CS107, Lecture 19

Assembly: Function Call

Reading: B&O 3.7

Ed Discussion

Based on slides created by Cynthia Lee, Chris Gregg, Jerry Cain, Lisa Yan, Nick Troccoli, and others.

Calling Functions In Assembly

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

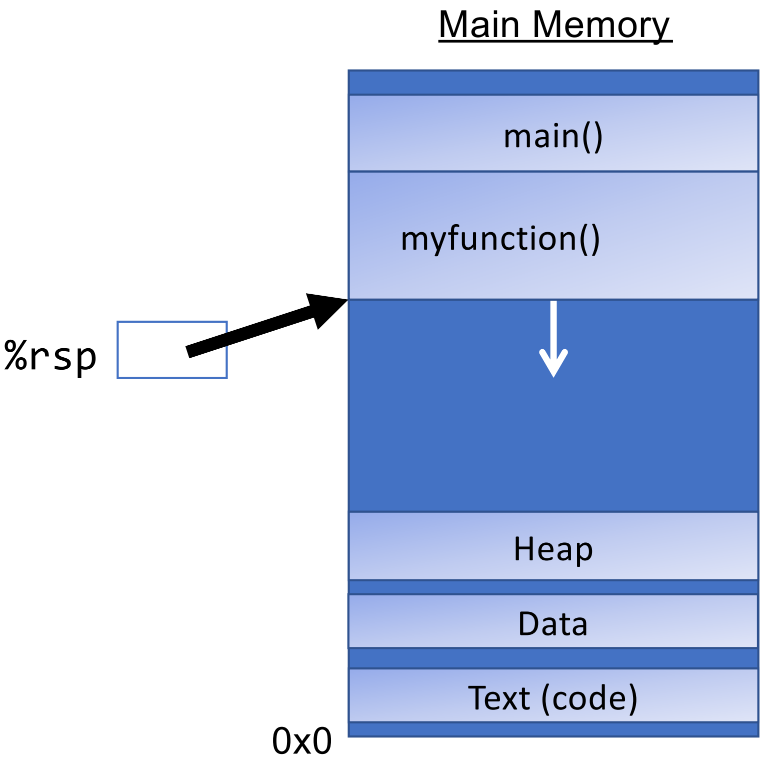
- **Transfer Control** – %rip must be adjusted to execute the callee’s instructions and then resume the caller’s instructions afterwards.
- **Pass Data** – we must pass parameters and extract return values.
- **Manage Memory** – we must handle all of the callee’s stack space needs.

How does assembly interact with the stack?

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

%rsp

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



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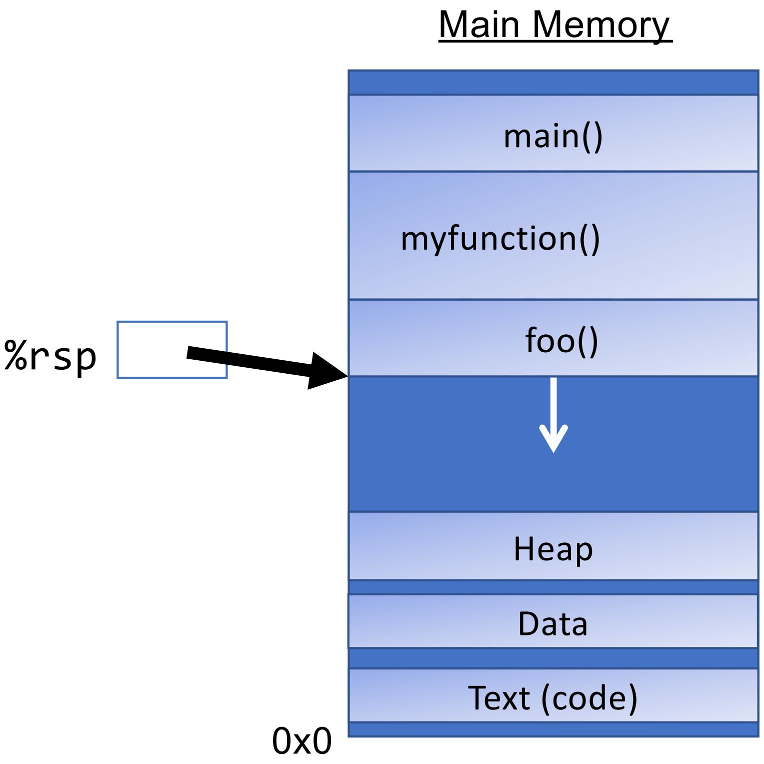

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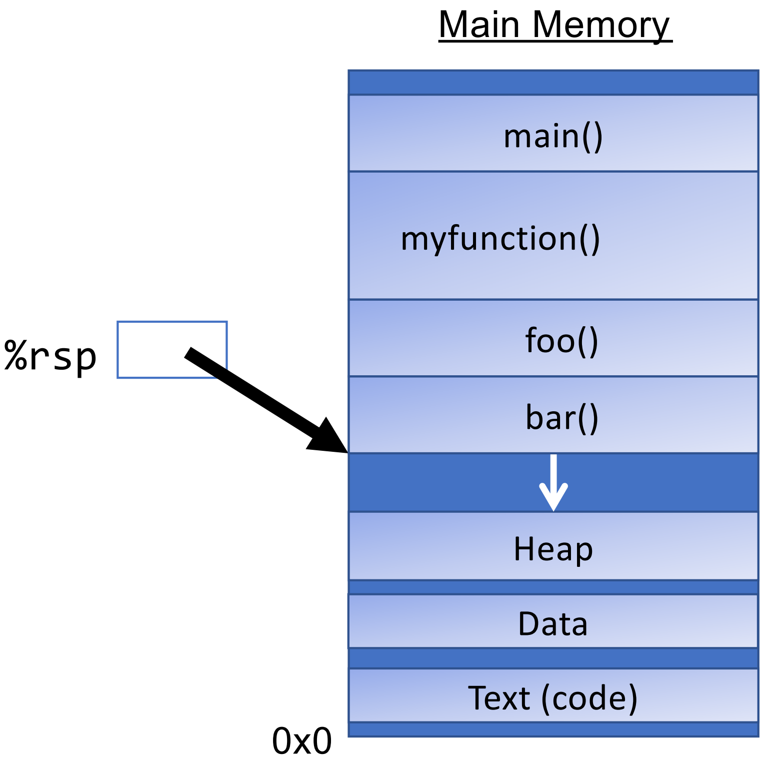

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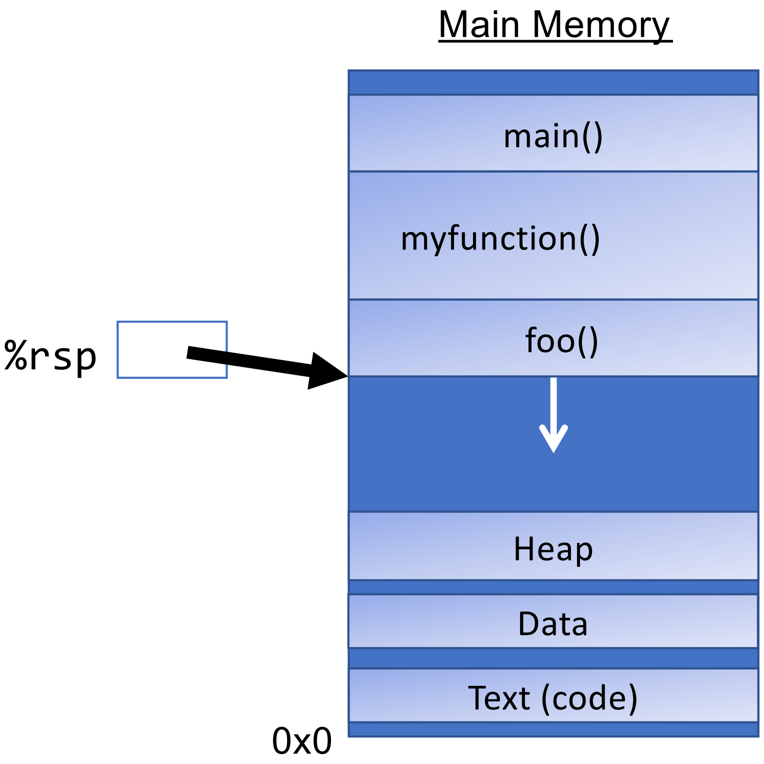

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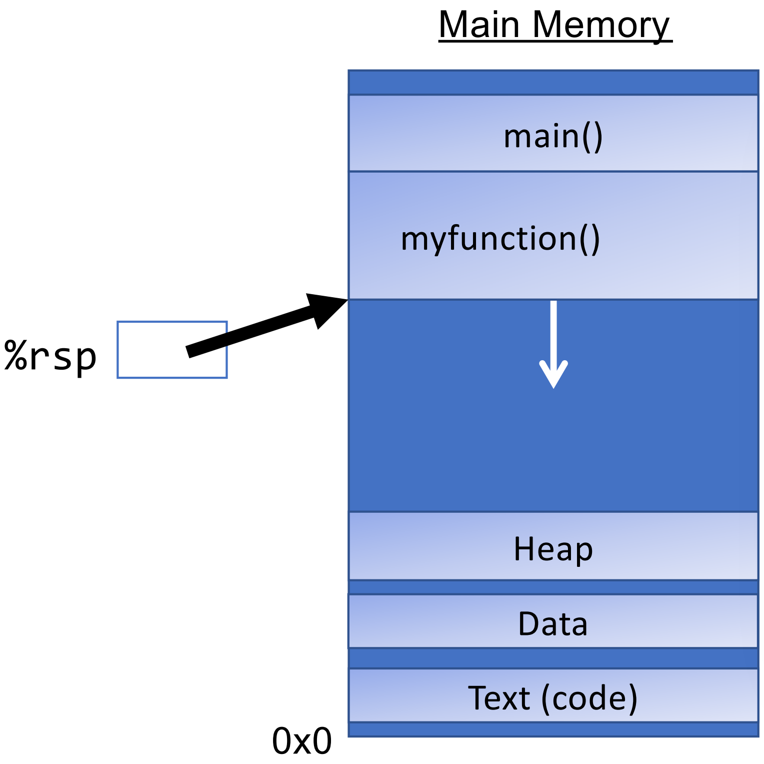

Key idea: %rsp must point to the same place before a function is called and after that function returns, since stack frames go away when a function finishes.

push

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

Instruction	Effect

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

push

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

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pushq S	R[%rsp] ⟵ R[%rsp] - 8; **M[R[%rsp]] ⟵ S**

push

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

Instruction	Effect

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

- 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 new local variables.

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 doesn't remove/clear out the data! It just increments %rsp to indicate the next push can overwrite that location.

pop

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

Instruction	Effect

`popq D`	`D ← M[R[%rsp]]`
	`R[%rsp] ← R[%rsp] + 8;`

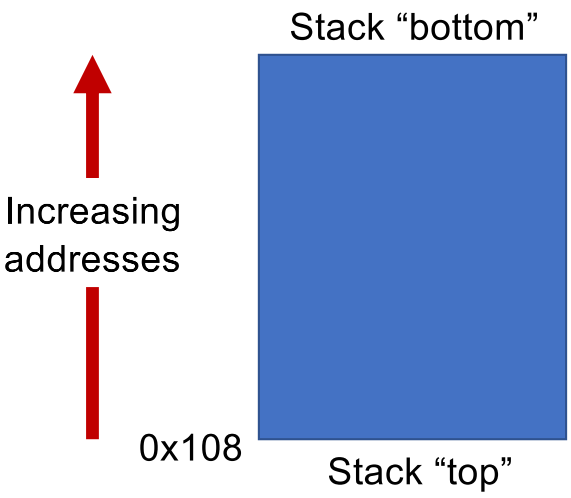
- This behavior is equivalent to the following, but popq is a shorter instruction:

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

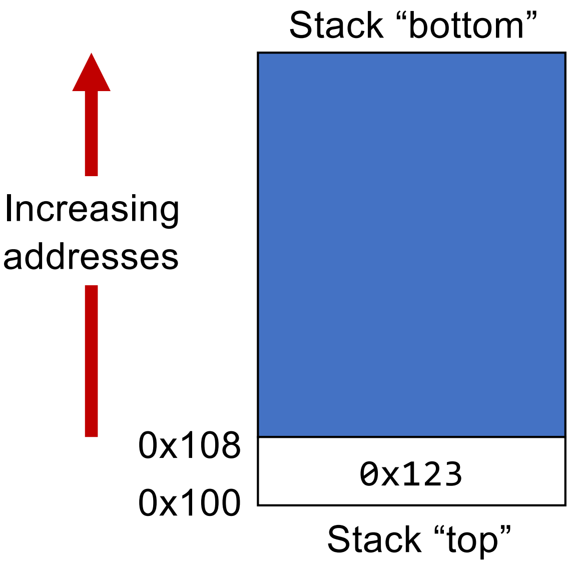
- Sometimes, you'll see instructions just explicitly increment the stack pointer to pop data.

