.L60:
    mov    w1, 1
    sub    w26, w26, #1
    cbz    w27, .L59
.L25:
    mov    w27, w26
    cbz    w1, .L60
    sub    w1, w1, #1
    mov    w19, w26
    b     .L28
.L62:
    mov    w23, w19
    mov    w1, 1
    sub    w19, w19, #1
    cbz    w23, .L61
.L28:
    add    w0, w19, 1
    cbz    w1, .L62
    sub    w1, w1, #1
    mov    w23, w19
    sub    w19, w19, #1
    bl    ack
    mov    w1, w0
    cbnz   w23, .L28
.L61:
    add    w1, w1, 1
    sub    w26, w26, #1
    cbnz   w27, .L25
.L59:
    add    w1, w1, 1
    sub    w20, w20, #1
    cbnz   w25, .L22
.L57:
    add    w1, w1, 1
    sub    w21, w21, #1
    cbnz   w24, .L19
.L55:
    add    w1, w1, 1
    sub    w22, w22, #1
    cbnz   w28, .L16
.L53:
    fmov   w0, s8
    add    w1, w1, 1
    sub    w0, w0, #1
    fmov   s8, w0
    fmov   w0, s9
    cbnz   w0, .L13
.L51:
    fmov   w0, s12
    add    w1, w1, 1
    sub    w0, w0, #1
    fmov   s12, w0
    fmov   w0, s15
    cbnz   w0, .L10
.L49:
    fmov   w0, s11
    add    w1, w1, 1
    sub    w0, w0, #1
    fmov   s11, w0
    fmov   w0, s14
    cbnz   w0, .L7
.L47:
    fmov   w0, s10
    add    w1, w1, 1
    sub    w0, w0, #1
    fmov   s10, w0
    fmov   w0, s13
    cbnz   w0, .L4
.L2:
    add    w0, w1, 1

```

```

ldp    d8, d9, [sp,96]
ldp    x19, x20, [sp,16]
ldp    d10, d11, [sp,112]
ldp    x21, x22, [sp,32]
ldp    d12, d13, [sp,128]
ldp    x23, x24, [sp,48]
ldp    d14, d15, [sp,144]
ldp    x25, x26, [sp,64]
ldp    x27, x28, [sp,80]
ldp    x29, x30, [sp], 160
ret

```

100.7.6 Non-optimizing GCC 4.4.5 (MIPS)

Listing 100.12: Non-optimizing GCC 4.4.5 (MIPS) (IDA)

```

f:          # CODE XREF: f+64
           # f+94 ...

var_C      = -0xC
var_8       = -8
var_4       = -4
arg_0      = 0
arg_4      = 4

addiu   $sp, -0x28
sw      $ra, 0x28+var_4($sp)
sw      $fp, 0x28+var_8($sp)
sw      $s0, 0x28+var_C($sp)
move   $fp, $sp
sw      $a0, 0x28+arg_0($fp)
sw      $a1, 0x28+arg_4($fp)
lw      $v0, 0x28+arg_0($fp)
or      $at, $zero
bnez   $v0, loc_40
or      $at, $zero
lw      $v0, 0x28+arg_4($fp)
or      $at, $zero
addiu   $v0, 1
b      loc_AC
or      $at, $zero

loc_40:      # CODE XREF: f+24
lw      $v0, 0x28+arg_4($fp)
or      $at, $zero
bnez   $v0, loc_74
or      $at, $zero
lw      $v0, 0x28+arg_0($fp)
or      $at, $zero
addiu   $v0, -1
move   $a0, $v0
li      $a1, 1
jal    f
or      $at, $zero
b      loc_AC
or      $at, $zero

loc_74:      # CODE XREF: f+48
lw      $v0, 0x28+arg_0($fp)
or      $at, $zero
addiu   $s0, $v0, -1
lw      $v0, 0x28+arg_4($fp)
or      $at, $zero
addiu   $v0, -1
lw      $a0, 0x28+arg_0($fp)
move   $a1, $v0
jal    f
or      $at, $zero

```

```

move    $a0, $s0
move    $a1, $v0
jal     f
or     $at, $zero

loc_AC:                                # CODE XREF: f+38
                                         # f+6C
move    $sp, $fp
lw      $ra, 0x28+var_4($sp)
lw      $fp, 0x28+var_8($sp)
lw      $s0, 0x28+var_C($sp)
addiu   $sp, 0x28
jr     $ra
or     $at, $zero

```

100.8 Exercise 2.17

This program prints some information to [stdout](#), each time different. What is that?

Compiled binaries:

- [Linux x64 \(beginners.re\)](#)
- [Mac OS X \(beginners.re\)](#)
- [Linux MIPS \(beginners.re\)](#)
- [Win32 \(beginners.re\)](#)
- [Win64 \(beginners.re\)](#)

As for the Windows versions, you may need to install [MSVC 2012 redist](#).

100.9 Exercise 2.18

This program requires a password. Find it.

By the way, multiple passwords may work. Try to find them.

As an additional exercise, try to change the password by patching the executable file.

- [Win32 \(beginners.re\)](#)
- [Linux x86 \(beginners.re\)](#)
- [Mac OS X \(beginners.re\)](#)
- [Linux MIPS \(beginners.re\)](#)

100.10 Exercise 2.19

The same as in exercise 2.18.

- [Win32 \(beginners.re\)](#)
- [Linux x86 \(beginners.re\)](#)
- [Mac OS X \(beginners.re\)](#)
- [Linux MIPS \(beginners.re\)](#)

100.11 Exercise 2.20

This program prints some numbers to [stdout](#). What is it?

Compiled binaries:

- [Linux x64 \(beginners.re\)](#)

- Mac OS X ([beginners.re](#))
- Linux ARM Raspberry Pi ([beginners.re](#))
- Linux MIPS ([beginners.re](#))
- Win64 ([beginners.re](#))

Chapter 101

Level 3

For solving level 3 tasks, you'll probably need a considerable amount of time, maybe up to one day.

101.1 Exercise 3.2

There is a small executable file with a well-known cryptosystem inside. Try to identify it.

- [Windows x86 \(beginners.re\)](#)
- [Linux x86 \(beginners.re\)](#)
- [Mac OS X \(x64\) \(beginners.re\)](#)
- [Linux MIPS \(beginners.re\)](#)

101.2 Exercise 3.3

There is a small executable file, some utility. It opens another file, reads it, calculate something and prints a [real number](#). Try to understand what it does.

- [Windows x86 \(beginners.re\)](#)
- [Linux x86 \(beginners.re\)](#)
- [Mac OS X \(x64\) \(beginners.re\)](#)
- [Linux MIPS \(beginners.re\)](#)

101.3 Exercise 3.4

There is an utility which encrypts/decrypts files using a password. There is an encrypted text file, the password is unknown. The encrypted file is a text in the English language. The utility uses a relatively strong cryptosystem, nevertheless, it was implemented with a serious blunder. With the mistake present, it is possible to decrypt the file with a little effort.

Try to find the mistake and decrypt the file.

- [Windows x86 \(beginners.re\)](#)
- Text file: <http://go.yurichev.com/17197>

101.4 Exercise 3.5

This is a software copy protection imitation, which uses a key file. The key file contain a user (or customer) name and a serial number.

There are two tasks:

- (Easy) with the help of [tracer](#) or any other debugger, force the program to accept a changed key file.
- (Medium) your goal is to modify the user name to another, without patching the program.

- Windows x86 ([beginners.re](#))
- Linux x86 ([beginners.re](#))
- Mac OS X (x64) ([beginners.re](#))
- Linux MIPS ([beginners.re](#))
- Key file: [beginners.re](#)

101.5 Exercise 3.6

Here is a very primitive toy web-server that supports only static files, without CGI¹,etc. At least 4 vulnerabilities are left here intentionally. Try to find them all and exploit them in order to break into a remote host.

- Windows x86 ([beginners.re](#))
- Linux x86 ([beginners.re](#))
- Mac OS X (x64) ([beginners.re](#))

101.6 Exercise 3.8

It's a well known data compression algorithm. However, due to a mistake (or typo), it decompresses incorrectly. Here we can see this bug in these examples.

This is a text used as a source: [beginners.re](#)

This is the text compressed correctly: [beginners.re](#)

This is the incorrectly uncompressed text: [beginners.re](#).

Try to find and fix the bug. With some effort, it can be done even by patching the binary.

- Windows x86 ([beginners.re](#))
- Linux x86 ([beginners.re](#))
- Mac OS X (x64) ([beginners.re](#))

¹Common Gateway Interface

Chapter 102

crackme / keygenme

Couple of my [keygenmes](#):

<http://go.yurichev.com/17315>

Afterword

Chapter 103

Questions?

Do not hesitate to mail any questions to the author: <dennis(a)yurichev.com>

Any suggestions what also should be added to my book?

Please, do not hesitate to send me 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

7th (byte number)	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

7th (byte number)	6th	5th	4th	3rd	2nd	1st	0th
RBX ^{x64}							
						EBX	
						BX	
						BH BL	

A.2.3 RCX/ECX/CX/CL

7th (byte number)	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

7th (byte number)	6th	5th	4th	3rd	2nd	1st	0th
RDX ^{x64}							
						EDX	
						DX	
						DH DL	

A.2.5 RSI/ESI/SI/SIL

7th (byte number)	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

7th (byte number)	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

7th (byte number)	6th	5th	4th	3rd	2nd	1st	0th
R8							
						R8D	
						R8W	
						R8L	

A.2.8 R9/R9D/R9W/R9L

7th (byte number)	6th	5th	4th	3rd	2nd	1st	0th
			R9				
					R9D		
						R9W	
							R9L

A.2.9 R10/R10D/R10W/R10L

7th (byte number)	6th	5th	4th	3rd	2nd	1st	0th
			R10				
					R10D		
						R10W	
							R10L

A.2.10 R11/R11D/R11W/R11L

7th (byte number)	6th	5th	4th	3rd	2nd	1st	0th
			R11				
					R11D		
						R11W	
							R11L

A.2.11 R12/R12D/R12W/R12L

7th (byte number)	6th	5th	4th	3rd	2nd	1st	0th
			R12				
					R12D		
						R12W	
							R12L

A.2.12 R13/R13D/R13W/R13L

7th (byte number)	6th	5th	4th	3rd	2nd	1st	0th
			R13				
					R13D		
						R13W	
							R13L

A.2.13 R14/R14D/R14W/R14L

7th (byte number)	6th	5th	4th	3rd	2nd	1st	0th
			R14				
					R14D		
						R14W	
							R14L

A.2.14 R15/R15D/R15W/R15L

7th (byte number)	6th	5th	4th	3rd	2nd	1st	0th
			R15				
					R15D		
						R15W	
							R15L

A.2.15 RSP/ESP/SP/SPL

7th (byte number)	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

7th (byte number)	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: ([7.1.2 on page 61](#)).

A.2.17 RIP/EIP/IP

7th (byte number)	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 ([94 on page 901](#)).

A.2.19 Flags register

AKA **EFLAGS**.

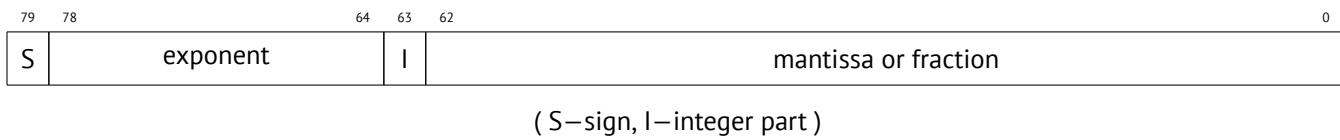
¹Sometimes also called “program counter”

Bit (mask)	Abbreviation (meaning)	Description
0 (1)	CF (Carry)	The CLC/STC/CMC instructions are used for setting/resetting/toggling this flag
2 (4)	PF (Parity)	(17.7.1 on page 230).
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:



A.3.1 Control Word

Register controlling the behaviour of the FPU.

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: ([17.7.1 on page 229](#)).

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:

- 00 – The register contains a non-zero value
- 01 – The register contains 0
- 10 – The register contains a special value ([NAN](#)², ∞ , 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 951](#)).

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 ([90 on page 890](#)).

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 ([89.2 on page 889](#)). 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 ([68.4 on page 732](#)).

REP is used with the MOV\$ and STOS\$ 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 MOV\$ ([A.6.2 on page 957](#)) and STOS\$ ([A.6.2 on page 959](#)) instructions.

The instructions prefixed by REP are sensitive to the DF flag, which is used to set the direction.

REPE/REPNE (AKA REPZ/REPNZ) used with CMPS\$ and SCAS\$ 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 960](#)) and SCASx ([A.6.2 on page 958](#)) 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: [24 on page 412](#).

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](#). The CF flag is not modified.

IMUL signed multiply

INC [increment](#). The CF flag is not modified.

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

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

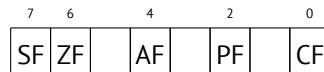
JPO jump if PF flag is cleared (Jump Parity Odd)

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
```

