CS 240
Foundations of Computer Systems

WELLESLEY

# x86: Procedures and the Call Stack

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

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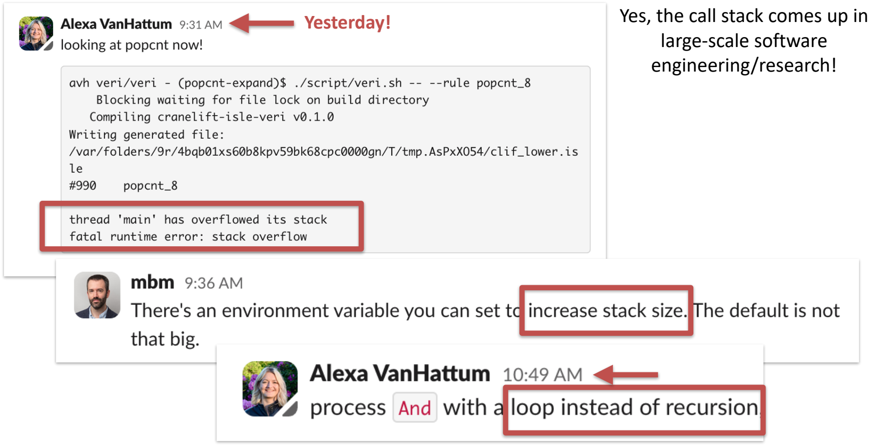
# x86: Procedures and the Call Stack

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

## Does the call stack really matter?



**Alexa VanHattum** 9:31 AM ← Yesterday!
looking at popcnt now!

```
avh veri/veri - (popcnt-expand)$ ./script/veri.sh -- --rule popcnt_8
    Blocking waiting for file lock on build directory
   Compiling cranelift-isle-veri v0.1.0
Writing generated file:
/var/folders/9r/4bqb01xs60b8kpv59bk68cpc0000gn/T/tmp.AsPxX054/clif_lower.is
le
#990    popcnt_8

thread 'main' has overflowed its stack
fatal runtime error: stack overflow
```

**mbm** 9:36 AM
There's an environment variable you can set to increase stack size. The default is not that big.

**Alexa VanHattum** 10:49 AM ←
process And with a loop instead of recursion

Yes, the call stack comes up in large-scale software engineering/research!

## 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*

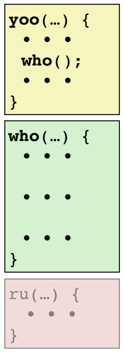
## Implementing procedures

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?

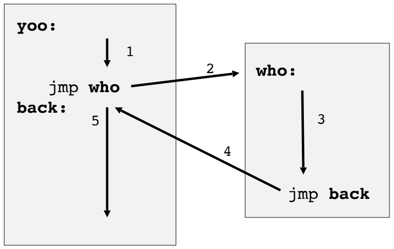
Call Chain



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

```
who(…) {
  • • •

  • • •

  • • •
}
```

```
ru(…) {
  • • •
}
```

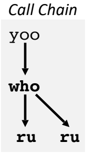


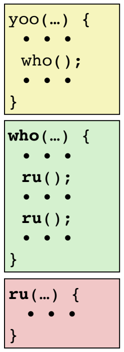
```
yoo:

   jmp who
back:
```

```
who:



   jmp back
```

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

## Procedure call/return: Jump? Broken!

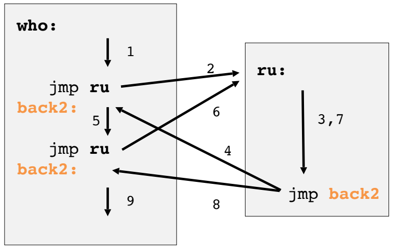

Call Chain



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

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

```
ru(…) {
  • • •
}
```



```
who:

   jmp ru
back2:

   jmp ru
back2:
```

```
ru:


   jmp back2
```

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? ✓

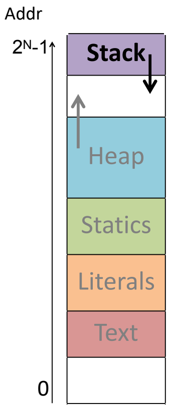
3. How does a procedure know where to return (what code to execute next when done)? ??

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 |

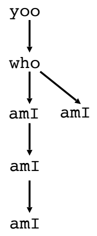
# Call stack tracks context

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

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

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

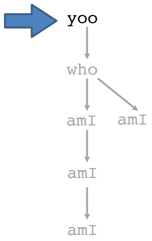
Example Call Chain

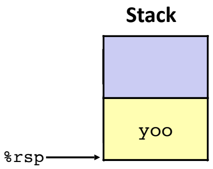


Procedure `amI` is recursive (calls itself)

