CS107, Lecture 19
Assembly: Control Flow Wrap, Function Call Take I

Reading: B&O 3.7

Ed Discussion: https://edstem.org/us/courses/46162/discussion/3796700

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

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

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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 executed
  - If n is large, right (alternative) is best b/c fewer instructions executed
- The compiler may emit a static instruction count that is longer than some alternative, but it may be more efficient if loop executes many times.
- Does the compiler *know* that a loop will execute many times? Of course not.
- What if our code has loops that always execute a small number of times? How do we know when gcc makes a bad decision?
  - (take EE108 and EE180!)

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
- Leaves other bytes of register (e.g., everything else in %rax) alone
- Typically followed by movzbl to zero those other 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 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
```

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)

Calling Functions In Assembly

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

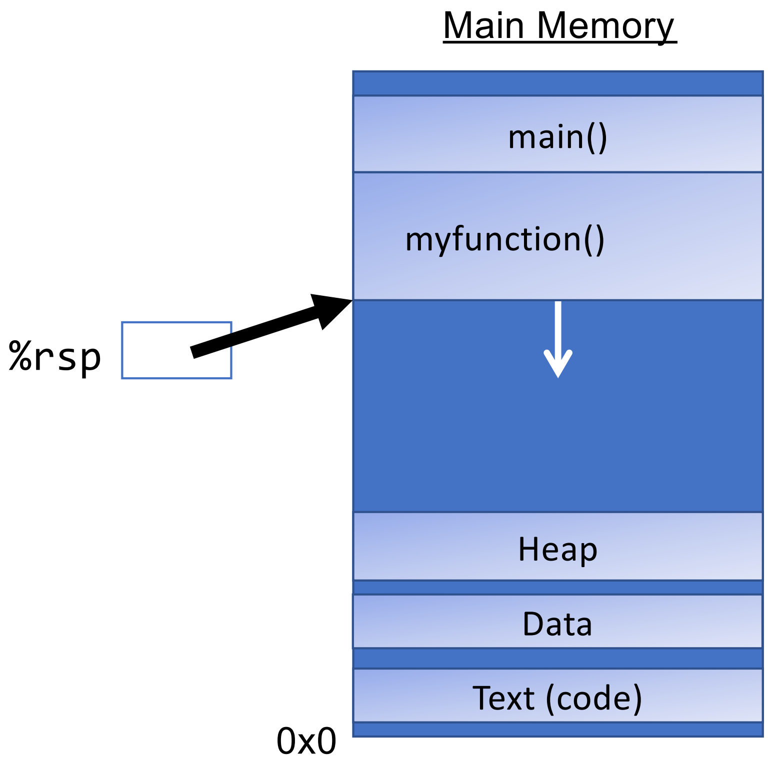
- **Transfer Control** – %rip must be adjusted to execute the callee's instructions, and then resume the caller's instructions afterwards.
- **Pass Data** – we must pass parameters and extract return values.
- **Manage Memory** – we must handle all of the callee's stack space needs.

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 "top" of the stack (the bottom in our diagrams, since the stack grows downwards).



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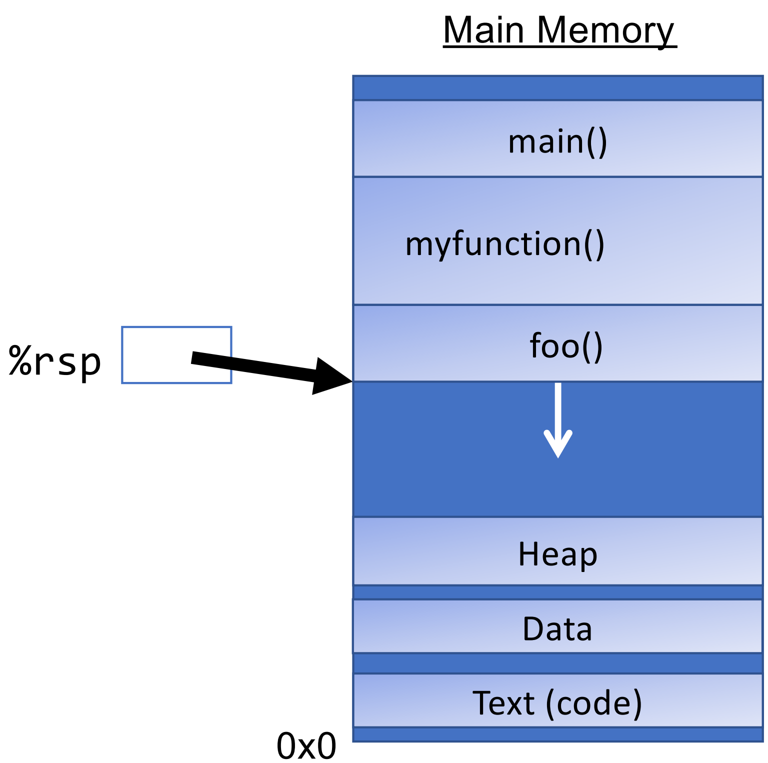

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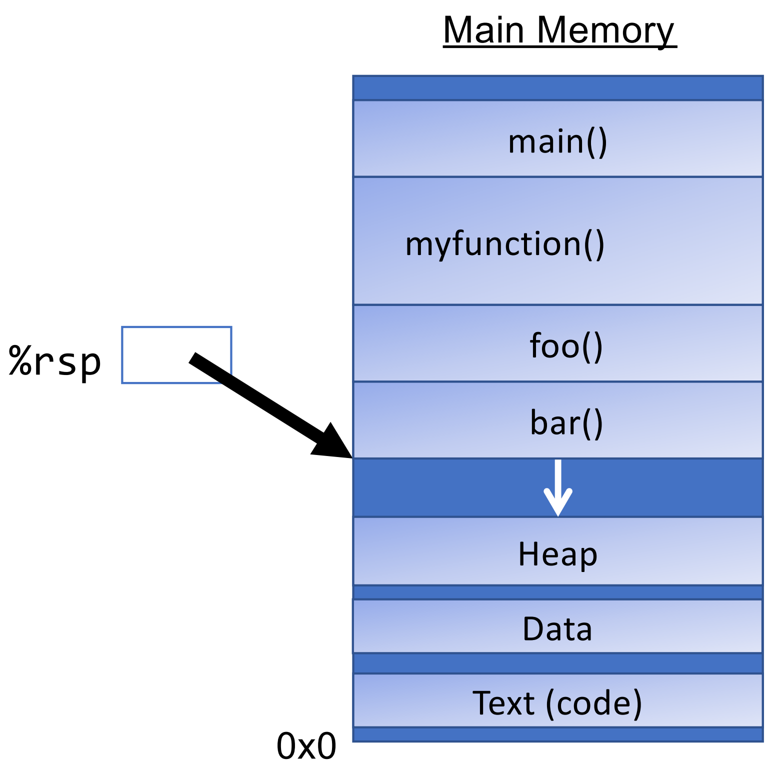

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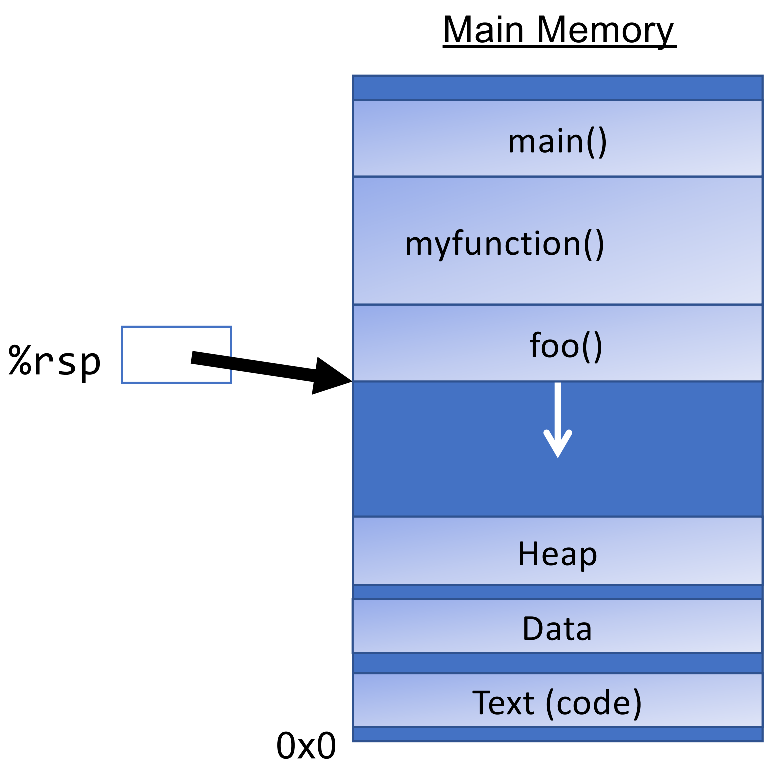

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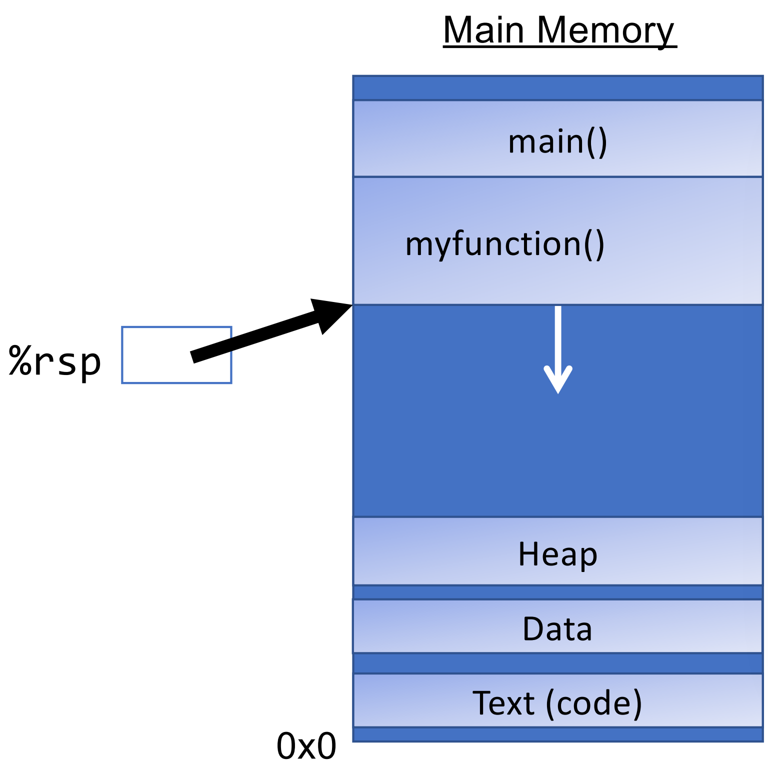

