CS107, Lecture 13

Assembly: Function Calls and the Runtime Stack

Reading: B&O 3.7

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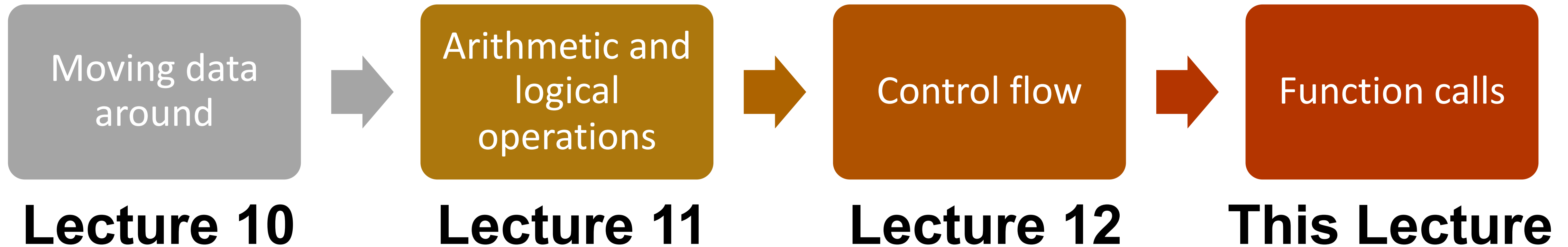
Based on slides created by Marty Stepp, Cynthia Lee, Chris Gregg, and others.

Learning Assembly



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

Learning Goals

- Learn how assembly calls functions and manages stack frames.
- Learn the rules of register use when calling functions.

Lecture Plan

- Revisiting %rip 5
- Calling Functions 19
  - The Stack 22
  - Passing Control 36
  - Passing Data 44
  - Local Storage 65
- Register Restrictions 69
- Pulling it all together: recursion example 78
- Optimizations 81
- Live session slides 93


```
cp -r /afs/ir/class/cs107/lecture-code/lect13 .
```

Lecture Plan

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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

```
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
```

%rip

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void loop() {
    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++;
    }
}
```

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```

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

%rip

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    int i = 0;
    while (i < 100) {
        i++;
    }
}
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%orip

```
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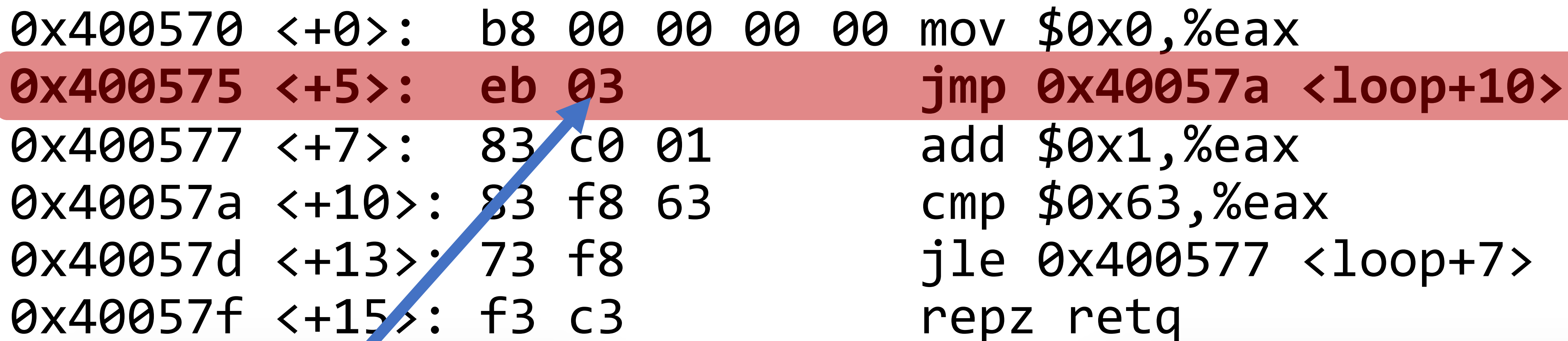
```

0xeb means **jmp**.

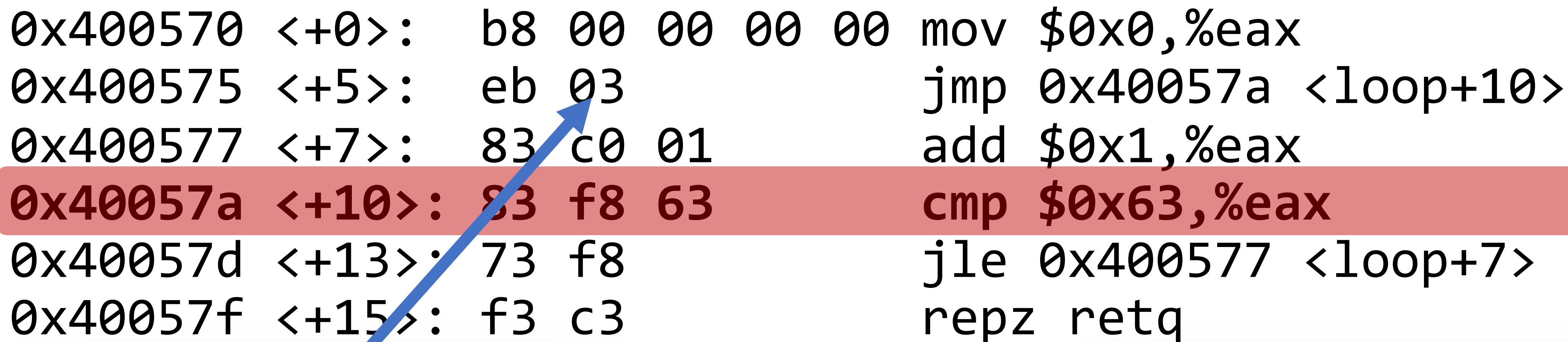
%rip



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 then go **3** bytes further!

%rip



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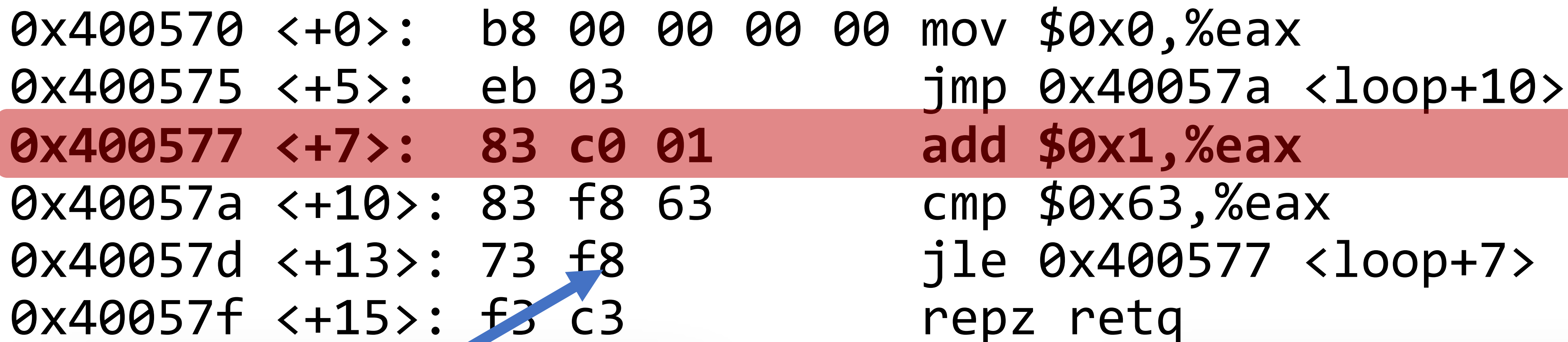
```

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



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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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```
cp -r /afs/ir/class/cs107/lecture-code/lect13 .
```

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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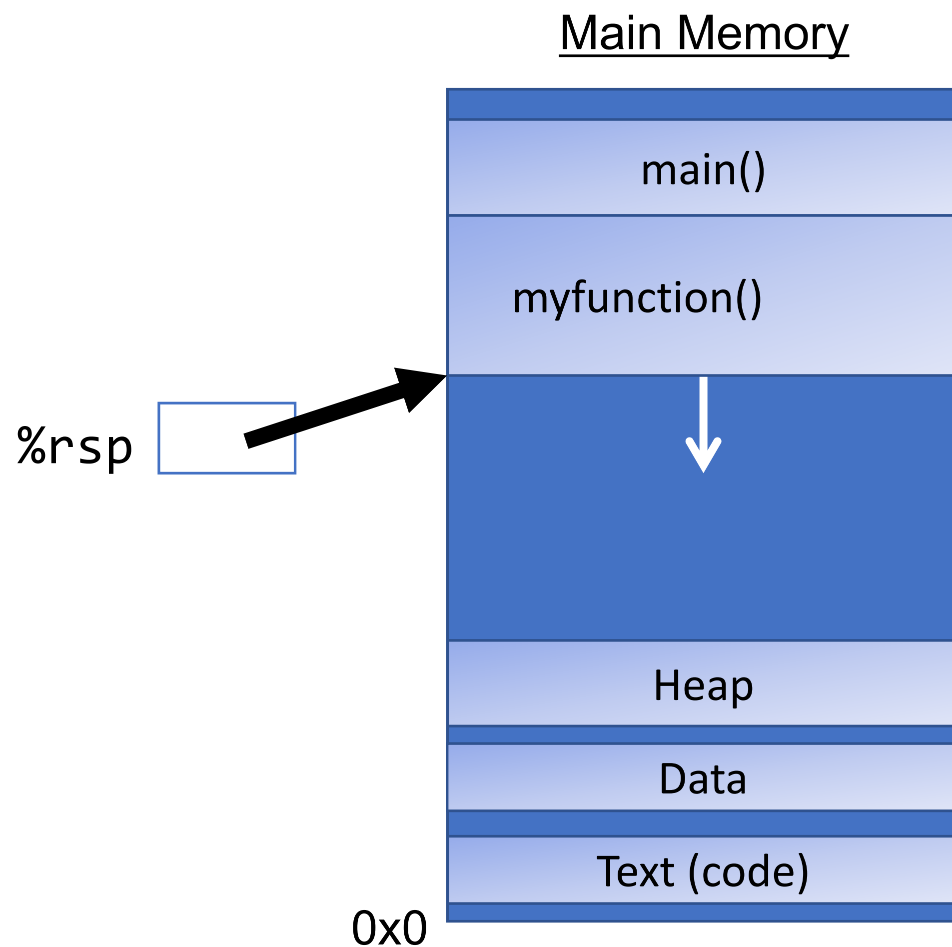
```

%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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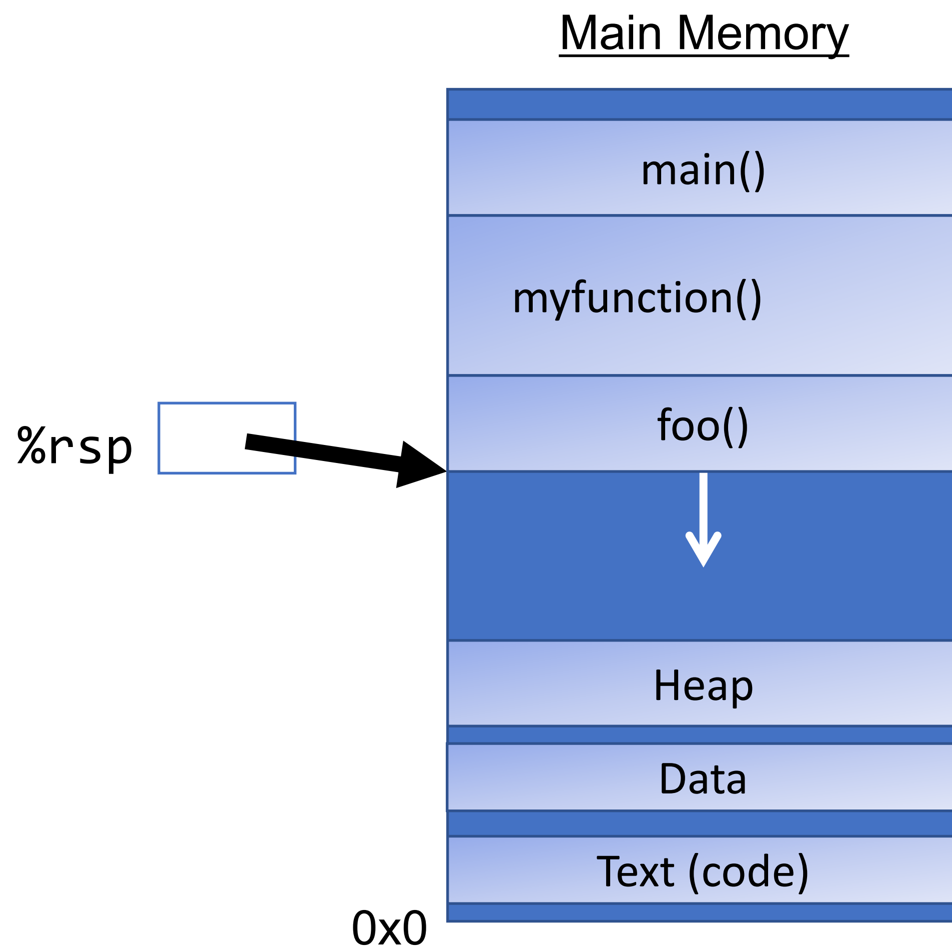

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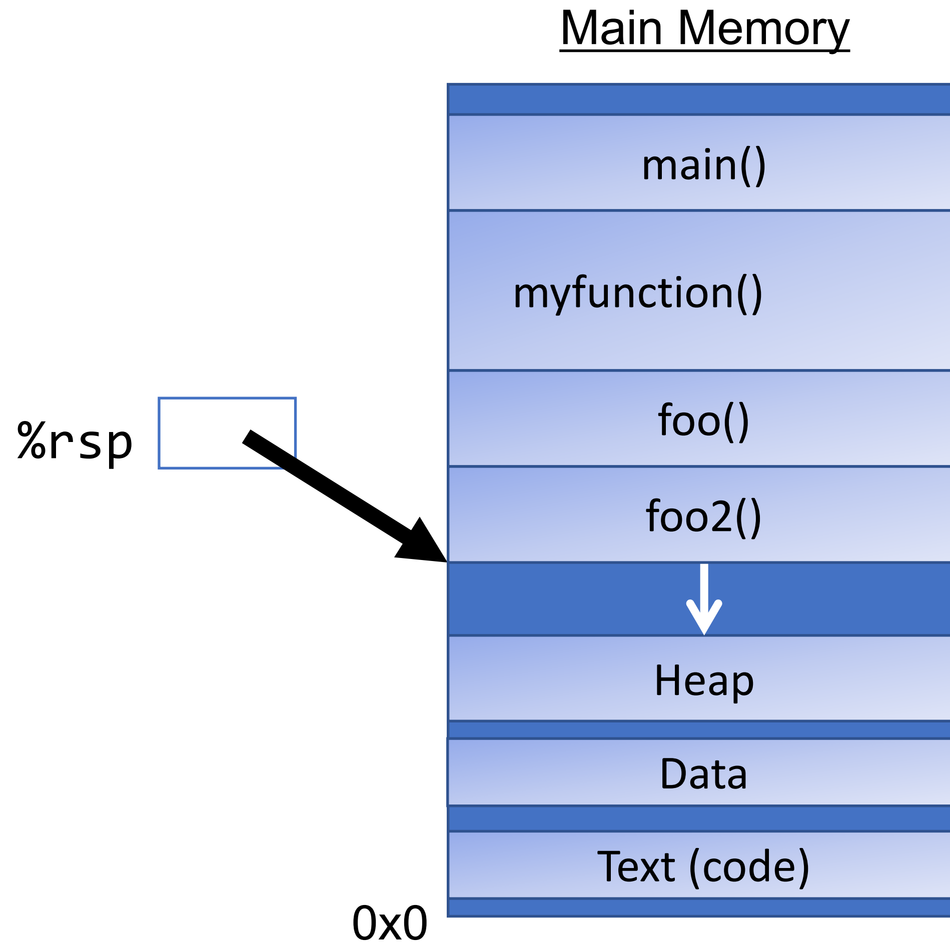

