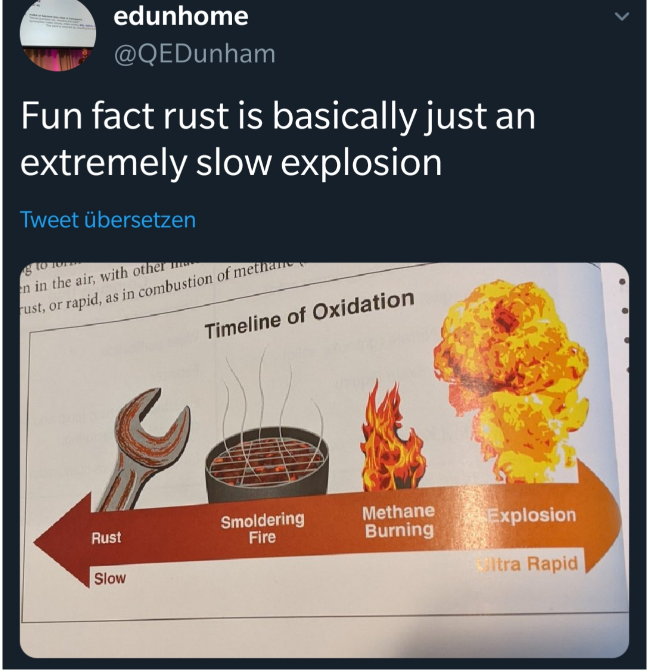
# Security Aspects in Software Development

Introduction and Low Level

**Daniel Gruss, Martin Schwarzl**

October 9, 2020



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@QEDunham

Fun fact rust is basically just an extremely slow explosion

Tweet übersetzen

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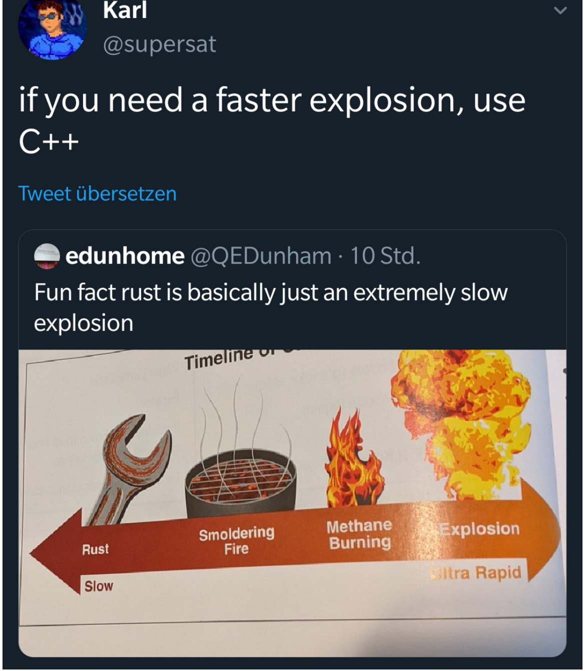
Timeline of Oxidation



Karl
@supersat

if you need a faster explosion, use C++

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Fun fact rust is basically just an extremely slow explosion

# Table of contents

# Privileges and Context Switches

# Memory configuration options

Memory configured through page tables

- Read / write
- Non-executable

- Separate configurations for different mappings and processes
- Separate configuration for kernel

# Context Switch: New Thread

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Act as if:

- Thread was running already
- We are returning from an interrupt

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   - `iret` (interrupt return) expects `ss`, `esp`, `eflags`, `cs`, `eip` on the stack
   - `iret` pops values from stack into the registers

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   - `iret` (interrupt return) expects `ss`, `esp`, `eflags`, `cs`, `eip` on the stack
   - `iret` pops values from stack into the registers

2. Instruction pointer has a new value, execution continues there

# Context Switch: Old Thread → New Thread

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- Store register values

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  - Copy all CPU register values from the stack into a struct

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- Old thread executes scheduling code ("the Scheduler")

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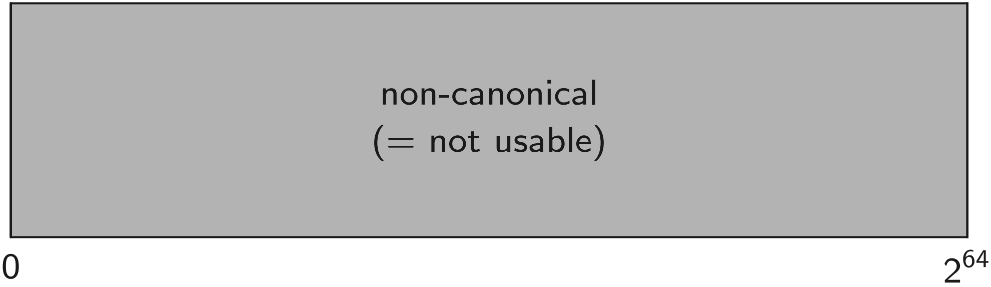
  - Only `eip` and `esp` are modified (which are already saved)
  - Copy all CPU register values from the stack into a struct
- Old thread executes scheduling code ("the Scheduler")
- Context switch to new thread as before

# Memory Layout and ELF

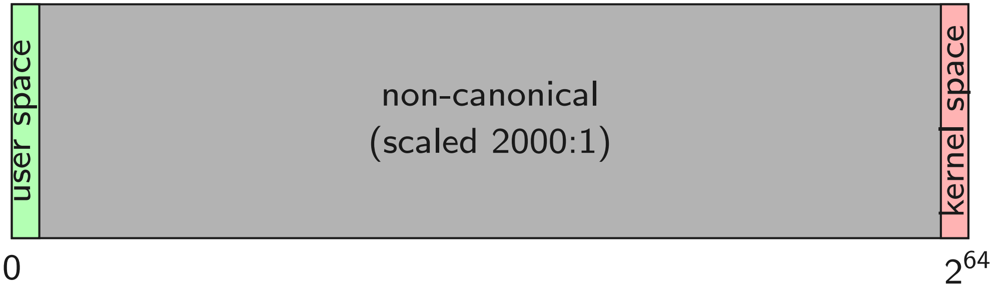
# Memory Layout



non-canonical

(= not usable)

# Memory Layout (scaled)



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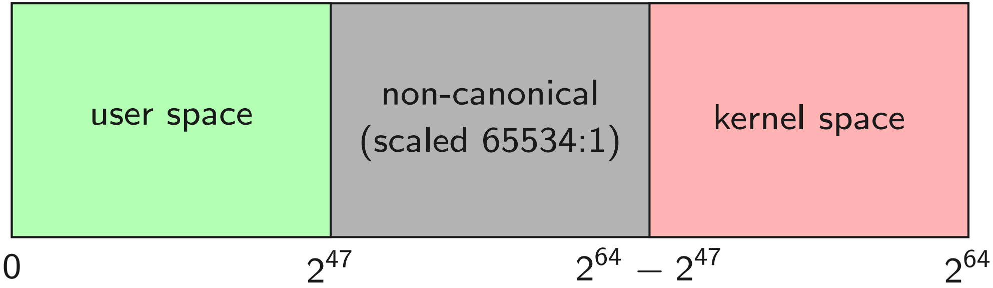
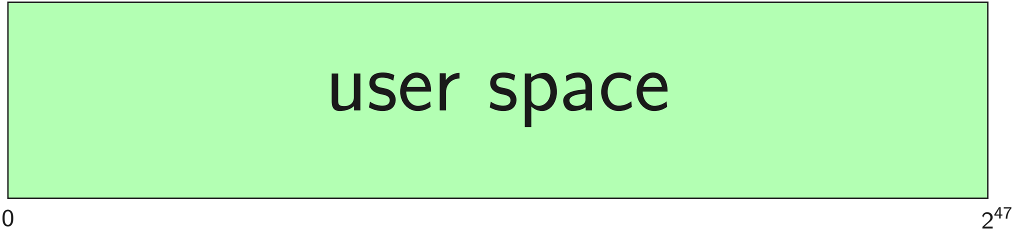