Key idea: %rsp must point to the same place before a function is called and after that function returns, since stack frames go away when a function finishes.

push

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

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

push

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

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

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- 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;`

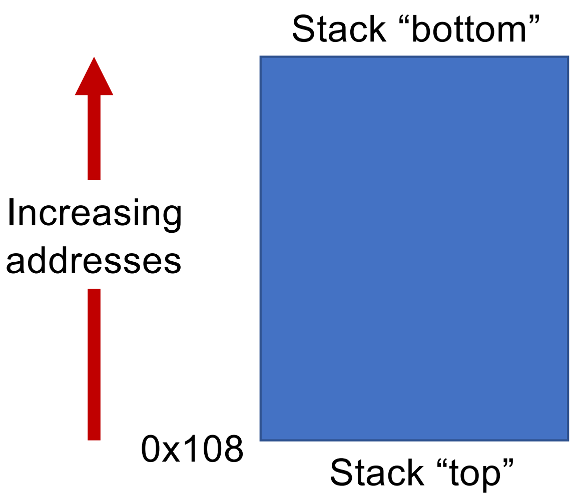
- This behavior is equivalent to the following, but popq is a shorter instruction:

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

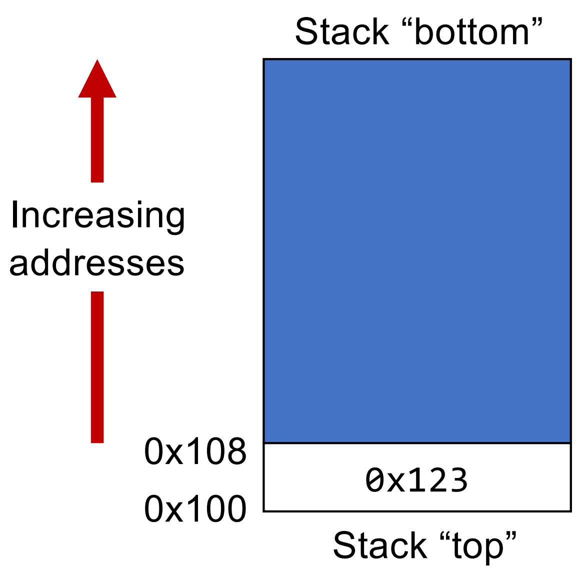
- Sometimes, you'll see instructions just explicitly increment the stack pointer to pop data.

Stack Example

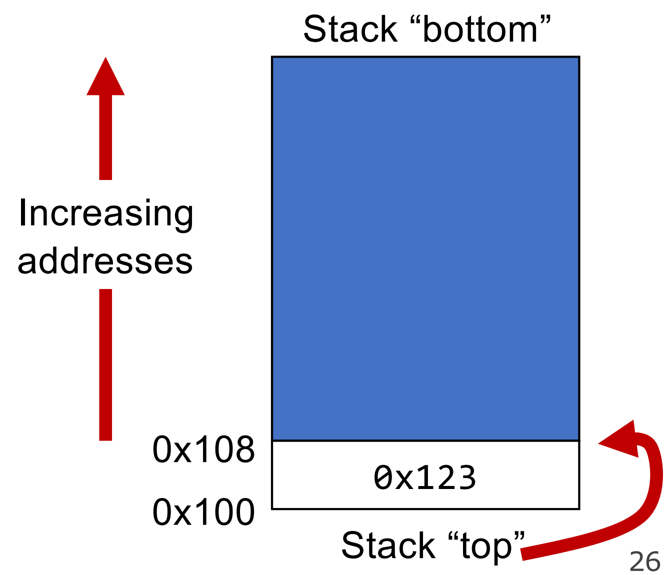
Initially	
`%rax`	`0x123`
`%rdx`	`0`
`%rsp`	`0x108`



`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:

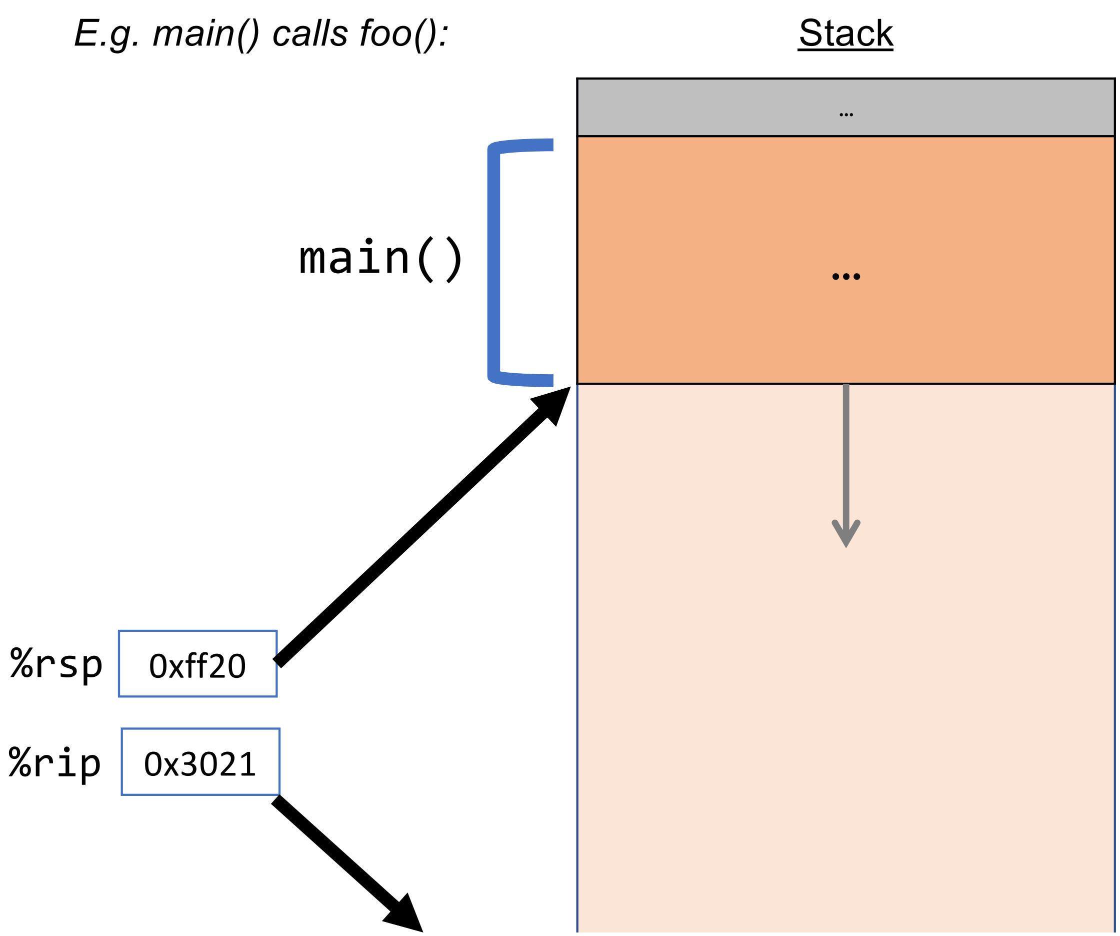
- **Pass Control** – **%rip** must be adjusted to execute the callee's instructions, and then resume the caller's instructions afterwards.
- **Pass Data** – we must pass any parameters and receive any return value.
- **Manage Memory** – we must handle any space needs of the callee on the stack.

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.



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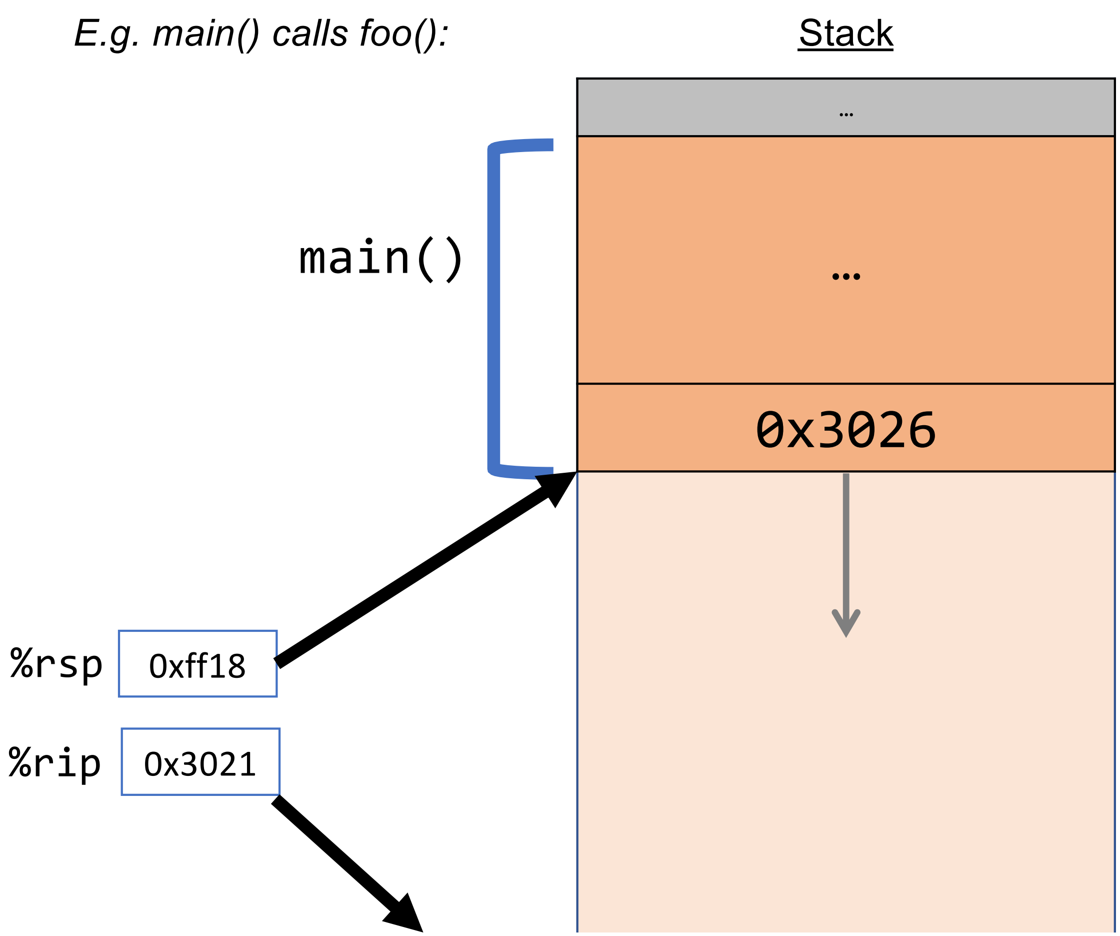

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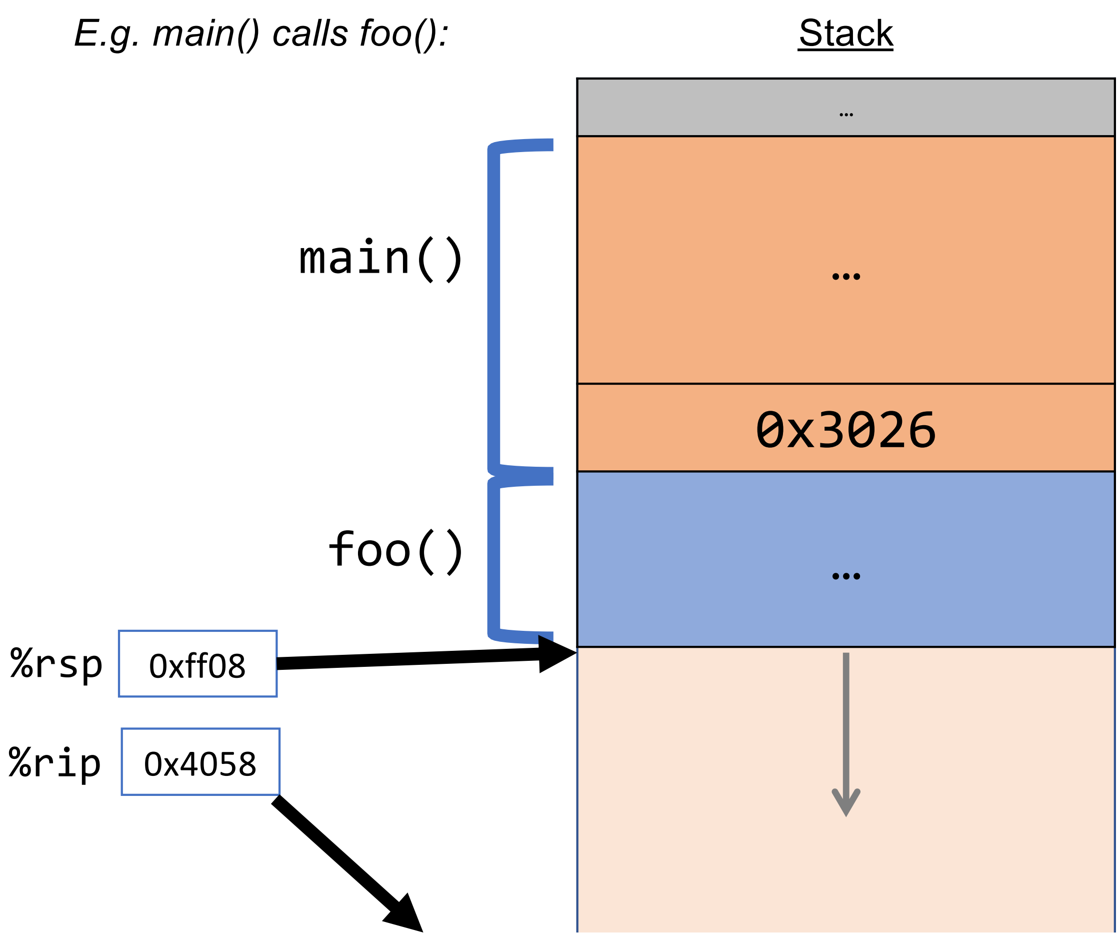

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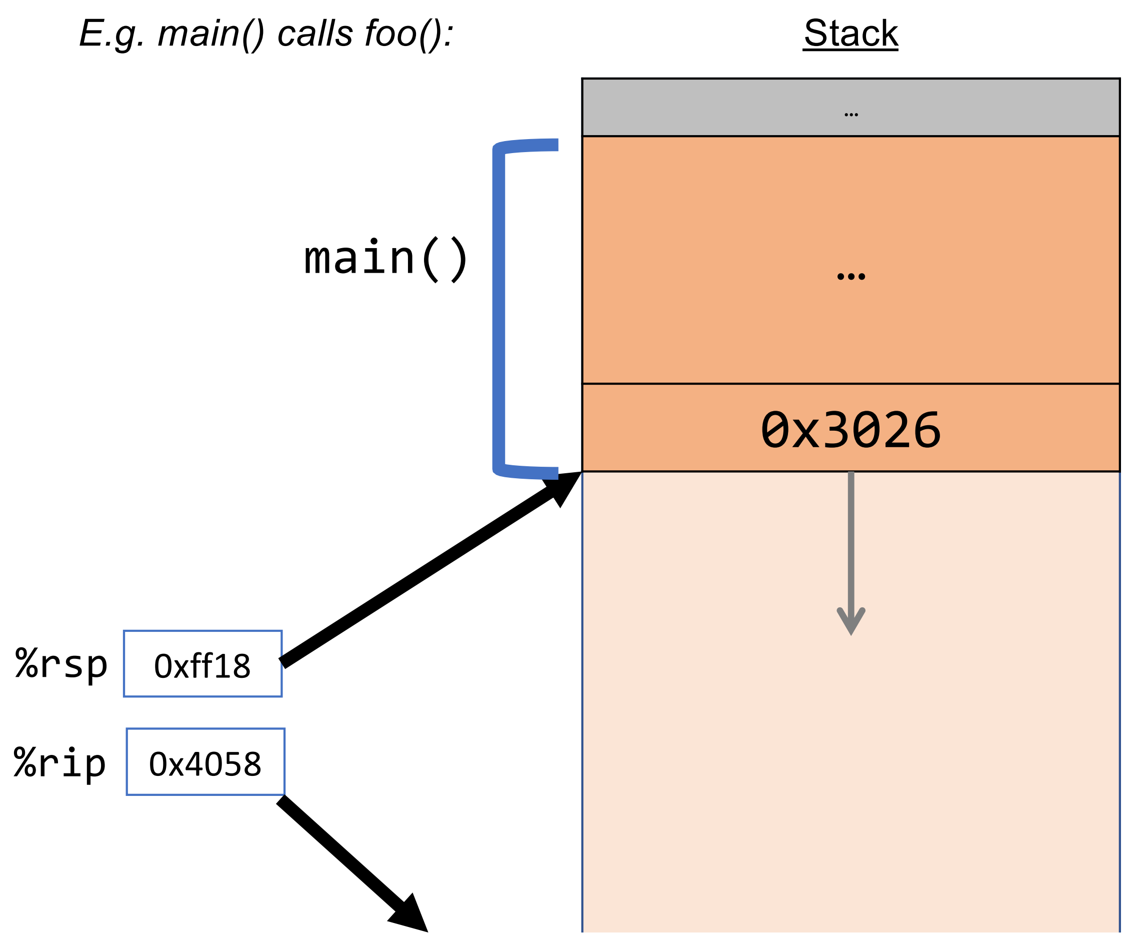

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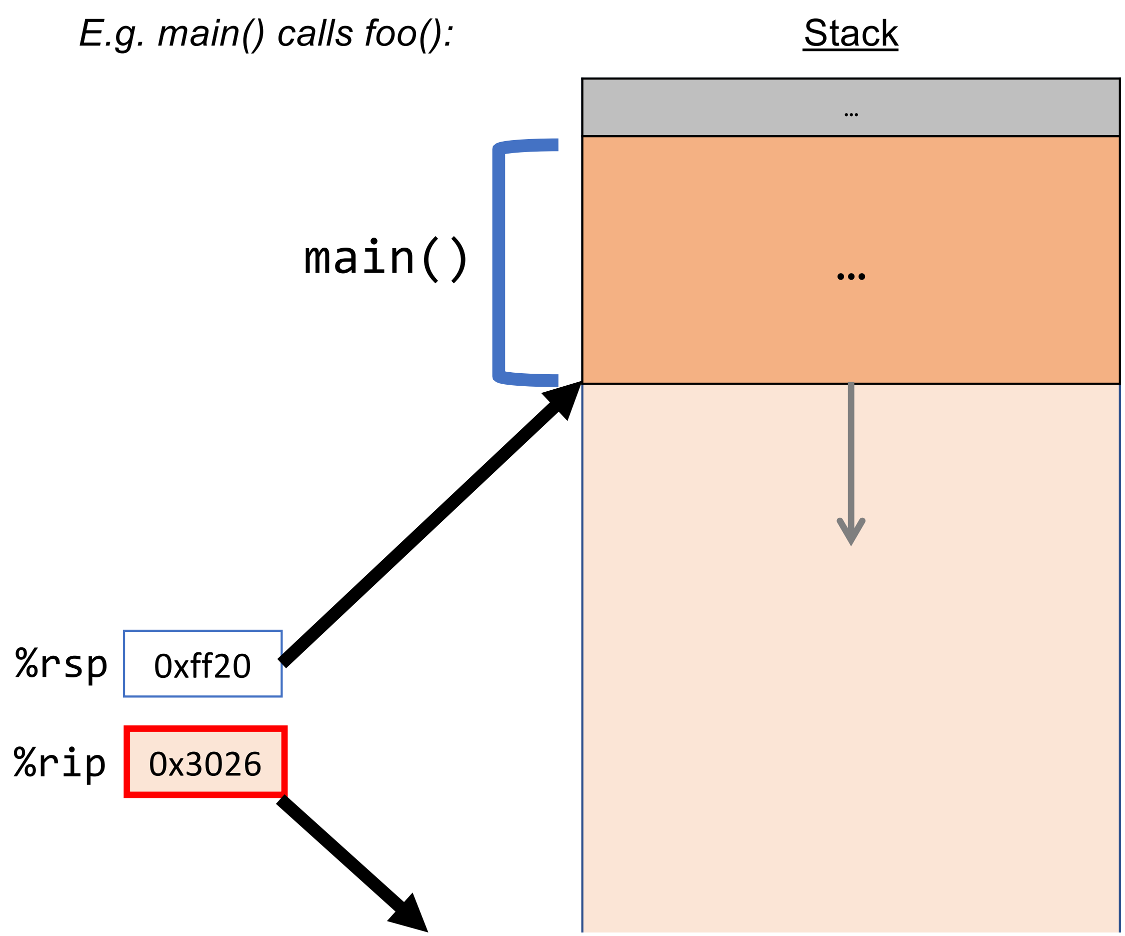


Call And Return

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 register must be flushed out to the stack.
  - The & operator is applied to a variable, so we need an address for it
  - The variables themselves are arrays or structs and we should anticipate the need for pointer arithmetic.

Local Storage

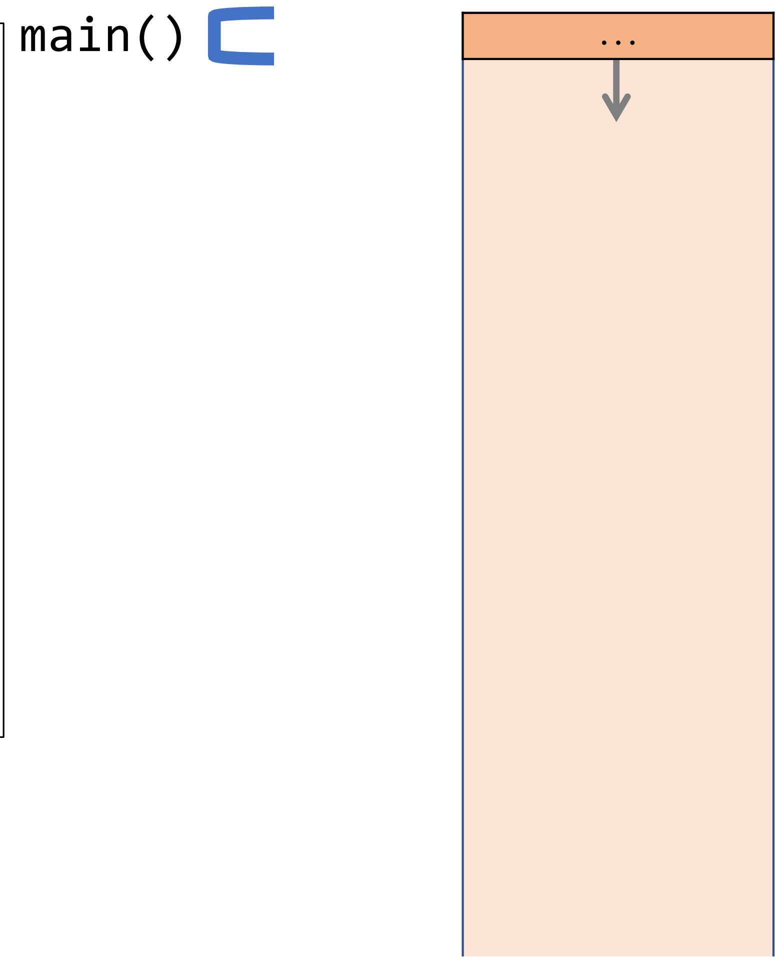
```
long caller() {
    long arg1 = 534;
    long arg2 = 1057;
    long sum = swap_add(&arg1, &arg2);
    ...
}
```