Stack Example

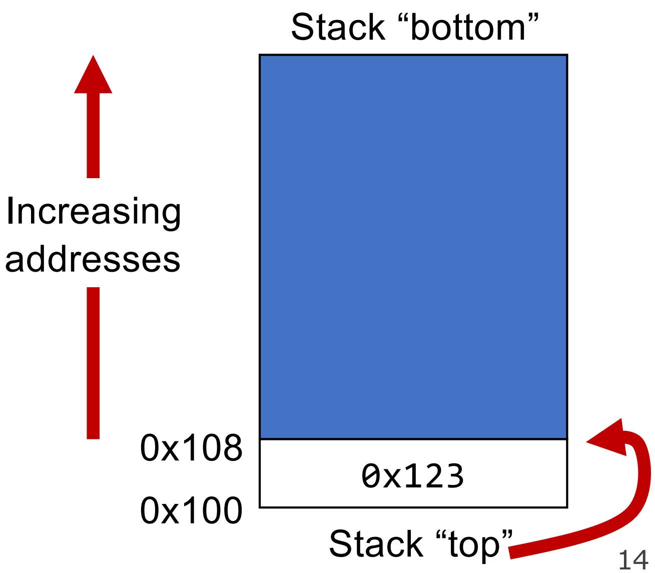
Initially	
`%rax`	`0x123`
`%rdx`	`0`
`%rsp`	`0x108`



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



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



Calling Functions In Assembly

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

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

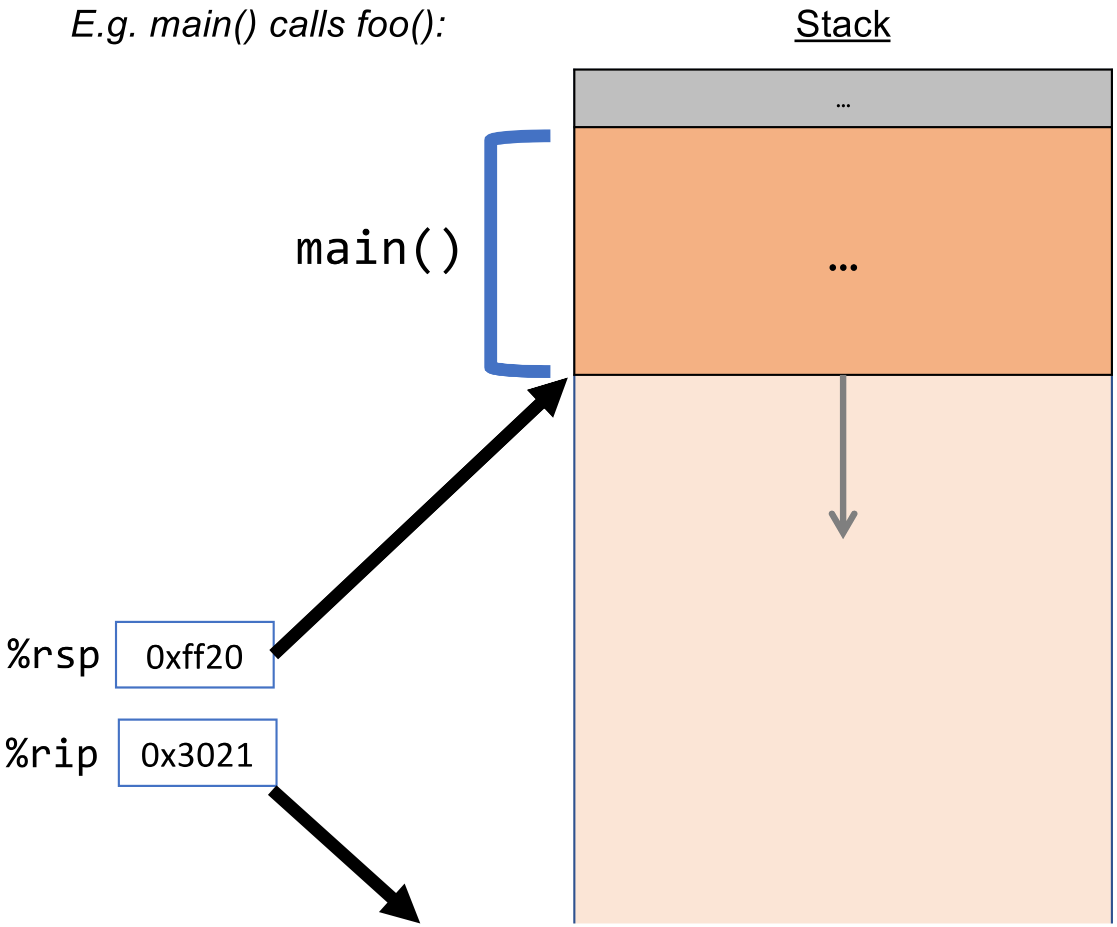
Terminology: **caller** function calls the **callee** function.

Remembering Where We Left Off

Problem: %rip points to the next instruction to execute. To call a function, we must remember that instruction address for later.

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 as if never interrupted by the function call.

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



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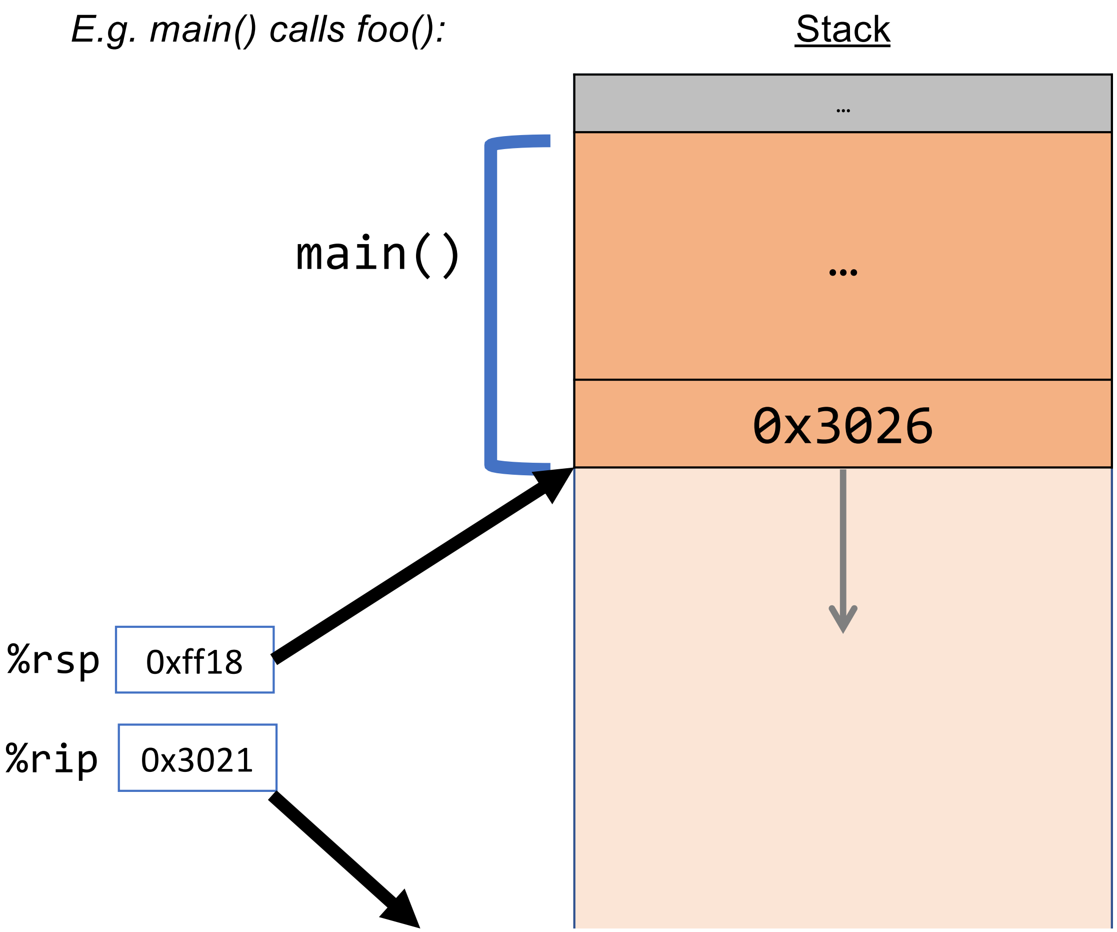

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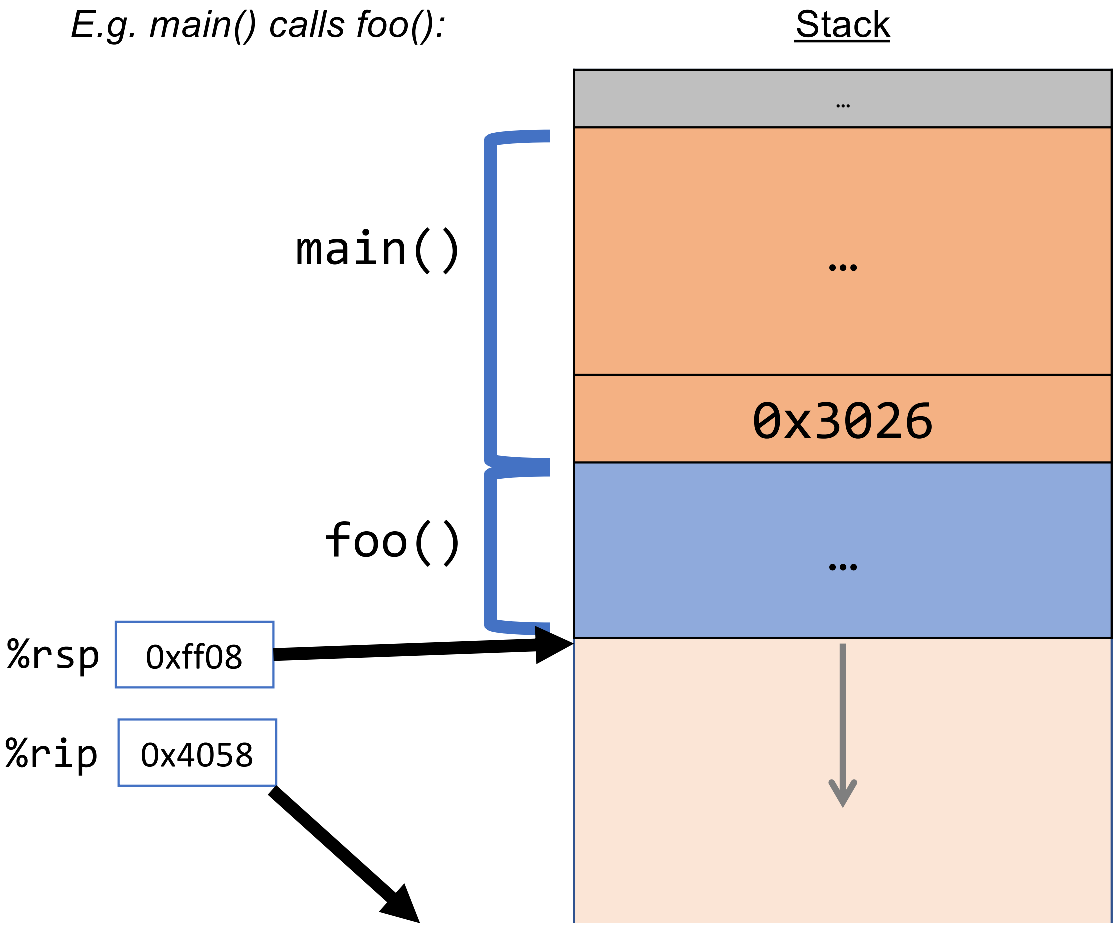

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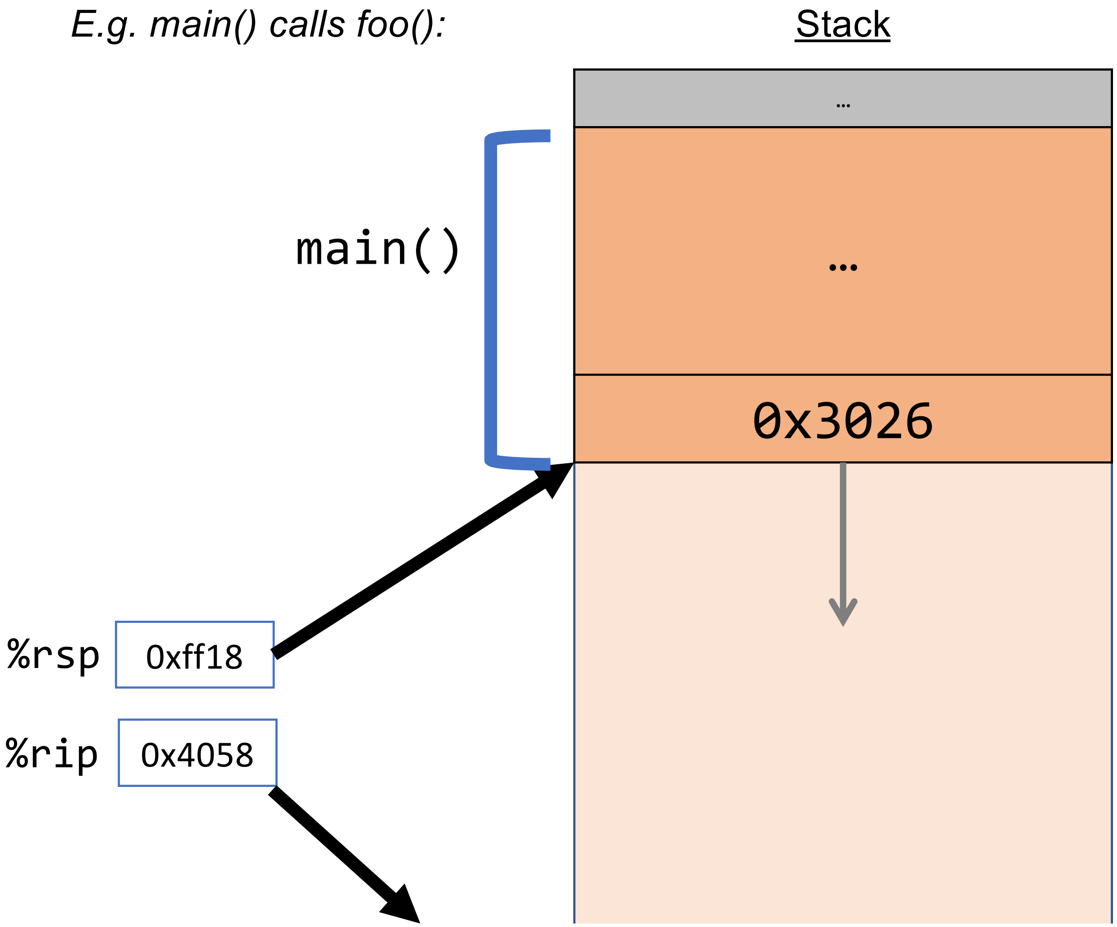