# Memory Layout User Space



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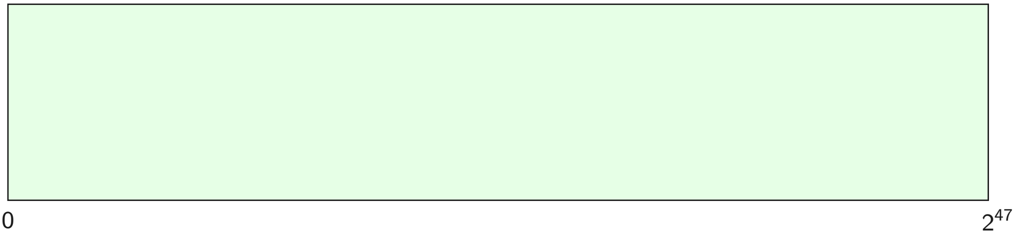

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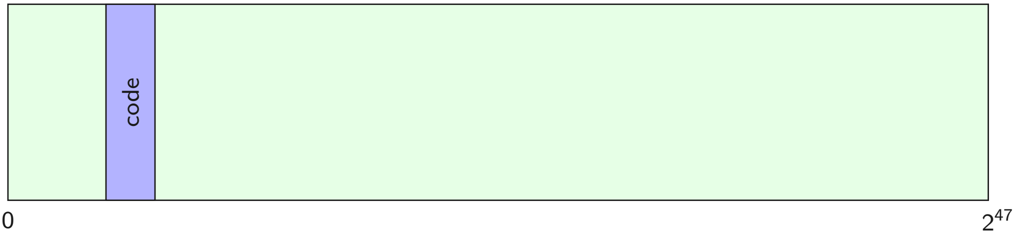

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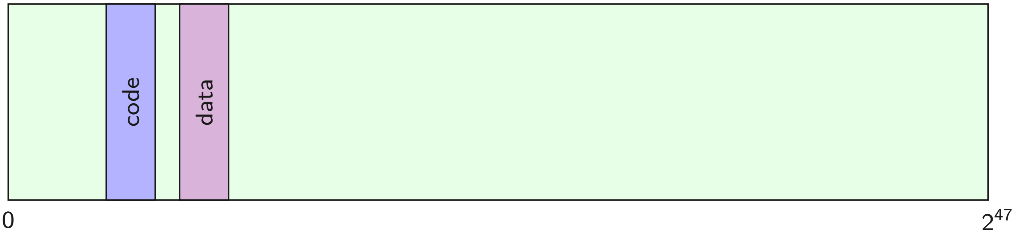

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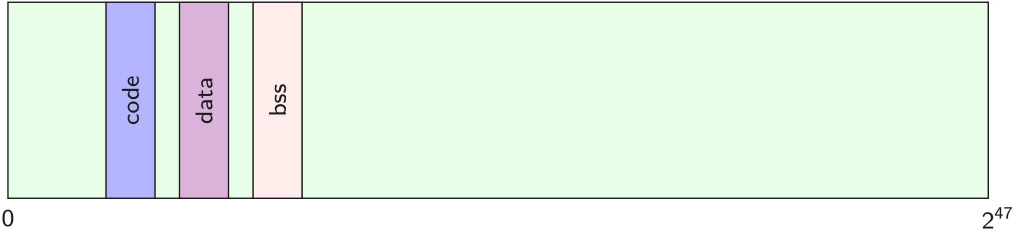

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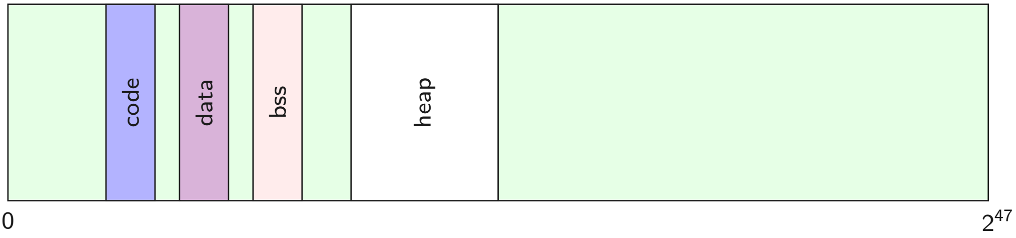

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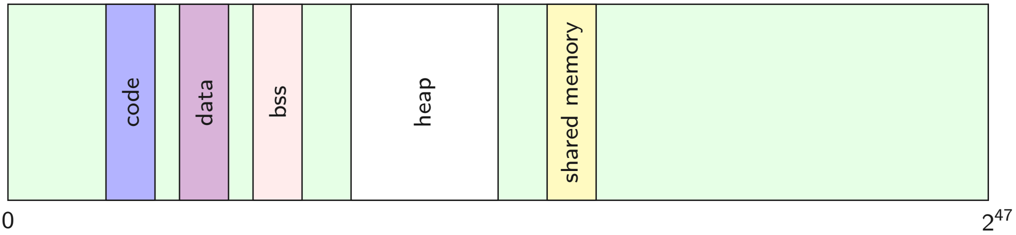

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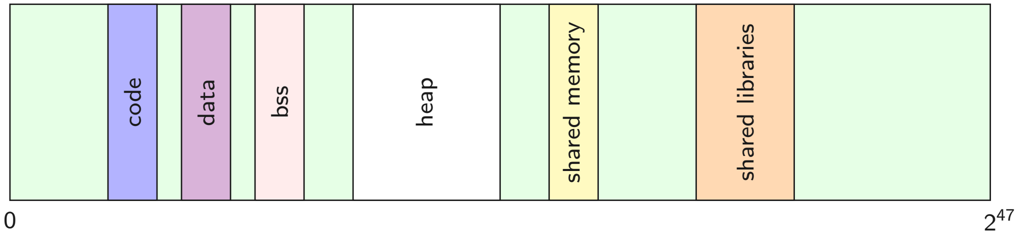

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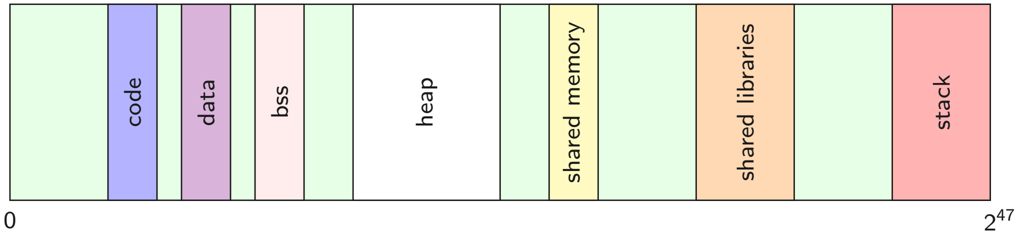

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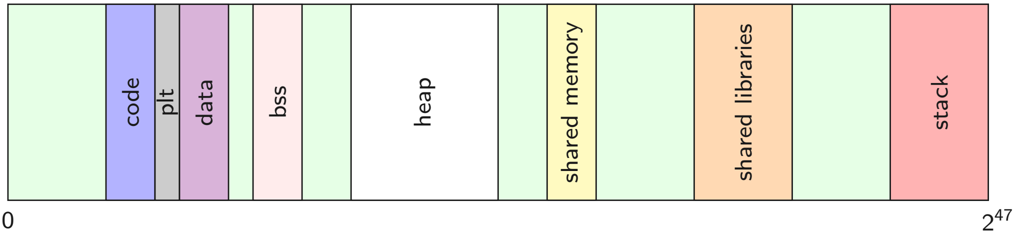