```
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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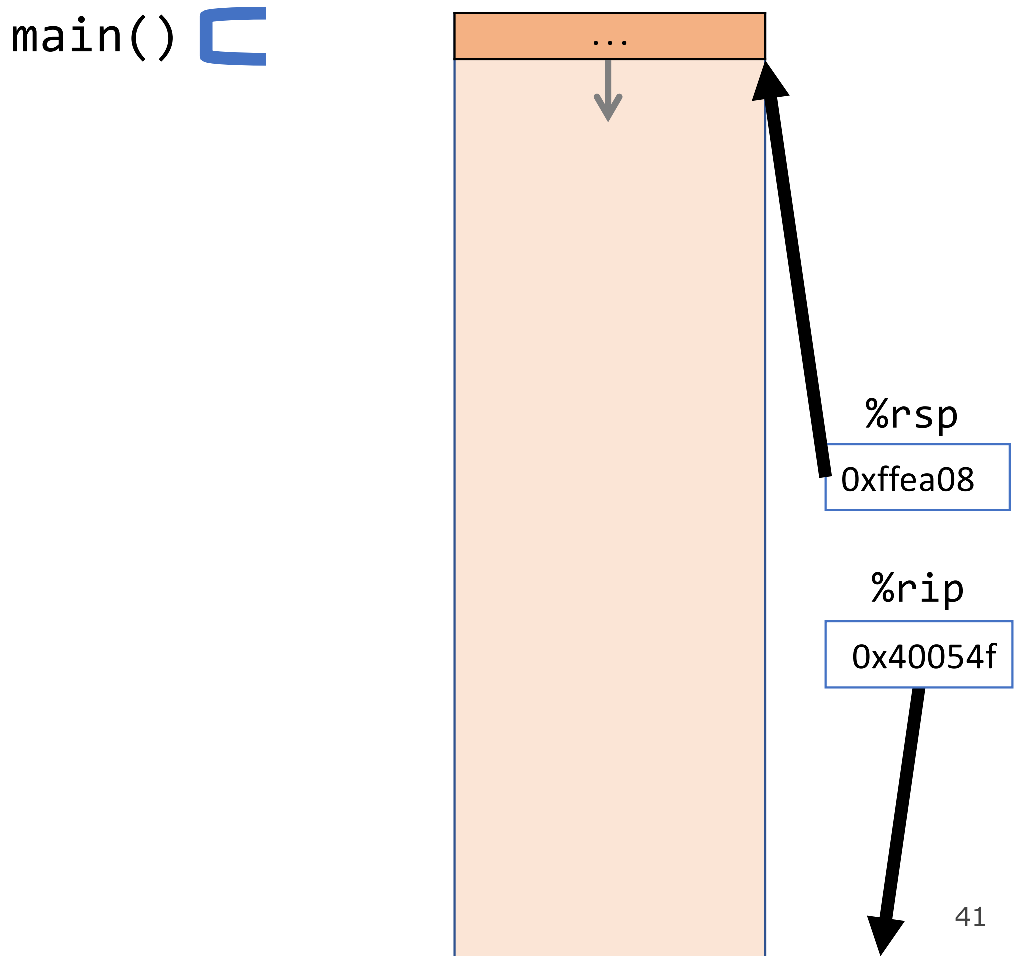

