x86: Procedures and the Call Stack

The call stack discipline
x86 procedure call and return instructions
x86 calling conventions
x86 register-saving conventions

x86: Procedures and the Call Stack

Outline

1. Motivation
   a. What we have seen so far
   b. Why we can’t implement procedure calls with jumps alone
2. High-level call stack example
3. Procedure control flow instructions: call and ret
4. Procedure call example (in depth!)
5. *(Finish with video)* Caller vs/callee example
6. *(Covered in lab, video)* Recursion example

Why procedures?

Why functions? Why methods?

```
int contains_char(char* haystack, char needle) {
  while (*haystack != '\0') {
    if (*haystack == needle) return 1;
    haystack++;
  }
  return 0;
}
```

Answer: procedural abstraction

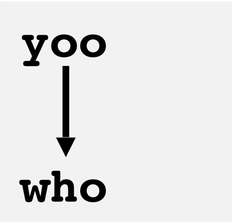
Implementing procedures

Have we already seen how this is done?

1. How does a caller pass arguments to a procedure? ✓
2. How does a caller receive a return value from a procedure? ✓
3. How does a procedure know where to return (what code to execute next when done)? ??
4. Where does a procedure store local variables? ✓?
5. How do procedures share limited registers and memory? ??

Procedure call/return: Jump?

Call Chain



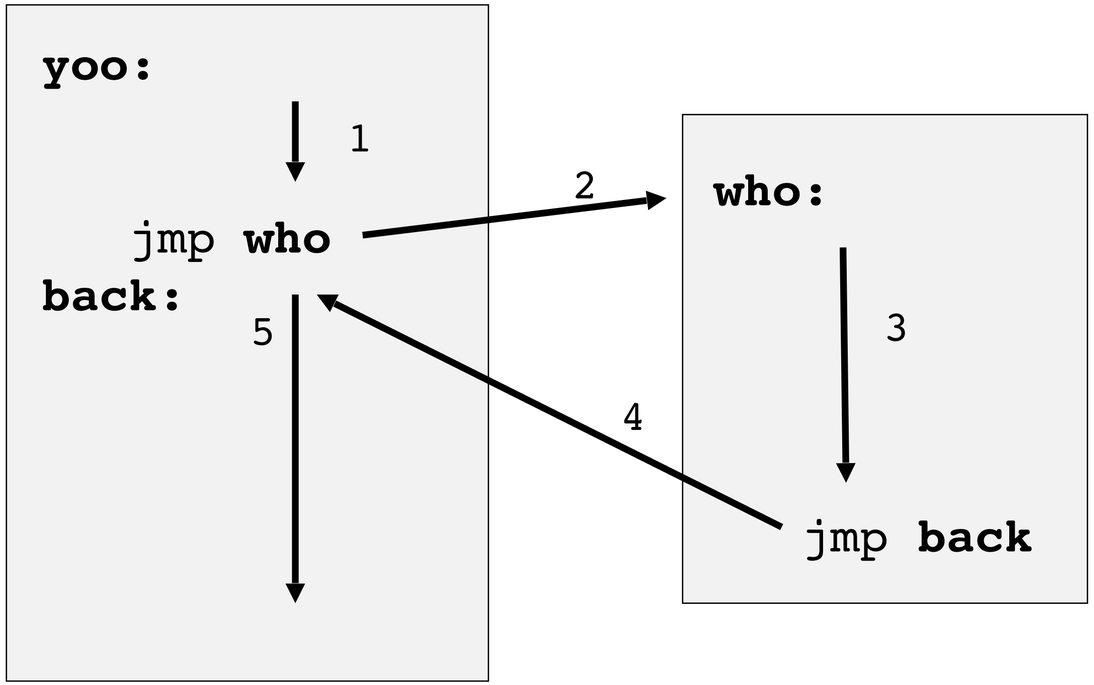

```
yoo(…) {
  • • •
  who();
  • • •
}
```

```
who(…) {
  • • •

  • • •

  • • •
}
```

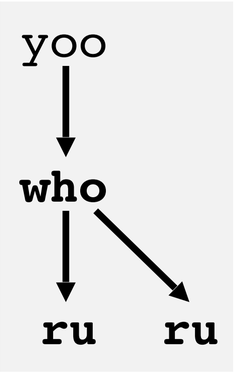
```
ru(…) {
  • • •
}
```



But what if we want to call a function from multiple places in the code?

Procedure call/return: Jump? Broken!

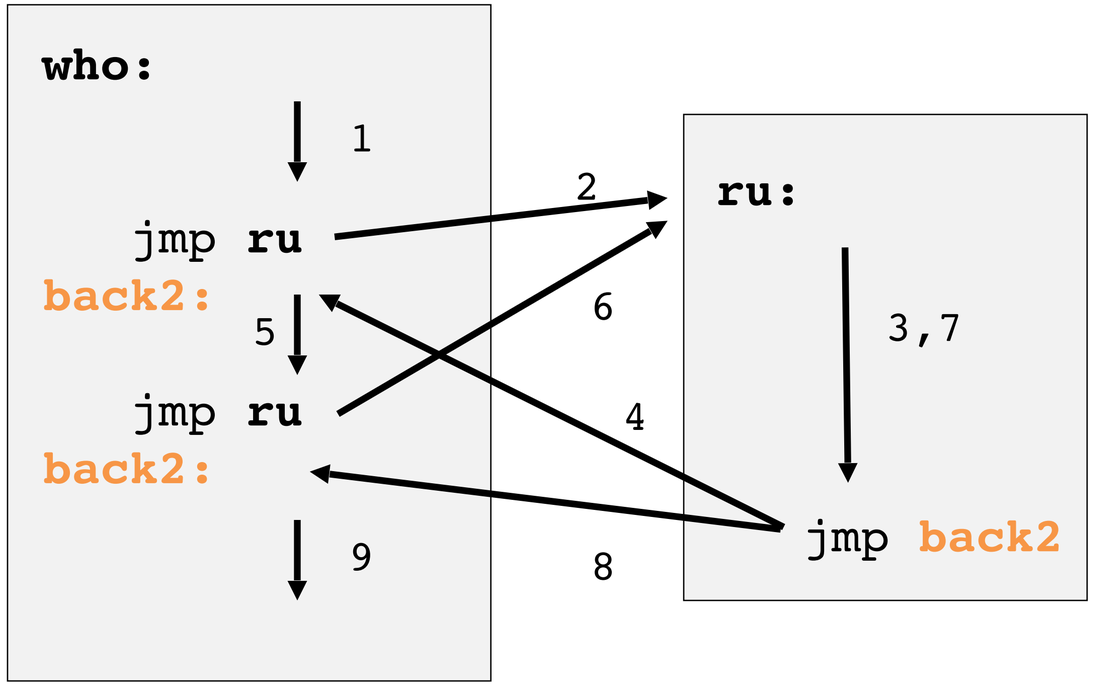
Call Chain




```
yoo(…) {
  • • •
  who();
  • • •
}
```

```
who(…) {
  • • •
  ru();
  • • •
  ru();
  • • •
}
```

```
ru(…) {
  • • •
}
```



But what if we want to call a function from multiple places in the code?

Broken: needs to track context.

Implementing procedures

requires **separate storage *per call!***

(not just per procedure)

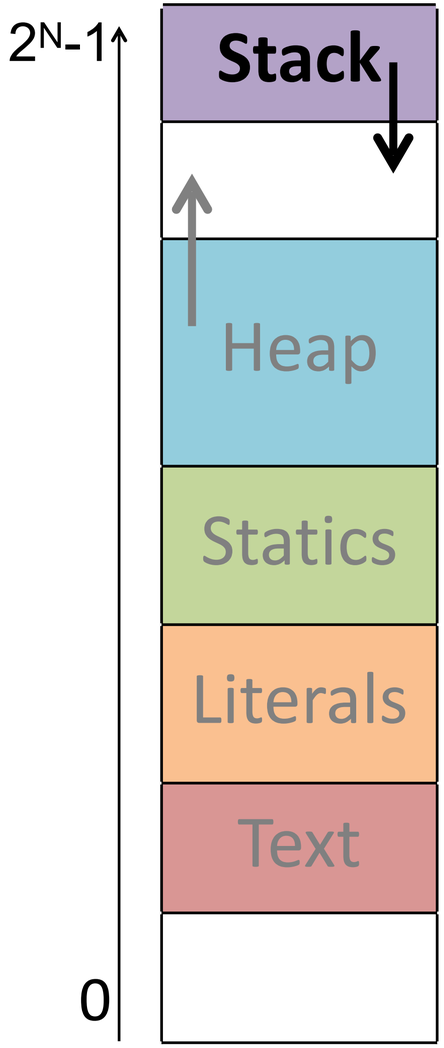
Have we already seen how this is done?

1. How does a caller pass arguments to a procedure? ✓
2. How does a caller receive a return value from a procedure? ✓
3. How does a procedure know where to return (what code to execute next when done)? ??
4. Where does a procedure store local variables? ✓?

1. How do procedures share limited registers and memory? ??

Memory Layout

reminder



	Perm	Contents	Managed by	Initialized
Stack	**RW**	**Procedure context**	**Compiler**	**Run-time**
Heap	RW	Dynamic data structures	Programmer, malloc/free, new/ GC	Run-time
Statics	RW	Global variables/ static data structures	Compiler/ Assembler/Linker	Startup
Literals	R	String literals	Compiler/ Assembler/Linker	Startup
Text	X	Instructions	Compiler/ Assembler/Linker	Startup

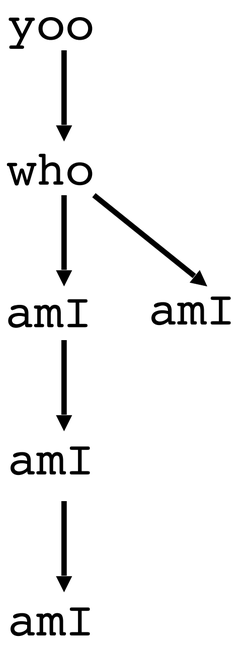
Call stack tracks context

```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```

```
who(…)
{
  •
  amI();
  •
  amI();
  •
}
```

```
amI(…)
{
   •
   if(…){
     amI()
   }
   •
}
```

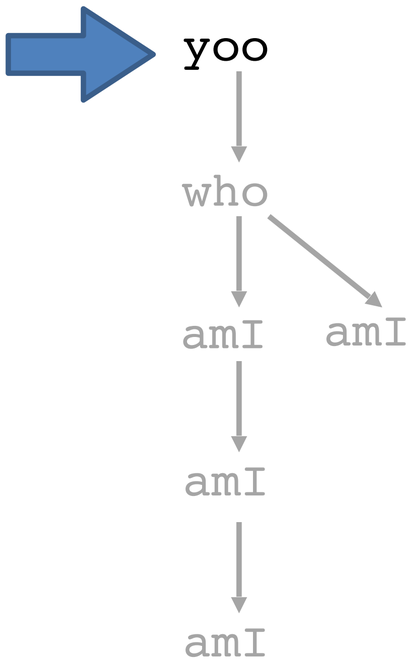
Example
Call Chain

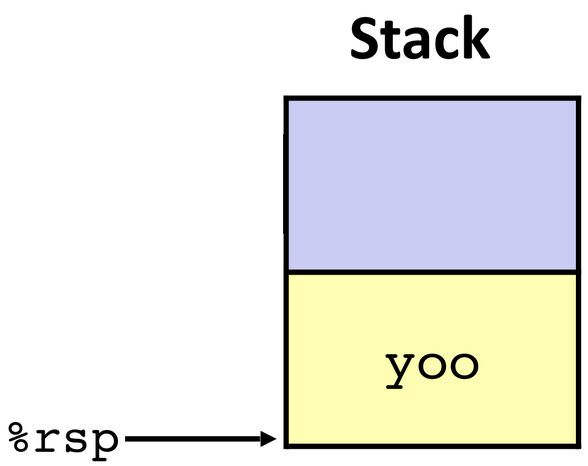


Procedure `amI` is recursive
(calls itself)

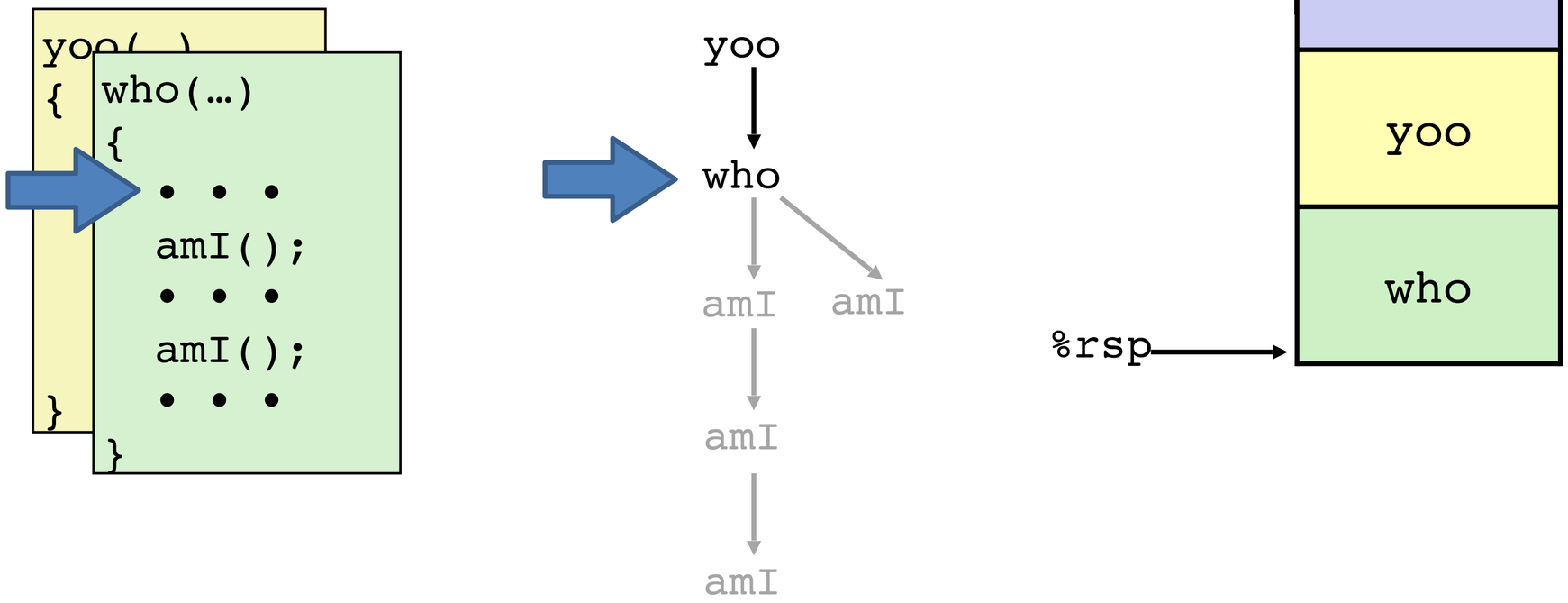
Call stack tracks context