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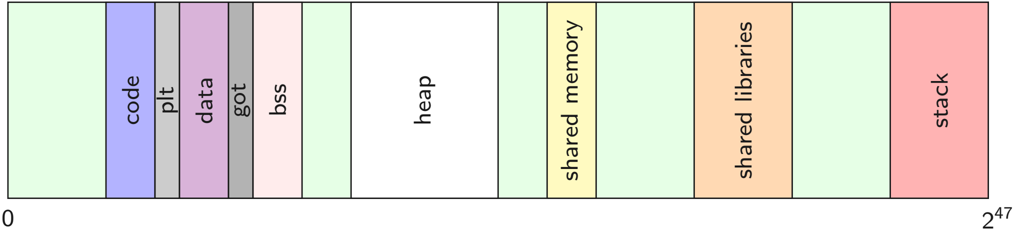
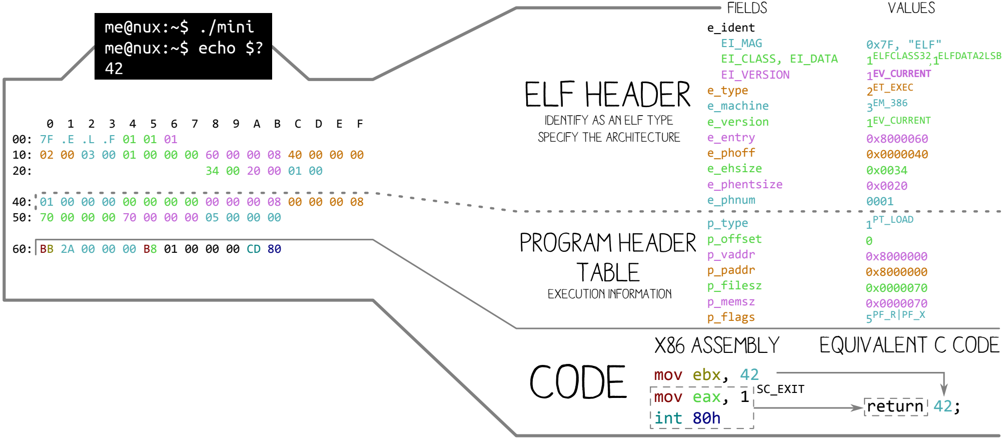


Let’s take a closer look at these 8 regions...

# Code

- Executable
- Usually readable
- Usually not writable

# ELF Binaries



```
me@nux:~$ ./mini
me@nux:~$ echo $?
42
```

```
     0  1  2  3  4  5  6  7  8  9  A  B  C  D  E  F
00: 7F .E .L .F 01 01 01
10: 02 00 03 00 01 00 00 00 60 00 00 08 40 00 00 00
20:                         34 00 20 00 01 00

40: 01 00 00 00 00 00 00 00 00 00 00 08 00 00 00 08
50: 70 00 00 00 70 00 00 00 05 00 00 00

60: BB 2A 00 00 00 B8 01 00 00 00 CD 80
```

ELF HEADER

IDENTIFY AS AN ELF TYPE

SPECIFY THE ARCHITECTURE

| FIELDS | VALUES |
|---|---|
| e_ident | |
| EI_MAG | 0x7F, "ELF" |
| EI_CLASS, EI_DATA | $1^{\text{ELFCLASS32}}$, $1^{\text{ELFDATA2LSB}}$ |
| EI_VERSION | $1^{\text{EV\_CURRENT}}$ |
| e_type | $2^{\text{ET\_EXEC}}$ |
| e_machine | $3^{\text{EM\_386}}$ |
| e_version | $1^{\text{EV\_CURRENT}}$ |
| e_entry | 0x8000060 |
| e_phoff | 0x0000040 |
| e_ehsize | 0x0034 |
| e_phentsize | 0x0020 |
| e_phnum | 0001 |
| p_type | $1^{\text{PT\_LOAD}}$ |
| p_offset | 0 |
| p_vaddr | 0x8000000 |
| p_paddr | 0x8000000 |
| p_filesz | 0x0000070 |
| p_memsz | 0x0000070 |
| p_flags | $5^{\text{PF\_R\|PF\_X}}$ |

PROGRAM HEADER TABLE

EXECUTION INFORMATION

CODE

X86 ASSEMBLY

```
mov ebx, 42
mov eax, 1
int 80h
```

SC_EXIT

EQUIVALENT C CODE

```
return 42;
```

# Challenge #1 - ELF binary

**Write an ELF binary which outputs your immatriculation number and exits**

- Size of the binary must be $\leq$ 100 bytes
- Binary must be a 32-bit or 64-bit ELF binary which runs in the reference VM
- Binary does not have to be 100% valid as specified in the standard
- Use whatever tool(s) you like, source code is not required

# PLT and GOT

# Dynamic Linking (PLT/GOT)

Dynamic loader (part of the OS)

- Loads dynamically linked libraries / shared libraries
- Maps corresponding memory on-demand
- Makes addresses valid on-demand (GOT)

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Dynamic loader (part of the OS)

- Loads dynamically linked libraries / shared libraries
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- Makes addresses valid on-demand (GOT)

→ But what address is compiled into the binary then?

# Procedure Linkage Table (PLT)

```
14c0:  ff 35 72 79 20 00  pushq  0x207972(%rip)
14c6:  ff 25 74 79 20 00  jmpq   *0x207974(%rip)
14cc:  0f 1f 40 00        nopl   0x0(%rax)
```

- *Trampoline* to real code
- Indirect jumps
- (typically) 16 bytes of code

# Global Offset Table (GOT)

- Addresses of exported/external variables and functions
- Absolute address (64 bit pointers → 8 bytes)
- Special part of the GOT:

.got.plt: Addresses of exported/external functions used by the PLT

# But what if I want to call a GOT function?

- .plt.got stubs
- Fixed offset stub for GOT entries
- Typically 8 bytes per stub

# GOT/PLT Example (C)

```c
#include <stdio.h>
int main()
{
  puts("hello world\n");
  return 0;
}
```

# GOT/PLT Example (ASM)

```
0000000000000570 <_start>:
 570:   xor    %ebp,%ebp
 572:   mov    %rdx,%r9
 575:   pop    %rsi
 576:   mov    %rsp,%rdx
 579:   and    $0xfffffffffffffff0,%rsp
 57d:   push   %rax
 57e:   push   %rsp
 57f:   lea    0x1aa(%rip),%r8  # __libc_csu_fini
 586:   lea    0x133(%rip),%rcx # __libc_csu_init
 58d:   lea    0x10c(%rip),%rdi # main
>594:   callq  *0x200a3e(%rip)  # __libc_start_main@GLIBC_2.2.5
 59a:   hlt
 59b:   nopl   0x0(%rax,%rax,1)
```

$$0x200a3e + 0x59a = 0x200fd8$$

Relative addressing: GOT offset ↔ instruction offset is constant

# GOT/PLT Example (ASM)

```
0000000000200fb0 <_GLOBAL_OFFSET_TABLE_>:
  200fb0:  f0 0d 20 00 00 00 00 00
  200fb8:  00 00 00 00 00 00 00 00
  200fc0:  00 00 00 00 00 00 00 00
  200fc8:  00 00 00 00 00 00 00 00
  200fd0:  00 00 00 00 00 00 00 00
> 200fd8:  00 00 00 00 00 00 00 00
  200fe0:  00 00 00 00 00 00 00 00
  200fe8:  00 00 00 00 00 00 00 00
  200ff0:  00 00 00 00 00 00 00 00
  200ff8:  00 00 00 00 00 00 00 00
```

GOT is filled at runtime.

