COMP201

Computer Systems & Programming

Lecture #24 – x86-64 Procedures

KOÇ UNIVERSITY

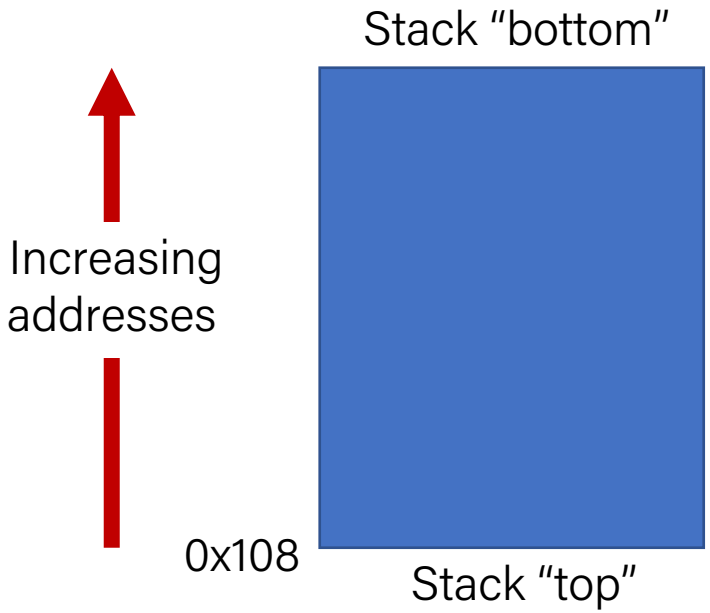
Aykut Erdem // Koç University // Fall 2020

Recap

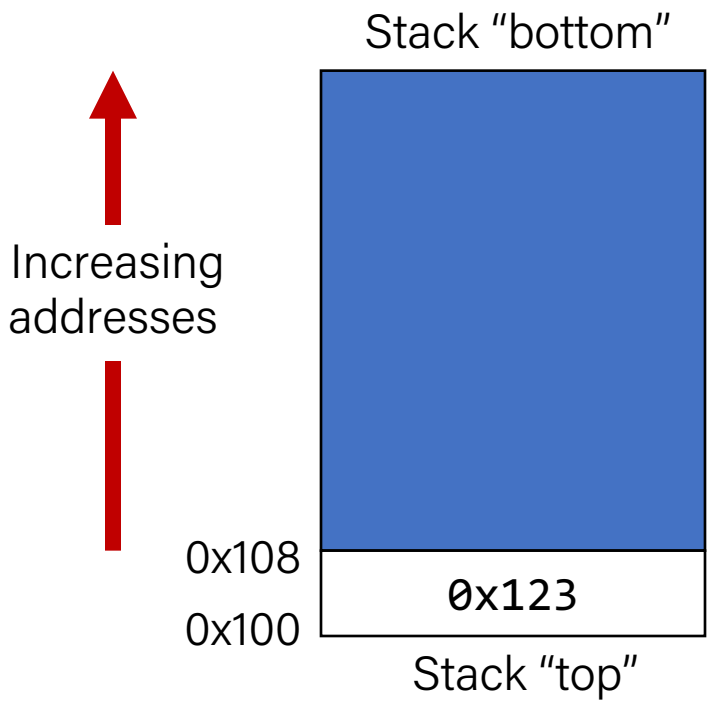
- Revisiting `%rip`
- Calling Functions
  - The Stack
  - Passing Control
  - Passing Data
  - Local Storage

Recap: The Stack

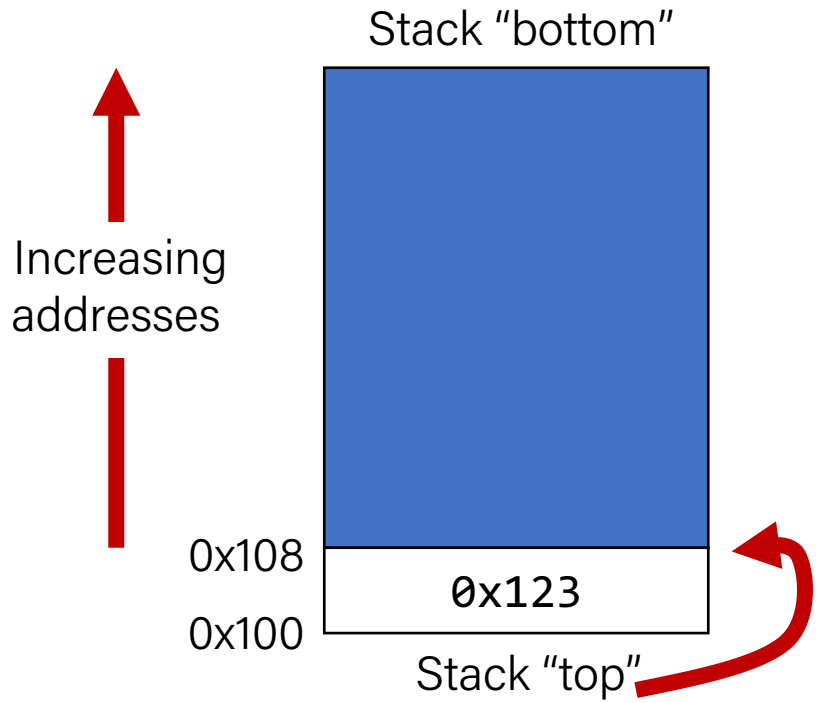
Initially	
%rax	0x123
%rdx	0
%rsp	0x108



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



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



Recap: 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.

Recap: 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).

Plan for Today

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

Lecture Plan

- 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.

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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```
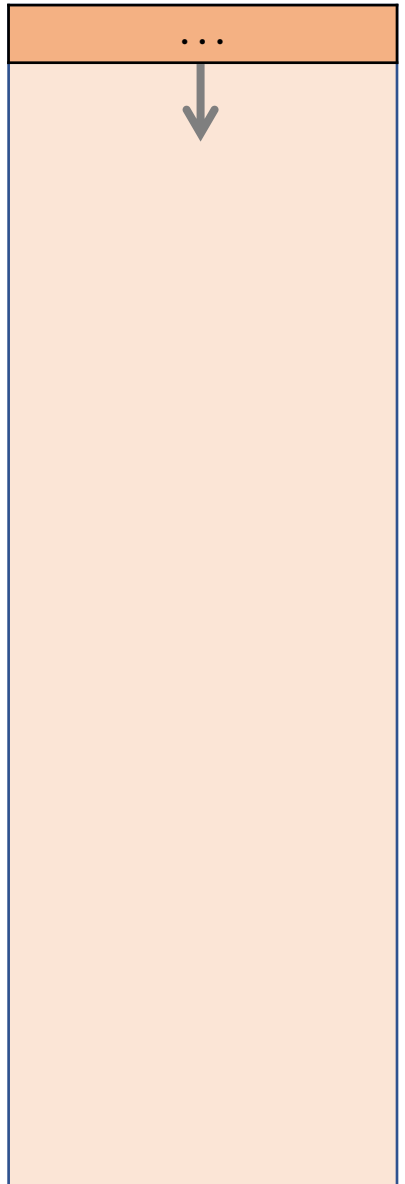