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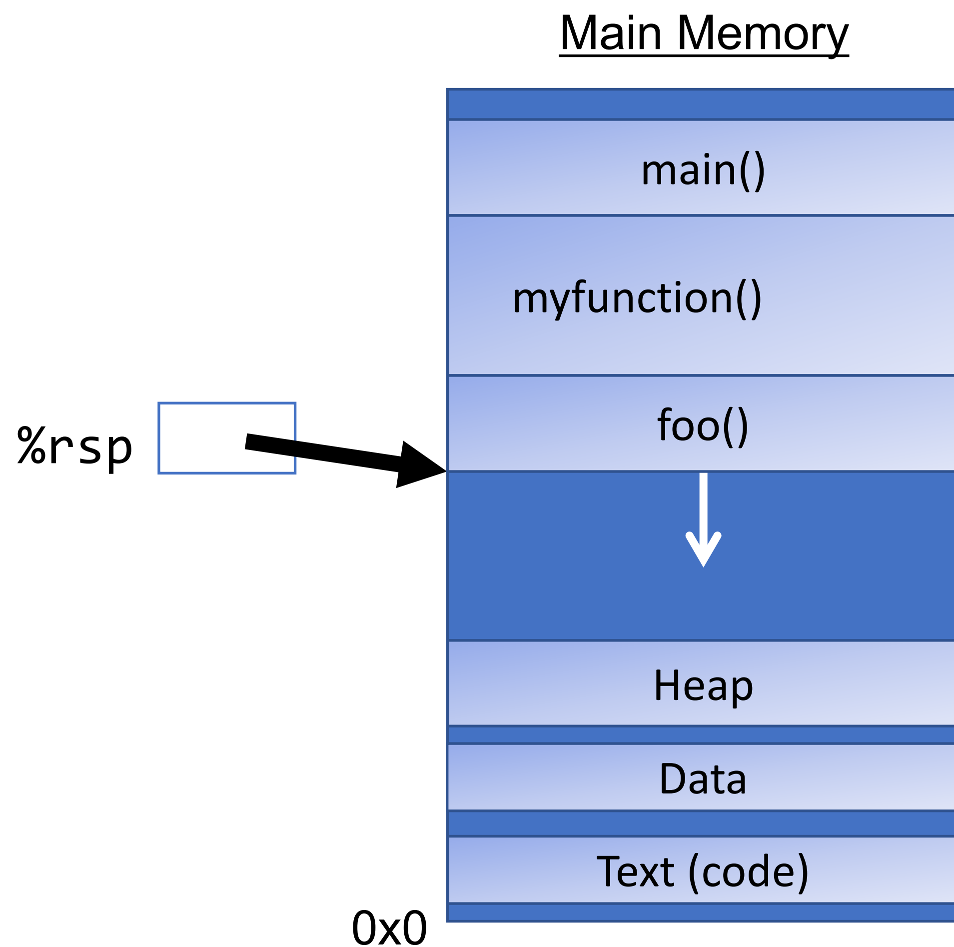

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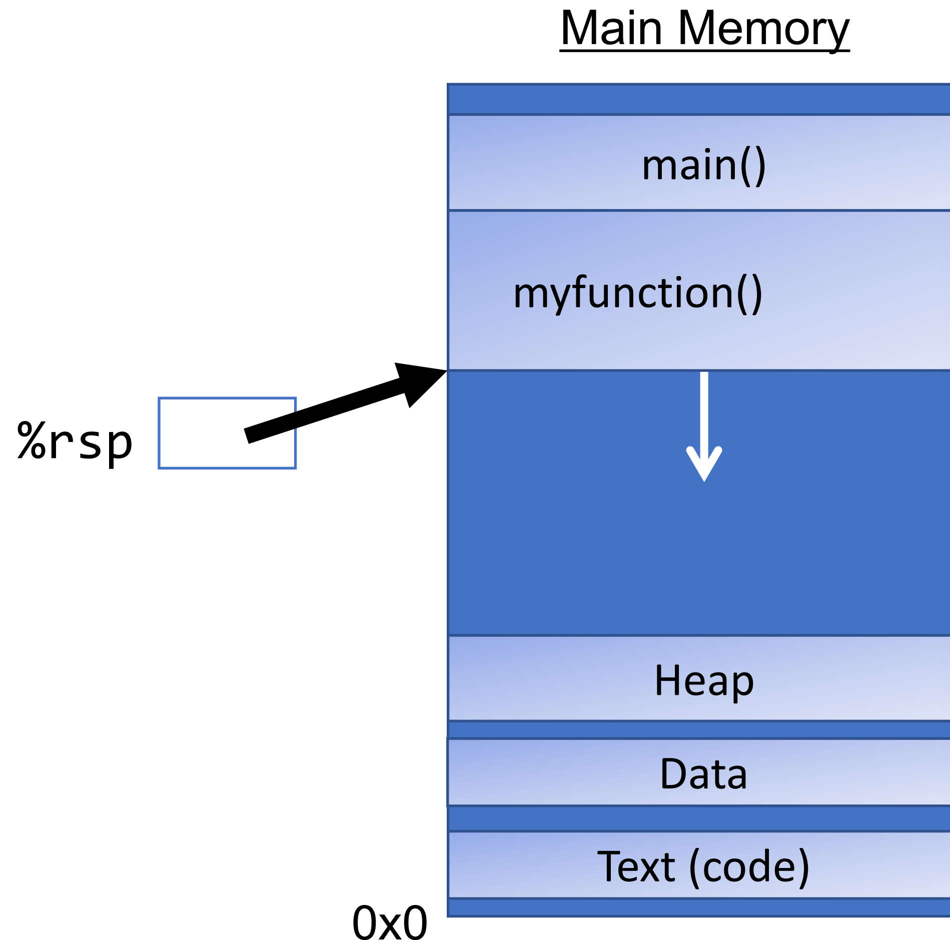

Key idea: %rsp must point to the same place before a function is called and after that function returns, since stack frames go away when a function finishes.

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.

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

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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;`

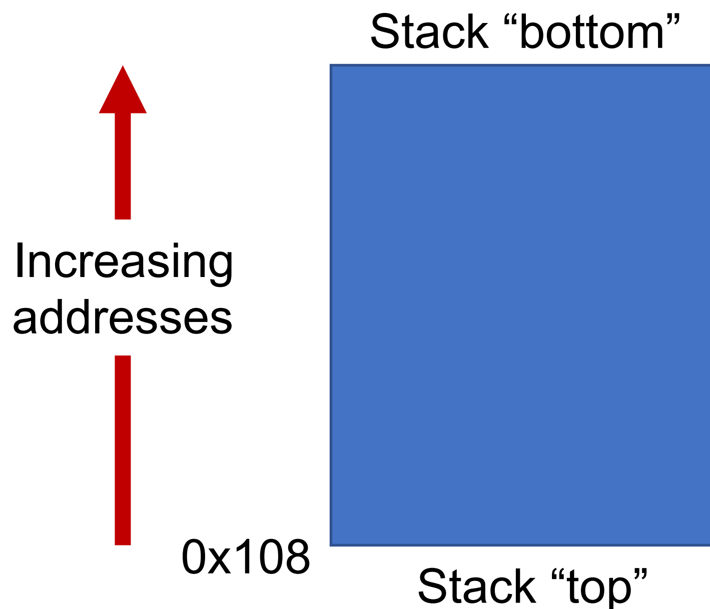
- This behavior is equivalent to the following, but popq is a shorter instruction:

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

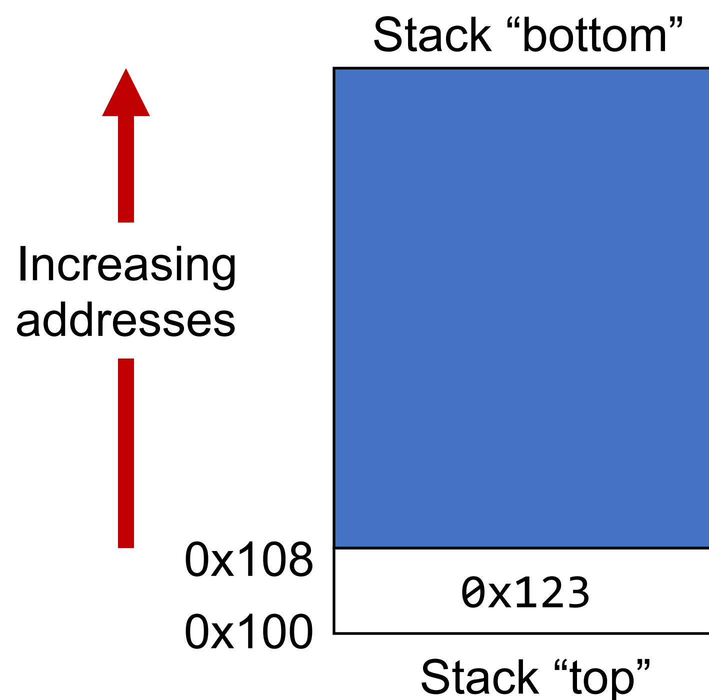
- Sometimes, you'll see instructions just explicitly increment the stack pointer to pop data.

Stack Example

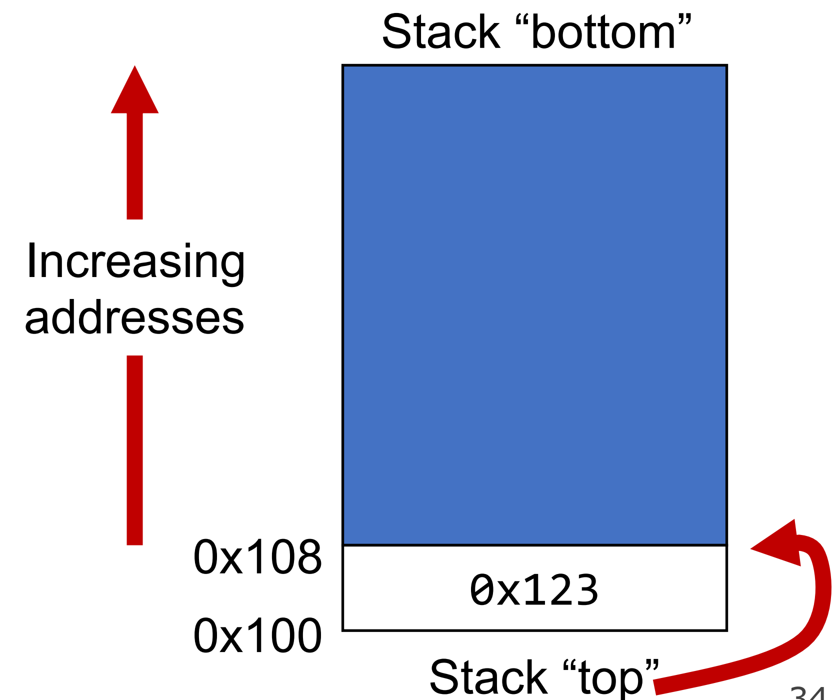
Initially	
%rax	0x123
%rdx	0
%rsp	0x108



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:

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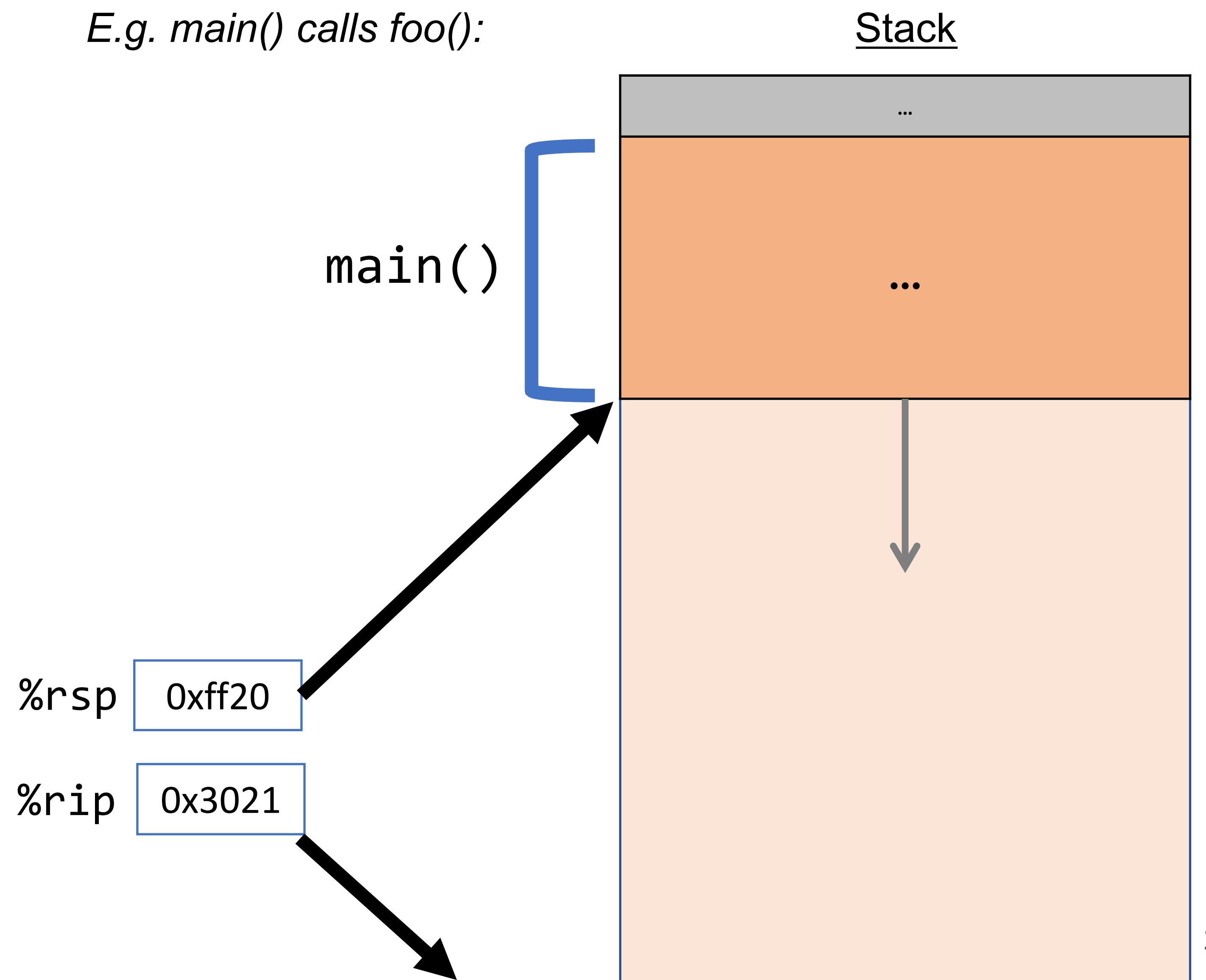
```
cp -r /afs/ir/class/cs107/lecture-code/lect13 .
```

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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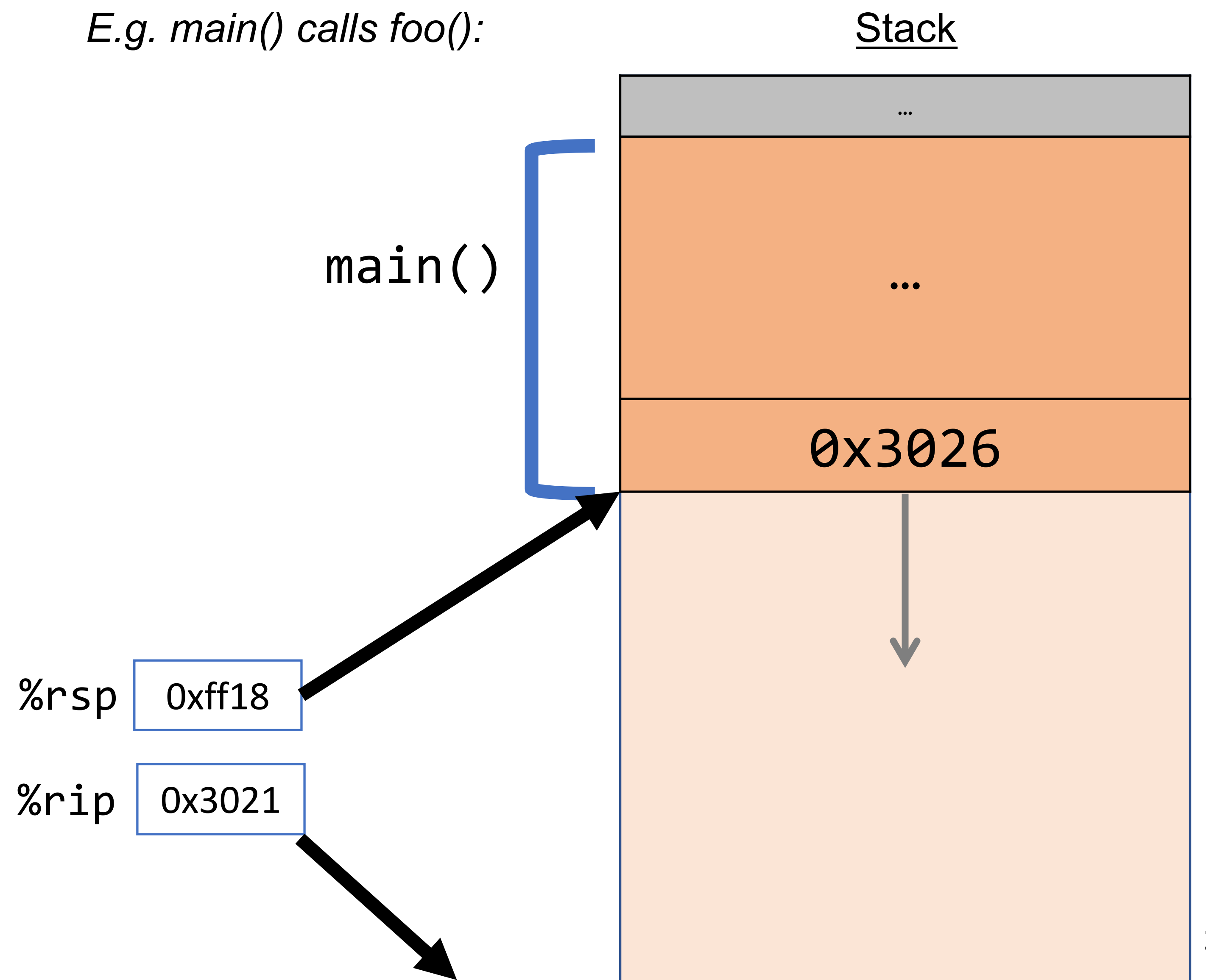