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.

³See also: [wikipedia](#)

Together with the REP prefix, it is to be repeated in a loop, the count is to be stored in the CX/ECX/RCX register: it works like `memcpy()` in C. If the block size is known to the compiler in the compile stage, `memcpy()` is often inlined into a short code fragment using REP MOVSx, sometimes even as several instructions.

The `memcpy(EDI, ESI, 15)` equivalent is:

```
; copy 15 bytes from ESI to EDI
CLD          ; set direction to "forward"
MOV ECX, 3
REP MOVSD   ; copy 12 bytes
MOVSW       ; copy 2 more bytes
MOVS     ; copy remaining byte
```

(Supposedly, it works faster than copying 15 bytes using just one REP MOVSb).

MOVSX load with sign extension see also: ([15.1.1 on page 195](#))

MOVZX load and clear all other bits see also: ([15.1.1 on page 195](#))

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

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: [6.1.1 on page 42](#).

More examples of such operations: ([88 on page 887](#)).

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

OR logical “or”

POP get a value from the stack: $value=SS:[ESP]$; $ESP=ESP+4$ (or 8)

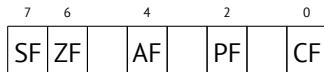
PUSH push a value into the stack: $ESP=ESP-4$ (or 8); $SS:[ESP]=value$

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 ([94 on page 901](#)), 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: [64.2 on page 681](#).

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
```

One more example: [24 on page 412](#).

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/EDX/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 [ASCII](#) 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 ASCII string.

; lets determine string length'
; current ECX = -1-strlen

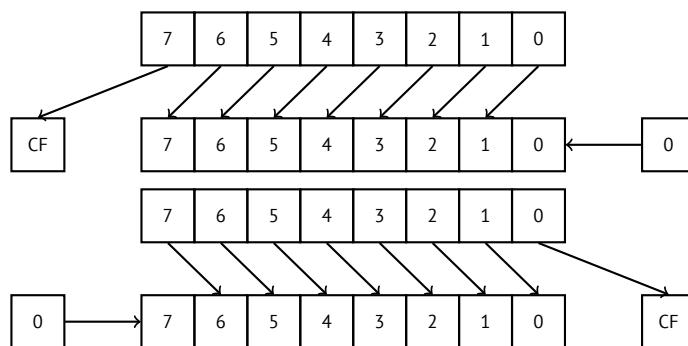
not   ecx
dec   ecx

; 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: [19 on page 312](#).

SHRD op1, op2, op3: shift value in op2 right by op3 bits, taking bits from op1.

Example: [24 on page 412](#).

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).

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: [19 on page 312](#)

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*.

⁴eXclusive OR

XOR is widely used when one need just to flip specific bit(s). Indeed, the XOR operation applied with 1 is effectively inverting a bit:

input A	input B	output
0	0	0
0	1	1
1	0	1
1	1	0

And on the contrary, 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.

A.6.3 Less frequently used instructions

BSF bit scan forward, see also: [25.2 on page 435](#)

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: [24.5 on page 421](#).

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 956](#)).

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
; )
```

```

; 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                ; clear direction
    mov     esi,RcmSource1 ; (esi) -> first block to compare
    mov     edi,RcmSource2 ; (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

;
; 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: ([21.6.1 on page 380](#)).

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 ([66 on page 694](#)), 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 ([78.3 on page 779](#)).

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.

OUT (M) output data to port. The instruction usually can be seen in OS drivers or in old MS-DOS code, for example ([78.3 on page 779](#)).

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.

⁵Microsoft Visual Studio

⁶[MSDN](#)

⁷[MSDN](#)

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 encryption 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.

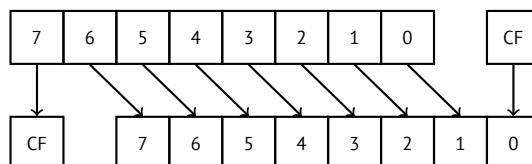
[Sch94]

POPF restore flags from the stack (AKA EFLAGS register)

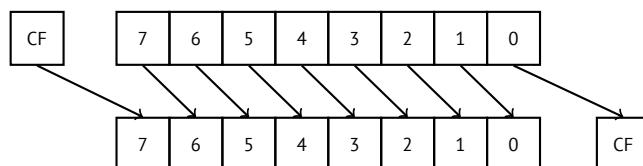
PUSHA (M) pushes the values of the (R|E)AX, (R|E)CX, (R|E)DX, (R|E)BX, (R|E)BP, (R|E)SI, (R|E)DI registers to the stack.

PUSHF push flags (AKA EFLAGS register)

RCL (M) rotate left via CF flag:

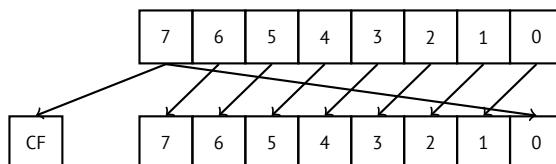


RCR (M) rotate right via CF flag:

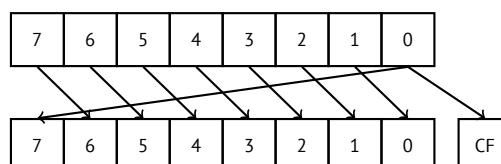


ROL/ROR (M) cyclic shift

ROL: rotate left:



ROR: rotate right:

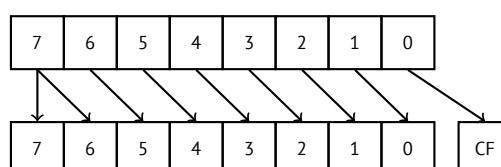


Despite the fact that almost all CPUs have these instructions, there are no corresponding operations in C/C++, so the compilers of these PLs usually do not generate these instructions.

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



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 956).

⁸MSDN

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 ([66 on page 694](#))**SYSENTER** (Intel) call syscall ([66 on page 694](#))**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 952](#)) from 16-bit op.**FLDZ** push zero to stack**FLD** op: push op to the stack.**FMUL** op: ST(0)=ST(0)*op**FMUL** ST(i), ST(j): ST(i)=ST(i)*ST(j)**FMULP** op: ST(0)=ST(0)*op; pop one element from the stack**FMULP** ST(i), ST(j): ST(i)=ST(i)*ST(j); pop one element from the stack**FSINCOS** : tmp=ST(0); ST(1)=sin(tmp); ST(0)=cos(tmp)**FSQRT** : ST(0) = $\sqrt{ST(0)}$ **FSTCW** op: store FPU control word ([A.3 on page 952](#)) into 16-bit op after checking for pending exceptions.**FNSTCW** op: store FPU control word ([A.3 on page 952](#)) into 16-bit op.**FSTSW** op: store FPU status word ([A.3.2 on page 953](#)) into 16-bit op after checking for pending exceptions.**FNSTSW** op: store FPU status word ([A.3.2 on page 953](#)) 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: [8.2.1 on page 840](#).

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
a	60	PUSHA
f	61	POPA
	66	(in 32-bit mode) switch to 16-bit operand size
g	67	in 32-bit mode) switch to 16-bit address size
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)
- X30—“Procedure Link Register” **AKA LR (link register)**.

- X31—register always contains zero **AKA** XZR or “Zero Register”. Its 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 are not modified 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

ll 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 [script](#)¹ for hiding some often used patterns of inline code.

F.2 OllyDbg

Hot-keys cheatsheet:

hot-key	meaning
F7	trace into
F8	step over
F9	run
Ctrl-F2	restart

¹[GitHub](#)

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 MSVCR*.DLL

Some information about MSVC versions: [55.1 on page 659](#).

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
r	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

Appendix G

Exercise solutions

G.1 Per chapter

G.1.1 “Hello, world!” chapter

Exercise #1

Exercise: [3.7.1 on page 22](#).

