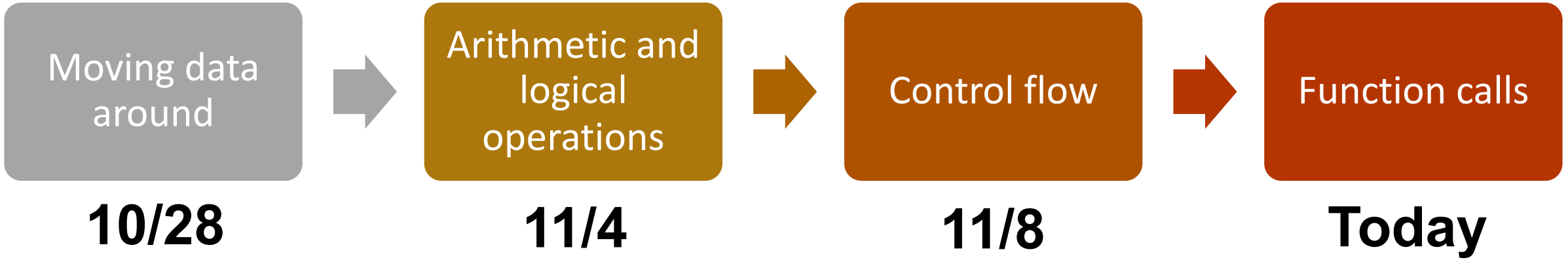
CS107, Lecture 14
Assembly: Function Calls and the Runtime Stack

Reading: B&O 3.7

Learning Assembly



Reference Sheet: `cs107.stanford.edu/resources/x86-64-reference.pdf`
See more guides on Resources page of course website!

Learning Goals

- Learn what %rip represents and how it is updated.
- Learn how assembly calls functions and manages stack frames.
- Learn the rules of register use when calling functions.

Plan For Today

- Recap: Control Flow
- The Instruction Pointer (%rip)
- Calling Functions
  - The Stack
  - Passing Control
  - **Break:** Announcements
  - Passing Data
  - Local Storage
- Register Restrictions
- Pulling it all together: recursion example

```
cp -r /afs/ir/class/cs107/samples/lectures/lect14 .
```

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Control

- In C, we have control flow statements like **if**, **else**, **while**, **for**, etc. to write programs that are more expressive than just one instruction following another.
- This is *conditional execution of statements*: executing statements if one condition is true, executing other statements if one condition is false, etc.
- How is this represented in assembly?
  - A way to store conditions that we will check later
  - Assembly instructions whose behavior is dependent on these conditions

Condition Codes

Alongside normal registers, the CPU also has single-bit *condition code* registers. They store the results of the most recent arithmetic or logical operation.

Most common condition codes:

- **CF:** Carry flag. The most recent operation generated a carry out of the most significant bit. Used to detect overflow for unsigned operations.
- **ZF:** Zero flag. The most recent operation yielded zero.
- **SF:** Sign flag. The most recent operation yielded a negative value.
- **OF:** Overflow flag. The most recent operation caused a two's-complement overflow-either negative or positive.

Condition Code-Dependent Instructions

There are three common instruction types that use condition codes:

- **set** instructions that conditionally set a byte to 0 or 1
- new versions of **mov** instructions that conditionally move data
- **jmp** instructions that conditionally jump to a different next instruction (there is also an unconditional jump that always jumps)

Register Responsibilities

Some registers take on special responsibilities during program execution.

- **%rax** stores the return value
- **%rdi** stores the first parameter to a function
- **%rsi** stores the second parameter to a function
- **%rdx** stores the third parameter to a function
- **%rip** stores the address of the next instruction to execute
- **%rsp** stores the address of the current top element on the stack

See the x86-64 Guide and Reference Sheet on the Resources webpage for more!

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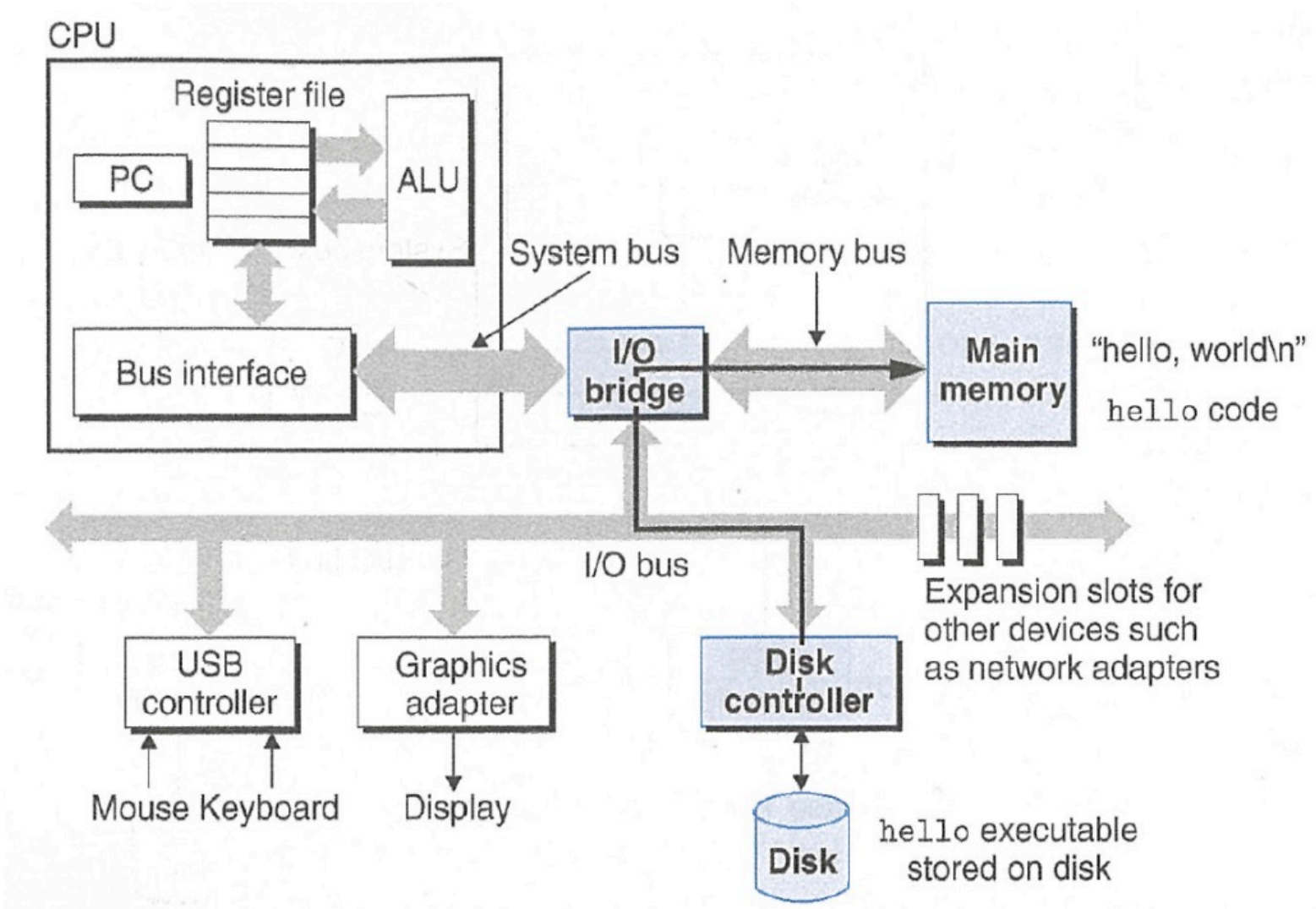
%rip

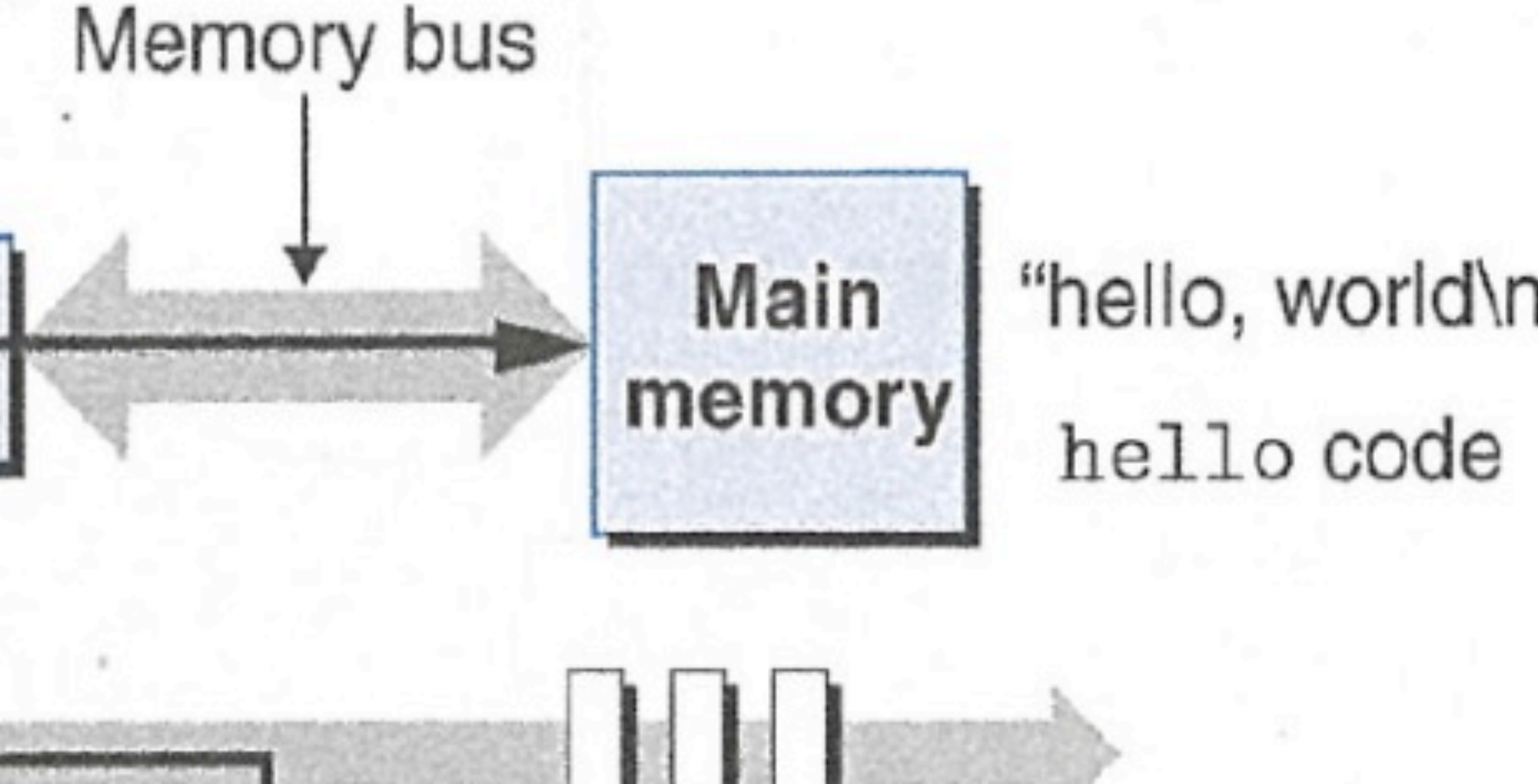
- **%rip** is a special register that points to the next instruction to execute.
- **Let's dive deeper into how %rip works, and how jumps modify it**.

%rip

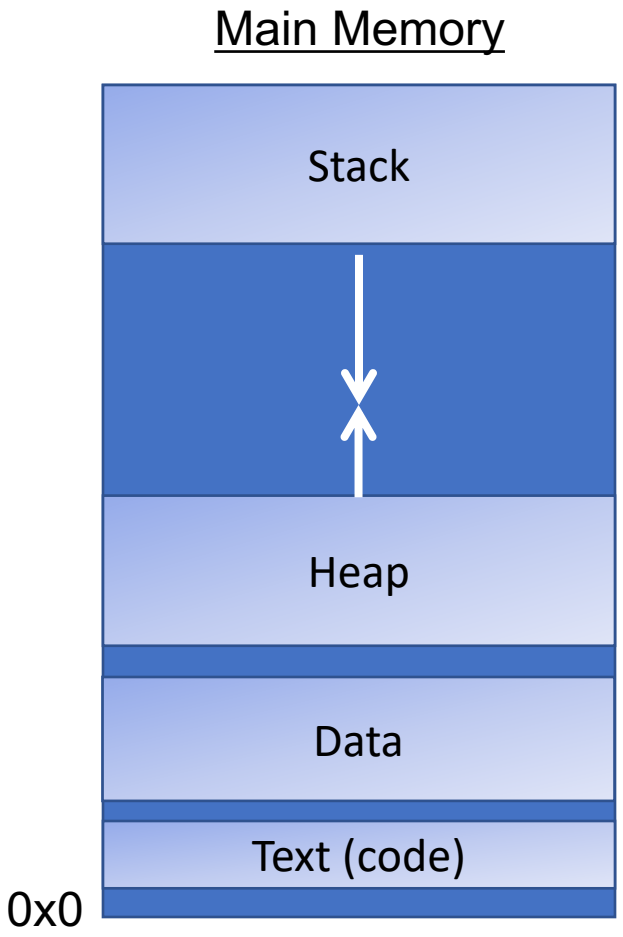
```
00000000004004ed <loop>:
4004ed: 55                              push
4004ee: 48 89 e5                        mov
4004f1: c7 45 fc 00 00 00 00            movl
4004f8: 83 45 fc 01                     addl
4004fc: eb fa                           jmp
```

Instructions Are Just Bytes!




Memory bus
Main memory
"hello, world\n
hello code

Instructions Are Just Bytes!



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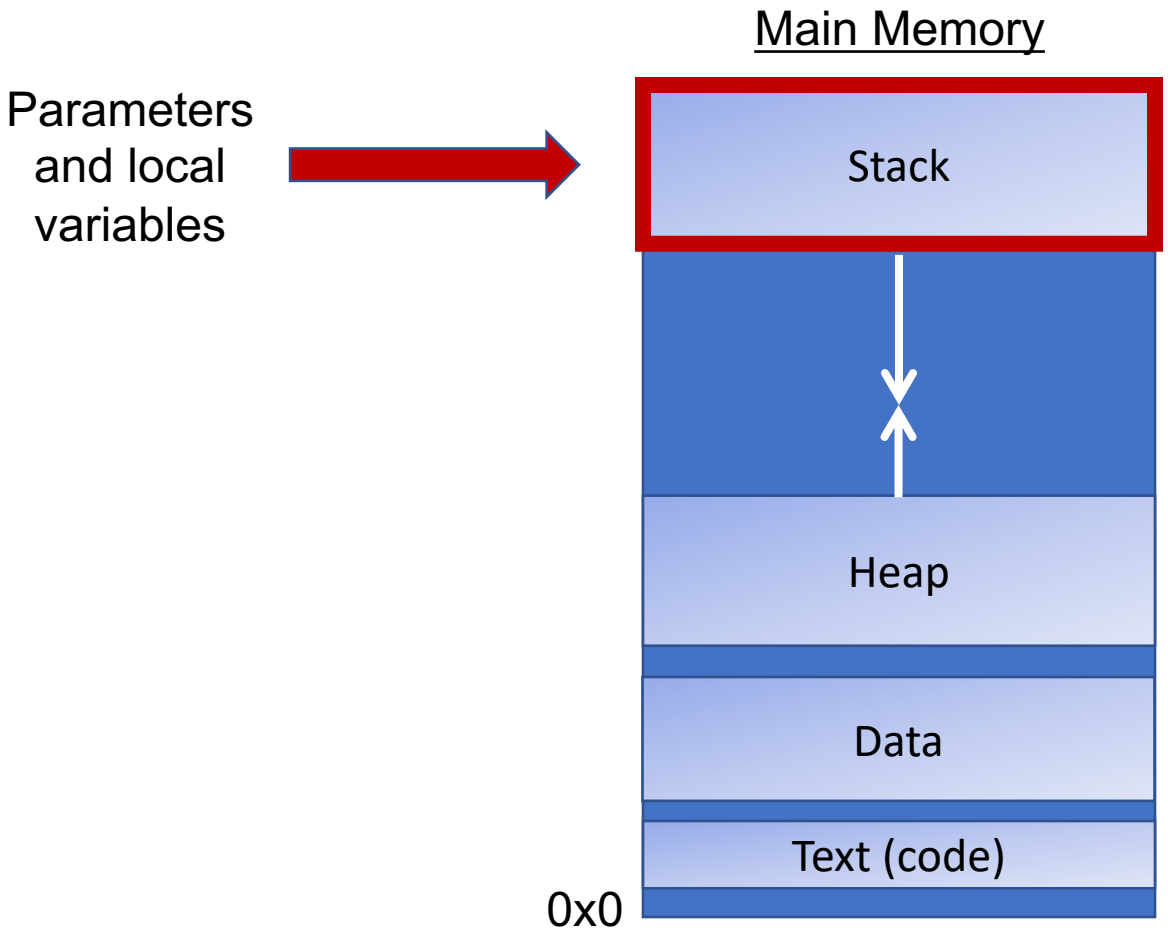

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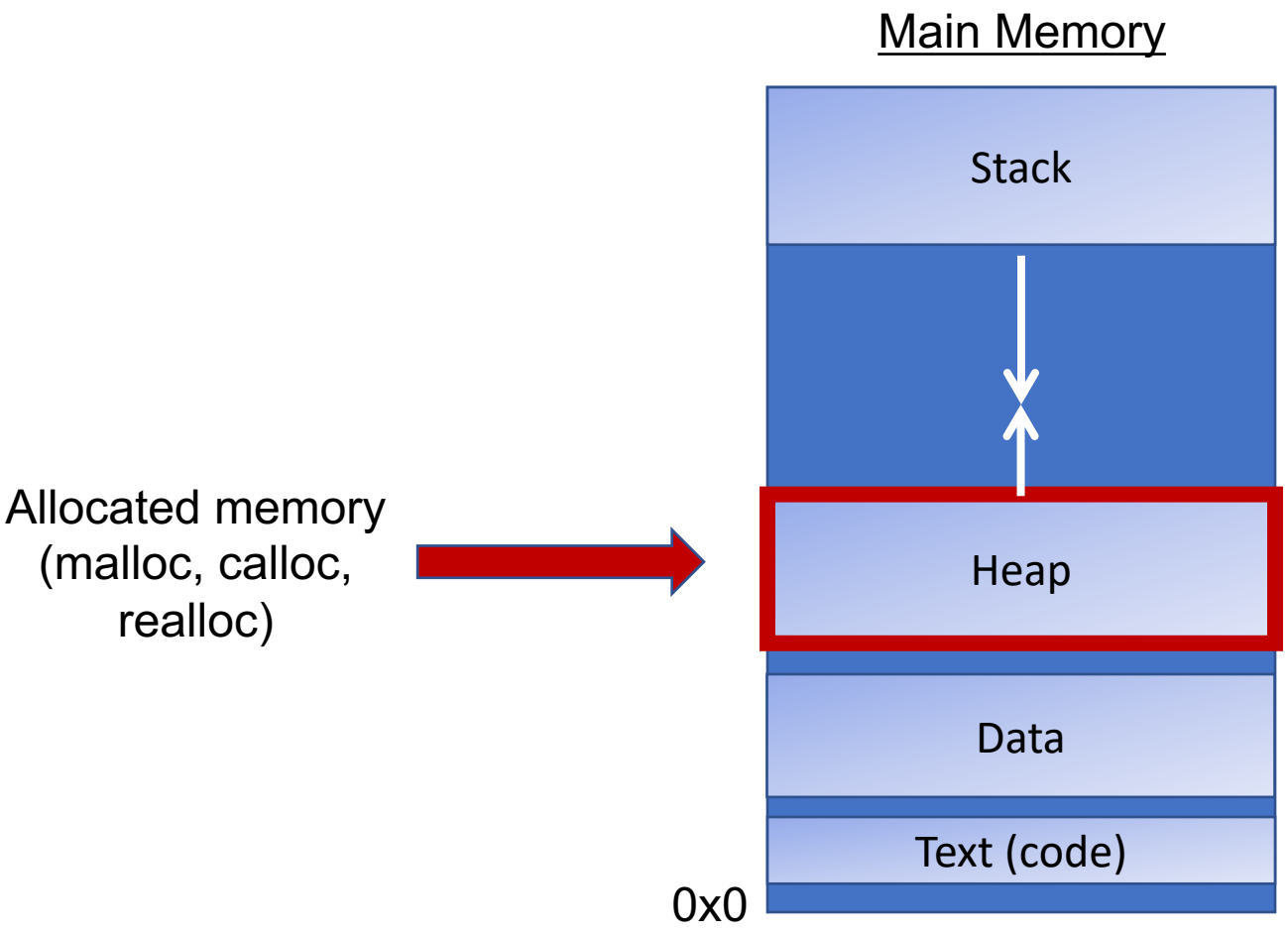