# GOT/PLT Example (ASM)

```
0000000000020300 <__libc_start_main@@GLIBC_2.2.5>:
 # ...
 203de:       48 8b 74 24 08          mov    0x8(%rsp),%rsi
 203e3:       8b 7c 24 14             mov    0x14(%rsp),%edi
 203e7:       48 8b 10                mov    (%rax),%rdx
 203ea:       48 8b 44 24 18          mov    0x18(%rsp),%rax
>203ef:       ff d0                   callq  *%rax                      # main
 203f1:       89 c7                   mov    %eax,%edi
 203f3:       e8 b8 9e 01 00          callq  3a2b0 <exit@@GLIBC_2.2.5>
 # ...
```

# GOT/PLT Example (ASM)

```
0000000000000570 <_start>:
 6a0:    sub    $0x8,%rsp
>6a4:    lea    0x99(%rip),%rdi
 6ab:    callq  560 <.plt.got>
 6b0:    mov    $0x0,%eax
 6b5:    add    $0x8,%rsp
 6b9:    retq
 6ba:    nopw   0x0(%rax,%rax,1)
```

$$0x6ab + 0x99 = 0x744$$

# GOT/PLT Example (ASM)

```
>744:   68 65 6c 6c 6f 20 77 6f 72 6c 64 0a 00   "hello world\n"
```

# GOT/PLT Example (ASM)

```
0000000000000570 <_start>:
 6a0:    sub    $0x8,%rsp
 6a4:    lea    0x99(%rip),%rdi
>6ab:    callq  560 <.plt.got>
 6b0:    mov    $0x0,%eax
 6b5:    add    $0x8,%rsp
 6b9:    retq
 6ba:    nopw   0x0(%rax,%rax,1)
```

# GOT/PLT Example (ASM)

```
0000000000000560 <.plt.got>:
>560:    jmpq   *0x200a6a(%rip)   # puts@GLIBC_2.2.5
 566:    xchg   %ax,%ax
```

$$0x200a6a + 0x566 = 0x200fd0$$

# GOT/PLT Example (ASM)

```
0000000000200fb0 <_GLOBAL_OFFSET_TABLE_>:
  200fb0:  f0 0d 20 00 00 00 00 00
  200fb8:  00 00 00 00 00 00 00 00
  200fc0:  00 00 00 00 00 00 00 00
  200fc8:  00 00 00 00 00 00 00 00
> 200fd0:  00 00 00 00 00 00 00 00
  200fd8:  00 00 00 00 00 00 00 00
  200fe0:  00 00 00 00 00 00 00 00
  200fe8:  00 00 00 00 00 00 00 00
  200ff0:  00 00 00 00 00 00 00 00
  200ff8:  00 00 00 00 00 00 00 00
```

And finally arrived in the shared library through absolute address in `0x200fd0`.

# Functions

```
int test()
{
  return 4 + 4;
}
```

# Functions

```
00000000000006a0 <test>:
 6a0:   55                      push   %rbp       # prologue
 6a1:   48 89 e5                mov    %rsp,%rbp  # prologue
 6a4:   b8 08 00 00 00          mov    $0x8,%eax  # body
 6a9:   5d                      pop    %rbp       # epilogue
 6aa:   c3                      retq              # epilogue
```

# Calling Conventions

# Calling Conventions (x86_32/x86_64)

- Many different calling conventions
  - passing arguments
    register contention vs. slow stack memory accesses
  - responsibility
    is it easier if the caller/callee save something?
- focus on cdecl (x86_32) and System V AMD64 ABI (x86_64)

# C Program

```c
size_t add(size_t a, size_t b) {
  return a + b;
}

int main() {
  size_t a = 7;
  size_t b = 14;
  size_t c = 0;

  c = add(a, b);

  return c;
}
```

# cdecl (x86_32)

# Assembler Program (gcc -S -m32)

```
main:
> pushl   %ebp
  movl    %esp, %ebp
  subl    $16, %esp
  movl    $7, -12(%ebp)
  movl    $14, -8(%ebp)
  movl    $0, -4(%ebp)
  pushl   -8(%ebp)
  pushl   -12(%ebp)
  call    add
  addl    $8, %esp
  movl    %eax, -4(%ebp)
  movl    -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl   %ebp
  movl    %esp, %ebp
  movl    8(%ebp), %edx
  movl    12(%ebp), %eax
  addl    %edx, %eax
  popl    %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | |
| 0xffec | |
| 0xffe8 | |
| 0xffe4 | |
| 0xffe0 | |
| 0xffdc | |
| 0xffd8 | |
| 0xffd4 | |
| 0xffd0 | |

| | |
|---|---|
| %ebp | <ebp> |
| %esp | 0xfff0 |
| %eax | ?? |
| %edx | ?? |

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  movl    %eax, -4(%ebp)
  movl    -4(%ebp), %eax
  leave
  ret
```

```
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  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> ← %esp |
| 0xffec | |
| 0xffe8 | |
| 0xffe4 | |
| 0xffe0 | |
| 0xffdc | |
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| 0xffd4 | |
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  movl   %eax, -4(%ebp)
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  popl   %ebp
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```

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```
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  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

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  ret
```

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  movl   %eax, -4(%ebp)
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```

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  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

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| 0xffd0 | |

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| %ebp | 0xfff0 |
| %esp | 0xffe0 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
> movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | | |
| 0xffe8 | | |
| 0xffe4 | | |
| 0xffe0 | | ← %esp |
| 0xffdc | | |
| 0xffd8 | | |
| 0xffd4 | | |
| 0xffd0 | | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffe0 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
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  pushl  -8(%ebp)
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  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
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  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | | |
| 0xffe8 | | |
| 0xffe4 | 7 | |
| 0xffe0 | | ← %esp |
| 0xffdc | | |
| 0xffd8 | | |
| 0xffd4 | | |
| 0xffd0 | | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffe0 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
main:
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  pushl  -8(%ebp)
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  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
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```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> ← %ebp |
| 0xffec | |
| 0xffe8 | |
| 0xffe4 | 7 |
| 0xffe0 | ← %esp |
| 0xffdc | |
| 0xffd8 | |
| 0xffd4 | |
| 0xffd0 | |

| | |
|---|---|
| %ebp | 0xfff0 |
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| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

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  pushl  -8(%ebp)
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  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | ← %esp |
| 0xffdc | | |
| 0xffd8 | | |
| 0xffd4 | | |
| 0xffd0 | | |

| | |
|---|---|
| %ebp | 0xfff0 |
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| %eax | ?? |
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# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
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  movl   $14, -8(%ebp)
> movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | ← %esp |
| 0xffdc | | |
| 0xffd8 | | |
| 0xffd4 | | |
| 0xffd0 | | |

| | |
|---|---|
| %ebp | 0xfff0 |
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| %eax | ?? |
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# Assembler Program (gcc -S -m32)

```
main:
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  movl   $14, -8(%ebp)
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  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> ← %ebp |
| 0xffec | 0 |
| 0xffe8 | 14 |
| 0xffe4 | 7 |
| 0xffe0 | ← %esp |
| 0xffdc | |
| 0xffd8 | |
| 0xffd4 | |
| 0xffd0 | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffe0 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
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  movl   $7, -12(%ebp)
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  movl   $0, -4(%ebp)
> pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
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| 0xffdc | |
| 0xffd8 | |
| 0xffd4 | |
| 0xffd0 | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffe0 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
main:
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  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
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  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
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| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | ← %esp |
| 0xffd8 | | |
| 0xffd4 | | |
| 0xffd0 | | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffdc |
| %eax | ?? |
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# Assembler Program (gcc -S -m32)

```
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  movl   $0, -4(%ebp)
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  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
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```

```
add:
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  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
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| 0xffe4 | 7 | |
| 0xffe0 | | |
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| 0xffd8 | | |
| 0xffd4 | | |
| 0xffd0 | | |

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| %ebp | 0xfff0 |
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| %eax | ?? |
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# Assembler Program (gcc -S -m32)

