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. (*video 1)* What we have seen so far
   b. (*video 1)* Why we can’t implement procedure calls with jumps alone
2. (*video 1)* High-level call stack example
3. Procedure control flow instructions: call and ret
4. Procedure call example (in depth!) on whiteboard
5. 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?

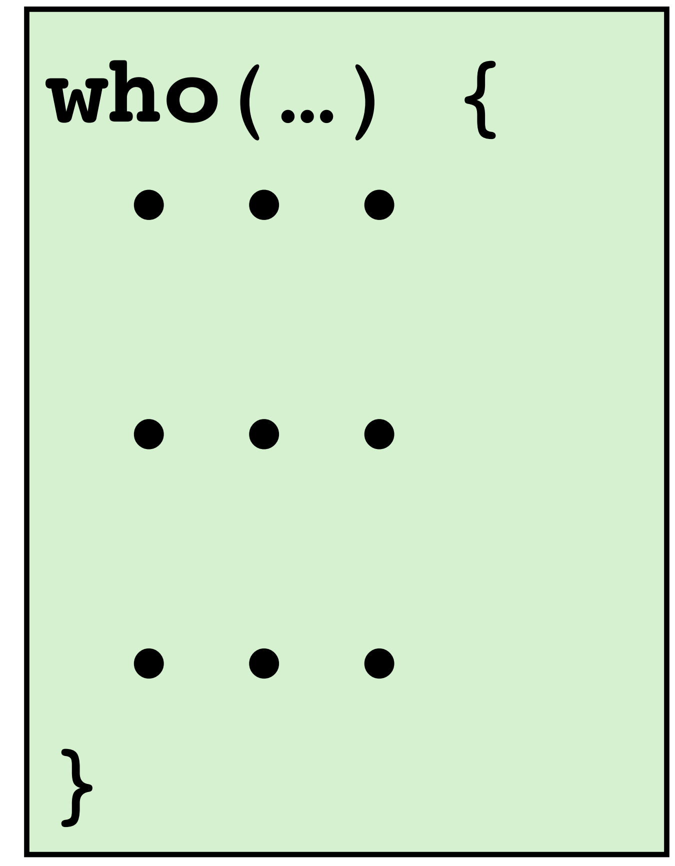
2. How does a caller receive a return value from a procedure?

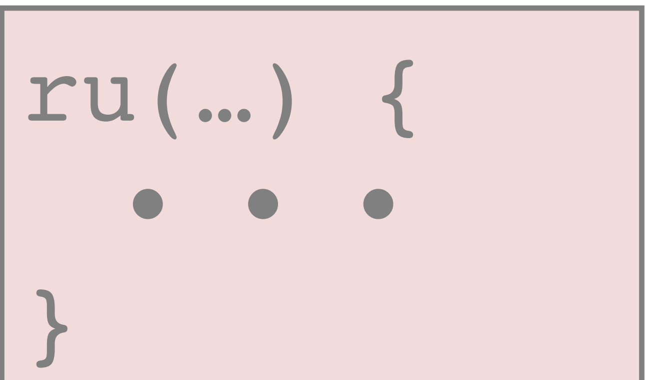
3. How does a procedure know where to return (what code to execute next when done)?

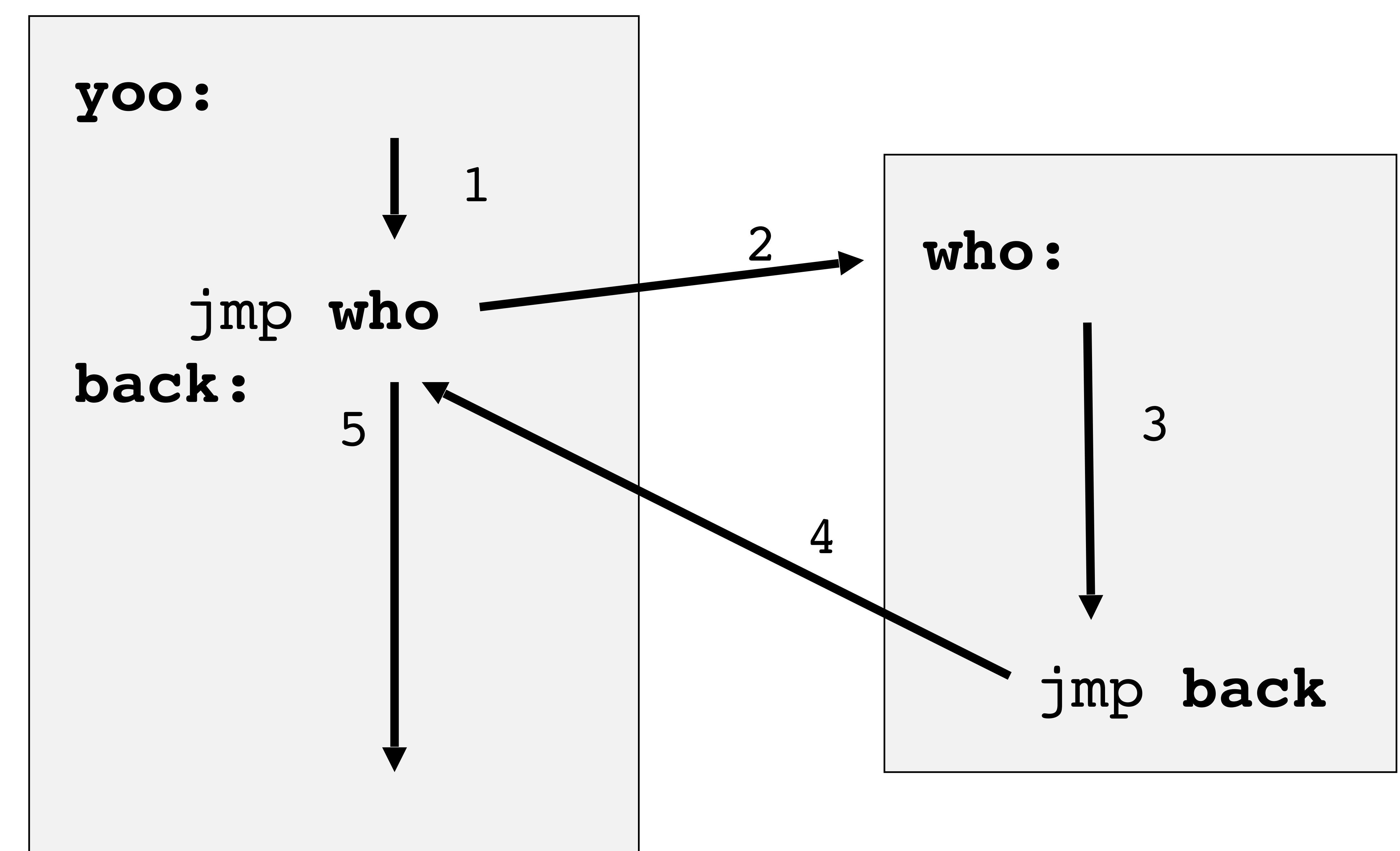
4. Where does a procedure store local variables?

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

Procedure call/return: Jump?







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

Procedure call/return: Jump? Broken!

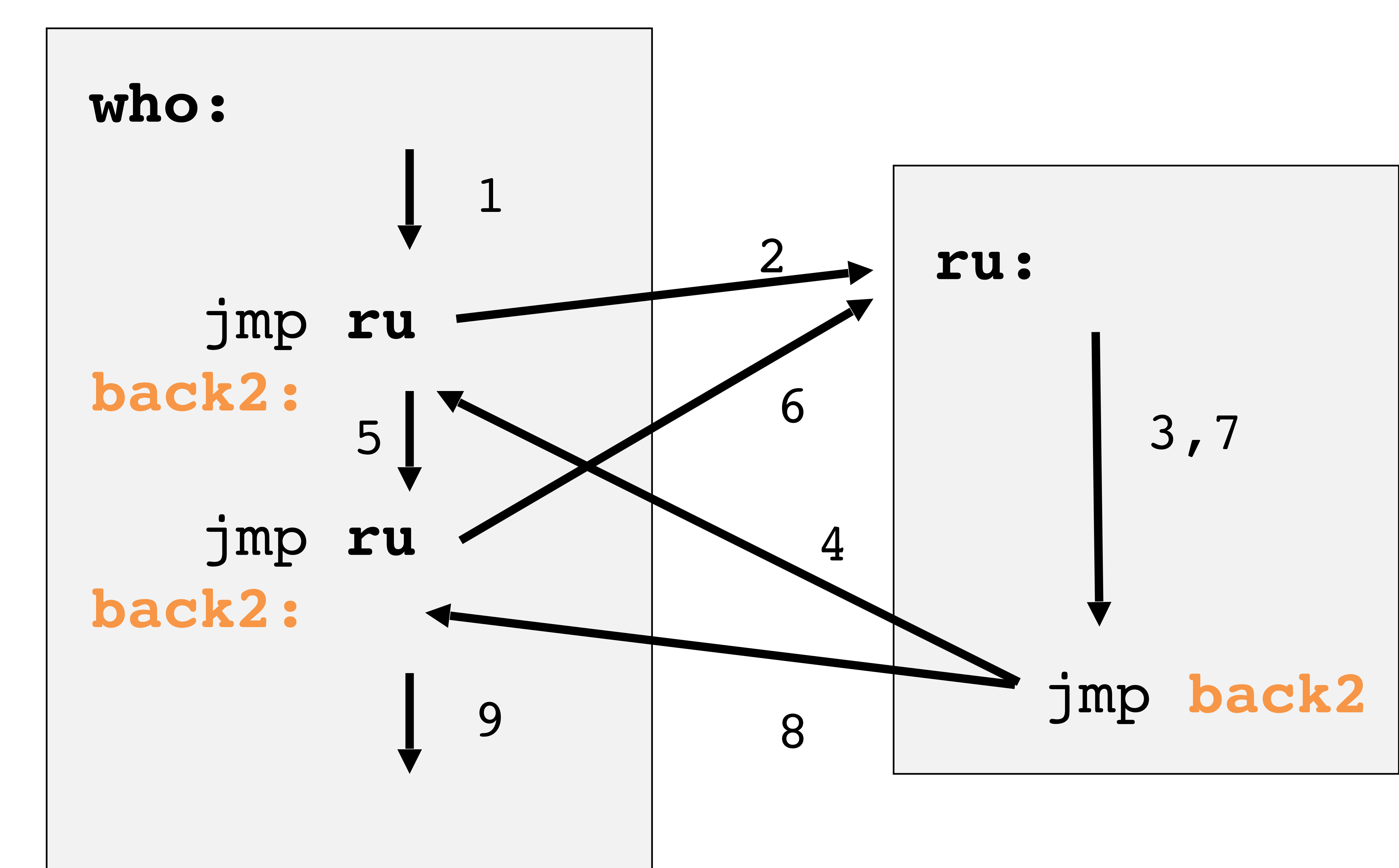
Call Chain

```
yoo
 ↓
who
 ↓    ↘
ru    ru
```

```
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)?

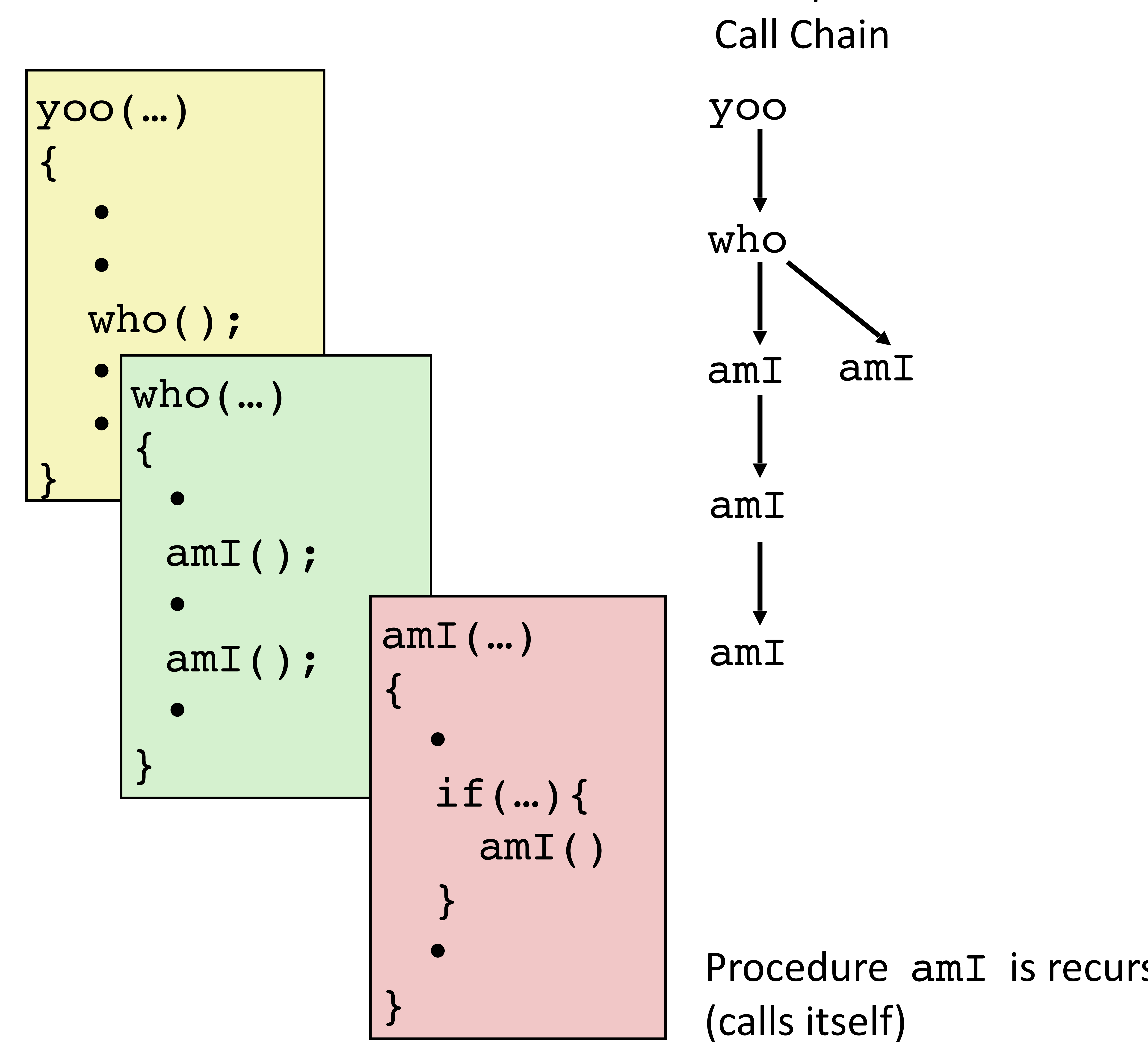
4. Where does a procedure store local variables?

1. How do procedures share limited registers and memory?

Memory Layout

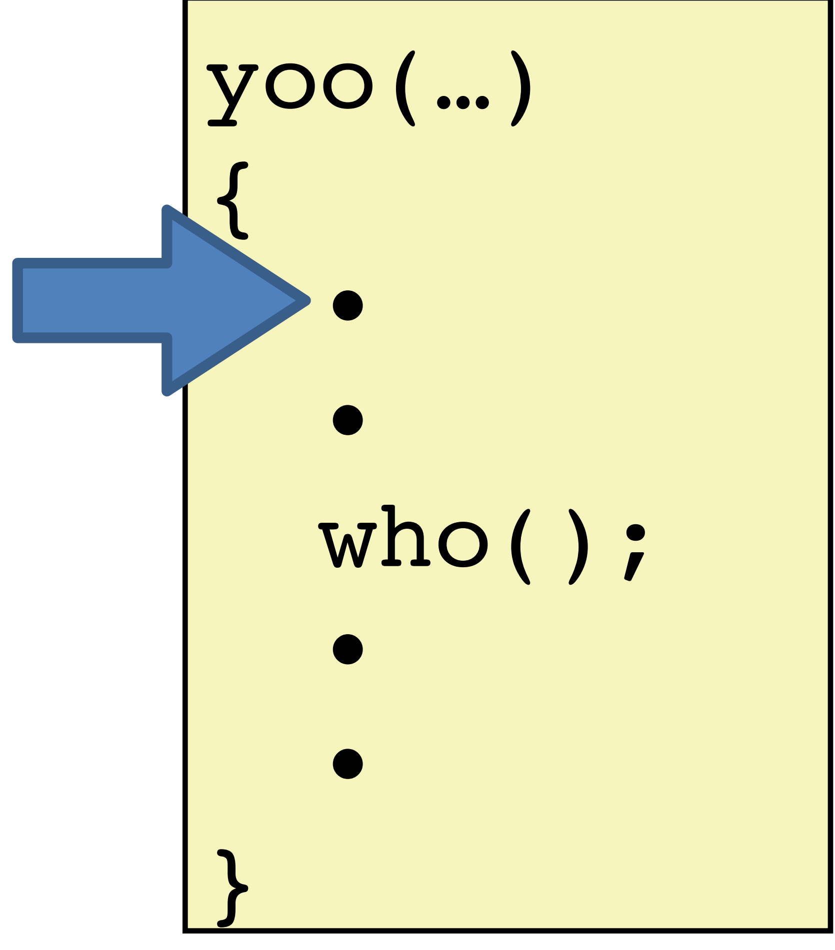
Perm	Contents	Managed by	Initialized
RW	**Procedure context**	**Compiler**	**Run-time**
RW	Dynamic data structures	Programmer, malloc/free, new/ GC	Run-time
RW	Global variables/ static data structures	Compiler/ Assembler/Linker	Startup
R	String literals	Compiler/ Assembler/Linker	Startup
X	Instructions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

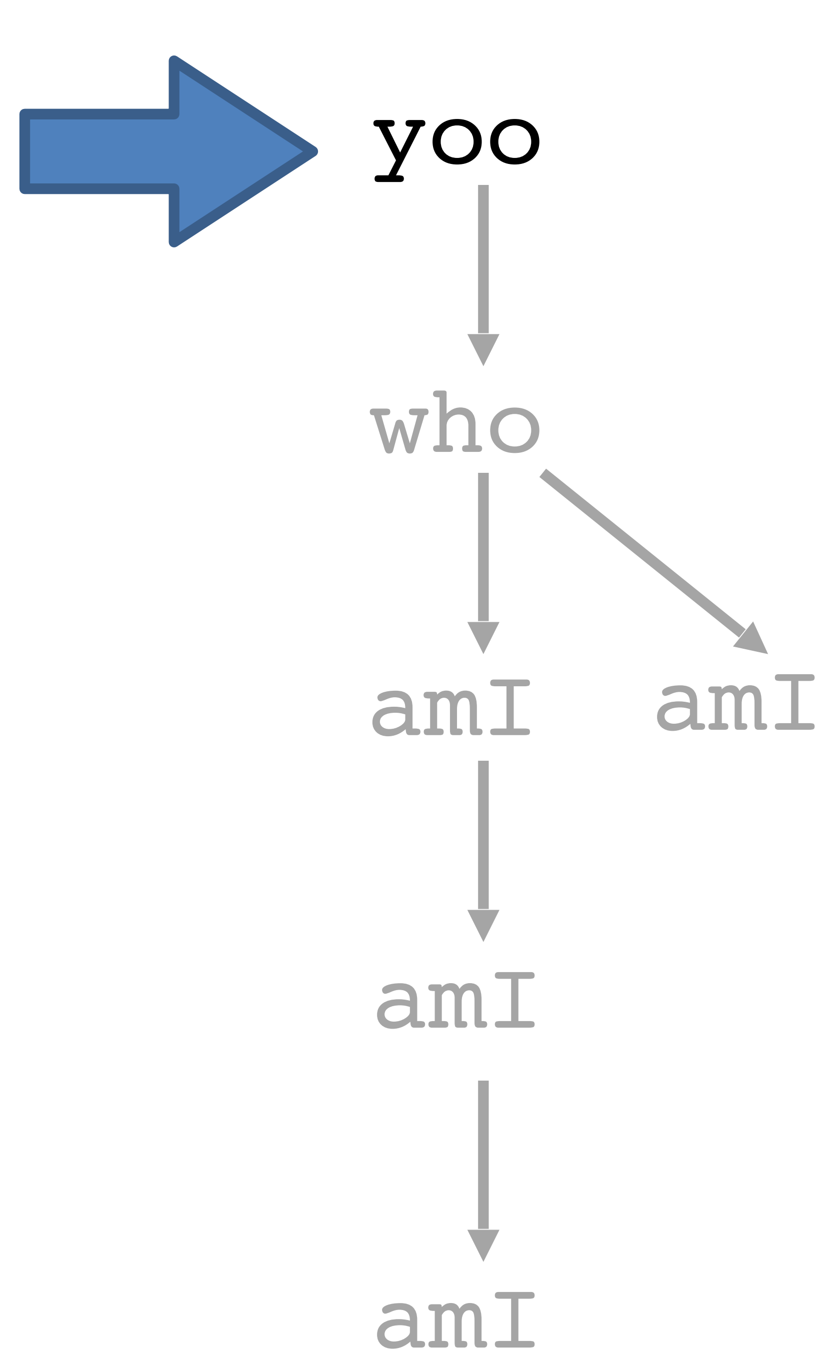
Call stack tracks context

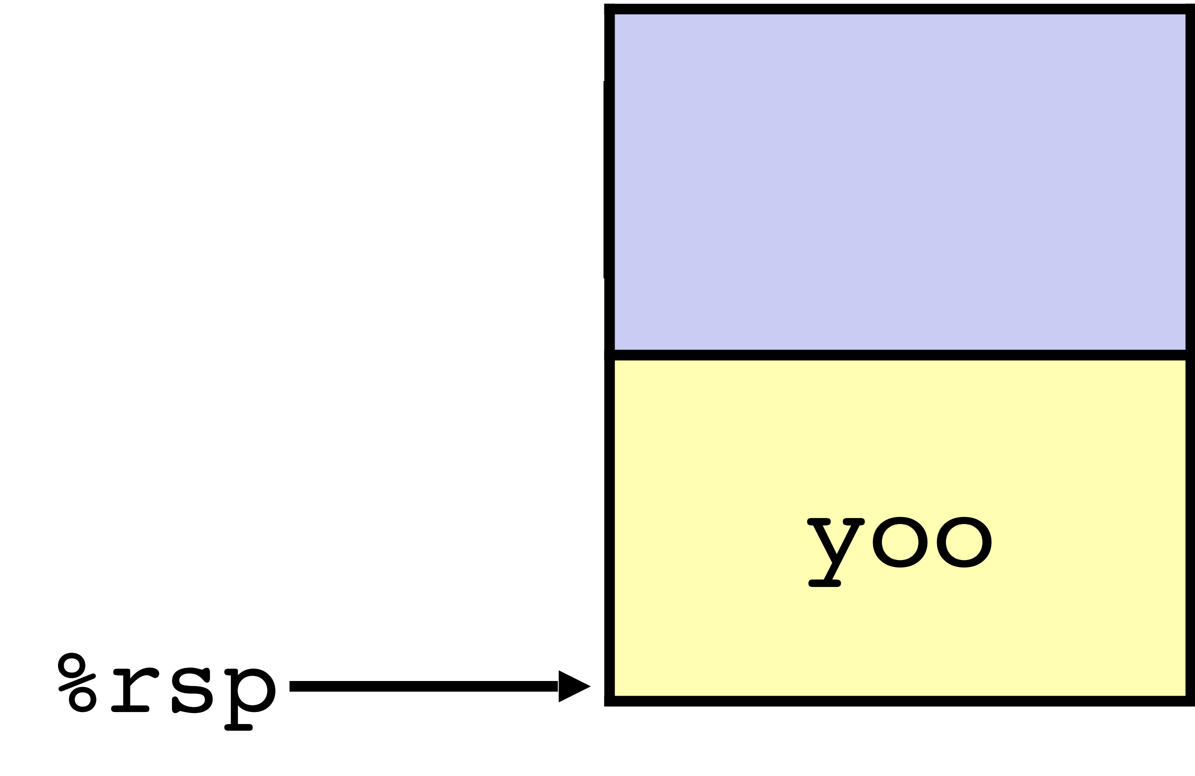


Procedure amI is recursive
(calls itself)

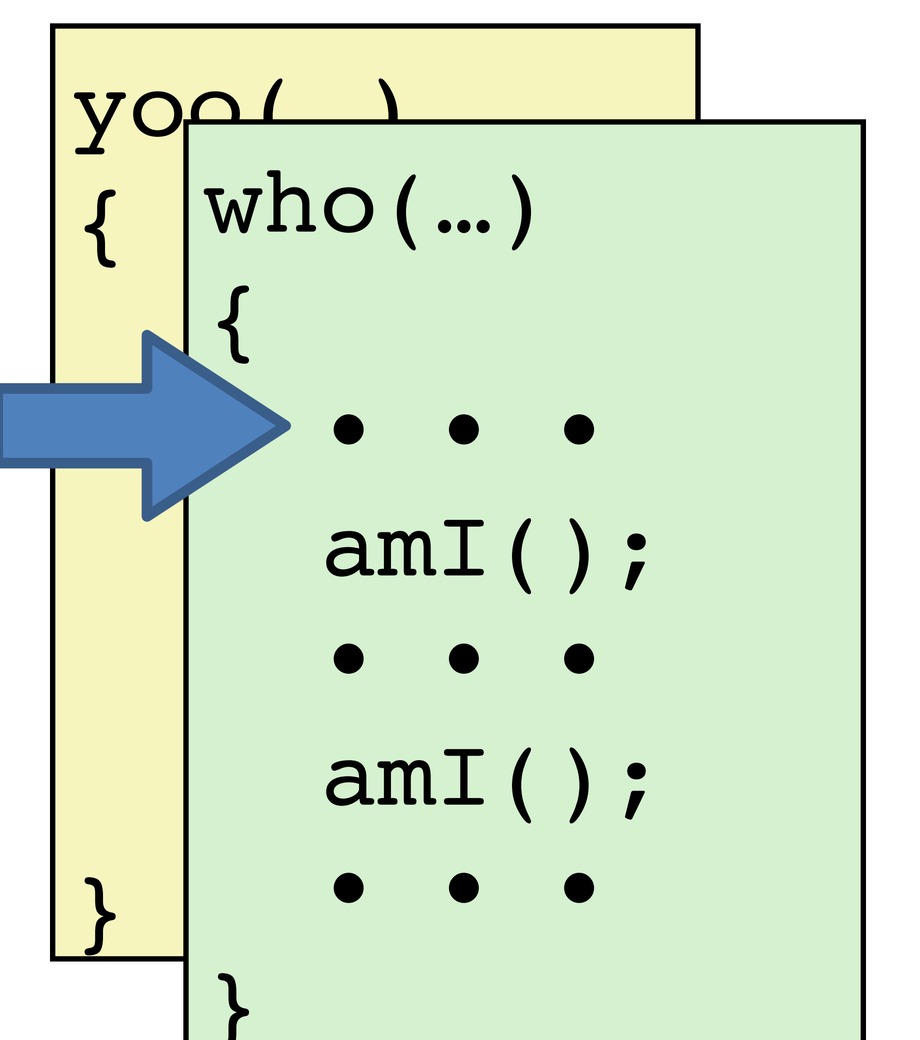
Call stack tracks context

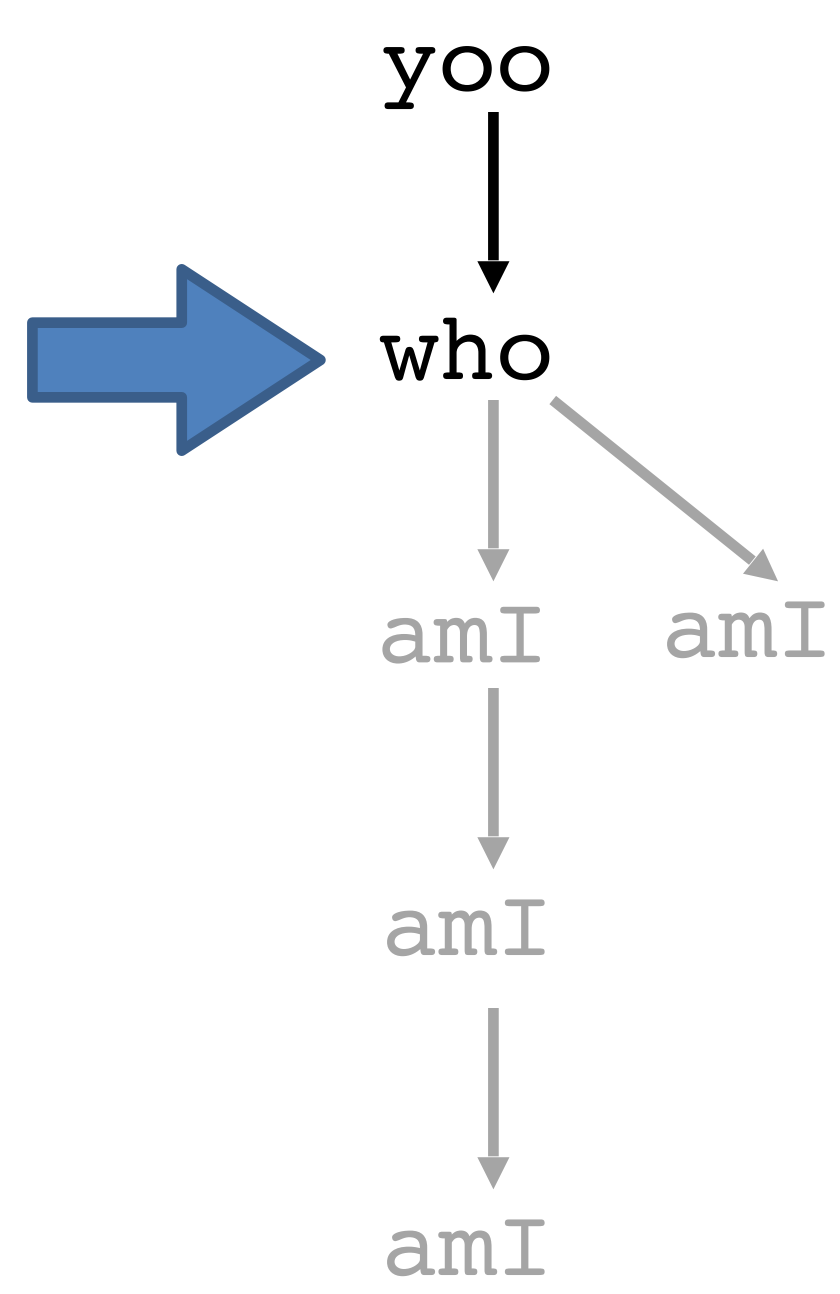




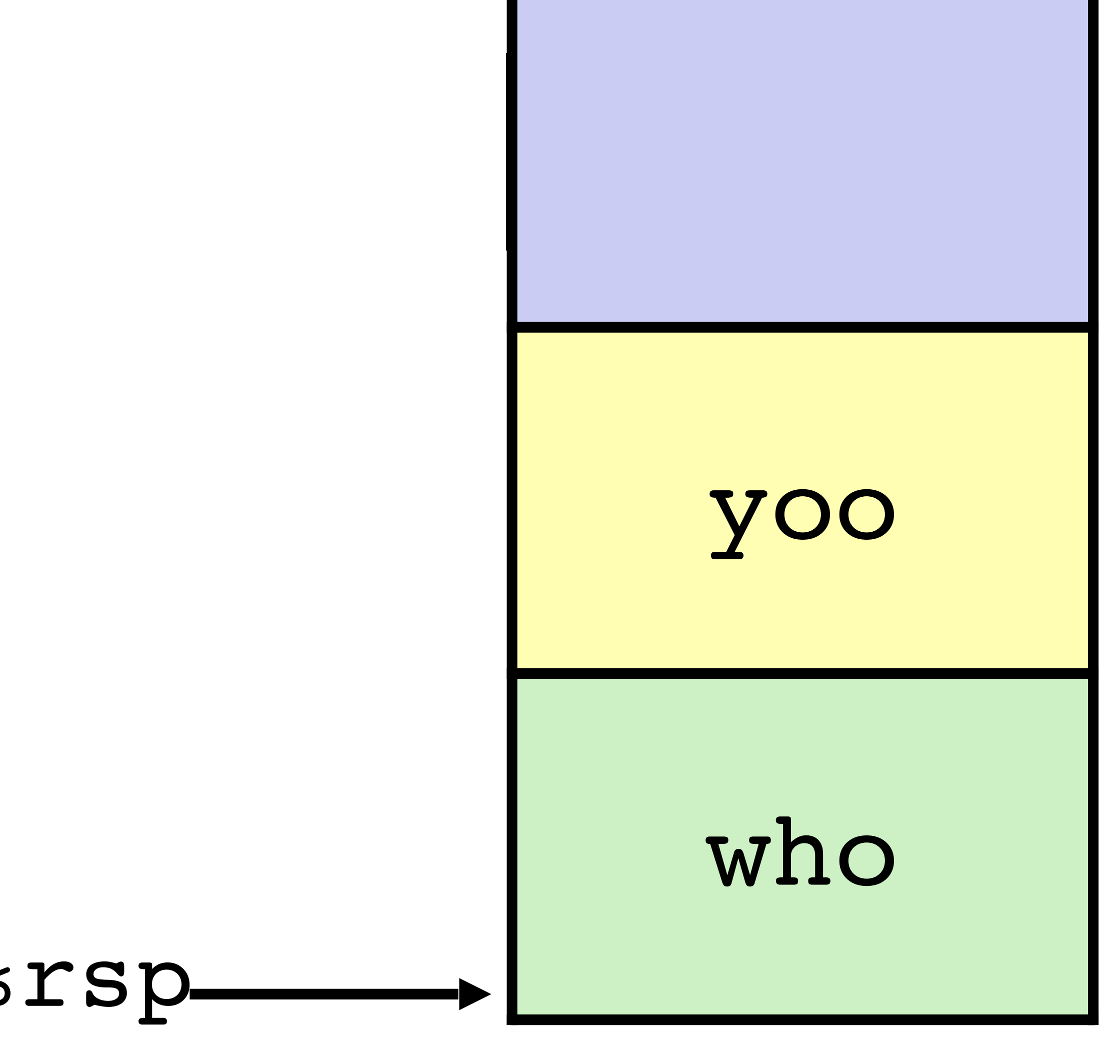


Call stack tracks context



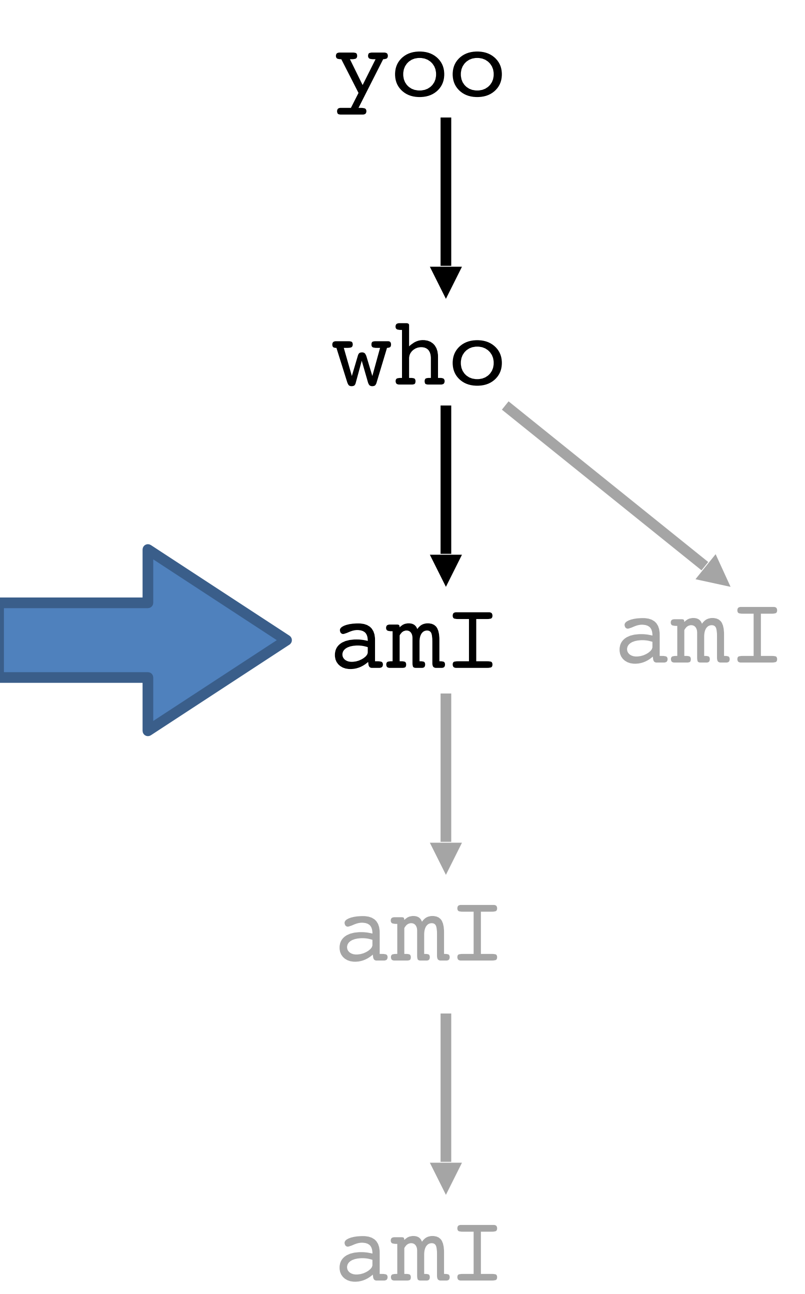


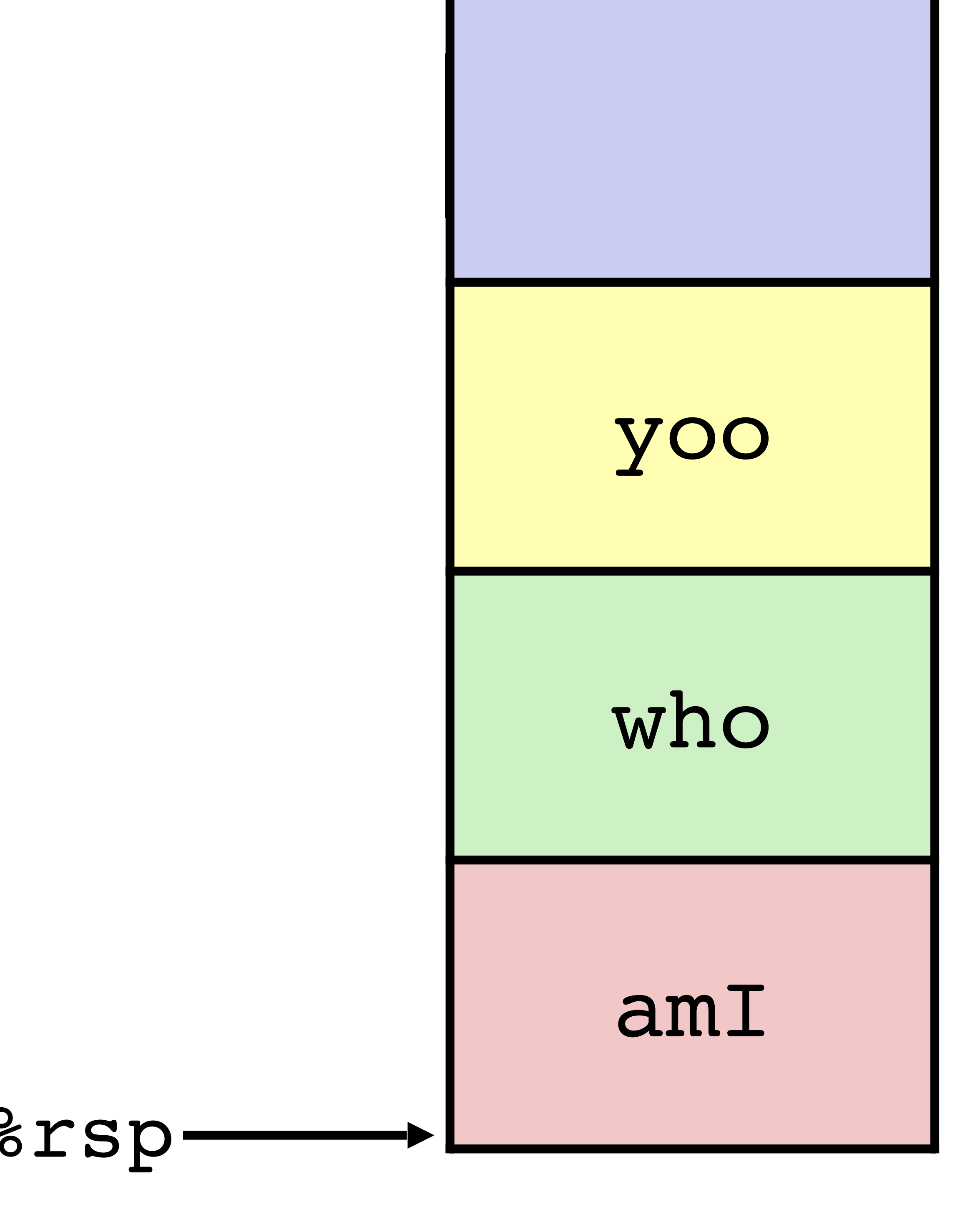
Stack



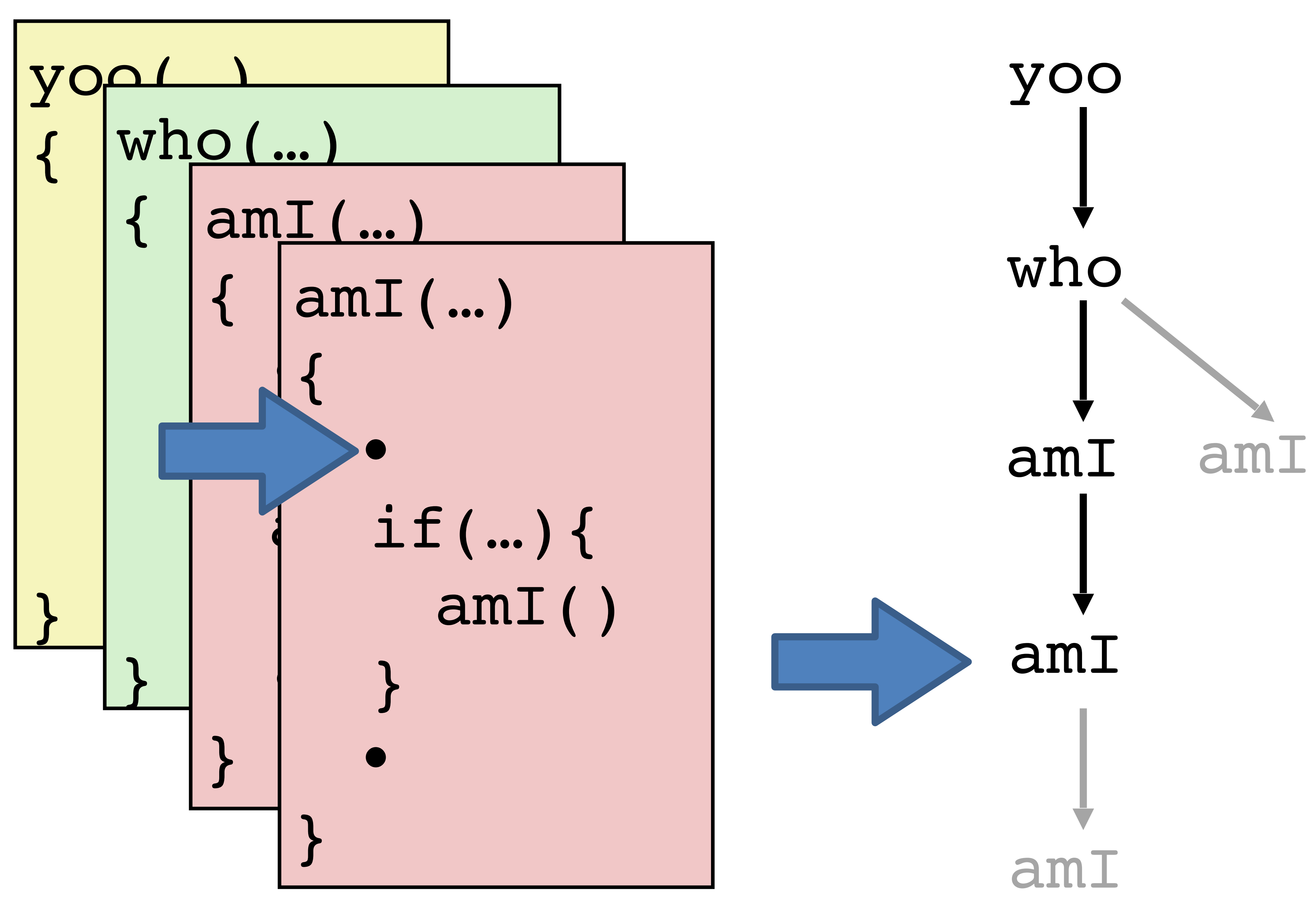
Call stack tracks context

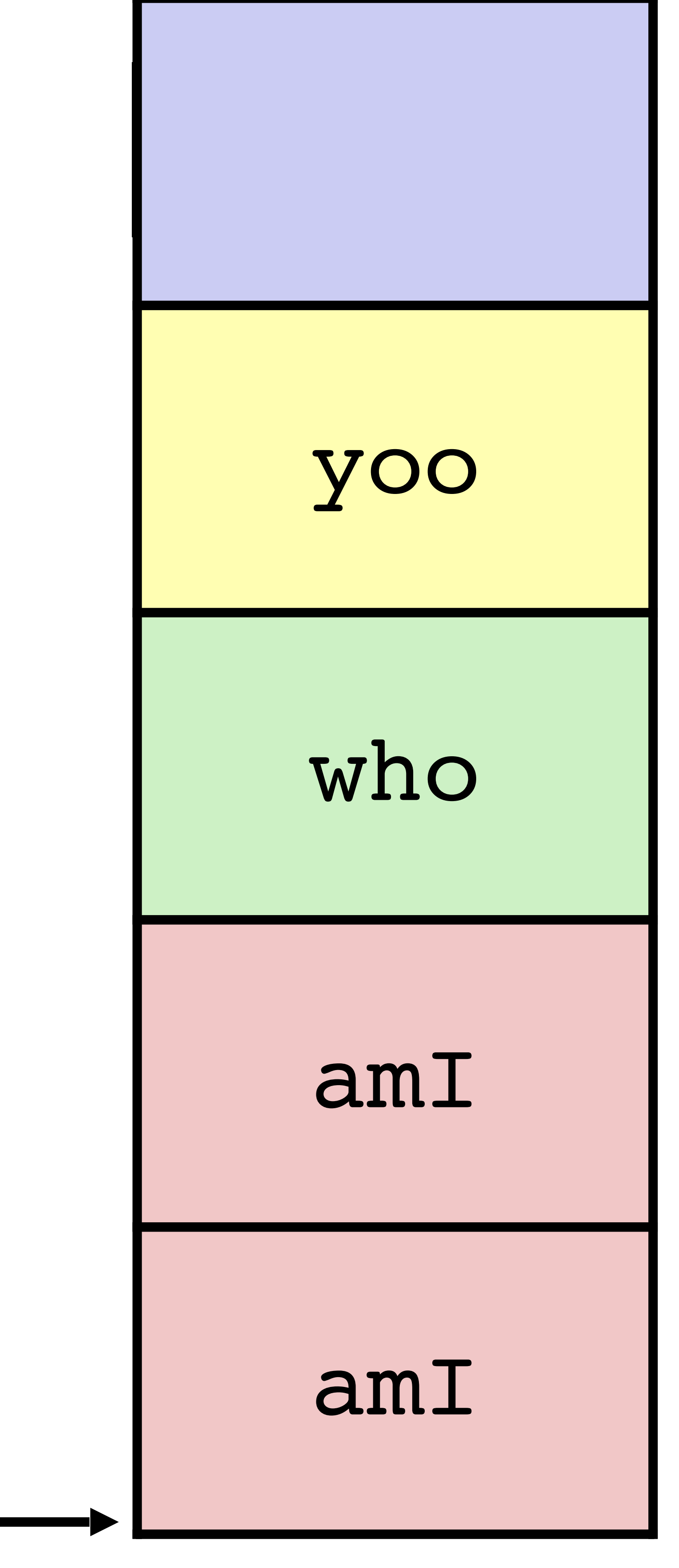
```
yoo(…)
{
}