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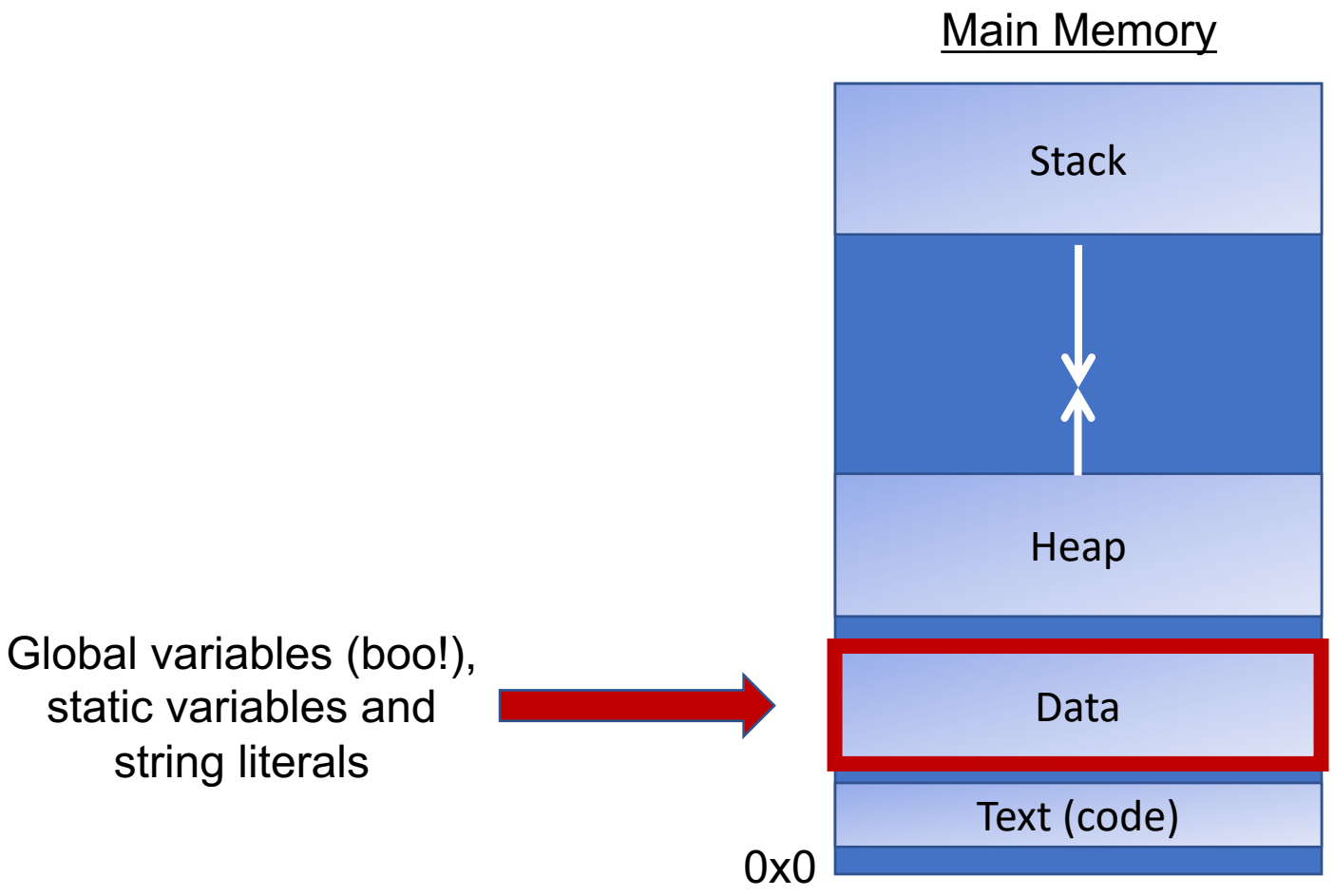

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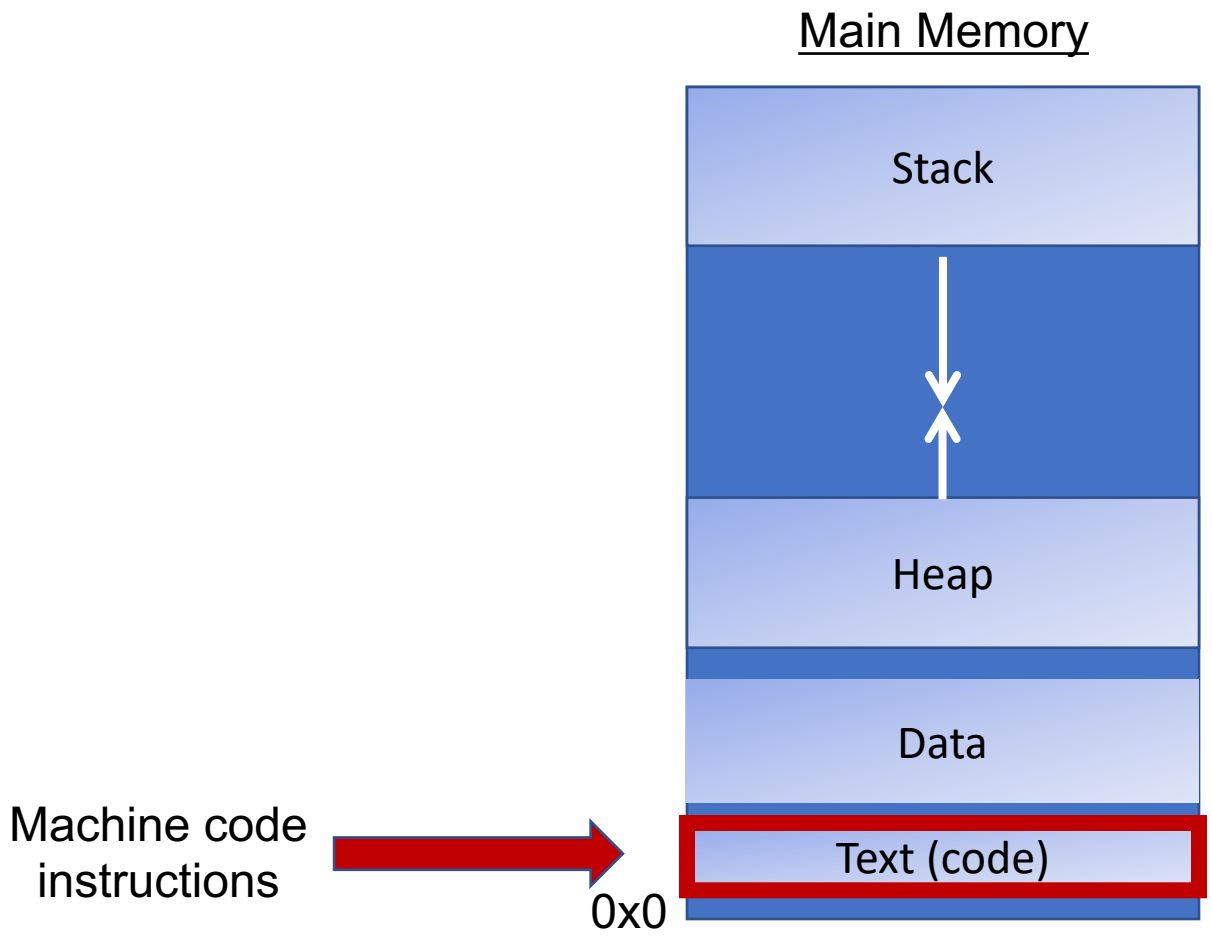

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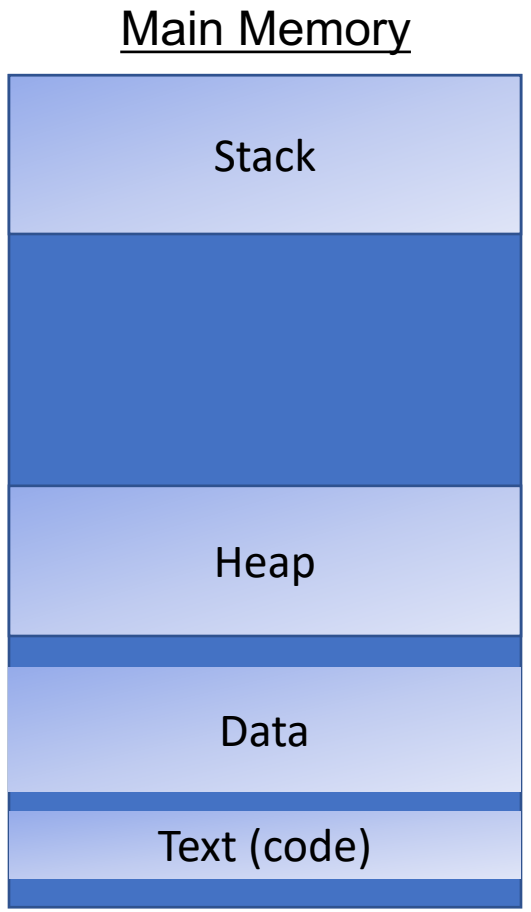

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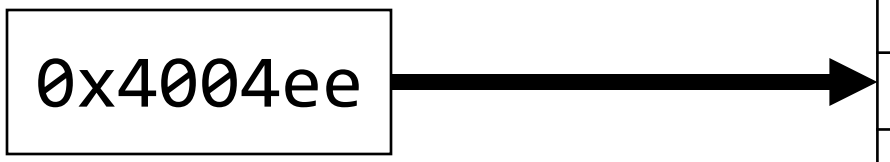
4004ed	55



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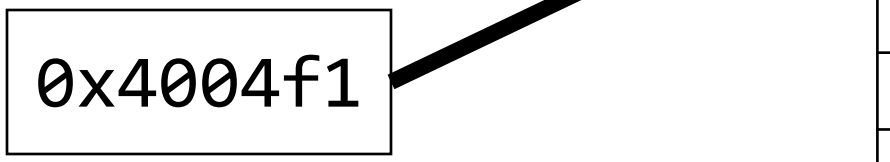

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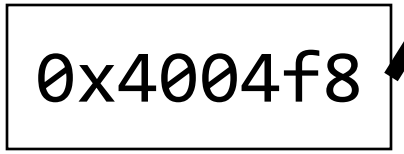

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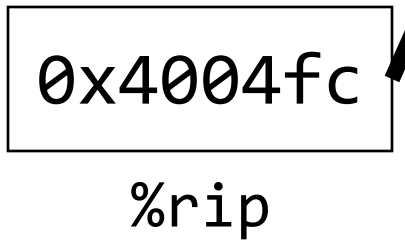

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4004f2	45
4004f1	c7
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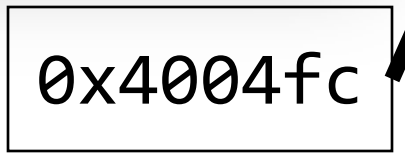
4004ef	89
4004ee	48
4004ed	55

%rip

```
0000000004004ed <loop>:
4004ed: 55                              push
400
400
400
400
```

Special hardware is responsible for setting %rip's value to the next instruction.

› it does %rip += size of current instruction (in bytes)



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4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

%rip

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x400570 <+0>:  b8 00 00 00 00 mov $0x0,%eax
0x400575 <+5>:  eb 03          jmp 0x40057a <loop+10>
0x400577 <+7>:  83 c0 01       add $0x1,%eax
0x40057a <+10>: 83 f8 63       cmp $0x63,%eax
0x40057d <+13>: 73 f8          jle 0x400577 <loop+7>
0x40057f <+15>: f3 c3          repz retq
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%rip

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    int i = 0;
    while (i < 100) {
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```

These are 0-based offsets in bytes for each instruction relative to the start of this function.

%rip

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x400570 <+0>:  b8 00 00 00 00  mov $0x0,%eax
0x400575 <+5>:  eb 03           jmp 0x40057a <loop+10>
0x400577 <+7>:  83 c0 01        add $0x1,%eax
0x40057a <+10>: 83 f8 63        cmp $0x63,%eax
0x40057d <+13>: 73 f8           jle 0x400577 <loop+7>
0x40057f <+15>: f3 c3           repz retq
```

These are bytes for the machine code instructions. Instructions are variable length.

%rip

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x400570 <+0>:  b8 00 00 00 00 mov $0x0,%eax
0x400575 <+5>:  eb 03          jmp 0x40057a <loop+10>
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0x40057d <+13>: 73 f8           jle 0x400577 <loop+7>
0x40057f <+15>: f3 c3           repz retq
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%rip

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0x400570 <+0>:   b8 00 00 00 00 mov $0x0,%eax
0x400575 <+5>:   eb 03          jmp 0x40057a <loop+10>
0x400577 <+7>:   83 c0 01       add $0x1,%eax
0x40057a <+10>:  83 f8 63       cmp $0x63,%eax
0x40057d <+13>:  73 f8          jle 0x400577 <loop+7>
0x40057f <+15>:  f3 c3          repz retq
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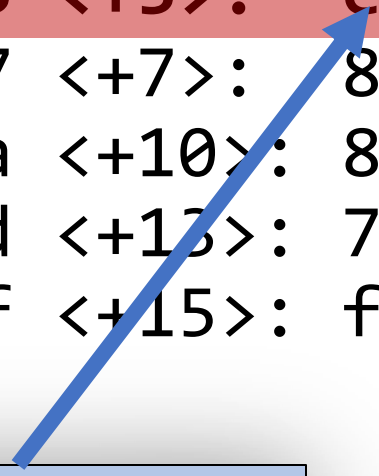

0xeb means **jmp**.

%rip

```
0x400570 <+0>:   b8 00 00 00 00 mov $0x0,%eax
0x400575 <+5>:   eb 03          jmp 0x40057a <loop+10>
0x400577 <+7>:   83 c0 01       add $0x1,%eax
0x40057a <+10>:  83 f8 63       cmp $0x63,%eax
0x40057d <+13>:  7e f8          jle 0x400577 <loop+7>
0x40057f <+15>:  f3 c3          repz retq
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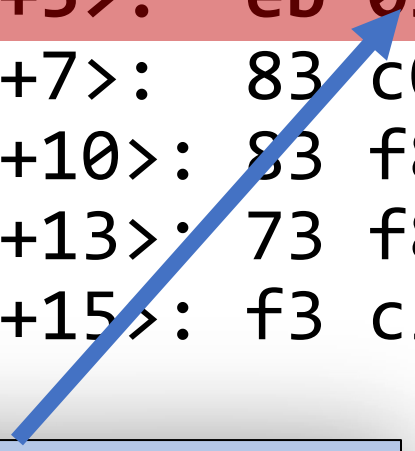

0x03 is the number of instruction bytes to jump relative to %rip.

With no jump, %rip would advance to the next line. This **jmp** says to <u>then</u> go **3** bytes further!

%rip

```
0x400570 <+0>:   b8 00 00 00 00 mov $0x0,%eax
0x400575 <+5>:   eb 03          jmp 0x40057a <loop+10>
0x400577 <+7>:   83 c0 01       add $0x1,%eax
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0x40057f <+15>:  f3 c3          repz retq
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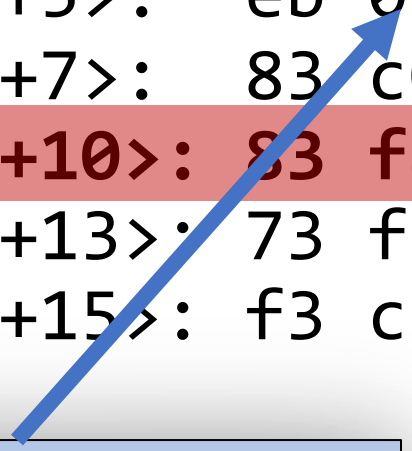

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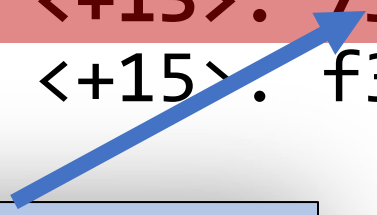

0x73 means **jle**.

%rip

```
0x400570 <+0>:   b8 00 00 00 00 mov $0x0,%eax
0x400575 <+5>:   eb 03          jmp 0x40057a <loop+10>
0x400577 <+7>:   83 c0 01       add $0x1,%eax
0x40057a <+10>: 83 f8 63        cmp $0x63,%eax
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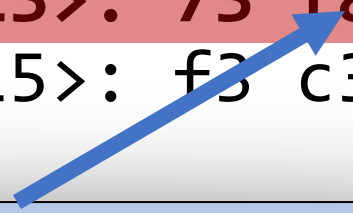

0xf8 is the number of instruction bytes to jump relative to %rip. This is -8 (in two's complement!).

With no jump, %rip would advance to the next line. This **jmp** says to then go **8** bytes back!

