photo by CGP Grey

COMP201

Computer Systems & Programming

Lecture #18 – x86-64 Procedures

KOÇ UNIVERSITY

Aykut Erdem // Koç University // Fall 2025

Recap

- Assembly Execution and `%rip`
- Control Flow Mechanics
  - Condition Codes
  - Assembly Instructions
- If statements
- Loops
  - While loops
  - For loops
- Other Instructions That Depend On Condition Codes

Recap: If Statements

<u>If-Else In C</u>

```
if (  arg > 3   ) {
    ret = 10;
} else {
    ret = 0;
}
 ret++;
```

```
400552 <+0>:   cmp   $0x3,%edi
400555 <+3>:   jle   0x40055e <if_else+12>
400557 <+5>:   mov   $0xa,%eax
40055c <+10>:  jmp   0x400563 <if_else+17>
40055e <+12>:  mov   $0x0,%eax
400563 <+17>:  add   $0x1,%eax
```

<u>If-Else In Assembly pseudocode</u>

```
Test
Jump to else-body if test fails
If-body
Jump to past else-body
Else-body
Past else body
```

Recap: While Loop Construction

C

```
while (test) {
        body
}
```

Assembly

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

From Previous Slide:

```
0x0000000000400570 <+0>:      mov    $0x0,%eax
0x0000000000400575 <+5>:      jmp    0x40057a <loop+10>
0x0000000000400577 <+7>:      add    $0x1,%eax
0x000000000040057a <+10>:     cmp    $0x63,%eax
0x000000000040057d <+13>:     jle    0x400577 <loop+7>
0x000000000040057f <+15>:     repz retq
```

Recap: For Loop Construction

C For loop

```
for (init; test; update) {
        body
}
```

C Equivalent While Loop

```
init
while(test) {
      body
      update
}
```

Assembly pseudocode

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

`for` loops and `while` loops are treated (essentially) the same when compiled down to assembly.

Condition Code-Dependent Instructions

There are three common instruction types that use condition codes:

- **`jmp`** instructions conditionally jump to a different next instruction
- **`set`** instructions conditionally set a byte to 0 or 1
- new versions of **`mov`** instructions conditionally move data

`set`: Read condition codes

`set` instructions conditionally set a byte to 0 or 1.

- Reads current state of flags
- Destination is a single-byte register (e.g., `%al`) or single-byte memory location
- Does not perturb other bytes of register
- Typically followed by `movzbl` to zero those bytes

```
int small(int x) {
    return x < 16;
}
```

```
cmp $0xf,%edi
setle %al
movzbl %al, %eax
retq
```

`set`: Read condition codes

Instruction	Synonym	Set Condition (1 if true, 0 if false)
`sete D`	`setz`	Equal / zero
`setne D`	`setnz`	Not equal / not zero
`sets D`		Negative
`setns D`		Nonnegative
`setg D`	`setnle`	Greater (signed >)
`setge D`	`setnl`	Greater or equal (signed >=)
`setl D`	`setnge`	Less (signed <)
`setle D`	`setng`	Less or equal (signed <=)
`seta D`	`setnbe`	Above (unsigned >)
`setae D`	`setnb`	Above or equal (unsigned >=)
`setb D`	`setnae`	Below (unsigned <)
`setbe D`	`setna`	Below or equal (unsigned <=)

`cmov`: Conditional move

`cmovx src,dst` conditionally moves data in `src` to data in `dst`.

- Mov `src` to `dst` if condition `x` holds; no change otherwise
- `src` is memory address/register, `dst` is register
- May be more efficient than branch (i.e., jump)
- Often seen with C ternary operator: `result = test ? then: else;`

```
int max(int x, int y) {
    return x > y ? x : y;
}
```

```
cmp    %edi,%esi
mov    %edi, %eax
cmovge %esi, %eax
retq
```

Ternary Operator

The ternary operator is a shorthand for using if/else to evaluate to a value.

```
condition ? expressionIfTrue : expressionIfFalse
```

```
int x;
if (argc > 1) {
     x = 50;
} else {
     x = 0;
}

// equivalent to
int x = argc > 1 ? 50 : 0;
```

`cmov`: Conditional move

Instruction	Synonym	Move Condition
`cmove S,R`	`cmovz`	Equal / zero (ZF = 1)
`cmovne S,R`	`cmovnz`	Not equal / not zero (ZF = 0)
`cmovs S,R`		Negative (SF = 1)
`cmovns S,R`		Nonnegative (SF = 0)
`cmovg S,R`	`cmovnle`	Greater (signed >) (SF = 0 and SF = OF)
`cmovge S,R`	`cmovnl`	Greater or equal (signed >=) (SF = OF)
`cmovl S,R`	`cmovnge`	Less (signed <) (SF != OF)
`cmovle S,R`	`cmovng`	Less or equal (signed <=) (ZF = 1 or SF! = OF)
`cmova S,R`	`cmovnbe`	Above (unsigned >) (CF = 0 and ZF = 0)
`cmovae S,R`	`cmovnb`	Above or equal (unsigned >=) (CF = 0)
`cmovb S,R`	`cmovnae`	Below (unsigned <) (CF = 1)
`cmovbe S,R`	`cmovna`	Below or equal (unsigned <=) (CF = 1 or ZF = 1)

Practice: Conditional Move

```
int signed_division(int x) {
    return x / 4;
}
```

-14/4 should yield -3 rather than -4

(See Sec. 2.3.7)

```
signed_division:
  leal 3(%rdi), %eax
  testl %edi, %edi
  cmovns %edi, %eax
  sarl $2, %eax
  ret
```

- `leal 3(%rdi), %eax` — Put **x** + 3 into **%eax** (add appropriate bias, 2^2-1)
- `testl %edi, %edi` — To see whether **x** is negative, zero, or positive
- `cmovns %edi, %eax` — If **x** is positive, put **x** into **%eax**
- `sarl $2, %eax` — Divide **%eax** by 4

Practice: Fill In The Blank

Note: .L2/.L3 are "labels" that make jumps easier to read.

C Code

```
long loop(long a, long b) {
    long result = _______;
    while (_________) {
      result = ____________;
      a = _________;
    }
    return result;
}
```

Common while loop construction:

Jump to test
Body
Test
Jump to body if success

What does this assembly code translate to?

```
// a in %rdi, b in %rsi
loop:
    movl $1, %eax
    jmp .L2
.L3
    leaq (%rdi,%rsi), %rdx
    imulq %rdx, %rax
    addq $1, %rdi
.L2
    cmpq %rsi, %rdi
    jl .L3
rep; ret
```

Practice: Fill In The Blank

Note: .L2/.L3 are "labels" that make jumps easier to read.

C Code

```
long loop(long a, long b) {
    long result = ___1___;
    while (__a < b__) {
      result = result*(a+b);
      a = __a + 1__;
    }
    return result;
}
```

Common while loop construction:

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

What does this assembly code translate to?

```
// a in %rdi, b in %rsi
loop:
    movl $1, %eax
    jmp .L2
.L3
    leaq (%rdi,%rsi), %rdx
    imulq %rdx, %rax
    addq $1, %rdi
.L2
    cmpq %rsi, %rdi
    jl .L3
rep; ret
```

Practice: “Escape Room”

```
escapeRoom:
  leal (%rdi,%rdi), %eax
  cmpl $5, %eax
  jg .L3
  cmpl $1, %edi
  jne .L4
  movl $1, %eax
  ret
.L3:
  movl $1, %eax
  ret
.L4:
  movl $0, %eax
  ret
```

What must be passed to the `escapeRoom` function such that it returns true (1) and not false (0)?

Practice: "Escape Room"

```
escapeRoom:
  leal (%rdi,%rdi), %eax
  cmpl $5, %eax
  jg .L3
  cmpl $1, %edi
  jne .L4
  movl $1, %eax
  ret
.L3:
  movl $1, %eax
  ret
.L4:
  movl $0, %eax
  ret
```

What must be passed to the `escapeRoom` function such that it returns true (1) and not false (0)?

First param > 2 or == 1.

Learning Assembly

Moving data around	→	Arithmetic and logical operations	→	Control flow	→	Function calls
Lecture 14		Lecture 15		Lecture 16-17		Today

Learning Goals

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

Plan for Today

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

Disclaimer: Slides for this lecture were borrowed from

—Nick Troccoli's Stanford CS107 class

—Randal E. Bryant and David R. O'Hallaroni's CMU 15-213 class

Lecture Plan

- Revisiting `%rip`
- Calling Functions
  - The Stack
  - Passing Control
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- Register Restrictions
- Pulling it all together: recursion example

`%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

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

```
0000000000400570 <loop>:
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

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

```
0000000000400570 <loop>:
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0x40057f <+15>: f3 c3          repz retq
```

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++;
    }
}
```

```
0000000000400570 <loop>:
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0x40057f <+15>: f3 c3          repz retq
```

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

%rip

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

```
0000000000400570 <loop>:
0x400570 <+0>:  b8 00 00 00 00 mov $0x0,%eax
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0x40057f <+15>: f3 c3          repz retq
```

0xeb means **jmp**.

%rip

```
0000000000400570 <loop>:
0x400570 <+0>:   b8 00 00 00 00 mov $0x0,%eax
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0x400577 <+7>:   83 c0 01       add $0x1,%eax
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0x40057d <+13>:  73 f8          jle 0x400577 <loop+7>
0x40057f <+15>:  f3 c3          repz retq
```

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

```
0000000000400570 <loop>:
0x400570 <+0>:  b8 00 00 00 00 mov $0x0,%eax
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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
```

0x73 means **jle**.

%rip

```
0000000000400570 <loop>:
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
```

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 <u>then</u> go **8** bytes back!

%rip

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0000000000400570 <loop>:
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With no jump, `%rip` would advance to the next line. This **`jmp`** says to <u>then</u> 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.

Lecture Plan

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

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.

Lecture Plan

- Revisiting %rip
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  - The Stack
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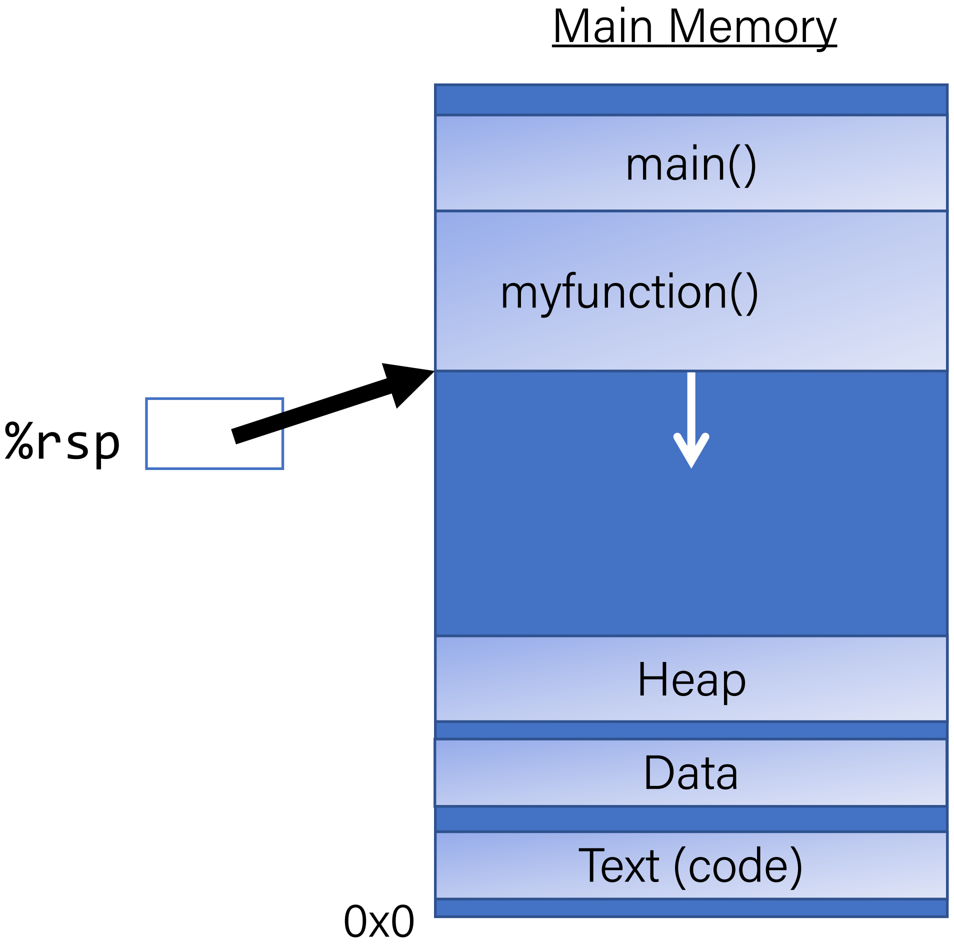
%rsp

- **%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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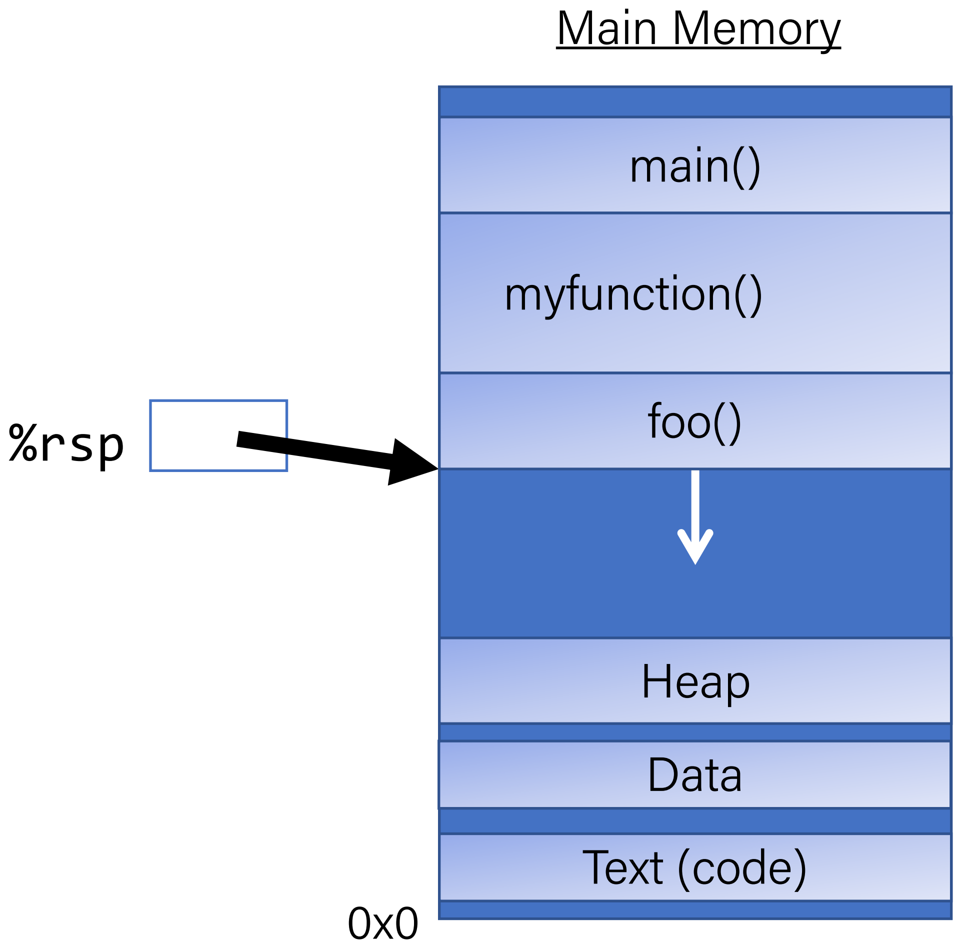

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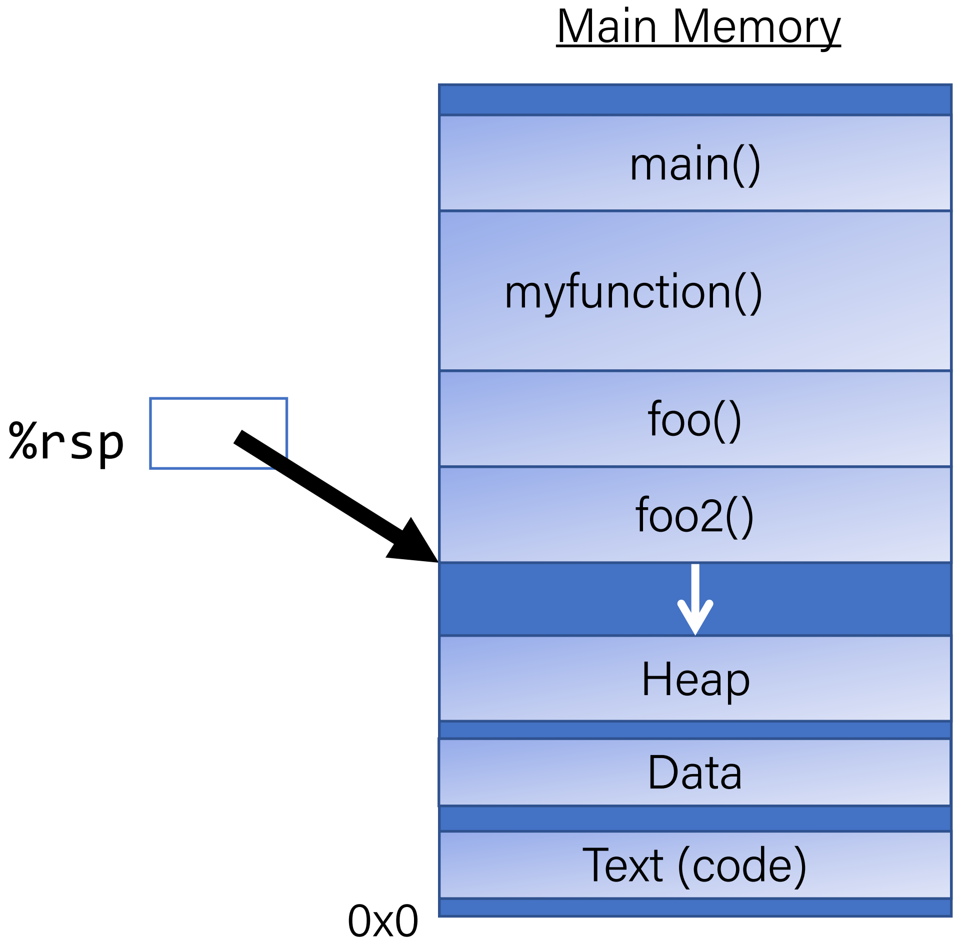

