

Secure Software Development

Introduction and Low Level

Daniel Gruss, Vedad Hadzic, Andreas Kogler, Martin Schwarzl, Marcel Nageler

October 13, 2022

Introduction



An error that effects only one bit can be enough to give an attacker full privileges on your computer

- Many programs are written in native code
- Programs get more and more complex

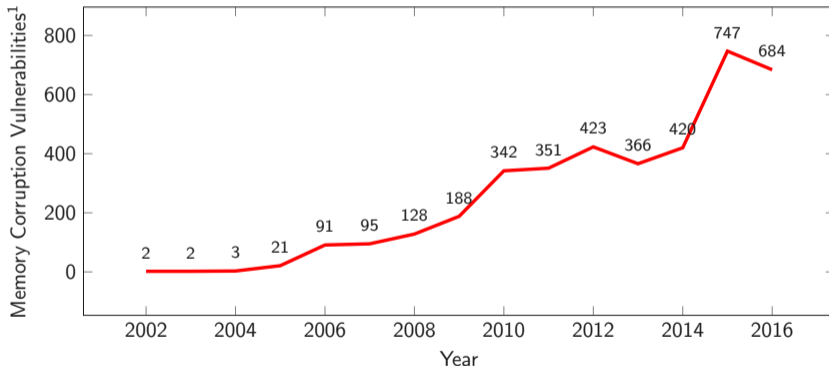




“Securing a computer system has traditionally been a battle of wits: the penetrator tries to find the holes, and the designer tries to close them.”

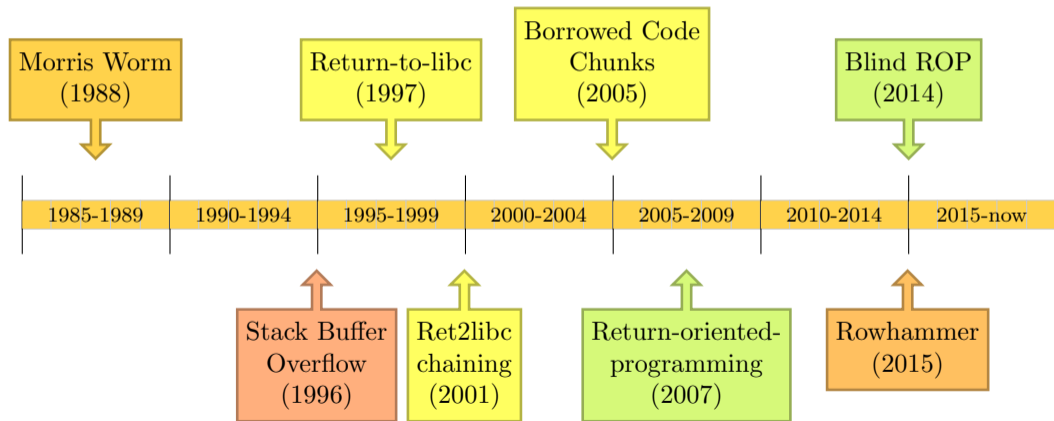
— M. Gosser

The more complex the programs, the more bugs



¹Source: <http://www.cvedetails.com/vulnerabilities-by-types.php>

- We had three decades of memory corruption attacks





IMPACT

aka “Do we really have to care about that?”



Zero-day - Wikipedia

A zero-day (also known as zero-hour or 0-day or day zero) vulnerability is an undisclosed computer-software vulnerability that hackers can exploit to adversely affect computer programs, data, additional computers or a network.

- Who is interested in zero-days?



Criminals



Vendors



Governments



Adobe Reader	5000 \$ - 30 000 \$
Mac OS X	20 000 \$ - 50 000 \$
Android	30 000 \$ - 60 000 \$
Flash/Java Browser Plugin	10 000 \$ - 100 000 \$
Microsoft Word	50 000 \$ - 100 000 \$
Windows	60 000 \$ - 120 000 \$
Firefox/Safari	60 000 \$ - 150 000 \$
Chrome/Internet Explorer	80 000 \$ - 200 000 \$
iOS	100 000 \$ - 250 000 \$

Source: Forbes



- A lot of zero-days received fancy names
 - Heartbleed: remote information leakage through OpenSSL
 - Shellshock: arbitrary command execution in Bash
 - Stagefright: remote code execution on Android through MMS
 - Dirty COW: root privileges on Linux



- Jailbreaks (e.g., getting root) on various devices:
 - iOS (multiple exploits)
 - Wii (buffer overflow in *The Legend of Zelda: Twilight Princess*).
 - PS2 (buffer overflow in the BIOS)
 - PS3 (heap overflow)
 - Xbox (buffer overflow in savegames)





Bug Bounty Programs (Google Chrome)



