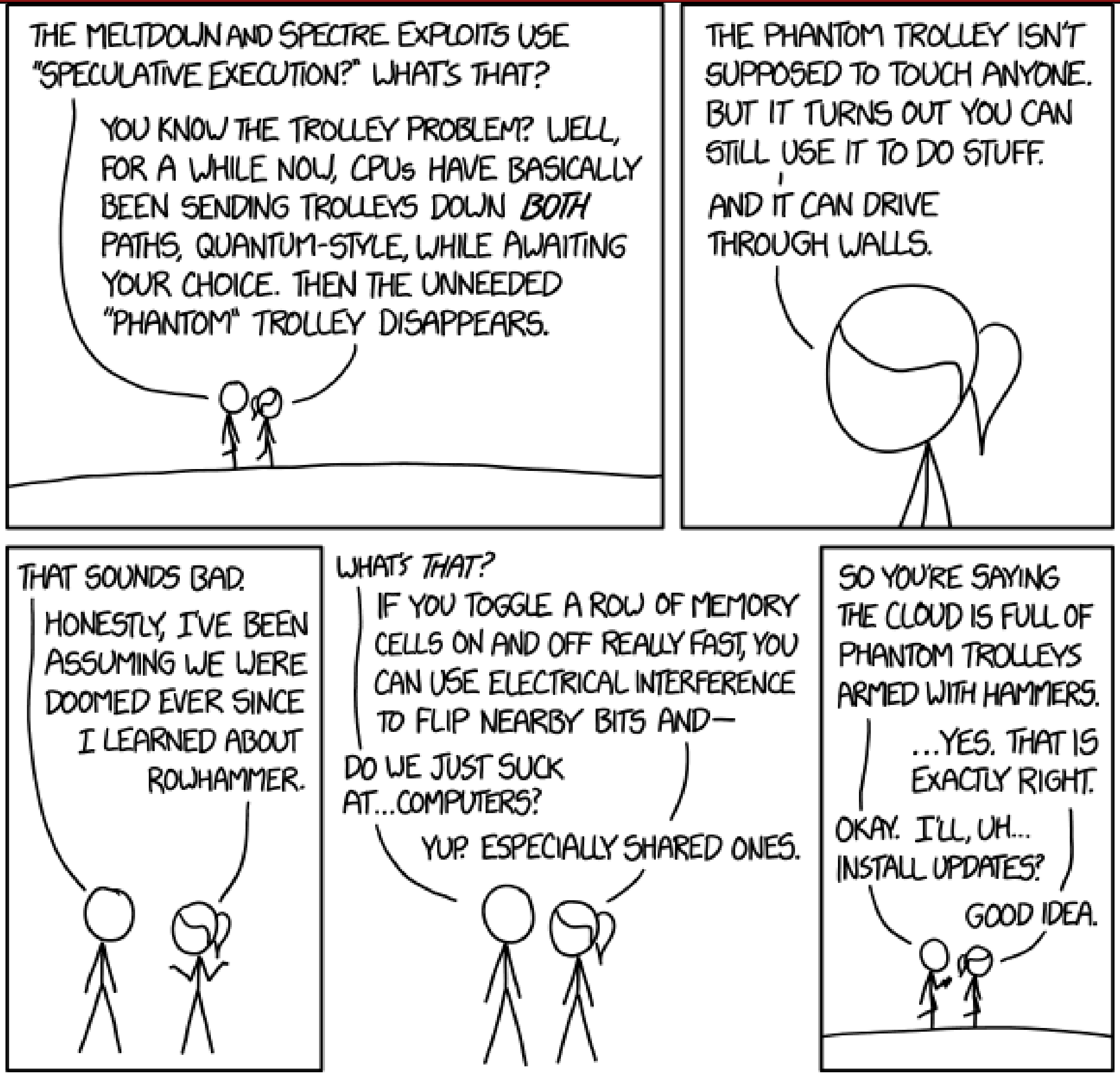
CS107, Lecture 14: Runtime Stack



Calling Functions In Assembly

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

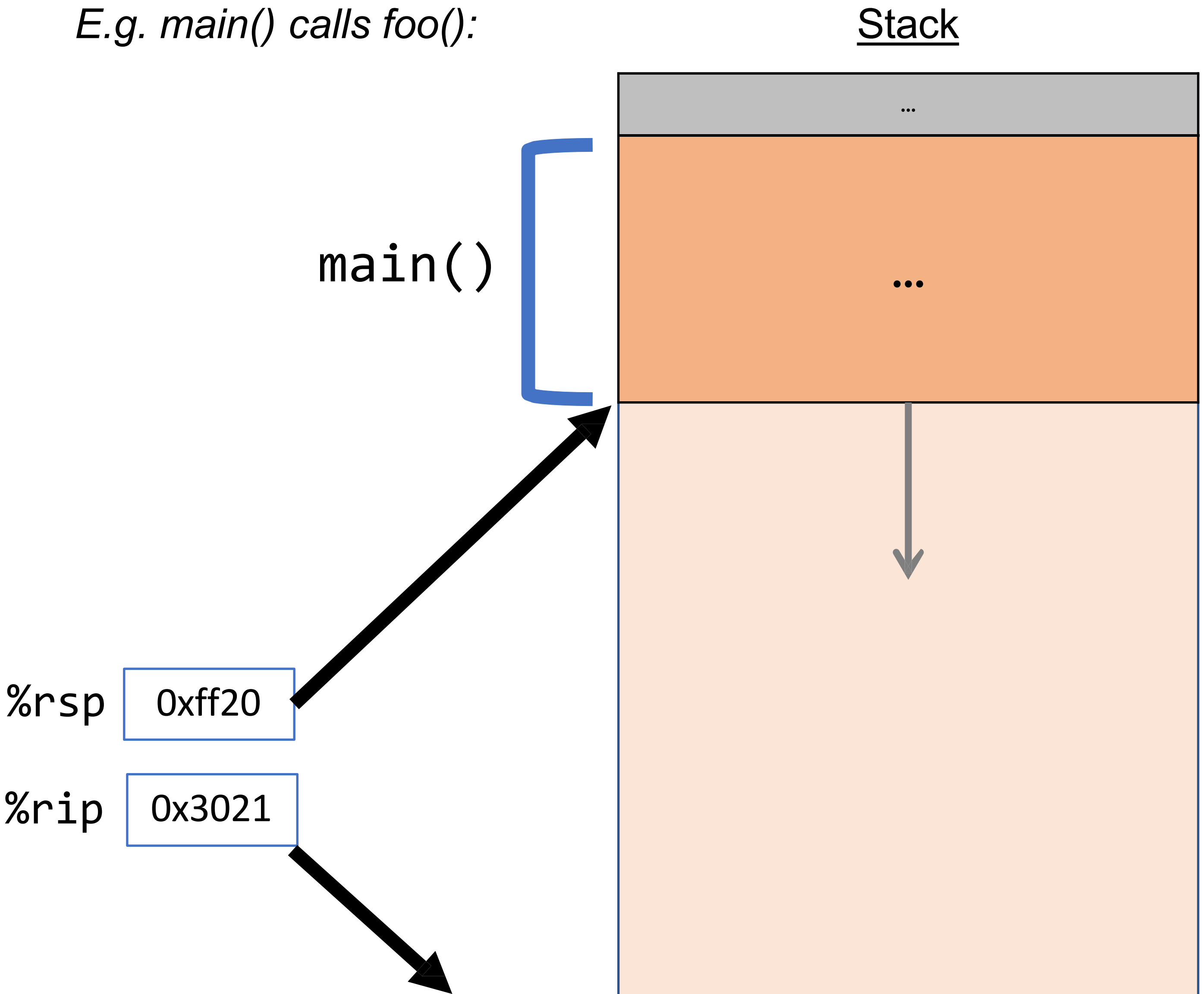
Terminology: **caller** function calls the **callee** function.

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.

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



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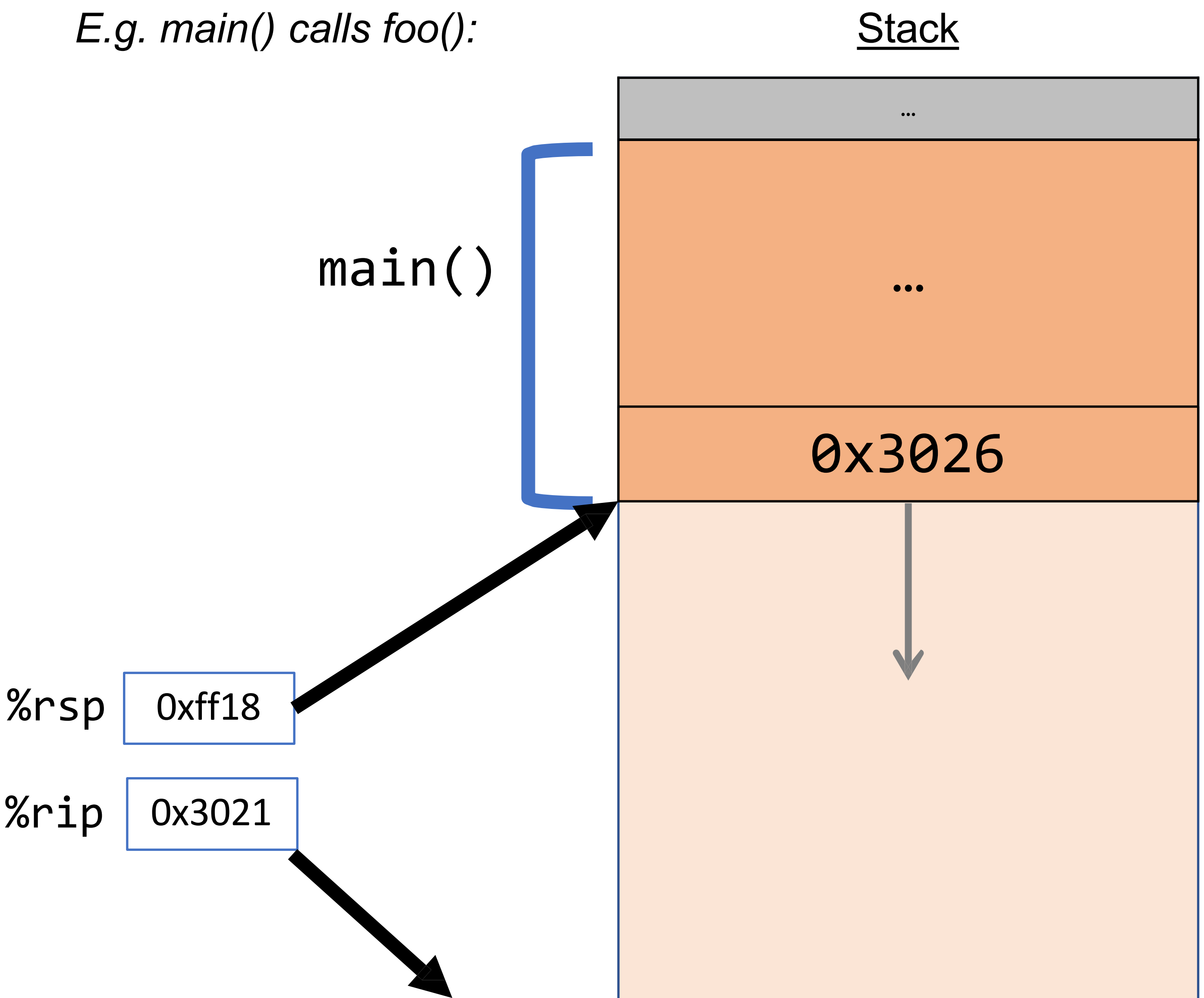

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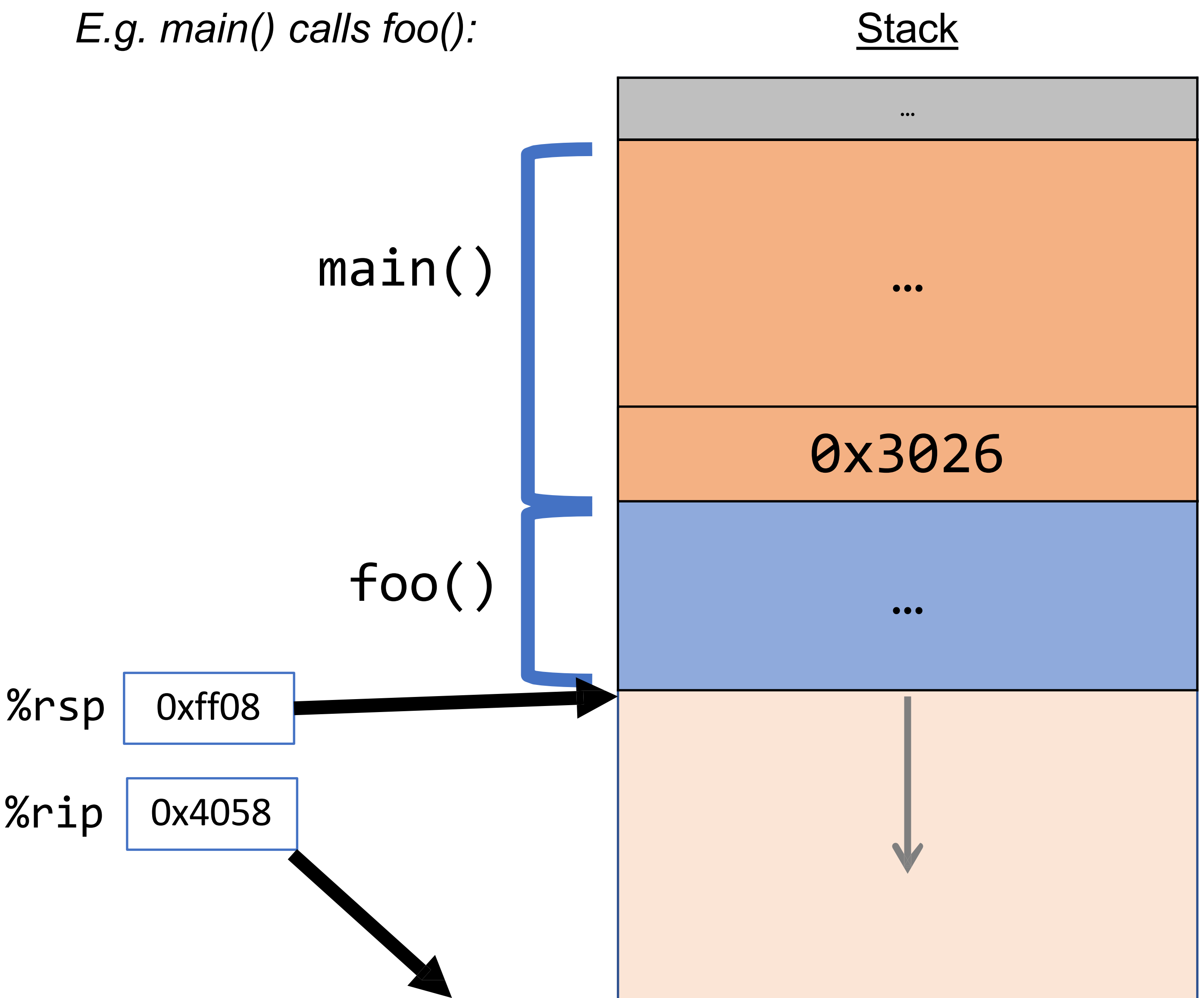