```
yoo(…)
{
  •
  •
  who();
  •
  •
}
```

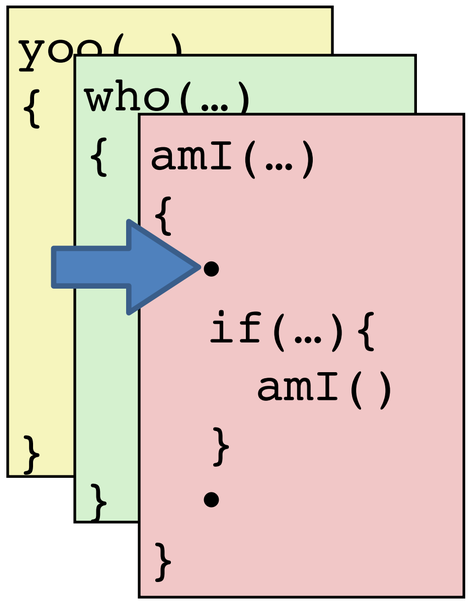


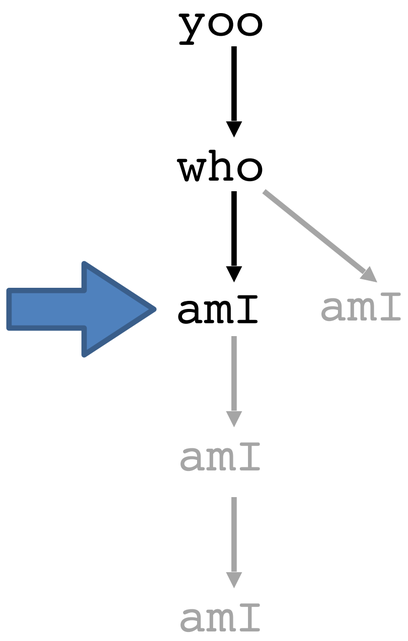


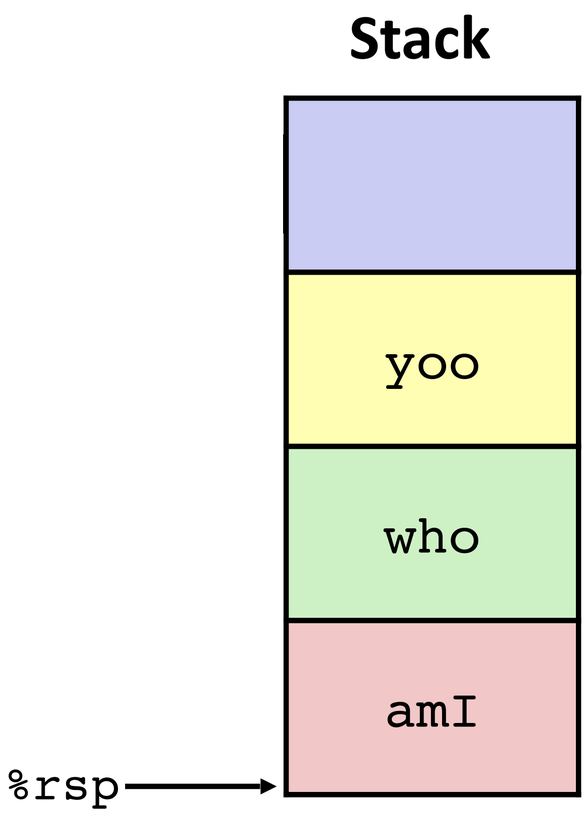
Call stack tracks context



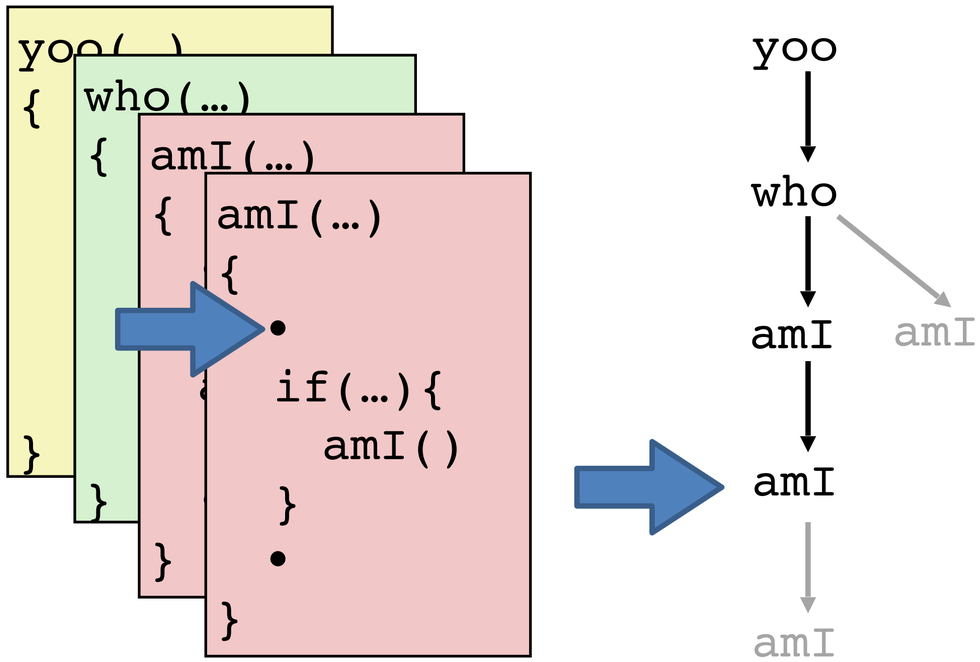
Call stack tracks context

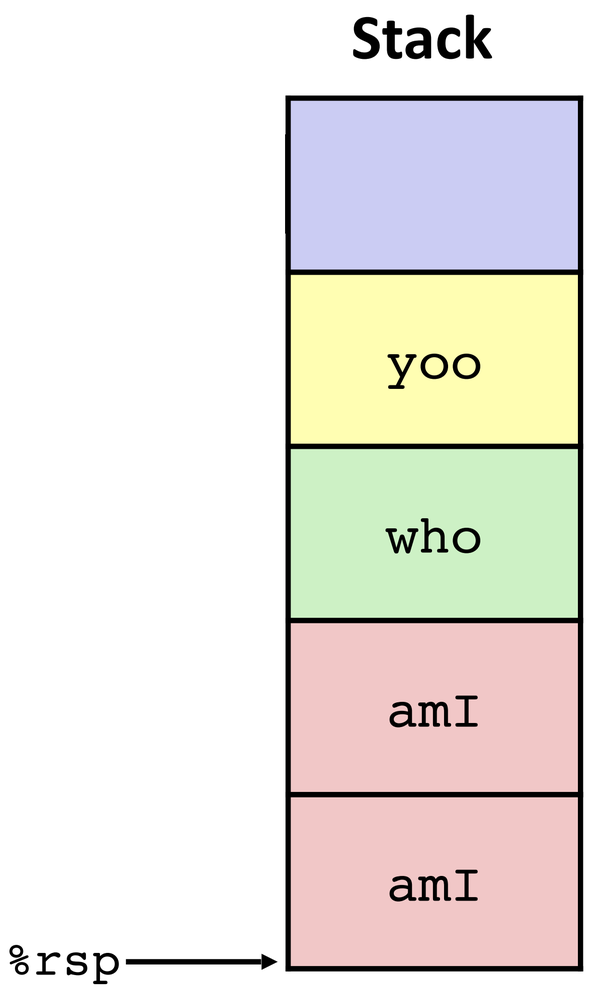




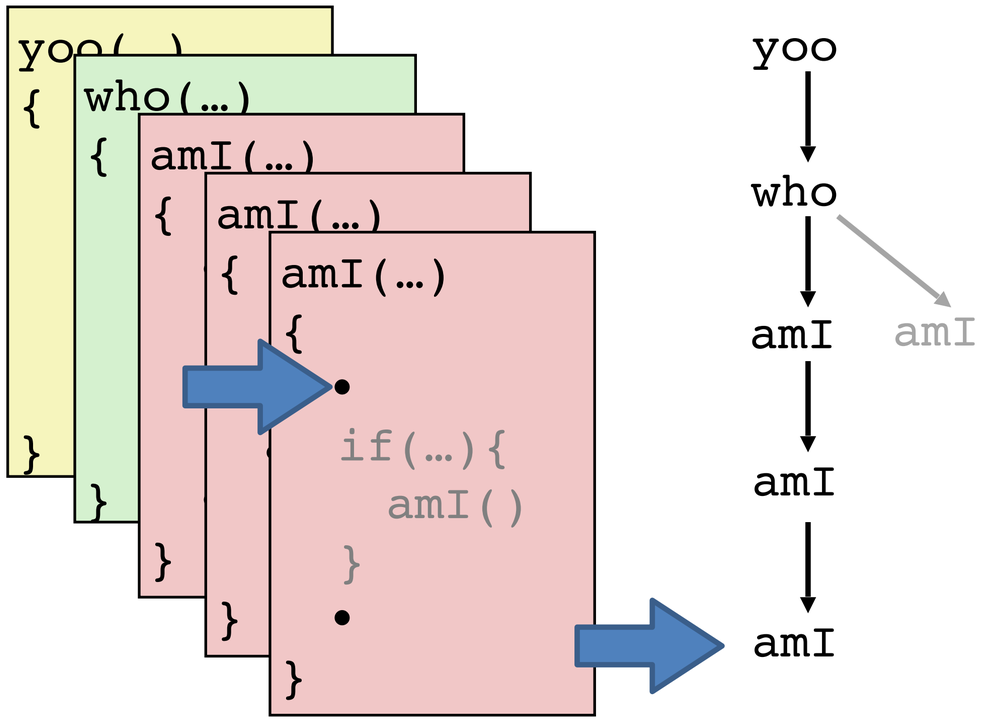


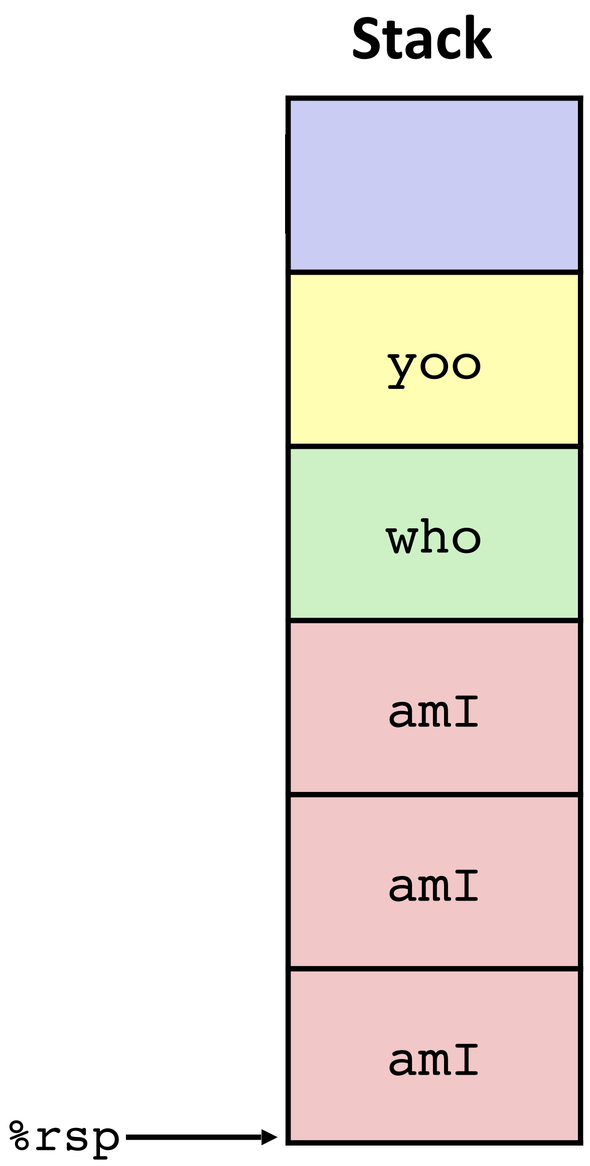
Call stack tracks context



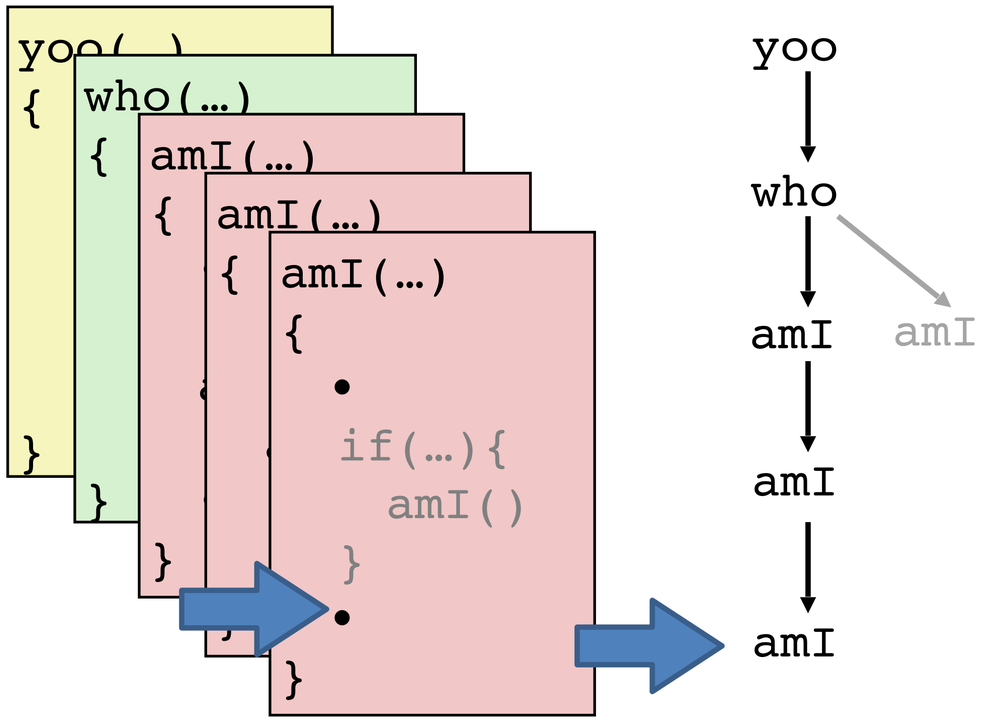


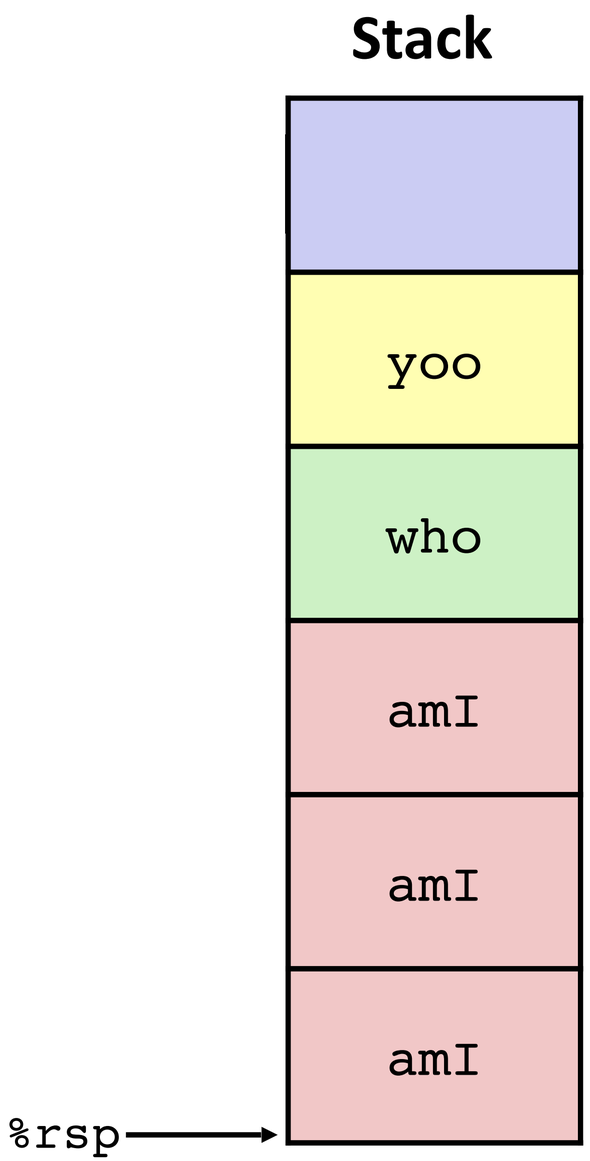
Call stack tracks context





Call stack tracks context





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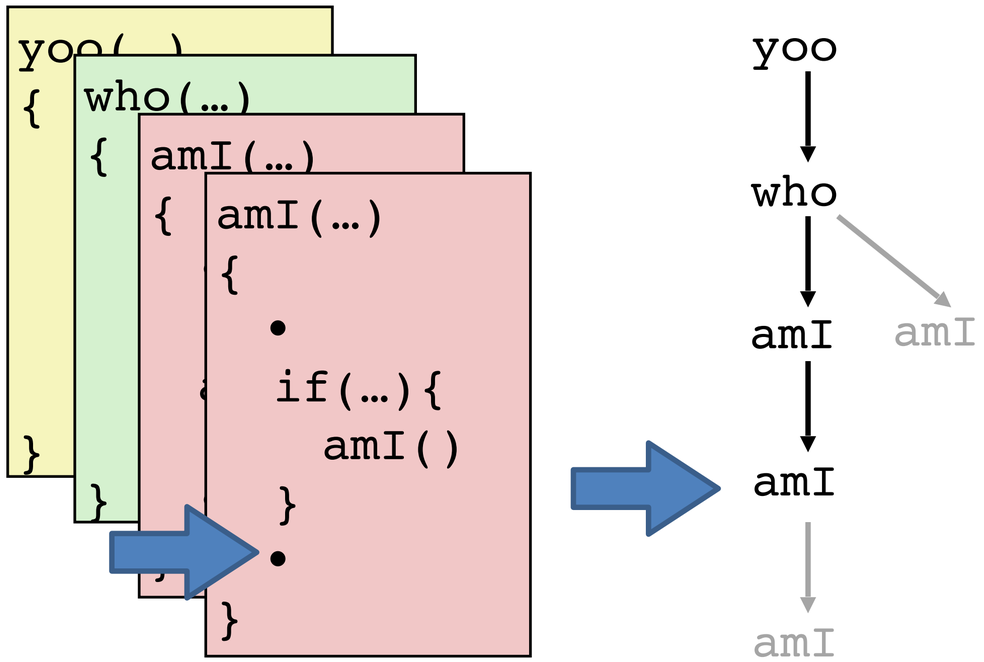
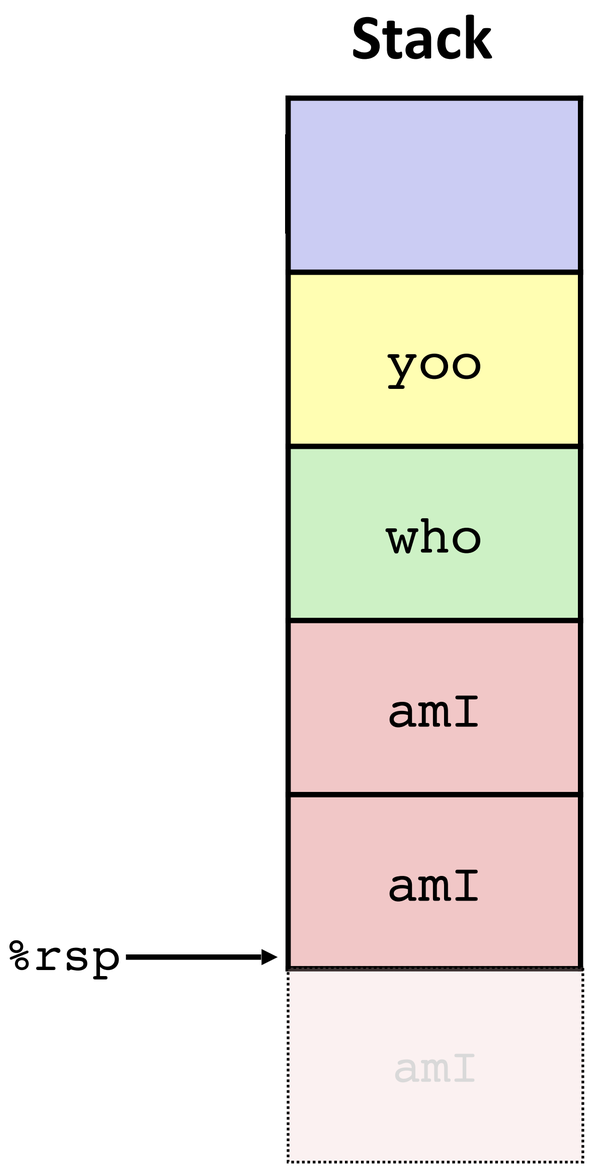
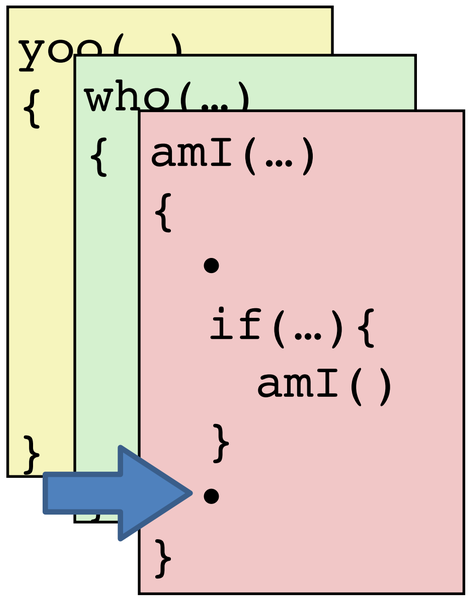
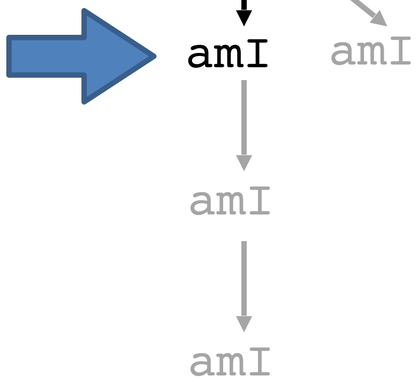
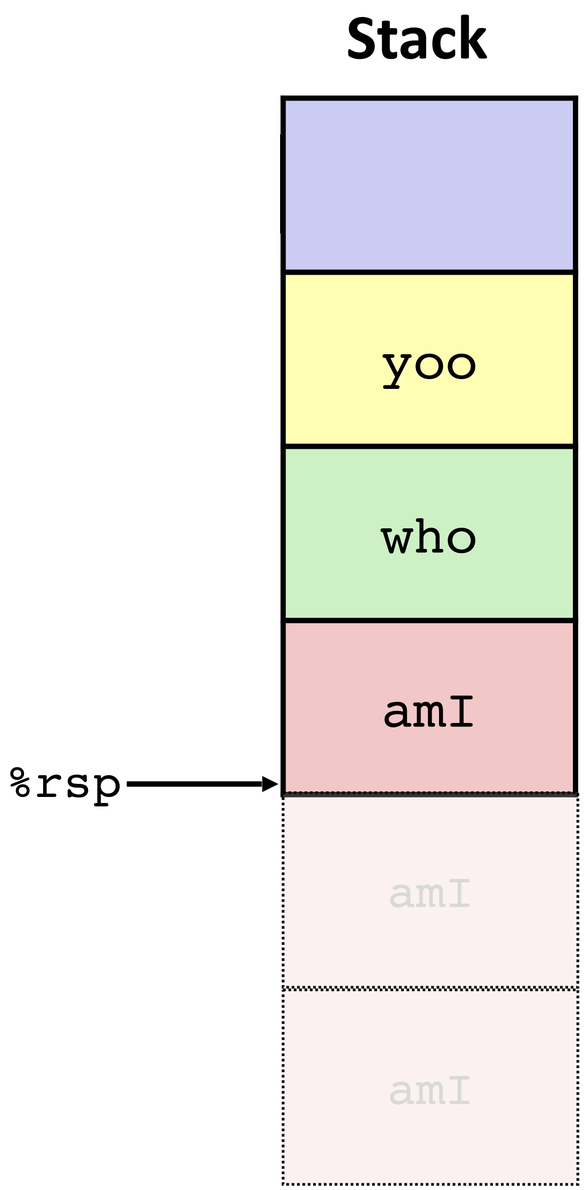




Call stack tracks context







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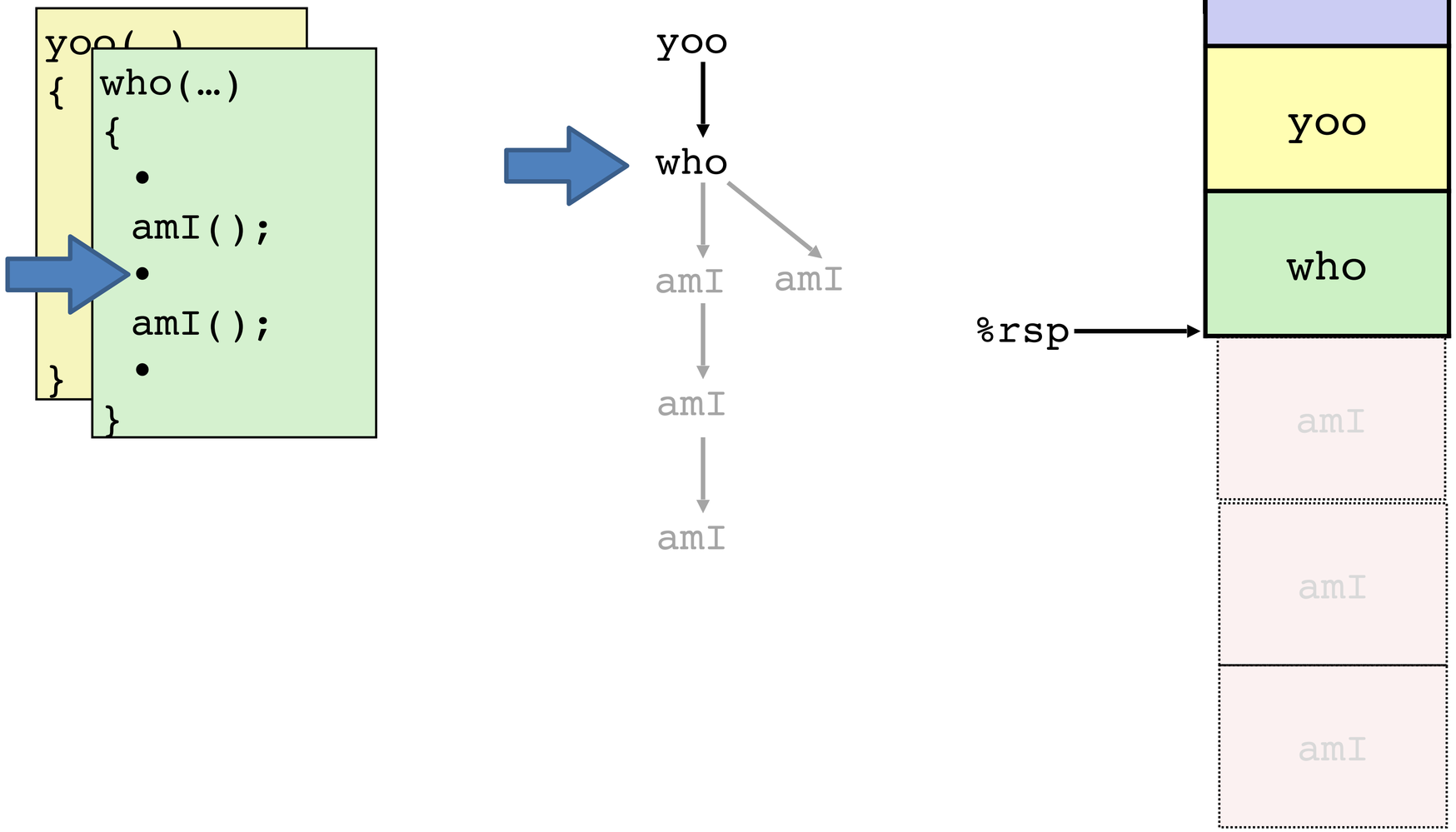
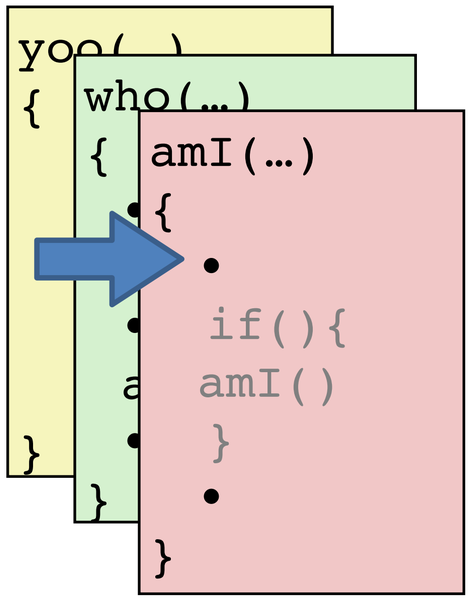
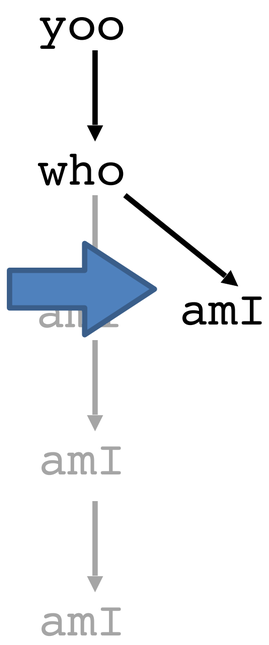
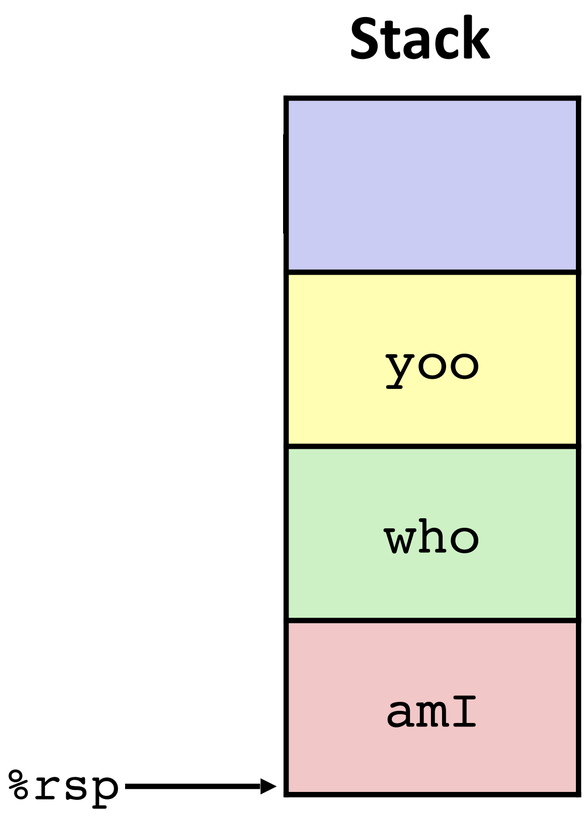


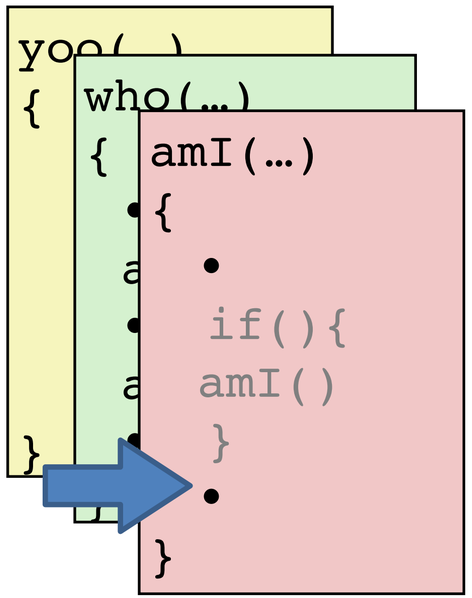
Call stack tracks context

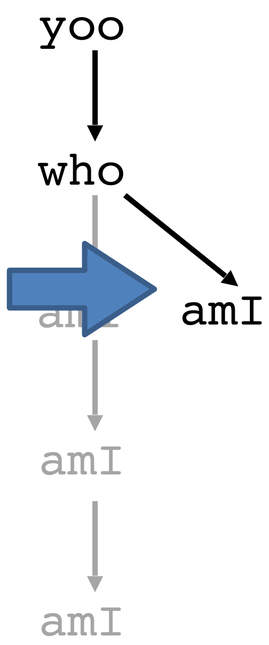


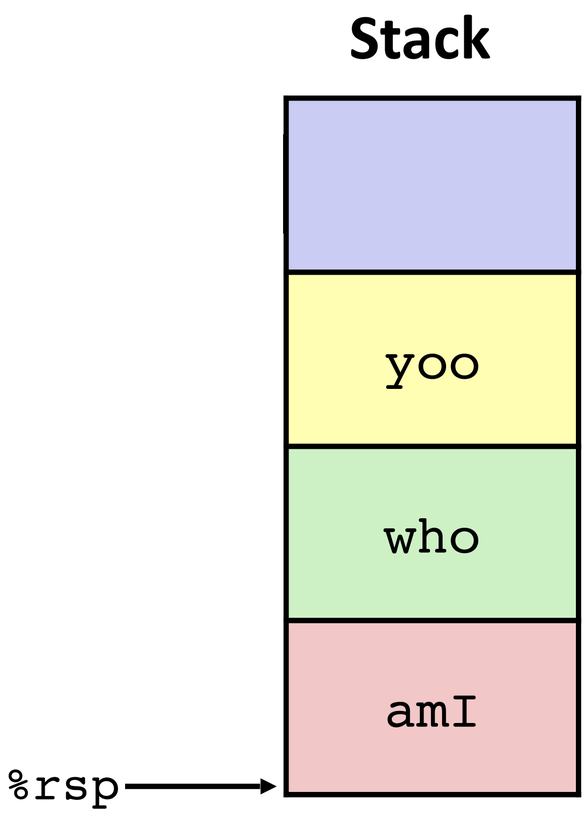




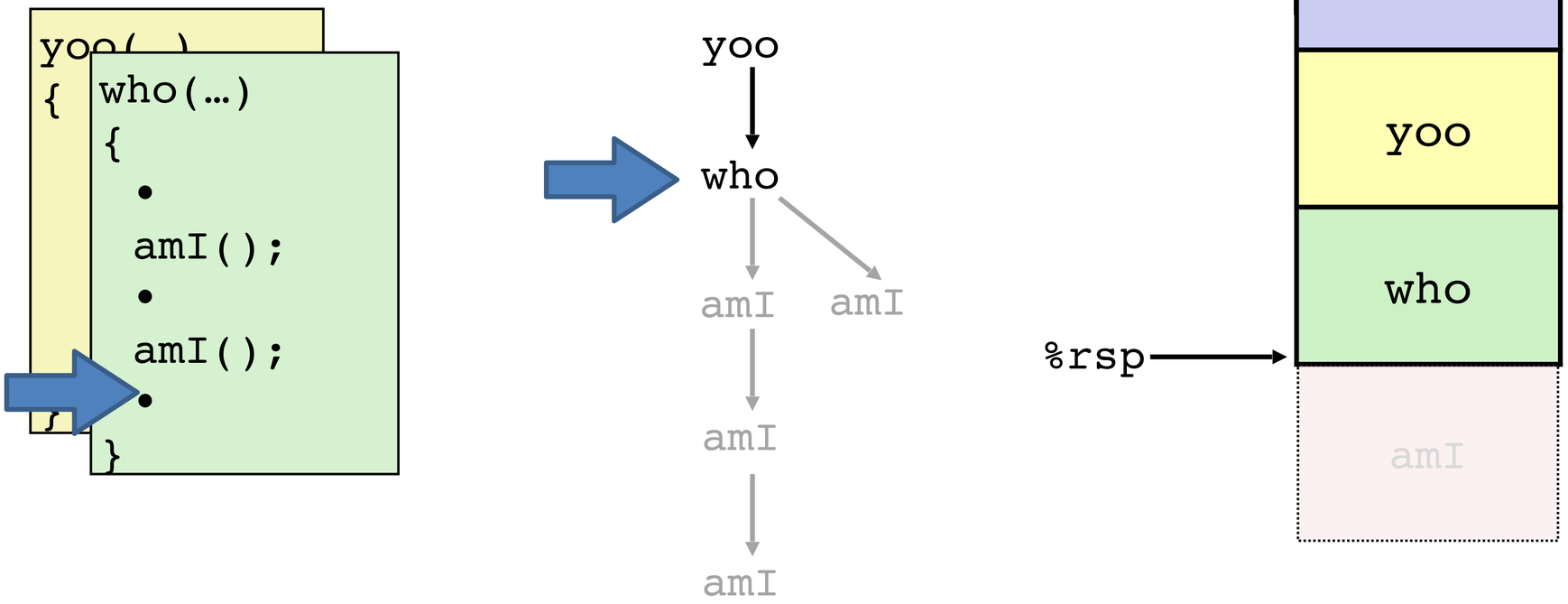
Call stack tracks context





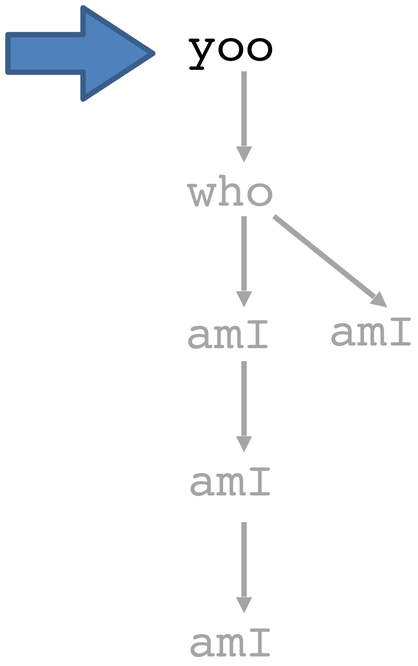


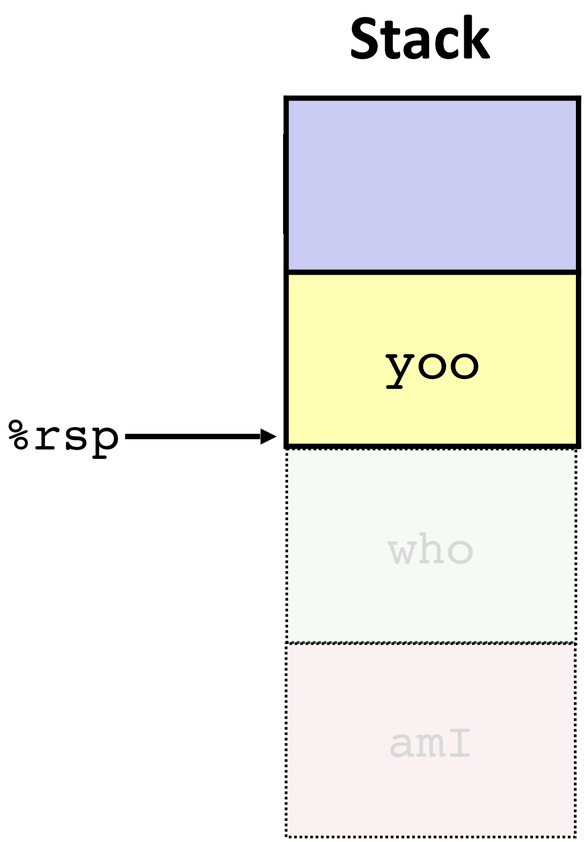
Call stack tracks context



Call stack tracks context