```
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```
add:
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```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
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| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | ← %esp |
| 0xffd4 | | |
| 0xffd0 | | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffd8 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
main:
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  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
> call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | 0 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | ← %esp |
| 0xffd4 | | |
| 0xffd0 | | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffd8 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
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  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
> call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> ← %ebp |
| 0xffec | 0 |
| 0xffe8 | 14 |
| 0xffe4 | 7 |
| 0xffe0 | |
| 0xffdc | 14 |
| 0xffd8 | 7 |
| 0xffd4 | <main+11> ← %esp |
| 0xffd0 | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffd4 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
> pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | 0 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | |
| 0xffd4 | <main+11> | ← %esp |
| 0xffd0 | | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffd4 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
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  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
> pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | 0 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | |
| 0xffd4 | <main+11> | |
| 0xffd0 | 0xfff0 | ← %esp |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffd0 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
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  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
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  movl   8(%ebp), %edx
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```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | 0 | |
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| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | |
| 0xffd4 | <main+11> | |
| 0xffd0 | 0xfff0 | ← %esp |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffd0 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
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  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
> movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> |
| 0xffec | 0 |
| 0xffe8 | 14 |
| 0xffe4 | 7 |
| 0xffe0 | |
| 0xffdc | 14 |
| 0xffd8 | 7 |
| 0xffd4 | <main+11> |
| 0xffd0 | 0xfff0 ← %esp,%ebp |

| | |
|---|---|
| %ebp | 0xffd0 |
| %esp | 0xffd0 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
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  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
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> movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | |
| 0xffec | 0 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | |
| 0xffd4 | <main+11> | |
| 0xffd0 | 0xfff0 | ← %esp,%ebp |

| | |
|---|---|
| %ebp | 0xffd0 |
| %esp | 0xffd0 |
| %eax | ?? |
| %edx | ?? |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
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  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
> movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> |
| 0xffec | 0 |
| 0xffe8 | 14 |
| 0xffe4 | 7 |
| 0xffe0 | |
| 0xffdc | 14 |
| 0xffd8 | 7 |
| 0xffd4 | <main+11> |
| 0xffd0 | 0xfff0 ← %esp,%ebp |

| | |
|---|---|
| %ebp | 0xffd0 |
| %esp | 0xffd0 |
| %eax | ?? |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
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  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
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  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> |
| 0xffec | 0 |
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| 0xffd0 | 0xfff0 ← %esp,%ebp |

| | |
|---|---|
| %ebp | 0xffd0 |
| %esp | 0xffd0 |
| %eax | ?? |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
> movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | |
| 0xffec | 0 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | |
| 0xffd4 | <main+11> | |
| 0xffd0 | 0xfff0 | ← %esp,%ebp |

| | |
|---|---|
| %ebp | 0xffd0 |
| %esp | 0xffd0 |
| %eax | 14 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
> addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> |
| 0xffec | 0 |
| 0xffe8 | 14 |
| 0xffe4 | 7 |
| 0xffe0 | |
| 0xffdc | 14 |
| 0xffd8 | 7 |
| 0xffd4 | <main+11> |
| 0xffd0 | 0xfff0 ← %esp,%ebp |

| | |
|---|---|
| %ebp | 0xffd0 |
| %esp | 0xffd0 |
| %eax | 14 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
> addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> |
| 0xffec | 0 |
| 0xffe8 | 14 |
| 0xffe4 | 7 |
| 0xffe0 | |
| 0xffdc | 14 |
| 0xffd8 | 7 |
| 0xffd4 | <main+11> |
| 0xffd0 | 0xfff0 ← %esp,%ebp |

| | |
|---|---|
| %ebp | 0xffd0 |
| %esp | 0xffd0 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
> popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | |
| 0xffec | 0 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | |
| 0xffd4 | <main+11> | |
| 0xffd0 | 0xfff0 | ← %esp,%ebp |

| | |
|---|---|
| %ebp | 0xffd0 |
| %esp | 0xffd0 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
> popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | 0 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | |
| 0xffd4 | <main+11> | ← %esp |
| 0xffd0 | 0xfff0 | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffd4 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
> ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | 0 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | |
| 0xffd4 | <main+11> | ← %esp |
| 0xffd0 | 0xfff0 | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffd4 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
> ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | 0 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | ← %esp |
| 0xffd4 | <main+11> | |
| 0xffd0 | 0xfff0 | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffd8 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
> addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> ← %ebp |
| 0xffec | 0 |
| 0xffe8 | 14 |
| 0xffe4 | 7 |
| 0xffe0 | |
| 0xffdc | 14 |
| 0xffd8 | 7 ← %esp |
| 0xffd4 | <main+11> |
| 0xffd0 | 0xfff0 |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffd8 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
> addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp |
| 0xffec | 0 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | ← %esp |
| 0xffdc | 14 | |
| 0xffd8 | 7 | |
| 0xffd4 | <main+11> | |
| 0xffd0 | 0xfff0 | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffe0 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl   %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl   -8(%ebp)
  pushl   -12(%ebp)
  call   add
  addl   $8, %esp
> movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl   %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> ← %ebp |
| 0xffec | 0 |
| 0xffe8 | 14 |
| 0xffe4 | 7 |
| 0xffe0 | ← %esp |
| 0xffdc | 14 |
| 0xffd8 | 7 |
| 0xffd4 | <main+11> |
| 0xffd0 | 0xfff0 |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffe0 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
> movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> ← %ebp |
| 0xffec | 21 |
| 0xffe8 | 14 |
| 0xffe4 | 7 |
| 0xffe0 | ← %esp |
| 0xffdc | 14 |
| 0xffd8 | 7 |
| 0xffd4 | <main+11> |
| 0xffd0 | 0xfff0 |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffe0 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
> movl   -4(%ebp), %eax
  leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> ← %ebp |
| 0xffec | 21 |
| 0xffe8 | 14 |
| 0xffe4 | 7 |
| 0xffe0 | ← %esp |
| 0xffdc | 14 |
| 0xffd8 | 7 |
| 0xffd4 | <main+11> |
| 0xffd0 | 0xfff0 |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffe0 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
> leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | |
|---|---|
| 0xfff0 | <ebp> ← %ebp |
| 0xffec | 21 |
| 0xffe8 | 14 |
| 0xffe4 | 7 |
| 0xffe0 | ← %esp |
| 0xffdc | 14 |
| 0xffd8 | 7 |
| 0xffd4 | <main+11> |
| 0xffd0 | 0xfff0 |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xffe0 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
> leave
  ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp,%esp |
| 0xffec | 21 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | |
| 0xffdc | 14 | |
| 0xffd8 | 7 | |
| 0xffd4 | <main+11> | |
| 0xffd0 | 0xfff0 | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xfff0 |
| %eax | 21 |
| %edx | 7 |

# Assembler Program (gcc -S -m32)

```
main:
  pushl  %ebp
  movl   %esp, %ebp
  subl   $16, %esp
  movl   $7, -12(%ebp)
  movl   $14, -8(%ebp)
  movl   $0, -4(%ebp)
  pushl  -8(%ebp)
  pushl  -12(%ebp)
  call   add
  addl   $8, %esp
  movl   %eax, -4(%ebp)
  movl   -4(%ebp), %eax
  leave
> ret
```

```
add:
  pushl  %ebp
  movl   %esp, %ebp
  movl   8(%ebp), %edx
  movl   12(%ebp), %eax
  addl   %edx, %eax
  popl   %ebp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <ebp> | ← %ebp,%esp |
| 0xffec | 21 | |
| 0xffe8 | 14 | |
| 0xffe4 | 7 | |
| 0xffe0 | | ← %esp |
| 0xffdc | 14 | |
| 0xffd8 | 7 | |
| 0xffd4 | <main+11> | |
| 0xffd0 | 0xfff0 | |

| | |
|---|---|
| %ebp | 0xfff0 |
| %esp | 0xfff0 |
| %eax | 21 |
| %edx | 7 |

# System V AMD64 ABI (x86_64)

# Assembler Program (gcc -S -m64)

```
main:
> pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | |
| 0xffe8 | |
| 0xffe0 | |
| 0xffd8 | |
| 0xffd0 | |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | <rbp> |
| %rsp | 0xfff0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
> pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rsp |
| 0xffe8 | |
| 0xffe0 | |
| 0xffd8 | |
| 0xffd0 | |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | <rbp> |
| %rsp | 0xfff0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
> movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rsp |
| 0xffe8 | |
| 0xffe0 | |
| 0xffd8 | |
| 0xffd0 | |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | <rbp> |
| %rsp | 0xfff0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
> movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rsp, %rbp |
| 0xffe8 | |
| 0xffe0 | |
| 0xffd8 | |
| 0xffd0 | |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xfff0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
   pushq  %rbp
   movq   %rsp, %rbp
>  subq   $32, %rsp
   movq   $7, -24(%rbp)
   movq   $14, -16(%rbp)
   movq   $0, -8(%rbp)
   movq   -16(%rbp), %rdx
   movq   -24(%rbp), %rax
   movq   %rdx, %rsi
   movq   %rax, %rdi
   call   add
   movq   %rax, -8(%rbp)
   movq   -8(%rbp), %rax
   leave
   ret
```