main() ⊂



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```

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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)
```

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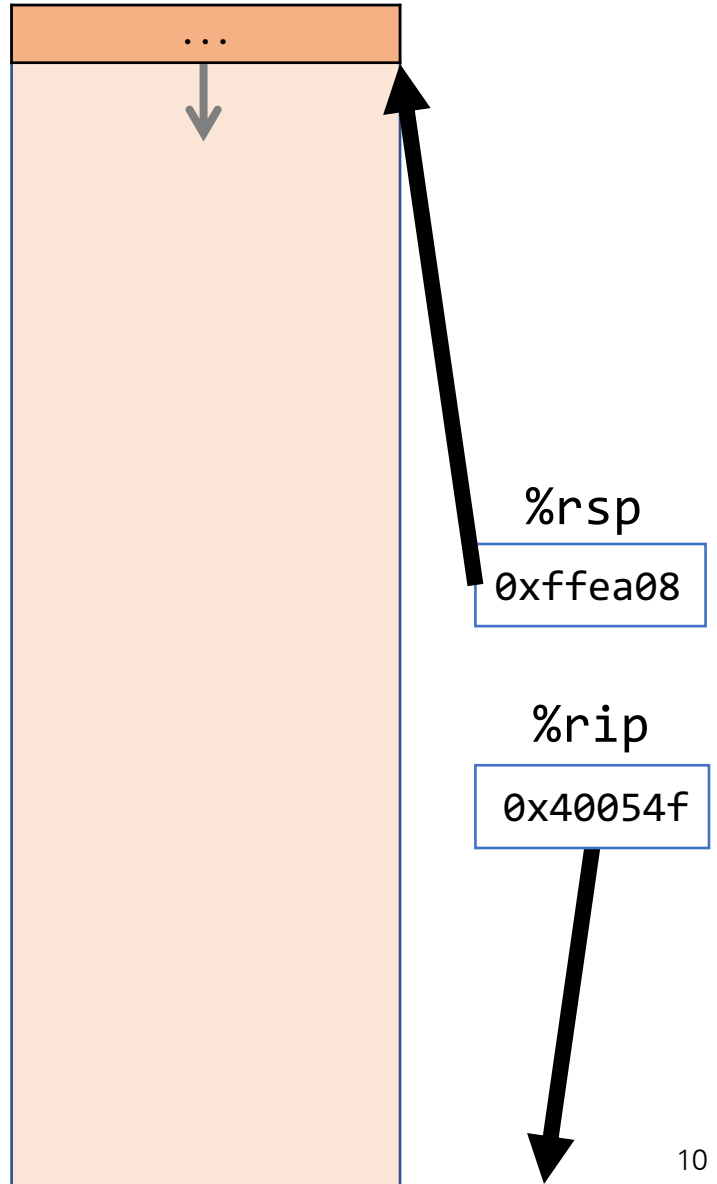

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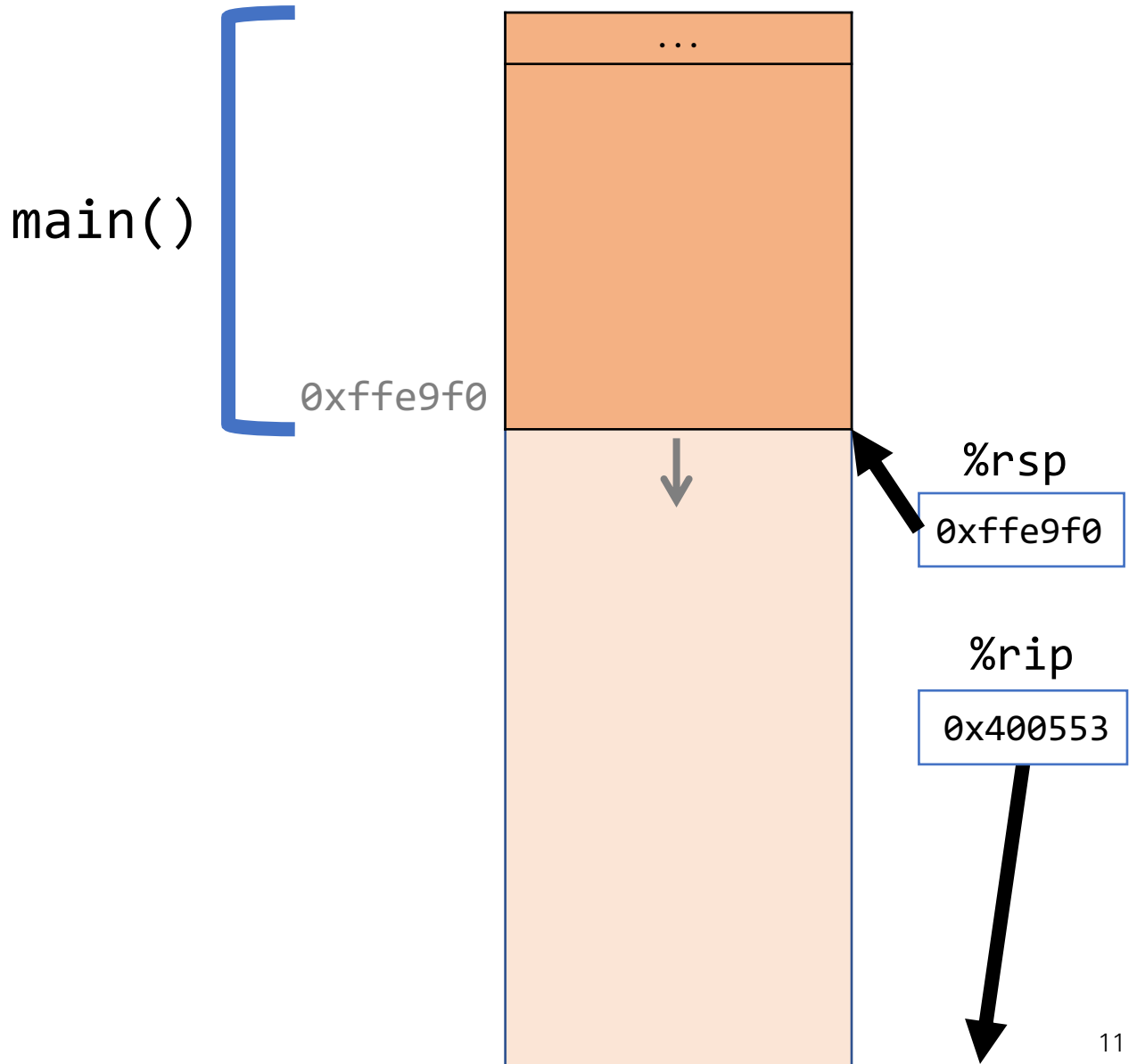

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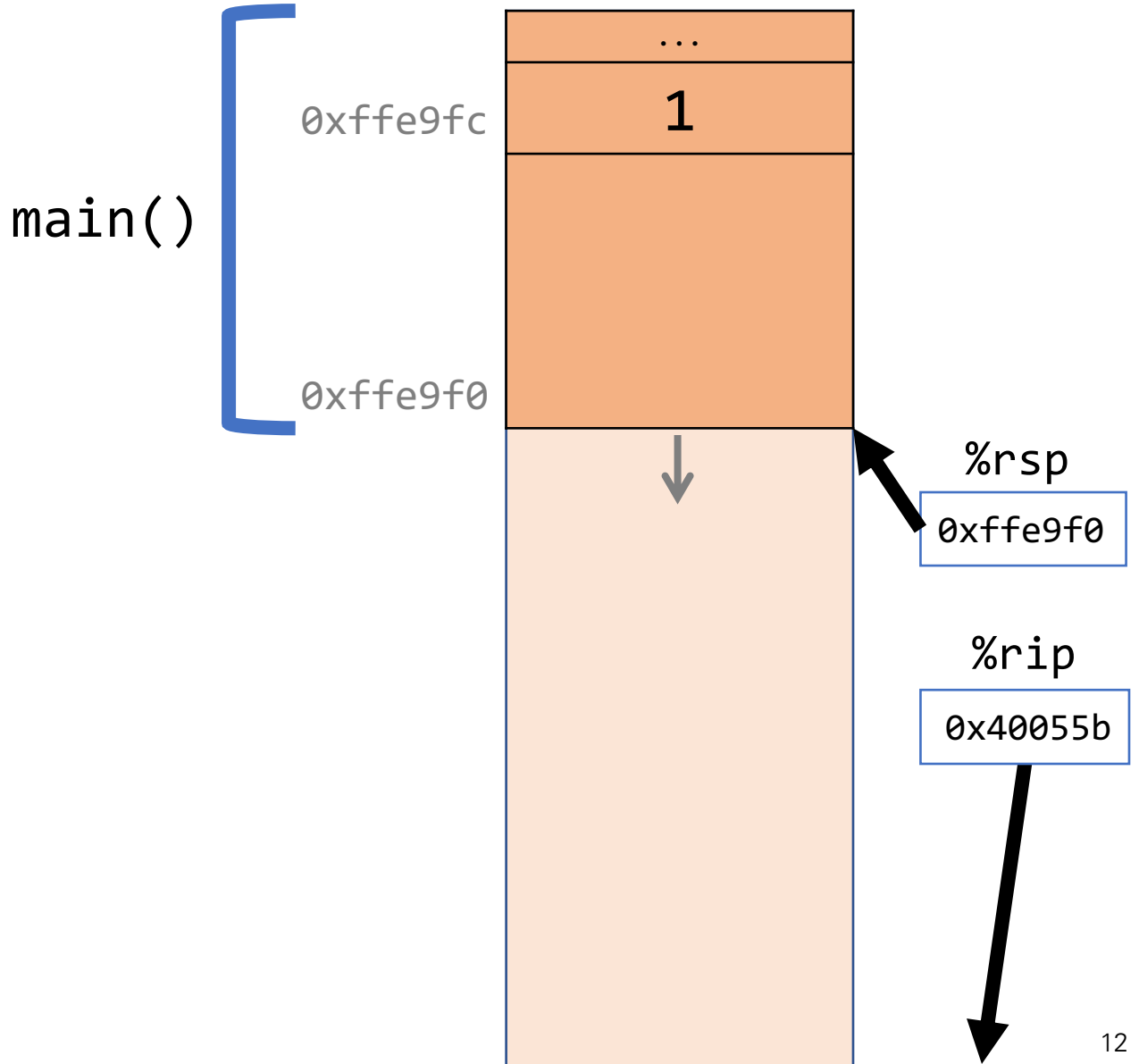

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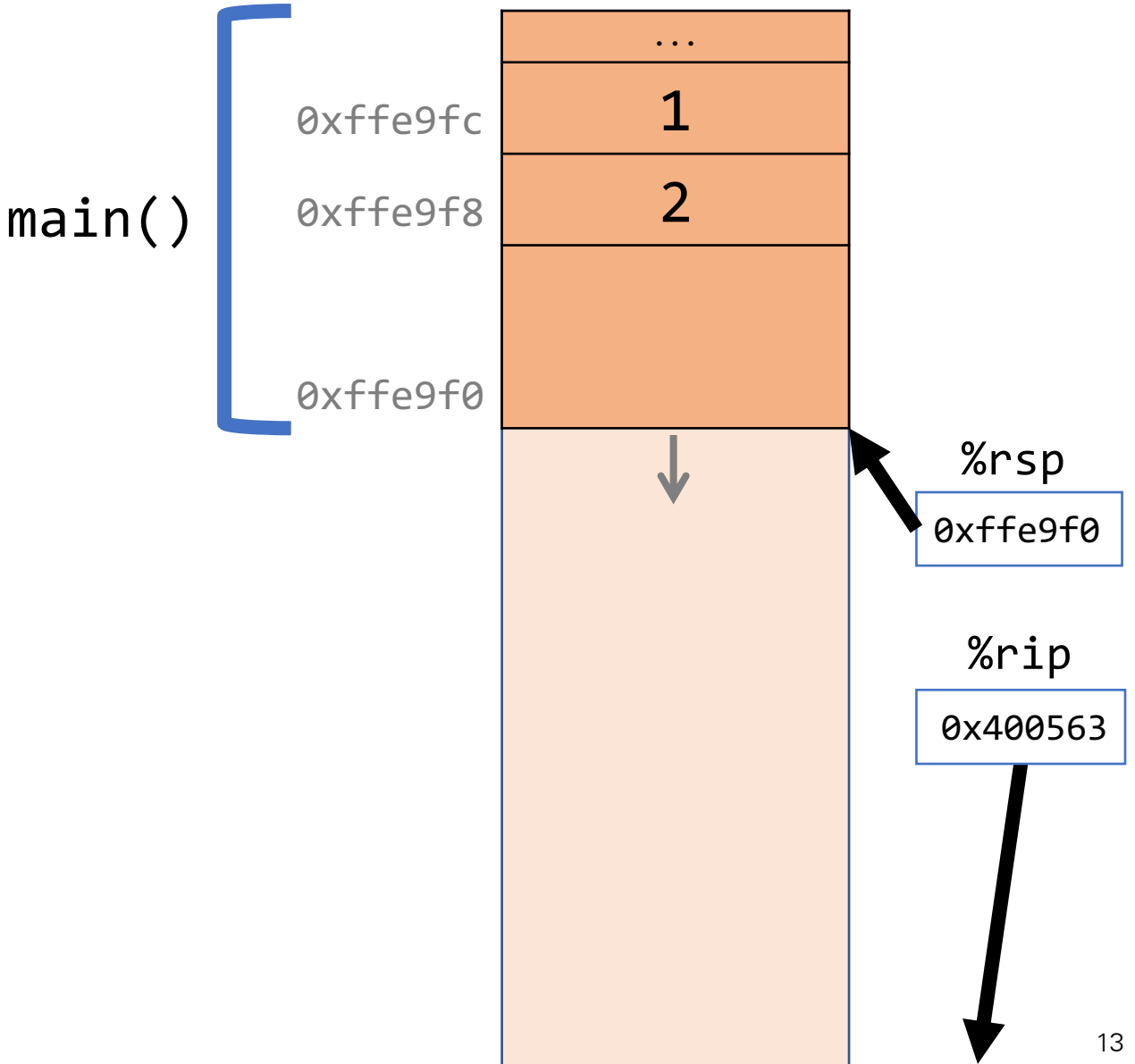