```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```



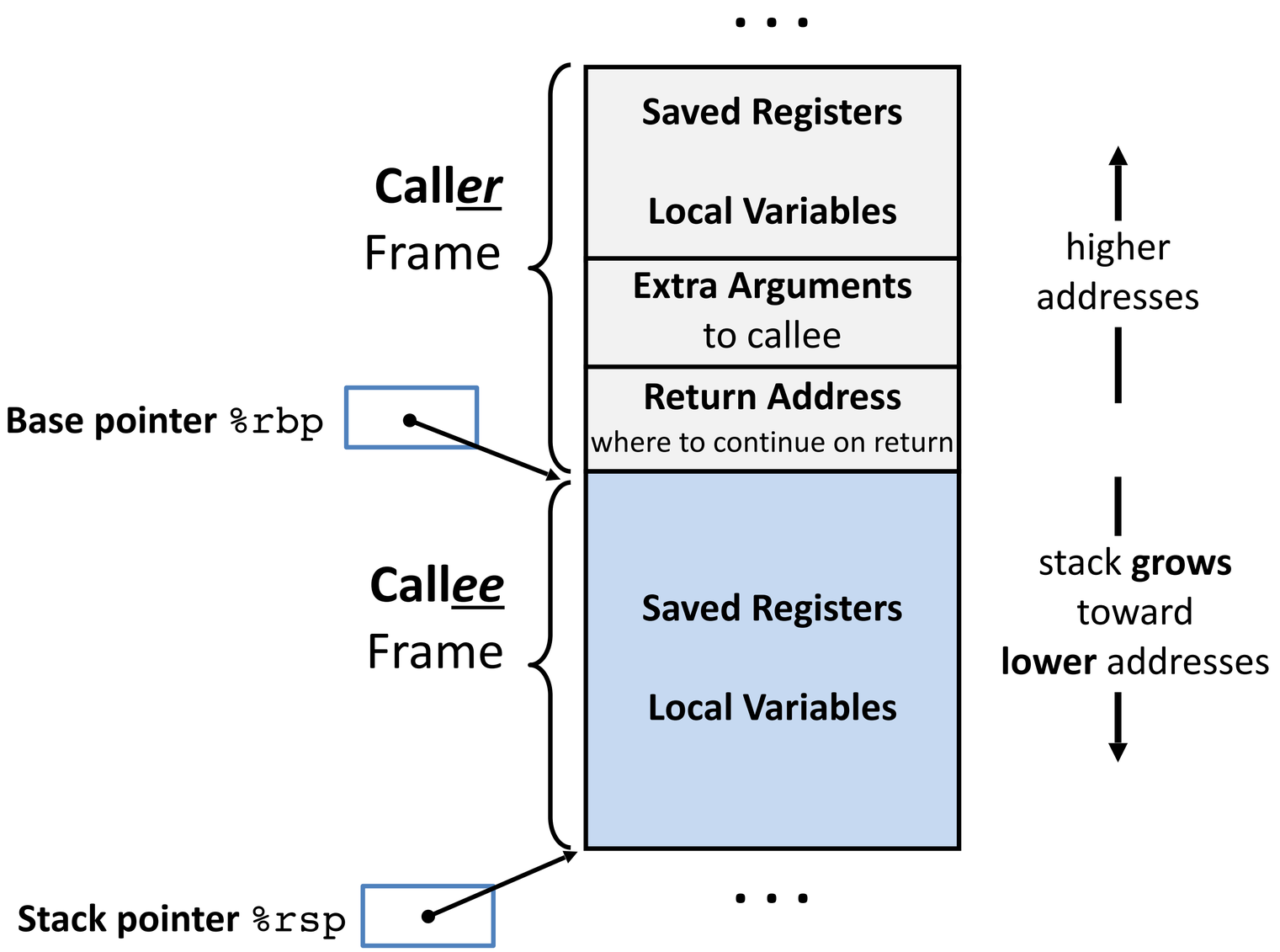


The call stack supports procedures

Stack frame: section of stack used by one procedure *call* to store context while running.

Procedure code manages stack frames explicitly.

- **Setup:** allocate space at start of procedure.
- **Cleanup:** deallocate space before return.



Procedure <u>control flow</u> instructions

Procedure call: `callq` *target*

1. Push return address on stack
2. Jump to *target*

Return address: Address of instruction after `call`.

```
400544: callq  400550 <mult2>
400549: movq   %rax,(%rbx)
```

Procedure return: `retq`

1. Pop return address from stack
2. Jump to return address

Call example

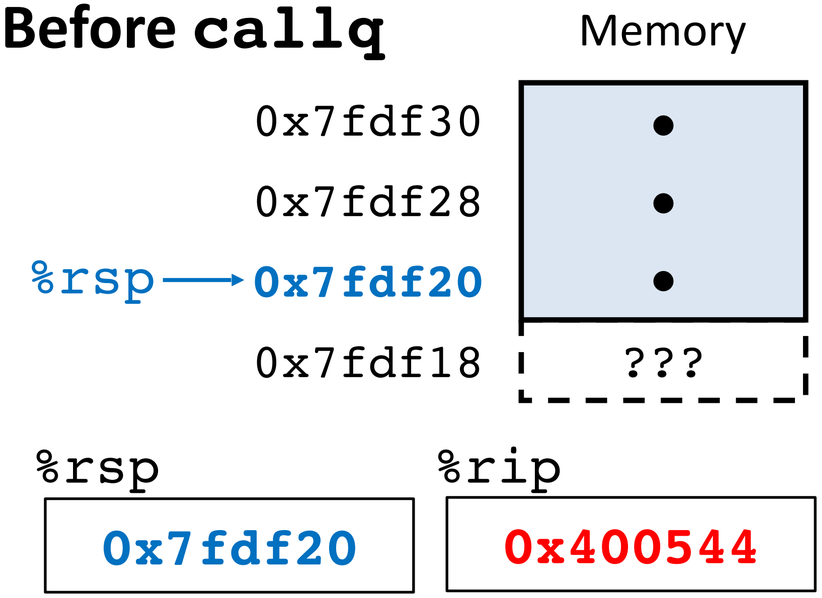
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```


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

`callq` *target*

1. Push return address on stack
2. Jump to *target*

Before `callq`



Call example

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


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

`callq` *target*

1. Push return address on stack
2. Jump to *target*

Before `callq`

Memory

0x7fdf30	•
0x7fdf28	•
%rsp → 0x7fdf20	•
0x7fdf18	???

%rsp	%rip
0x7fdf20	0x400544

After `callq`

Memory

0x7fdf30	•
0x7fdf28	•
0x7fdf20	•
%rsp → 0x7fdf18	0x400549

%rsp	%rip
0x7fdf18	0x400550

Return example

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


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

retq

1. Pop return address from stack
2. Jump to return address

Before `retq`

	Memory
0x7fdf30	•
0x7fdf28	•
0x7fdf20	•
%rsp → 0x7fdf18	0x400549

%rsp	%rip
0x7fdf18	0x400557

Return example

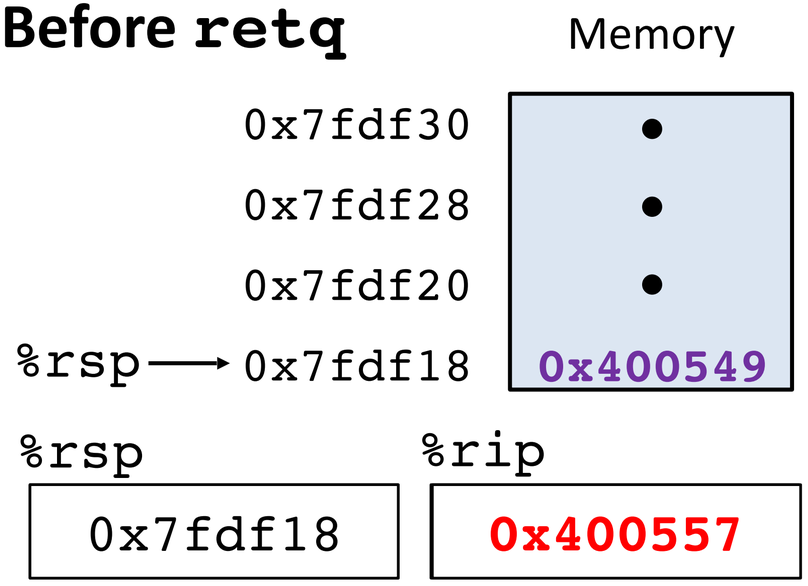
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

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

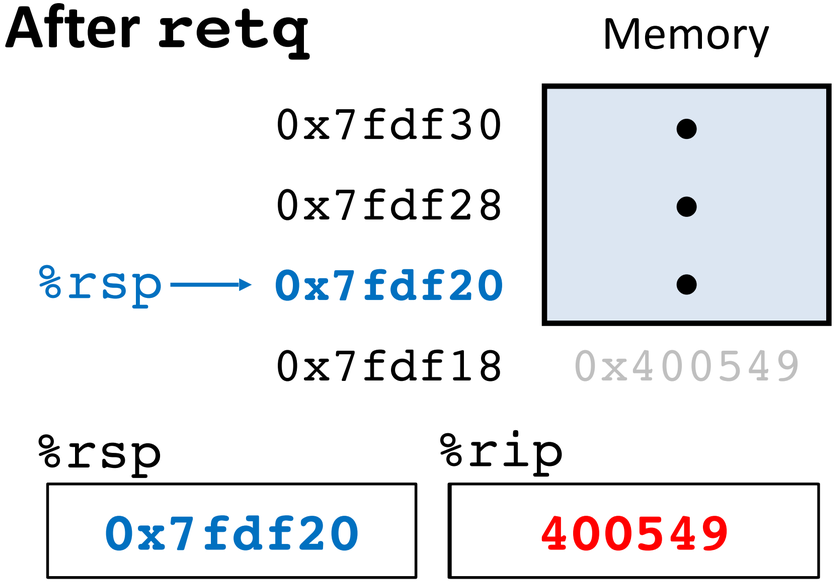
retq

1. Pop return address from stack
2. Jump to return address

Before `retq`



After `retq`



Procedure <u>data flow</u> conventions

Recall:

First 6 arguments: passed in **registers**

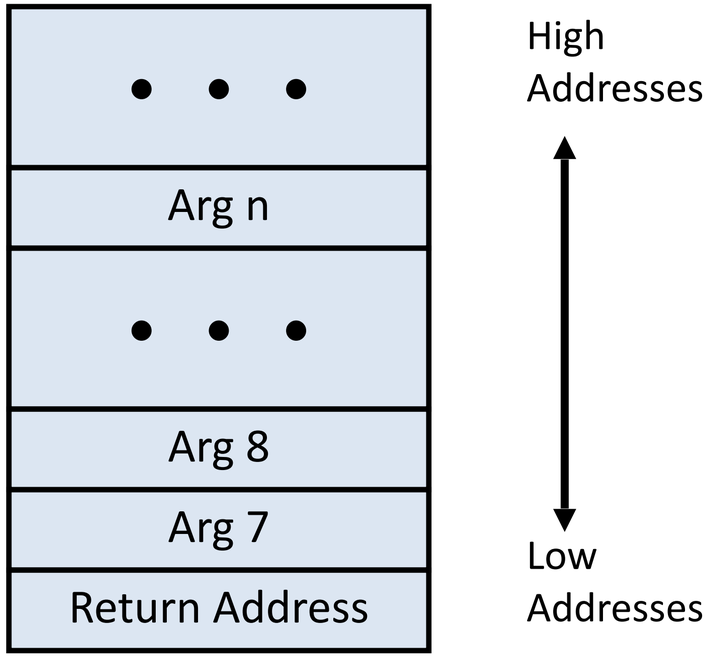
Arg 1	`%rdi`
Arg 2	`%rsi`
Arg 3	`%rdx`
Arg 4	`%rcx`
Arg 5	`%r8`
Arg 6	`%r9`

Diane's
Silk
Dress
Costs
$8 9

Return value: passed in **`%rax`**

`%rax`

Remaining arguments:
passed on **stack** (in memory)



Procedure call / stack frame example

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

Passes address of local variable (in stack).

Uses memory through pointer.

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```

```
long increment(long* p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

Procedure call example (step 0)

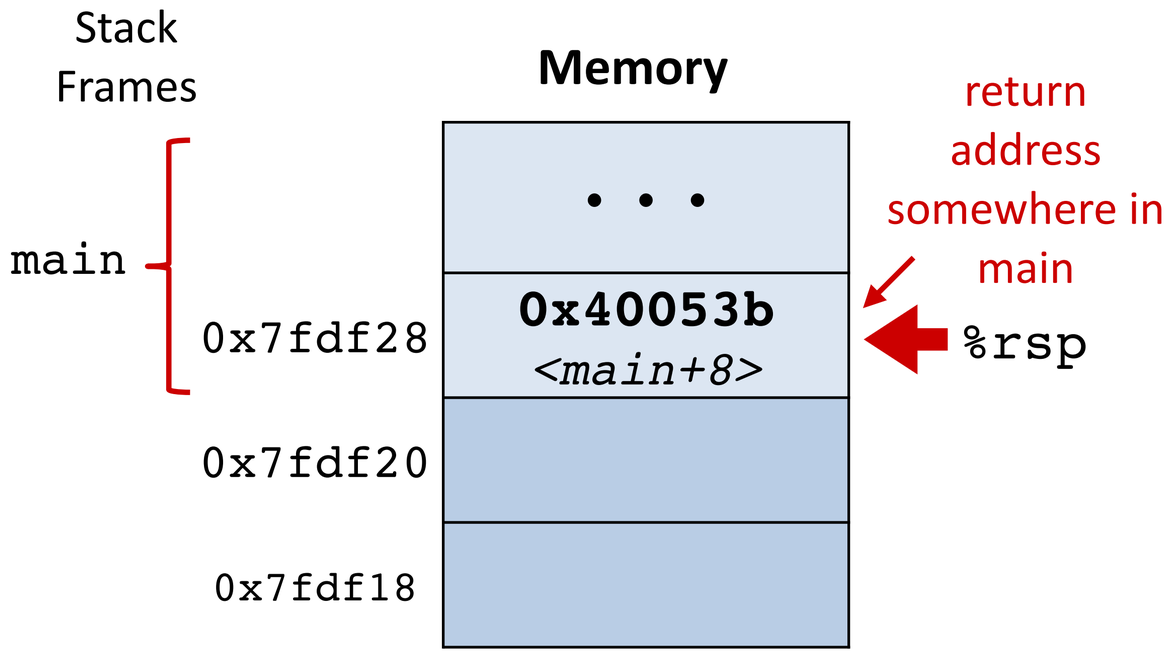
```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

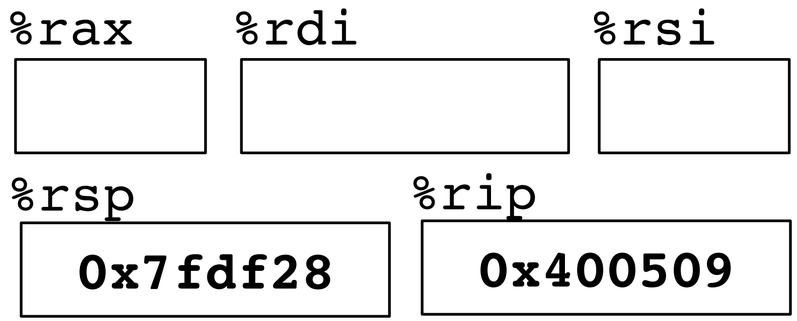
red line shows %rip

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```

main called step_up





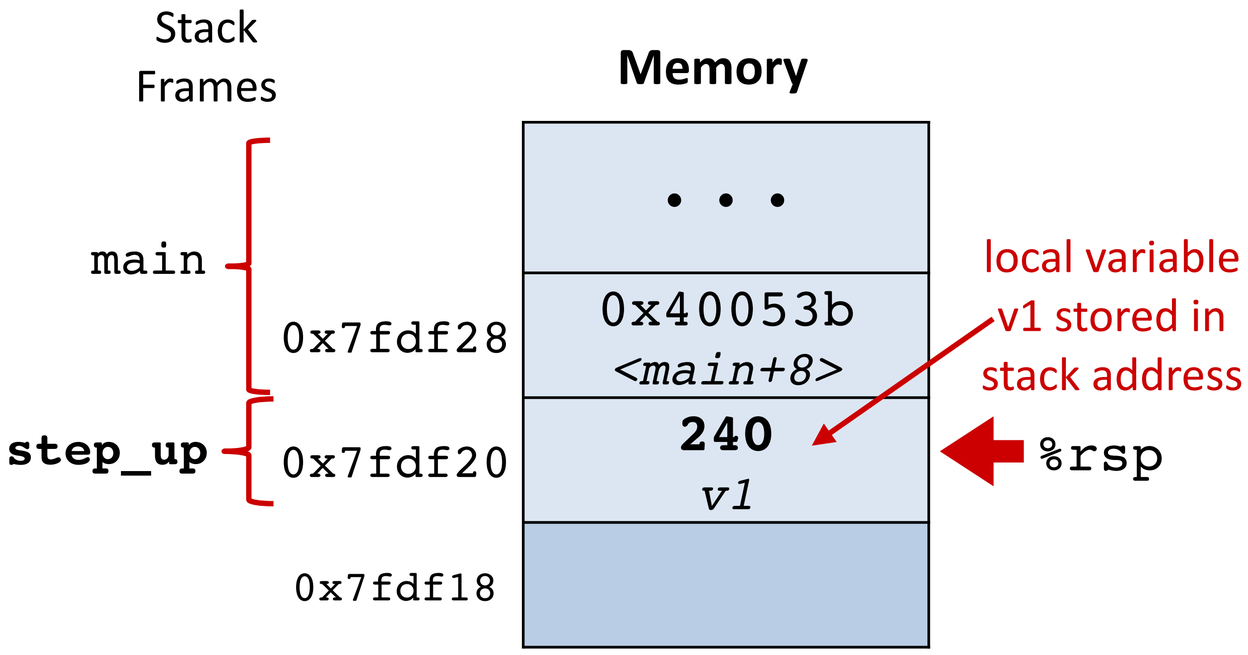
Procedure call example (step 1)