# Call stack tracks context

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

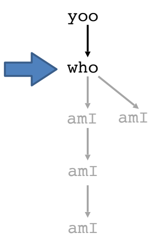


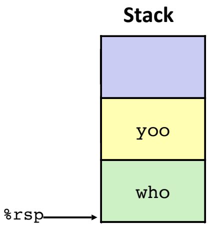


# Call stack tracks context

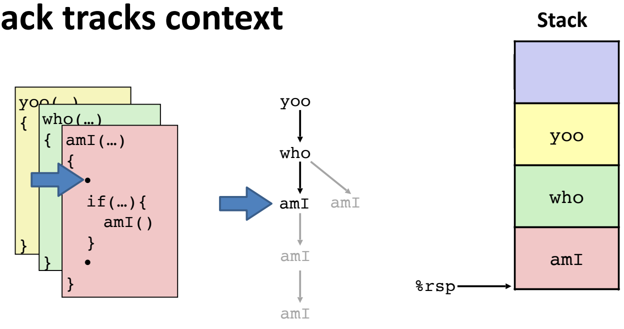
```
yoo(…)
{
}
```

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

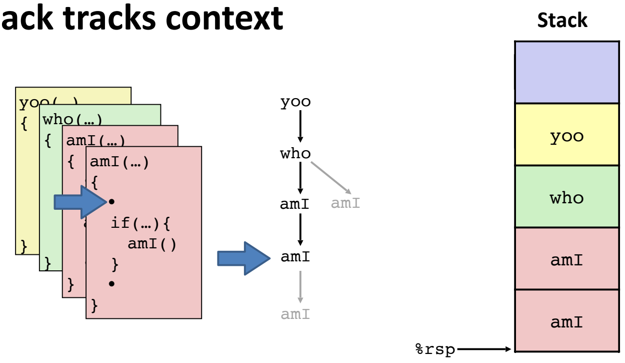




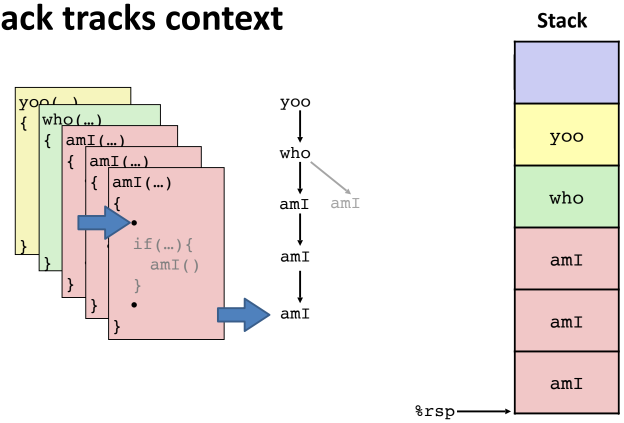
# Call stack tracks context



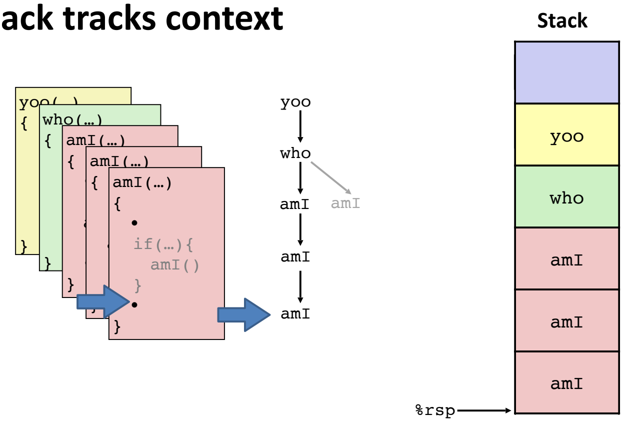
# Call stack tracks context

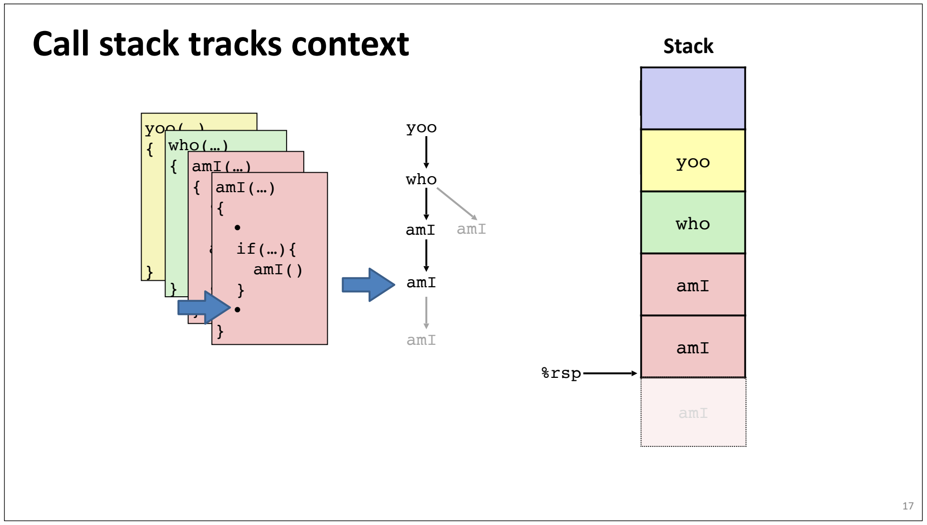


# Call stack tracks context



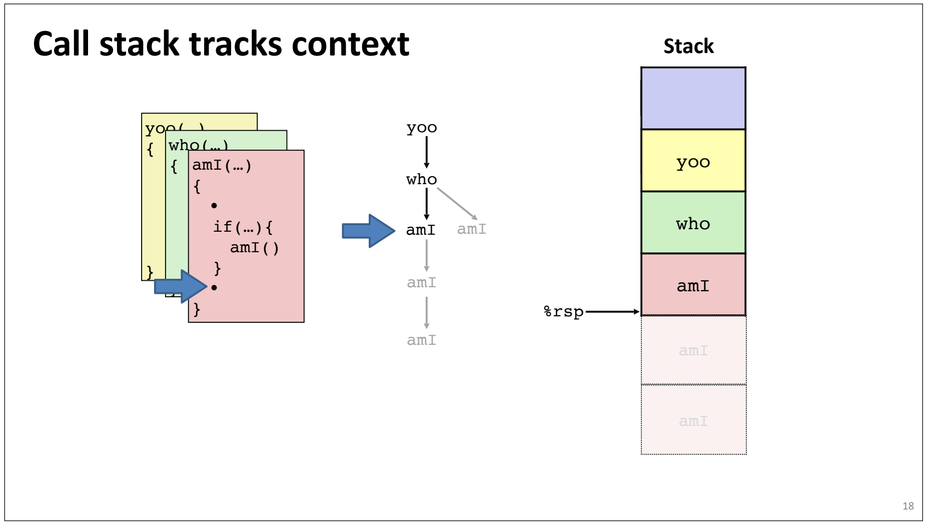
# Call stack tracks context





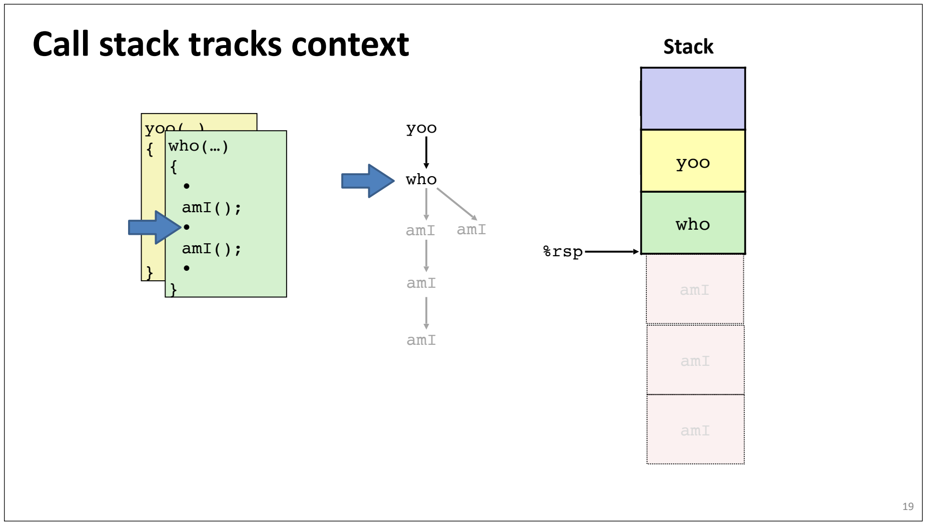
## Call stack tracks context

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



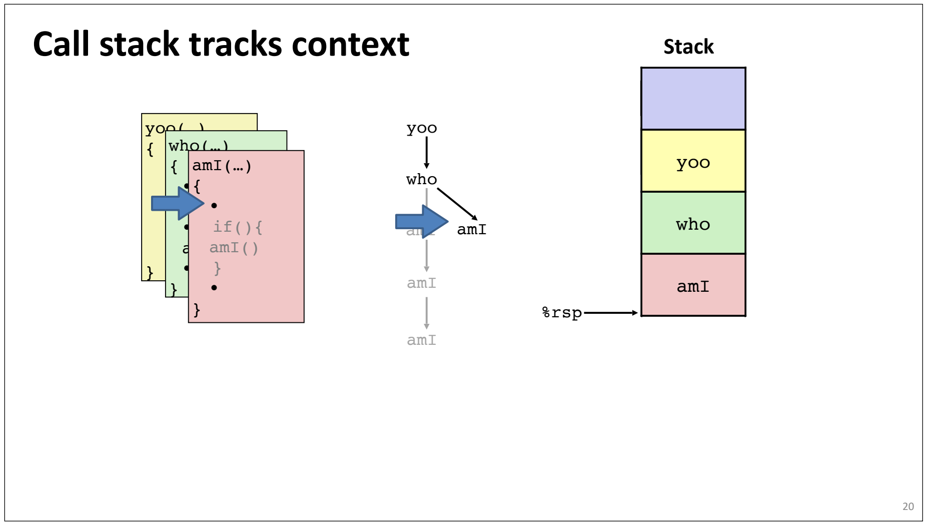
## Call stack tracks context

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



## Call stack tracks context

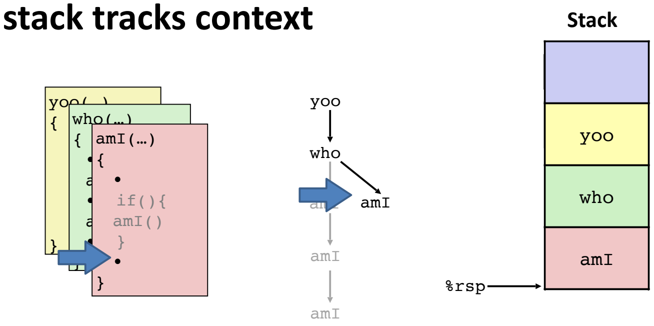
```
who(…)
{
  •
  amI();
  •
  amI();
  •
}
```



## Call stack tracks context

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

## Call stack tracks context

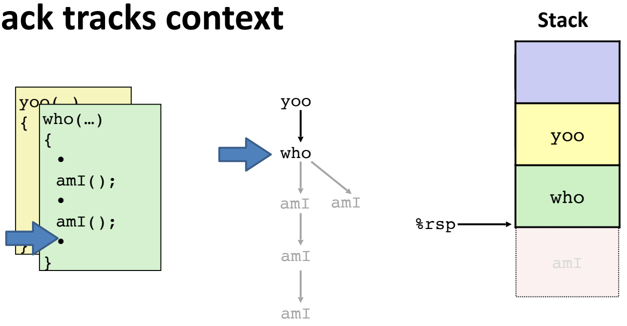


```
yoo(…)
{
}
```

```
who(…)
{
```

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

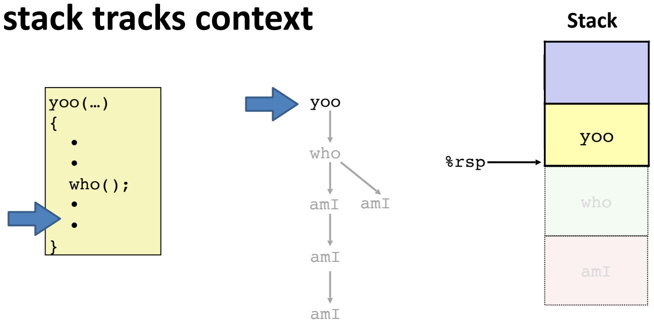
## Call stack tracks context



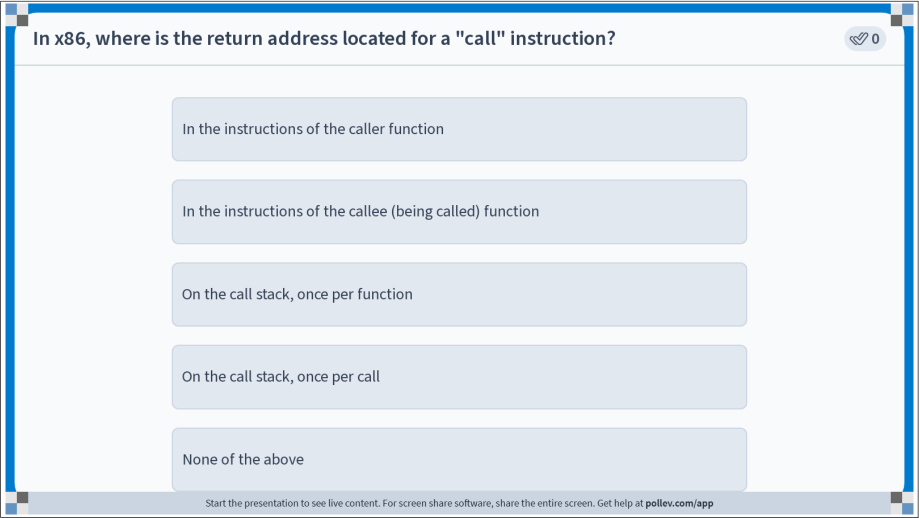
```
yoo(…)
{
```

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

## Call stack tracks context



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



In x86, where is the return address located for a "call" instruction?

- In the instructions of the caller function
- In the instructions of the callee (being called) function
- On the call stack, once per function
- On the call stack, once per call
- None of the above

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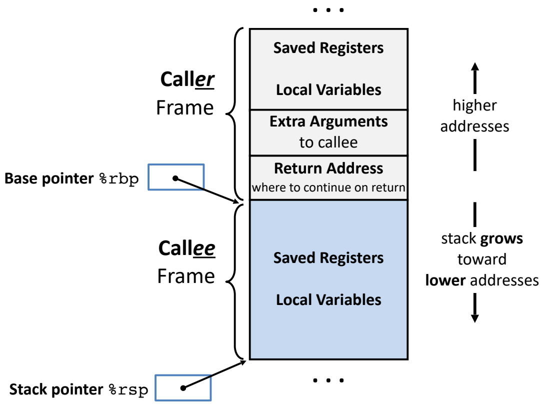
# The call stack supports procedures

**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.


. . .

Caller Frame

Saved Registers

Local Variables

Extra Arguments to callee

Return Address
where to continue on return

Base pointer `%rbp`

Callee Frame

Saved Registers

Local Variables

Stack pointer `%rsp`

. . .

higher addresses

stack **grows** toward **lower** addresses

# 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`

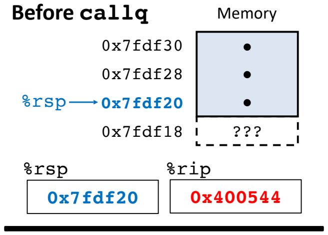
1. Pop return address from stack
2. Jump to return address

# 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*


**Before `callq`**

Memory

| Address | Memory |
|---|---|
| 0x7fdf30 | • |
| 0x7fdf28 | • |
| `%rsp` → 0x7fdf20 | • |
| 0x7fdf18 | ??? |

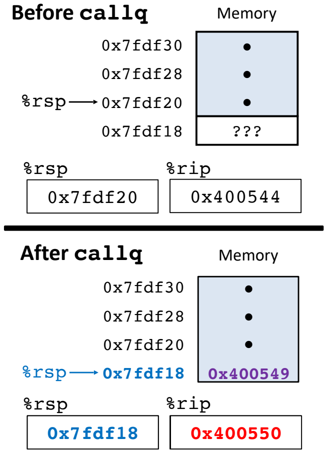
| %rsp | %rip |
|---|---|
| 0x7fdf20 | 0x400544 |

# 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

| Address | Memory |
|---|---|
| 0x7fdf30 | • |
| 0x7fdf28 | • |
| `%rsp` → 0x7fdf20 | • |
| 0x7fdf18 | ??? |

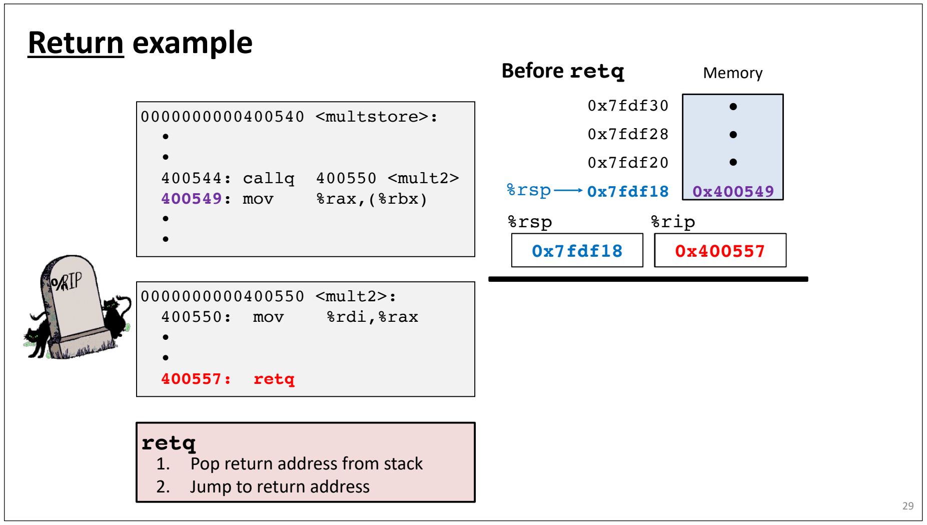
| %rsp | %rip |
|---|---|
| 0x7fdf20 | 0x400544 |