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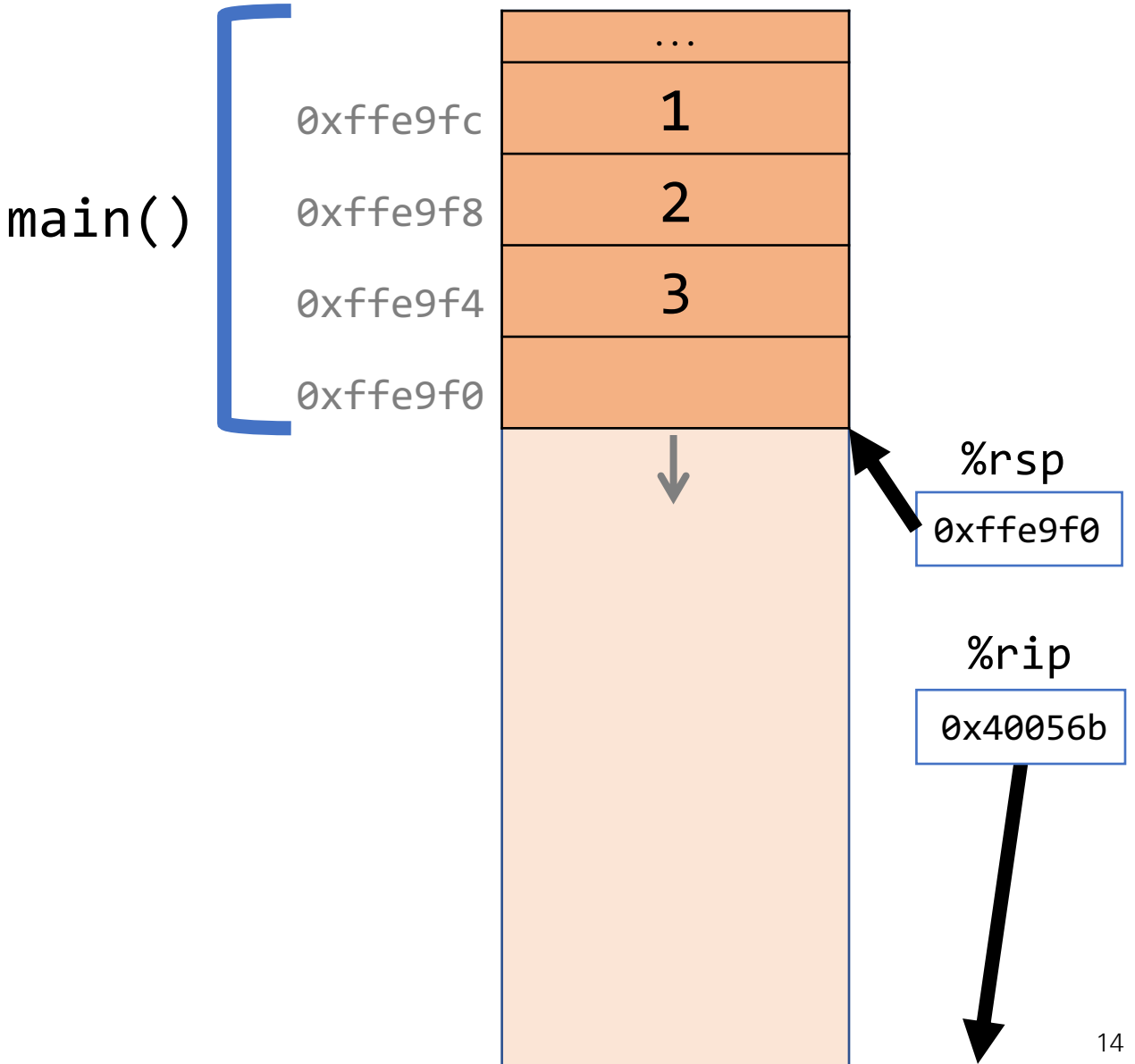

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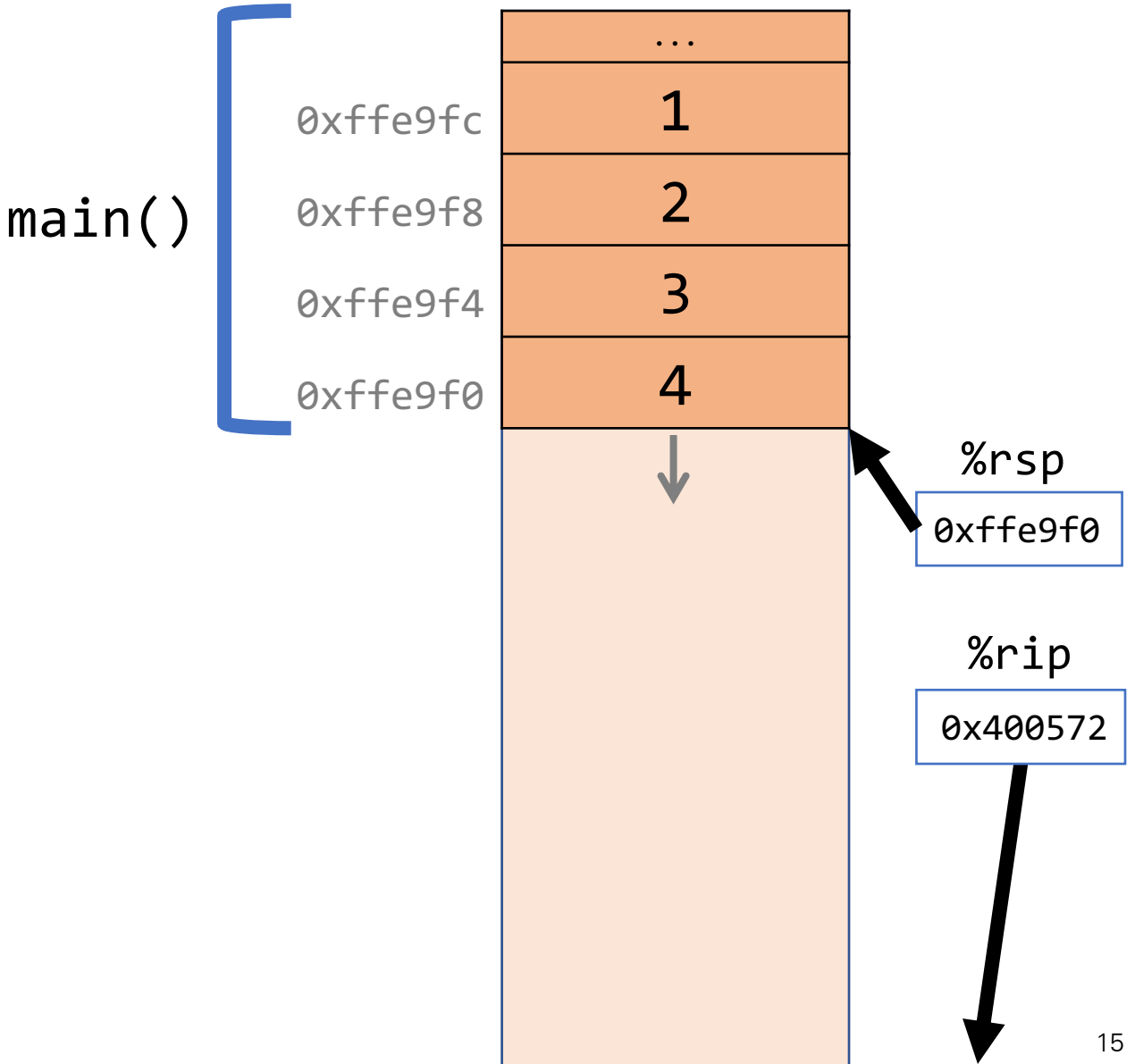

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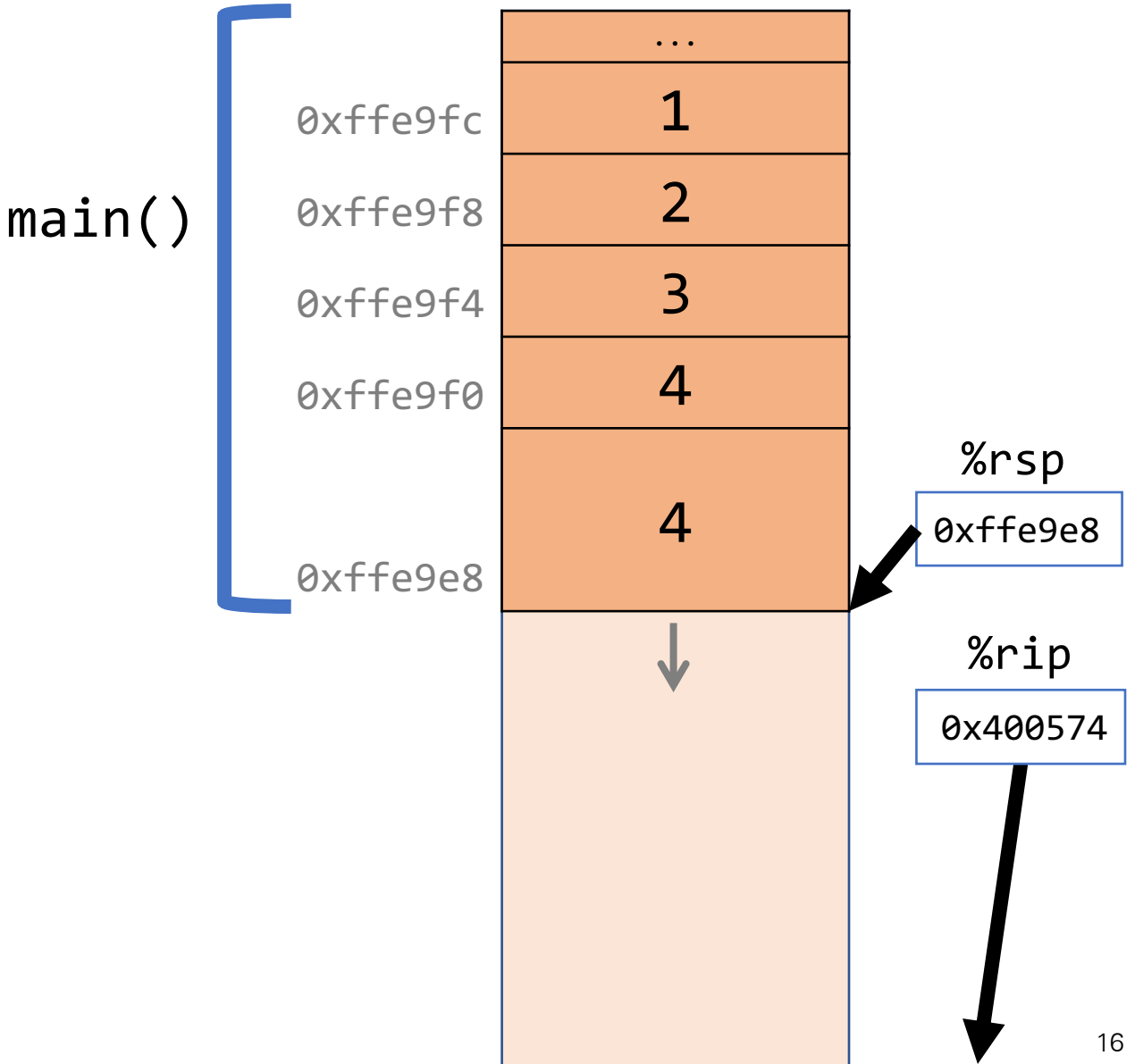

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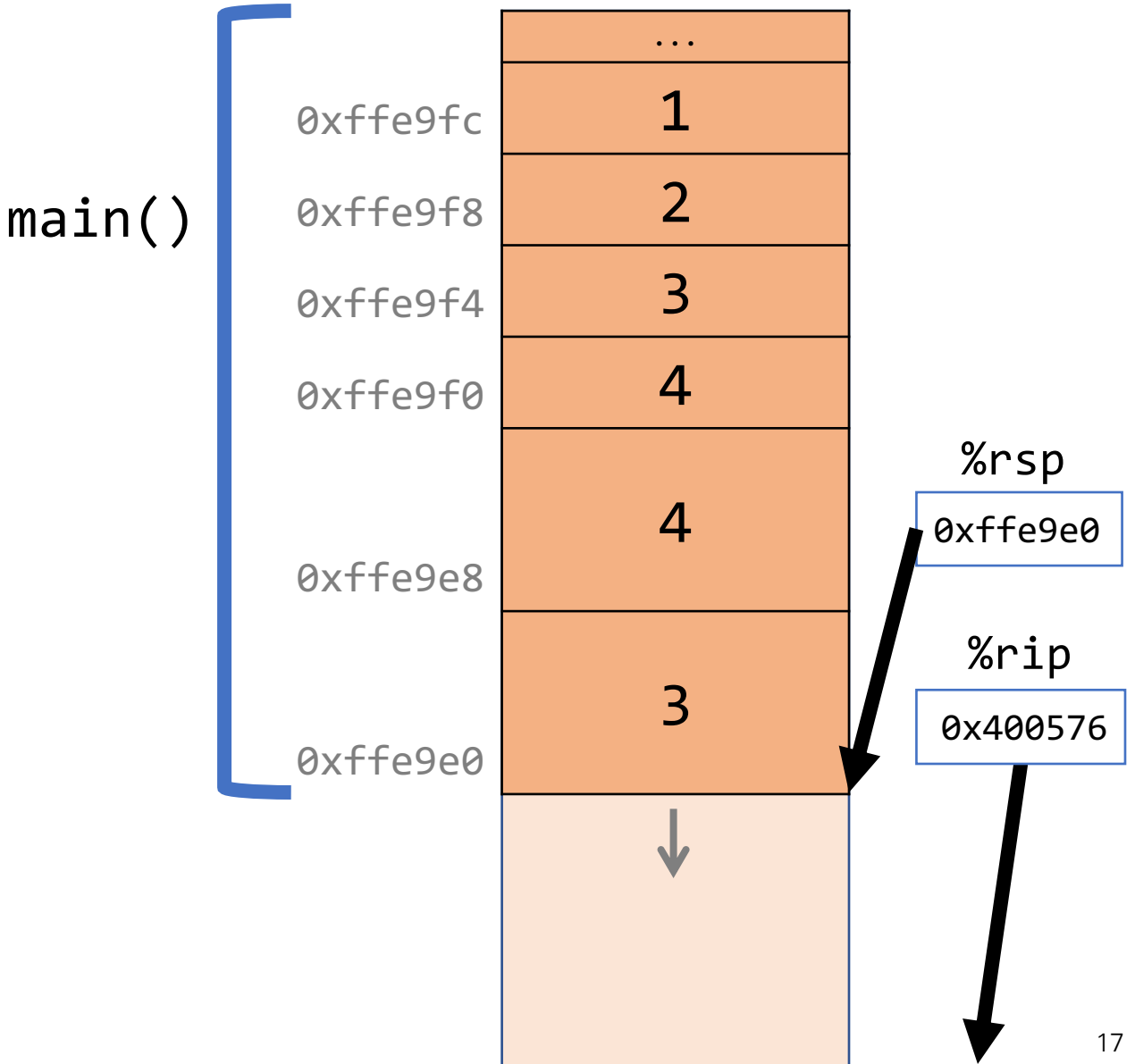

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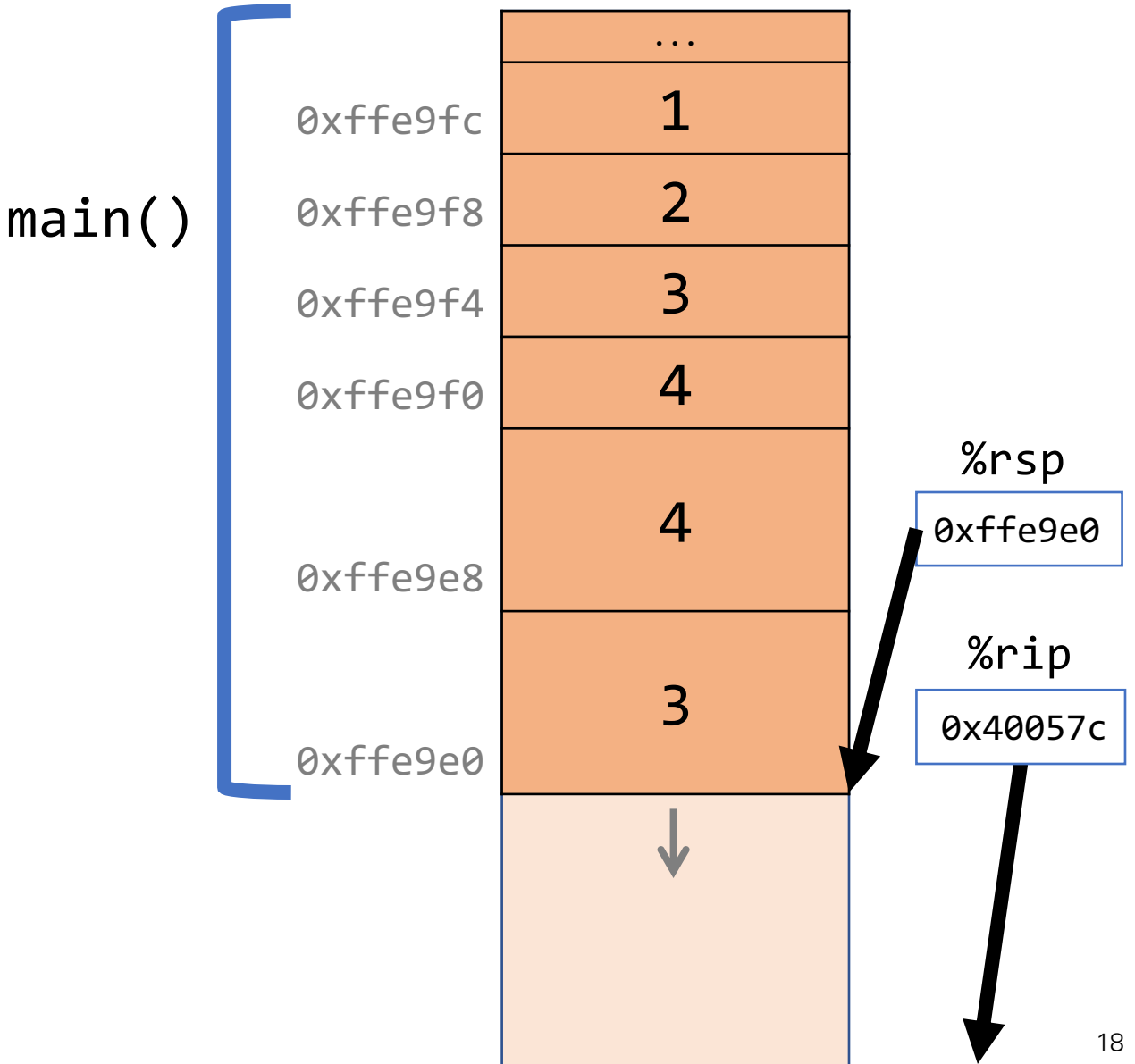

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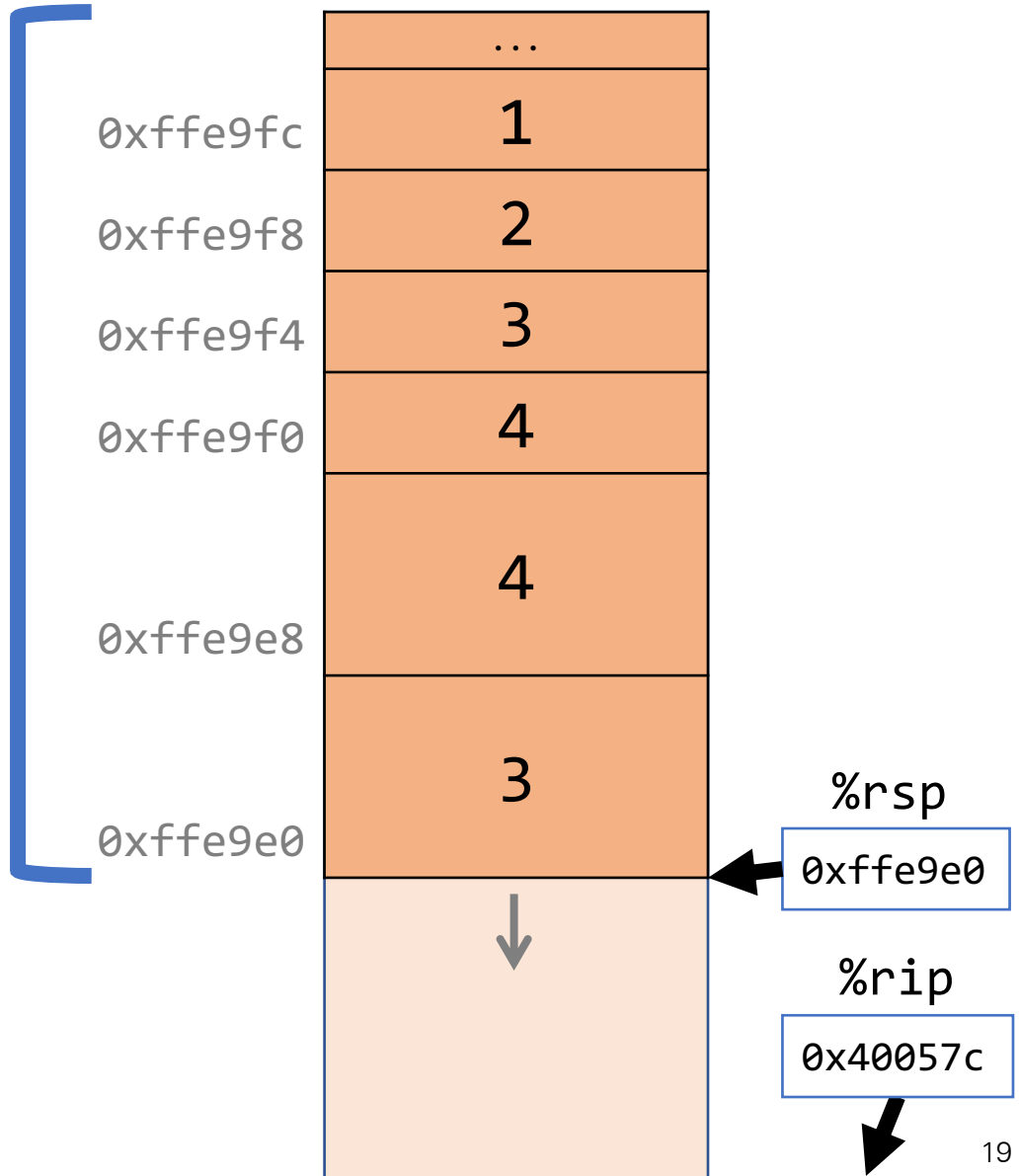