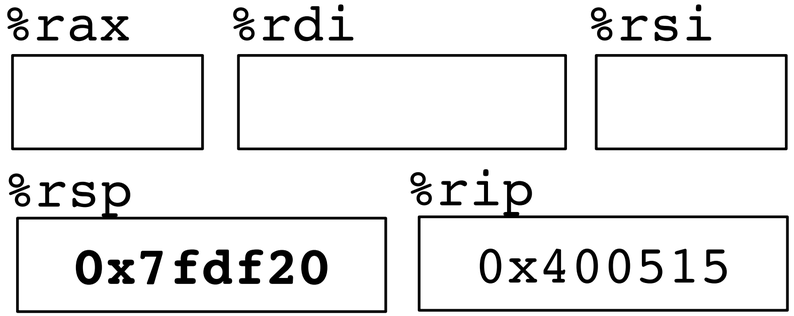
Allocate space
for local vars

```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```





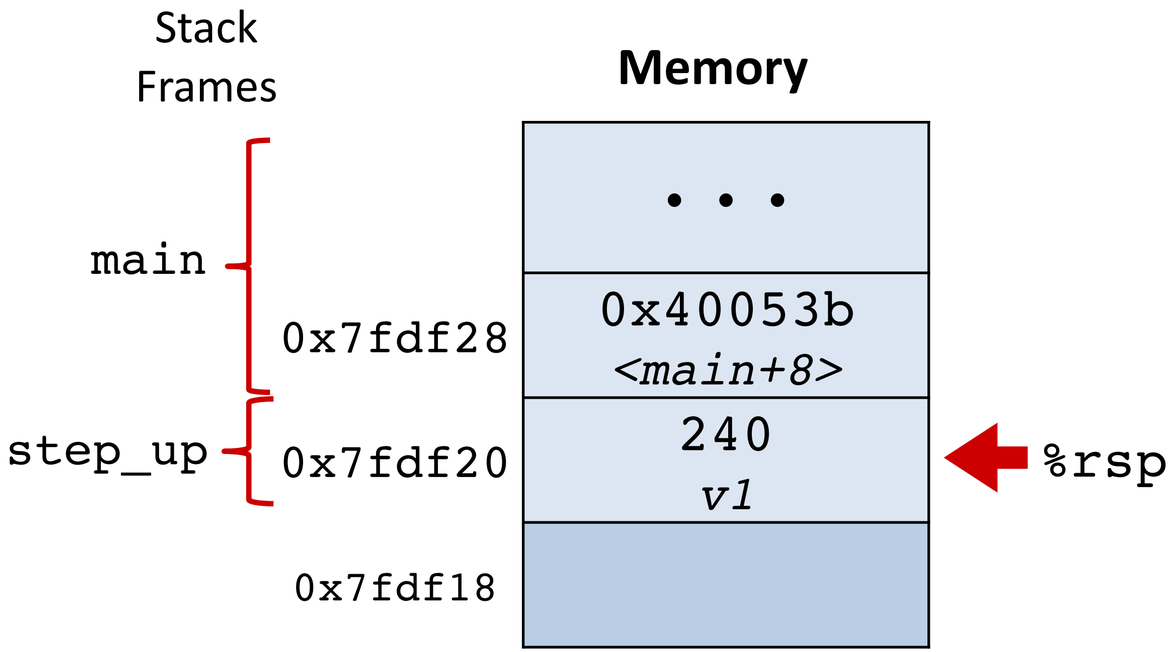
Procedure call example (step 2)

Set up args for call to `increment`

```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```



Place args in registers before call

Move the two args to the right registers

%rax	%rdi	%rsi

%rsp	%rip
0x7fdf20	0x40051d

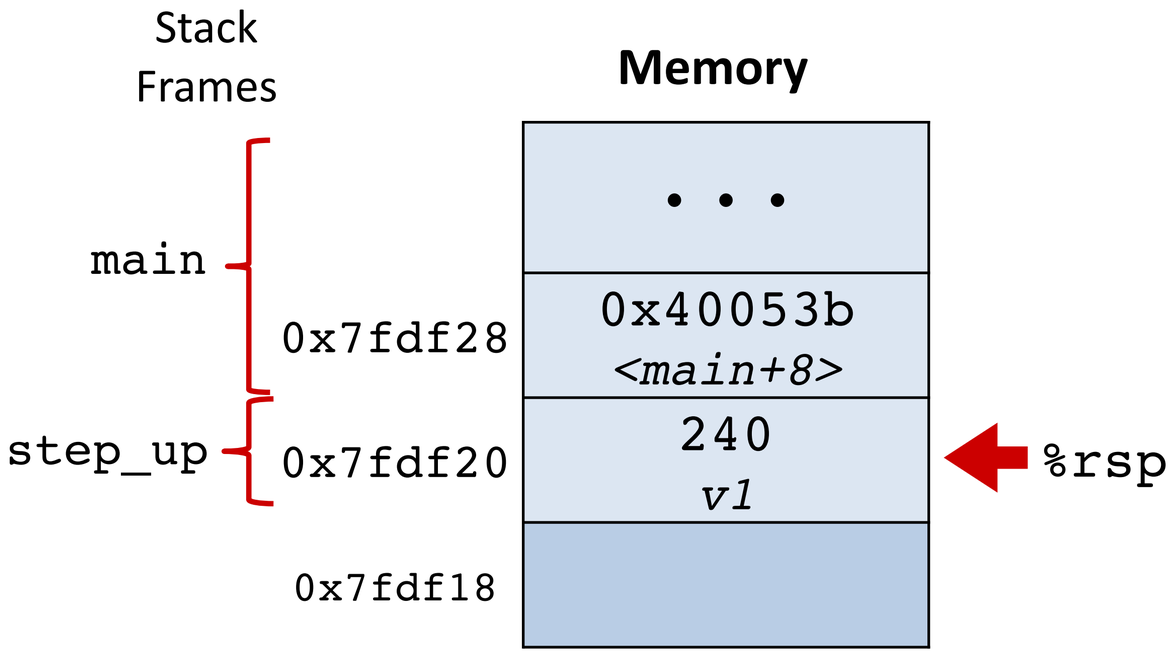
Procedure call example (step 2)

Set up args for call to `increment`

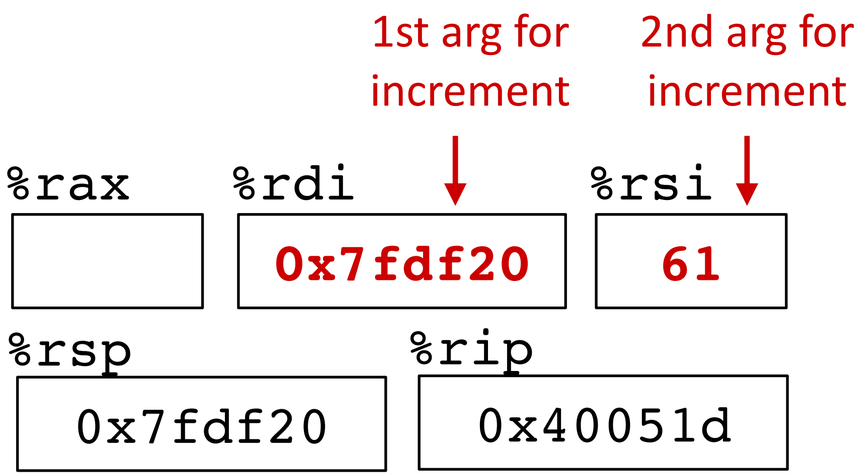
```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```



Place args in registers before call



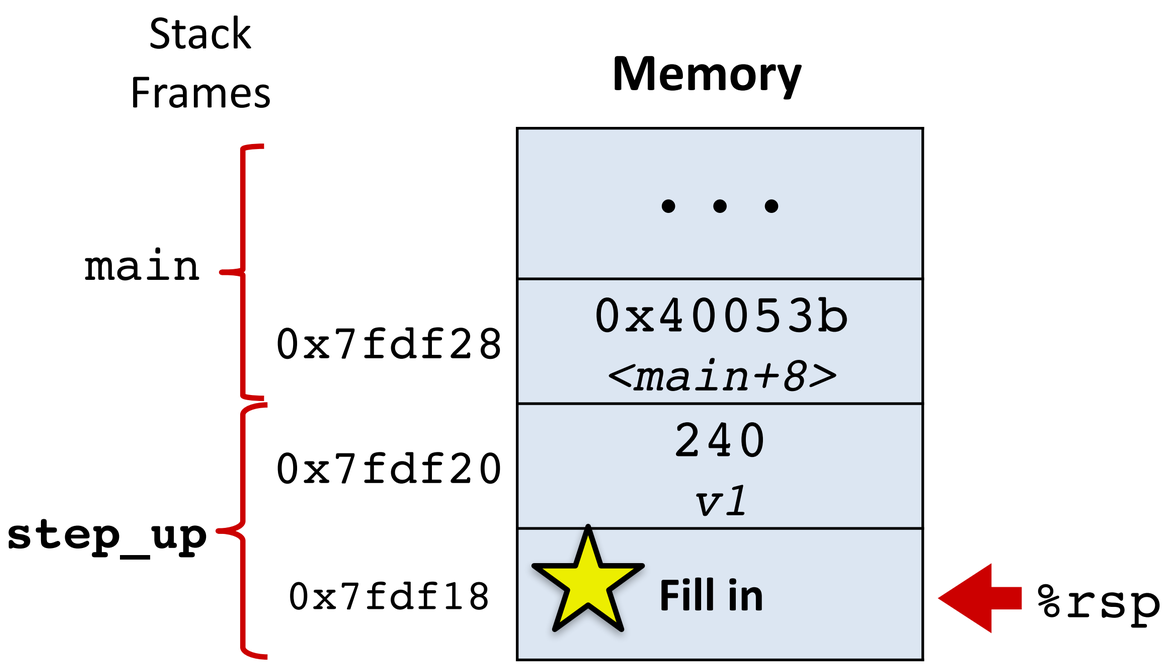
Procedure call example (step 3)

Call `increment`

```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

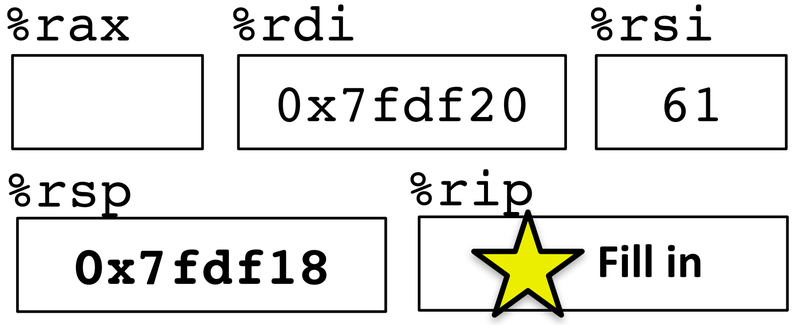
```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```



`call` has two steps

(1) Push return address on stack

(2) Jump to target



Procedure call example (step 3)

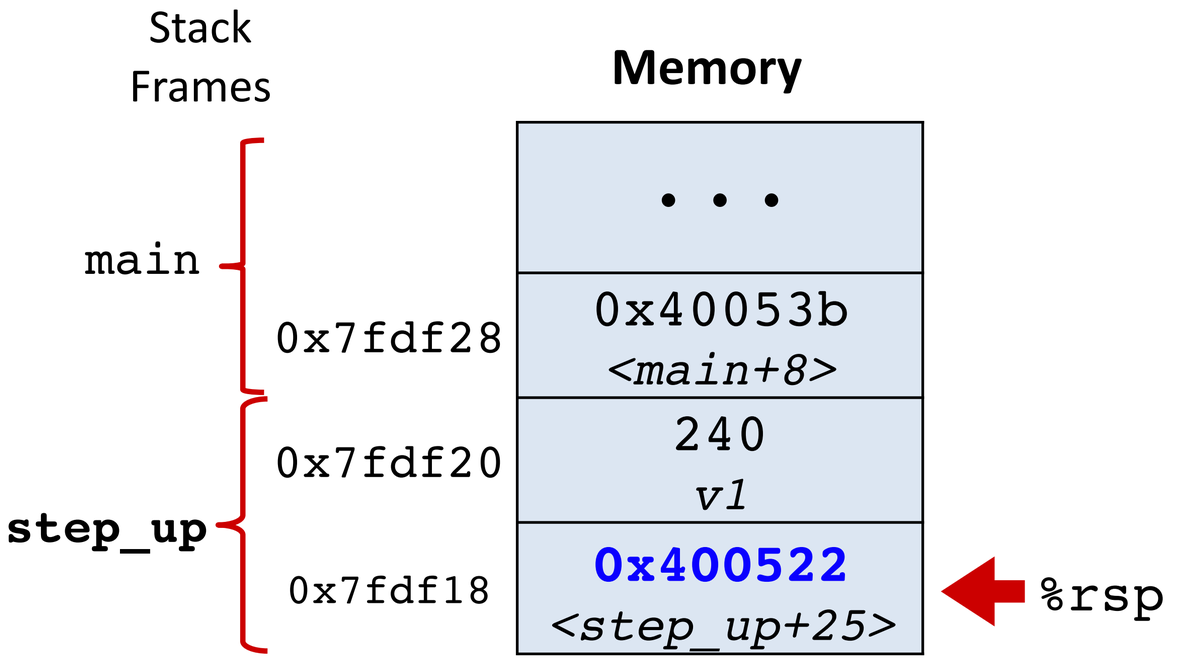
Call `increment`

```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```

(2) Jump to target



`call` has two steps

(1) Push return address on stack

%rax	%rdi	%rsi
	0x7fdf20	61

%rsp	%rip
0x7fdf18	0x4004cd

Procedure call example (step 4)

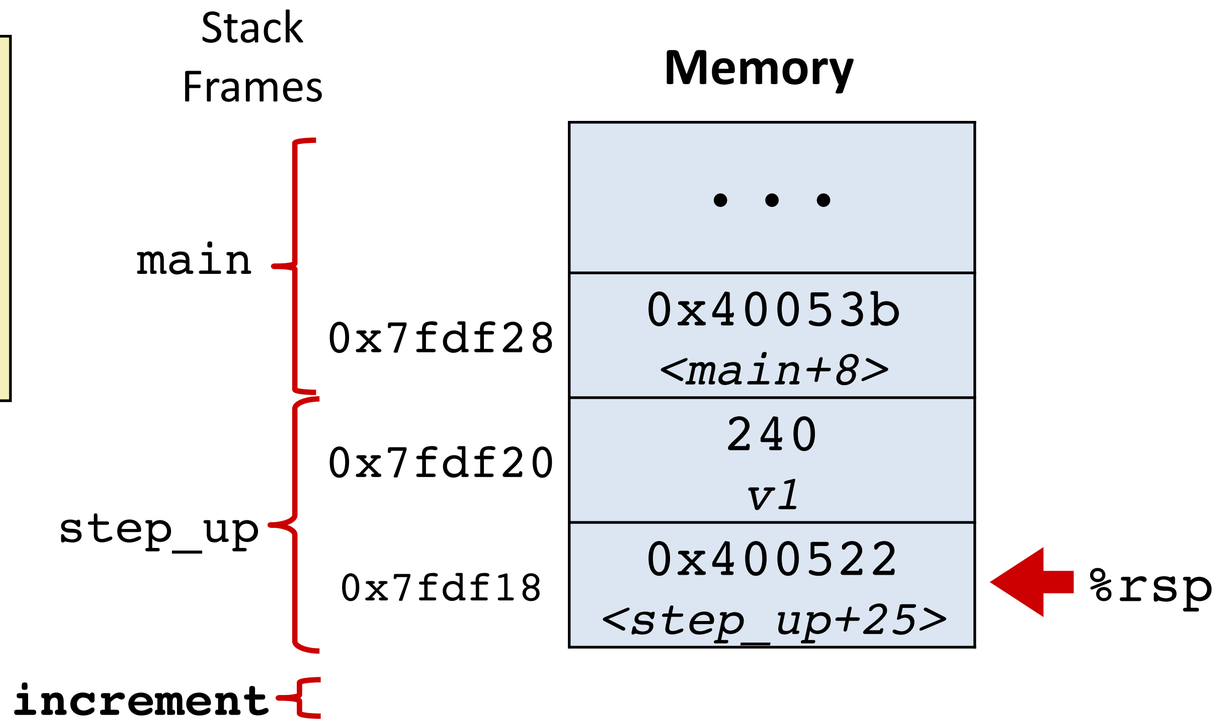
Run `increment`

```
long increment(long* p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```

Execute these 3 instructions



%rax	%rdi	%rsi
	0x7fdf20	61

%rsp	%rip
0x7fdf18	0x4004d6

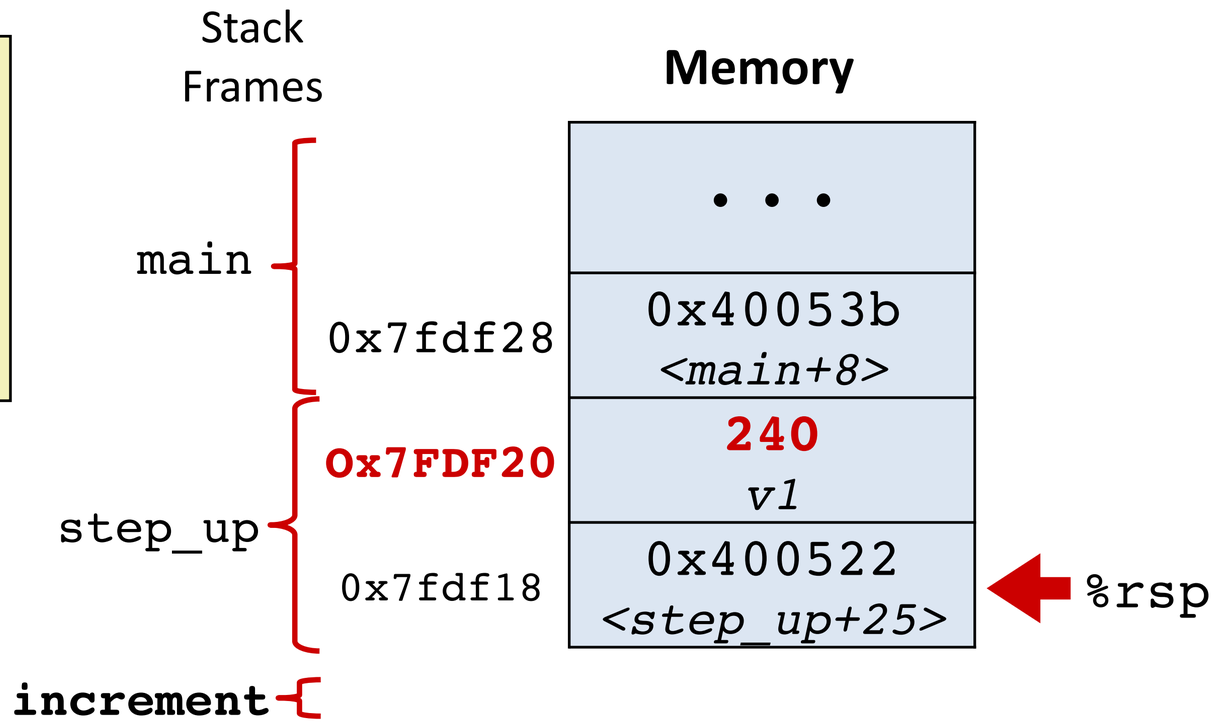
Procedure call example (step 4)

Run `increment`

```
long increment(long* p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```



%rax	%rdi	%rsi
240	0x7fdf20	61

%rsp	%rip
0x7fdf18	0x4004d0

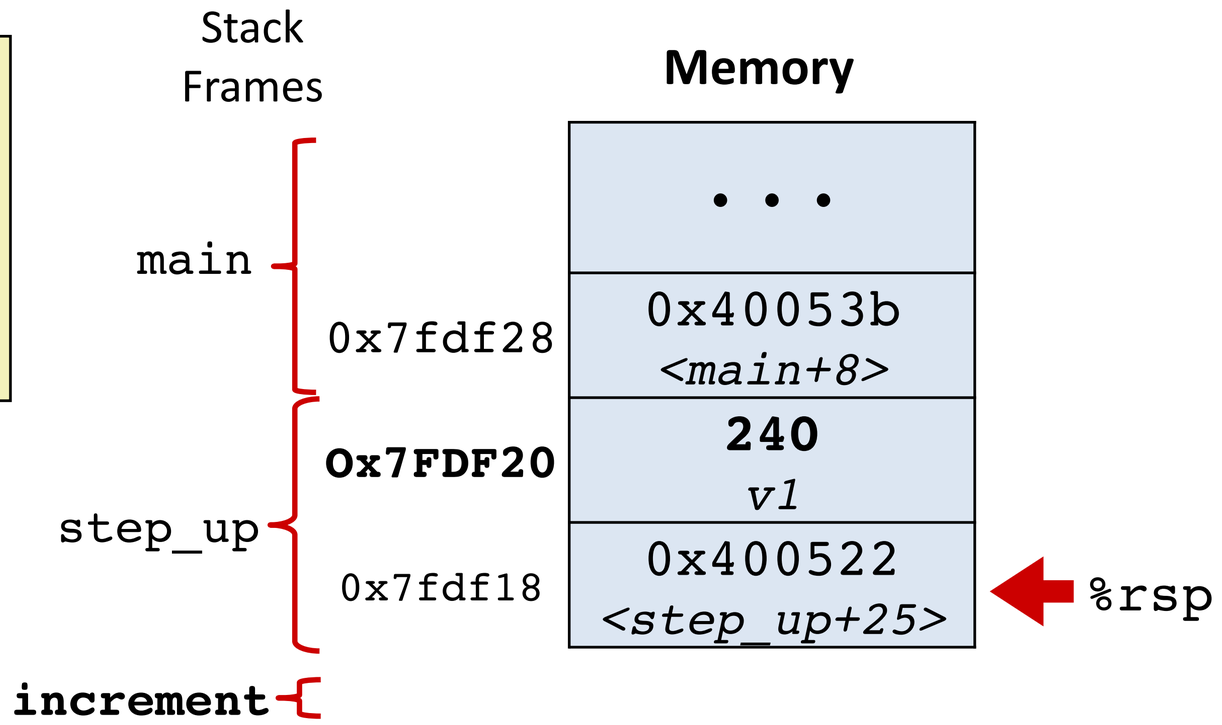
Procedure call example (step 4)