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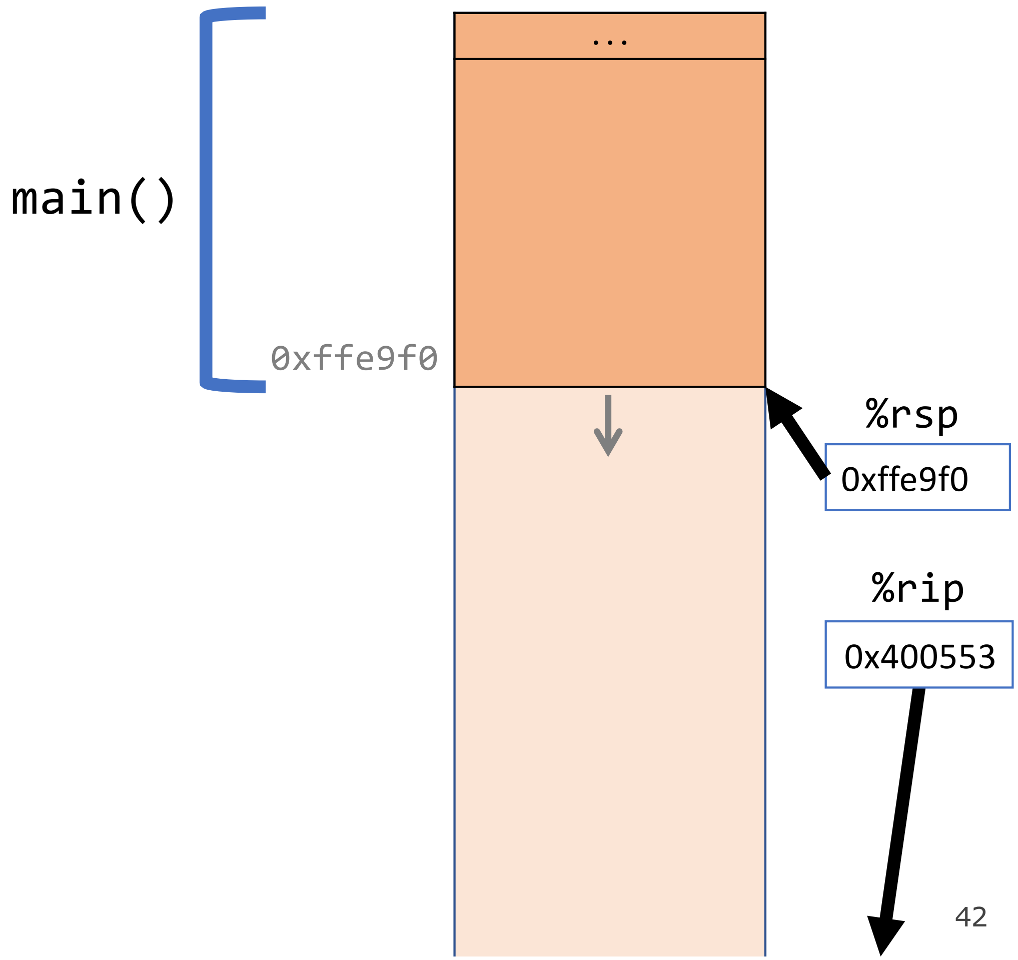

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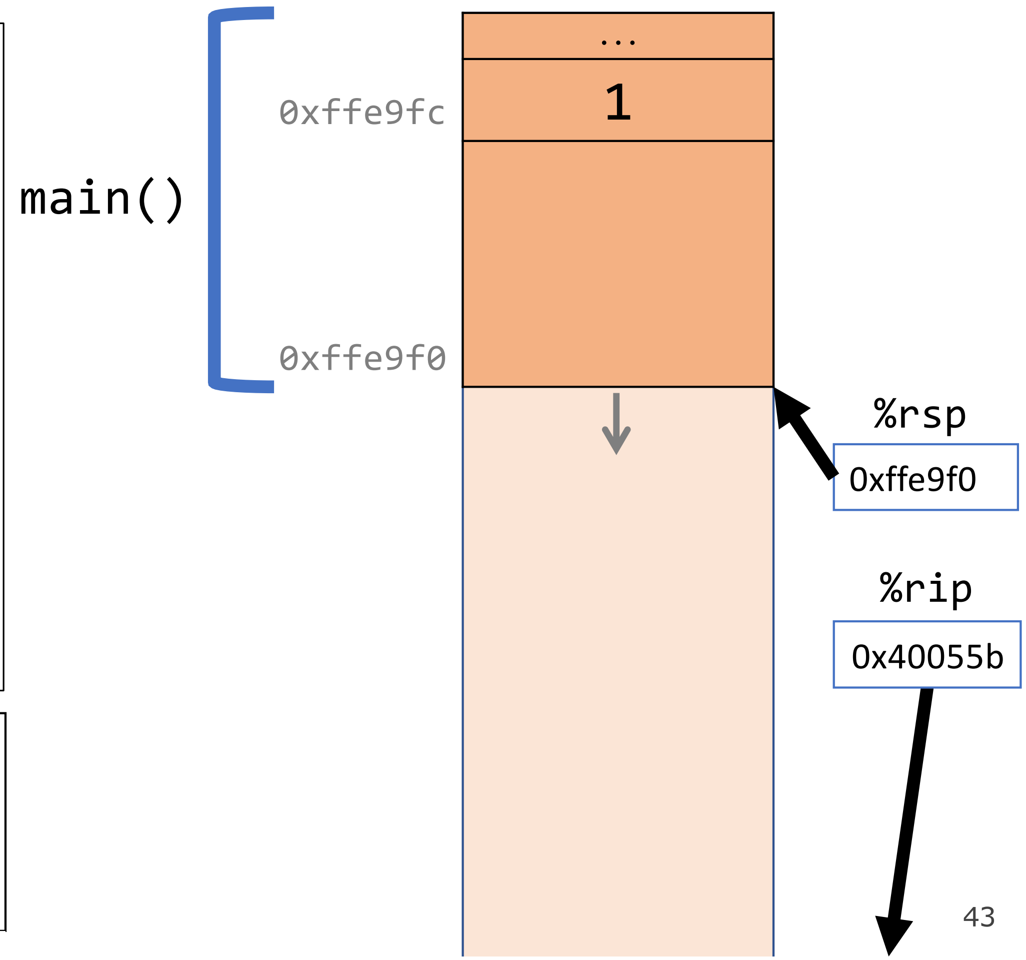

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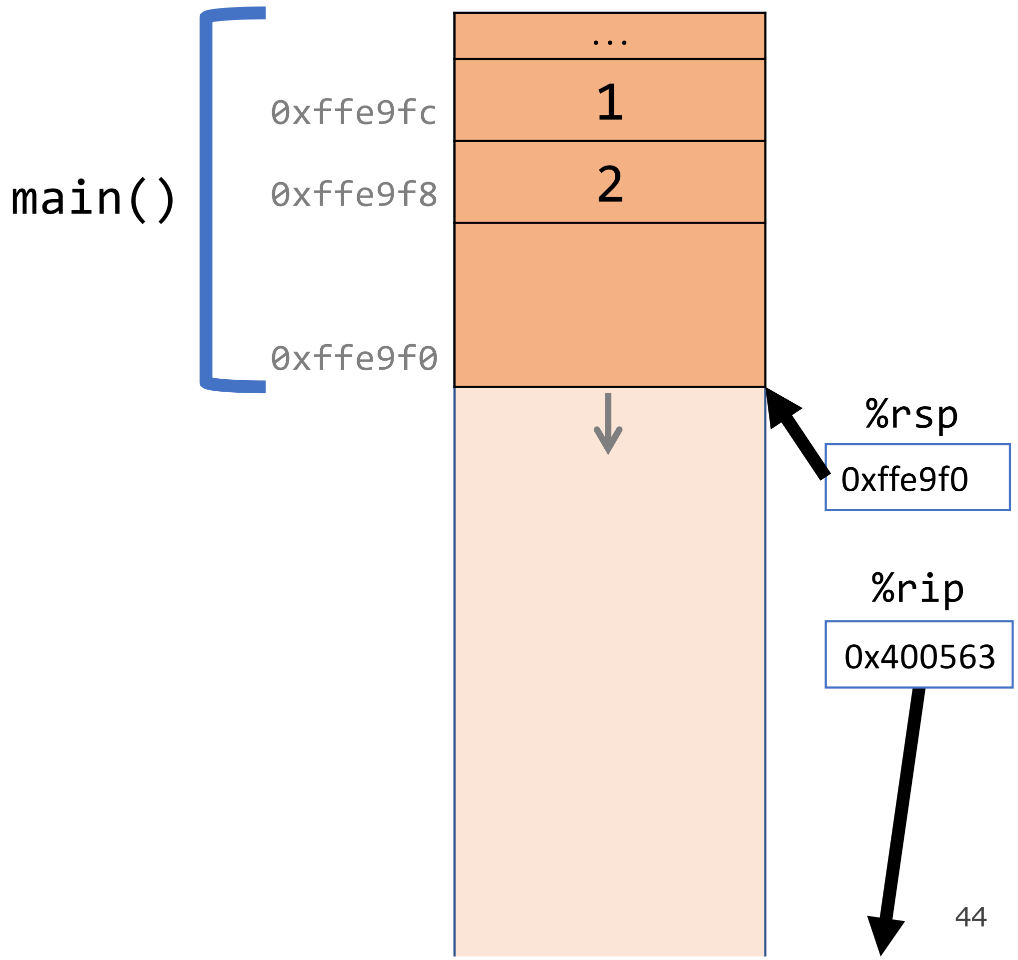