```
MessageBeep (0xFFFFFFFF); // A simple beep. If the sound card is not available, the sound is ↴
                           ↴ generated using the speaker.
```

Exercise #2

Exercise: [3.7.2 on page 22](#).

```
#include <unistd.h>

int main()
{
    sleep(2);
}
```

G.1.2 “Stack” chapter

Exercise #1

Exercise: [5.5.1 on page 33](#).

In Non-optimizing MSVC, these numbers are: the saved EBP value, [RA](#) and argc. It's easy to check that by running the example with a different number of arguments on the command line.

In Optimizing MSVC, these numbers are: [RA](#), argc and a pointer to the argv[] array.

GCC 4.8.x allocates 16-byte space in main() function's prologue, hence the different output numbers.

Exercise #2

Exercise: [5.5.2 on page 33](#).

This code prints the UNIX time.

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

int main()
{
    printf ("%d\n", time(NULL));
}
```

G.1.3 “scanf()” chapter

Exercise #1

Exercise: [7.4.1 on page 89.](#)

GCC for Linux places all text strings info .rodata data segment, which is explicitly read-only (“read only data”):

```
$ objdump -s 1

...
Contents of section .rodata:
400600 01000200 52657375 6c743a20 25730a00 ....Result: %s..
400610 48656c6c 6f2c2077 6f726c64 210a00    Hello, world!..
```

When alter_string() function tries to write there, exception occurred.

Things are different in the code generated by MSVC, strings are located in .data segment, which has no READONLY flag:

```
C:\...>objdump -s 1.exe

...
Contents of section .data:
40b000 476f6f64 62796521 00000000 52657375 Goodbye!....Resu
40b010 6c743a20 25730a00 48656c6c 6f2c2077 lt: %s..Hello, w
40b020 6f726c64 210a0000 00000000 00000000 orld!.....
40b030 01000000 00000000 c0cb4000 00000000 .....@.....
...
C:\...>objdump -x 1.exe

...
Sections:
Idx Name      Size    VMA       LMA       File off  Algn
 0 .text      00006d2a 00401000 00401000 00000400 2**2
              CONTENTS, ALLOC, LOAD, READONLY, CODE
 1 .rdata     00002262 00408000 00408000 00007200 2**2
              CONTENTS, ALLOC, LOAD, READONLY, DATA
 2 .data      00000e00 0040b000 0040b000 00009600 2**2
              CONTENTS, ALLOC, LOAD, DATA
 3 .reloc     00000b98 0040e000 0040e000 0000a400 2**2
              CONTENTS, ALLOC, LOAD, READONLY, DATA
```

G.1.4 “switch()/case/default” chapter

G.1.5 Exercise #1

Exercise: [13.5.1 on page 174.](#)

Hint: printf() may be called only from a single place.

G.1.6 “Loops” chapter

G.1.7 Exercise #3

Exercise: [14.4.3 on page 189.](#)

```
#include <stdio.h>

int main()
{
    int i;
    for (i=100; i>0; i--)
```

```
        printf ("%d\n", i);
};
```

G.1.8 Exercise #4

Exercise: [14.4.4 on page 191](#).

```
#include <stdio.h>

int main()
{
    int i;
    for (i=1; i<100; i=i+3)
        printf ("%d\n", i);
};
```

G.1.9 “Simple C-strings processing” chapter

Exercise #1

Exercise: [15.2.1 on page 204](#).

This is a function that counts spaces in the input C string.

```
int f(char *s)
{
    int rt=0;
    for (;*s;s++)
    {
        if (*s==' ')
            rt++;
    };
    return rt;
};
```

G.1.10 “Replacing arithmetic instructions to other ones” chapter

Exercise #2

Exercise: [16.3.1 on page 212](#).

```
int f(int a)
{
    return a*7;
};
```

G.1.11 “Floating-point unit” chapter

Exercise #1

Exercise: [17.10.2 on page 261](#).

Calculates the arithmetic mean for 5 *double* values.

```
double f(double a1, double a2, double a3, double a4, double a5)
{
    return (a1+a2+a3+a4+a5) / 5;
};
```

6.1.12 “Arrays” chapter

Exercise #1

Exercise: [18.9.1 on page 298](#).

Solution: addition of two 100*200 matrices of type *double*.

C/C++ source code:

```
#define M    100
#define N    200

void s(double *a, double *b, double *c)
{
    for(int i=0;i<N;i++)
        for(int j=0;j<M;j++)
            *(c+i*M+j)=*(a+i*M+j) + *(b+i*M+j);
}
```

Exercise #2

Exercise: [18.9.2 on page 301](#).

Solution: multiplication of two matrices (one is 100*200, second is 100*300) of type *double*, result: 100*300 matrix.

C/C++ source code:

```
#define M    100
#define N    200
#define P    300

void m(double *a, double *b, double *c)
{
    for(int i=0;i<M;i++)
        for(int j=0;j<P;j++)
    {
        *(c+i*M+j)=0;
        for (int k=0;k<N;k++) *(c+i*M+j)+=*(a+i*M+j) * *(b+i*M+j);
    }
}
```

Exercise #3

Exercise: [18.9.3 on page 305](#).

```
double f(double array[50][120], int x, int y)
{
    return array[x][y];
}
```

Exercise #4

Exercise: [18.9.4 on page 306](#).

```
int f(int array[50][60][80], int x, int y, int z)
{
    return array[x][y][z];
}
```

Exercise #5

Exercise: [18.9.5 on page 307](#).

This code just calculates the multiplication table.

```
int tbl[10][10];

int main()
{
    int x, y;
    for (x=0; x<10; x++)
        for (y=0; y<10; y++)
            tbl[x][y]=x*y;
}
```

G.1.13 “Manipulating specific bit(s)” chapter**Exercise #1**

Exercise: [19.7.1 on page 345](#). This is a function, which changes the [endianness](#) of a 32-bit value.

```
unsigned int f(unsigned int a)
{
    return ((a>>24)&0xff) | ((a<<8)&0xff0000) | ((a>>8)&0xff00) | ((a<<24)&0xff000000);
}
```

Additional question: a x86 instruction can do this. Which one?

Exercise #2

Exercise: [19.7.2 on page 346](#).