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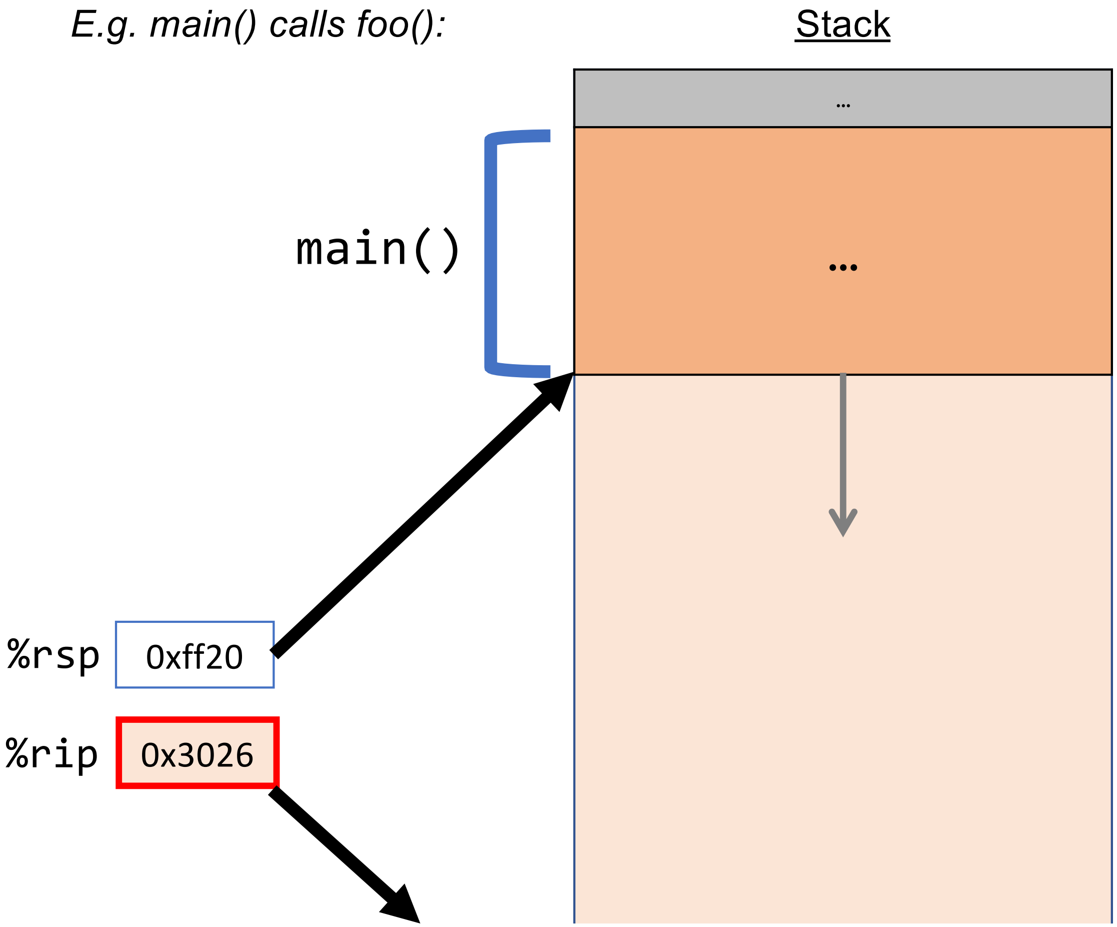


Call And Return

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** is called the **return address.** It is the address of the instruction where execution would have continued had flow not been interrupted by the function call. (Don't confuse this with **return value**, which is the value returned by the function via **%rax** or a subset of it).

Registers

What does **call** do?

call pushes the next instruction address onto the stack and overwrites %rip to address another function’s very first instruction.

Registers

What does **ret** do?

ret pops off the 8 bytes from the top of the stack and places it in %rip, thereby resuming execution in the caller.

ret is separate from the *return value* of the function (put in %rax).

Function Pointers

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
```

- Why would we use **call** with a register instead of hardcoding the function name in the assembly? *When would we not know the function to call until we run the code?*
- Function pointers! e.g., qsort – qsort calls a function passed through as a parameter and stored in a register.

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 placed directly on the stack.
- If the caller expects a return value, it looks in **%rax** after the callee completes.

Local Storage

- So far, all local variables have been stored directly in registers.
- There are **four** common reasons that a local variable must be stored in memory instead of a register:
  - We’ve simply run out of registers—we only have 16, some of which are special-purpose.
  - Registers aren’t protected against function call, so any variables or important partial results stored in registers must be flushed out to the stack.
  - The & operator is applied to a variable, so we need an true address for it
  - The variables themselves are arrays or structs and we should anticipate the need for pointer arithmetic.

Local Storage

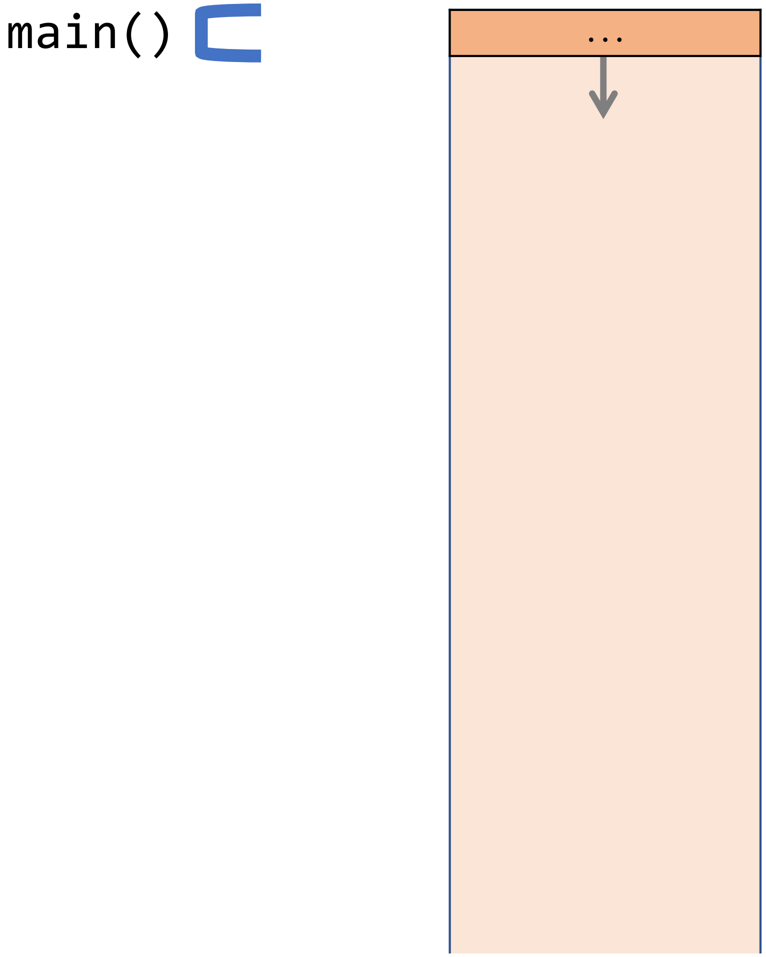
```
long caller() {
    long arg1 = 534;
    long arg2 = 1057;
    long sum = swap_add(&arg1, &arg2);
    ...
}
```