	High-quality report with functional exploit [1]	High-quality report [2]	Baseline [3]	Low-quality report [4]
Sandbox Escape [5]	\$15,000	\$10,000	\$2,000 - \$5,000	\$500
Renderer Remote Code Execution	\$7,500	\$5,000	\$1,000 - \$3,000	\$500
Universal XSS (local bypass or equivalent)	\$7,500	\$5,000	N/A	N/A
Information Leak	\$4,000	\$2,000	\$0 - \$1000	\$0
Download Protection bypass [6]	N/A	\$1,000	\$0 - \$500	\$0

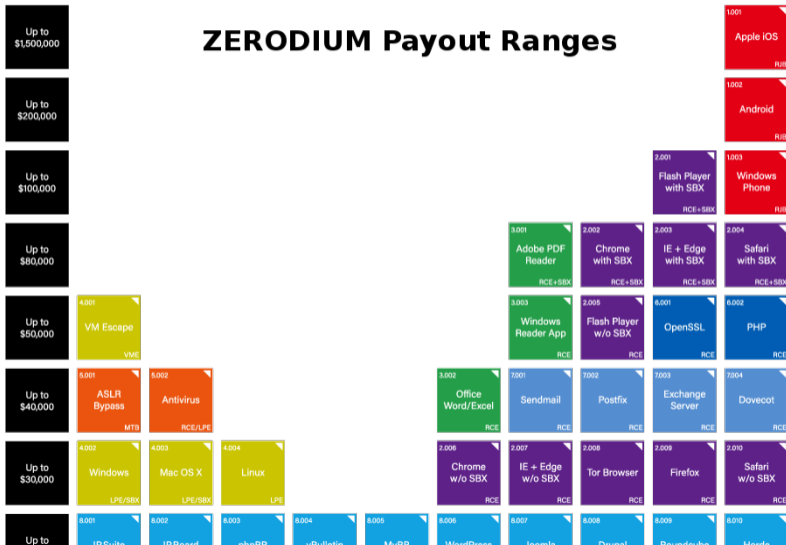
Bug Bounty Programs (Google Android)



Severity	Complete Report* + PoC	Payment range (if report includes an exploit leading to Kernel compromise)**	Payment range (if report includes an exploit leading to TEE compromise)**
Critical	Required	Up to \$150,000	Up to \$200,000
High	Required	Up to \$75,000	Up to \$100,000
Moderate	Required	Up to \$20,000	Up to \$35,000
Low	Required	Up to \$330	Up to \$330



ZERODIUM Payout Ranges





- Nation-state malware, such as Stuxnet, Duqu, Duqu2, Flame, and Gauss



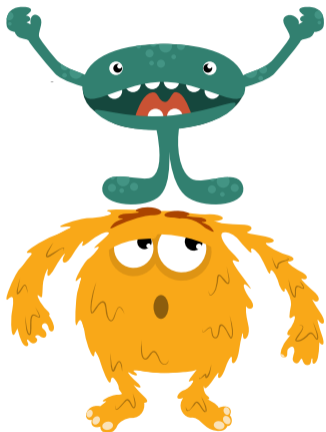


- Computer and network surveillance
- Sometimes use state-sponsored trojan horses (govware)

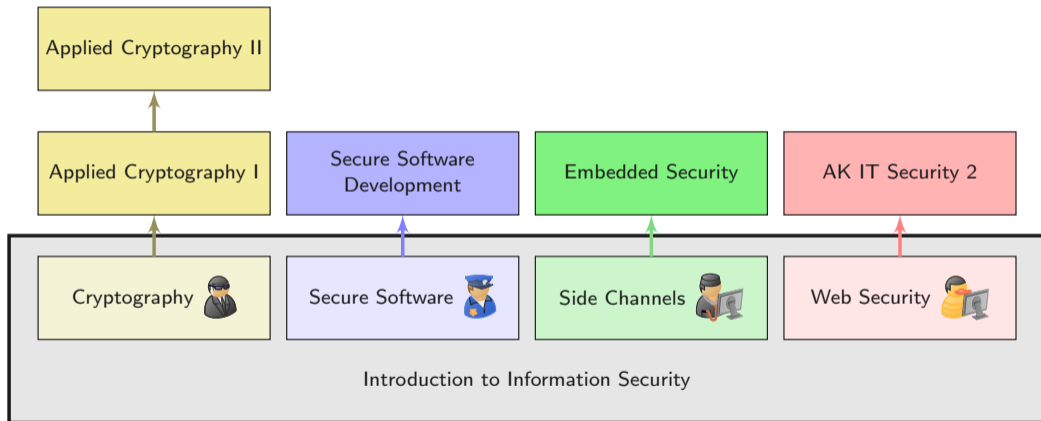


- Bundestrojaner (Germany)
- MiniPanzer and MegaPanzer (Switzerland)
- “Sicherheitspaket” (Austria)
- NSA Exploits (Shadow Broker Leak)

This Course



- We will learn about bugs...
- ...and even more bugs
 - Types of bugs
 - How to find them
 - How to exploit them
 - How to fix them
 - How to prevent them in the first place



- Starts on time (12:00)
- Presentation in English
- Always held online
- Questions in English or German



- 90 minutes
- Questions in English
- Answers in English or German
- Covers everything from Low Level to Countermeasures



Register for the Practicalcs in TUGRAZonline!