This function converts a [BCD](#)-packed 32-bit value into a normal one.

```
#include <stdio.h>

unsigned int f(unsigned int a)
{
    int i=0;
    int j=1;
    unsigned int rt=0;
    for (;i<=28; i+=4, j*=10)
        rt+=((a>>i)&0xF) * j;
    return rt;
};

int main()
{
    // test
    printf ("%d\n", f(0x12345678));
    printf ("%d\n", f(0x1234567));
    printf ("%d\n", f(0x123456));
    printf ("%d\n", f(0x12345));
    printf ("%d\n", f(0x1234));
    printf ("%d\n", f(0x123));
    printf ("%d\n", f(0x12));
    printf ("%d\n", f(0x1));
}
```

Exercise #3

Exercise: [19.7.3 on page 349](#).

```
#include <windows.h>

int main()
{
    MessageBox(NULL, "hello, world!", "caption",
               MB_TOPMOST | MB_ICONINFORMATION | MB_HELP | MB_YESNOCANCEL);
}
```

Exercise #4

Exercise: [19.7.4 on page 349](#).

This function just multiplies two 32-bit numbers, returning a 64-bit `product`. This is a case when the simple observation of inputs and outputs may solve the problem faster.

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

// source code taken from
// http://www4.wittenberg.edu/academics/mathcomp/shelburne/comp255/notes/binarymultiplication.✓
// ↴ pdf

uint64_t mult (uint32_t m, uint32_t n)
{
    uint64_t p = 0; // initialize product p to 0
    while (n != 0) // while multiplier n is not 0
    {
        if (n & 1) // test LSB of multiplier
            p = p + m; // if 1 then add multiplicand m
        m = m << 1; // left shift multiplicand
        n = n >> 1; // right shift multiplier
    }
    return p;
}

int main()
{
    printf ("%d\n", mult (2, 7));
    printf ("%d\n", mult (3, 11));
    printf ("%d\n", mult (4, 111));
}
```

G.1.14 “Structures” chapter**Exercise #1**

Exercise: [21.7.1 on page 387](#).

This program shows the user ID of the file's owner.

```
#include <sys/types.h>
#include <sys/stat.h>
#include <time.h>
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char *argv[])
{
    struct stat sb;

    if (argc != 2)
    {
        fprintf(stderr, "Usage: %s <pathname>\n", argv[0]);
        return 0;
    }
```

```

if (stat(argv[1], &sb) == -1)
{
    // error
    return 0;
}

printf("%ld\n", (long) sb.st_uid);
}

```

Exercise #1

Exercise: [21.7.2 on page 387](#).

Hint (x86): you may get some information from how the values are treated by the Jcc, MOVSX and MOVZX instructions.

```

#include <stdio.h>

struct some_struct
{
    int a;
    unsigned int b;
    float f;
    double d;
    char c;
    unsigned char uc;
};

void f(struct some_struct *s)
{
    if (s->a > 1000)
    {
        if (s->b > 10)
        {
            printf ("%f\n", s->f * 444 + s->d * 123);
            printf ("%c, %d\n", s->c, s->uc);
        }
        else
        {
            printf ("error #2\n");
        };
    }
    else
    {
        printf ("error #1\n");
    };
}

```

G.1.15 “Obfuscation” chapter**Exercise #1**

Exercise: [50.5.1 on page 554](#).

Source code: [beginners.re](#).

G.1.16 “Division by 9” chapter**Exercise #1**

Exercise: [41.6 on page 506](#).

```

int f(int a)
{
    return a/661;
}

```

G.2 Level 1

G.2.1 Exercise 1.1

That is a function that returns the maximal value from two.

G.2.2 Exercise 1.4

Source code: [beginners.re](#)

G.3 Level 2

G.3.1 Exercise 2.1

This function calculates a square root by Newton's method, the algorithm is taken from [ASS96].

Source code: [beginners.re](#)

G.3.2 Exercise 2.4

Solution: `strstr()`.

C source code:

```
char * strstr (
    const char * str1,
    const char * str2
)
{
    char *cp = (char *) str1;
    char *s1, *s2;

    if ( !*str2 )
        return((char *)str1);

    while (*cp)
    {
        s1 = cp;
        s2 = (char *) str2;

        while ( *s1 && *s2 && !( *s1-*s2 ) )
            s1++, s2++;

        if ( !*s2 )
            return(cp);

        cp++;
    }

    return(NULL);
}
```

G.3.3 Exercise 2.6

Hint: it might be helpful to google the constant used here.

Solution: [TEA¹](#) encryption algorithm.

C source code (taken from [wikipedia](#)):

¹Tiny Encryption Algorithm

```

void f (unsigned int* v, unsigned int* k) {
    unsigned int v0=v[0], v1=v[1], sum=0, i;          /* set up */
    unsigned int delta=0x9e3779b9;                  /* a key schedule constant */
    unsigned int k0=k[0], k1=k[1], k2=k[2], k3=k[3]; /* cache key */
    for (i=0; i < 32; i++) {                         /* basic cycle start */
        sum += delta;
        v0 += ((v1<<4) + k0) ^ (v1 + sum) ^ ((v1>>5) + k1);
        v1 += ((v0<<4) + k2) ^ (v0 + sum) ^ ((v0>>5) + k3);
    }                                                 /* end cycle */
    v[0]=v0; v[1]=v1;
}

```

G.3.4 Exercise 2.13

The cryptographic algorithm is a linear feedback shift register ².

Source code: [beginners.re](#)

G.3.5 Exercise 2.14

This is an algorithm for finding the greater common divisor (GCD).

Source code: [beginners.re](#)

G.3.6 Exercise 2.15

Pi value calculation using the Monte-Carlo method.

Source code: [beginners.re](#)

G.3.7 Exercise 2.16

It is the Ackermann function ³.