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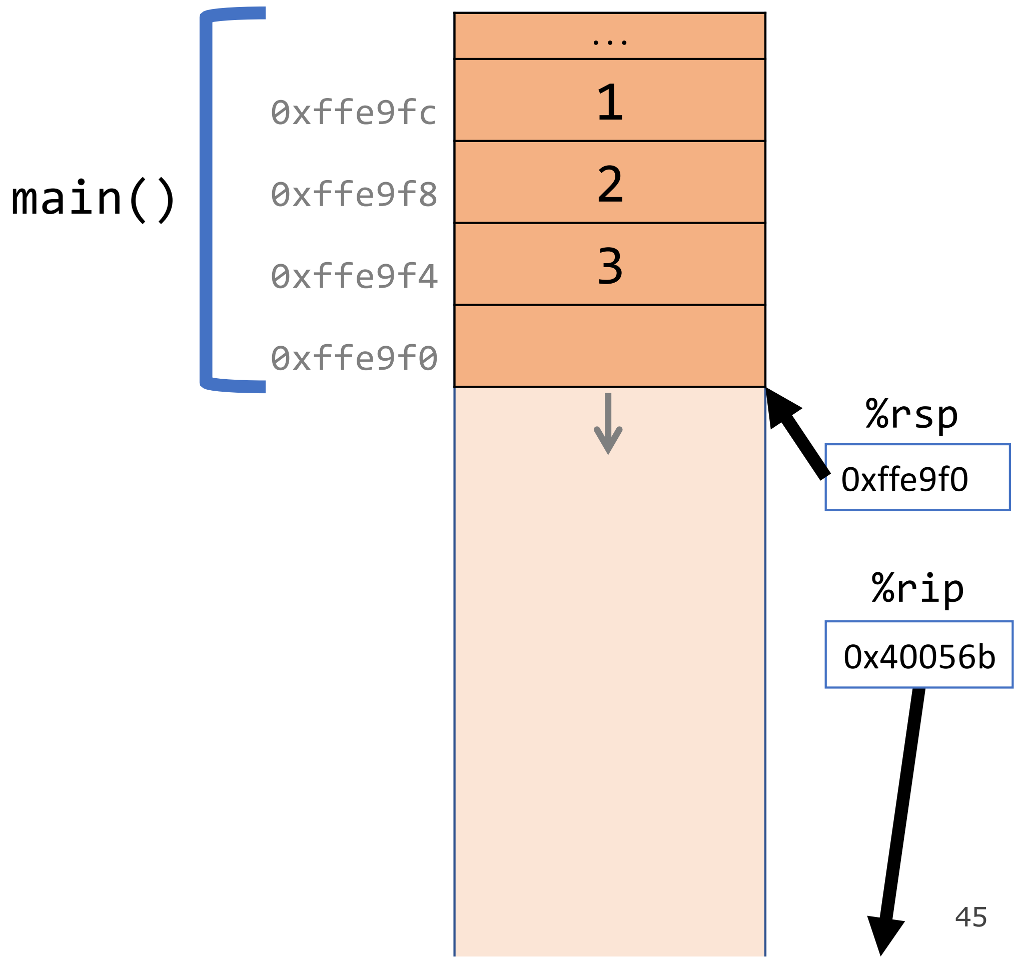