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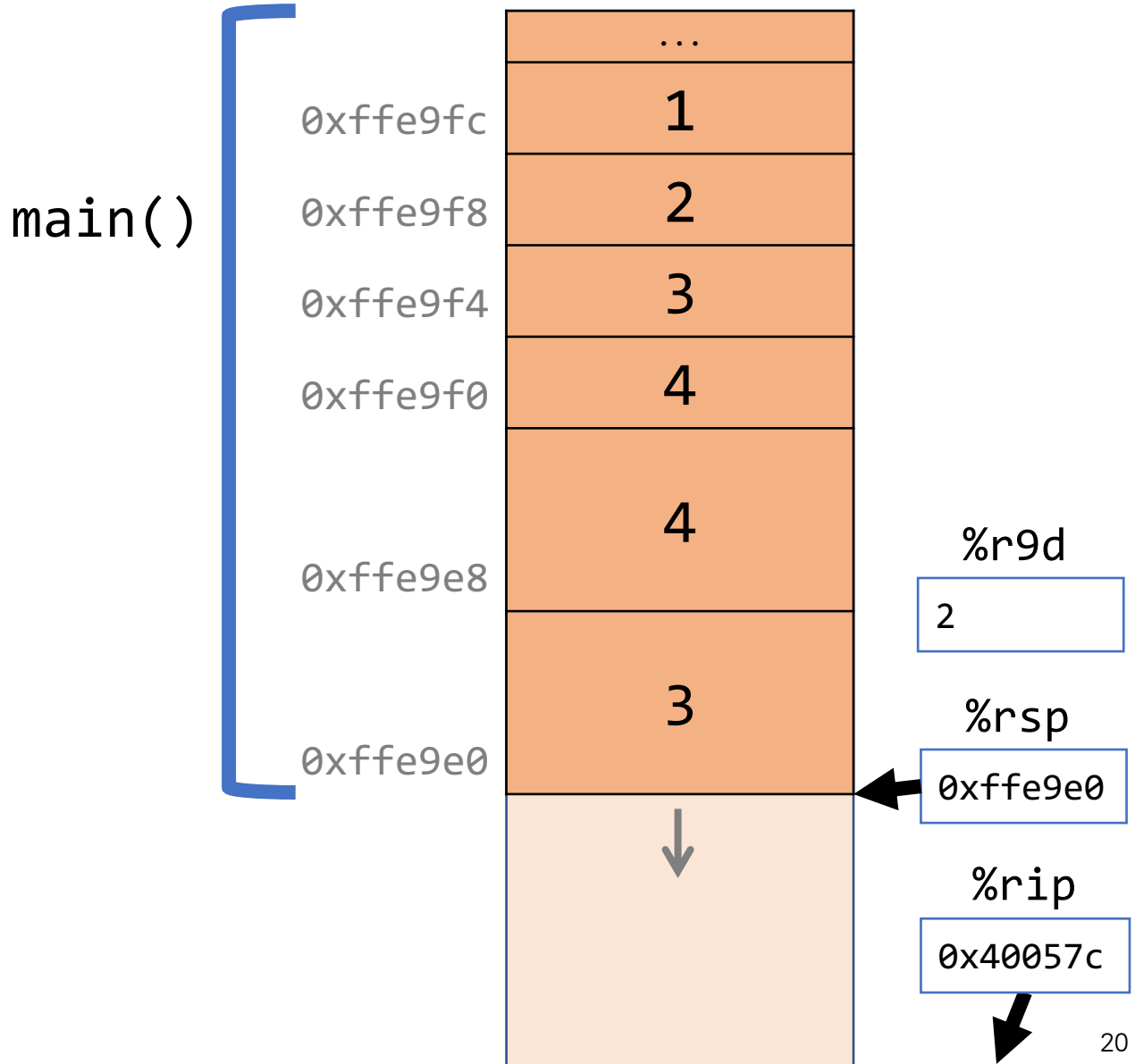

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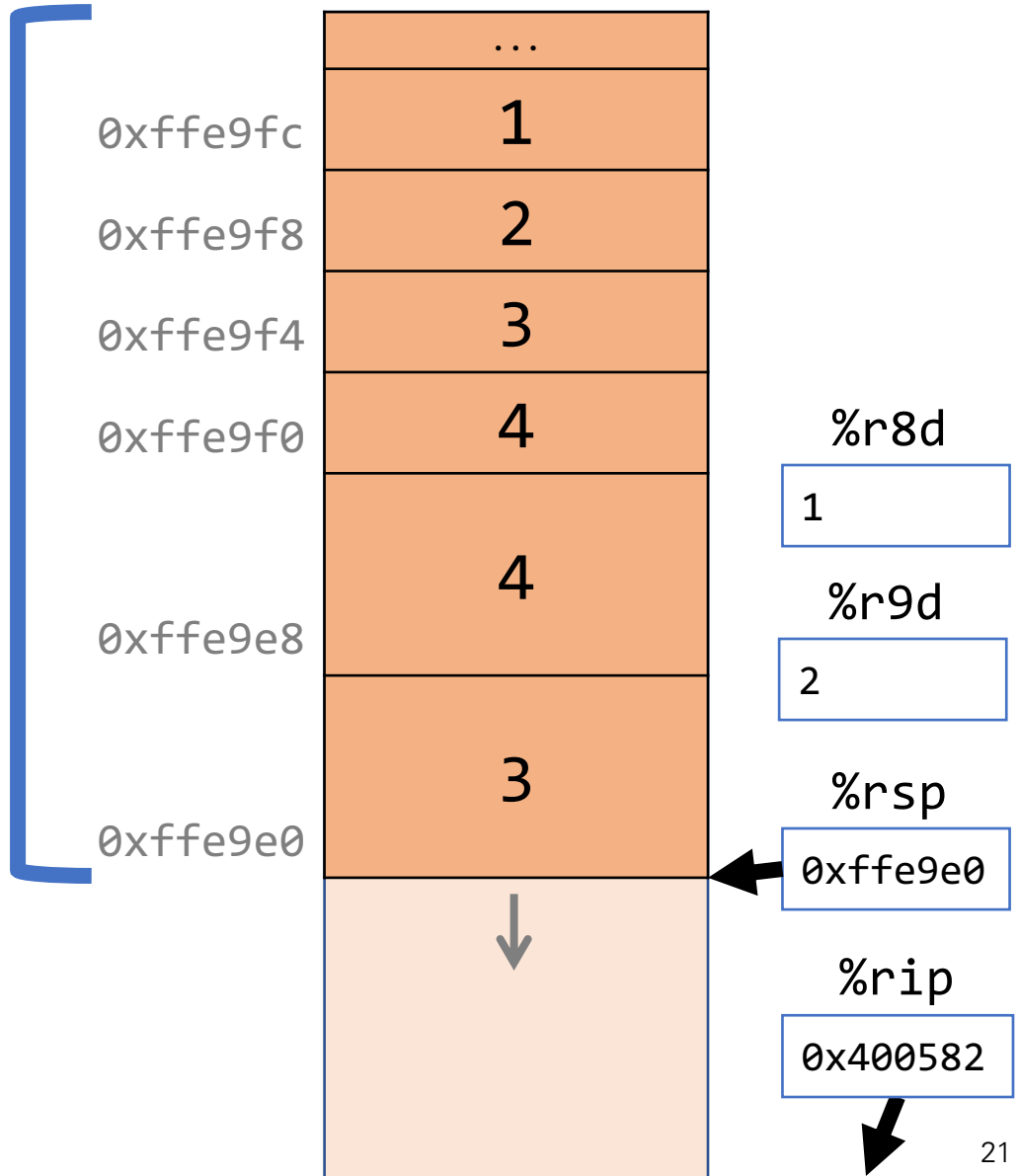

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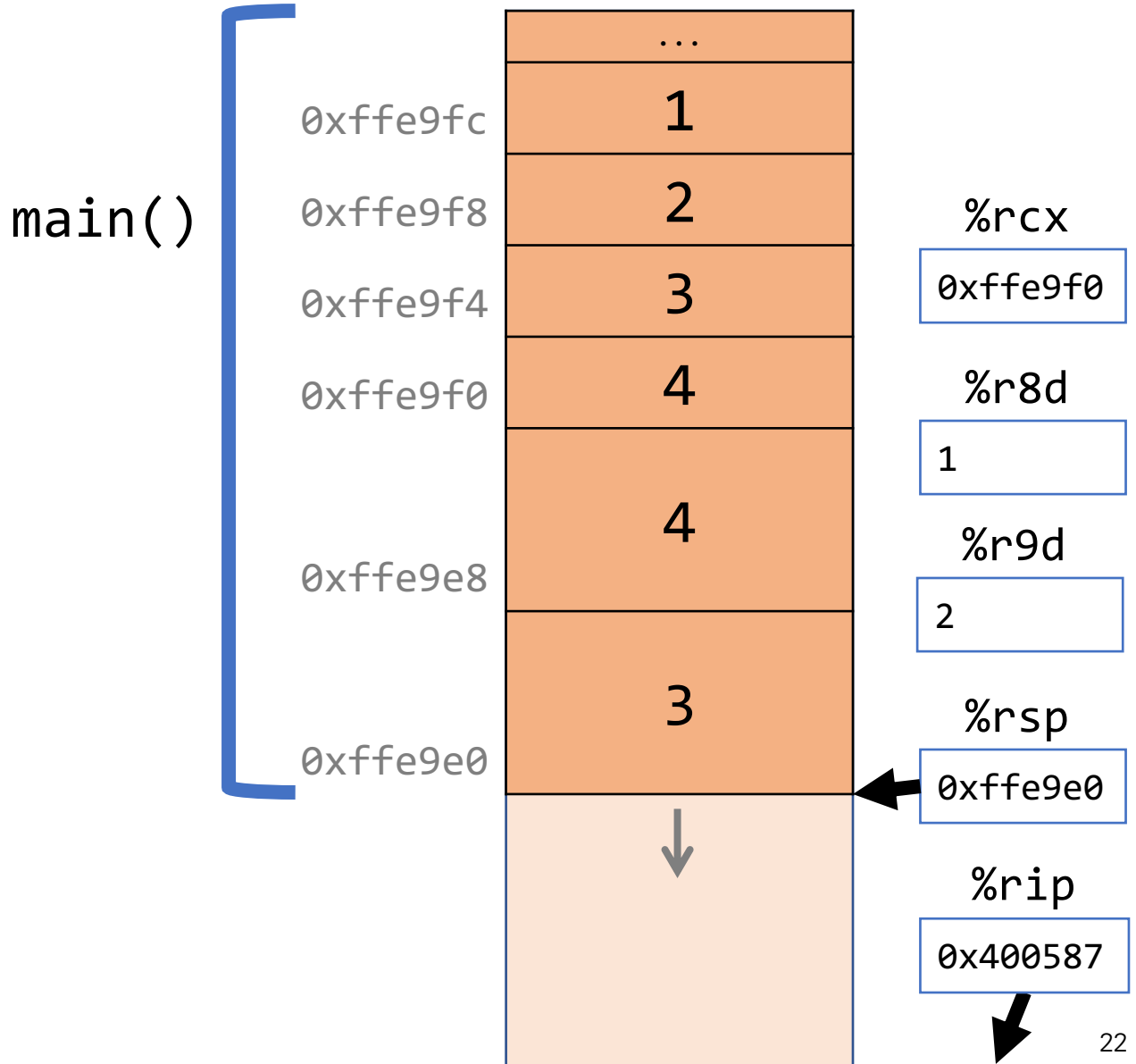

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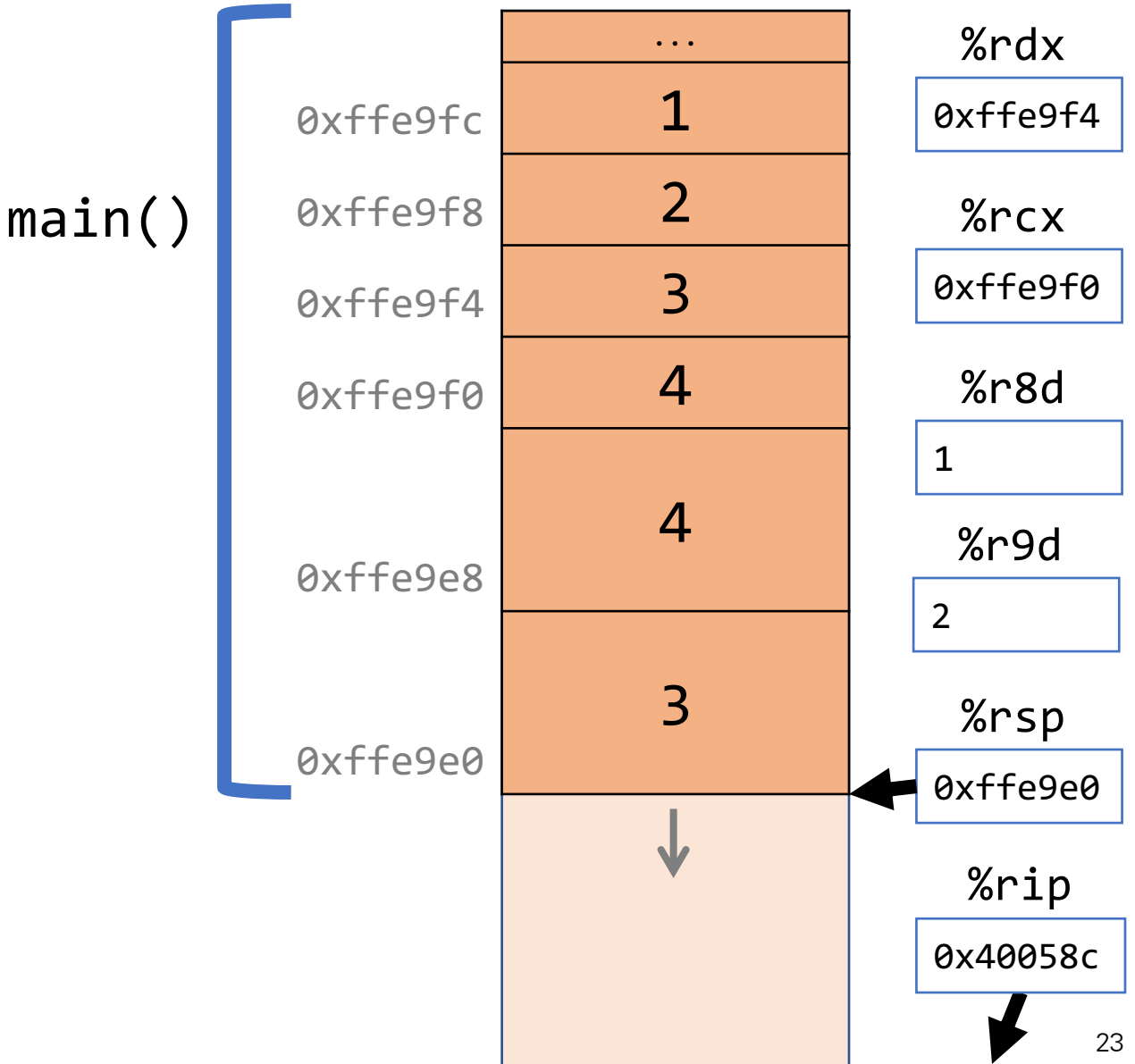

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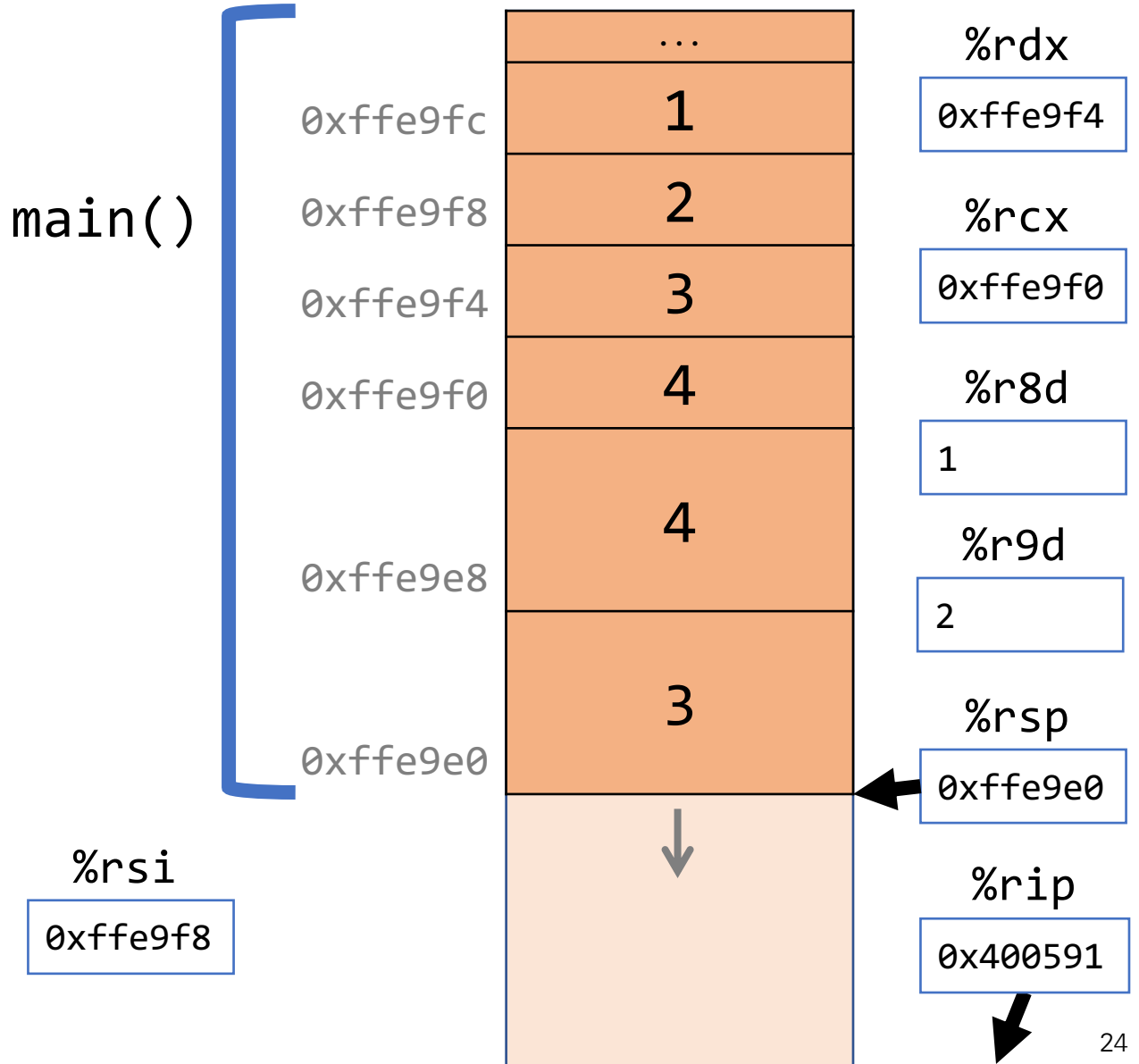
0x40058c <+61>:    lea    0x18(%rsp),%rsi
0x400591 <+66>:    lea    0x1c(%rsp),%rdi
0x400596 <+71>:    callq  0x400546 <func>
```