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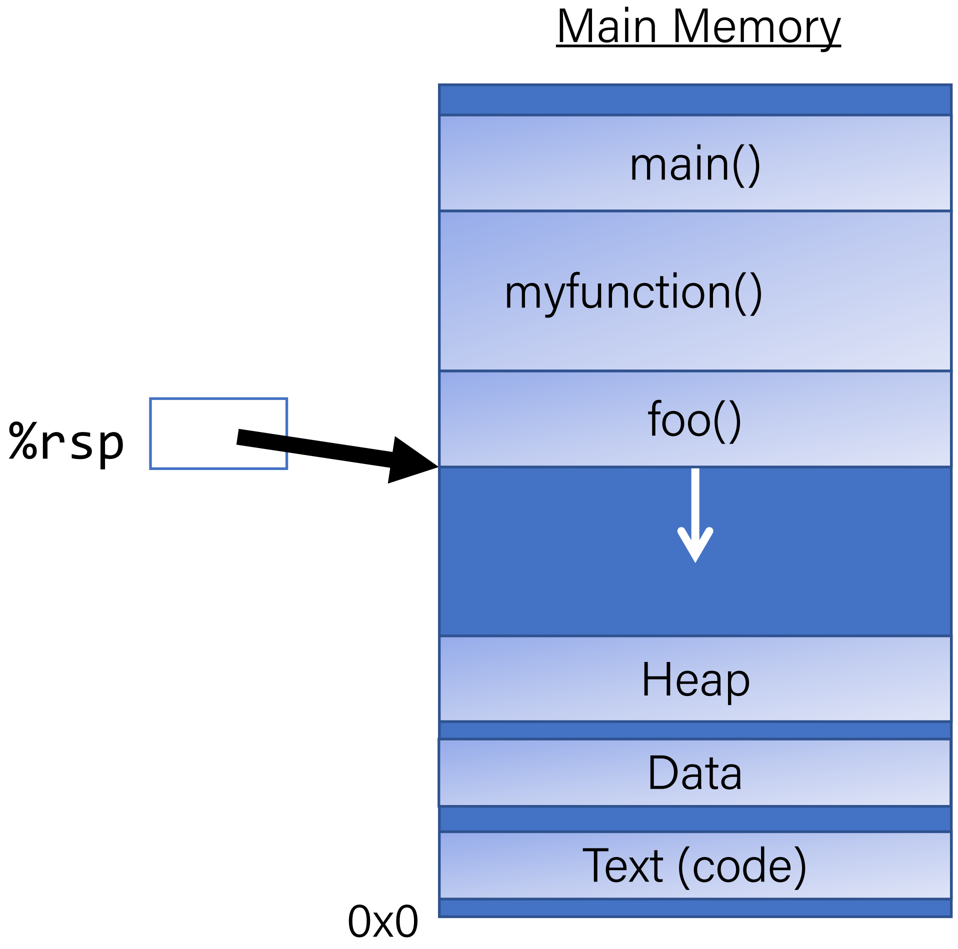

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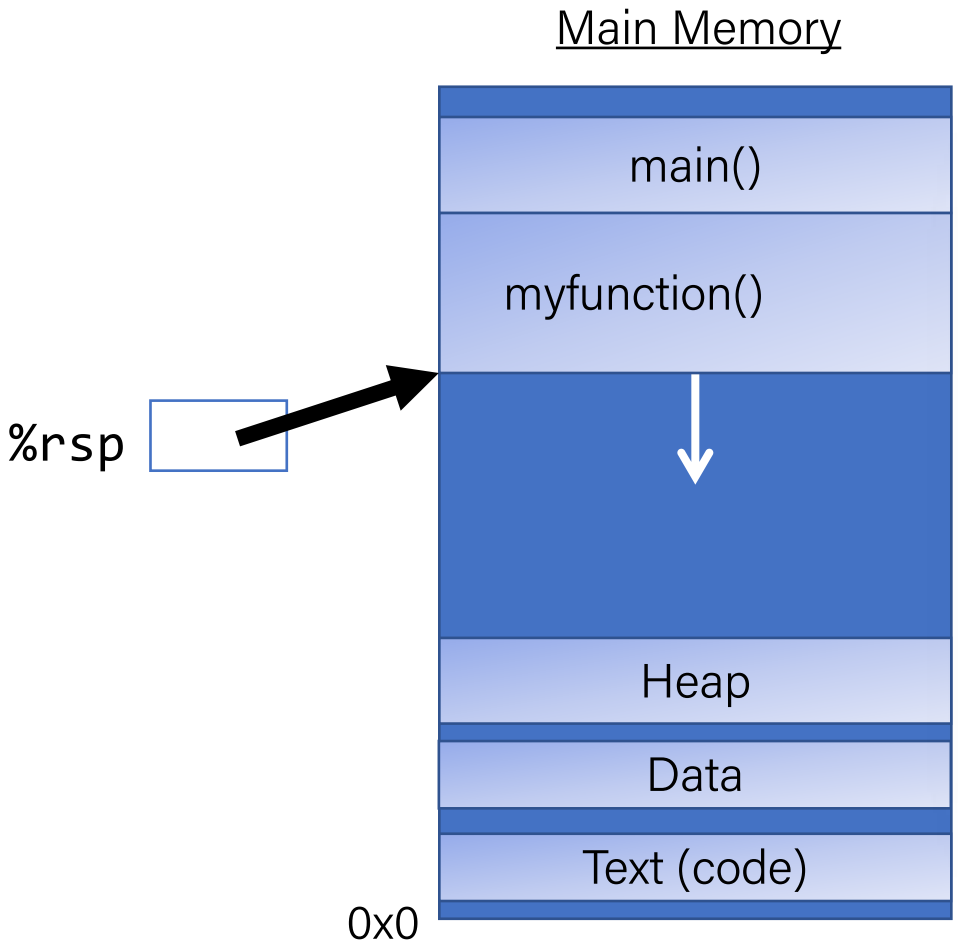

Key idea: %rsp must point to the same place before a function is called and after that function returns, since stack frames go away when a function finishes.

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

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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`

- 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. More on this later!

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`	$D \longleftarrow M[R[\%rsp]]$ $R[\%rsp] \longleftarrow R[\%rsp] + 8;$

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

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

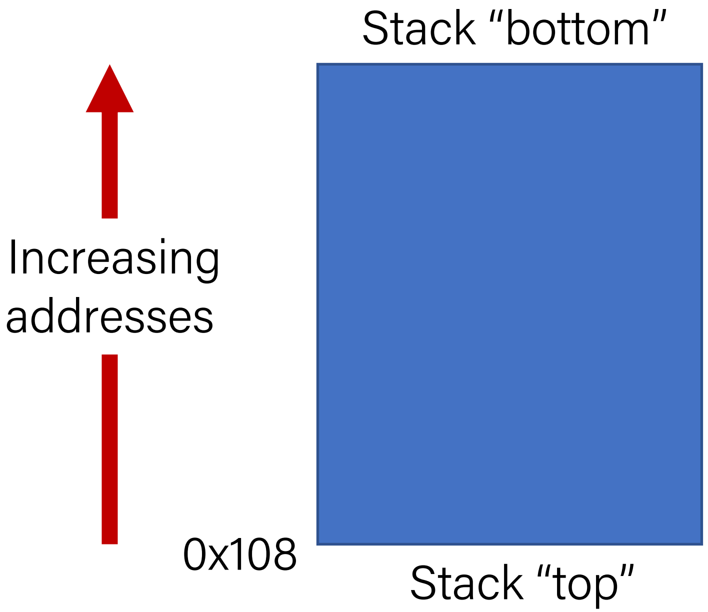
- Sometimes, you'll see instructions just explicitly increment the stack pointer to pop data.

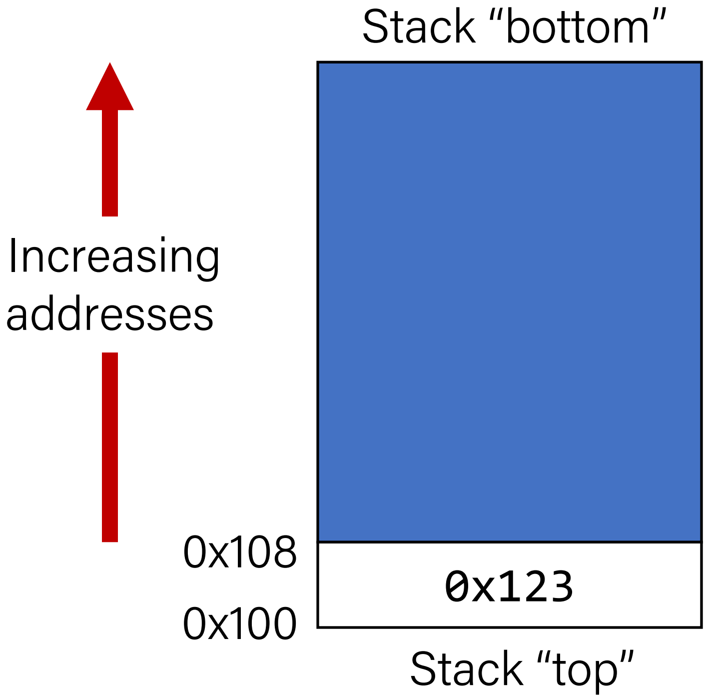
Stack Example

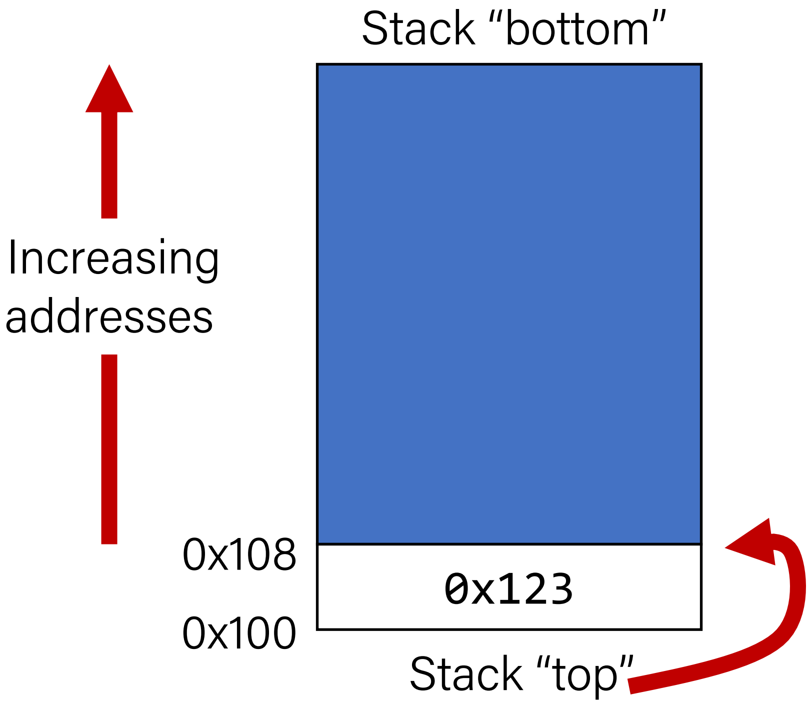
Initially	
`%rax`	`0x123`
`%rdx`	`0`
`%rsp`	`0x108`

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

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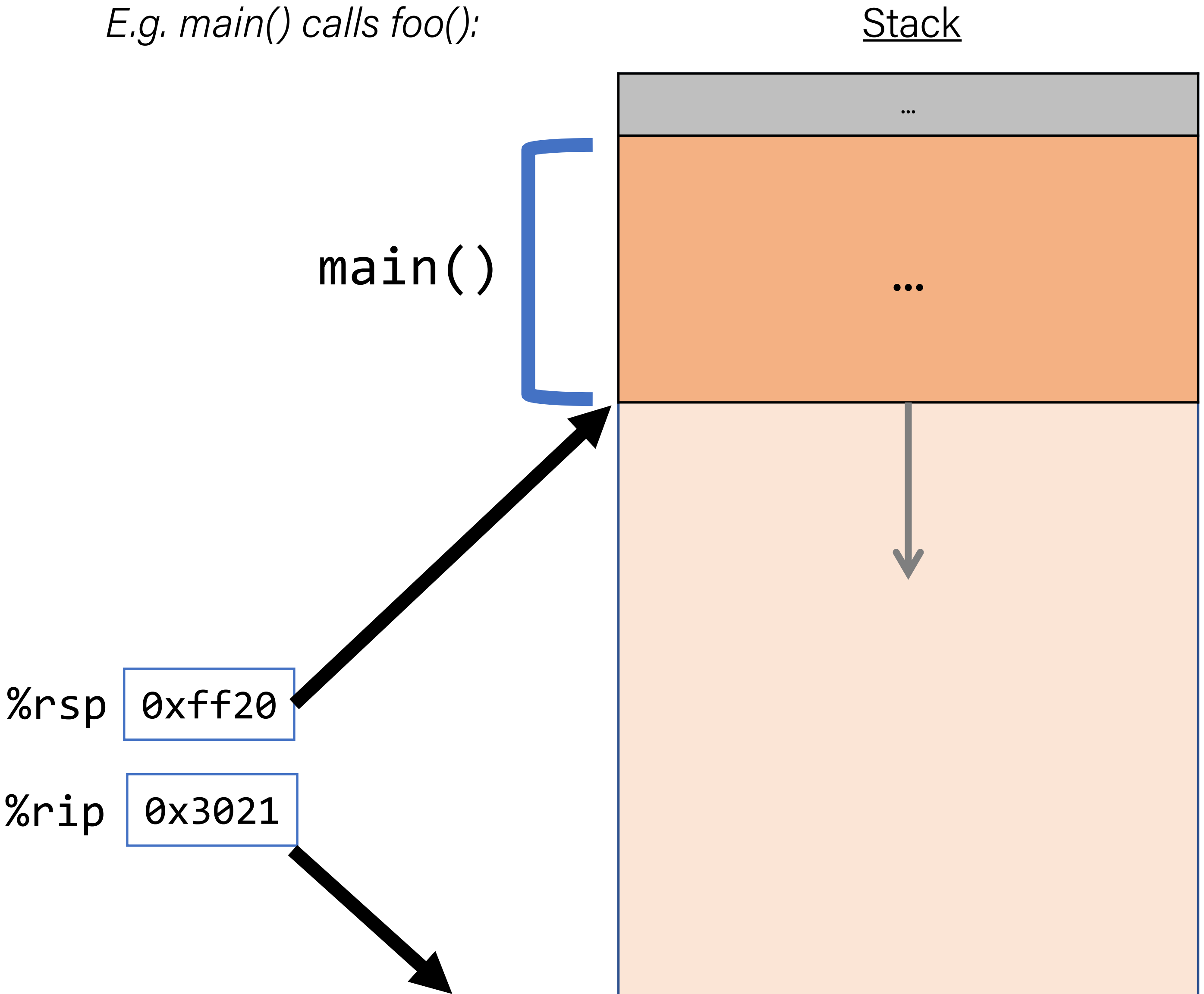
Remembering Where We Left Off

Problem: `%rip` points to the next instruction to execute. To call a function, we must <u>remember</u> 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.

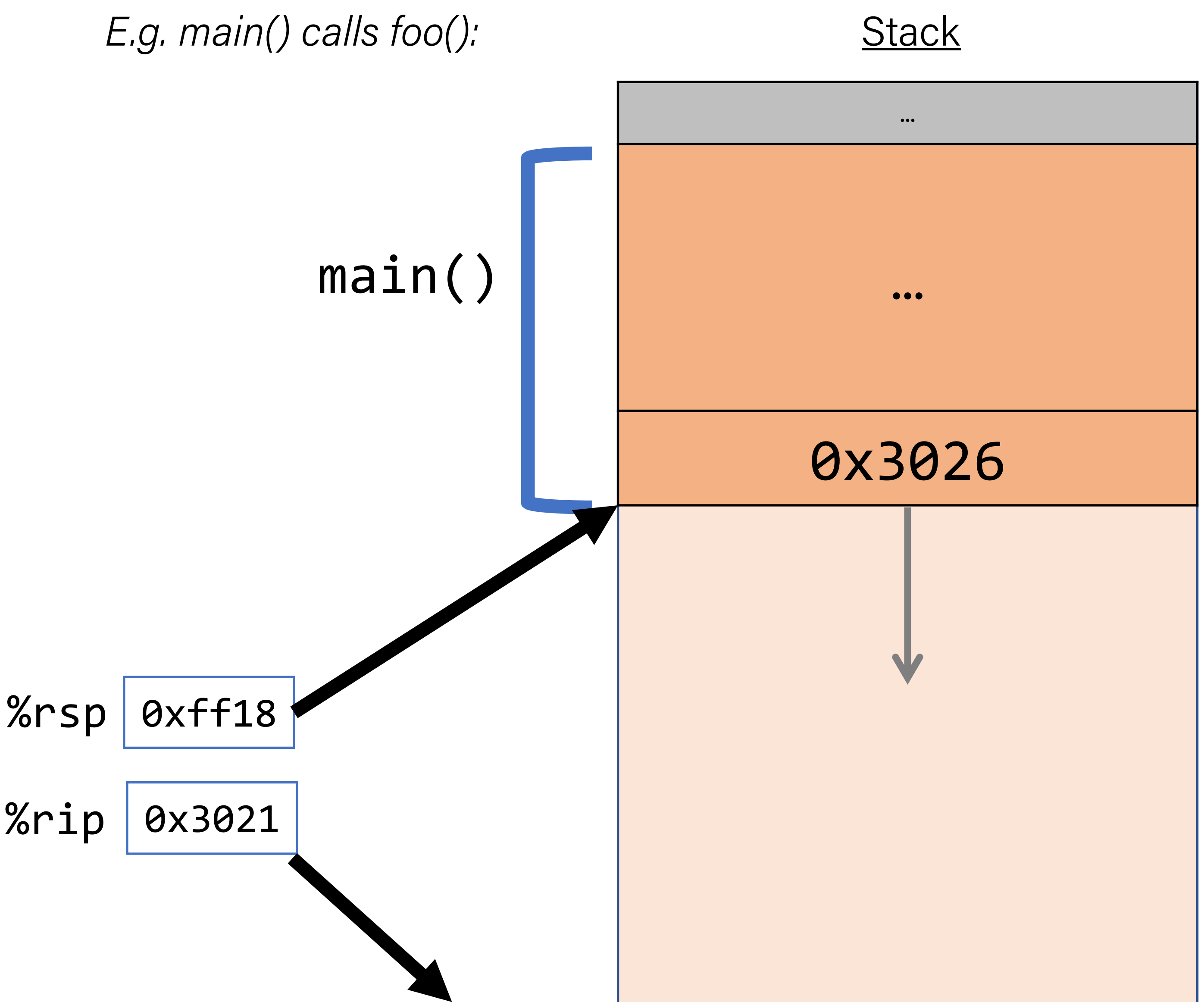
E.g. main() calls foo():