```

int ack (int m, int n)
{
    if (m==0)
        return n+1;
    if (n==0)
        return ack (m-1, 1);
    return ack(m-1, ack (m, n-1));
}

```

G.3.8 Exercise 2.17

This is 1D cellular automaton working by *Rule 110*:
[wikipedia](#).

Source code: [beginners.re](#)

G.3.9 Exercise 2.18

Source code: [beginners.re](#)

G.3.10 Exercise 2.19

Source code: [beginners.re](#)

²[wikipedia](#)

³[wikipedia](#)

G.3.11 Exercise 2.20

Hint: the On-Line Encyclopedia of Integer Sequences (OEIS)) may help.

Answer: these are *hailstone numbers*, which relate to the Collatz conjecture⁴.

Source code: [beginners.re](#)

G.4 Level 3

G.4.1 Exercise 3.2

Hint: the easiest way is to search by value in the tables.

Commented C source code:
[beginners.re](#)

G.4.2 Exercise 3.3

Commented C source code:
[beginners.re](#)

G.4.3 Exercise 3.4

Commented C source code, and also the decrypted file: [beginners.re](#)

G.4.4 Exercise 3.5

Hint: as we can see, the string with the user name does not occupy the whole file.

Bytes after the terminating zero till offset 0x7F are ignored by the program.

Commented C source code:
[beginners.re](#)

G.4.5 Exercise 3.6

Commented C source code:
[beginners.re](#)

As another exercise, now you may try to fix all the vulnerabilities you found in this web server.

G.4.6 Exercise 3.8

Commented C source code:
[beginners.re](#)

G.5 Other

G.5.1 “Minesweeper (Windows XP)” example

Example: [76 on page 750](#).

Hint: think about *border bytes* (0x10).

⁴[wikipedia](#)

Acronyms used

OS Operating System	xxi
OOP Object-Oriented Programming	556
PL Programming language	3
PRNG Pseudorandom number generator	xii
ROM Read-only memory	73
ALU Arithmetic logic unit	19
RA Return Address	16
PE Portable Executable: 68.2 on page 704	704
SP stack pointer. SP/ESP/RSP in x86/x64. SP in ARM	13
DLL Dynamic-link library	704
PC Program Counter. IP/EIP/RIP in x86/64. PC in ARM	13
LR Link Register	6
IDA Interactive Disassembler and debugger developed by Hex-Rays	6
IAT Import Address Table	705
INT Import Name Table	705
RVA Relative Virtual Address	704
VA Virtual Address	704
OEP Original Entry Point	693
MSVC Microsoft Visual C++	
MSVS Microsoft Visual Studio	962
ASLR Address Space Layout Randomization	705
MFC Microsoft Foundation Classes	707
TLS Thread Local Storage	xx
AKA Also Known As	
CRT C runtime library : 68.1 on page 701	8
CPU Central processing unit	xxi

FPU Floating-point unit	vii
CISC Complex instruction set computing	13
RISC Reduced instruction set computing	3
GUI Graphical user interface	701
RTTI Run-time type information	570
BSS Block Started by Symbol	18
SIMD Single instruction, multiple data	185
BSOD Black Screen of Death	694
DBMS Database management systems	xx
ISA Instruction Set Architecture	iii
CGI Common Gateway Interface	943
HPC High-Performance Computing	526
SEH Structured Exception Handling : 68.3 on page 710	29
ELF Executable file format widely used in *NIX systems including Linux	xx
TIB Thread Information Block	279
TEA Tiny Encryption Algorithm	984
PIC Position Independent Code: 67.1 on page 696	xx
NAN Not a Number	954
NOP No OPeration	20
BEQ (PowerPC, ARM) Branch if Equal	87
BNE (PowerPC, ARM) Branch if Not Equal	202
BLR (PowerPC) Branch to Link Register	764
XOR eXclusive OR	959
MCU Microcontroller unit	499
RAM Random-access memory	74
EGA Enhanced Graphics Adapter	901

VGA Video Graphics Array	901
API Application programming interface	662
ASCII American Standard Code for Information Interchange	508
ASCIIZ ASCII Zero (null-terminated ASCII string)	85
IA64 Intel Architecture 64 (Itanium): 93 on page 898	467
EPIC Explicitly parallel instruction computing	898
OoE Out-of-order execution	469
MSDN Microsoft Developer Network	349
MSB Most significant bit/byte	324
LSB Least significant bit/byte	
STL (C++) Standard Template Library: 51.4 on page 572	577
PODT (C++) Plain Old Data Type	588
HDD Hard disk drive	599
VM Virtual Memory	
WRK Windows Research Kernel	675
GPR General Purpose Registers	xviii
SSDT System Service Dispatch Table	694
RE Reverse Engineering	ii
BCD Binary-coded decimal	843
BOM Byte order mark	665
GDB GNU debugger	41
FP Frame Pointer	17
MBR Master Boot Record	670
JPE Jump Parity Even (x86 instruction)	234
CIDR Classless Inter-Domain Routing	487
STMFD Store Multiple Full Descending (ARM instruction)	

LDMFD Load Multiple Full Descending (ARM instruction)

STMED Store Multiple Empty Descending (ARM instruction)	24
LDMED Load Multiple Empty Descending (ARM instruction)	24
STMFA Store Multiple Full Ascending (ARM instruction)	24
LDMFA Load Multiple Full Ascending (ARM instruction)	24
STMEA Store Multiple Empty Ascending (ARM instruction)	24
LDMEA Load Multiple Empty Ascending (ARM instruction)	24
APSR (ARM) Application Program Status Register	257
FPSCR (ARM) Floating-Point Status and Control Register	257
PID Program/process ID	754
LF Line feed (10 or '\n' in C/C++)	534
CR Carriage return (13 or '\r' in C/C++)	534
RFC Request for Comments	668
TOS Top Of Stack	621
LVA (Java) Local Variable Array	627
JVM Java virtual machine	xii
JIT Just-in-time compilation	620
EOF End of file	78

Glossary

real number numbers which may contain a dot. this is *float* and *double* in C/C++. [212](#), [941](#)

decrement Decrease by 1. [13](#), [175](#), [196](#), [456](#), [677](#), [805](#), [955](#), [957](#), [961](#)

increment Increase by 1. [14](#), [175](#), [179](#), [196](#), [201](#), [332](#), [335](#), [456](#), [801](#), [955](#)

integral data type usual numbers, but not a real ones. may be used for passing variables of boolean data type and enumerations. [228](#)

product Multiplication result. [91](#), [220](#), [223](#), [423](#), [448](#), [503](#), [981](#)

arithmetic mean a sum of all values divided by their count . [528](#)

stack pointer A register pointing to a place in the stack. [8](#), [9](#), [14](#), [24](#), [27](#), [36](#), [48](#), [49](#), [67](#), [92](#), [557](#), [608](#), [680–683](#), [950](#), [956](#), [966](#), [987](#)

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](#). [482](#)

quotient Division result. [212](#), [216](#), [218](#), [219](#), [223](#), [447](#), [500](#), [529](#), [757](#)

anti-pattern Generally considered as bad practice. [26](#), [69](#), [467](#)

atomic operation “*ατομός*” stands for “indivisible” in Greek, so an atomic operation is guaranteed not to be interrupted by other threads. [731](#), [894](#)

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 . [647](#), [901](#), [902](#)

callee A function being called by another. [23](#), [26](#), [40](#), [60](#), [78](#), [90](#), [92](#), [94](#), [146](#), [435](#), [467](#), [557](#), [608](#), [680–682](#), [685](#), [686](#), [969](#)

caller A function calling another. [5](#), [6](#), [8](#), [40](#), [78](#), [90](#), [91](#), [93](#), [100](#), [146](#), [435](#), [471](#), [557](#), [680](#), [682](#), [683](#), [686](#)

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: ([90](#) on page [890](#)). [961](#)

CP/M Control Program for Microcomputers: a very basic disk [OS](#) used before MS-DOS. [840](#)

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. [762](#)

endianness Byte order: [31 on page 466](#). [15](#), [71](#), [358](#), [959](#), [980](#)

GiB Gibibyte: 2^{30} or 1024 mebibytes or 1073741824 bytes. [11](#)

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. [24](#), [26](#), [359](#), [572](#), [575](#), [587](#), [589](#), [702](#), [703](#)