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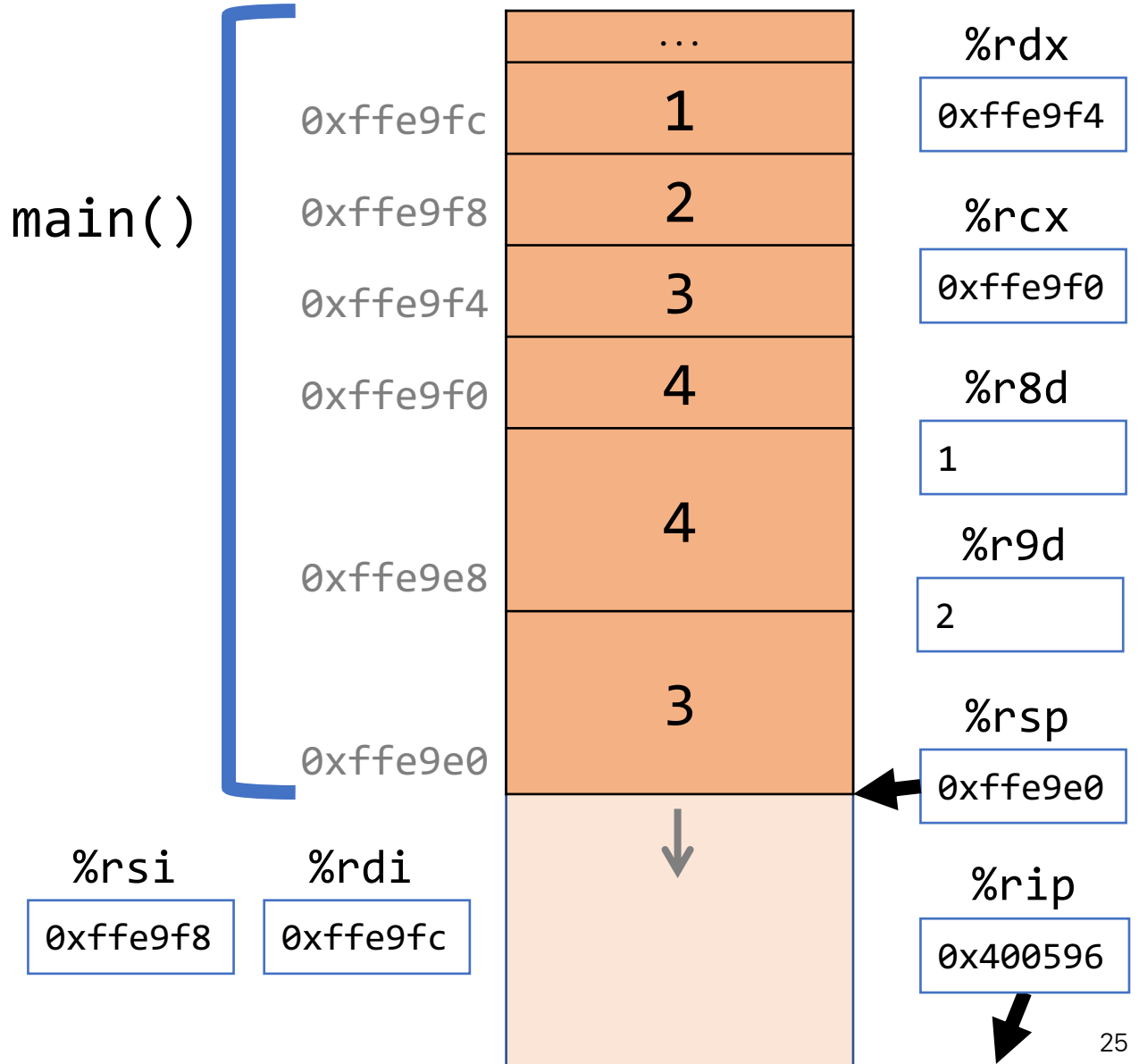
```
0x400587 <+56>:   lea    0x14(%rsp),%rdx
0x40058c <+61>:   lea    0x18(%rsp),%rsi
0x400591 <+66>:   lea    0x1c(%rsp),%rdi
0x400596 <+71>:   callq  0x400546 <func>
0x40059b <+76>:   add    $0x10,%rsp
```