- Register at Discord server using <https://discord.gg/DCpzjqWBD3>
- Ask questions regarding the lecture and practicals
- Questions in English or German
- For more detailed questions use dm or email



- <https://sasectf.student.iaik.tugraz.at/>
- Register an account (**student mail address** recommended)
- Hacklet challenges used in practical part of exam

The x86 Architecture

- Backwards-compatibility
- Heavily stack-oriented
 - Function calls require a stack
 - Context switches (interrupts) require a stack
- Complex instruction set with variable-length op codes
- Unaligned memory access and execution



- General purpose: eax, ebx, ecx, edx, edi, esi
- Stack pointer: esp
- Base pointer: ebp
- Instruction pointer: eip
- Control registers: cr3 (cr0-cr15)
- Segment registers: cs, ds, ss, es, fs, gs



- General purpose: rax, rbx, rcx, rdx, rdi, rsi, r8-r15
- Stack pointer: rsp
- Base pointer: rbp
- Instruction pointer: rip
- Control registers: cr3 (cr0-cr15)
- Segment registers: cs, ds, ss, es, fs, gs

- High-level abstraction for
 - Op codes
 - Addresses
 - Variable storage

Op codes

```
#include <stdio.h>
int main()
{
    puts("hello world");
    for (size_t i = 0; i < 10; ++i)
        putchar('0'+i);
    putchar('\n');
    return 0;
}
```

Op code example

```
55          pushq %rbp
4889e5     movq  %rsp, %rbp
4883ec10   subq  $0x10, %rsp
bf84304a00 movl  $0x4a3084, %edi
e870f50000 callq 0xf582
48c745f800000000 movq  $0, -8(%rbp)
eb13      jmp   0x2f
488b45f8   movq  -8(%rbp), %rax
83c030    addl  $0x30, %eax
89c7      movl  %eax, %edi
e868f70000 callq 0xf792
488345f801 addq  $1, -8(%rbp)
48837df809 cmpq  $9, -8(%rbp)
76e6      jbe   0x1c
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9        leave
c3        retq
```

Op code example

55

```
4889e5      movq  %rsp, %rbp
4883ec10    subq  $0x10, %rsp
bf84304a00  movl  $0x4a3084, %edi
e870f50000  callq 0xf582
48c745f800000000  movq  $0, -8(%rbp)
eb13       jmp   0x2f
488b45f8    movq  -8(%rbp), %rax
83c030     addl  $0x30, %eax
89c7       movl  %eax, %edi
e868f70000  callq 0xf792
488345f801  addq  $1, -8(%rbp)
48837df809  cmpq  $9, -8(%rbp)
76e6       jbe   0x1c
bf0a000000  movl  $0xa, %edi
e852f70000  callq 0xf792
b800000000  movl  $0, %eax
c9        leave
c3        retq
```

But what if we misalign?

```
55
48
89e5      movl  %esp, %ebp
4883ec10  subq  $0x10, %rsp
bf84304a00 movl  $0x4a3084, %edi
e870f50000 callq 0xf582
48c745f800000000 movq  $0, -8(%rbp)
eb13      jmp   0x2f
488b45f8  movq  -8(%rbp), %rax
83c030   addl  $0x30, %eax
89c7     movl  %eax, %edi
e868f70000 callq 0xf792
488345f801 addq  $1, -8(%rbp)
48837df809 cmpq  $9, -8(%rbp)
76e6     jbe   0x1c
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9      leave
c3      retq
```

But what if we misalign?

```
55
48
89e5      movl  %esp, %ebp
4883ec10  subq  $0x10, %rsp
bf84304a0 movl  $0x4a3084, %edi
e870f50000 callq 0xf582
48c745f800000000 movq  $0, -8(%rbp)
eb13     jmp   0x2f
488b45f8  movq  -8(%rbp), %rax
83c030   addl  $0x30, %eax
89c7     movl  %eax, %edi
e868f70000 callq 0xf792
488345f801 addq  $1, -8(%rbp)
48837df809 cmpq  $9, -8(%rbp)
76e6     jbe   0x1c
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9      leave
c3      retq
```

But what if we misalign?

```
55
4889
e548      inl   $0x48, %eax
83ec10    subl  $0x10, %esp
bf84304a00 movl  $0x4a3084, %edi
e870f50000 callq 0xf582
48c745f800000000 movq  $0, -8(%rbp)
eb13      jmp   0x2f
488b45f8   movq  -8(%rbp), %rax
83c030    addl  $0x30, %eax
89c7      movl  %eax, %edi
e868f70000 callq 0xf792
488345f801 addq  $1, -8(%rbp)
48837df809 cmpq  $9, -8(%rbp)
76e6     jbe   0x1c
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9       leave
c3       retq
```

But what if we misalign?