```
add:
   pushq  %rbp
   movq   %rsp, %rbp
   movq   %rdi, -8(%rbp)
   movq   %rsi, -16(%rbp)
   movq   -8(%rbp), %rdx
   movq   -16(%rbp), %rax
   addq   %rdx, %rax
   popq   %rbp
   ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rsp, %rbp |
| 0xffe8 | |
| 0xffe0 | |
| 0xffd8 | |
| 0xffd0 | |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xfff0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
> subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp |
| 0xffe8 | |
| 0xffe0 | |
| 0xffd8 | |
| 0xffd0 | ← %rsp |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
> movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | | |
| 0xffe0 | | |
| 0xffd8 | | |
| 0xffd0 | | ← %rsp |
| 0xffc8 | | |
| 0xffc0 | | |
| 0xffb8 | | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
> movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp |
| 0xffe8 | |
| 0xffe0 | |
| 0xffd8 | 7 |
| 0xffd0 | ← %rsp |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
> movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp |
| 0xffe8 | |
| 0xffe0 | |
| 0xffd8 | 7 |
| 0xffd0 | ← %rsp |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
> movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | ← %rsp |
| 0xffc8 | | |
| 0xffc0 | | |
| 0xffb8 | | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
> movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp |
| 0xffe8 | |
| 0xffe0 | 14 |
| 0xffd8 | 7 |
| 0xffd0 | ← %rsp |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
> movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp |
| 0xffe8 | 0 |
| 0xffe0 | 14 |
| 0xffd8 | 7 |
| 0xffd0 | ← %rsp |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
   pushq %rbp
   movq  %rsp, %rbp
   subq  $32, %rsp
   movq  $7, -24(%rbp)
   movq  $14, -16(%rbp)
   movq  $0, -8(%rbp)
>  movq  -16(%rbp), %rdx
   movq  -24(%rbp), %rax
   movq  %rdx, %rsi
   movq  %rax, %rdi
   call  add
   movq  %rax, -8(%rbp)
   movq  -8(%rbp), %rax
   leave
   ret
```

```
add:
   pushq %rbp
   movq  %rsp, %rbp
   movq  %rdi, -8(%rbp)
   movq  %rsi, -16(%rbp)
   movq  -8(%rbp), %rdx
   movq  -16(%rbp), %rax
   addq  %rdx, %rax
   popq  %rbp
   ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | ← %rsp |
| 0xffc8 | | |
| 0xffc0 | | |
| 0xffb8 | | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | ?? |
| %rdx | ?? |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
> movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | ← %rsp |
| 0xffc8 | | |
| 0xffc0 | | |
| 0xffb8 | | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | ?? |
| %rdx | 14 |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
> movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | ← %rsp |
| 0xffc8 | | |
| 0xffc0 | | |
| 0xffb8 | | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | ?? |
| %rdx | 14 |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
> movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp |
| 0xffe8 | 0 |
| 0xffe0 | 14 |
| 0xffd8 | 7 |
| 0xffd0 | ← %rsp |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
> movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | ← %rsp |
| 0xffc8 | | |
| 0xffc0 | | |
| 0xffb8 | | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | ?? |
| %rsi | ?? |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
> movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | ← %rsp |
| 0xffc8 | | |
| 0xffc0 | | |
| 0xffb8 | | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | ?? |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
> movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp |
| 0xffe8 | 0 |
| 0xffe0 | 14 |
| 0xffd8 | 7 |
| 0xffd0 | ← %rsp |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | ?? |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
> movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp |
| 0xffe8 | 0 |
| 0xffe0 | 14 |
| 0xffd8 | 7 |
| 0xffd0 | ← %rsp |
| 0xffc8 | |
| 0xffc0 | |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
   pushq %rbp
   movq  %rsp, %rbp
   subq  $32, %rsp
   movq  $7, -24(%rbp)
   movq  $14, -16(%rbp)
   movq  $0, -8(%rbp)
   movq  -16(%rbp), %rdx
   movq  -24(%rbp), %rax
   movq  %rdx, %rsi
   movq  %rax, %rdi
>  call  add
   movq  %rax, -8(%rbp)
   movq  -8(%rbp), %rax
   leave
   ret
```

```
add:
   pushq %rbp
   movq  %rsp, %rbp
   movq  %rdi, -8(%rbp)
   movq  %rsi, -16(%rbp)
   movq  -8(%rbp), %rdx
   movq  -16(%rbp), %rax
   addq  %rdx, %rax
   popq  %rbp
   ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | ← %rsp |
| 0xffc8 | | |
| 0xffc0 | | |
| 0xffb8 | | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffd0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
> call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | |
| 0xffc8 | <main+13> | ← %rsp |
| 0xffc0 | | |
| 0xffb8 | | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffc8 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
> pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | |
| 0xffc8 | <main+13> | ← %rsp |
| 0xffc0 | | |
| 0xffb8 | | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffc8 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
> pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | |
| 0xffc8 | <main+13> | |
| 0xffc0 | 0xfff0 | ← %rsp |
| 0xffb8 | | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffc0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
> movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp |
| 0xffe8 | 0 |
| 0xffe0 | 14 |
| 0xffd8 | 7 |
| 0xffd0 | |
| 0xffc8 | <main+13> |
| 0xffc0 | 0xfff0 ← %rsp |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xfff0 |
| %rsp | 0xffc0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
> movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> |
| 0xffe8 | 0 |
| 0xffe0 | 14 |
| 0xffd8 | 7 |
| 0xffd0 | |
| 0xffc8 | <main+13> |
| 0xffc0 | 0xfff0 ← %rsp,%rbp |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
> movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> |
| 0xffe8 | 0 |
| 0xffe0 | 14 |
| 0xffd8 | 7 |
| 0xffd0 | |
| 0xffc8 | <main+13> |
| 0xffc0 | 0xfff0 ← %rsp,%rbp |
| 0xffb8 | |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
> movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | |
| 0xffc8 | <main+13> | |
| 0xffc0 | 0xfff0 | ← %rsp,%rbp |
| 0xffb8 | 7 | |
| 0xffb0 | | |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
> movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | |
|---|---|
| 0xfff0 | <rbp> |
| 0xffe8 | 0 |
| 0xffe0 | 14 |
| 0xffd8 | 7 |
| 0xffd0 | |
| 0xffc8 | <main+13> |
| 0xffc0 | 0xfff0 ← %rsp,%rbp |
| 0xffb8 | 7 |
| 0xffb0 | |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
> movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | |
| 0xffc8 | <main+13> | |
| 0xffc0 | 0xfff0 | ← %rsp,%rbp |
| 0xffb8 | 7 | |
| 0xffb0 | 14 | |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
> movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | |
| 0xffc8 | <main+13> | |
| 0xffc0 | 0xfff0 | ← %rsp,%rbp |
| 0xffb8 | 7 | |
| 0xffb0 | 14 | |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
| %rax | 7 |
| %rdx | 14 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
   pushq %rbp
   movq  %rsp, %rbp
   subq  $32, %rsp
   movq  $7, -24(%rbp)
   movq  $14, -16(%rbp)
   movq  $0, -8(%rbp)
   movq  -16(%rbp), %rdx
   movq  -24(%rbp), %rax
   movq  %rdx, %rsi
   movq  %rax, %rdi
   call  add
   movq  %rax, -8(%rbp)
   movq  -8(%rbp), %rax
   leave
   ret
```