%rip

```
0x400570 <+0>:   b8 00 00 00 00 mov $0x0,%eax
0x400575 <+5>:   eb 03          jmp 0x40057a <loop+10>
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0xf8 is the number of instruction bytes to jump relative to %rip. This is -8 (in two's complement!).

With no jump, %rip would advance to the next line. This **jmp** says to then go **8** bytes back!

Summary: Instruction Pointer

- Machine code instructions live in main memory, just like stack and heap data.
- %rip is a register that stores a number (an address) of the next instruction to execute. It marks our place in the program's instructions.
- To advance to the next instruction, special hardware adds the size of the current instruction in bytes.
- **jmp** instructions work by adjusting %rip by a specified amount.

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How do we call functions in assembly?

Calling Functions In Assembly

To call a function in assembly, we must do a few things:

- **Pass Control** – %rip must be adjusted to execute the callee's instructions, and then resume the caller's instructions afterwards.
- **Pass Data** – we must pass any parameters and receive any return value.
- **Manage Memory** – we must handle any space needs of the callee on the stack.

How does assembly interact with the stack?

Terminology: **caller** function calls the **callee** function.

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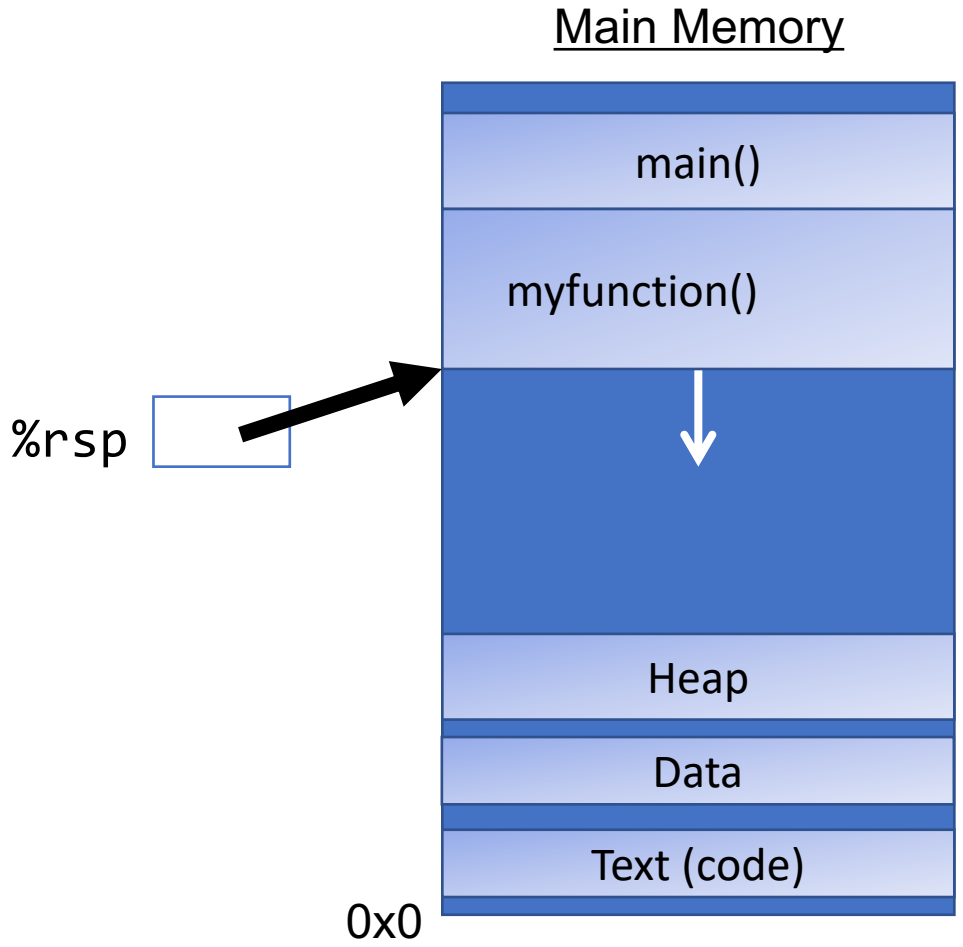
%rsp

- **%rsp** is a special register that stores the address of the current "top" of the stack (the bottom in our diagrams, since the stack grows downwards).



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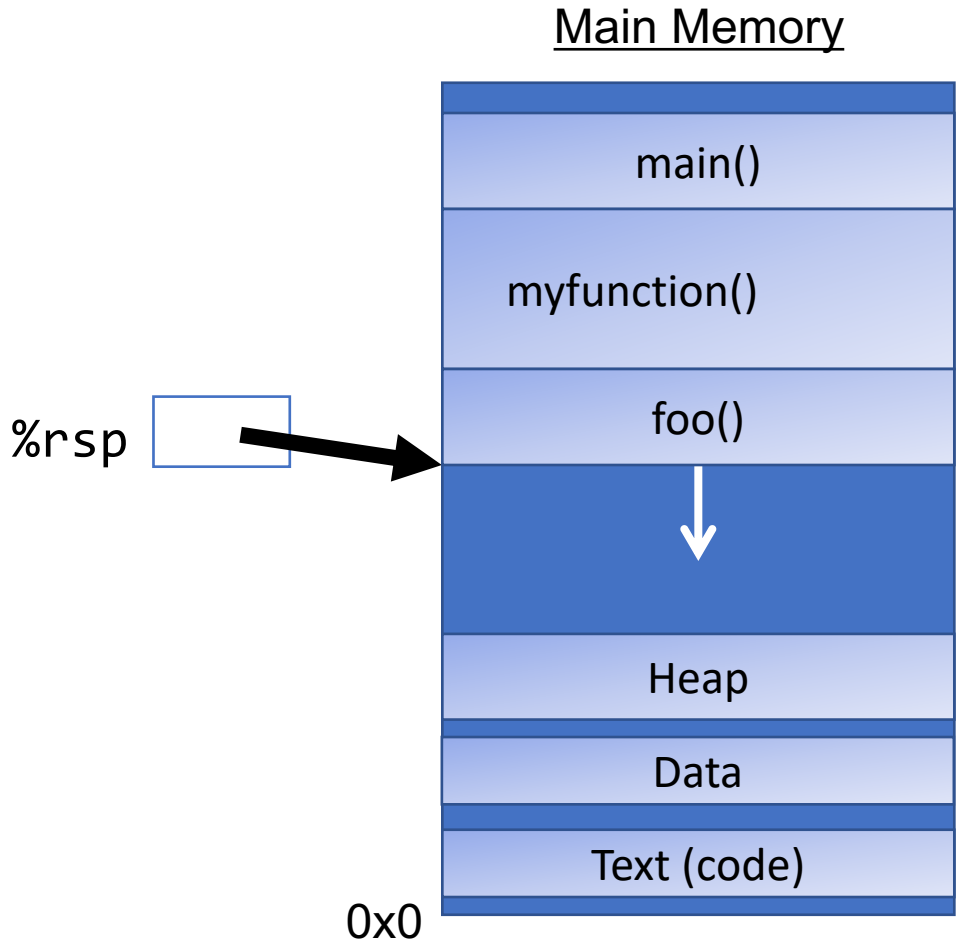

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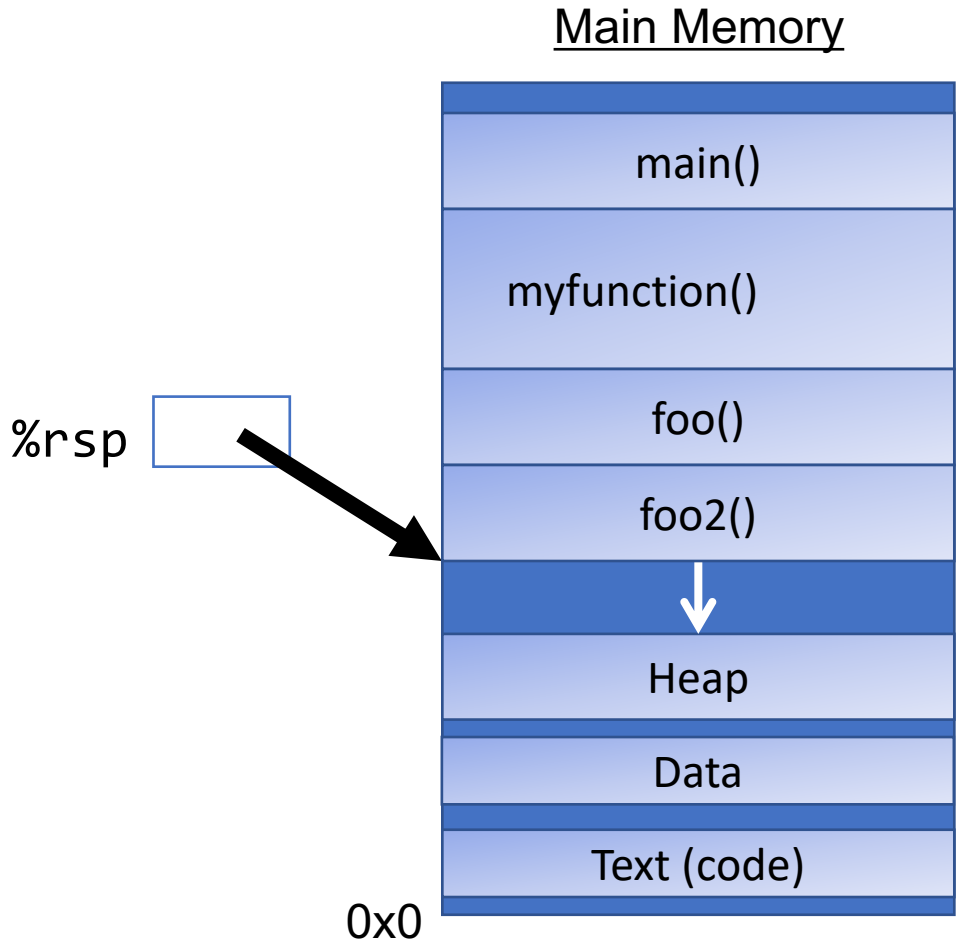

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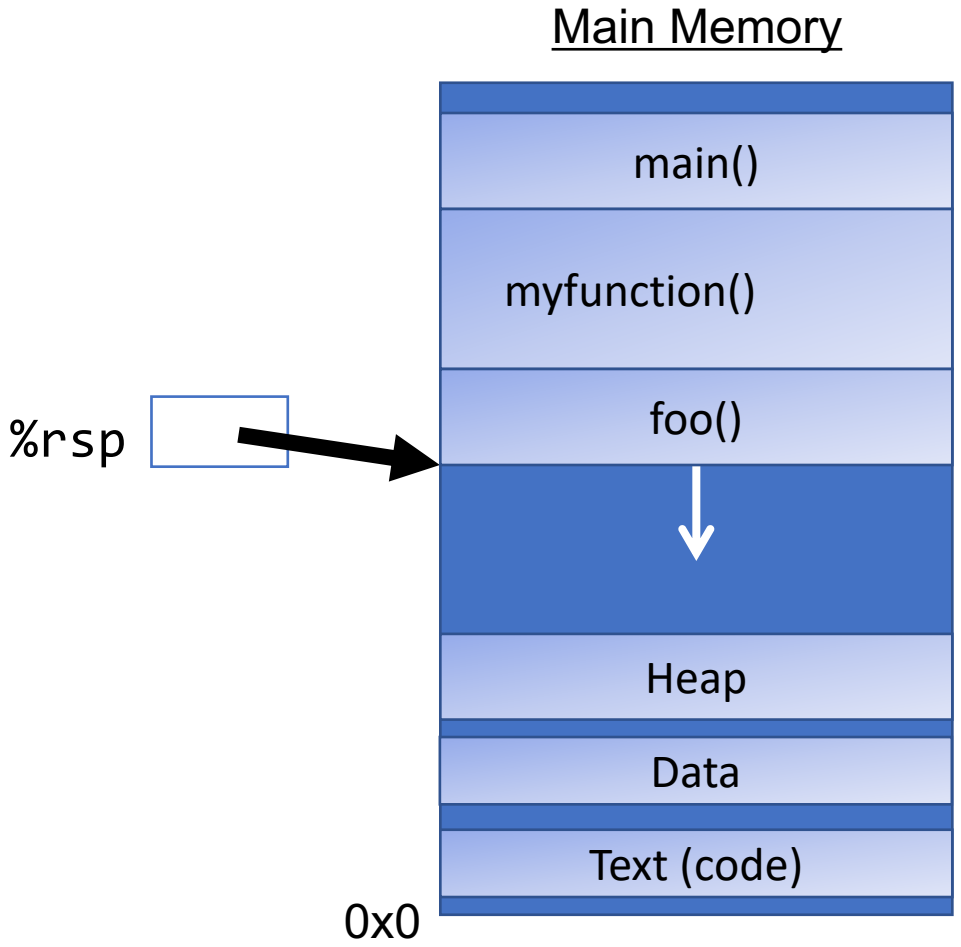

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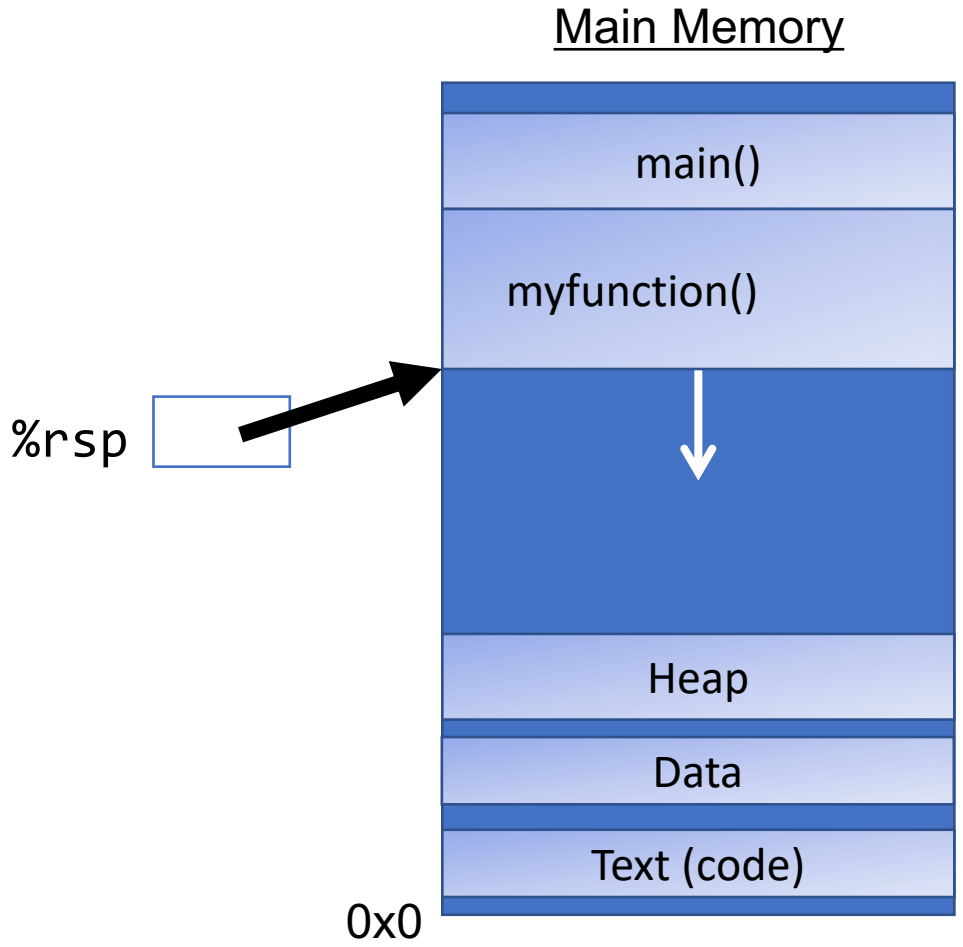

Key idea: %rsp must point to the same place before a function is called and after that function returns, since stack frames go away when a function finishes.

push

- The **push** instruction pushes the data at the specified source onto the top of the stack, adjusting **%rsp** accordingly.

Instruction	Effect
`pushq S`	`R[%rsp] ⟵ R[%rsp] - 8;` `M[R[%rsp]] ⟵ S`

push

- The **push** instruction pushes the data at the specified source onto the top of the stack, adjusting **%rsp** accordingly.

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Instruction	Effect
`pushq S`	`R[%rsp] ⟵ R[%rsp] - 8;` `M[R[%rsp]] ⟵ S`

- This behavior is equivalent to the following, but pushq is a shorter instruction:

```
subq $8, %rsp
movq  S, (%rsp)
```

- Sometimes, you'll see instructions just explicitly decrement the stack pointer to make room for future data.

pop

- The **pop** instruction pops the topmost data from the stack and stores it in the specified destination, adjusting **%rsp** accordingly.

Instruction	Effect
`popq D`	`D ⟵ M[R[%rsp]]` `R[%rsp] ⟵ R[%rsp] + 8;`

- **Note**: this *does not* remove/clear out the data! It just increments %rsp to indicate the next push can overwrite that location.

pop

- The **pop** instruction pops the topmost data from the stack and stores it in the specified destination, adjusting **%rsp** accordingly.

Instruction	Effect
popq D	D ⟵ M[R[%rsp]] R[%rsp] ⟵ R[%rsp] + 8;

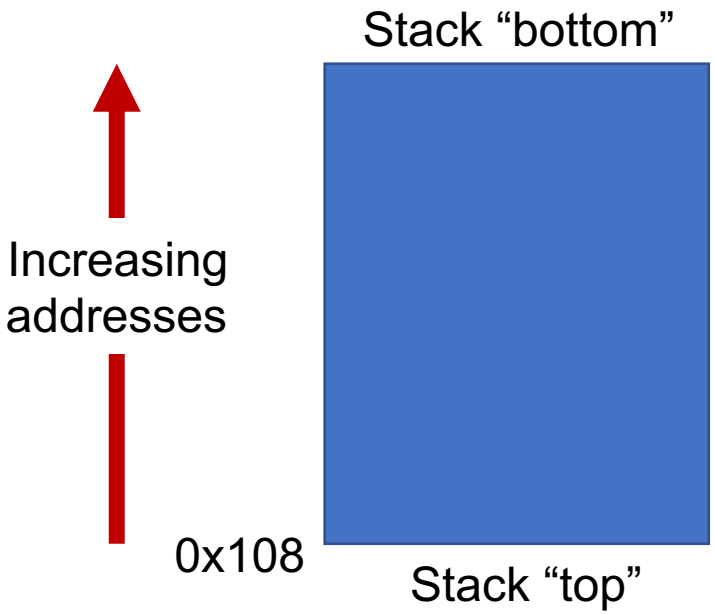
- This behavior is equivalent to the following, but popq is a shorter instruction:

```
movq (%rsp), D
addq $8, %rsp
```

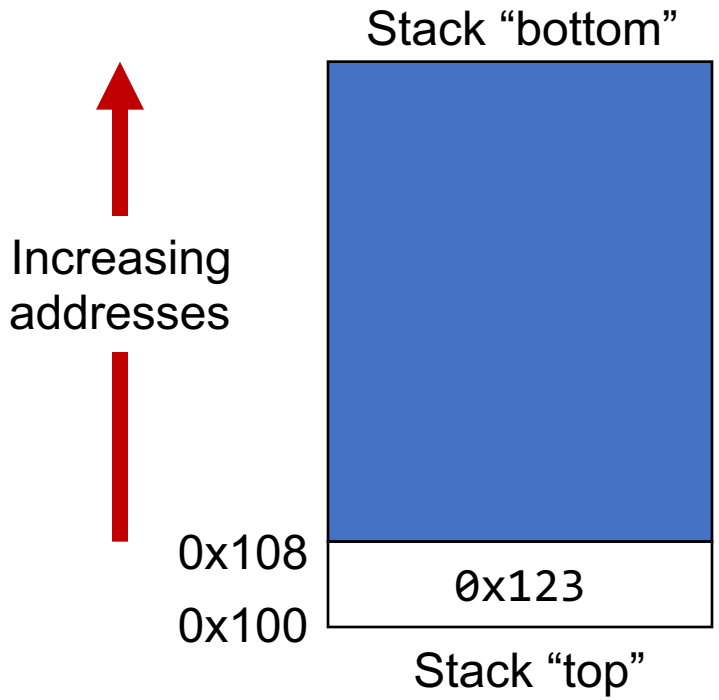
- Sometimes, you'll see instructions just explicitly increment the stack pointer to pop data.

Stack Example

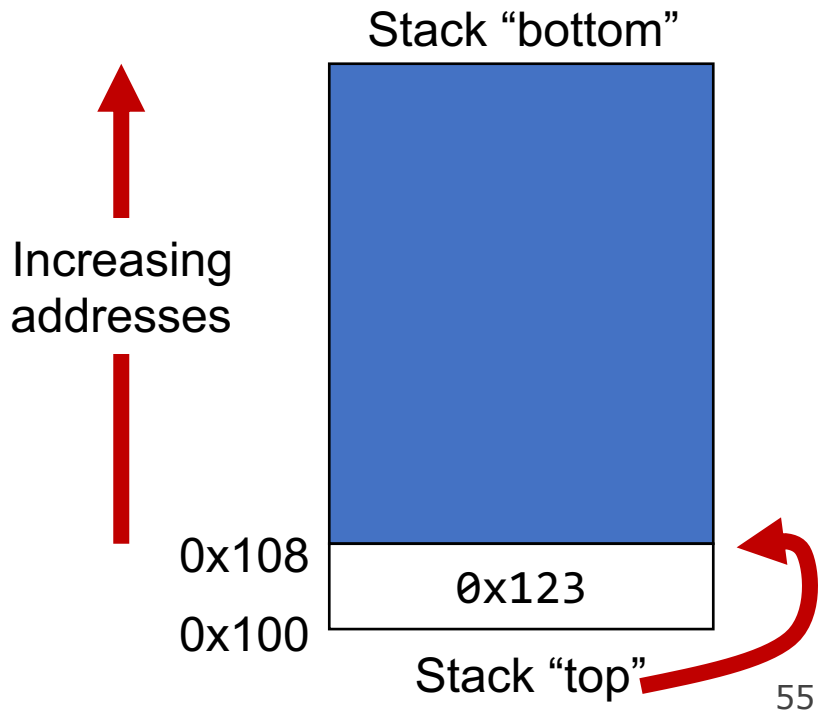
Initially	
%rax	0x123
%rdx	0
%rsp	0x108



pushq %rax	
%rax	0x123
%rdx	0
%rsp	0x100



popq %rdx	
%rax	0x123
%rdx	0x123
%rsp	0x108



Calling Functions In Assembly

To call a function in assembly, we must do a few things:

- **Pass Control** – %rip must be adjusted to execute the callee's instructions, and then resume the caller's instructions afterwards.
- **Pass Data** – we must pass any parameters and receive any return value.
- **Manage Memory** – we must handle any space needs of the callee on the stack.

Terminology: **caller** function calls the **callee** function.

Plan For Today

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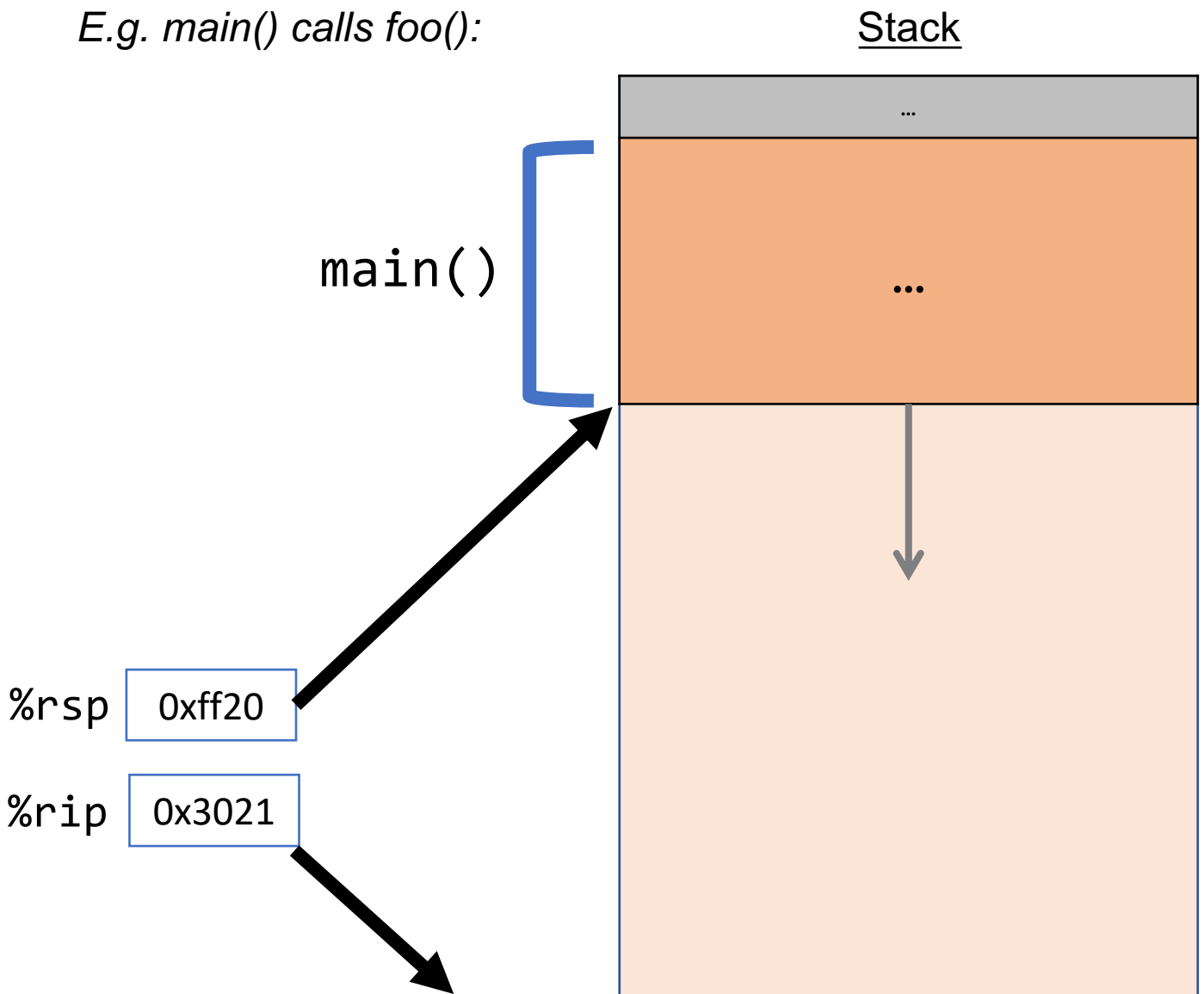
Remembering Where We Left Off

Problem: %rip points to the next instruction to execute. To call a function, we must remember the *next* caller instruction to resume at after.

Solution: push the next value of %rip onto the stack. Then call the function. When it is finished, put this value back into %rip and continue executing.



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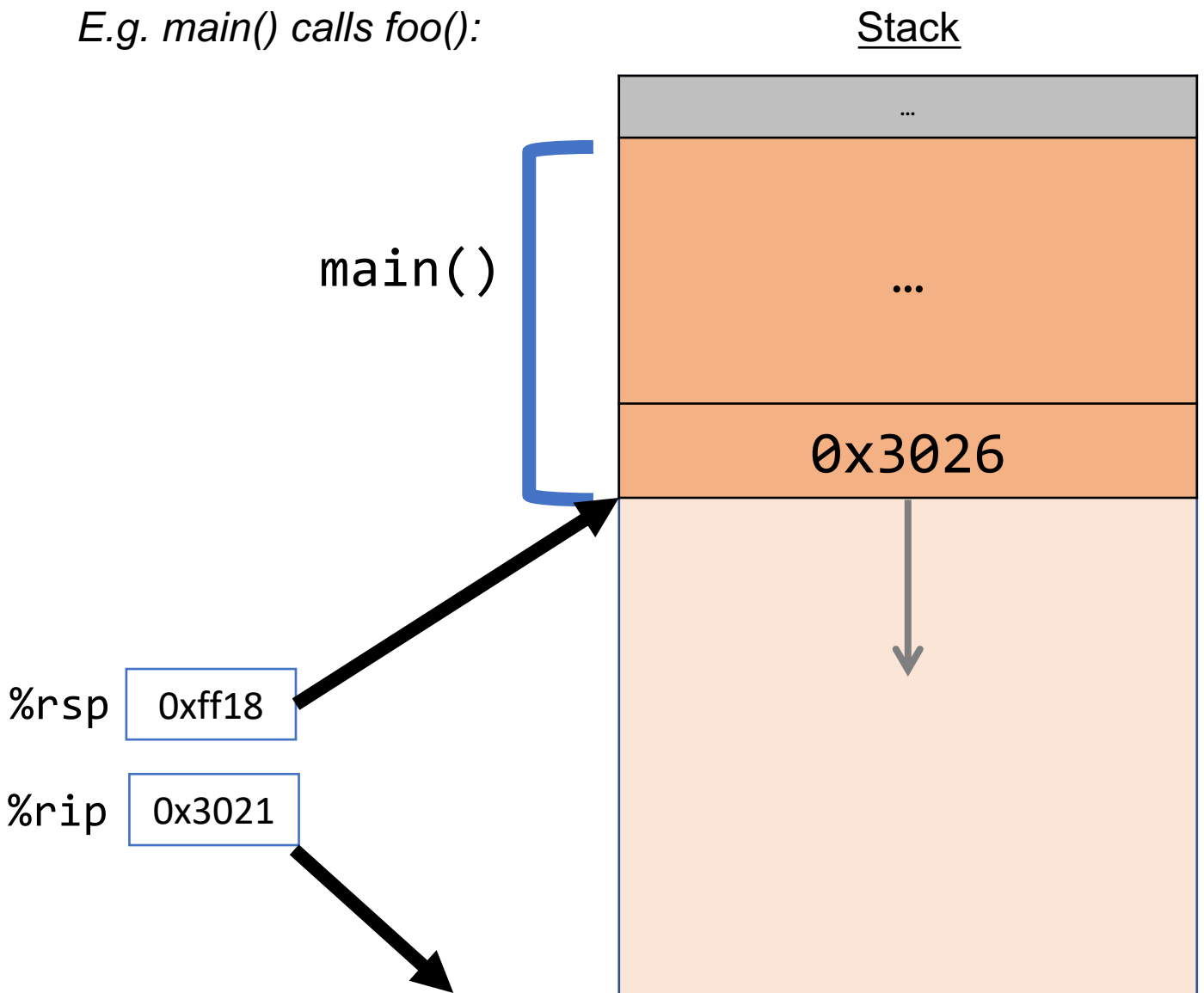

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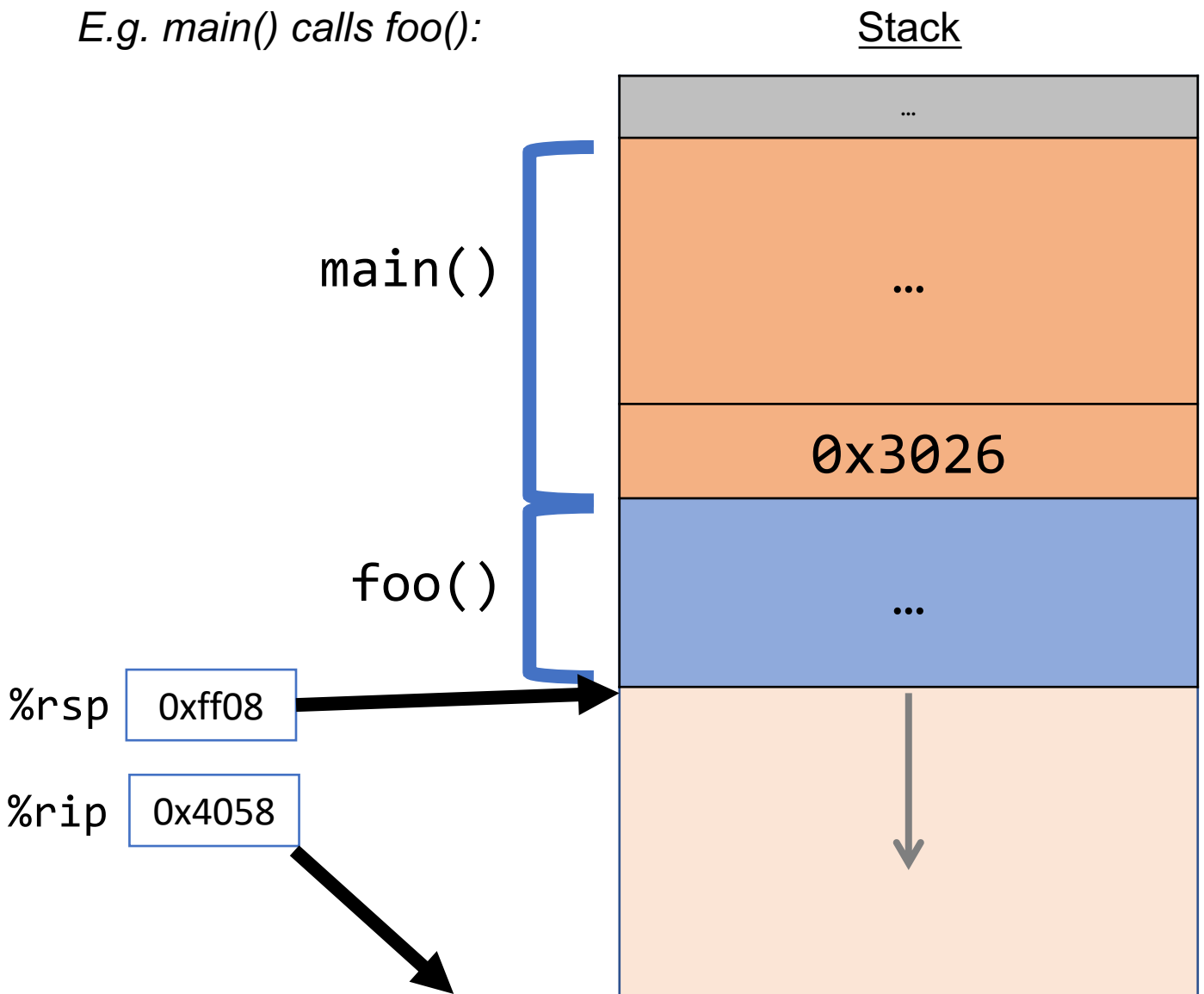

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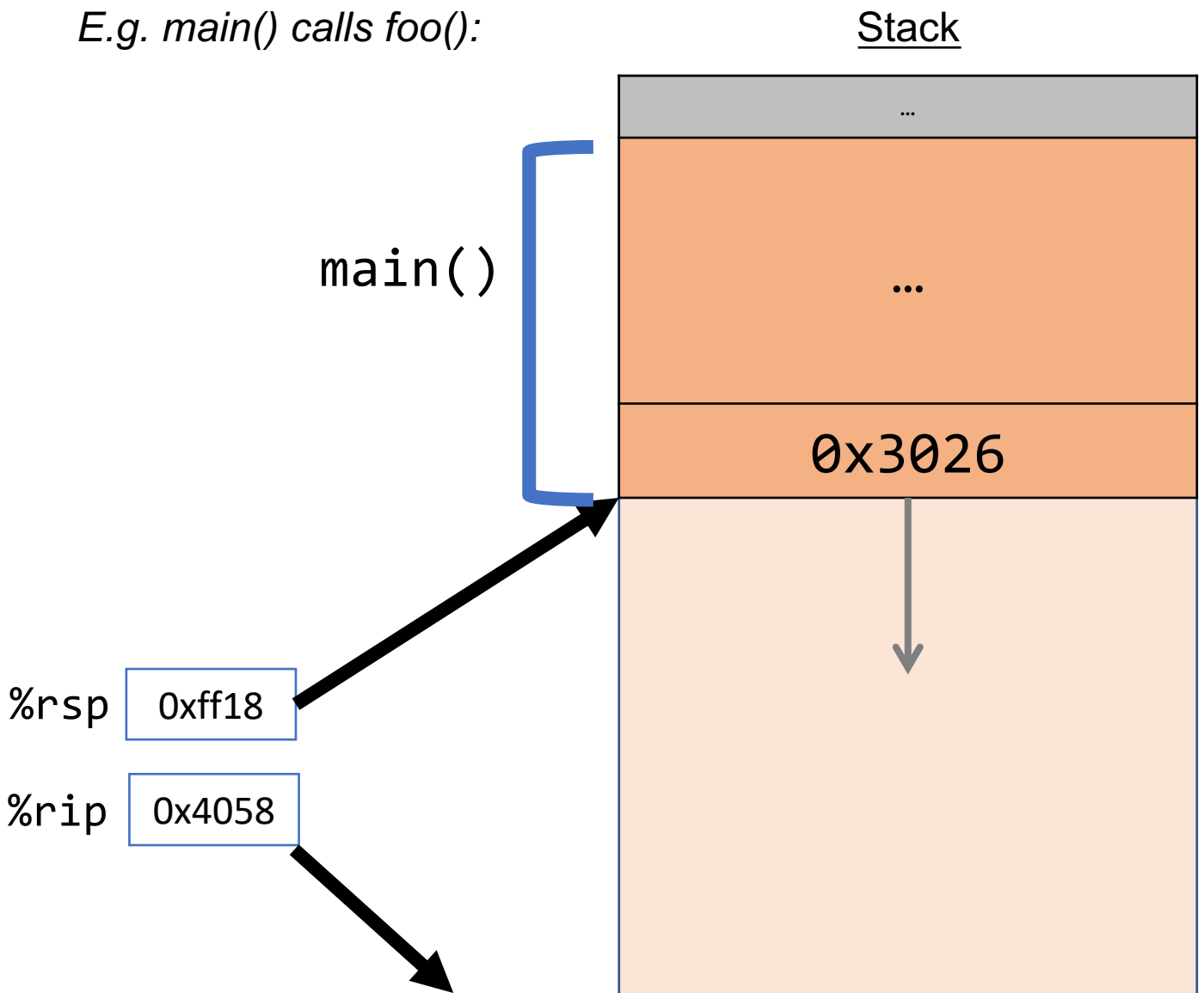

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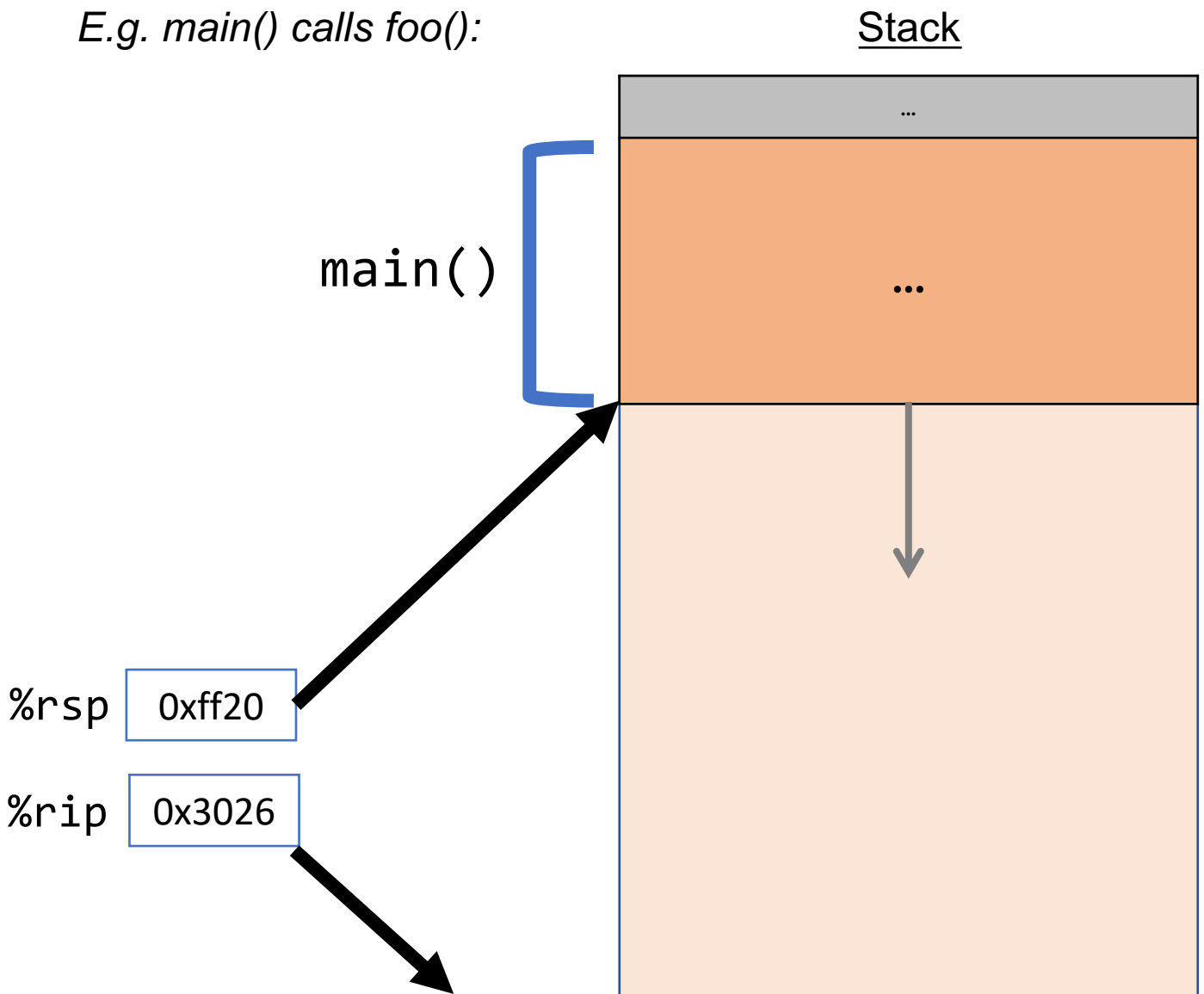

Call And Return

The **call** instruction pushes the address of the instruction immediately following the **call** instruction onto the stack and sets %rip to point to the beginning of the specified function's instructions.

```
call Label
call *Operand
```

The **ret** instruction pops this instruction address from the stack and stores it in %rip.

```
ret
```

The stored %rip value for a function is called its **return address.** It is the address of the instruction at which to resume the function's execution. (not to be confused with **return value**, which is the value returned from a function).

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To call a function in assembly, we must do a few things:

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Mid-Lecture Check-In

We can now answer the following questions:

1. What does %rip store?
2. How does %rip update as we execute instructions?
3. When we call a function, where do we store the instruction to resume executing at in the caller after we return?
4. When the callee is finished, %rip must be updated to the instruction to resume at in the caller. What instruction does this?

Plan For Today

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Parameters and Return

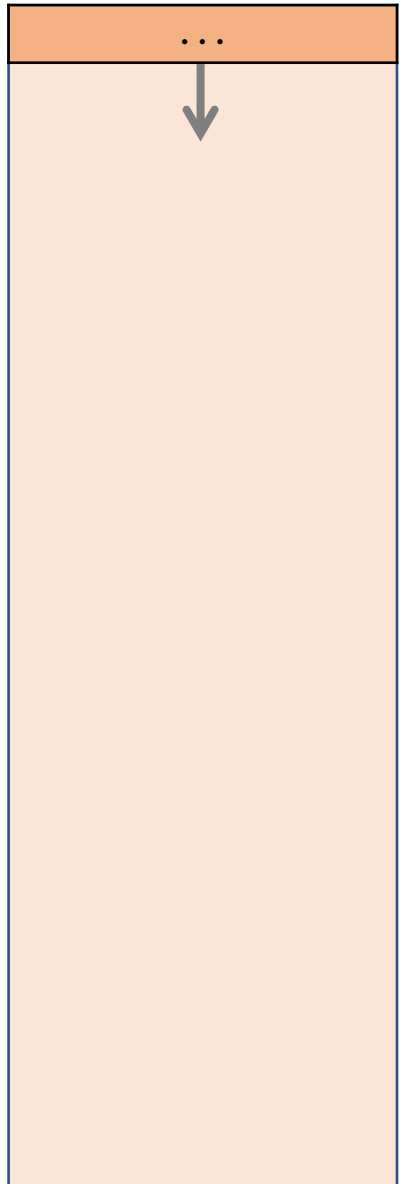
- There are special registers that store parameters and the return value.
- To call a function, we must put any parameters we are passing into the correct registers. (%rdi, %rsi, %rdx, %rcx, %r8, %r9, in that order)
- Parameters beyond the first 6 are put on the stack.
- If the caller expects a return value, it looks in %rax after the callee completes.

Parameters and Return