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>
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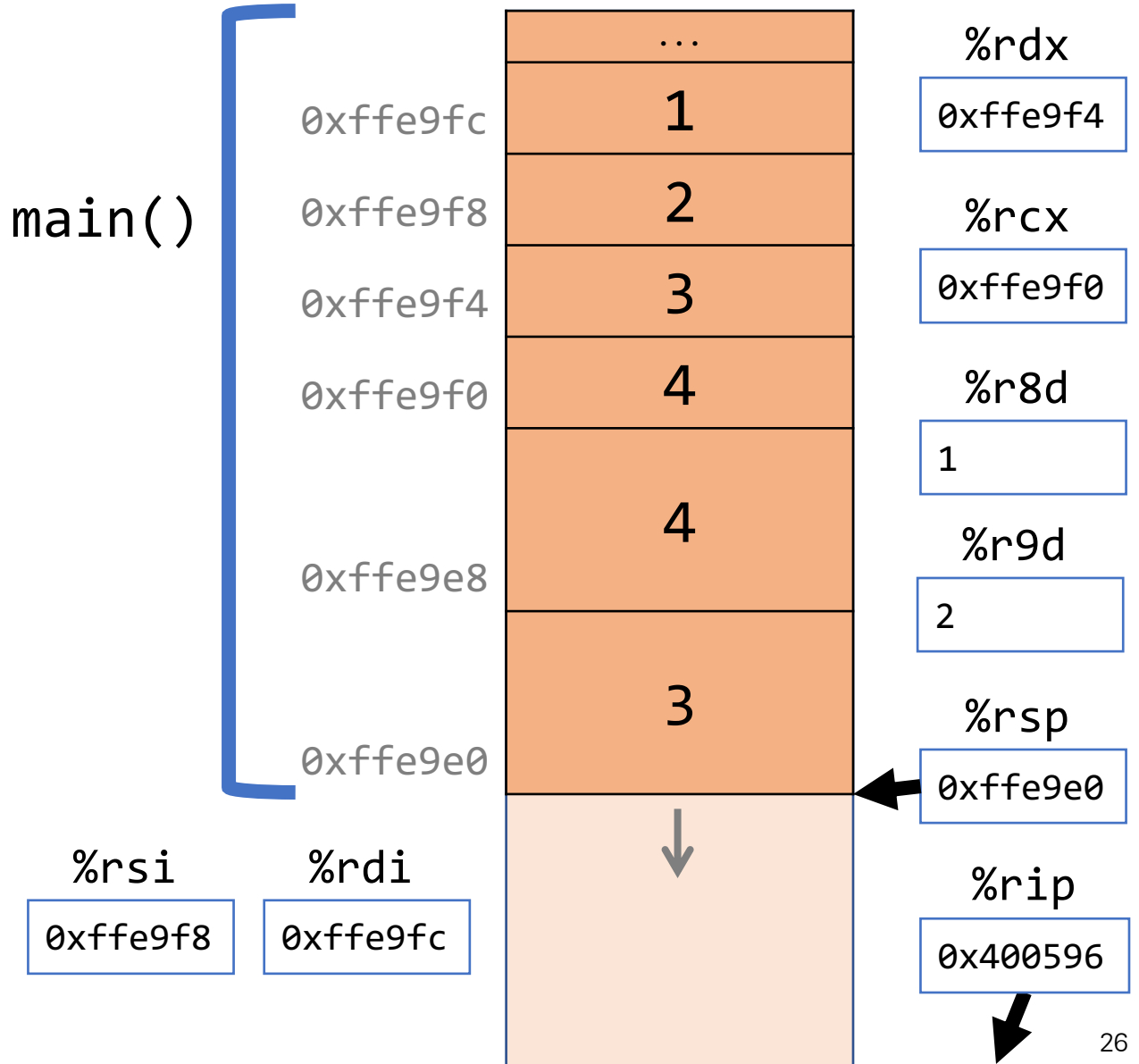
…
```



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}
```