who(…)
{
}

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



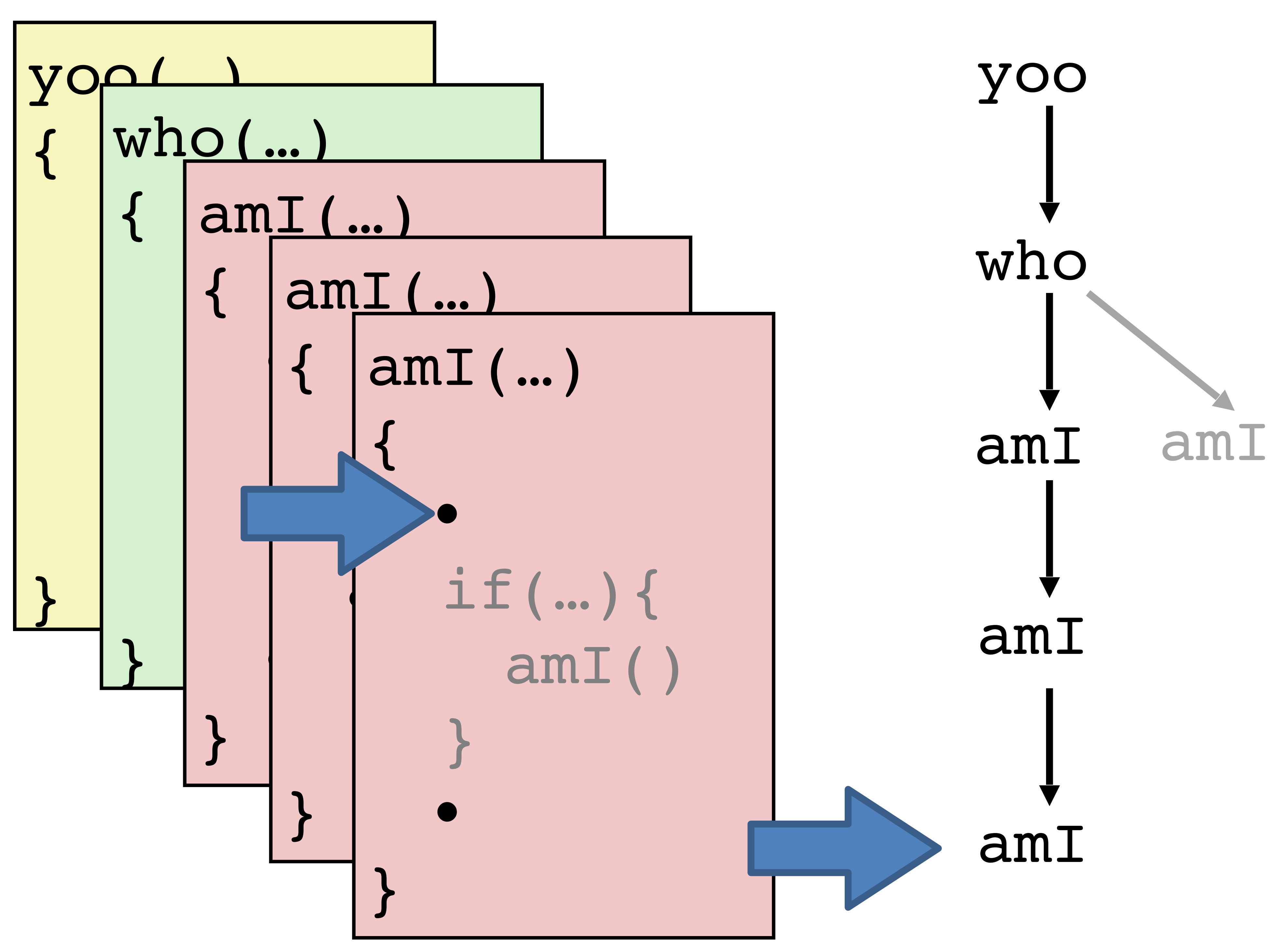


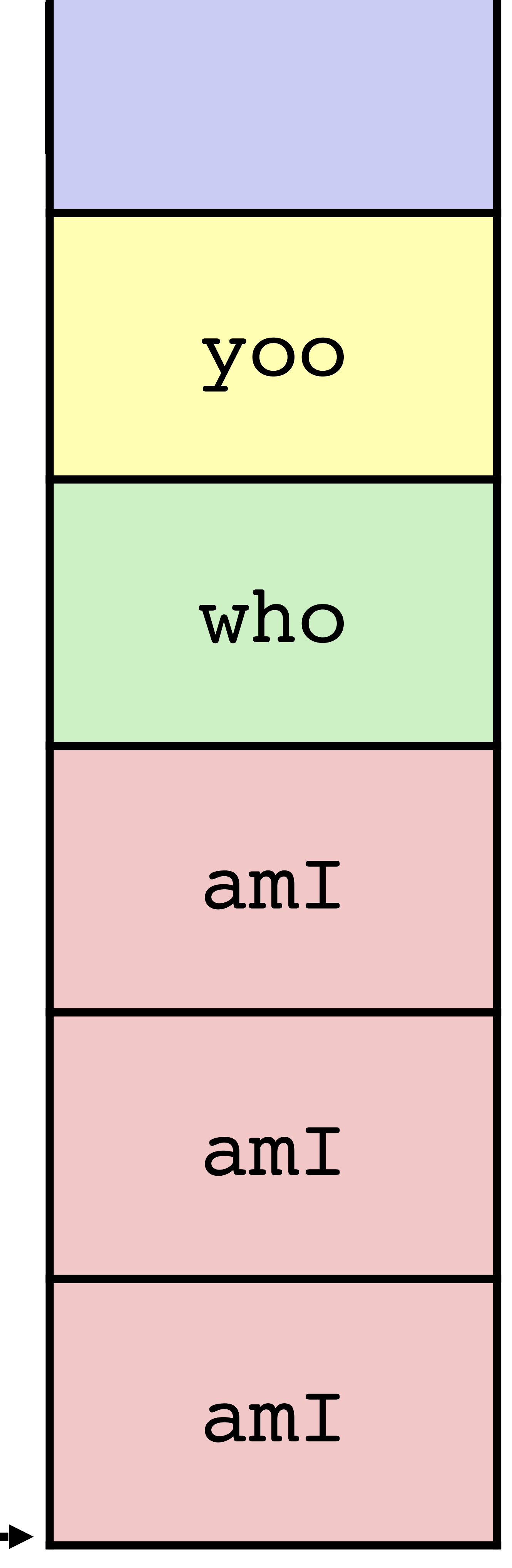
Call stack tracks context



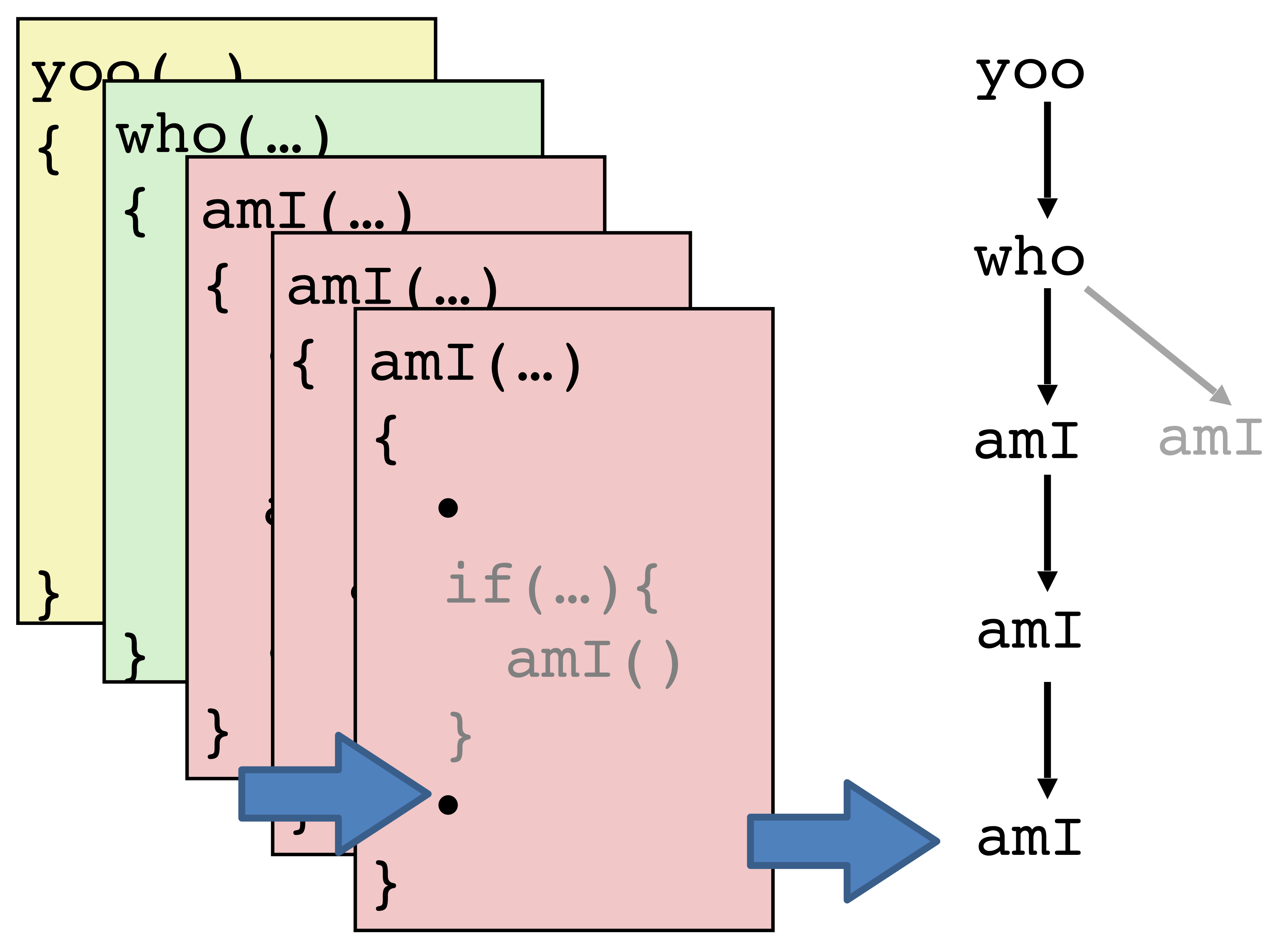


Call stack tracks context

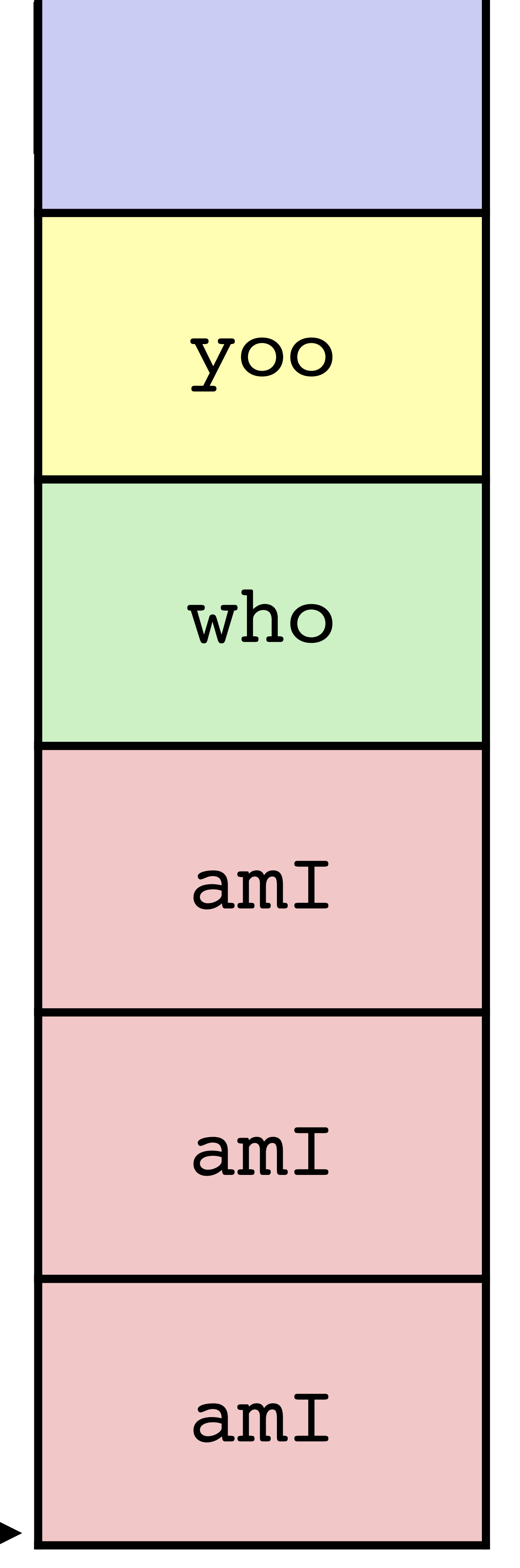




Call stack tracks context



Stack



Call stack tracks context

```
yoo(…)
{
}
```

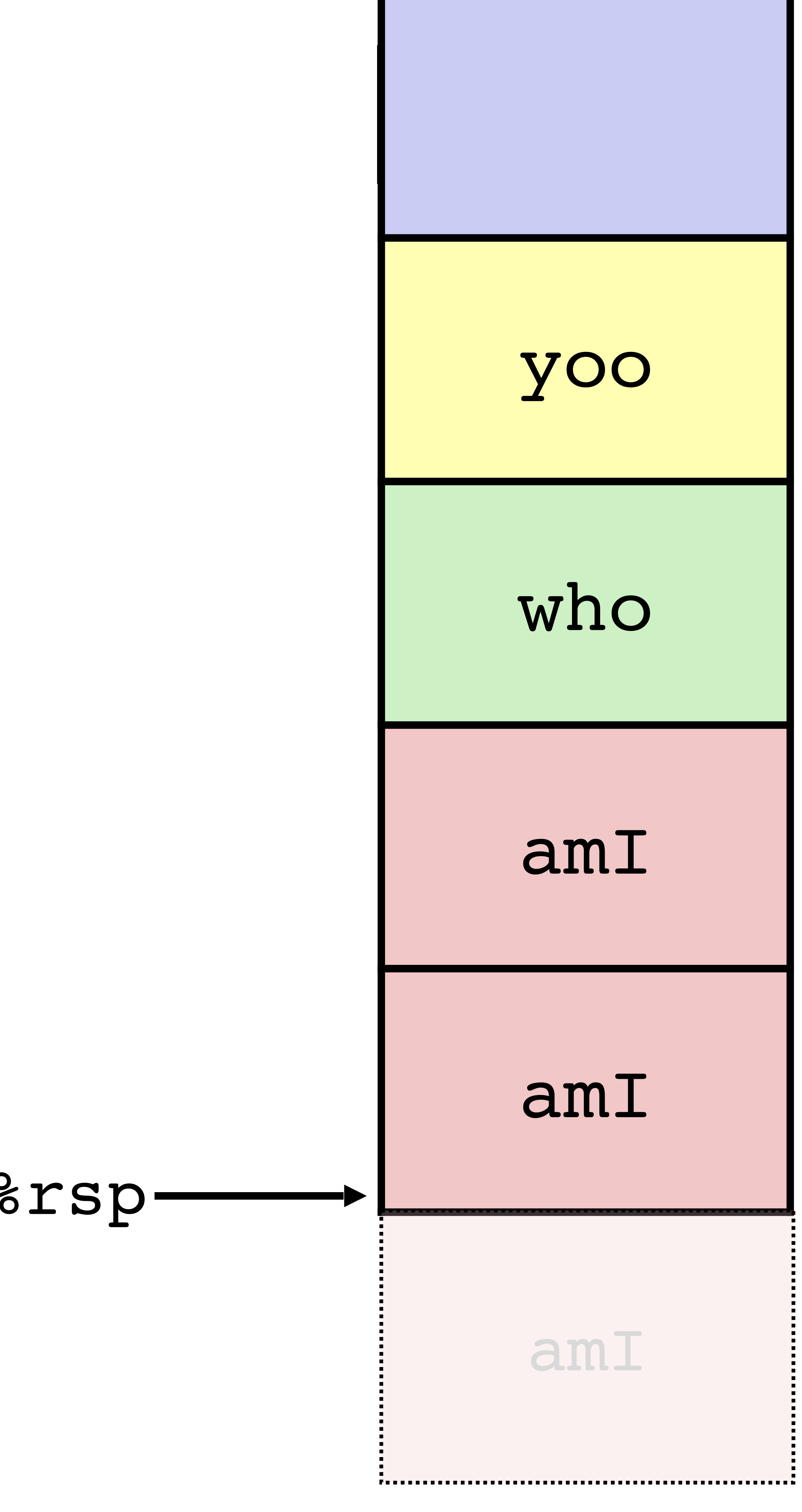
```
who(…)
{
}
```

```
amI(…)
{
}
```

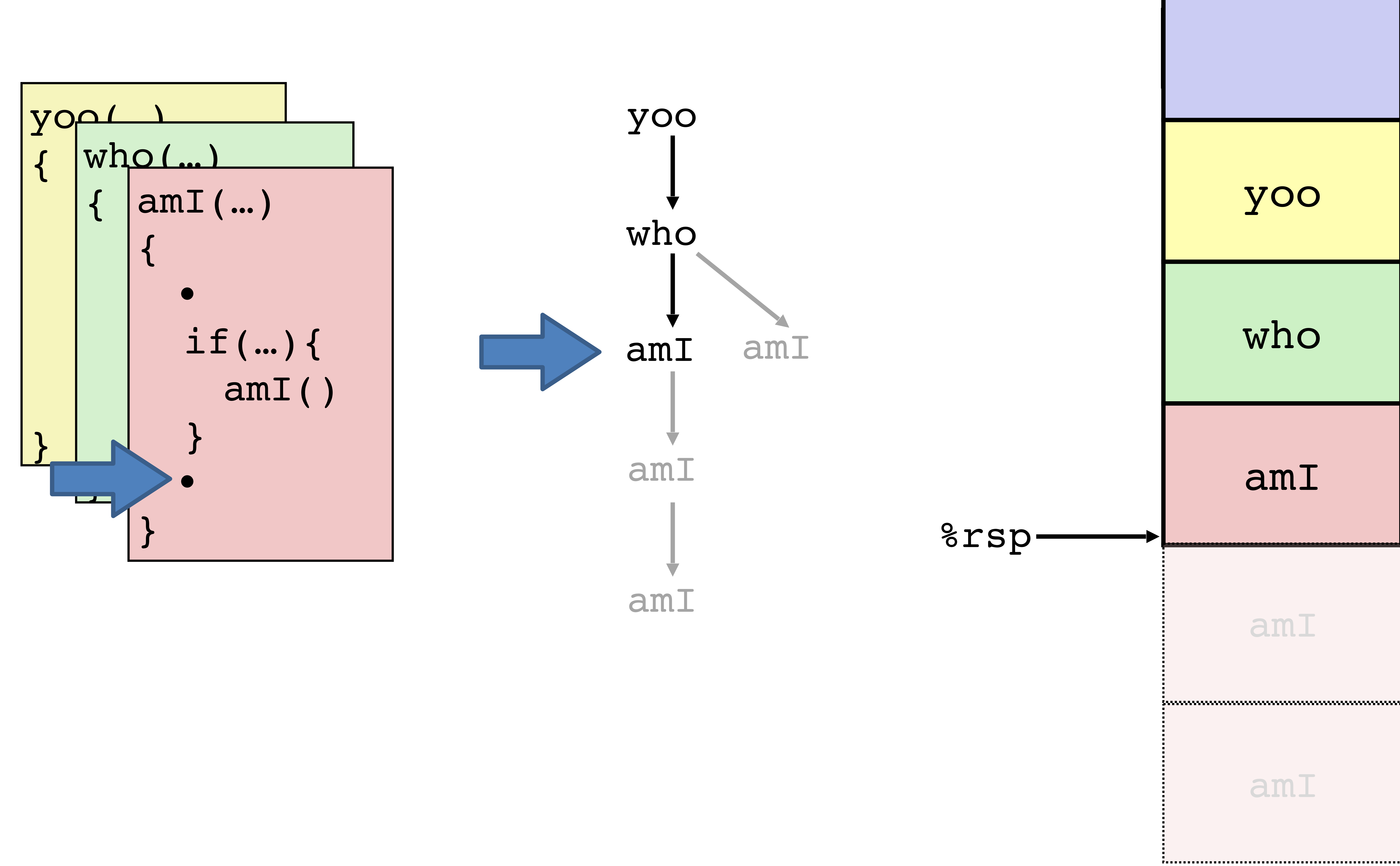
```
amI(…)
{
  •
  if(…){
    amI()
  }
  •
}
```

yoo → who → amI → amI → amI

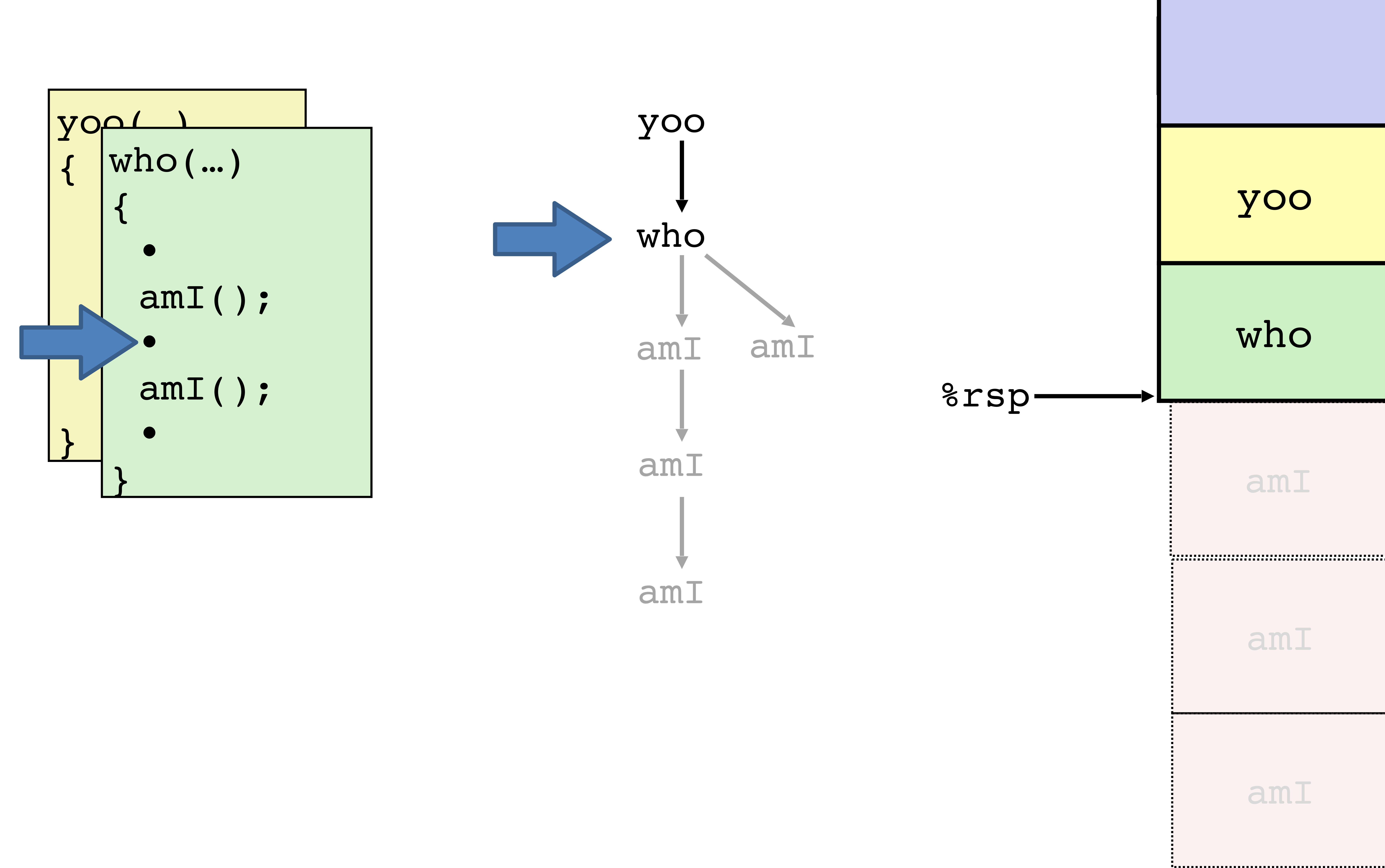
who → amI



Call stack tracks context

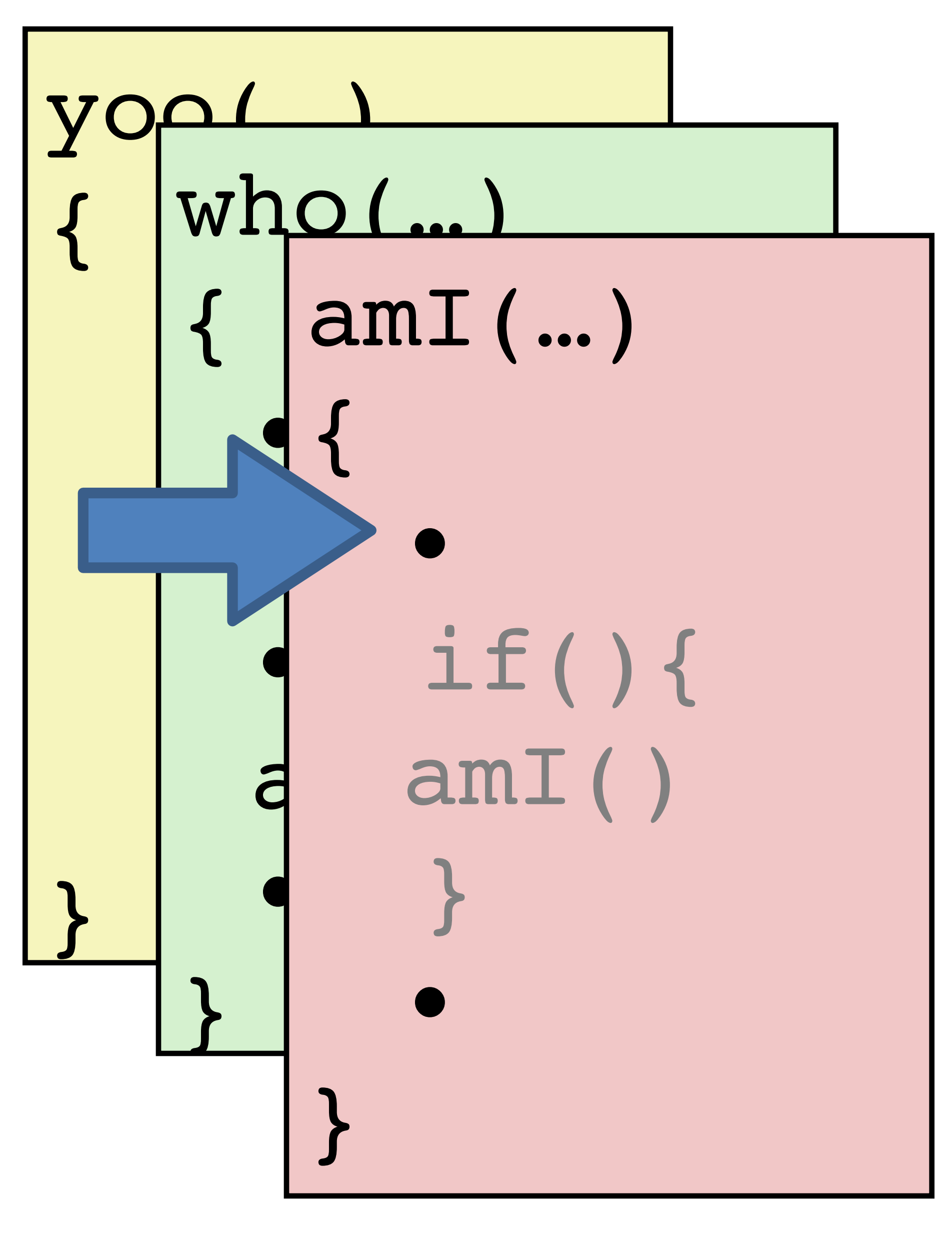


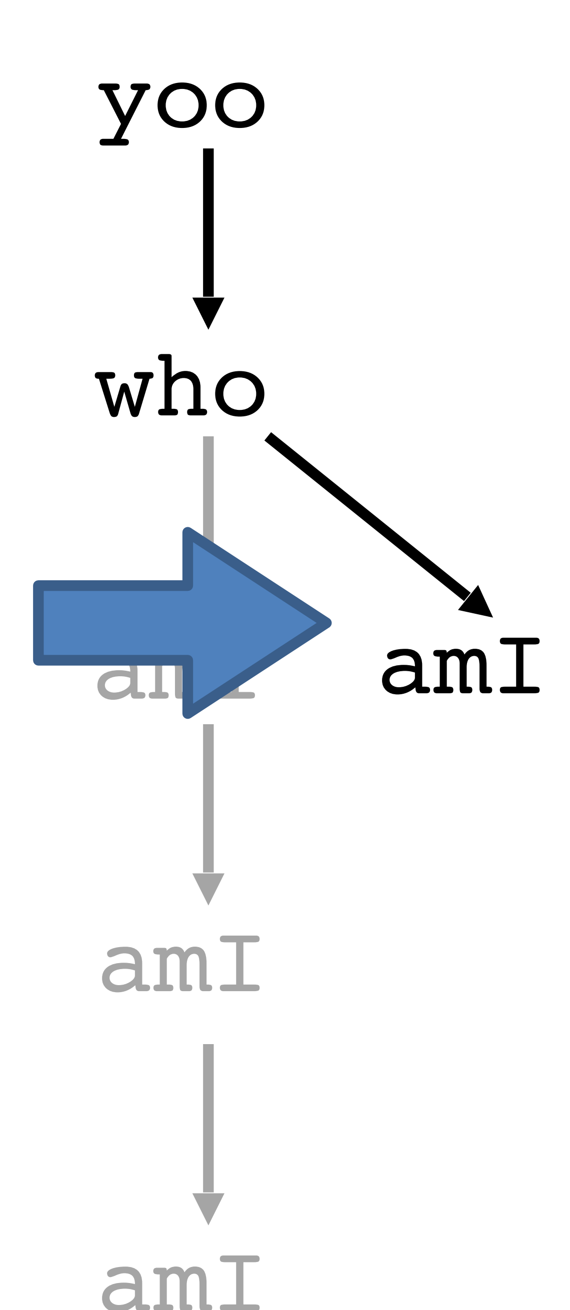
Call stack tracks context

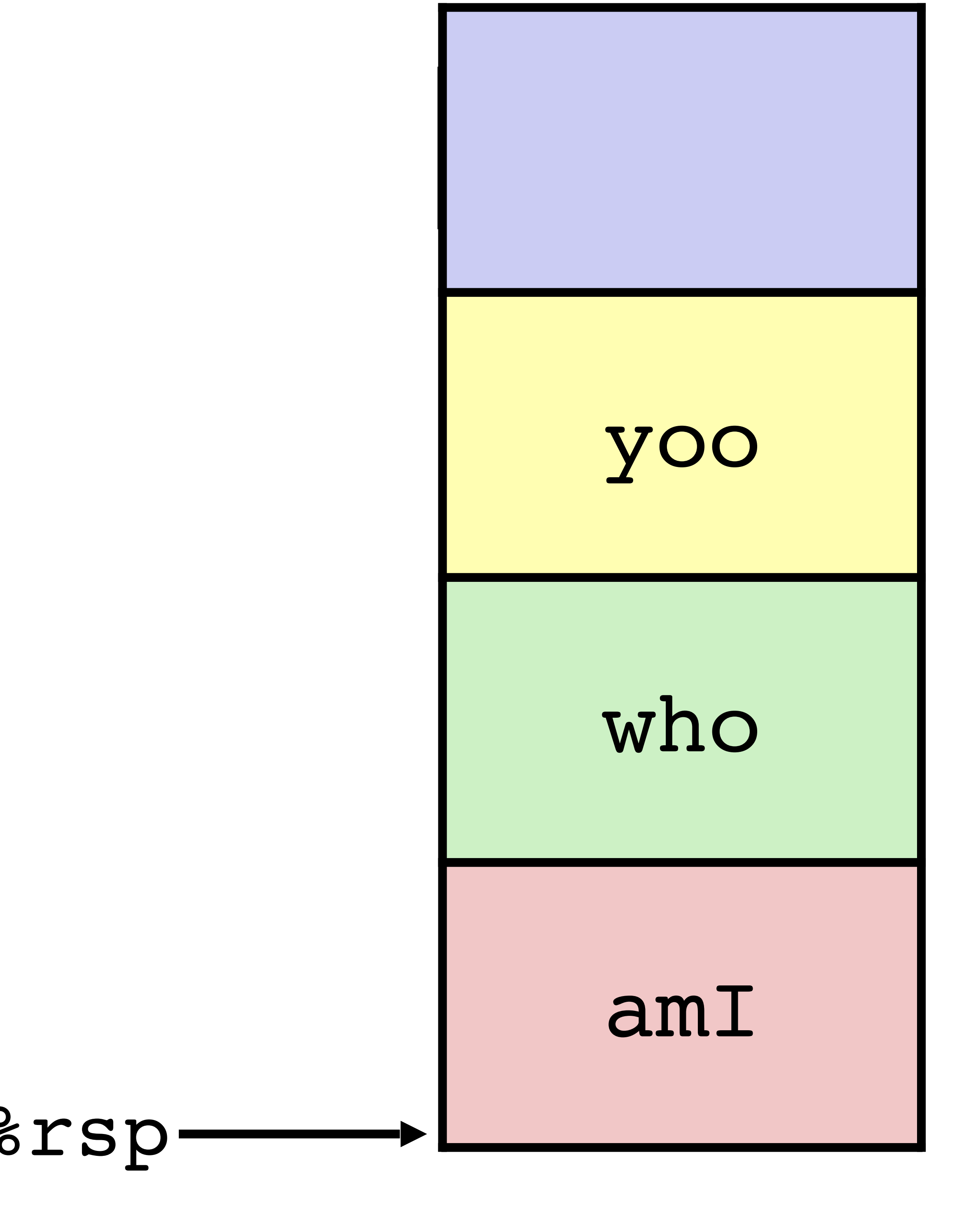


Stack

Call stack tracks context

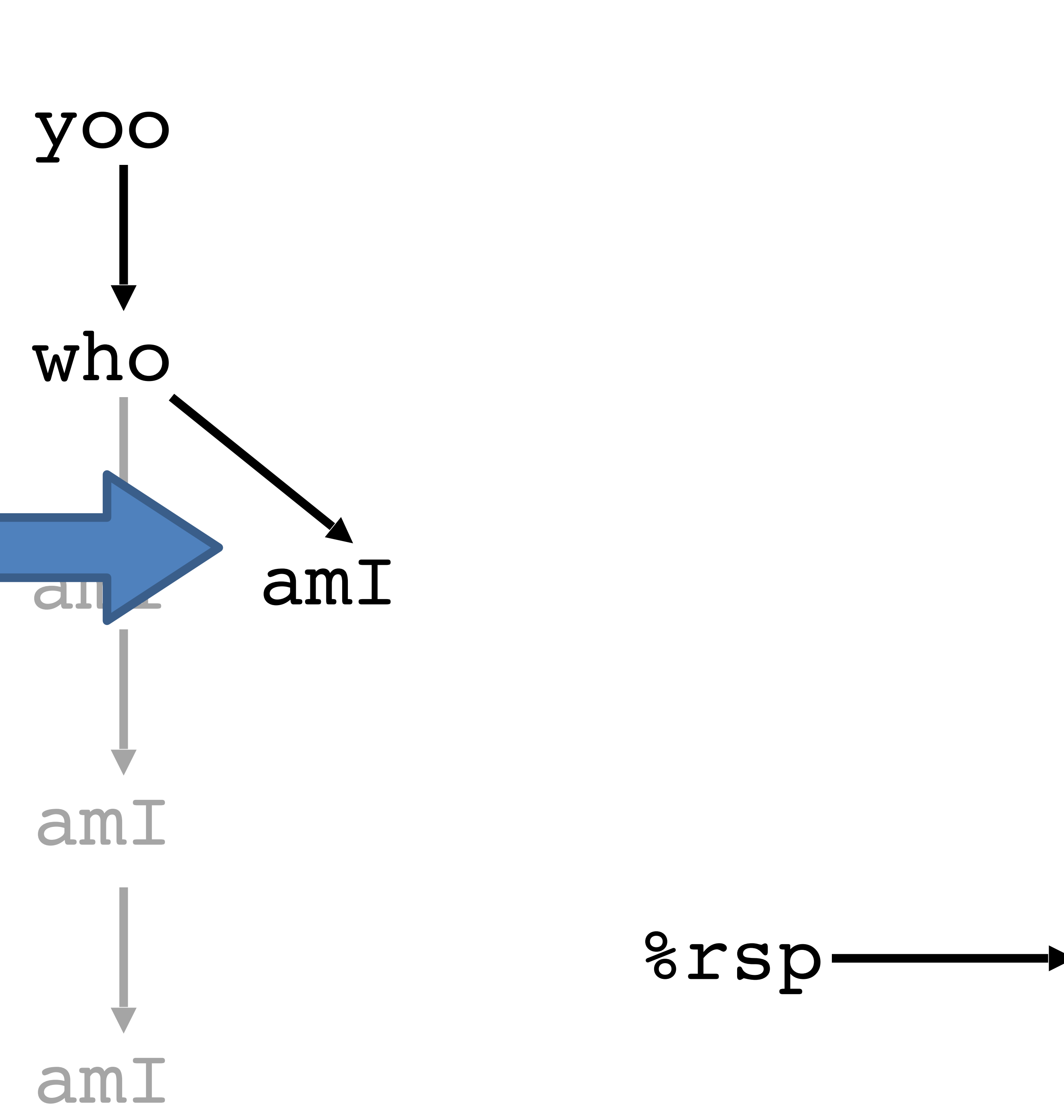






Call stack tracks context

```
yoo(…)
{
}

who(…)
{
}

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



yoo

who

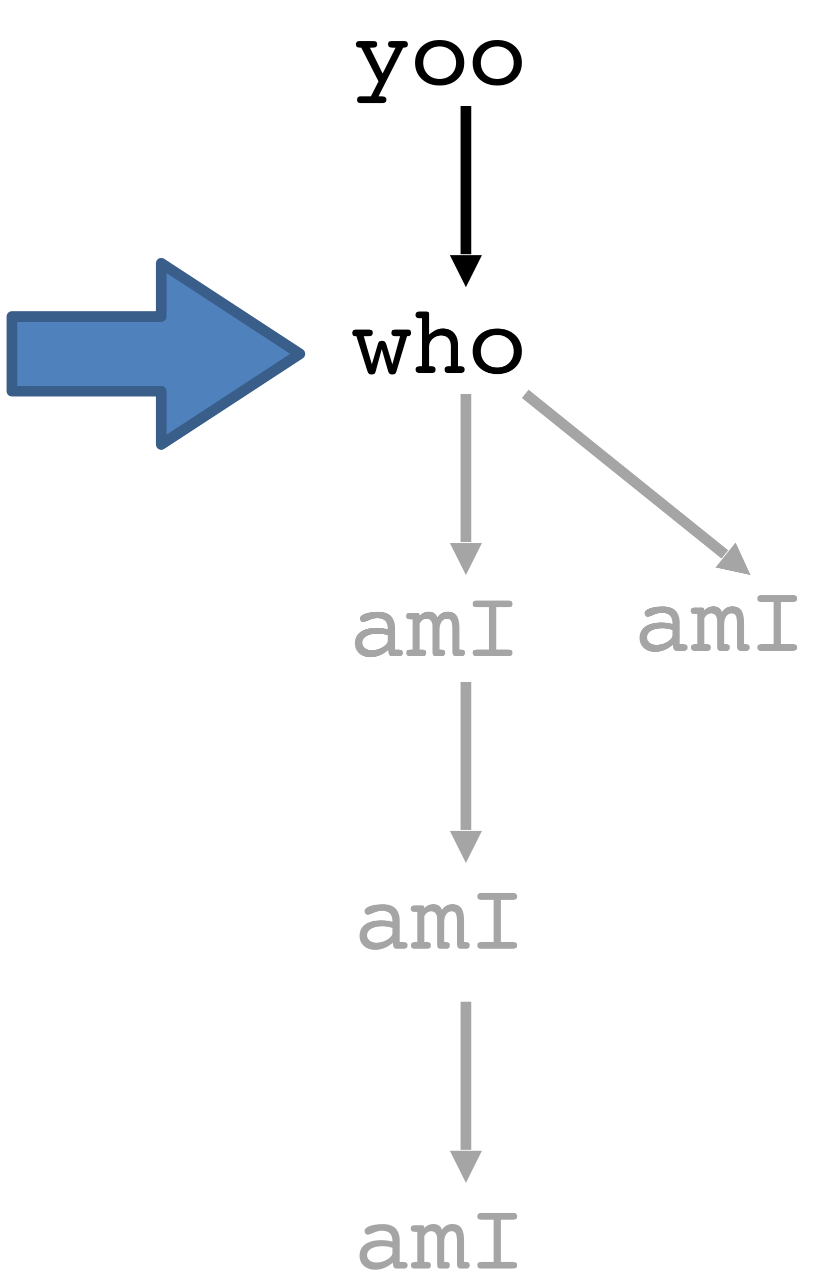
amI

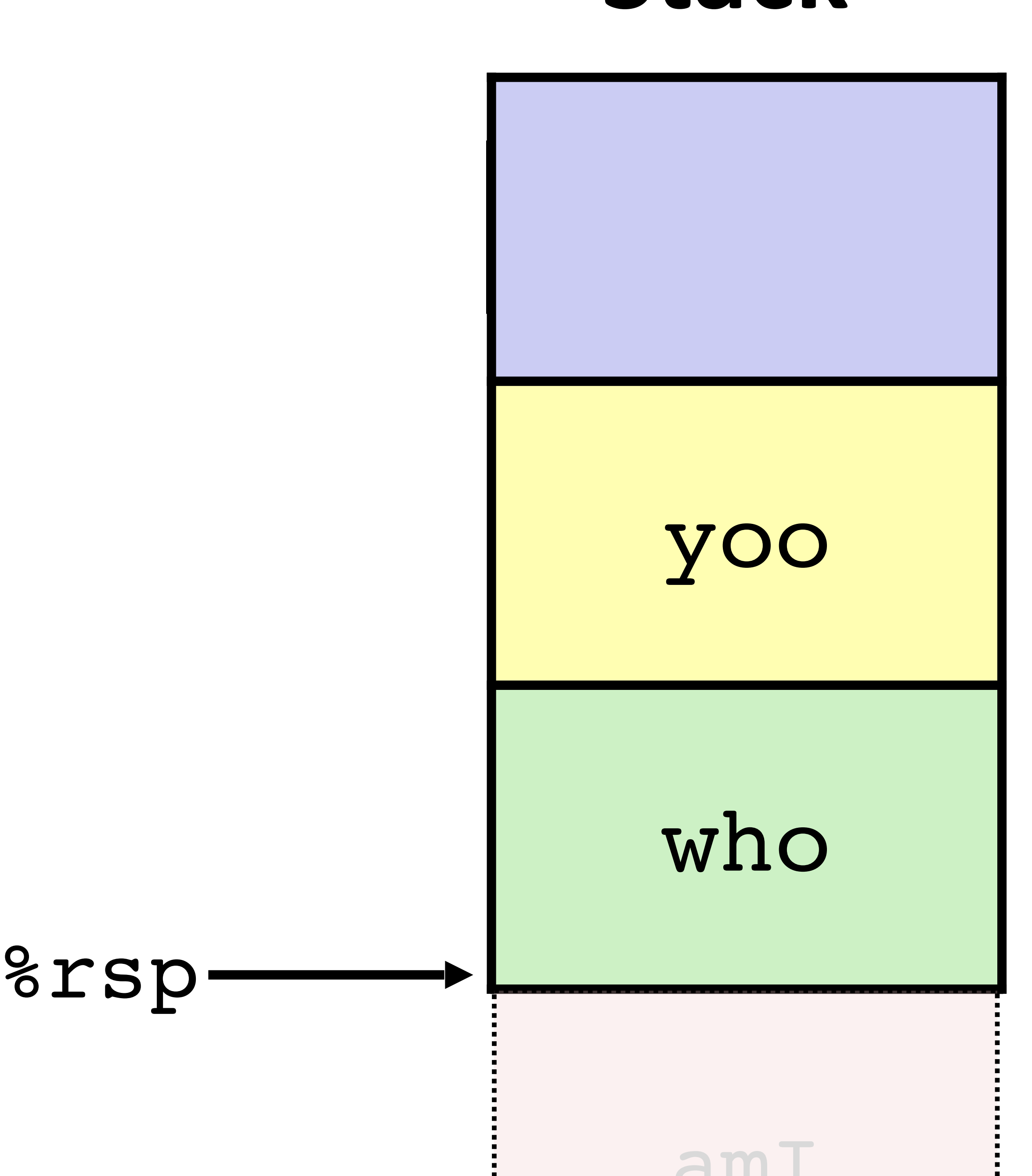
%rsp

Call stack tracks context

```
yoo(…)
{
```

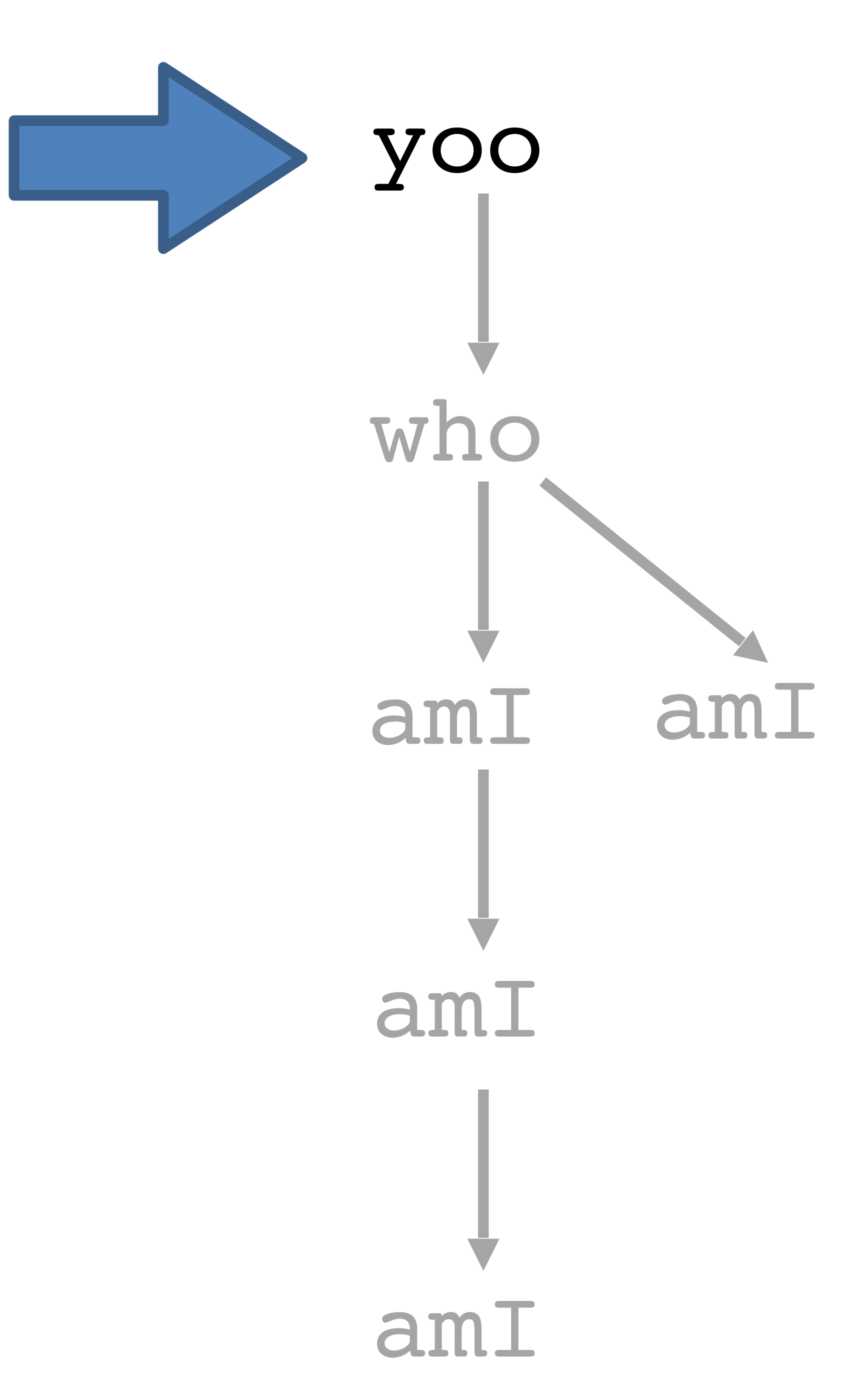
```
who(…)
{
  •
  amI();
  •
  amI();
  •
}
```

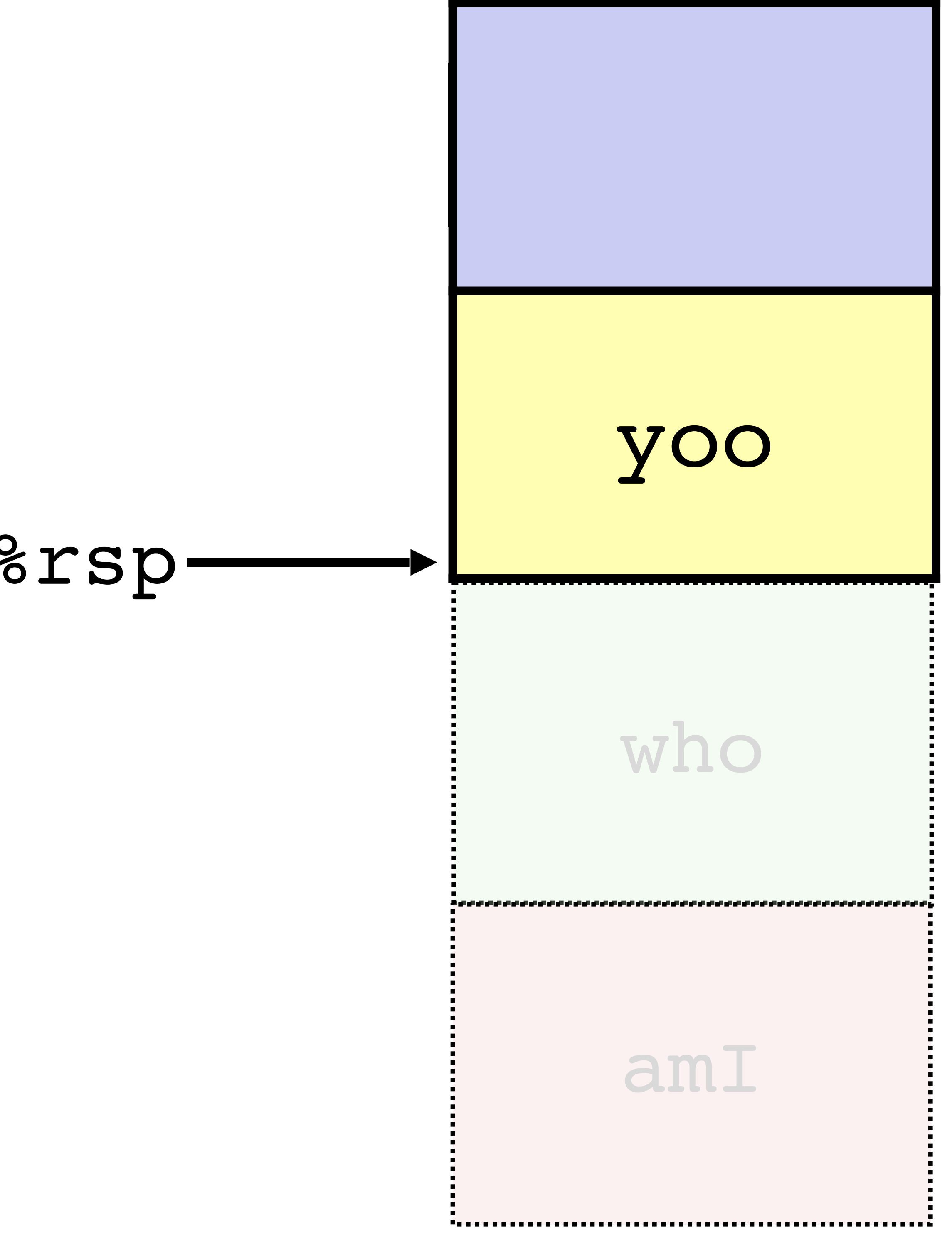




Call stack tracks context

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



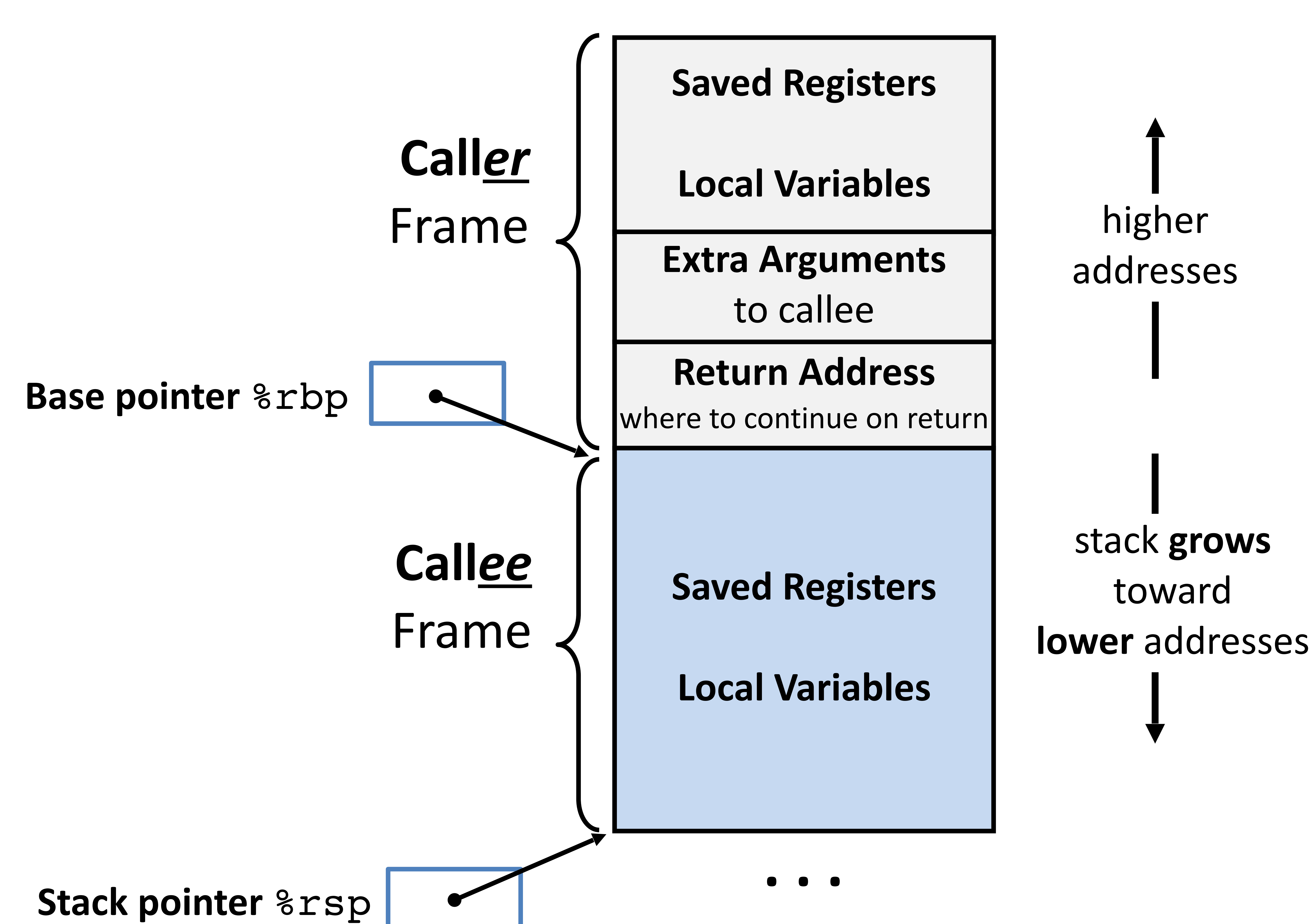


The call stack supports procedures

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 control flow 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

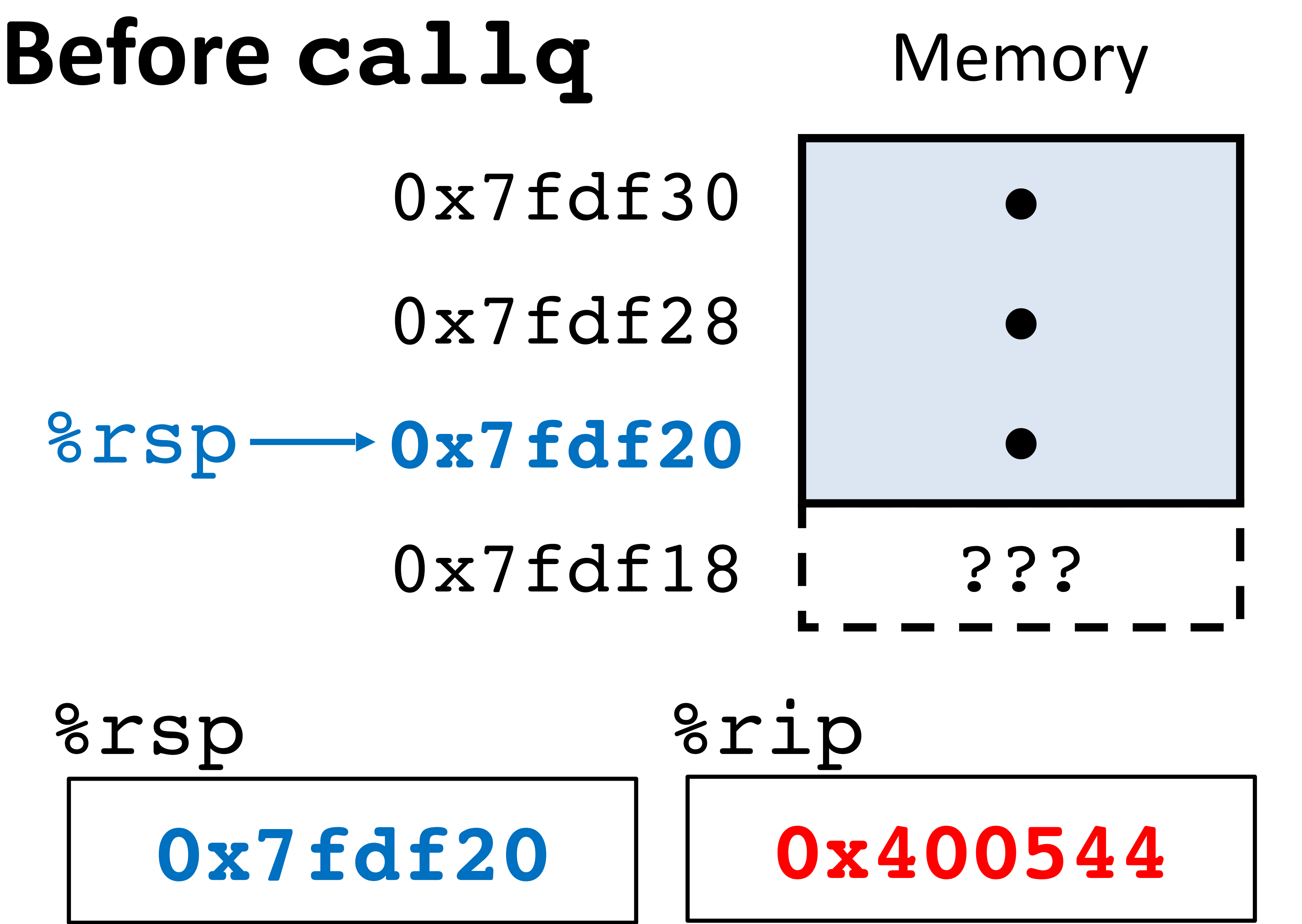
Call example