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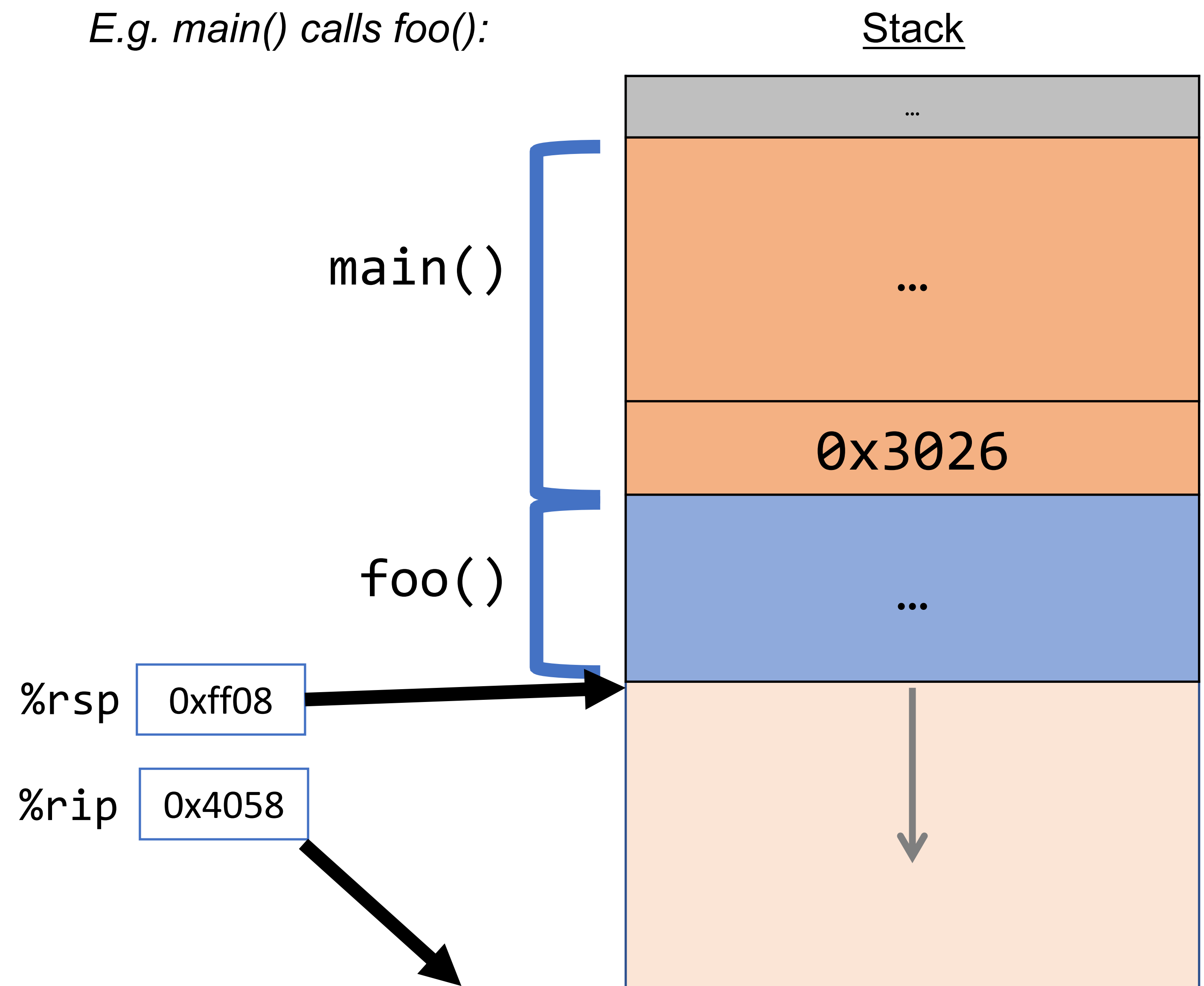

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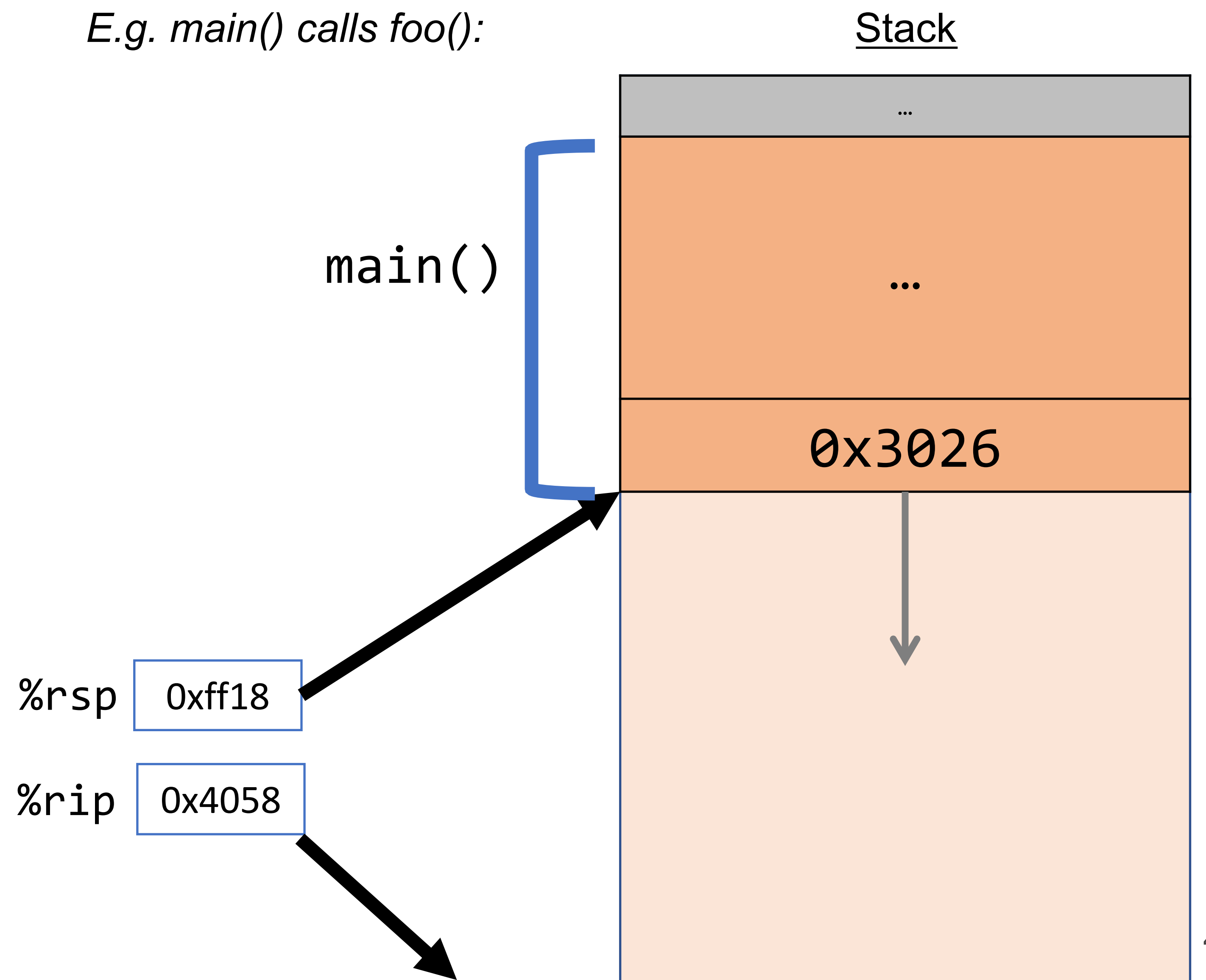

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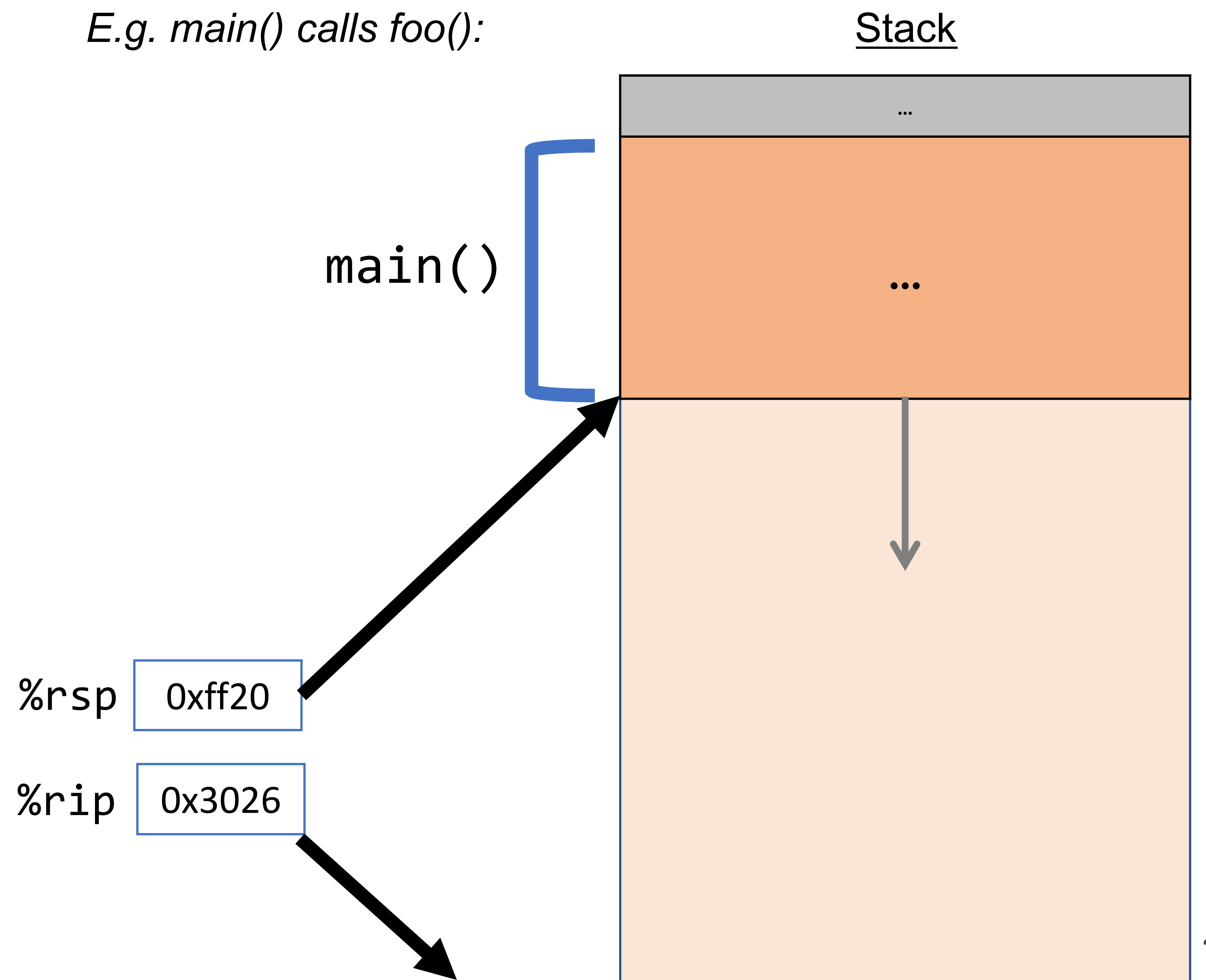

Call And Return

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).

Calling Functions In Assembly

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

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```

Parameters and Return

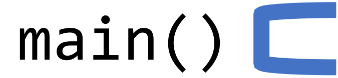
- There are special registers that store parameters and the return value.
- To call a function, we must put any parameters we are passing into the correct registers. (%rdi, %rsi, %rdx, %rcx, %r8, %r9, in that order)
- Parameters beyond the first 6 are put on the stack.
- If the caller expects a return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