**After `callq`**

Memory

| Address | 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
```

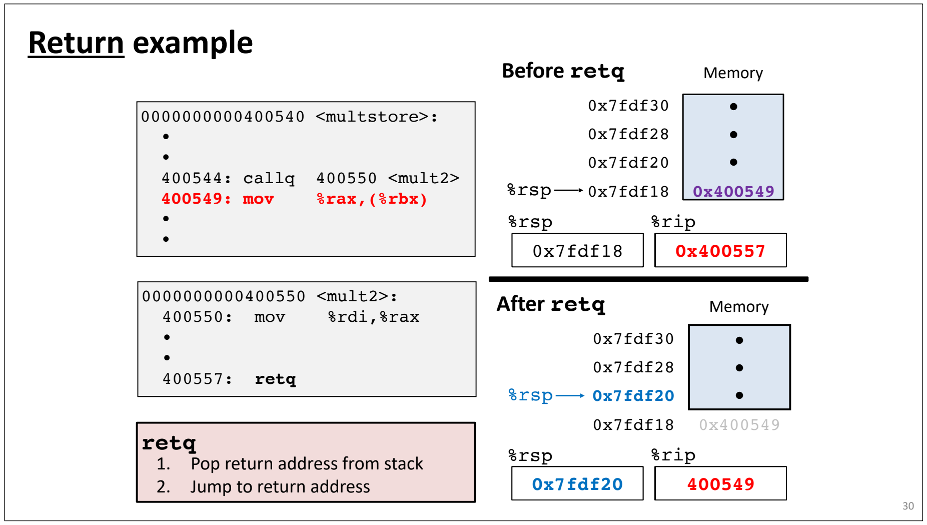
**retq**

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**

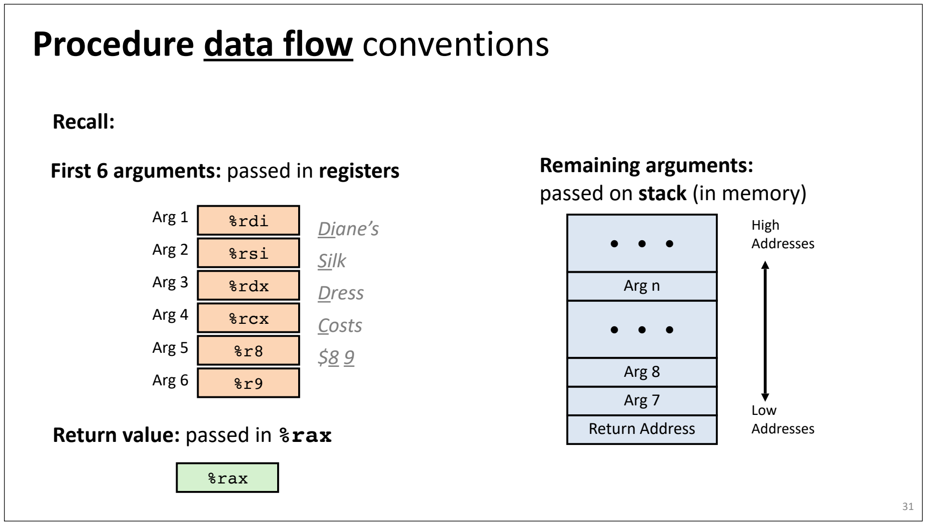
```
                     Memory
       0x7fdf30     •
       0x7fdf28     •
       0x7fdf20     •
%rsp → 0x7fdf18  0x400549

%rsp          %rip
0x7fdf18      0x400557
```

**After retq**

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

%rsp          %rip
0x7fdf20      400549
```



## Procedure data flow conventions

**Recall:**

**First 6 arguments:** passed in **registers**

| | | |
|---|---|---|
| Arg 1 | %rdi | *Diane's* |
| Arg 2 | %rsi | *Silk* |
| Arg 3 | %rdx | *Dress* |
| Arg 4 | %rcx | *Costs* |
| Arg 5 | %r8 | *$8 9* |
| Arg 6 | %r9 | |

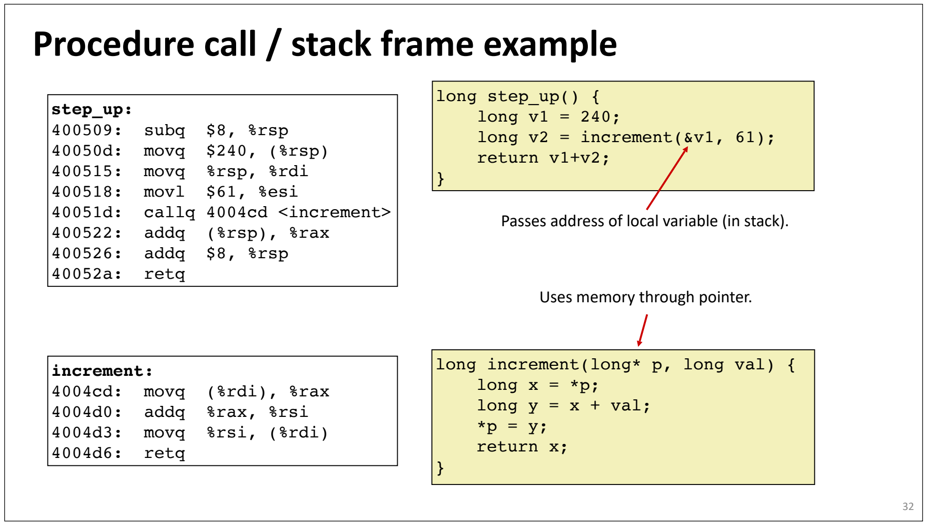
**Return value:** passed in **%rax**

%rax

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

• • •
Arg n
• • •
Arg 8
Arg 7
Return Address

High Addresses
Low Addresses



## 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
```

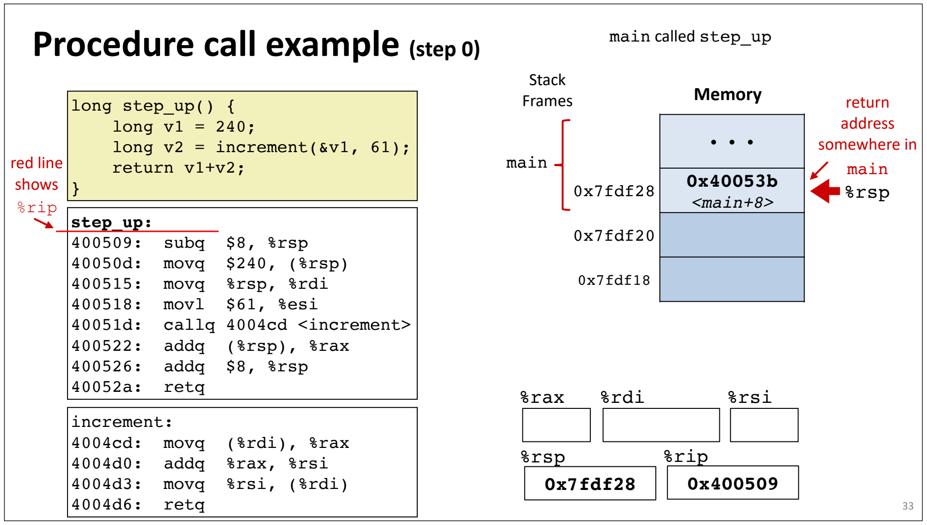
```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

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)

main called step_up

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

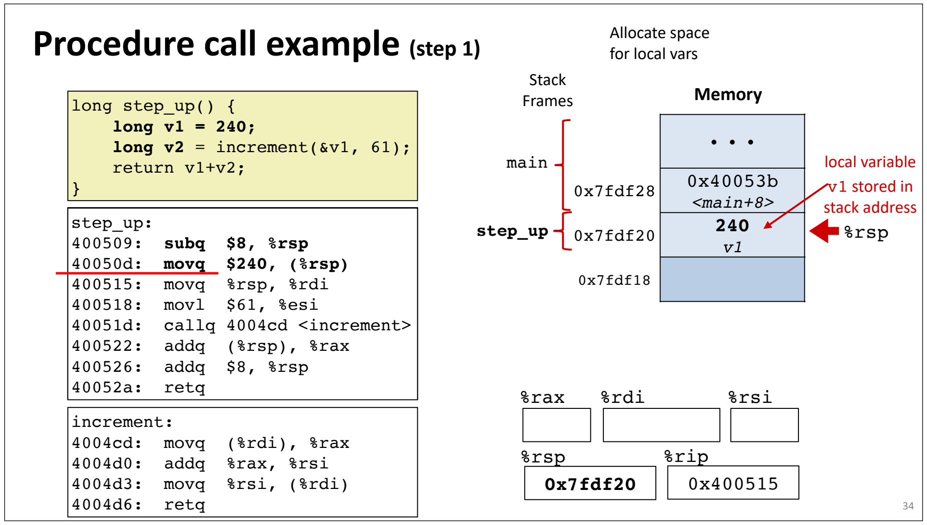
red line shows %rip

```
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
```

Stack Frames
Memory
main
. . .
0x7fdf28
0x40053b
<main+8>
0x7fdf20
0x7fdf18
return address somewhere in main
%rsp

%rax
%rdi
%rsi
%rsp 0x7fdf28
%rip 0x400509



## Procedure call example (step 1)

Allocate space for local vars

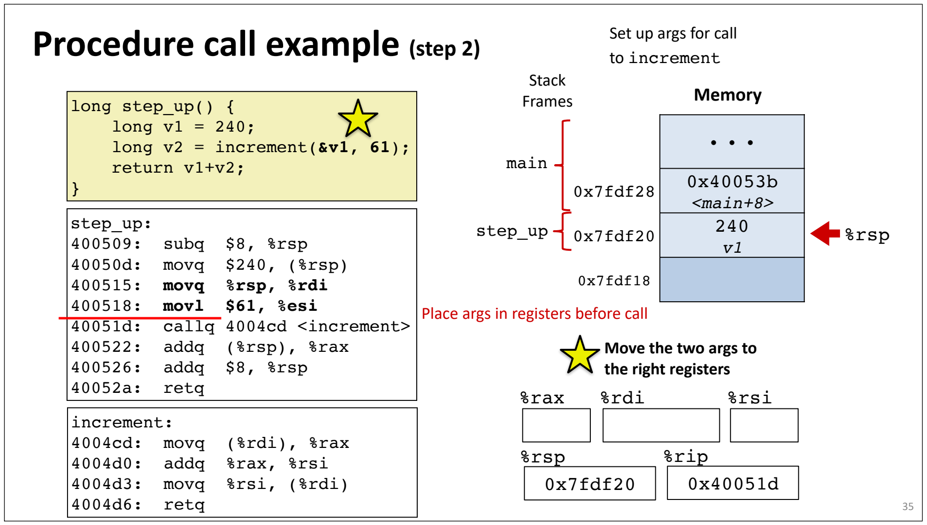
```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
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
```