```
caller:
    sub   $0x10, %rsp         // 16 bytes for stack frame
    movq  $0x216, 0x8(%rsp)   // store 534 in arg1
    movq  $0x421, (%rsp)      // store 1057 in arg2
    mov   %rsp, %rsi          // compute &arg2 as second arg
    lea   0x8(%rsp), %rdi     // compute &arg1 as first arg
    callq swap_add            // call swap_add(&arg1, &arg2)
```

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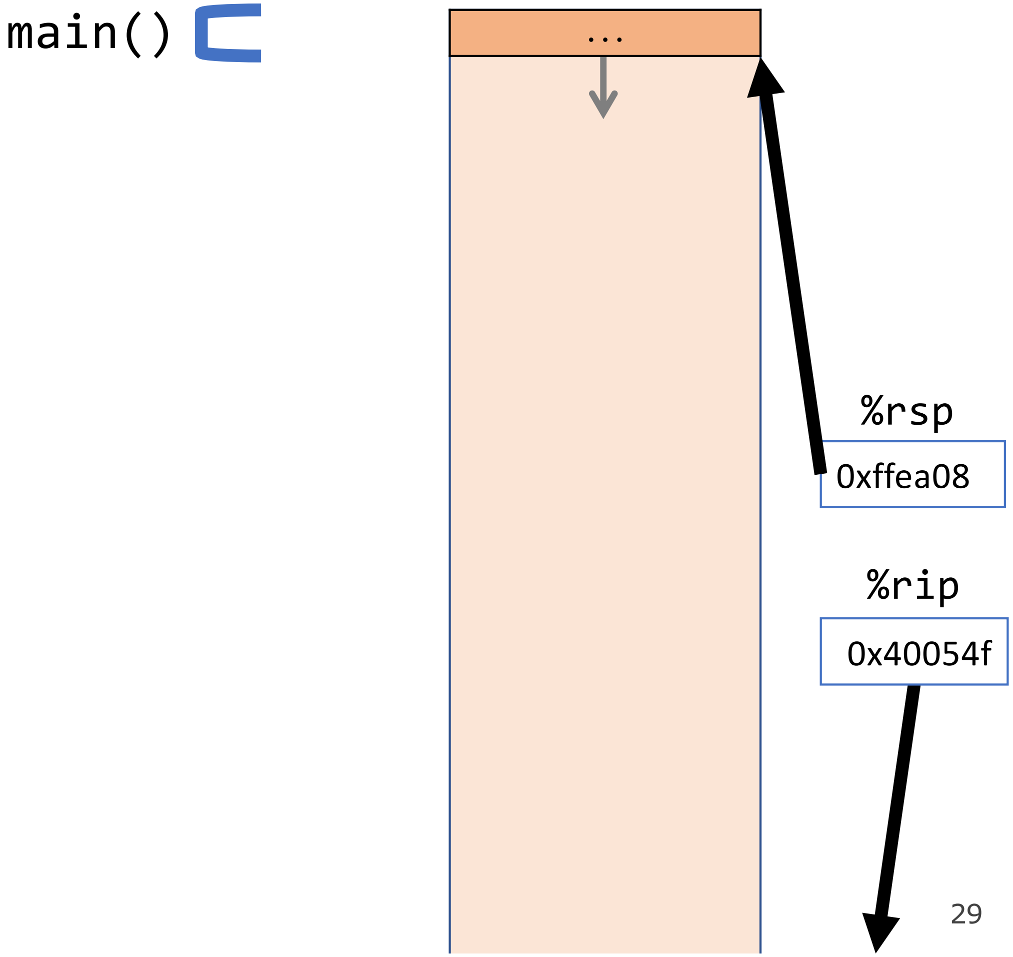

main()

…

%rsp

0xffea08

%rip

0x40054f

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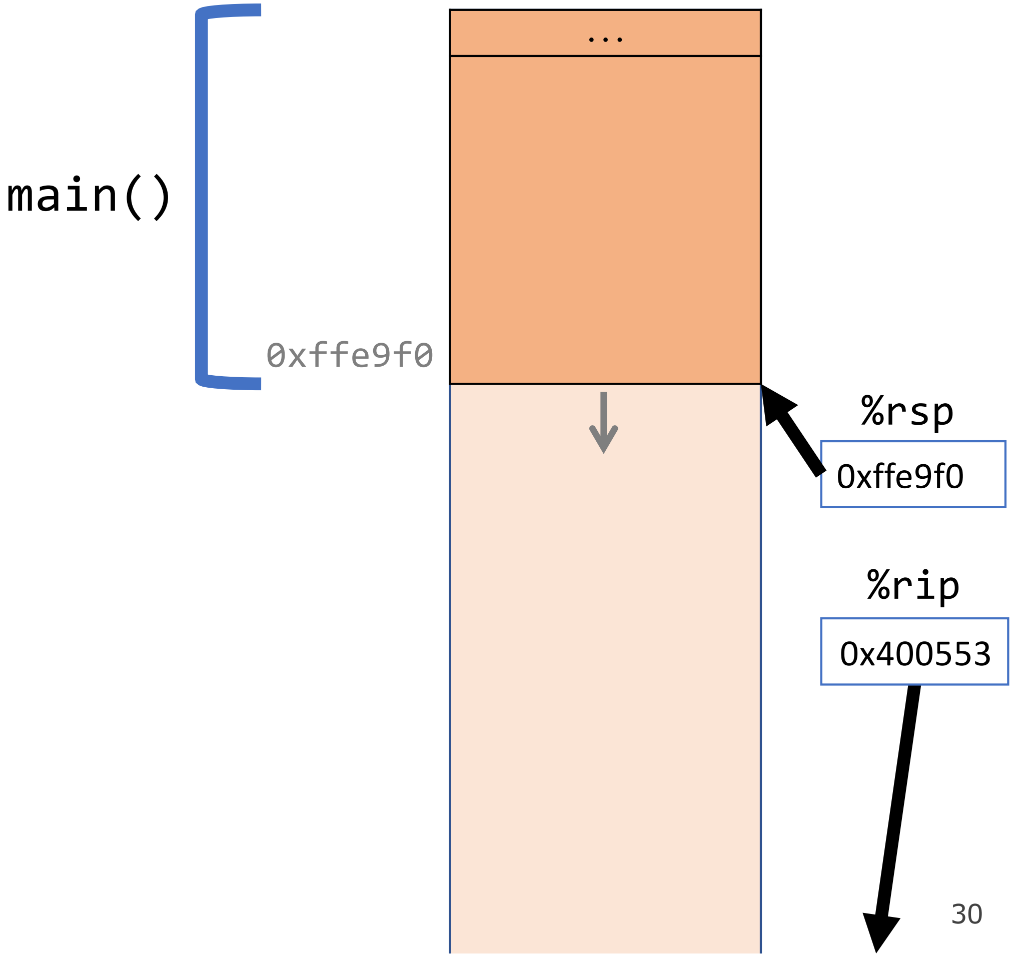

Parameters and Return

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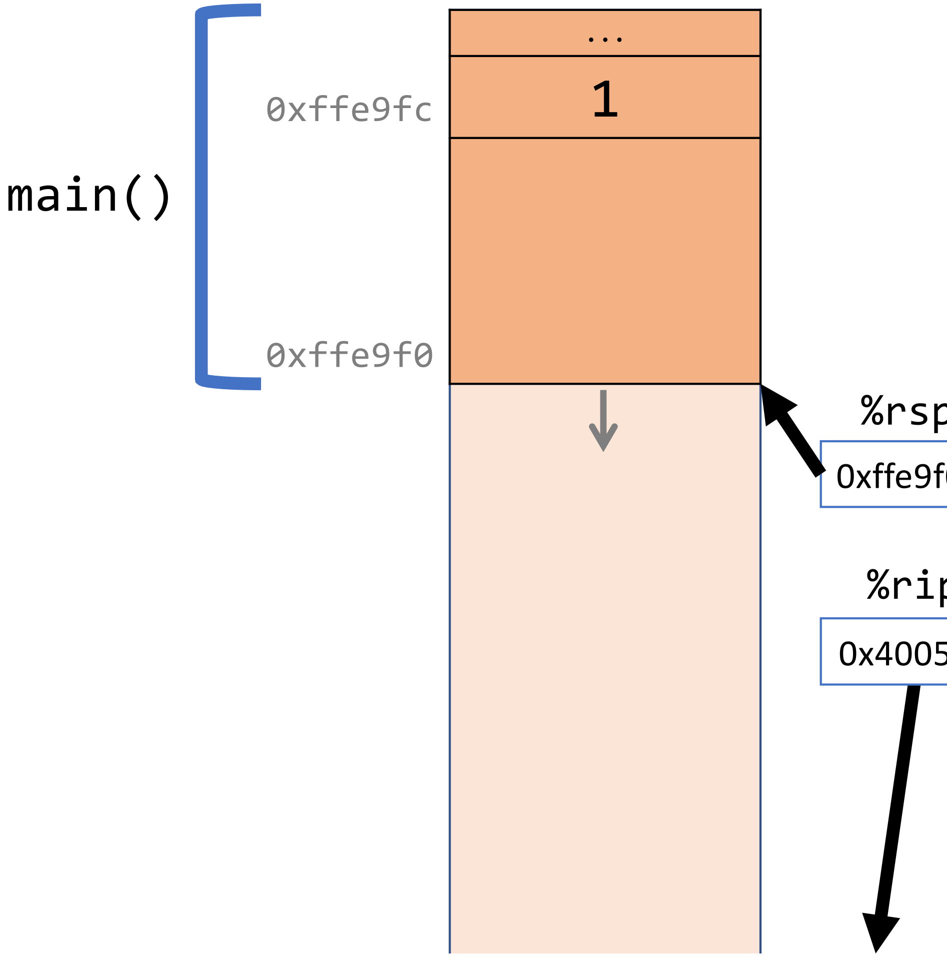

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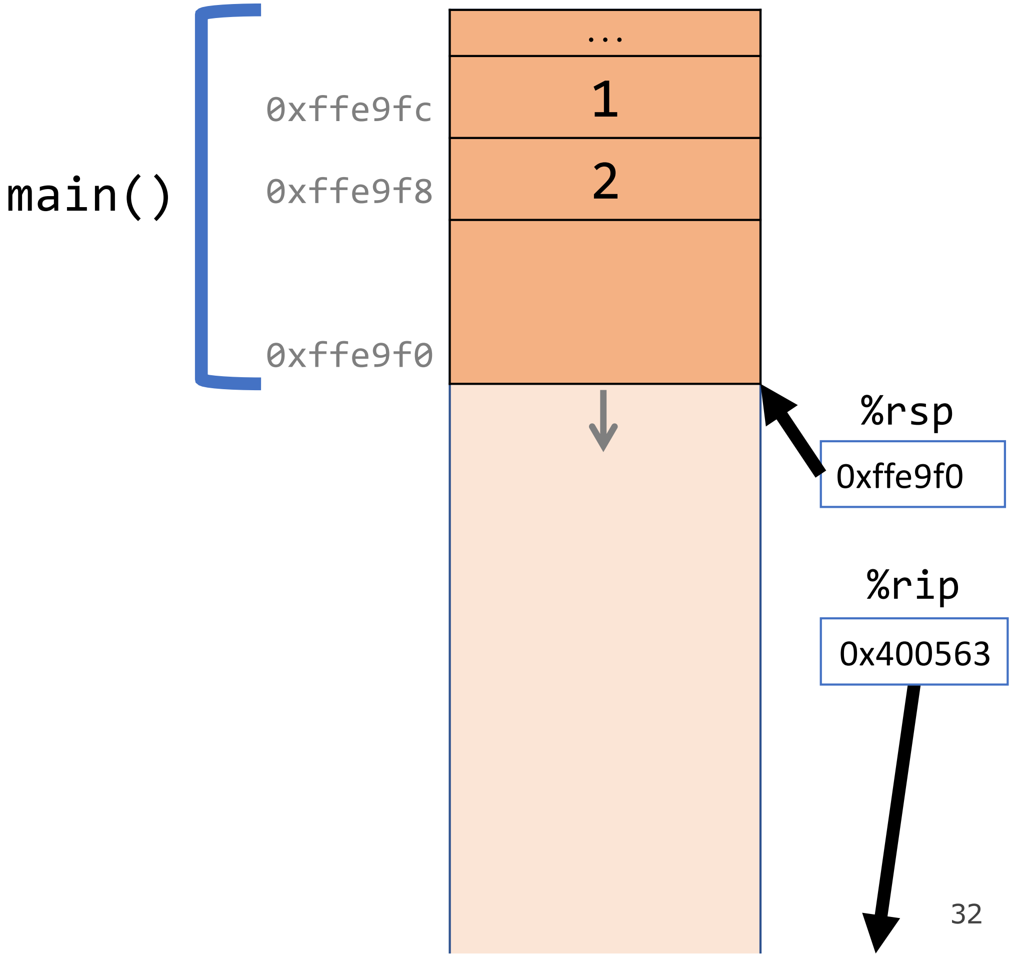