55

4889e5

```
4883ec10      subq  $0x10, %rsp
bf84304a00    movl  $0x4a3084, %edi
e870f50000    callq 0xf582
48c745f800000000 movq  $0, -8(%rbp)
eb13         jmp   0x2f
488b45f8      movq  -8(%rbp), %rax
83c030      addl  $0x30, %eax
89c7        movl  %eax, %edi
e868f70000    callq 0xf792
488345f801    addq  $1, -8(%rbp)
48837df809    cmpq  $9, -8(%rbp)
76e6        jbe   0x1c
bf0a000000    movl  $0xa, %edi
e852f70000    callq 0xf792
b800000000    movl  $0, %eax
c9         leave
c3         retq
```


But what if we misalign?

```
55
4889e5
48
83ec10      subl  $0x10, %esp
bf84304a00 movl  $0x4a3084, %edi
e870f50000 callq 0xf582
48c745f800000000 movq  $0, -8(%rbp)
eb13       jmp   0x2f
488b45f8   movq  -8(%rbp), %rax
83c030    addl  $0x30, %eax
89c7      movl  %eax, %edi
e868f70000 callq 0xf792
488345f801 addq  $1, -8(%rbp)
48837df809 cmpq  $9, -8(%rbp)
76e6     jbe  0x1c
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9       leave
c3       retq
```

But what if we misalign?

```
55
4889e5
4883
ec          inb   %dx, %al
10bf84304a00  adcb  %bh, 0x4a3084(%rdi)
e870f50000   callq 0xf582
48c745f800000000  movq  $0, -8(%rbp)
eb13        jmp   0x2f
488b45f8     movq  -8(%rbp), %rax
83c030     addl  $0x30, %eax
89c7       movl  %eax, %edi
e868f70000   callq 0xf792
488345f801   addq  $1, -8(%rbp)
48837df809   cmpq  $9, -8(%rbp)
76e6       jbe   0x1c
bf0a000000   movl  $0xa, %edi
e852f70000   callq 0xf792
b800000000   movl  $0, %eax
c9        leave
c3        retq
```

But what if we misalign?

```
4889e5
4883ec10
bf
8430          testb %dh, (%rax)
4a00e8          addb %bpl, %al
70f5          jo     5
0000          addb %al, (%rax)
48c745f800000000  movq $0, -8(%rbp)
eb13          jmp   0x2f
488b45f8          movq -8(%rbp), %rax
83c030          addl $0x30, %eax
89c7          movl %eax, %edi
e868f70000      callq 0xf792
488345f801      addq $1, -8(%rbp)
48837df809      cmpq $9, -8(%rbp)
76e6          jbe   0x1c
bf0a000000      movl $0xa, %edi
e852f70000      callq 0xf792
b800000000      movl $0, %eax
c9          leave
```

But what if we misalign?

```
4889e5
4883ec10
bf84
304a00    xorb  %cl, (%rdx)
e870f50000    callq 0xf582
48c745f800000000    movq  $0, -8(%rbp)
eb13        jmp   0x2f
488b45f8        movq  -8(%rbp), %rax
83c030        addl  $0x30, %eax
89c7        movl  %eax, %edi
e868f70000    callq 0xf792
488345f801    addq  $1, -8(%rbp)
48837df809    cmpq  $9, -8(%rbp)
76e6        jbe   0x1c
bf0a000000    movl  $0xa, %edi
e852f70000    callq 0xf792
b800000000    movl  $0, %eax
c9        leave
c3        retq
```

But what if we misalign?

```
4889e5
4883ec10
bf8430
4a00e8          addb %bpl, %al
70f5           jo    5
0000          addb %al, (%rax)
48c745f800000000 movq $0, -8(%rbp)
eb13          jmp   0x2f
488b45f8      movq -8(%rbp), %rax
83c030       addl $0x30, %eax
89c7         movl %eax, %edi
e868f70000   callq 0xf792
488345f801   addq $1, -8(%rbp)
48837df809   cmpq $9, -8(%rbp)
76e6         jbe   0x1c
bf0a000000   movl $0xa, %edi
e852f70000   callq 0xf792
b800000000   movl $0, %eax
c9           leave
c3           retq
```

But what if we misalign?

```
4883ec10
bf84304a00
e8
70f5      jo      5
0000      addb   %al, (%rax)
48c745f800000000      movq   $0, -8(%rbp)
eb13      jmp    0x2f
488b45f8      movq   -8(%rbp), %rax
83c030      addl   $0x30, %eax
89c7      movl   %eax, %edi
e868f70000      callq  0xf792
488345f801      addq   $1, -8(%rbp)
48837df809      cmpq   $9, -8(%rbp)
76e6      jbe    0x1c
bf0a000000      movl   $0xa, %edi
e852f70000      callq  0xf792
b800000000      movl   $0, %eax
c9      leave
c3      retq
```