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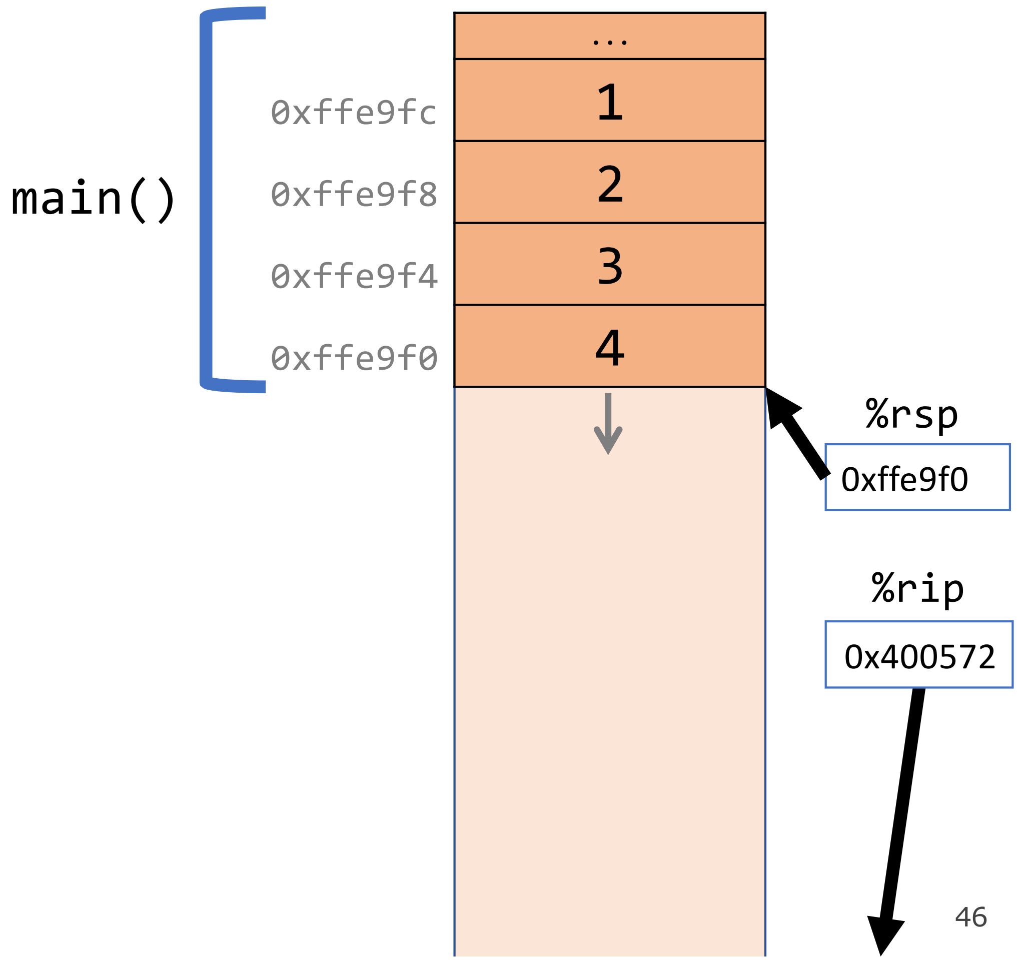
0x400574 <+37>:   pushq  $0x3
```

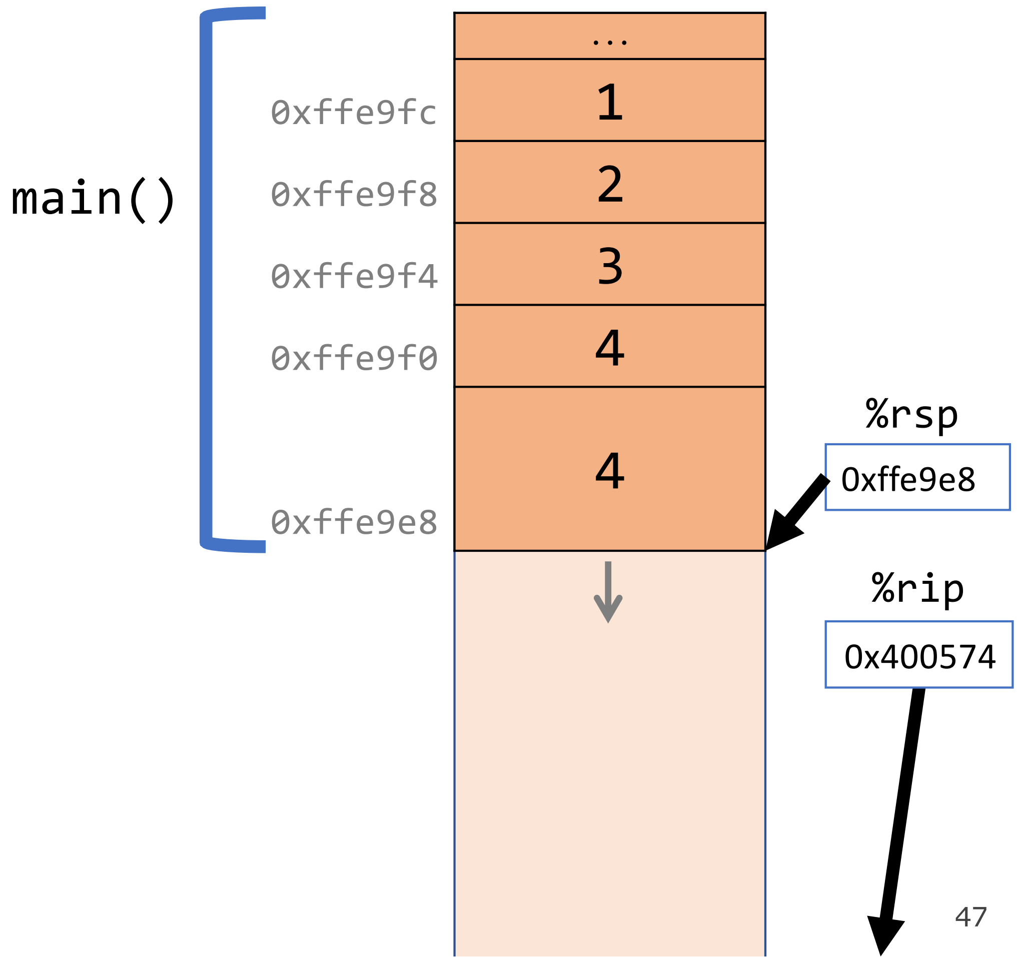


Parameters and Return

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

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

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

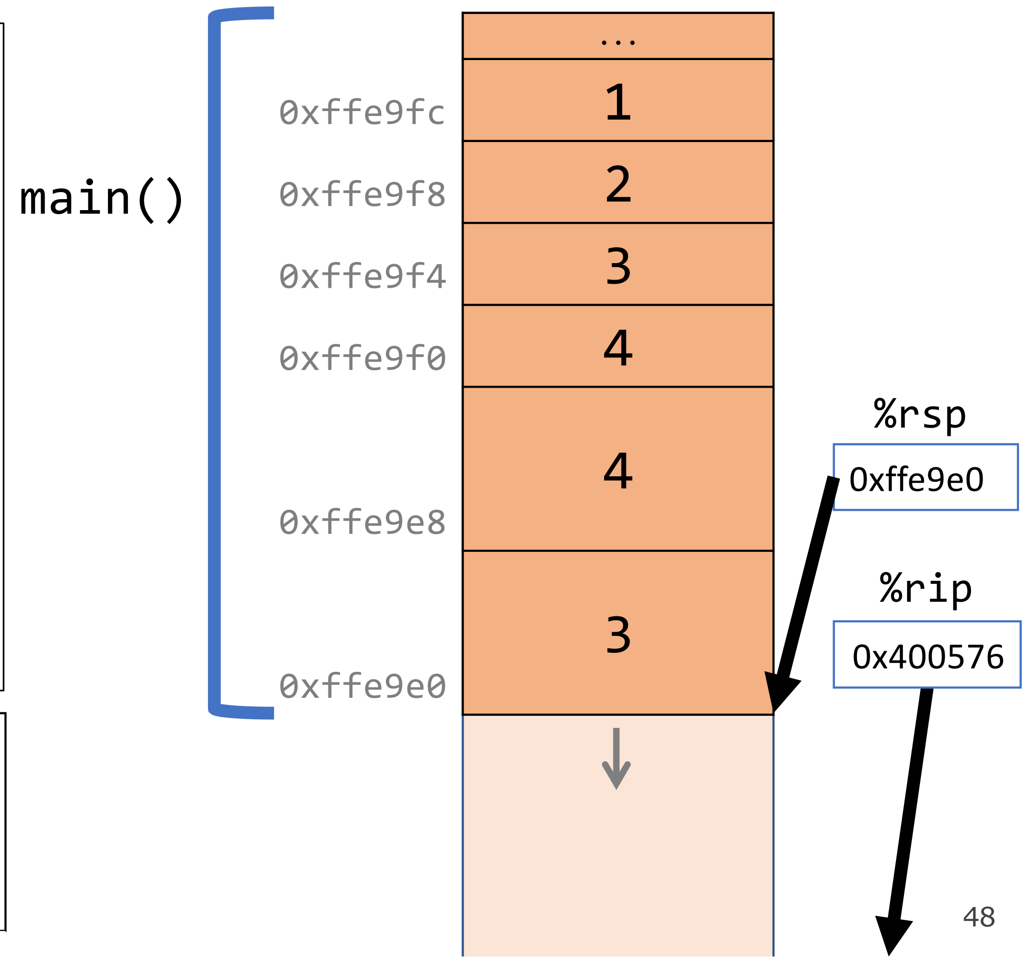


Parameters and Return

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

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

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

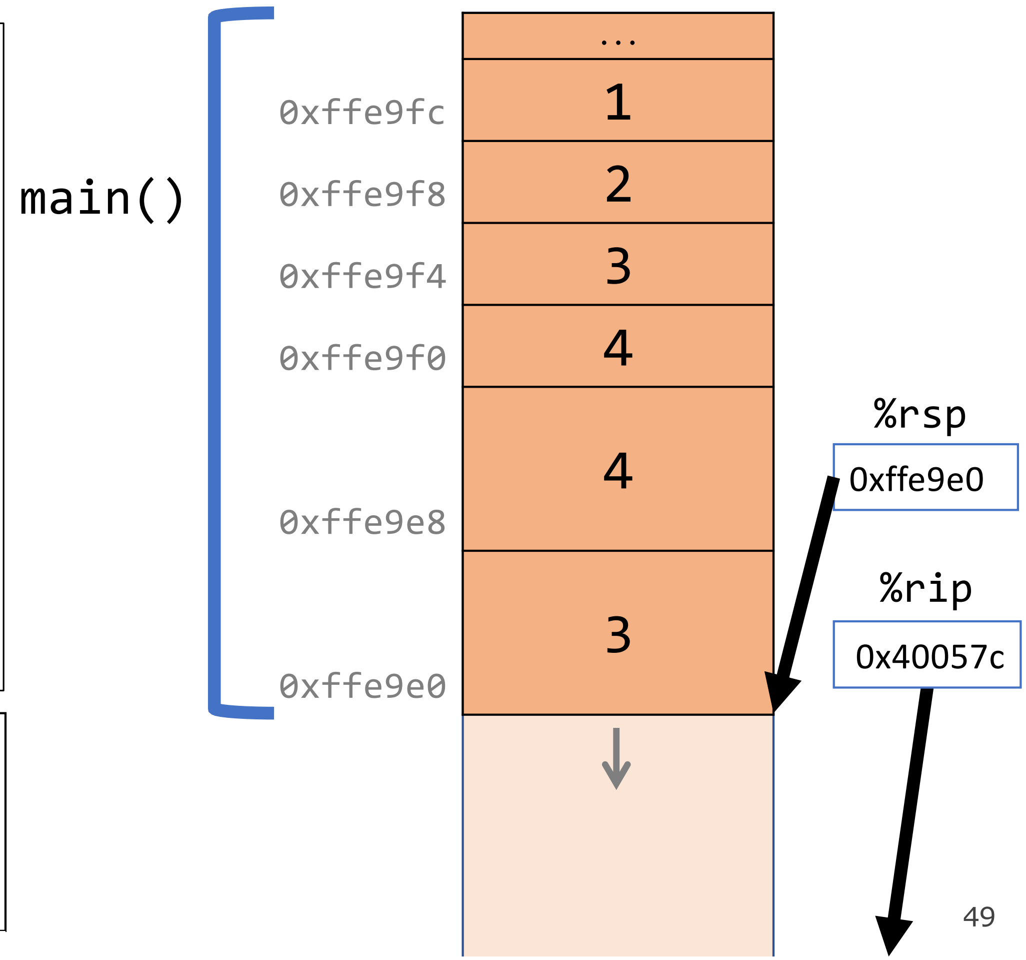


Parameters and Return

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

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

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

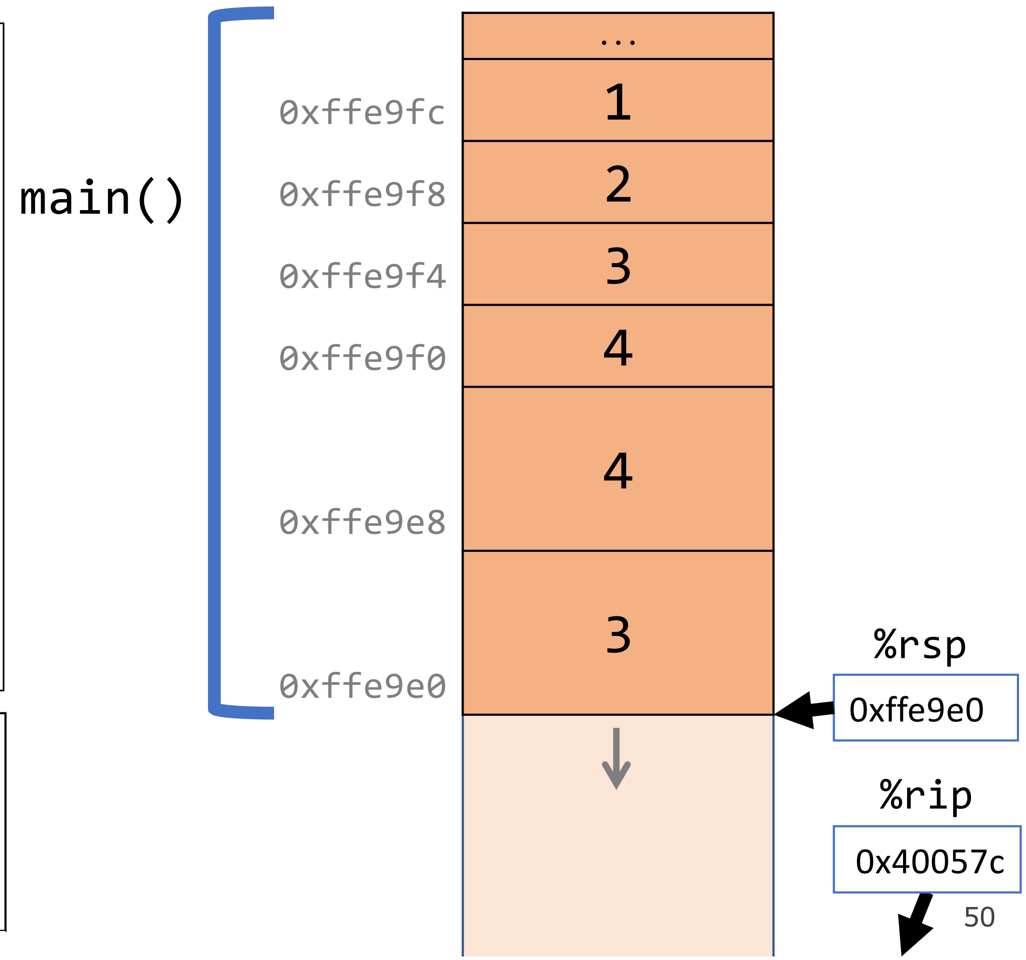


Parameters and Return

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

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

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

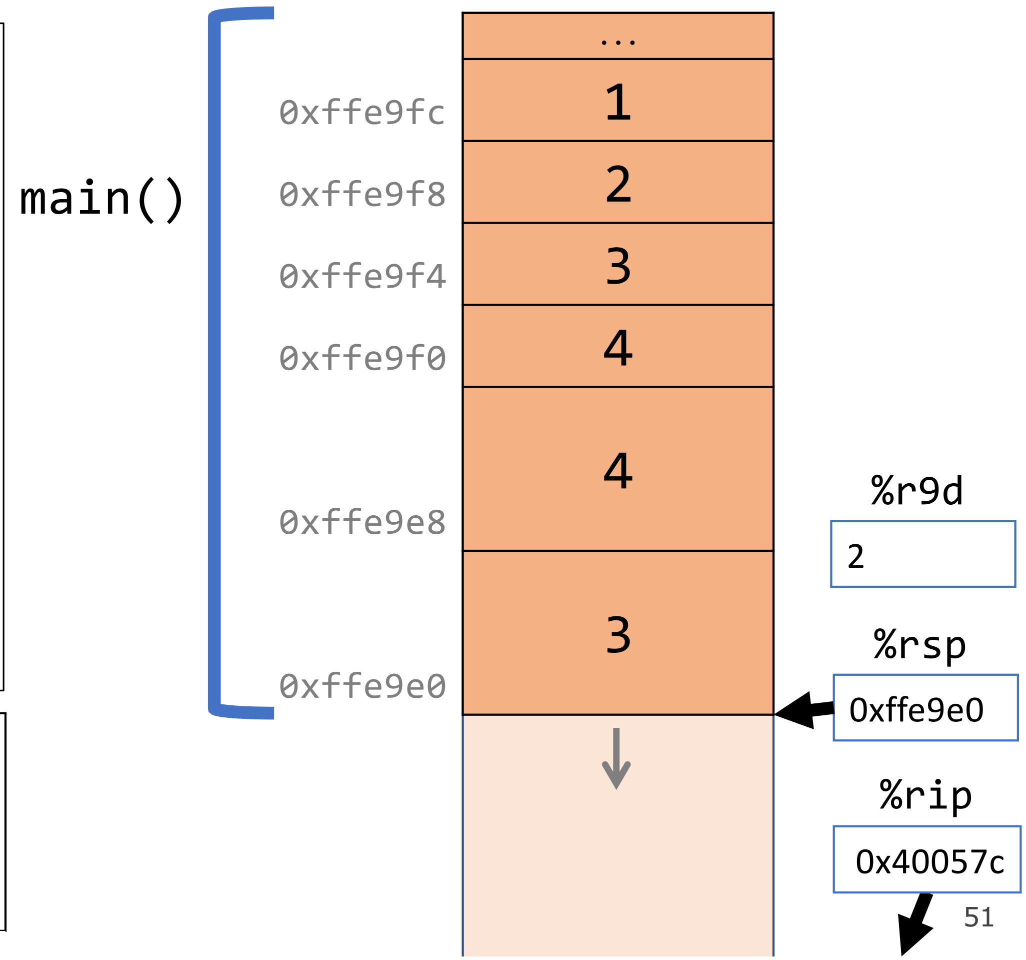


Parameters and Return

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

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

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

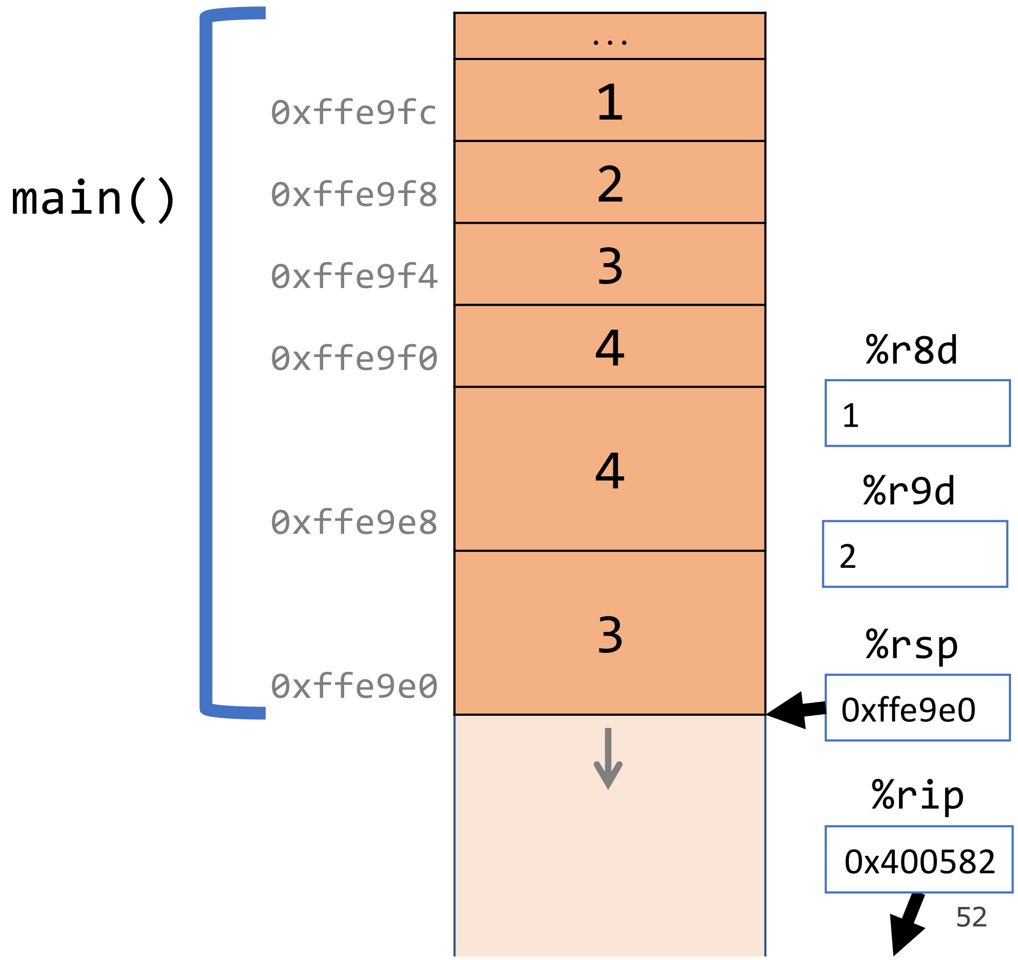


Parameters and Return