Stack Frames
Memory
main
step_up
. . .
0x7fdf28
0x40053b
<main+8>
0x7fdf20
240
v1
0x7fdf18
local variable v1 stored in stack address
%rsp

%rax
%rdi
%rsi
%rsp 0x7fdf20
%rip 0x400515



## 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
```

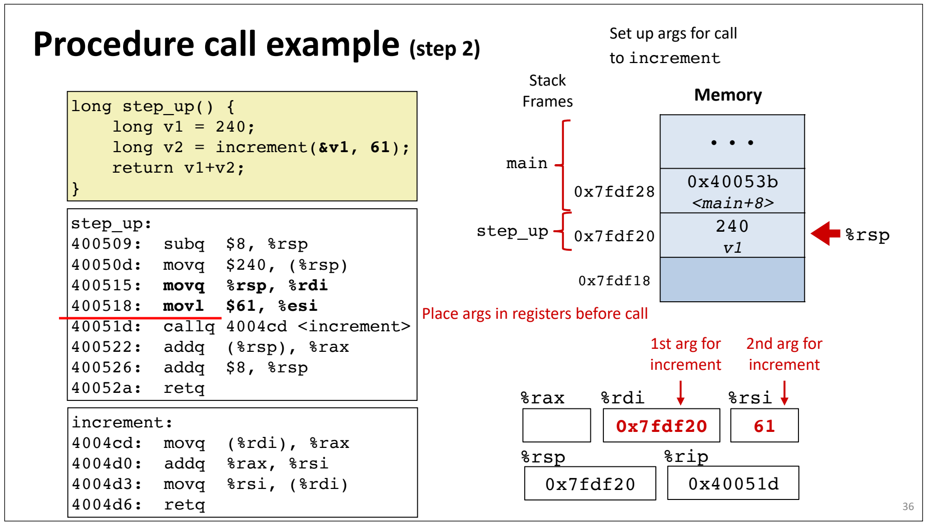
```
increment:
4004cd:  movq  (%rdi), %rax
4004d0:  addq  %rax, %rsi
4004d3:  movq  %rsi, (%rdi)
4004d6:  retq
```

Stack Frames
Memory
main
step_up
. . .
0x7fdf28
0x40053b
<main+8>
0x7fdf20
240
v1
0x7fdf18
%rsp

Place args in registers before call

☆ Move the two args to the right registers

%rax
%rdi
%rsi
%rsp 0x7fdf20
%rip 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
```

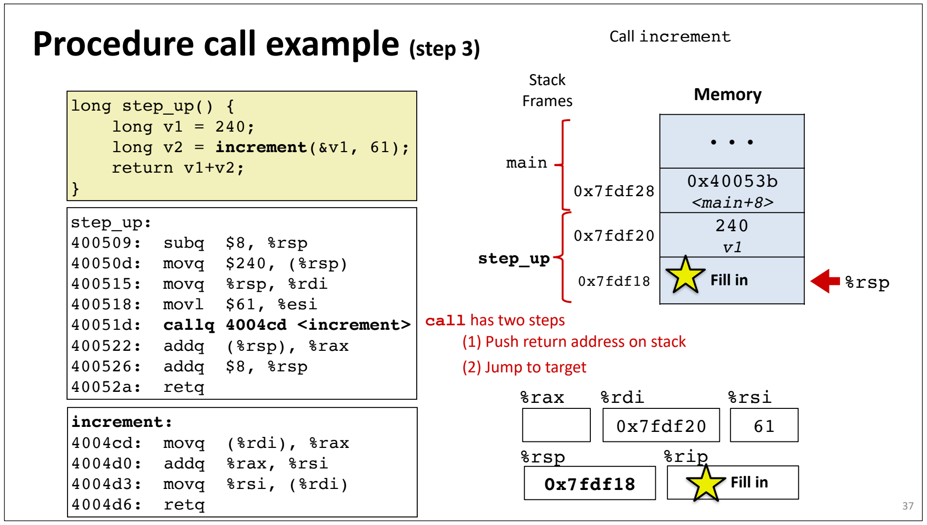
Stack Frames
Memory
main
step_up
. . .
0x7fdf28
0x40053b
<main+8>
0x7fdf20
240
v1
0x7fdf18
%rsp

Place args in registers before call

1st arg for increment

2nd arg for increment

%rax
%rdi 0x7fdf20
%rsi 61
%rsp 0x7fdf20
%rip 0x40051d



# 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

main

. . .

0x7fdf28 0x40053b *<main+8>*

step_up

0x7fdf20 240 *v1*

0x7fdf18 Fill in

%rsp

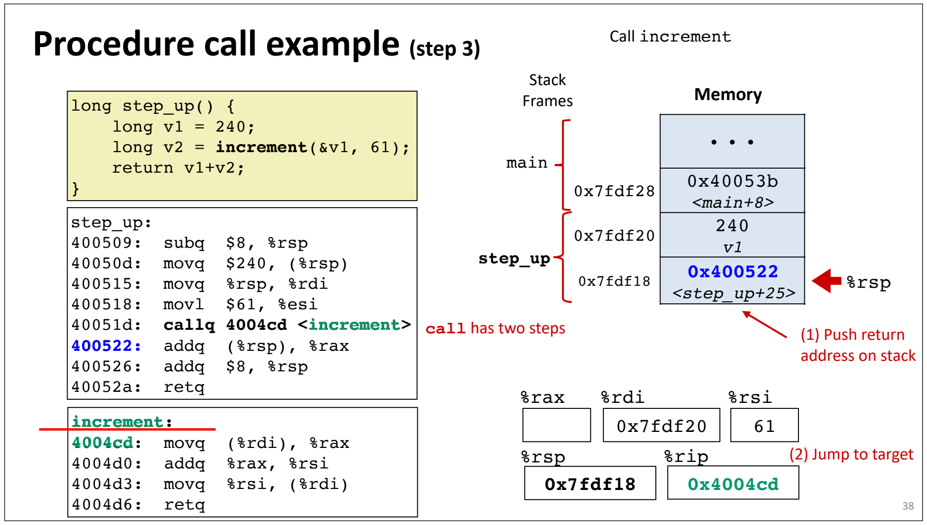
call has two steps

(1) Push return address on stack

(2) Jump to target

| %rax | %rdi | %rsi |
|---|---|---|
| | 0x7fdf20 | 61 |

| %rsp | %rip |
|---|---|
| **0x7fdf18** | Fill in |



# 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

main

. . .

0x7fdf28 0x40053b *<main+8>*

step_up

0x7fdf20 240 *v1*

0x7fdf18 **0x400522** *<step_up+25>*

%rsp

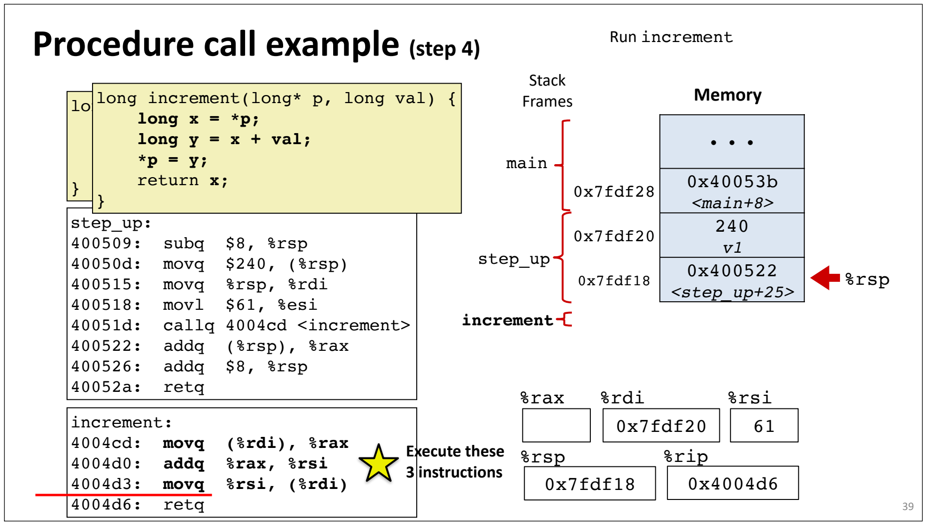
call has two steps

(1) Push return address on stack

(2) Jump to target

| %rax | %rdi | %rsi |
|---|---|---|
| | 0x7fdf20 | 61 |

| %rsp | %rip |
|---|---|
| **0x7fdf18** | **0x4004cd** |



# Procedure call example (step 4)

Run increment

lo

}

```
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

Stack Frames

Memory

main

. . .

0x7fdf28 0x40053b *<main+8>*

step_up

0x7fdf20 240 *v1*

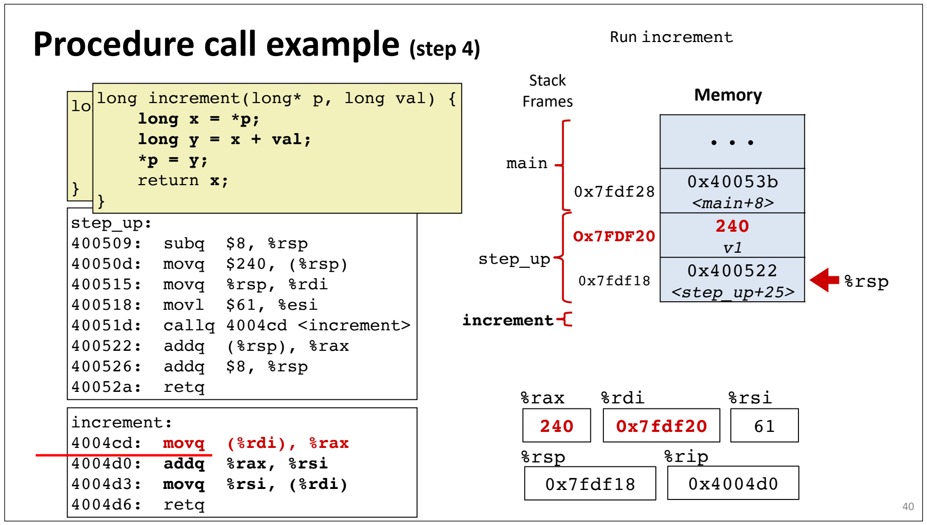
0x7fdf18 0x400522 *<step_up+25>*

%rsp

**increment**

| %rax | %rdi | %rsi |
|---|---|---|
| | 0x7fdf20 | 61 |

| %rsp | %rip |
|---|---|
| 0x7fdf18 | 0x4004d6 |



# Procedure call example (step 4)

Run increment

lo

}

```
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
```

Stack Frames

Memory

main

. . .

0x7fdf28 0x40053b *<main+8>*

step_up

**0x7FDF20** **240** *v1*

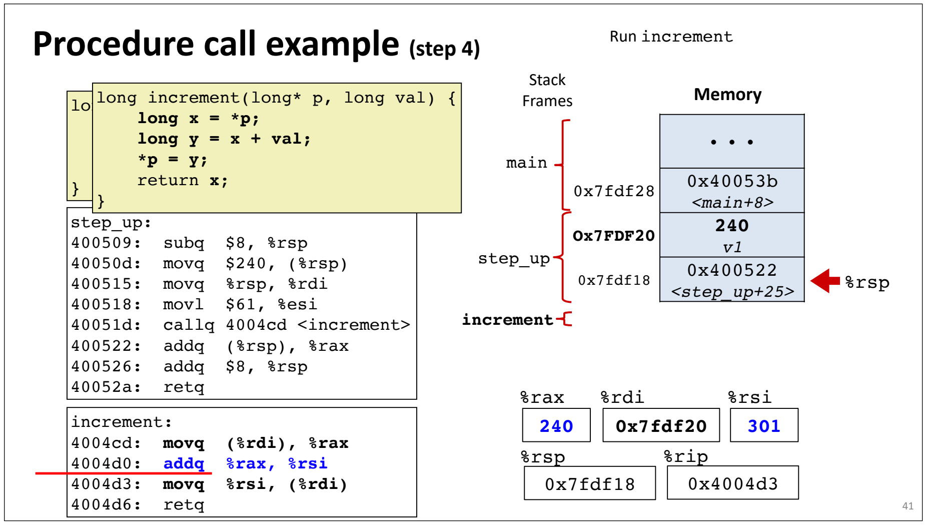
0x7fdf18 0x400522 *<step_up+25>*

%rsp

**increment**

| %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
```

Stack Frames

Memory

main

step_up

increment

. . .