```
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*



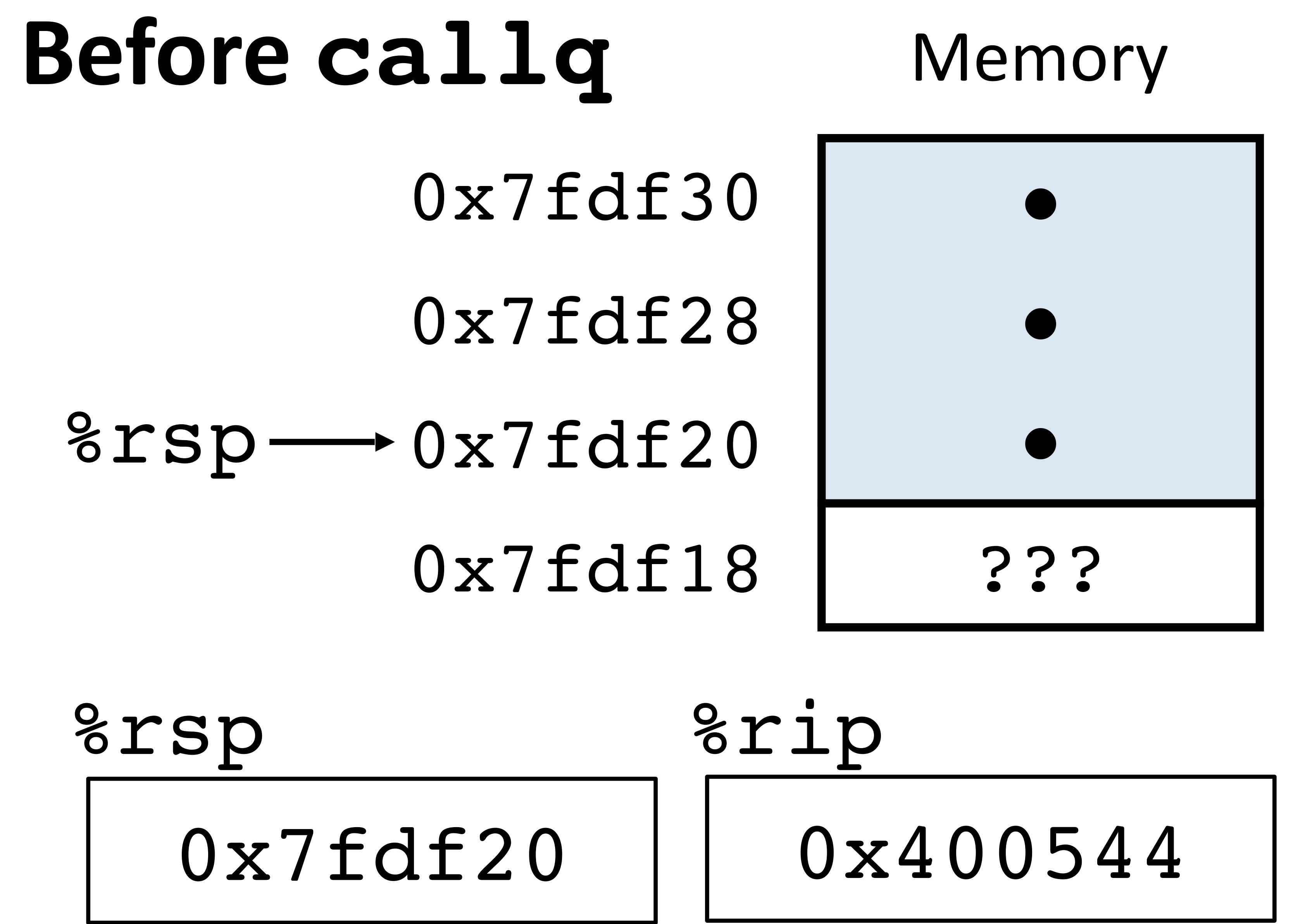
Call example

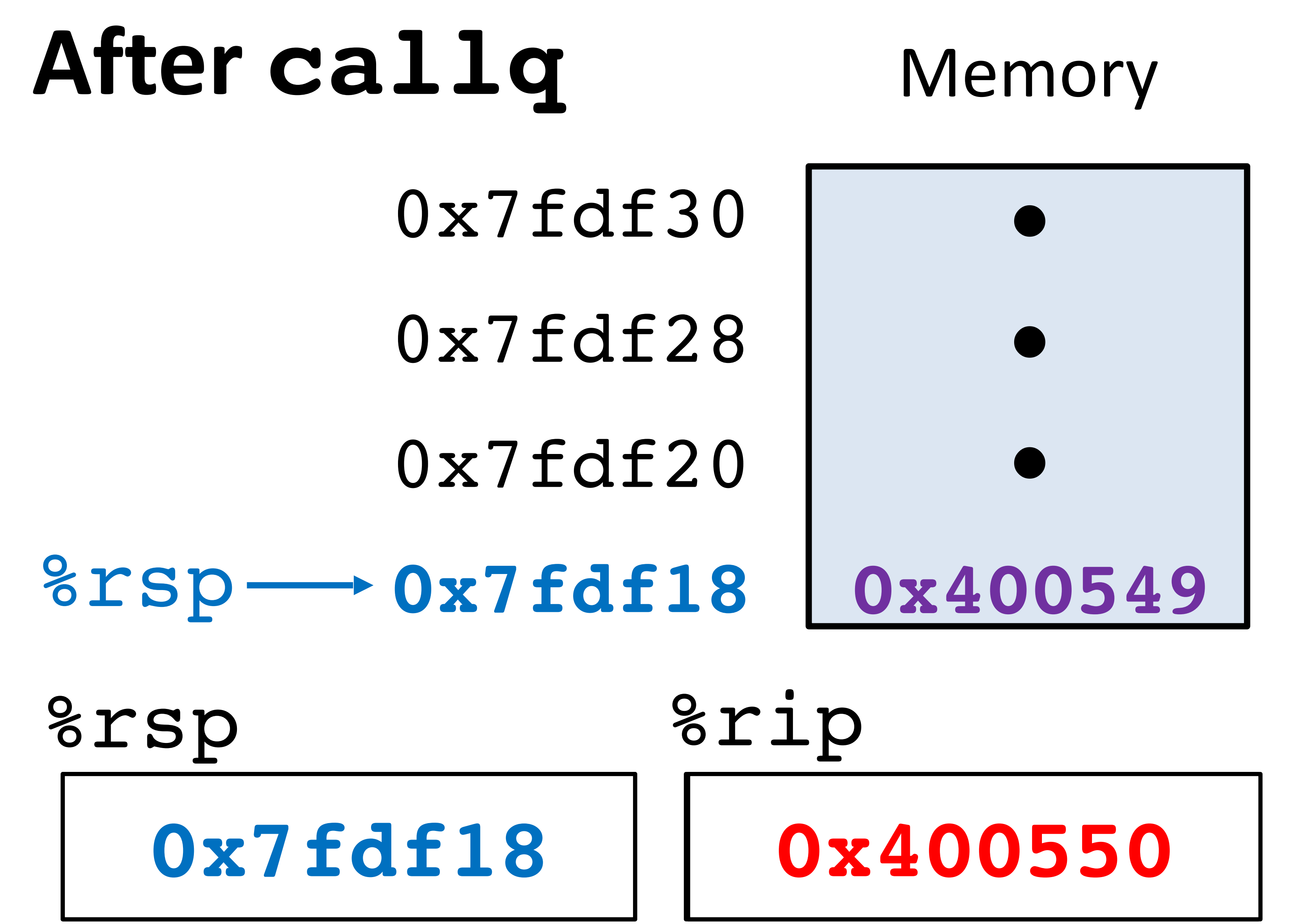
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

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

callq ***target***

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



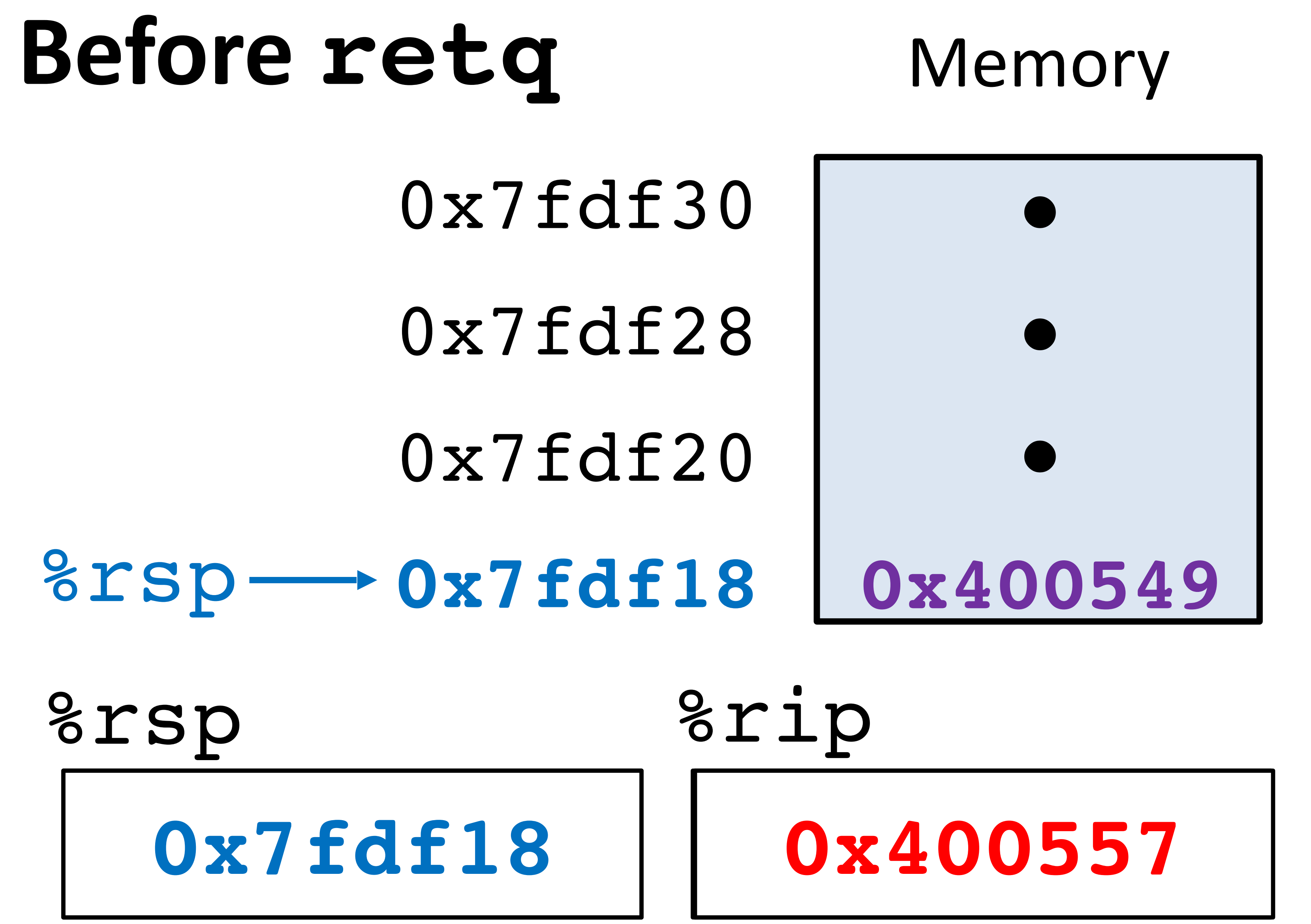


Return example

```
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



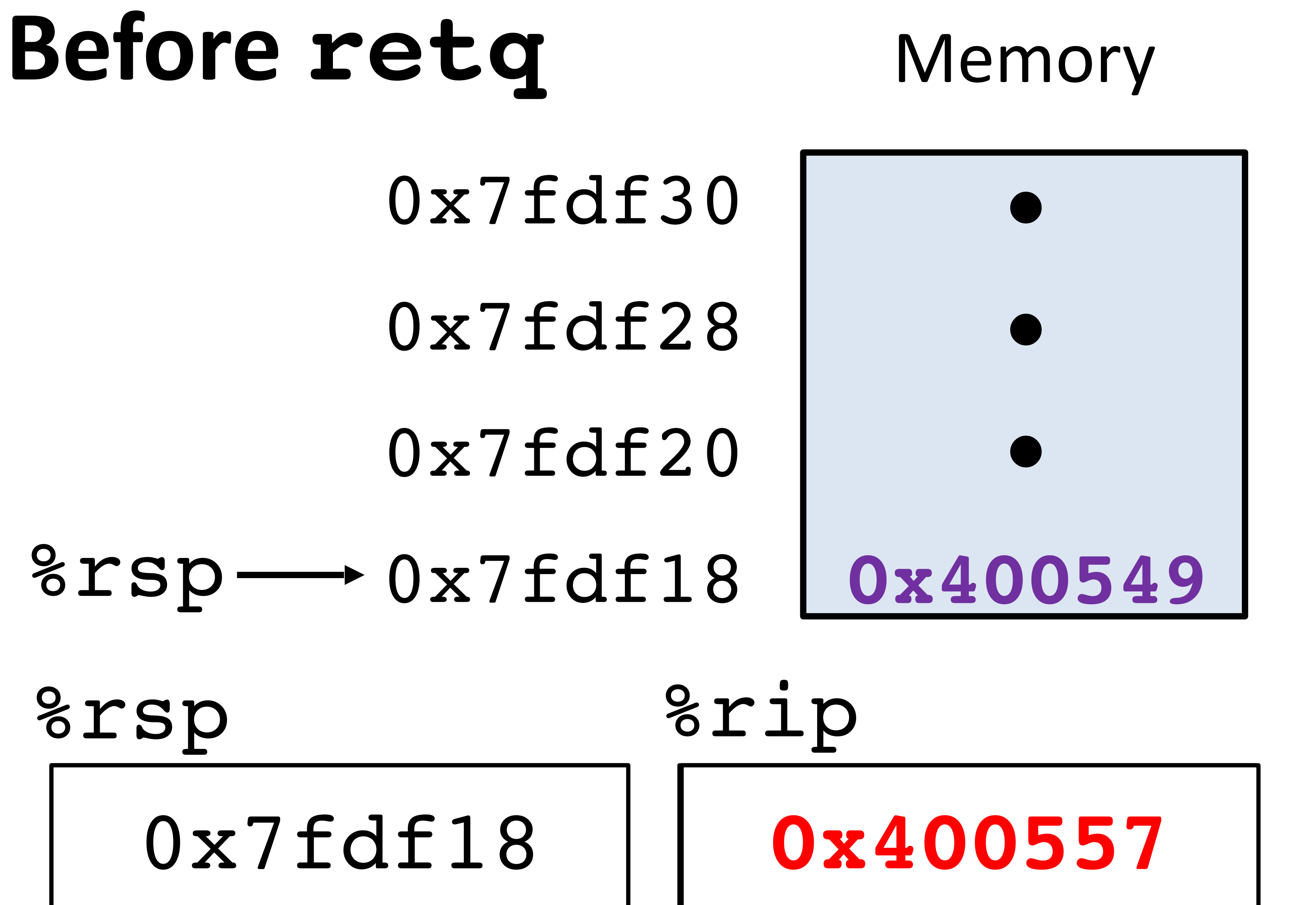
Return example

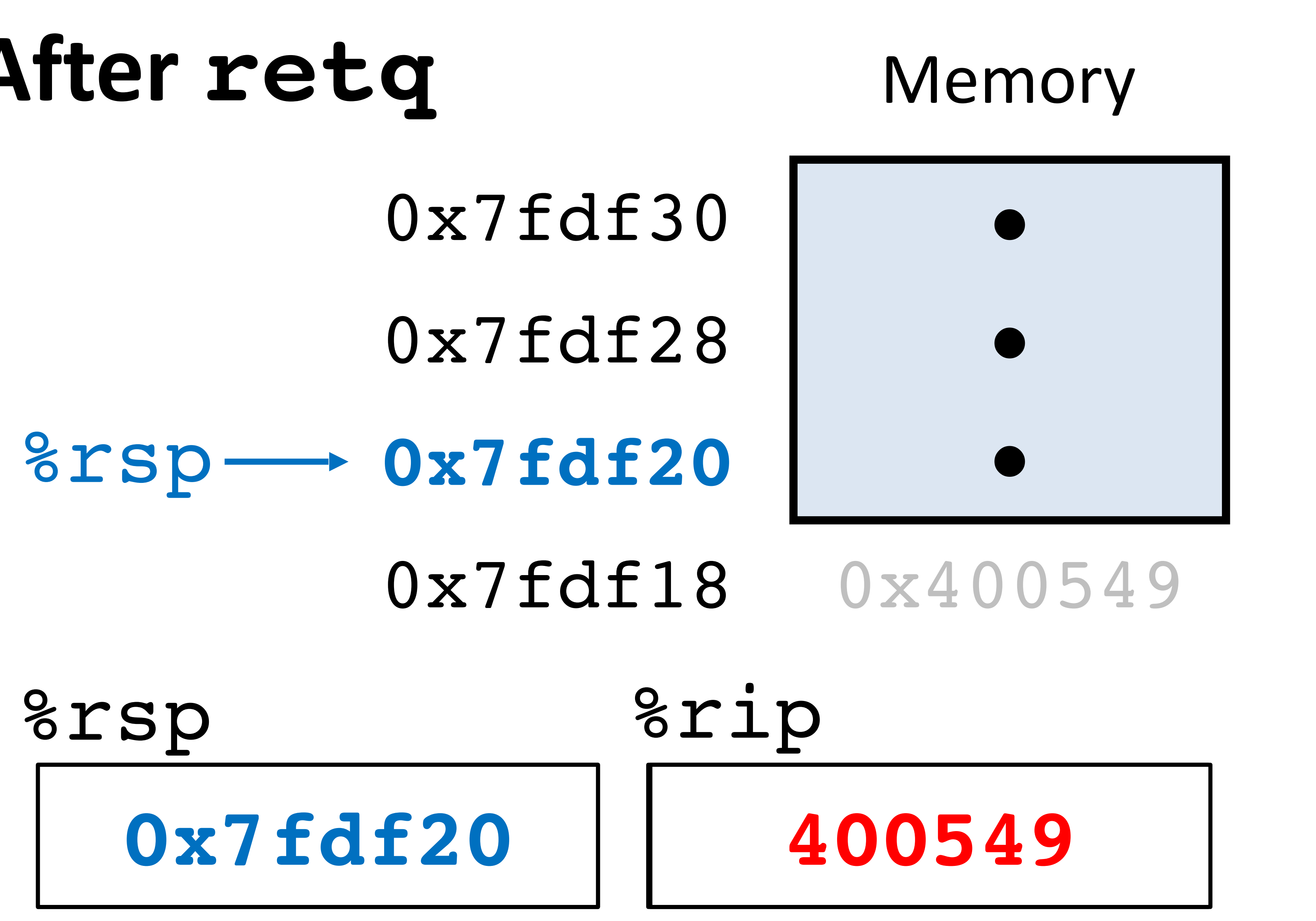
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

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

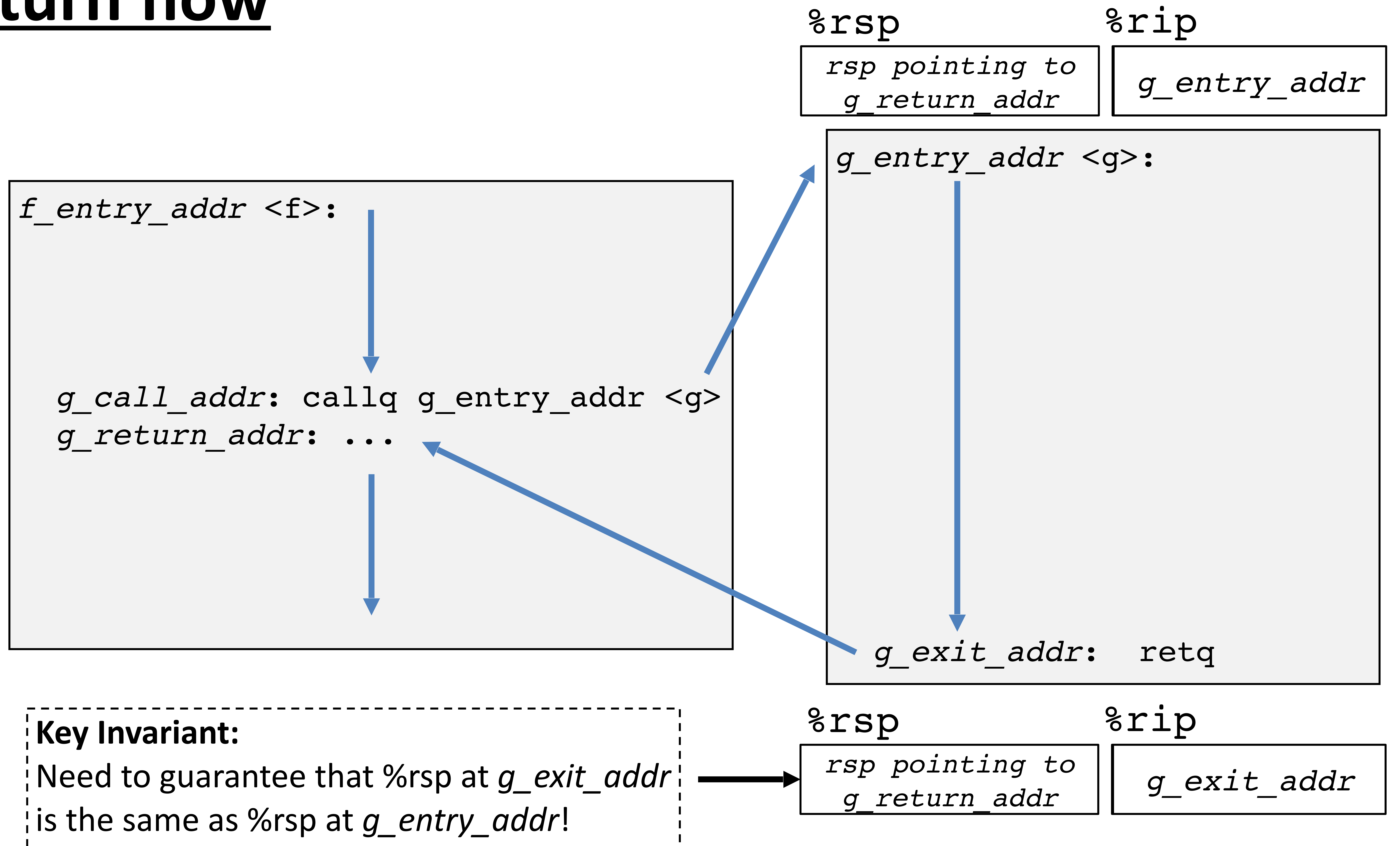
retq

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

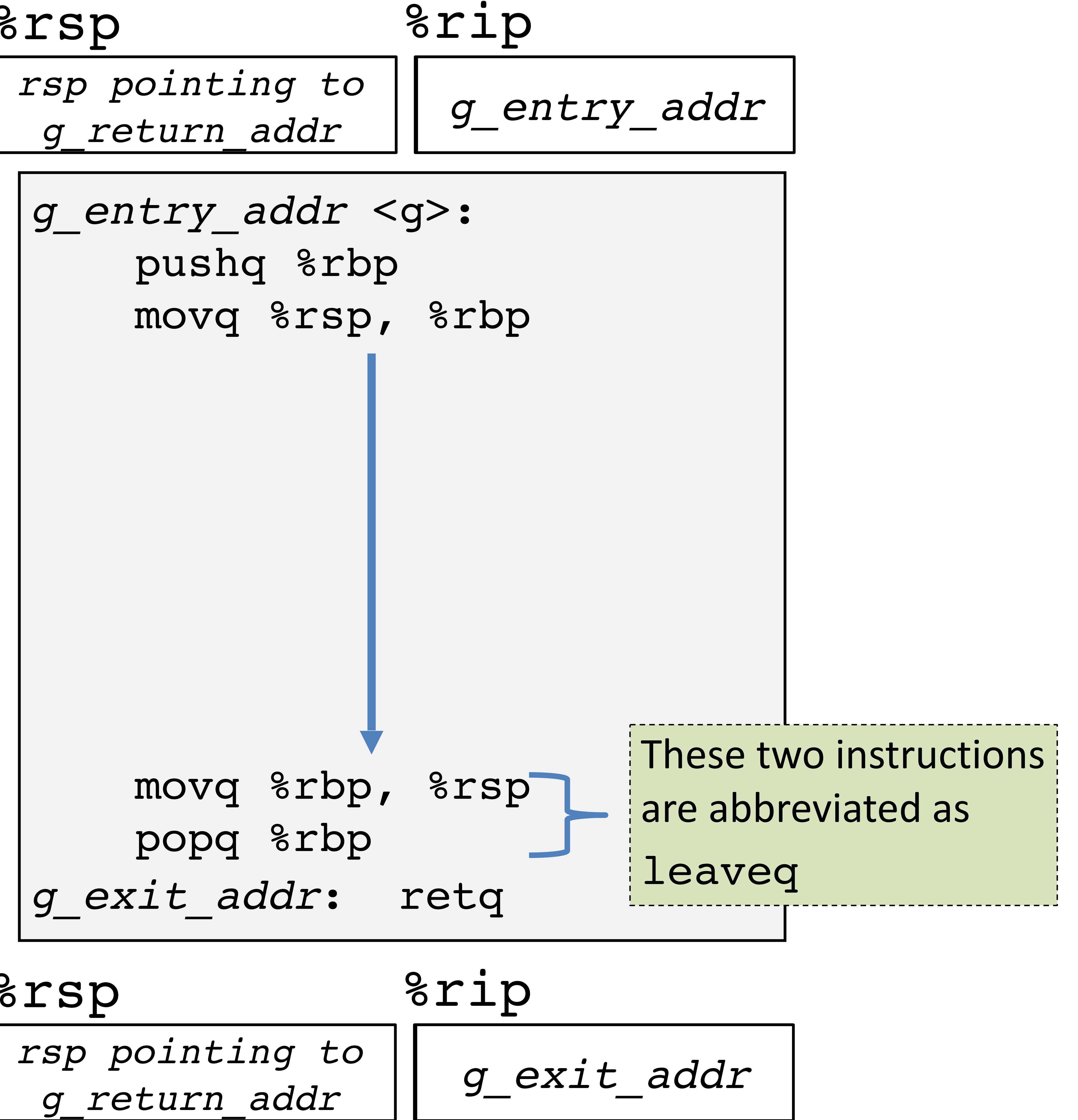




Call/Return flow



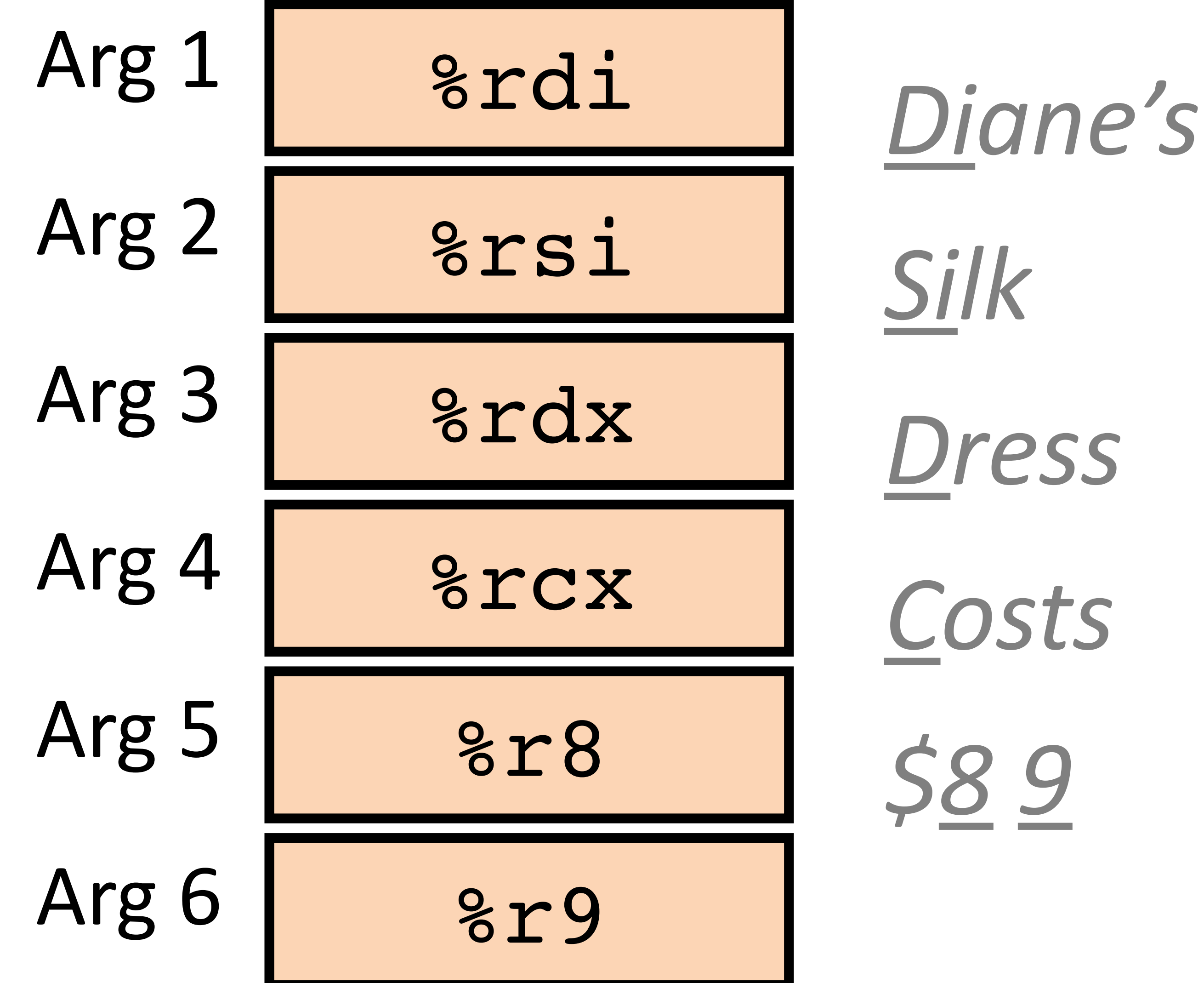
%rbp prologue/epilog is easy way to guarantee %rsp invariant



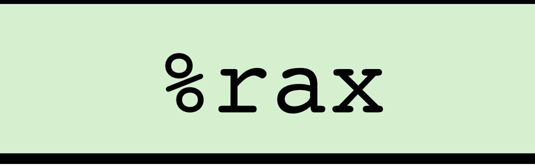
Procedure **data flow** conventions

Recall:

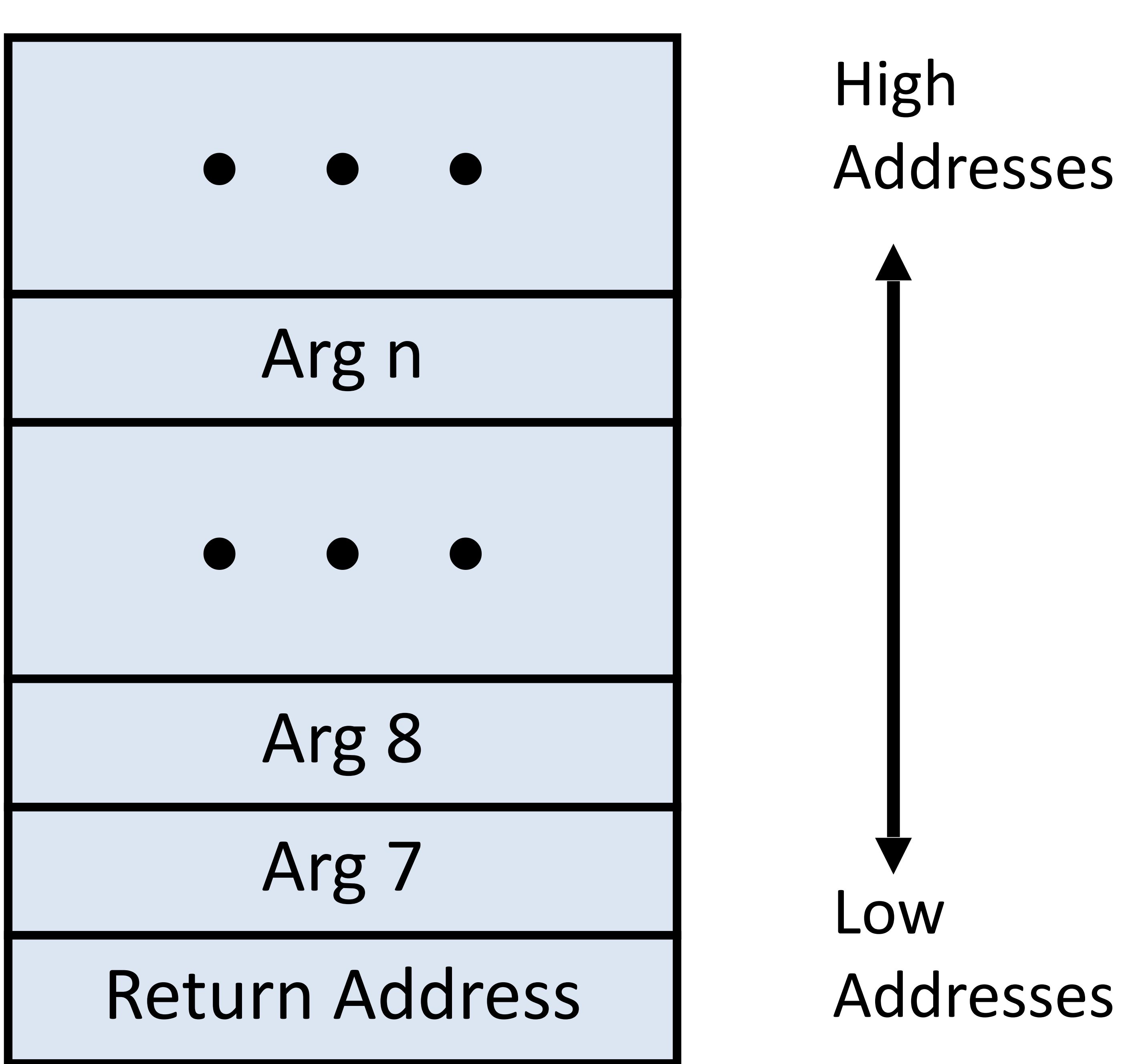
First 6 arguments: passed in **registers**



Return value: passed in **%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).

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

Uses memory through pointer.

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

Procedure call example (step 0)

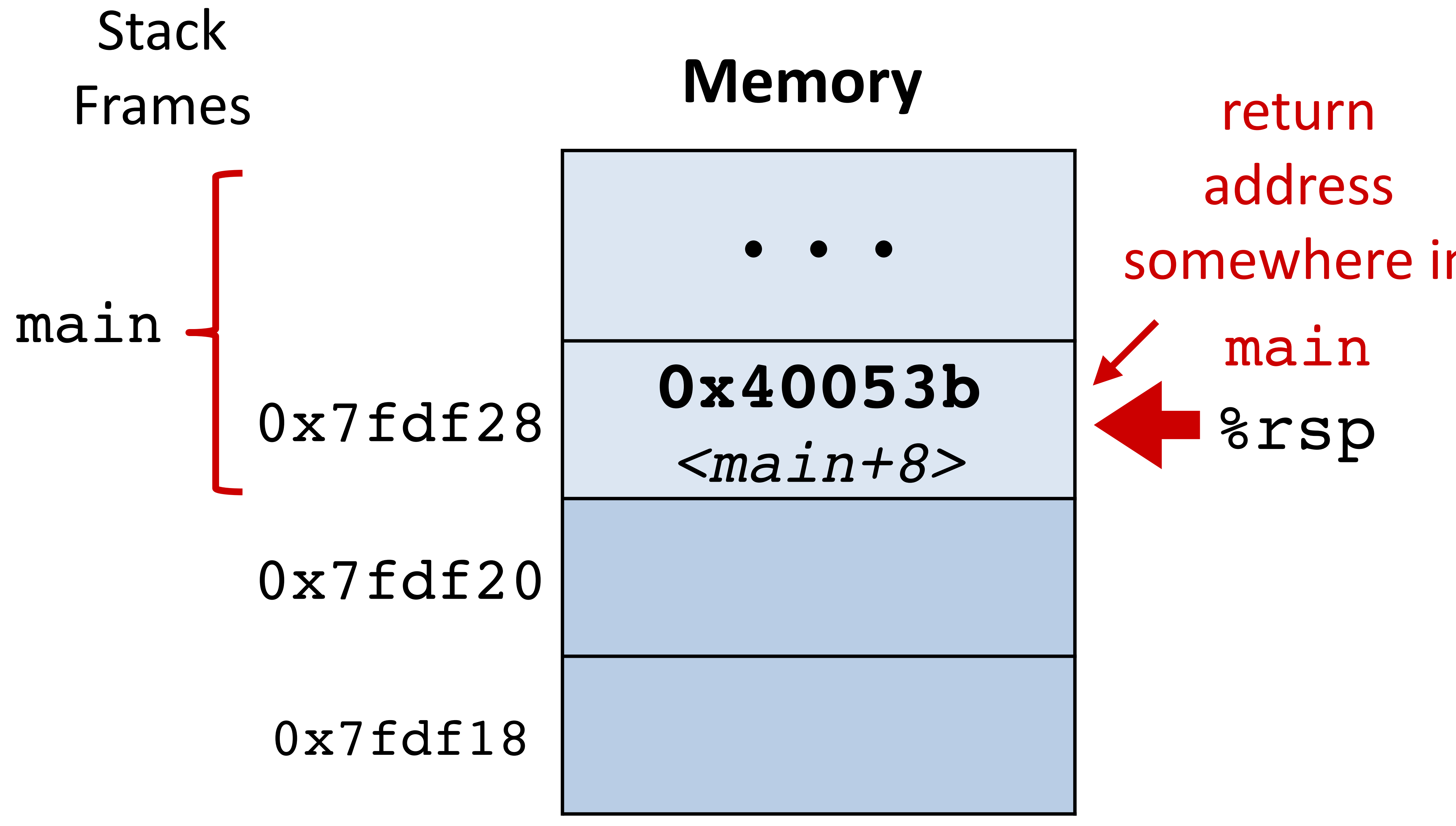
red line shows %rip

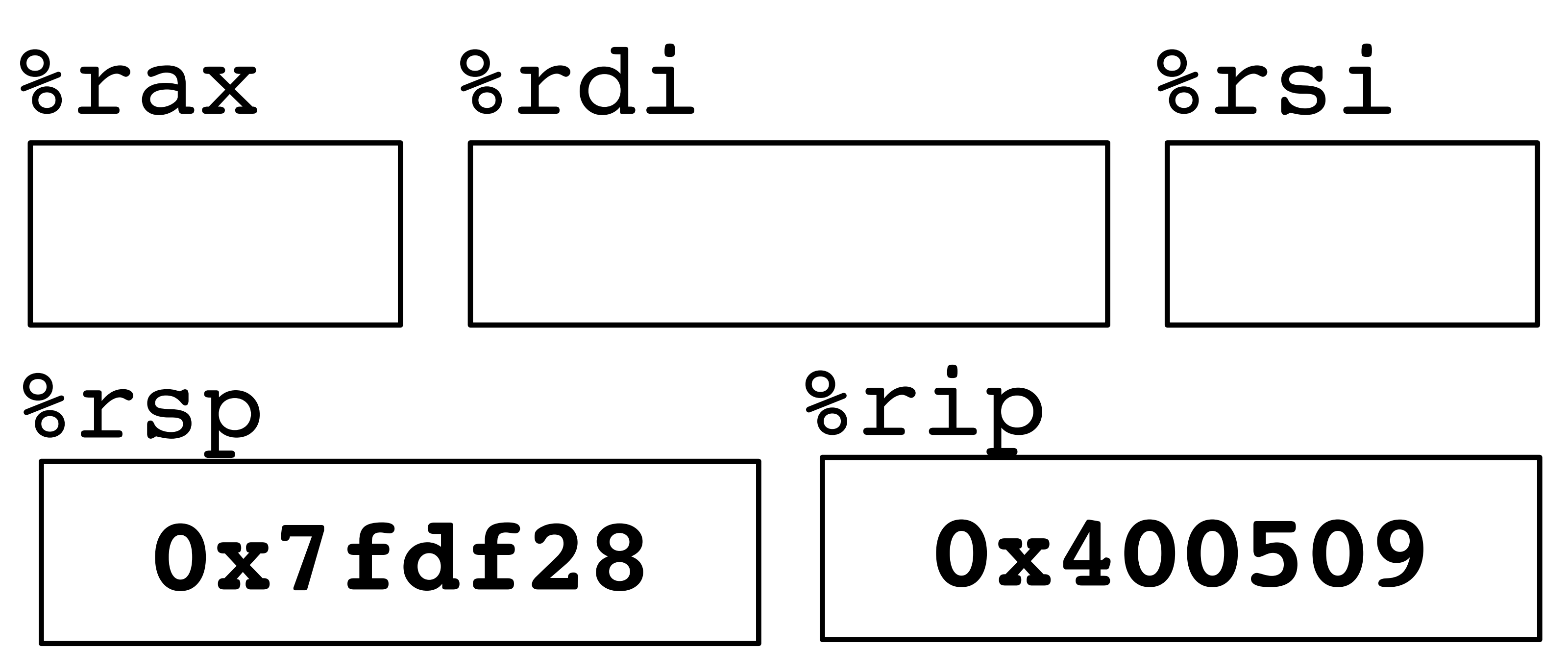
```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
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
```

main called step_up





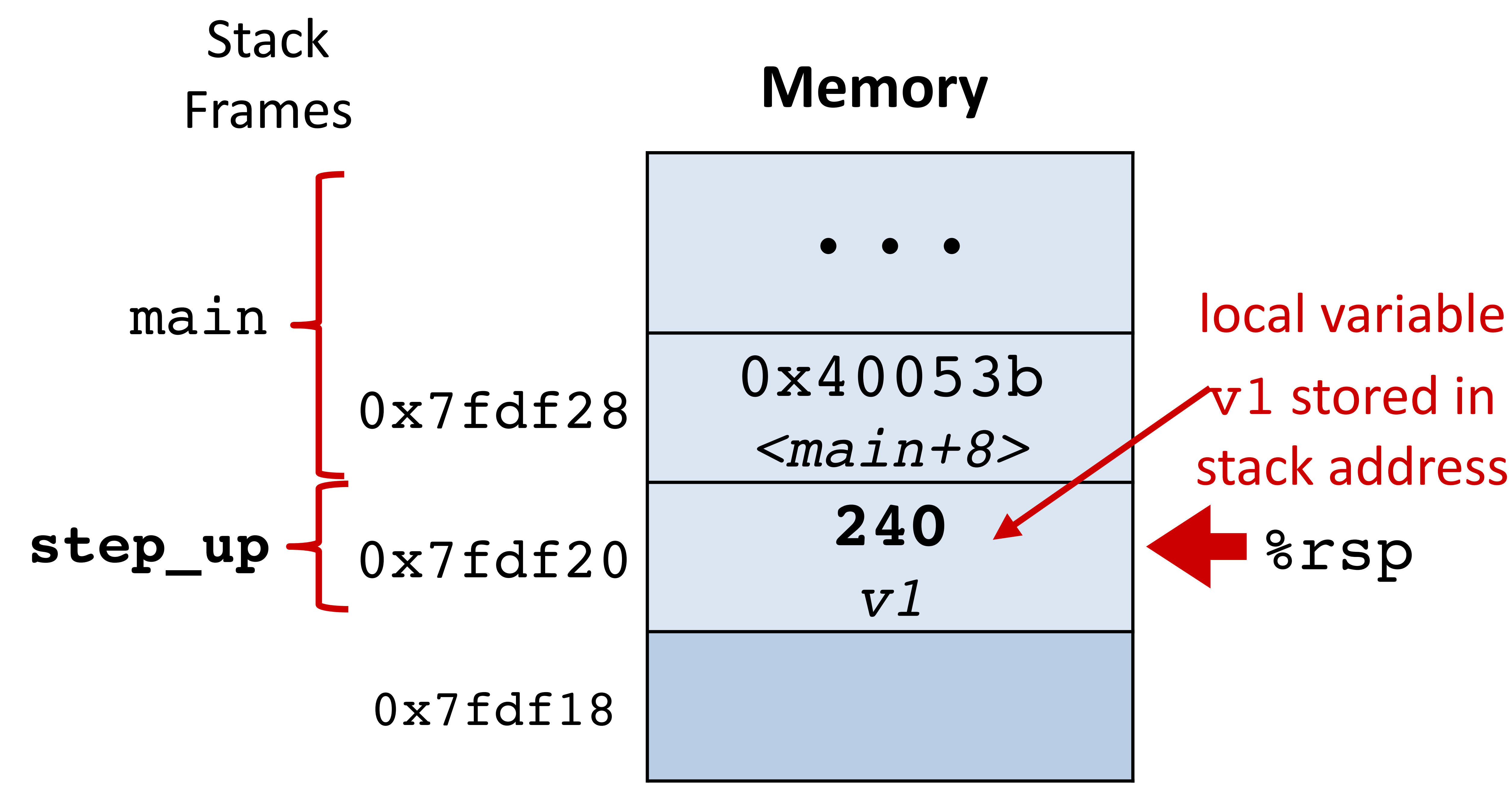
Procedure call example (step 1)

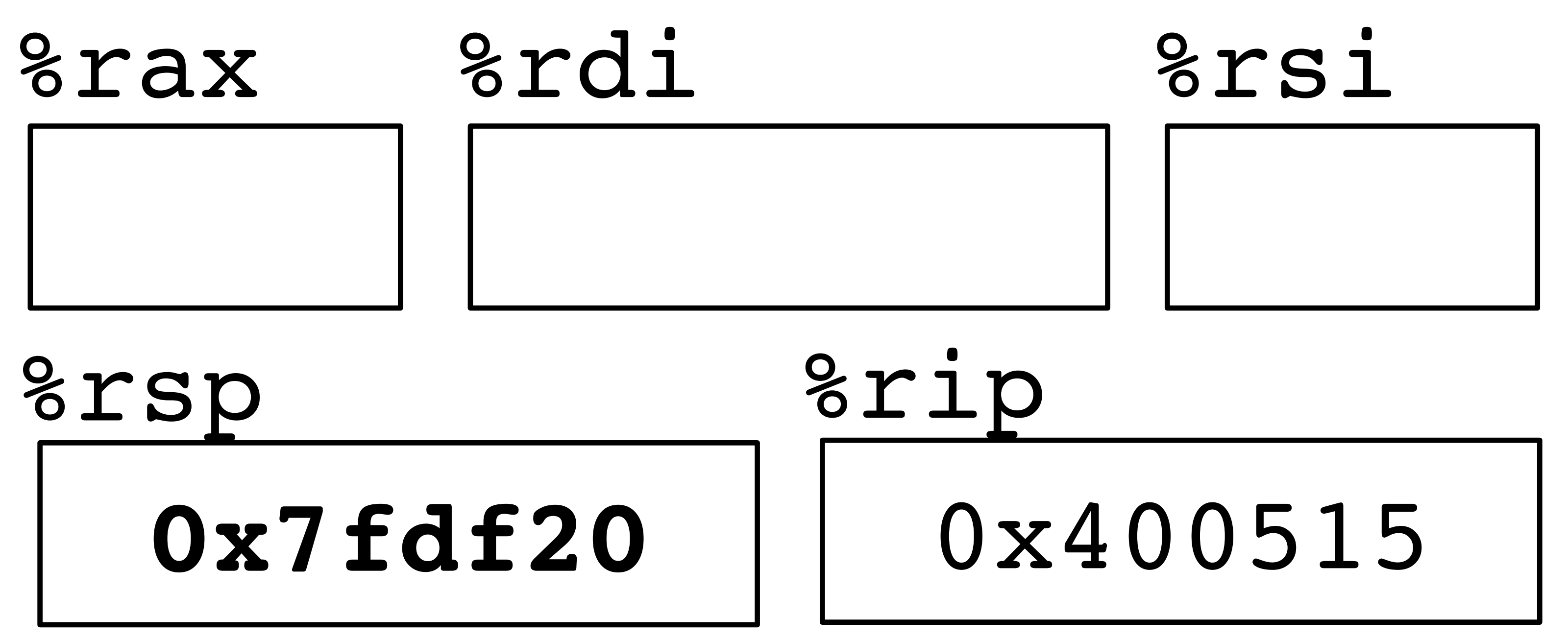
Allocate space for local vars