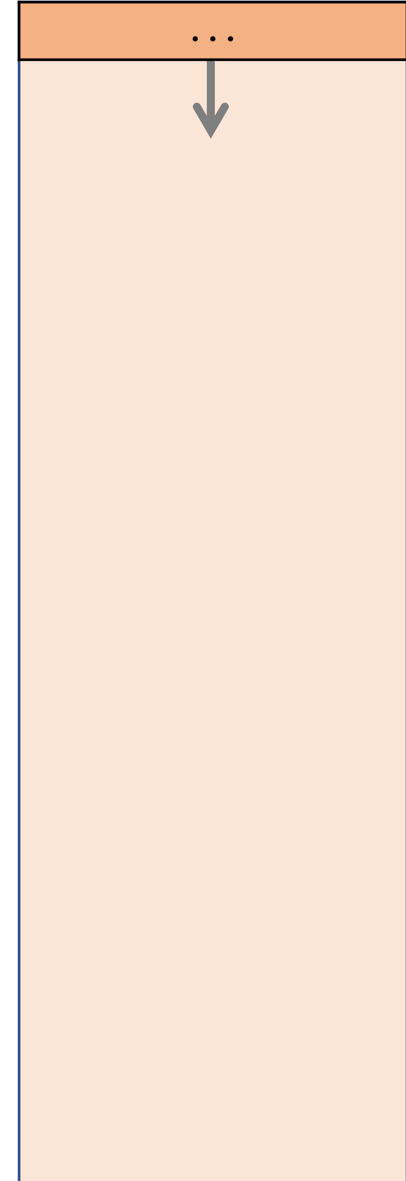
Parameters and Return

```
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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0x400553 <+4>:     movl   $0x1,0xc(%rsp)
0x40055b <+12>:    movl   $0x2,0x8(%rsp)
0x400563 <+20>:    movl   $0x3,0x4(%rsp)
0x40056b <+28>:    movl   $0x4,(%rsp)
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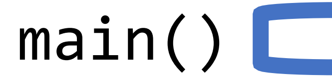

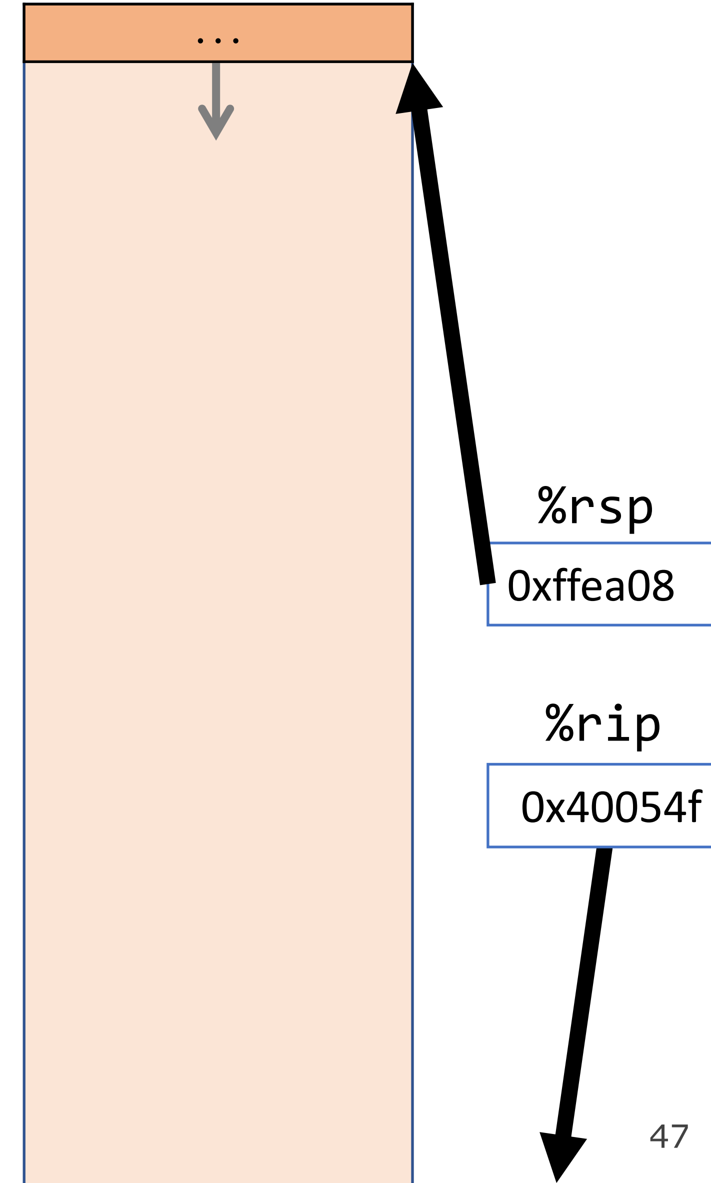

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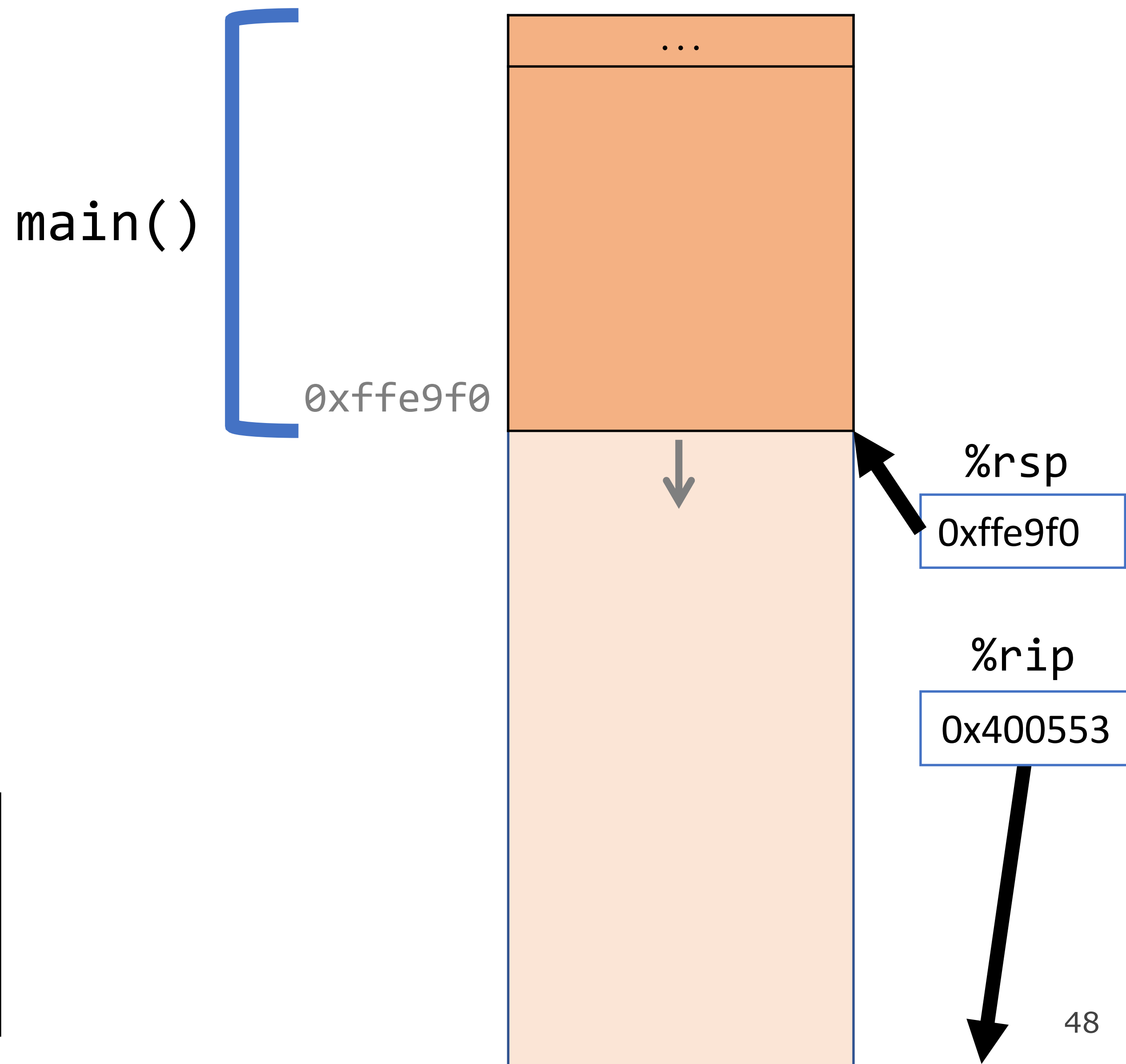

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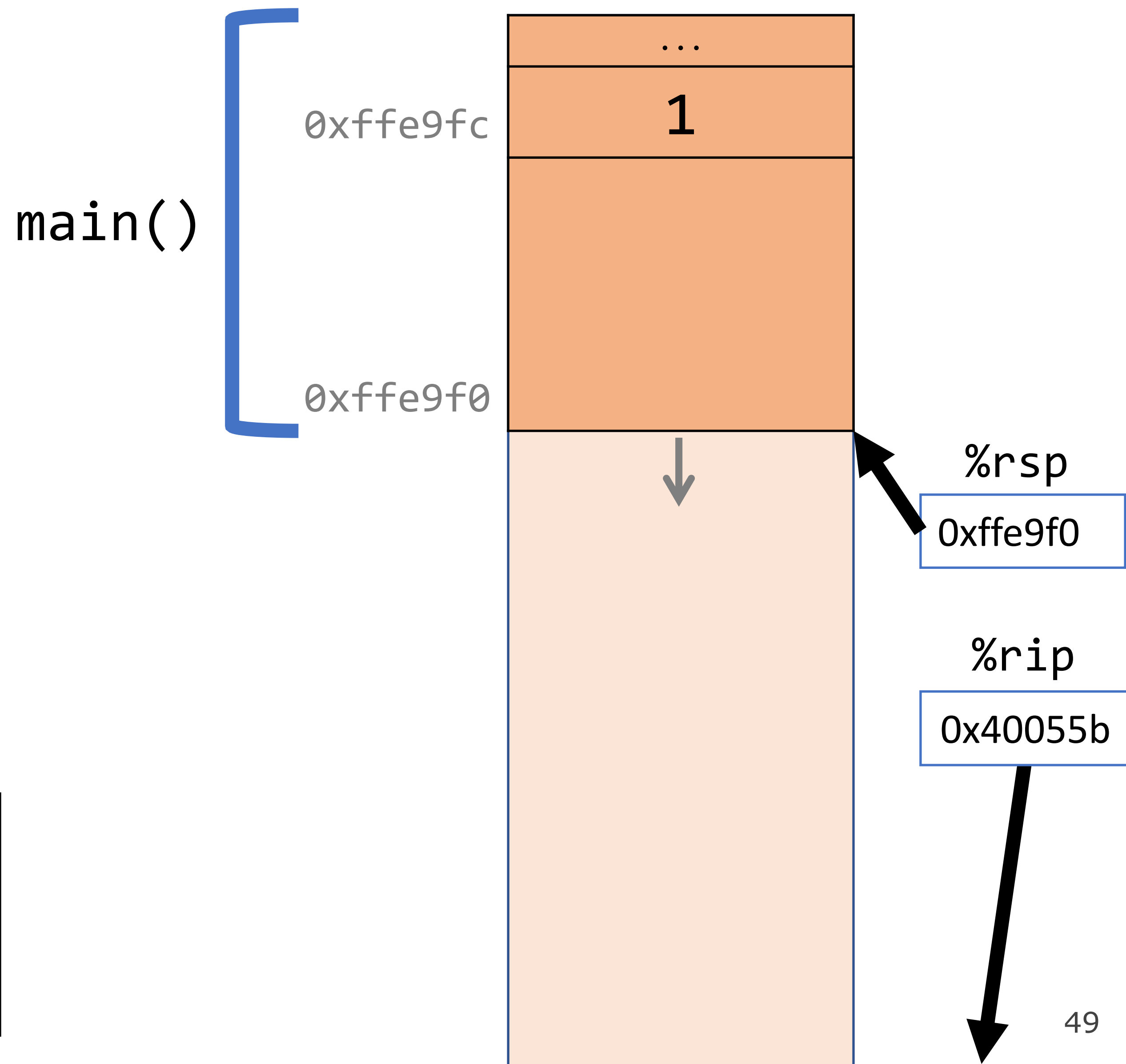
0x400563 <+20>:   movl   $0x3,0x4(%rsp)
0x40056b <+28>:   movl   $0x4,(%rsp)
```



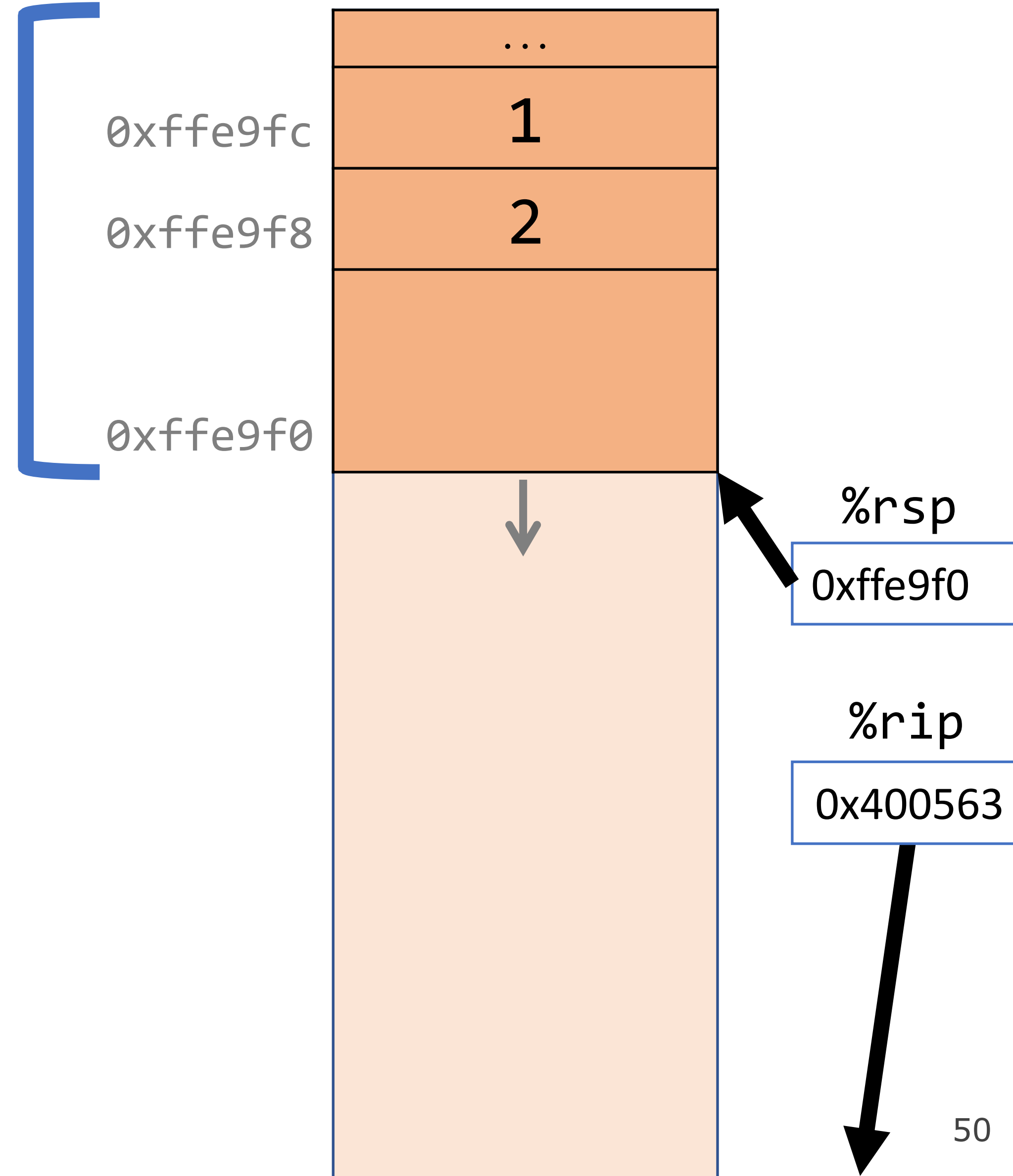
Parameters and Return

```
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) {
    …
}
```

```
0x40054f <+0>:    sub    $0x18,%rsp
0x400553 <+4>:    movl   $0x1,0xc(%rsp)
0x40055b <+12>:   movl   $0x2,0x8(%rsp)
0x400563 <+20>:   movl   $0x3,0x4(%rsp)
0x40056b <+28>:   movl   $0x4,(%rsp)
```

main()



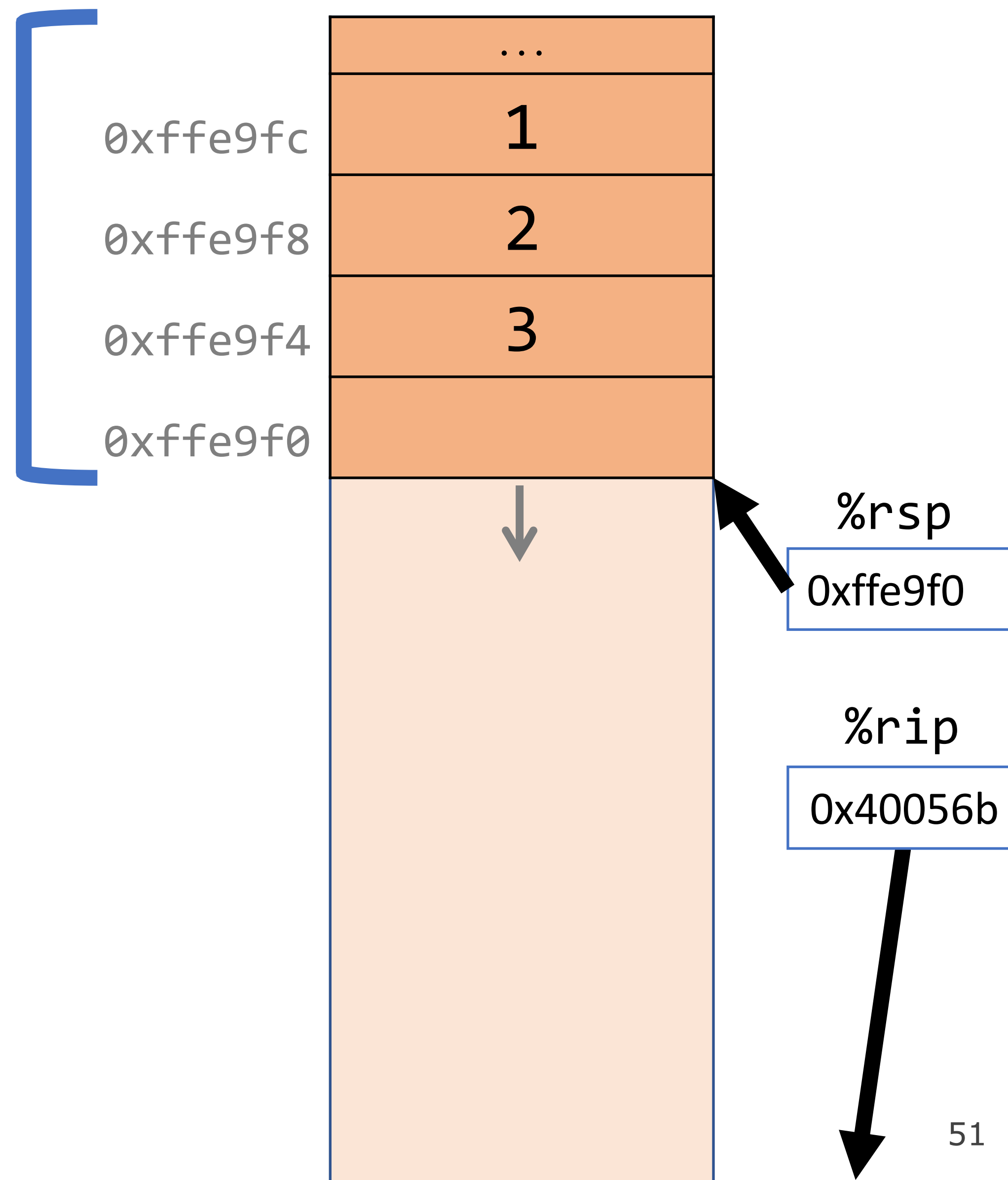
Parameters and Return

```
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) {
    …
}
```

```
0x400553 <+4>:    movl   $0x1,0xc(%rsp)
0x40055b <+12>:   movl   $0x2,0x8(%rsp)
0x400563 <+20>:   movl   $0x3,0x4(%rsp)
0x40056b <+28>:   movl   $0x4,(%rsp)
0x400572 <+35>:   pushq  $0x4
```

main()

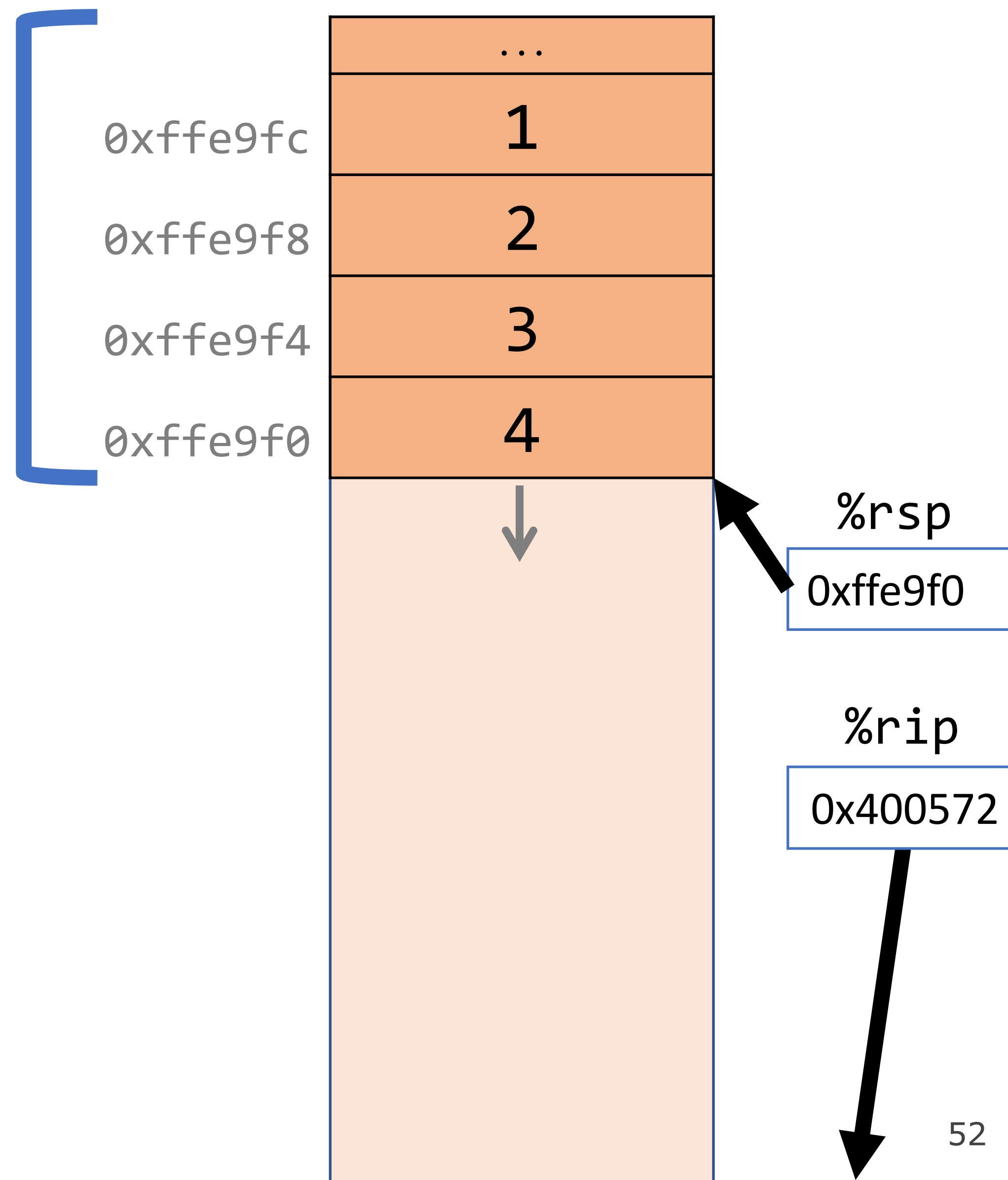


Parameters and Return

```
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) {
    …
}
```

```
0x40055b <+12>:    movl    $0x2,0x8(%rsp)
0x400563 <+20>:    movl    $0x3,0x4(%rsp)
0x40056b <+28>:    movl    $0x4,(%rsp)
0x400572 <+35>:    pushq   $0x4
0x400574 <+37>:    pushq   $0x3
```