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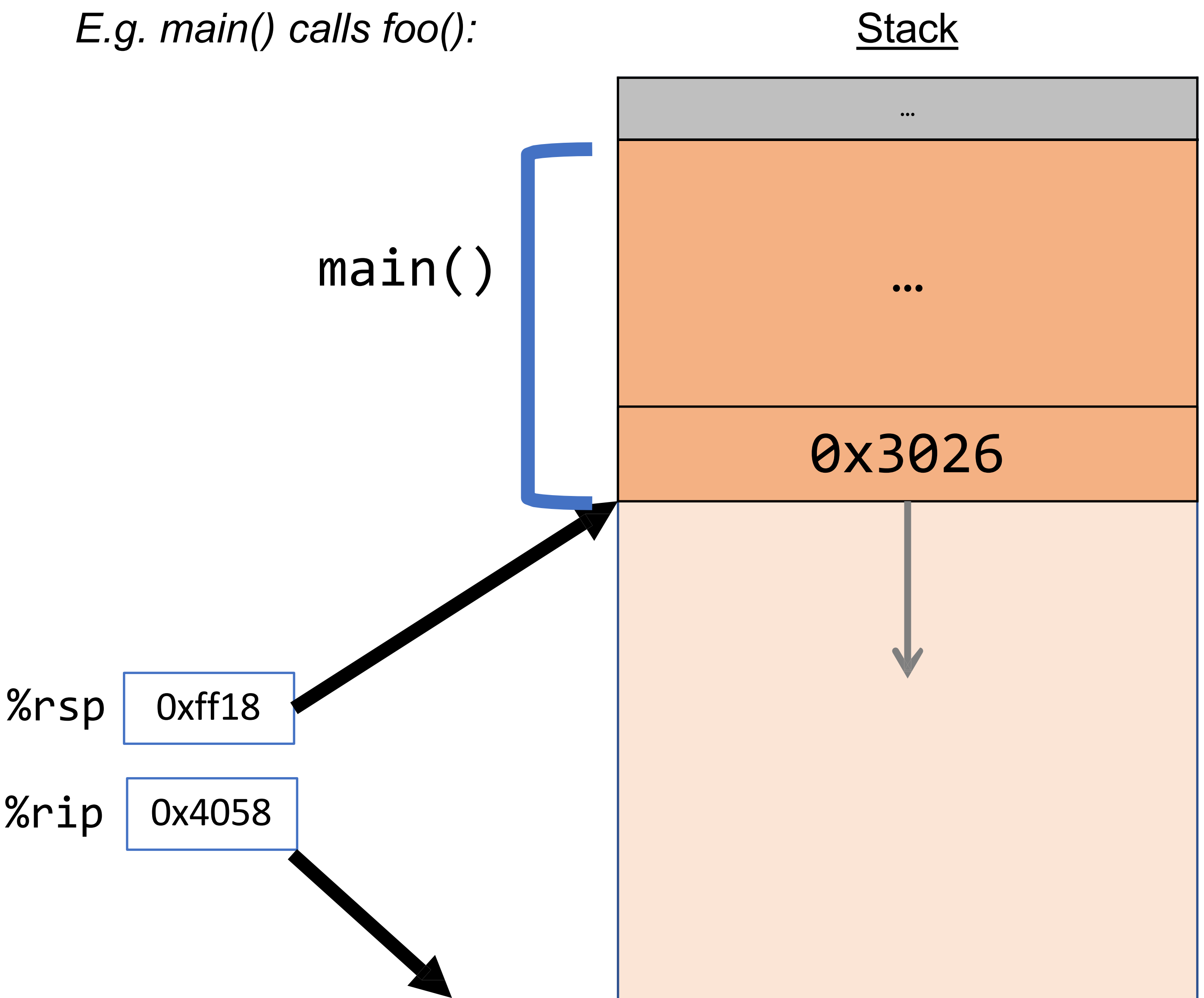

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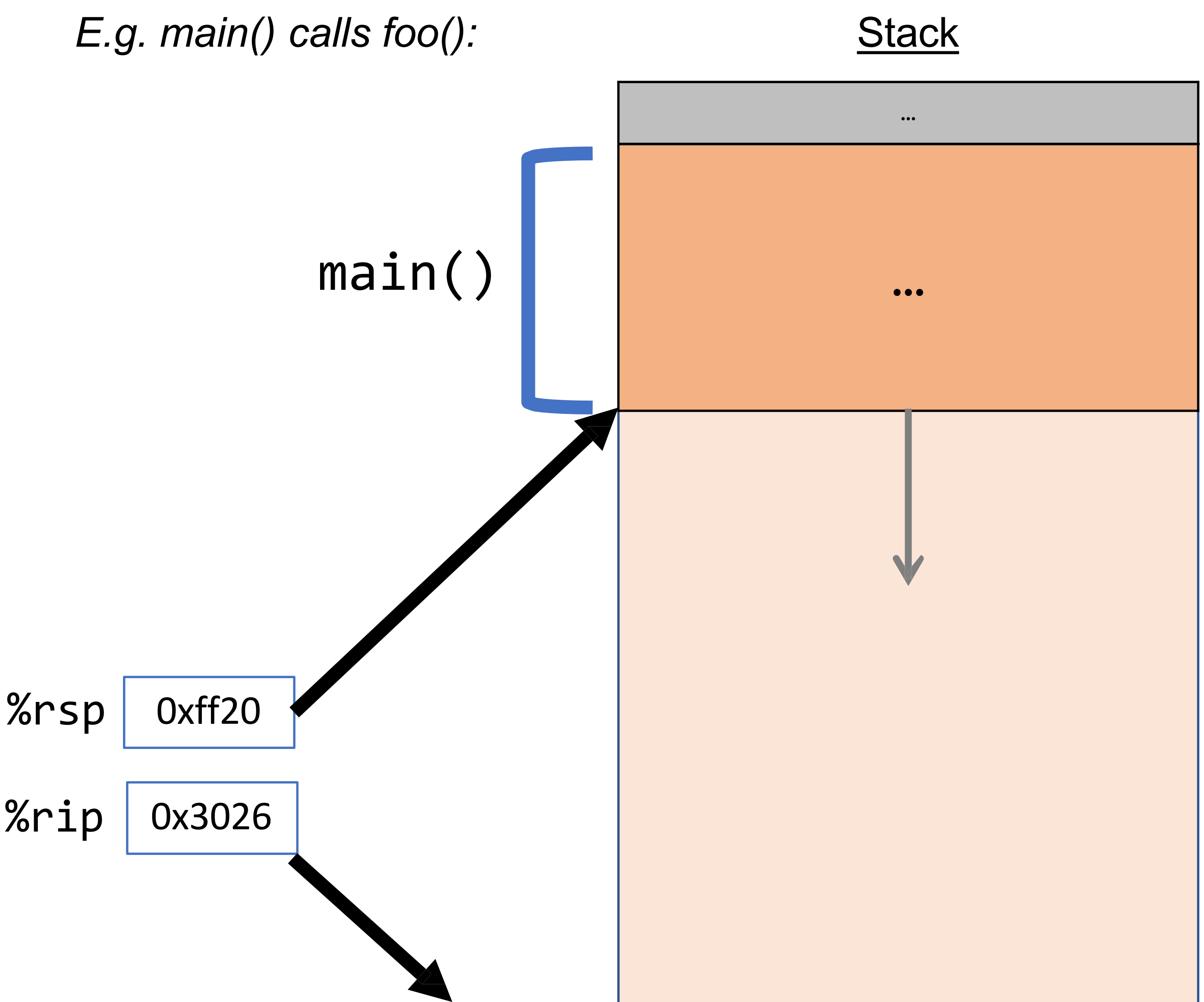

Call And Return

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

```
call Label
call *Operand
```

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

```
ret
```

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

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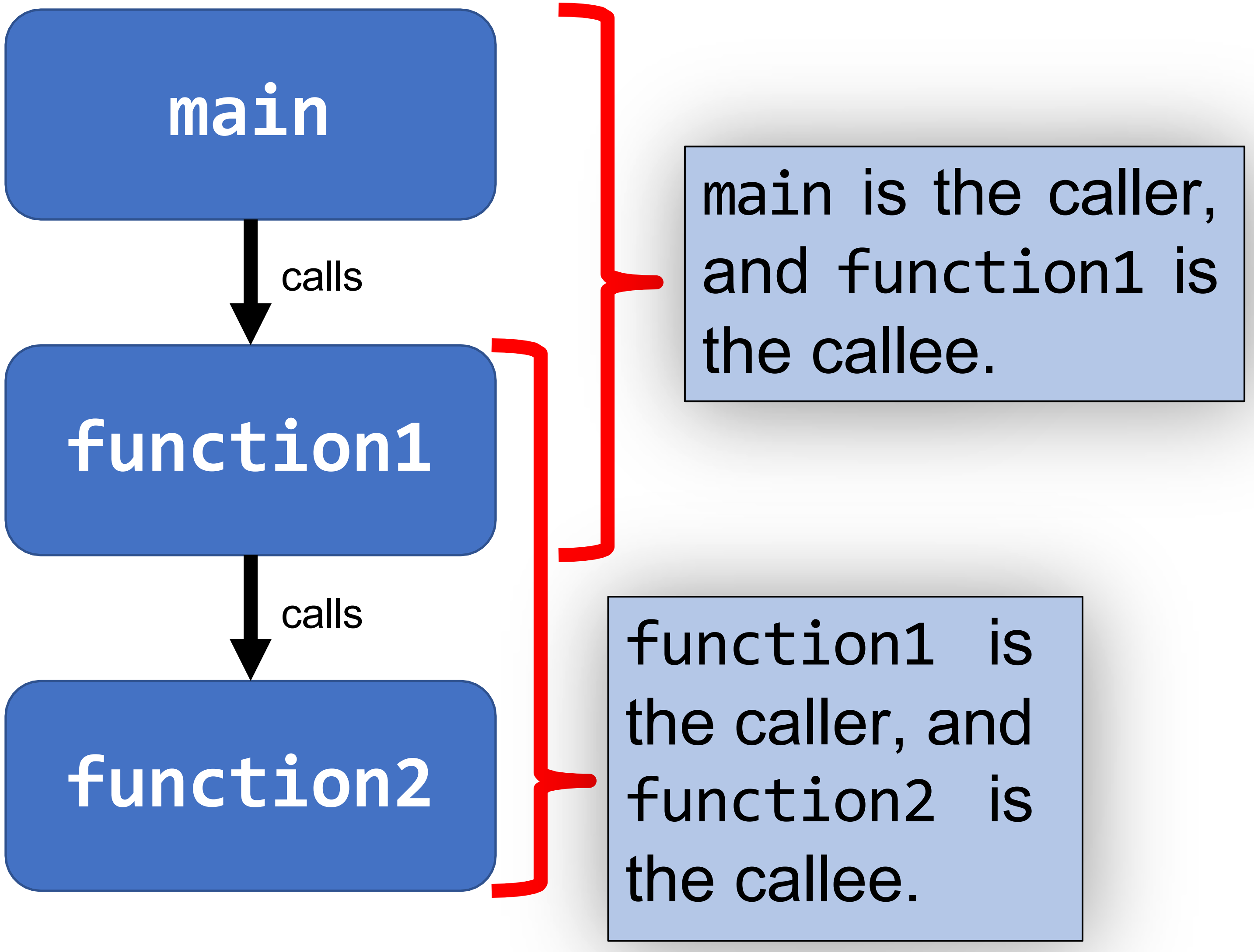
Register Restrictions

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

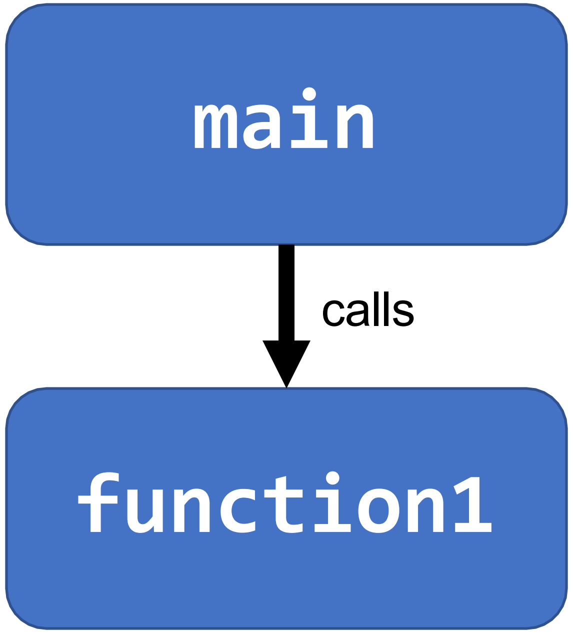
Caller-Owned

- 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.

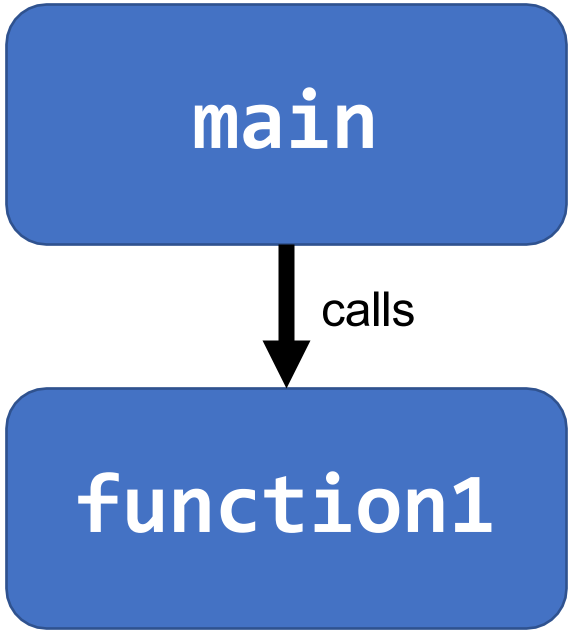
Caller-Owned Registers



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

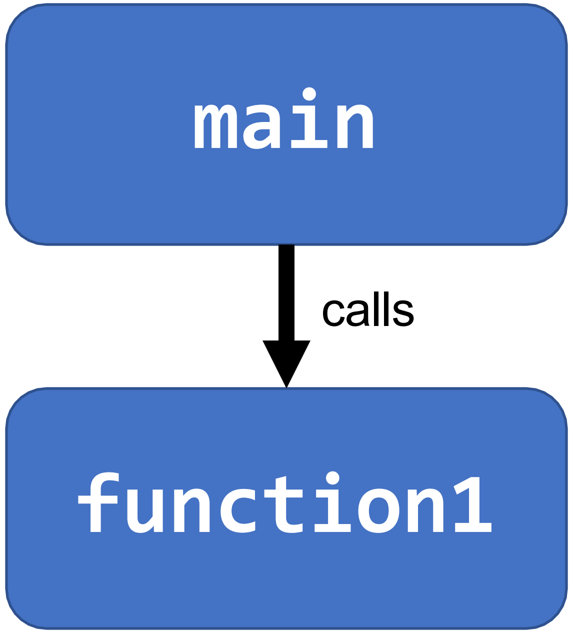
If function1 wants to use any caller-owned registers, it must save the existing values and restore them before returning.