```
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
```





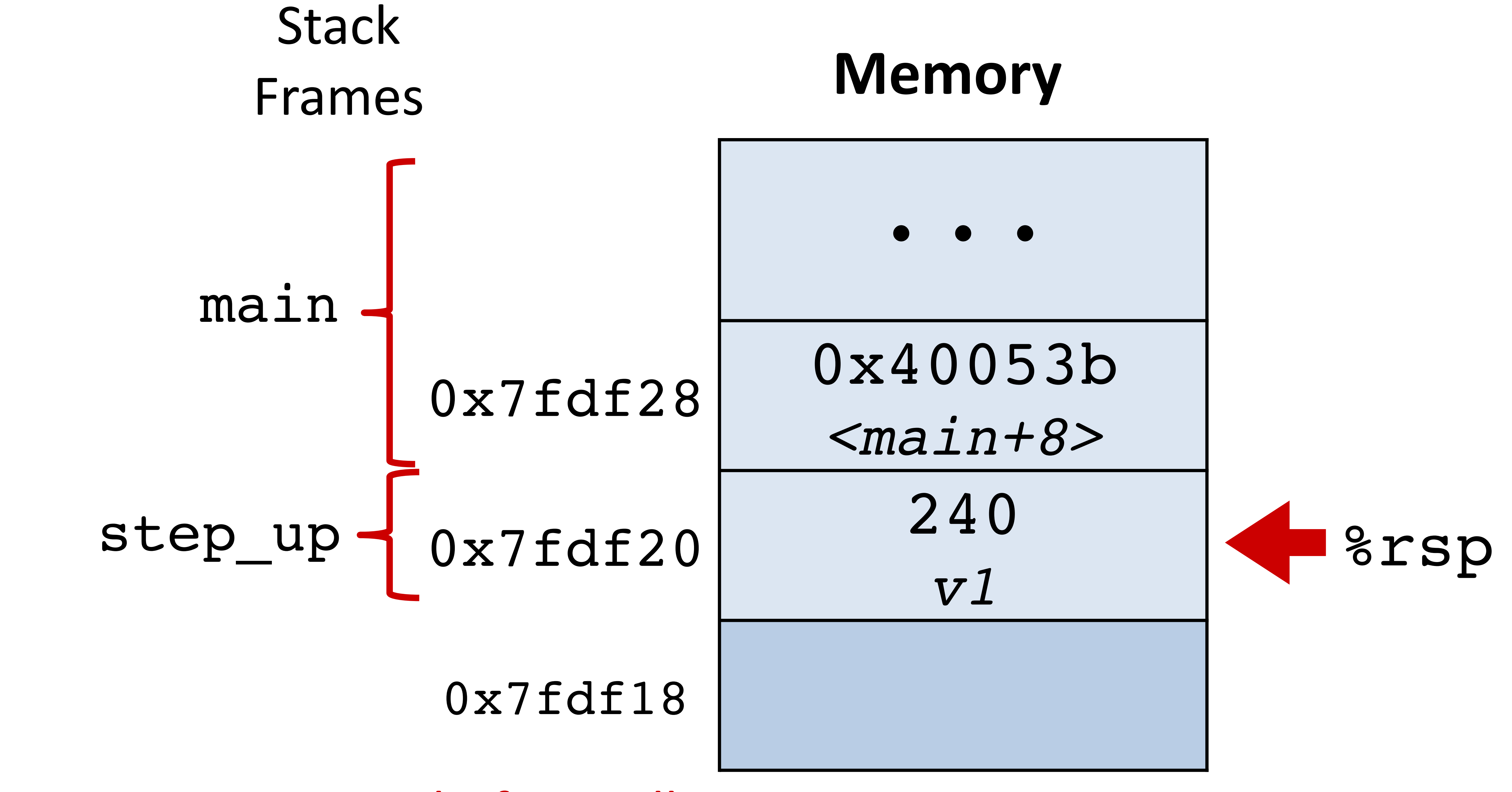
Procedure call example (step 2)

Set up args for call to `increment`

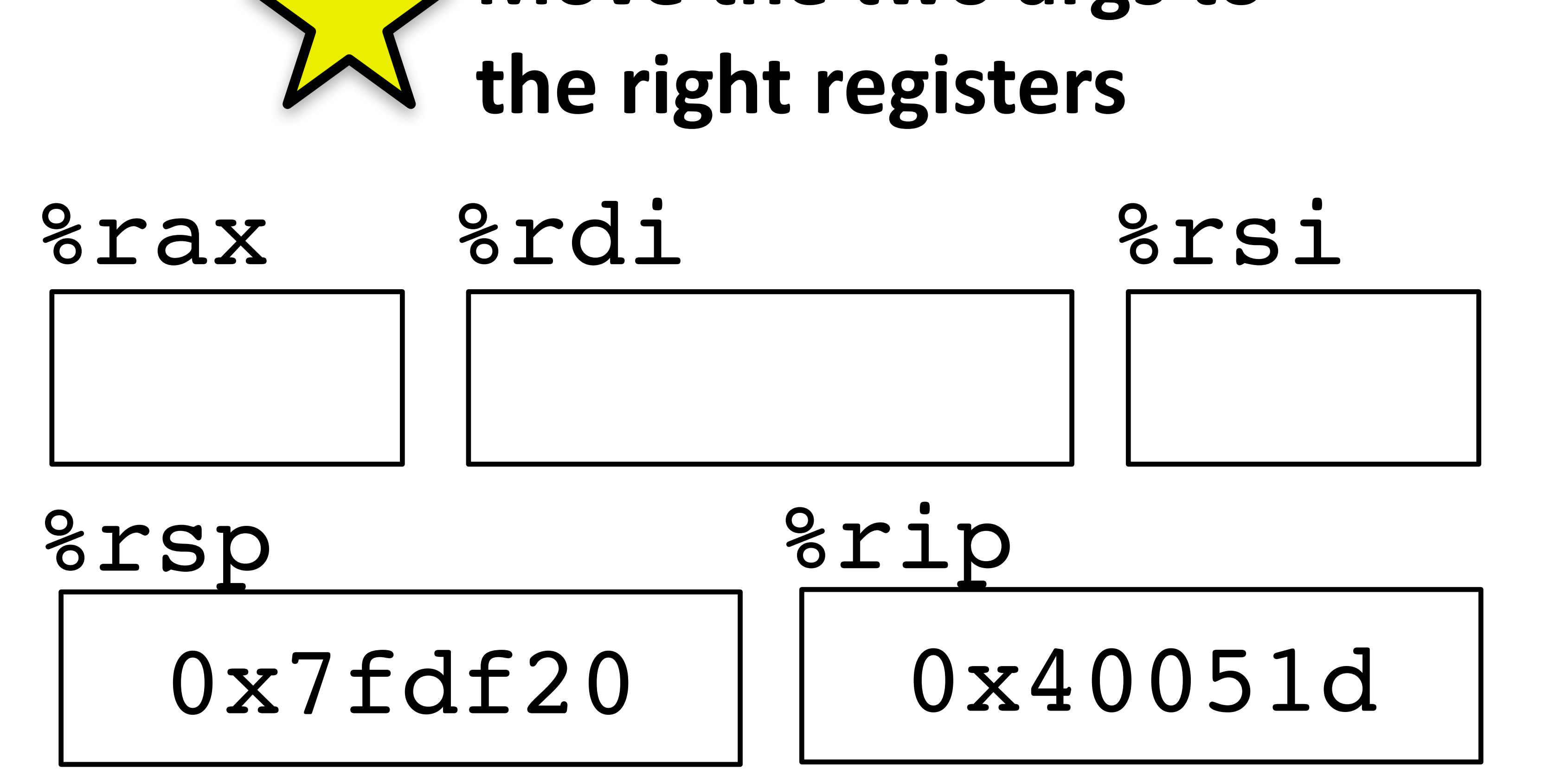
```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
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



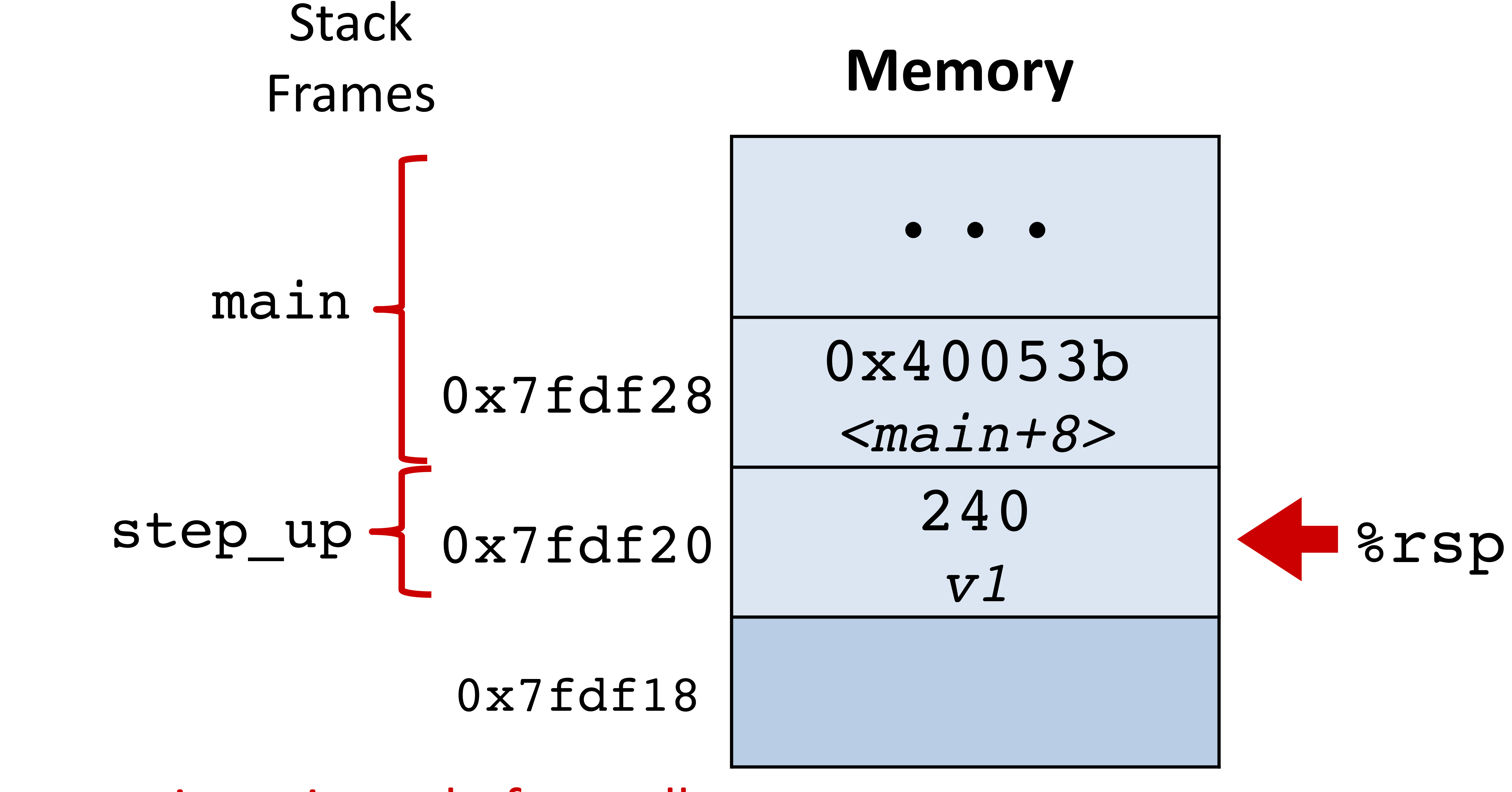
Procedure call example (step 2)

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

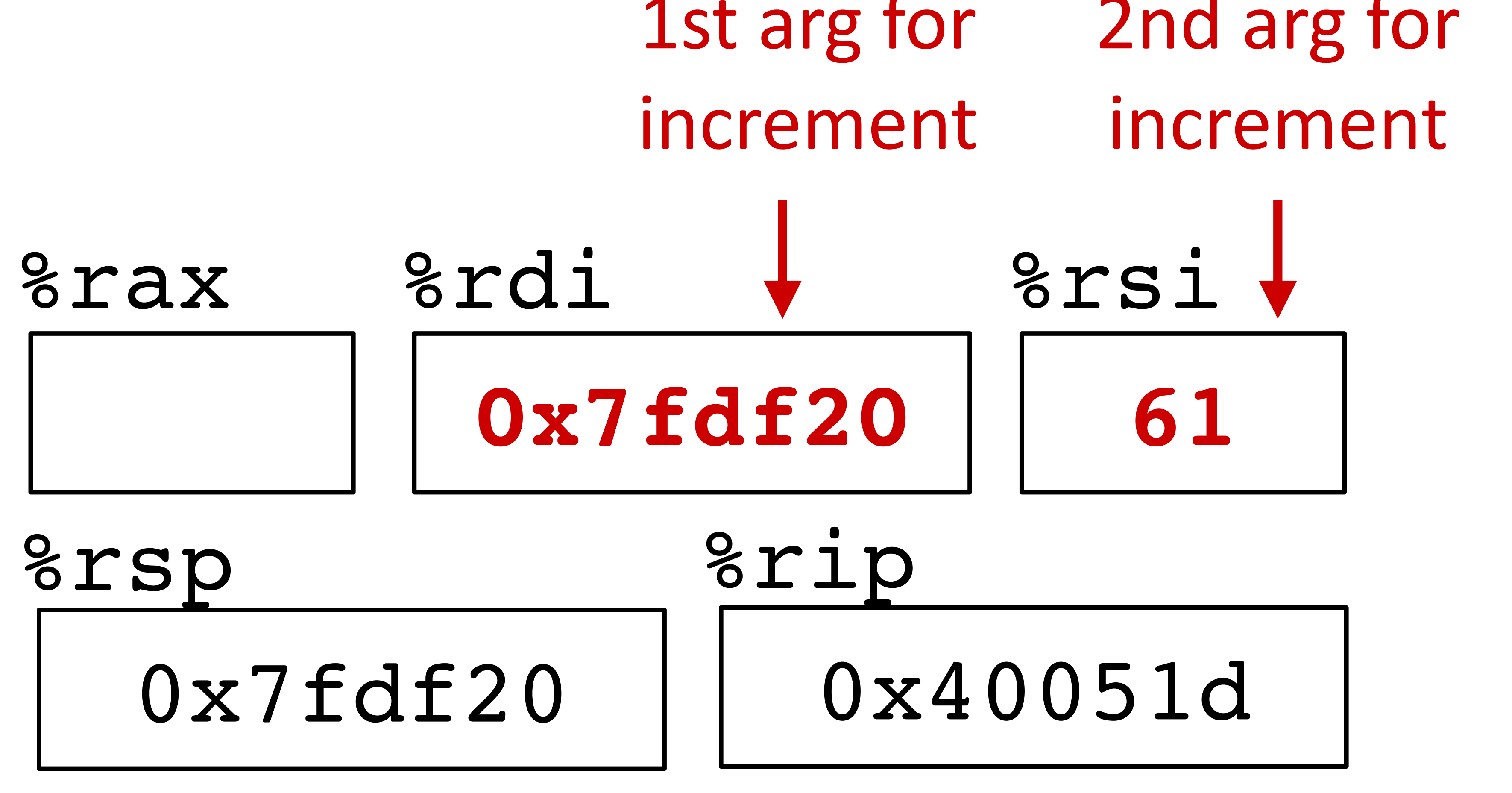
```
step_up:
400509:  subq   $8, %rsp
40050d:  movq   $240, (%rsp)
400515:  movq   %rsp, %rdi
400518:  movl   $61, %esi
40051d:  callq  4004cd <increment>
400522:  addq   (%rsp), %rax
400526:  addq   $8, %rsp
40052a:  retq
```

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

Set up args for call to increment



Place args in registers before call



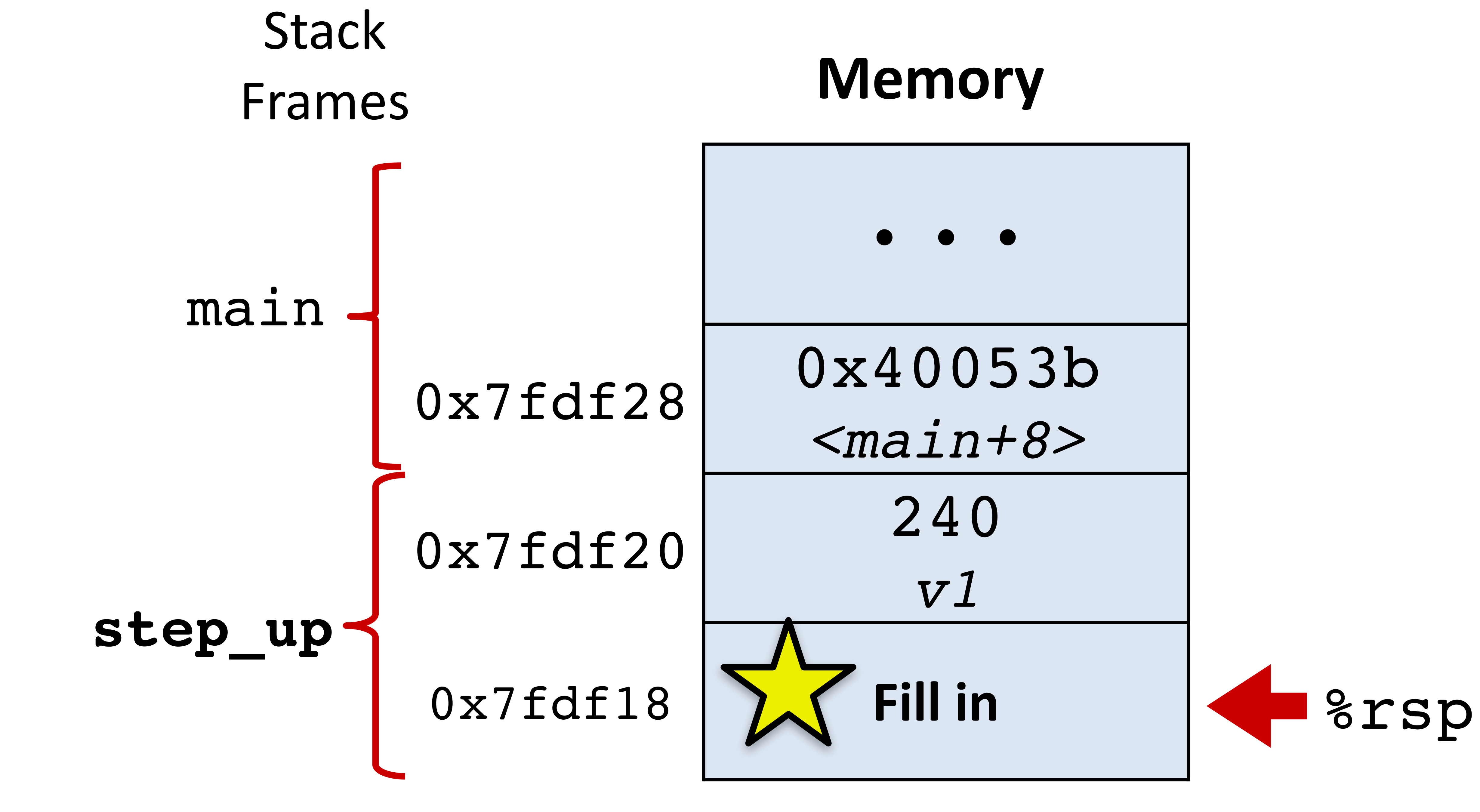
Procedure call example (step 3)

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
```

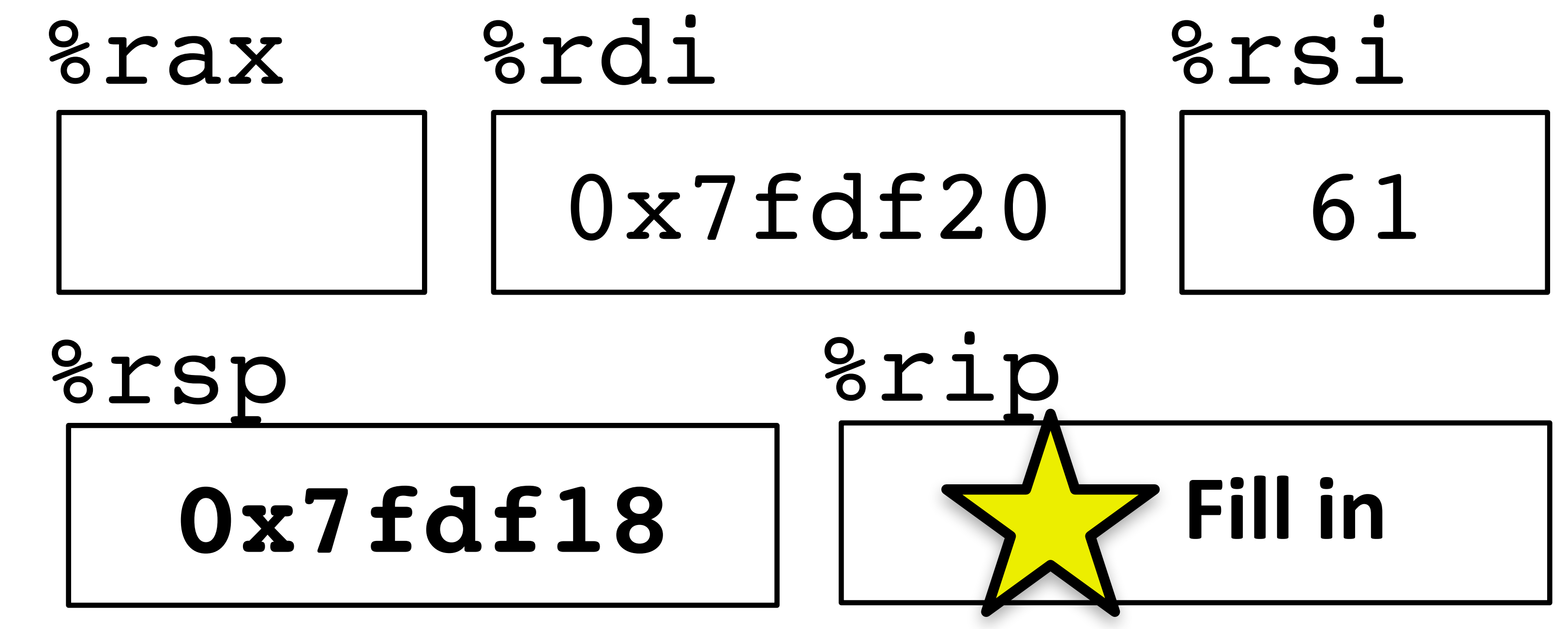
```
increment:
4004cd:   movq   (%rdi), %rax
4004d0:   addq   %rax, %rsi
4004d3:   movq   %rsi, (%rdi)
4004d6:   retq
```



`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
```

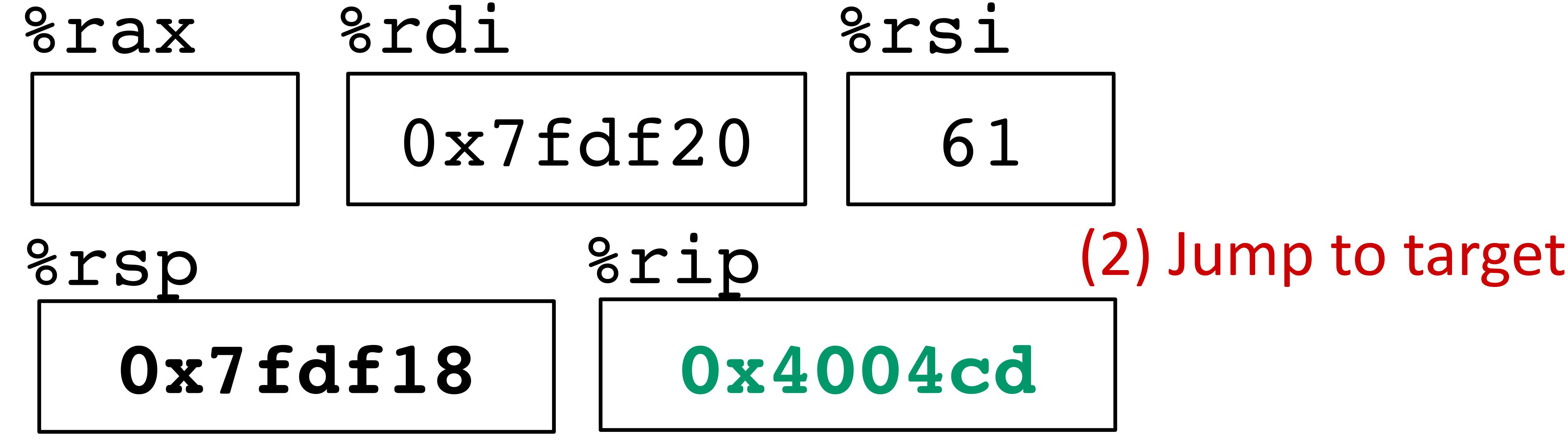
Stack Frames

Memory

Stack frame	Address	Memory
main		. . .
main	0x7fdf28	0x40053b *<main+8>*
step_up	0x7fdf20	240 *v1*
step_up	0x7fdf18	**0x400522** *<step_up+25>* ← %rsp

`call` has two steps

(1) Push return address on stack



Procedure call example (step 4)

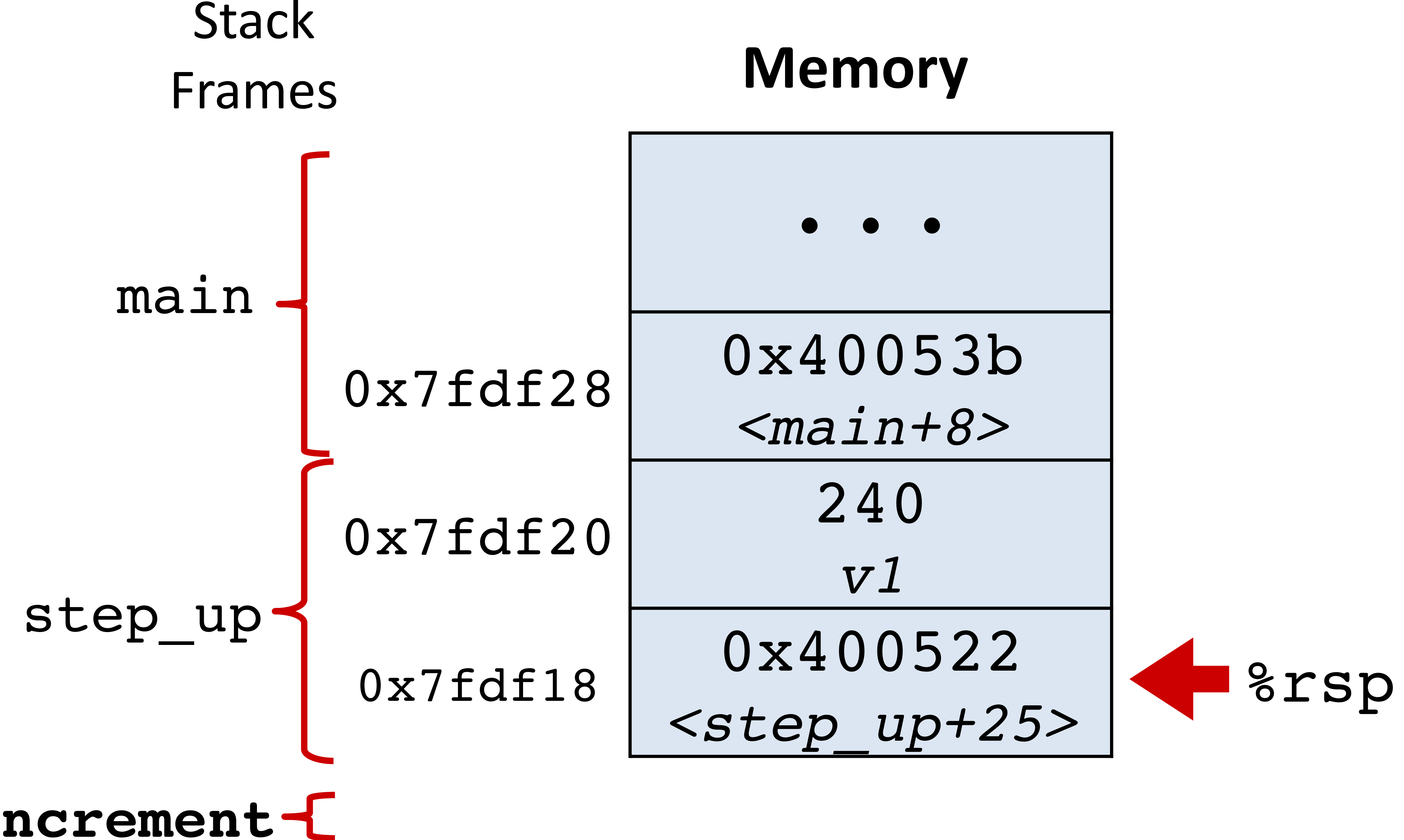
Run increment

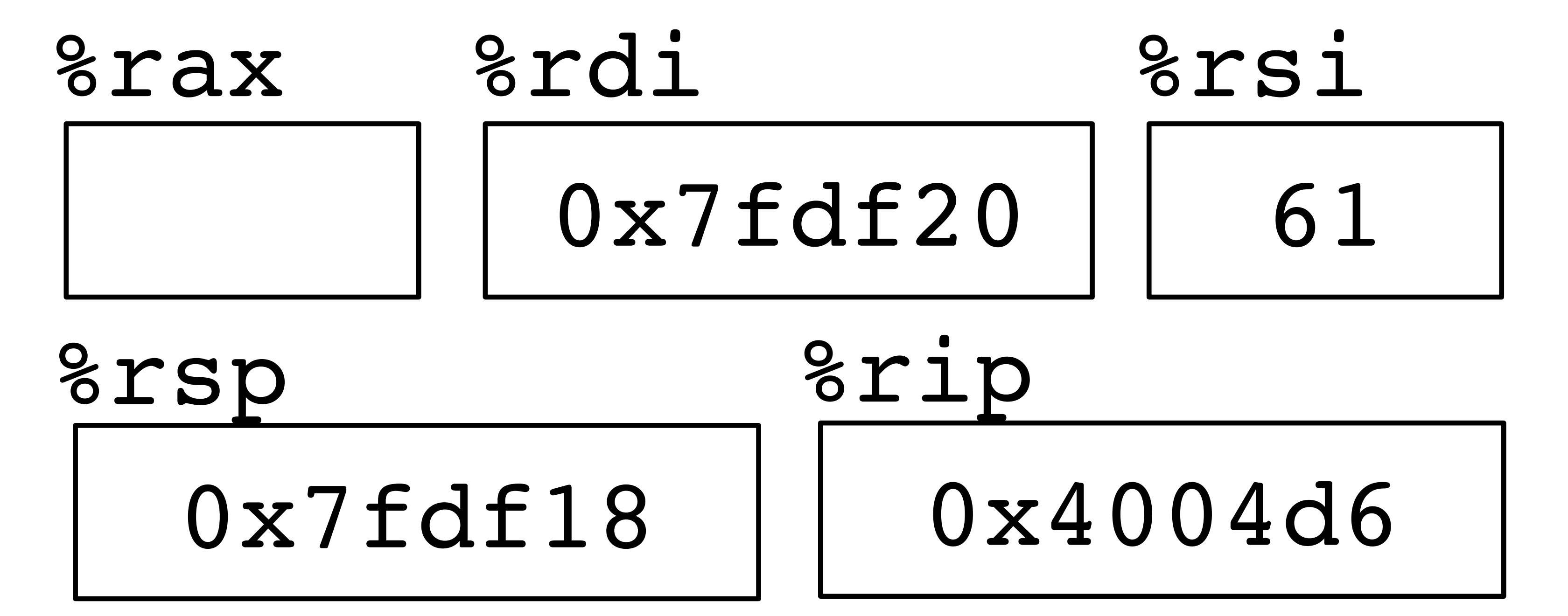
```
long increment(long* p, long val) {
     long x = *p;
     long y = x + val;
     *p = y;
     return x;
}
```

```
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





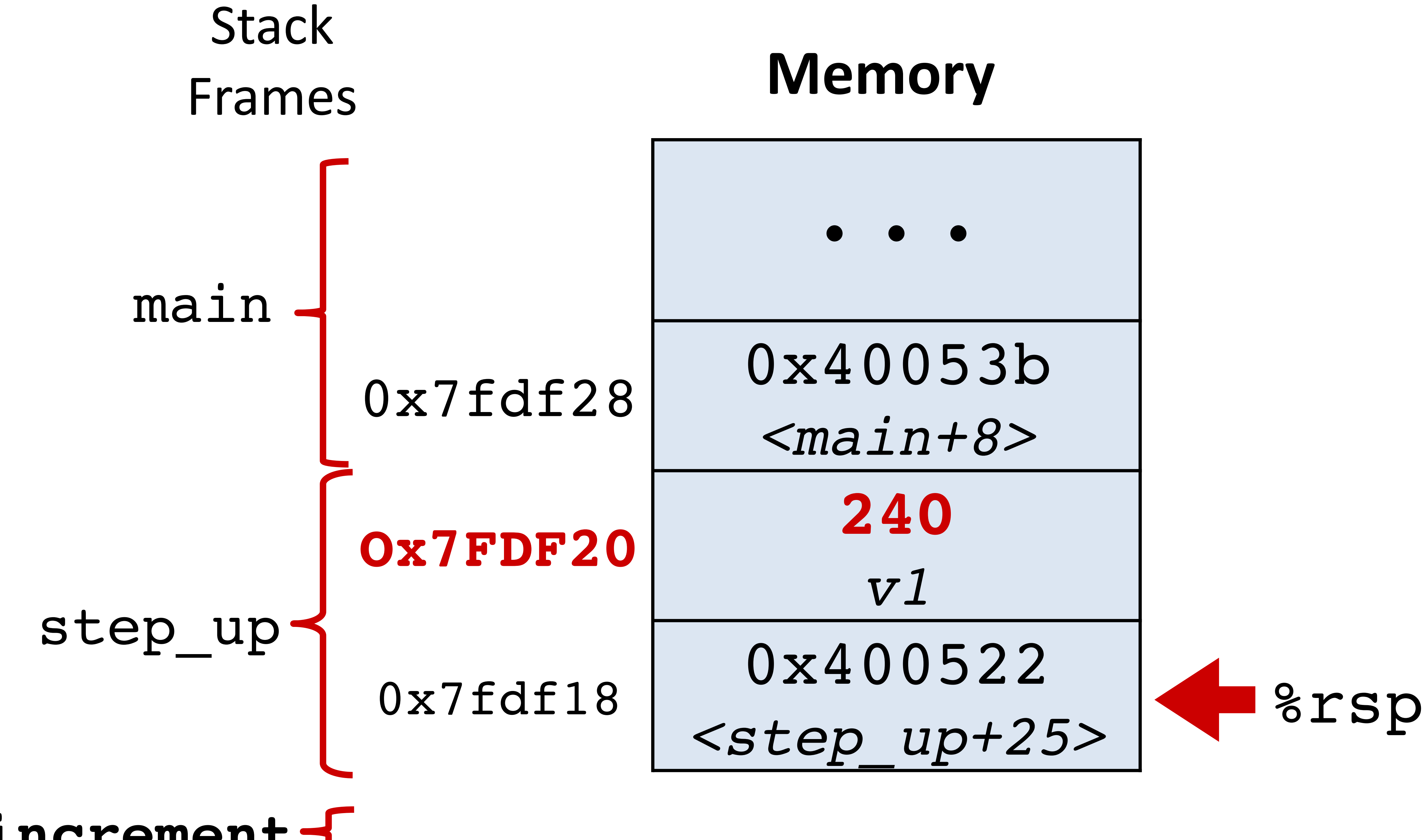
Procedure call example (step 4)

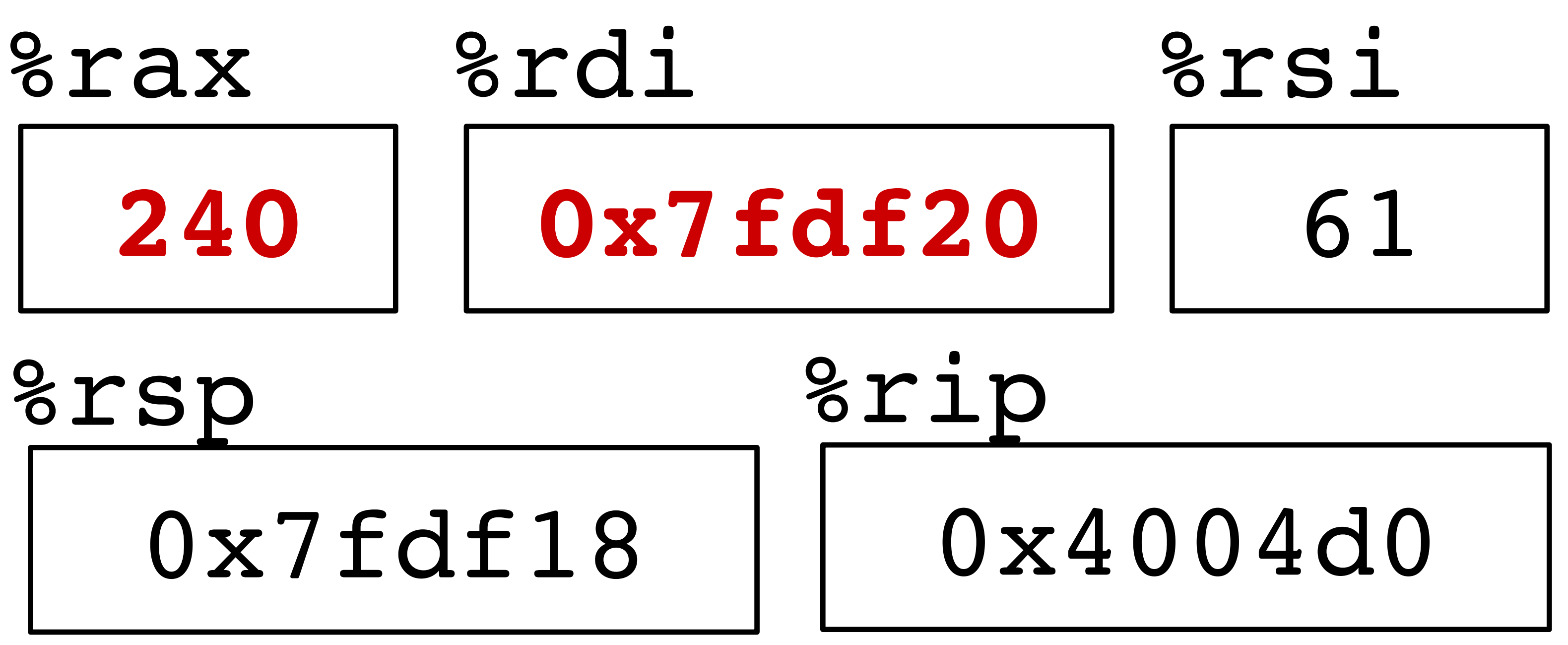
Run increment

```
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
```





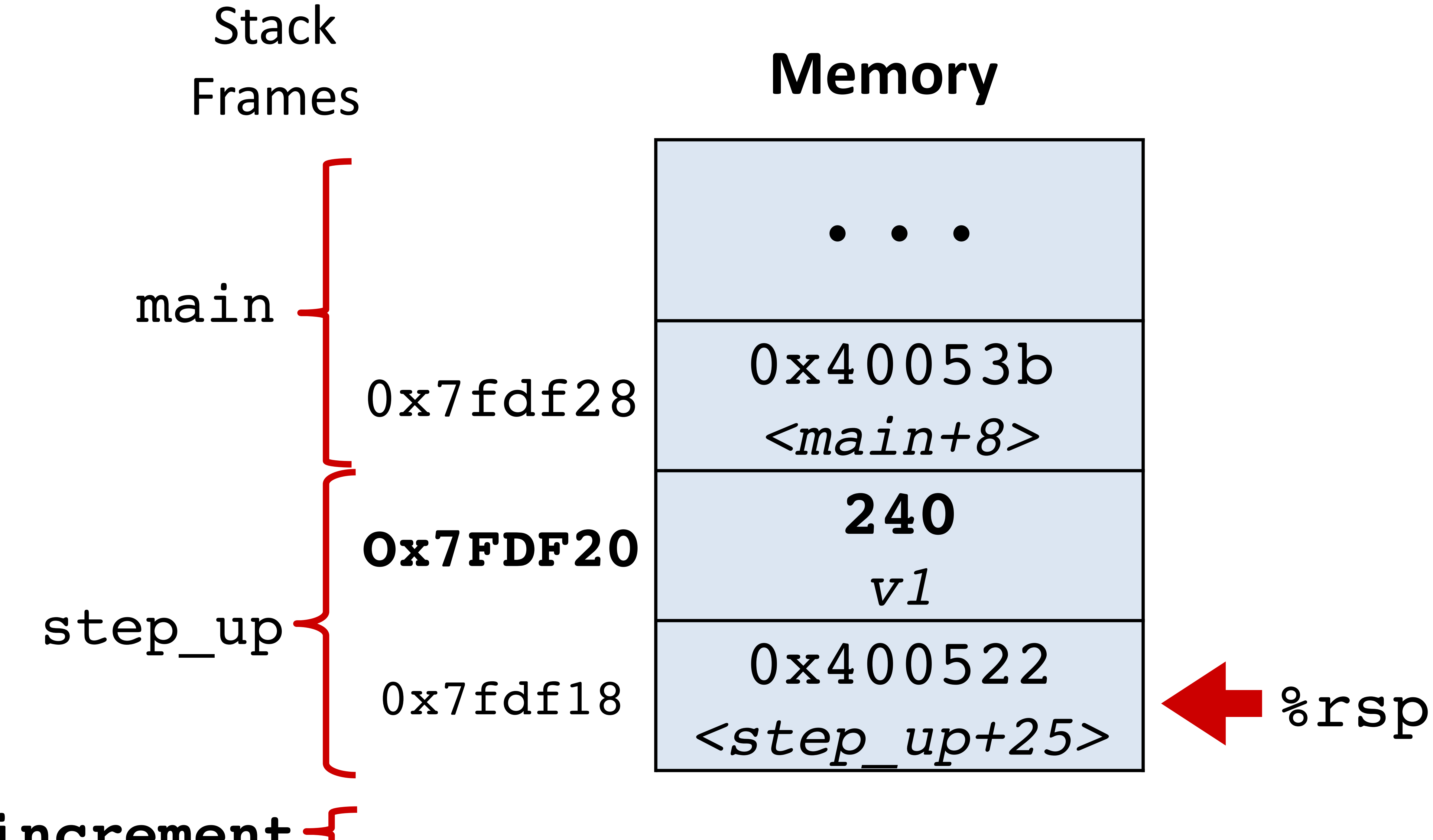
Procedure call example (step 4)

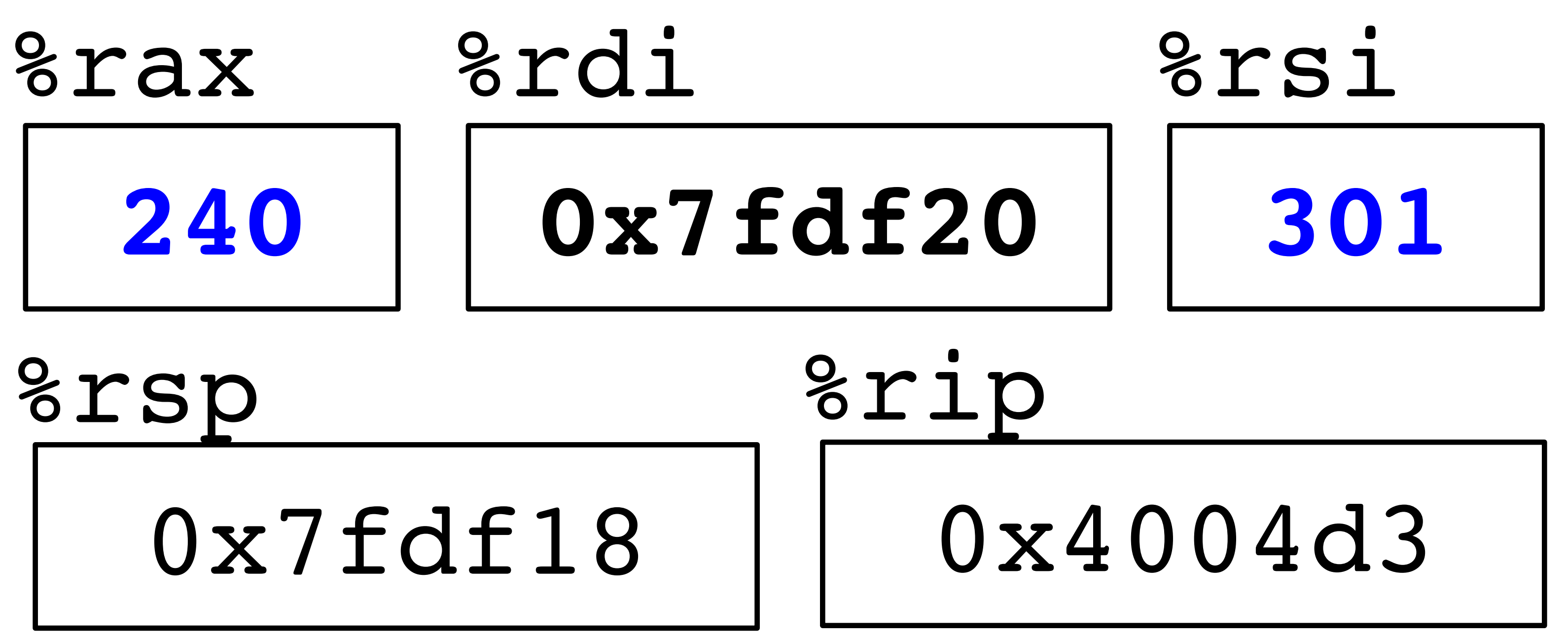
Run increment

```
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
```





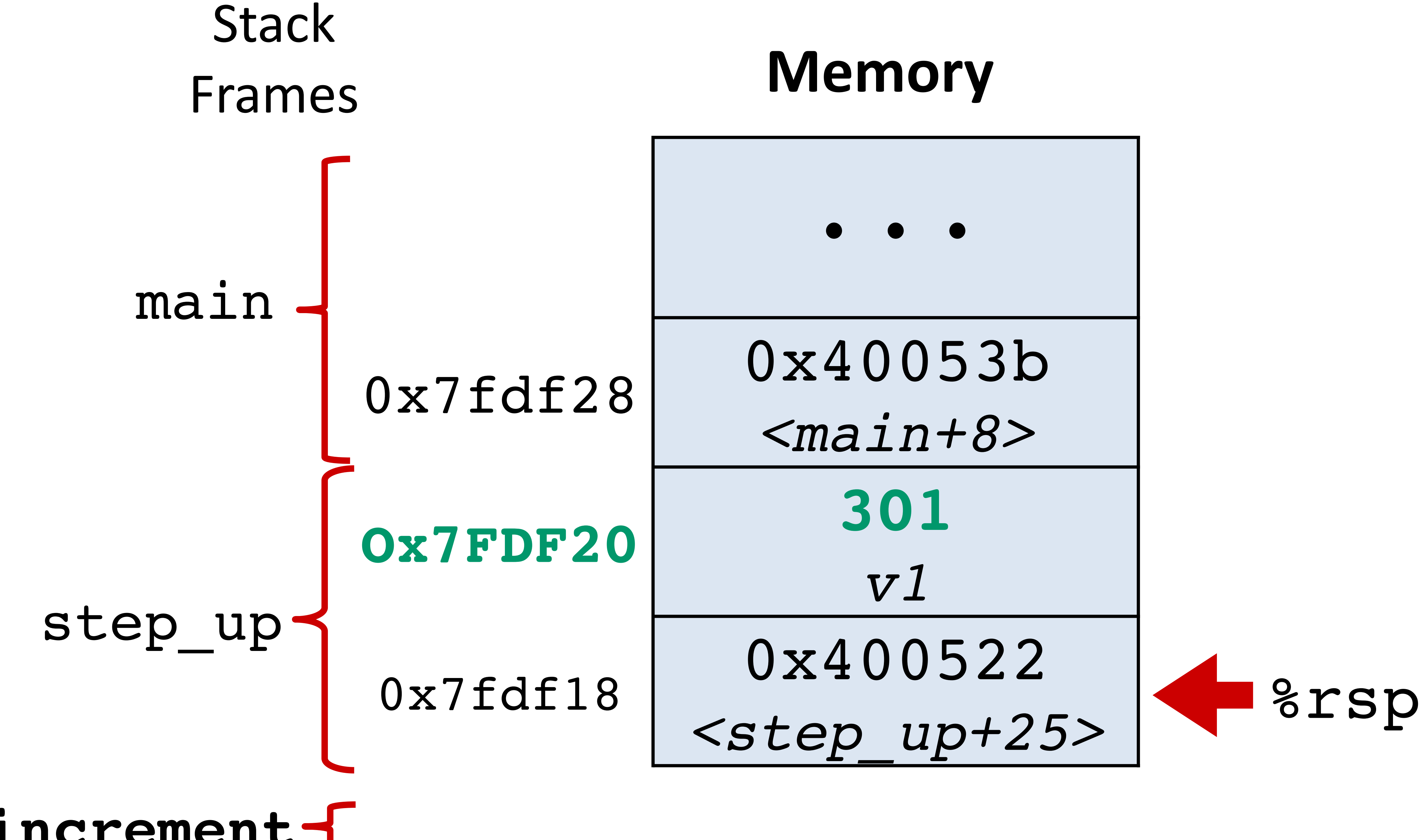
Procedure call example (step 4)

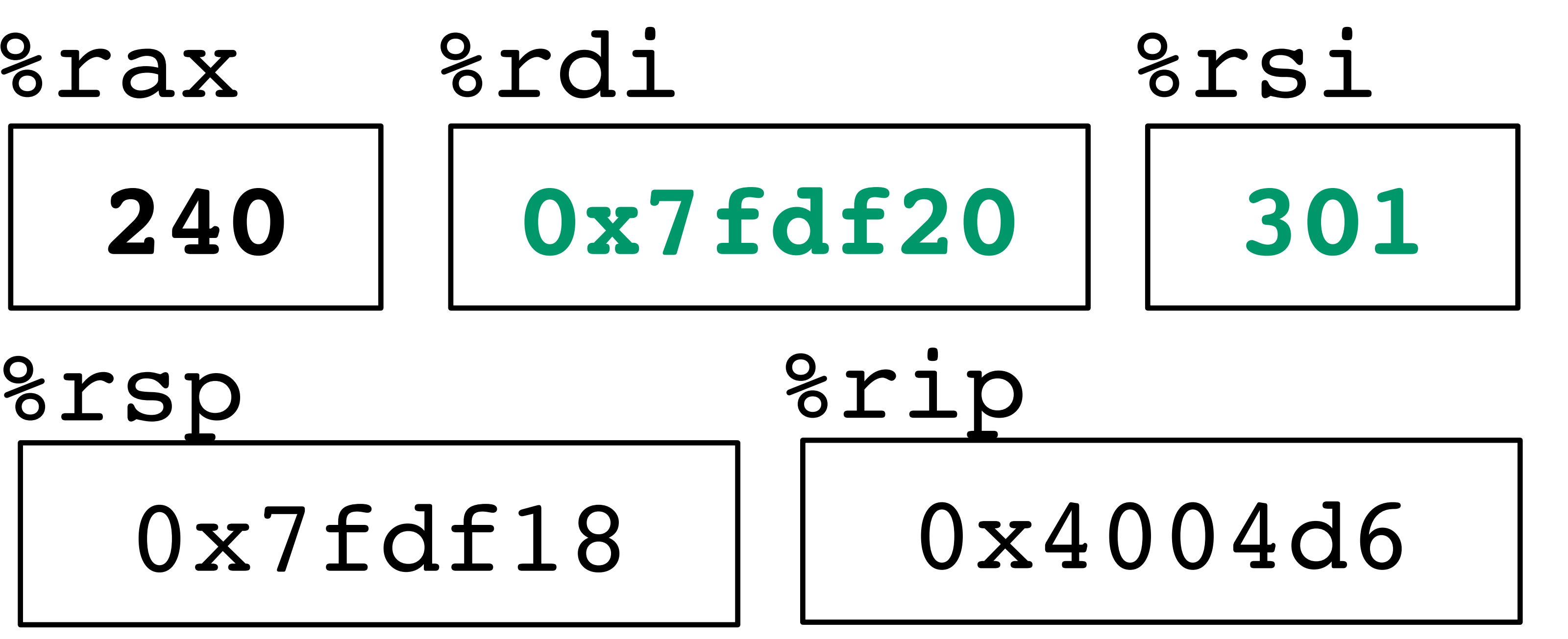
Run increment