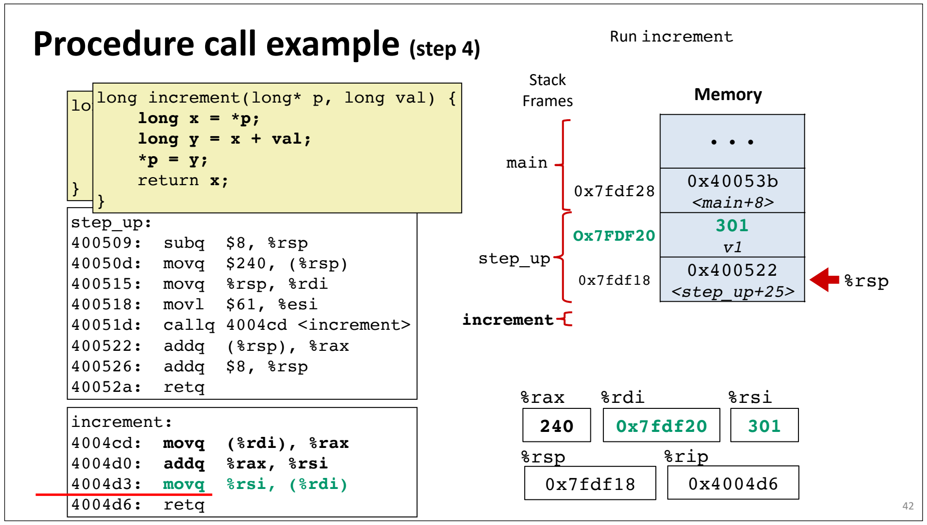
0x7fdf28  0x40053b *<main+8>*

0x7FDF20  240 *v1*

0x7fdf18  0x400522 *<step_up+25>*  ← %rsp

| %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
```

Stack Frames

Memory

main

step_up

increment

. . .

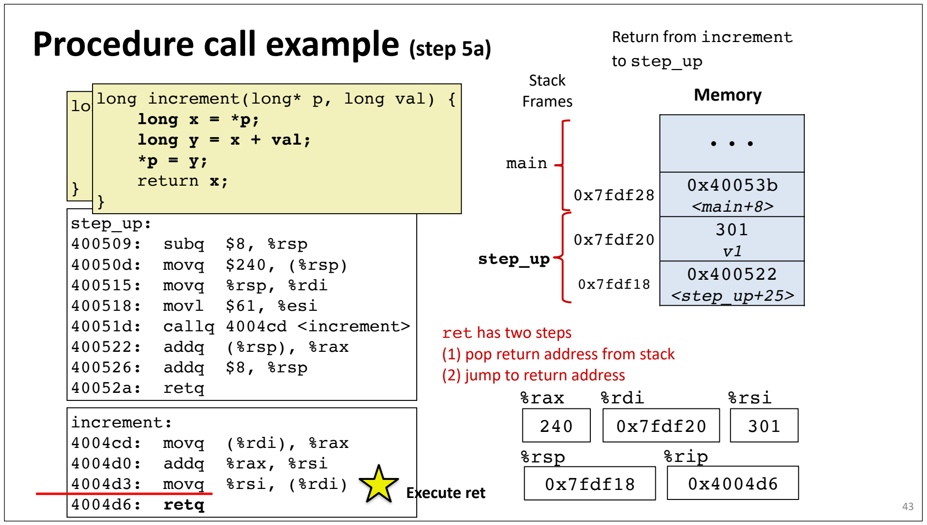
0x7fdf28  0x40053b *<main+8>*

0x7FDF20  301 *v1*

0x7fdf18  0x400522 *<step_up+25>*  ← %rsp

| %rax | %rdi | %rsi |
|---|---|---|
| 240 | 0x7fdf20 | 301 |

| %rsp | %rip |
|---|---|
| 0x7fdf18 | 0x4004d6 |



## 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
```

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

Execute ret

Stack Frames

Memory

main

step_up

. . .

0x7fdf28  0x40053b *<main+8>*

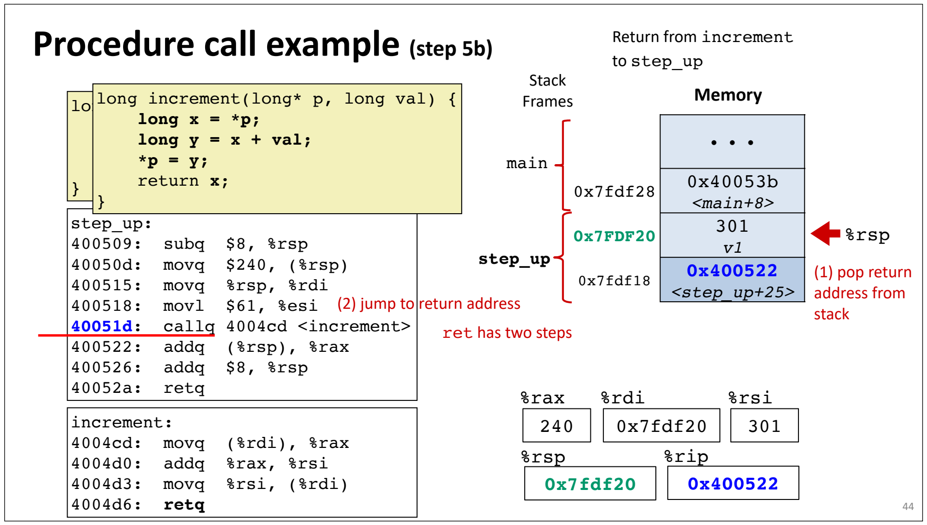
0x7fdf20  301 *v1*

0x7fdf18  0x400522 *<step_up+25>*

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 5b)

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
```

(2) jump to return address

ret has two steps

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

Stack Frames

Memory

main

step_up

. . .

0x7fdf28  0x40053b *<main+8>*

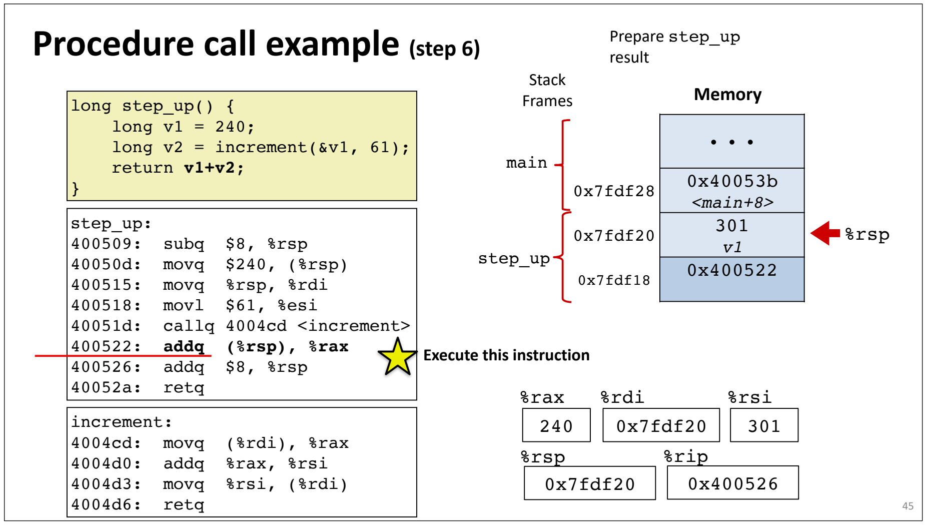
0x7FDF20  301 *v1*  ← %rsp

0x7fdf18  0x400522 *<step_up+25>*

(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
```

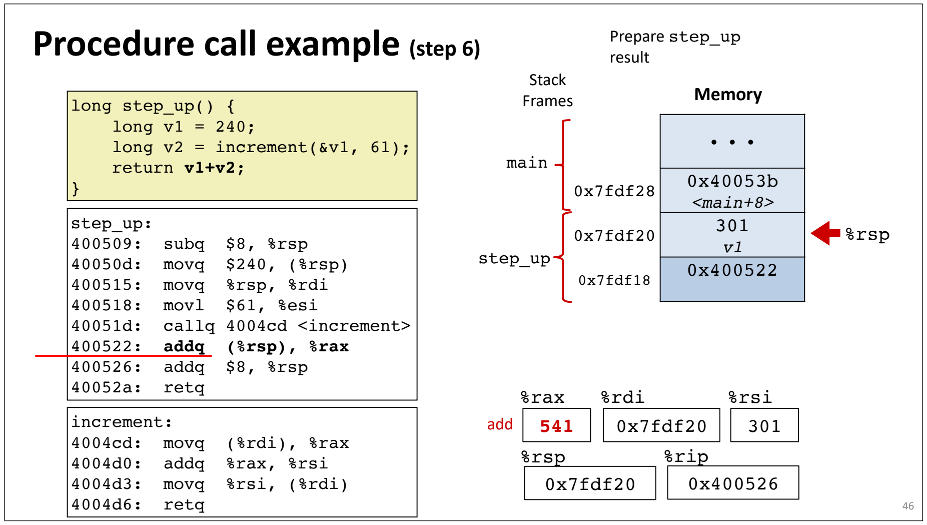
Execute this instruction

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

| Stack Frames | | Memory | |
|---|---|---|---|
| main | | • • • | |
| main | 0x7fdf28 | 0x40053b<br>*<main+8>* | |
| step_up | 0x7fdf20 | 301<br>*v1* | ← %rsp |
| step_up | 0x7fdf18 | 0x400522 | |

| %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;
}
```

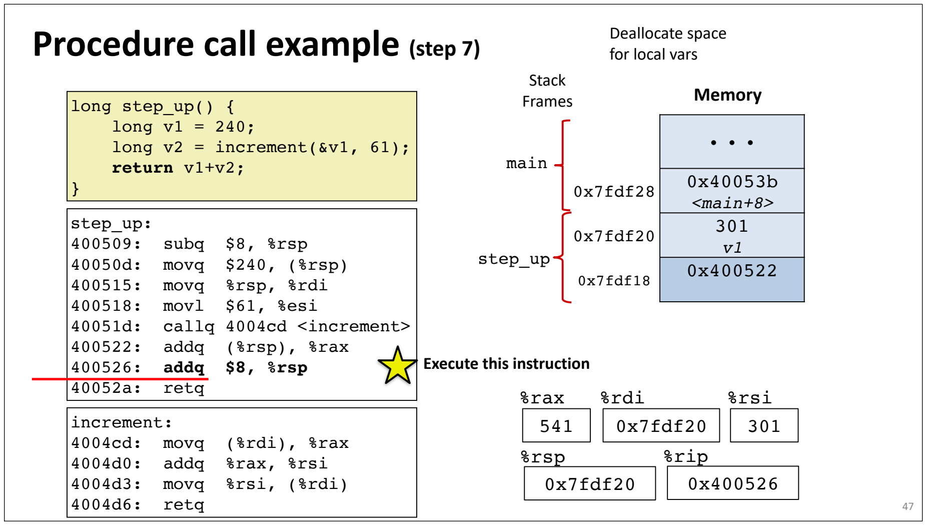
```
step_up:
400509:  subq  $8, %rsp
40050d:  movq  $240, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  (%rsp), %rax
400526:  addq  $8, %rsp
40052a:  retq
```

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

| Stack Frames | | Memory | |
|---|---|---|---|
| main | | • • • | |
| main | 0x7fdf28 | 0x40053b<br>*<main+8>* | |
| step_up | 0x7fdf20 | 301<br>*v1* | ← %rsp |
| step_up | 0x7fdf18 | 0x400522 | |

| | %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
```