Caller-Owned Registers




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

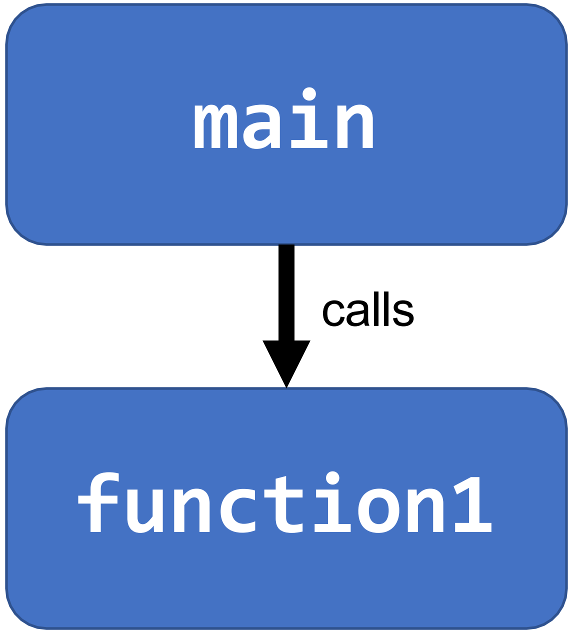
Callee-Owned Registers



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

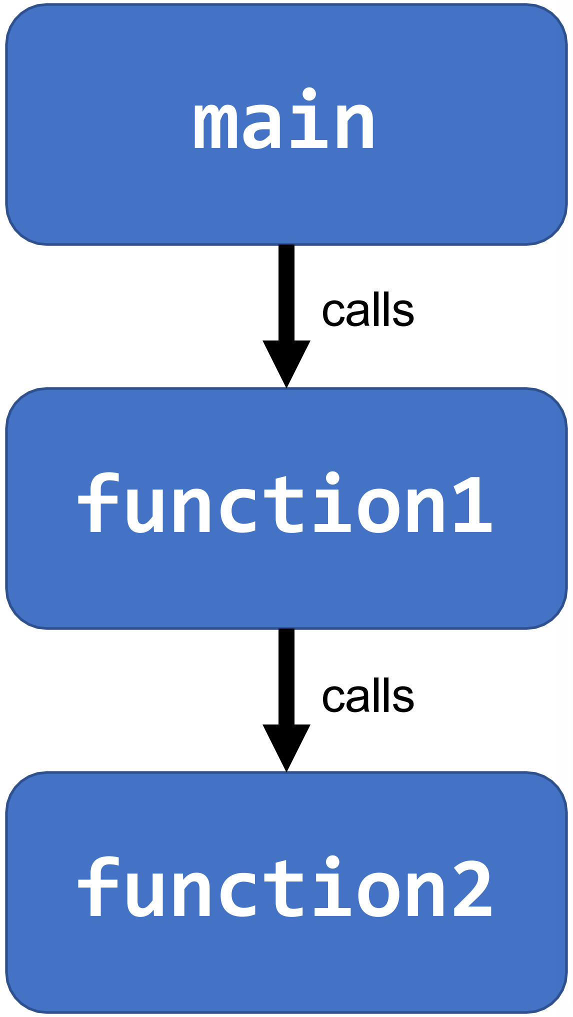
If function1 wants to use any callee-owned registers, it can do so without saving the existing values.

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.

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.

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int func(int *p1, int *p2, int *p3, int *p4,
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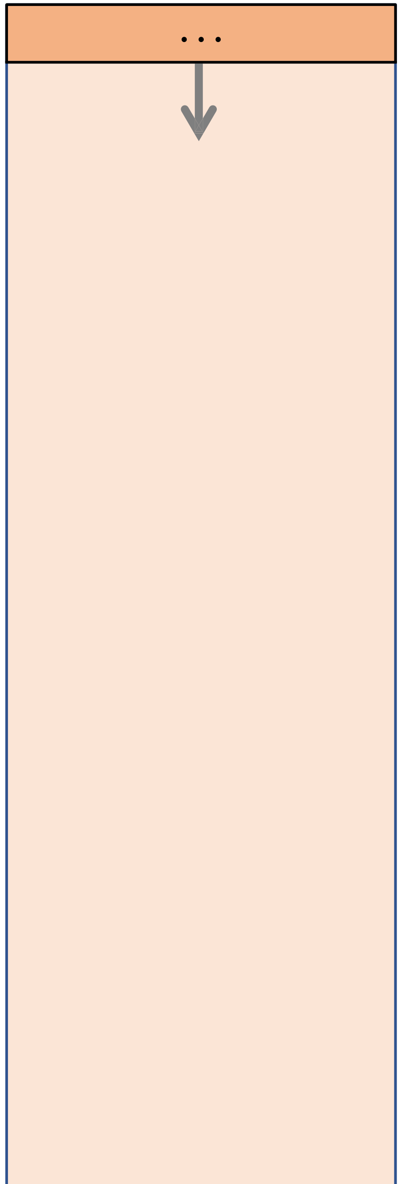
main()



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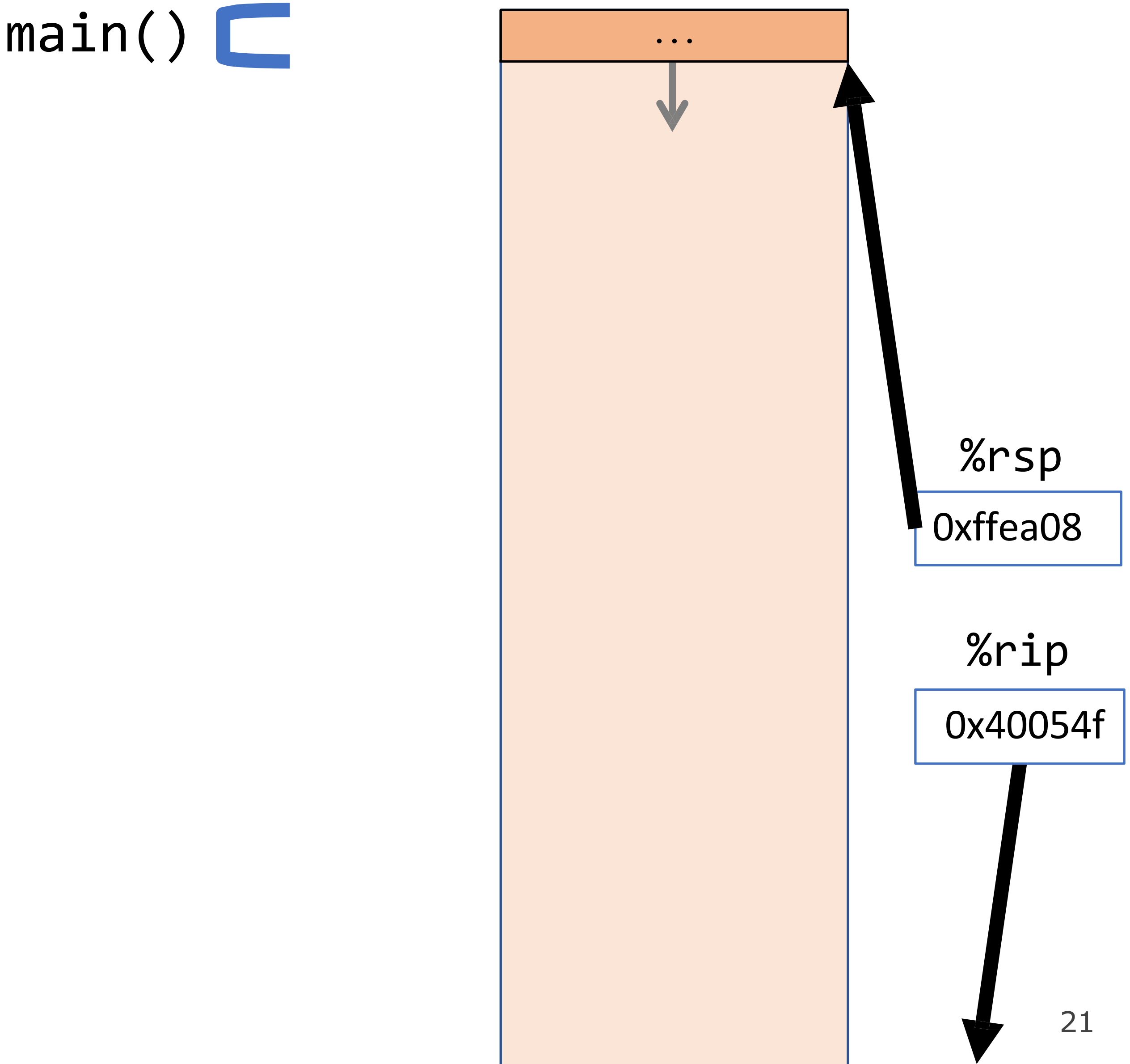

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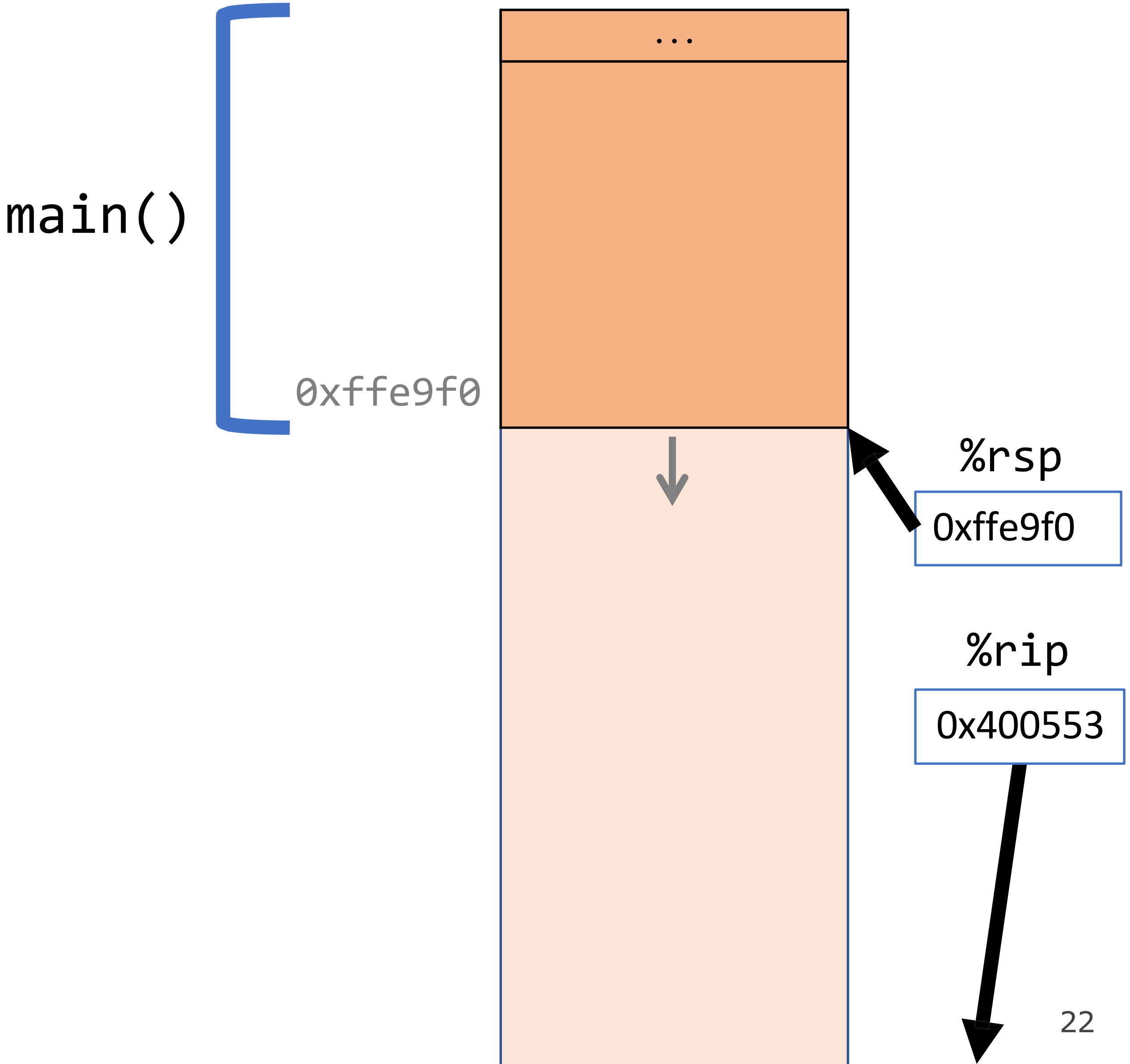

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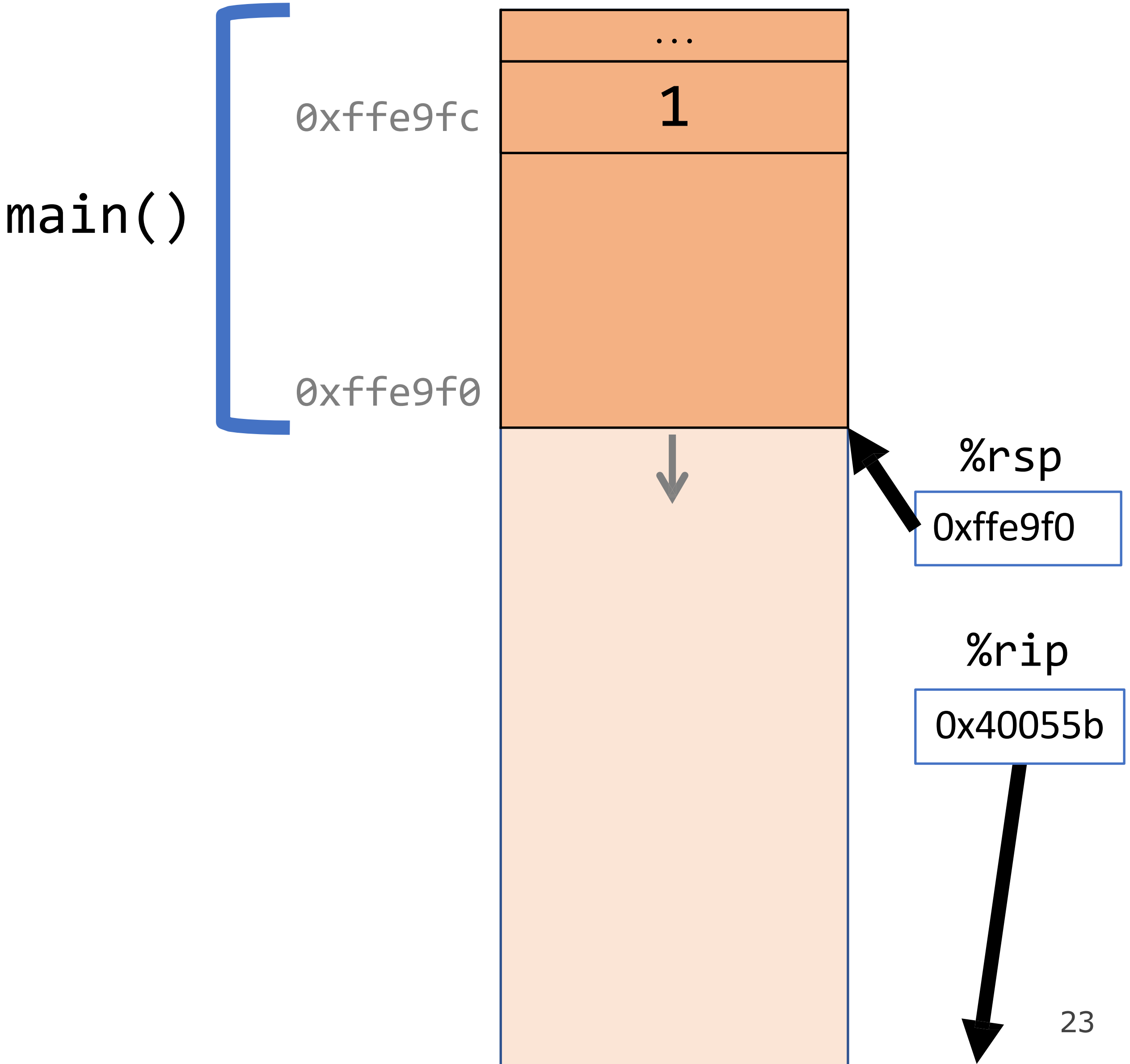