Run `increment`

```
long increment(long* p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```



%rax	%rdi	%rsi
240	0x7fdf20	301

%rsp	%rip
0x7fdf18	0x4004d3

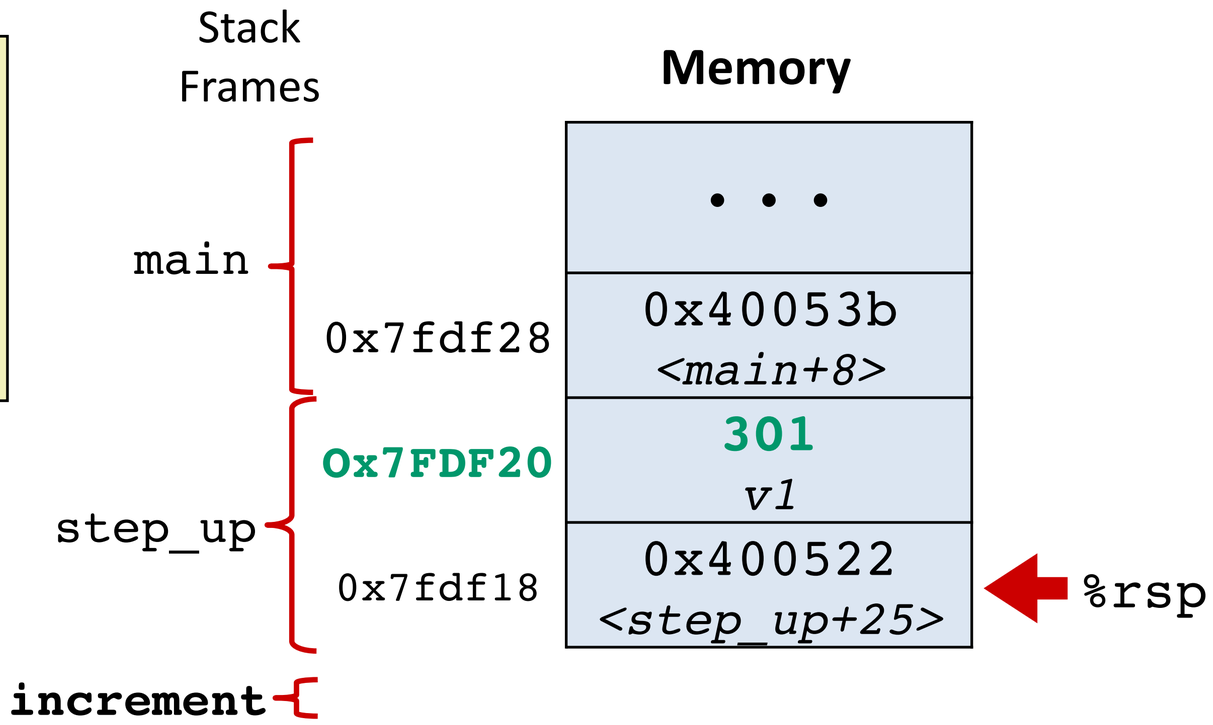
Procedure call example (step 4)

Run `increment`

```
long increment(long* p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```



%rax	%rdi	%rsi
240	0x7fdf20	301

%rsp	%rip
0x7fdf18	0x4004d6

Procedure call example (step 5a)

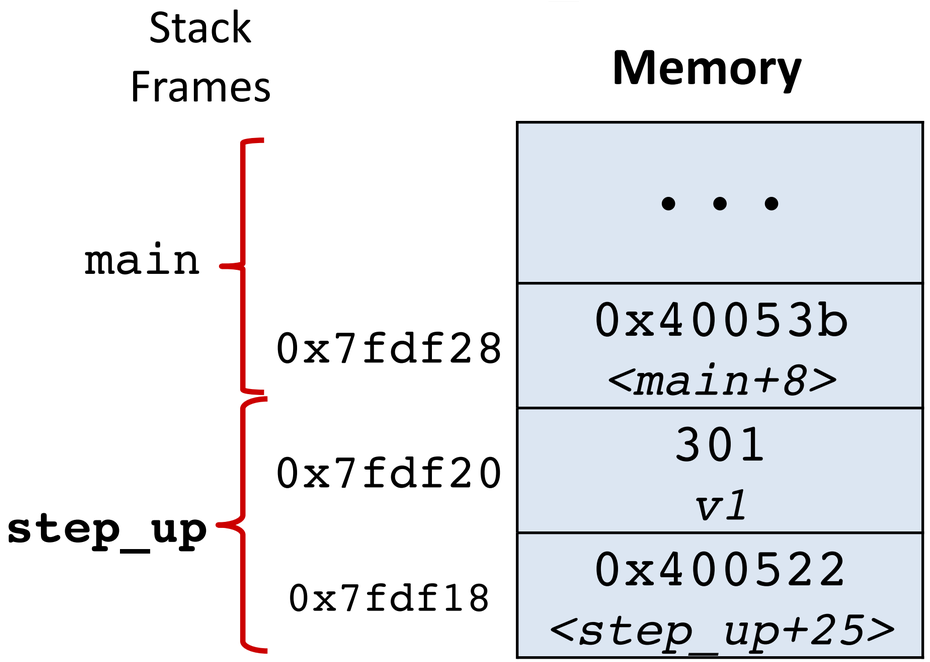
```
long increment(long* p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```

Execute ret

Return from `increment` to `step_up`



ret has two steps
(1) pop return address from stack
(2) jump to return address

%rax	%rdi	%rsi
240	0x7fdf20	301

%rsp	%rip
0x7fdf18	0x4004d6

Procedure call example (step 5a)

```
long increment(long* p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

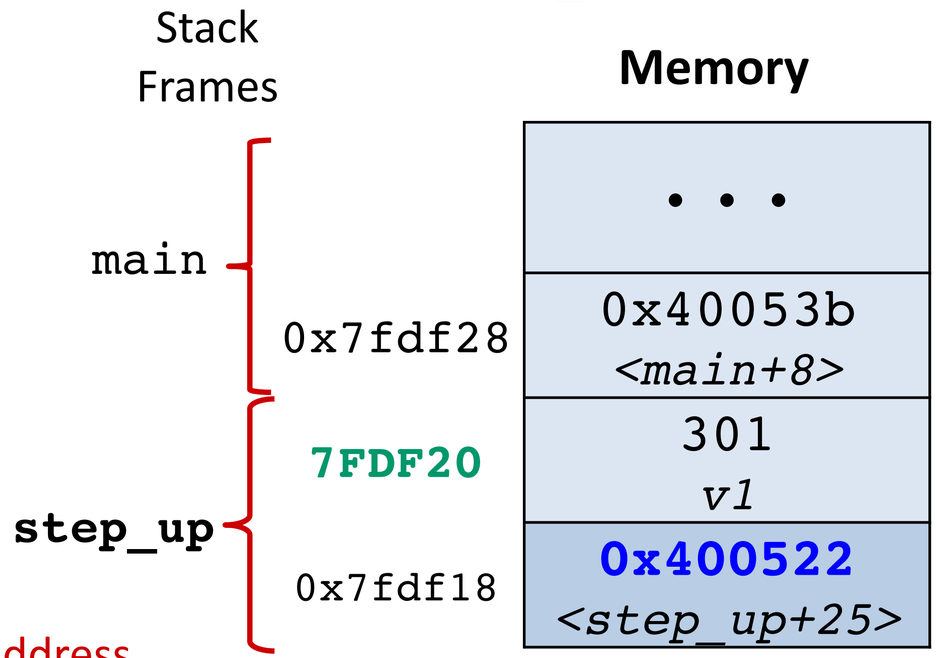
```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

(2) jump to return address

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```

`ret` has two steps

Return from `increment` to `step_up`



(1) pop return address from stack

%rax	%rdi	%rsi
240	0x7fdf20	301

%rsp	%rip
0x7fdf20	0x400522

Procedure call example (step 6)

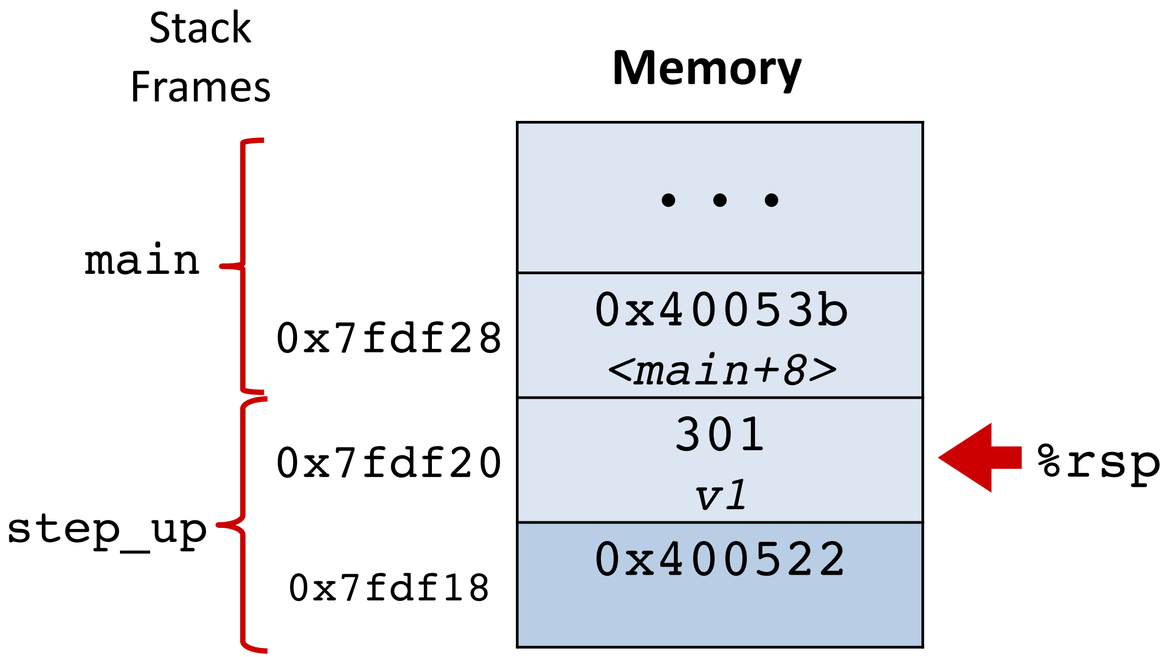
Prepare `step_up` result

```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

Execute this instruction

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```



%rax	%rdi	%rsi
240	0x7fdf20	301

%rsp	%rip
0x7fdf20	0x400526

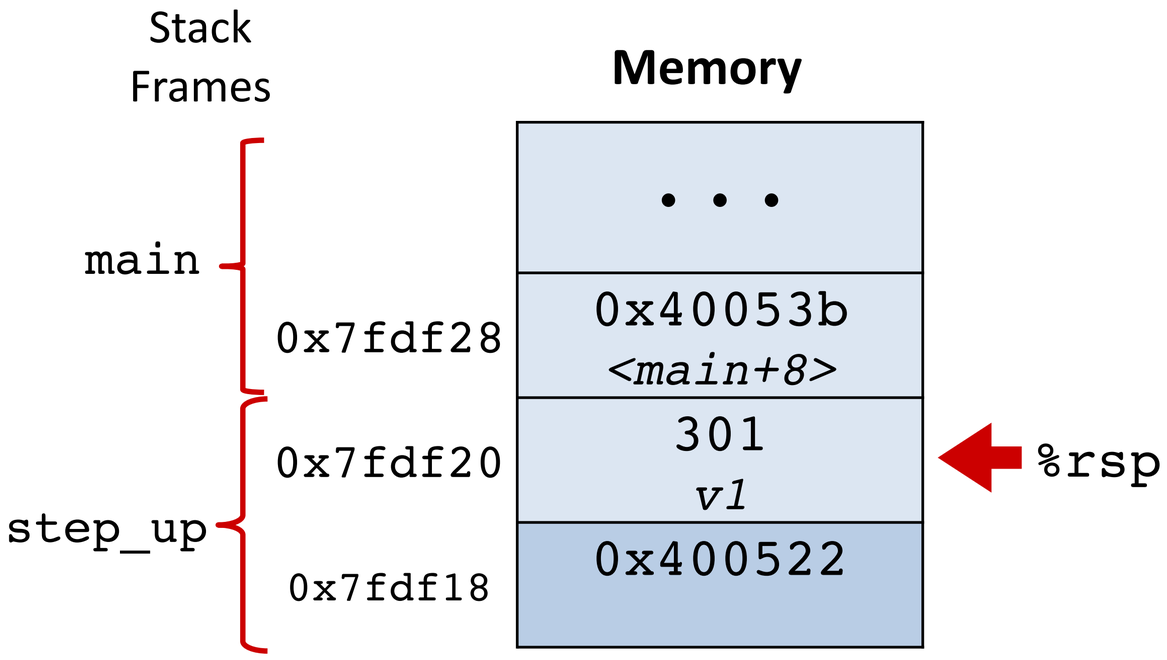
Procedure call example (step 6)

Prepare `step_up` result

```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```



	%rax	%rdi	%rsi
add	541	0x7fdf20	301

%rsp	%rip
0x7fdf20	0x400526

Procedure call example (step 7)

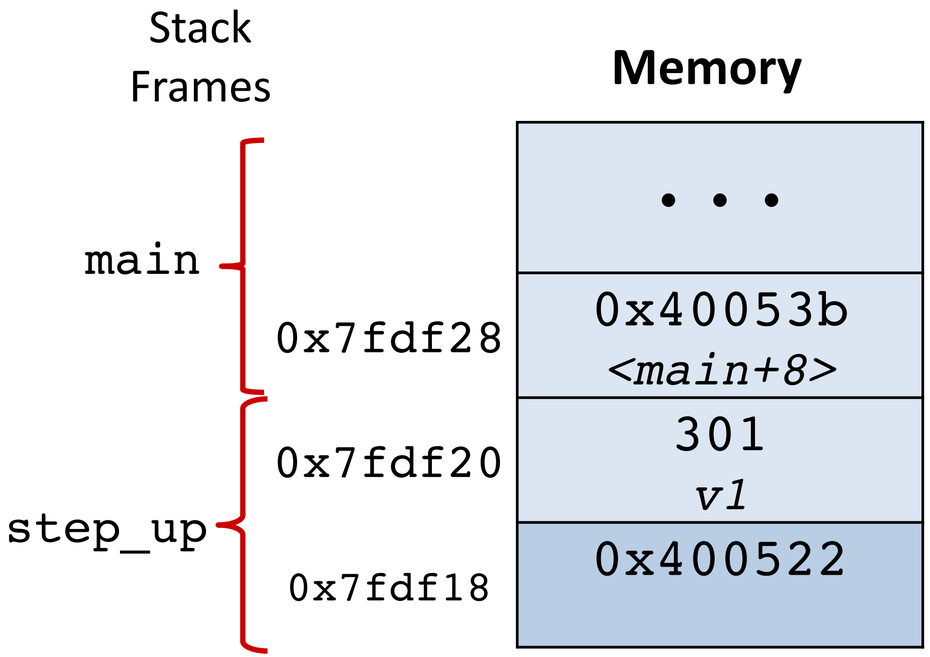
Deallocate space
for local vars

```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

Execute this instruction

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```



%rax	%rdi	%rsi
541	0x7fdf20	301

%rsp	%rip
0x7fdf20	0x400526

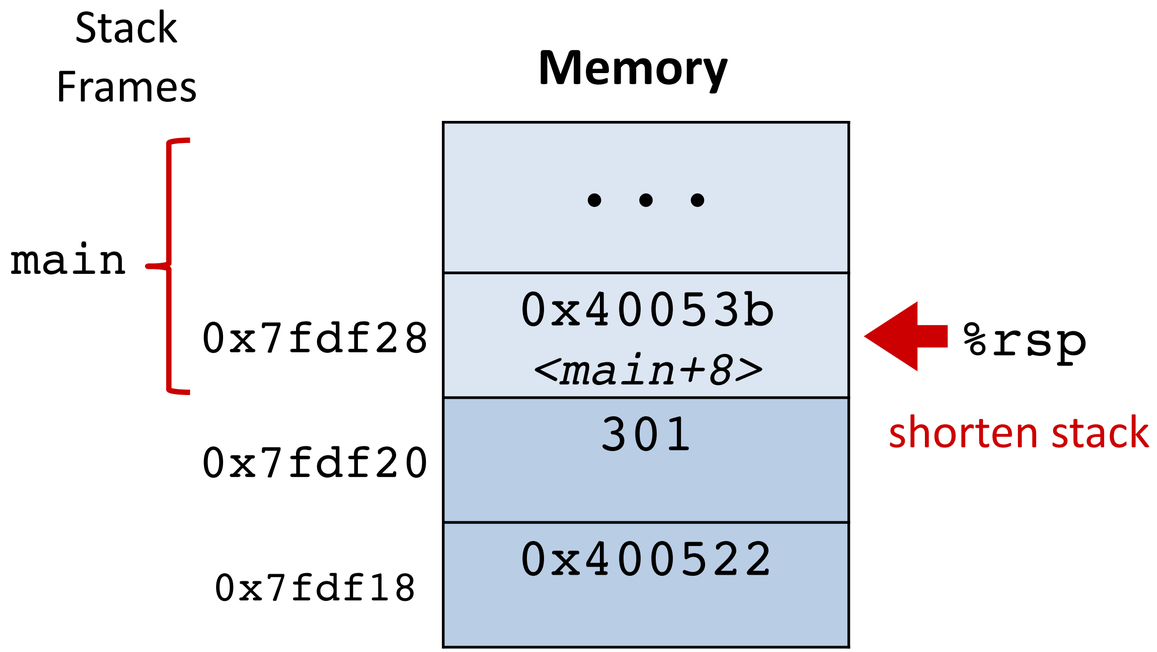
Procedure call example (step 7)

```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```

Deallocate space for local vars



%rax	%rdi	%rsi
541	0x7fdf20	301

%rsp	%rip
0x7fdf28	0x400526

higher address

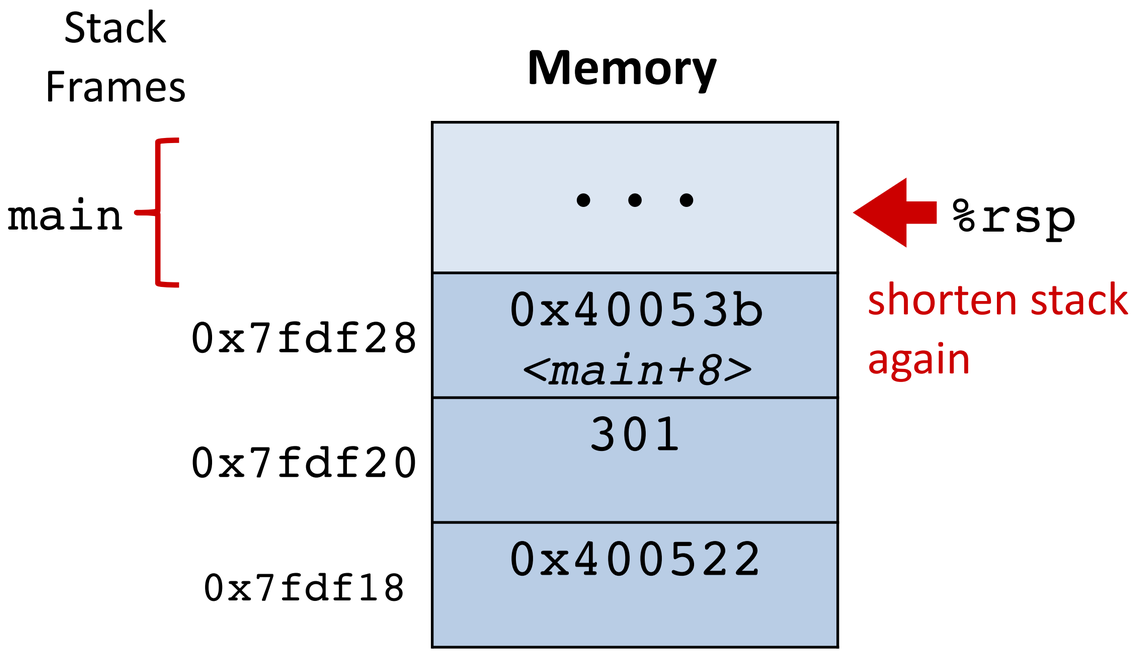
Procedure call example (step 8)

```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```

Return from `step_up` to `main`



%rax	%rdi	%rsi
541	0x7fdf20	301

%rsp	%rip
0x7fdf30	**0x40053b**

Implementing procedures

Have we now seen how this is done?

1. How does a caller pass arguments to a procedure? ✓
2. How does a caller receive a return value from a procedure? ✓
3. How does a procedure know where to return (what code to execute next when done)? ✓
4. Where does a procedure store local variables? ✓
5. How do procedures share limited registers and memory? ??

Register saving conventions

yoo calls who:

Caller ***Callee***

```
yoo(…) {
  • • •
  who();
  • • •
}
```

Will register contents still be there after a procedure call?

```
yoo:
    • • •
  movq $12345, %rbx
  call who
  addq %rbx, %rax
    • • •
  ret
```

?

```
who:
    • • •
  addq %rdi, %rbx
    • • •
  ret
```

Conventions:

Caller Save

Callee Save

x86-64 register conventions

`%rax`	Return value – Caller saved
`%rbx`	**Callee** saved
`%rcx`	Argument #4 – Caller saved
`%rdx`	Argument #3 – Caller saved
`%rsi`	Argument #2 – Caller saved
`%rdi`	Argument #1 – Caller saved
`%rsp`	Stack pointer
`%rbp`	**Callee** saved

`%r8`	Argument #5 – Caller saved
`%r9`	Argument #6 – Caller saved
`%r10`	Caller saved
`%r11`	Caller Saved
`%r12`	**Callee** saved
`%r13`	**Callee** saved
`%r14`	**Callee** saved
`%r15`	**Callee** saved

Callee-save example (step 0)

Similar function, but now takes an arg for the local variable

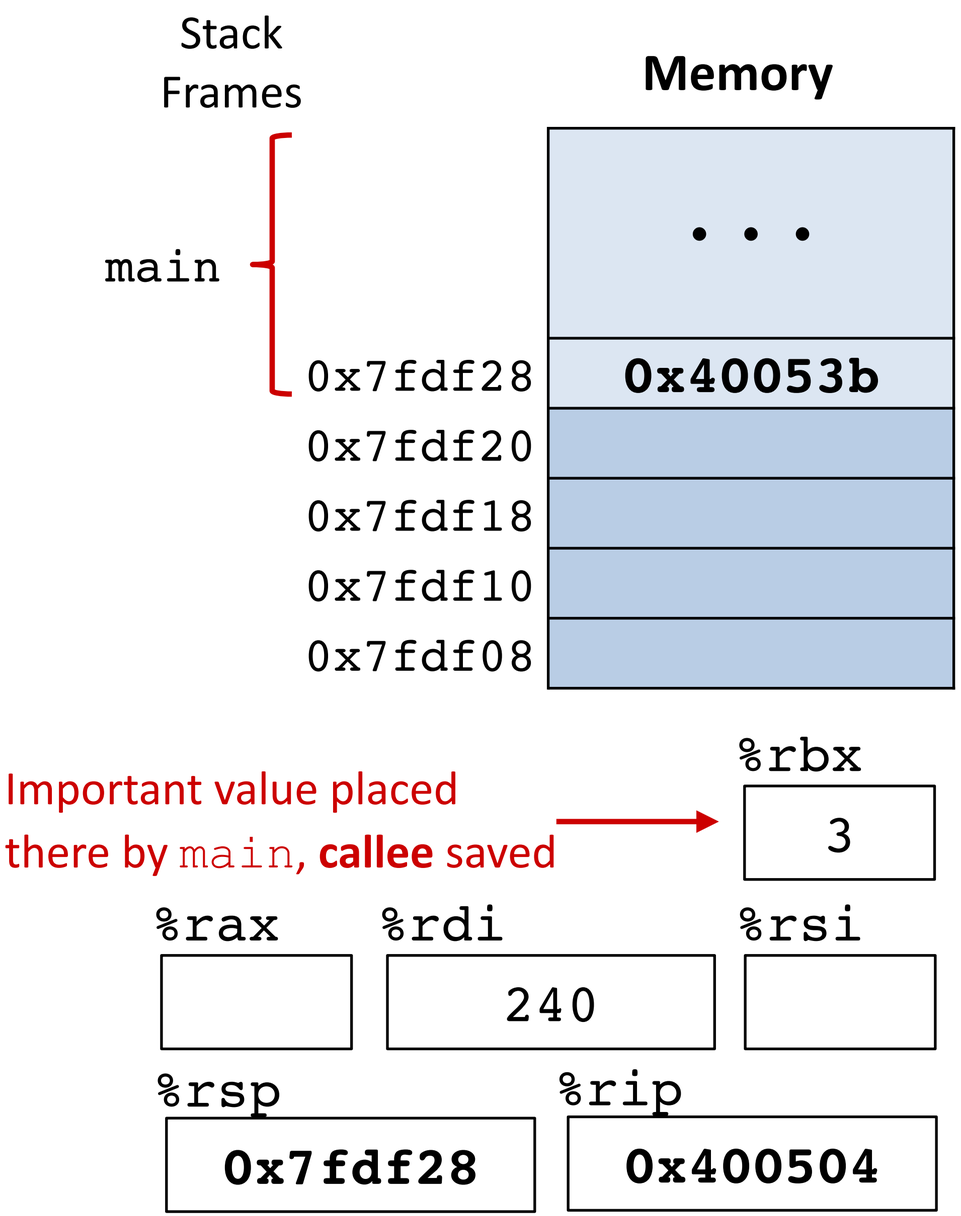
```
long step_by(long x) {
    long v1 = x;
    long v2 = increment(&v1, 61);
    return x + v2;
}
```

```
step_by:
400504:  pushq %rbx
400506:  movq  %rdi, %rbx
400509:  subq  $16, %rsp
40050d:  movq  %rdi, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  %rbx, %rax
400525:  addq  $16, %rsp
400529:  popq  %rbx
40052b:  retq
```

caller saved: `%rax, %rdi, %rsi`

callee saved: `%rbx`

`main` called `step_by(240)`



Callee-save example (step 1)