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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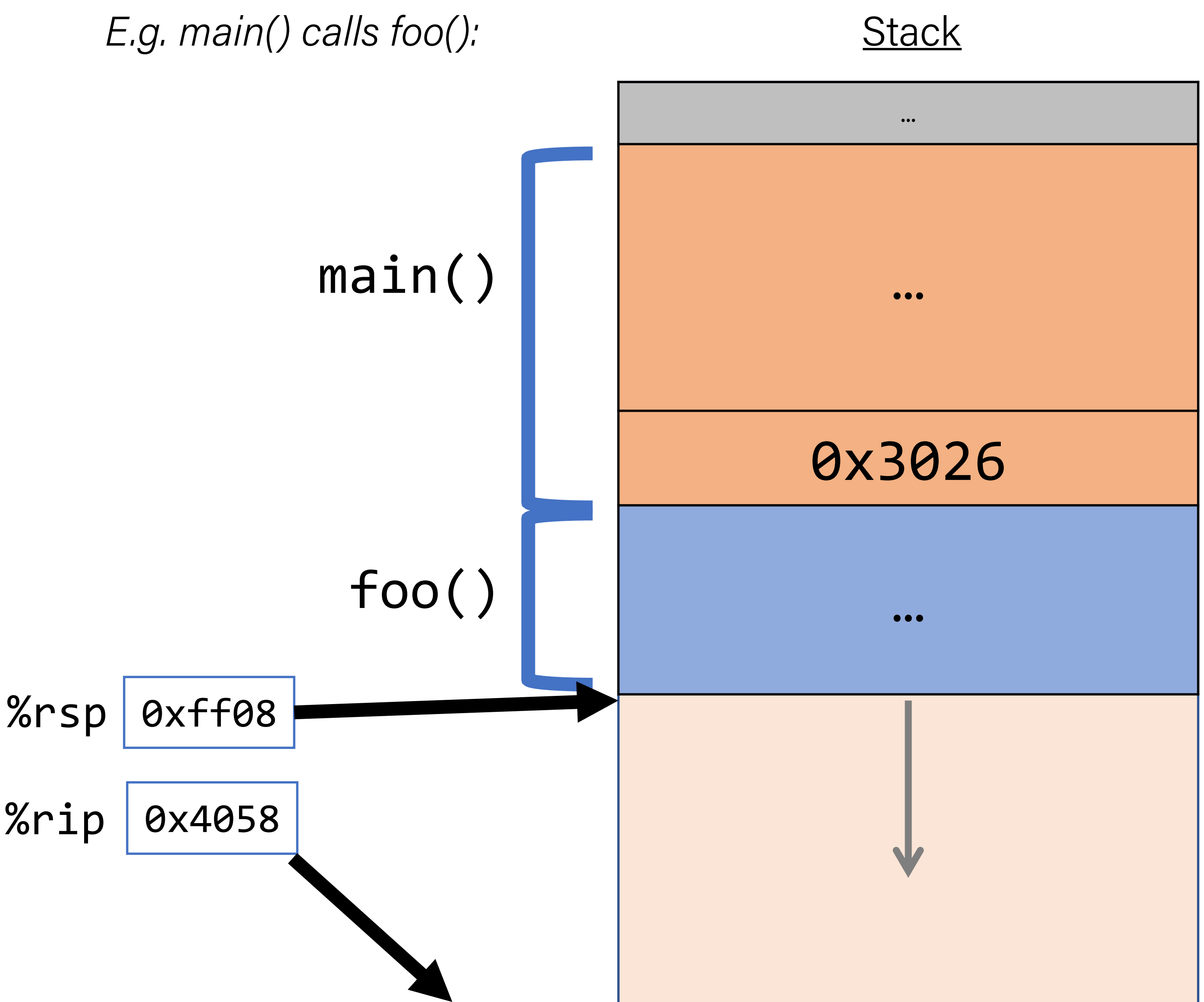

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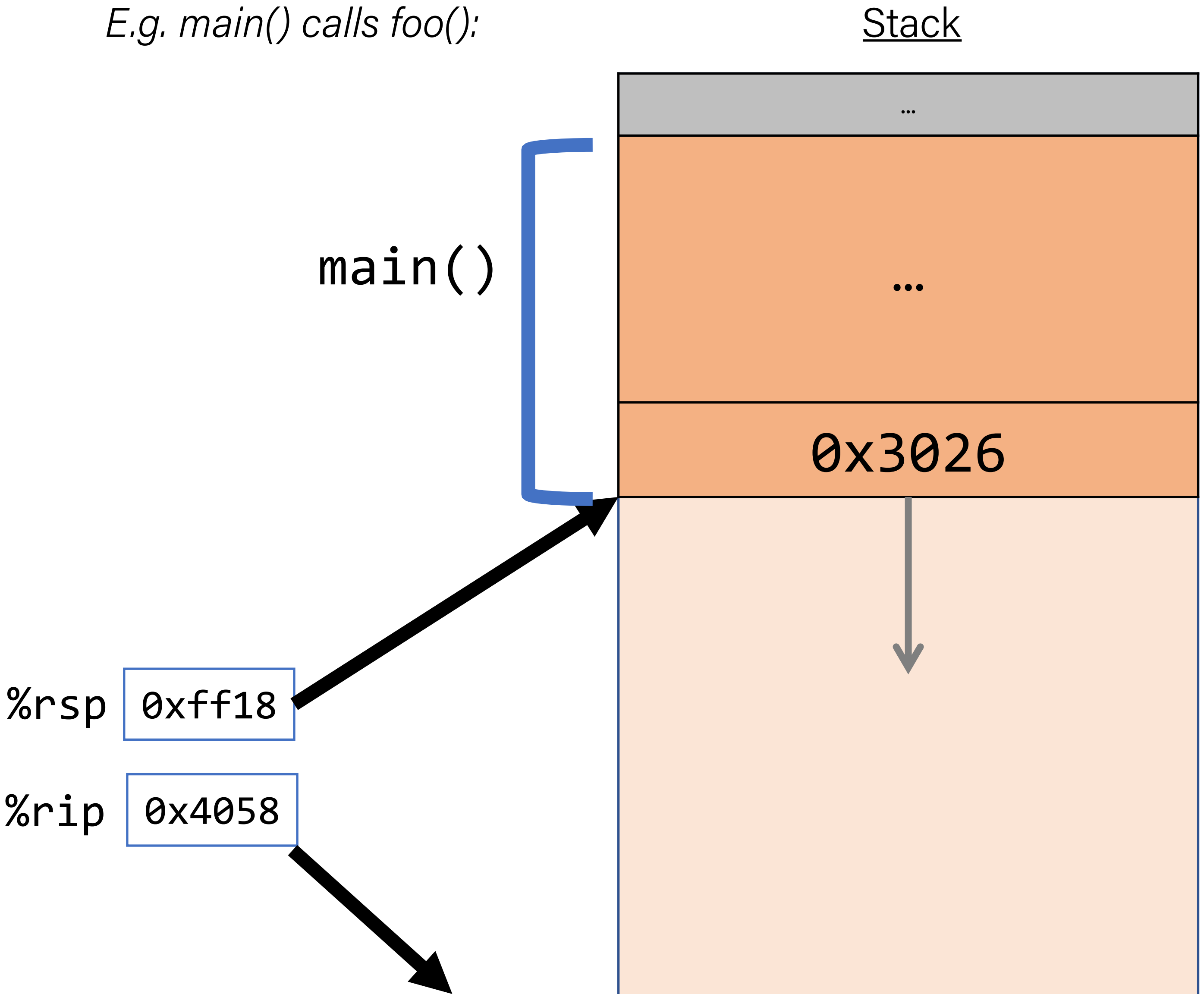

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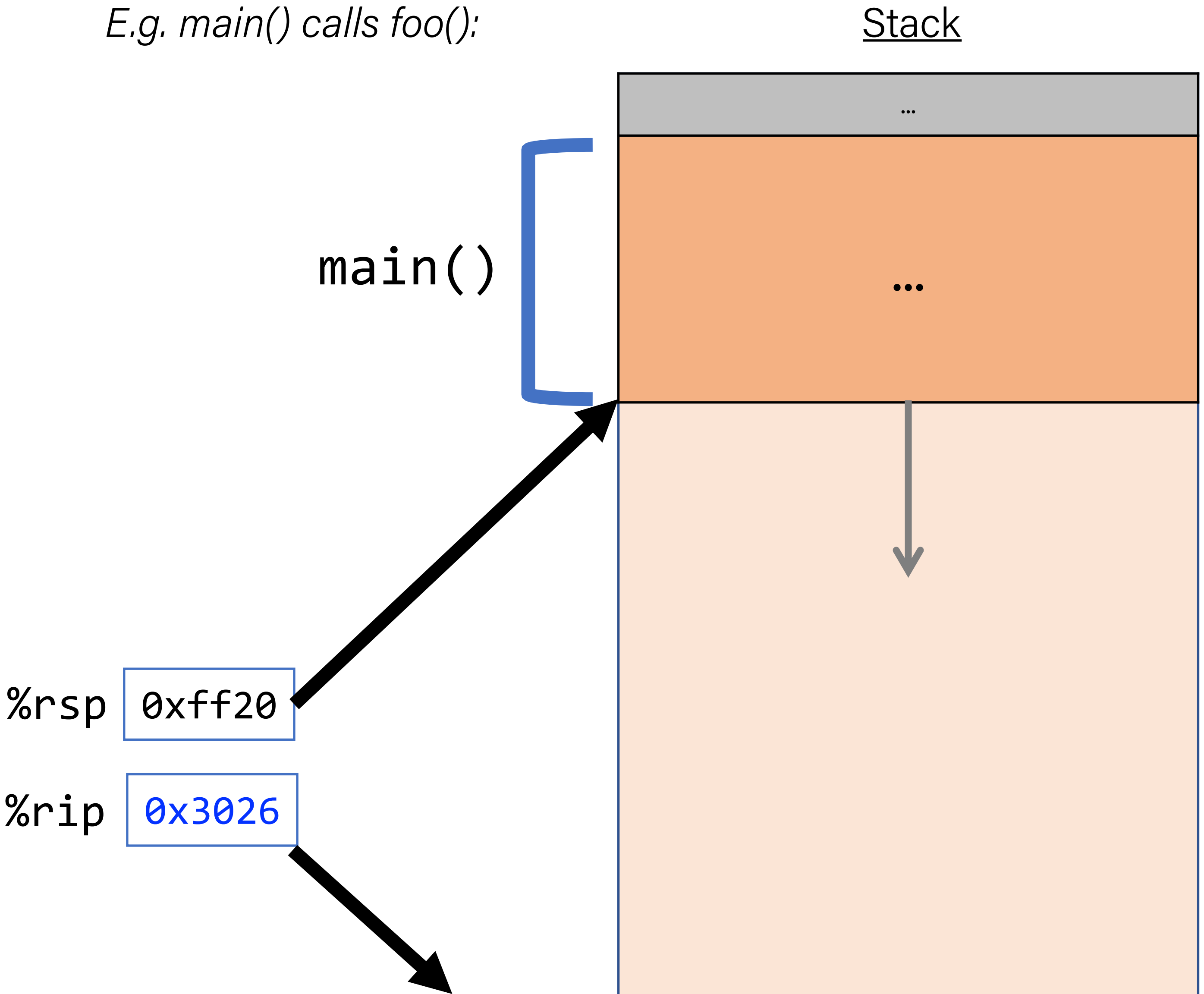
Solution: push the next value of `%rip` onto the stack. Then call the function. When it is finished, put this value back into `%rip` and continue executing.

E.g. main() calls foo():



Example: Remembering Where We Left Off

```
void multstore
 (long x, long y, long *dest) {
    long t = mult2(x, y);
    *dest = t;
}
```

```
0000000000400540 <multstore>:
  400540: push   %rbx                  # Save %rbx
  400541: mov    %rdx,%rbx             # Save dest
  400544: callq  400550 <mult2>        # mult2(x,y)
  400549: mov    %rax,(%rbx)           # Save at dest
  40054c: pop    %rbx                  # Restore %rbx
  40054d: retq                         # Return
```

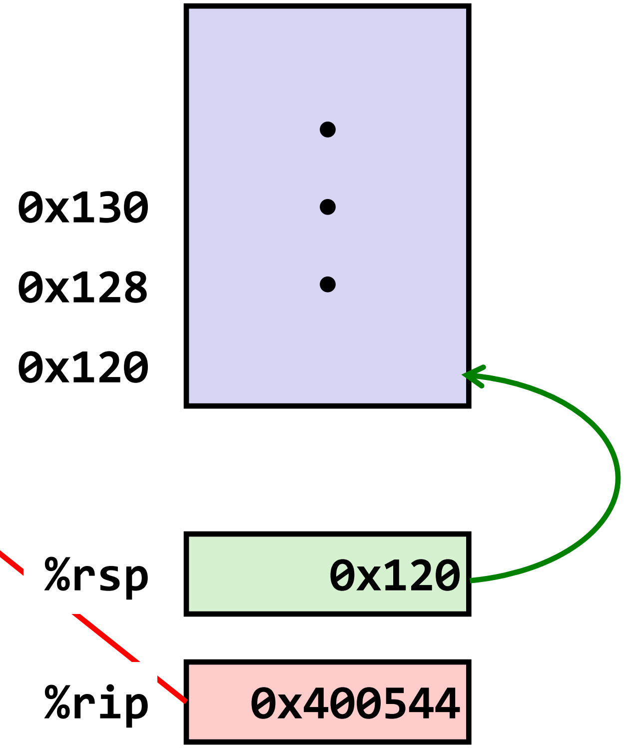
```
long mult2
  (long a, long b)
{
  long s = a * b;
  return s;
}
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax            # a
  400553:  imul   %rsi,%rax            # a * b
  400557:  retq                        # Return
```

Example: Remembering Where We Left Off

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



Example: Remembering Where We Left Off

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
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  •
  •
```

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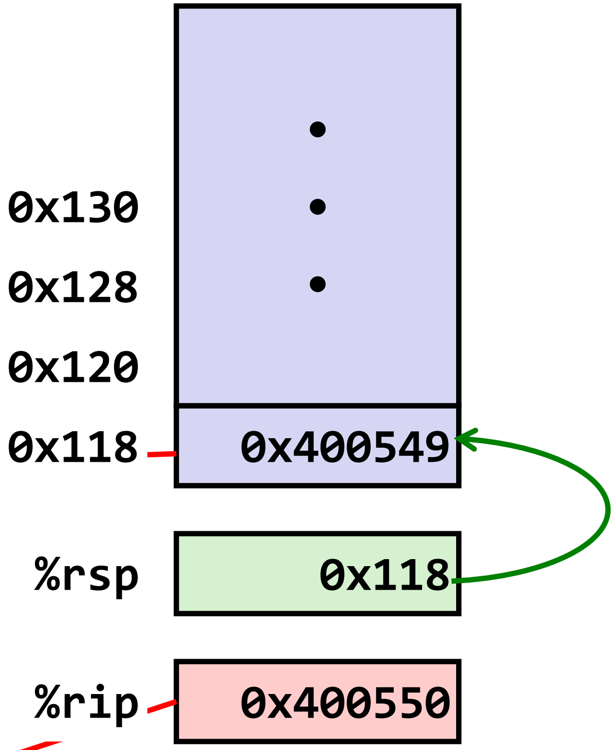
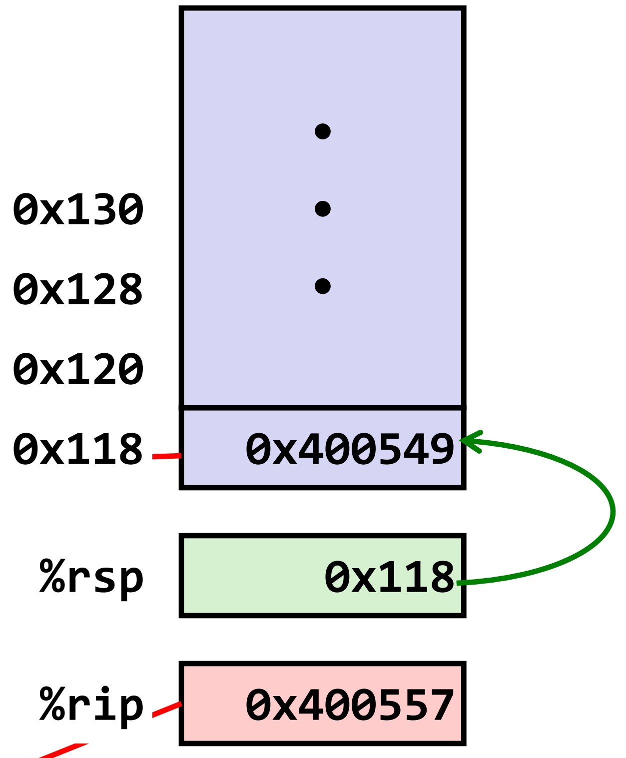
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



Example: Remembering Where We Left Off

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```




```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```

Example: Remembering Where We Left Off

```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

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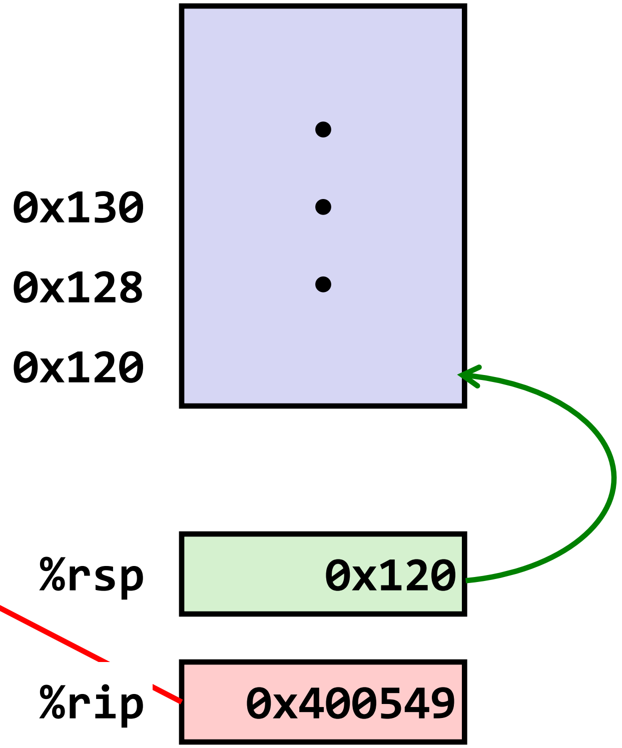
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



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).

What's left? 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.

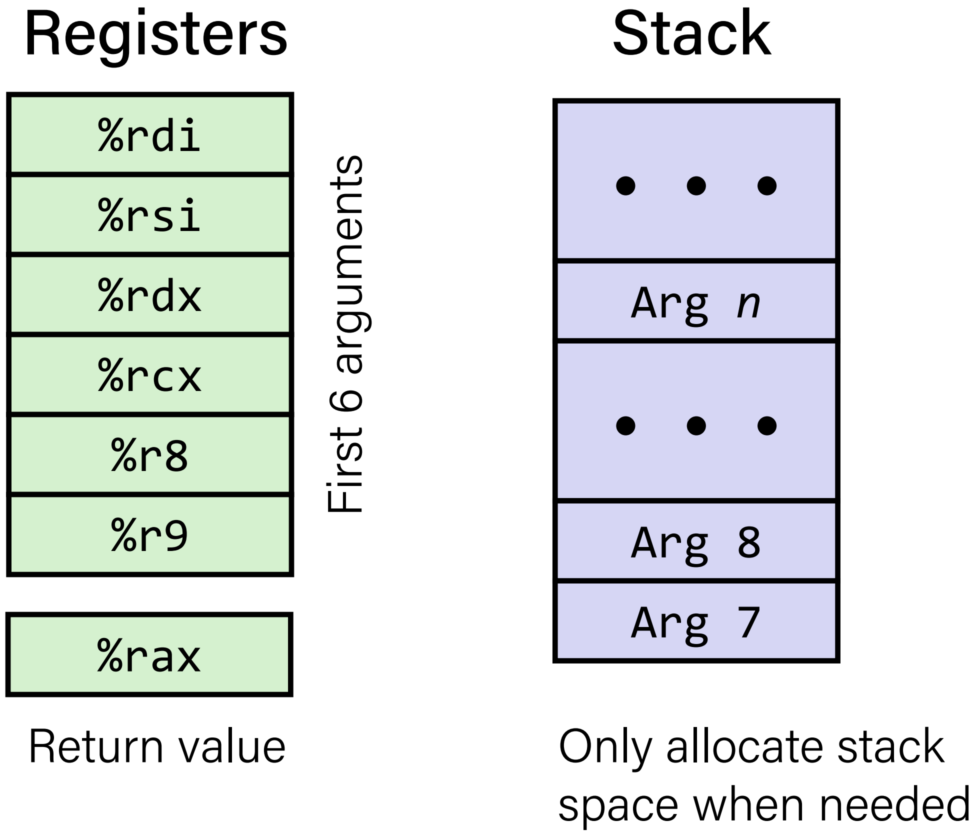
Terminology: **caller** function calls the **callee** function.

Lecture Plan

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

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.



Example 1: Parameters and Return