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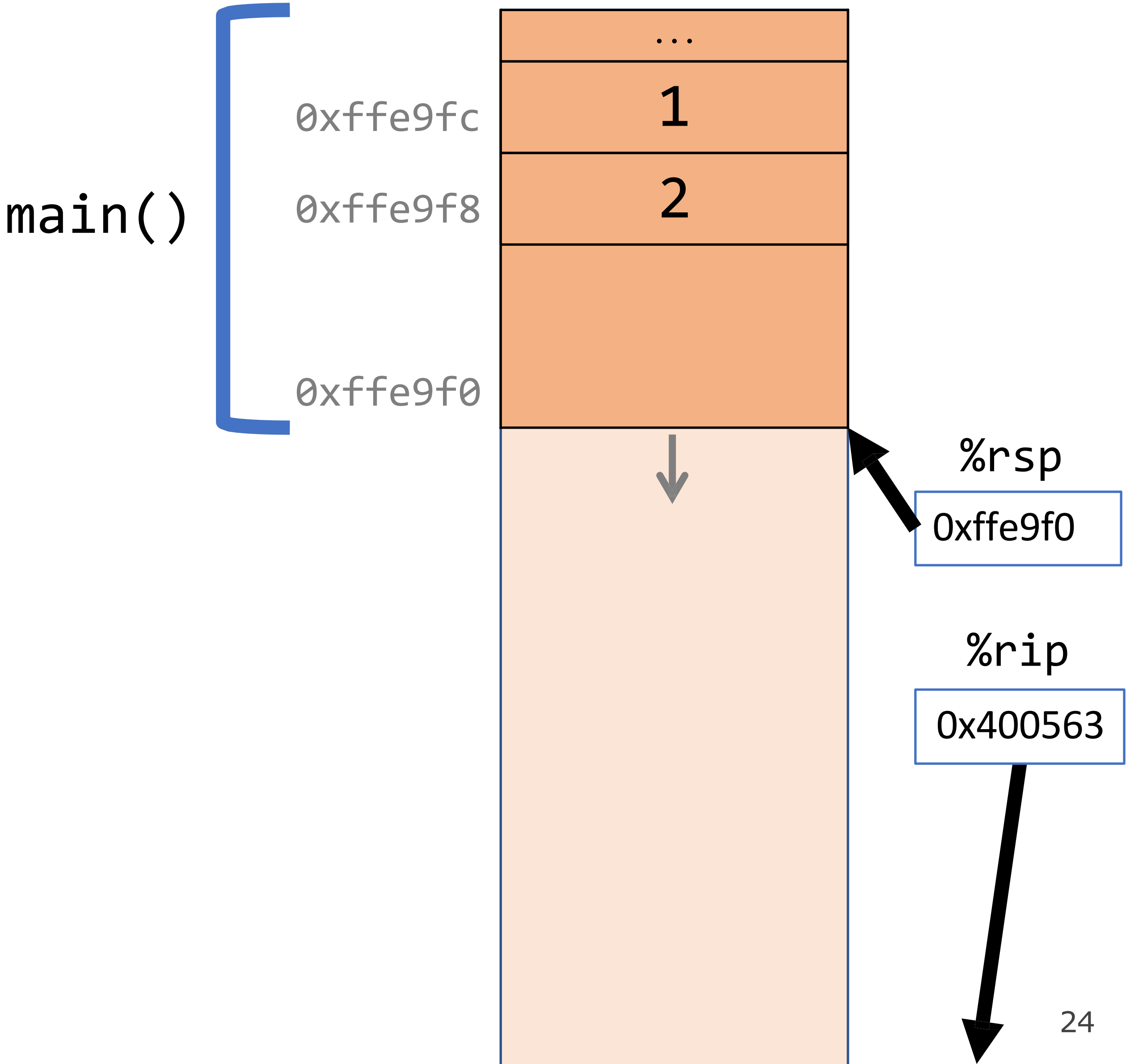

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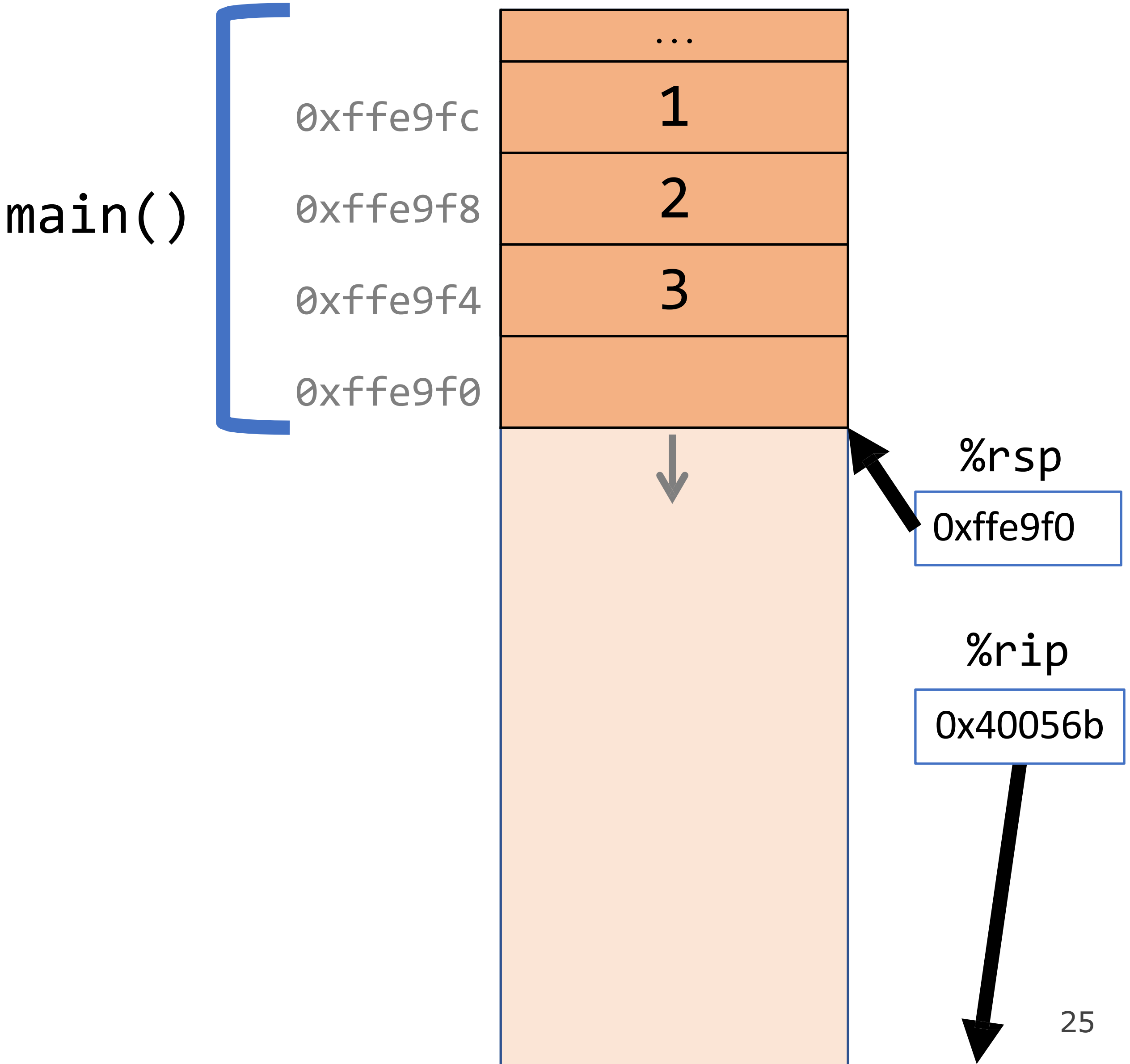

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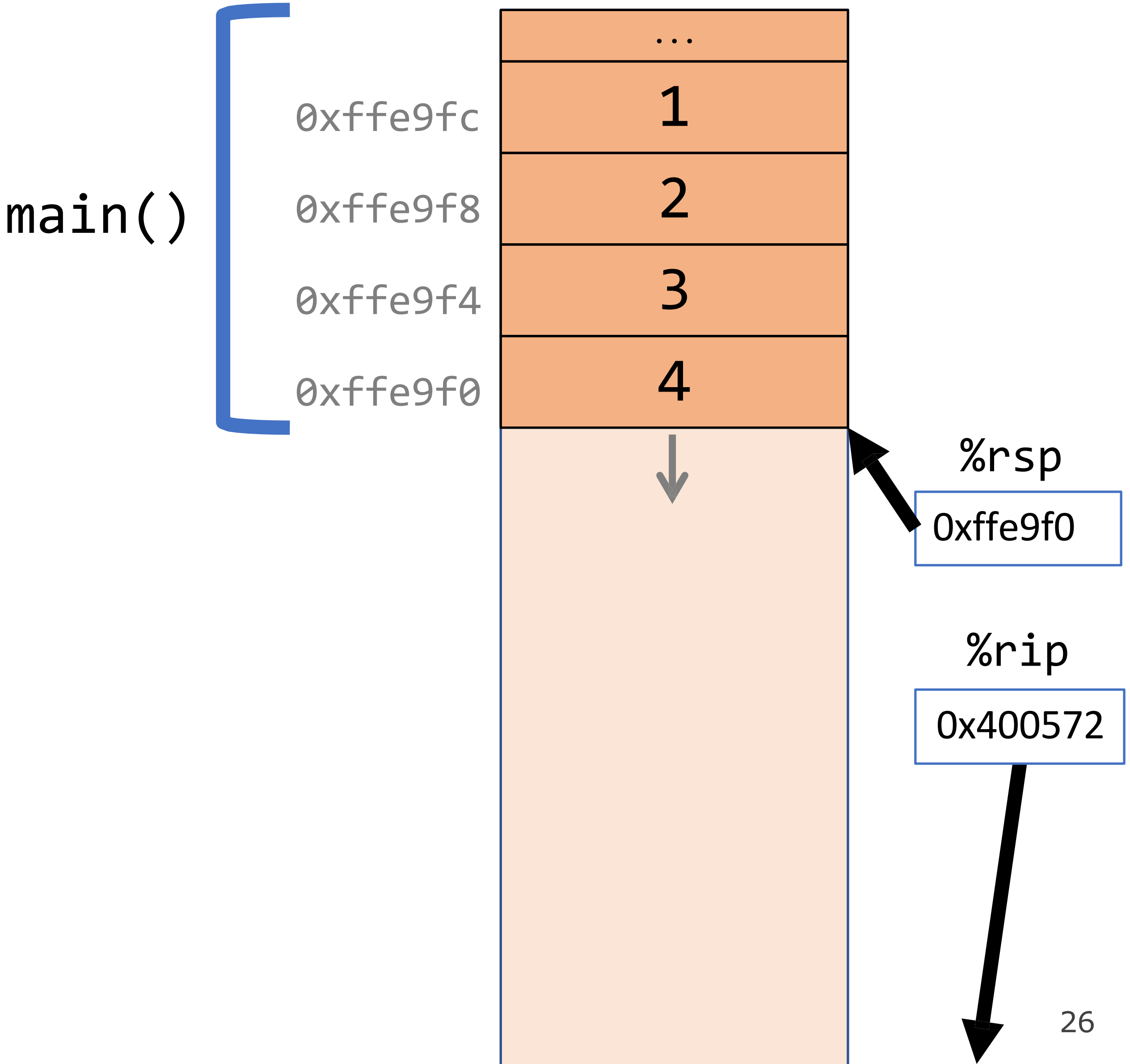

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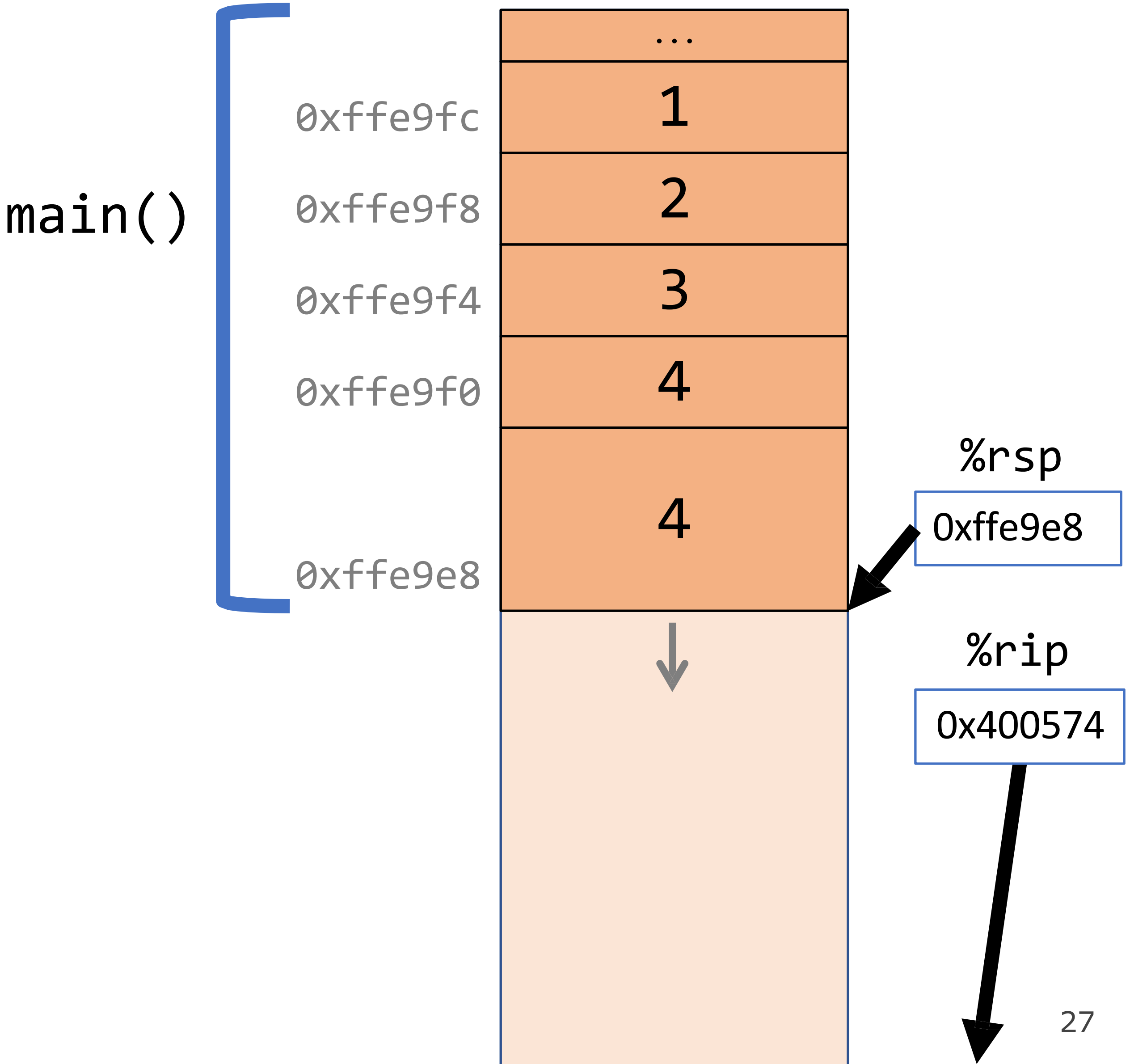