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. [86](#), [125](#), [955](#)

kernel mode A restrictions-free CPU mode in which the OS kernel and drivers execute. cf. [user mode](#). [992](#)

keygenme A program which imitates software protection, for which one needs to make a key/license generator. [943](#)

leaf function A function which does not call any other function. [21](#), [26](#)

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. [26](#), [763](#), [966](#), [967](#)

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. [177](#)

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: [51.1.1 on page 556](#). [555](#), [658](#), [659](#)

NaN not a number: a special cases for floating point numbers, usually signaling about errors . [230](#), [252](#), [899](#)

NEON AKA “Advanced SIMD”—SIMD from ARM. [967](#)

NOP “no operation”, idle instruction. [677](#)

NTAPI API available only in the Windows NT line. Largely not documented by Microsoft. [741](#)

PDB (Win32) Debugging information file, usually just function names, but sometimes also function arguments and local variables names. [657](#), [705](#), [741](#), [742](#), [749](#), [753](#), [822](#)

POKE BASIC language instruction for writing a byte at a specific address. [677](#)

register allocator The part of the compiler that assigns CPU registers to local variables. [195](#), [313](#), [435](#)

reverse engineering act of understanding how the thing works, sometimes in order to clone it. [iv](#), [961](#)

security cookie A random value, different at each execution. You can read more about it here: [18.3 on page 278](#). [722](#)

stack frame A part of the stack that contains information specific to the current function: local variables, function arguments, RA, etc. [61](#), [91](#), [479](#), [722](#)

stdout standard output. [15](#), [27](#), [146](#), [939](#)

thunk function Tiny function with a single role: call another function. [16](#), [407](#), [763](#), [771](#)

tracer My own simple debugging tool. You can read more about it here: [70.3 on page 736](#). [179–181](#), [662](#), [671](#), [675](#), [718](#), [727](#), [823](#), [830](#), [834](#), [836](#), [888](#), [941](#)

user mode A restricted CPU mode in which all application software code is executed. cf. **kernel mode**. [778](#), [991](#)

Windows NT Windows NT, 2000, XP, Vista, 7, 8. [287](#), [433](#), [607](#), [665](#), [693](#), [704](#), [731](#), [843](#), [961](#)

word data type fitting in **GPR**. In the computers older than PCs, the memory size was often measured in words rather than bytes. [578](#)

xoring often used in the English language, which implying applying the **XOR** operation. [722](#), [774](#), [776](#)

Index

.NET, 708
AT&T syntax, 10, 29
Buffer Overflow, 270, 722
C language elements
 Pointers, 60, 67, 102, 399, 435
 Post-decrement, 456
 Post-increment, 456
 Pre-decrement, 456
 Pre-increment, 456
 C99, 101
 bool, 311
 restrict, 523
 variable length arrays, 281
 const, 7, 74
 for, 175, 484
 if, 116, 145
 return, 8, 79, 100
 switch, 144, 145, 154
 while, 194
C standard library
 alloca(), 27, 281, 467, 714
 assert(), 286, 668
 atexit(), 577
 atoi(), 507, 812
 calloc(), 794
 close(), 698
 exit(), 471
 free(), 467
 fseek(), 794
 ftell(), 794
 getenv(), 813
 localtime(), 616
 localtime_r(), 367
 longjmp(), 146
 malloc(), 360, 467
 memchr(), 957
 memcmp(), 521, 670, 959
 memcpy(), 10, 60, 519, 956
 memset(), 517, 834, 958
 open(), 698
 pow(), 225
 puts(), 15
 qsort(), 399
 rand(), 351, 661, 746, 749, 782
 read(), 698
 realloc(), 467
 scanf(), 60
 strcmp(), 515, 698
 strcpy(), 10, 517, 783
 strlen(), 194, 432, 517, 534, 957
 strstr(), 983
 time(), 616
 tolower(), 800
 toupper(), 542
 va_arg, 528
 va_list, 531
 vprintf, 531
Compiler's anomalies, 138, 225, 296, 321, 338, 494, 539, 890
C++, 825
 exceptions, 714
 C++11, 587, 688
 ostream, 570
 References, 571
 RTTI, 569
 STL, 657
 std::forward_list, 587
 std::list, 578
 std::map, 594
 std::set, 594
 std::string, 571
 std::vector, 587
Garbage collector, 641
grep usage, 181, 258, 657, 671, 675, 823
Hash functions, 469
Intel syntax, 10, 13
Mac OS X, 736
position-independent code, 13, 695
RAM, 73
ROM, 73, 74
Base address, 703
Global variables, 69
Binary tree, 594
Dynamically loaded libraries, 16
Linker, 74, 555
RISC pipeline, 128
Non-a-numbers (NaNs), 252
OOP
 Polymorphism, 555
Reverse Polish notation, 261
Buffer overflow, 276
Entropy, 857
Recursion, 23, 25, 482
 Tail recursion, 482
Stack, 24, 90, 146
 Stack overflow, 25
 Stack frame, 61
Syntactic Sugar, 145
Thumb-2 mode, 15
iPod/iPhone/iPad, 12
OllyDbg, 38, 63, 71, 91, 103, 119, 160, 179, 197, 217, 231, 242, 265, 272, 275, 288, 289, 330, 358, 374, 375, 379, 382, 402, 706, 735, 973
Oracle RDBMS, 8, 422, 667, 711, 826, 833, 835, 870, 879, 890, 901
Ada, 98
Alpha AXP, 4

AMD, 685
 Angry Birds, 257, 258
 ARM, 202, 549, 762, 966
 ARM mode, 3
 Instructions
 ADC, 414
 ADD, 15, 97, 128, 182, 327, 338, 502, 968
 ADDAL, 128
 ADDCC, 165
 ADDS, 96, 414, 968
 ADR, 13, 128
 ADRcc, 128, 154, 468
 ADRP/ADD pair, 17, 48, 74, 285, 297, 458
 ANDcc, 544
 ASR, 342
 ASRS, 321, 502
 B, 48, 128, 129
 Bcc, 88, 89, 139
 BCS, 129, 259
 BEQ, 87, 154
 BGE, 129
 BIC, 320, 321, 326, 343
 BL, 13–17, 128, 459
 BLcc, 128
 BLE, 129
 BLS, 129
 BLT, 182
 BLX, 15, 16
 BNE, 129
 BX, 96, 166
 CLZ, 923
 CMP, 87, 88, 128, 154, 165, 182, 338, 968
 CSEL, 136, 141, 143, 339
 EOR, 326
 FCMPE, 259
 FCSEL, 259
 FMOV, 458
 FMRS, 327
 IT, 143, 257, 281
 LDMccFD, 128
 LDMEA, 24
 LDMED, 24
 LDMFA, 24
 LDMFD, 14, 24, 128
 LDP, 18
 LDR, 49, 67, 74, 267, 284, 456
 LDR.W, 293
 LDRB, 375
 LDRB.W, 202
 LDRSB, 201
 LSL, 339, 342
 LSL.W, 339
 LSLR, 544
 LSLS, 267, 326, 544
 LSR, 342
 LSRS, 326
 MADD, 96
 MLA, 95, 96
 MOV, 5, 14, 15, 338, 501
 MOVcc, 139, 143
 MOVK, 457
 MOVT, 15, 501
 MOVT.W, 16
 MOVW, 16
 MUL, 97
 MULS, 96
 MVNS, 202
 NEG, 512
 ORR, 320
 POP, 13, 14, 24, 26
 PUSH, 14, 24, 26
 RET, 18
 RSB, 133, 293, 338, 512
 SBC, 414
 SMMUL, 502
 STMIA, 24
 STMED, 24
 STMFA, 24, 51
 STMFD, 13, 24
 STMIA, 49
 STMIB, 51
 STP, 17, 48
 STR, 49, 267
 SUB, 49, 293, 338
 SUBcc, 544
 SUBEQ, 203
 SUBS, 414
 SXTB, 376
 SXTW, 297
 TEST, 195
 TST, 314, 338, 339
 VADD, 222
 VDIV, 222
 VLDR, 222
 VMOV, 222, 257
 VMOVG, 257
 VMRS, 257
 VMUL, 222
 XOR, 134, 327
 Pipeline, 165
 Mode switching, 96, 166
 Addressing modes, 456
 mode switching, 16
 Registers
 APSR, 257
 FPSCR, 257
 Link Register, 13, 14, 26, 48, 166, 966
 R0, 966
 scratch registers, 202, 966
 X0, 967
 Z, 87, 967
 Thumb mode, 3, 129, 166
 Thumb-2 mode, 3, 166, 257, 258
 armel, 223
 armhf, 223
 Condition codes, 128
 D-registers, 222, 967
 Data processing instructions, 502
 DCB, 14
 hard float, 223
 if-then block, 257
 Leaf function, 26
 Optional operators
 ASR, 338, 502
 LSL, 267, 293, 338, 339, 457
 LSR, 338, 502
 ROR, 338
 RRX, 338

Registers
 R0, 99
S-registers, 222, 967
soft float, 223

ARM64
 lo12, 48

ASLR, 704

AWK, 673

Base64, 666

base64, 667

bash, 100

BASIC
 POKE, 677

binary grep, 670, 738

BIND.EXE, 708

binutils, 395

Bitcoin, 891

Borland C++Builder, 659

Borland Delphi, 659, 663, 888

BSoD, 693

BSS, 705

C11, 688

Callbacks, 399

Canary, 278

cdecl, 36, 680

COFF, 769
 column-major order, 288

Compiler intrinsic, 28, 889

CRC32, 469, 483

CRT, 700, 719

Cygwin, 658, 662, 709, 736

DES, 422, 435

dlopen(), 698