```
int main(int argc, char *argv[]) {
    int i1 = 1;
    int i2 = 2;
    int i3 = 3;
    int i4 = 4;
    int result = func(&i1, &i2, &i3, &i4,
                      i1, i2, i3, i4);
    …
}

int func(int *p1, int *p2, int *p3, int *p4,
         int v1, int v2, int v3, int v4) {
    …
}
```

main()



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```

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0x40054f <+0>:    sub    $0x18,%rsp
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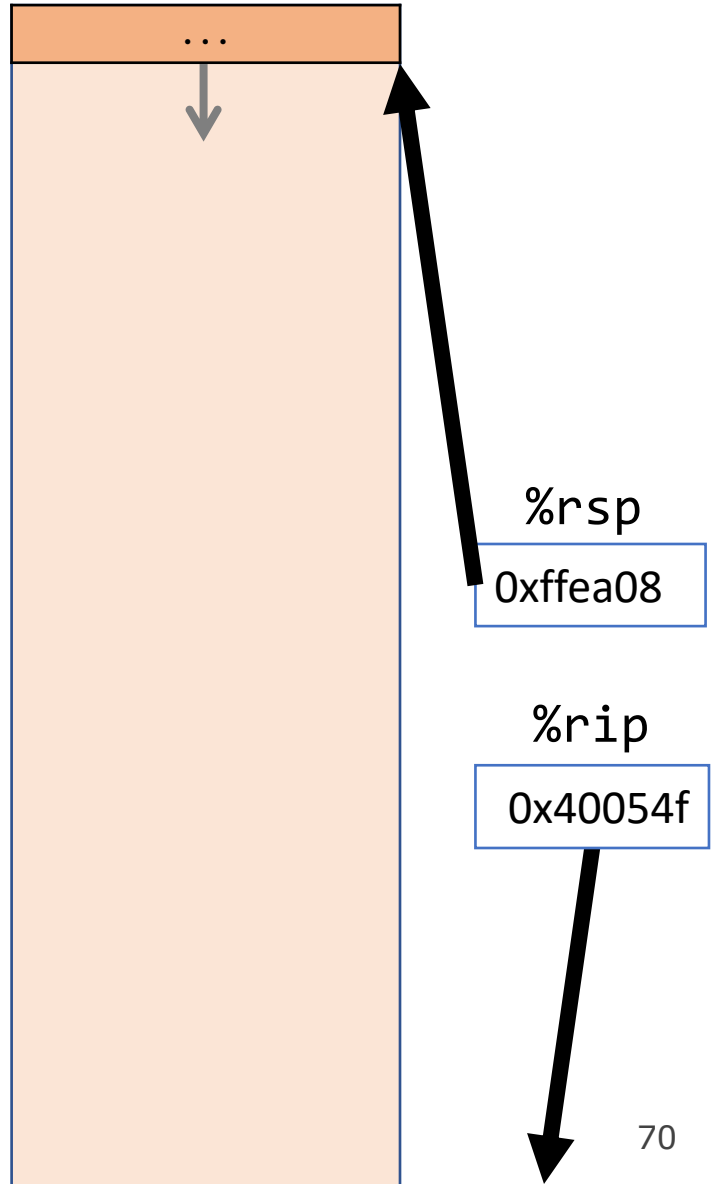

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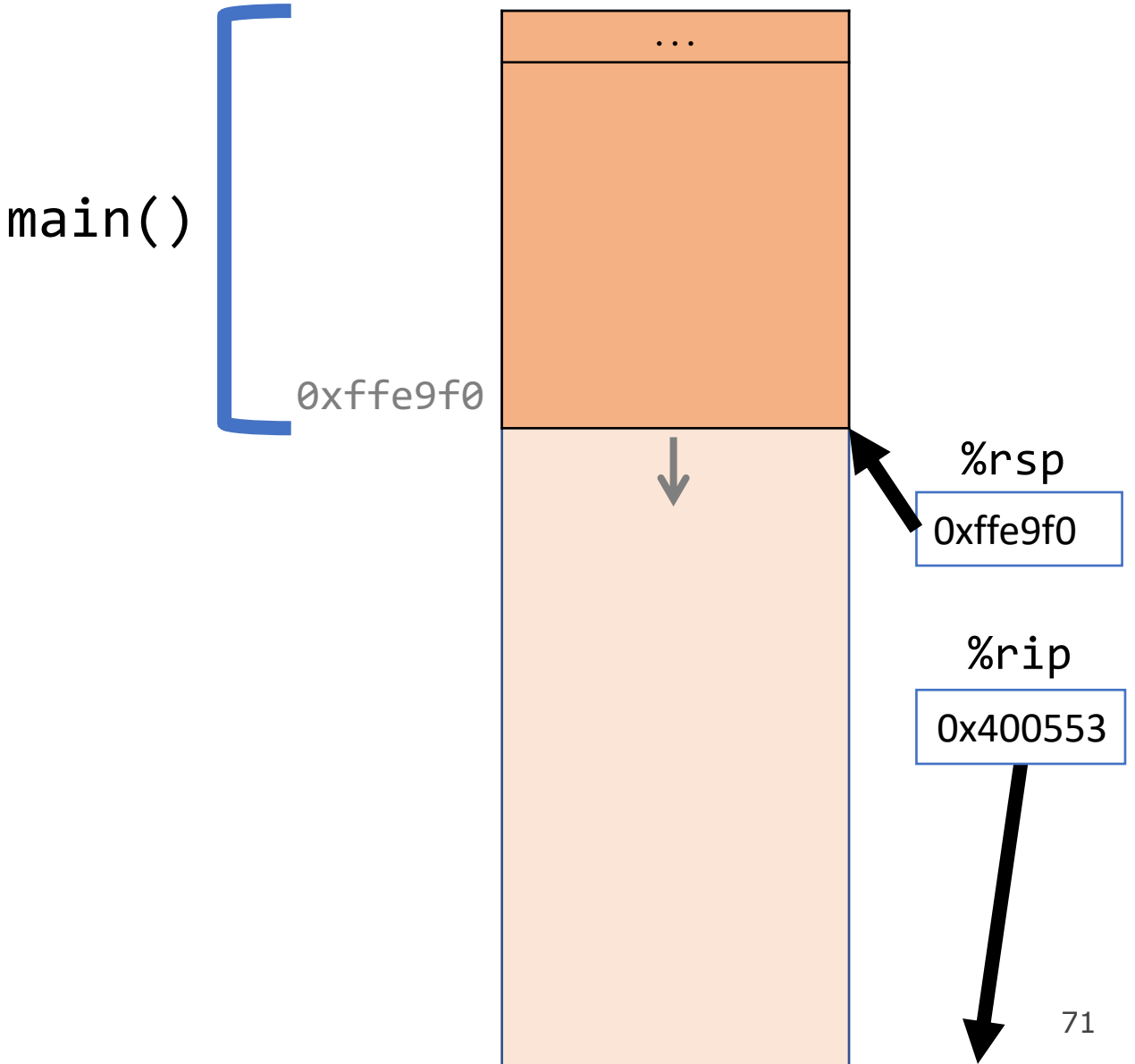

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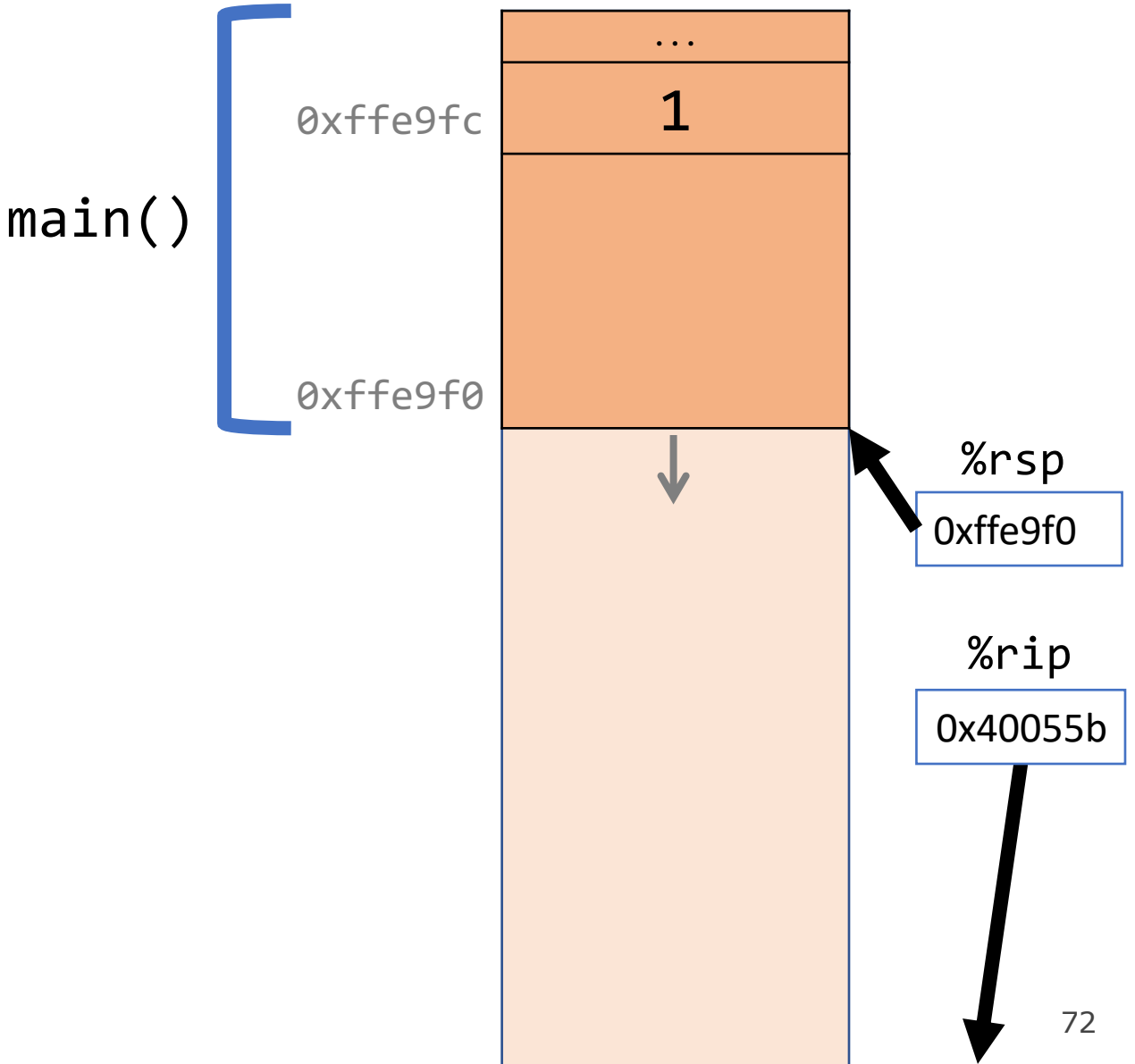

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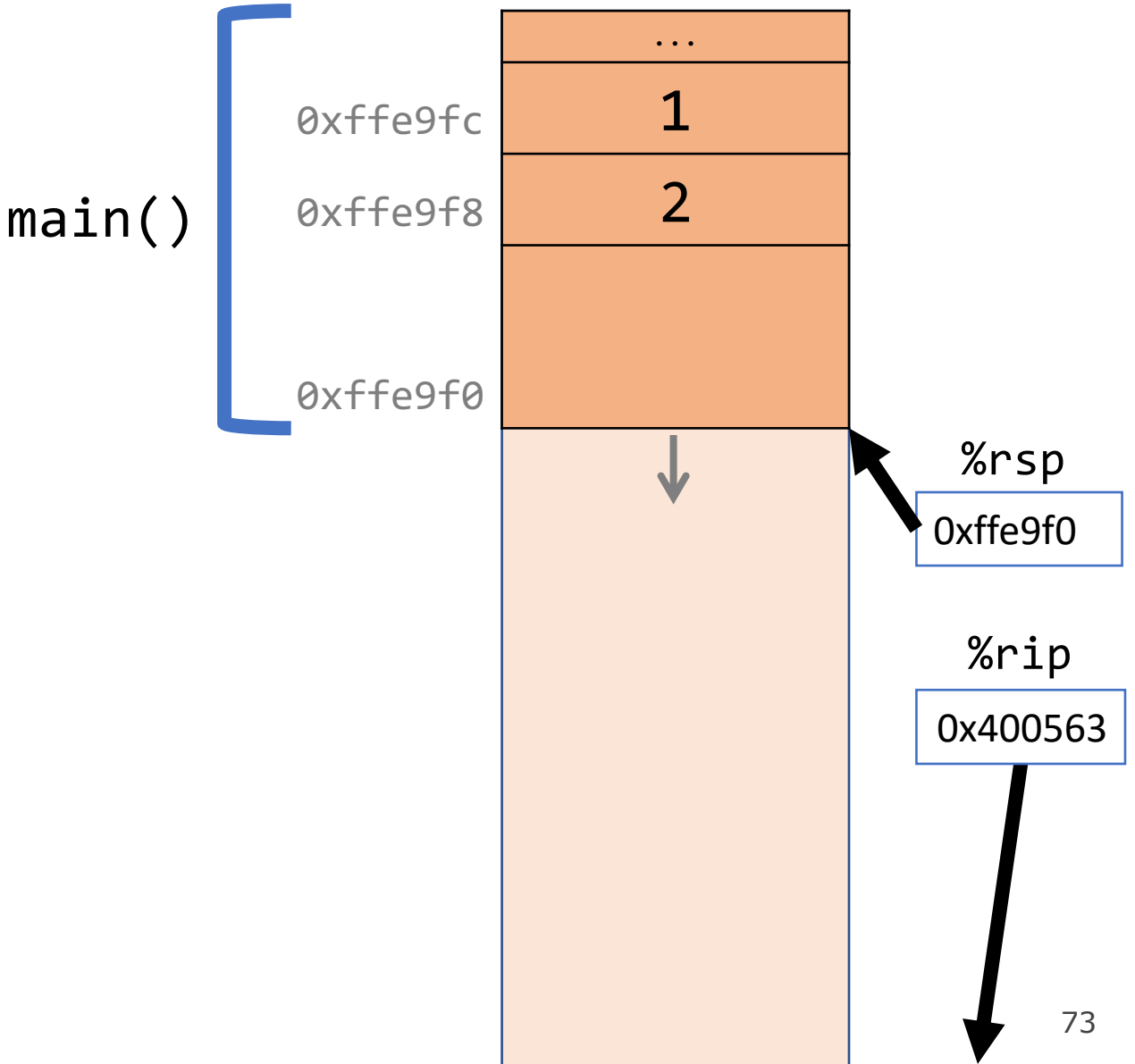

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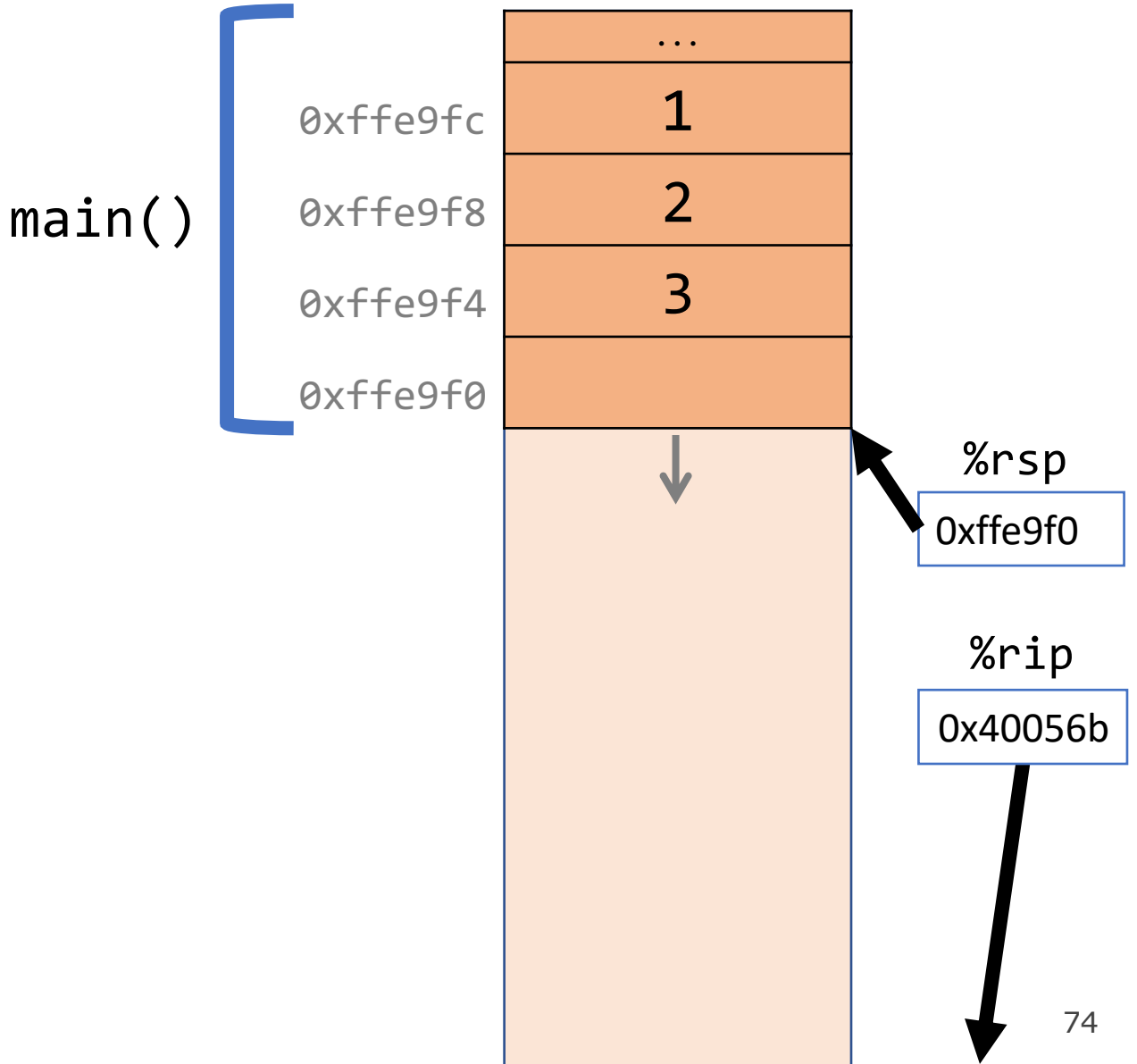

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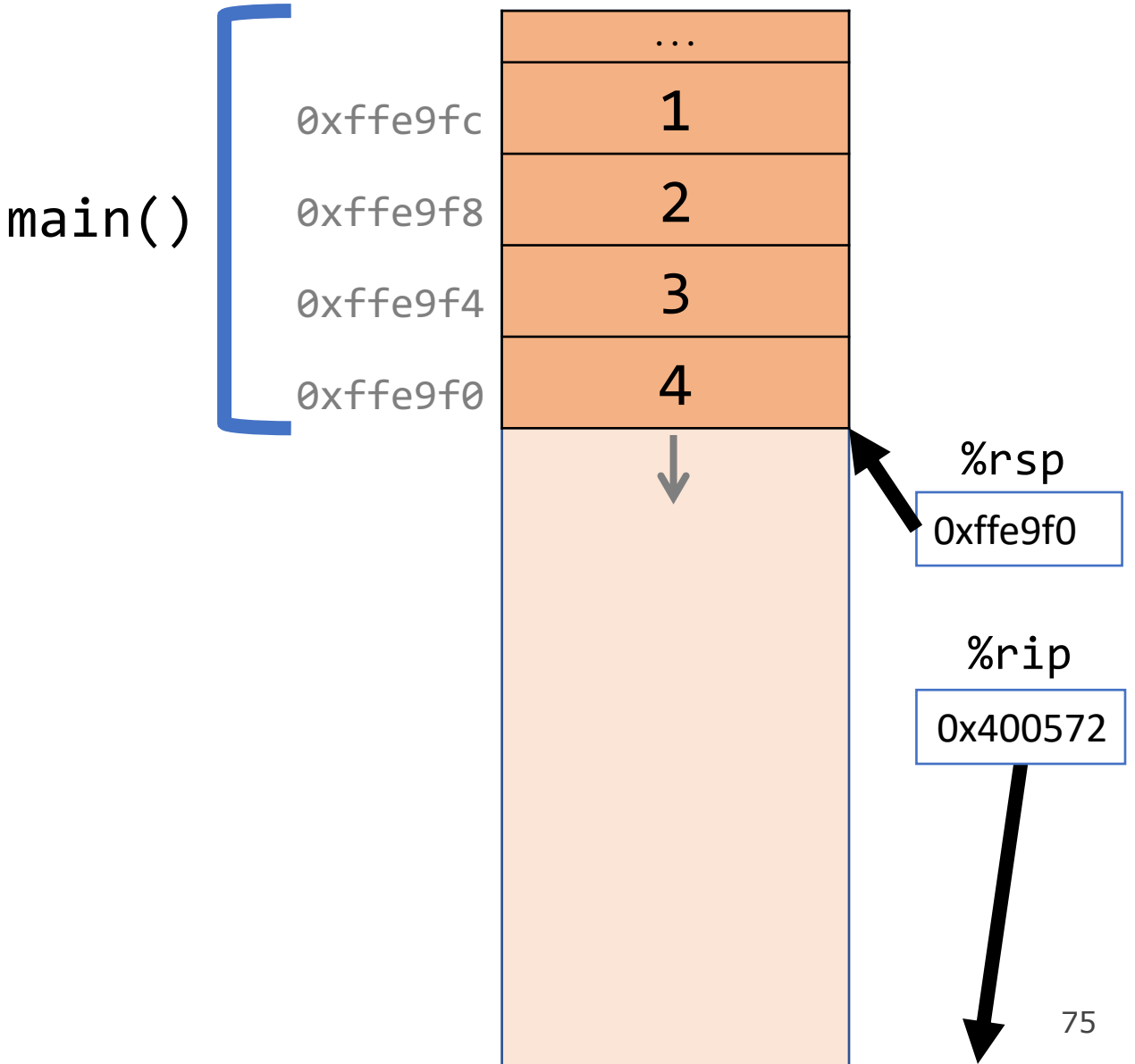

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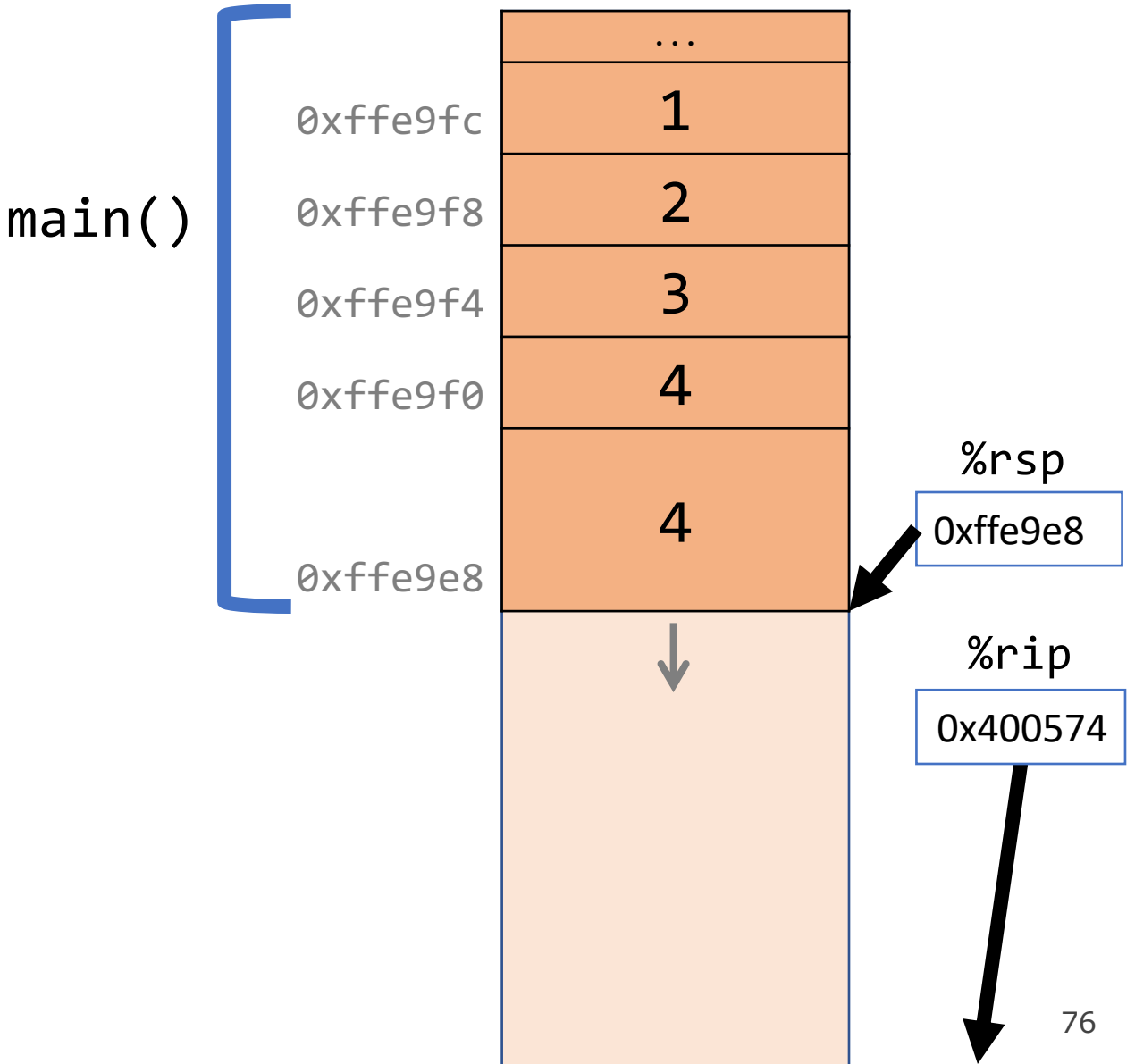

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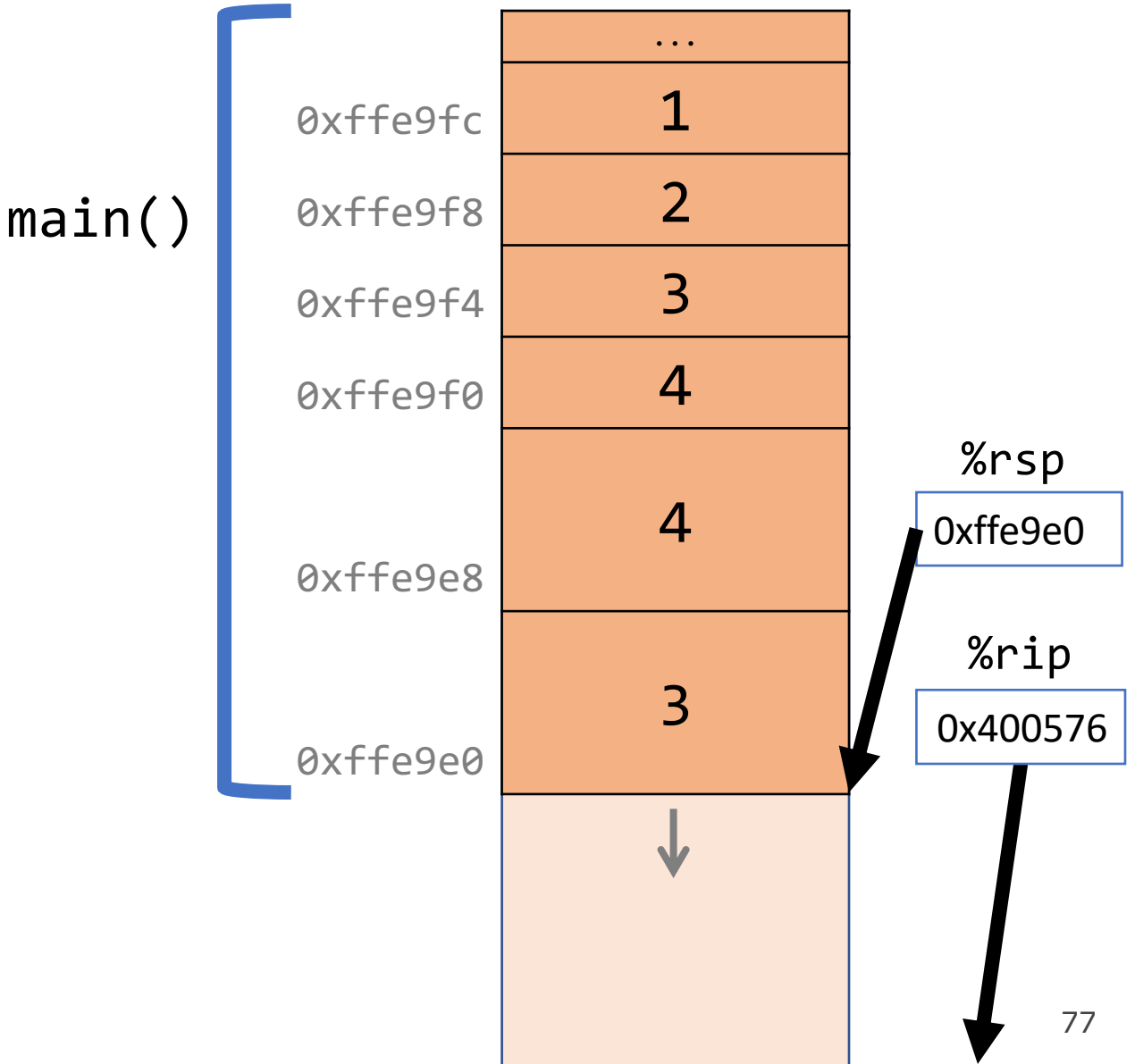

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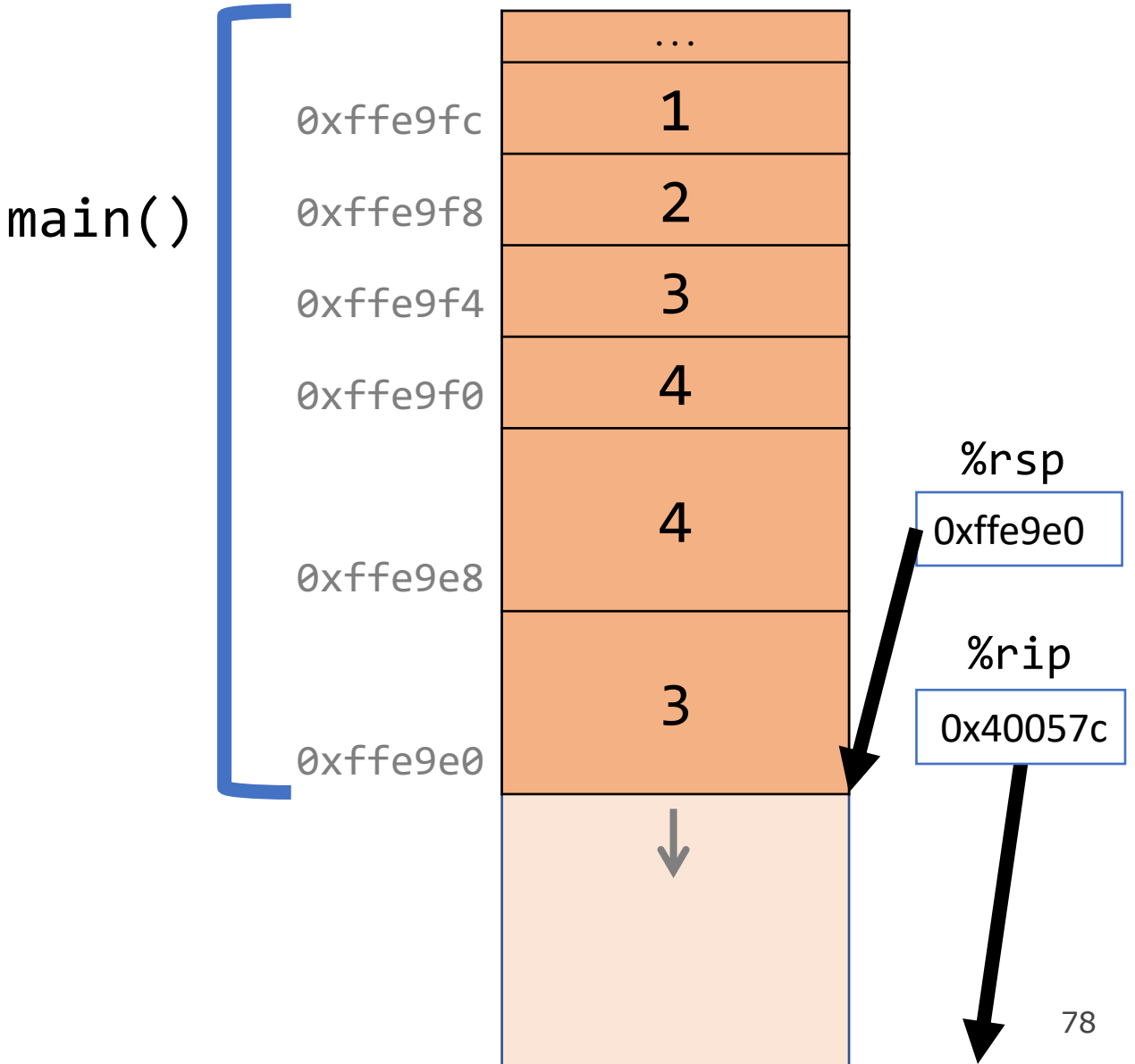
0x400582 <+51>:    lea     0x10(%rsp),%rcx
```