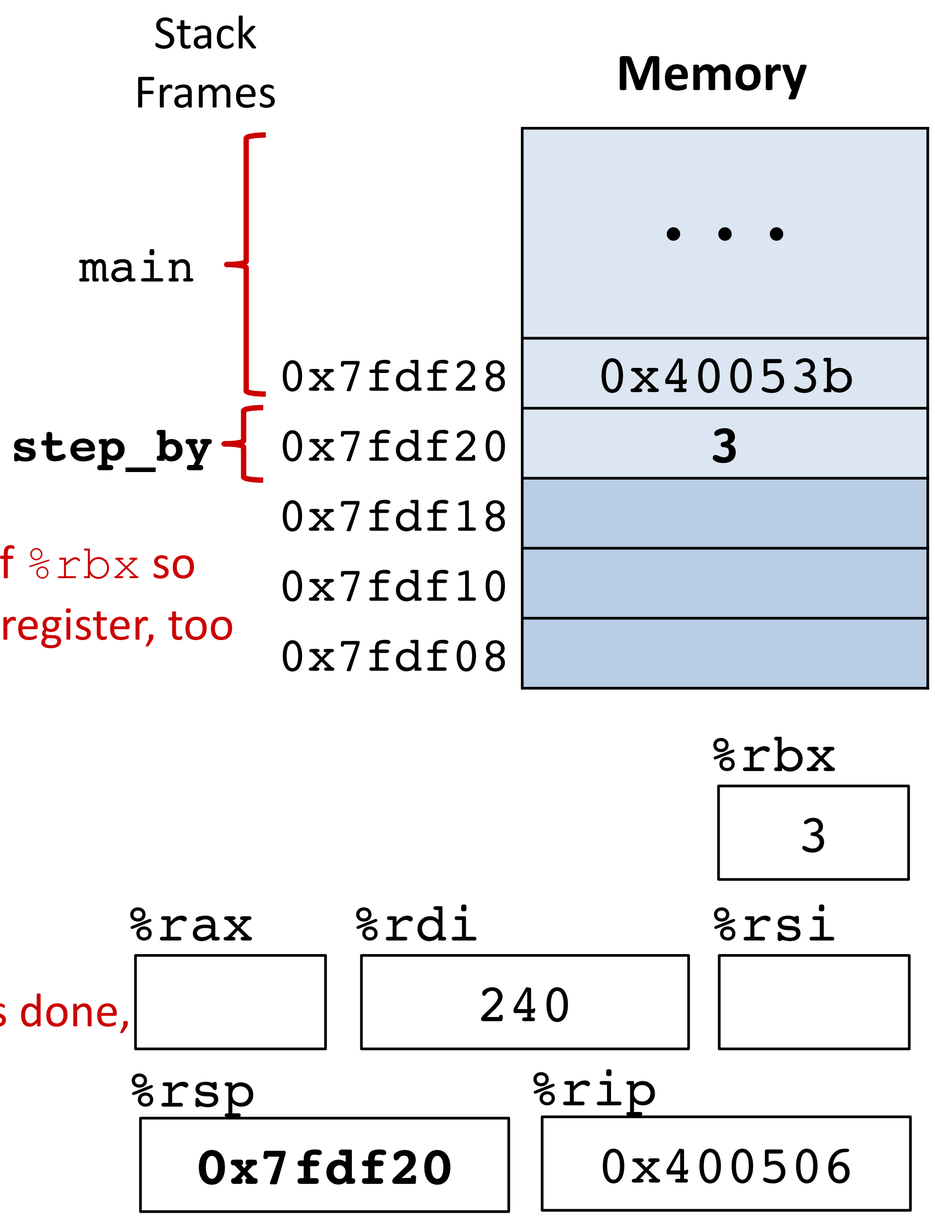
Save register %rbx

```
long step_by(long x) {
    long v1 = x;
    long v2 = increment(&v1, 61);
    return x + v2;
}
```

```
step_by:
400504:  pushq %rbx
400506:  movq  %rdi, %rbx
400509:  subq  $16, %rsp
40050d:  movq  %rdi, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  %rbx, %rax
400525:  addq  $16, %rsp
400529:  popq  %rbx
40052b:  retq
```

Save the value of %rbx so we can use that register, too

Once this function is done, restore saved value



caller saved: %rax, %rdi, %rsi

callee saved: %rbx

Callee-save example (step 2)

```
long step_by(long x) {
    long v1 = x;
    long v2 = increment(&v1, 61);
    return x + v2;
}
```

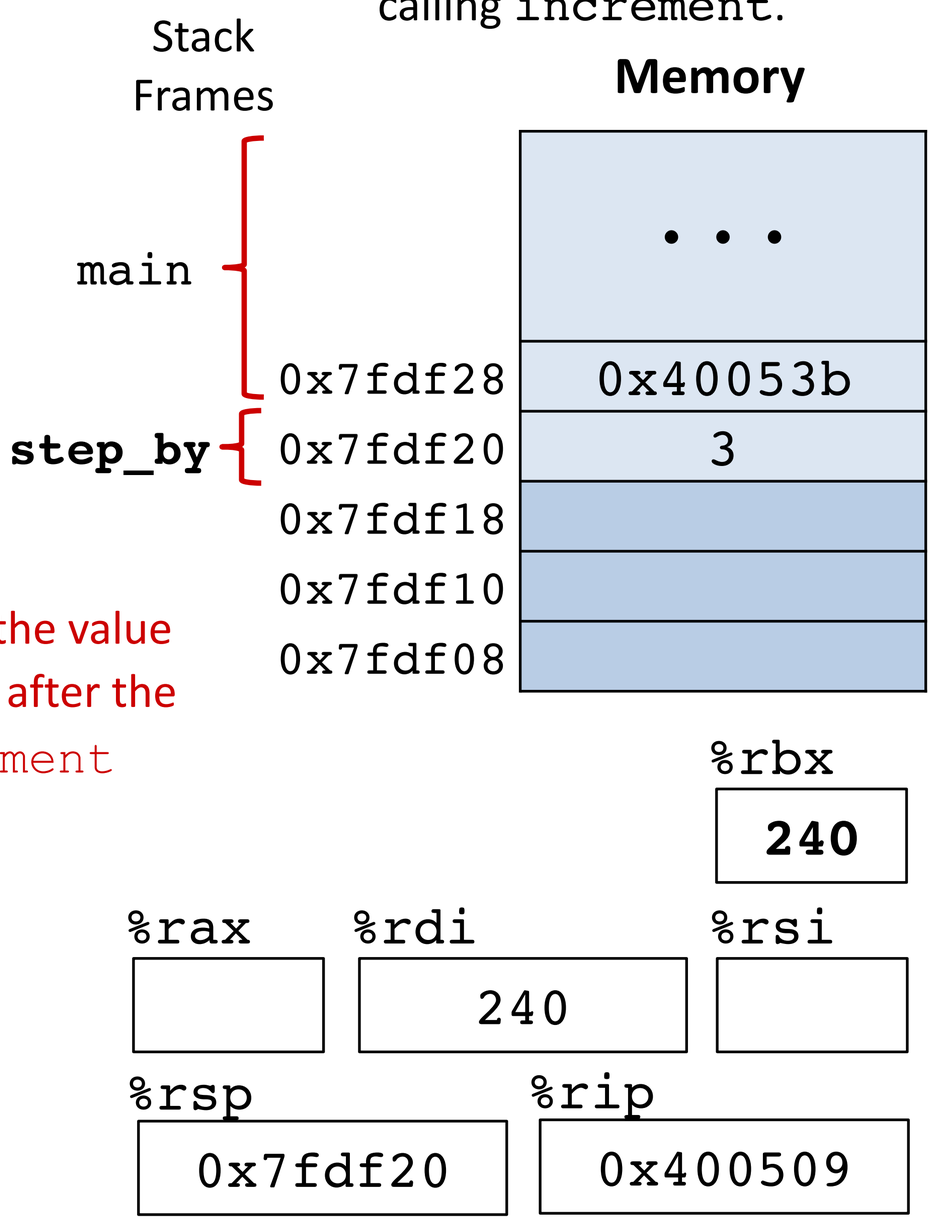
```
step_by:
400504:  pushq %rbx
400506:  movq  %rdi, %rbx
400509:  subq  $16, %rsp
40050d:  movq  %rdi, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  %rbx, %rax
400525:  addq  $16, %rsp
400529:  popq  %rbx
40052b:  retq
```

Need to save the value `x` to use later, after the call to `increment`

caller saved: `%rax, %rdi, %rsi`

callee saved: `%rbx`

Copy argument `x` to `%rbx` for continued use after calling `increment`.



Callee-save example (step 3)

```
long step_by(long x) {
    long v1 = x;
    long v2 = increment(&v1, 61);
    return x + v2;
}
```

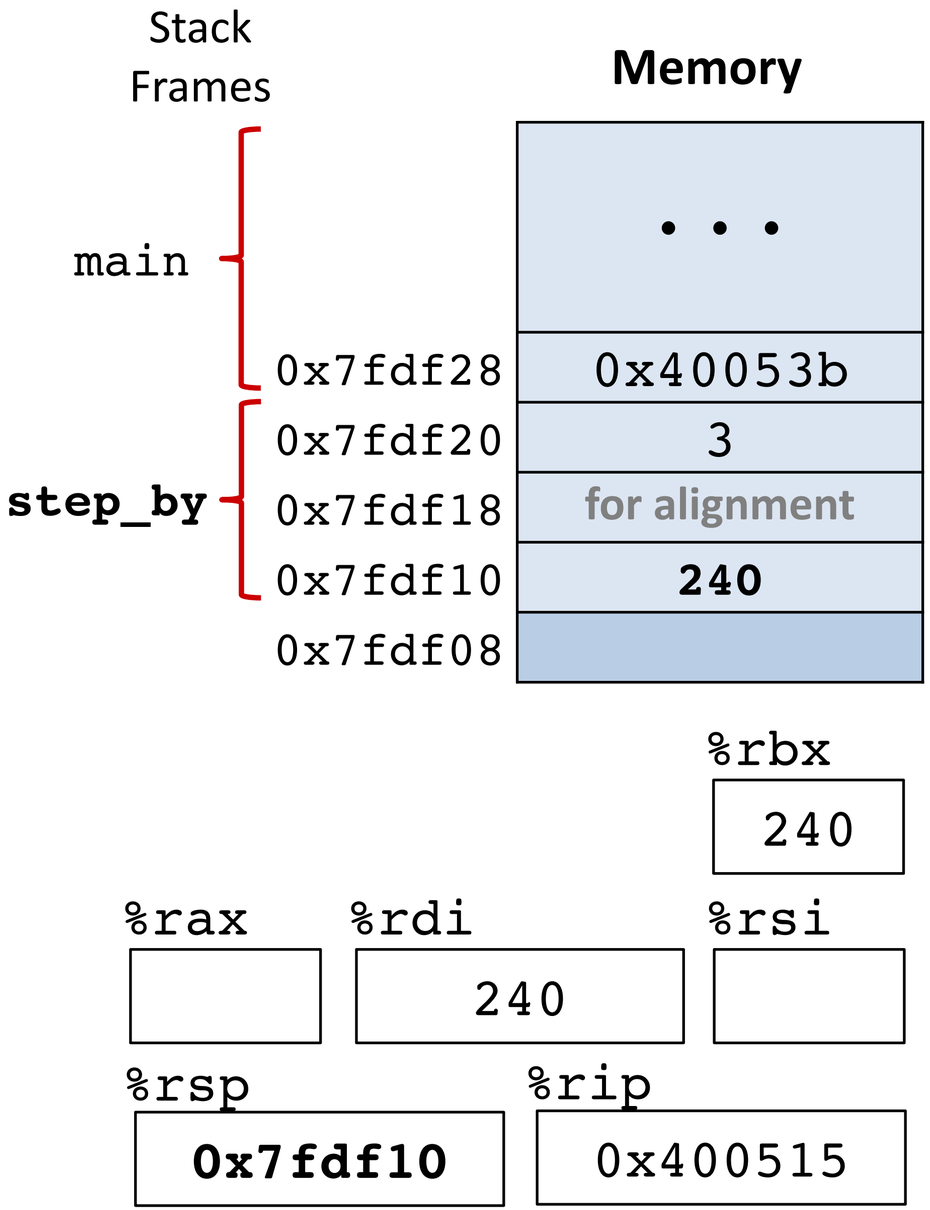
```
step_by:
400504:  pushq %rbx
400506:  movq  %rdi, %rbx
400509:  subq  $16, %rsp
40050d:  movq  %rdi, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  %rbx, %rax
400525:  addq  $16, %rsp
400529:  popq  %rbx
40052b:  retq
```

caller saved: `%rax, %rdi, %rsi`

callee saved: `%rbx`

Set up stack frame

Initialize `v1`



Convention: at call, %rsp must be a multiple of 16

Callee-save example (step 4)

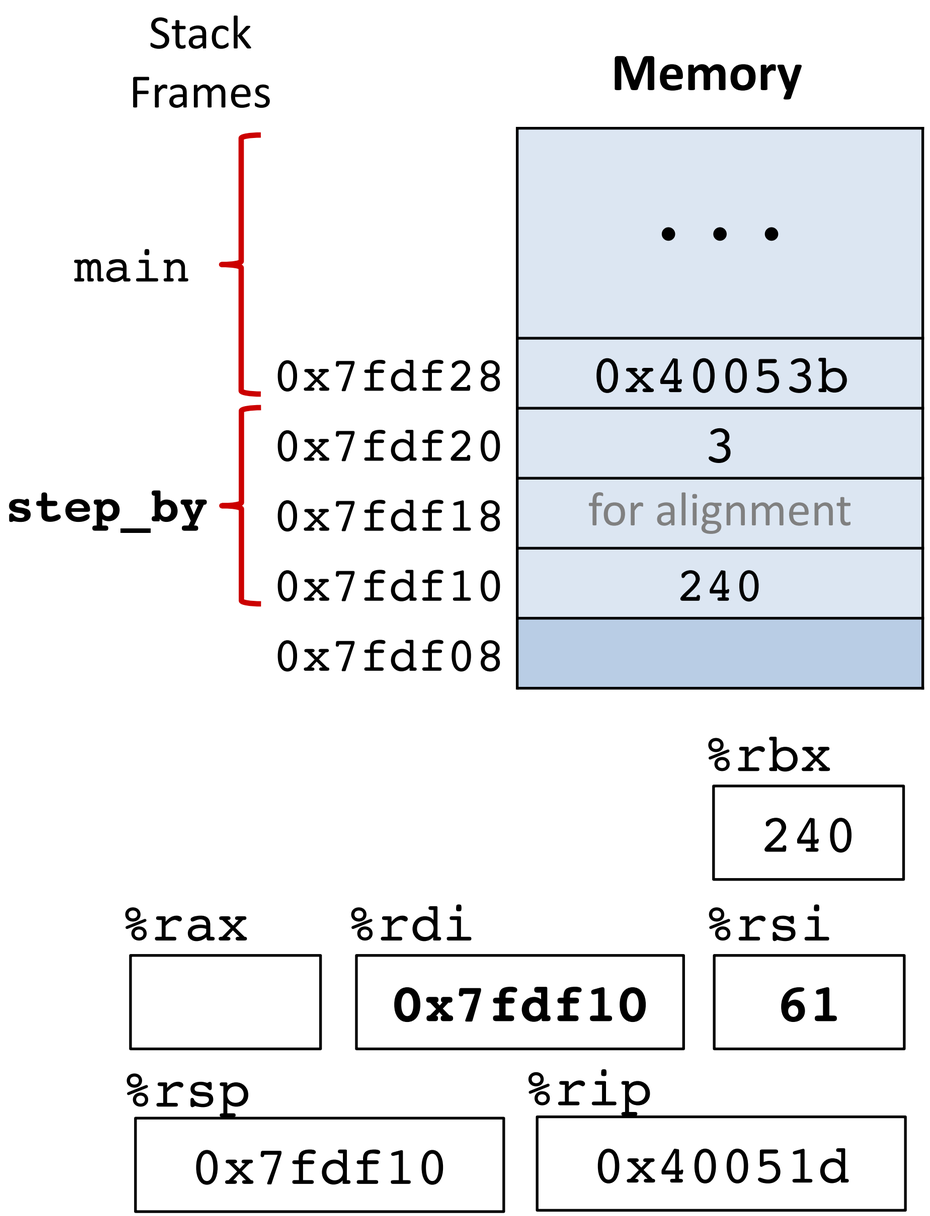
```
long step_by(long x) {
    long v1 = x;
    long v2 = increment(&v1, 61);
    return x + v2;
}
```

```
step_by:
400504:  pushq %rbx
400506:  movq  %rdi, %rbx
400509:  subq  $16, %rsp
40050d:  movq  %rdi, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  %rbx, %rax
400525:  addq  $16, %rsp
400529:  popq  %rbx
40052b:  retq
```

caller saved: `%rax, %rdi, %rsi`

callee saved: `%rbx`

Set up arguments



Callee-save example (step 5)

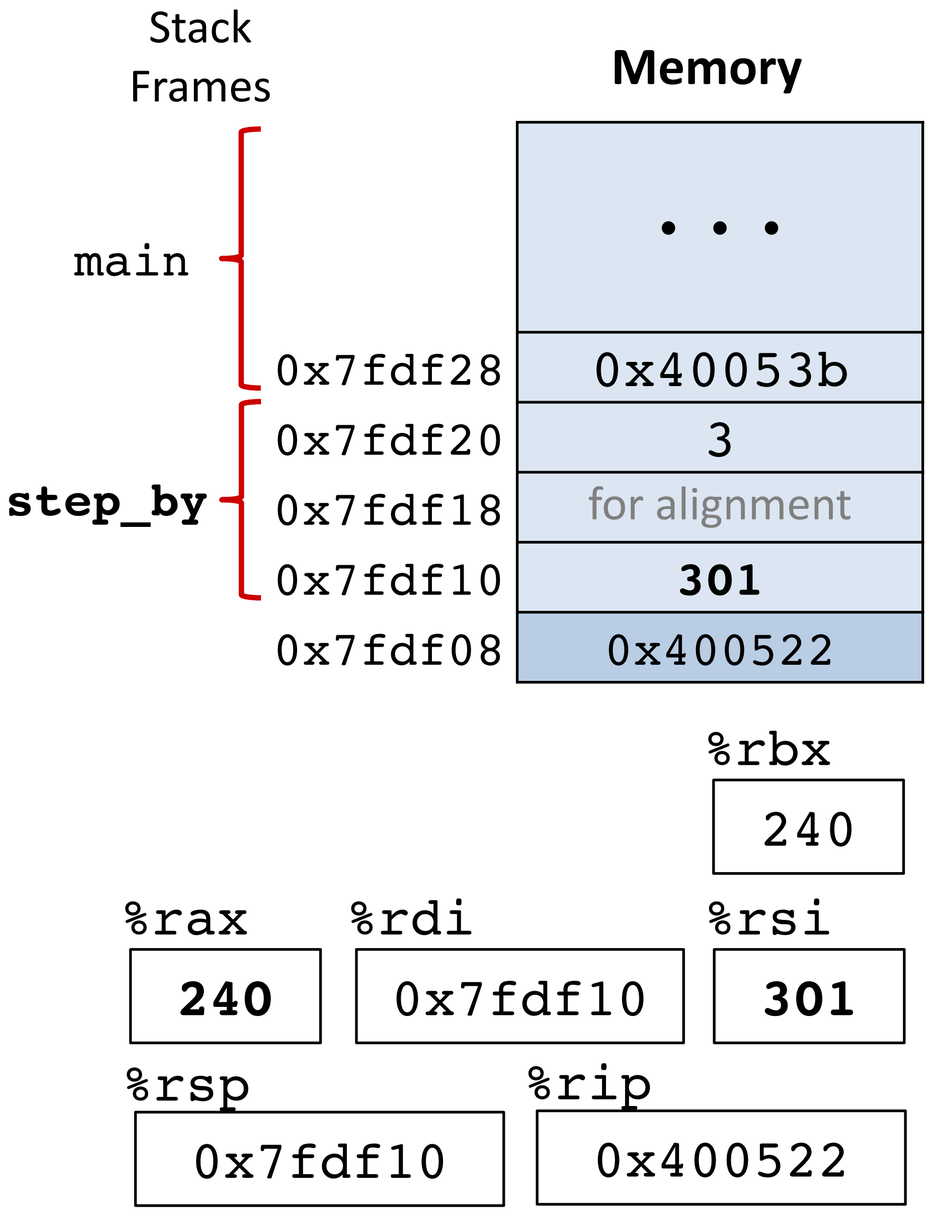
```
long step_by(long x) {
    long v1 = x;
    long v2 = increment(&v1, 61);
    return x + v2;
}
```

```
step_by:
400504:  pushq %rbx
400506:  movq  %rdi, %rbx
400509:  subq  $16, %rsp
40050d:  movq  %rdi, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  %rbx, %rax
400525:  addq  $16, %rsp
400529:  popq  %rbx
40052b:  retq
```

caller saved: `%rax, %rdi, %rsi`

callee saved: `%rbx`

Call, execute, and return from `increment`



Callee-save example (step 6)