```
void multstore
 (long x, long y, long *dest) {
    long t = mult2(x, y);
    *dest = t;
}
```

```
0000000000400540 <multstore>:
  # x in %rdi, y in %rsi, dest in %rdx
  • • •
  400541: mov    %rdx,%rbx          # Save dest
  400544: callq  400550 <mult2>     # mult2(x,y)
  # t in %rax
  400549: mov    %rax,(%rbx)        # Save at dest
  • • •
```

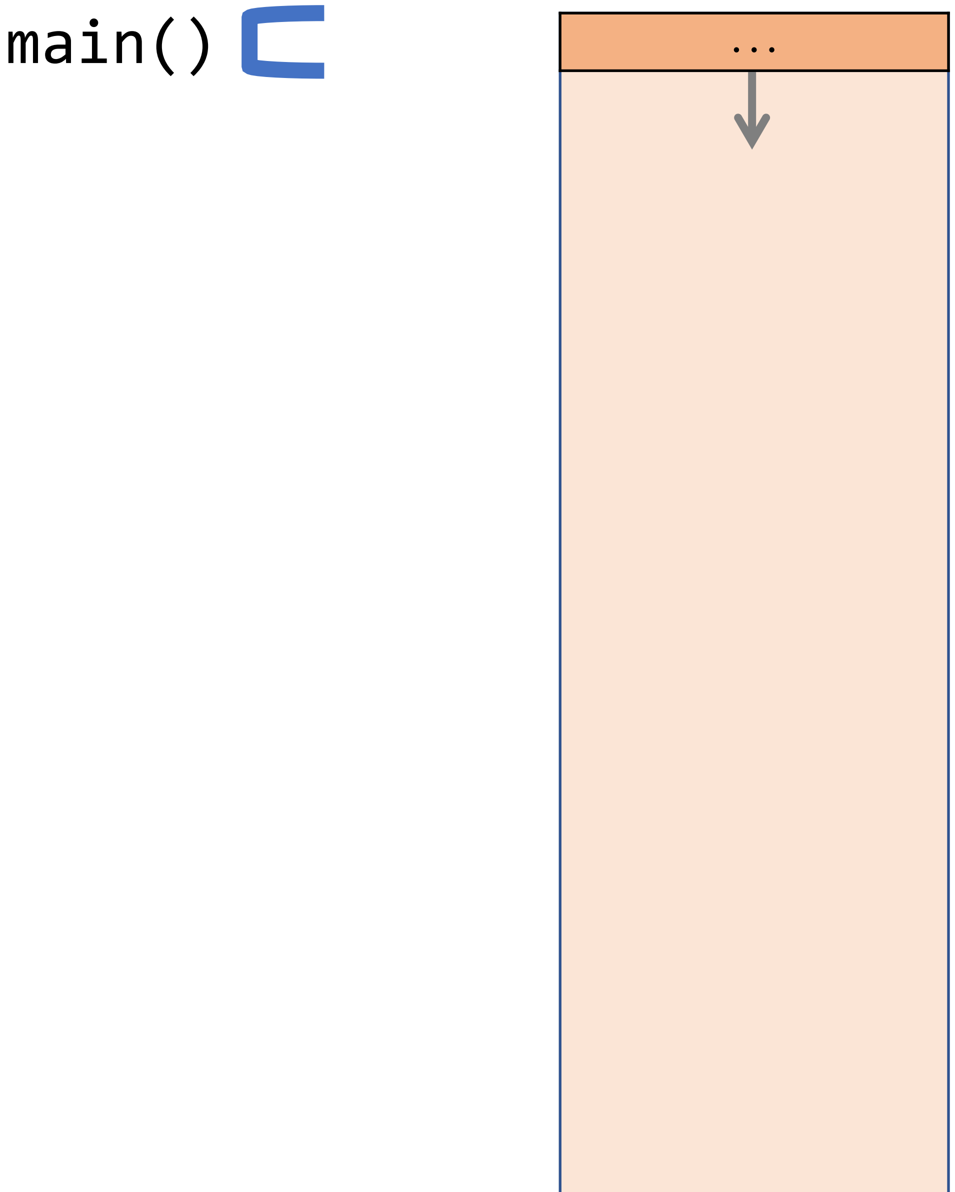
```
long mult2
  (long a, long b)
{
  long s = a * b;
  return s;
}
```

```
0000000000400550 <mult2>:
  # a in %rdi, b in %rsi
  400550:  mov    %rdi,%rax         # a
  400553:  imul   %rsi,%rax         # a * b
  # s in %rax
  400557:  retq                     # Return
```

Example 2: 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) {
    …
}
```

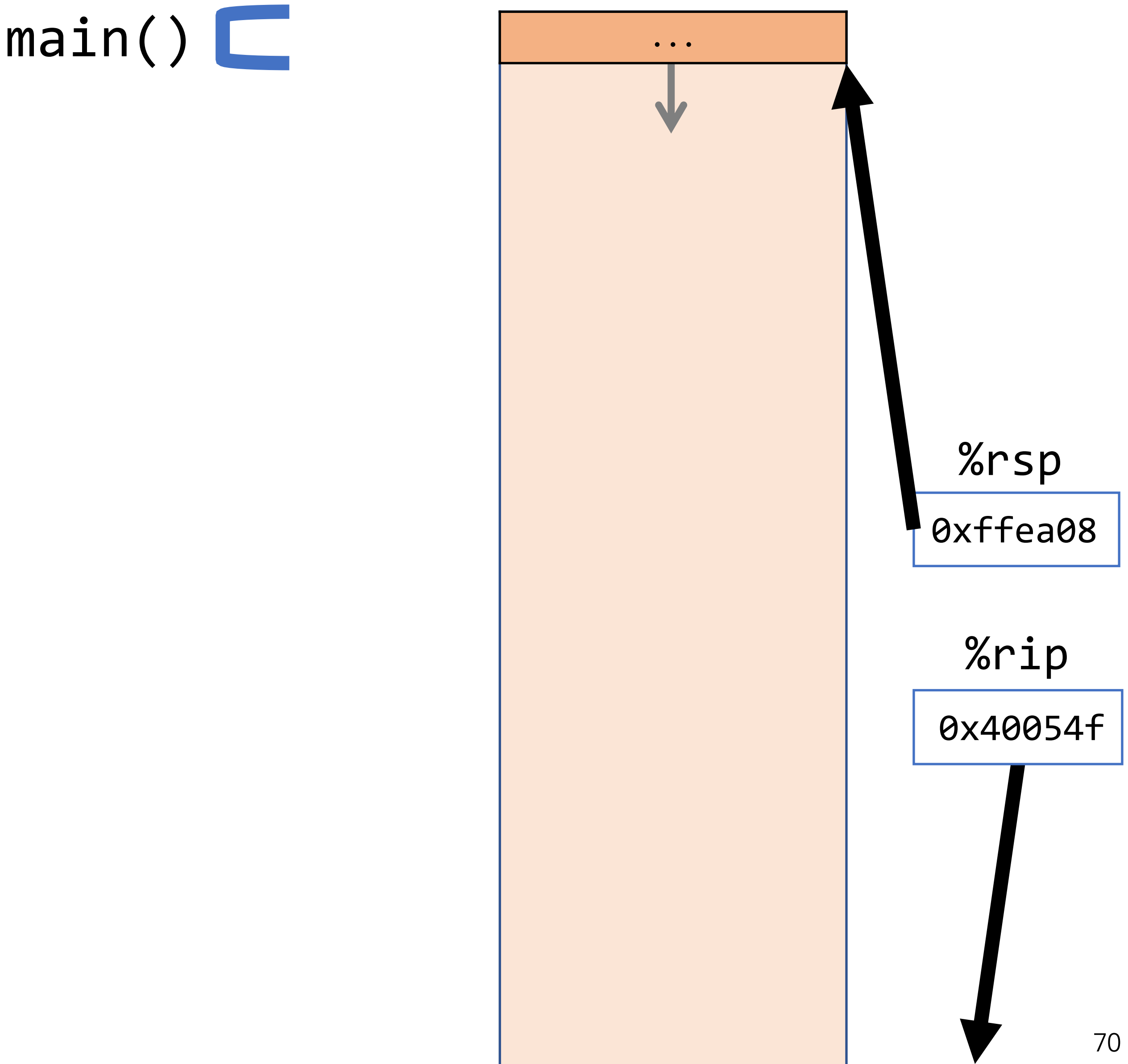


Example 2: Parameters and Return

```
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)
```



Example 2: 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) {
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}
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0x40054f <+0>:     sub     $0x18,%rsp
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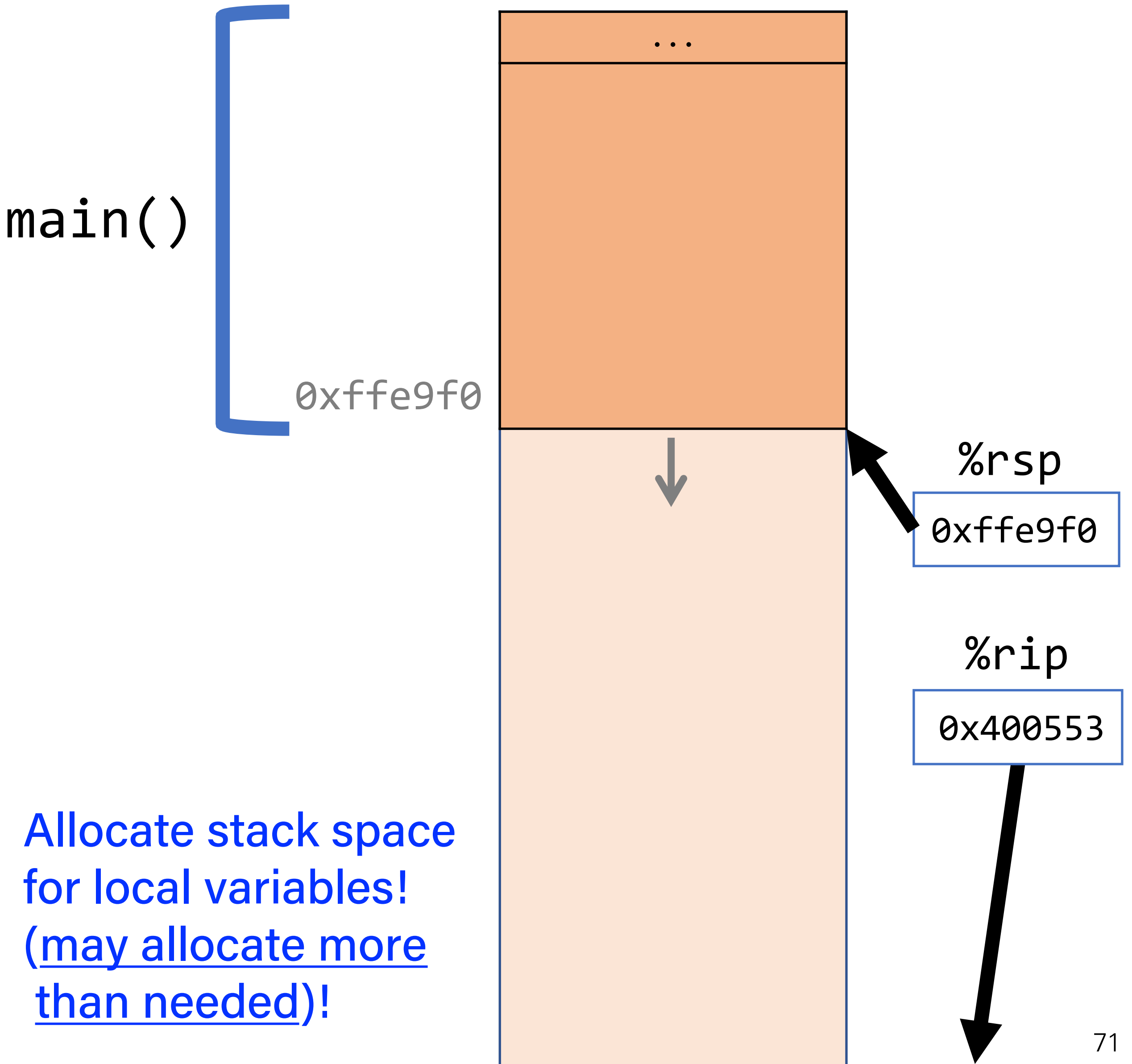

Allocate stack space for local variables! (may allocate more than needed)!

Example 2: 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) {
    …
}
```

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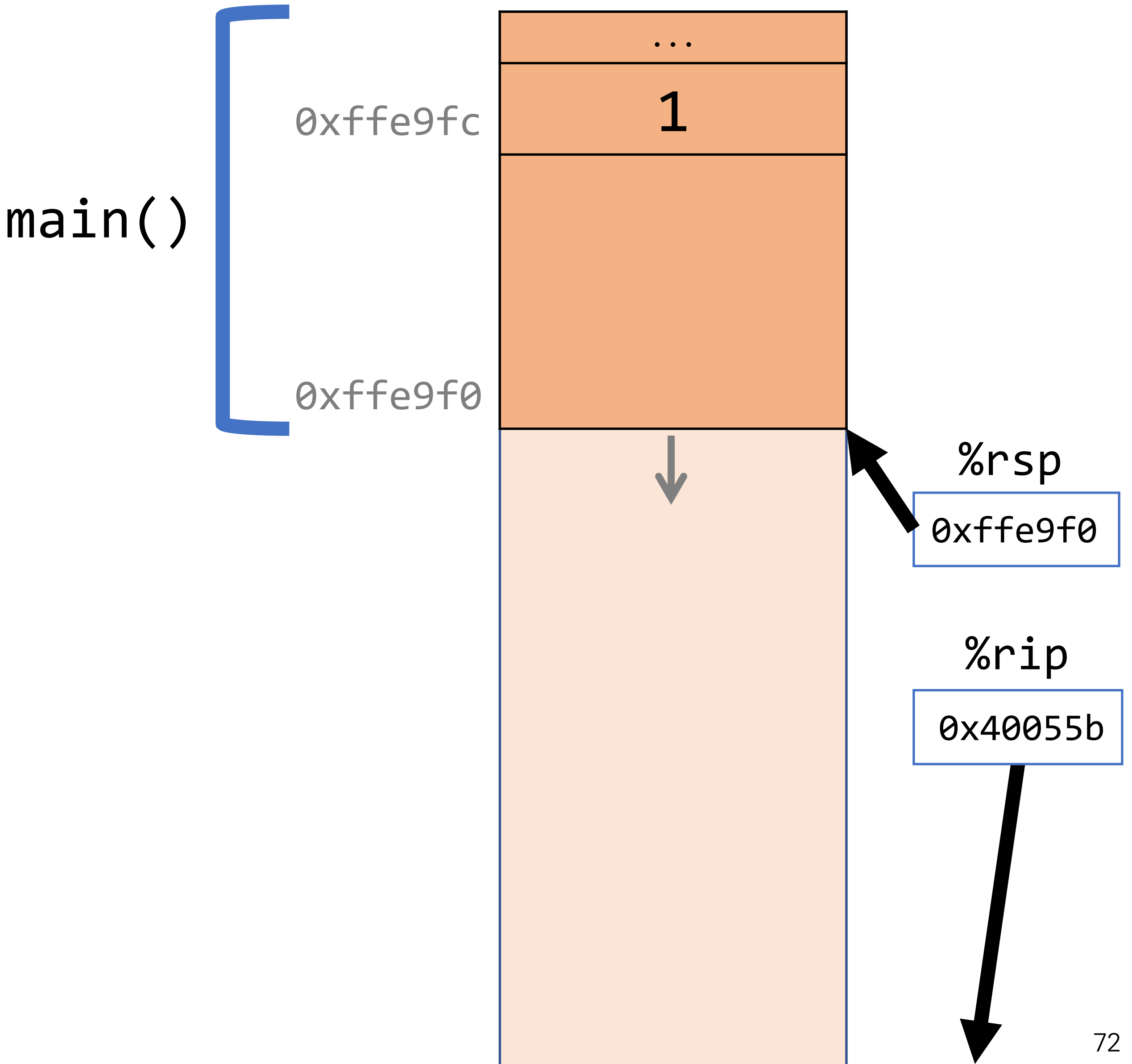

Example 2: Parameters and Return

```
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) {
    …
}
```

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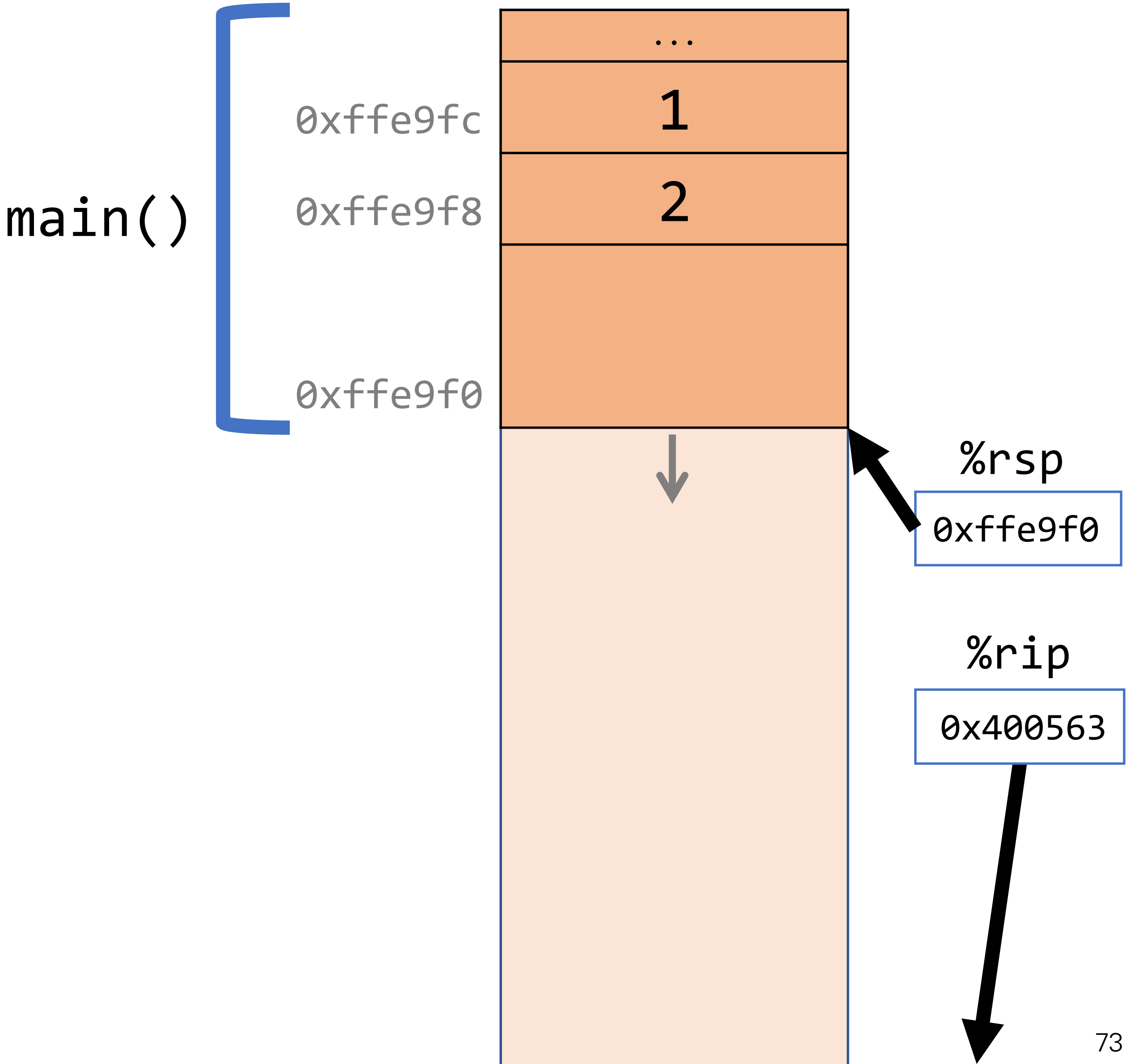

Example 2: Parameters and Return