```
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
```



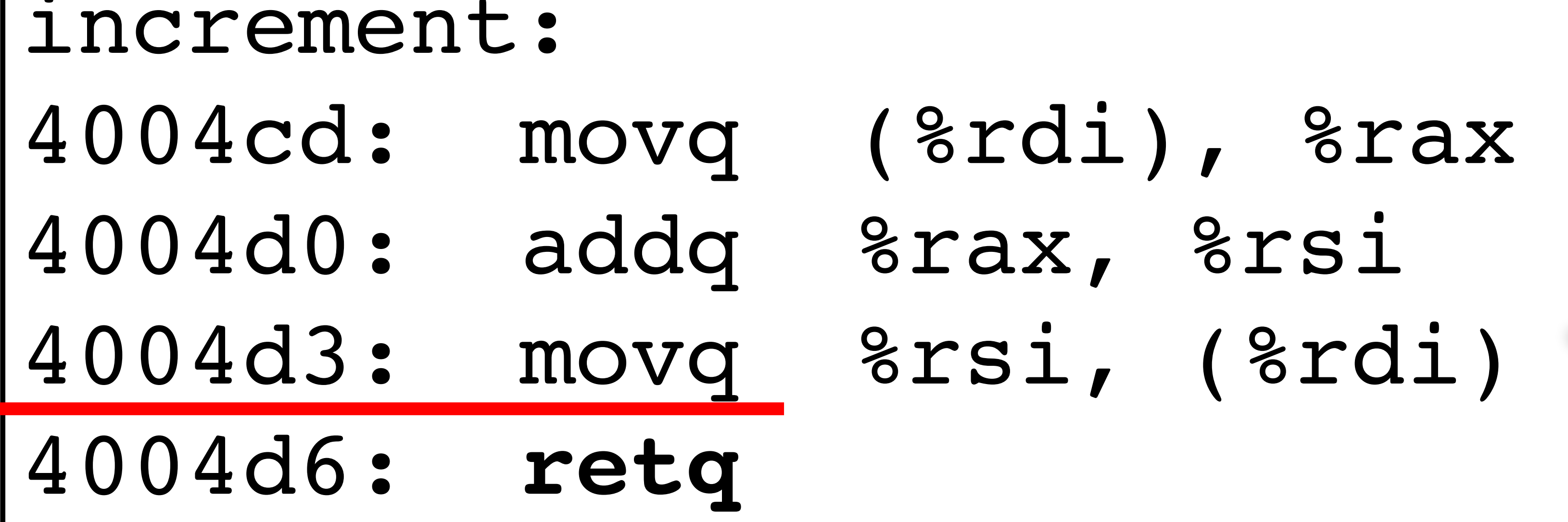


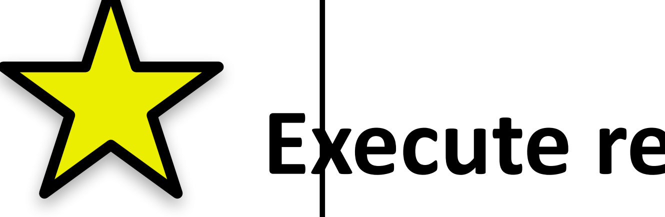
Procedure call example (step 5a)

Return from `increment` to `step_up`

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

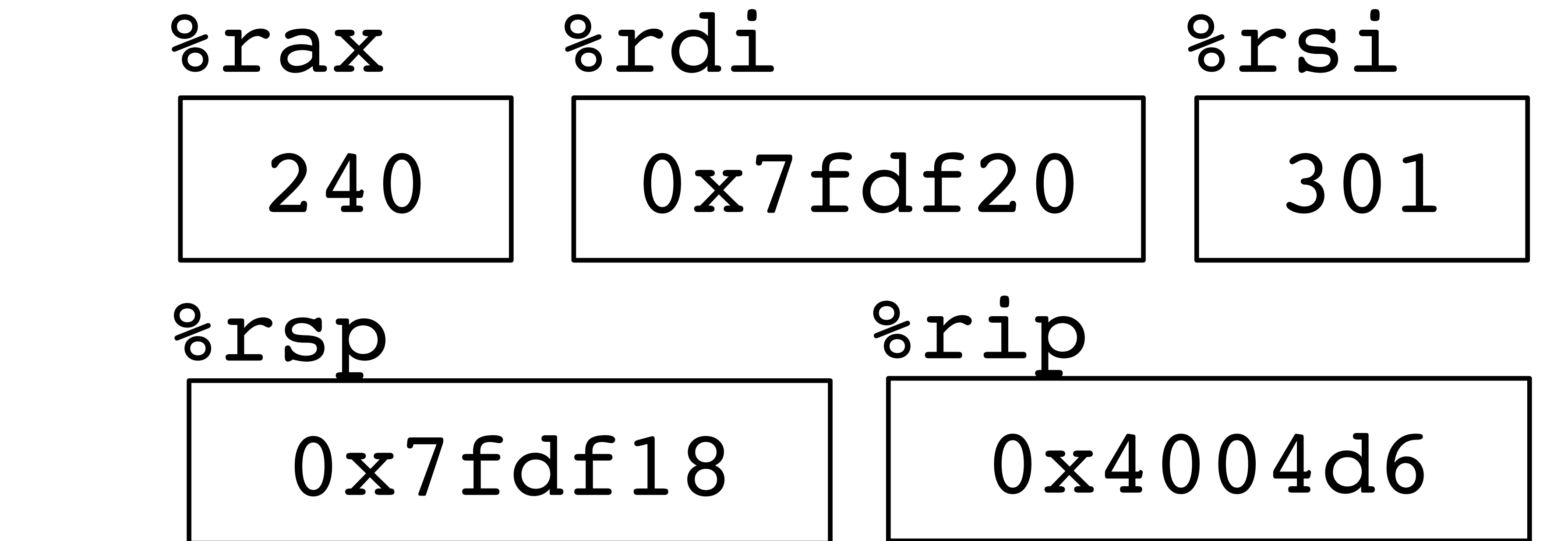
```
step_up:
400509:   subq   $8, %rsp
40050d:   movq   $240, (%rsp)
400515:   movq   %rsp, %rdi
400518:   movl   $61, %esi
40051d:   callq  4004cd <increment>
400522:   addq   (%rsp), %rax
400526:   addq   $8, %rsp
40052a:   retq
```





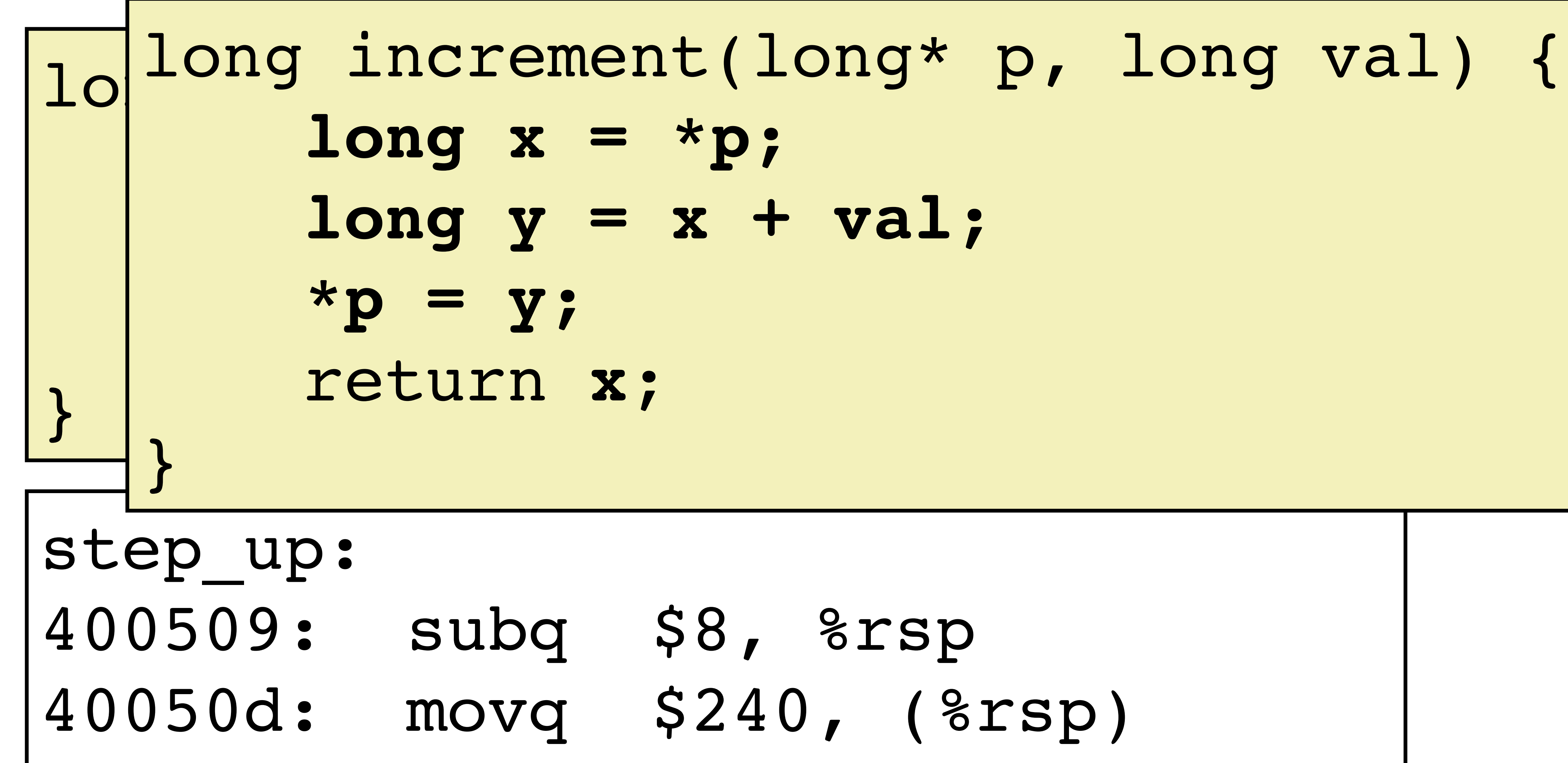
Stack Frames	Address	Memory
main		. . .
main	0x7fdf28	0x40053b <main+8>
step_up	0x7fdf20	301 *v1*
step_up	0x7fdf18	0x400522 <step_up+25>

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



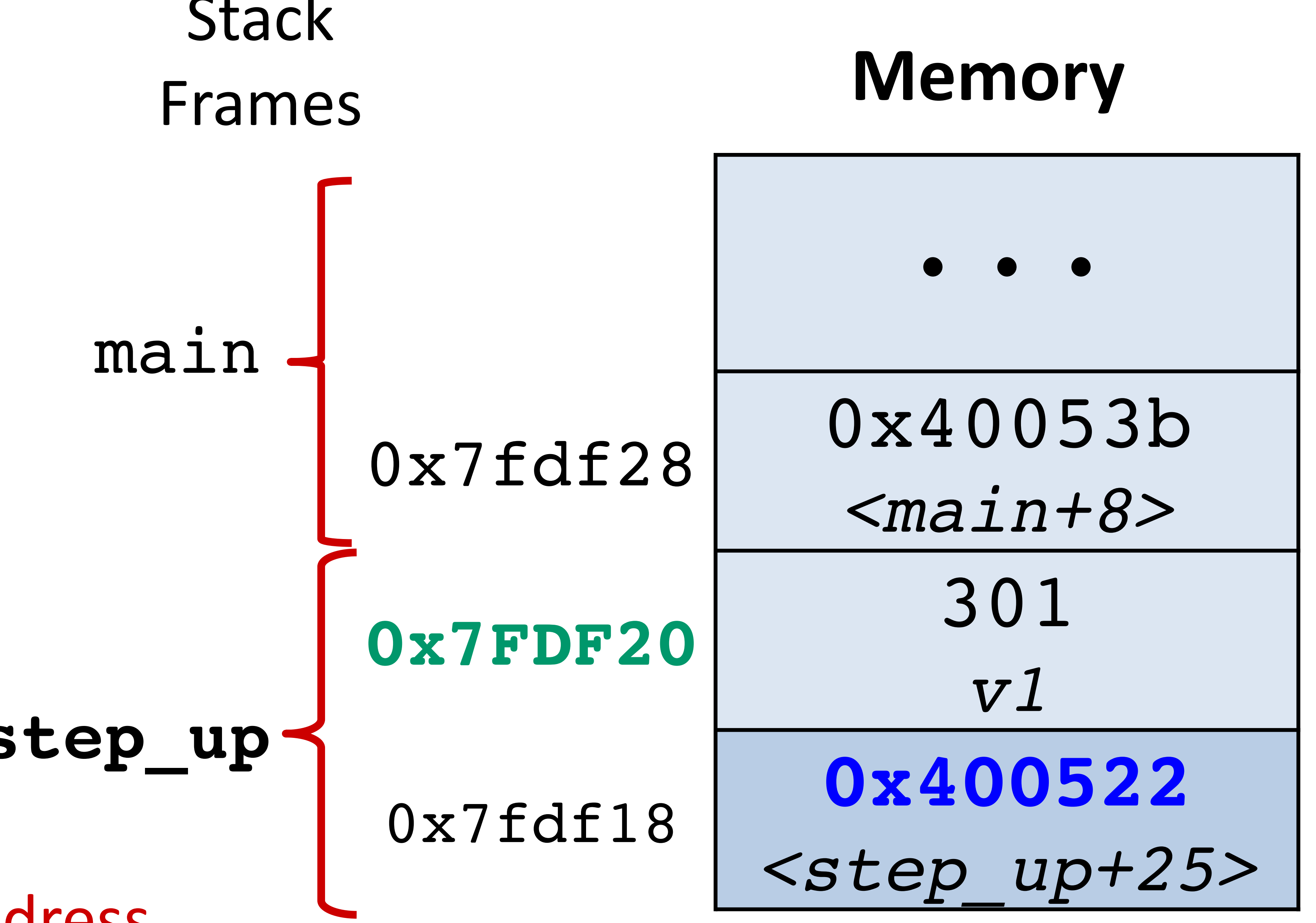
Procedure call example (step 5b)

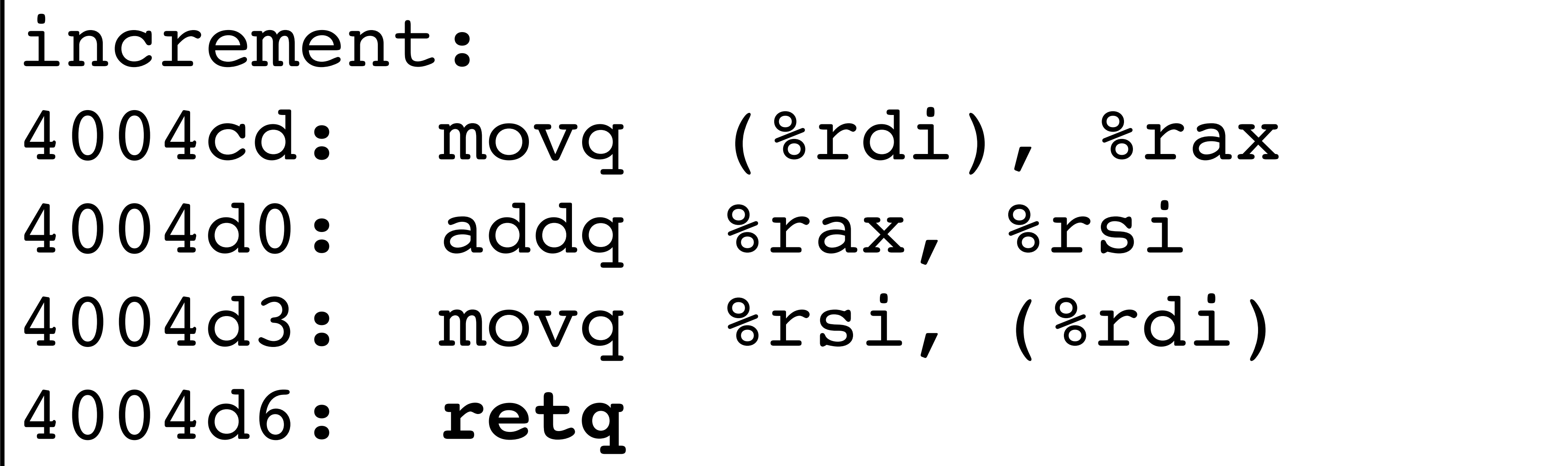
Return from increment to step_up

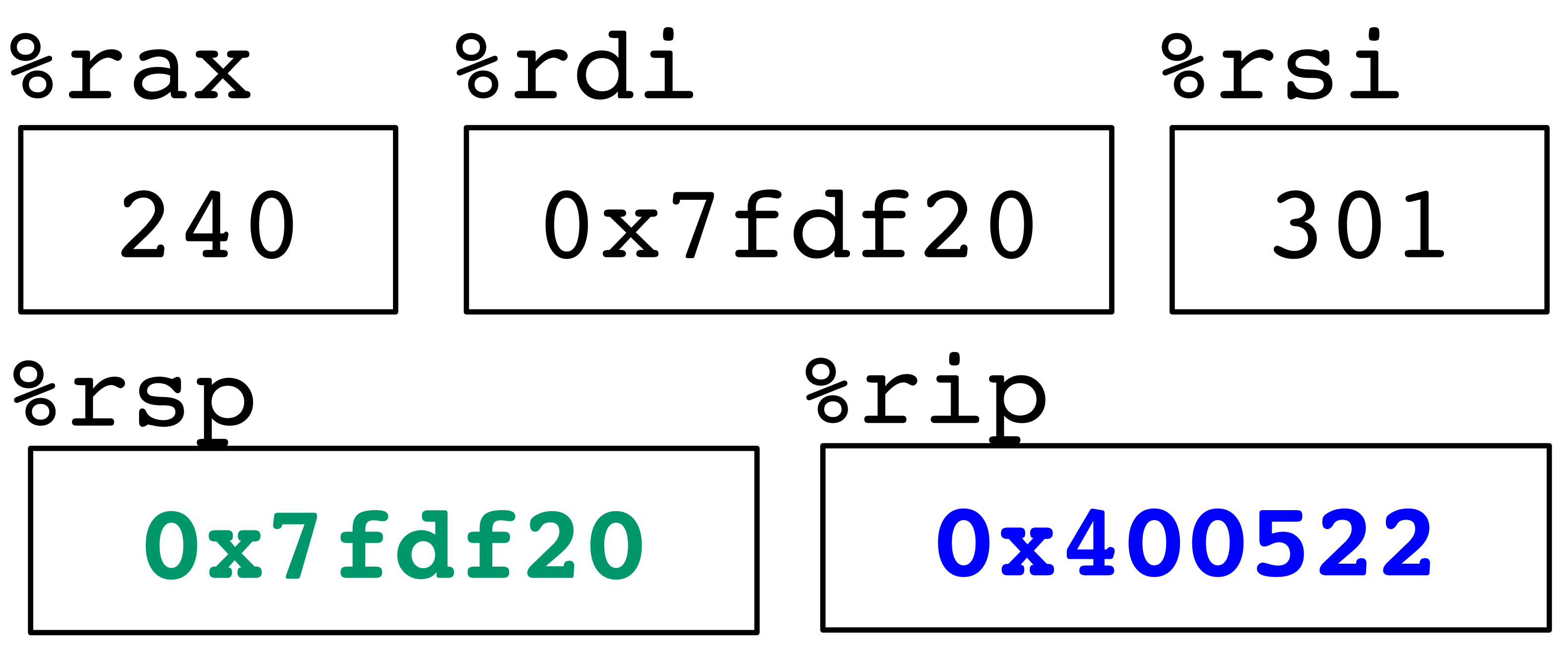


(2) jump to return address

ret has two steps







Procedure call example (step 6)

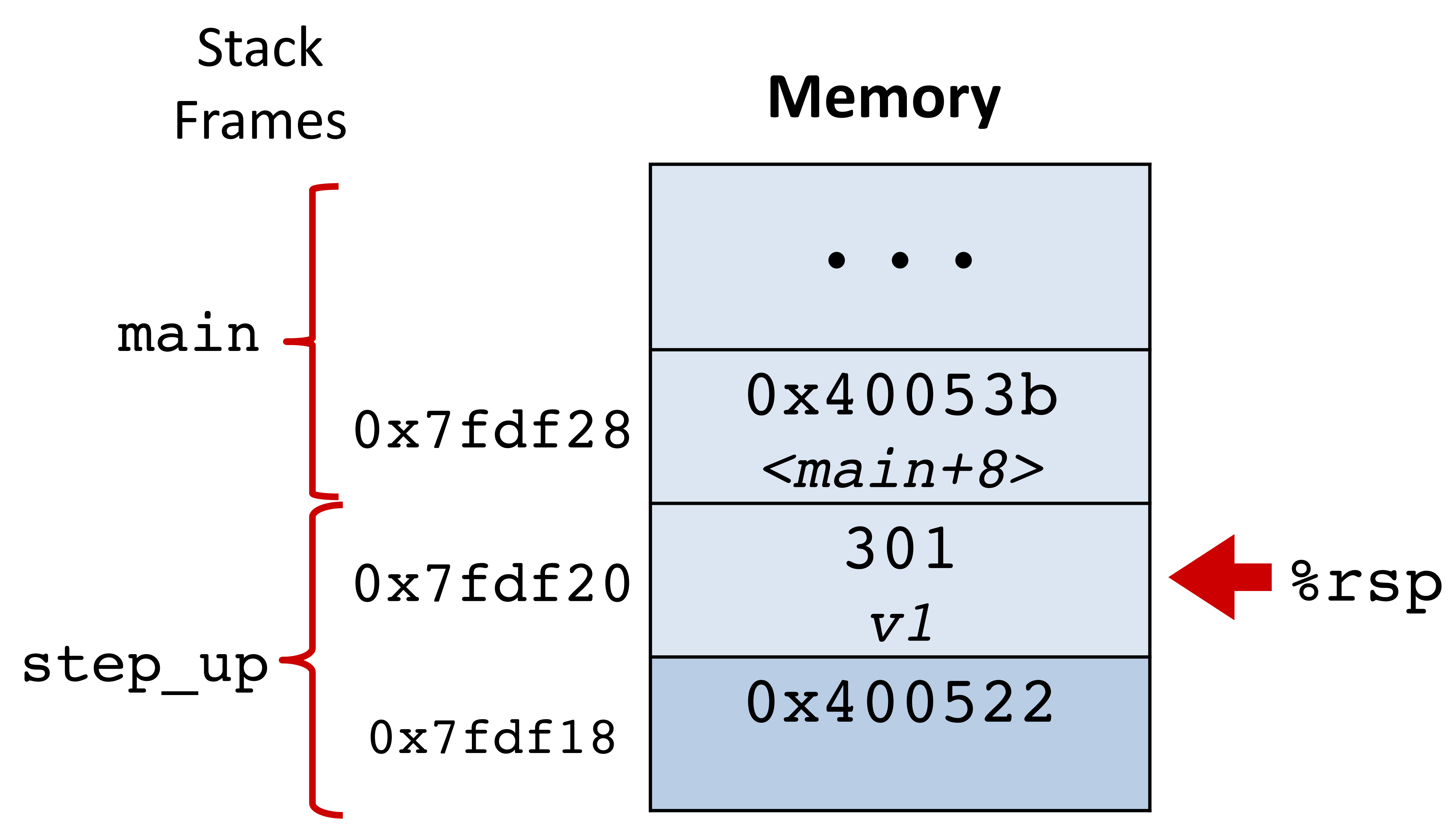
Prepare `step_up` result

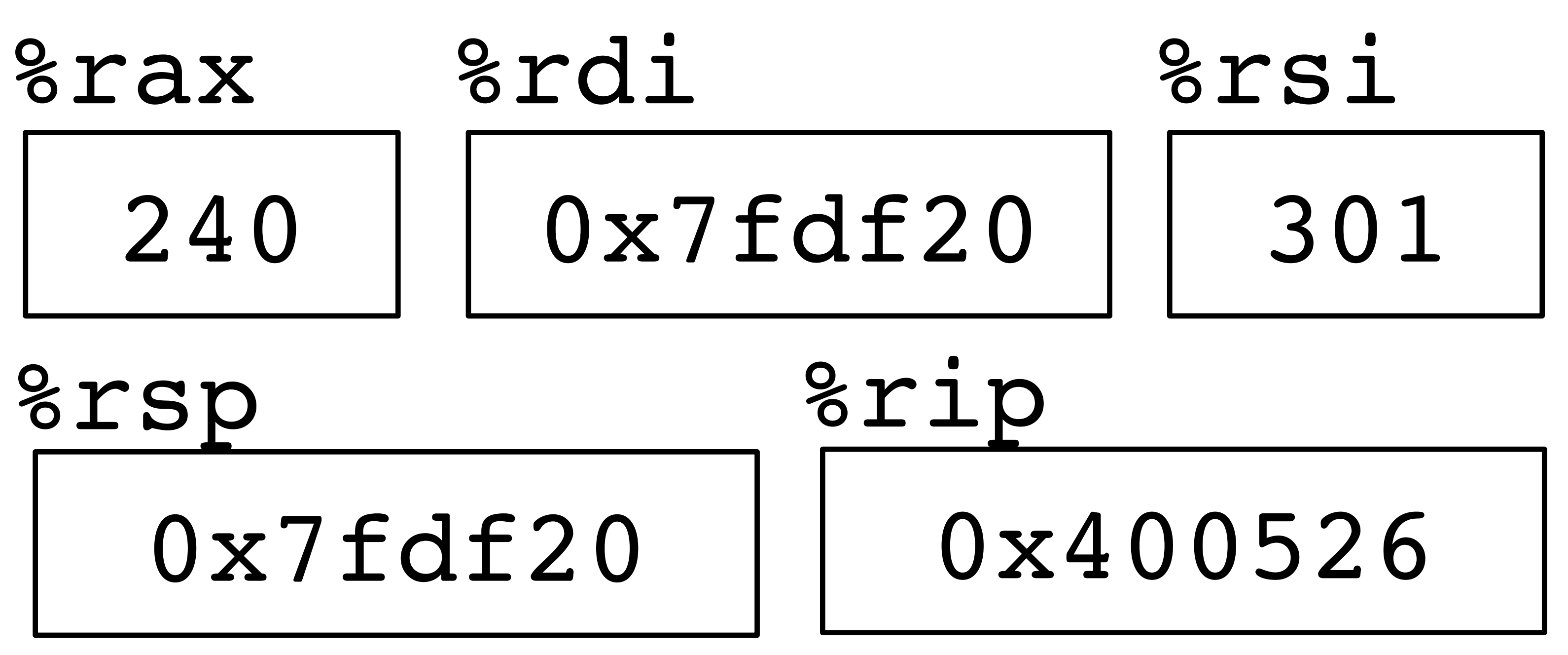
```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
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
```

Execute this instruction





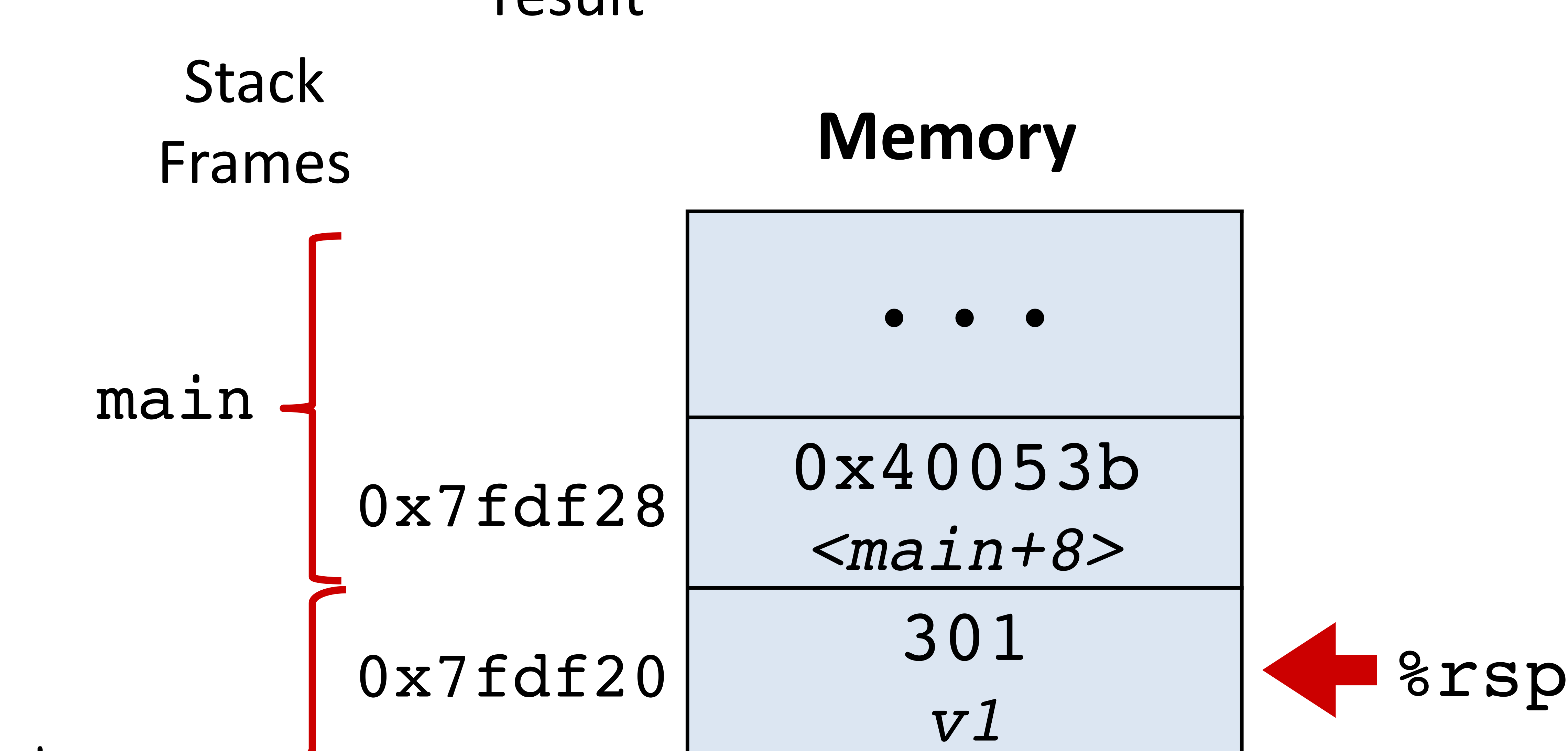
Procedure call example (step 6)

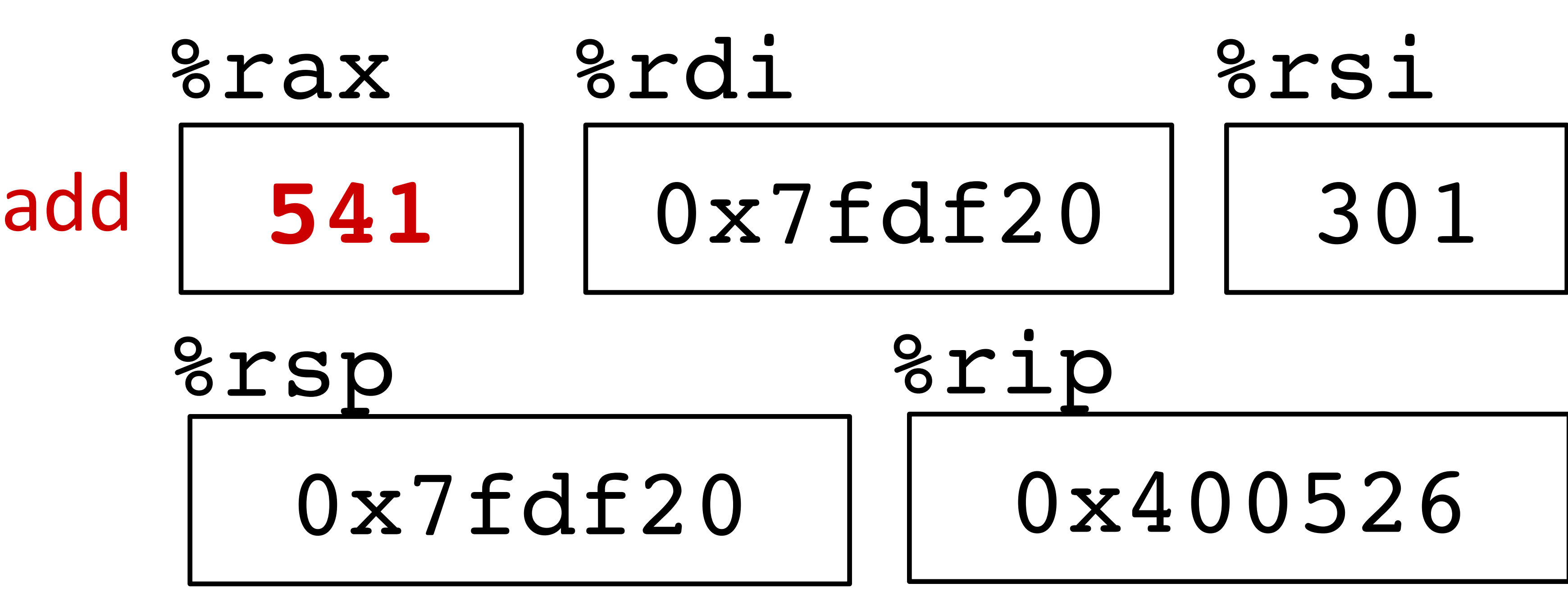
Prepare step_up result

```
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
```





Procedure call example (step 7)

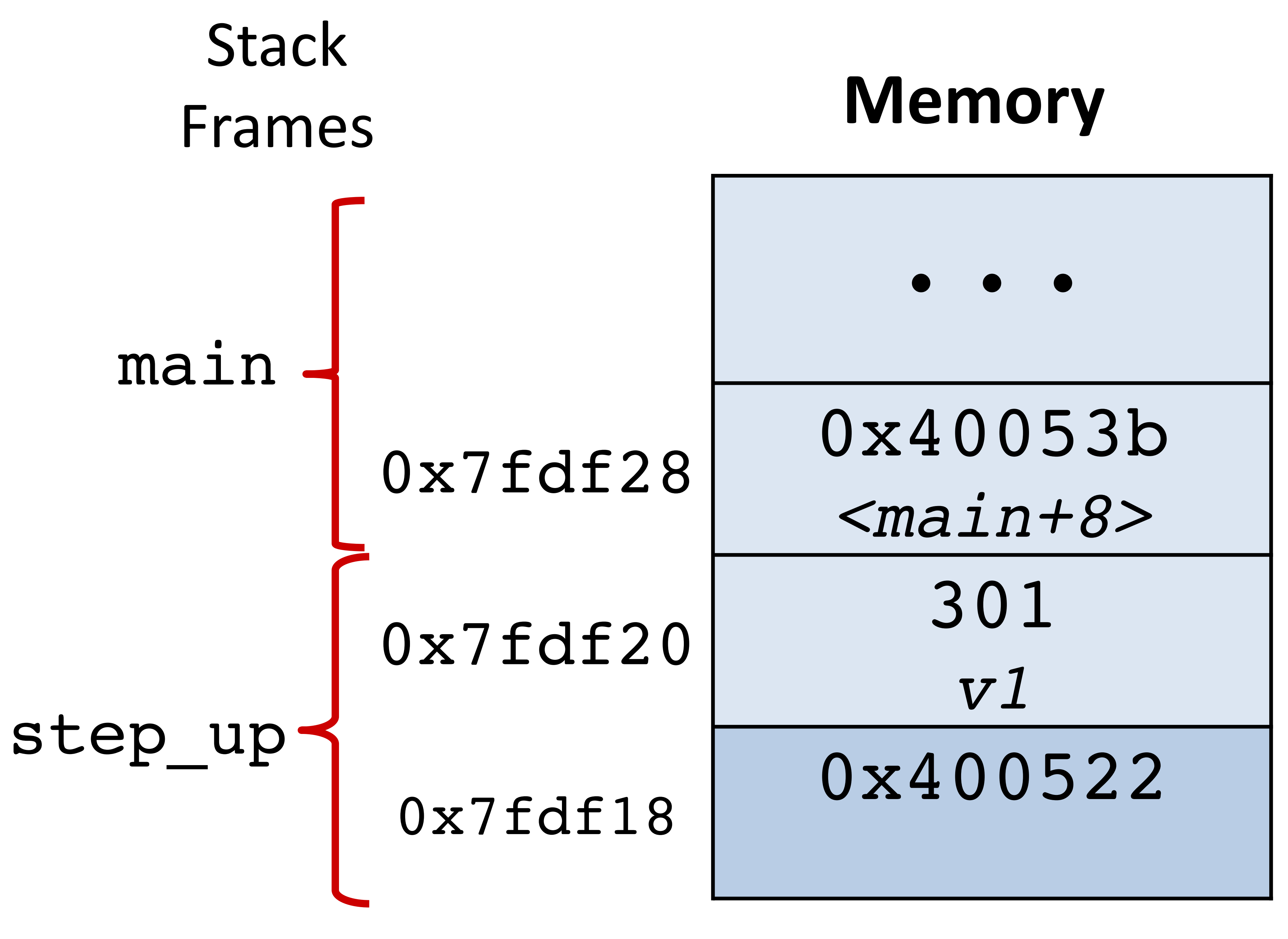
Deallocate space
for local vars

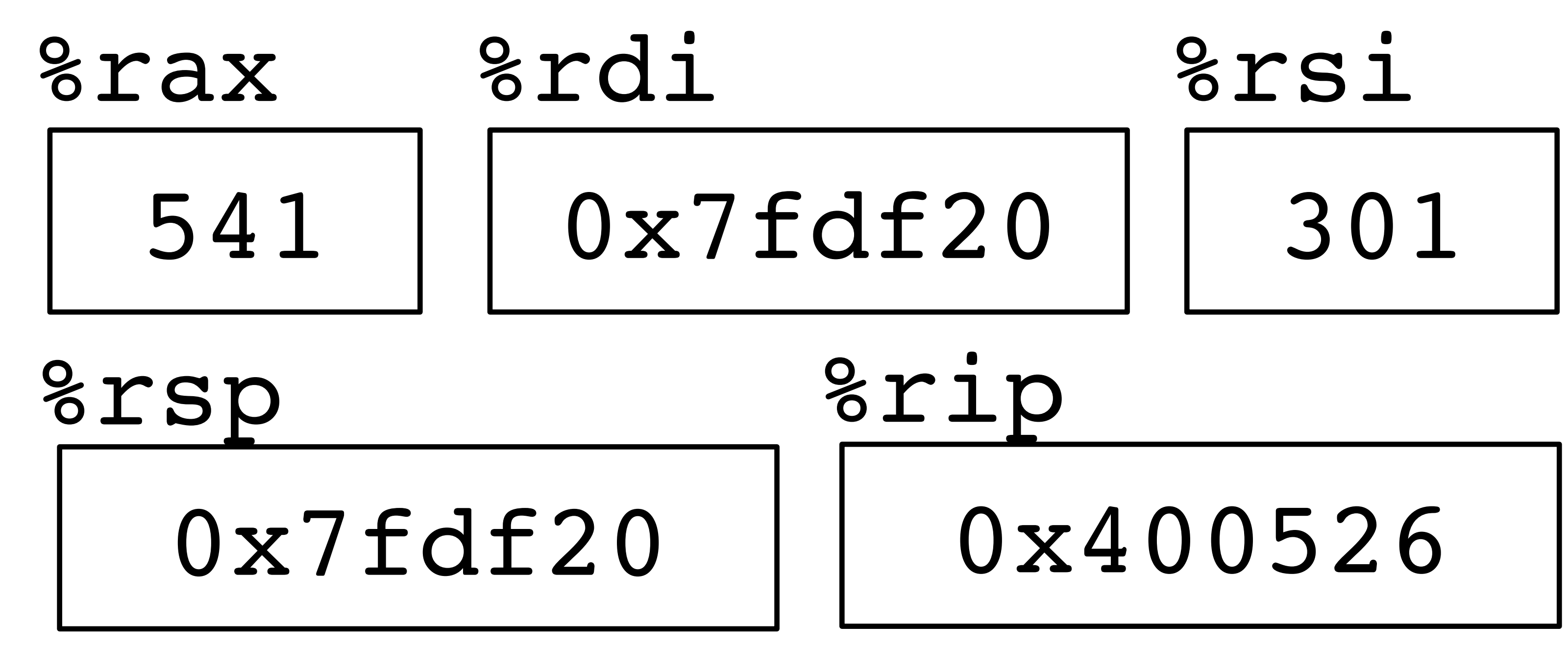
```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
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
```





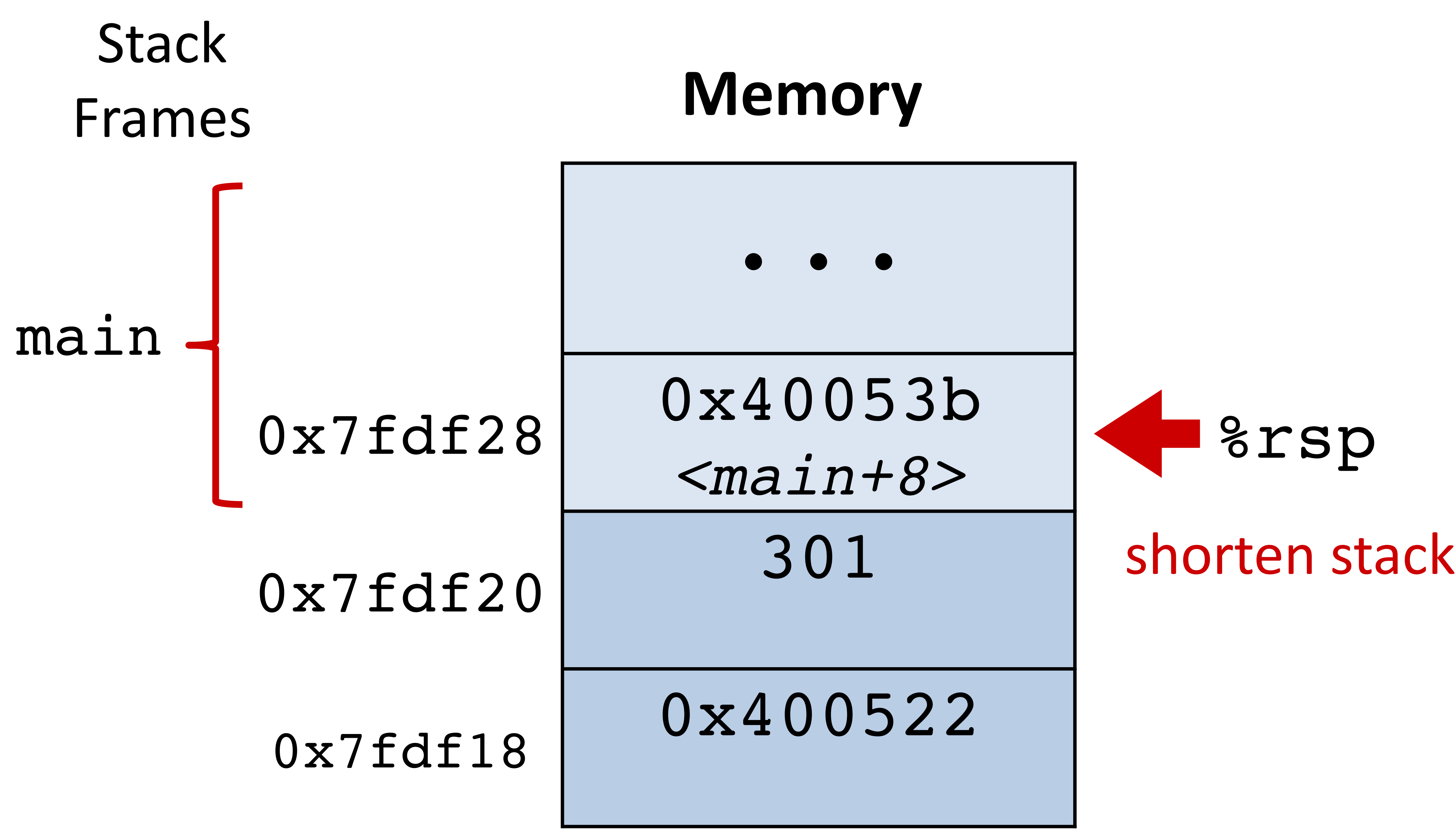
Procedure call example (step 7)

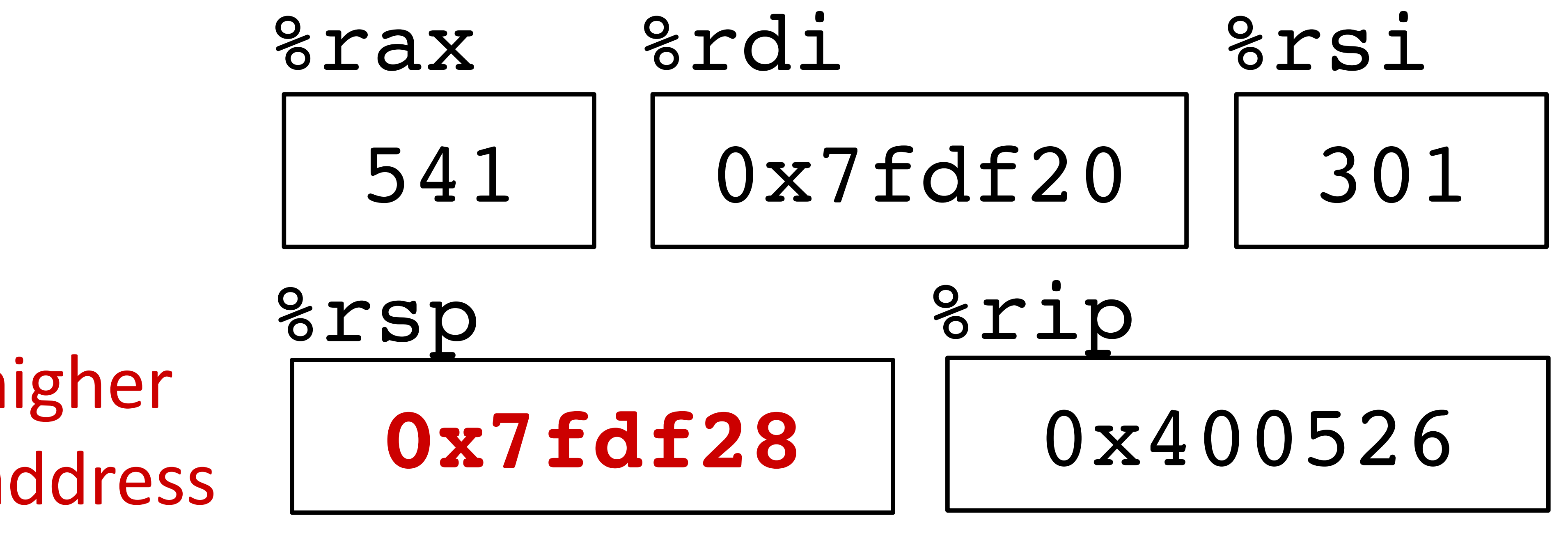
Deallocate space for local vars

```
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
```

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





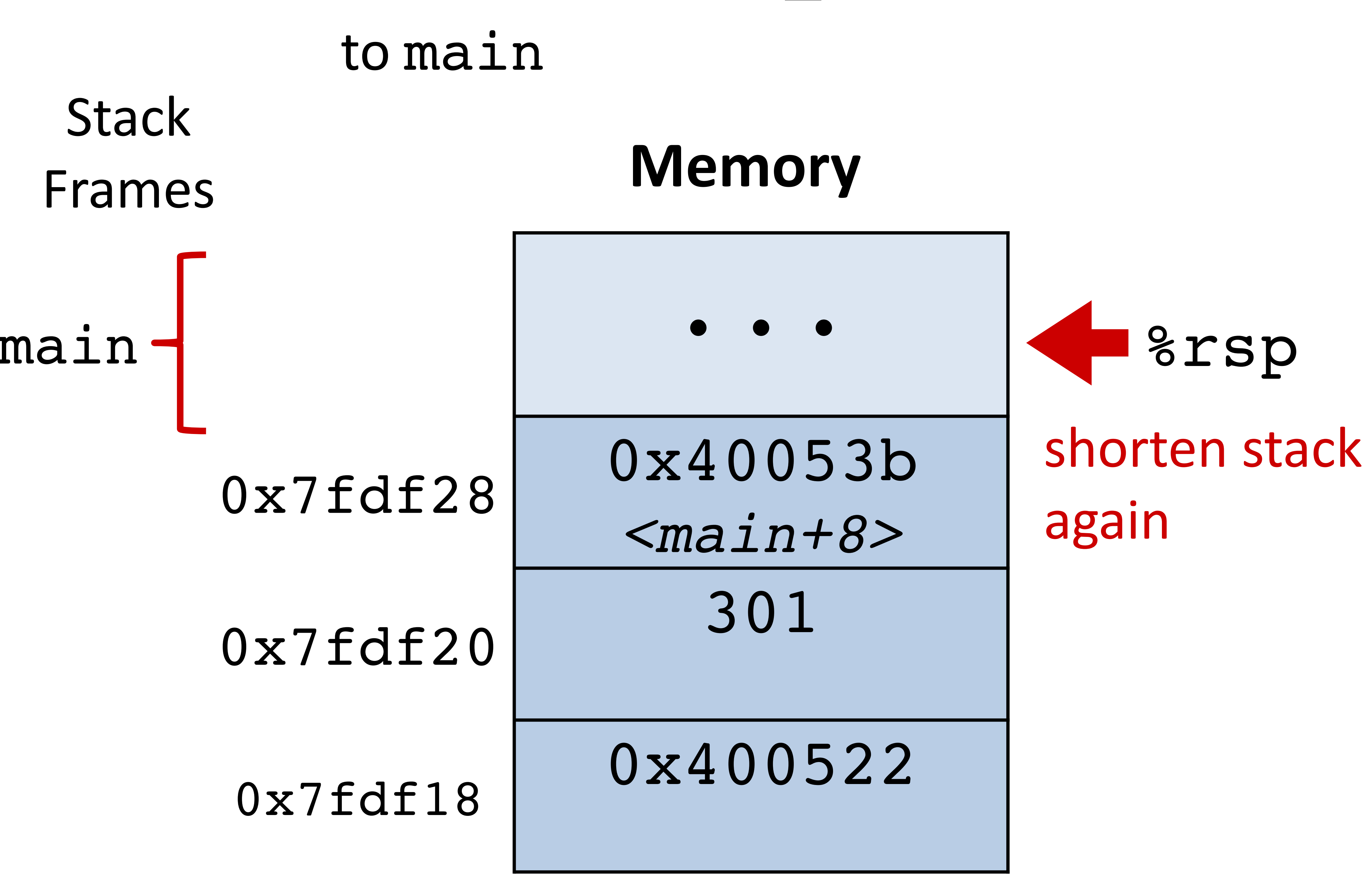
Procedure call example (step 8)

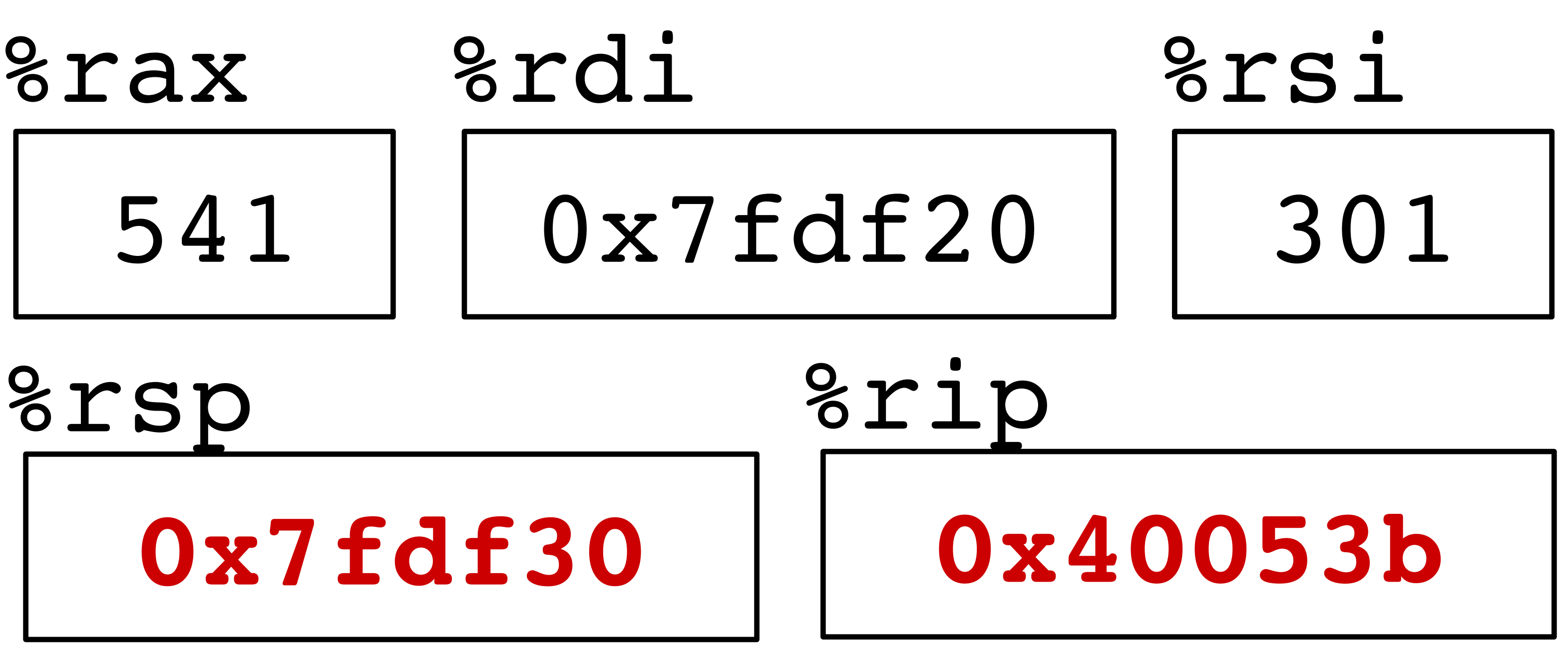
Return from `step_up` to `main`