But what if we misalign?

```
4883ec10
bf84304a00
e870
f5          cmc
0000       addb  %al, (%rax)
48c745f800000000  movq  $0, -8(%rbp)
eb13      jmp   0x2f
488b45f8    movq  -8(%rbp), %rax
83c030     addl  $0x30, %eax
89c7      movl  %eax, %edi
e868f70000  callq 0xf792
488345f801  addq  $1, -8(%rbp)
48837df809  cmpq  $9, -8(%rbp)
76e6      jbe   0x1c
bf0a000000  movl  $0xa, %edi
e852f70000  callq 0xf792
b800000000  movl  $0, %eax
c9        leave
c3        retq
```

But what if we misalign?

```
4883ec10
bf84304a00
e870f5
0000      addb  %al, (%rax)
48c745f800000000      movq  $0, -8(%rbp)
eb13      jmp   0x2f
488b45f8      movq  -8(%rbp), %rax
83c030      addl  $0x30, %eax
89c7      movl  %eax, %edi
e868f70000      callq 0xf792
488345f801      addq  $1, -8(%rbp)
48837df809      cmpq  $9, -8(%rbp)
76e6      jbe  0x1c
bf0a000000      movl  $0xa, %edi
e852f70000      callq 0xf792
b800000000      movl  $0, %eax
c9      leave
c3      retq
```


But what if we misalign?

```
4883ec10
bf84304a00
e870f500
0048c7          addb  %cl, -0x39(%rax)
45f8           clc
0000           addb  %al, (%rax)
0000           addb  %al, (%rax)
eb13           jmp   0x2f
488b45f8       movq  -8(%rbp), %rax
83c030        addl  $0x30, %eax
89c7           movl  %eax, %edi
e868f70000    callq 0xf792
488345f801    addq  $1, -8(%rbp)
48837df809    cmpq  $9, -8(%rbp)
76e6           jbe   0x1c
bf0a000000    movl  $0xa, %edi
e852f70000    callq 0xf792
b800000000    movl  $0, %eax
c9            leave
c3           retq
```

But what if we misalign?

```
4883ec10
bf84304a00
e870f50000
48c745f800000000    movq  $0, -8(%rbp)
eb13                jmp   0x2f
488b45f8            movq  -8(%rbp), %rax
83c030            addl  $0x30, %eax
89c7                movl  %eax, %edi
e868f70000        callq 0xf792
488345f801        addq  $1, -8(%rbp)
48837df809        cmpq  $9, -8(%rbp)
76e6                jbe   0x1c
bf0a000000        movl  $0xa, %edi
e852f70000        callq 0xf792
b800000000        movl  $0, %eax
c9                leave
c3                retq
```

But what if we misalign?

```
bf84304a00
e870f50000
48
c745f800000000    movl  $0, -8(%rbp)
eb13              jmp   0x2f
488b45f8          movq  -8(%rbp), %rax
83c030           addl  $0x30, %eax
89c7             movl  %eax, %edi
e868f70000       callq 0xf792
488345f801       addq  $1, -8(%rbp)
48837df809       cmpq  $9, -8(%rbp)
76e6            jbe   0x1c
bf0a000000       movl  $0xa, %edi
e852f70000       callq 0xf792
b800000000       movl  $0, %eax
c9              leave
c3              retq
```

But what if we misalign?

```
bf84304a00
e870f50000
48c7
45f8          clc
0000          addb  %al, (%rax)
0000          addb  %al, (%rax)
eb13          jmp   0x2f
488b45f8      movq  -8(%rbp), %rax
83c030       addl  $0x30, %eax
89c7         movl  %eax, %edi
e868f70000   callq 0xf792
488345f801   addq  $1, -8(%rbp)
48837df809   cmpq  $9, -8(%rbp)
76e6         jbe   0x1c
bf0a000000   movl  $0xa, %edi
e852f70000   callq 0xf792
b800000000   movl  $0, %eax
c9          leave
c3          retq
```

But what if we misalign?

```
bf84304a00
e870f50000
48c745
f8          clc
0000       addb  %al, (%rax)
0000       addb  %al, (%rax)
eb13       jmp   0x2f
488b45f8   movq  -8(%rbp), %rax
83c030     addl  $0x30, %eax
89c7       movl  %eax, %edi
e868f70000 callq 0xf792
488345f801 addq  $1, -8(%rbp)
48837df809 cmpq  $9, -8(%rbp)
76e6       jbe   0x1c
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9        leave
c3        retq
```

But what if we misalign?

```
bf84304a00
e870f50000
48c745f8
0000      addb  %al, (%rax)
0000      addb  %al, (%rax)
eb13      jmp   0x2f
488b45f8  movq  -8(%rbp), %rax
83c030    addl  $0x30, %eax
89c7      movl  %eax, %edi
e868f70000 callq 0xf792
488345f801 addq  $1, -8(%rbp)
48837df809 cmpq  $9, -8(%rbp)
76e6      jbe   0x1c
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9        leave
c3        retq
```