Parameters and Return

```
int main(int argc, char *argv[]) {
    int i1 = 1;
    int i2 = 2;
    int i3 = 3;
    int i4 = 4;
    int result = func(&i1, &i2, &i3, &i4,
                      i1, i2, i3, i4);
    …
}

int func(int *p1, int *p2, int *p3, int *p4,
         int v1, int v2, int v3, int v4) {
    …
}
```

```
0x400572 <+35>:    pushq   $0x4
0x400574 <+37>:    pushq   $0x3
0x400576 <+39>:    mov     $0x2,%r9d
0x40057c <+45>:    mov     $0x1,%r8d
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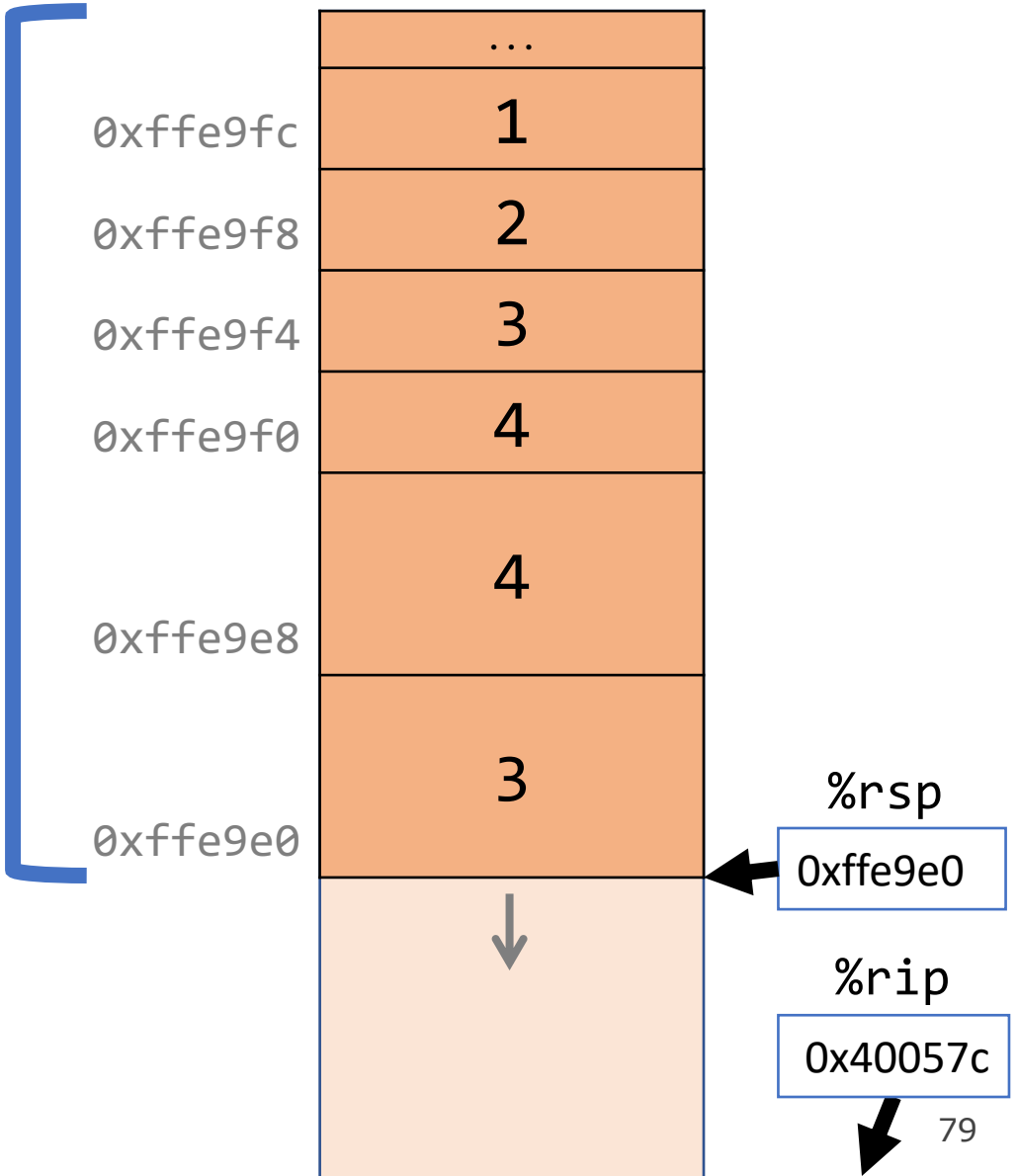
```

main()



Parameters and Return

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int main(int argc, char *argv[]) {
    int i1 = 1;
    int i2 = 2;
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    int result = func(&i1, &i2, &i3, &i4,
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    …
}

int func(int *p1, int *p2, int *p3, int *p4,
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    …
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```

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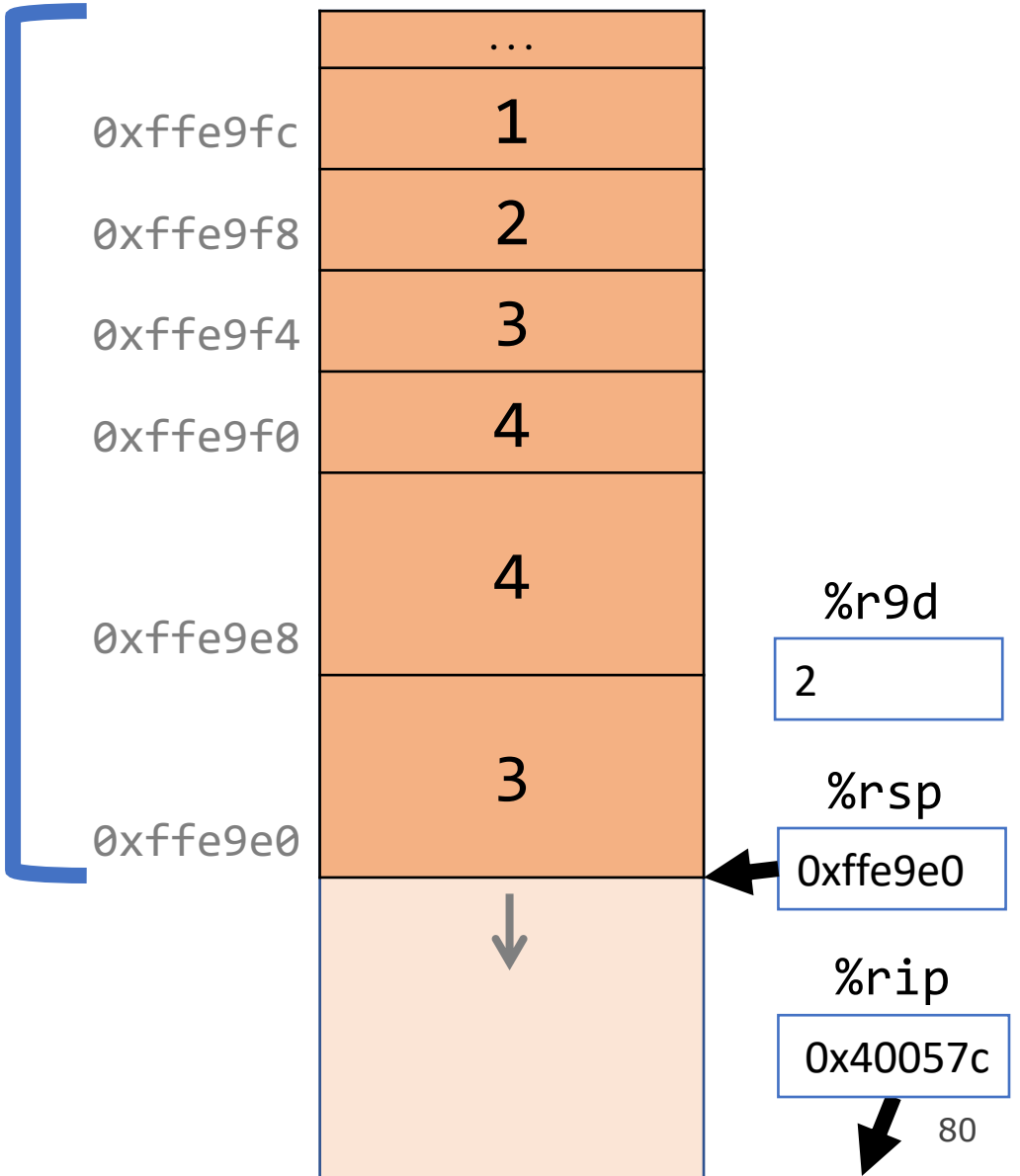