```
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    int i1 = 1;
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    int i3 = 3;
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    int result = func(&i1, &i2, &i3, &i4,
                      i1, i2, i3, i4);
    …
}

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

```
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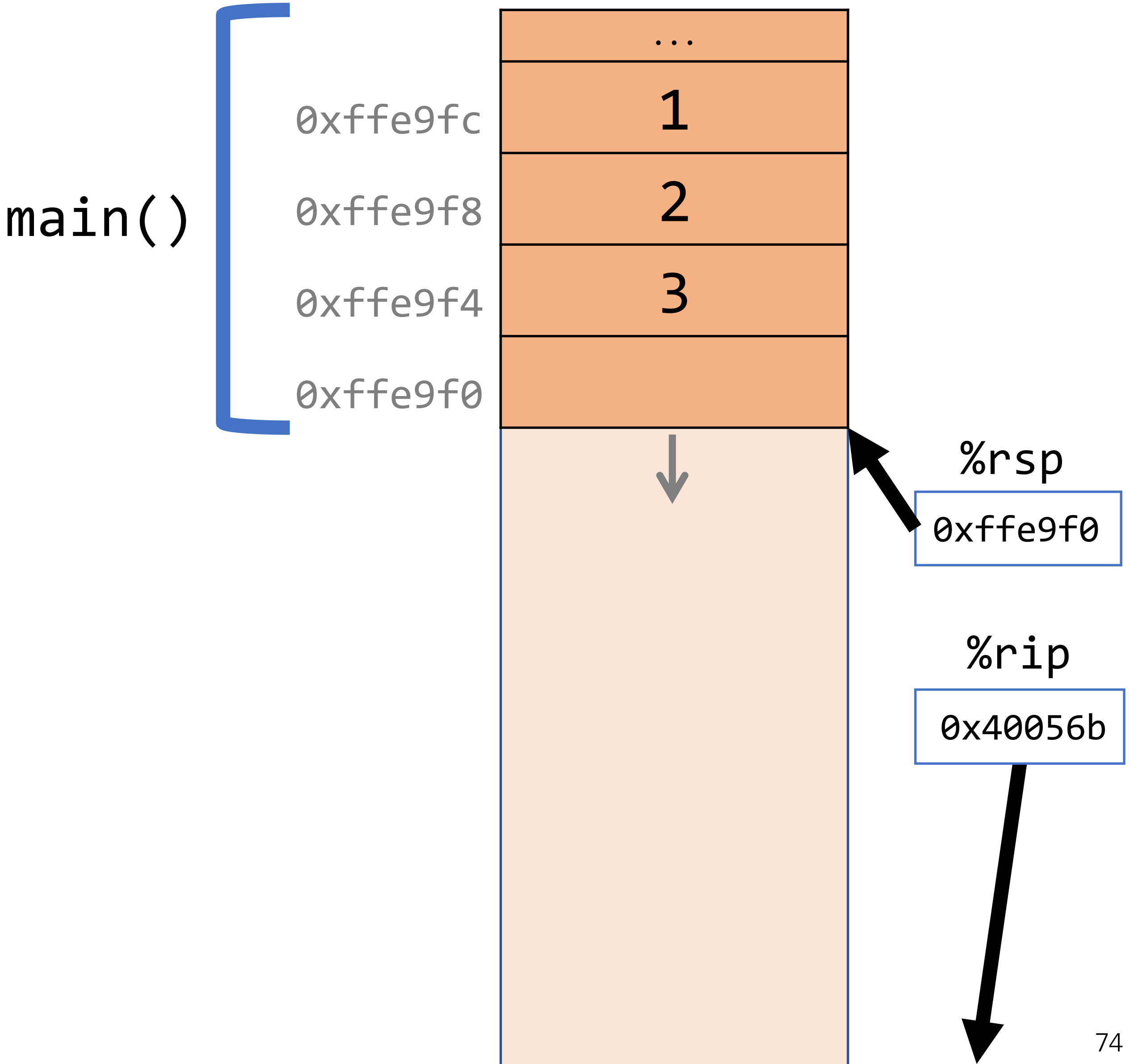
0x400563 <+20>:   movl   $0x3,0x4(%rsp)
0x40056b <+28>:   movl   $0x4,(%rsp)
0x400572 <+35>:   pushq  $0x4
```



Example 2: 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) {
    …
}
```

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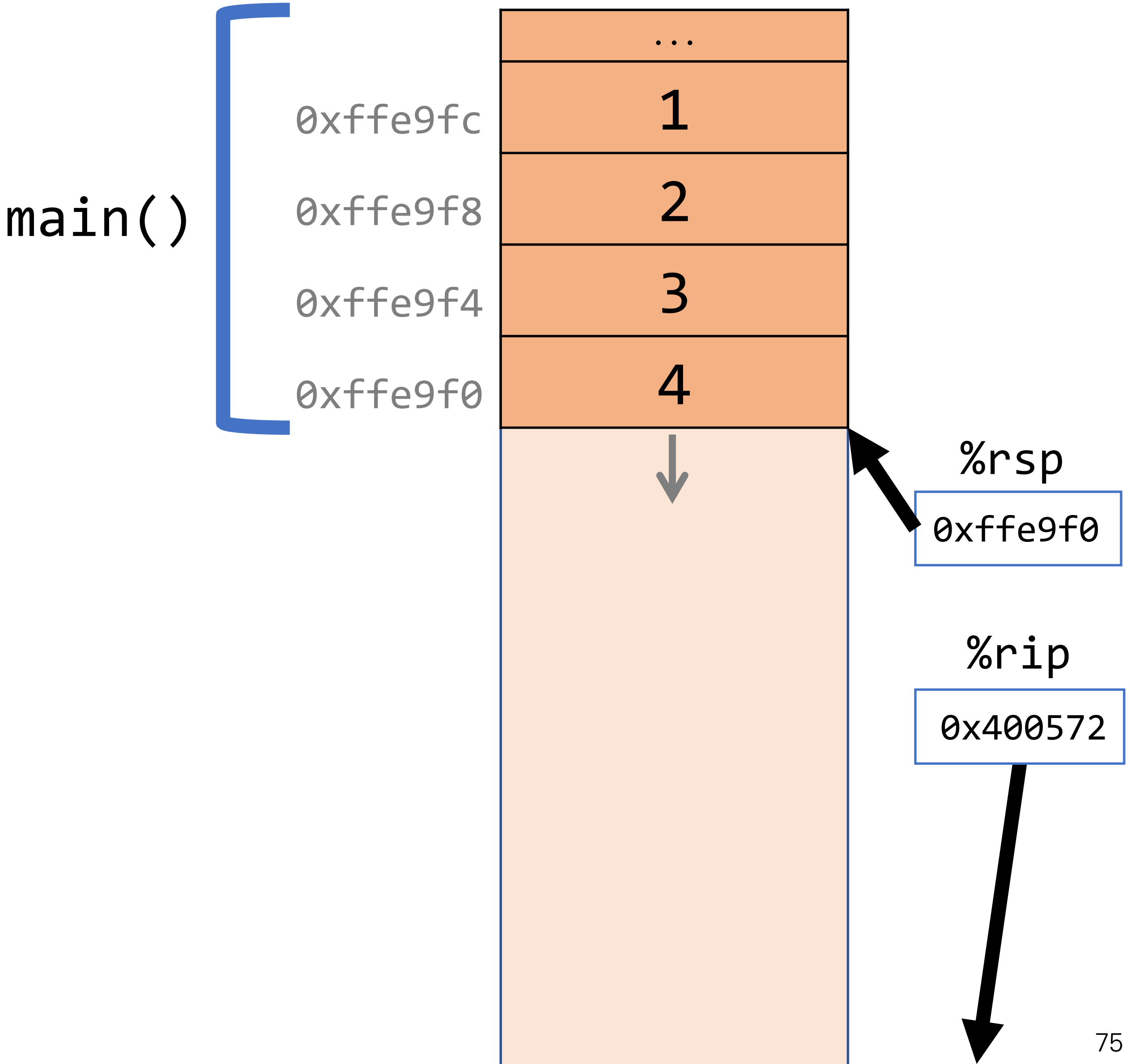
0x400572 <+35>:    pushq   $0x4
0x400574 <+37>:    pushq   $0x3
```



Example 2: Parameters and Return

```
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    int i1 = 1;
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    int i3 = 3;
    int i4 = 4;
    int result = func(&i1, &i2, &i3, &i4,
                      i1, i2, i3, i4);
    …
}

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         int v1, int v2, int v3, int v4) {
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}
```

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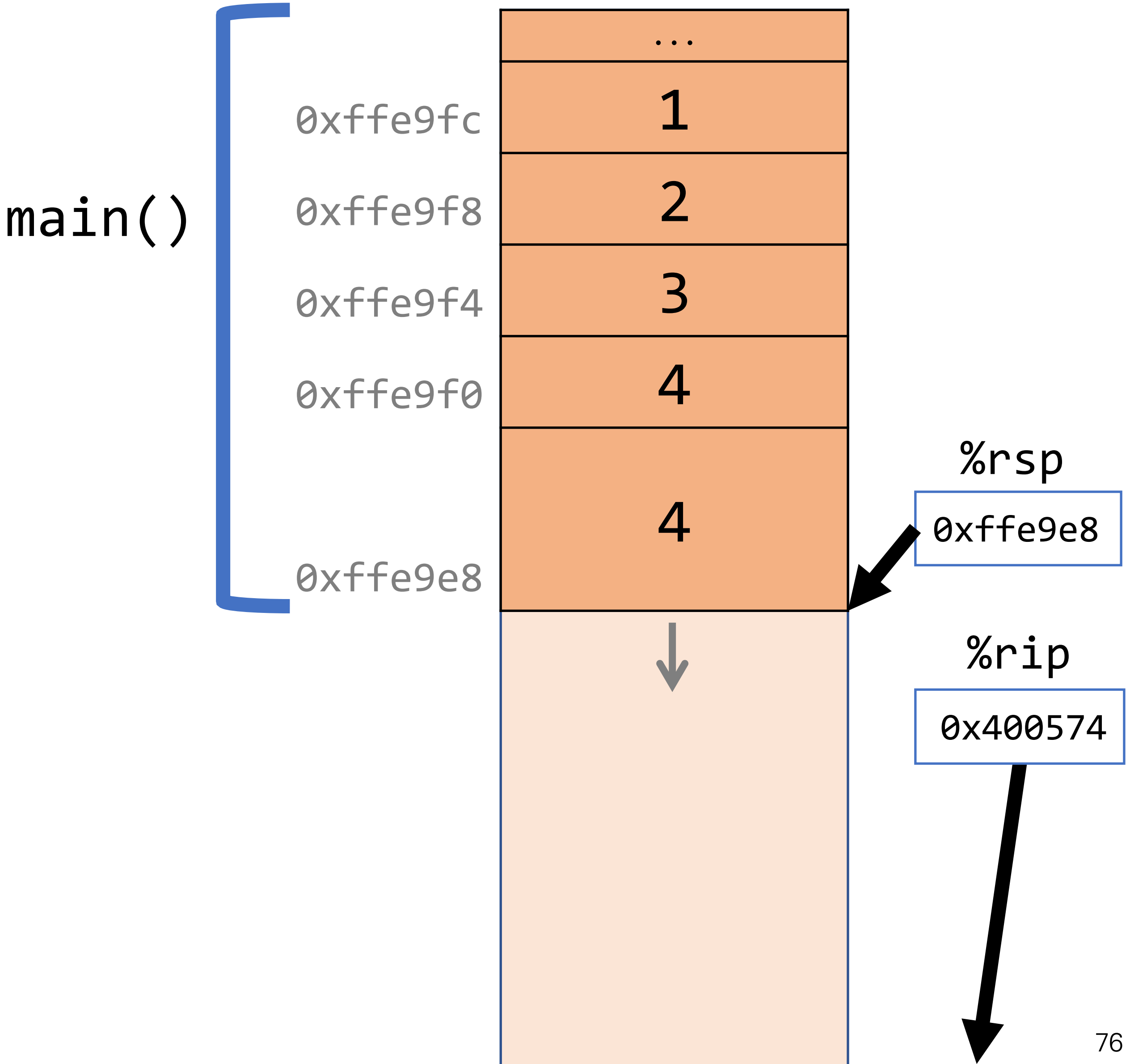
0x400572 <+35>:   pushq  $0x4
0x400574 <+37>:   pushq  $0x3
0x400576 <+39>:   mov    $0x2,%r9d
```



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```
int main(int argc, char *argv[]) {
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    …
}

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

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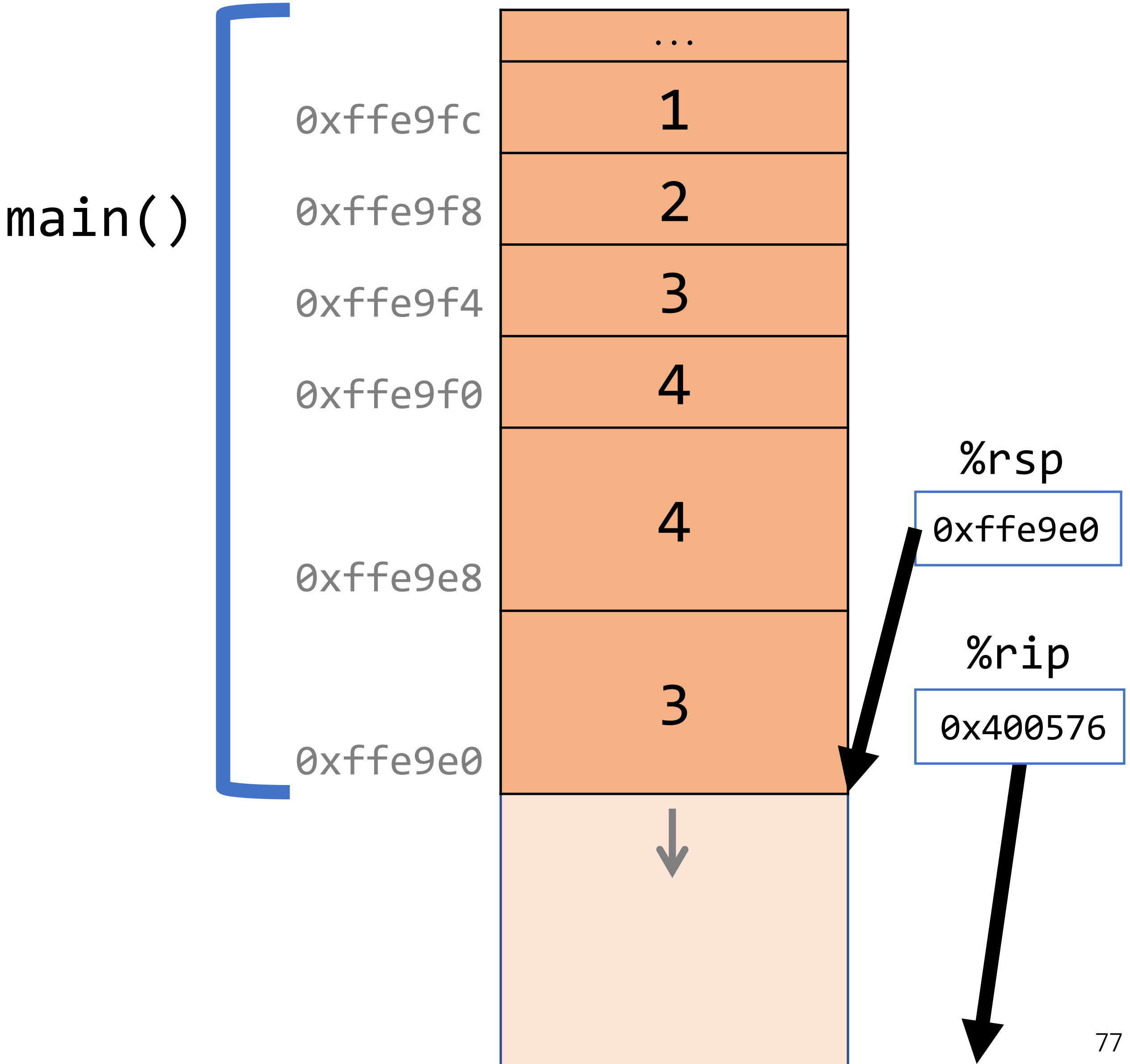
0x400572 <+35>:    pushq   $0x4
0x400574 <+37>:    pushq   $0x3
0x400576 <+39>:    mov     $0x2,%r9d
0x40057c <+45>:    mov     $0x1,%r8d
```



Example 2: Parameters and Return

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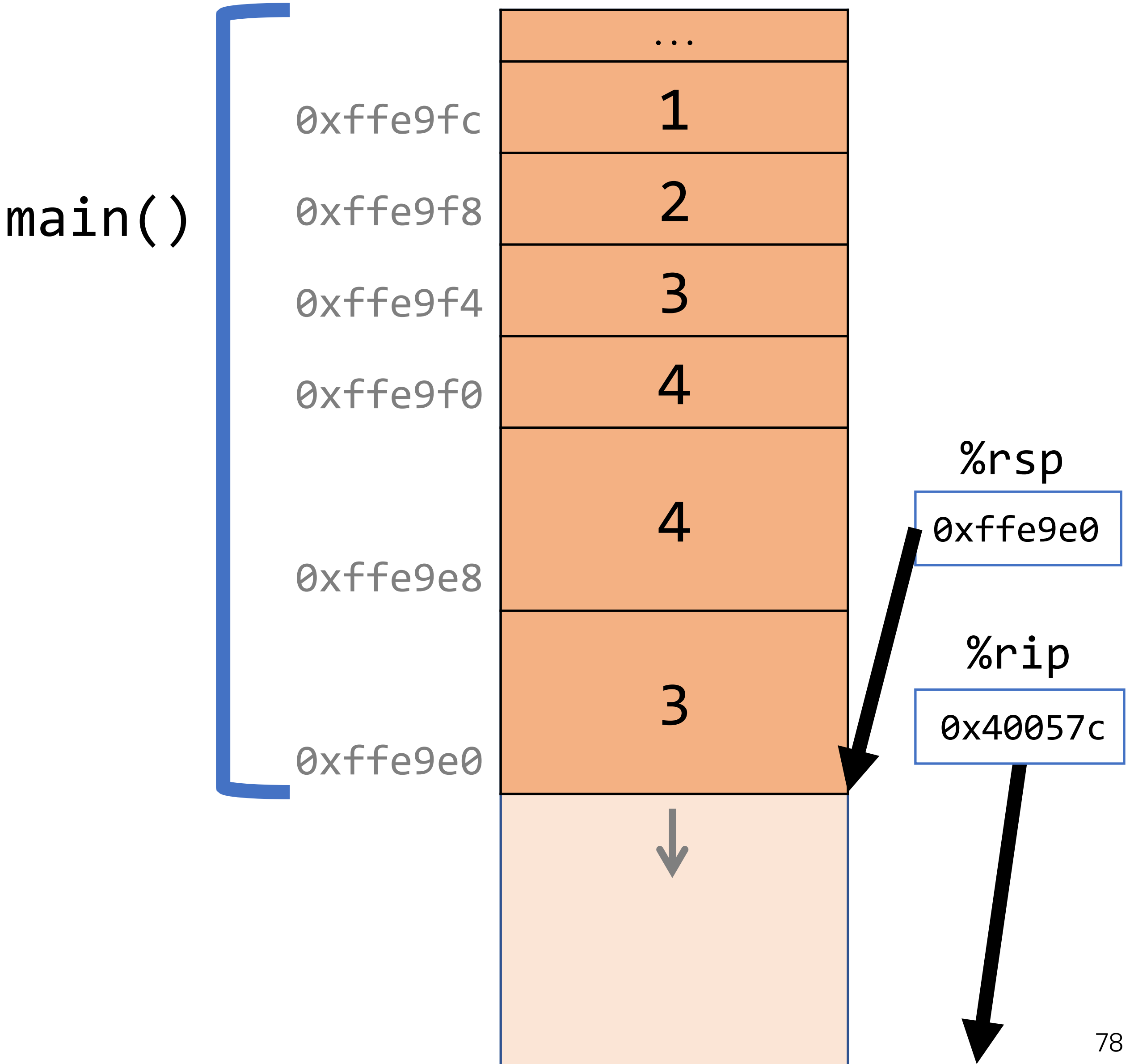
    …
}