```
add:
   pushq %rbp
   movq  %rsp, %rbp
   movq  %rdi, -8(%rbp)
   movq  %rsi, -16(%rbp)
>  movq  -8(%rbp), %rdx
   movq  -16(%rbp), %rax
   addq  %rdx, %rax
   popq  %rbp
   ret
```

| | |
|---|---|
| 0xfff0 | <rbp> |
| 0xffe8 | 0 |
| 0xffe0 | 14 |
| 0xffd8 | 7 |
| 0xffd0 | |
| 0xffc8 | <main+13> |
| 0xffc0 | 0xfff0 ← %rsp,%rbp |
| 0xffb8 | 7 |
| 0xffb0 | 14 |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
| %rax | 7 |
| %rdx | 7 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
> movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | |
| 0xffc8 | <main+13> | |
| 0xffc0 | 0xfff0 | ← %rsp,%rbp |
| 0xffb8 | 7 | |
| 0xffb0 | 14 | |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
| %rax | 7 |
| %rdx | 7 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
   pushq %rbp
   movq  %rsp, %rbp
   subq  $32, %rsp
   movq  $7, -24(%rbp)
   movq  $14, -16(%rbp)
   movq  $0, -8(%rbp)
   movq  -16(%rbp), %rdx
   movq  -24(%rbp), %rax
   movq  %rdx, %rsi
   movq  %rax, %rdi
   call  add
   movq  %rax, -8(%rbp)
   movq  -8(%rbp), %rax
   leave
   ret
```

```
add:
   pushq %rbp
   movq  %rsp, %rbp
   movq  %rdi, -8(%rbp)
   movq  %rsi, -16(%rbp)
   movq  -8(%rbp), %rdx
> movq  -16(%rbp), %rax
   addq  %rdx, %rax
   popq  %rbp
   ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | |
| 0xffc8 | <main+13> | |
| 0xffc0 | 0xfff0 | ← %rsp,%rbp |
| 0xffb8 | 7 | |
| 0xffb0 | 14 | |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
| %rax | 14 |
| %rdx | 7 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
> addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | |
| 0xffc8 | <main+13> | |
| 0xffc0 | 0xfff0 | ← %rsp,%rbp |
| 0xffb8 | 7 | |
| 0xffb0 | 14 | |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
| %rax | 14 |
| %rdx | 7 |
| %rdi | 7 |
| %rsi | 14 |

# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
> addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | |
| 0xffc8 | <main+13> | |
| 0xffc0 | 0xfff0 | ← %rsp,%rbp |
| 0xffb8 | 7 | |
| 0xffb0 | 14 | |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
| %rax | 21 |
| %rdx | 7 |
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# Assembler Program (gcc -S -m64)

```
main:
  pushq %rbp
  movq  %rsp, %rbp
  subq  $32, %rsp
  movq  $7, -24(%rbp)
  movq  $14, -16(%rbp)
  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
> popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | |
| 0xffe8 | 0 | |
| 0xffe0 | 14 | |
| 0xffd8 | 7 | |
| 0xffd0 | | |
| 0xffc8 | <main+13> | |
| 0xffc0 | 0xfff0 | ← %rsp,%rbp |
| 0xffb8 | 7 | |
| 0xffb0 | 14 | |

| | |
|---|---|
| %rbp | 0xffc0 |
| %rsp | 0xffc0 |
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  movq  %rdx, %rsi
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| | | |
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  popq  %rbp
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```

| | | |
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  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
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add:
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```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp |
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| 0xffd8 | 7 |
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| 0xffc8 | <main+13> |
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    movq  $0, -8(%rbp)
    movq  -16(%rbp), %rdx
    movq  -24(%rbp), %rax
    movq  %rdx, %rsi
    movq  %rax, %rdi
    call  add
>   movq  %rax, -8(%rbp)
    movq  -8(%rbp), %rax
    leave
    ret
```

```
add:
    pushq %rbp
    movq  %rsp, %rbp
    movq  %rdi, -8(%rbp)
    movq  %rsi, -16(%rbp)
    movq  -8(%rbp), %rdx
    movq  -16(%rbp), %rax
    addq  %rdx, %rax
    popq  %rbp
    ret
```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp |
| 0xffe8 | 0 |
| 0xffe0 | 14 |
| 0xffd8 | 7 |
| 0xffd0 | ← %rsp |
| 0xffc8 | <main+13> |
| 0xffc0 | 0xfff0 |
| 0xffb8 | 7 |
| 0xffb0 | 14 |

| | |
|---|---|
| %rbp | 0xfff0 |
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# Assembler Program (gcc -S -m64)

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  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
> movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
  ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
  movq  %rdi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp |
| 0xffe8 | 21 | |
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| 0xffd0 | | ← %rsp |
| 0xffc8 | <main+13> | |
| 0xffc0 | 0xfff0 | |
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  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
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  leave
  ret
```

```
add:
  pushq %rbp
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  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
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   movq  $0, -8(%rbp)
   movq  -16(%rbp), %rdx
   movq  -24(%rbp), %rax
   movq  %rdx, %rsi
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   movq  %rax, -8(%rbp)
   movq  -8(%rbp), %rax
>  leave
   ret
```

```
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   movq  -8(%rbp), %rdx
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   addq  %rdx, %rax
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```

| | |
|---|---|
| 0xfff0 | <rbp> ← %rbp,%rsp |
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| | |
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  movq  $0, -8(%rbp)
  movq  -16(%rbp), %rdx
  movq  -24(%rbp), %rax
  movq  %rdx, %rsi
  movq  %rax, %rdi
  call  add
  movq  %rax, -8(%rbp)
  movq  -8(%rbp), %rax
  leave
> ret
```

```
add:
  pushq %rbp
  movq  %rsp, %rbp
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  movq  %rsi, -16(%rbp)
  movq  -8(%rbp), %rdx
  movq  -16(%rbp), %rax
  addq  %rdx, %rax
  popq  %rbp
  ret
```

| | | |
|---|---|---|
| 0xfff0 | <rbp> | ← %rbp,%rsp |
| 0xffe8 | 21 | |
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| 0xffd0 | | |
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| 0xffc0 | 0xfff0 | |
| 0xffb8 | 7 | |
| 0xffb0 | 14 | |

| | |
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| %rbp | 0xfff0 |
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| %rax | 21 |
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# Variadic Functions

cdecl / System V AMD64 ABI: both allows variable-length argument lists

- cdecl: push all arguments in opposite order on the stack
- AMD64 ABI: fill register first, then push all remaining arguments in opposite order on the stack

# Variadic Functions

cdecl / System V AMD64 ABI: both allows variable-length argument lists

- cdecl: push all arguments in opposite order on the stack
- AMD64 ABI: fill register first, then push all remaining arguments in opposite order on the stack

How does the function know:

- how many parameters?
- which data types?

# Variadic Functions: Format strings, argument count, etc.

```
printf("%c %u %f %s\n", 'a', 123, 3.14, "hello");
```

libc parses format string and pops from stack:

1. a `char`

# Variadic Functions: Format strings, argument count, etc.

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printf("%c %u %f %s\n", 'a', 123, 3.14, "hello");
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```

libc parses format string and pops from stack:

1. a `char`
2. an `unsigned int`
3. a `float`
4. a `char*`

What if format string and data on stack do not fit together?

# Call Stack

maybe:

# Call Stack

maybe:

- local variables

# Call Stack

maybe:

- local variables
- function arguments

# Call Stack

maybe:

- local variables
- function arguments

always:

# Call Stack

maybe:

- local variables
- function arguments

always:

- return addresses

# Call Stack

maybe:

- local variables
- function arguments

always:

- return addresses
  - many nested calls → many return addresses

# C++ Classes

# C++ Class Objects

- Basically structs in memory
- struct contains all member variables
  - including any member objects or parent objects

# C++ Class Objects

- Basically structs in memory
- struct contains all member variables
    - including any member objects or parent objects
- By default, pointers for methods (function pointers) are not stored in the object
    - Only used implicitly by the compiler
    - Important exception: virtual methods → vtables (next slide)

# Virtual Tables (vtables)

- Fundamental feature enabling “polymorphism”
- Table with function pointers
- First member of every object
- Specialized (derived) class simply overwrites previous function pointer