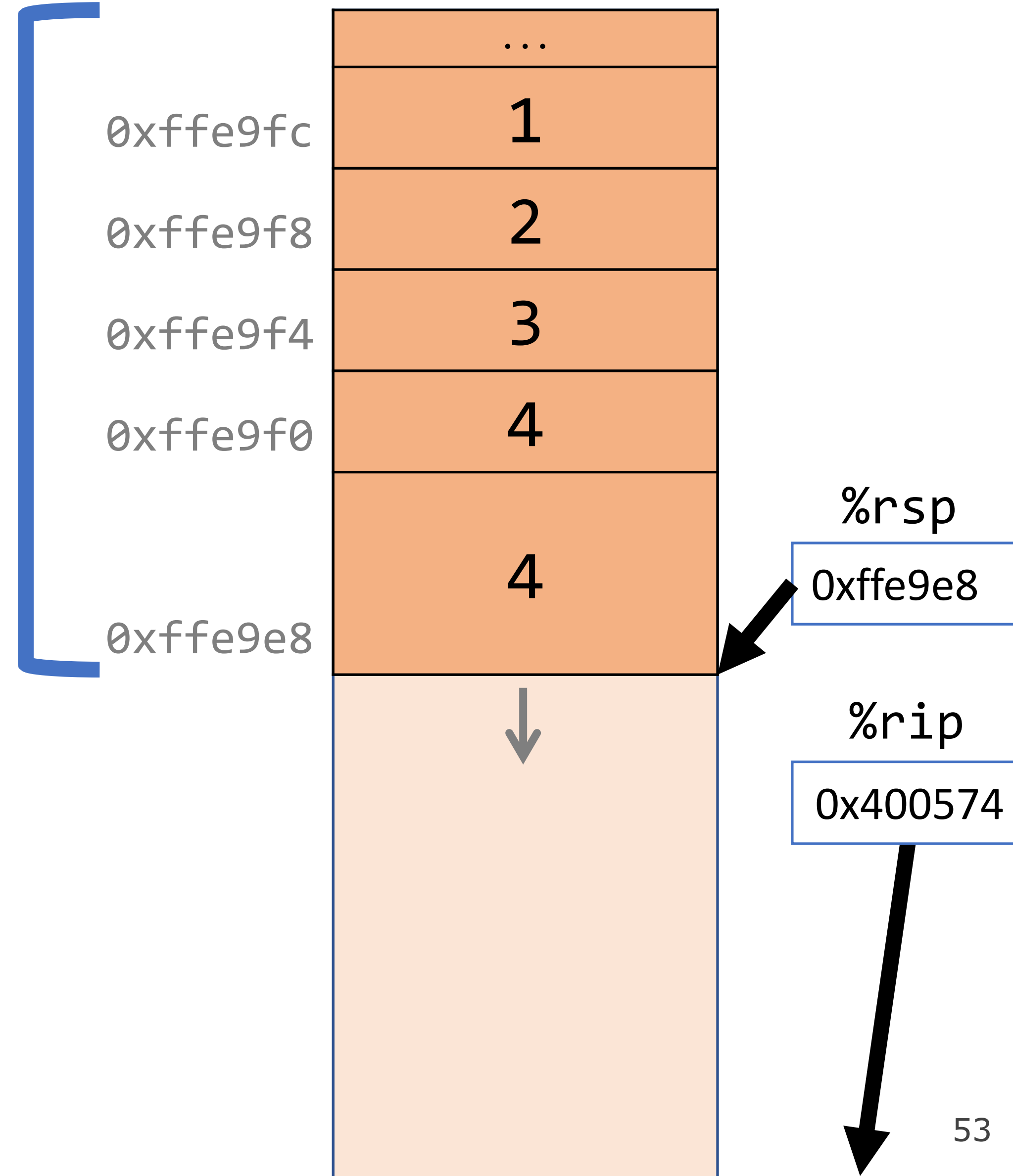
Parameters and Return

```
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) {
    …
}
```

```
0x400563 <+20>:    movl   $0x3,0x4(%rsp)
0x40056b <+28>:    movl   $0x4,(%rsp)
0x400572 <+35>:    pushq  $0x4
0x400574 <+37>:    pushq  $0x3
0x400576 <+39>:    mov    $0x2,%r9d
```

main()

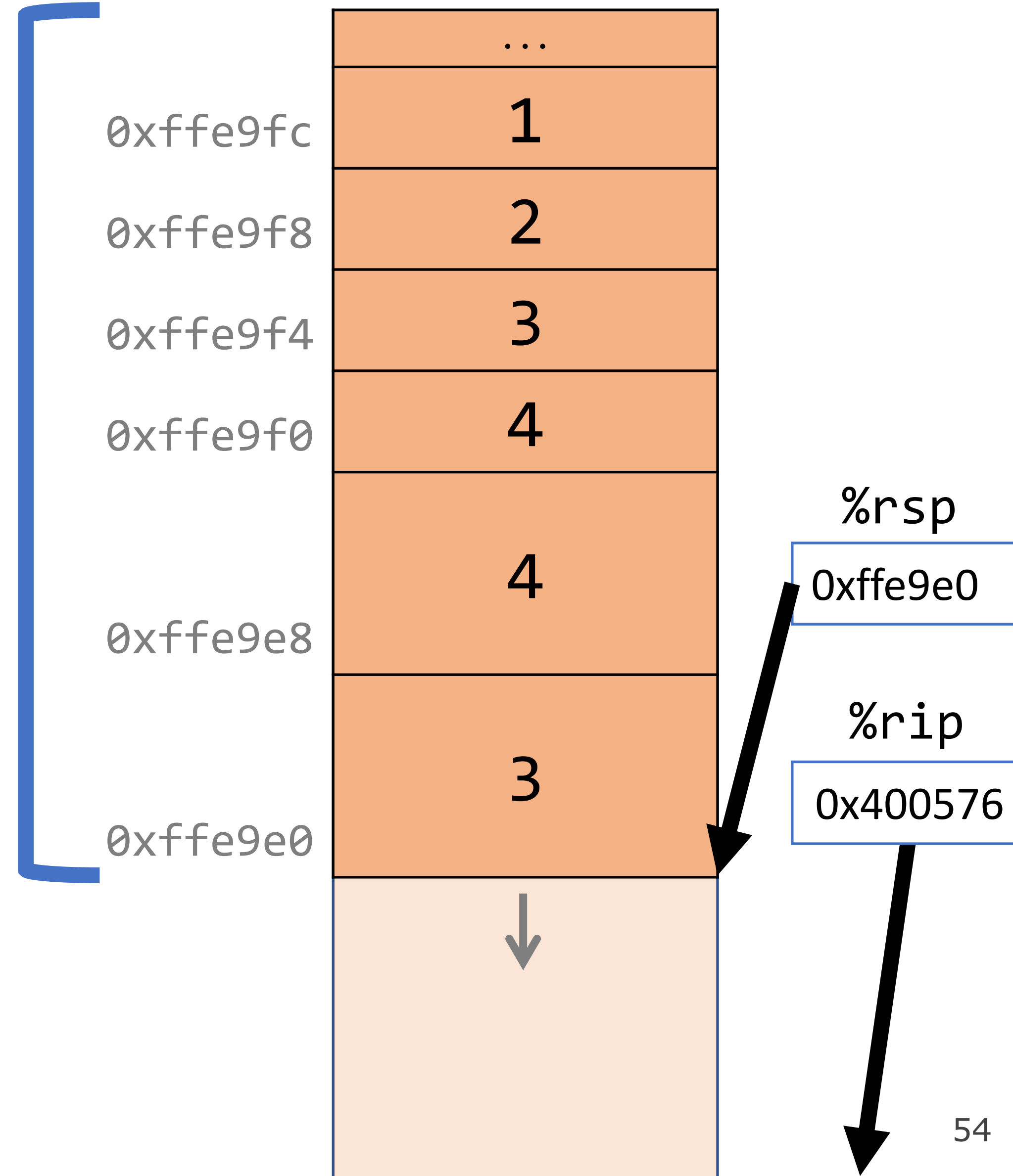


Parameters and Return

```
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) {
    …
}
```

```
0x40056b <+28>:    movl    $0x4,(%rsp)
0x400572 <+35>:    pushq   $0x4
0x400574 <+37>:    pushq   $0x3
0x400576 <+39>:    mov     $0x2,%r9d
0x40057c <+45>:    mov     $0x1,%r8d
```