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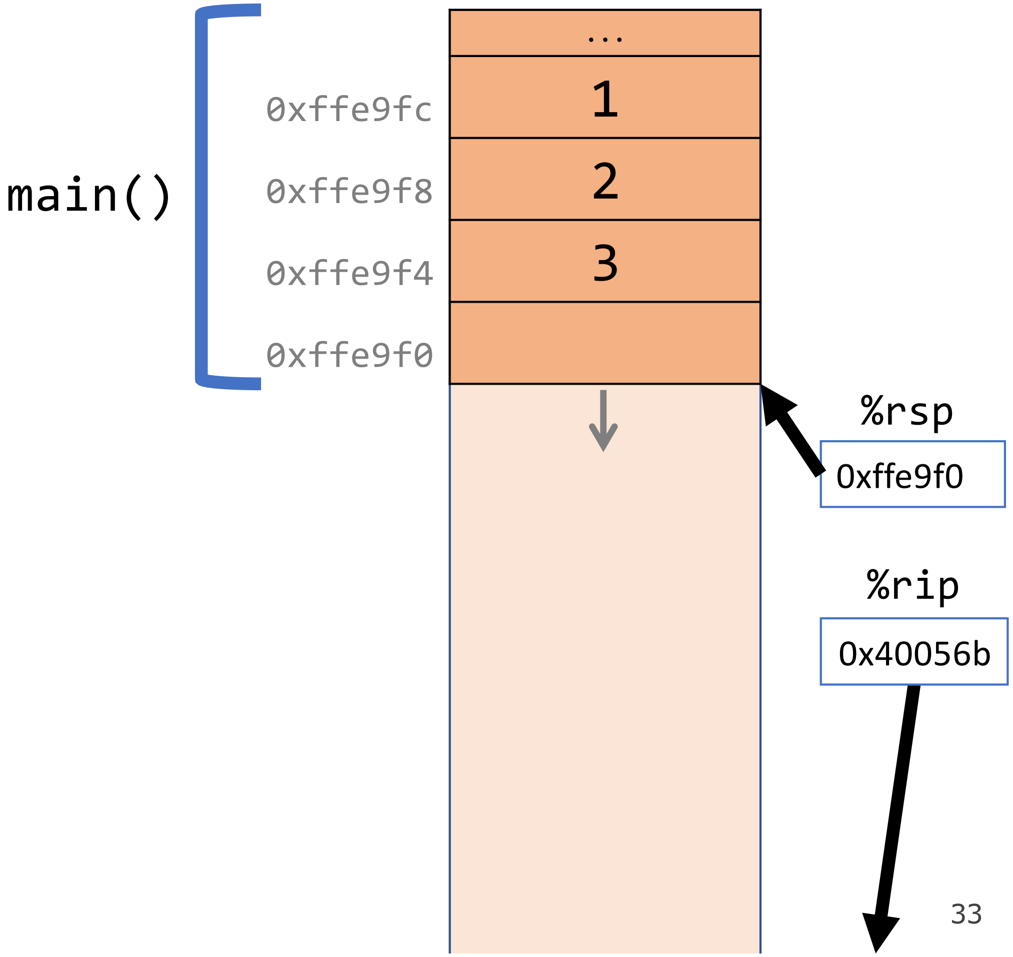

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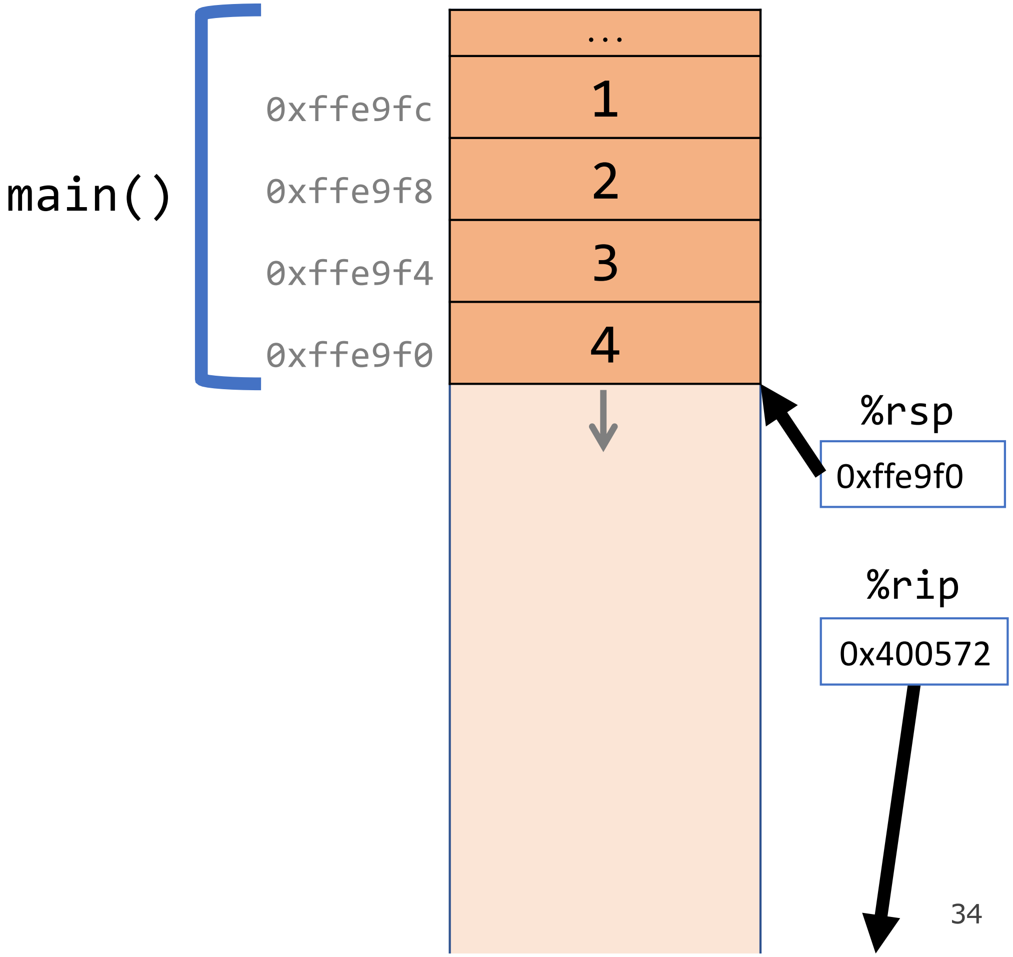

Parameters and Return

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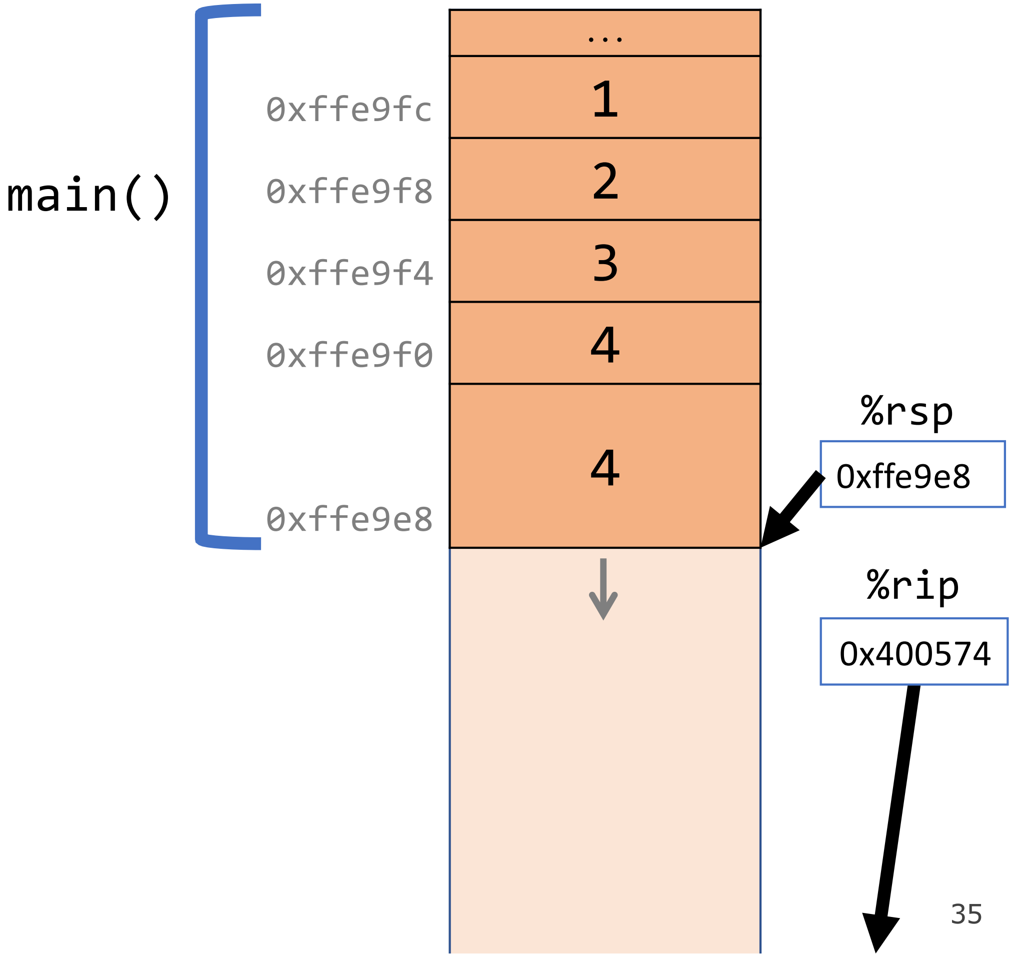

Parameters and Return

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    …
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0x40057c <+45>:   mov    $0x1,%r8d
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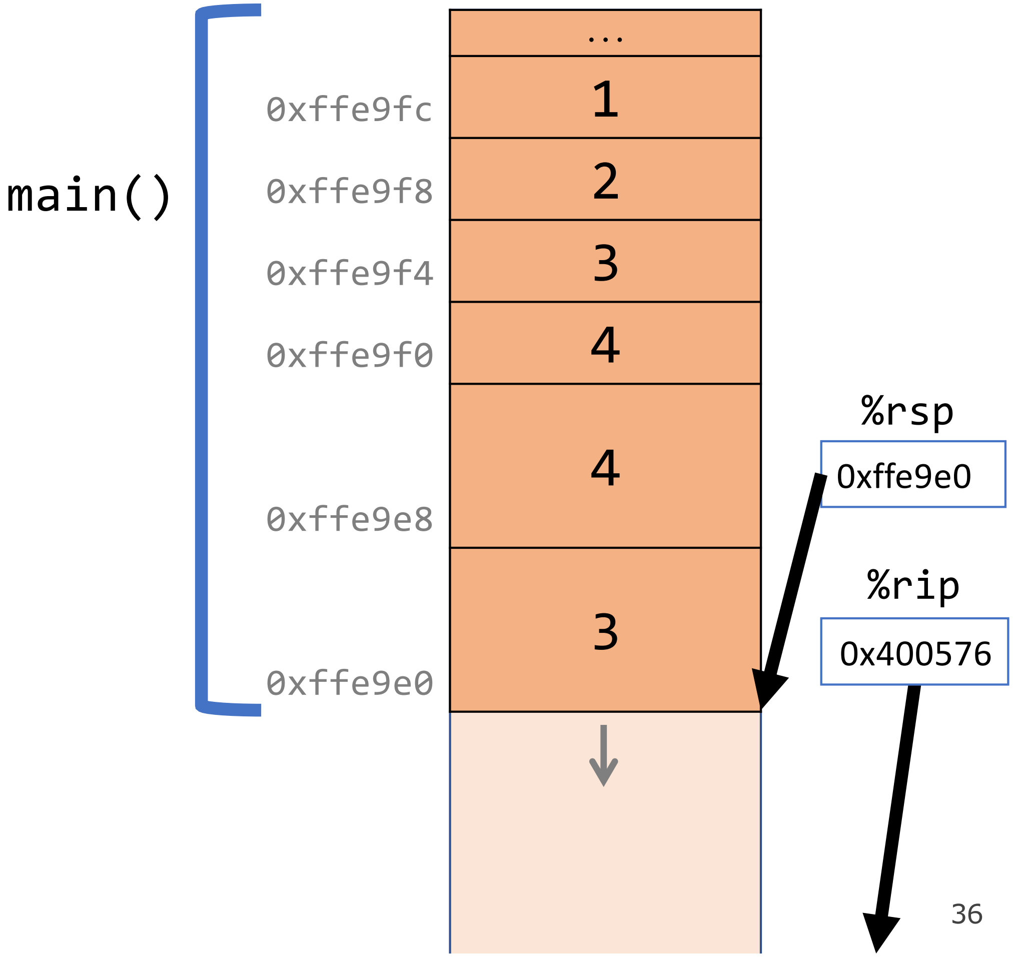

Parameters and Return

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    …
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    …
}
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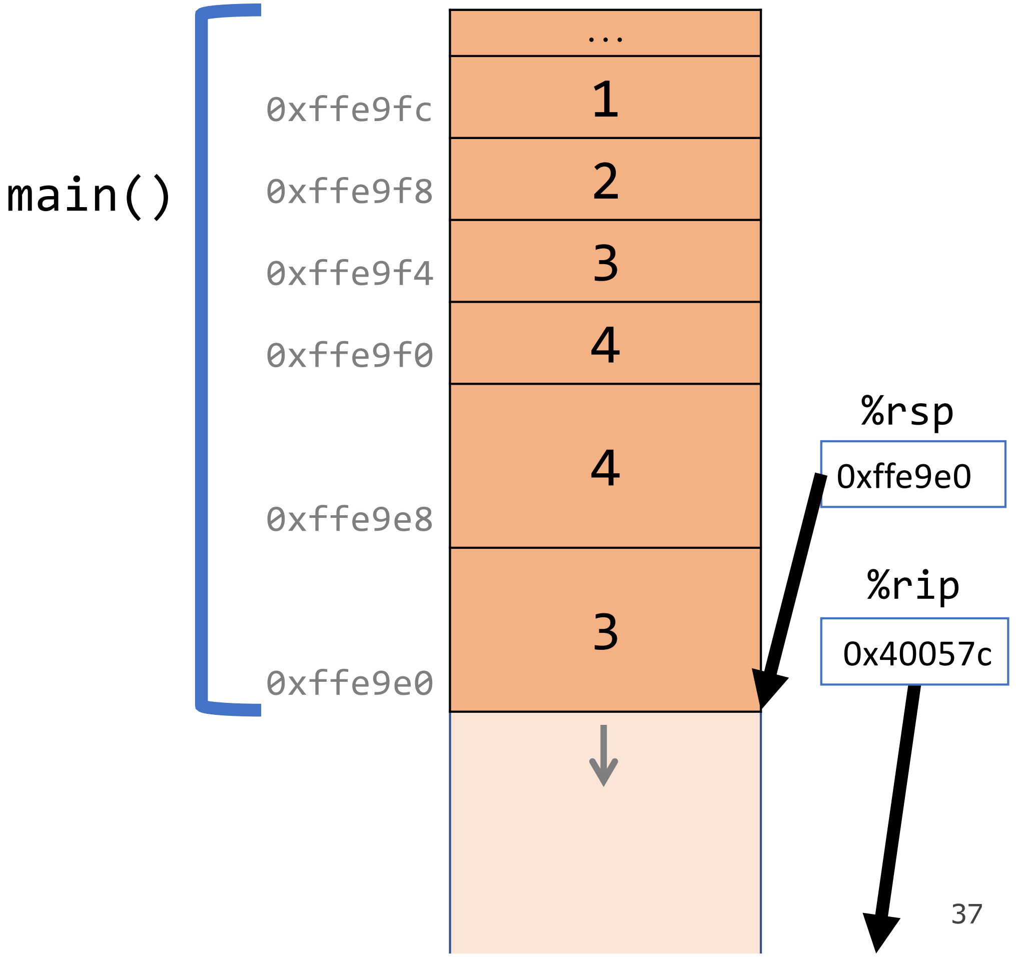
0x40057c <+45>:   mov    $0x1,%r8d
0x400582 <+51>:   lea    0x10(%rsp),%rcx
```