dlsym(), 698

DOSBox, 843

DosBox, 675

double, 214, 685

dtruss, 736

Duff's device, 497

EICAR, 839

ELF, 72

Error messages, 667

fastcall, 11, 59, 312, 681

float, 214, 685

Forth, 640

FORTRAN, 288, 523, 604, 659

Function epilogue, 23, 48, 49, 128, 375, 673

Function prologue, 9, 23, 26, 49, 278, 673

Fused multiply-add, 95, 96

Fuzzing, 513

GCC, 658, 971, 974

GDB, 21, 41, 45, 277, 407, 408, 735, 974

Glibc, 407, 693

Hex-Rays, 754

Hiew, 85, 125, 663, 705, 706, 709, 888

IDA, 79, 395, 522, 650, 665, 876, 973
 var_?, 49, 67

IEEE 754, 214, 322, 391, 443, 947

Inline code, 183, 320, 514, 561, 591

Integer overflow, 98

Intel
 8080, 202
 8086, 202, 320, 778
 Memory model, 614, 900
 8253, 842
 80286, 778, 900
 80386, 320, 900
 80486, 214
 FPU, 214

Intel C++, 8, 423, 890, 901, 956

Itanium, 897

Java, 619

jumptable, 158, 166

Keil, 12

kernel panic, 693

kernel space, 693

LD_PRELOAD, 697

Linux, 313, 695, 826
 libc.so.6, 312, 407

LLVM, 12

long double, 214

Loop unwinding, 177

Mac OS Classic, 762

MD5, 469, 669

MFC, 706, 813

MIDI, 669

MinGW, 658

minifloat, 458

MIPS, 4, 550, 676, 705, 762
 Global Pointer, 18

Instructions
 ADD, 98
 ADD.D, 225
 ADDIU, 19, 77
 ADDU, 98
 AND, 322
 BC1F, 261
 BC1T, 261
 BEQ, 89, 130
 BLTZ, 134
 BNE, 130
 BNEZ, 168
 BREAK, 502
 C.LT.D, 261
 DIV.D, 225
 J, 6, 19
 JAL, 98
 JALR, 19, 98
 JR, 157
 LB, 187
 LBU, 187
 LI, 460
 LUI, 19, 77, 225, 325, 460
 LW, 19, 68, 77, 157
 LWC1, 225
 MFC1, 228
 MFHI, 98, 502, 969
 MFLO, 98, 502, 969
 MTC1, 397

MUL.D, 225
 MULT, 98
 NOR, 204
 OR, 21
 ORI, 322, 460
 SB, 187
 SLL, 168, 208, 341
 SLLV, 341
 SLT, 130
 SLTIU, 168
 SLTU, 130, 131, 168
 SRL, 212
 SUBU, 134
 SW, 55

Pseudoinstructions
 B, 185
 BEQZ, 131
 L.D, 225
 LA, 21
 LI, 6
 MOVE, 19, 76
 NEGU, 134
 NOP, 21, 76
 NOT, 204

Registers
 FCCR, 261
 HI, 502
 LO, 502

Branch delay slot, 6
 Global Pointer, 293
 Load delay slot, 157
 O32, 55, 59, 969

MS-DOS, 279, 611, 669, 675, 677, 703, 778, 839, 841, 863, 888, 900, 947, 957, 961
 DOS extenders, 900

MSVC, 972, 974

Name mangling, 555
 Native API, 704
 NEC V20, 843

objdump, 395, 697, 709
 OEP, 703, 708
 opaque predicate, 552
 OpenMP, 660, 891
 OpenWatcom, 659, 682

Page (memory), 433
 Pascal, 663
 PDP-11, 456
 PowerPC, 4, 18, 762
 puts() instead of printf(), 15, 65, 99, 126

Quake III Arena, 398

Raspberry Pi, 12
 ReactOS, 716
 Register allocation, 435
 Relocation, 16
 row-major order, 288
 RVA, 703

SAP, 657, 821
 SCO OpenServer, 769
 Scratch space, 684

Security cookie, 278, 722
 Security through obscurity, 667
 SHA1, 469
 SHA512, 891
 Shadow space, 93, 94, 444
 Shellcode, 551, 693, 704, 840, 964
 Signed numbers, 117, 463
 SIMD, 443, 521
 SSE, 443
 SSE2, 443
 stdcall, 680, 888
 strace, 697, 736
 syscall, 312, 693, 736

TCP/IP, 466
 thiscall, 555, 557, 682
 thunk-functions, 16, 707, 763, 771
 TLS, 279, 688, 705, 708, 950
 Callbacks, 691
 Callbacks, 709
 tracer, 179, 404, 406, 662, 671, 675, 718, 727, 735, 823, 830, 834, 836, 888, 941

Unicode, 664
 Unrolled loop, 183, 281, 518
 uptime, 697
 USB, 764
 user space, 693
 UTF-16LE, 664, 665
 UTF-8, 664

VA, 703

Watcom, 659
 Windows, 731
 API, 947
 IAT, 704
 INT, 704
 KERNEL32.DLL, 311
 MSVCR80.DLL, 400
 NTAPI, 741
 ntoskrnl.exe, 826
 PDB, 657, 705, 741, 749, 821
 Structured Exception Handling, 29, 709
 TIB, 279, 709, 950
 Win32, 311, 665, 697, 703, 900
 GetProcAddress, 708
 LoadLibrary, 708
 Ordinal, 706
 RaiseException(), 709
 SetUnhandledExceptionFilter(), 711

Windows 2000, 704
 Windows 3.x, 607, 900
 Windows NT4, 704
 Windows Vista, 703, 741
 Windows XP, 704, 708, 749

Wine, 716
 Wolfram Mathematica, 504, 505, 756, 857

x86
 Flags
 CF, 955, 957, 959, 962
 DF, 959, 962
 IF, 959, 962
 Instructions

AAA, 965
 AAS, 965
 ADC, 413, 611, 955
 ADD, 8, 36, 91, 508, 611, 955
 ADDSD, 444
 ADDSS, 454
 ADRcc, 136
 AND, 9, 312, 315, 328, 342, 381, 955, 958
 BSF, 434, 922, 959
 BSR, 959
 BSWAP, 466, 959
 BT, 959
 BTC, 324, 959
 BTR, 324, 731, 959
 BTS, 324, 959
 CALL, 8, 25, 547, 707, 955
 CBW, 464, 959
 CDQ, 420, 464, 959
 CDQE, 464, 959
 CLD, 959
 CLI, 959
 CMC, 959
 CMOVcc, 128, 135, 137, 139, 143, 468, 959
 CMP, 78, 79, 955, 965
 CMPSB, 670, 959
 CMPSD, 959
 CMPSQ, 959
 CMPSW, 959
 COMISD, 452
 COMISS, 454
 CPUID, 379, 961
 CWD, 464, 611, 851, 959
 CWDE, 464, 959
 DEC, 196, 955, 965
 DIV, 464, 961
 DIVSD, 443, 672
 FABS, 963
 FADD, 963
 FADDP, 216, 222, 963
 FATRET, 337, 338
 FCHS, 963
 FCMOVcc, 253
 FCOM, 241, 252, 963
 FCOMP, 229, 963
 FCOMPP, 963
 FDIV, 216, 671, 963
 FDIVP, 216, 963
 FDIVR, 222, 963
 FDIVRP, 963
 FILD, 963
 FIST, 963
 FISTP, 963
 FLD, 226, 229, 963
 FLD1, 963
 FLDCW, 963
 FLDZ, 963
 FMUL, 216, 963
 FMULP, 963
 FNSTCW, 963
 FNSTSW, 230, 252, 963
 FSINCOS, 963
 FSQRT, 963
 FST, 963
 FSTCW, 963
 FSTP, 226, 963
 FSTSW, 963
 FSUB, 964
 FSUBP, 964
 FSUBR, 963
 FSUBRP, 963
 FUCOM, 252, 964
 FUCOMI, 253
 FUCOMP, 964
 FUCOMPP, 252, 964
 FWAIT, 214
 FXCH, 964
 IDIV, 464, 500, 961
 IMUL, 91, 296, 464, 955, 965
 IN, 547, 778, 842, 961
 INC, 196, 888, 955, 965
 INT, 840, 961
 INT3, 662
 IRET, 961
 JA, 117, 253, 463, 955, 965
 JAE, 117, 955, 965
 JB, 117, 463, 955, 965
 JBE, 117, 955, 965
 JC, 955
 Jcc, 89, 138
 JCXZ, 955
 JE, 146, 955, 965
 JECXZ, 955
 JG, 117, 463, 955
 JGE, 117, 955
 JL, 117, 463, 955
 JLE, 117, 955
 JMP, 25, 48, 707, 888, 955
 JNA, 955
 JNAE, 955
 JNB, 955
 JNBE, 252, 955
 JNC, 955
 JNE, 78, 79, 117, 955, 965
 JNG, 955
 JNGE, 955
 JNL, 955
 JNLE, 955
 JNO, 955, 965
 JNS, 955, 965
 JNZ, 955
 JO, 955, 965
 JP, 230, 843, 955, 965
 JPO, 955
 JRCXZ, 955
 JS, 955, 965
 JZ, 87, 146, 890, 955
 LAHF, 956
 LEA, 62, 93, 362, 472, 485, 508, 684, 744, 956
 LEAVE, 9, 956
 LES, 783, 851
 LOCK, 731
 LODSB, 842
 LOOP, 175, 189, 673, 851, 961
 MAXSD, 452
 MOV, 5, 8, 10, 518, 519, 547, 706, 888, 957
 MOVDQA, 425
 MOVDQU, 425
 MOVS, 956

MOVSD, 451, 519, 799, 956
 MOVSDX, 451
 MOVSQ, 956
 MOVSS, 454
 MOVSW, 956
 MOVSX, 195, 201, 374–376, 464, 957
 MOVSD, 282
 MOVZX, 195, 360, 762, 957
 MUL, 464, 957
 MULSD, 444
 NEG, 511, 957
 NOP, 485, 886, 888, 957
 NOT, 200, 202, 803, 957
 OR, 315, 534, 957
 OUT, 547, 778, 961
 PADDD, 425
 PCMPEQB, 434
 PLMULHW, 423
 PLMULLD, 423
 PMOVMSKB, 434
 POP, 8, 24, 25, 957, 965
 POPA, 961, 965
 POPCNT, 961
 POPF, 842, 962
 PUSH, 8, 9, 24, 25, 61, 547, 957, 965
 PUSHA, 962, 965
 PUSHF, 962
 PXOR, 434
 RCL, 673, 962
 RCR, 962
 RET, 5, 8, 25, 278, 557, 608, 888, 957
 ROL, 337, 889, 962
 ROR, 889, 962
 SAHF, 252, 957
 SAL, 962
 SALC, 843
 SAR, 342, 464, 526, 851, 962
 SBB, 413, 957
 SCASB, 842, 843, 957
 SCASD, 957
 SCASQ, 957
 SCASW, 957
 SETALC, 843
 SETcc, 130, 196, 252, 962
 SHL, 208, 264, 342, 958
 SHR, 212, 342, 381, 958
 SHRD, 419, 958
 STC, 962
 STD, 962
 STI, 962
 STOSB, 958
 STOSD, 958
 STOSQ, 518, 958
 STOSW, 958
 SUB, 8, 9, 79, 146, 508, 955, 958
 SYSCALL, 961, 962
 SYSENTER, 694, 961, 963
 TEST, 195, 312, 314, 342, 958
 UD2, 963
 XADD, 732
 XCHG, 957, 958
 XOR, 8, 79, 200, 526, 673, 774, 888, 958, 965

Prefixes
 LOCK, 731, 954

REP, 954, 956, 958
 REPE/REPNE, 954
 REPNE, 957
 Registers
 Flags, 79, 119, 950
 AH, 956, 957
 CS, 900
 DR6, 953
 DR7, 953
 DS, 900
 EAX, 78, 99
 EBP, 61, 91
 ECX, 555
 ES, 851, 900
 ESP, 36, 61
 FS, 689
 GS, 279, 689, 692
 JMP, 164
 RIP, 696
 SS, 900
 ZF, 79, 312
 AVX, 422
 FPU, 951
 Instructions
 STOSB, 499
 MMX, 422
 SSE, 422
 SSE2, 422
 x86-64, 10, 11, 44, 60, 66, 86, 92, 435, 443, 548, 682, 696, 947, 953
 Xcode, 12
 Z3, 754, 757

Bibliography