Prepare return value

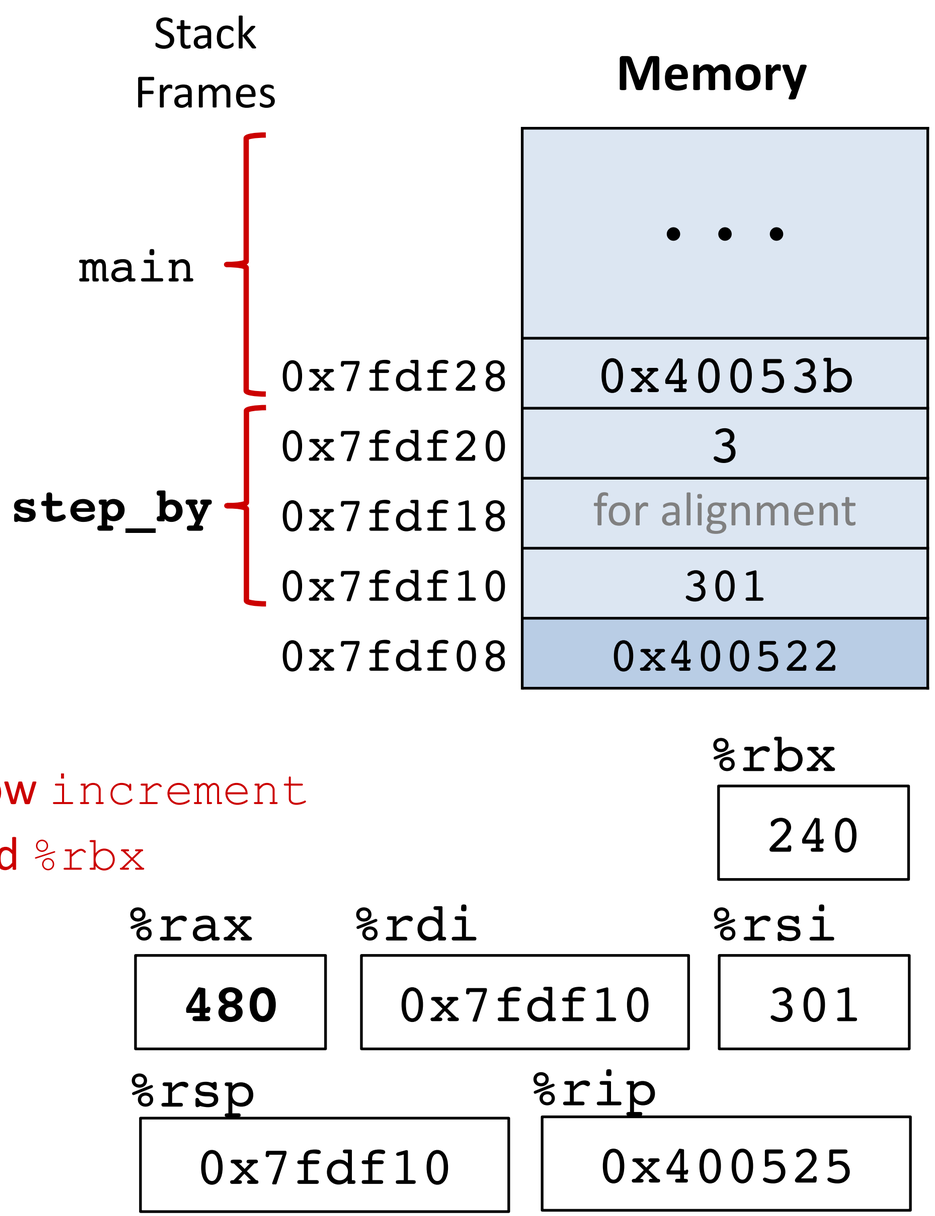
```
long step_by(long x) {
    long v1 = x;
    long v2 = increment(&v1, 61);
    return x + v2;
}
```

```
step_by:
400504:  pushq %rbx
400506:  movq  %rdi, %rbx
400509:  subq  $16, %rsp
40050d:  movq  %rdi, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  %rbx, %rax
400525:  addq  $16, %rsp
400529:  popq  %rbx
40052b:  retq
```

We know `increment` restored `%rbx`

caller saved: `%rax, %rdi, %rsi`

callee saved: `%rbx`



Callee-save example (step 7)

Clean up stack frame

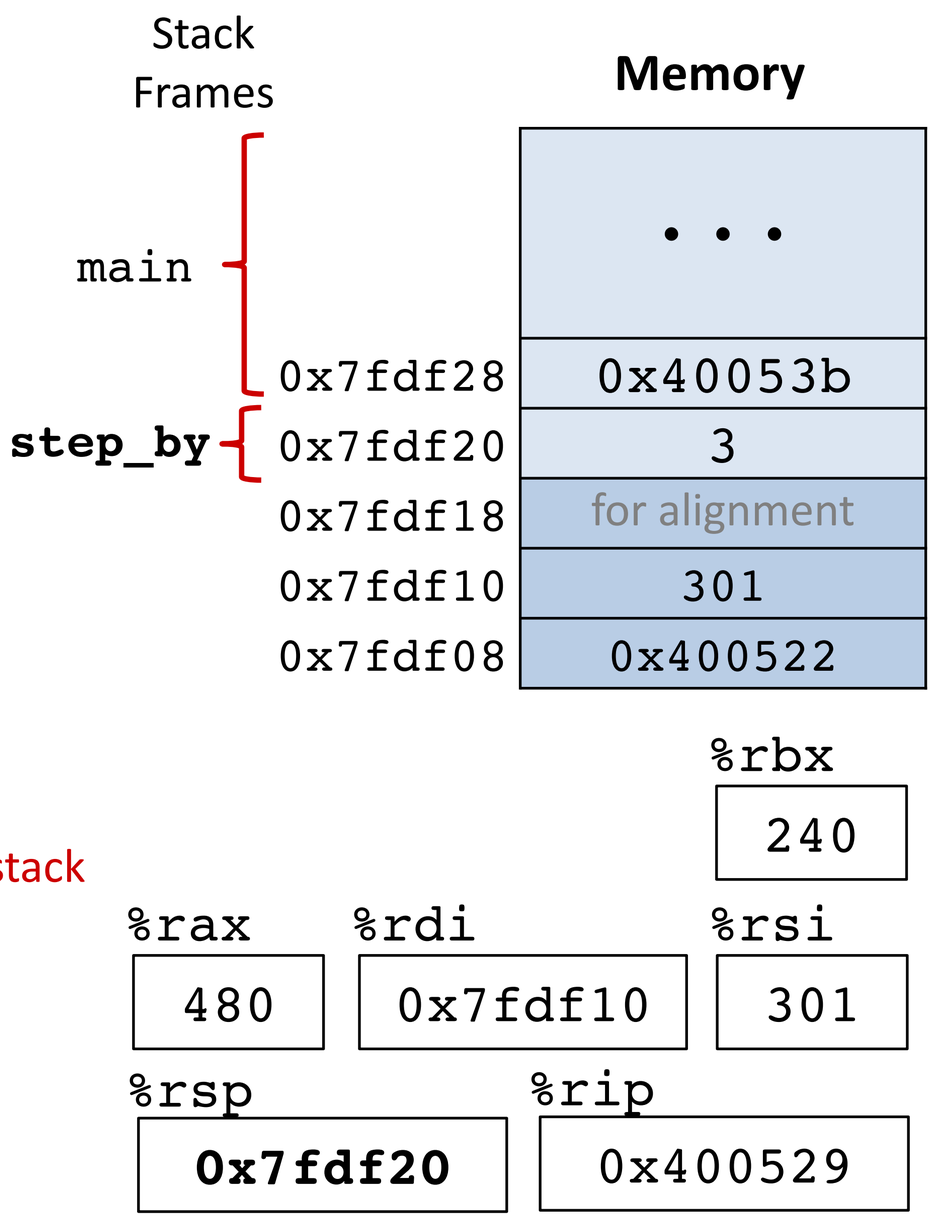
```
long step_by(long x) {
    long v1 = x;
    long v2 = increment(&v1, 61);
    return x + v2;
}
```

```
step_by:
400504:  pushq %rbx
400506:  movq  %rdi, %rbx
400509:  subq  $16, %rsp
40050d:  movq  %rdi, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  %rbx, %rax
400525:  addq  $16, %rsp
400529:  popq  %rbx
40052b:  retq
```

Shrink stack

caller saved: `%rax, %rdi, %rsi`

callee saved: `%rbx`



Callee-save example (step 8)

```
long step_by(long x) {
    long v1 = x;
    long v2 = increment(&v1, 61);
    return x + v2;
}
```

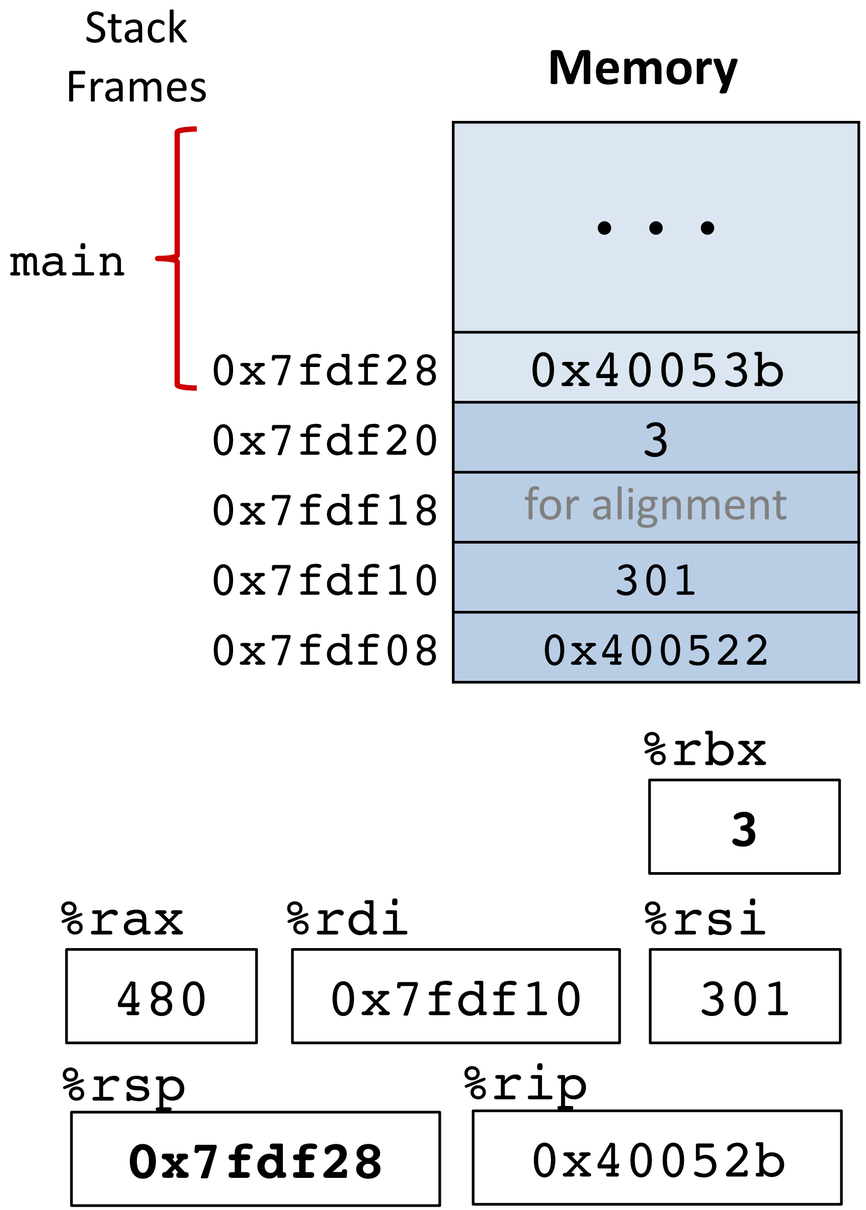
```
step_by:
400504:  pushq %rbx
400506:  movq  %rdi, %rbx
400509:  subq  $16, %rsp
40050d:  movq  %rdi, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  %rbx, %rax
400525:  addq  $16, %rsp
400529:  popq  %rbx
40052b:  retq
```

Restore `%rbx` for `main`

caller saved: `%rax, %rdi, %rsi`

callee saved: `%rbx`

Restore register `%rbx`
Ready to return



Recursion example: code

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

base case/ condition

recursive case

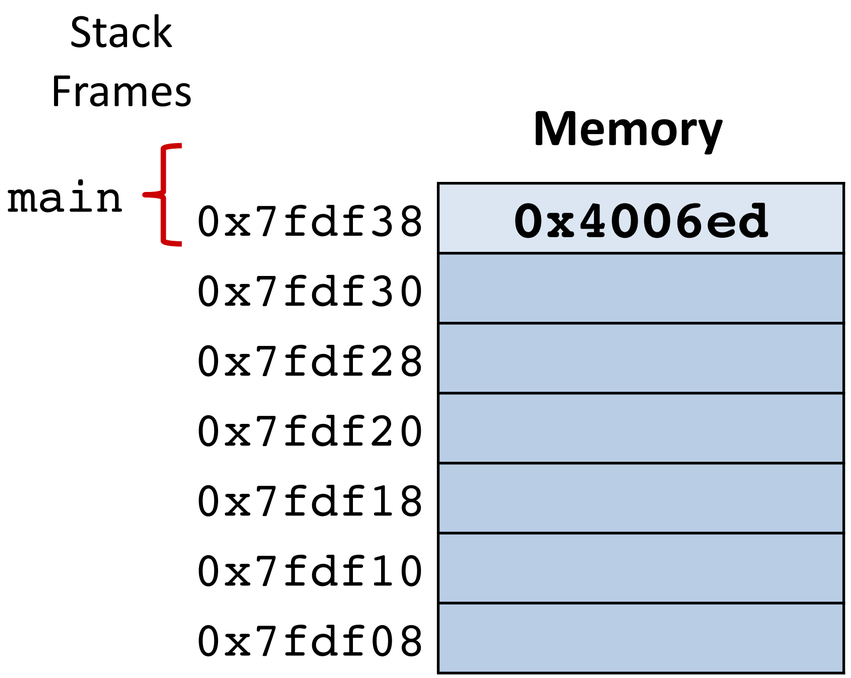
x&1 in %rbx across call

save/restore %rbx (callee-save)

Recursion Example: `pcount(2)`

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```



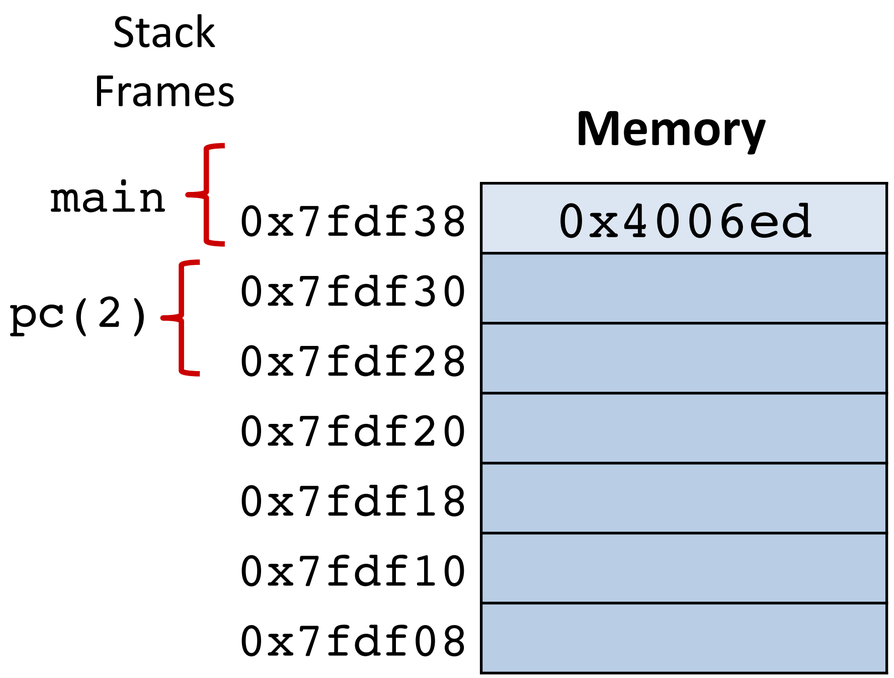
%rax	%rdi	%rbx
?	2	42

%rsp	%rip
0x7fdf38	**0x4005dd**

Recursion Example: `pcount(2)`

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```



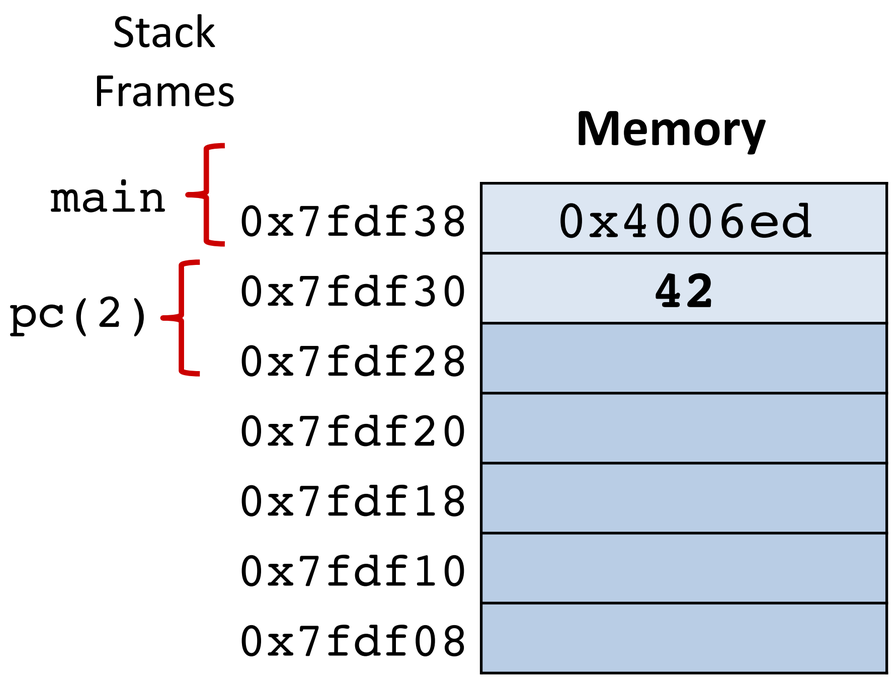
%rax	%rdi	%rbx
0	2	42

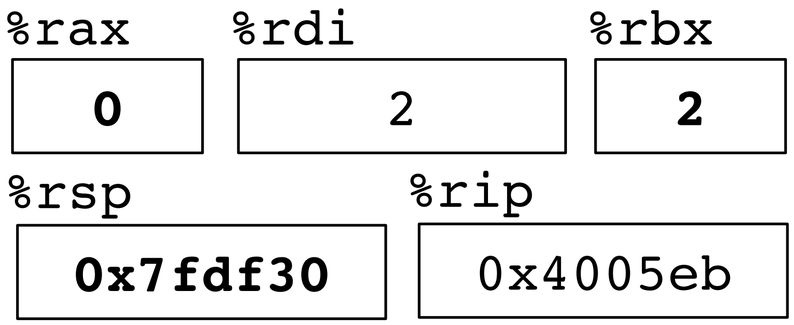
%rsp	%rip
0x7fdf38	**0x4005e7**

Recursion Example: `pcount(2)`

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

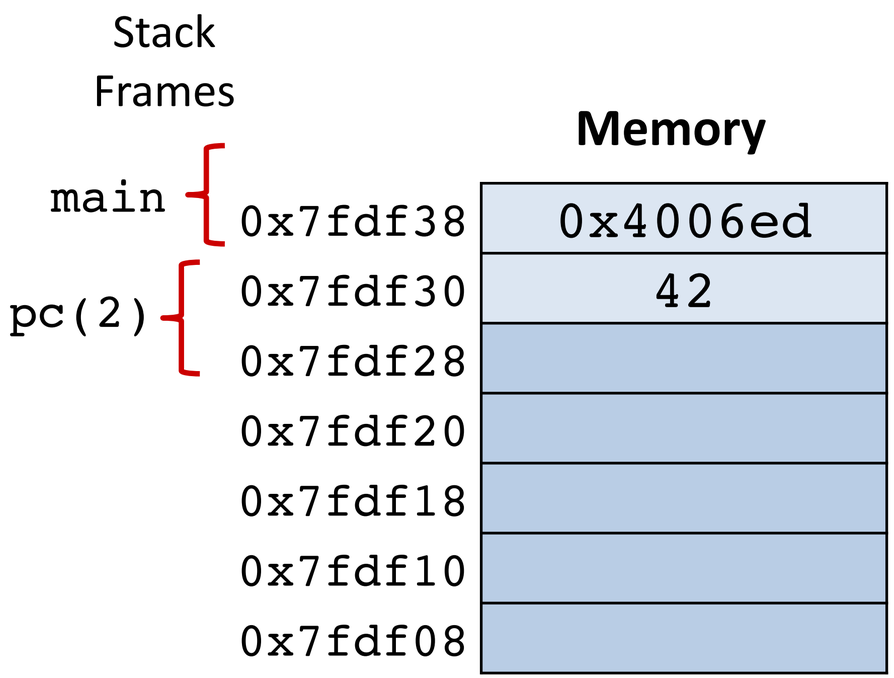


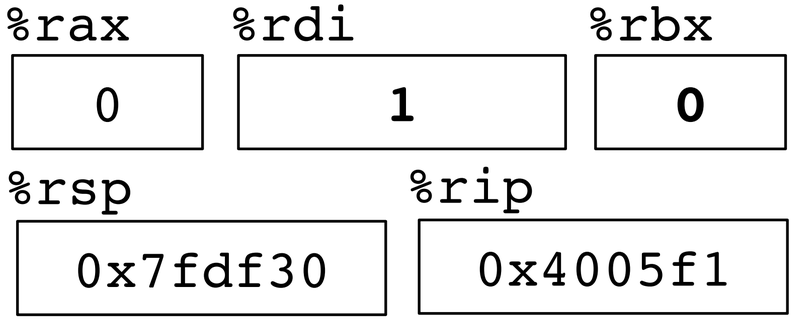


Recursion Example: `pcount(2)`

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

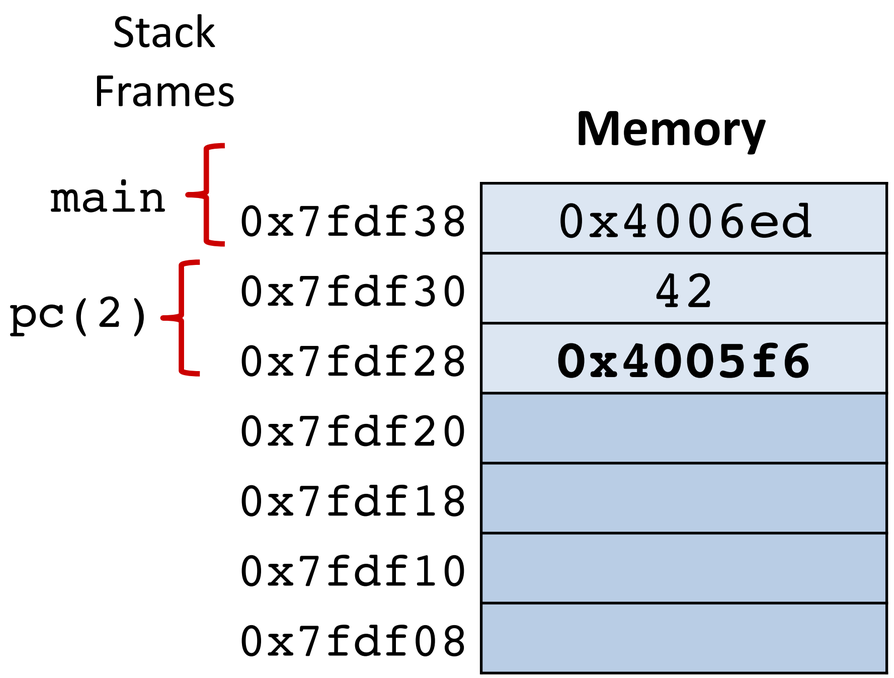




Recursion Example: `pcount(2)` → **`pcount(1)`**

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```



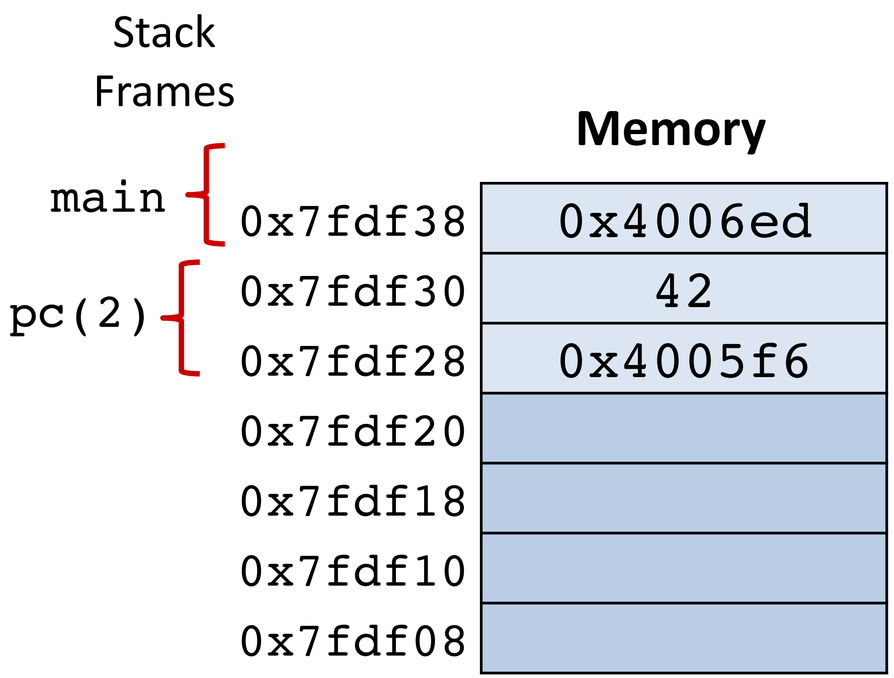
%rax	%rdi	%rbx
0	1	0

%rsp	%rip
0x7fdf28	**0x4005dd**

Recursion Example: `pcount(2)` → **`pcount(1)`**

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```



%rax	%rdi	%rbx
0	1	0

%rsp	%rip
0x7fdf28	**0x4005e7**

Recursion Example: `pcount(2)` → **`pcount(1)`**

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

Stack Frames

Memory

Frame	Address	Value
main	0x7fdf38	0x4006ed
pc(2)	0x7fdf30	42
	0x7fdf28	0x4005f6
pc(1)	0x7fdf20	**0**
	0x7fdf18	
	0x7fdf10	
	0x7fdf08	