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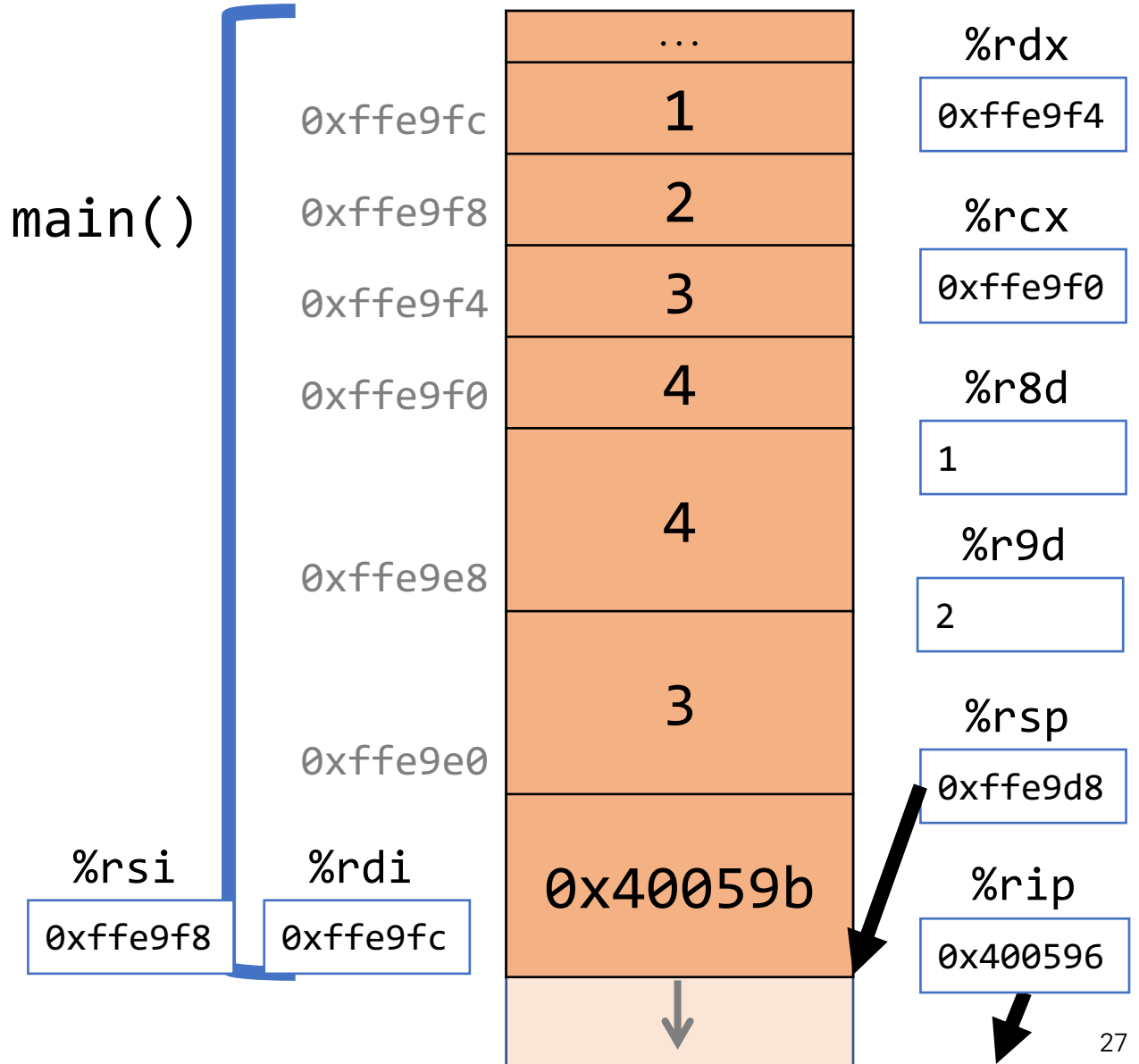