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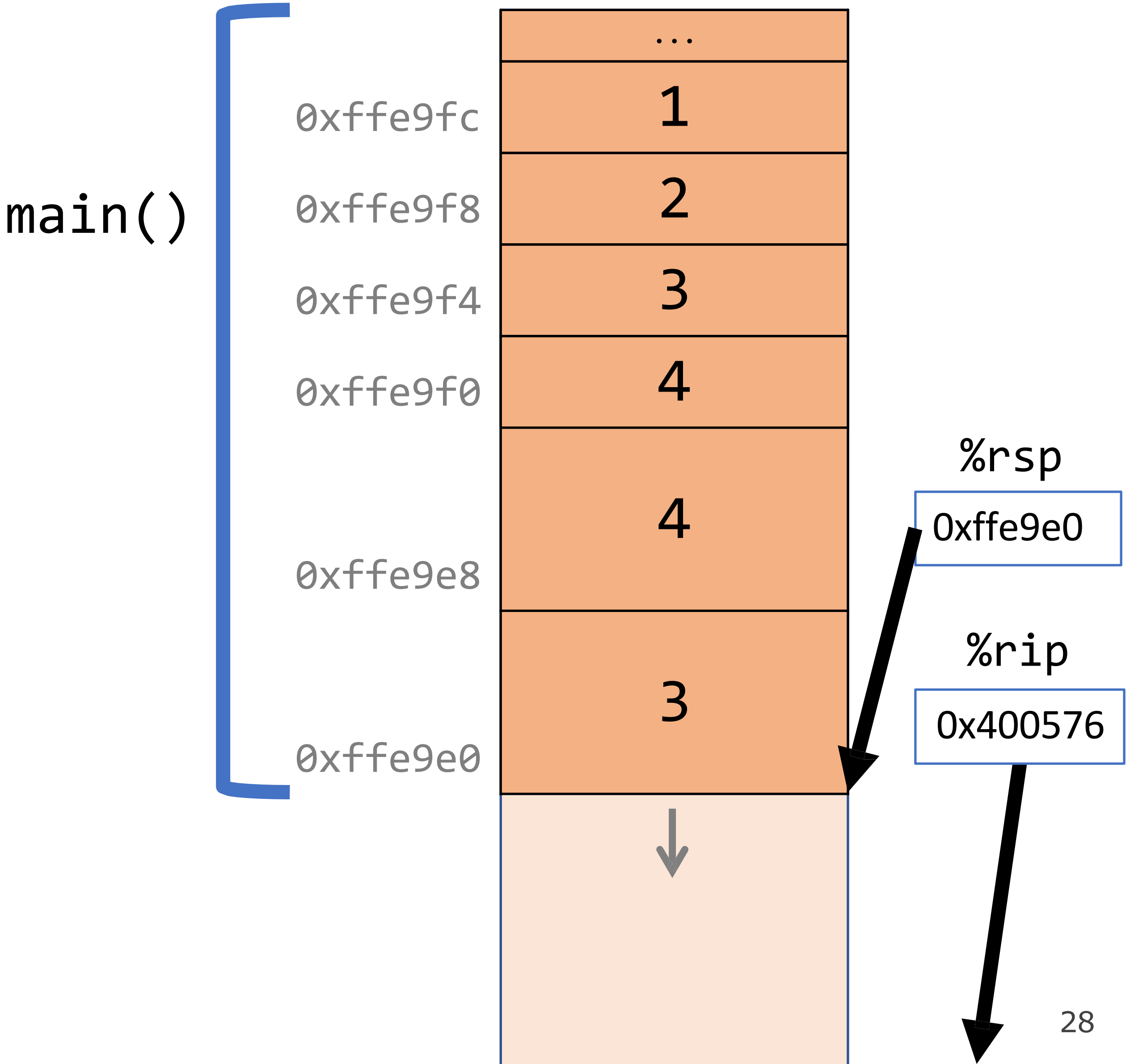


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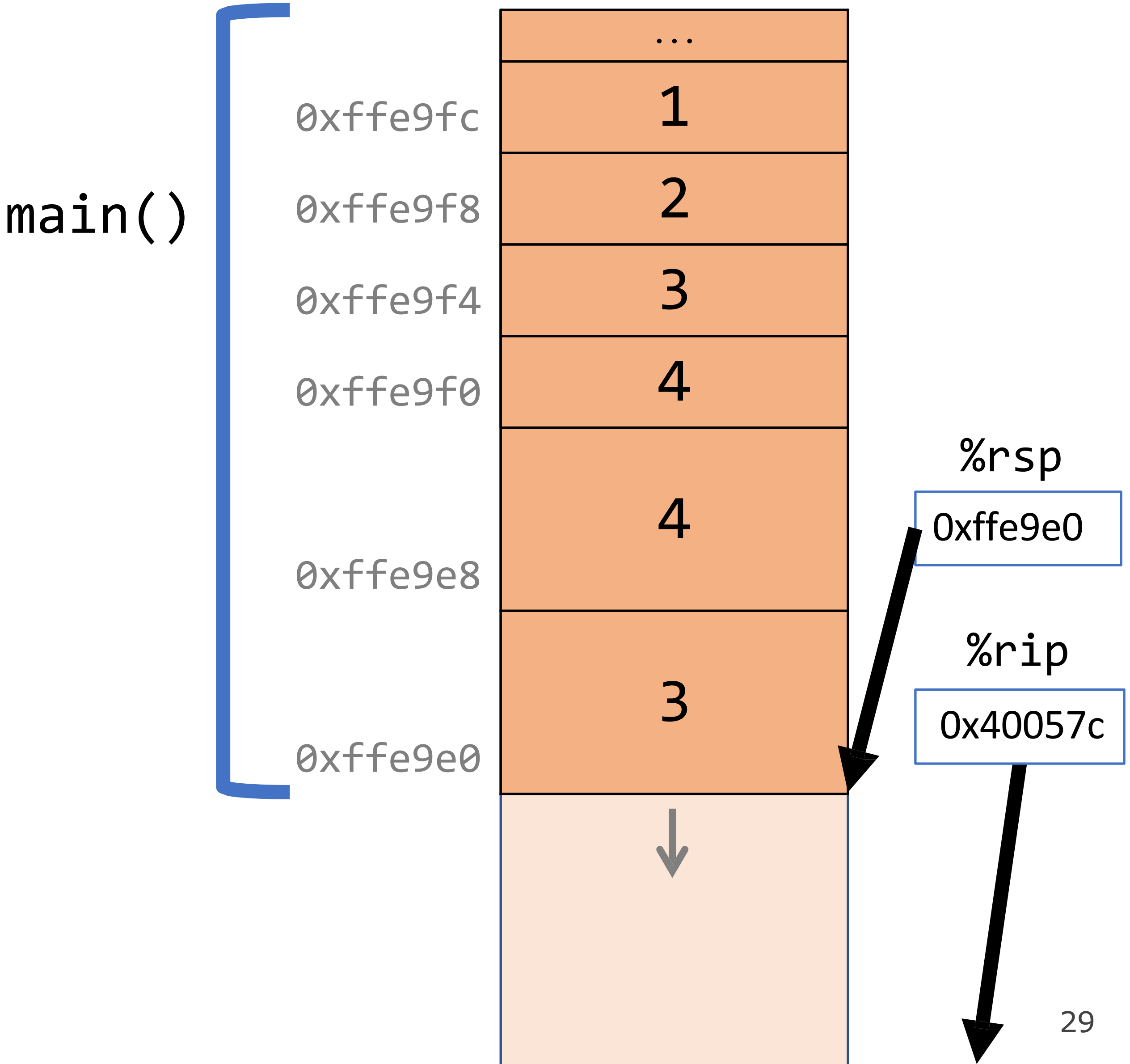

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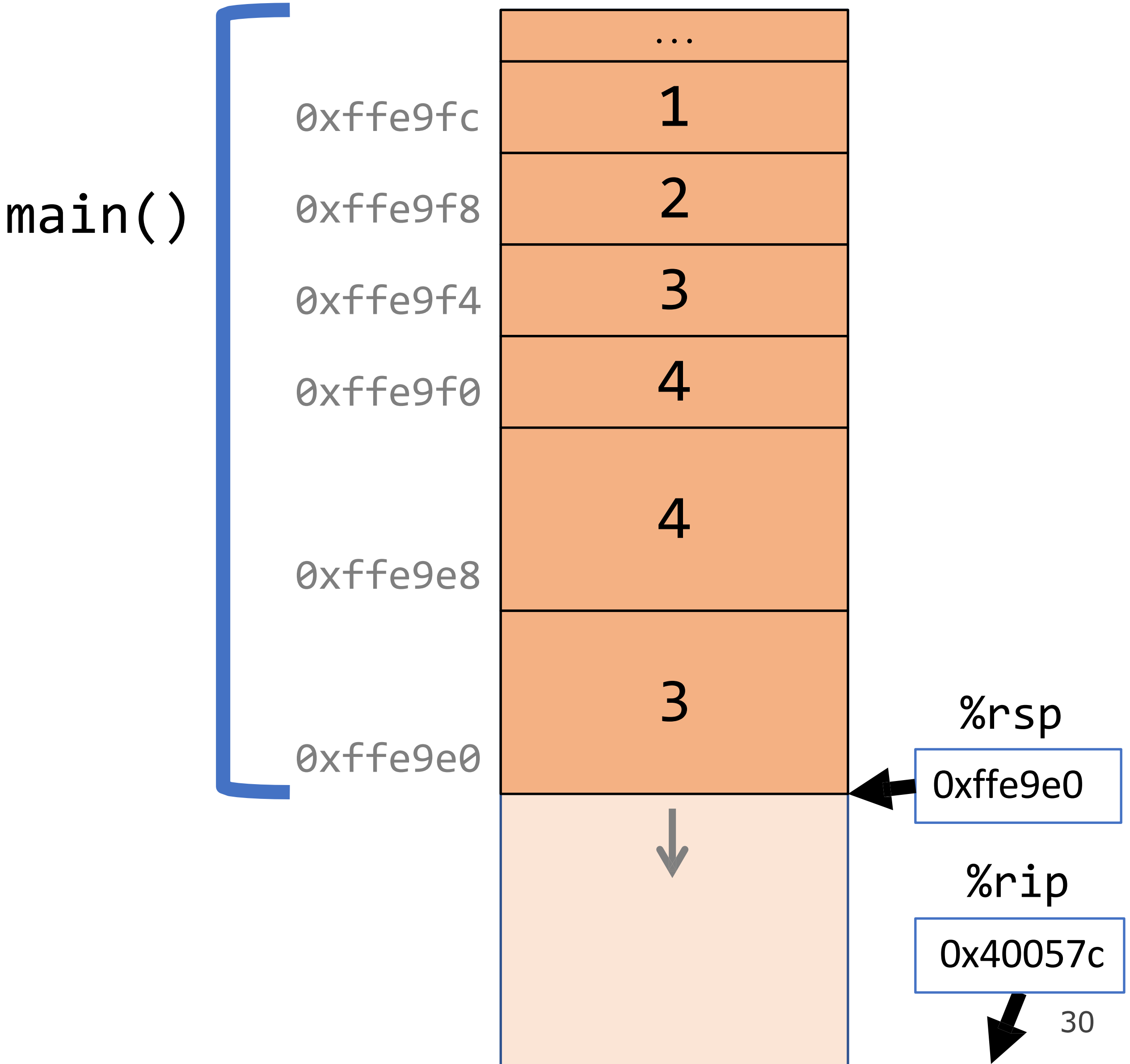

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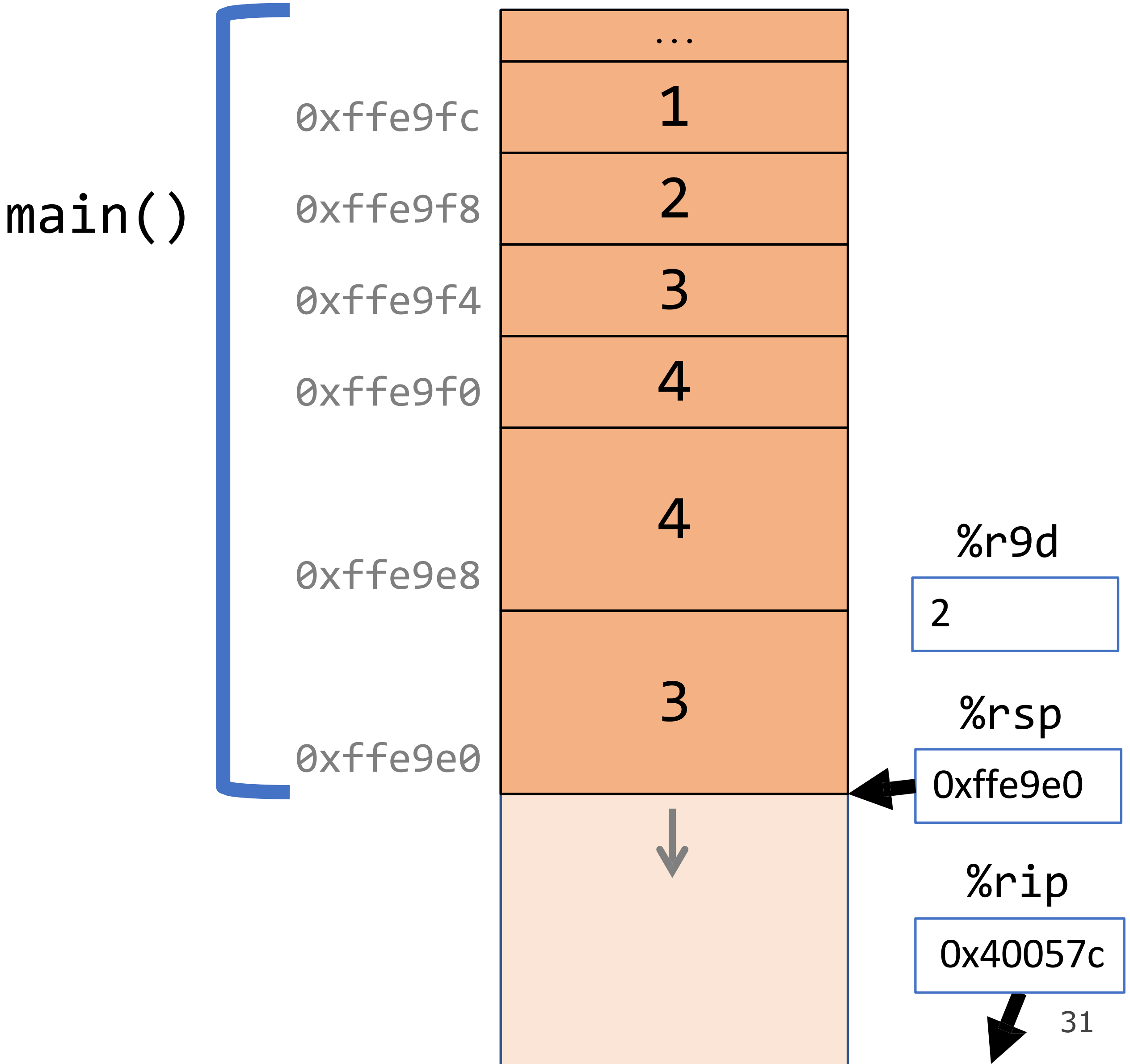