```
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
```





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

Register	Convention	Register	Convention
`%rax`	Return value – Caller saved	`%r8`	Argument #5 – Caller saved
`%rbx`	**Callee** saved	`%r9`	Argument #6 – Caller saved
`%rcx`	Argument #4 – Caller saved	`%r10`	Caller saved
`%rdx`	Argument #3 – Caller saved	`%r11`	Caller Saved
`%rsi`	Argument #2 – Caller saved	`%r12`	**Callee** saved
`%rdi`	Argument #1 – Caller saved	`%r13`	**Callee** saved
`%rsp`	Stack pointer	`%r14`	**Callee** saved
`%rbp`	**Callee** saved	`%r15`	**Callee** saved

Callee-save example (step 0)

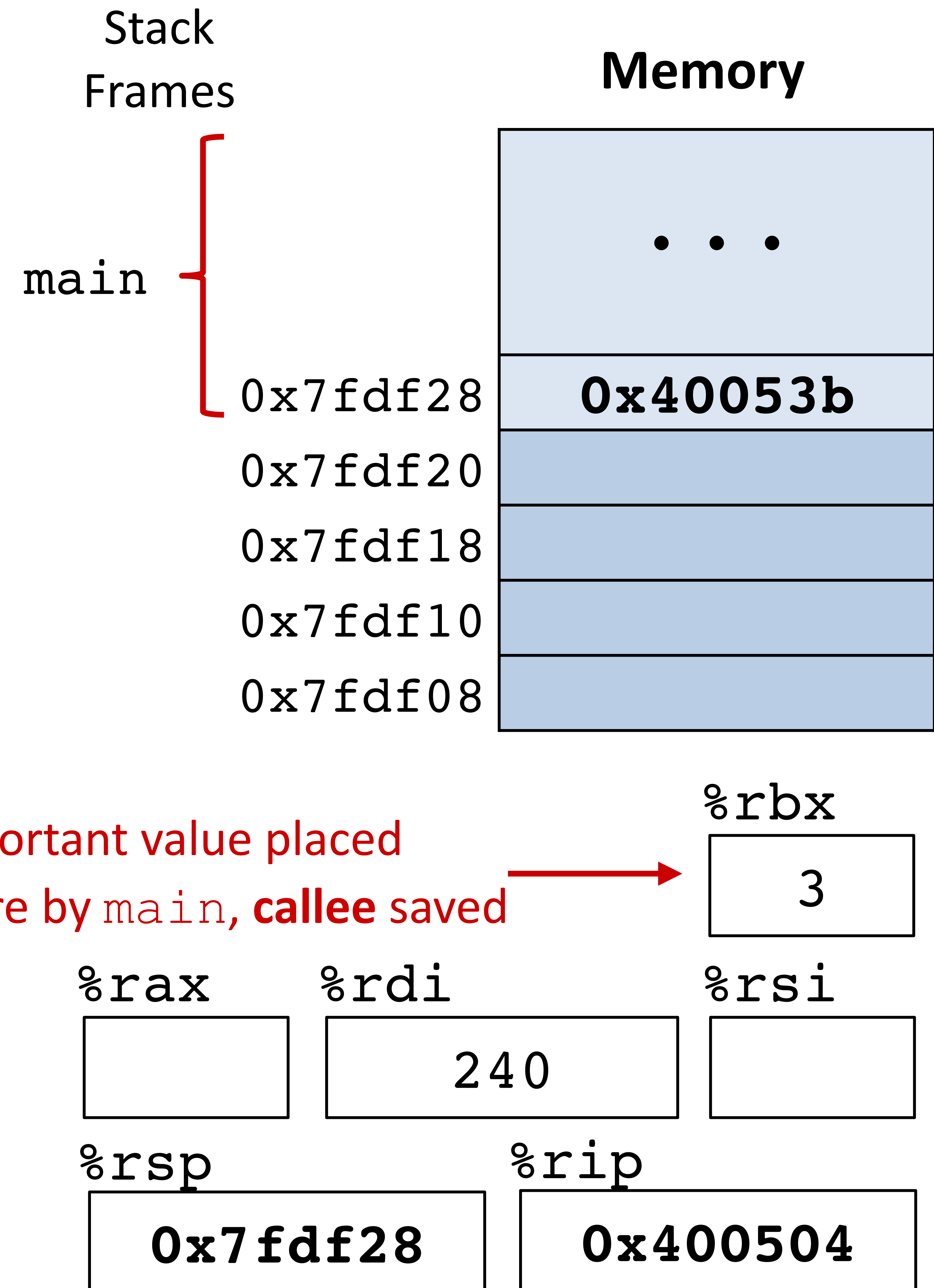
Similar function, but now takes an arg for the local variable

```
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`



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

Stack Frames

Memory

Stack Frame	Address	Value
main		. . .
main	0x7fdf28	0x40053b
step_by	0x7fdf20	3
	0x7fdf18	
	0x7fdf10	
	0x7fdf08	

Register	Value
%rbx	3
%rax	
%rdi	240
%rsi	
%rsp	0x7fdf20
%rip	0x400506

caller saved: %rax, %rdi, %rsi

callee saved: %rbx

Callee-save example (step 2)

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

```
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`

Stack Frames | Memory

Stack frame	Address	Memory
main		. . .
main	0x7fdf28	0x40053b
step_by	0x7fdf20	3
	0x7fdf18	
	0x7fdf10	
	0x7fdf08	

Register	Value
%rbx	**240**
%rax	
%rdi	240
%rsi	
%rsp	0x7fdf20
%rip	0x400509

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

callee saved: `%rbx`

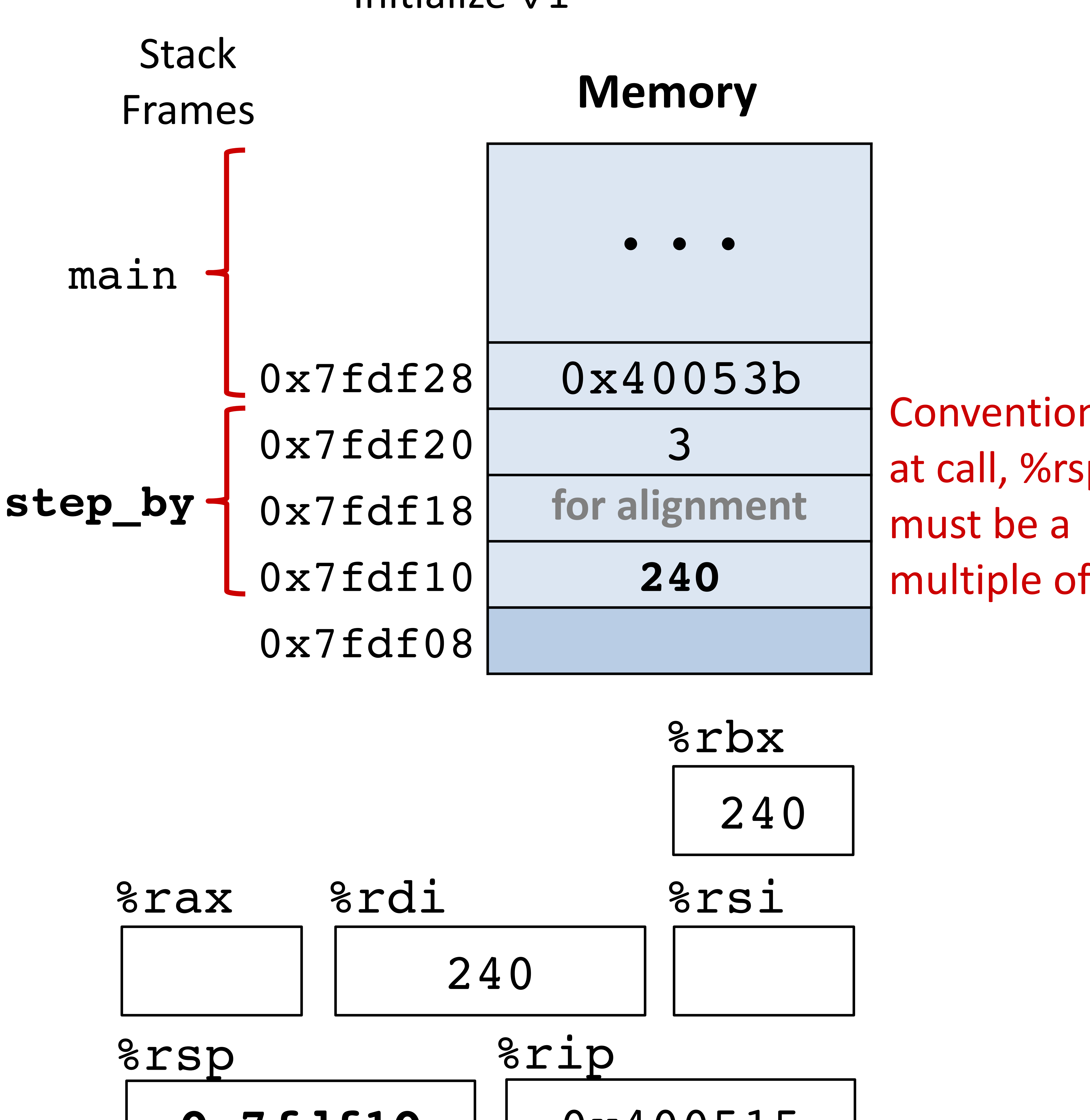
Callee-save example (step 3)

```
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



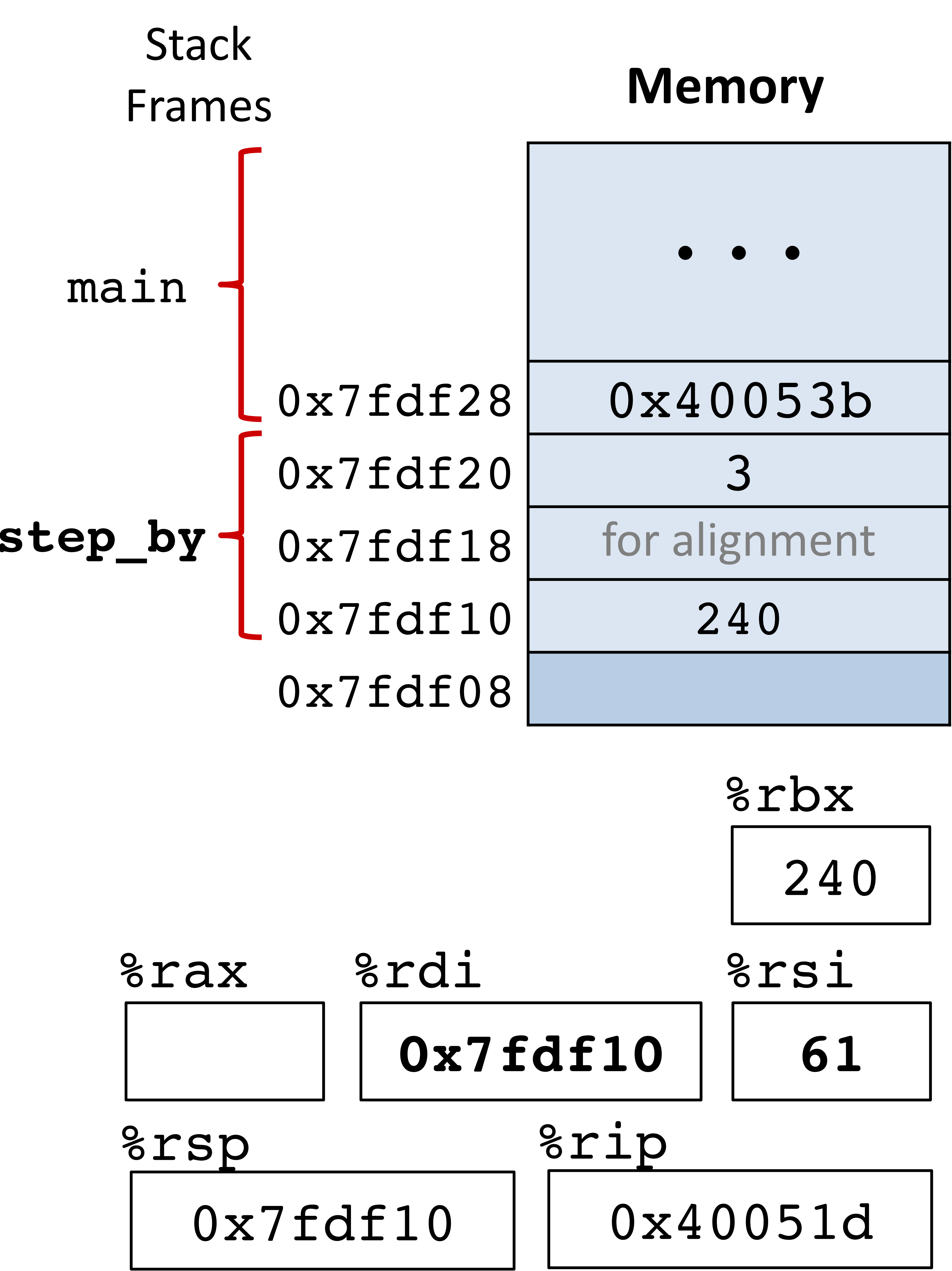
Callee-save example (step 4)

```
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



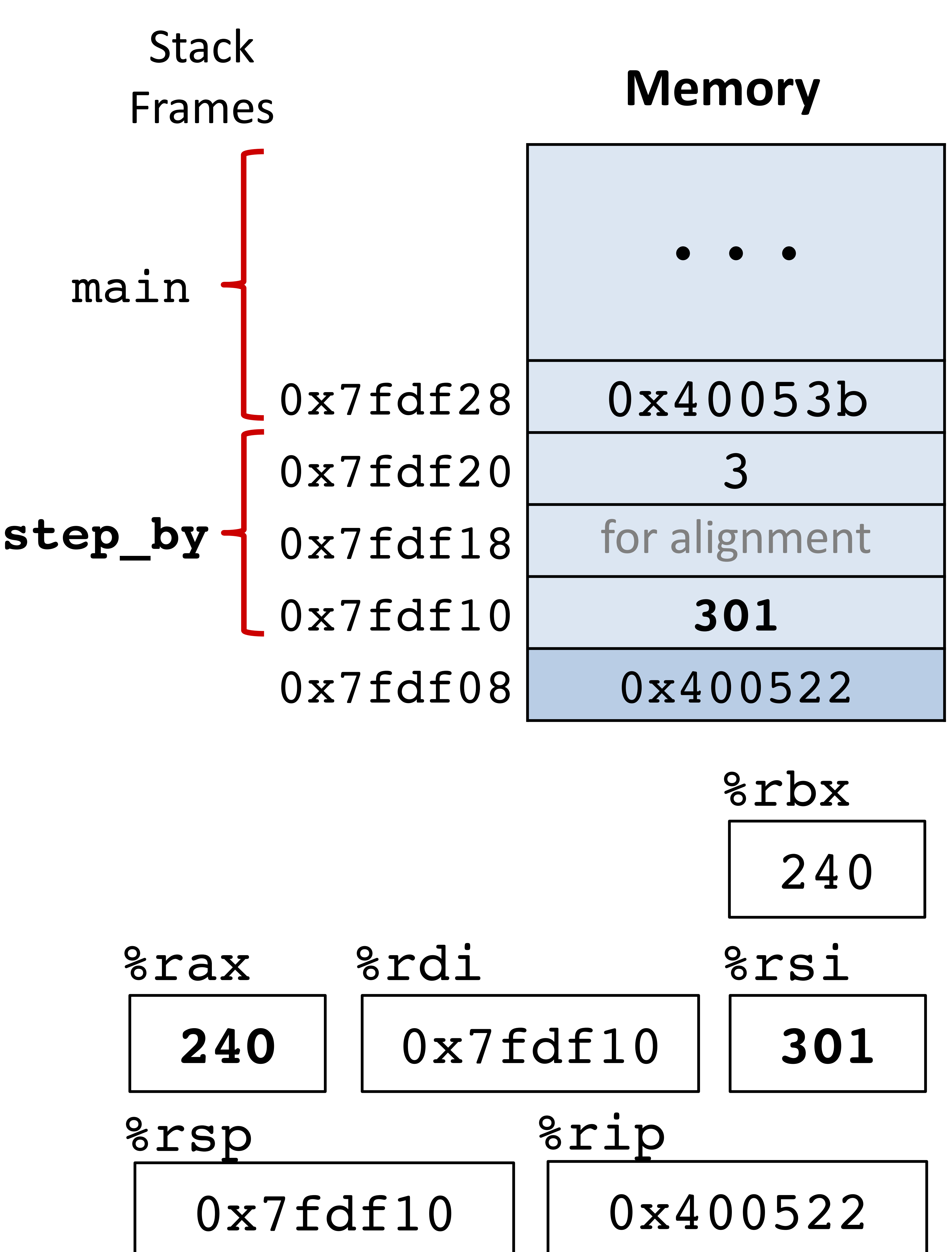
Callee-save example (step 5)

```
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



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`

Stack Frames / Memory

Stack Frame	Address	Memory
main		. . .
main	0x7fdf28	0x40053b
step_by	0x7fdf20	3
step_by	0x7fdf18	for alignment
step_by	0x7fdf10	301
	0x7fdf08	0x400522

Register	Value
%rbx	240
%rax	**480**
%rdi	0x7fdf10
%rsi	301
%rsp	0x7fdf10
%rip	0x400525

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

Stack Frames

Memory

Stack frame	Address	Memory
main		. . .
main	0x7fdf28	0x40053b
step_by	0x7fdf20	3
	0x7fdf18	for alignment
	0x7fdf10	301
	0x7fdf08	0x400522

Register	Value
%rbx	240
%rax	480
%rdi	0x7fdf10
%rsi	301
%rsp	**0x7fdf20**
%rip	0x400529

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;
}
```

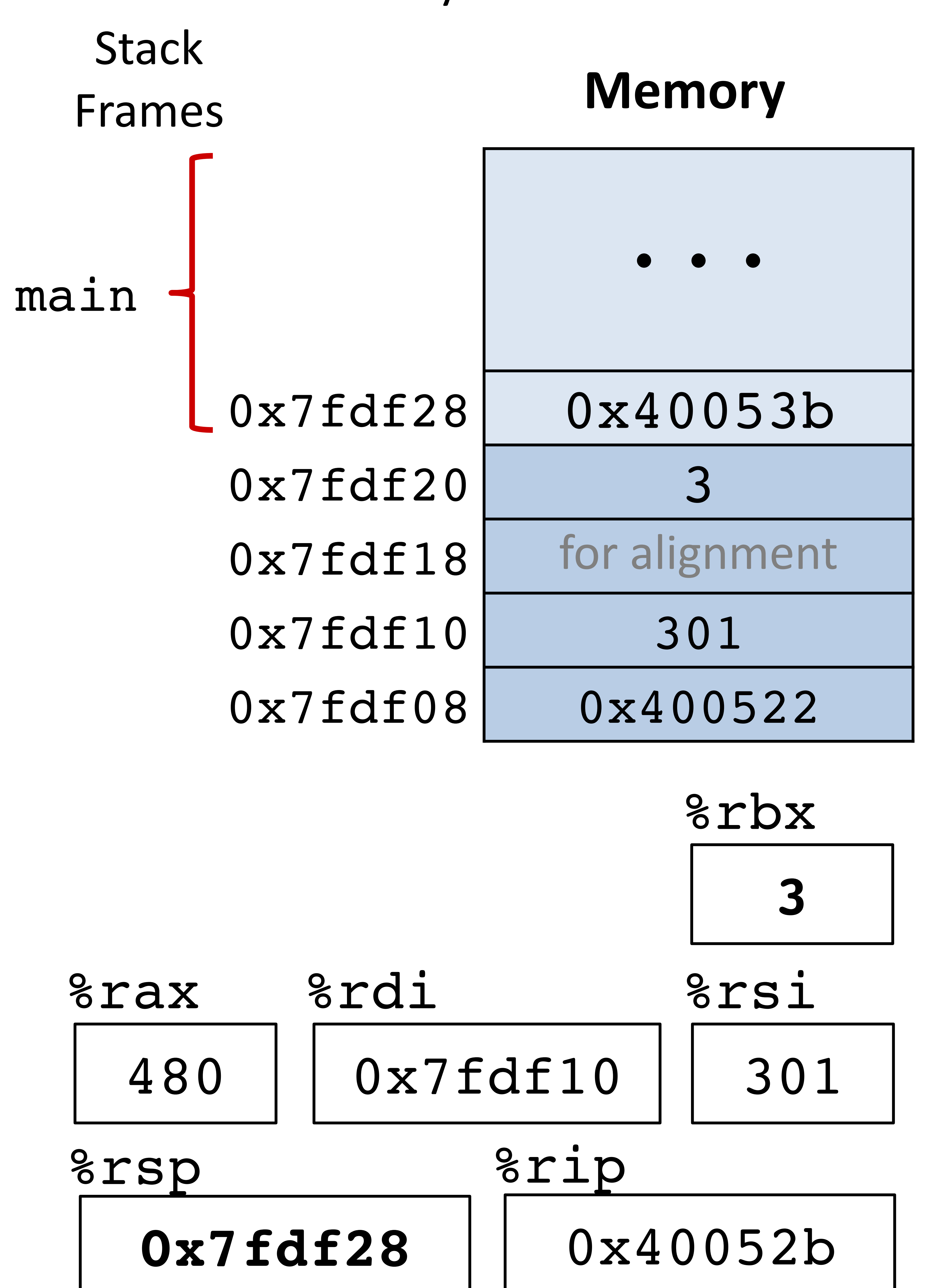
```
step_by:
400504:  pushq %rbx
400506:  movq  %rdi, %rbx
400509:  subq  $16, %rsp
40050d:  movq  %rdi, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  %rbx, %rax
400525:  addq  $16, %rsp
400529:  popq  %rbx
40052b:  retq
```

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

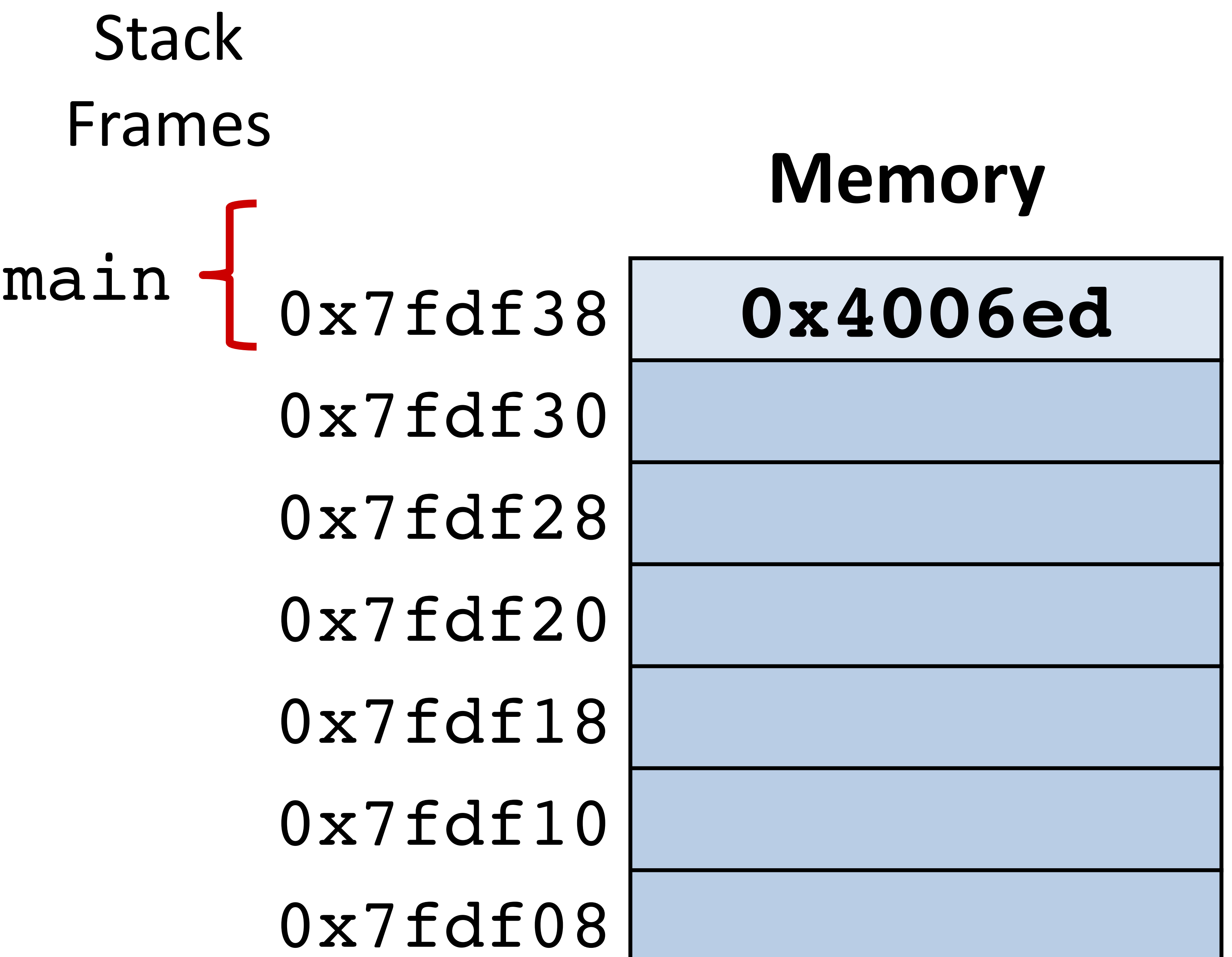
x&1 in %rbx across call

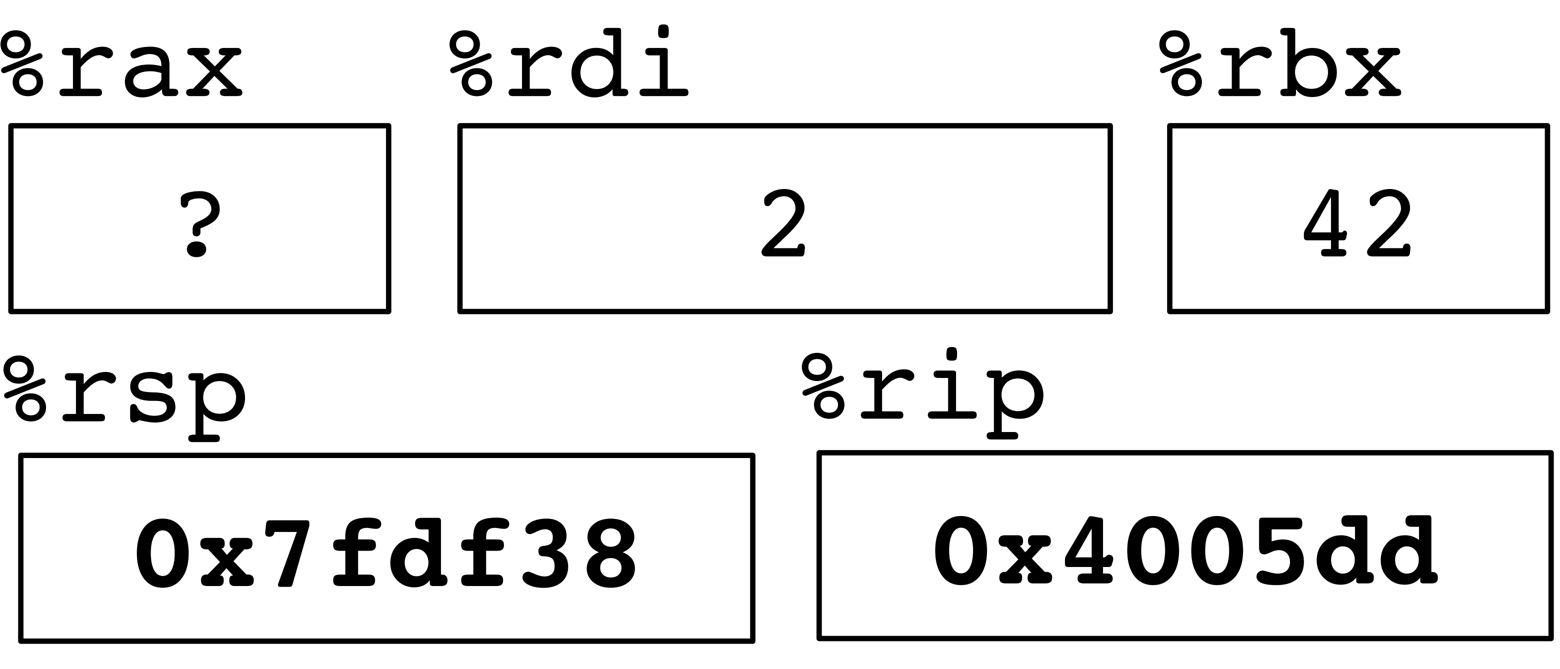
save/restore %rbx (callee-save)

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
```

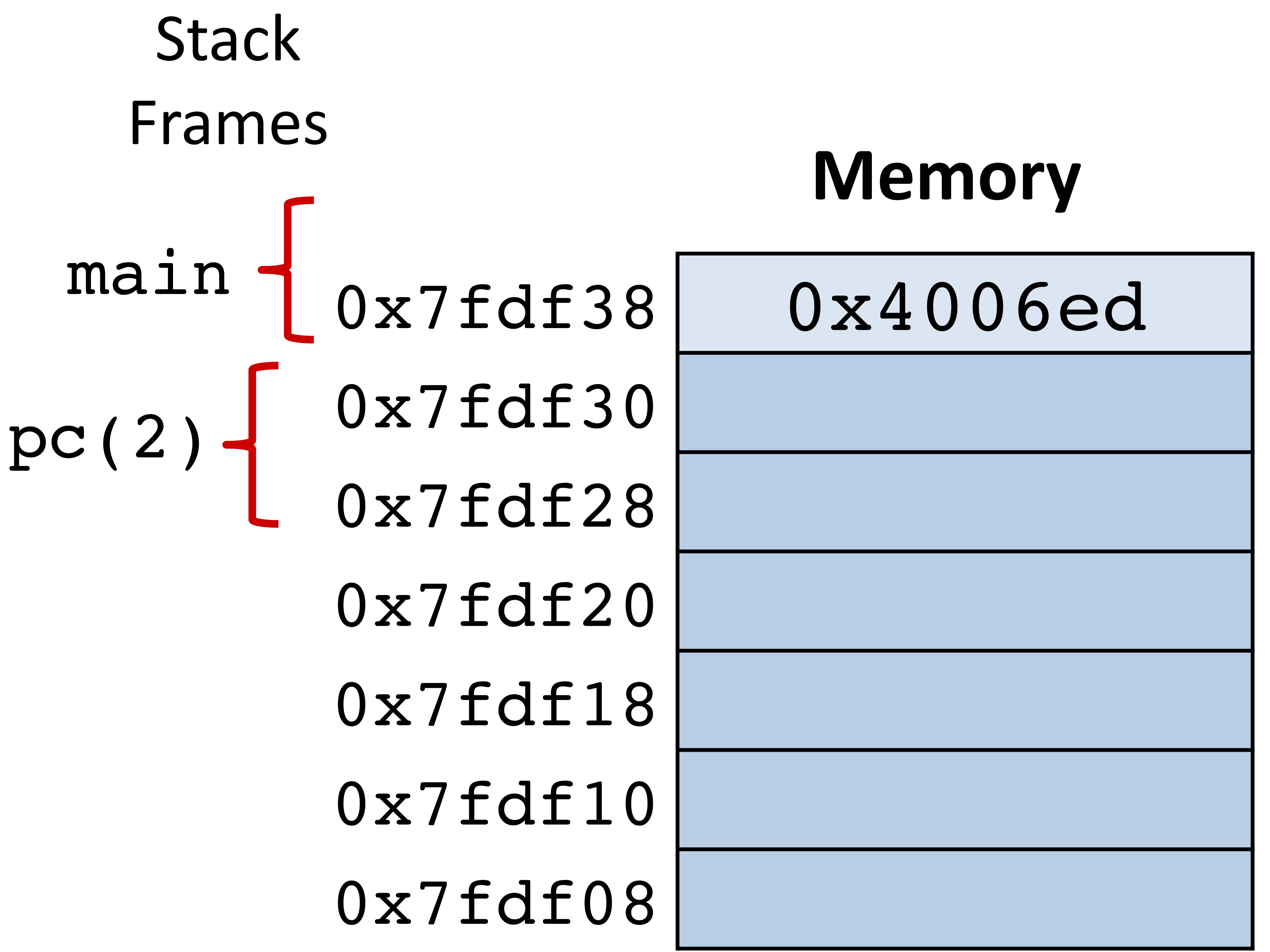


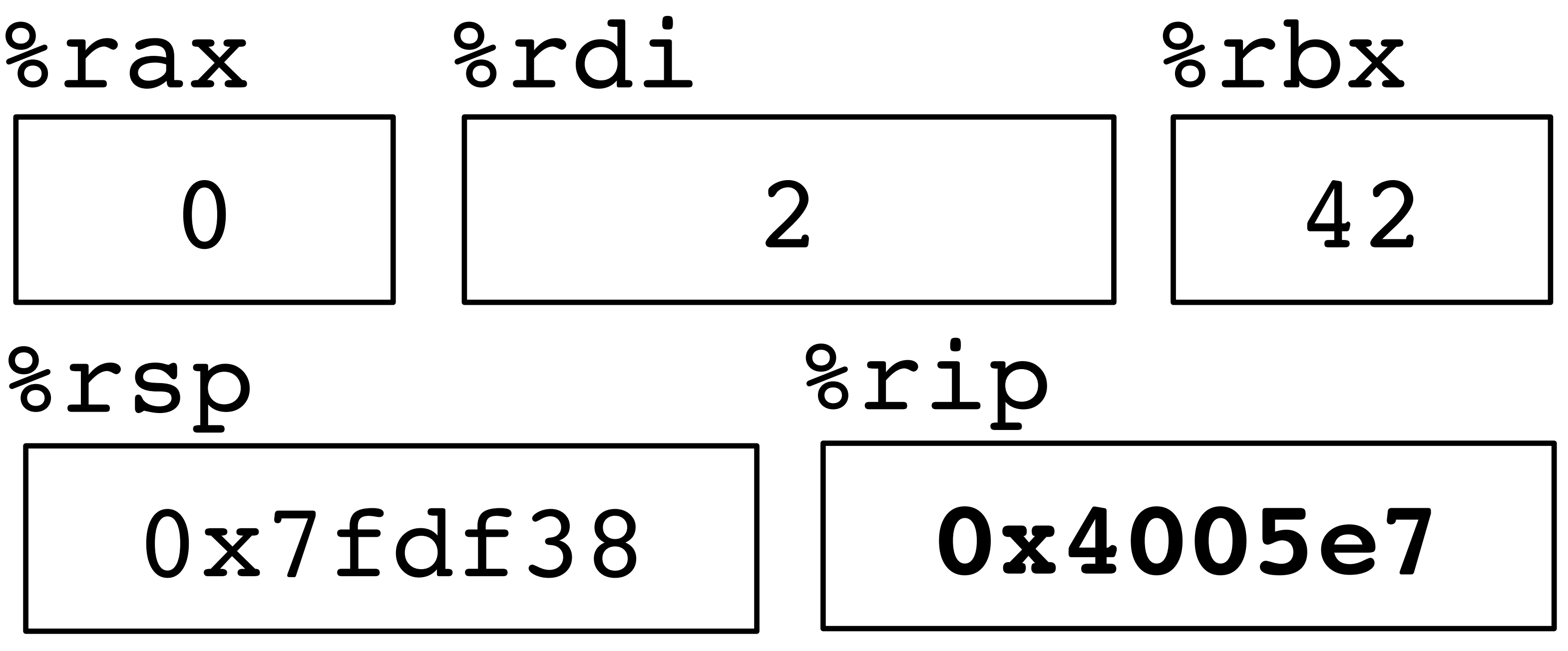


Recursion Example: `pcount(2)`

```
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
```

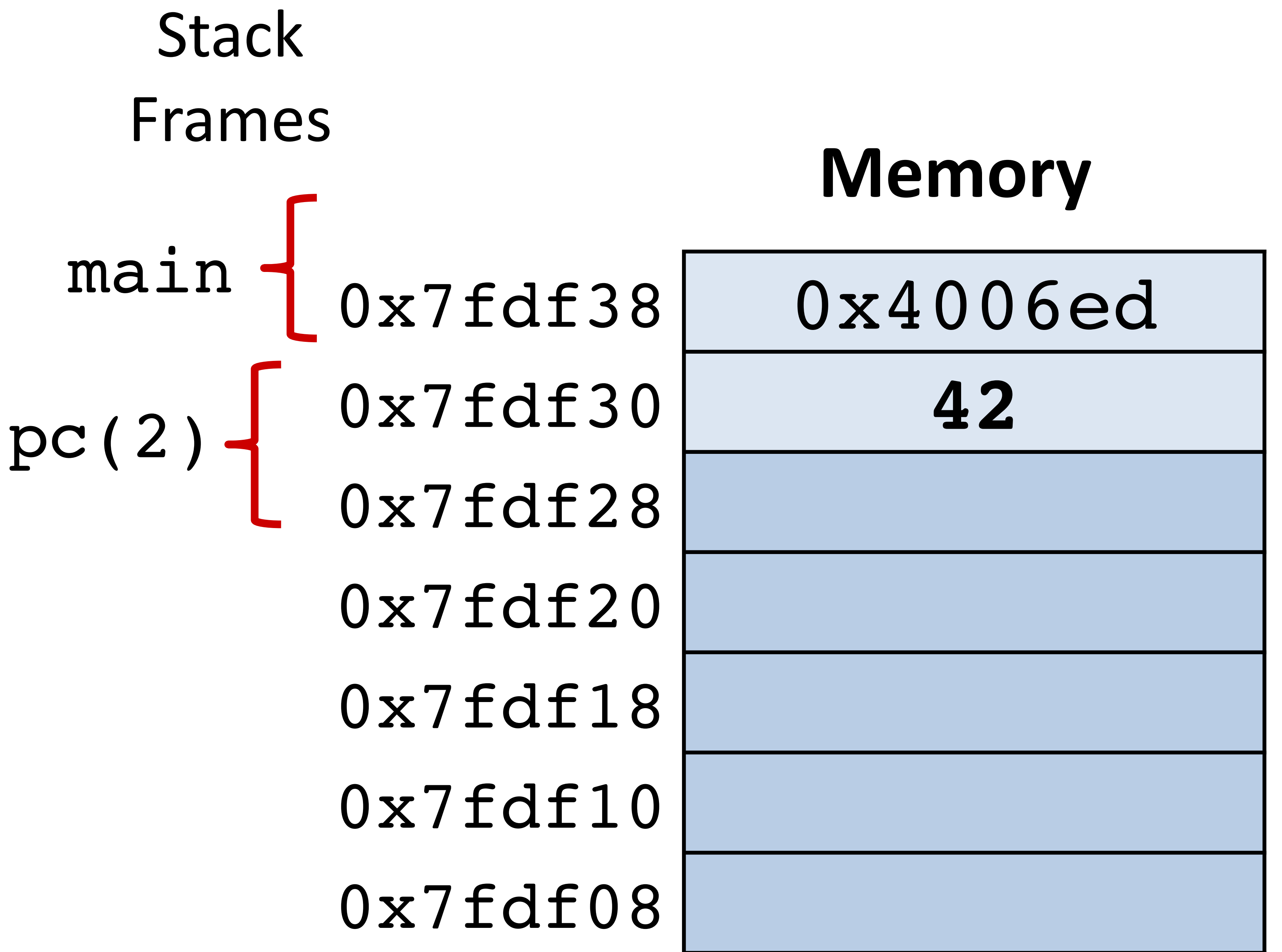


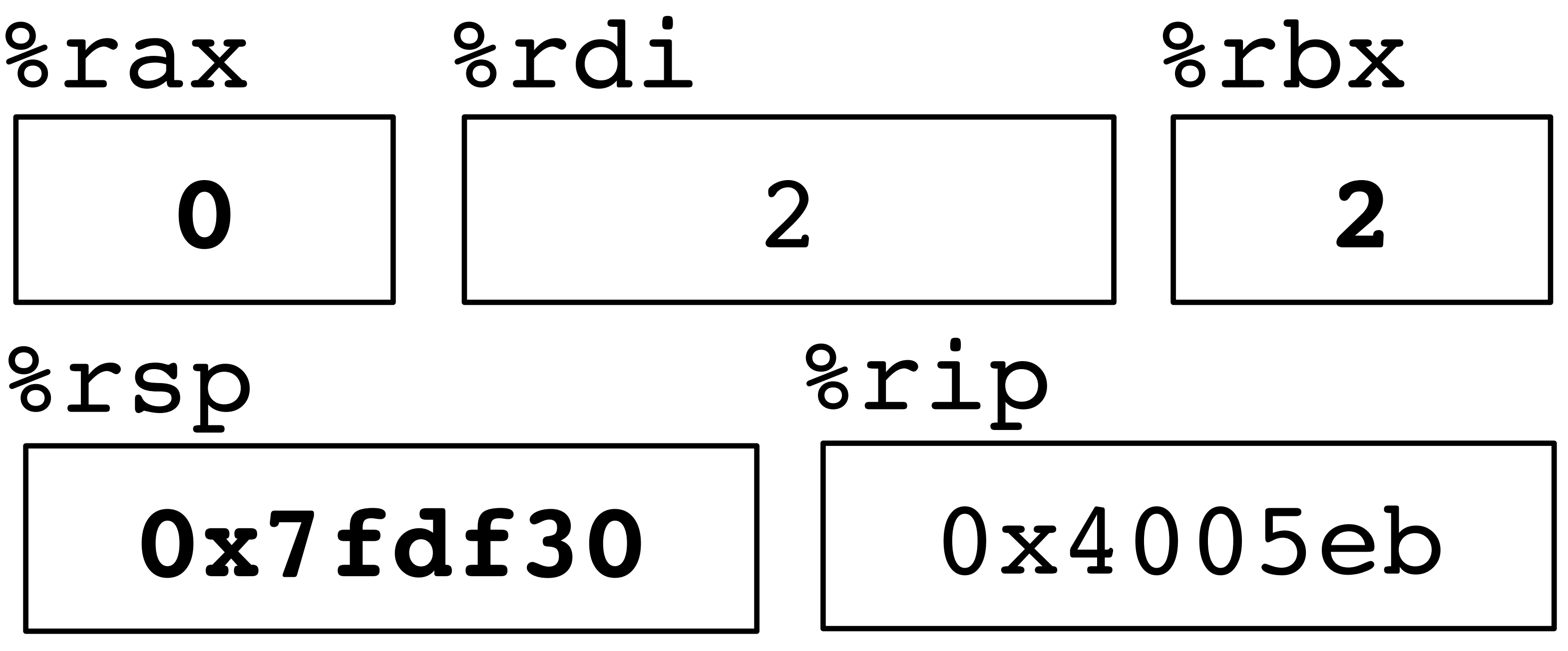


Recursion Example: `pcount(2)`

```
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
```

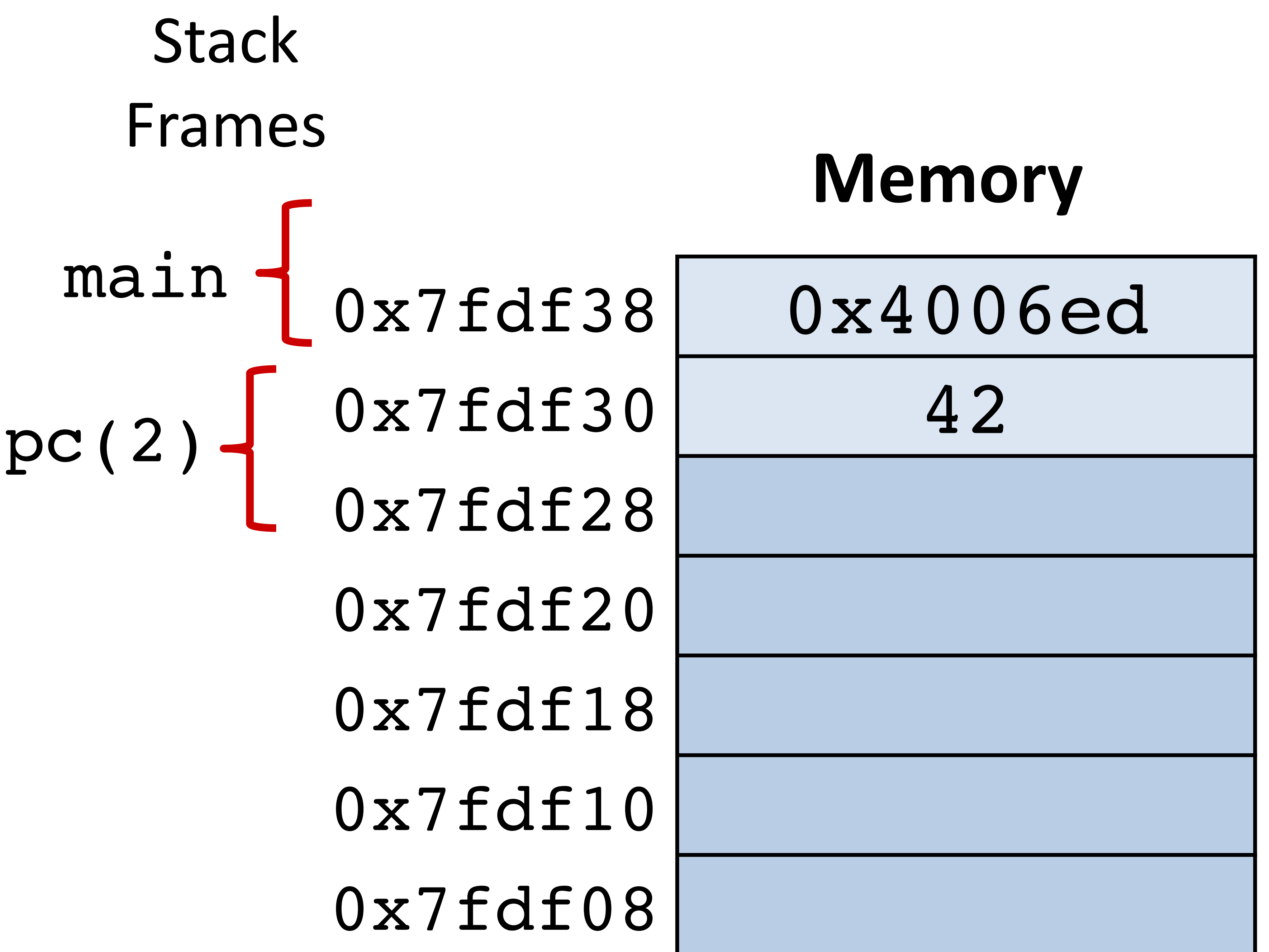


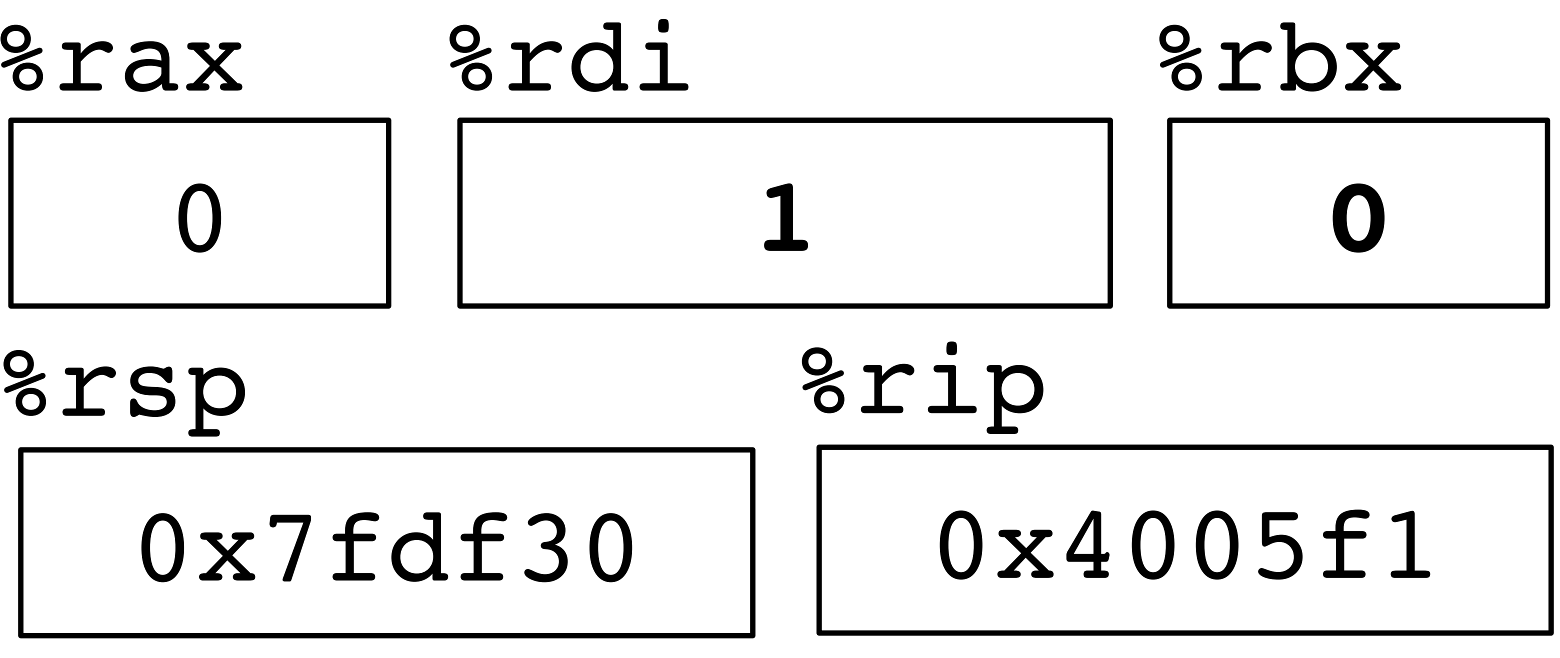


Recursion Example: `pcount(2)`

```
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
```