Lecture Plan

- 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)
```

Question Break

Lecture Plan

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

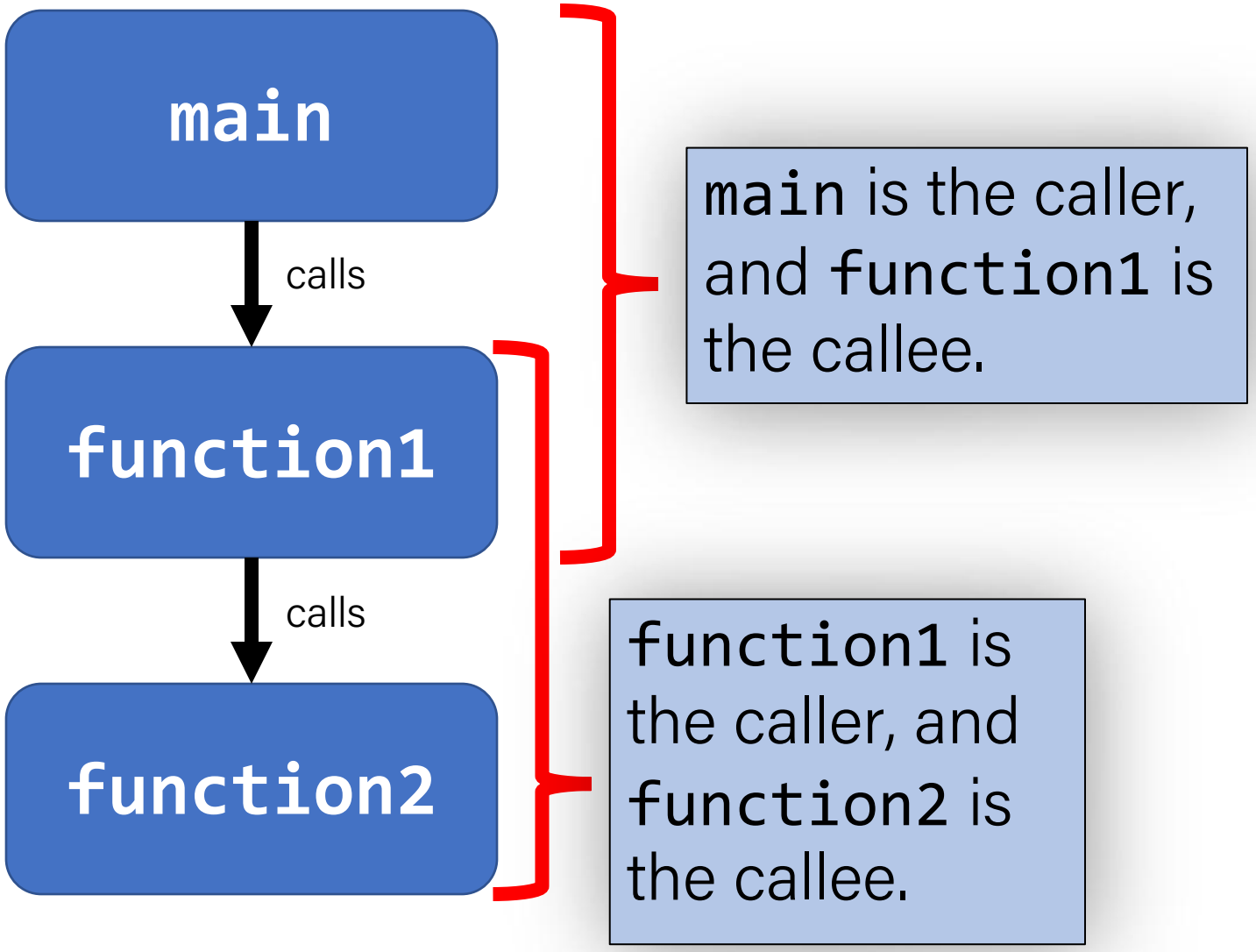
Register Restrictions

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**
  - **callee-owned:** `%rbx, %rbp, %r12-%r15`
  - **caller-owned:** all other registers, except the stack pointer `%rsp`

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

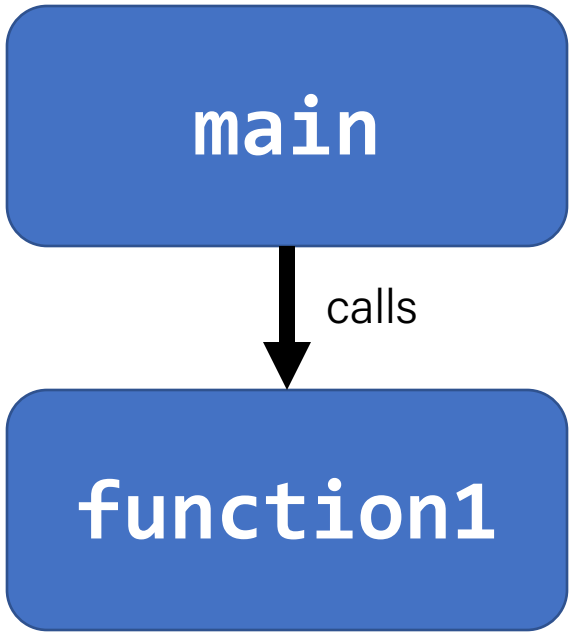
Caller-Owned

- 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.

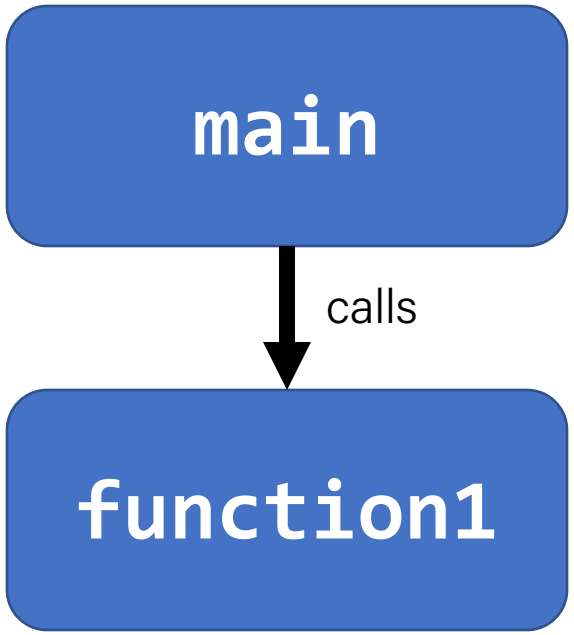
Caller-Owned Registers



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

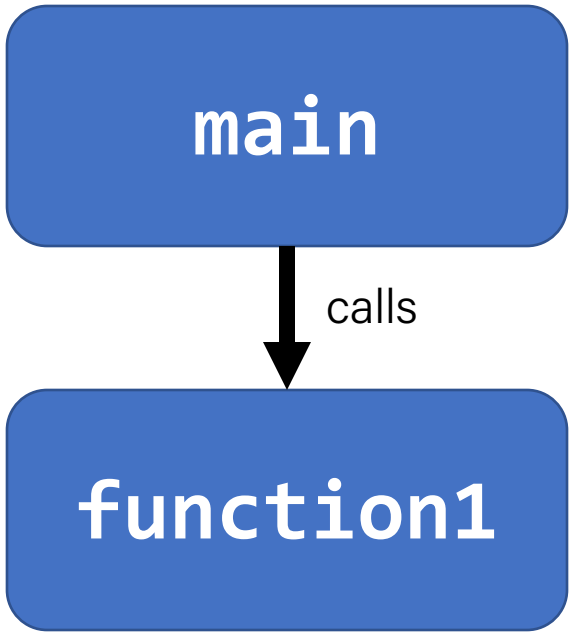
If `function1` wants to use any caller-owned registers, it must save the existing values and restore them before returning.

Caller-Owned Registers




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

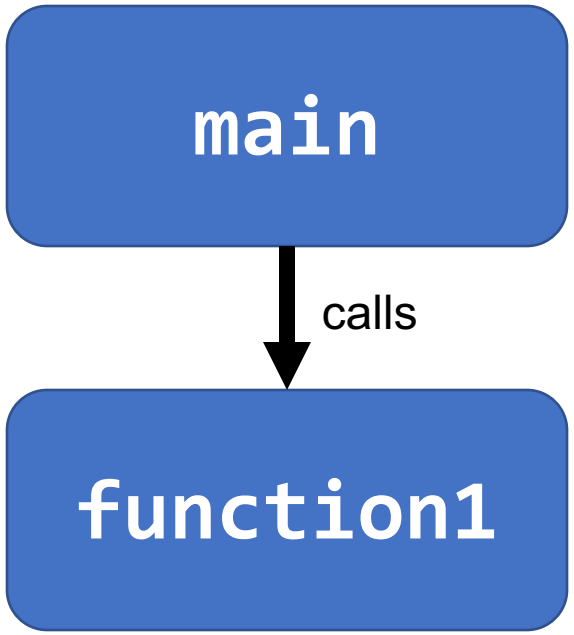
Callee-Owned Registers



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

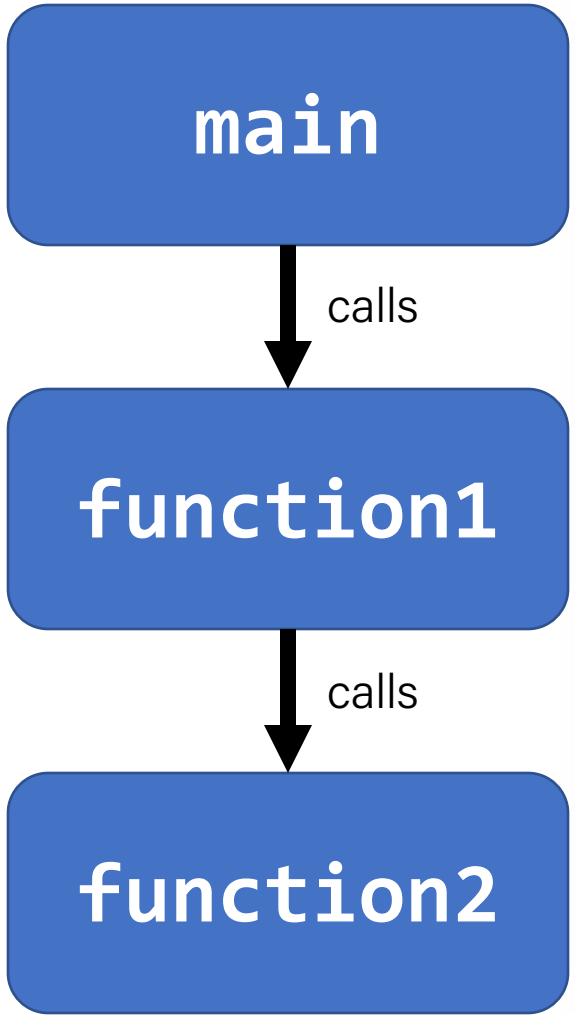
If `function1` wants to use any callee-owned registers, it can do so without saving the existing values.

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.

Question Break

Lecture Plan

- Revisiting `%rip`
- Calling Functions
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- Pulling it all together: recursion example

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`

Extra Practice – Escape Room 2

https://godbolt.org/z/jch_D2

`escape_room`

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.

```
0000000004005b6 <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
```

Recap

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

Next time: Data and Stack Frames