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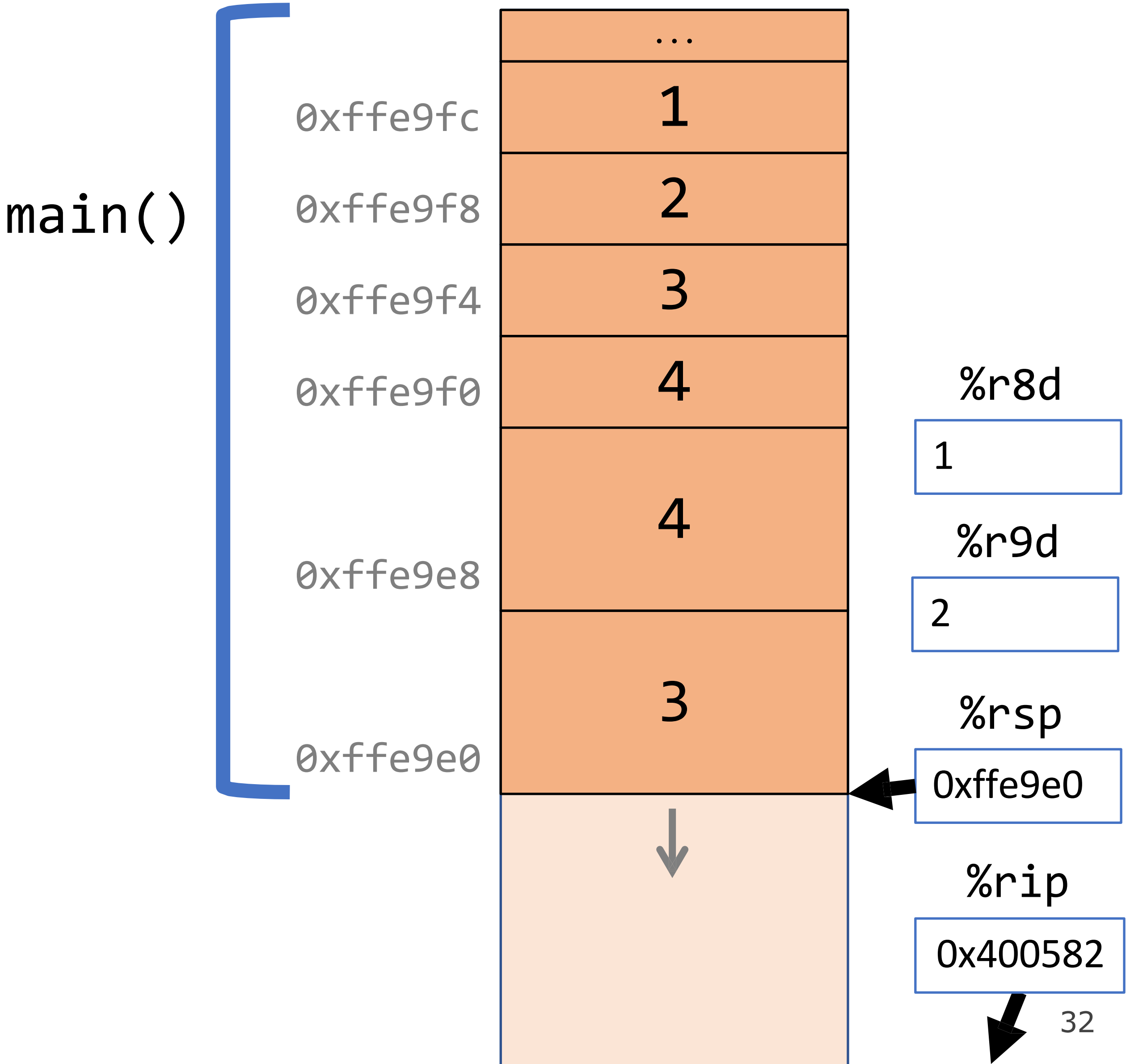

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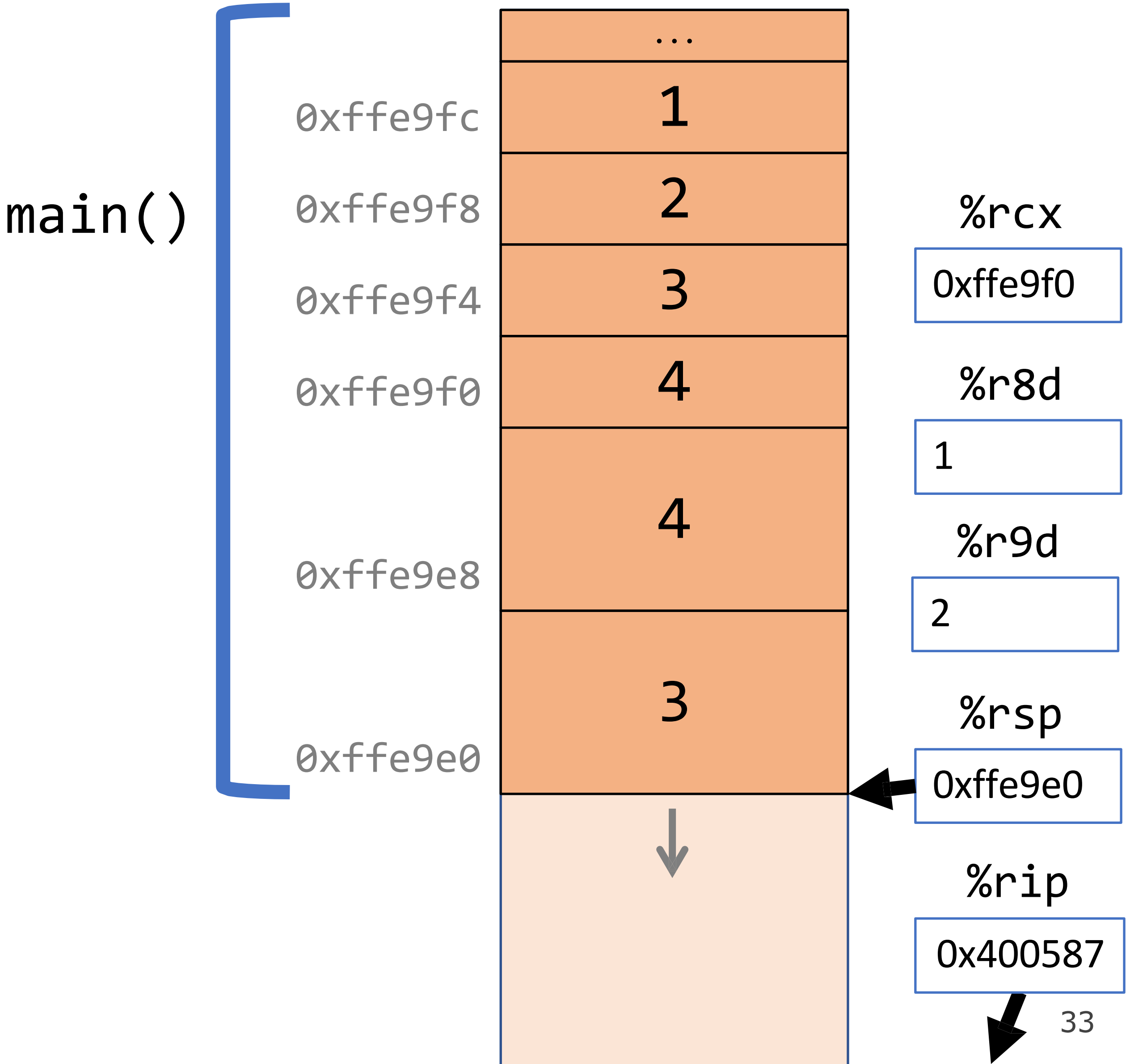

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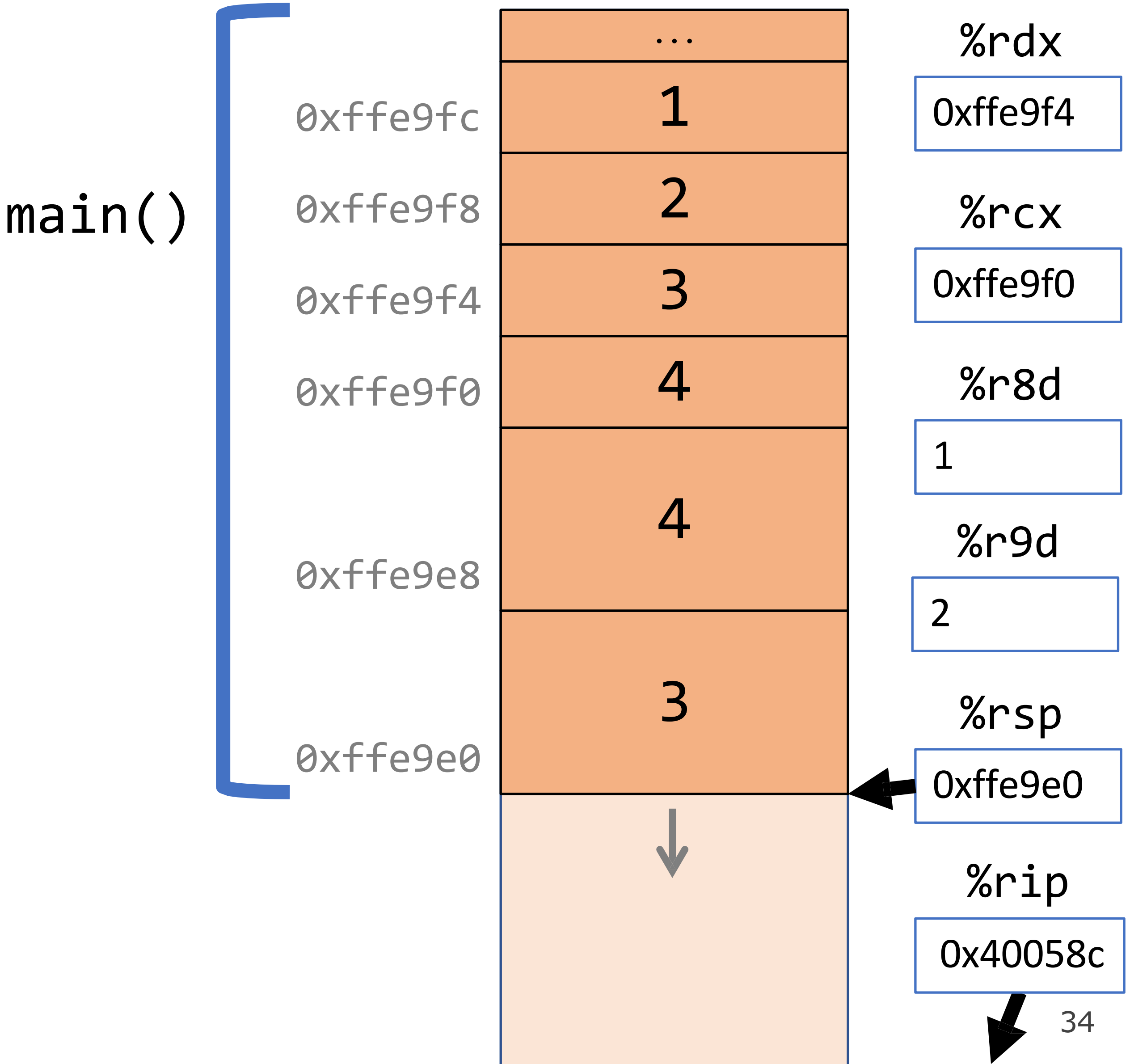
    int i4 = 4;
    int result = func(&i1, &i2, &i3, &i4,
                      i1, i2, i3, i4);
    …
}

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



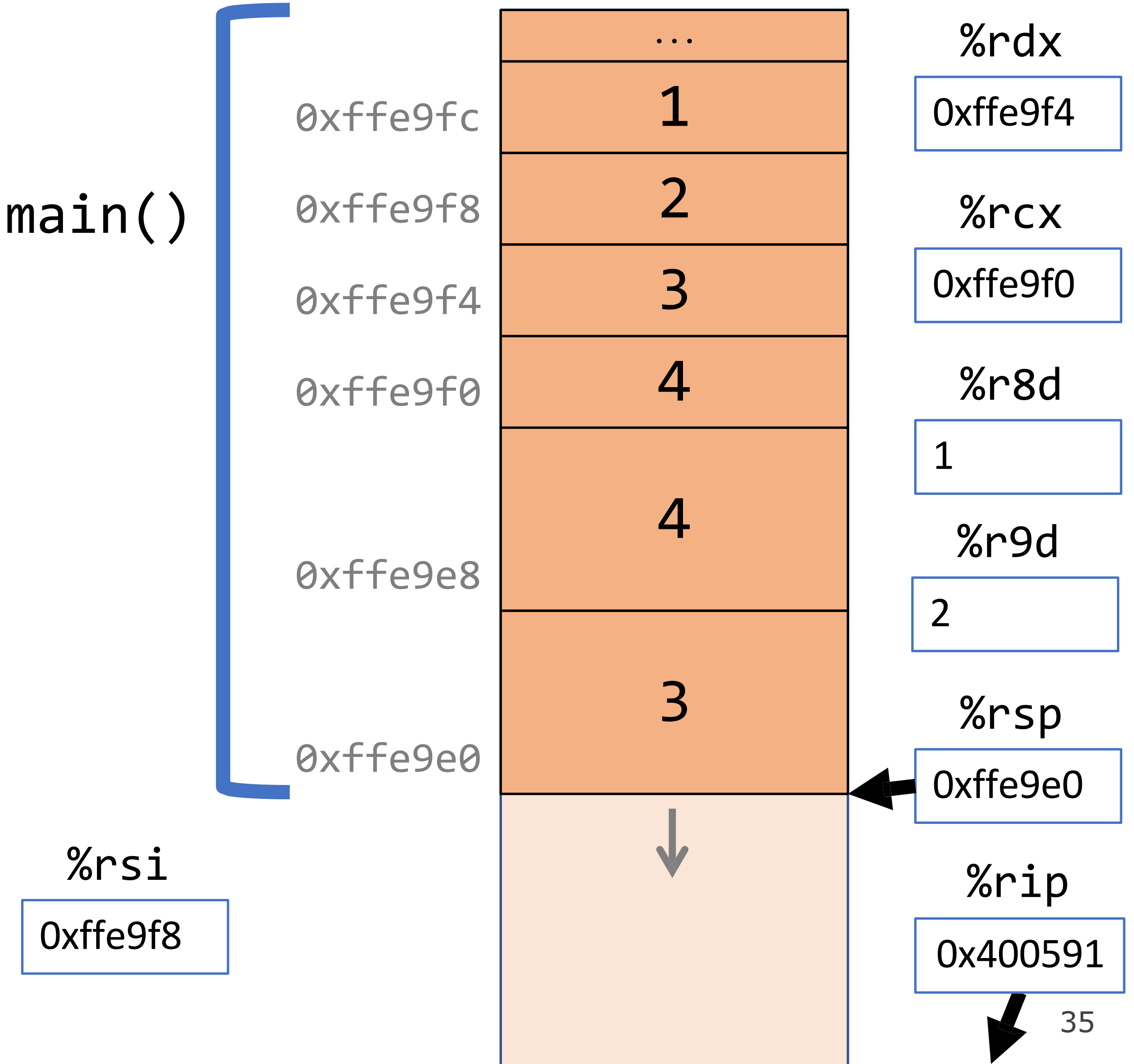

```
0x40057c <+45>:    mov    $0x1,%r8d
0x400582 <+51>:    lea    0x10(%rsp),%rcx
0x400587 <+56>:    lea    0x14(%rsp),%rdx
0x40058c <+61>:    lea    0x18(%rsp),%rsi
0x400591 <+66>:    lea    0x1c(%rsp),%rdi
```