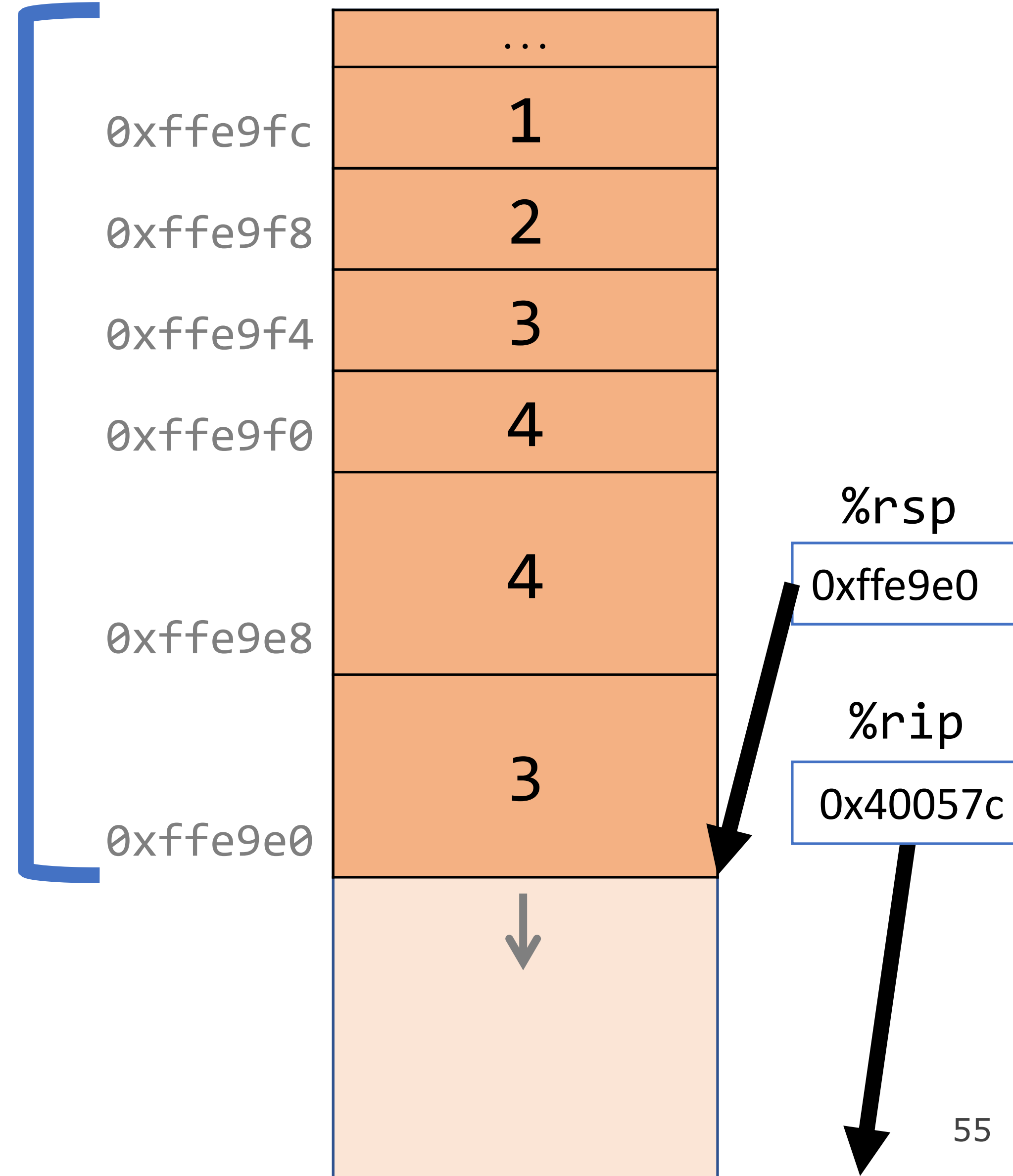


Parameters and Return

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

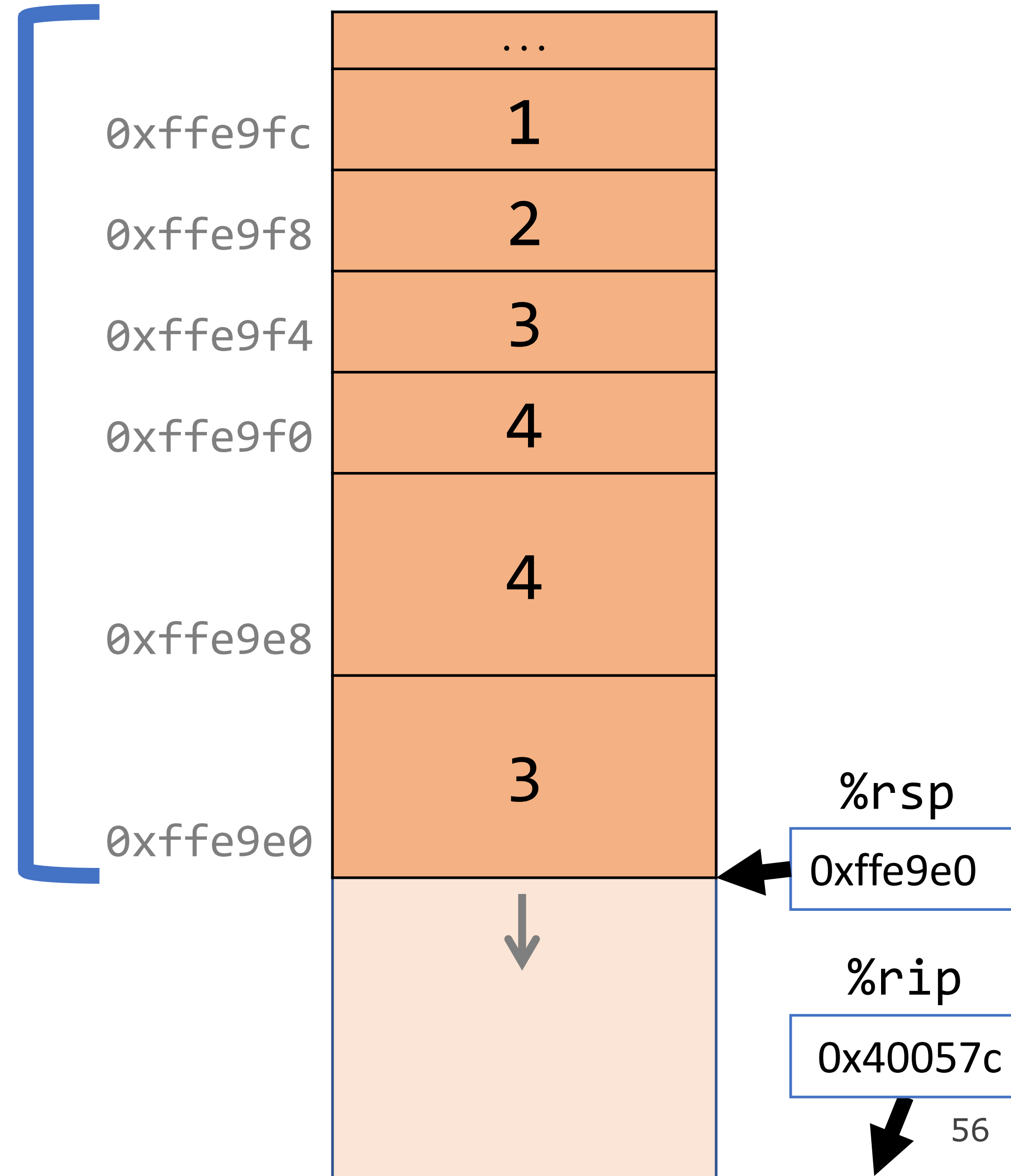


Parameters and Return

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



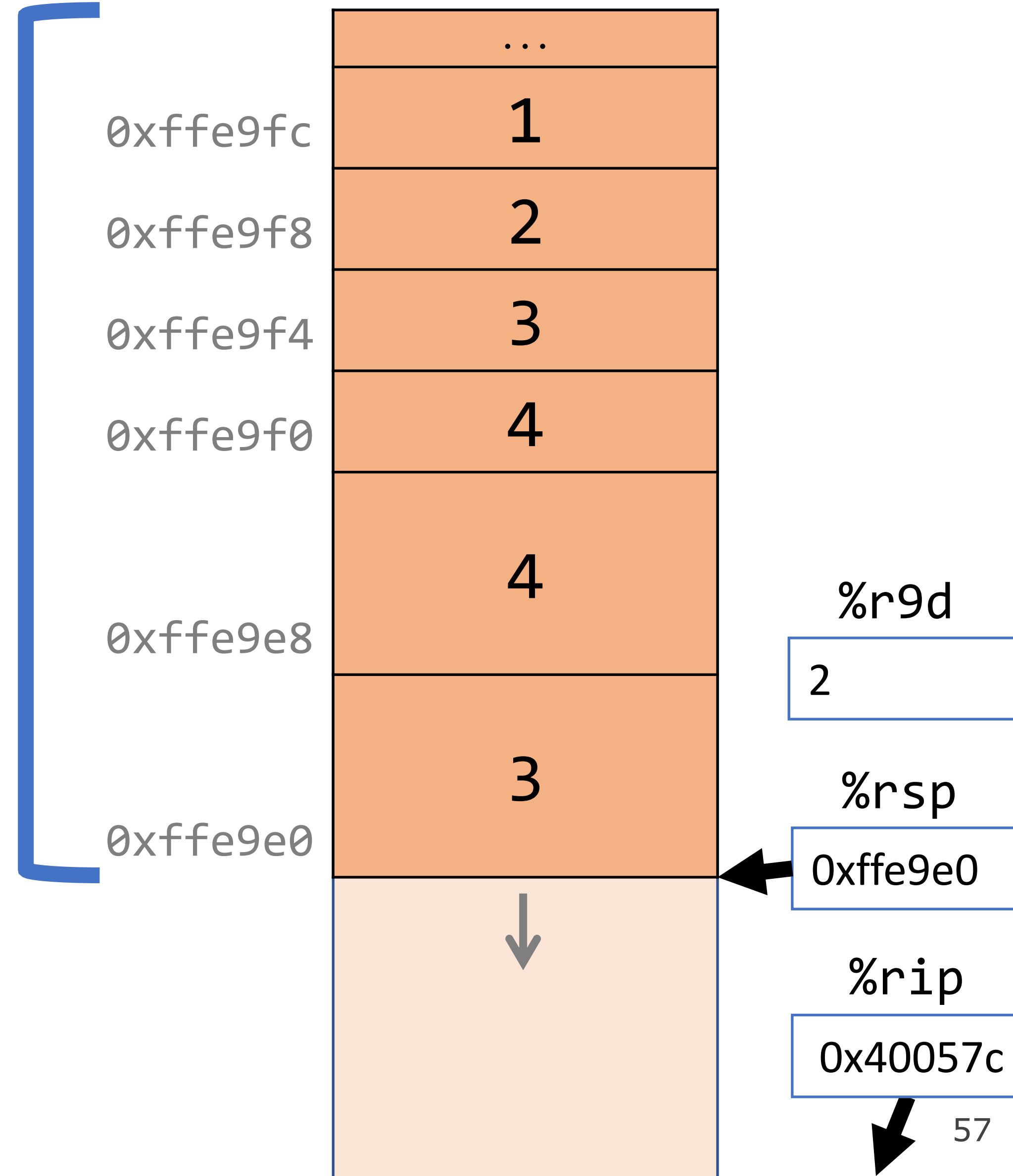
Parameters and Return

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

main()

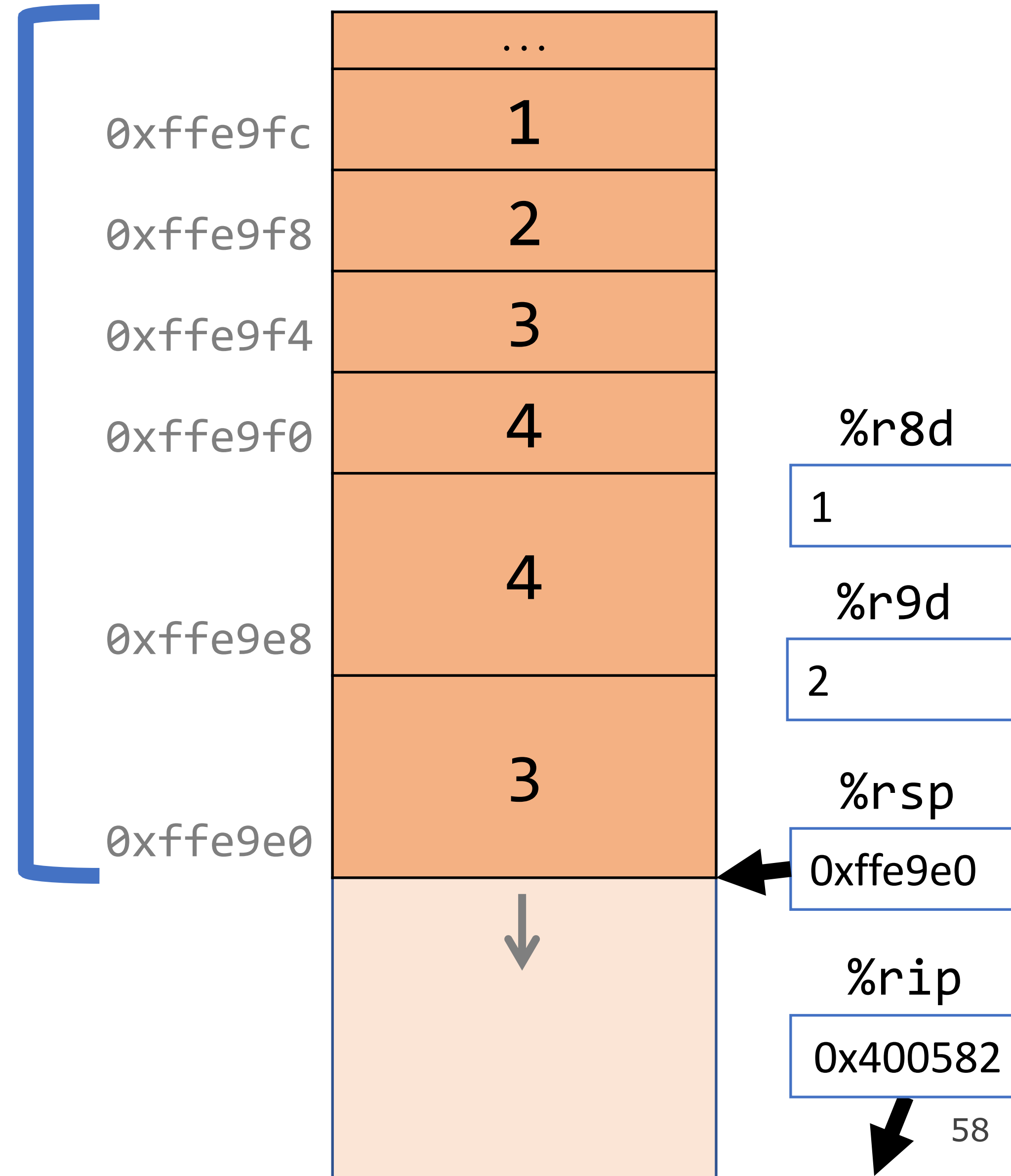


Parameters and Return

```
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) {
    …
}
```

```
0x400574 <+37>:    pushq   $0x3
0x400576 <+39>:    mov     $0x2,%r9d
0x40057c <+45>:    mov     $0x1,%r8d
0x400582 <+51>:    lea     0x10(%rsp),%rcx
0x400587 <+56>:    lea     0x14(%rsp),%rdx
```



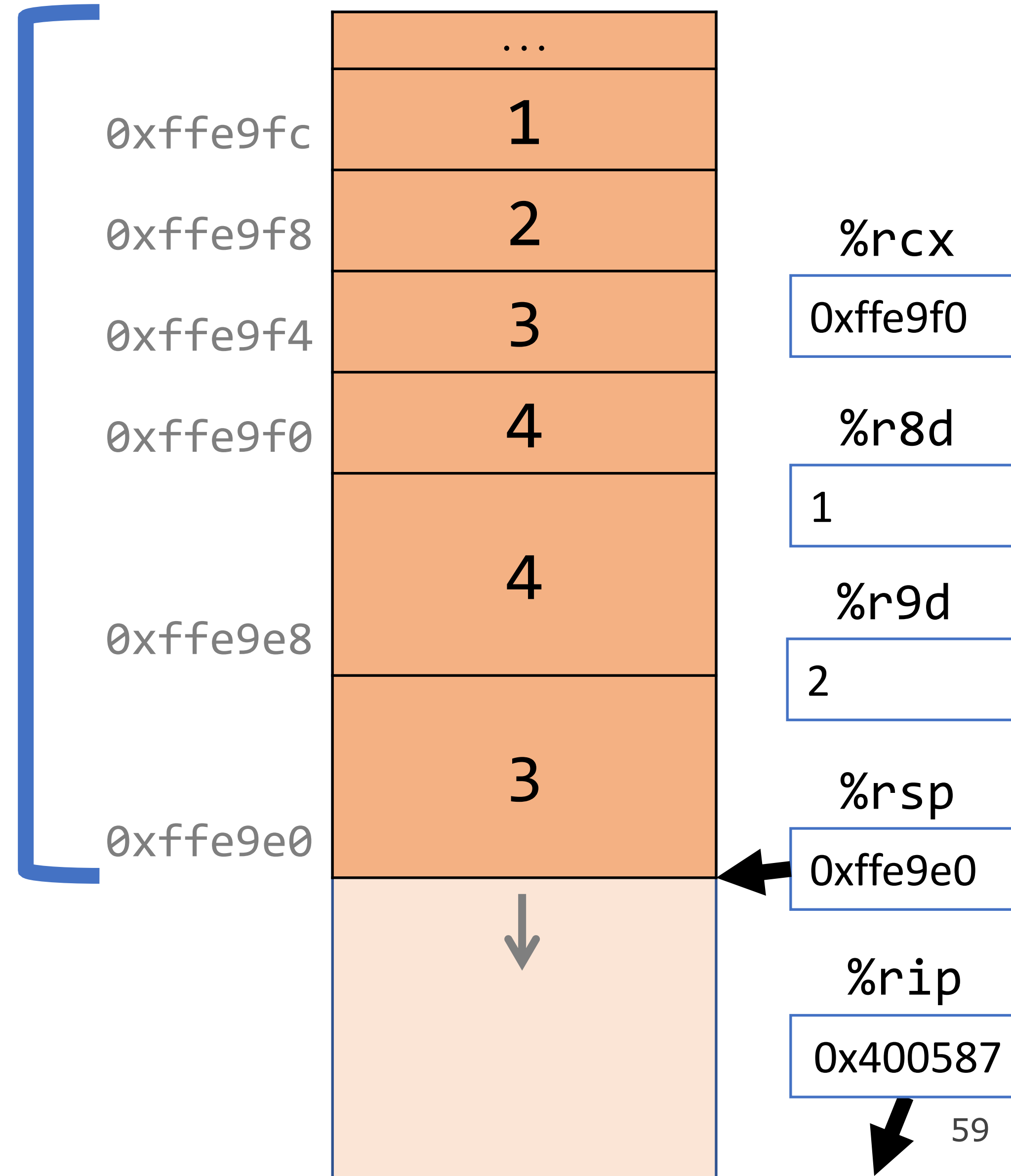
Parameters and Return

```
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) {
    …
}
```

```
0x400576 <+39>:    mov     $0x2,%r9d
0x40057c <+45>:    mov     $0x1,%r8d
0x400582 <+51>:    lea     0x10(%rsp),%rcx
0x400587 <+56>:    lea     0x14(%rsp),%rdx
0x40058c <+61>:    lea     0x18(%rsp),%rsi
```

main()



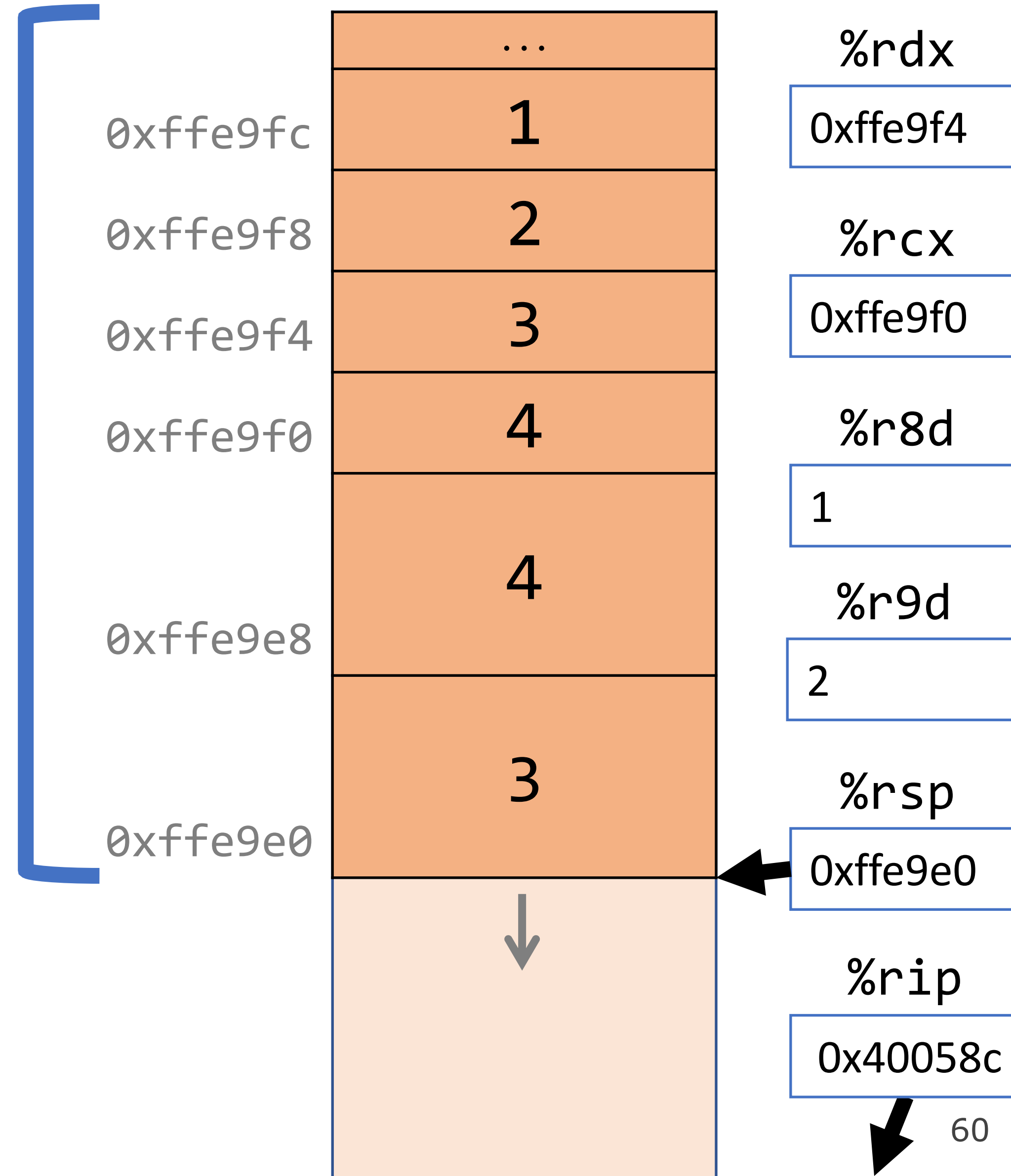
Parameters and Return

```
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) {
    …
}
```

```
0x40057c <+45>:   mov    $0x1,%r8d
0x400582 <+51>:   lea    0x10(%rsp),%rcx
0x400587 <+56>:   lea    0x14(%rsp),%rdx
0x40058c <+61>:   lea    0x18(%rsp),%rsi
0x400591 <+66>:   lea    0x1c(%rsp),%rdi
```

main()