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    int i1 = 1;
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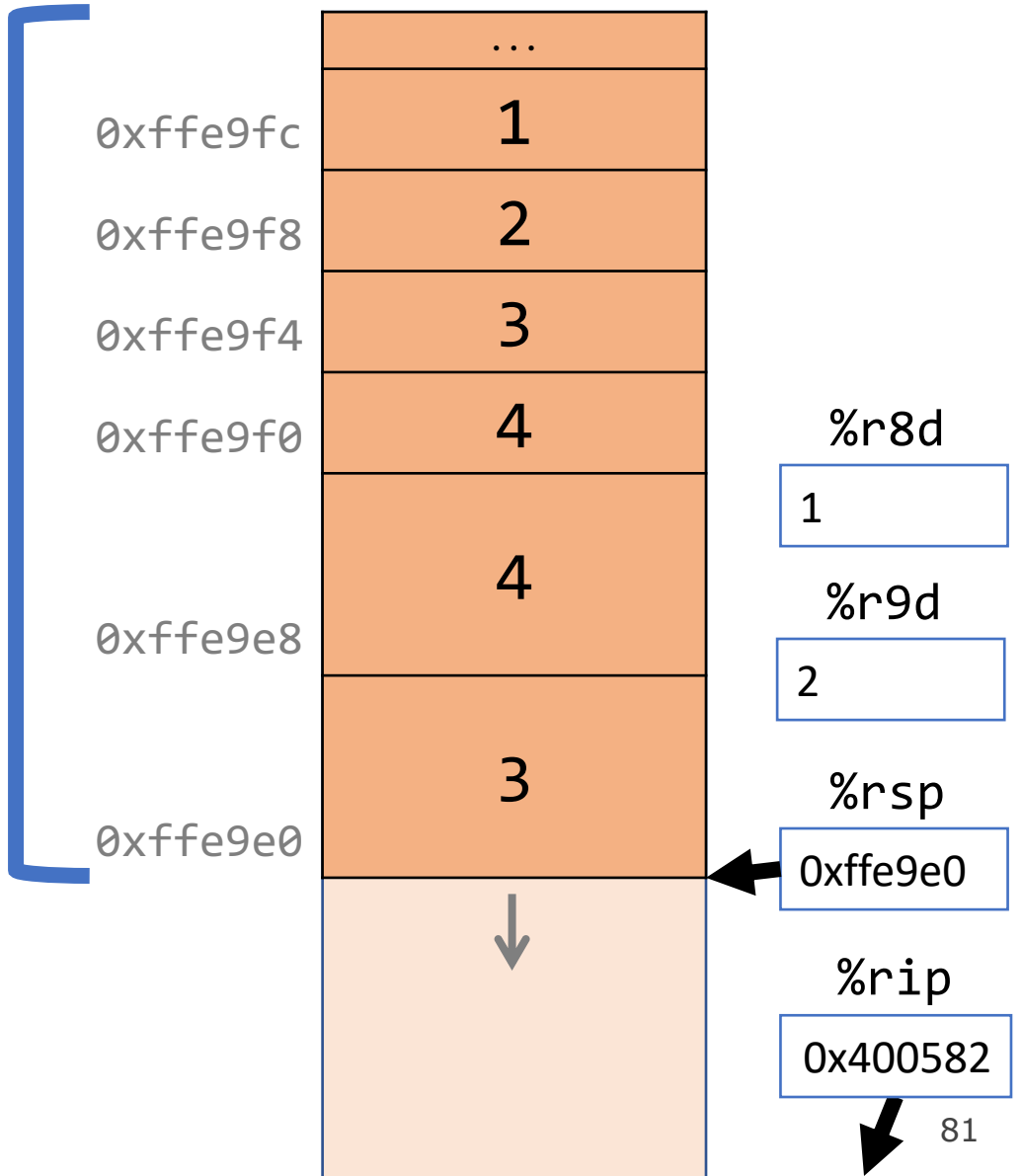
0x400587 <+56>:    lea     0x14(%rsp),%rdx
```



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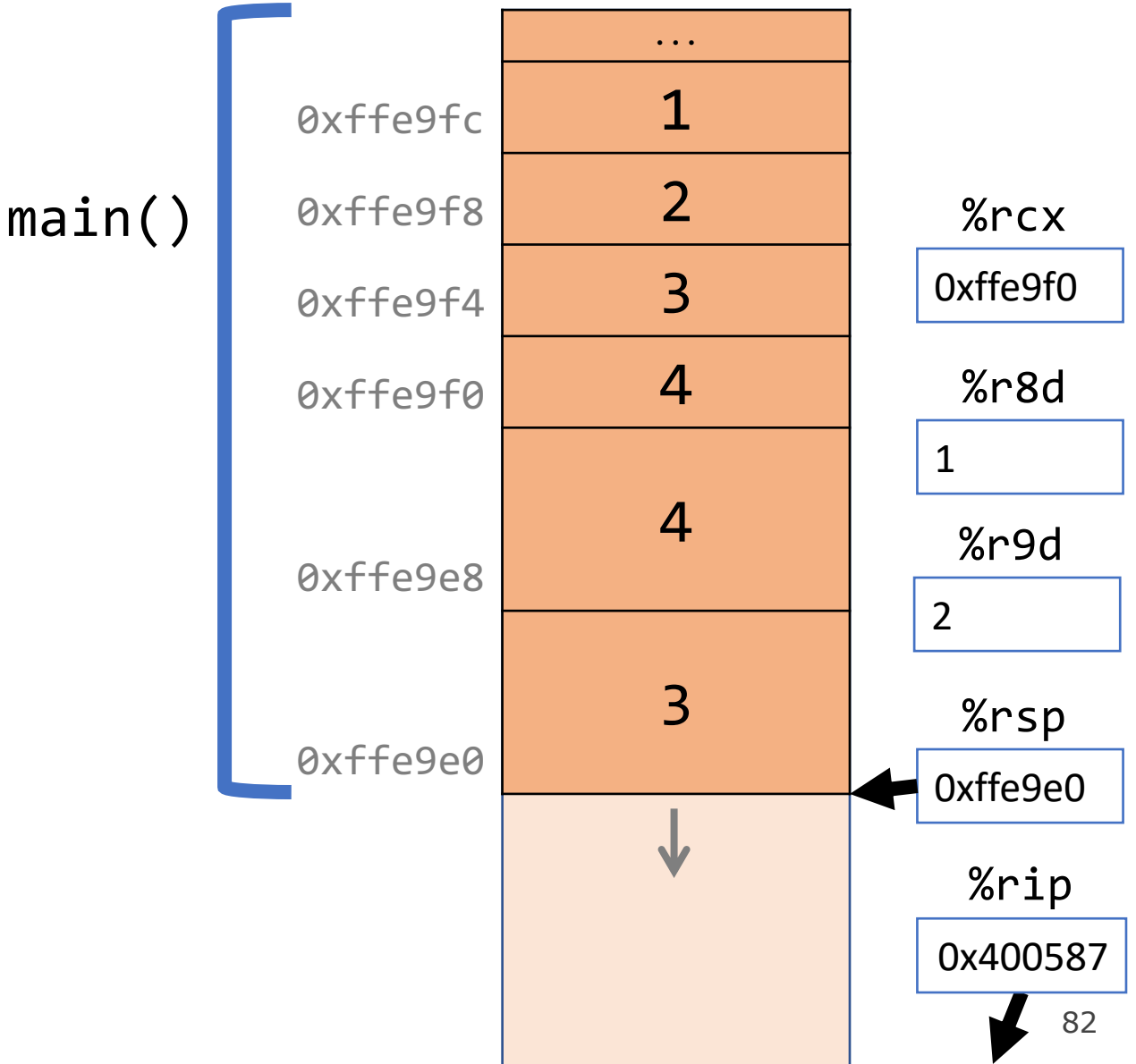

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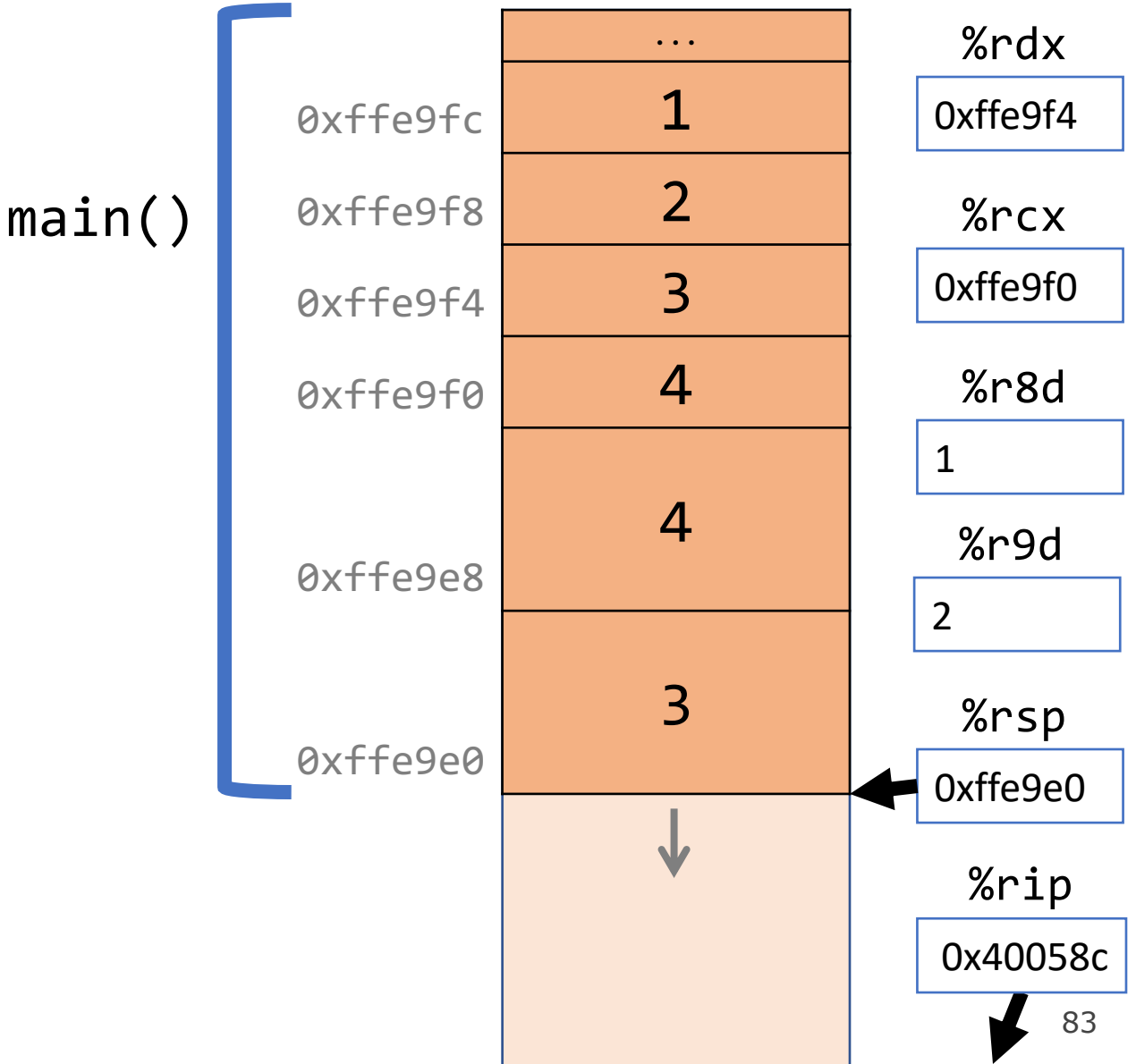

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int func(int *p1, int *p2, int *p3, int *p4,
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```

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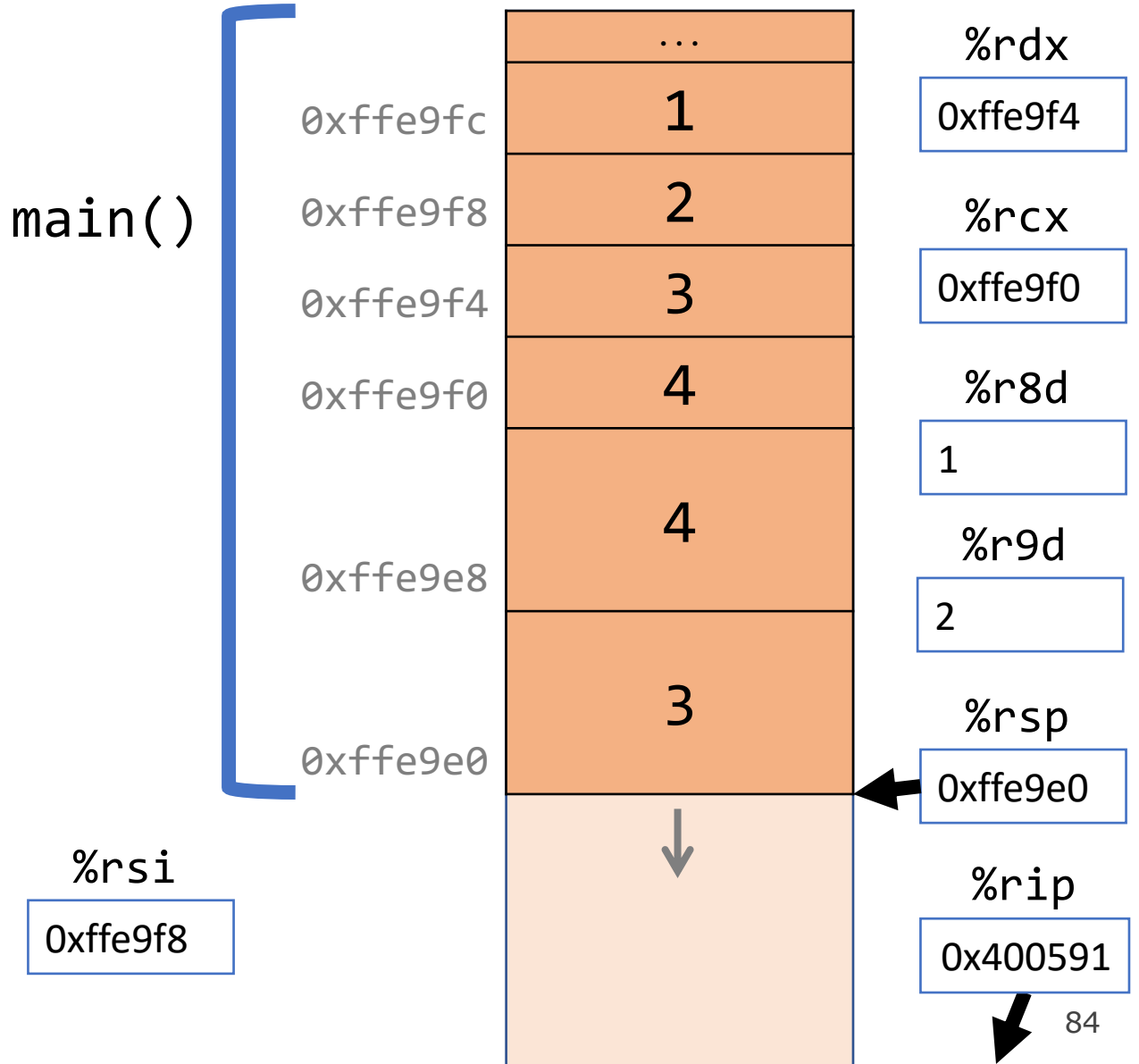
0x400591 <+66>:    lea    0x1c(%rsp),%rdi
0x400596 <+71>:    callq  0x400546 <func>
```



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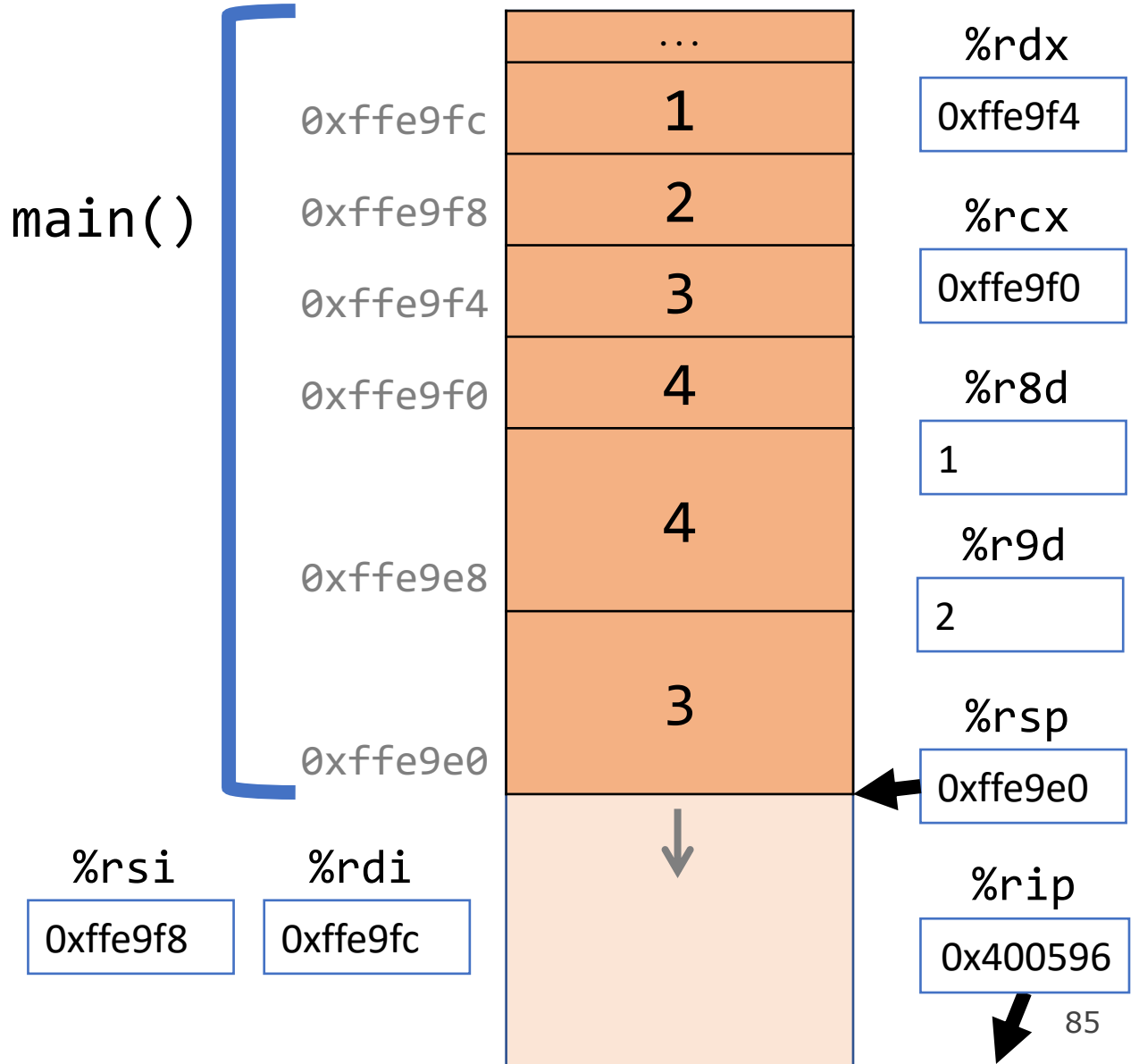
0x400596 <+71>:   callq  0x400546 <func>
0x40059b <+76>:   add    $0x10,%rsp
```



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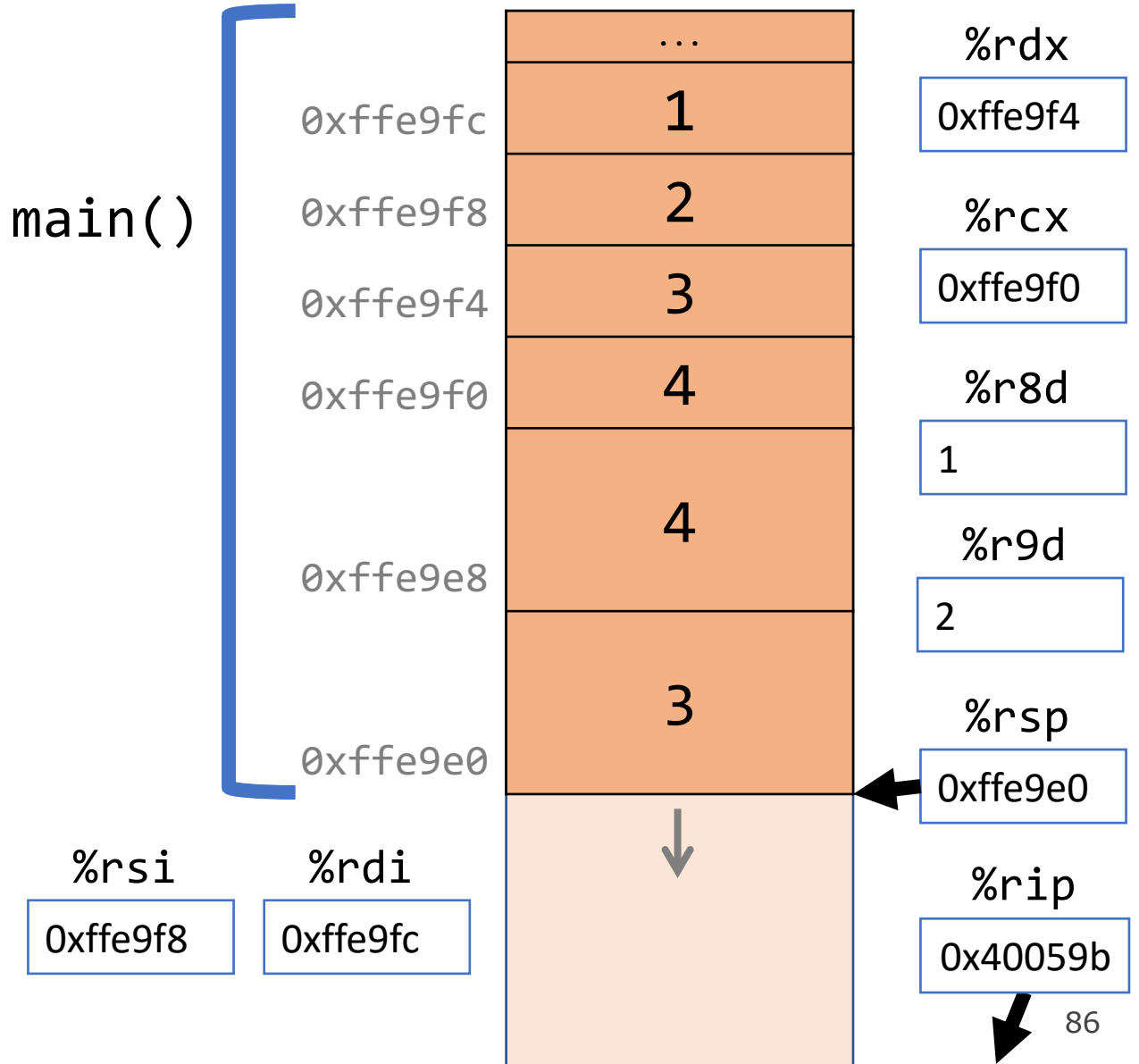

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int main(int argc, char *argv[]) {
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    …
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int func(int *p1, int *p2, int *p3, int *p4,
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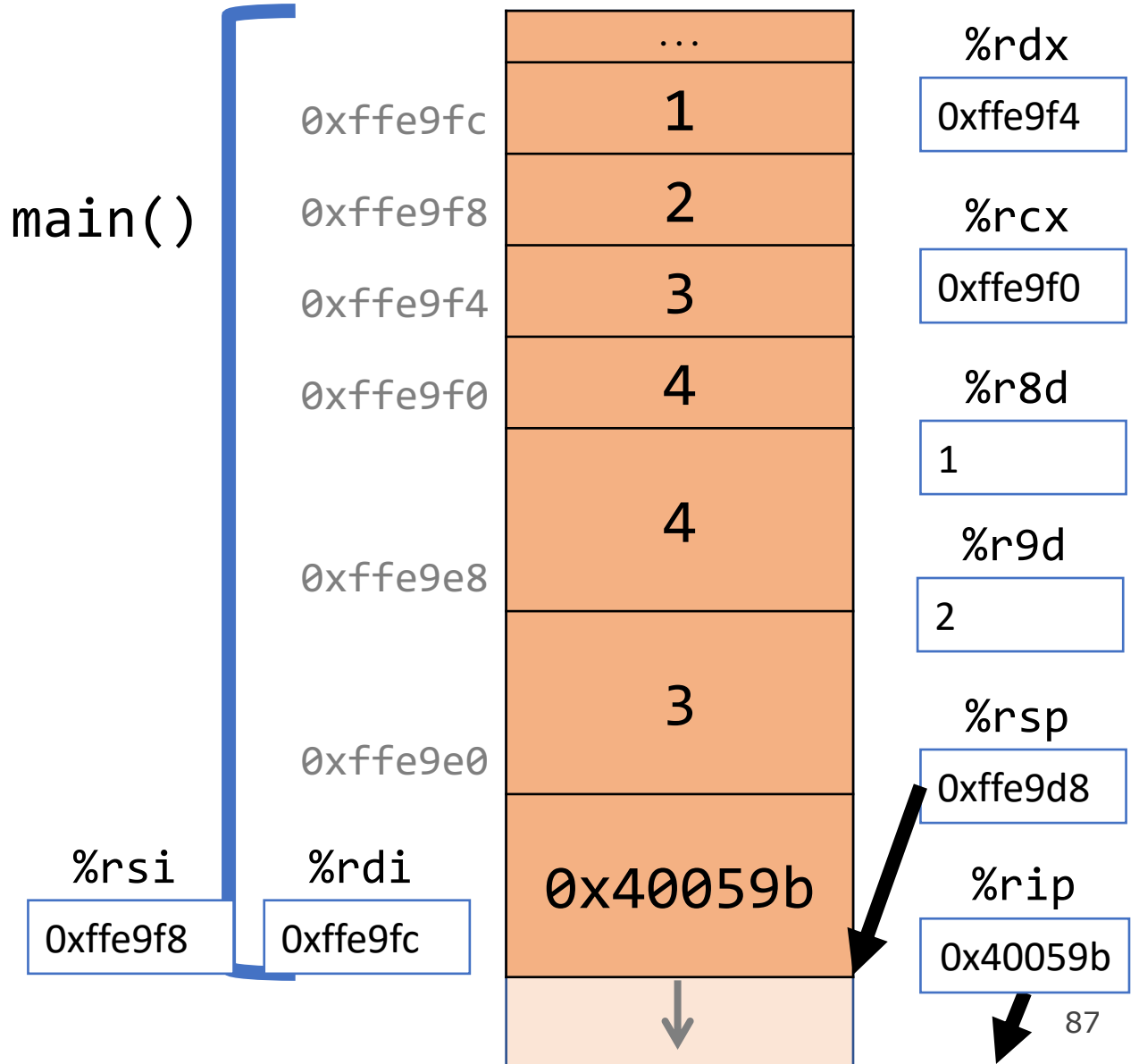

Parameters and Return