Stack Management

```
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>
```

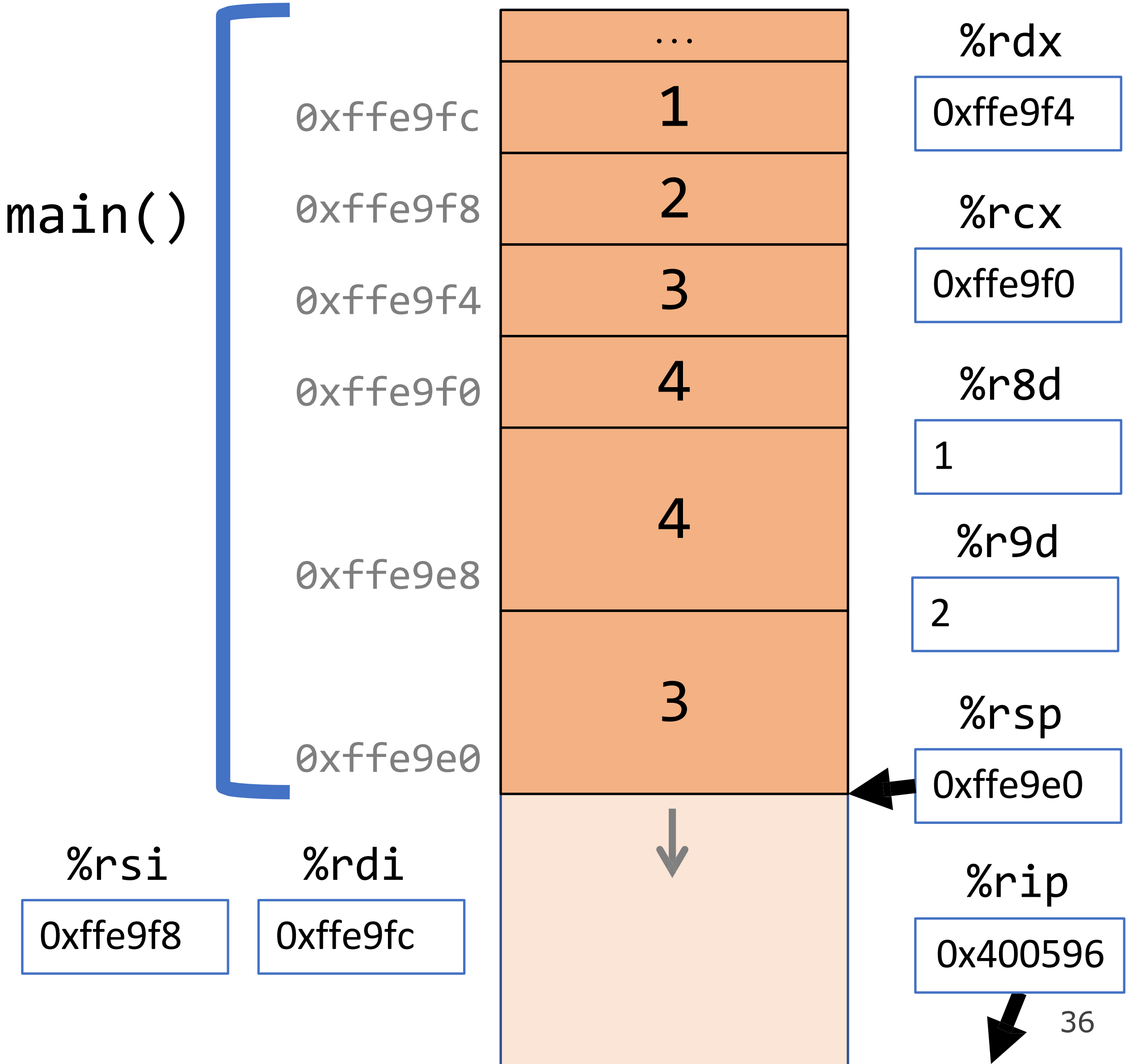


Stack Management

```
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
```

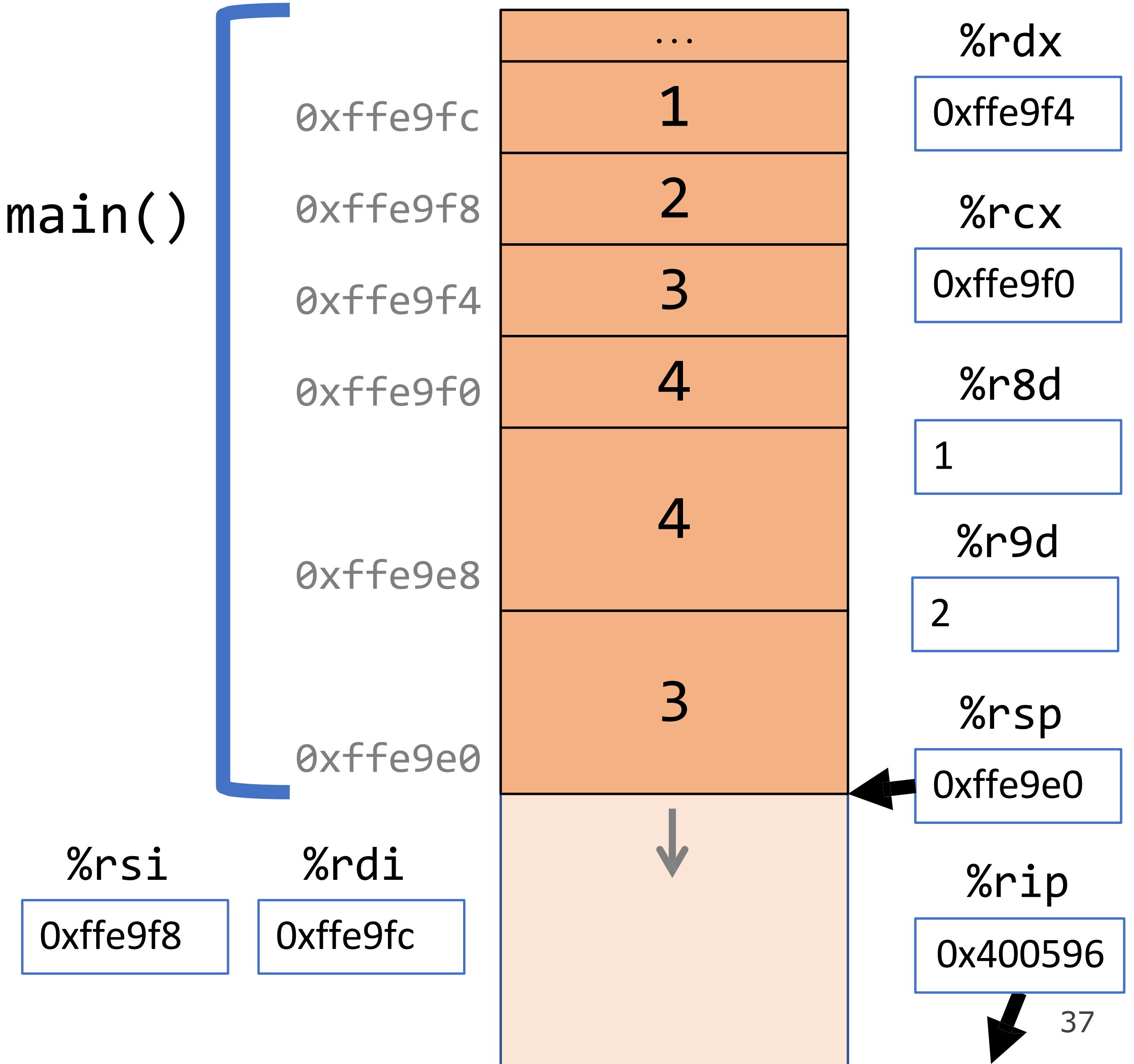


Stack Management

```
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
…
```

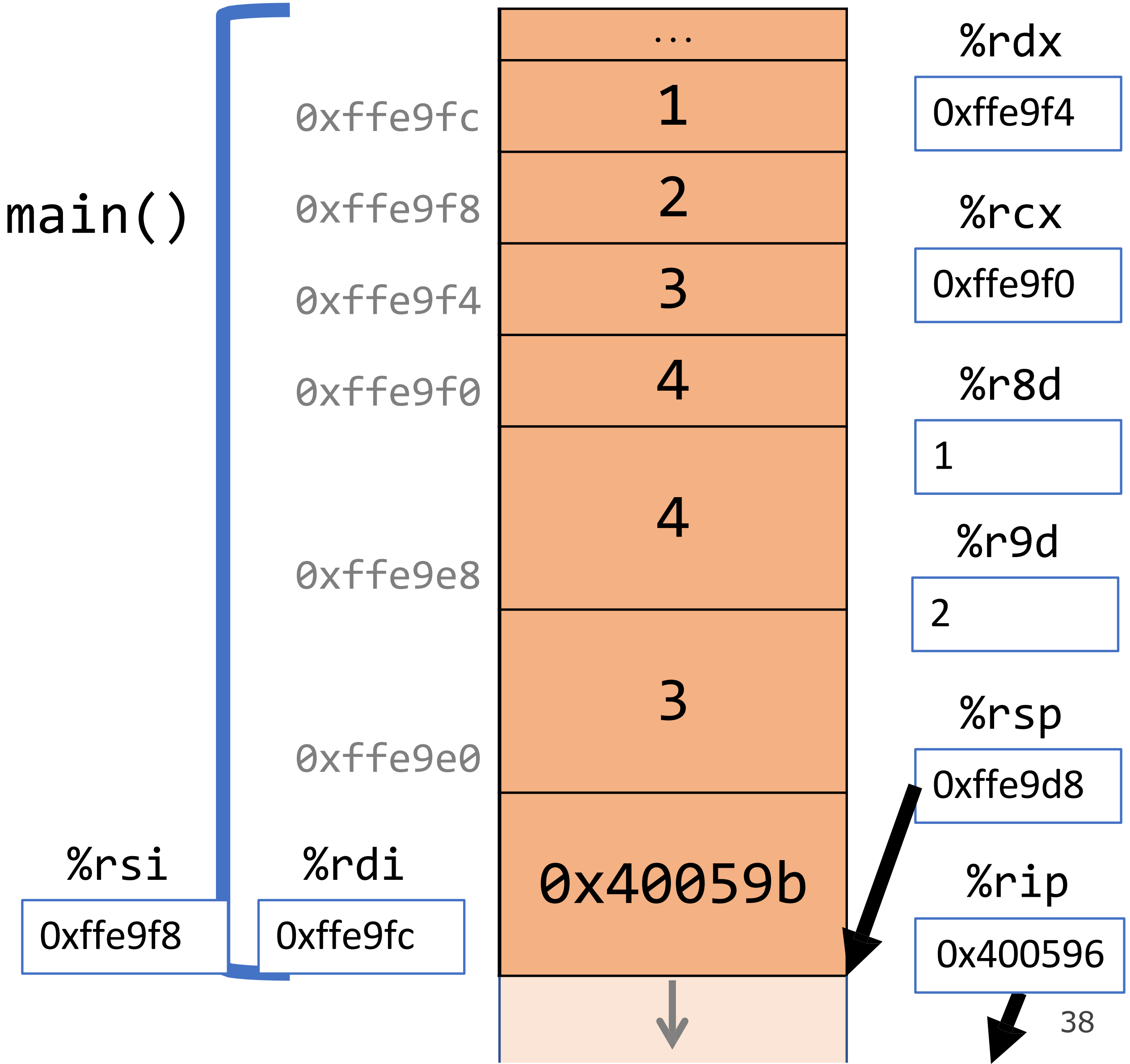


Stack Management

```
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
…
```



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)

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.

```
0000000000401136 <sum_array>:
  401136 <+0>:  mov    $0x0,%eax
  40113b <+5>:  mov    $0x0,%edx
  401140 <+10>: cmp    %esi,%eax
  401142 <+12>: jge    0x40114f <sum_array+25>
  401144 <+14>: movslq %eax,%rcx
  401147 <+17>: add    (%rdi,%rcx,4),%edx
  40114a <+20>: add    $0x1,%eax
  40114d <+23>: jmp    0x401140 <sum_array+10>
  40114f <+25>: mov    %edx,%eax
  401151 <+27>: retq
```

GCC Optimizations

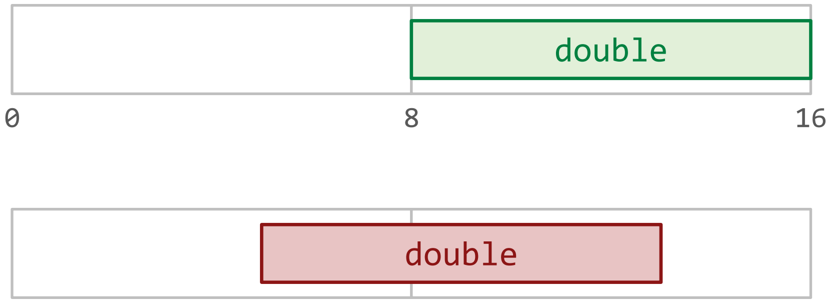
Data Alignment

- Computer systems restrict the allowable addresses for primitive data types: an object's address must be a multiple of some value ***K*** (normally 2, 4, or 8).
- These *alignment restrictions* simplify the design of the hardware.
- Suppose the processor always fetches 8 bytes at a time. If every `double` is guaranteed to sit at a multiple of 8, a single access reads or writes it.

Intel's recommended alignment for x86-64

K	Types
1	`char`
2	`short`
4	`int, float`
8	`long, double, char *`

The processor fetches 8 aligned bytes at a time:



aligned → 1 access

unaligned → 2 accesses

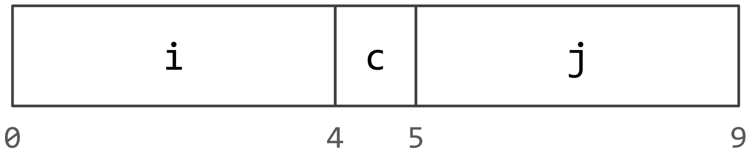
Data Alignment

- The compiler enforces alignment by laying out each data type so that every field within the struct satisfies its own alignment restriction.

```c
struct S1 {
    int  i;
    char c;
    int  j;
};
```

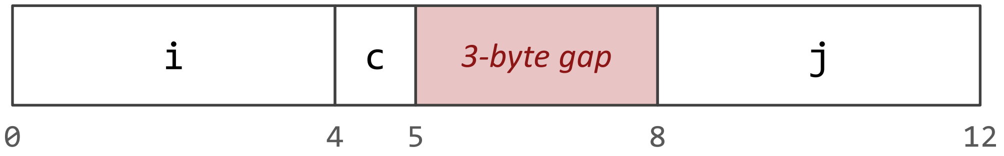
Don't be surprised when `sizeof()` reports more bytes than you counted.

Minimal allocation — 9 bytes



`j` lands at offset 5, which is not a multiple of 4.

With compiler-inserted padding — 12 bytes



Every field is now aligned: `sizeof(struct S1) == 12`

Rule of thumb: every field sits at an offset that is a multiple of its own K, and the struct is padded so its total size is a multiple of the largest K it contains.

Registers Vs Addresses

- So far, we've often seen local variables stored directly in registers, rather than on the stack.

- 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)

Optimization

Most of what you need to do with optimization can be summarized by:

1) If doing something seldom and only on small inputs, do whatever is simplest to code, understand, and debug
2) If doing things a lot, or on big inputs, make the primary algorithm's Big-O cost reasonable
3) **Let gcc do its magic from there**
4) Optimize explicitly as a last resort

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 Common For Loop Output

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

Possible Alternative

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

GCC For Loop Output

GCC Common For Loop Output

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

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

GCC For Loop Output

GCC Common For Loop Output

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

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
...
```

GCC For Loop Output

GCC Common For Loop Output

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

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
...
```

GCC For Loop Output

```
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
...
```

Possible Alternative

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

GCC For Loop Output

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
...
```

Possible Alternative

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

GCC For Loop Output

GCC Common For Loop Output

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

Possible Alternative

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

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, left (GCC common output) is best b/c fewer instructions
  - If n is large, right (alternative) 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.

GCC Optimization

- Today, we'll be comparing two levels of optimization in the gcc compiler:
  - `gcc –O0   // mostly just literal translation of C`
  - `gcc –O2   // enable nearly all reasonable optimizations`
  - (we also use –Og, like –O0 but more debugging friendly)

- There are other custom and more aggressive levels of optimization, e.g.:
  - `-O3      //more aggressive than O2, trade size for speed`
  - `-Os      //optimize for size`
  - `-Ofast   //disregard standards compliance (!!)`

- Exhaustive list of gcc optimization-related flags:
  - https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html

Compiler optimizations

How many GCC optimization levels are there?

Asked 11 years, 3 months ago Active 5 months ago Viewed 62k times

109

35

How many GCC optimization levels are there?

I tried gcc -O1, gcc -O2, gcc -O3, and gcc -O4

If I use a really large number, it won't work.

However, I have tried

```
gcc -O100
```

and it compiled.

How many optimization levels are there?

Gcc supports numbers up to 3. Anything above is interpreted as 3

https://stackoverflow.com/questions/1778538/how-many-gcc-optimization-levels-are-there

GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- Dead Code
- Strength Reduction
- Code Motion
- Tail Recursion
- Loop Unrolling

Constant Folding

Constant Folding pre-calculates constants at compile-time where possible.