main()

	…
0xffe9fc	1
0xffe9f8	2
0xffe9f4	3
0xffe9f0	4
0xffe9e8	4
0xffe9e0	3

%rsp
0xffe9e0

%rip
0x40057c

Parameters and Return

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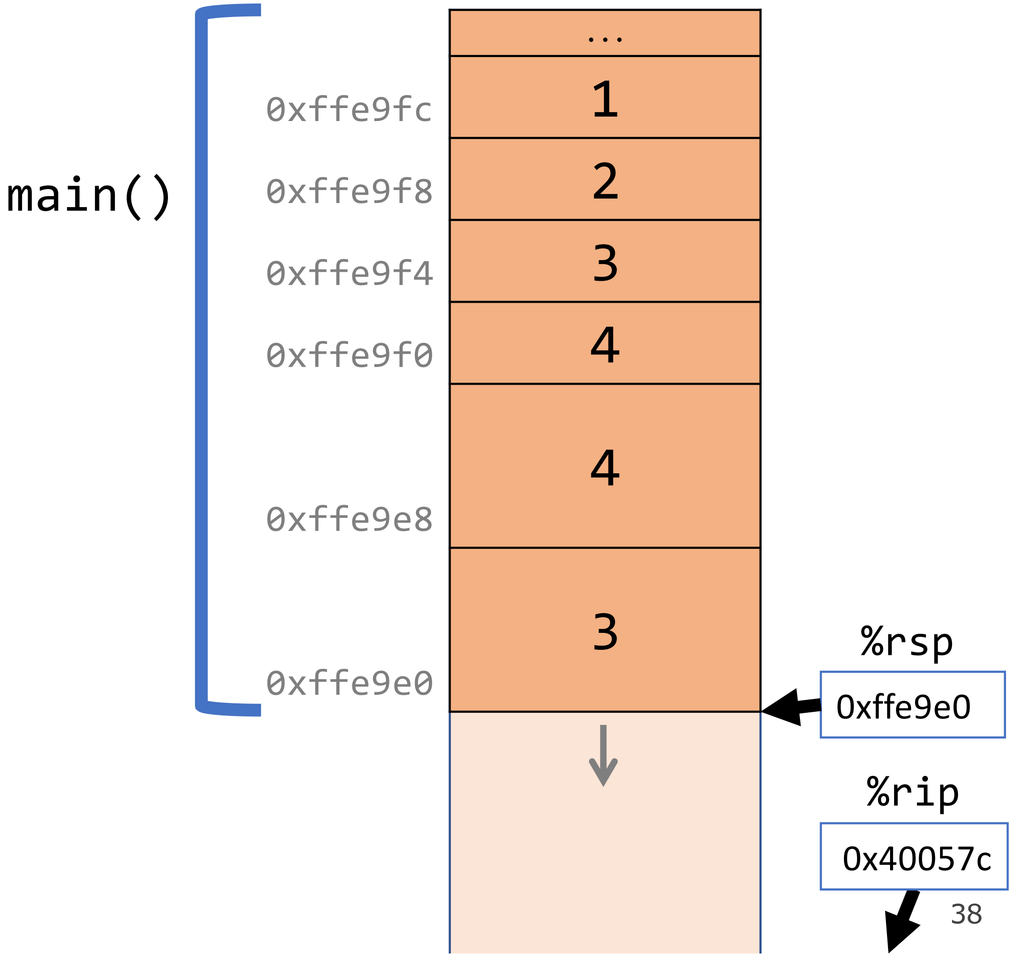
0x400582 <+51>:   lea    0x10(%rsp),%rcx
```

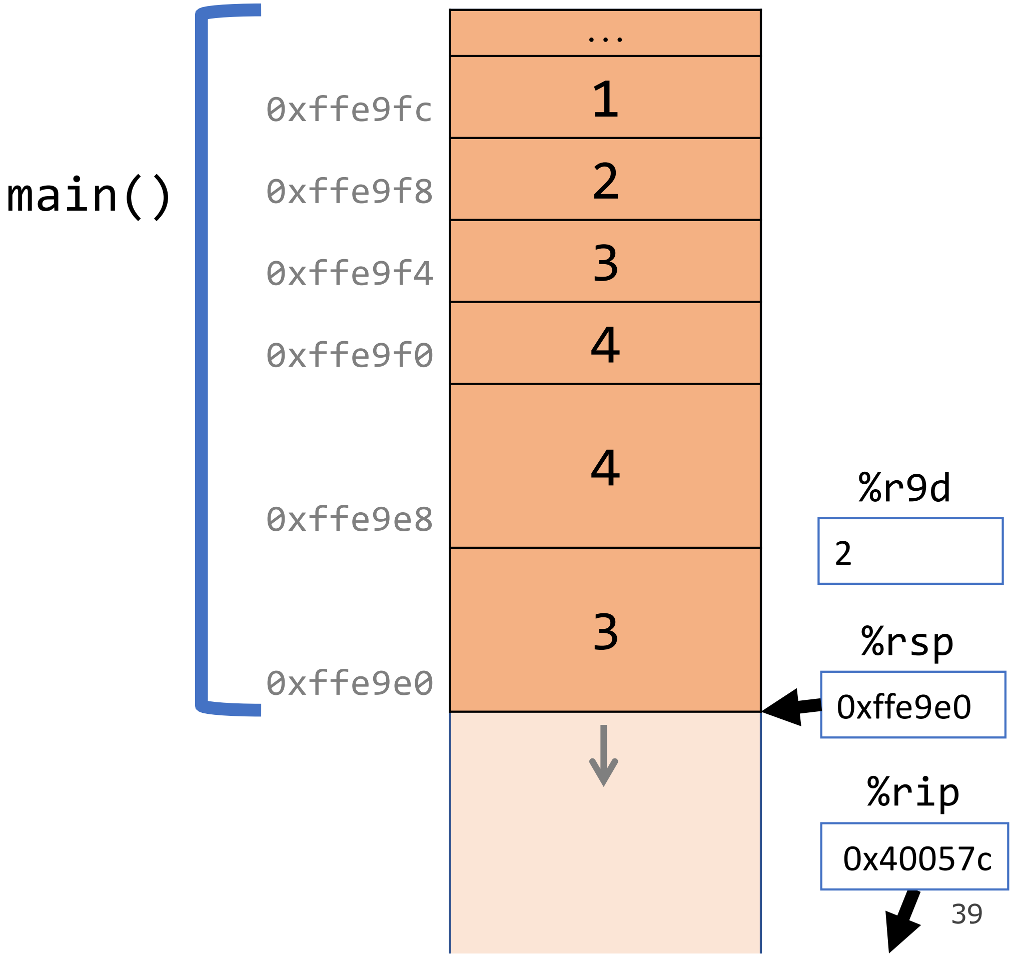


Parameters and Return

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

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

```
0x400572 <+35>:   pushq  $0x4
0x400574 <+37>:   pushq  $0x3
0x400576 <+39>:   mov    $0x2,%r9d
0x40057c <+45>:   mov    $0x1,%r8d
0x400582 <+51>:   lea    0x10(%rsp),%rcx
```



main()

	…
0xffe9fc	1
0xffe9f8	2
0xffe9f4	3
0xffe9f0	4
0xffe9e8	4
0xffe9e0	3

%r9d: 2

%rsp: 0xffe9e0

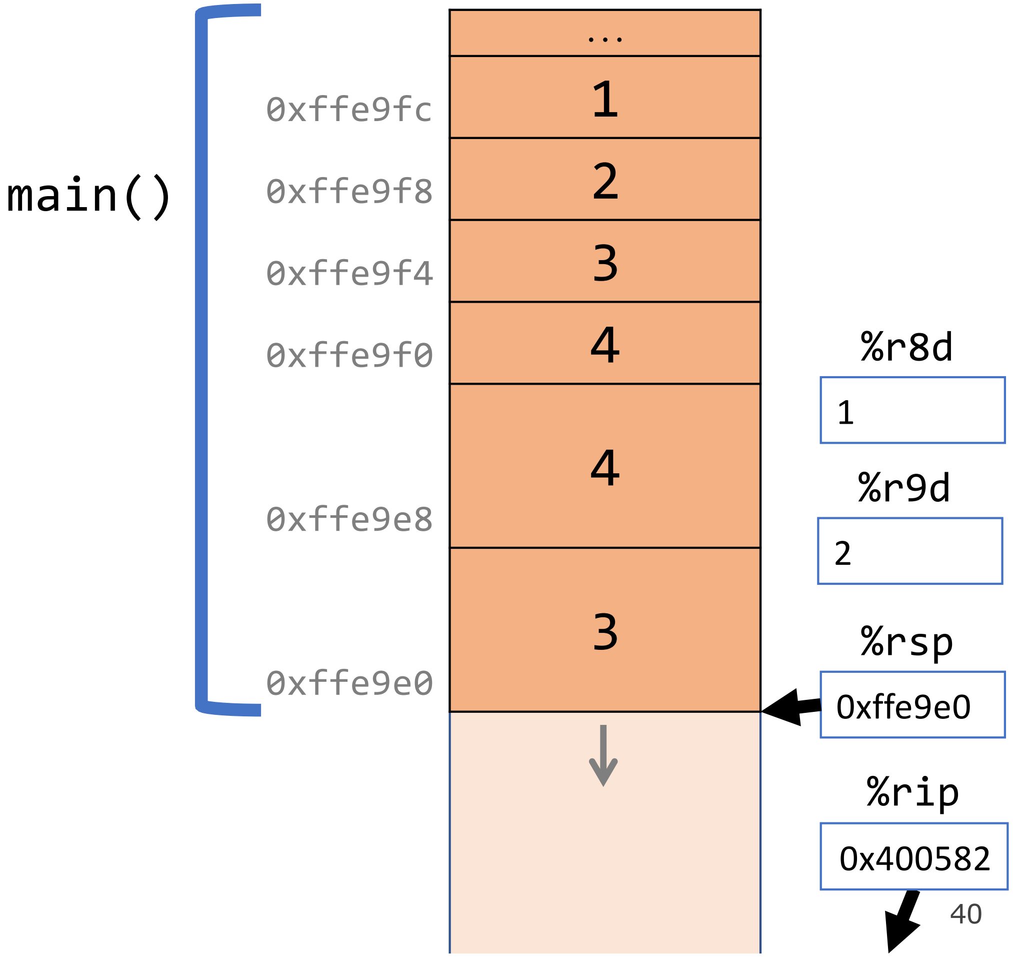
%rip: 0x40057c

Parameters and Return

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

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

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

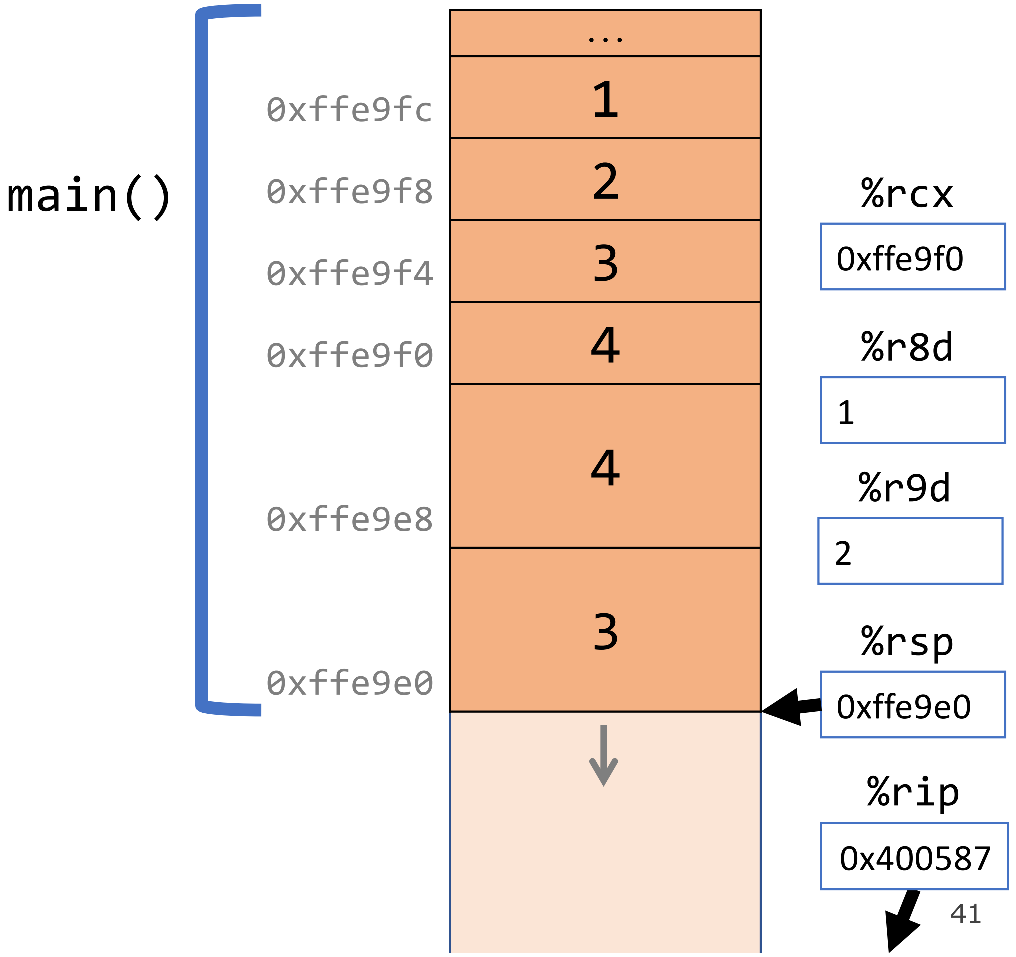


Parameters and Return

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

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

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

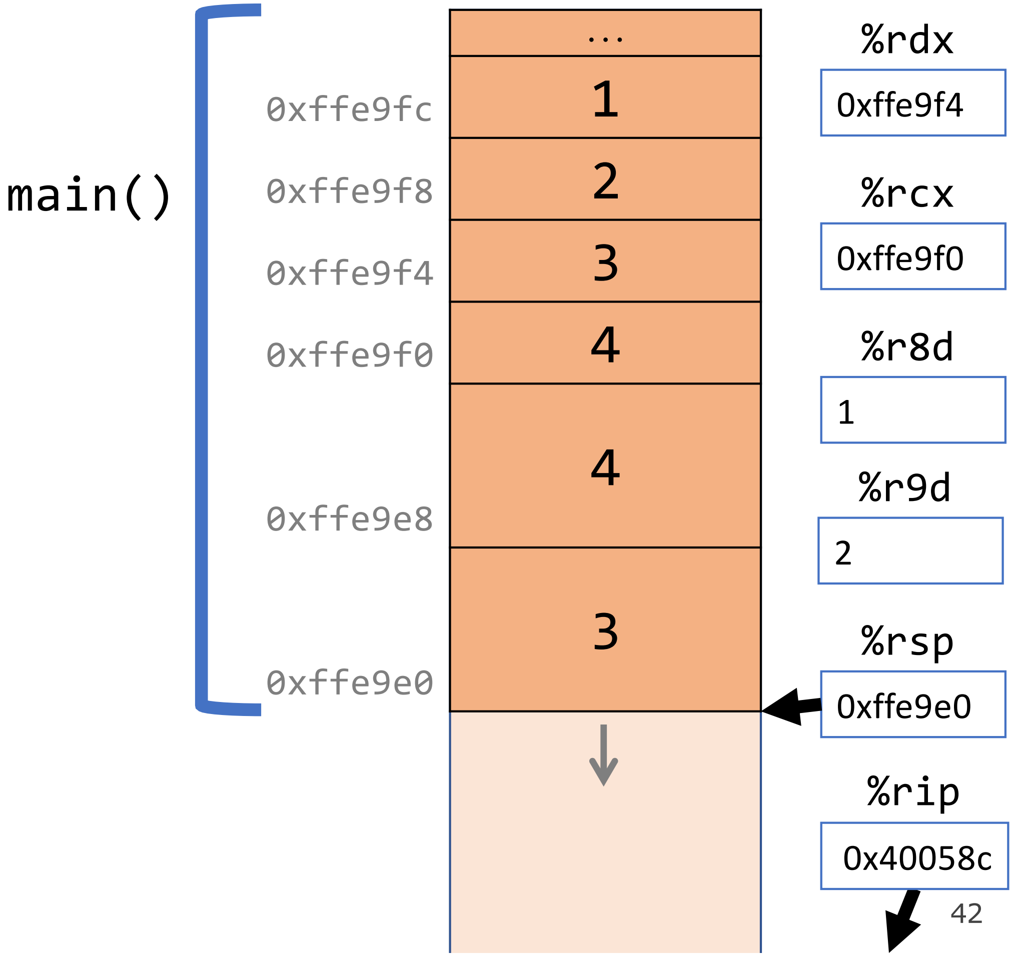


Parameters and Return