But what if we misalign?

```
bf84304a00
e870f50000
48c745f800
0000      addb  %al, (%rax)
00eb      addb  %ch, %bl
13488b    adcl  -0x75(%rax), %ecx
45f8      clc
83c030    addl  $0x30, %eax
89c7      movl  %eax, %edi
e868f70000 callq 0xf792
488345f801 addq  $1, -8(%rbp)
48837df809 cmpq  $9, -8(%rbp)
76e6     jbe   0x1c
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9       leave
c3       retq
```

But what if we misalign?

```
bf84304a00
e870f50000
48c745f80000
0000      addb  %al, (%rax)
eb13      jmp   0x2f
488b45f8  movq  -8(%rbp), %rax
83c030    addl  $0x30, %eax
89c7      movl  %eax, %edi
e868f70000 callq 0xf792
488345f801 addq  $1, -8(%rbp)
48837df809 cmpq  $9, -8(%rbp)
76e6      jbe   0x1c
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9        leave
c3        retq
```


But what if we misalign?

```
bf84304a00
e870f50000
48c745f8000000
00eb          addb  %ch, %bl
13488b       adcl  -0x75(%rax), %ecx
45f8          clc
83c030       addl  $0x30, %eax
89c7         movl  %eax, %edi
e868f70000   callq 0xf792
488345f801   addq  $1, -8(%rbp)
48837df809   cmpq  $9, -8(%rbp)
76e6         jbe   0x1c
bf0a000000   movl  $0xa, %edi
e852f70000   callq 0xf792
b800000000   movl  $0, %eax
c9           leave
c3           retq
```

But what if we misalign?

```
bf84304a00
e870f50000
48c745f800000000
eb13          jmp     0x2f
488b45f8      movq   -8(%rbp), %rax
83c030       addl   $0x30, %eax
89c7         movl   %eax, %edi
e868f70000   callq  0xf792
488345f801   addq   $1, -8(%rbp)
48837df809   cmpq   $9, -8(%rbp)
76e6         jbe    0x1c
bf0a000000   movl   $0xa, %edi
e852f70000   callq  0xf792
b800000000   movl   $0, %eax
c9          leave
c3          retq
```

But what if we misalign?

```
e870f50000
48c745f800000000
eb
13488b      adcl  -0x75(%rax), %ecx
45f8       clc
83c030     addl  $0x30, %eax
89c7       movl  %eax, %edi
e868f70000 callq 0xf792
488345f801 addq  $1, -8(%rbp)
48837df809 cmpq  $9, -8(%rbp)
76e6       jbe  0x1c
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9        leave
c3        retq
```

But what if we misalign?

e870f50000

48c745f800000000

eb13

```
488b45f8      movq  -8(%rbp), %rax
83c030      addl  $0x30, %eax
89c7        movl  %eax, %edi
e868f70000   callq 0xf792
488345f801   addq  $1, -8(%rbp)
48837df809   cmpq  $9, -8(%rbp)
76e6        jbe   0x1c
bf0a000000   movl  $0xa, %edi
e852f70000   callq 0xf792
b800000000   movl  $0, %eax
c9          leave
c3          retq
```

But what if we misalign?

48c745f800000000

eb13

48

8b45f8 **movl** -8(%rbp), %eax

83c030 **addl** \$0x30, %eax

89c7 **movl** %eax, %edi

e868f70000 **callq** 0xf792

488345f801 **addq** \$1, -8(%rbp)

48837df809 **cmpq** \$9, -8(%rbp)

76e6 **jbe** 0x1c

bf0a000000 **movl** \$0xa, %edi

e852f70000 **callq** 0xf792

b800000000 **movl** \$0, %eax

c9 **leave**

c3 **retq**

But what if we misalign?

48c745f800000000

eb13

488b

45f8

clc

83c030

addl \$0x30, %eax

89c7

movl %eax, %edi

e868f70000

callq 0xf792

488345f801

addq \$1, -8(%rbp)

48837df809

cmpq \$9, -8(%rbp)

76e6

jbe 0x1c

bf0a000000

movl \$0xa, %edi

e852f70000

callq 0xf792

b800000000

movl \$0, %eax

c9

leave

c3

retq

But what if we misalign?

48c745f800000000

eb13

488b45

f8

clc

83c030

addl \$0x30, %eax

89c7

movl %eax, %edi

e868f70000

callq 0xf792

488345f801

addq \$1, -8(%rbp)

48837df809

cmpq \$9, -8(%rbp)

76e6

jbe 0x1c

bf0a000000

movl \$0xa, %edi

e852f70000

callq 0xf792

b800000000

movl \$0, %eax

c9

leave

c3

retq

But what if we misalign?

```
eb13
488b45f8
83
c03089          salb  $0x89, (%rax)
c7             invalid opcode
e868f70000     callq 0xf792
488345f801     addq  $1, -8(%rbp)
48837df809     cmpq  $9, -8(%rbp)
76e6          jbe   0x1c
bf0a000000     movl  $0xa, %edi
e852f70000     callq 0xf792
b800000000     movl  $0, %eax
c9            leave
c3            retq
```