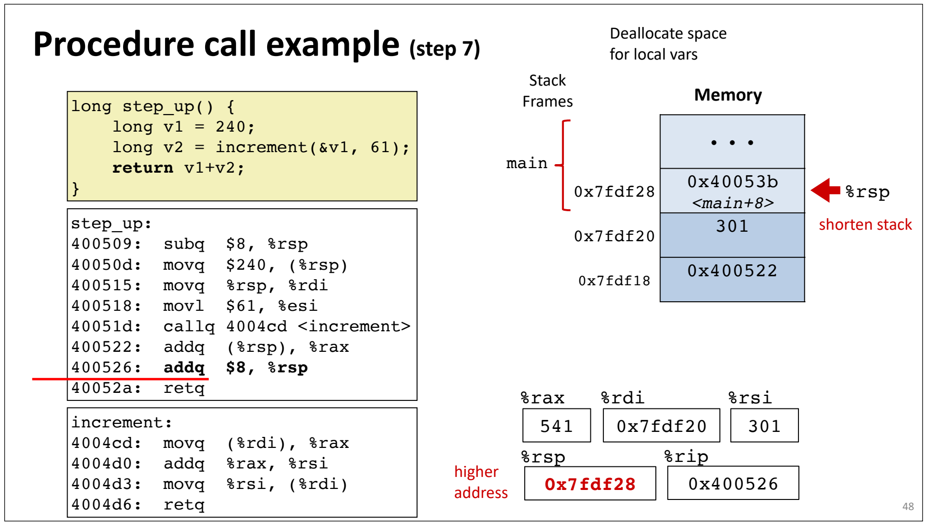
Execute this instruction

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

| Stack Frames | | Memory |
|---|---|---|
| main | | • • • |
| main | 0x7fdf28 | 0x40053b<br>*<main+8>* |
| step_up | 0x7fdf20 | 301<br>*v1* |
| step_up | 0x7fdf18 | 0x400522 |

| %rax | %rdi | %rsi |
|---|---|---|
| 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
```

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

| Stack Frames | | Memory | |
|---|---|---|---|
| main | | • • • | |
| main | 0x7fdf28 | 0x40053b<br>*<main+8>* | ← %rsp |
| | 0x7fdf20 | 301 | shorten stack |
| | 0x7fdf18 | 0x400522 | |

| %rax | %rdi | %rsi |
|---|---|---|
| 541 | 0x7fdf20 | 301 |

| | %rsp | %rip |
|---|---|---|
| higher address | **0x7fdf28** | 0x400526 |

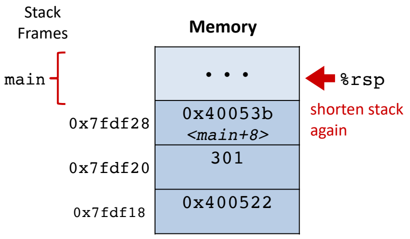
## Procedure call example (step 8)

```
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 541

%rdi 0x7fdf20

%rsi 301

%rsp **0x7fdf30**

%rip **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
```

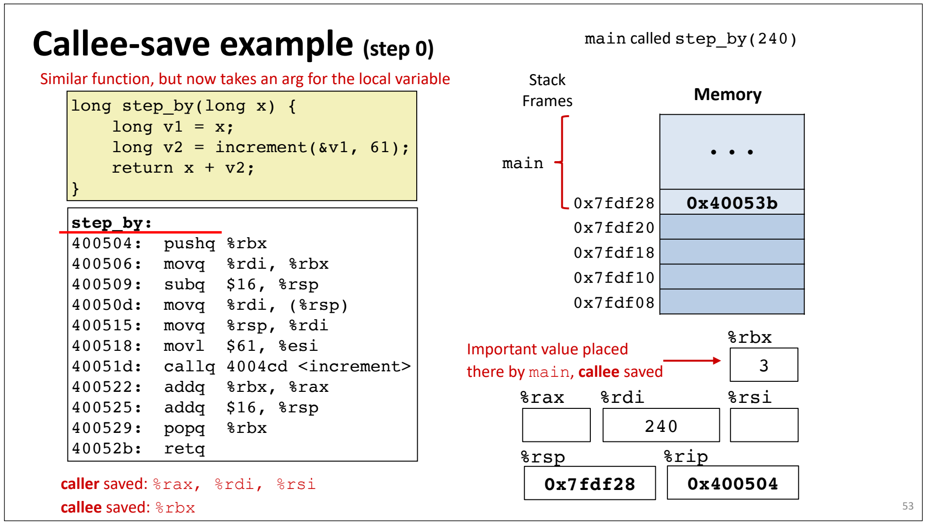
Conventions:

***Caller Save***

***Callee Save***

## x86-64 register conventions

| | | | |
|---|---|---|---|
| %rax | Return value – Caller saved | %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)

main called step_by(240)

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
```

| Stack Frames | Address | Memory |
|---|---|---|
| main | | . . . |
| | 0x7fdf28 | 0x40053b |
| | 0x7fdf20 | |
| | 0x7fdf18 | |
| | 0x7fdf10 | |
| | 0x7fdf08 | |

Important value placed there by main, callee saved

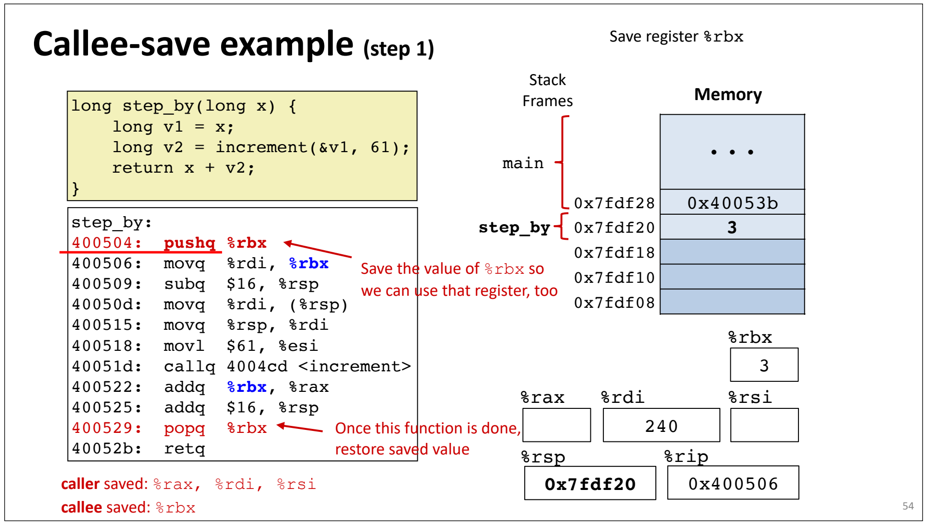
| %rbx |
|---|
| 3 |

| %rax | %rdi | %rsi |
|---|---|---|
| | 240 | |

| %rsp | %rip |
|---|---|
| 0x7fdf28 | 0x400504 |

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 | Address | Memory |
|---|---|---|
| main | | . . . |
| | 0x7fdf28 | 0x40053b |
| step_by | 0x7fdf20 | 3 |
| | 0x7fdf18 | |
| | 0x7fdf10 | |
| | 0x7fdf08 | |

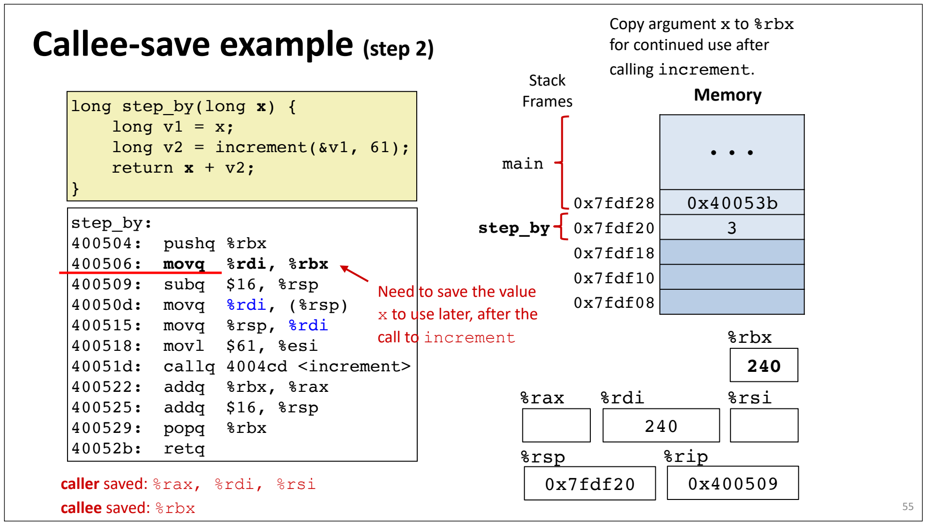
| %rbx |
|---|
| 3 |

| %rax | %rdi | %rsi |
|---|---|---|
| | 240 | |

| %rsp | %rip |
|---|---|
| 0x7fdf20 | 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 | Address | Memory |
|---|---|---|
| main | | . . . |
| | 0x7fdf28 | 0x40053b |
| step_by | 0x7fdf20 | 3 |
| | 0x7fdf18 | |
| | 0x7fdf10 | |
| | 0x7fdf08 | |