```
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
```

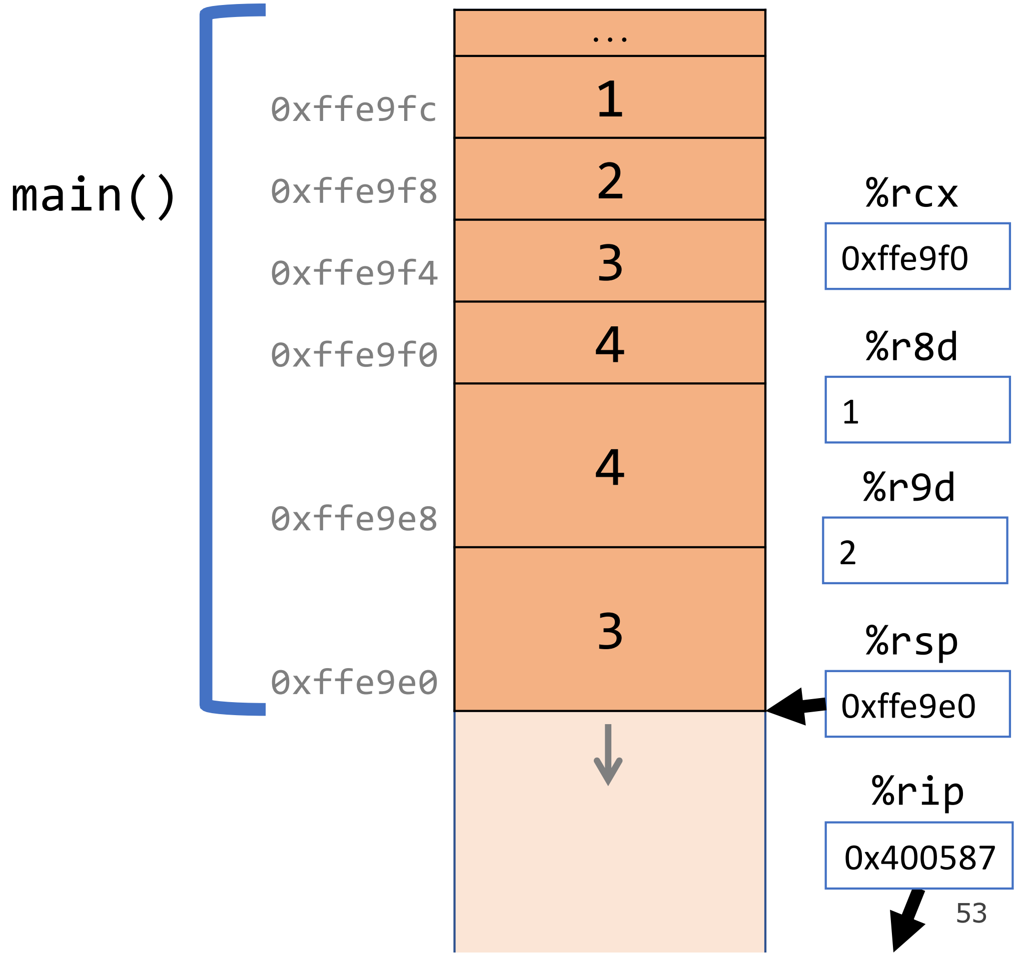


Parameters and Return

```
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
```

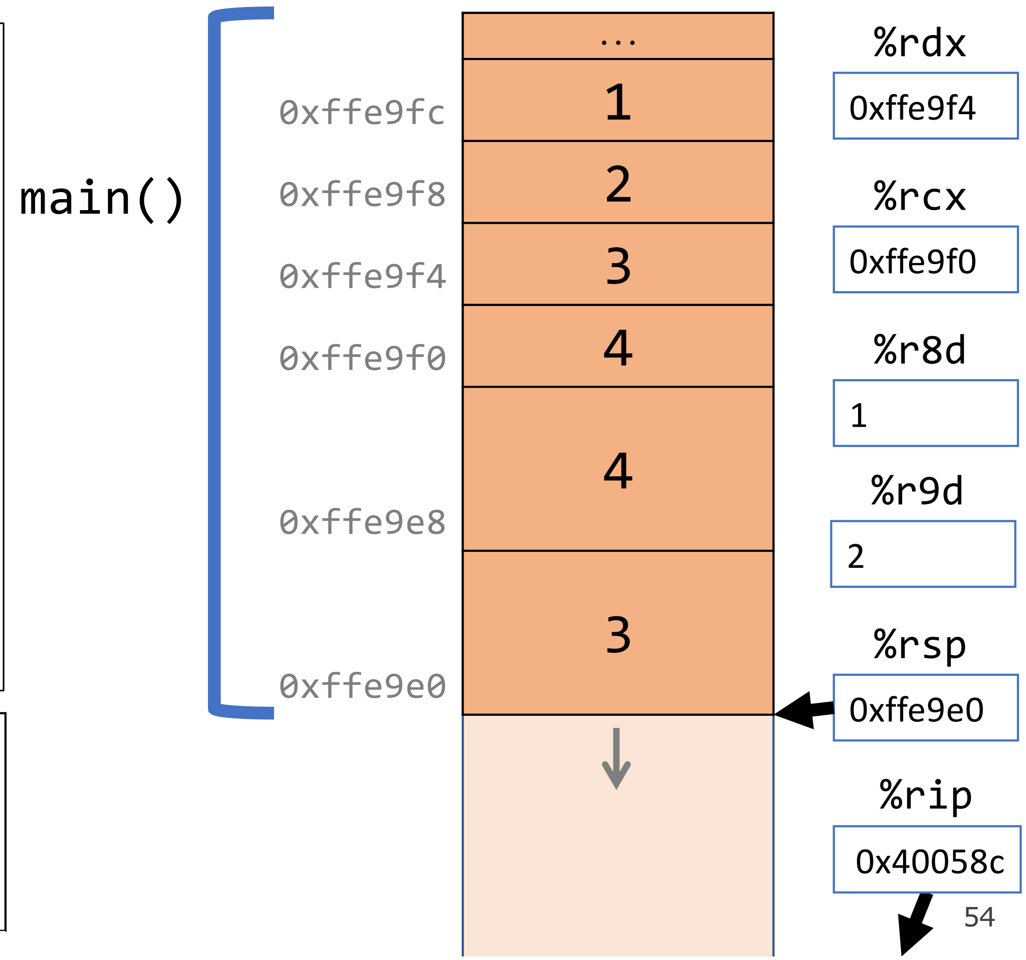


Parameters and Return