But what if we misalign?

```
eb13
488b45f8
83c0
3089c7e868f7    xorb  %cl, -0x8971739(%rcx)
0000            addb  %al, (%rax)
488345f801      addq  $1, -8(%rbp)
48837df809      cmpq  $9, -8(%rbp)
76e6            jbe   0x1c
bf0a000000      movl  $0xa, %edi
e852f70000      callq 0xf792
b800000000      movl  $0, %eax
c9              leave
c3              retq
```

But what if we misalign?

```
eb13
488b45f8
83c030
89c7      movl    %eax, %edi
e868f70000 callq   0xf792
488345f801 addq   $1, -8(%rbp)
48837df809 cmpq   $9, -8(%rbp)
76e6      jbe    0x1c
bf0a000000 movl   $0xa, %edi
e852f70000 callq   0xf792
b800000000 movl   $0, %eax
c9        leave  %edi
c3        retq
```

But what if we misalign?

488b45f8

83c030

89

c7 invalid opcode

e868f70000 **callq** 0xf792

488345f801 **addq** \$1, -8(%rbp)

48837df809 **cmpq** \$9, -8(%rbp)

76e6 **jbe** 0x1c

bf0a000000 **movl** \$0xa, %edi

e852f70000 **callq** 0xf792

b800000000 **movl** \$0, %eax

c9 **leave**

c3 **retq**

But what if we misalign?

488b45f8

83c030

89c7

e868f70000

`callq 0xf792`

488345f801

`addq $1, -8(%rbp)`

48837df809

`cmpq $9, -8(%rbp)`

76e6

`jbe 0x1c`

bf0a000000

`movl $0xa, %edi`

e852f70000

`callq 0xf792`

b800000000

`movl $0, %eax`

c9

`leave`

c3

`retq`

But what if we misalign?

```
83c030
89c7
e8
68f7000048      pushq $0x480000f7
8345f801      addl $1, -8(%rbp)
48837df809     cmpq $9, -8(%rbp)
76e6          jbe 0x1c
bf0a000000     movl $0xa, %edi
e852f70000     callq 0xf792
b800000000     movl $0, %eax
c9            leave
c3            retq
```

But what if we misalign?

```
83c030
89c7
e868
f70000488345      testl $0x45834800, (%rax)
f8                clc
014883            addl  %ecx, -0x7d(%rax)
7df8             jge   0x2b
0976e6            orl   %esi, -0x1a(%rsi)
bf0a000000       movl  $0xa, %edi
e852f70000       callq 0xf792
b800000000       movl  $0, %eax
c9               leave
c3               retq
```

But what if we misalign?

83c030

89c7

e868f7

0000

addb %al, (%rax)

488345f801

addq \$1, -8(%rbp)

48837df809

cmpq \$9, -8(%rbp)

76e6

jbe 0x1c

bf0a000000

movl \$0xa, %edi

e852f70000

callq 0xf792

b800000000

movl \$0, %eax

c9

leave

c3

retq

But what if we misalign?

```
83c030
89c7
e868f700
004883      addb  %cl, -0x7d(%rax)
45f8       clc
014883      addl  %ecx, -0x7d(%rax)
7df8       jge   0x2b
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9        leave
c3        retq
```


But what if we misalign?

83c030

89c7

e868f70000

488345f801 **addq** \$1, -8(%rbp)

48837df809 **cmpq** \$9, -8(%rbp)

76e6 **jbe** 0x1c

bf0a000000 **movl** \$0xa, %edi

e852f70000 **callq** 0xf792

b800000000 **movl** \$0, %eax

c9 **leave**

c3 **retq**

But what if we misalign?

```
89c7
e868f70000
48
8345f801      addl  $1, -8(%rbp)
48837df809    cmpq  $9, -8(%rbp)
76e6          jbe   0x1c
bf0a000000    movl  $0xa, %edi
e852f70000    callq 0xf792
b800000000    movl  $0, %eax
c9            leave
c3            retq
```

But what if we misalign?

```
89c7
e868f70000
4883
45f8          clc
014883       addl  %ecx, -0x7d(%rax)
7df8        jge  0x2b
0976e6       orl  %esi, -0x1a(%rsi)
bf0a000000  movl  $0xa, %edi
e852f70000  callq 0xf792
b800000000  movl  $0, %eax
c9          leave
c3          retq
```

But what if we misalign?

```
89c7
e868f70000
488345
f8          clc
014883     addl %ecx, -0x7d(%rax)
7df8     jge 0x2b
0976e6     orl %esi, -0x1a(%rsi)
bf0a000000 movl $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl $0, %eax
c9          leave
c3          retq
```

But what if we misalign?

```
89c7
e868f70000
488345f8
014883      addl  %ecx, -0x7d(%rax)
7df8       jge   0x2b
0976e6     orl   %esi, -0x1a(%rsi)
bf0a000000 movl  $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9        leave
c3        retq
```