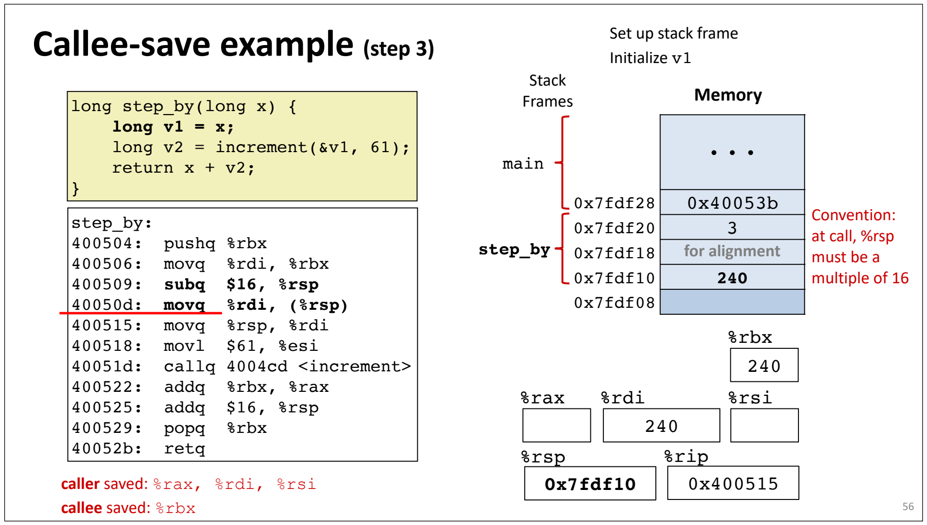
| %rbx |
|---|
| 240 |

| %rax | %rdi | %rsi |
|---|---|---|
| | 240 | |

| %rsp | %rip |
|---|---|
| 0x7fdf20 | 0x400509 |

caller saved: %rax, %rdi, %rsi

callee saved: %rbx



## Callee-save example (step 3)

Set up stack frame

Initialize v1

```
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
```

| Stack Frames | Address | Memory |
|---|---|---|
| main | | . . . |
| | 0x7fdf28 | 0x40053b |
| step_by | 0x7fdf20 | 3 |
| | 0x7fdf18 | for alignment |
| | 0x7fdf10 | 240 |
| | 0x7fdf08 | |

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

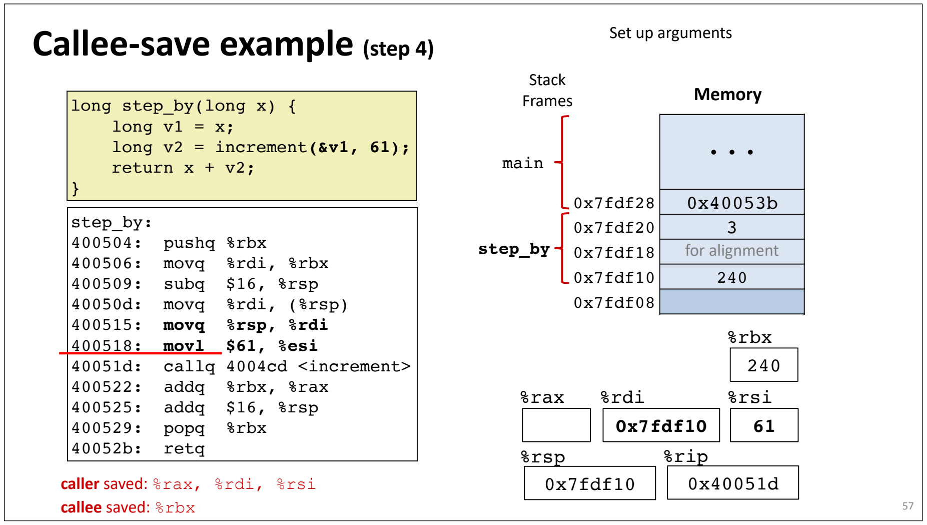
| %rbx |
|---|
| 240 |

| %rax | %rdi | %rsi |
|---|---|---|
| | 240 | |

| %rsp | %rip |
|---|---|
| 0x7fdf10 | 0x400515 |

caller saved: %rax, %rdi, %rsi

callee saved: %rbx



## Callee-save example (step 4)

Set up arguments

```
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
```

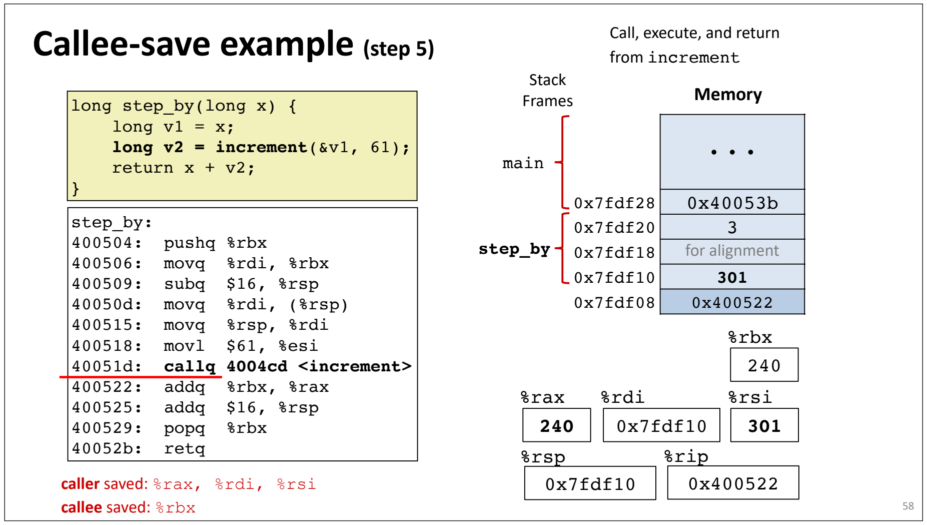
| Stack Frames | | Memory |
|---|---|---|
| main | | . . . |
| | 0x7fdf28 | 0x40053b |
| step_by | 0x7fdf20 | 3 |
| | 0x7fdf18 | for alignment |
| | 0x7fdf10 | 240 |
| | 0x7fdf08 | |

| %rax | %rdi | %rsi | %rbx |
|---|---|---|---|
| | **0x7fdf10** | **61** | 240 |

| %rsp | %rip |
|---|---|
| 0x7fdf10 | 0x40051d |

caller saved: %rax, %rdi, %rsi

callee saved: %rbx



## Callee-save example (step 5)

Call, execute, and return from 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
```

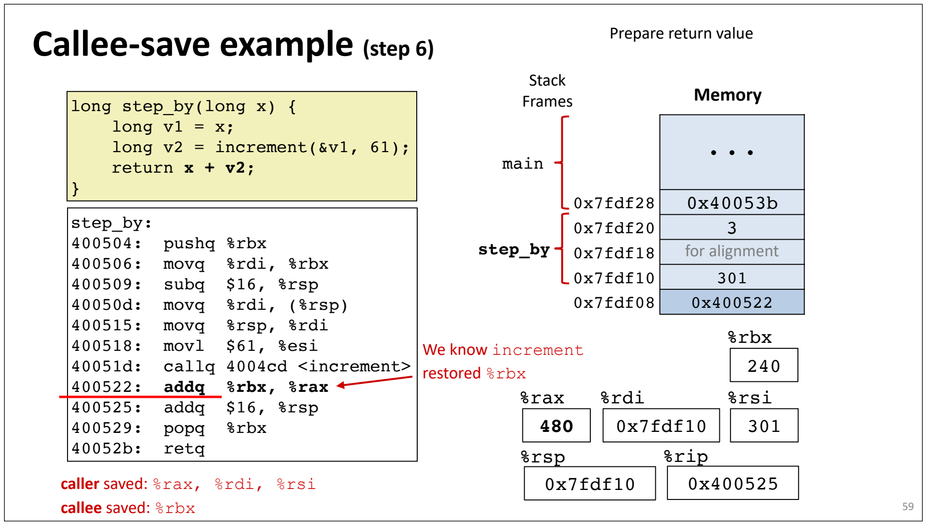
| Stack Frames | | Memory |
|---|---|---|
| main | | . . . |
| | 0x7fdf28 | 0x40053b |
| step_by | 0x7fdf20 | 3 |
| | 0x7fdf18 | for alignment |
| | 0x7fdf10 | **301** |
| | 0x7fdf08 | 0x400522 |

| %rax | %rdi | %rsi | %rbx |
|---|---|---|---|
| **240** | 0x7fdf10 | **301** | 240 |

| %rsp | %rip |
|---|---|
| 0x7fdf10 | 0x400522 |

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

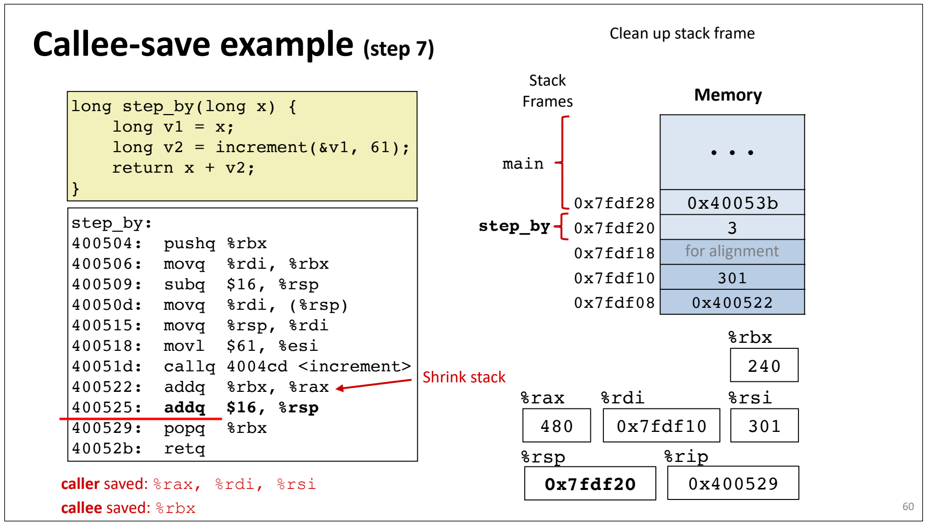
| Stack Frames | | Memory |
|---|---|---|
| main | | . . . |
| | 0x7fdf28 | 0x40053b |
| step_by | 0x7fdf20 | 3 |
| | 0x7fdf18 | for alignment |
| | 0x7fdf10 | 301 |
| | 0x7fdf08 | 0x400522 |

| %rax | %rdi | %rsi | %rbx |
|---|---|---|---|
| **480** | 0x7fdf10 | 301 | 240 |

| %rsp | %rip |
|---|---|
| 0x7fdf10 | 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

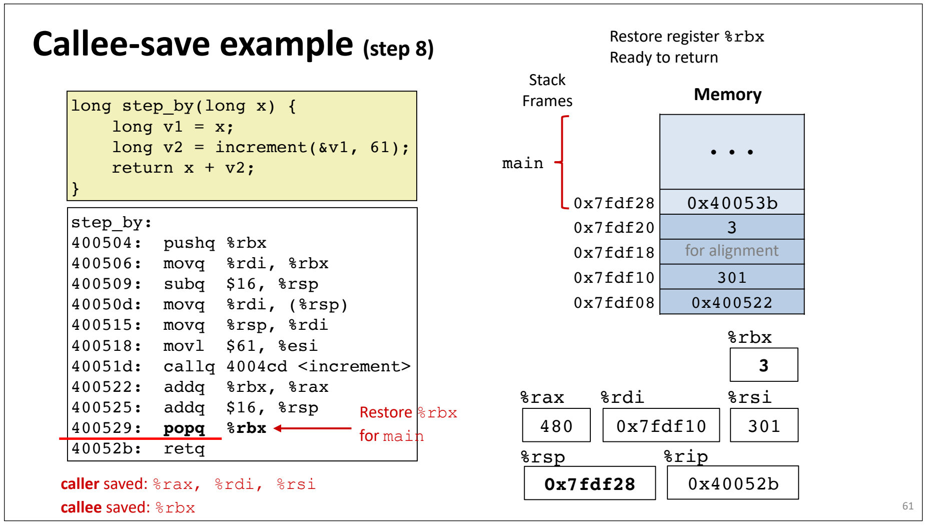
| Stack Frames | | Memory |
|---|---|---|
| main | | . . . |
| | 0x7fdf28 | 0x40053b |
| step_by | 0x7fdf20 | 3 |
| | 0x7fdf18 | for alignment |
| | 0x7fdf10 | 301 |
| | 0x7fdf08 | 0x400522 |

| %rax | %rdi | %rsi | %rbx |
|---|---|---|---|
| 480 | 0x7fdf10 | 301 | 240 |

| %rsp | %rip |
|---|---|
| **0x7fdf20** | 0x400529 |

caller saved: %rax, %rdi, %rsi

callee saved: %rbx



## Callee-save example (step 8)

Restore register %rbx
Ready to return