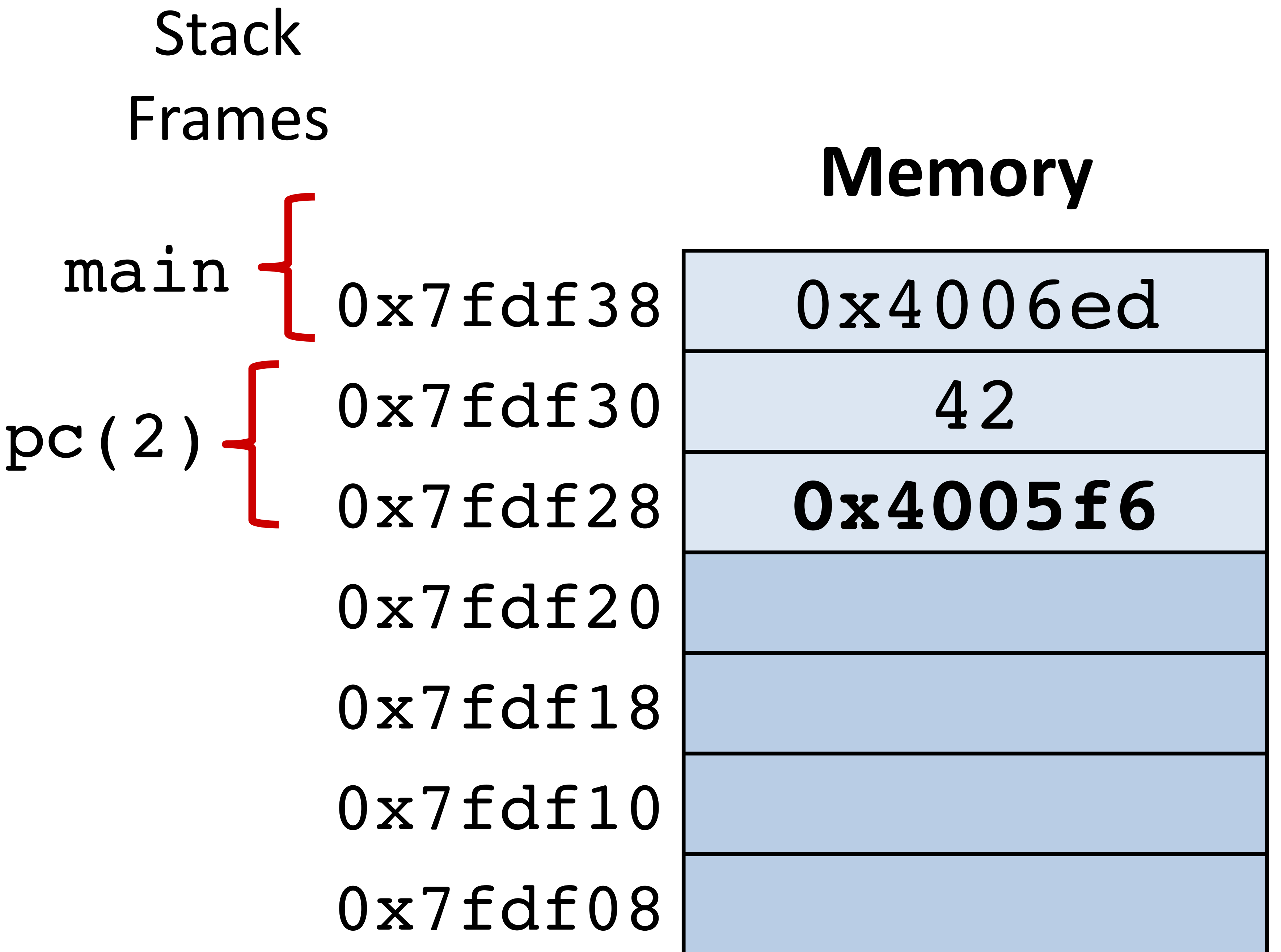


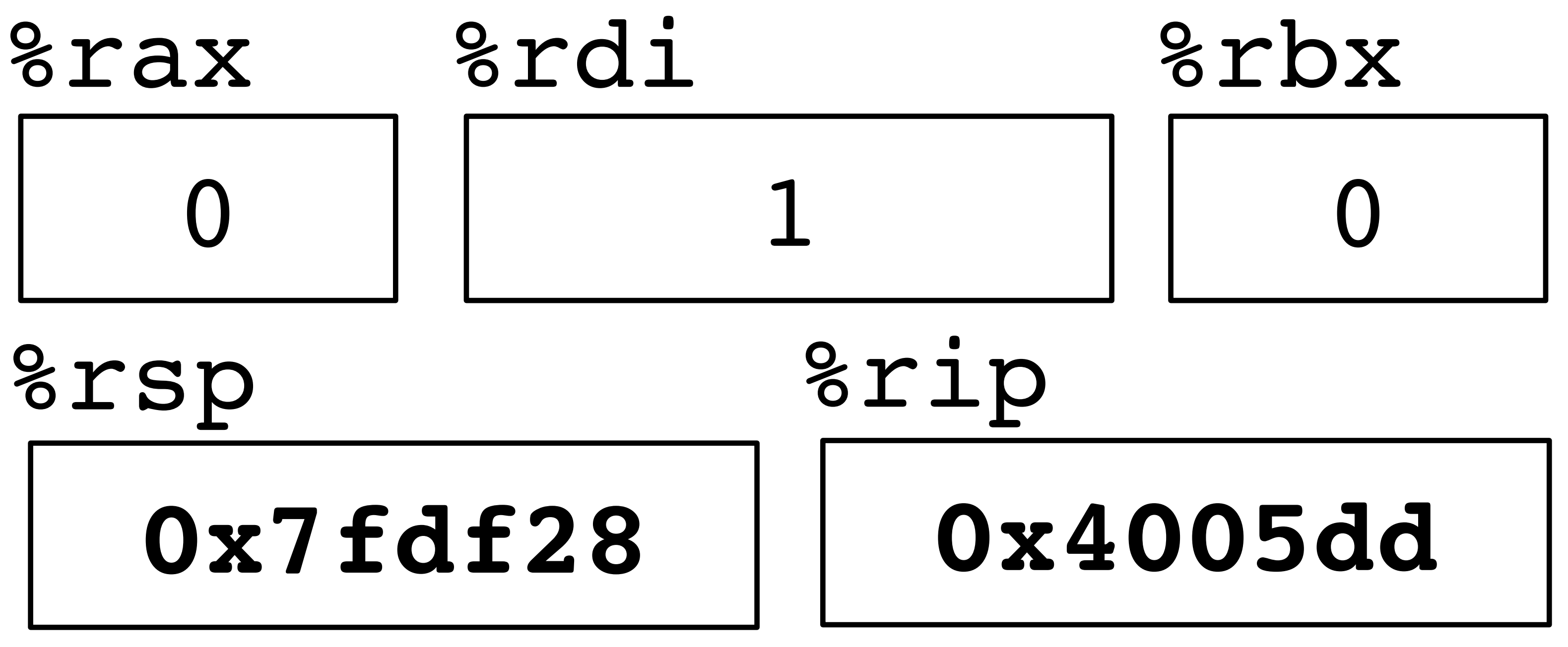


Recursion Example: `pcount(2)` → **`pcount(1)`**

```
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
```

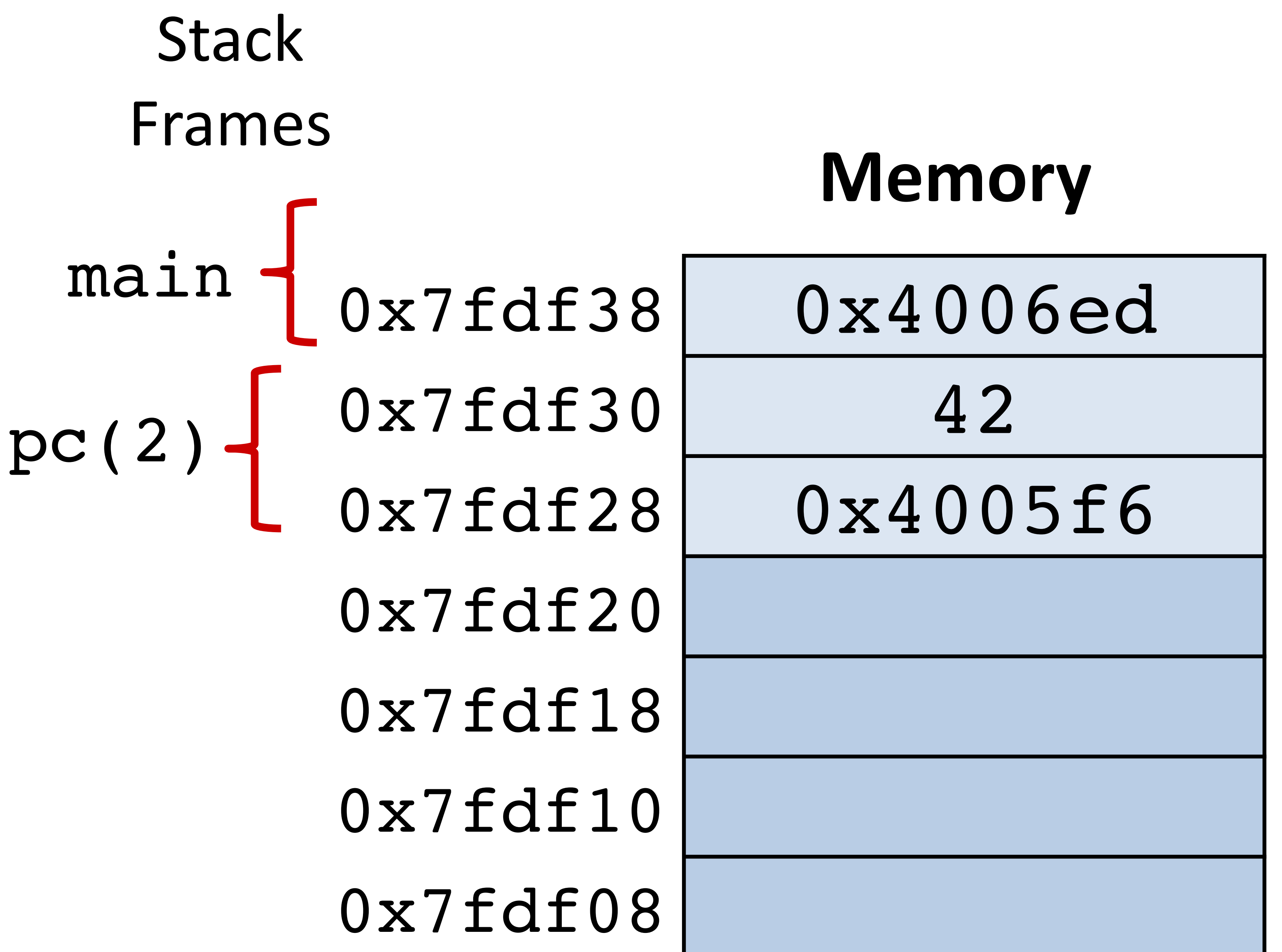


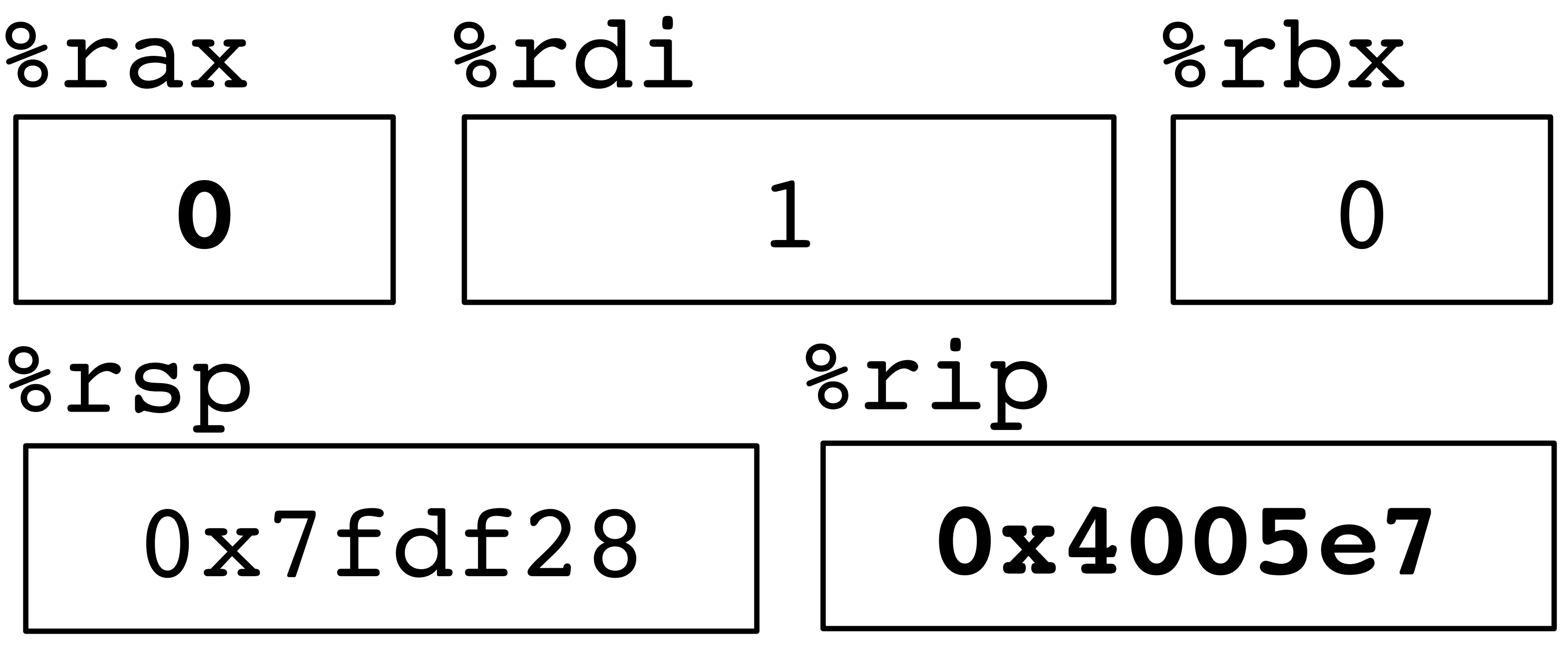


Recursion Example: `pcount(2)` → **`pcount(1)`**

```
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
```

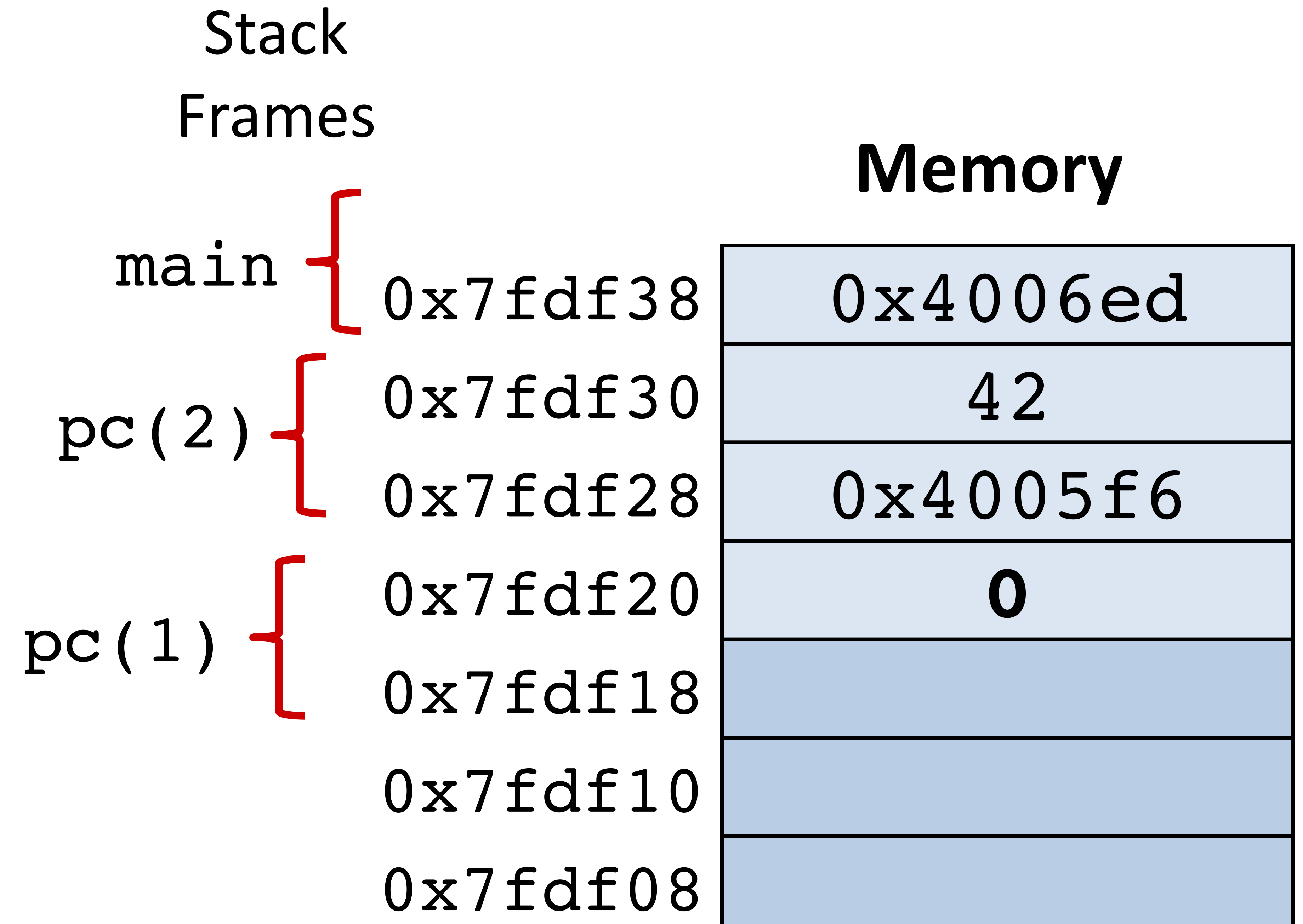


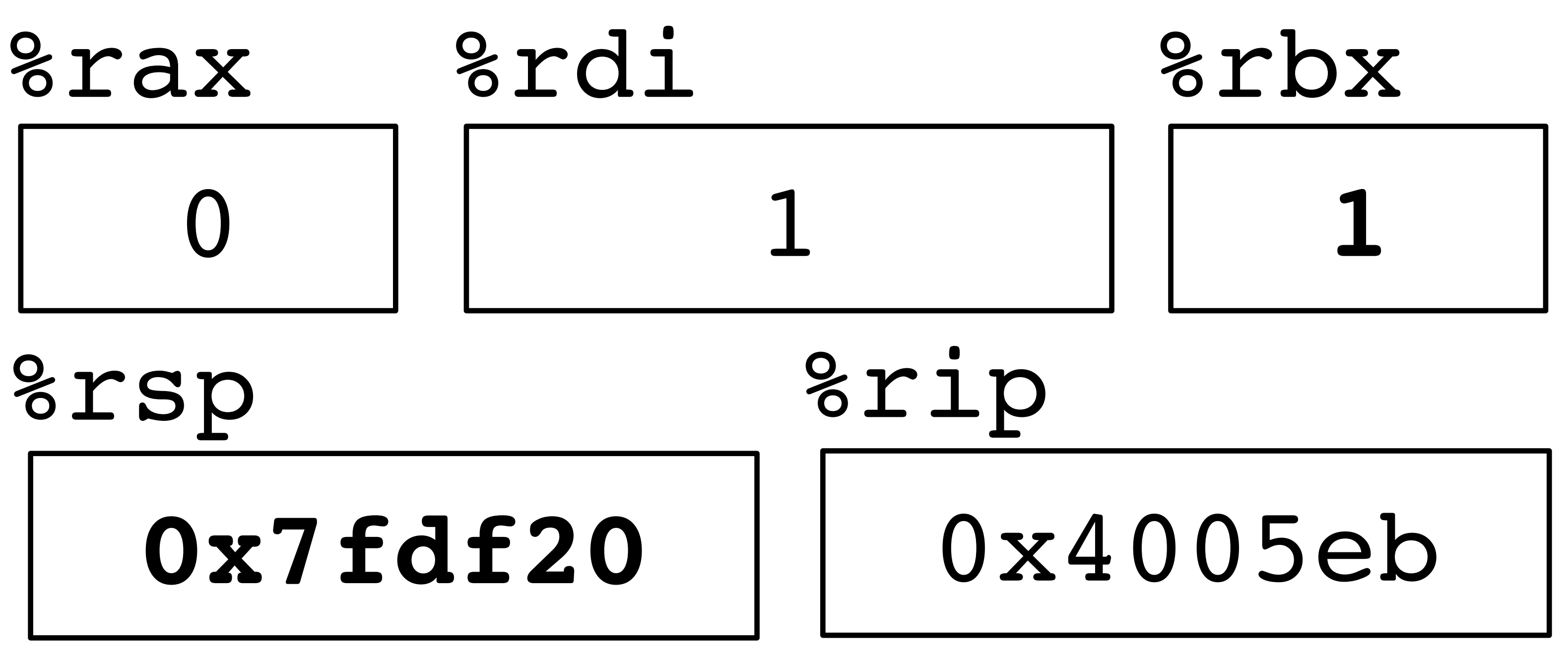


Recursion Example: `pcount(2)` → **`pcount(1)`**

```
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
```

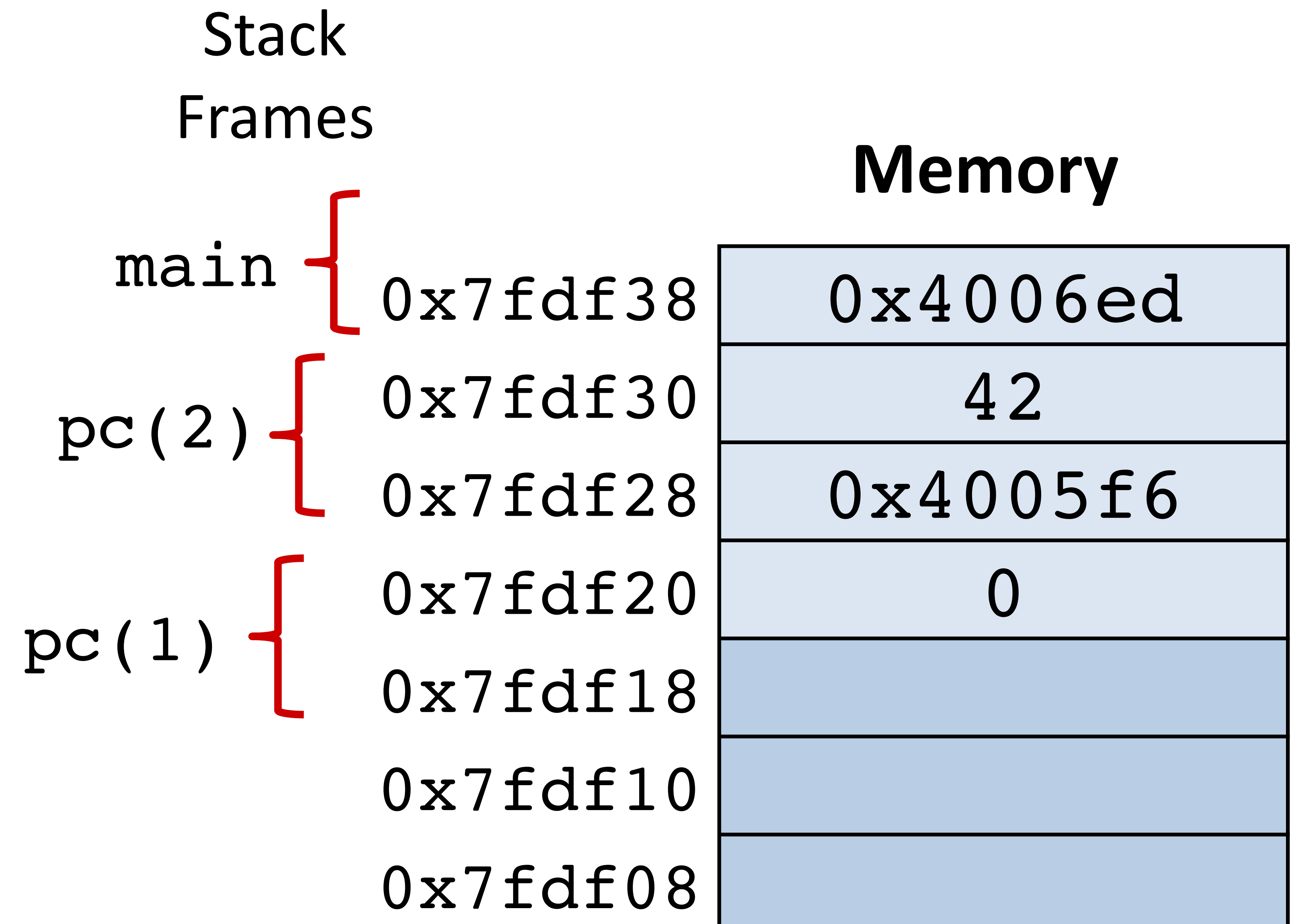


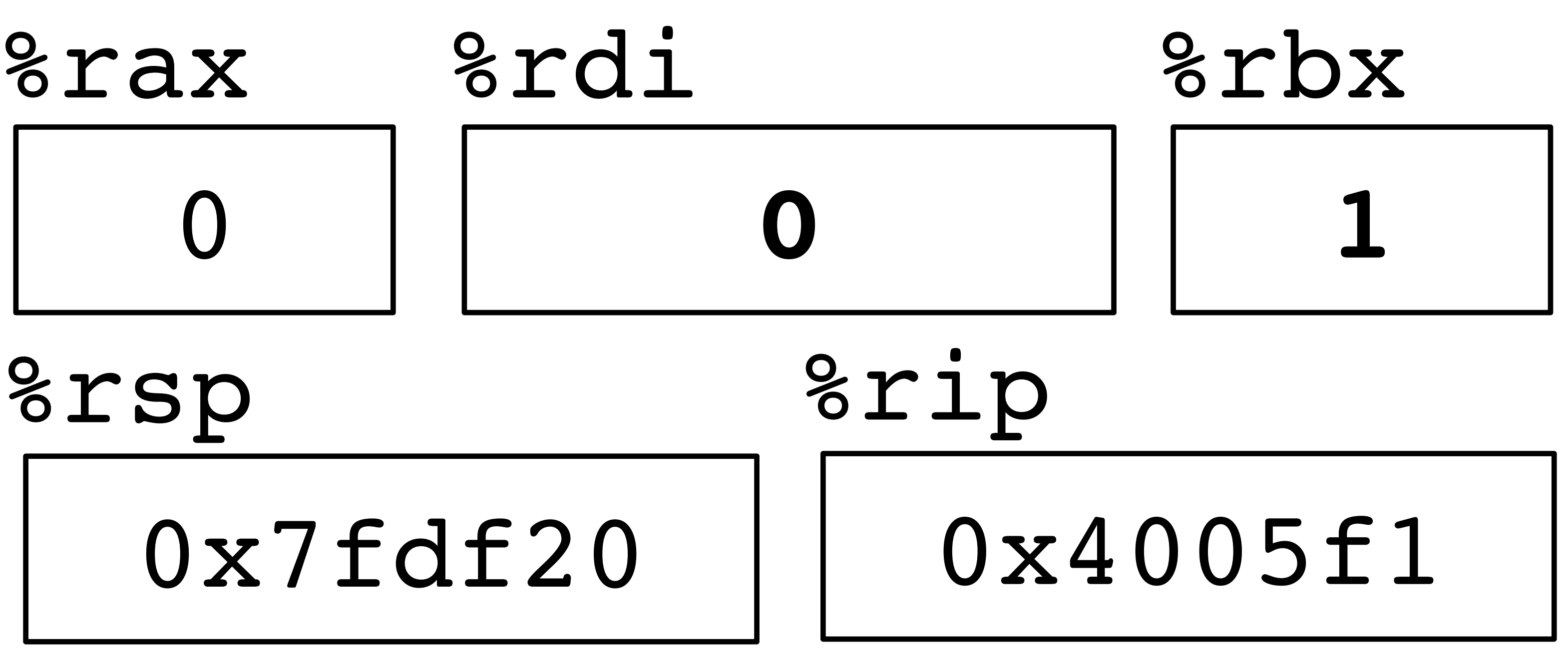


Recursion Example: `pcount(2)` → **`pcount(1)`**

```
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
```

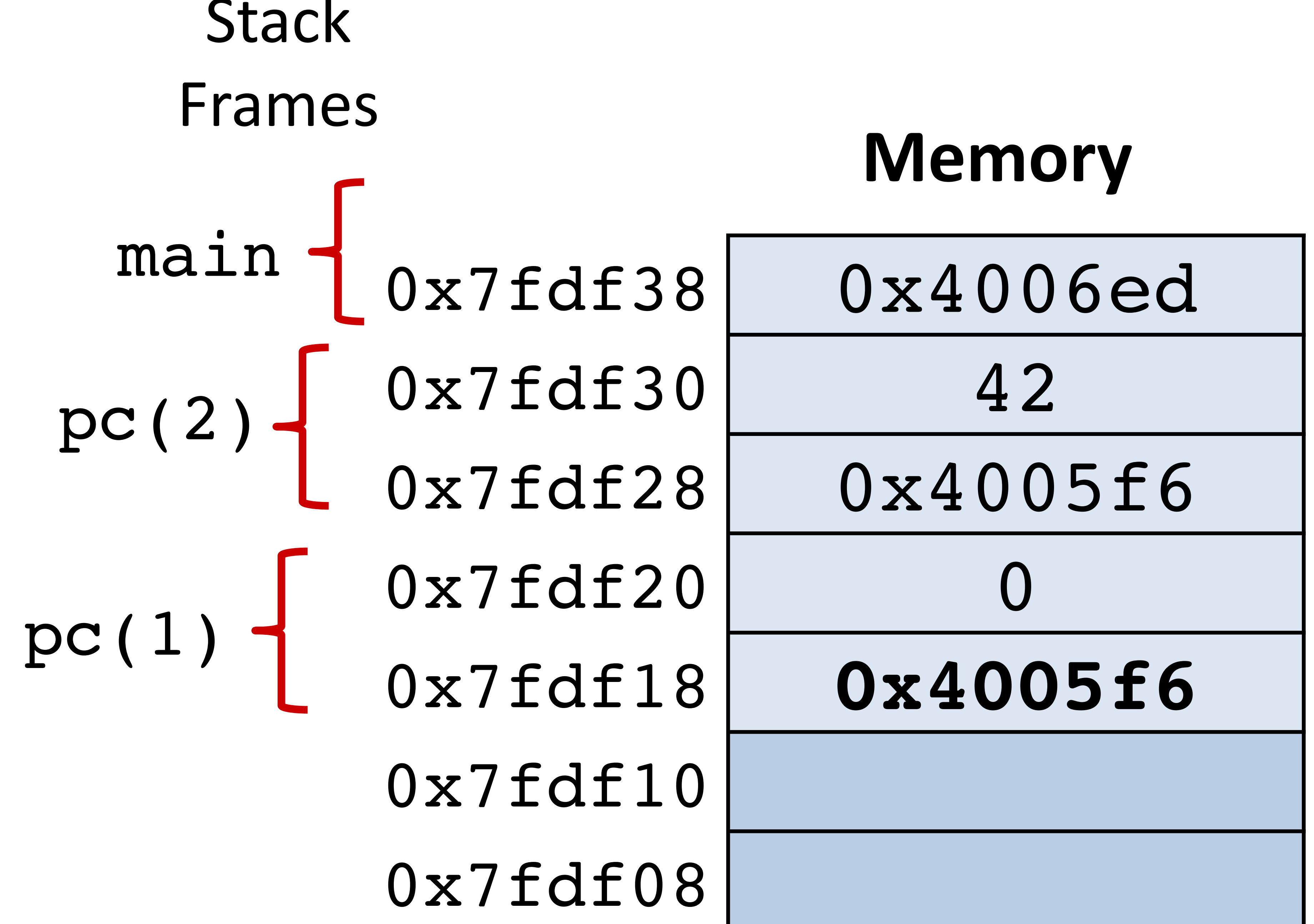


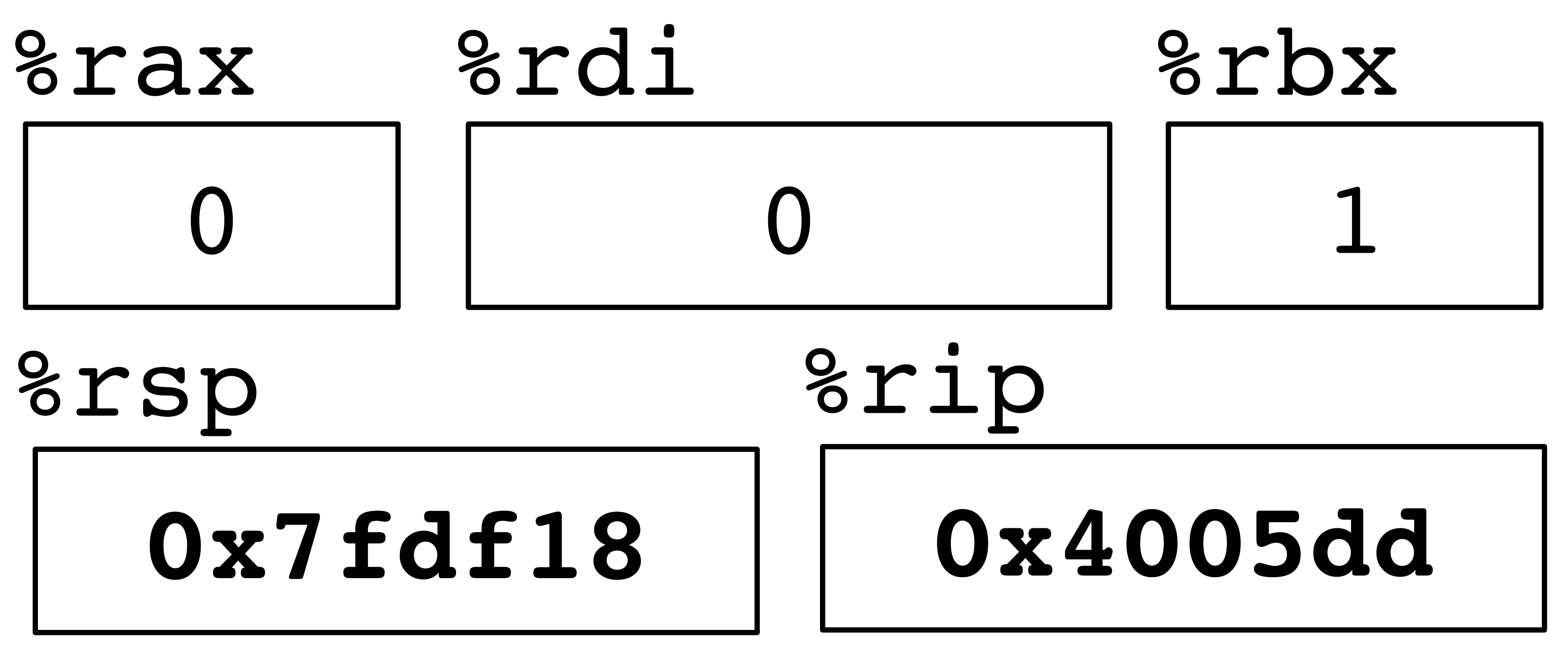


Recursion Example: `pcount(2)` → `pcount(1)` → **`pcount(0)`**

```
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
```

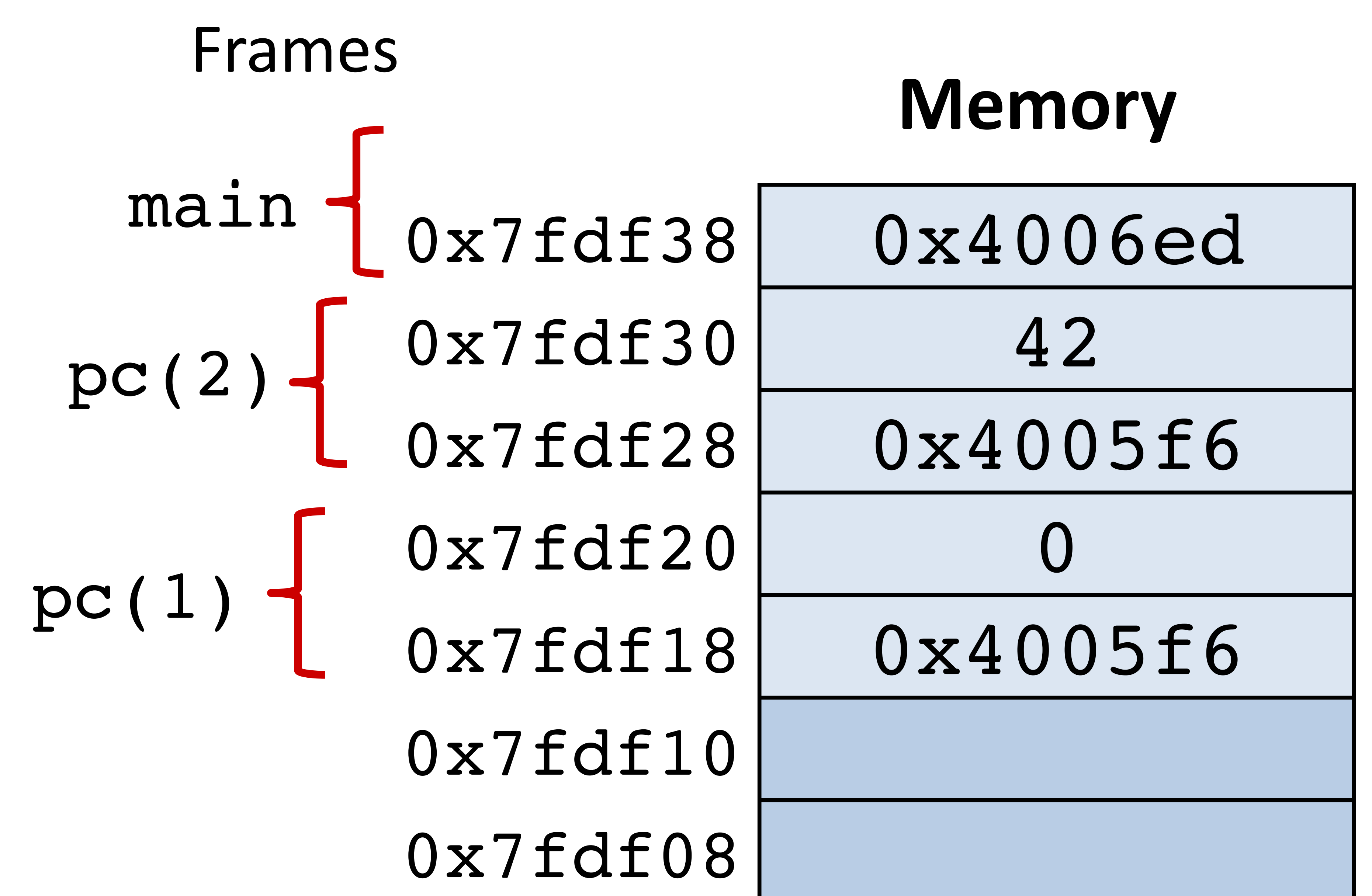


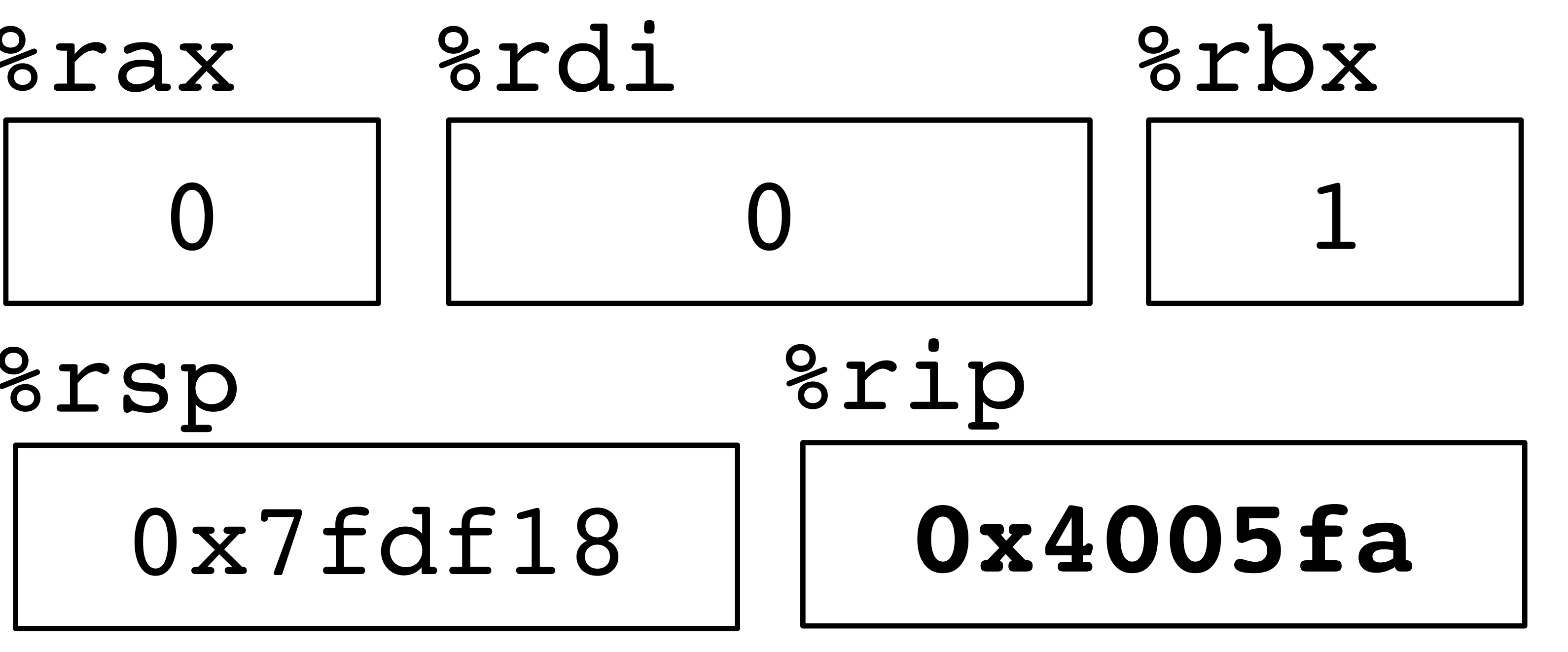


Recursion Example: pcount(2) → pcount(1) → **pcount(0)**

```
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
```

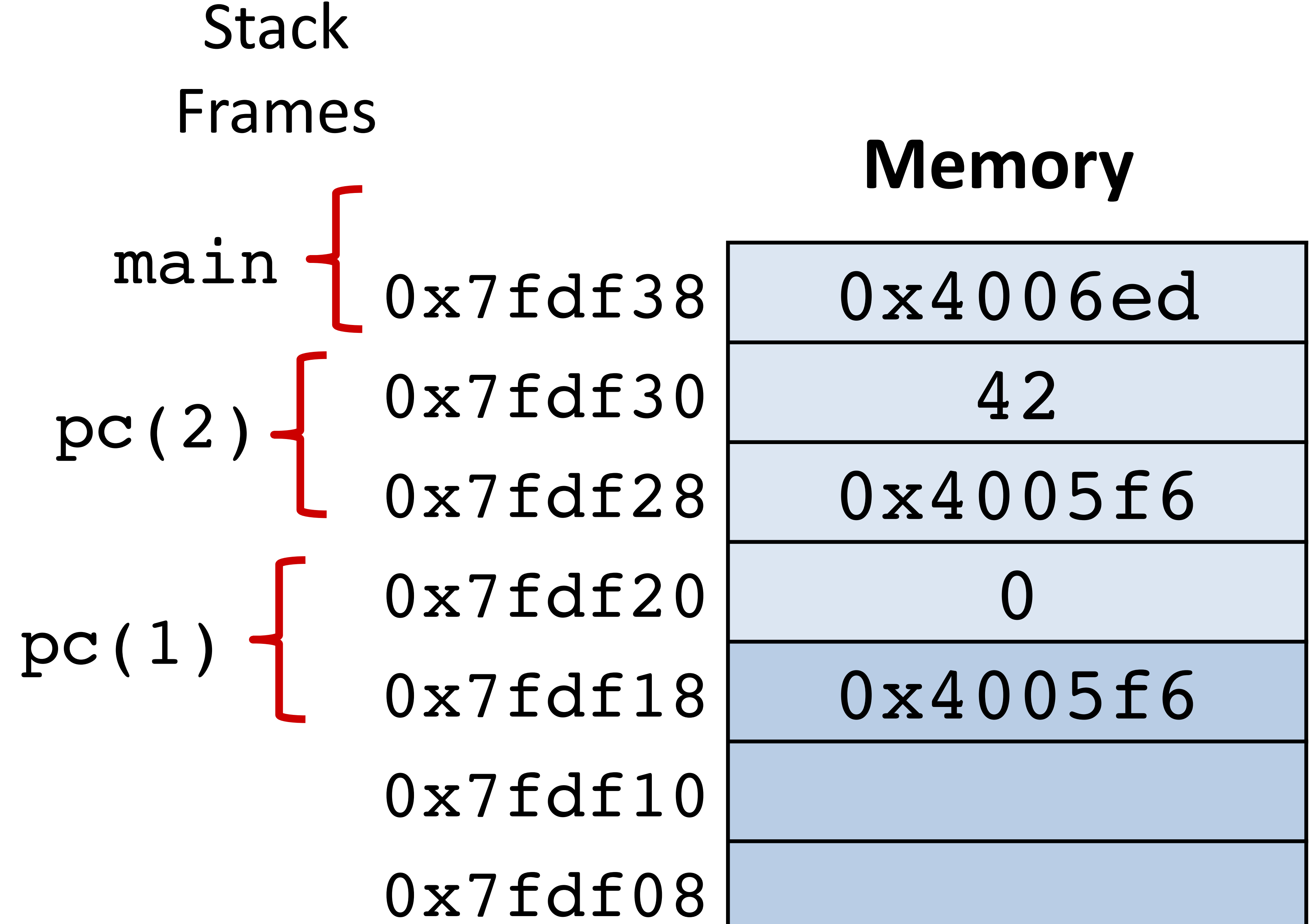


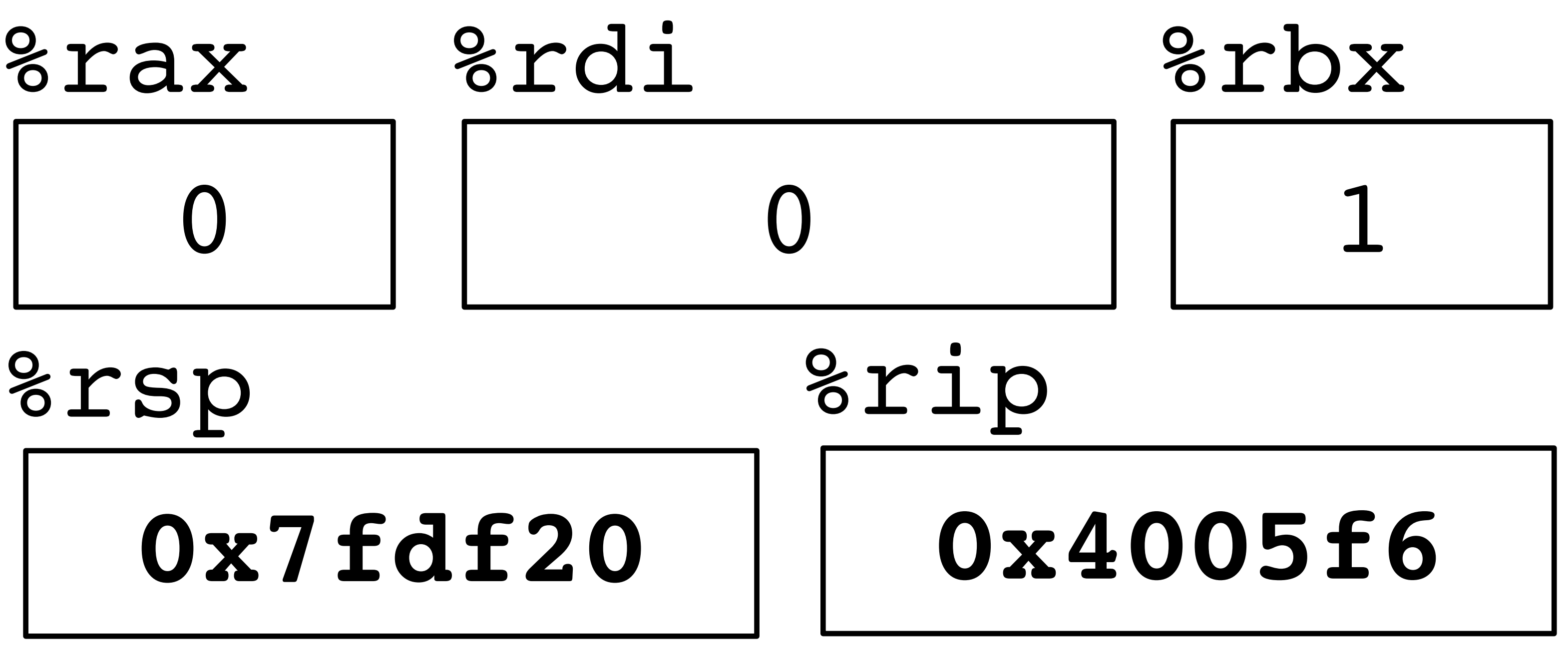


Recursion Example: pcount(2) → pcount(1) → pcount(0)

```
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
```

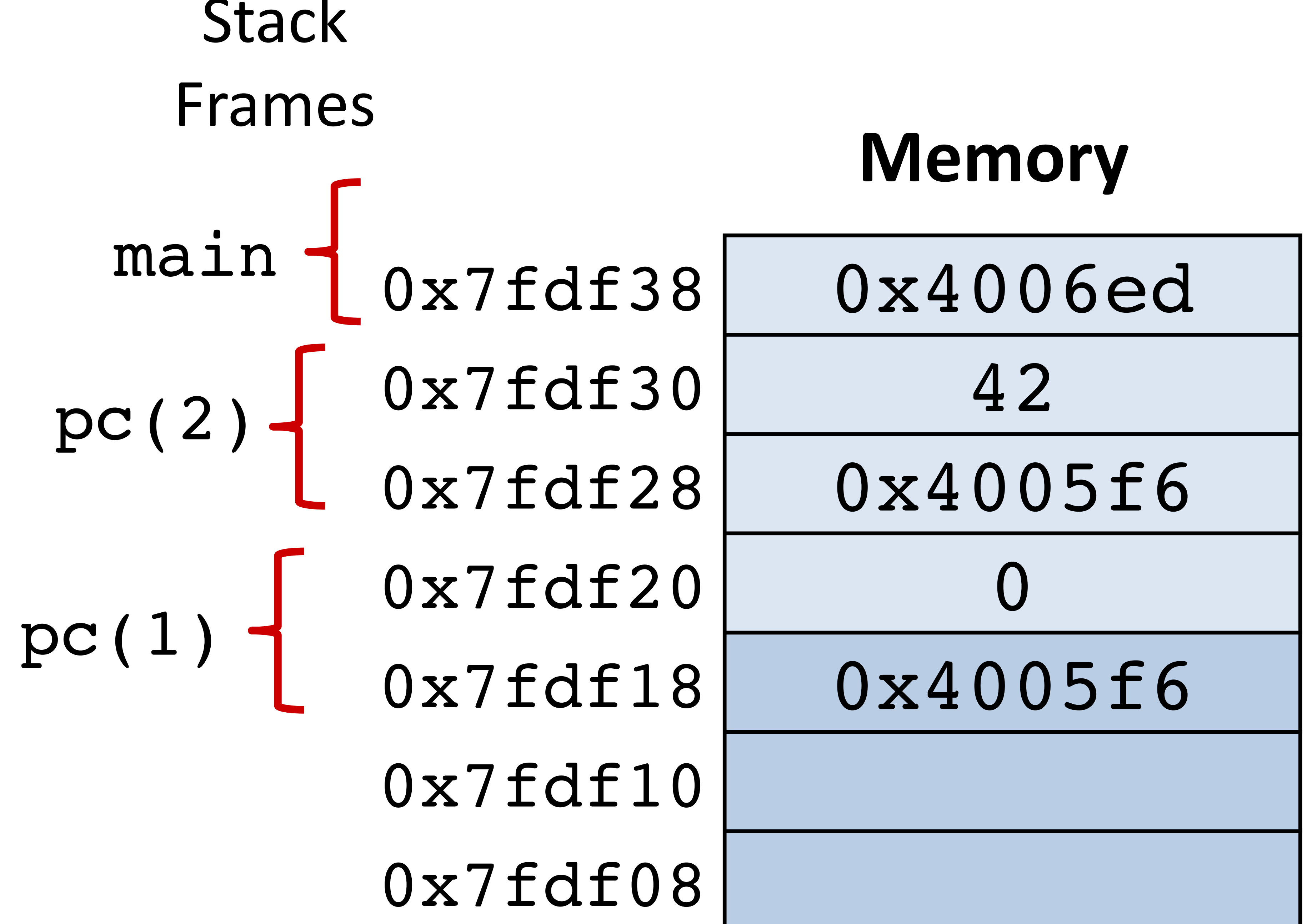


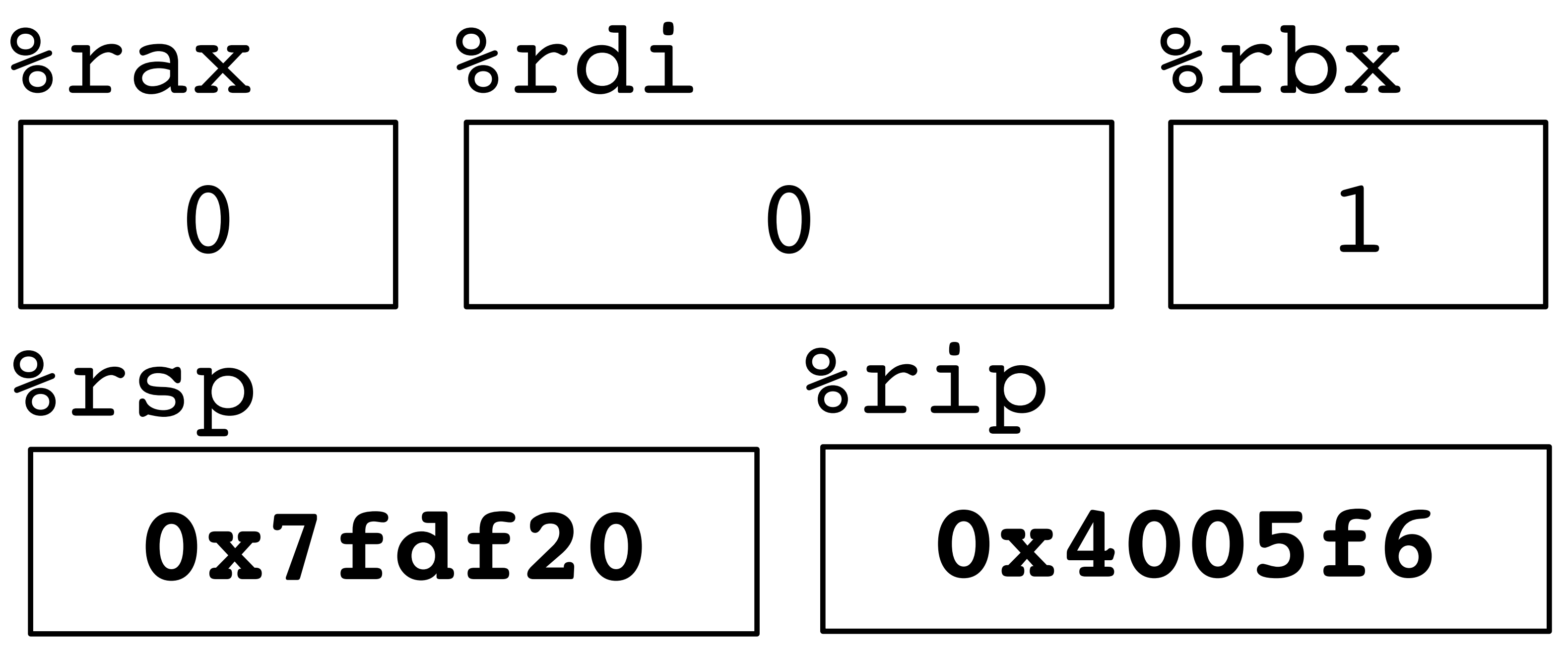


Recursion Example: `pcount(2)` → `pcount(1)` → **`pcount(0)`**

```
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
```