- [al12] Nick Montfort et al. [10 PRINT CHR\\$\(205.5+RND\(1\)\); : GOTO 10](#). Also available as <http://go.yurichev.com/17286>. The MIT Press, 2012.
- [AMD13a] AMD. [AMD64 Architecture Programmer's Manual](#). Also available as <http://go.yurichev.com/17284>. 2013.
- [AMD13b] AMD. [Software Optimization Guide for AMD Family 16h Processors](#). Also available as <http://go.yurichev.com/17285>. 2013.
- [App10] Apple. [iOS ABI Function Call Guide](#). Also available as <http://go.yurichev.com/17276>. 2010.
- [ARM12] ARM. [ARM® Architecture Reference Manual, ARMv7-A and ARMv7-R edition](#). 2012.
- [ARM13a] ARM. [ARM Architecture Reference Manual, ARMv8, for ARMv8-A architecture profile](#). 2013.
- [ARM13b] ARM. [ELF for the ARM 64-bit Architecture \(AArch64\)](#). Also available as <http://go.yurichev.com/17288>. 2013.
- [ARM13c] ARM. [Procedure Call Standard for the ARM 64-bit Architecture \(AArch64\)](#). Also available as <http://go.yurichev.com/17287>. 2013.
- [ASS96] Harold Abelson, Gerald Jay Sussman, and Julie Sussman. [Structure and Interpretation of Computer Programs](#). 1996.
- [Bro] Ralf Brown. [The x86 Interrupt List](#). Also available as <http://go.yurichev.com/17292>.
- [Bur] Mike Burrell. "Writing Efficient Itanium 2 Assembly Code". In: (). Also available as <http://go.yurichev.com/17265>.
- [Cli] Marshall Cline. [C++ FAQ](#). Also available as <http://go.yurichev.com/17291>.
- [Cor+09] Thomas H. Cormen et al. [Introduction to Algorithms, Third Edition](#). 3rd. The MIT Press, 2009. ISBN: 0262033844, 9780262033848.
- [Dij68] Edsger W. Dijkstra. "Letters to the editor: go to statement considered harmful". In: [Commun. ACM](#) 11.3 (Mar. 1968), pp. 147–148. ISSN: 0001-0782. DOI: [10.1145/362929.362947](https://doi.org/10.1145/362929.362947). URL: <http://go.yurichev.com/17299>.
- [Dol13] Stephen Dolan. "mov is Turing-complete". In: (2013). Also available as <http://go.yurichev.com/17269>.
- [Dre07] Ulrich Drepper. [What Every Programmer Should Know About Memory](#). Also available as <http://go.yurichev.com/17341>. 2007.
- [Dre13] Ulrich Drepper. "ELF Handling For Thread-Local Storage". In: (2013). Also available as <http://go.yurichev.com/17272>.
- [Eic11] Jens Eickhoff. [Onboard Computers, Onboard Software and Satellite Operations: An Introduction](#). 2011.
- [Fog13a] Agner Fog. [Optimizing software in C++: An optimization guide for Windows, Linux and Mac platforms](#). <http://go.yurichev.com/17279>. 2013.
- [Fog13b] Agner Fog. [The microarchitecture of Intel, AMD and VIA CPUs / An optimization guide for assembly programmers and compilers](#). <http://go.yurichev.com/17278>. 2013.
- [Fog14] Agner Fog. [Calling conventions](#). <http://go.yurichev.com/17280>. 2014.
- [haq] papasutra of haquebright. "WRITING SHELLCODE FOR IA-64". In: (). Also available as <http://go.yurichev.com/17340>.
- [IBM00] IBM. [PowerPC\(tm\) Microprocessor Family: The Programming Environments for 32-Bit Microprocessors](#). Also available as <http://go.yurichev.com/17281>. 2000.
- [Int13] Intel. [Intel® 64 and IA-32 Architectures Software Developer's Manual Combined Volumes:1, 2A, 2B, 2C, 3A, 3B, and 3C](#). Also available as <http://go.yurichev.com/17283>. 2013.
- [Int14] Intel. [Intel® 64 and IA-32 Architectures Optimization Reference Manual](#). Also available as <http://go.yurichev.com/17342>. September 2014.
- [ISO07] ISO. [ISO/IEC 9899:TC3 \(C99 standard\)](#). Also available as <http://go.yurichev.com/17274>. 2007.

- [ISO13] ISO. ISO/IEC 14882:2011 (C++ 11 standard). Also available as <http://go.yurichev.com/17275>. 2013.
- [Jav13] Java. The Java® Virtual Machine Specification Java SE 7 Edition. Also available as <http://go.yurichev.com/17345> and <http://go.yurichev.com/17346>. February 2013.
- [Ker88] Brian W. Kernighan. The C Programming Language. Ed. by Dennis M. Ritchie. 2nd. Prentice Hall Professional Technical Reference, 1988. ISBN: 0131103709.
- [Knu74] Donald E. Knuth. "Structured Programming with go to Statements". In: ACM Comput. Surv. 6.4 (Dec. 1974). Also available as <http://go.yurichev.com/17271>, pp. 261–301. ISSN: 0360-0300. DOI: [10.1145/356635.356640](https://doi.org/10.1145/356635.356640). URL: <http://go.yurichev.com/17300>.
- [Knu98] Donald E. Knuth. The Art of Computer Programming Volumes 1-3 Boxed Set. 2nd. Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc., 1998. ISBN: 0201485419.
- [Loh10] Eugene Loh. "The Ideal HPC Programming Language". In: Queue 8.6 (June 2010), 30:30–30:38. ISSN: 1542-7730. DOI: [10.1145/1810226.1820518](https://doi.org/10.1145/1810226.1820518). URL: <http://go.yurichev.com/17298>.
- [Ltd94] Advanced RISC Machines Ltd. The ARM Cookbook. Also available as <http://go.yurichev.com/17273>. 1994.
- [Mit13] Michael Matz / Jan Hubicka / Andreas Jaeger / Mark Mitchell. System V Application Binary Interface. AMD64 Architecture P
- [Mor80] Also available as <http://go.yurichev.com/17295>. 2013.
- [Mor80] Stephen P. Morse. The 8086 Primer. Also available as <http://go.yurichev.com/17351>. 1980.
- [One96] Aleph One. "Smashing The Stack For Fun And Profit". In: Phrack (1996). Also available as <http://go.yurichev.com/17266>.
- [Pie] Matt Pietrek. "A Crash Course on the Depths of Win32™ Structured Exception Handling". In: MSDN magazine (). URL: <http://go.yurichev.com/17293>.
- [Pie02] Matt Pietrek. "An In-Depth Look into the Win32 Portable Executable File Format". In: MSDN magazine (2002). URL: <http://go.yurichev.com/17318>.
- [Pre+07] William H. Press et al. Numerical Recipes. 2007.
- [RA09] Mark E. Russinovich and David A. Solomon with Alex Ionescu. Windows® Internals: Including Windows Server 2008 and W 2009.
- [Ray03] Eric S. Raymond. The Art of UNIX Programming. Also available as <http://go.yurichev.com/17277>. Pearson Education, 2003. ISBN: 0131429019.
- [Rit79] Dennis M. Ritchie. "The Evolution of the Unix Time-sharing System". In: (1979).
- [Rit86] Dennis M. Ritchie. Where did ++ come from? (net.lang.c). <http://go.yurichev.com/17296>. [Online; accessed 2013]. 1986.
- [Rit93] Dennis M. Ritchie. "The development of the C language". In: SIGPLAN Not. 28.3 (Mar. 1993). Also available as <http://go.yurichev.com/17264>, pp. 201–208. ISSN: 0362-1340. DOI: [10.1145/155360.155580](https://doi.org/10.1145/155360.155580). URL: <http://go.yurichev.com/17297>.
- [RT74] D. M. Ritchie and K. Thompson. "The UNIX Time Sharing System". In: (1974). Also available as <http://go.yurichev.com/17270>.
- [Sch94] Bruce Schneier. Applied Cryptography: Protocols, Algorithms, and Source Code in C. 1994.
- [SK95] SunSoft Steve Zucker and IBM Kari Karhi. SYSTEM V APPLICATION BINARY INTERFACE: PowerPC Processor Supplement. Also available as <http://go.yurichev.com/17282>. 1995.
- [Sko12] Igor Skochinsky. Compiler Internals: Exceptions and RTTI. Also available as <http://go.yurichev.com/17294>. 2012.
- [Str13] Bjarne Stroustrup. The C++ Programming Language, 4th Edition. 2013.
- [Swe10] Dominic Sweetman. See MIPS Run, Second Edition. 2010.
- [War02] Henry S. Warren. Hacker's Delight. Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc., 2002. ISBN: 0201914654.
- [Yur12] Dennis Yurichev. "Finding unknown algorithm using only input/output pairs and Z3 SMT solver". In: (2012). Also available as <http://go.yurichev.com/17268>.
- [Yur13] Dennis Yurichev. C/C++ programming language notes. Also available as <http://go.yurichev.com/17289>. 2013.