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
```



Example 2: 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
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0x400582 <+51>:    lea    0x10(%rsp),%rcx
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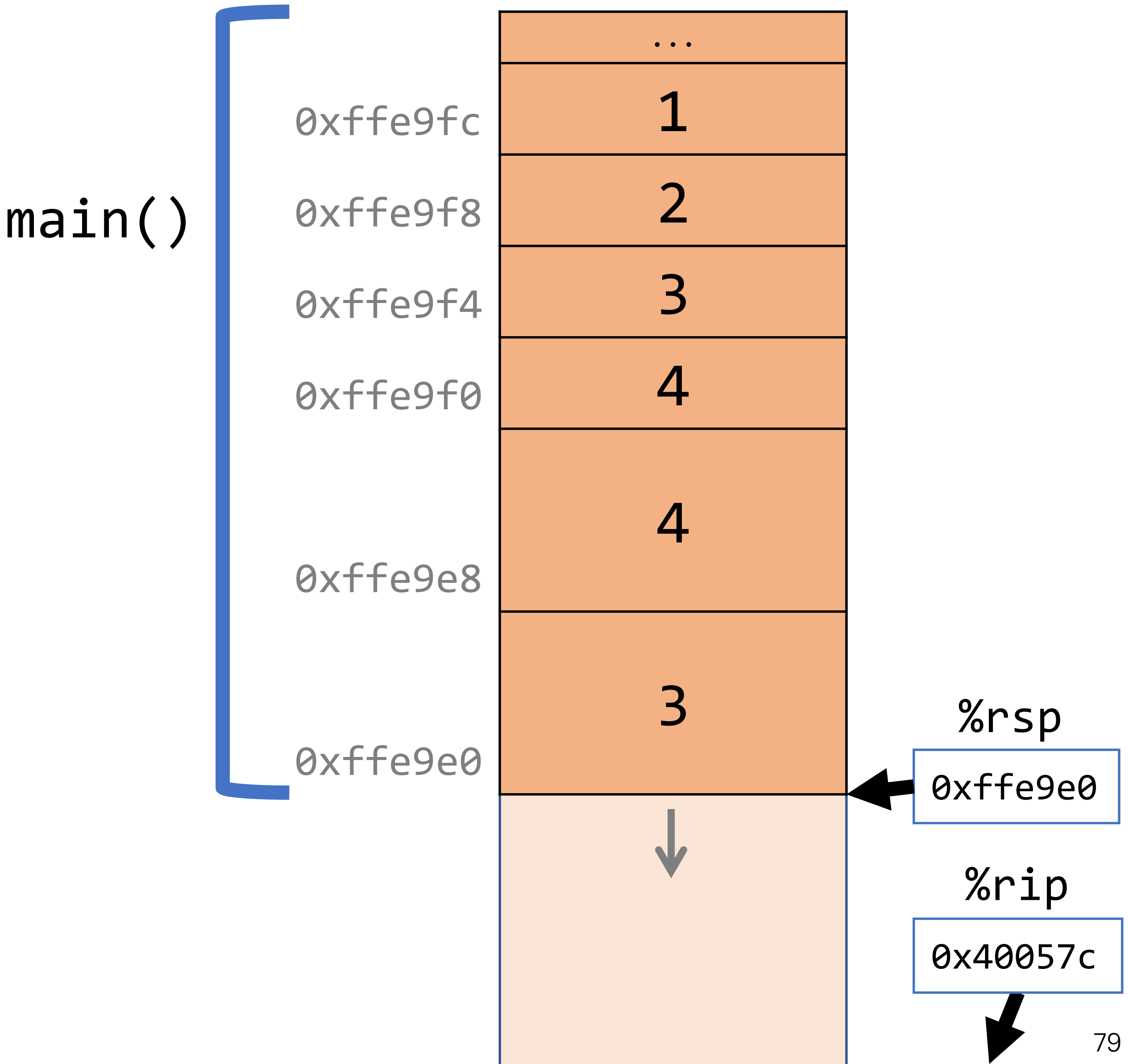
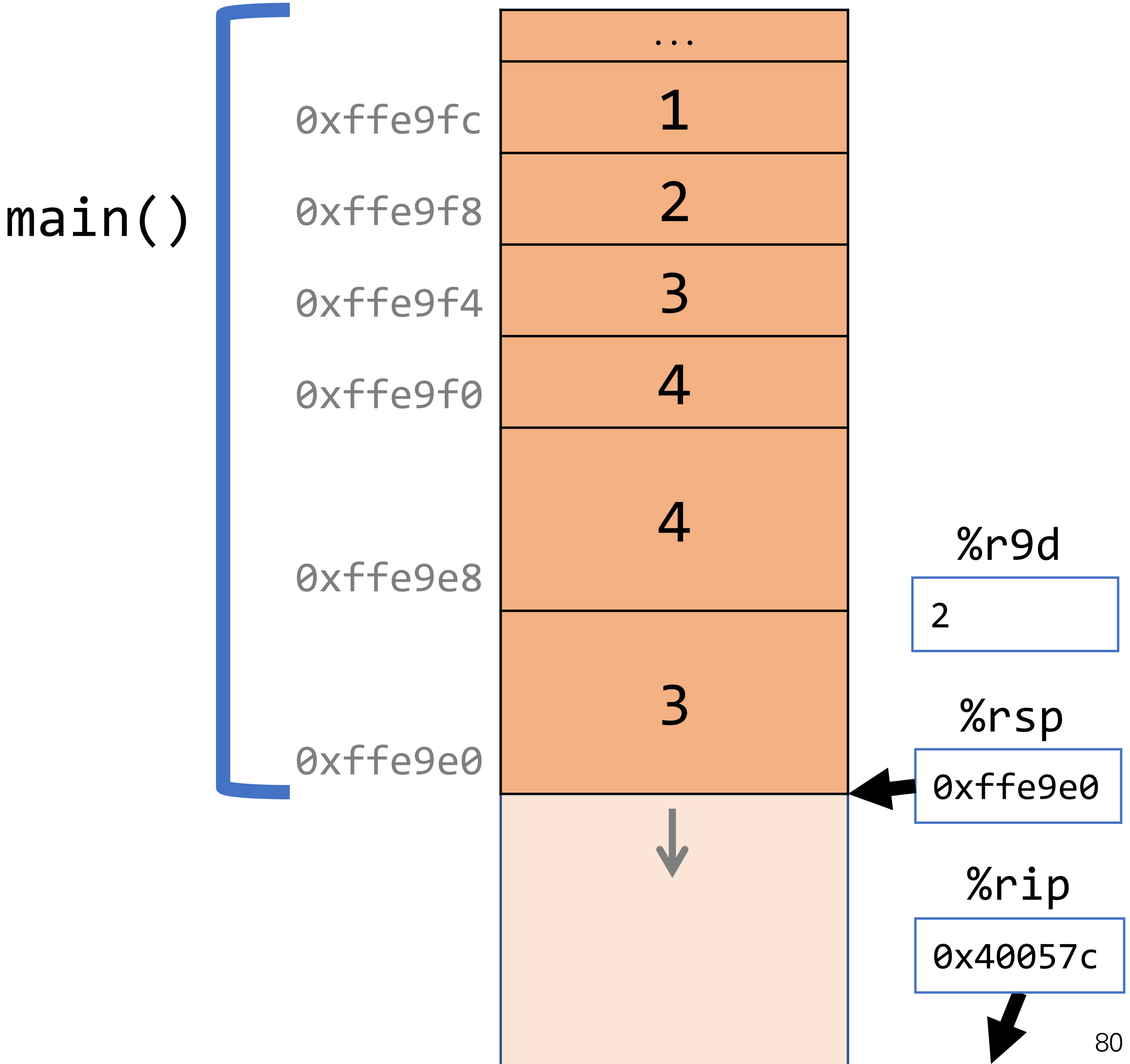


Example 2: Parameters and Return

```
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
```

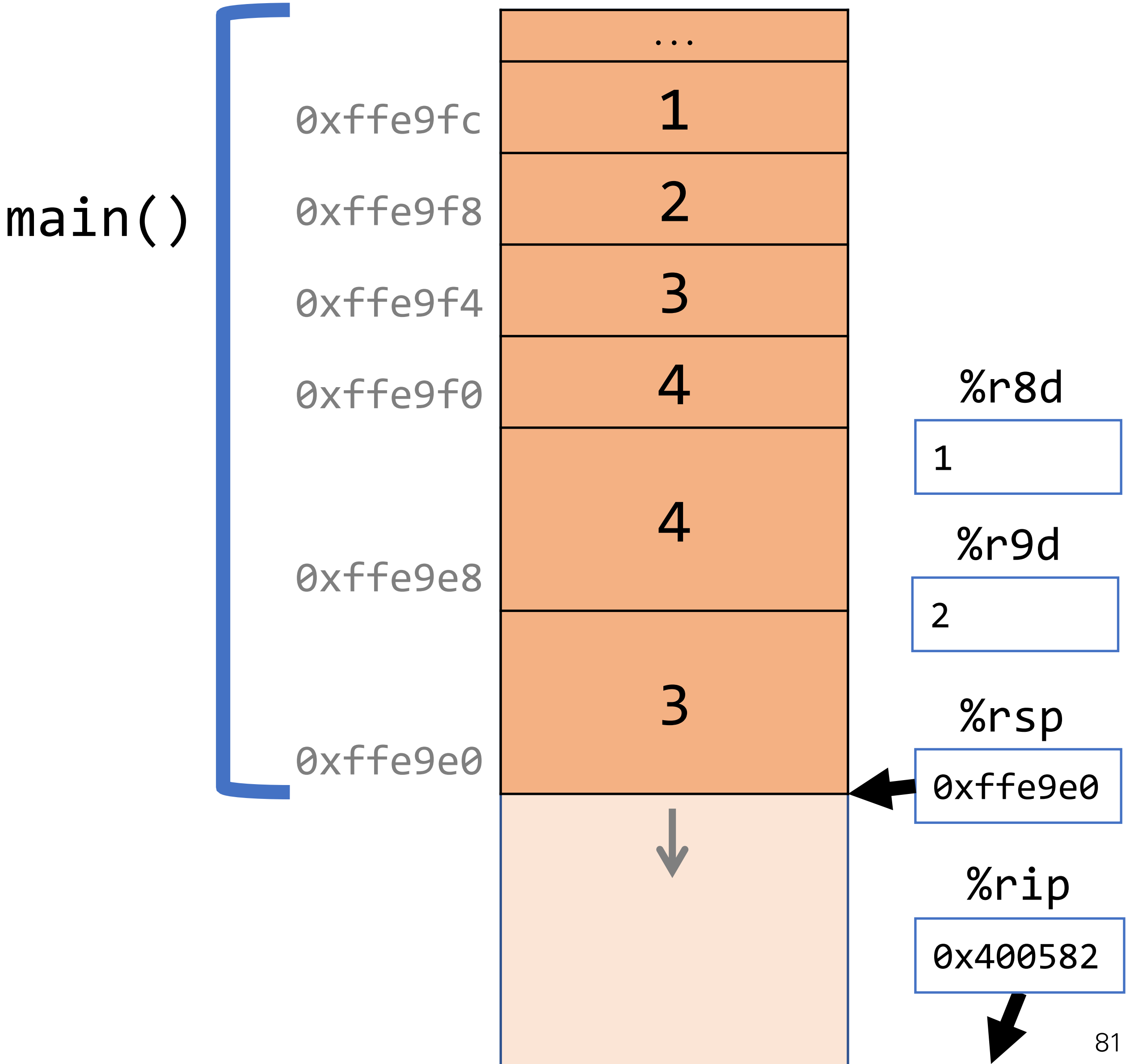


Example 2: Parameters and Return

```c
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
```

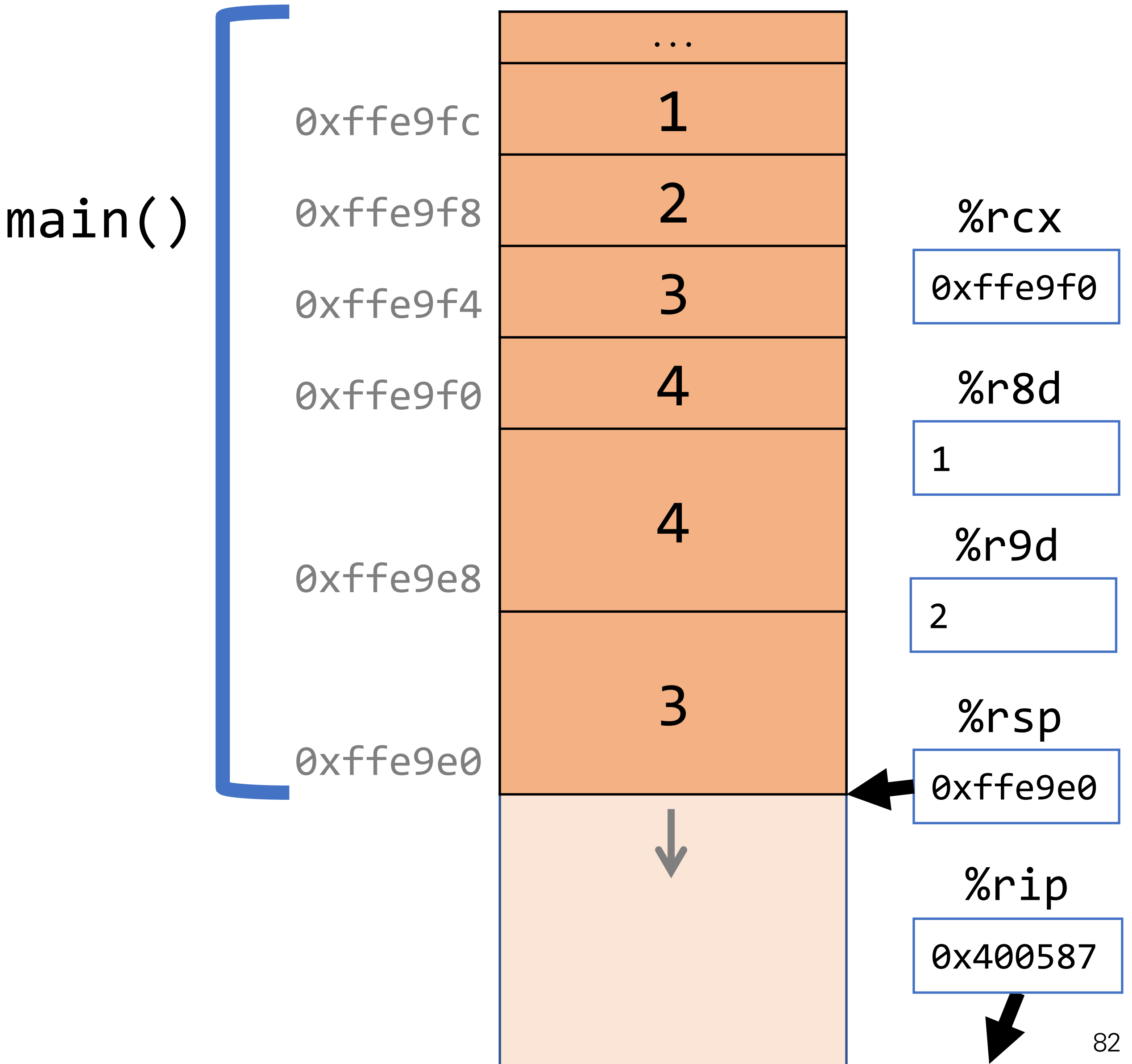


Example 2: Parameters and Return

```
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
```

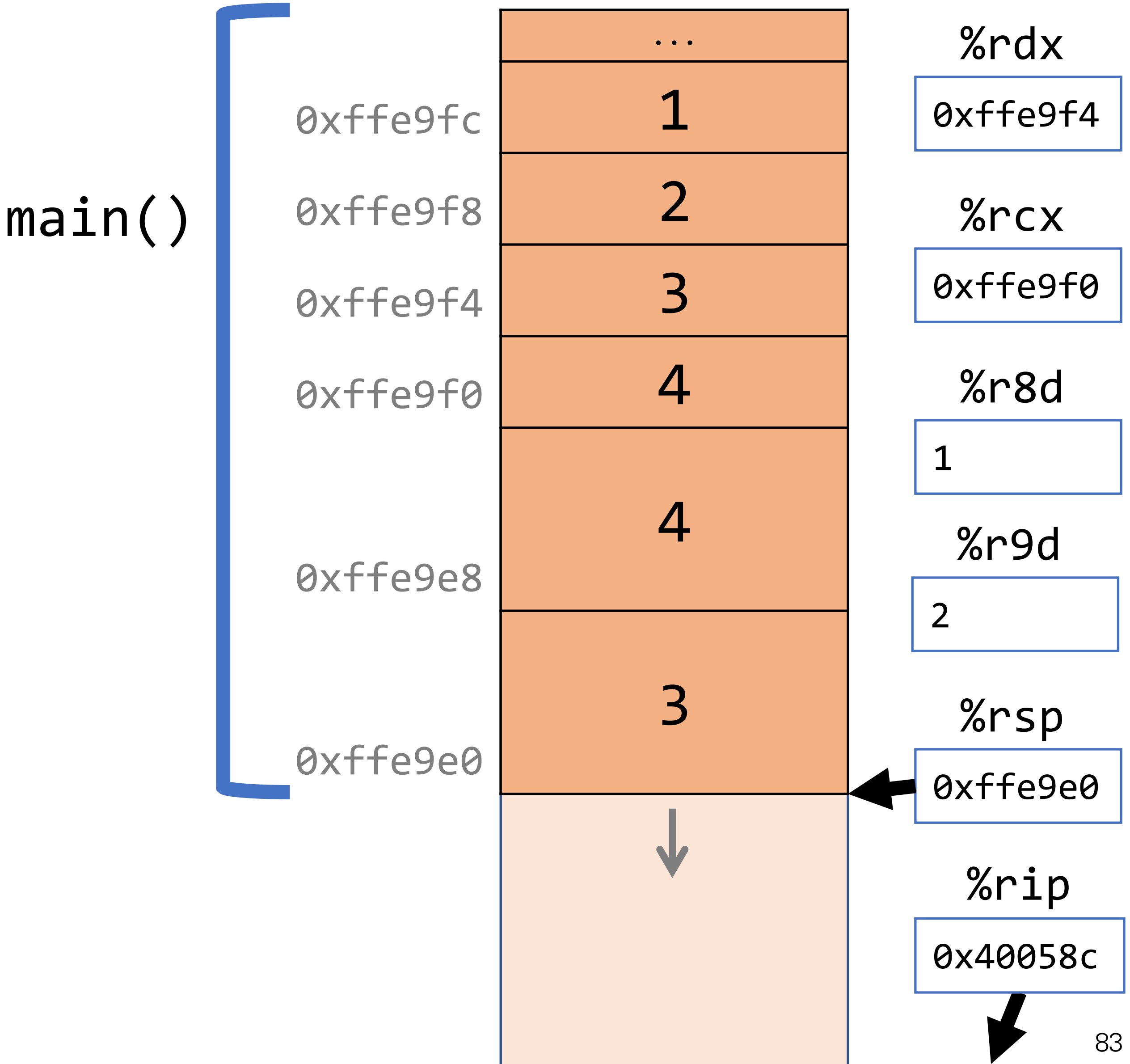


Example 2: Parameters and Return