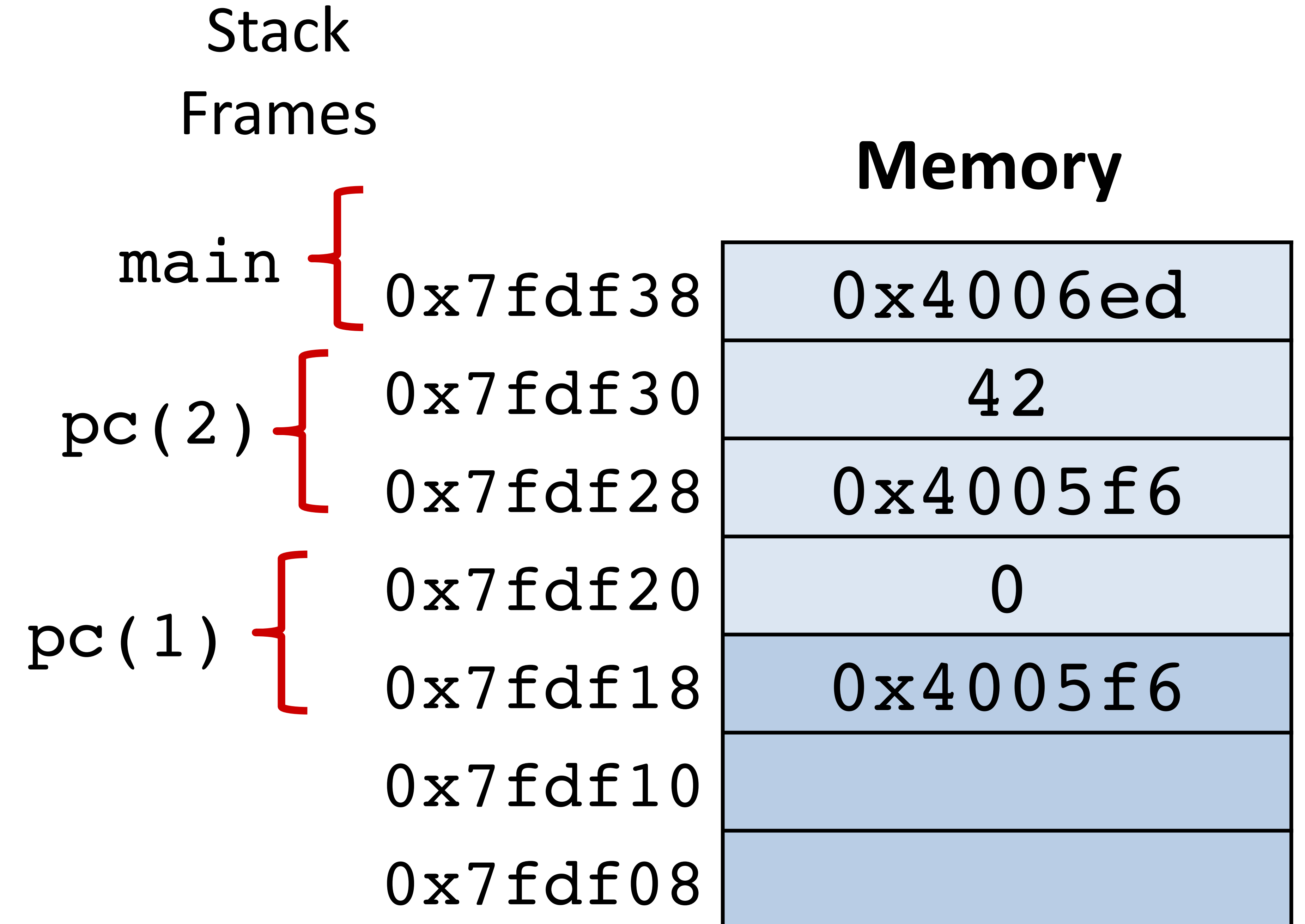


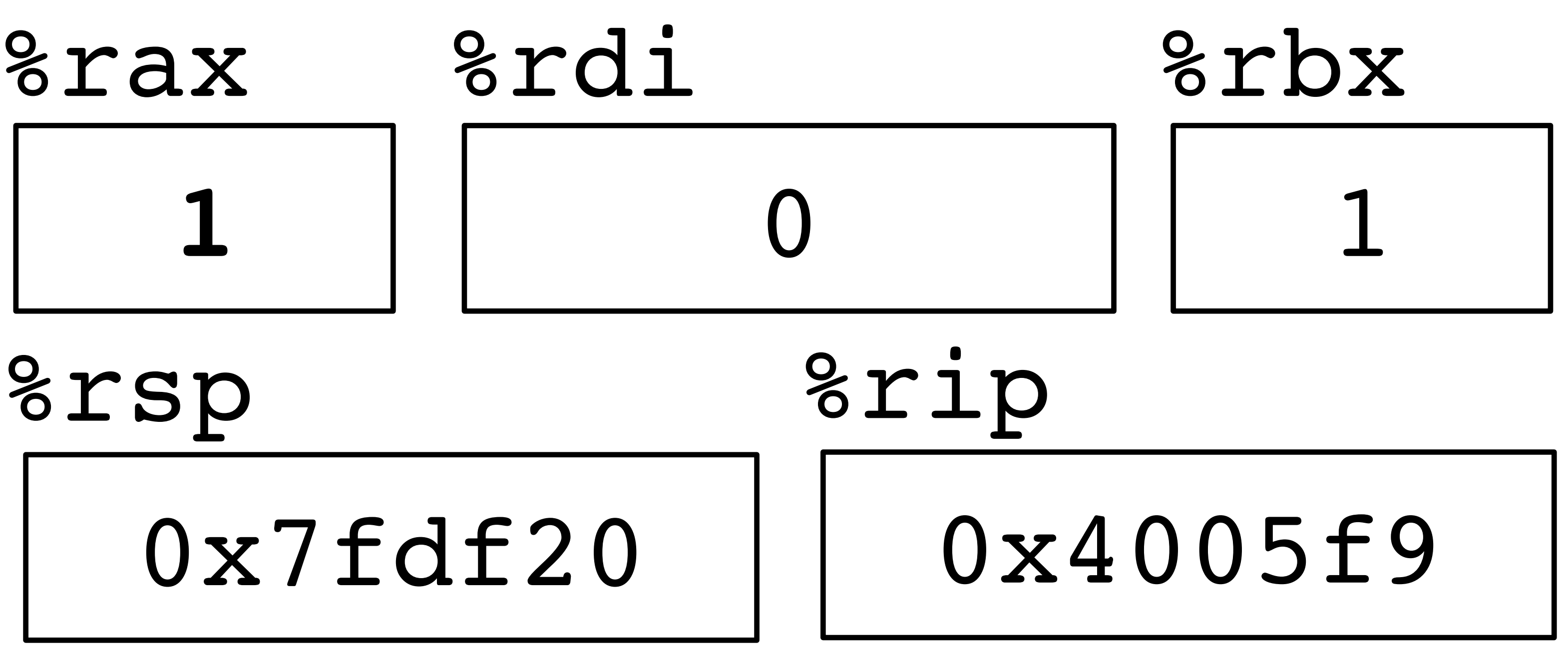


Recursion Example: pcount(2) → **pcount(1)** → pcount(0)

```
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
```

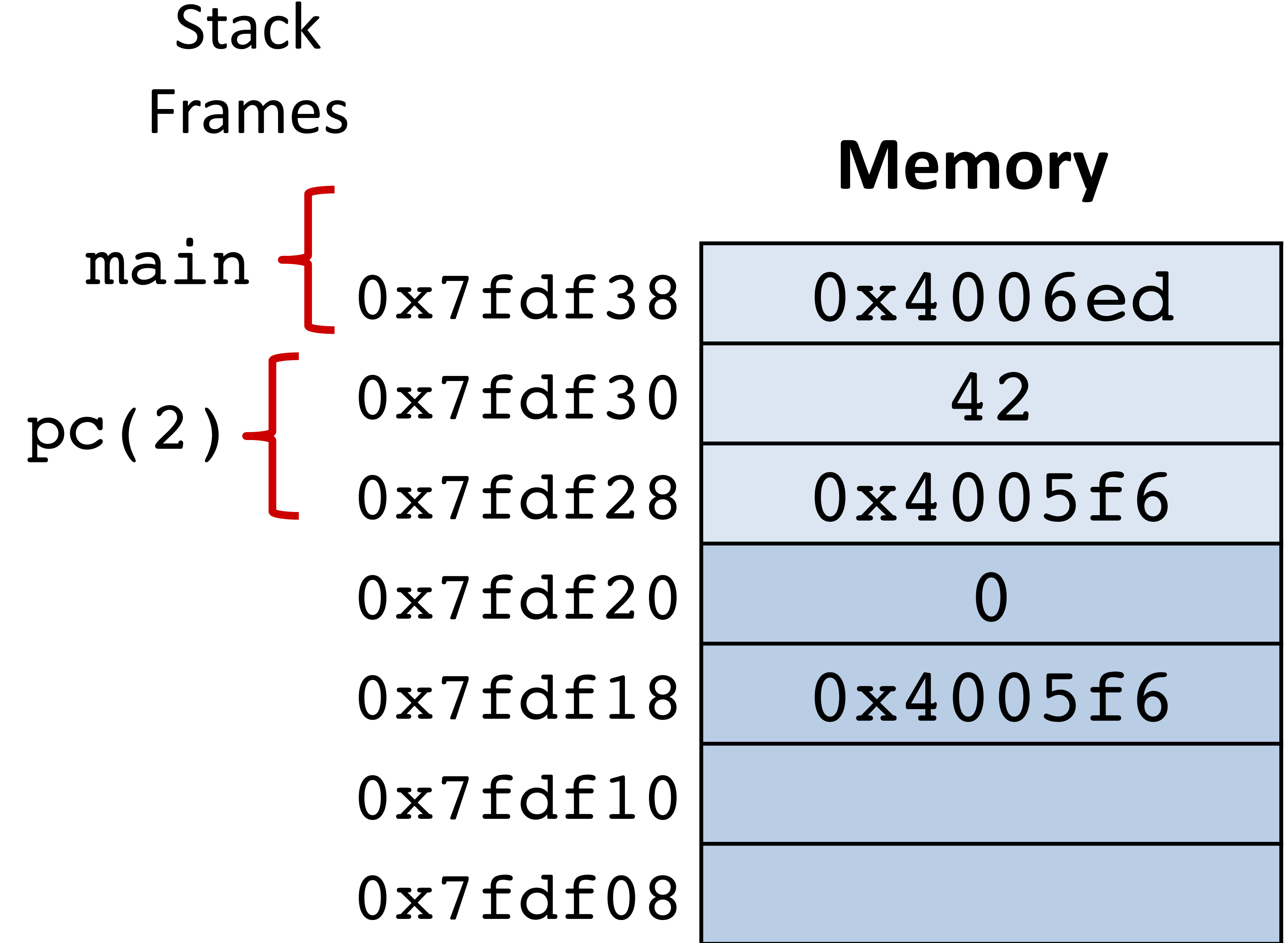


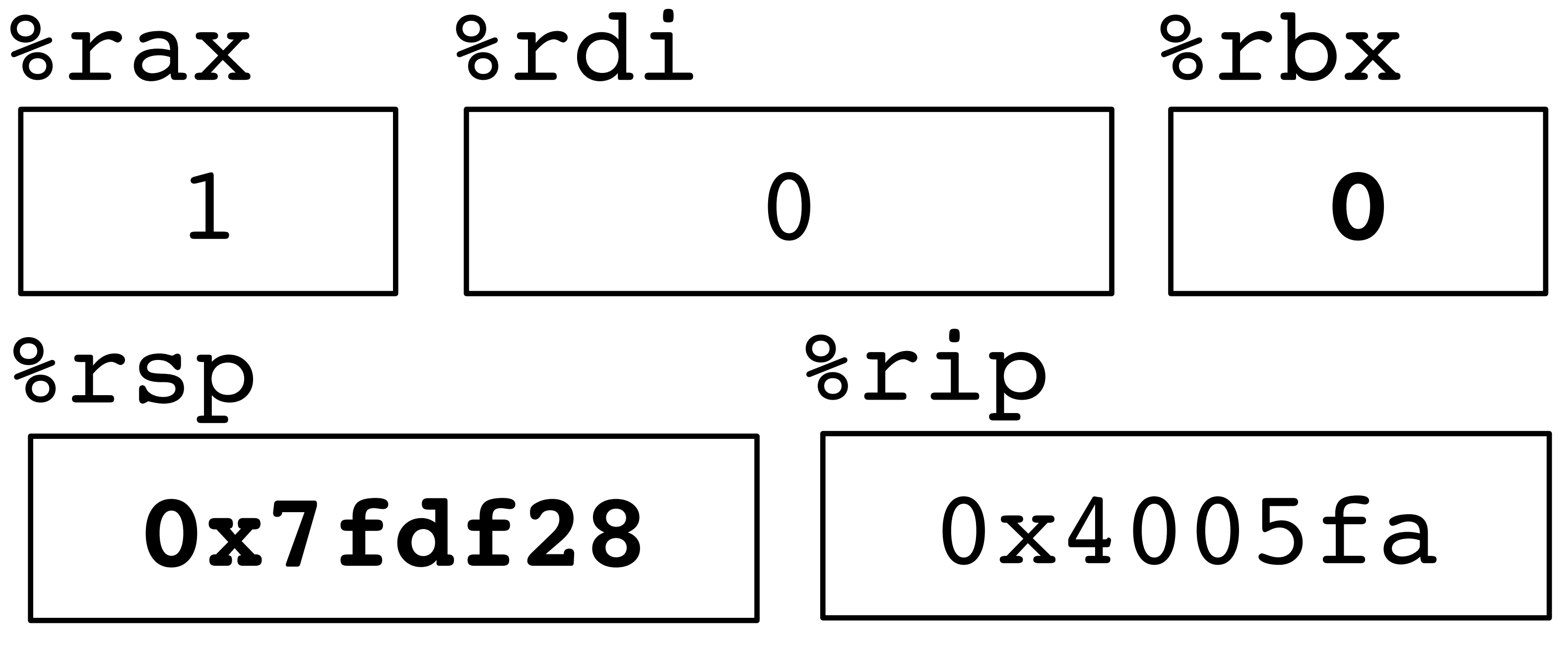


Recursion Example: pcount(2) → **pcount(1)** → pcount(0)

```
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
```

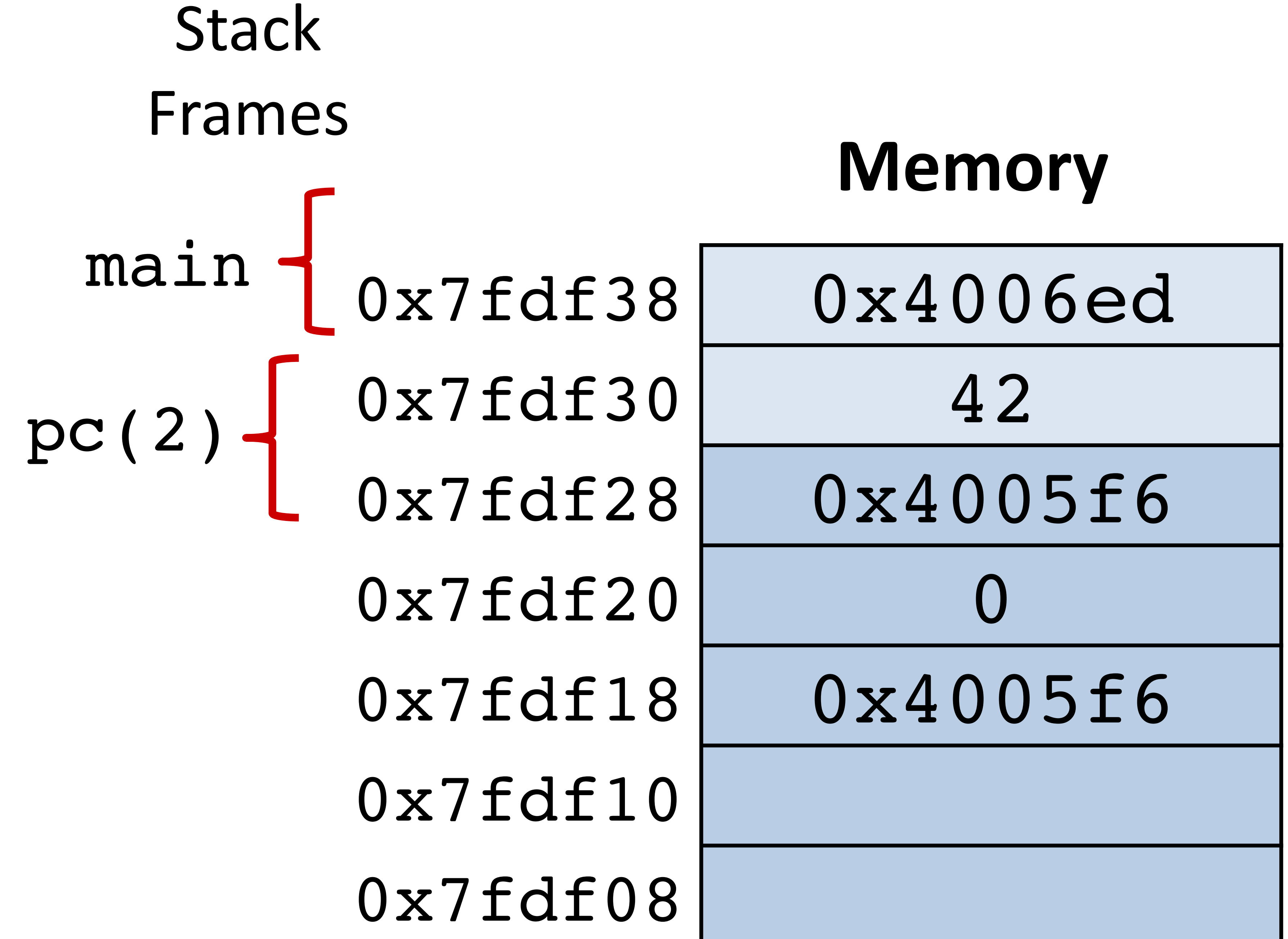


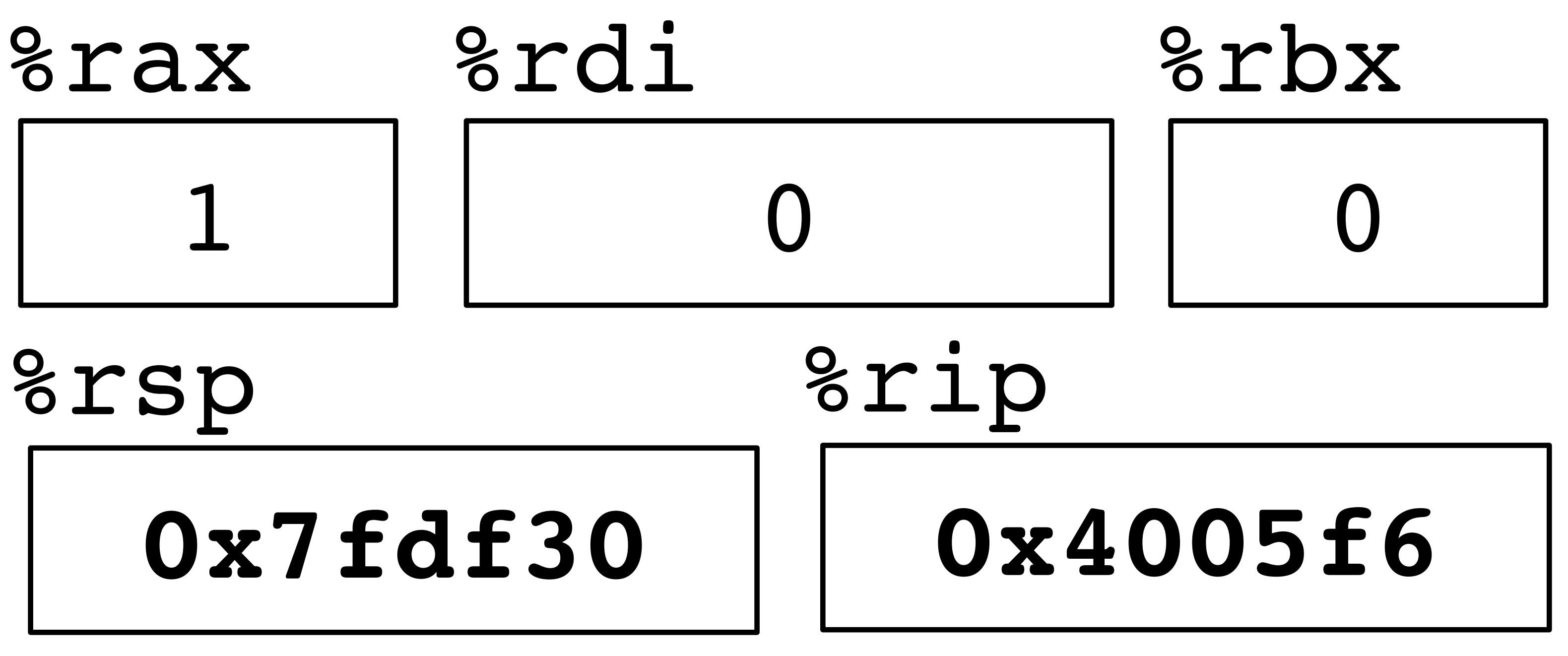


Recursion Example: pcount(2) → **pcount(1)** → pcount(0)

```
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
```

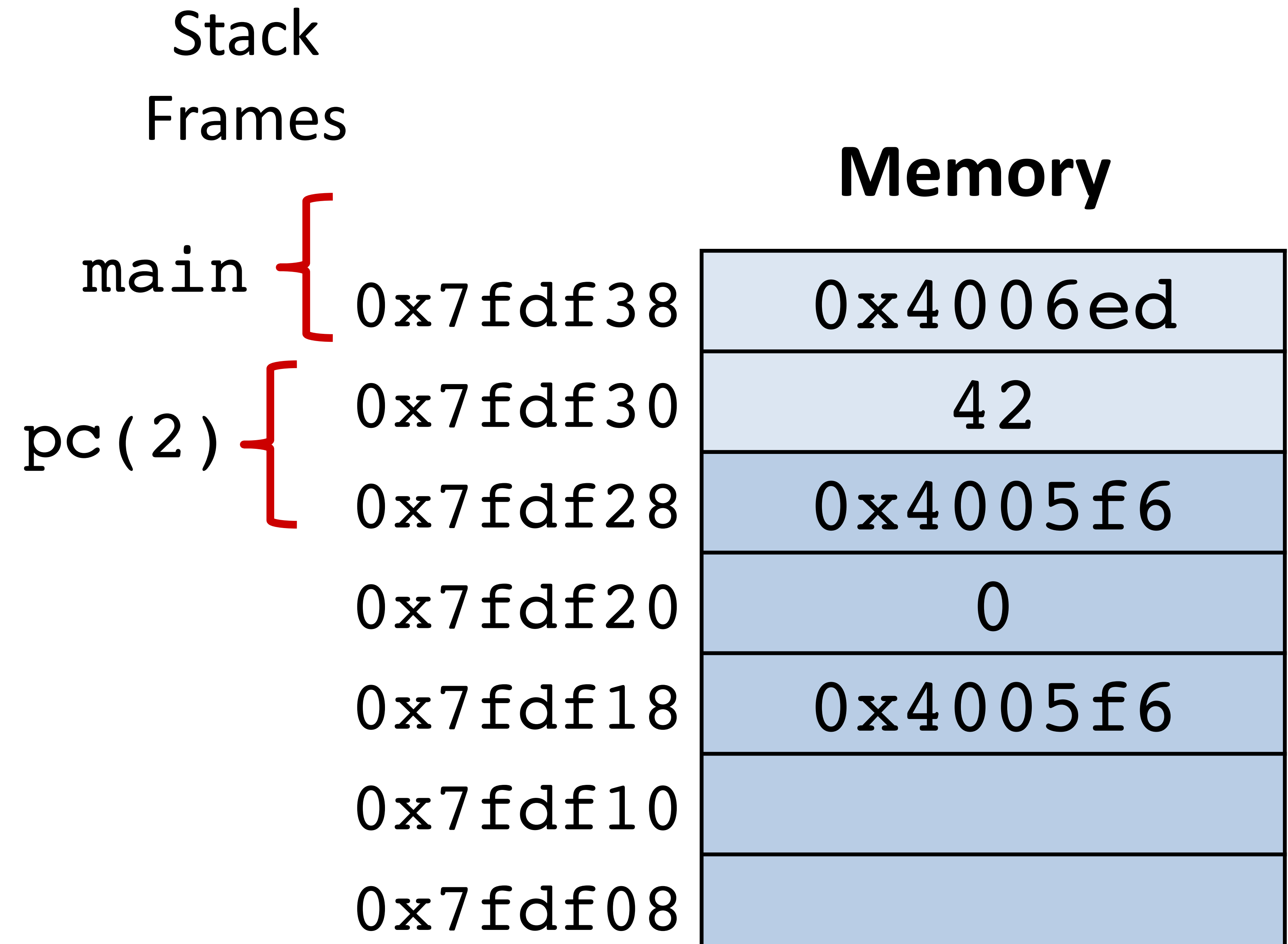


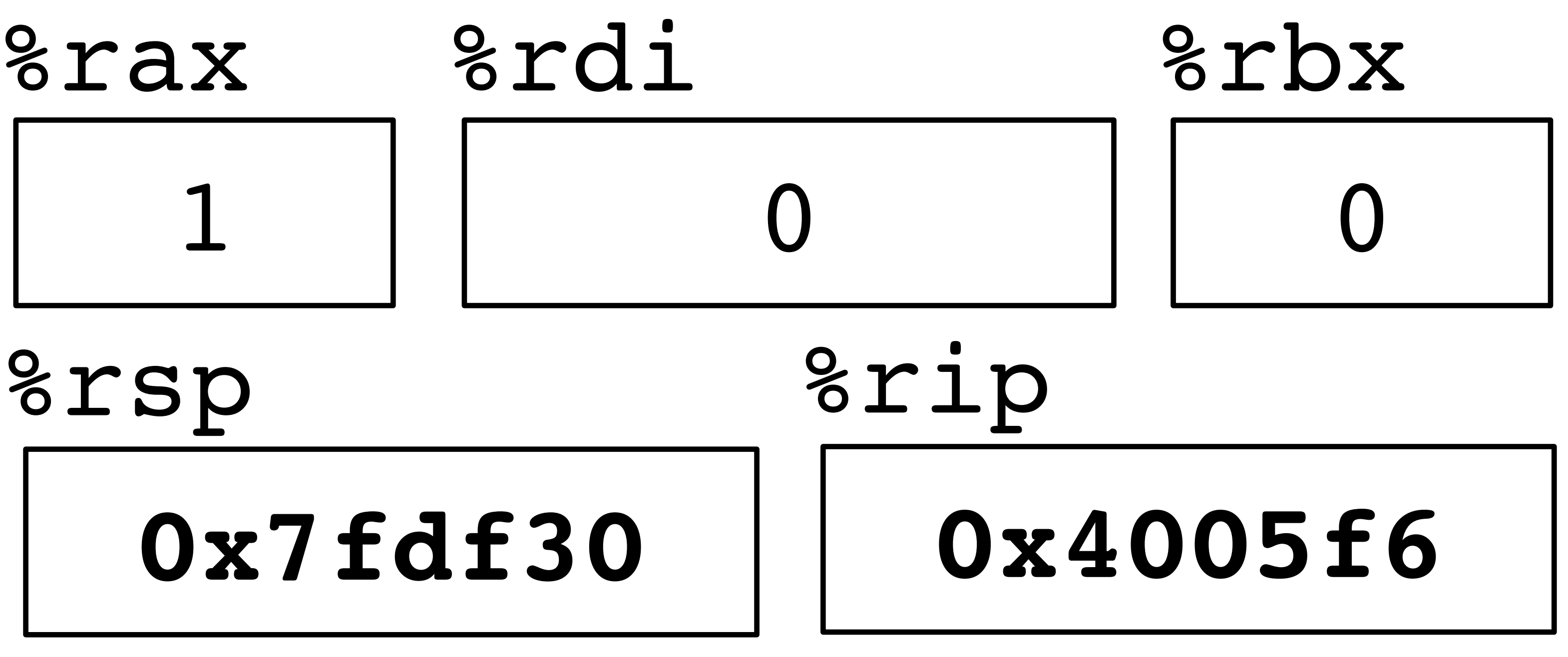


Recursion Example: pcount(2) → **pcount(1)** → pcount(0)

```
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
```





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

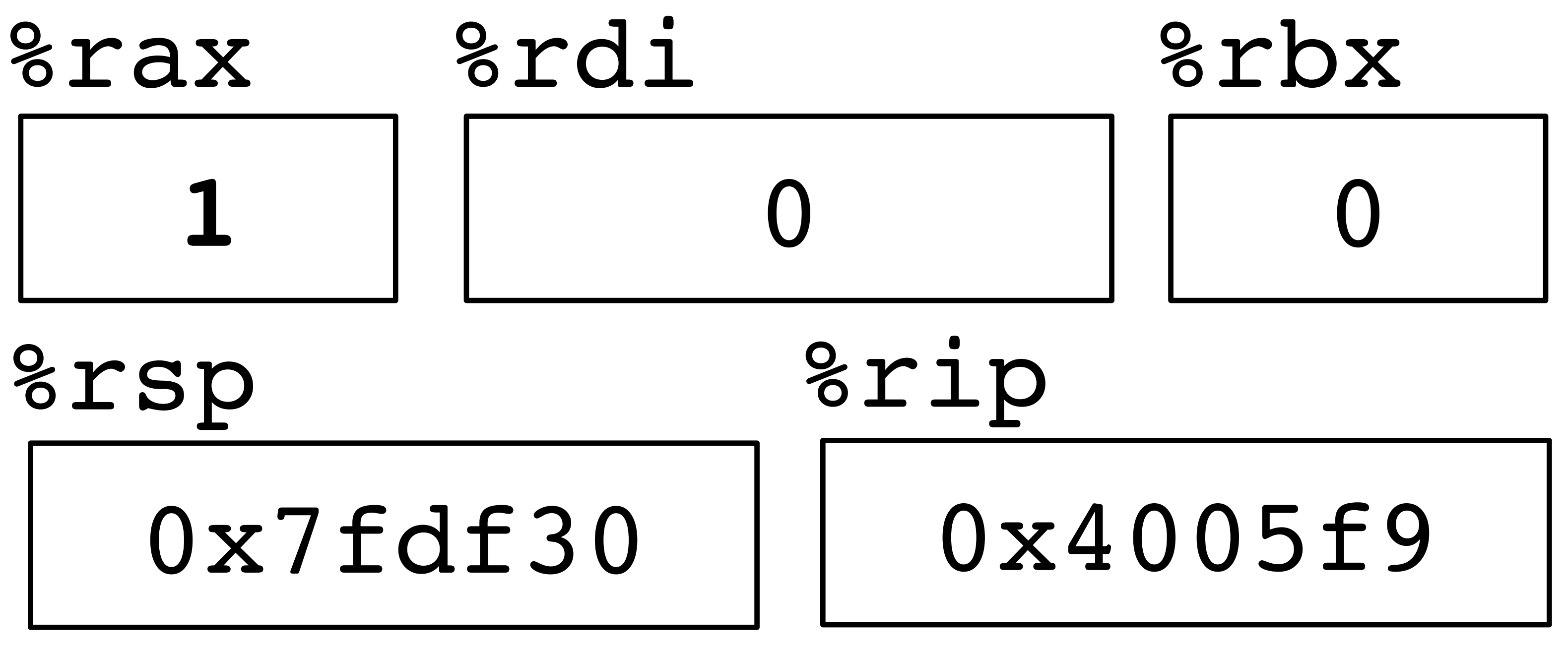
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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

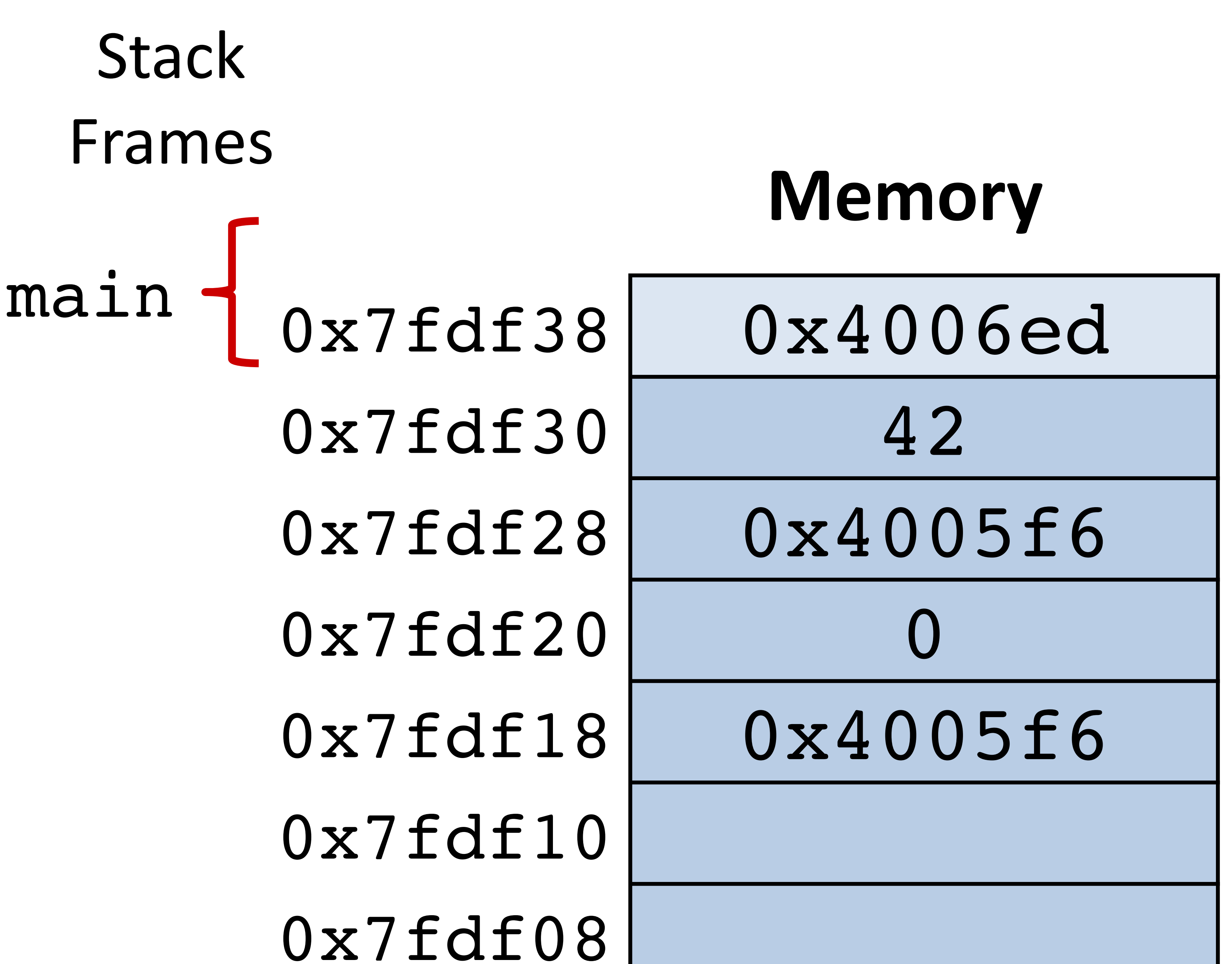
Stack Frame	Address	Value
main	0x7fdf38	0x4006ed
pc(2)	0x7fdf30	42
pc(2)	0x7fdf28	0x4005f6
	0x7fdf20	0
	0x7fdf18	0x4005f6
	0x7fdf10	
	0x7fdf08	

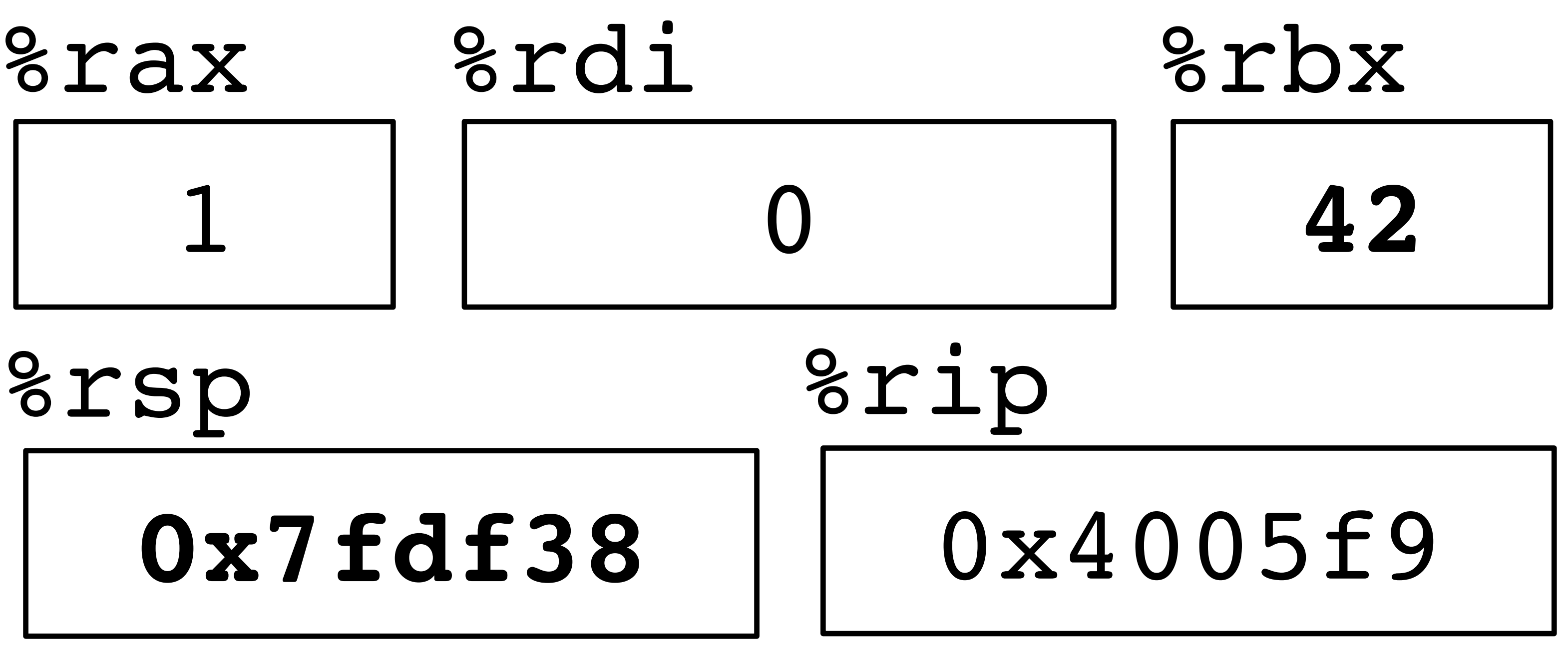


Recursion Example: `pcount(2)` → `pcount(1)` → `pcount(0)`

```
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
```





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

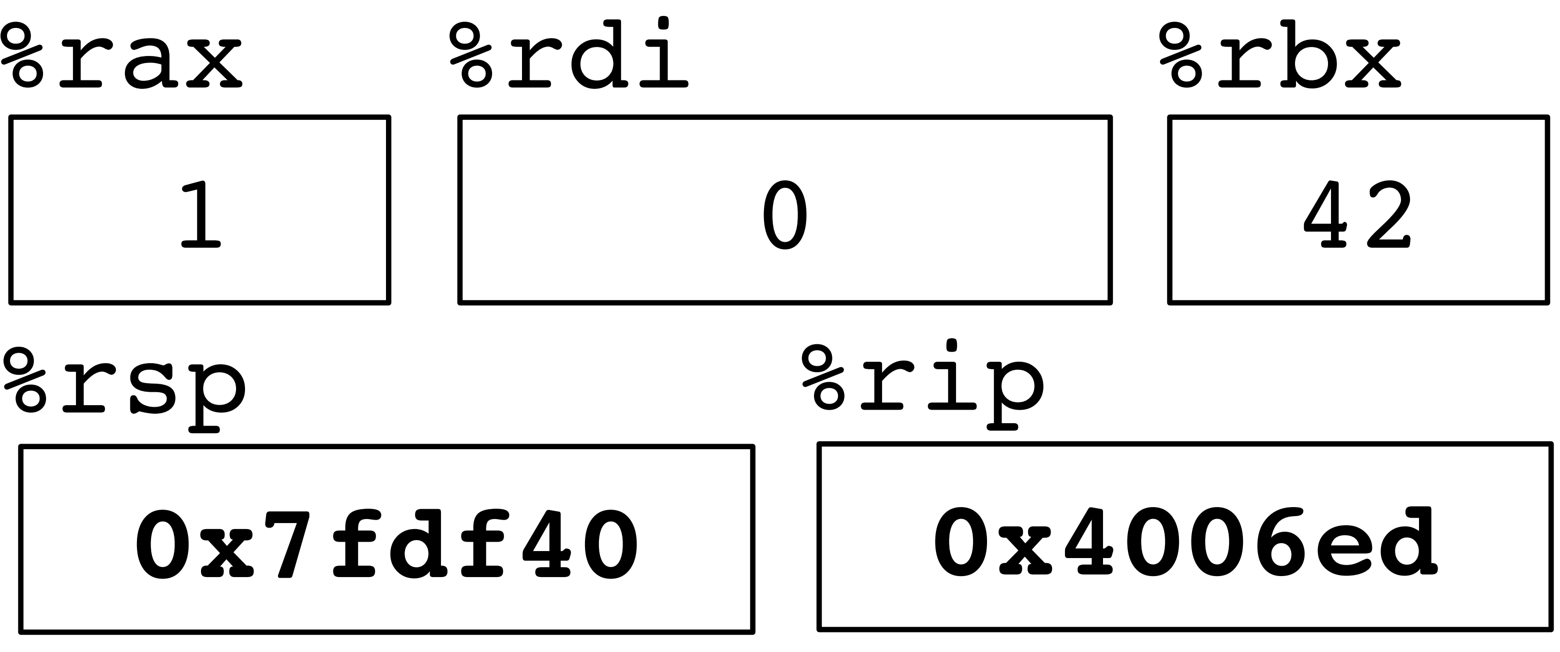
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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

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



Recursion Exercise: `pcount(13)`

(1) What do the stack & registers look like at the base case?
(2) What is the final value returned by pcount(13)?

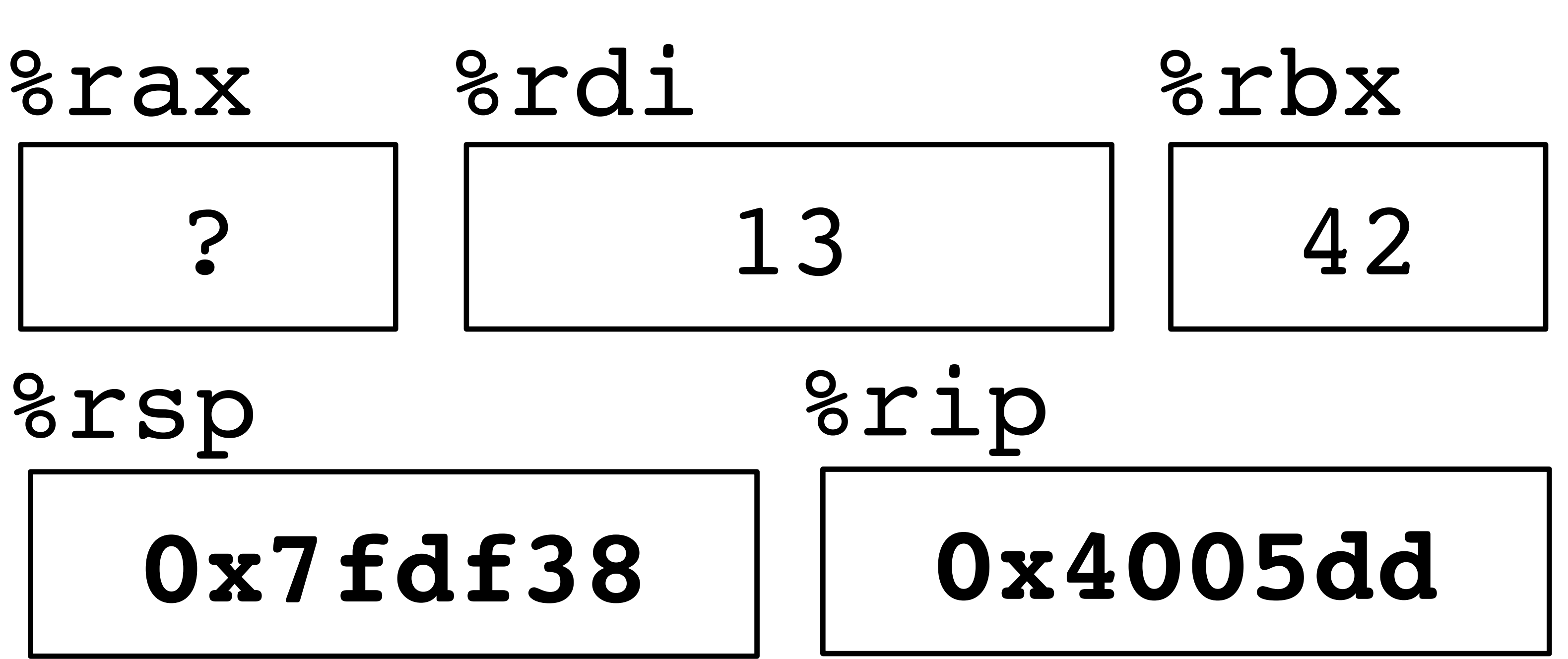
```c
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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
```

Memory

Stack Frames

Stack frame	Address	Memory
main	0x7fdf38	**0x4006ed**
	0x7fdf30	
	0x7fdf28	
	0x7fdf20	
	0x7fdf18	
	0x7fdf10	
	0x7fdf08	
	0x7fdf00	
	0x7fdef8	



Recursion Exercise: `pcount(13)` Solutions

(1) Q: What do the stack & registers look like at the base case?
A: See below

```
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
```

Memory — Stack Frames

Stack Frame	Address	Value
main	0x7fdf38	0x4006ed
	0x7fdf30	42
	0x7fdf28	0x4005f6
	0x7fdf20	1
	0x7fdf18	0x4005f6
	0x7fdf10	0
	0x7fdf08	0x4005f6
	0x7fdf00	1
	0x7fdef8	0x4005f6

%rax	%rdi	%rbx
0	0	1

%rsp	%rip
0x7fdef8	0x4005dd

(2) Q: What is the final value returned by pcount(13)? A: 3

Stack storage example (1)

```
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
  • • •
```

Return address to caller of `call_proc`	←%rsp

Stack storage example

(2) Allocate local vars

```
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
  • • •
```

Return address to caller of `call_proc`				
x4		x3	x2	24
x1				16
				8
				←%rsp

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
  • • •
```

Return address to caller of `call_proc`				
x4		x3	x2	24
x1				16
Arg 8				8
Arg 7				←%rsp

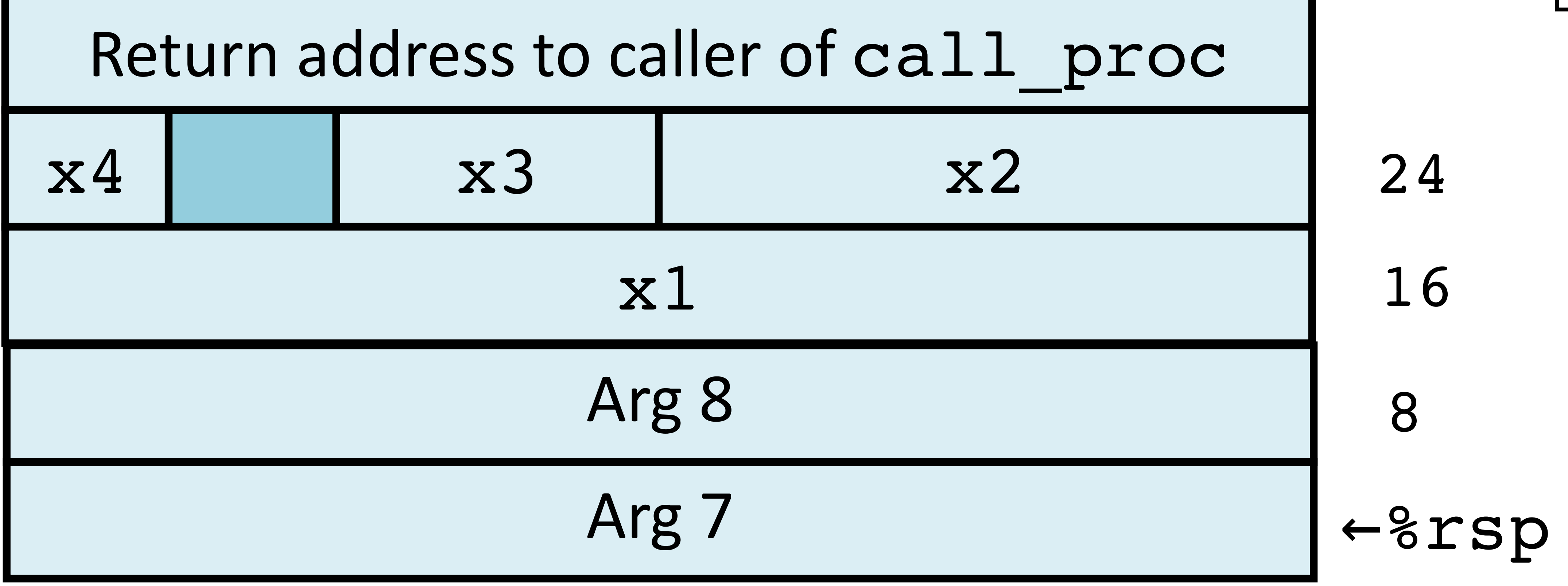
Arguments passed in (in order):

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

Stack storage example

(4) after call to `proc`

```
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

```
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);
}
```

Return address to caller of call_proc

←%rsp

```
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`

Register	Use
`%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

Register	Use
`%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

Caller Frame
...
Extra Arguments to callee
Return Address

Callee Frame
Saved Registers + Local Variables
Extra Arguments for next call

Stack pointer `%rsp`

128-byte red zone

functions allowed to use this before changing `%rsp`