```
int main(int argc, char *argv[]) {
    int i1 = 1;
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    int i3 = 3;
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    int result = func(&i1, &i2, &i3, &i4,
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int func(int *p1, int *p2, int *p3, int *p4,
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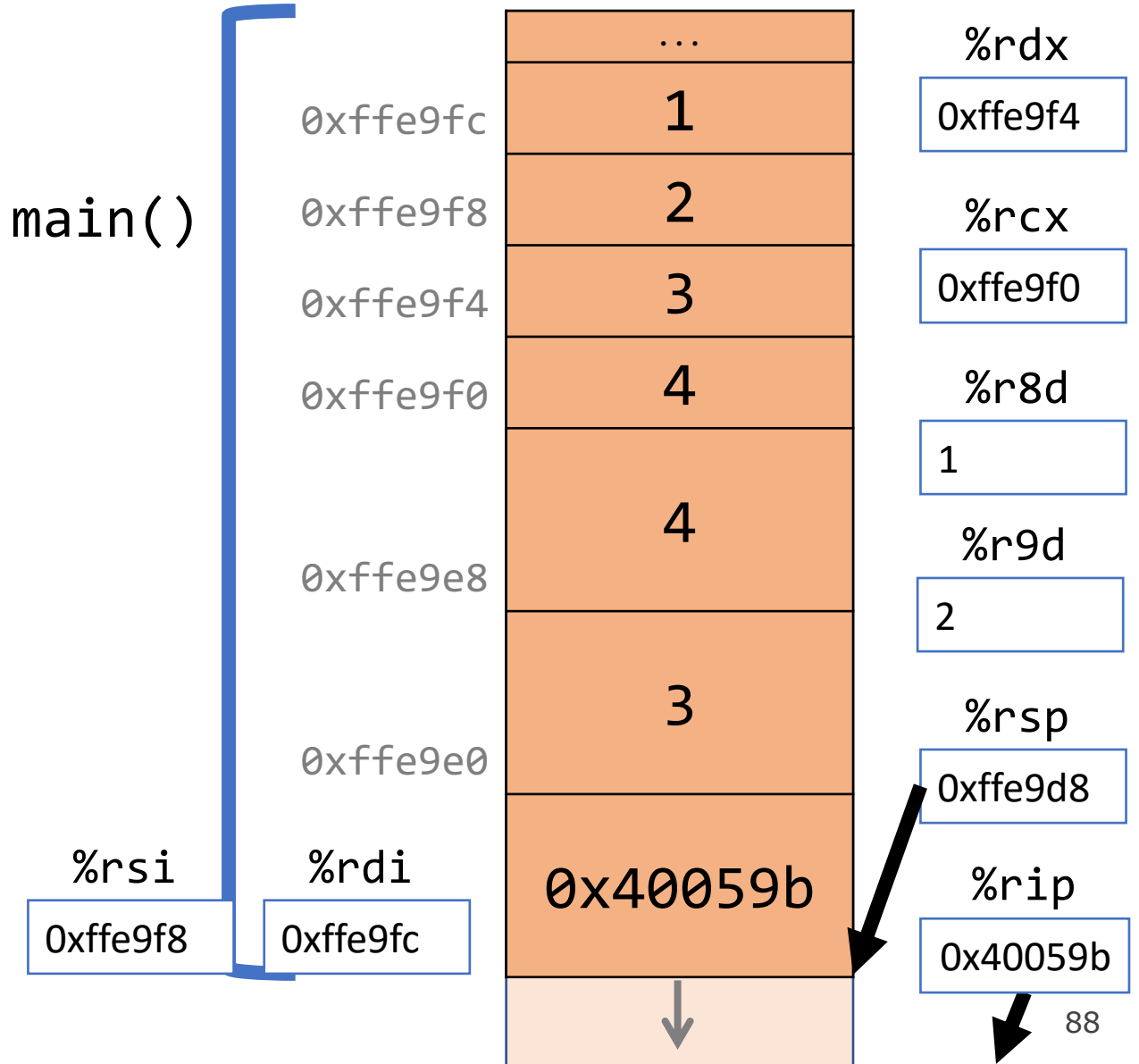

Plan For Today

- Recap: Control Flow
- The Instruction Pointer (%rip)
- **Calling Functions**
  - The Stack
  - Passing Control
  - **Break**: Announcements
  - Passing Data
  - **Local Storage**
- Register Restrictions
- Pulling it all together: recursion example

Calling Functions In Assembly

To call a function in assembly, we must do a few things:

- **Pass Control** – %rip must be adjusted to execute the function being called and then resume the caller function afterwards.
- **Pass Data** – we must pass any parameters and receive any return value.
- **Manage Memory** – we must handle any space needs of the callee on the stack.

Terminology: **caller** function calls the **callee** function.

Local Storage

- So far, we've often seen local variables stored directly in registers, rather than on the stack as we'd expect. This is for optimization reasons.
- There are **three** common reasons that local data must be in memory:
  - We've run out of registers
  - The '&' operator is used on it, so we must generate an address for it
  - They are arrays or structs (need to use address arithmetic)

Local Storage

```
long caller() {
    long arg1 = 534;
    long arg2 = 1057;
    long sum = swap_add(&arg1, &arg2);
    ...
}
```

```
caller:
    subq $16, %rsp          // 16 bytes for stack frame
    movq $534, (%rsp)       // store 534 in arg1
    movq $1057, 8(%rsp)     // store 1057 in arg2
    leaq 8(%rsp), %rsi      // compute &arg2 as second arg
    movq %rsp, %rdi         // compute &arg1 as first arg
    call swap_add           // call swap_add(&arg1, &arg2)
```

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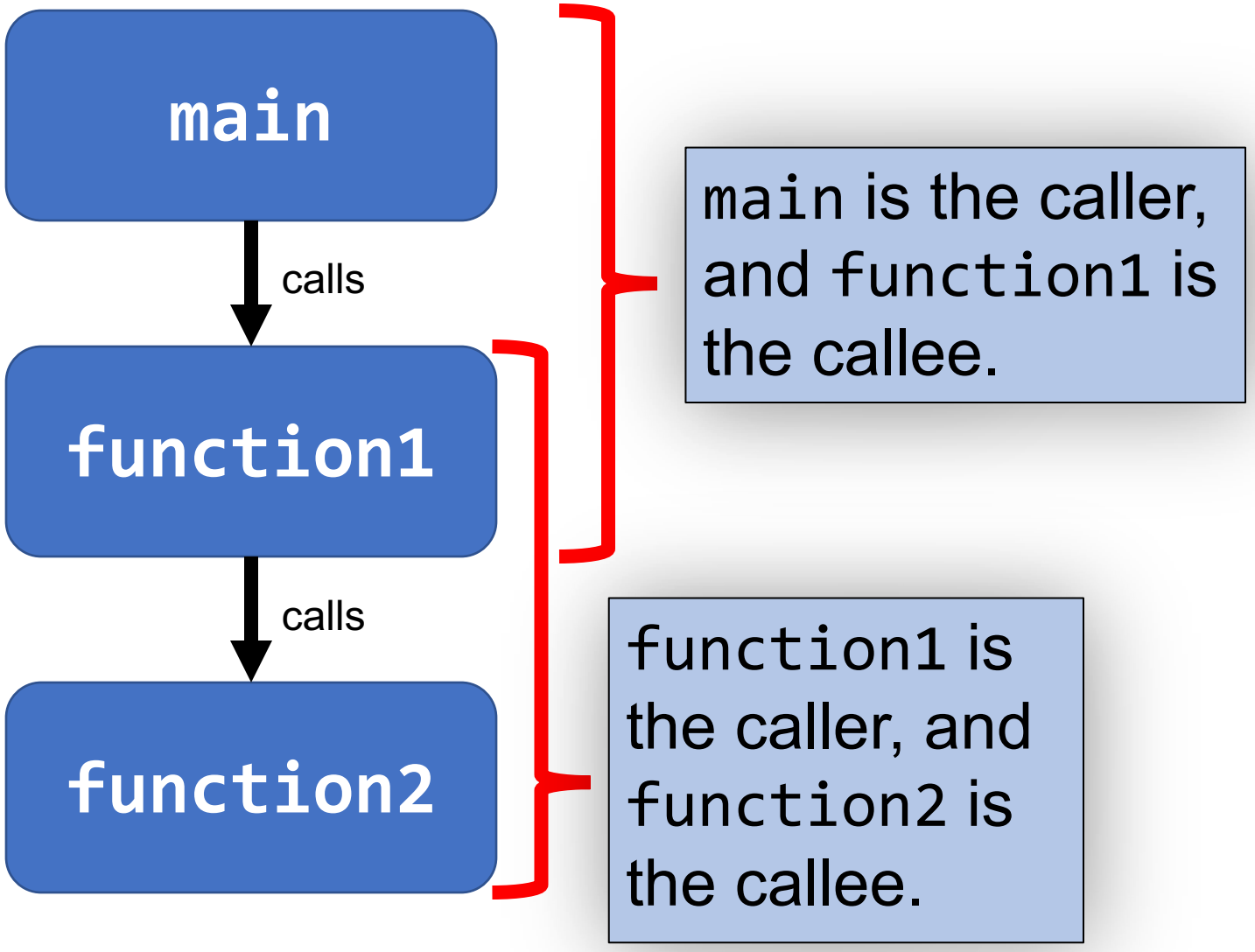
Register Restrictions

- There is only one copy of registers for all programs and instructions.
- Therefore, there are some rules that callers and callees must follow when using registers so they do not interfere with one another.
- There are two types of registers: **caller-owned** and **callee-owned**

Caller/Callee

Caller/callee is terminology that refers to a pair of functions. A single function may be both a caller and callee simultaneously (e.g. `function1` at right).



Register Restrictions

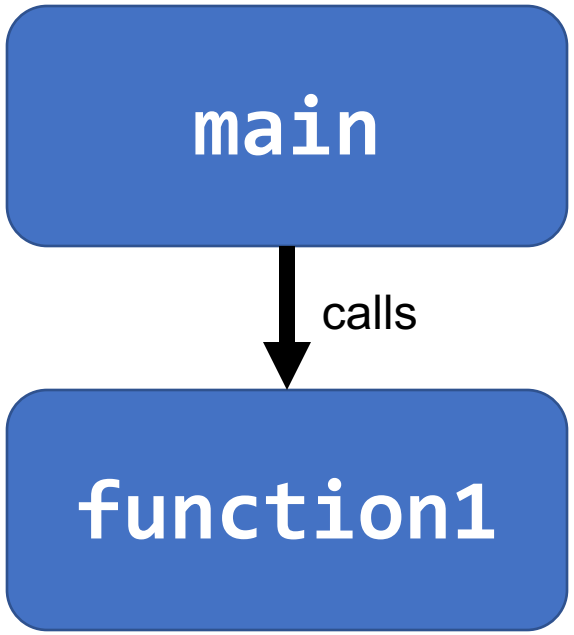
Caller-Owned

- Callee must *save* the existing value and *restore* it when done.
- Caller can store values and assume they will be preserved across function calls.

Callee-Owned

- Callee does not need to save the existing value.
- Caller's values could be overwritten by a callee! The caller may consider saving values elsewhere before calling functions.

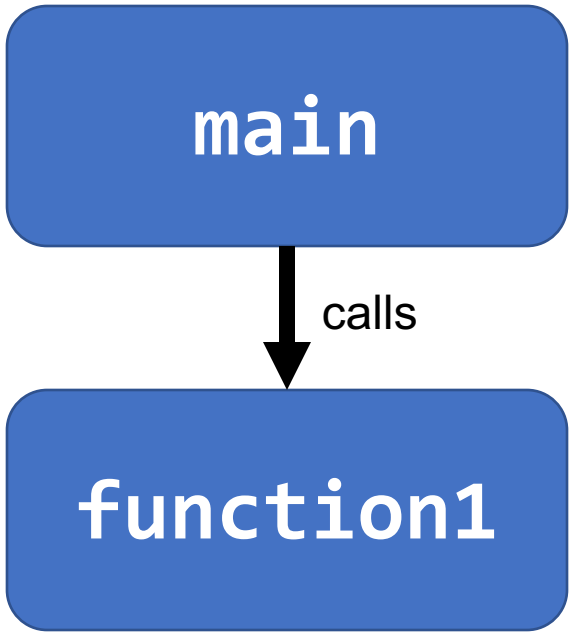
Caller-Owned Registers



`main` can use caller-owned registers and know that `function1` will not permanently modify their values.

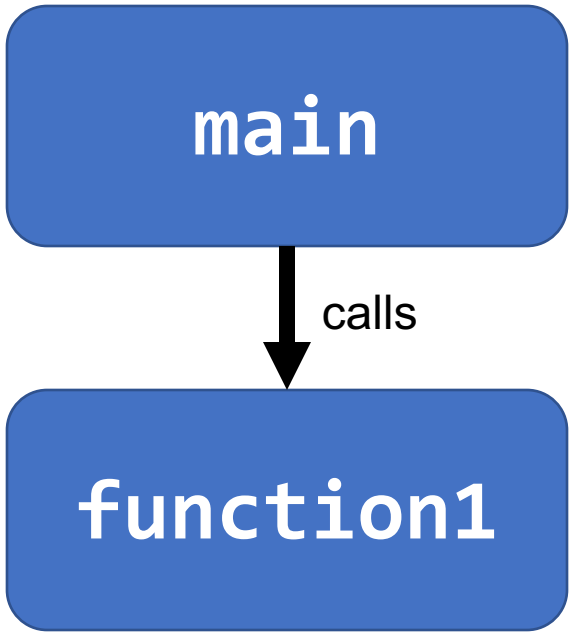
If function1 wants to use any caller-owned registers, it must save the existing values and restore them before returning.

Caller-Owned Registers




```
function1:
  push %rbp
  push %rbx
  ...
  pop %rbx
  pop %rbp
  retq
```

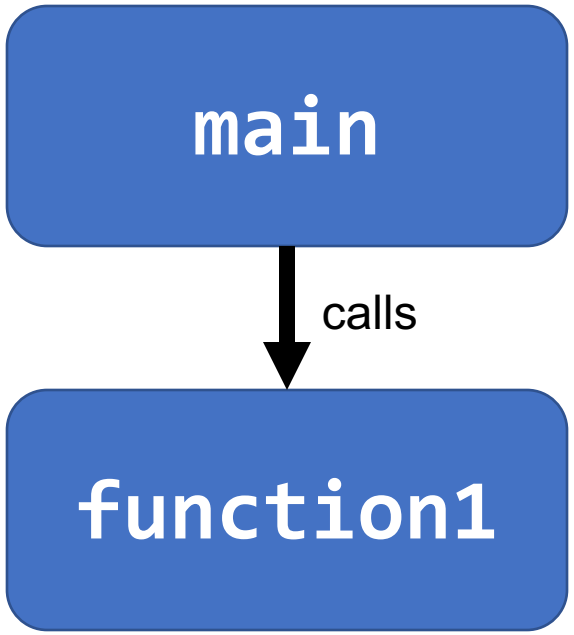
Callee-Owned Registers



`main` can use callee-owned registers but calling `function1` may permanently modify their values.

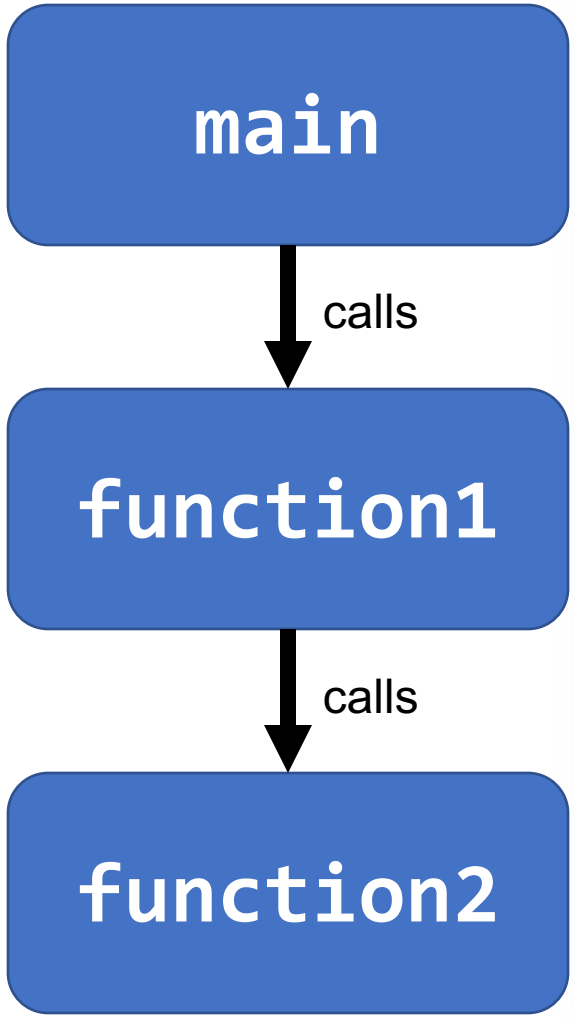
If function1 wants to use any callee-owned registers, it can do so without saving the existing values.

Callee-Owned Registers




```
main:
   ...
   push %r10
   push %r11
   callq function1
   pop %r11
   pop %r10
   ...
```

A Day In the Life of `function1`



Caller-owned registers:

- **`function1`** must save/restore existing values of any that are used by **`main`**.
- **`function1`** can assume that calling **`function2`** will not permanently change their values.

Callee-owned registers:

- **`function1`** does not need to save/restore existing values of any that are used by **`main`**.
- calling **`function2`** may permanently change their values.

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Example: Recursion

- Let’s look at an example of recursion at the assembly level.
- We’ll use everything we’ve learned about registers, the stack, function calls, parameters, and assembly instructions!
- We’ll also see how helpful GDB can be when tracing through assembly.

`factorial.c and factorial`

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That's it for assembly! **Next time:** managing the heap