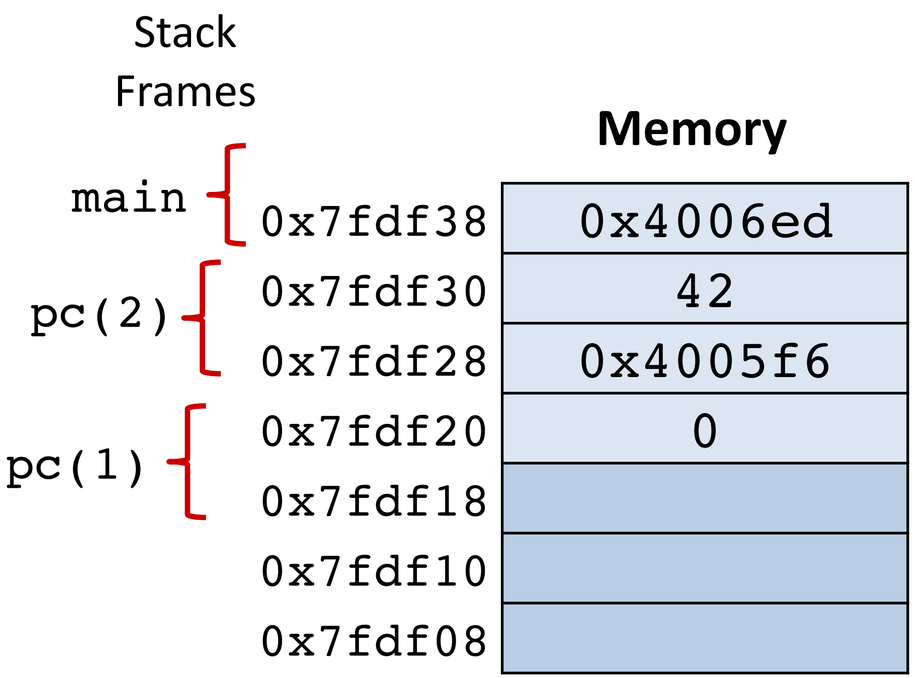
%rax	%rdi	%rbx
0	1	**1**

%rsp	%rip
0x7fdf20	0x4005eb

Recursion Example: `pcount(2)` → **`pcount(1)`**

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```



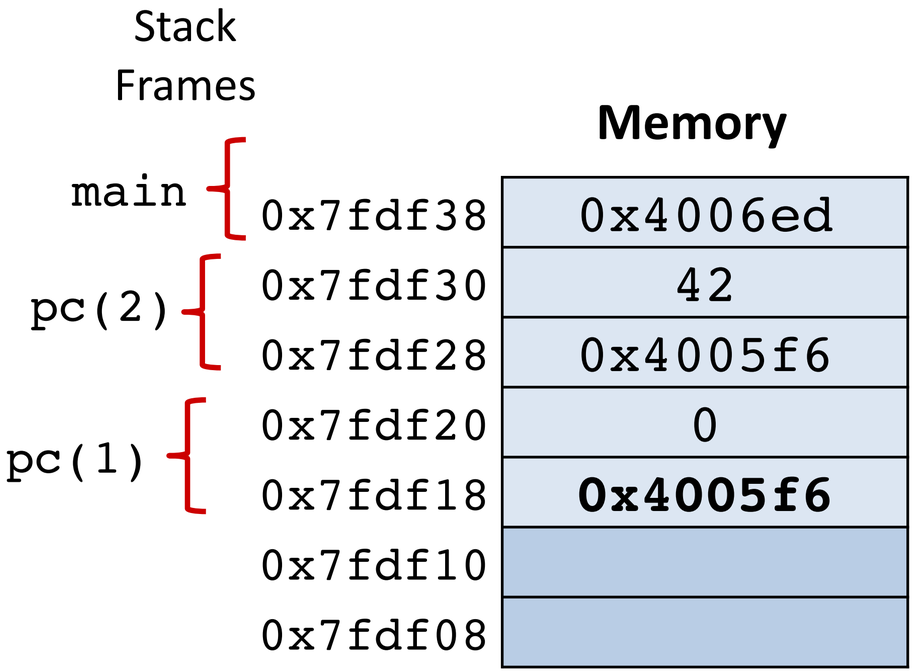
%rax	%rdi	%rbx
0	**0**	**1**

%rsp	%rip
0x7fdf20	0x4005f1

Recursion Example: `pcount(2)` → `pcount(1)` → **`pcount(0)`**

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```



%rax	%rdi	%rbx
0	0	1

%rsp	%rip
0x7fdf18	**0x4005dd**

Recursion Example: `pcount(2)` → `pcount(1)` → **`pcount(0)`**

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

Stack Frames

		Memory
main	0x7fdf38	0x4006ed
pc(2)	0x7fdf30	42
	0x7fdf28	0x4005f6
pc(1)	0x7fdf20	0
	0x7fdf18	0x4005f6
	0x7fdf10	
	0x7fdf08	

%rax	%rdi	%rbx
0	0	1

%rsp	%rip
0x7fdf18	**0x4005fa**

Recursion Example: `pcount(2)` → `pcount(1)` → **`pcount(0)`**

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

Stack Frames

Memory

Frame	Address	Value
main	0x7fdf38	0x4006ed
pc(2)	0x7fdf30	42
	0x7fdf28	0x4005f6
pc(1)	0x7fdf20	0
	0x7fdf18	0x4005f6
	0x7fdf10	
	0x7fdf08	

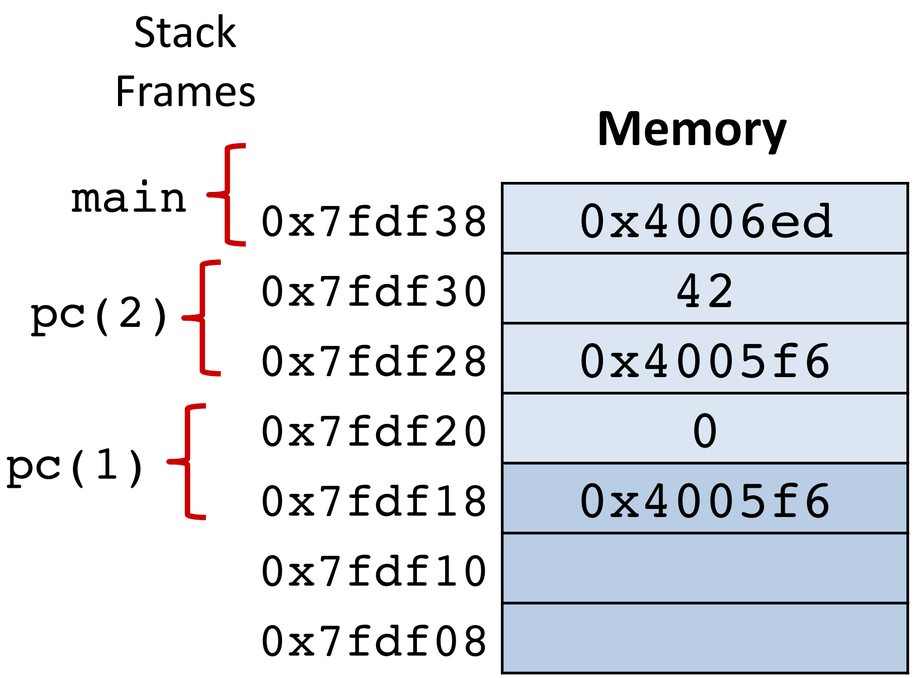
%rax	%rdi	%rbx
0	0	1

%rsp	%rip
0x7fdf20	**0x4005f6**

Recursion Example: `pcount(2)` → `pcount(1)` → **`pcount(0)`**

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```



%rax	%rdi	%rbx
0	0	1

%rsp	%rip
0x7fdf20	**0x4005f6**

Recursion Example: `pcount(2)` → **`pcount(1)`** → `pcount(0)`

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

Stack Frames

		Memory
main	0x7fdf38	0x4006ed
pc(2)	0x7fdf30	42
	0x7fdf28	0x4005f6
pc(1)	0x7fdf20	0
	0x7fdf18	0x4005f6
	0x7fdf10	
	0x7fdf08	

%rax	%rdi	%rbx
1	0	1

%rsp	%rip
0x7fdf20	0x4005f9

Recursion Example: `pcount(2)` → **`pcount(1)`** → `pcount(0)`

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

Stack Frames

		Memory
main	0x7fdf38	0x4006ed
pc(2)	0x7fdf30	42
	0x7fdf28	0x4005f6
	0x7fdf20	0
	0x7fdf18	0x4005f6
	0x7fdf10	
	0x7fdf08	

%rax	%rdi	%rbx
1	0	**0**

%rsp	%rip
0x7fdf28	0x4005fa

Recursion Example: `pcount(2)` → **`pcount(1)`** → `pcount(0)`

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

Stack Frames

	Memory	
main	0x7fdf38	0x4006ed
pc(2)	0x7fdf30	42
	0x7fdf28	0x4005f6
	0x7fdf20	0
	0x7fdf18	0x4005f6
	0x7fdf10	
	0x7fdf08	

%rax	%rdi	%rbx
1	0	0

%rsp	%rip
0x7fdf30	**0x4005f6**

Recursion Example: `pcount(2)` → **`pcount(1)`** → `pcount(0)`

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

Stack Frames

	Memory	
main	0x7fdf38	0x4006ed
pc(2)	0x7fdf30	42
	0x7fdf28	0x4005f6
	0x7fdf20	0
	0x7fdf18	0x4005f6
	0x7fdf10	
	0x7fdf08	

%rax	%rdi	%rbx
1	0	0

%rsp	%rip
0x7fdf30	**0x4005f6**

Recursion Example: `pcount(2)` → `pcount(1)` → `pcount(0)`

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

Stack Frames

		Memory
main	0x7fdf38	0x4006ed
pc(2)	0x7fdf30	42
	0x7fdf28	0x4005f6
	0x7fdf20	0
	0x7fdf18	0x4005f6
	0x7fdf10	
	0x7fdf08	

%rax	%rdi	%rbx
1	0	0

%rsp	%rip
0x7fdf30	0x4005f9

Recursion Example: `pcount(2)` → `pcount(1)` → `pcount(0)`

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

Stack Frames

Memory

main	0x7fdf38	0x4006ed
	0x7fdf30	42
	0x7fdf28	0x4005f6
	0x7fdf20	0
	0x7fdf18	0x4005f6
	0x7fdf10	
	0x7fdf08	

%rax	%rdi	%rbx
1	0	**42**

%rsp	%rip
0x7fdf38	0x4005f9

Recursion Example: `pcount(2)` → `pcount(1)` → `pcount(0)`

```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

Stack Frames

main

Memory

0x7fdf38	0x4006ed
0x7fdf30	42
0x7fdf28	0x4005f6
0x7fdf20	0
0x7fdf18	0x4005f6
0x7fdf10	
0x7fdf08	

%rax	%rdi	%rbx
1	0	42

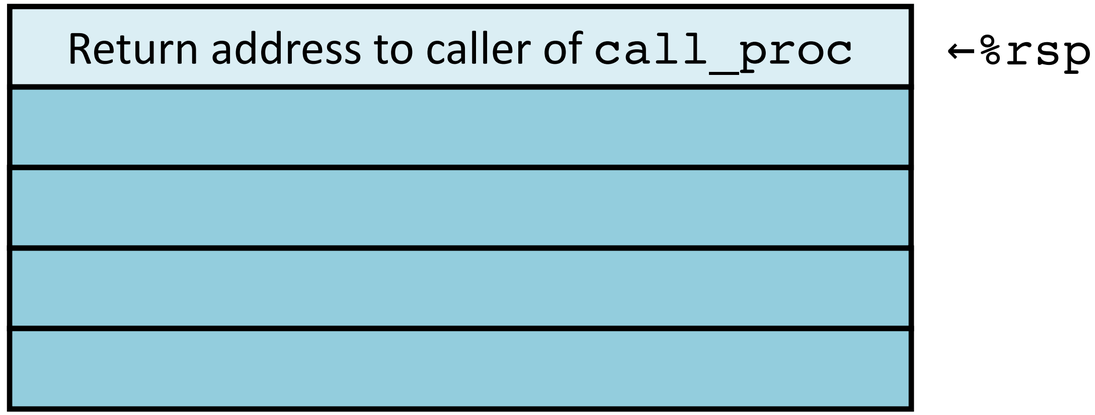
%rsp	%rip
0x7fdf40	**0x4006ed**

Stack storage example (1)

optional

```
long int call_proc()
{
  long  x1 = 1;
  int   x2 = 2;
  short x3 = 3;
  char  x4 = 4;
  proc(x1, &x1, x2, &x2,
       x3, &x3, x4, &x4);
  return (x1+x2)*(x3-x4);
}
```

```
call_proc:
  subq  $32,%rsp
  movq  $1,16(%rsp) # x1
  movl  $2,24(%rsp) # x2
  movw  $3,28(%rsp) # x3
  movb  $4,31(%rsp) # x4
  • • •
```

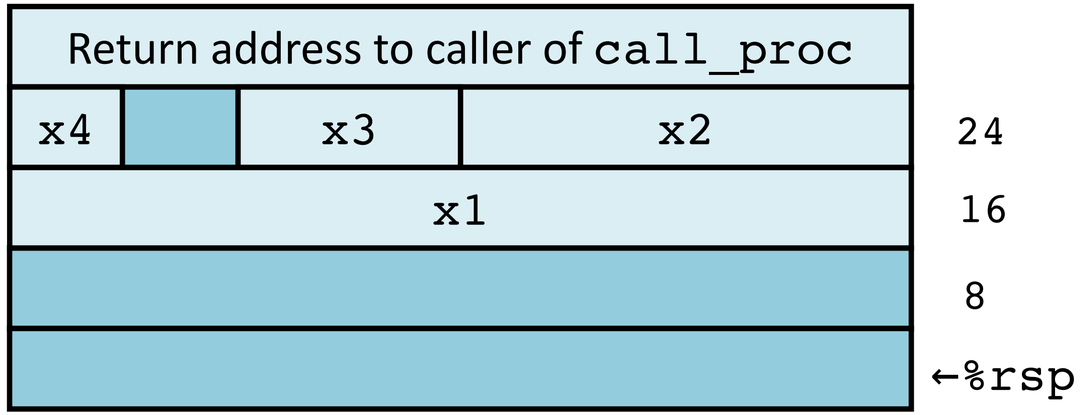


Stack storage example
(2) Allocate local vars

optional

```
long int call_proc()
{
  long  x1 = 1;
  int   x2 = 2;
  short x3 = 3;
  char  x4 = 4;
  proc(x1, &x1, x2, &x2,
       x3, &x3, x4, &x4);
  return (x1+x2)*(x3-x4);
}
```

```
call_proc:
  subq  $32,%rsp
  movq  $1,16(%rsp) # x1
  movl  $2,24(%rsp) # x2
  movw  $3,28(%rsp) # x3
  movb  $4,31(%rsp) # x4
  • • •
```

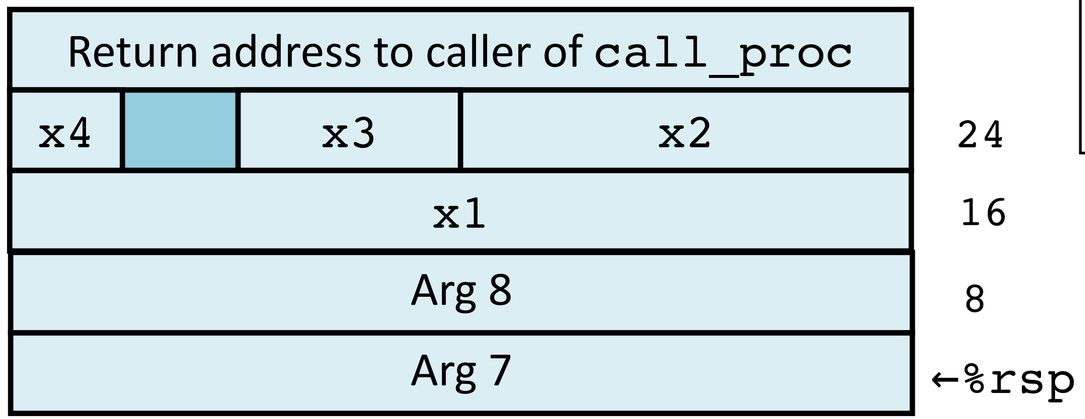


Stack storage example

(3) setup args to `proc`

optional

```
long int call_proc()
{
  long  x1 = 1;
  int   x2 = 2;
  short x3 = 3;
  char  x4 = 4;
  proc(x1, &x1, x2, &x2,
       x3, &x3, x4, &x4);
  return (x1+x2)*(x3-x4);
}
```




```
call_proc:
  • • •
  leaq  24(%rsp),%rcx # &x2
  leaq  16(%rsp),%rsi # &x1
  leaq  31(%rsp),%rax # &x4
  movq  %rax,8(%rsp)  # ...
  movl  $4,(%rsp)     # 4
  leaq  28(%rsp),%r9  # &x3
  movl  $3,%r8d       # 3
  movl  $2,%edx       # 2
  movq  $1,%rdi       # 1
  call  proc
  • • •
```

Arguments passed in (in order):

`%rdi, %rsi, %rdx, %rcx, %r8, %r9`

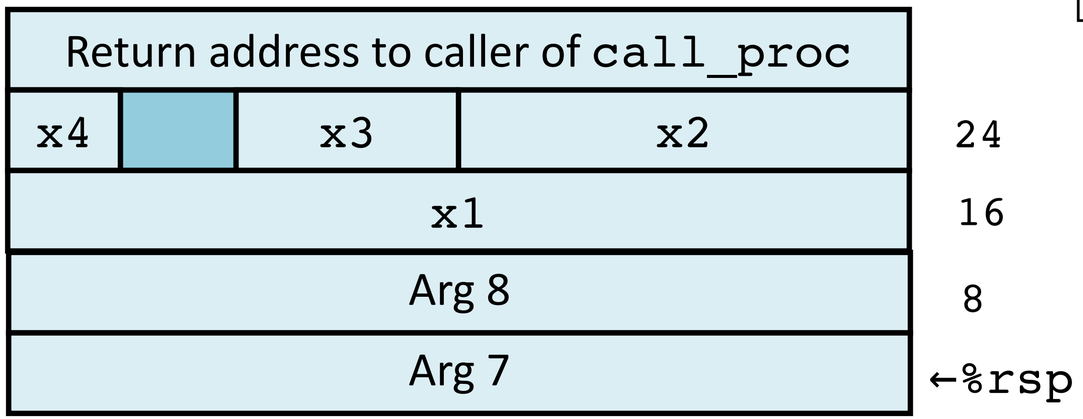
Stack storage example

(4) after call to `proc`

optional

```
long int call_proc()
{
  long  x1 = 1;
  int   x2 = 2;
  short x3 = 3;
  char  x4 = 4;
  proc(x1, &x1, x2, &x2,
       x3, &x3, x4, &x4);
  return (x1+x2)*(x3-x4);
}
```

```
call_proc:
  • • •
  movswl 28(%rsp),%eax # x3
  movsbl 31(%rsp),%edx # x4
  subl   %edx,%eax     # x3-x4
  cltq   # sign-extend %eax->%rax
  movslq 24(%rsp),%rdx # x2
  addq   16(%rsp),%rdx # x1+x2
  imulq  %rdx,%rax     # *
  addq   $32,%rsp
  ret
```

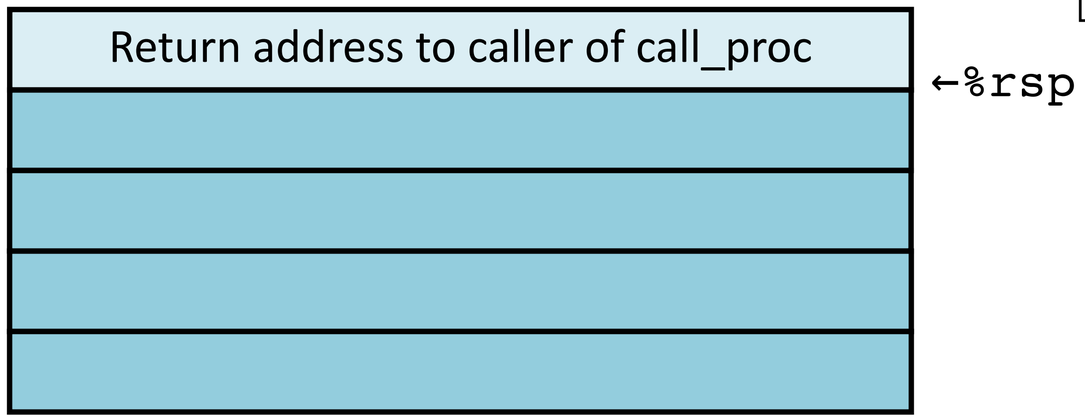


Stack storage example
(5) deallocate local vars

optional

```
long int call_proc()
{
  long  x1 = 1;
  int   x2 = 2;
  short x3 = 3;
  char  x4 = 4;
  proc(x1, &x1, x2, &x2,
       x3, &x3, x4, &x4);
  return (x1+x2)*(x3-x4);
}
```

```
call_proc:
  • • •
  movswl 28(%rsp),%eax
  movsbl 31(%rsp),%edx
  subl   %edx,%eax
  cltq
  movslq 24(%rsp),%rdx
  addq   16(%rsp),%rdx
  imulq  %rdx,%rax
  addq   $32,%rsp
  ret
```



Procedure Summary

`call, ret, push, pop`

Stack discipline fits procedure call / return.*

- If P calls Q: Q (and calls by Q) returns before P

Conventions support arbitrary function calls.

- Register-save conventions.
- Stack frame saves extra args or local variables. Result returned in `%rax`

`%rax`	Return value – Caller saved
`%rbx`	Callee saved
`%rcx`	Argument #4 – Caller saved
`%rdx`	Argument #3 – Caller saved
`%rsi`	Argument #2 – Caller saved
`%rdi`	Argument #1 – Caller saved
`%rsp`	Stack pointer
`%rbp`	Callee saved

`%r8`	Argument #5 – Caller saved
`%r9`	Argument #6 – Caller saved
`%r10`	Caller saved
`%r11`	Caller Saved
`%r12`	Callee saved
`%r13`	Callee saved
`%r14`	Callee saved
`%r15`	Callee saved