```
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
```

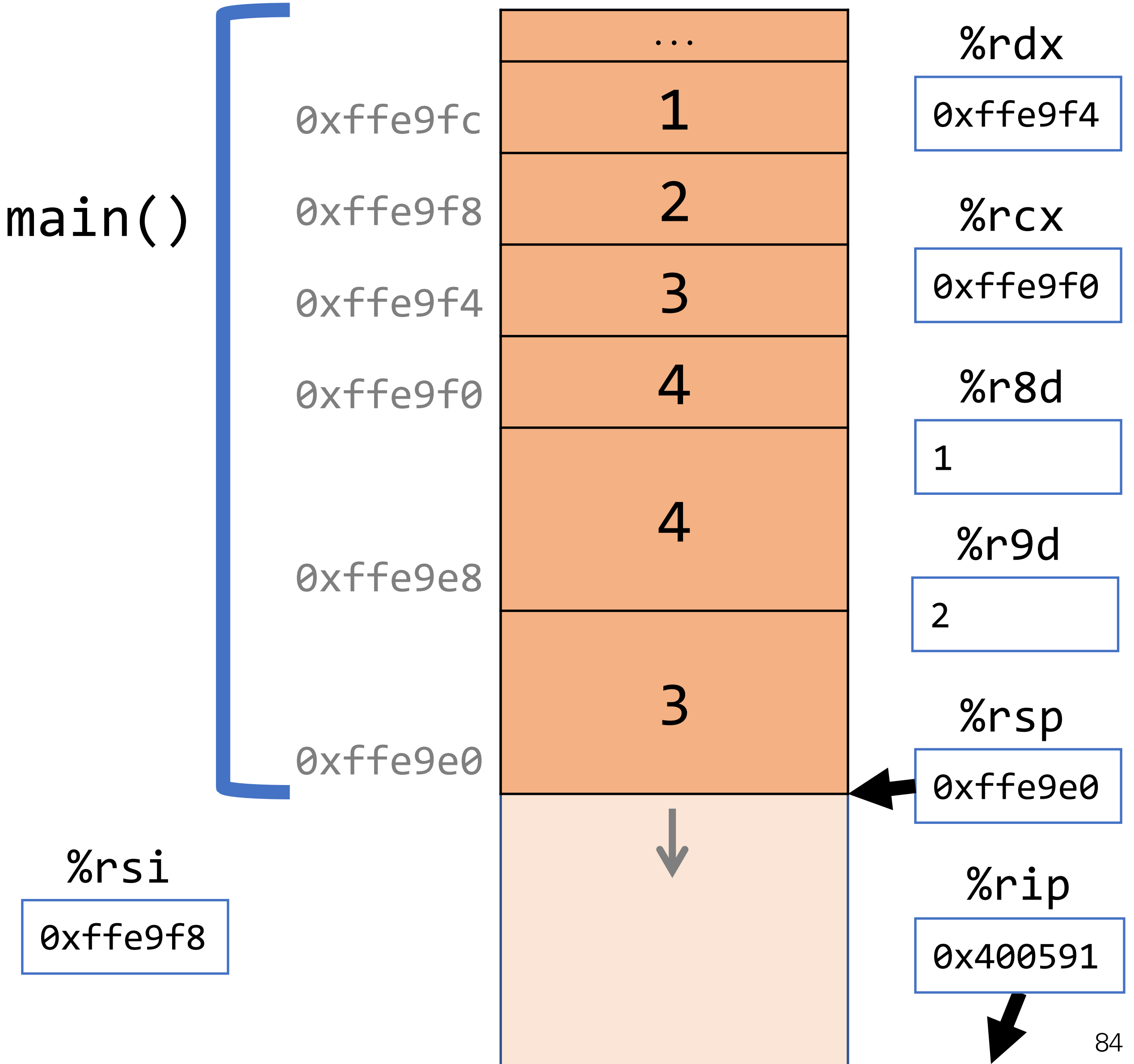


Example 2: Parameters and Return

```
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>
```

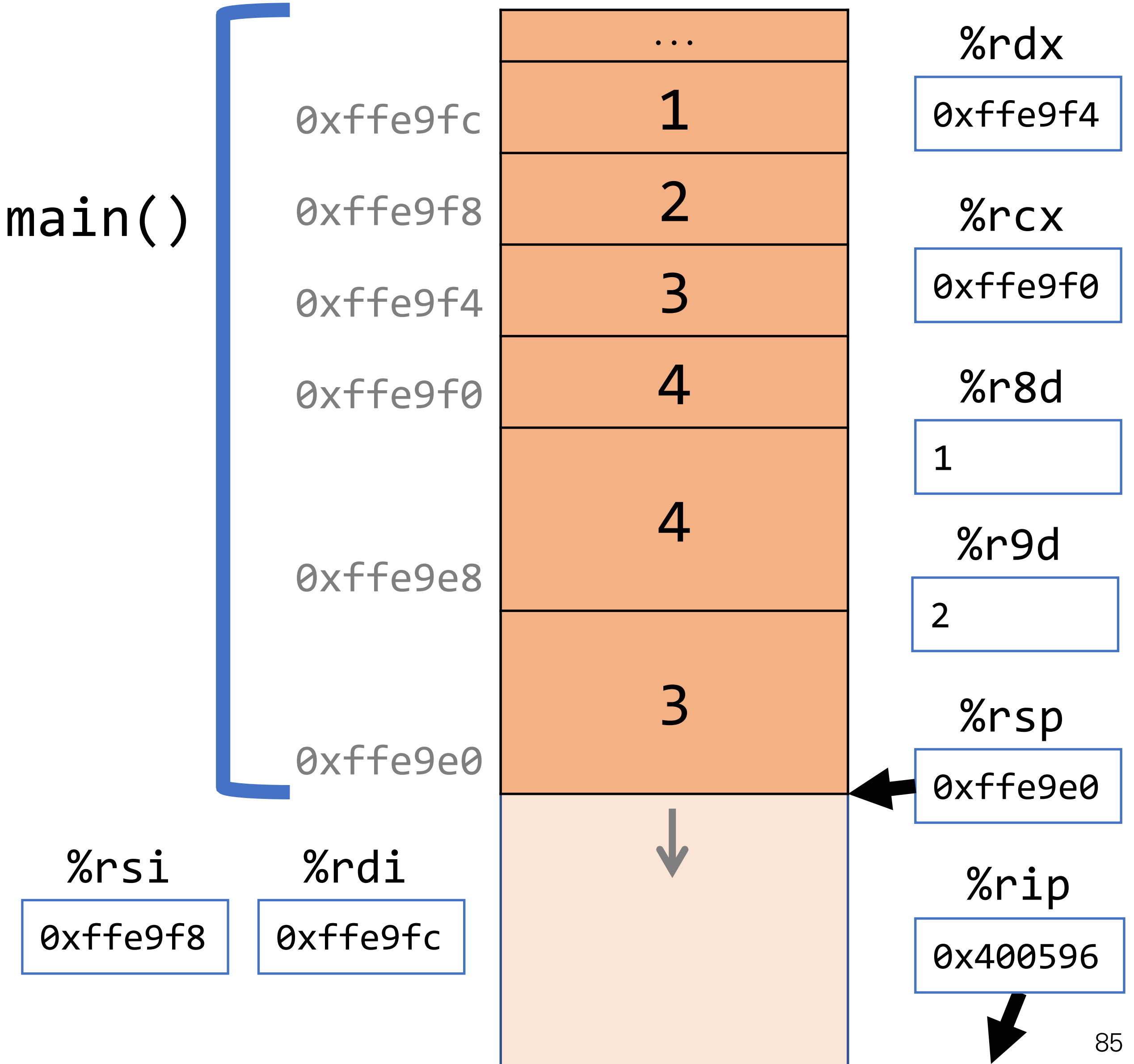


Example 2: Parameters and Return

```
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
```



Example 2: 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>
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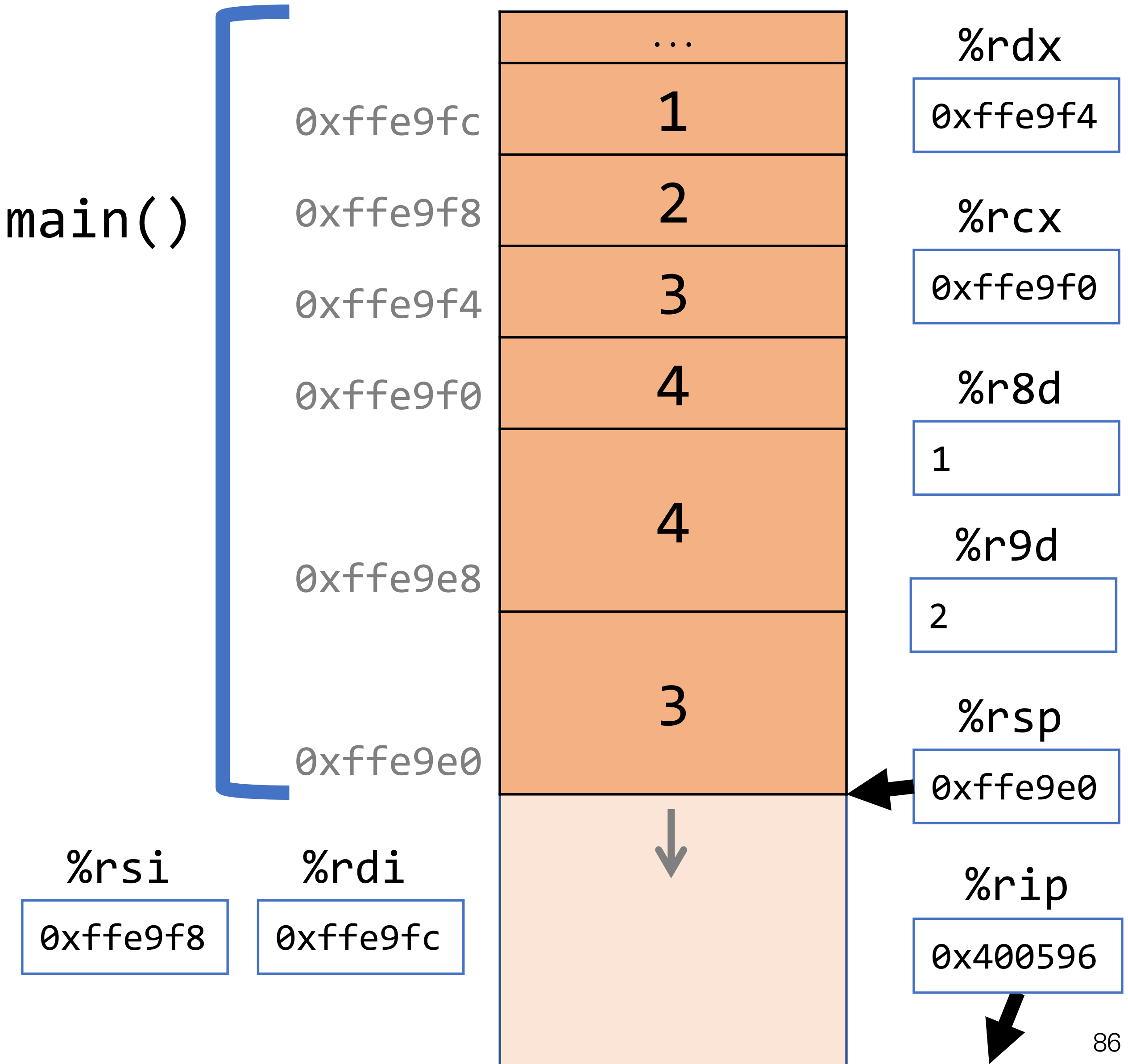
…
```



Example 2: 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
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…
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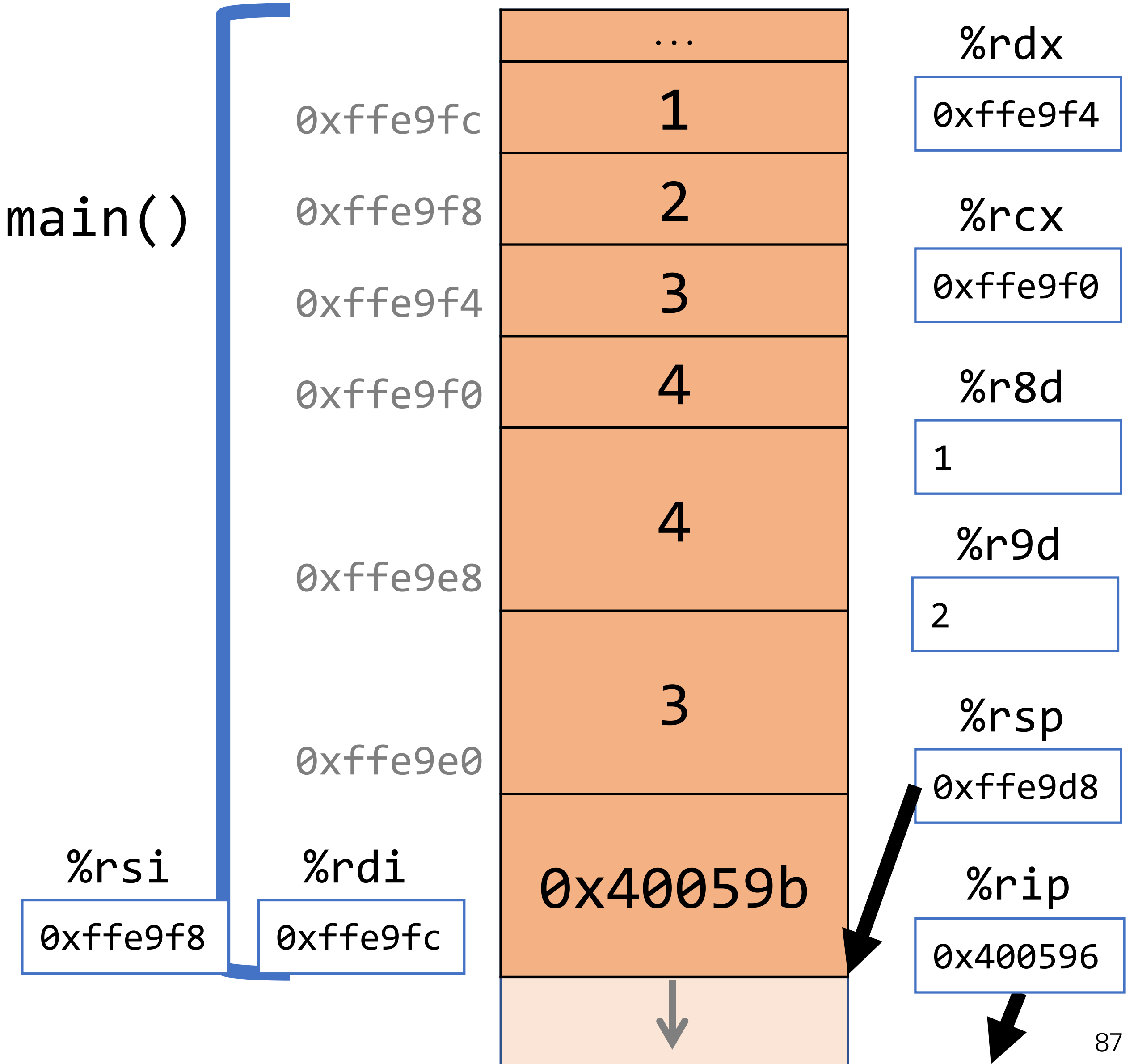

Lecture Plan

- Revisiting `%rip`
- Calling Functions
  - The Stack
  - Passing Control
  - 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 $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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Register Restrictions

- When procedure `yoo` calls `who`:
  - `yoo` is the **caller**
  - `who` is the **callee**
- Can register be used for temporary storage?

```
yoo:
    • • •
    movq $15213, %rdx
    call who
    addq %rdx, %rax
    • • •
    ret
```

```
who:
    • • •
    subq $18213, %rdx
    • • •
    ret
```

  - Contents of register `%rdx` overwritten by `who`
  - This could be trouble → something should be done!
    - Need some coordination

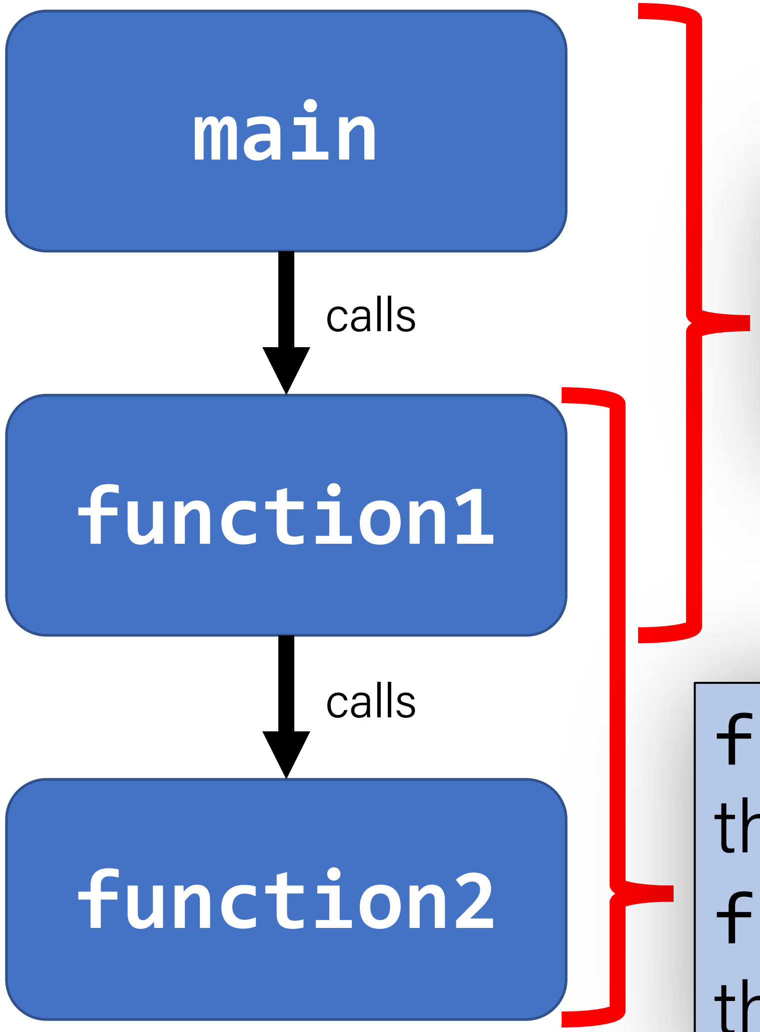
Register Restrictions

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).