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);
    …
}

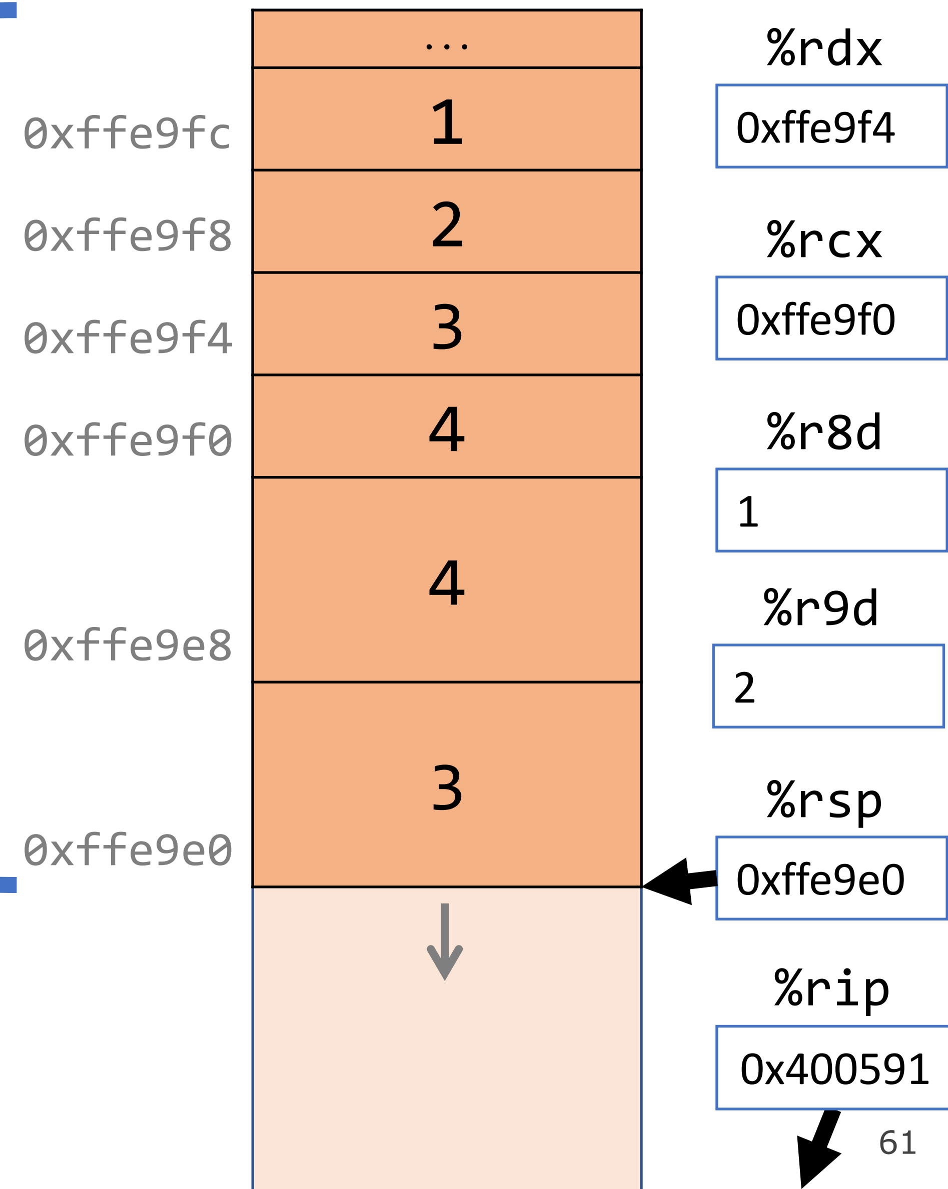
int func(int *p1, int *p2, int *p3, int *p4,
         int v1, int v2, int v3, int v4) {
    …
}
```

```
0x400582 <+51>:    lea    0x10(%rsp),%rcx
0x400587 <+56>:    lea    0x14(%rsp),%rdx
0x40058c <+61>:    lea    0x18(%rsp),%rsi
0x400591 <+66>:    lea    0x1c(%rsp),%rdi
0x400596 <+71>:    callq  0x400546 <func>
```

main()

%rsi

0xffe9f8

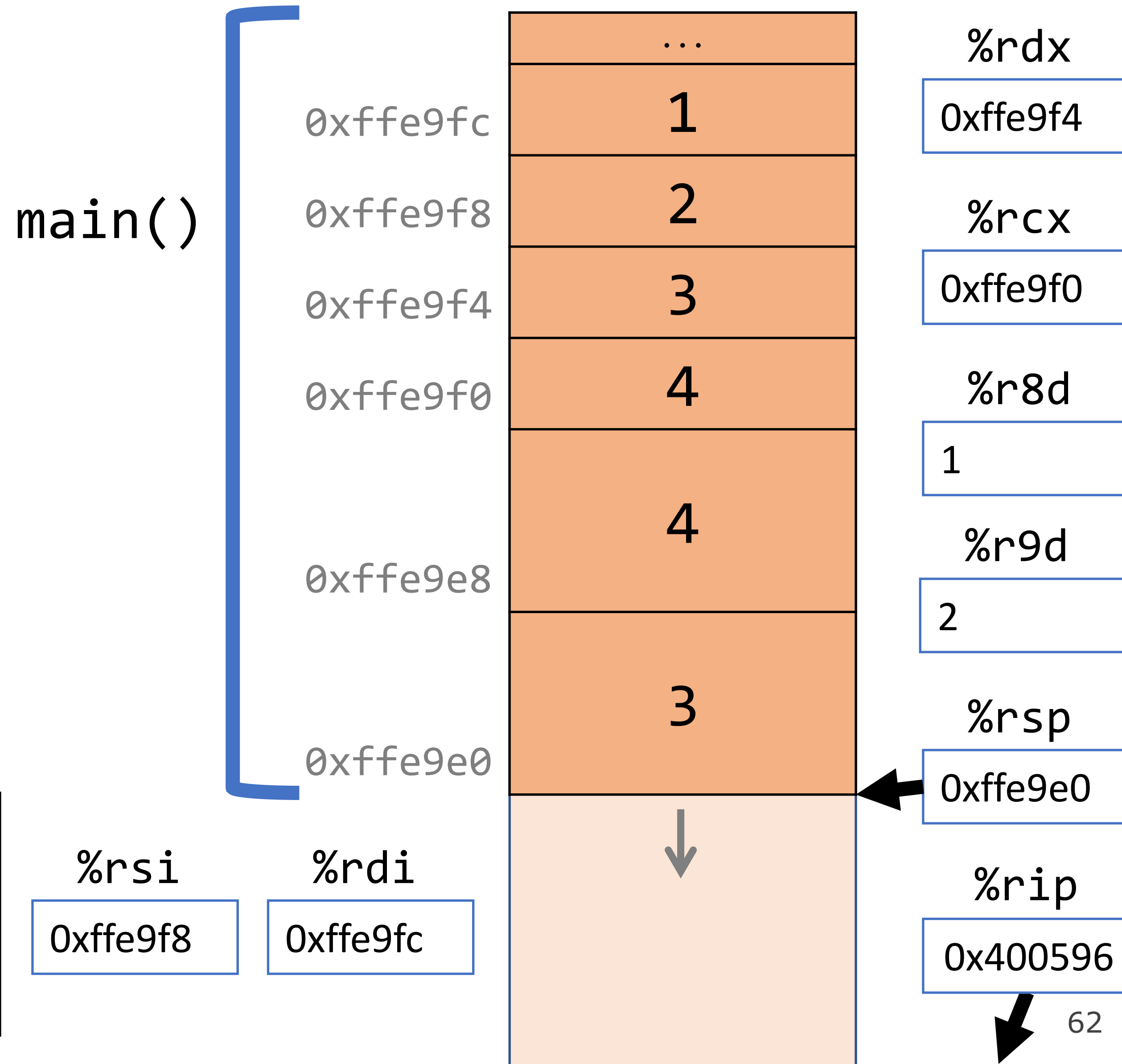


Parameters and Return

```
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) {
    …
}
```

```
0x400587 <+56>:    lea    0x14(%rsp),%rdx
0x40058c <+61>:    lea    0x18(%rsp),%rsi
0x400591 <+66>:    lea    0x1c(%rsp),%rdi
0x400596 <+71>:    callq  0x400546 <func>
0x40059b <+76>:    add    $0x10,%rsp
```

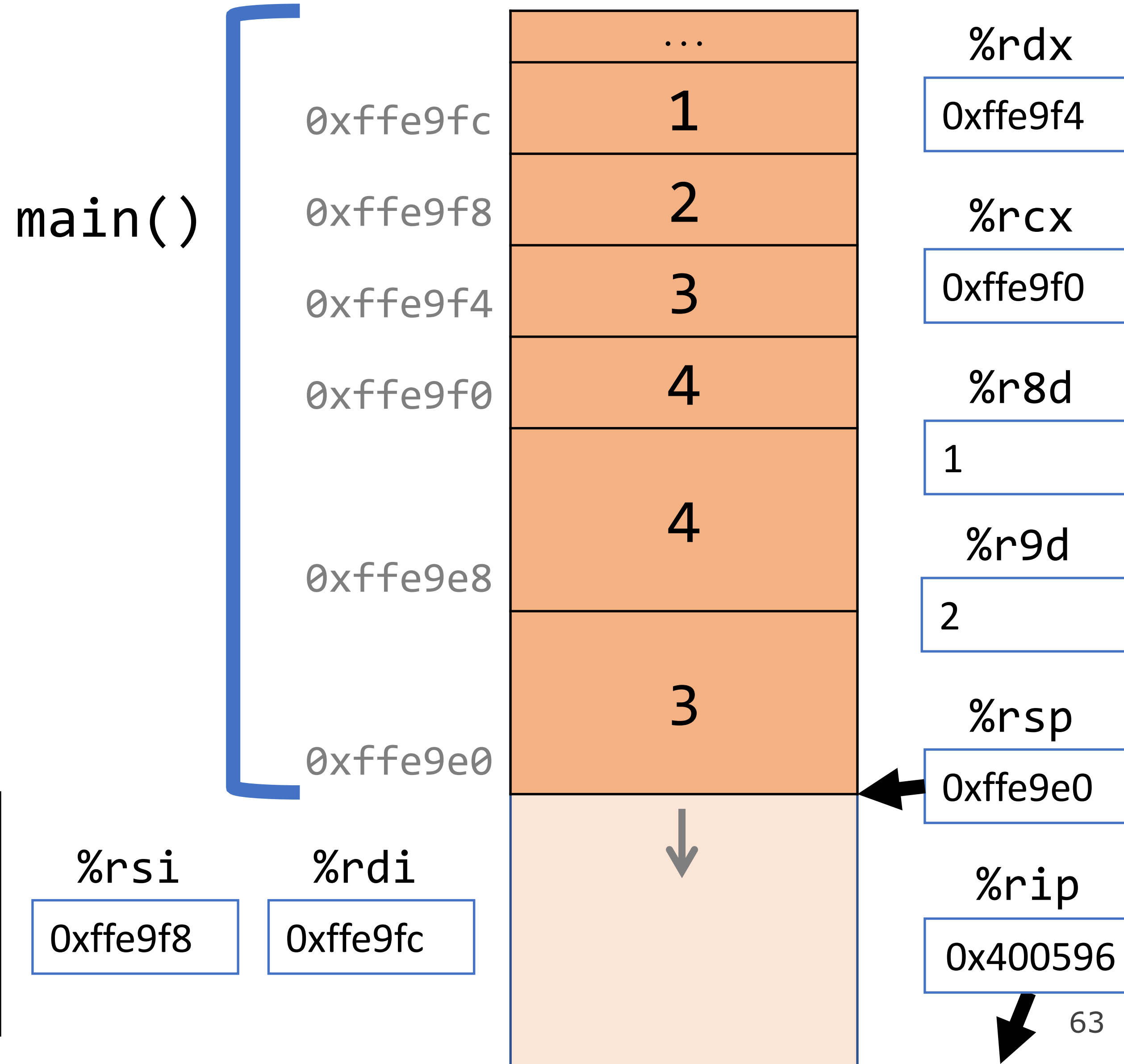


Parameters and Return

```
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) {
    …
}
```

```
0x40058c <+61>:    lea    0x18(%rsp),%rsi
0x400591 <+66>:    lea    0x1c(%rsp),%rdi
0x400596 <+71>:    callq  0x400546 <func>
0x40059b <+76>:    add    $0x10,%rsp
…
```

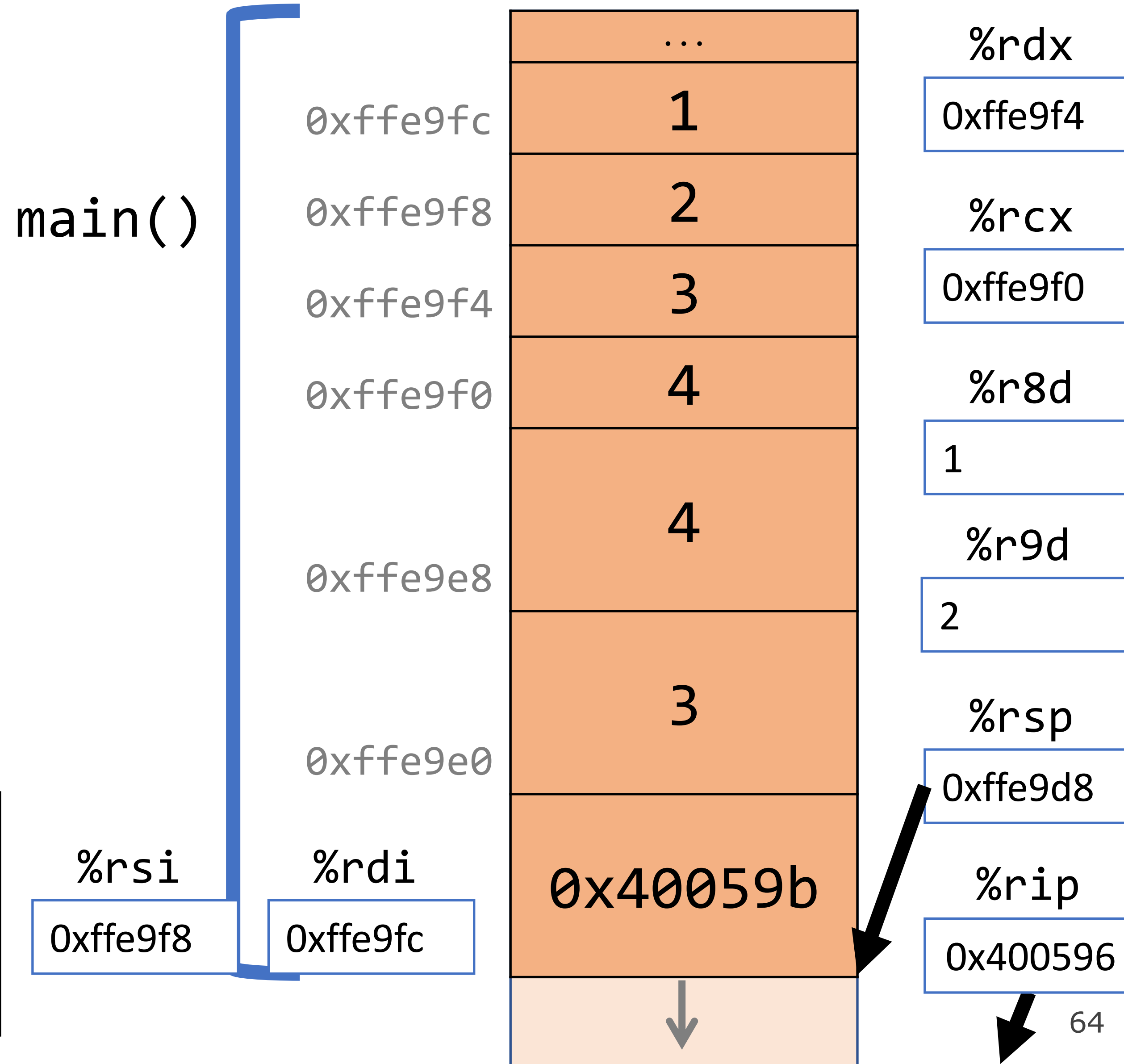


Parameters and Return

```
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) {
    …
}
```

```
0x40058c <+61>:    lea    0x18(%rsp),%rsi
0x400591 <+66>:    lea    0x1c(%rsp),%rdi
0x400596 <+71>:    callq  0x400546 <func>
0x40059b <+76>:    add    $0x10,%rsp
…
```



Lecture Plan

- Revisiting %rip 5
- **Calling Functions 19**
  - The Stack 22
  - Passing Control 36
  - Passing Data 44
  - **Local Storage 65**
- Register Restrictions 69
- Pulling it all together: recursion example 78
- Optimizations 81
- Live session slides 93


```
cp -r /afs/ir/class/cs107/lecture-code/lect13 .
```

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 $0x10, %rsp        // 16 bytes for stack frame
    movq $0x216, (%rsp)     // store 534 in arg1
    movq $0x421, 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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```
cp -r /afs/ir/class/cs107/lecture-code/lect13 .
```

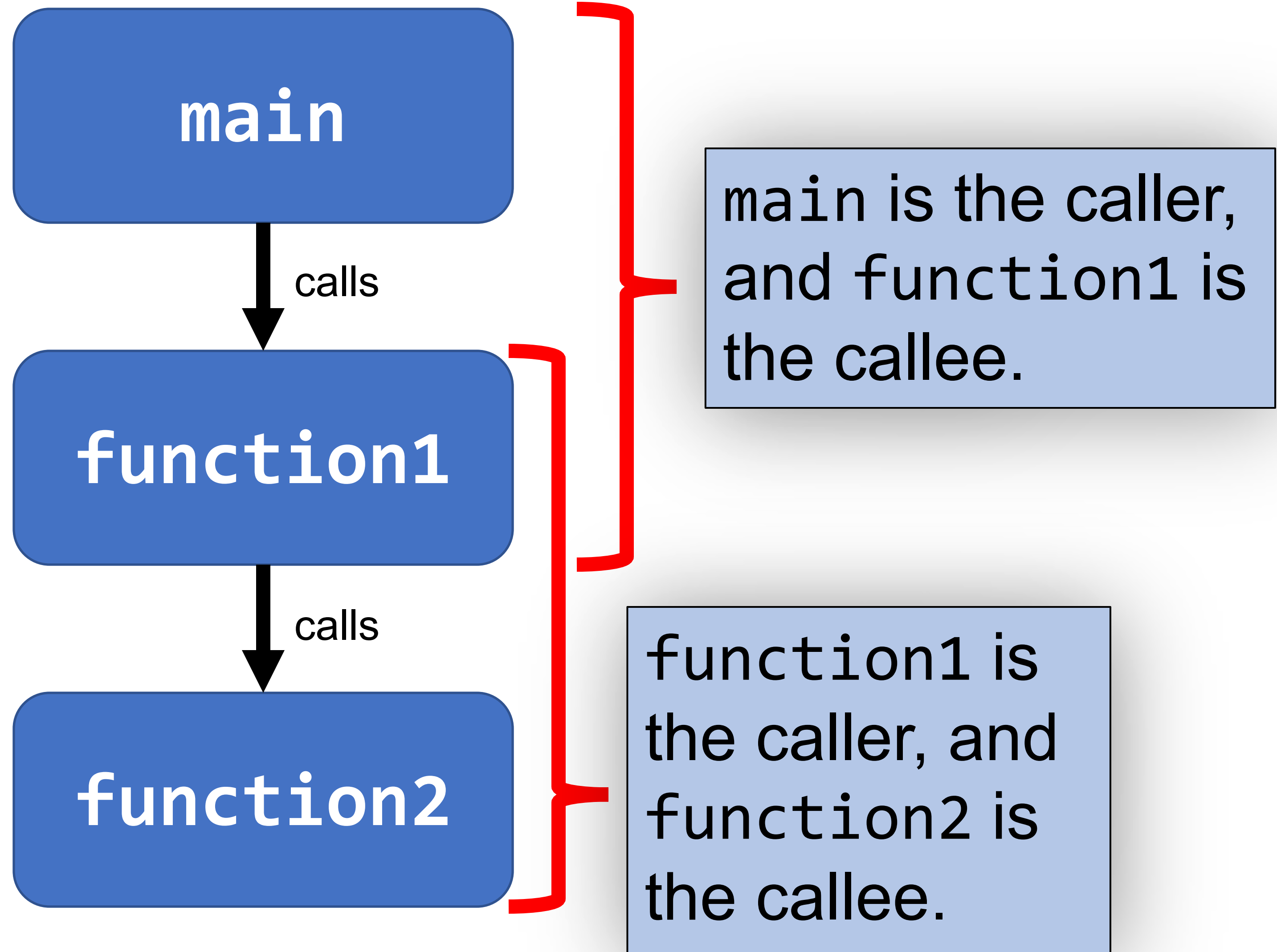
Register Restrictions

There is only one copy of registers for all programs and functions.