```
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
```

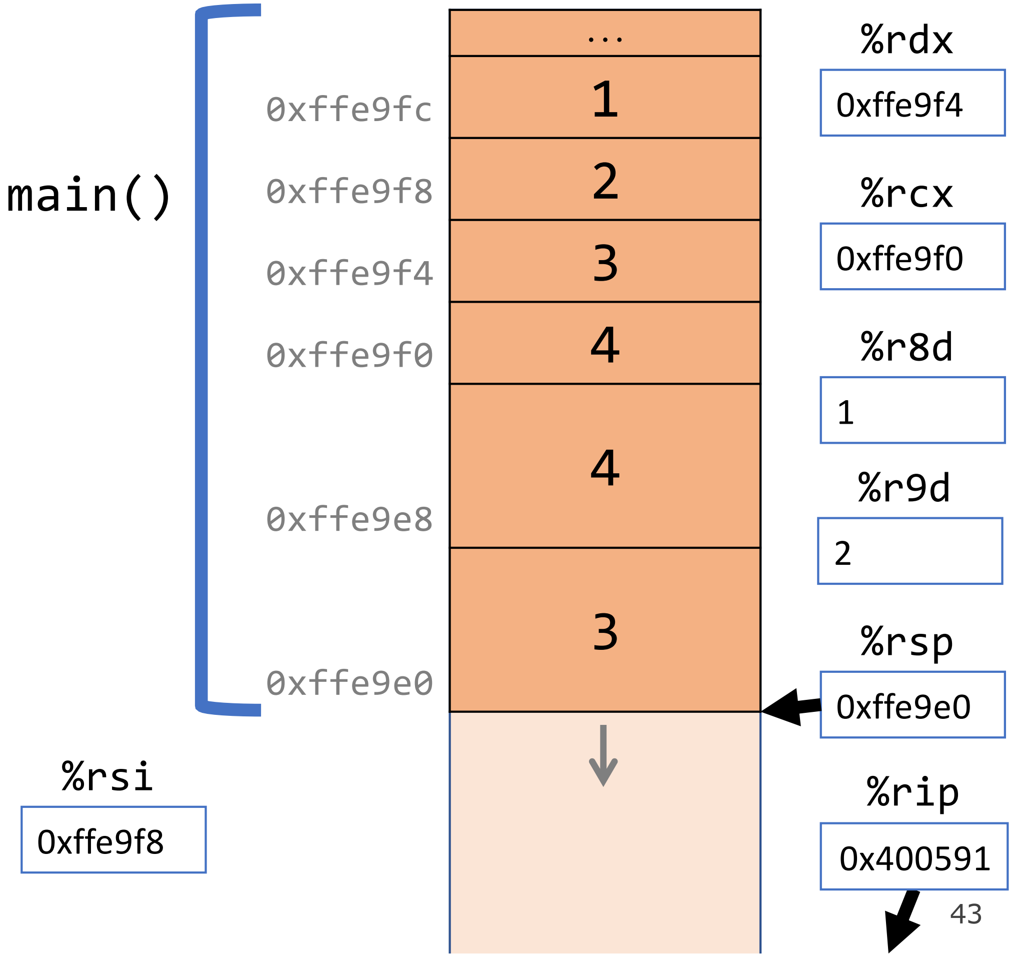


Parameters and Return

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

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

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



main()

	…
0xffe9fc	1
0xffe9f8	2
0xffe9f4	3
0xffe9f0	4
0xffe9e8	4
0xffe9e0	3

%rdx: 0xffe9f4

%rcx: 0xffe9f0

%r8d: 1

%r9d: 2

%rsp: 0xffe9e0

%rip: 0x400591

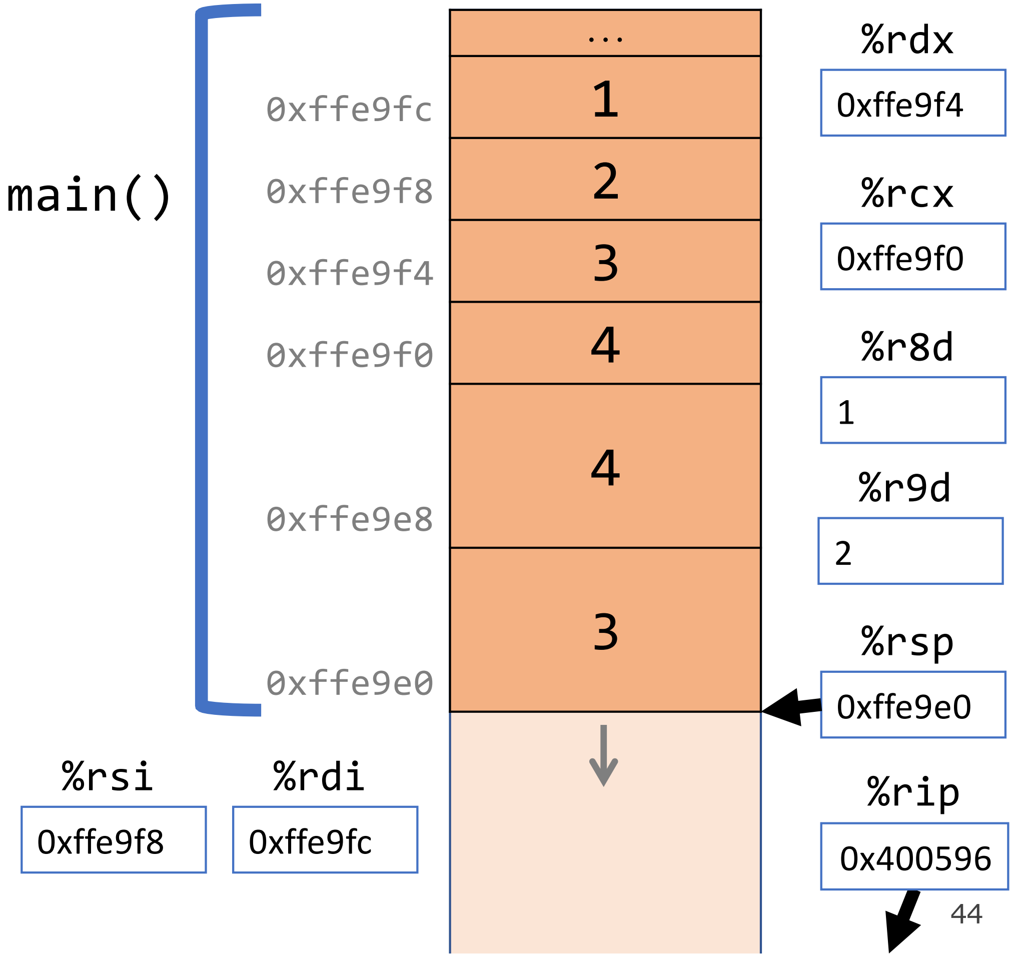
%rsi: 0xffe9f8

Parameters and Return

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

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

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

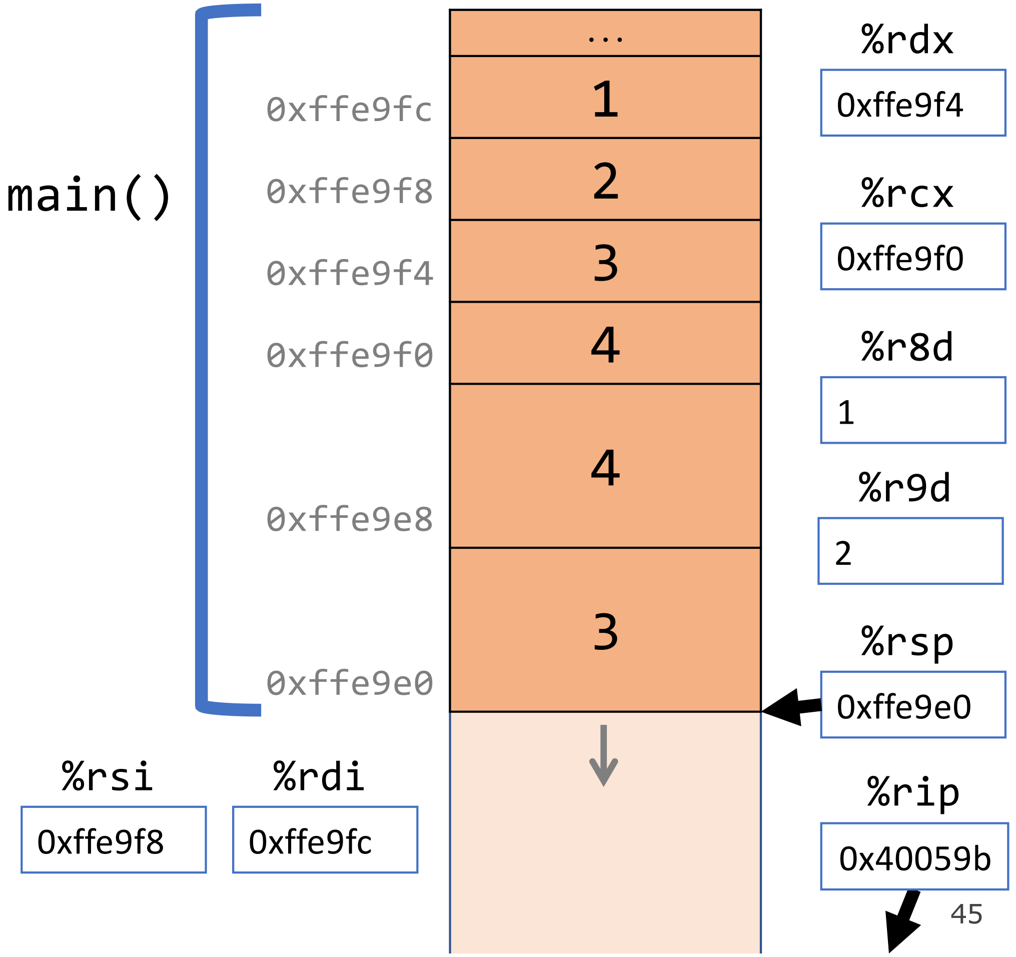


Parameters and Return

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

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

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



main()

Address	Value
	…
0xffe9fc	1
0xffe9f8	2
0xffe9f4	3
0xffe9f0	4
0xffe9e8	4
0xffe9e0	3

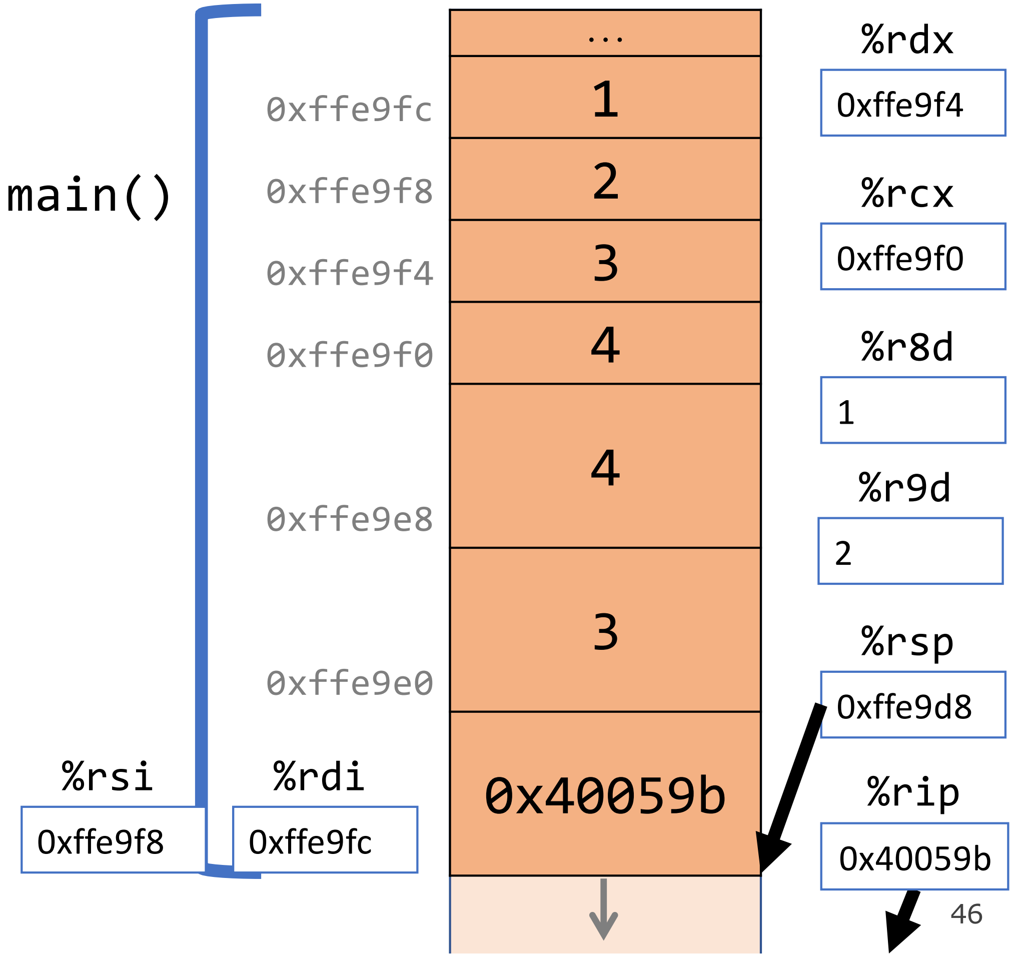
Register	Value
%rdx	0xffe9f4
%rcx	0xffe9f0
%r8d	1
%r9d	2
%rsp	0xffe9e0
%rip	0x40059b
%rsi	0xffe9f8
%rdi	0xffe9fc

Parameters and Return

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

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

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



main()

	…
0xffe9fc	1
0xffe9f8	2
0xffe9f4	3
0xffe9f0	4
0xffe9e8	4
0xffe9e0	3
	0x40059b

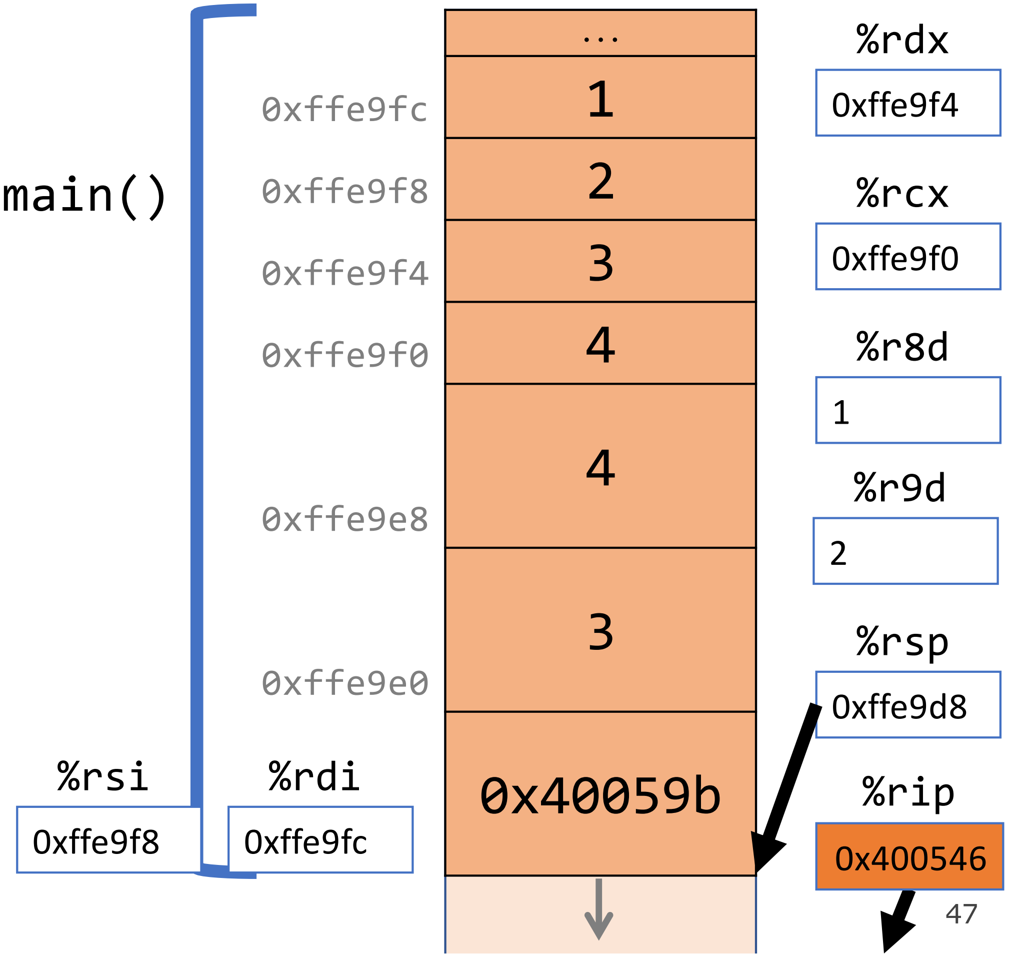
%rdx	0xffe9f4
%rcx	0xffe9f0
%r8d	1
%r9d	2
%rsp	0xffe9d8
%rip	0x40059b