But what if we misalign?

```
89c7
e868f70000
488345f801
48837df809      cmpq   $9, -8(%rbp)
76e6            jbe    0x1c
bf0a000000      movl   $0xa, %edi
e852f70000      callq 0xf792
b800000000      movl   $0, %eax
c9             leave
c3             retq
```

But what if we misalign?

```
e868f70000
488345f801
48
837df809      cmpl  $9, -8(%rbp)
76e6          jbe   0x1c
bf0a000000    movl  $0xa, %edi
e852f70000    callq 0xf792
b800000000    movl  $0, %eax
c9            leave
c3            retq
```

But what if we misalign?

```
e868f70000
488345f801
4883
7df8      jge    0x2b
0976e6    orl    %esi, -0x1a(%rsi)
bf0a000000 movl   $0xa, %edi
e852f70000 callq  0xf792
b800000000 movl   $0, %eax
c9        leave
c3        retq
```


But what if we misalign?

```
e868f70000
488345f801
48837d
f8          clc
0976e6     orl  %esi, -0x1a(%rsi)
bf0a000000 movl $0xa, %edi
e852f70000 callq 0xf792
b800000000 movl $0, %eax
c9         leave
c3         retq
```

But what if we misalign?

```
e868f70000
488345f801
48837df8
0976e6      orl    %esi, -0x1a(%rsi)
bf0a000000  movl   $0xa, %edi
e852f70000  callq  0xf792
b800000000  movl   $0, %eax
c9          leave
c3          retq
```

But what if we misalign?

e868f70000

488345f801

48837df809

76e6

`jbe 0x1c`

bf0a000000

`movl $0xa, %edi`

e852f70000

`callq 0xf792`

b800000000

`movl $0, %eax`

c9

`leave`

c3

`retq`

But what if we misalign?

```
488345f801
48837df809
76
e6bf          outb  %al, $0xbf
0a00          orb   (%rax), %al
0000          addb  %al, (%rax)
e852f70000    callq 0xf792
b800000000    movl  $0, %eax
c9           leave
c3           retq
```

But what if we misalign?

488345f801

48837df809

76e6

bf0a000000

`movl $0xa, %edi`

e852f70000

`callq 0xf792`

b800000000

`movl $0, %eax`

c9

`leave`

c3

`retq`

But what if we misalign?

```
48837df809
76e6
bf
0a00      orb    (%rax), %al
0000      addb  %al, (%rax)
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9      leave
c3      retq
```

But what if we misalign?

```
48837df809
76e6
bf0a
0000          addb  %al, (%rax)
00e8          addb  %ch, %al
52           pushq %rdx
f70000b80000 testl $0xb800, (%rax)
0000          addb  %al, (%rax)
c9           leave
c3           retq
```

But what if we misalign?

```
48837df809
76e6
bf0a00
0000      addb  %al, (%rax)
e852f70000 callq 0xf792
b800000000 movl  $0, %eax
c9        leave
c3        retq
```


But what if we misalign?

48837df809

76e6

bf0a0000

00e8 `addb %ch, %al`

52 `pushq %rdx`

f70000b80000 `testl $0xb800, (%rax)`

0000 `addb %al, (%rax)`

c9 `leave`

c3 `retq`

But what if we misalign?

48837df809

76e6

bf0a000000

e852f70000

callq 0xf792

b800000000

movl \$0, %**eax**

c9

leave

c3

retq

But what if we misalign?

```
76e6  
bf0a000000  
e8  
52          pushq %rdx  
f70000b80000 testl $0xb800, (%rax)  
0000       addb %al, (%rax)  
c9         leave  
c3         retq
```

But what if we misalign?

```
76e6  
bf0a000000  
e852f7  
0000      addb  %al, (%rax)  
b800000000 movl  $0, %eax  
c9      leave  
c3      retq
```

But what if we misalign?

76e6

bf0a000000

e852f700

00b800000000 `addb %bh, (%rax)`

c9 `leave`

c3 `retq`

But what if we misalign?

```
76e6  
bf0a000000  
e852f70000  
b800000000      movl  $0, %eax  
c9              leave  
c3              retq
```

But what if we misalign?

bf0a000000

e852f70000

b8

0000 `addb %al, (%rax)`

0000 `addb %al, (%rax)`

c9 `leave`

c3 `retq`

But what if we misalign?

```
bf0a000000
e852f70000
b800
0000      addb  %al, (%rax)
00c9      addb  %cl, %cl
c3        retq
```


But what if we misalign?

bf0a000000

e852f70000

b80000

0000 `addb %al, (%rax)`

c9 `leave`

c3 `retq`

But what if we misalign?

bf0a000000

e852f70000

b8000000

00c9

`addb %cl, %cl`

c3

`retq`

But what if we misalign?



bf0a000000

e852f70000

b800000000

c9

`leave`

c3

`retq`