- **Problem:** what if ***funcA*** is building up a value in register %r10, and calls ***funcB*** in the middle, which also has instructions that modify %r10? ***funcA***'s value will be overwritten!
- **Solution:** make some "rules of the road" that callers and callees must follow when using registers so they do not interfere with one another.
- These rules define 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

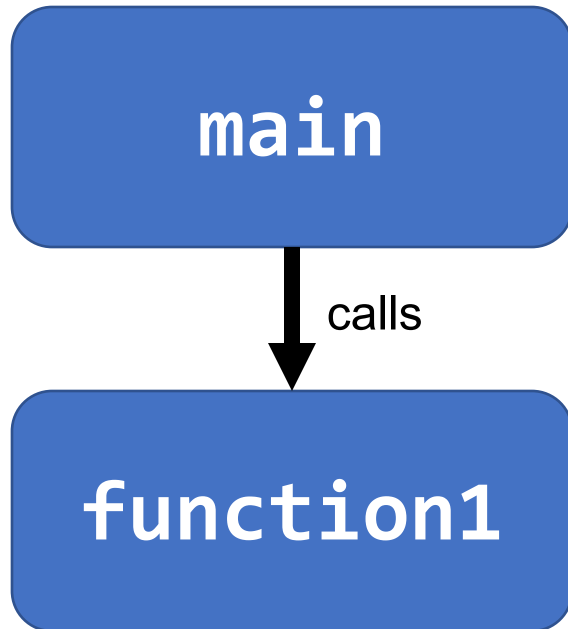
Caller-Owned

- 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.

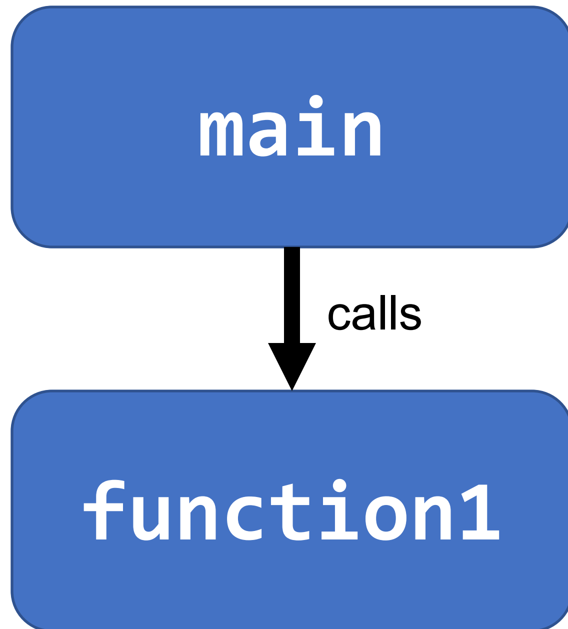
Caller-Owned Registers



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

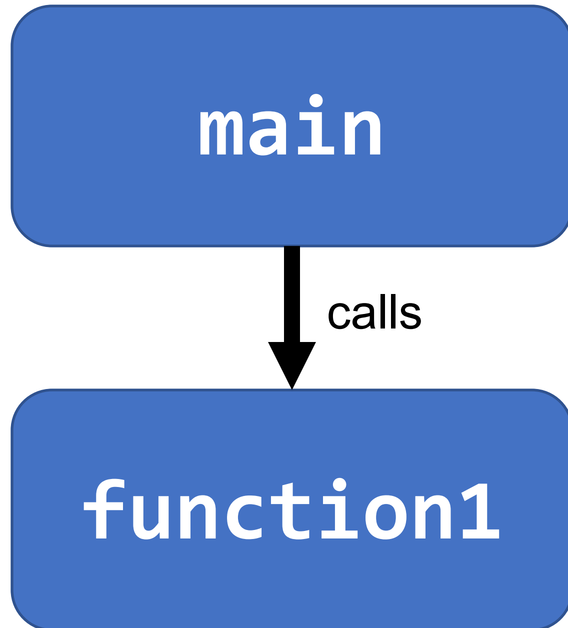
If function1 wants to use any caller-owned registers, it must save the existing values and restore them before returning.

Caller-Owned Registers




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

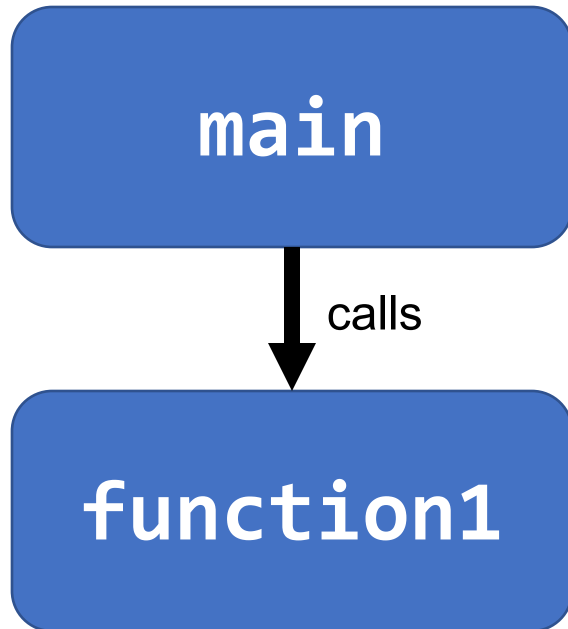
Callee-Owned Registers



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

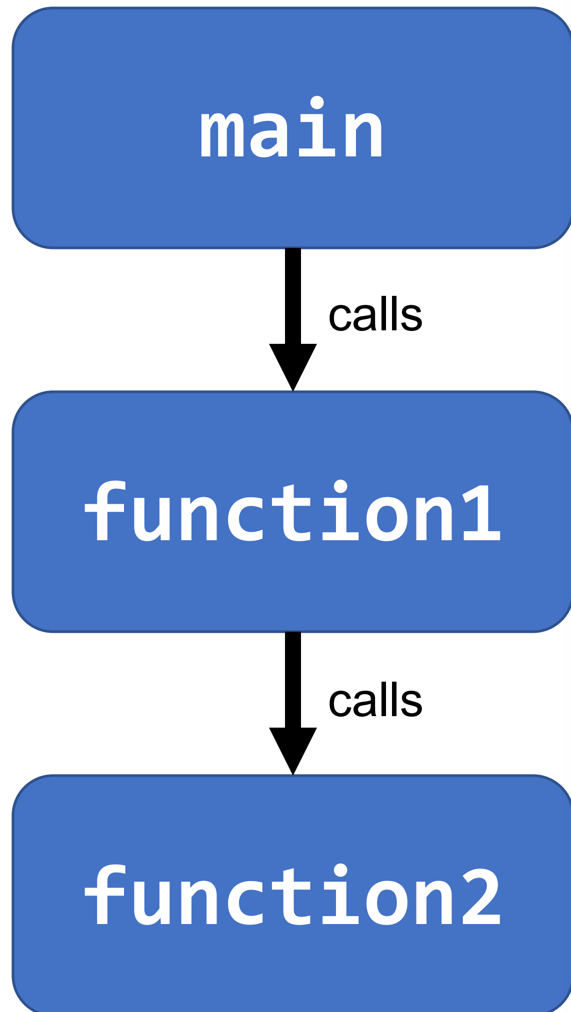
If function1 wants to use any callee-owned registers, it can do so without saving the existing values.

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 it wants to use.
- **`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 it wants to use.
- calling **`function2`** may permanently change their values.

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```
cp -r /afs/ir/class/cs107/lecture-code/lect13 .
```

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`

Our First Assembly

```
int sum_array(int arr[], int nelems) {
   int sum = 0;
   for (int i = 0; i < nelems; i++) {
      sum += arr[i];
   }
   return sum;
}
```

We’re done with all our assembly lectures! Now we can fully understand what’s going on in the assembly below, including how someone would call sum_array in assembly and what the **ret** instruction does.

```
00000000004005b6 <sum_array>:
  4005b6:    ba 00 00 00 00        mov    $0x0,%edx
  4005bb:    b8 00 00 00 00        mov    $0x0,%eax
  4005c0:    eb 09                 jmp    4005cb <sum_array+0x15>
  4005c2:    48 63 ca              movslq %edx,%rcx
  4005c5:    03 04 8f              add    (%rdi,%rcx,4),%eax
  4005c8:    83 c2 01              add    $0x1,%edx
  4005cb:    39 f2                 cmp    %esi,%edx
  4005cd:    7c f3                 jl     4005c2 <sum_array+0xc>
  4005cf:    f3 c3                 repz retq
```

Lecture Plan

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```
cp -r /afs/ir/class/cs107/lecture-code/lect13 .
```

Optimizations you'll see

`nop`

- **`nop/nopl`** are "no-op" instructions – they do nothing!
- Intent: Make functions align on address boundaries that are nice multiples of 8.
- "Sometimes, doing nothing is how to be most productive" – Philosopher Nick

`mov %ebx,%ebx`

- Zeros out the top 32 register bits (because a `mov` on an `e`-register zeros out rest of 64 bits).

`xor %ebx,%ebx`

- Optimizes for performance as well as code size (read more here):

```
b8 00 00 00 00          mov $0x0,%eax
31 c0                   xor %eax,%eax
```

GCC For Loop Output

GCC For Loop Output

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

Possible Alternative?

```
Initialization
Test
Jump past loop if fails
Body
Update
Jump to test
```

GCC For Loop Output

GCC For Loop Output

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

```
for (int i = 0; i < n; i++)          // n = 100
```

GCC For Loop Output

GCC For Loop Output

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

```
for (int i = 0; i < n; i++)          // n = 100

Initialization
Jump to test
Test
Jump to body
Body
Update
Test
Jump to body
Body
Update
Test
Jump to body
...
```

GCC For Loop Output

GCC For Loop Output

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

```
for (int i = 0; i < n; i++)          // n = 100

Initialization
Jump to test
Test
Jump to body
Body
Update
Test
Jump to body
Body
Update
Test
Jump to body
...
```

GCC For Loop Output

```
for (int i = 0; i < n; i++)          // n = 100

Initialization
Test
No jump
Body
Update
Jump to test
Test
No jump
Body
Update
Jump to test
...
```

Possible Alternative?

```
Initialization
Test
Jump past loop if fails
Body
Update
Jump to test
```

GCC For Loop Output

```
for (int i = 0; i < n; i++)          // n = 100

Initialization
Test
No jump
Body
Update
Jump to test
Test
No jump
Body
Update
Jump to test
...
```

Possible Alternative?

```
Initialization
Test
Jump past loop if fails
Body
Update
Jump to test
```

GCC For Loop Output

GCC For Loop Output

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

Possible Alternative?

```
Initialization
Test
Jump past loop if fails
Body
Update
Jump to test
```

Which instructions are better when n = 0? n = 1000?

for (int i = 0; i < n; i++)

Optimizing Instruction Counts

- Both versions have the same static **instruction count** (# of written instructions).
- But they have different dynamic **instruction counts** (# of executed instructions when program is run).
  - If n = 0, right (possible alternative) is best b/c fewer instructions
  - If n is large, left (gcc is best) is best b/c fewer instructions
- The compiler may emit a static instruction count that is several times longer than an alternative, but it may be more efficient if loop executes many times.

- Does the compiler *know* that a loop will execute many times? (in general, no)
- So what if our code had loops that always execute a small number of times? How do we know when gcc makes a bad decision?
- (take EE108, EE180, CS316 for more!)

Optimizations

- **Conditional Moves** can sometimes eliminate "branches" (jumps), which are particularly inefficient on modern computer hardware.
- Processors try to *predict* the future execution of instructions for maximum performance. This is difficult to do with jumps.

Recap

- Revisiting %rip
- Calling Functions
  - The Stack
  - Passing Control
  - Passing Data
  - Local Storage
- Register Restrictions
- Pulling it all together: recursion example
- Optimizations

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

Live Session Slides

Plan For Today

- **10 minutes:** general review
- **5 minutes:** post questions or comments on Ed for what we should discuss
- **15 minutes**: open Q&A
- **25 minutes**: extra practice

Lecture 13 takeaway: Function calls rely on the special %rip and %rsp registers to execute another function's instructions and make stack space. We rely on special registers to pass parameters and the return value between functions. And there are caller and callee owned registers to manage use across functions.

Key GDB Tips For Assembly

- Examine 4 giant words (8 bytes) on the stack:

```
(gdb) x/4g $rsp
0x7fffffffe870: 0x0000000000000005      0x0000000000400559
0x7fffffffe880: 0x0000000000000000      0x0000000000400575
```

- display/undisplay (prints out things every time you step/next)

```
(gdb) display/4w $rsp
1: x/4xw $rsp
0x7fffffffe8a8:
0xf7a2d830      0x00007fff      0x00000000      0x00000000
```

Key GDB Tips For Assembly

- `stepi`/`finish`: step into current function call/return to caller:

```
(gdb) finish
```

- Set register values during the run

```
(gdb) p $rdi = $rdi + 1
```

(Might be useful to write down the original value of $rdi somewhere)

- Tui things
  - `refresh`
  - `focus cmd` – use up/down arrows on gdb command line (vs `focus asm`, `focus regs`)
  - `layout regs`, `layout asm`

Plan For Today

- **10 minutes:** general review
- **5 minutes:** post questions or comments on Ed for what we should discuss
- **15 minutes**: open Q&A
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Lecture 13 takeaway: Function calls rely on the special %rip and %rsp registers to execute another function's instructions and make stack space. We rely on special registers to pass parameters and the return value between functions. And there are caller and callee owned registers to manage use across functions.

Extra Practice – Escape Room 2

https://godbolt.org/z/8e31fG4r5

`escape_room`

Escape room assembly code

```
000000000000115b <escape_room>:
    115b:   48 83 ec 08             sub    $0x8,%rsp
    115f:   ba 0a 00 00 00          mov    $0xa,%edx
    1164:   be 00 00 00 00          mov    $0x0,%esi
    1169:   e8 d2 fe ff ff          callq  1040 <strtol@plt>
    116e:   48 89 c7                mov    %rax,%rdi
    1171:   e8 d3 ff ff ff          callq  1149 <transform>
    1176:   a8 01                   test   $0x1,%al
    1178:   74 0a                   je     1184 <escape_room+0x29>
    117a:   b8 00 00 00 00          mov    $0x0,%eax
    117f:   48 83 c4 08             add    $0x8,%rsp
    1183:   c3                      retq
    1184:   b8 01 00 00 00          mov    $0x1,%eax
    1189:   eb f4                   jmp    117f <escape_room+0x24>
```

Escape room assembly code

```
0000000000001149 <transform>:
    1149:   8d 04 bd 00 00 00 00  lea    0x0(,%rdi,4),%eax
    1150:   8d 50 01              lea    0x1(%rax),%edx
    1153:   83 fa 32              cmp    $0x32,%edx
    1156:   7f 02                 jg     115a <transform+0x11>
    1158:   89 d0                 mov    %edx,%eax
    115a:   c3                    retq
```