`main` is the caller, and `function1` is the callee.

`function1` is the caller, and `function2` is the callee.

Register Restrictions

Caller-Owned (Callee Saved)

- 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 (Caller Saved)

- 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.

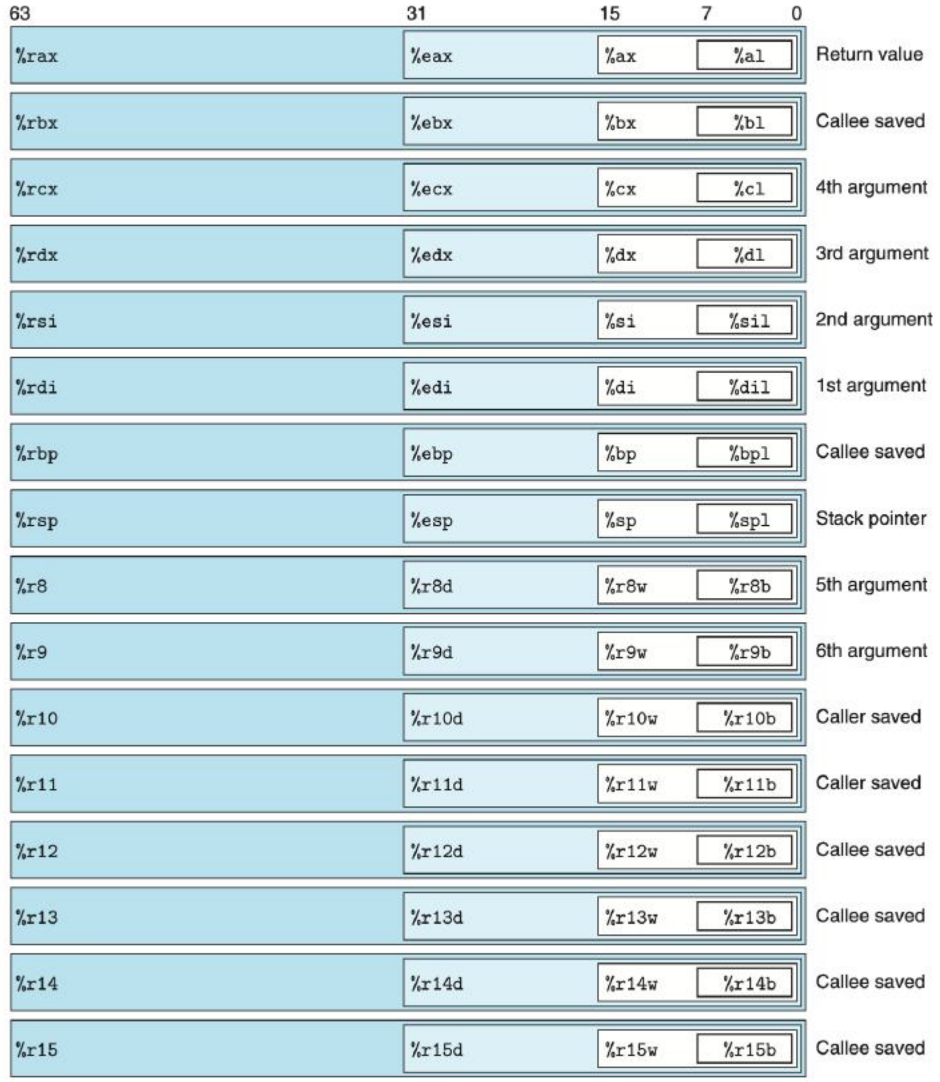
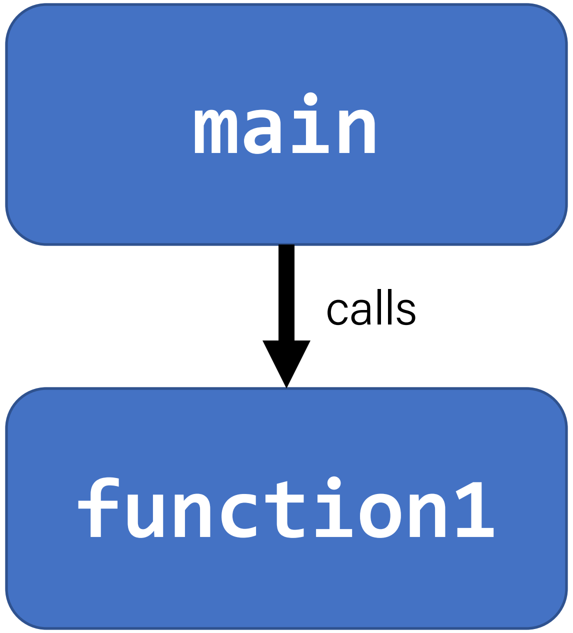


Figure 3.2 Integer registers. The low-order portions of all 16 registers can be accessed as byte, word (16-bit), double word (32-bit), and quad word (64-bit) quantities.

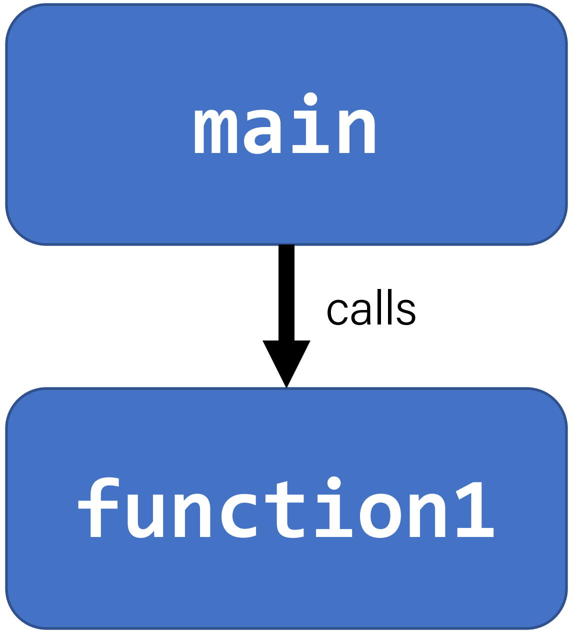
Caller-Owned Registers



`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
```

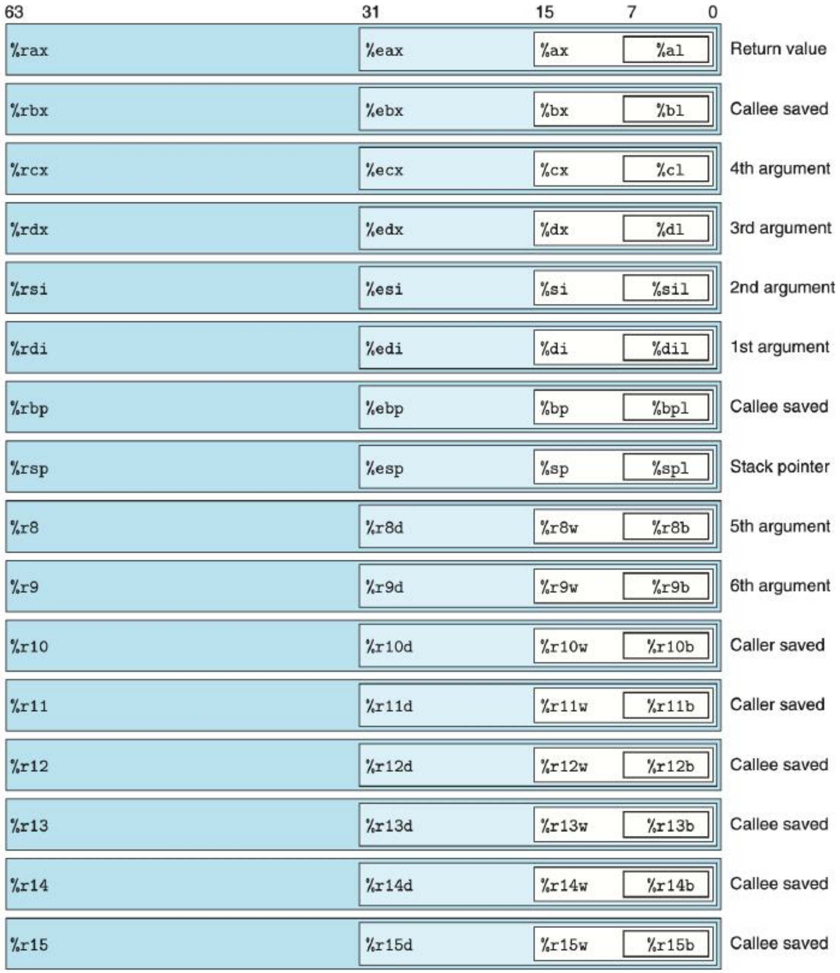
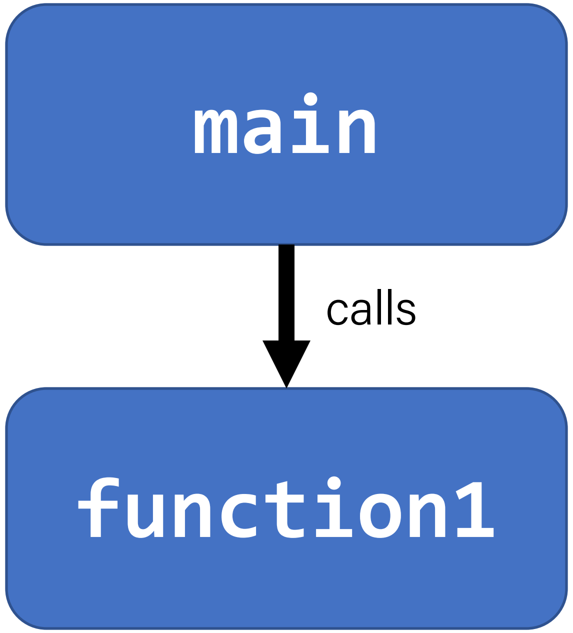


Figure 3.2 **Integer registers.** The low-order portions of all 16 registers can be accessed as byte, word (16-bit), double word (32-bit), and quad word (64-bit) quantities.

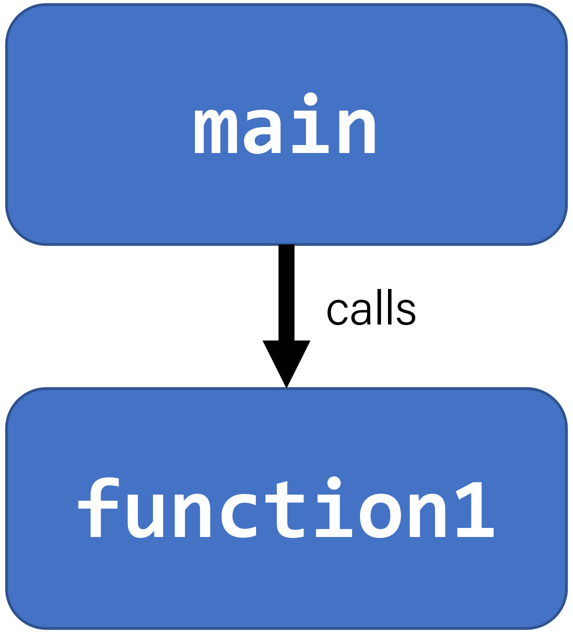
Callee-Owned Registers



`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
   ...
```

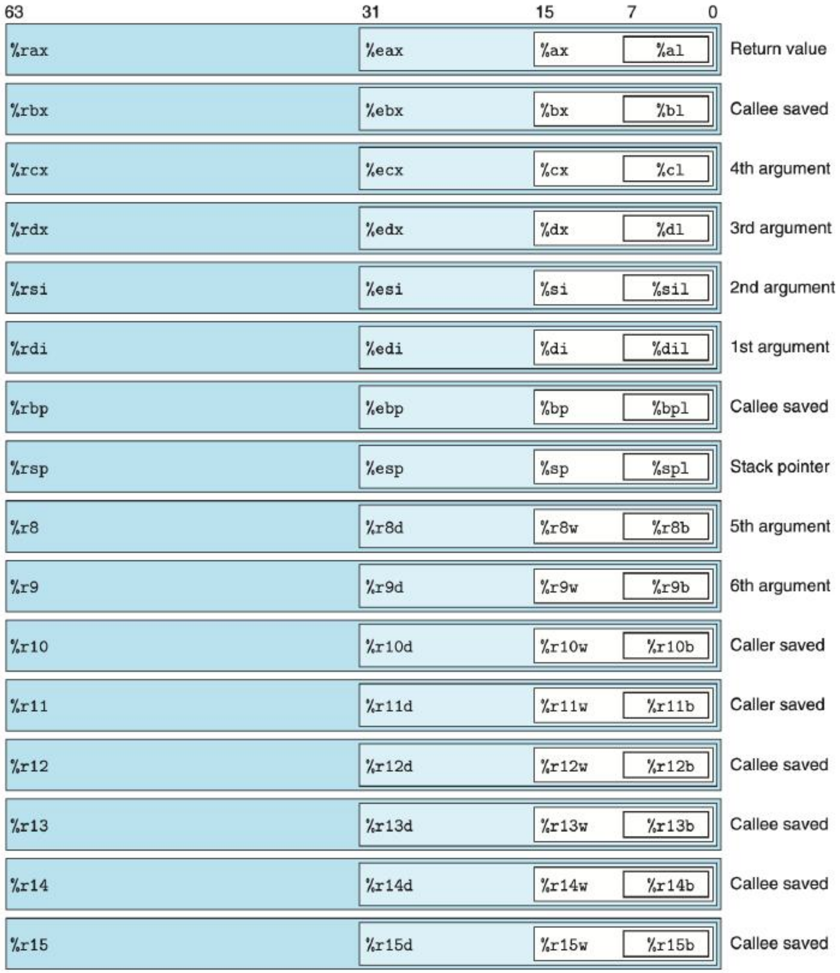
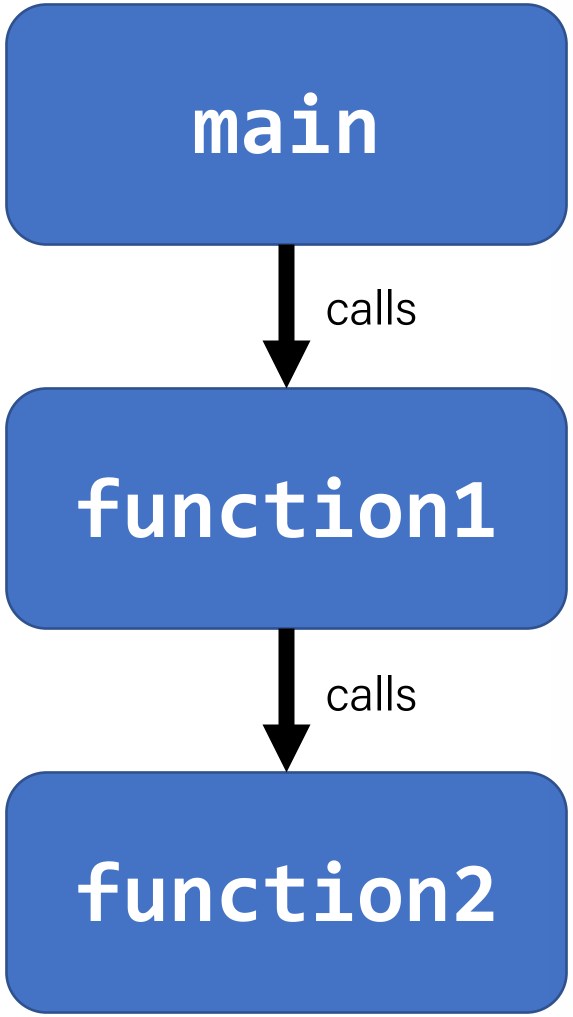


Figure 3.2 **Integer registers.** The low-order portions of all 16 registers can be accessed as byte, word (16-bit), double word (32-bit), and quad word (64-bit) quantities.

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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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!

https://godbolt.org/z/f43dz1

`factorial.c` and `factorial`

Our First Assembly

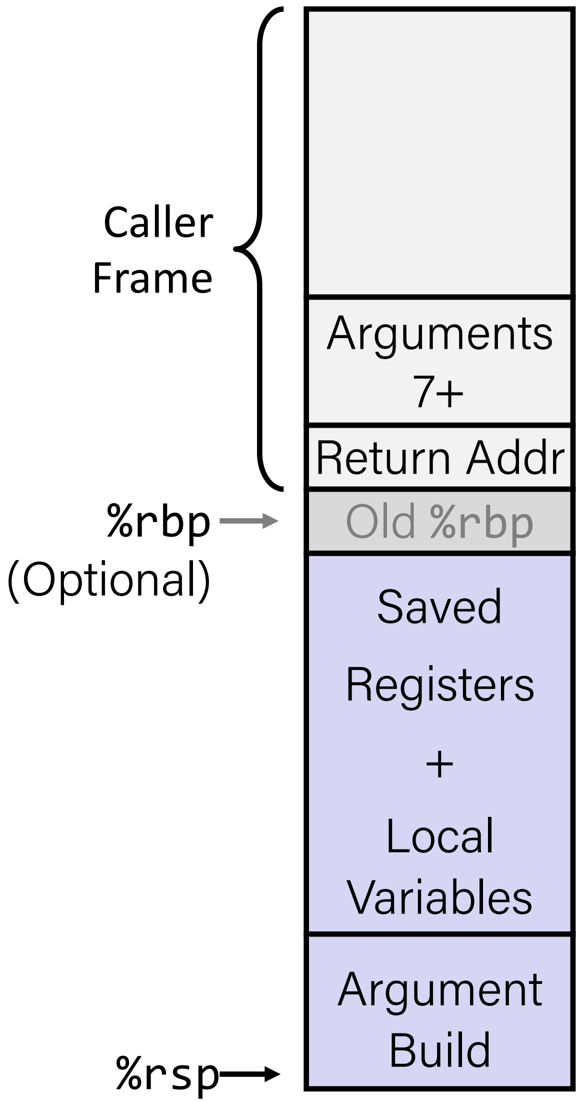
```
int sum_array(int arr[], int nelems) {
    int sum = 0;
    for (int i = 0; i < nelems; i++) {
        sum += arr[i];
    }
    return sum;
}
```

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
```

x86-64 Procedure Summary

- Important Points
  - Stack is the right data structure for procedure call/return
    - If P calls Q, then Q returns before P
- Recursion (& mutual recursion) handled by normal calling conventions
  - Can safely store values in local stack frame and in callee-saved registers
  - Put function arguments at top of stack
  - Result return in **`%rax`**
- Pointers are addresses of values
  - On stack or global



Recap

- Revisiting `%rip`
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Next time: *data stack frames*