```
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
```

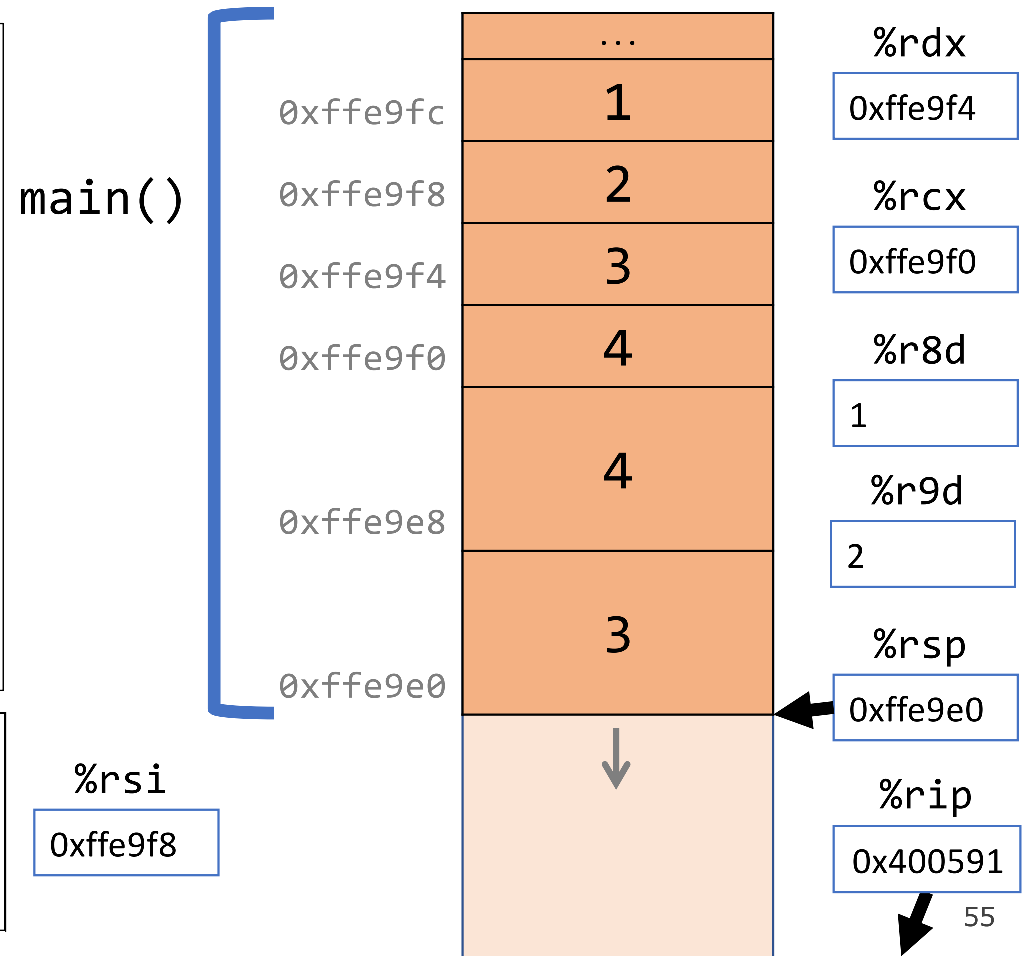


Parameters and Return

```
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>
```

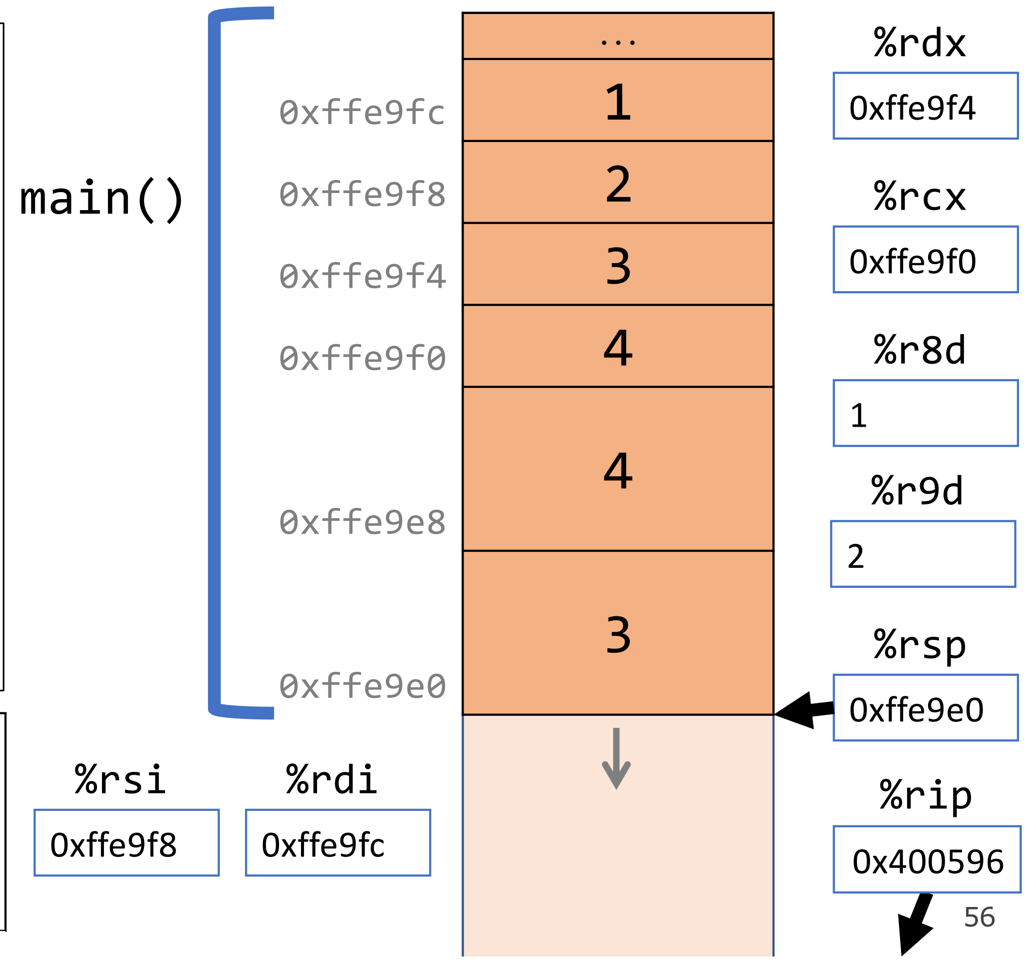


Parameters and Return

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

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

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

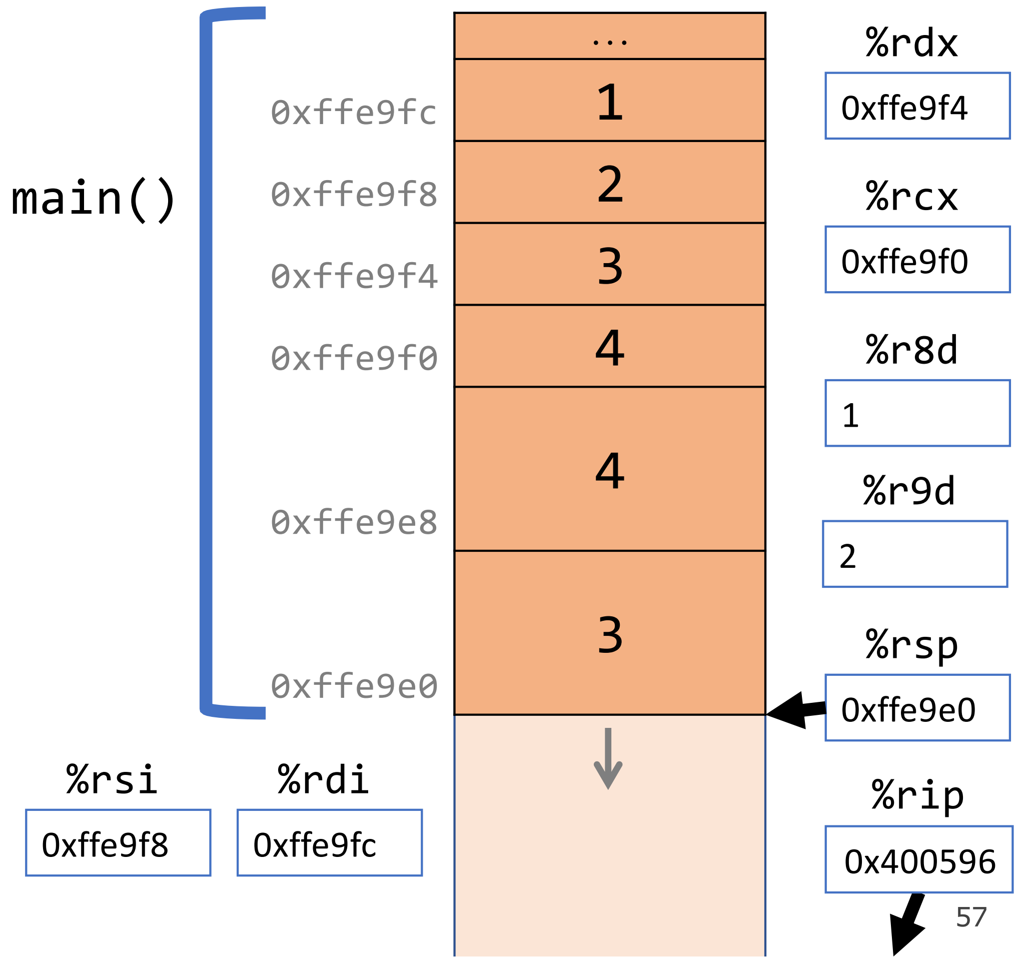


Parameters and Return

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

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

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

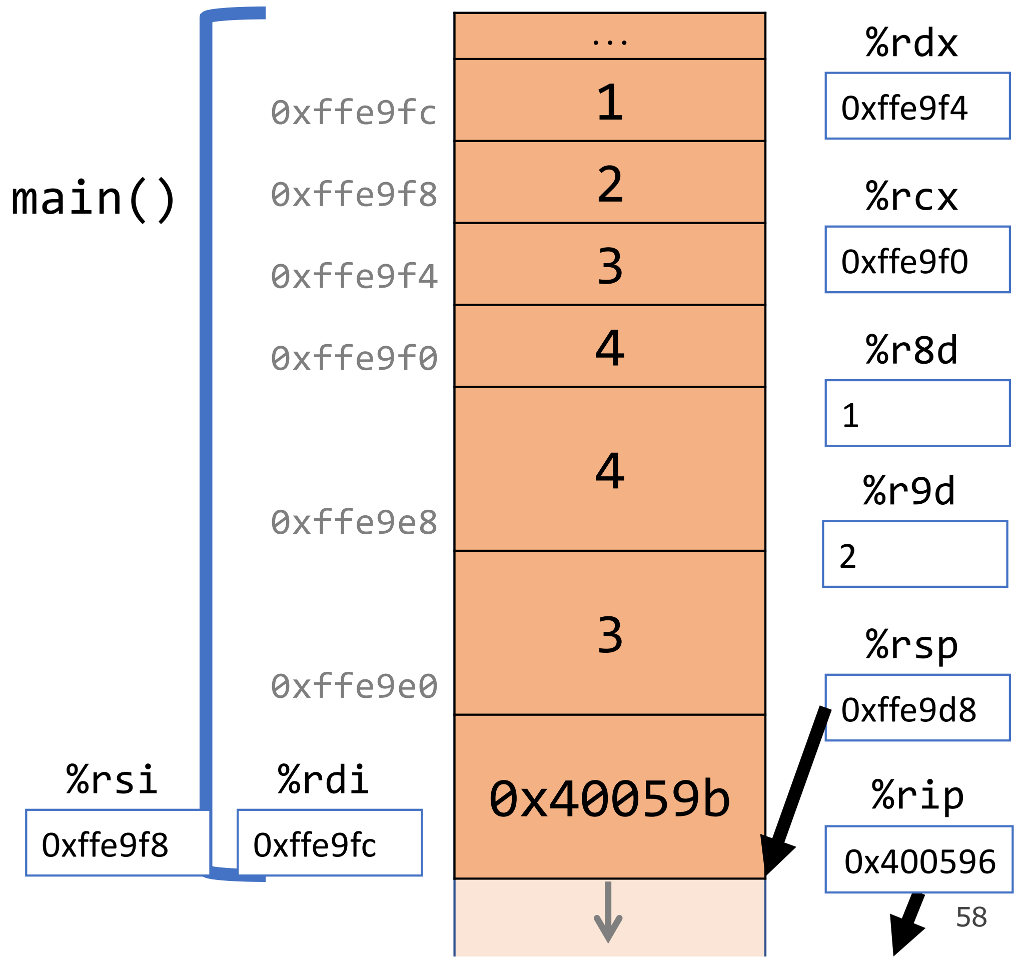


Parameters and Return

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

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

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



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
…
```