# VTable example

```
class Animal { public:
  Animal() { p("Animal ctor"); }
  virtual void makesound() = 0;
  virtual void move() { p("moving"); }
  virtual ~Animal() { p("Animal dtor"); }
};
class Bird : public Animal { public:
  Bird() { p("Bird ctor"); }
  virtual void makesound() { p("cheep"); }
  virtual ~Bird() { p("Bird dtor"); }
};
class Cat : public Animal { public:
  Cat() { p("Cat ctor"); }
  virtual void makesound() { p("meow"); }
  virtual void move() { p("prowling"); }
  ~Cat() { p("Cat dtor"); }
};
```

```
int main(void) {
> Animal* b = new Bird();
  Animal* c = new Cat();
  b->makesound();
  c->makesound();
  b->move();
  c->move();
  delete b;
  delete c;
  return 0;
}
```

# VTable example

```
class Animal { public:
  Animal() { p("Animal ctor"); }
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  Cat() { p("Cat ctor"); }
  virtual void makesound() { p("meow"); }
  virtual void move() { p("prowling"); }
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};
```

```
int main(void) {
> Animal* b = new Bird();
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  b->makesound();
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  c->move();
  delete b;
  delete c;
  return 0;
}
```

**vtable for b**

| | |
|---|---|
| [0] | |
| [1] | |

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  c->move();
  delete b;
  delete c;
  return 0;
}
```

**vtable for b**

| | |
|---|---|
| [0] | 0x0 <Animal::makesound()> |
| [1] | 0x555555554bf6 <Animal::move()> |

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class Animal { public:
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  virtual void makesound() = 0;
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> Bird() { p("Bird ctor"); }
  virtual void makesound() { p("cheep"); }
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  Cat() { p("Cat ctor"); }
  virtual void makesound() { p("meow"); }
  virtual void move() { p("prowling"); }
  ~Cat() { p("Cat dtor"); }
};
```

```
int main(void) {
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  c->move();
  delete b;
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}
```

**vtable for b**

| | |
|---|---|
| [0] | 0x0 <Animal::makesound()> |
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# VTable example

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```
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  c->move();
  delete b;
  delete c;
  return 0;
}
```

**vtable for b**

| | |
|---|---|
| [0] | 0x555555554cbe <Bird::makesound()> |
| [1] | 0x555555554bf6 <Animal::move()> |

# VTable example

```
class Animal { public:
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};
class Bird : public Animal { public:
  Bird() { p("Bird ctor"); }
  virtual void makesound() { p("cheep"); }
  virtual ~Bird() { p("Bird dtor"); }
};
class Cat : public Animal { public:
  Cat() { p("Cat ctor"); }
  virtual void makesound() { p("meow"); }
  virtual void move() { p("prowling"); }
  ~Cat() { p("Cat dtor"); }
};
```

```
int main(void) {
> Animal* b = new Bird();
  Animal* c = new Cat();
  b->makesound();
  c->makesound();
  b->move();
  c->move();
  delete b;
  delete c;
  return 0;
}
```

**vtable for b**

| | |
|---|---|
| [0] | 0x555555554cbe <Bird::makesound()> |
| [1] | 0x555555554bf6 <Animal::move()> |

# VTable example

```
class Animal { public:
  Animal() { p("Animal ctor"); }
  virtual void makesound() = 0;
  virtual void move() { p("moving"); }
  virtual ~Animal() { p("Animal dtor"); }
};
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  Bird() { p("Bird ctor"); }
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| [0] | 0x555555554cbe <Bird::makesound()> |
| [1] | 0x555555554bf6 <Animal::move()> |

**vtable for c**

| | |
|---|---|
| [0] | |
| [1] | |

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class Animal { public:
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| [0] | 0x555555554cbe <Bird::makesound()> |
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| [0] | 0x555555554cbe <Bird::makesound()> |
| [1] | 0x555555554bf6 <Animal::move()> |

**vtable for c**

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| [0] | 0x0 <Animal::makesound()> |
| [1] | 0x555555554bf6 <Animal::move()> |

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class Animal { public:
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**vtable for b**

| | |
|---|---|
| [0] | 0x555555554cbe <Bird::makesound()> |
| [1] | 0x555555554bf6 <Animal::move()> |

**vtable for c**

| | |
|---|---|
| [0] | 0x555555554d92 <Cat::makesound()> |
| [1] | 0x555555554dae <Cat::move()> |

# VTable example

```
class Animal { public:
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  virtual void makesound() = 0;
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  Animal* b = new Bird();
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# VTable example

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```

```
int main(void) {
  Animal* b = new Bird();
  Animal* c = new Cat();
  b->makesound();
  c->makesound();
  b->move();
> c->move();
  delete b;
  delete c;
  return 0;
}
```

**vtable for b**

| | |
|---|---|
| [0] | 0x555555554cbe <Bird::makesound()> |
| [1] | 0x555555554bf6 <Animal::move()> |

**vtable for c**

| | |
|---|---|
| [0] | 0x555555554d92 <Cat::makesound()> |
| [1] | 0x555555554dae <Cat::move()> |

# VTable example

```
class Animal { public:
  Animal() { p("Animal ctor"); }
  virtual void makesound() = 0;
  virtual void move() { p("moving"); }
  virtual ~Animal() { p("Animal dtor"); }
};
class Bird : public Animal { public:
  Bird() { p("Bird ctor"); }
  virtual void makesound() { p("cheep"); }
  virtual ~Bird() { p("Bird dtor"); }
};
class Cat : public Animal { public:
  Cat() { p("Cat ctor"); }
  virtual void makesound() { p("meow"); }
  virtual void move() { p("prowling"); }
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};
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int main(void) {
  Animal* b = new Bird();
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  b->makesound();
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  delete b;
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  return 0;
}
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int main(void) {
  Animal* b = new Bird();
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  b->makesound();
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> c->move();
  delete b;
  delete c;
  return 0;
}
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int main(void) {
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  Cat() { p("Cat ctor"); }
  virtual void makesound() { p("meow"); }
  virtual void move() { p("prowling"); }
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};
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```
int main(void) {
  Animal* b = new Bird();
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  c->makesound();
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  c->move();
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  return 0;
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**vtable for c**

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```

```
int main(void) {
  Animal* b = new Bird();
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  b->move();
  c->move();
  delete b;
> delete c;
  return 0;
}
```

**vtable for c**

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|---|---|
| [0] | 0x555555554d92 <Cat::makesound()> |
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# VTable example

```cpp
class Animal { public:
  Animal() { p("Animal ctor"); }
  virtual void makesound() = 0;
  virtual void move() { p("moving"); }
  virtual ~Animal() { p("Animal dtor"); }
};
class Bird : public Animal { public:
  Bird() { p("Bird ctor"); }
  virtual void makesound() { p("cheep"); }
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class Cat : public Animal { public:
  Cat() { p("Cat ctor"); }
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  virtual void move() { p("prowling"); }
  ~Cat() { p("Cat dtor"); }
};
```

```cpp
int main(void) {
  Animal* b = new Bird();
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  b->makesound();
  c->makesound();
  b->move();
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  delete b;
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# VTable example

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  b->makesound();
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  delete b;
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> return 0;
}
```

# Signal example

- Powerful concept for inter-process communication
- Some are similar to exceptions
- Sometimes used for exploits

# Signal example

```
int main()
{

  if (i != -1ULL/4096) {
    printState();
    laststate = currentstate;
    ++i;
    currentstate = VALID;
    *(volatile size_t*)(i*4096);
  }
  return 0;
}
```

# Signal example

```c
static void unblock_signal(int signum
    __attribute__((__unused__))) {
  sigset_t sigs;
  sigemptyset(&sigs);
  sigaddset(&sigs, signum);
  sigprocmask(SIG_UNBLOCK, &sigs, NULL);
}
void segfaulthandler(int signum) {
  currentstate = INVALID;
  unblock_signal(SIGSEGV);

}
```

```c
int main() {
  signal(SIGSEGV, segfaulthandler);

  if (i != -1ULL/4096) {
    printState();
    laststate = currentstate;
    ++i;
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    *(volatile size_t*)(i*4096);
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}
void segfaulthandler(int signum) {
  currentstate = INVALID;
  unblock_signal(SIGSEGV);
  longjmp(buf,0);
}
```

```
int main() {
> signal(SIGSEGV, segfaulthandler);
  setjmp(buf);
  if (i != -1ULL/4096) {
    printState();
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