%rsi	0xffe9f8
%rdi	0xffe9fc

Parameters and Return

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

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

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



main()

…

0xffe9fc 1

0xffe9f8 2

0xffe9f4 3

0xffe9f0 4

4

0xffe9e8

3

0xffe9e0

0x40059b

%rsi 0xffe9f8

%rdi 0xffe9fc

%rdx 0xffe9f4

%rcx 0xffe9f0

%r8d 1

%r9d 2

%rsp 0xffe9d8

%rip 0x400546

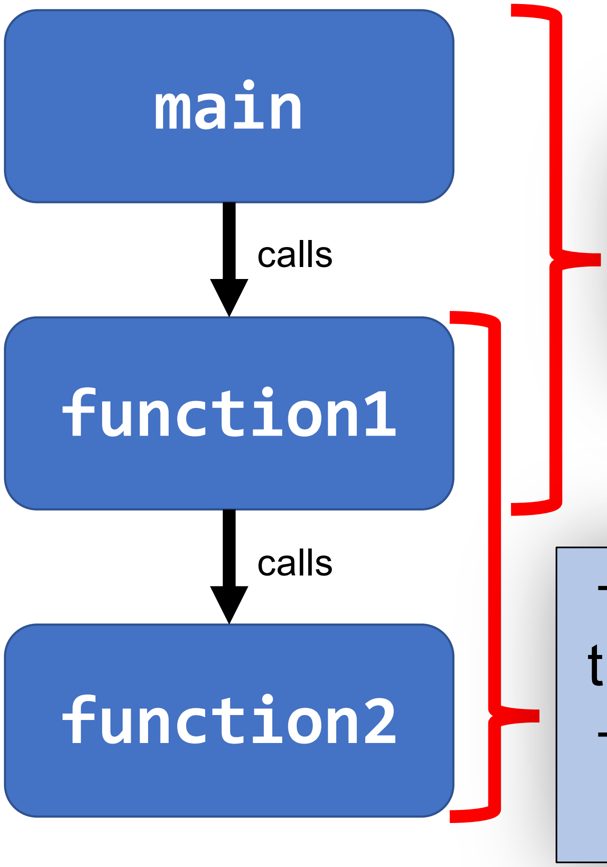
Register Restrictions

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 itself has instructions that modify %r10? ***funcA***'s value will be destroyed!
- **Solution:** lay down 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

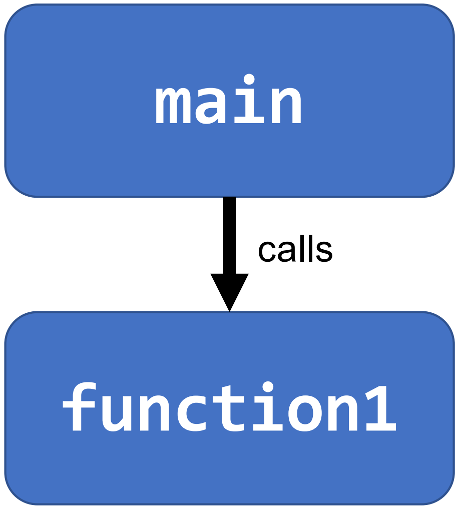
Caller-Owned

- Callee must *save* the existing value and *restore* it when done.
- Caller can store values in them and assume they’ll 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.

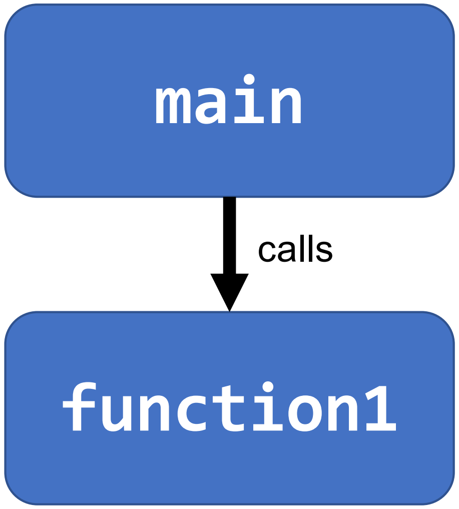
Caller-Owned Registers



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



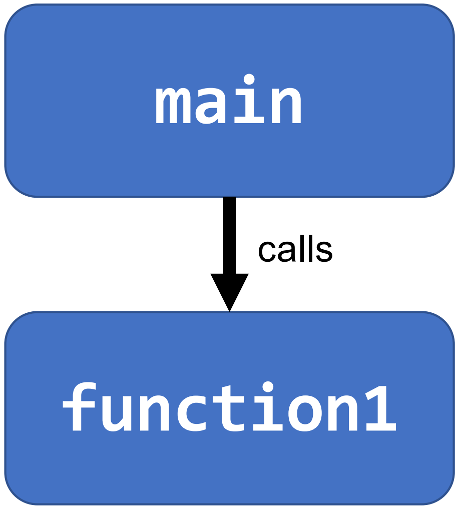
main

calls

function1

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

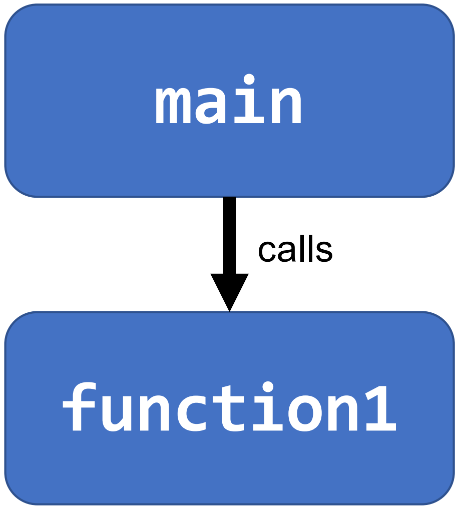
Callee-Owned Registers



`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



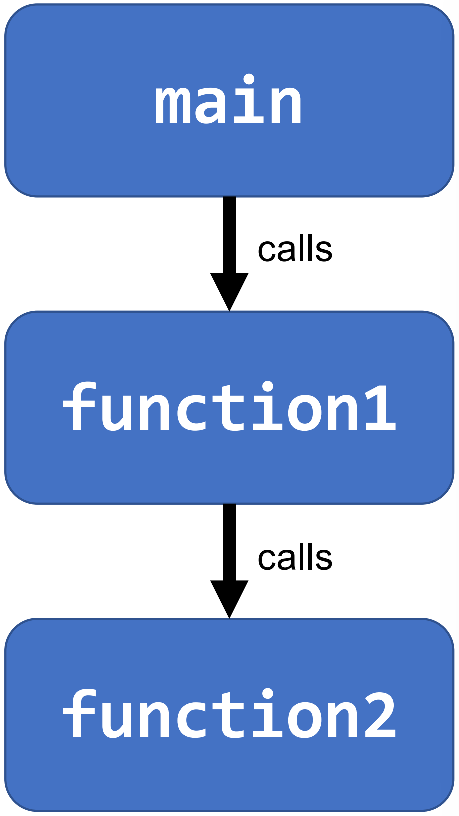
main

calls

function1

```
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.

Example: Recursion

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

`rfact.c and rfact`

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
```