```
int seconds = 60 * 60 * 24 * n_days;
```

Constant Folding

Constant Folding pre-calculates constants at compile-time where possible.

```
int seconds = 60 * 60 * 24 * n_days;
```

```
int seconds = 86400 * n_days;
```

Constant Folding

```
int fold(int param) {
    char arr[5];
    int a = 0x107;
    int b = a * sizeof(arr);
    int c = 1;
    return a * param + (a + 0x15 / c + strlen("Hello") * b - 0x37) / 4;
}
```

Constant Folding

```
int fold(int param) {
    char arr[5];
    int a = 0x107;
    int b = a * sizeof(arr);
    int c = 1;
    return a * param + (a + 0x15 / c + strlen("Hello") * b - 0x37) / 4;
}
```

```
int fold(int param) {
    char arr[5];
    int a = 0x107;
    int b = a * 5;
    int c = 1;
    return a * param + (a + 0x15 / c + 5 * b - 0x37) / 4;
}
```

Constant Folding

```
int fold(int param) {
    int a = 0x107;
    int b = a * 5;
    int c = 1;
    return a * param + (a + 0x15 / c + 5 * b - 0x37) / 4;
}

int fold(int param) {
    int b = 0x107 * 5;
    int c = 1;
    return 0x107*param+(0x107+0x15/c+5*b-0x37) / 4;
}
```

Constant Folding

```
int fold(int param) {
    int b = 0x107 * 5;
    int c = 1;
    return 0x107*param+(0x107+0x15/c+5*b-0x37) / 4;
}

int fold(int param) {
    return 0x107*param+(0x11c/1+5* 0x107 * 5 -0x37) / 4;
}
```

Constant Folding

```
int fold(int param) {
    int b = 0x107 * 5;
    int c = 1;
    return 0x107*param+(0x107+0x15/c+5*b-0x37) / 4;
}

int fold(int param) {
    return 0x107*param+(0x107 + 0x15/1+5* 0x107 * 5 -0x37) / 4;
}

int fold(int param) {
    return 0x107 * param + 1701;
}
```

Constant Folding: Before (-O0)

```
0000000000011b9 <fold>:
    11b9:   55                      push   %rbp
    11ba:   48 89 e5                mov    %rsp,%rbp
    11bd:   41 54                   push   %r12
    11bf:   53                      push   %rbx
    11c0:   48 83 ec 30             sub    $0x30,%rsp
    11c4:   89 7d cc                mov    %edi,-0x34(%rbp)
    11c7:   c7 45 ec 07 01 00 00    movl   $0x107,-0x14(%rbp)
    11ce:   8b 45 ec                mov    -0x14(%rbp),%eax
    11d1:   48 98                   cltq
    11d3:   89 c2                   mov    %eax,%edx
    11d5:   89 d0                   mov    %edx,%eax
    11d7:   c1 e0 02                shl    $0x2,%eax
    11da:   01 d0                   add    %edx,%eax
    11dc:   89 45 e8                mov    %eax,-0x18(%rbp)
    11df:   48 8b 05 2a 0e 00 00    mov    0xe2a(%rip),%rax        # 2010 <_IO_stdin_used+0x10>
    11e6:   66 48 0f 6e c0          movq   %rax,%xmm0
    11eb:   e8 b0 fe ff ff          callq  10a0 <sqrt@plt>
    11f0:   f2 0f 2c c0             cvttsd2si %xmm0,%eax
    11f4:   89 45 e4                mov    %eax,-0x1c(%rbp)
    11f7:   8b 45 ec                mov    -0x14(%rbp),%eax
    11fa:   0f af 45 cc             imul   -0x34(%rbp),%eax
    11fe:   41 89 c4                mov    %eax,%r12d
    1201:   b8 15 00 00 00          mov    $0x15,%eax
    1206:   99                      cltd
    1207:   f7 7d e4                idivl  -0x1c(%rbp)
    120a:   89 c2                   mov    %eax,%edx
    120c:   8b 45 ec                mov    -0x14(%rbp),%eax
    120f:   01 d0                   add    %edx,%eax
    1211:   48 63 d8                movslq %eax,%rbx
    1214:   48 8d 3d ed 0d 00 00    lea    0xded(%rip),%rdi        # 2008 <_IO_stdin_used+0x8>
    121b:   e8 20 fe ff ff          callq  1040 <strlen@plt>
    1220:   8b 55 e8                mov    -0x18(%rbp),%edx
    1223:   48 63 d2                movslq %edx,%rdx
    1226:   48 0f af c2             imul   %rdx,%rax
    122a:   48 01 d8                add    %rbx,%rax
    122d:   48 83 e8 37             sub    $0x37,%rax
    1231:   48 c1 e8 02             shr    $0x2,%rax
    1235:   44 01 e0                add    %r12d,%eax
    1238:   48 83 c4 30             add    $0x30,%rsp
    123c:   5b                      pop    %rbx
    123d:   41 5c                   pop    %r12
    123f:   5d                      pop    %rbp
    1240:   c3                      retq
```

Constant Folding: After (-O2)

```
0000000000011b0 <fold>:
    11b0:   69 c7 07 01 00 00       imul   $0x107,%edi,%eax
    11b6:   05 a5 06 00 00          add    $0x6a5,%eax
    11bb:   c3                      retq
```

What is the consequence of this for you as a programmer? What should you do differently or the same knowing that compilers can do this for you?

GCC Optimizations

- Constant Folding
- **<u>Common Sub-expression Elimination</u>**
- Dead Code
- Strength Reduction
- Code Motion
- Tail Recursion
- Loop Unrolling

Common Sub-Expression Elimination

Common Sub-Expression Elimination prevents the recalculation of the same thing many times by doing it once and saving the result.

```
int a = (param2 + 0x107);
int b = param1 * (param2 + 0x107) + a;
return a * (param2 + 0x107) + b * (param2 + 0x107);
```

Common Sub-Expression Elimination

Common Sub-Expression Elimination prevents the recalculation of the same thing many times by doing it once and saving the result.

```
int a = (param2 + 0x107);
int b = param1 * (param2 + 0x107) + a;
return a * (param2 + 0x107) + b * (param2 + 0x107);
// = 2 * a * a + param1 * a * a
```

```
00000000000011b0 <subexp>:  // param1 in %edi, param2 in %esi
    11b0:  lea    0x107(%rsi),%eax        // %eax stores a
    11b6:  imul   %eax,%edi               // param1 * a
    11b9:  lea    (%rdi,%rax,2),%esi      // 2 * a + param1 * a
    11bc:  imul   %esi,%eax               // a * (2 * a + param1 * a)
    11bf:  retq
```

Common Sub-Expression Elimination

Why should we bother saving repeated calculations in variables if the compiler has common subexpression elimination?

1) The compiler may not always be able to optimize every instance.
2) Helps reduce redundancy!
3) Makes code more readable!

GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- **<u>Dead Code</u>**
- Strength Reduction
- Code Motion
- Tail Recursion
- Loop Unrolling

Dead Code

Dead code elimination removes code that doesn't serve a purpose:

```
if (param1 < param2 && param1 > param2) {
    printf("This test can never be true!\n");
}

// Empty for loop
for (int i = 0; i < 1000; i++);

// If/else that does the same operation in both cases
if (param1 == param2) {
    param1++;
} else {
    param1++;
}

// If/else that more trickily does the same operation in both cases
if (param1 == 0) {
    return 0;
} else {
    return param1;
}
```

Dead Code: Before (-O0)

```
0000000000011a9 <dead_code>:
    11a9: 55                      push   %rbp
    11aa: 48 89 e5                mov    %rsp,%rbp
    11ad: 48 83 ec 20             sub    $0x20,%rsp
    11b1: 89 7d ec                mov    %edi,-0x14(%rbp)
    11b4: 89 75 e8                mov    %esi,-0x18(%rbp)
    11b7: 8b 45 ec                mov    -0x14(%rbp),%eax
    11ba: 3b 45 e8                cmp    -0x18(%rbp),%eax
    11bd: 7d 19                   jge    11d8 <dead_code+0x2f>
    11bf: 8b 45 ec                mov    -0x14(%rbp),%eax
    11c2: 3b 45 e8                cmp    -0x18(%rbp),%eax
    11c5: 7e 11                   jle    11d8 <dead_code+0x2f>
    11c7: 48 8d 3d 36 0e 00 00    lea    0xe36(%rip),%rdi        # 2004 <_IO_stdin_used+0x4>
    11ce: b8 00 00 00 00          mov    $0x0,%eax
    11d3: e8 68 fe ff ff          callq  1040 <printf@plt>
    11d8: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
    11df: eb 04                   jmp    11e5 <dead_code+0x3c>
    11e1: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
    11e5: 81 7d fc e7 03 00 00    cmpl   $0x3e7,-0x4(%rbp)
    11ec: 7e f3                   jle    11e1 <dead_code+0x38>
    11ee: 8b 45 ec                mov    -0x14(%rbp),%eax
    11f1: 3b 45 e8                cmp    -0x18(%rbp),%eax
    11f4: 75 06                   jne    11fc <dead_code+0x53>
    11f6: 83 45 ec 01             addl   $0x1,-0x14(%rbp)
    11fa: eb 04                   jmp    1200 <dead_code+0x57>
    11fc: 83 45 ec 01             addl   $0x1,-0x14(%rbp)
    1200: 83 7d ec 00             cmpl   $0x0,-0x14(%rbp)
    1204: 75 07                   jne    120d <dead_code+0x64>
    1206: b8 00 00 00 00          mov    $0x0,%eax
    120b: eb 03                   jmp    1210 <dead_code+0x67>
    120d: 8b 45 ec                mov    -0x14(%rbp),%eax
    1210: c9                      leaveq
    1211: c3                      retq
```

Dead Code: After (-O2)

```
0000000000011b0 <dead_code>:
    11b0:   8d 47 01                lea    0x1(%rdi),%eax
    11b3:   c3                      retq
```

GCC Optimizations

- Constant Folding
- Common Sub-expression Elimination
- Dead Code
- **Strength Reduction**
- Code Motion
- Tail Recursion
- Loop Unrolling

Strength Reduction

Strength reduction changes divide to multiply, multiply to add/shift, and mod to AND to avoid using instructions that cost many cycles (multiply and divide).

```
int a = param2 * 32;
int b = a * 7;
int c = b / 2;
int d = param2 % 2;

for (int i = 0; i <= param2; i++) {
    c += param1[i] + 0x107 * i;
}
return c + d;
```

Shifting into Shifts

- `int a = param2 * 32;`

  Becomes:
- `int a = param2 << 5;`

- `int b = a * 7;`

  Becomes:
- `int b = a + (a << 2) + (a << 1); or // (a << 3) - a`

- `int c = b / 2;`

  Becomes
- `int c = b >> 1 // Division by odd numbers is more complex`

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Code Motion

Code motion moves code outside of a loop if possible.

```
for (int i = 0; i < n; i++) {
  sum += arr[i] + foo * (bar + 3);
}
```

Common subexpression elimination deals with expressions that appear multiple times in the code. Here, the expression appears once, but is calculated each loop iteration, even though none of its values change during the loop.

Code Motion

Code motion moves code outside of a loop if possible.

```
int temp = foo * (bar + 3);
for (int i = 0; i < n; i++) {
  sum += arr[i] + temp;
}
```

Moving it out of the loop allows the computation to happen only once.

Practice: GCC Optimization

```
int char_sum(char *s) {
    int sum = 0;
    for (size_t i = 0; i < strlen(s); i++) {
        sum += s[i];
    }
    return sum;
}
```

What is the bottleneck? What (if anything) can GCC do?

Practice: GCC Optimization

```
int char_sum(char *s) {
    int sum = 0;
    for (size_t i = 0; i < strlen(s); i++) {
        sum += s[i];
    }
    return sum;
}
```

What is the bottleneck? What (if anything) can GCC do?

strlen is called every loop iteration – code motion can pull it out of the loop

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Recursion -> Tail Recursion

Recursion -> Tail Recursion

Tail recursion is an example of where GCC can identify recursive patterns that can be more efficiently implemented iteratively.

```
long factorial(int n) {
  if (n <= 1) {
      return 1;
  }
  else return n * factorial(n - 1);
}
```

Recursion With A Bug

Recall the factorial problem from assembly lectures:

```
unsigned int factorial(unsigned int n) {
    if (n <= 1) {
        return 1;
    }
    return n * factorial(n - 1);
}
```

What happens with **`factorial(-1)`**?

- Infinite recursion → Literal stack overflow!
- Compiled with `-0g`!

Factorial: -Og vs –O2

```
401146 <+0>:  cmp    $0x1,%edi
401149 <+3>:  jbe    0x40115b <factorial+21>
40114b <+5>:  push   %rbx
40114c <+6>:  mov    %edi,%ebx
40114e <+8>:  lea    -0x1(%rdi),%edi
401151 <+11>:callq   0x401146 <factorial>
401156 <+16>:imul    %ebx,%eax
401159 <+19>:pop     %rbx
40115a <+20>:retq
40115b <+21>:mov     $0x1,%eax
401160 <+26>:retq
```

-O2:

- What happened?
- Did the compiler "fix" the infinite recursion?

```
4011e0 <+0>:  mov    $0x1,%eax
4011e5 <+5>:  cmp    $0x1,%edi
4011e8 <+8>:  jbe    0x4011fd <factorial+29>
4011ea <+10>:nopw    0x0(%rax,%rax,1)
4011f0 <+16>:mov     %edi,%edx
4011f2 <+18>:sub     $0x1,%edi
4011f5 <+21>:imul    %edx,%eax
4011f8 <+24>:cmp     $0x1,%edi
4011fb <+27>:jne     0x4011f0 <factorial+16>
4011fd <+29>:retq
```

Breaking Down the –O2

```
4011e0 <+0>:  mov    $0x1,%eax                   # Initialize %eax with 1.
4011e5 <+5>:  cmp    $0x1,%edi                   # Compare input value (%edi) with 1.
4011e8 <+8>:  jbe    0x4011fd <factorial+29>     # If input <= 1 (unsigned check), jump to return.
4011ea <+10>: nopw   0x0(%rax,%rax,1)            # No operation (probably for alignment).
4011f0 <+16>: mov    %edi,%edx                   # Copy current value of %edi to %edx.
4011f2 <+18>: sub    $0x1,%edi                   # Decrement %edi.
4011f5 <+21>: imul   %edx,%eax                   # Multiply %eax by %edx and store result in %eax.
4011f8 <+24>: cmp    $0x1,%edi                   # Compare decremented value of %edi with 1.
4011fb <+27>: jne    0x4011f0 <factorial+16>     # If %edi is not 1, repeat the multiplication.
4011fd <+29>: retq                               # Return with the result in %eax.
```

-02:

- Recursive -> Iterative
- No Stack Overflow, Saves Memory and Operations
- Bug still there, harder to find

GCC Optimizations

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Loop Unrolling

Loop Unrolling: Do **n** loop iterations' worth of work per actual loop iteration, so we save ourselves from doing the loop overhead (test and jump) every time, and instead incur overhead only every n-th time.

```
for (int i = 0; i <= n - 4; i += 4) {
    sum += arr[i];
    sum += arr[i + 1];
    sum += arr[i + 2];
    sum += arr[i + 3];
} // after the loop handle any leftovers
```