```
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

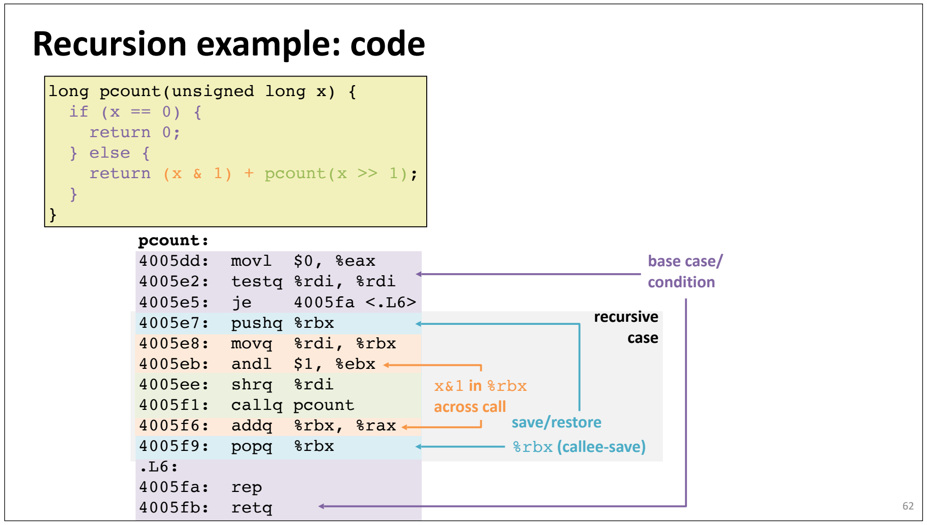
caller saved: %rax, %rdi, %rsi
callee saved: %rbx

| Stack Frames |  | Memory |
|---|---|---|
| main |  | • • • |
|  | 0x7fdf28 | 0x40053b |
|  | 0x7fdf20 | 3 |
|  | 0x7fdf18 | for alignment |
|  | 0x7fdf10 | 301 |
|  | 0x7fdf08 | 0x400522 |

| %rbx |
|---|
| 3 |

| %rax | %rdi | %rsi |
|---|---|---|
| 480 | 0x7fdf10 | 301 |

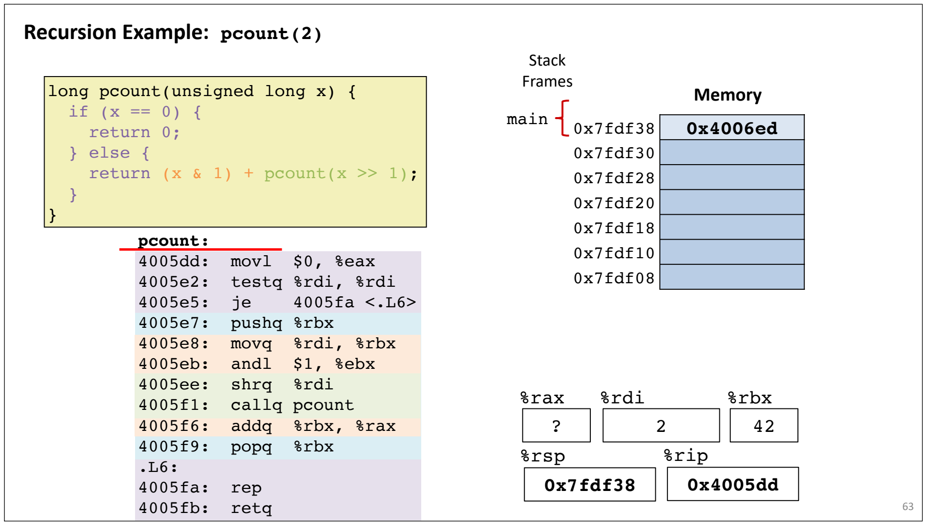
| %rsp | %rip |
|---|---|
| 0x7fdf28 | 0x40052b |



## 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
```



### Recursion Example: pcount(2)

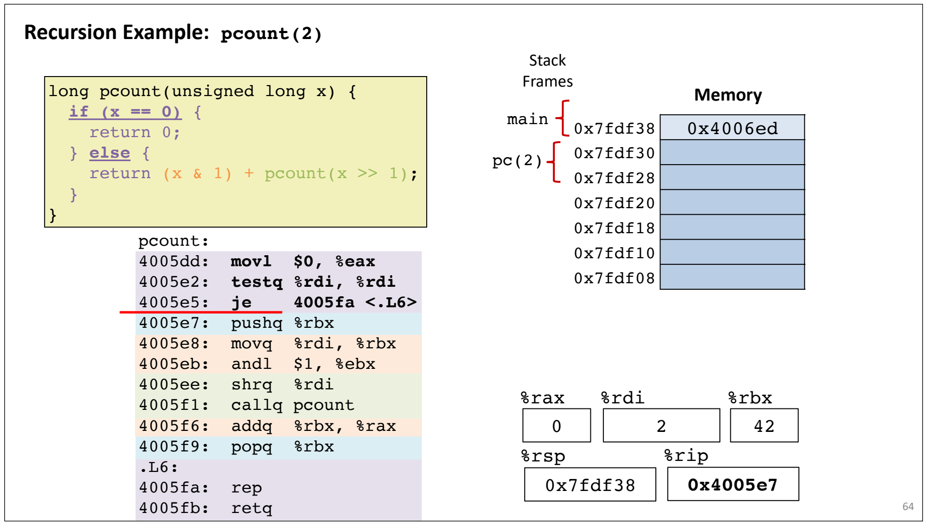
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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
```

| Stack Frames |  | Memory |
|---|---|---|
| main | 0x7fdf38 | 0x4006ed |
|  | 0x7fdf30 |  |
|  | 0x7fdf28 |  |
|  | 0x7fdf20 |  |
|  | 0x7fdf18 |  |
|  | 0x7fdf10 |  |
|  | 0x7fdf08 |  |

| %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);
  }
}
```

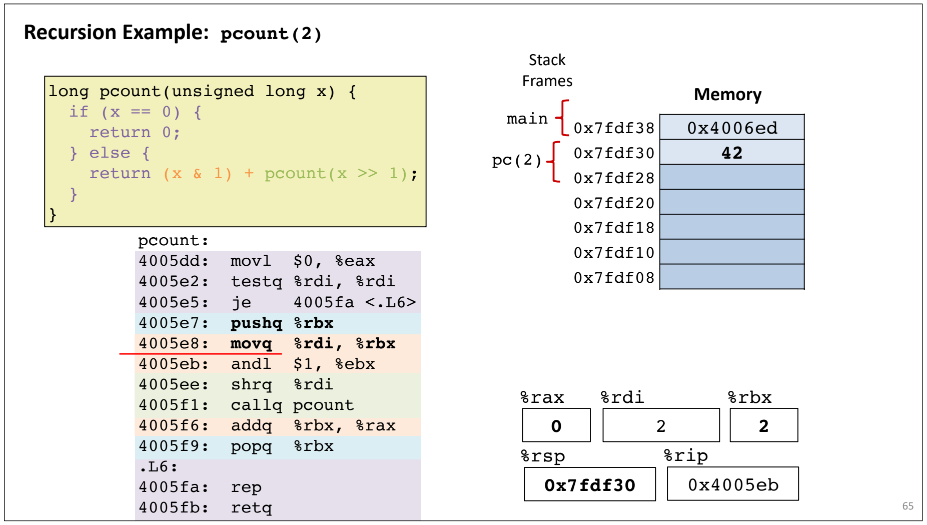
```
pcount:
4005dd:  movl  $0, %eax
4005e2:  testq %rdi, %rdi
4005e5:  je    4005fa <.L6>
4005e7:  pushq %rbx
4005e8:  movq  %rdi, %rbx
4005eb:  andl  $1, %ebx
4005ee:  shrq  %rdi
4005f1:  callq pcount
4005f6:  addq  %rbx, %rax
4005f9:  popq  %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

| Stack Frames |  | Memory |
|---|---|---|
| main | 0x7fdf38 | 0x4006ed |
| pc(2) | 0x7fdf30 |  |
|  | 0x7fdf28 |  |
|  | 0x7fdf20 |  |
|  | 0x7fdf18 |  |
|  | 0x7fdf10 |  |
|  | 0x7fdf08 |  |

| %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);
  }
}
```

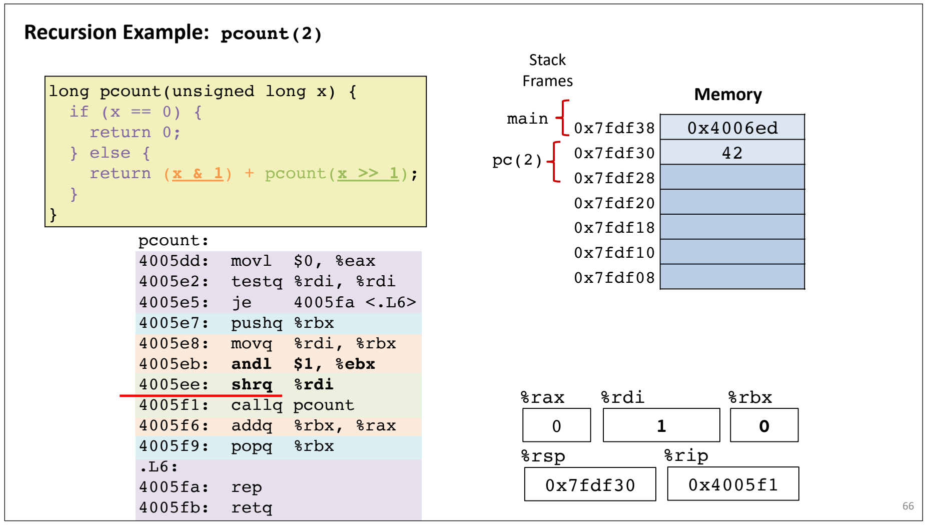
```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

| Stack Frames | | Memory |
|---|---|---|
| main | 0x7fdf38 | 0x4006ed |
| pc(2) | 0x7fdf30 | **42** |
| | 0x7fdf28 | |
| | 0x7fdf20 | |
| | 0x7fdf18 | |
| | 0x7fdf10 | |
| | 0x7fdf08 | |

| %rax | %rdi | %rbx |
|---|---|---|
| **0** | 2 | **2** |

| %rsp | %rip |
|---|---|
| **0x7fdf30** | 0x4005eb |

## Recursion Example: **pcount(2)**



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

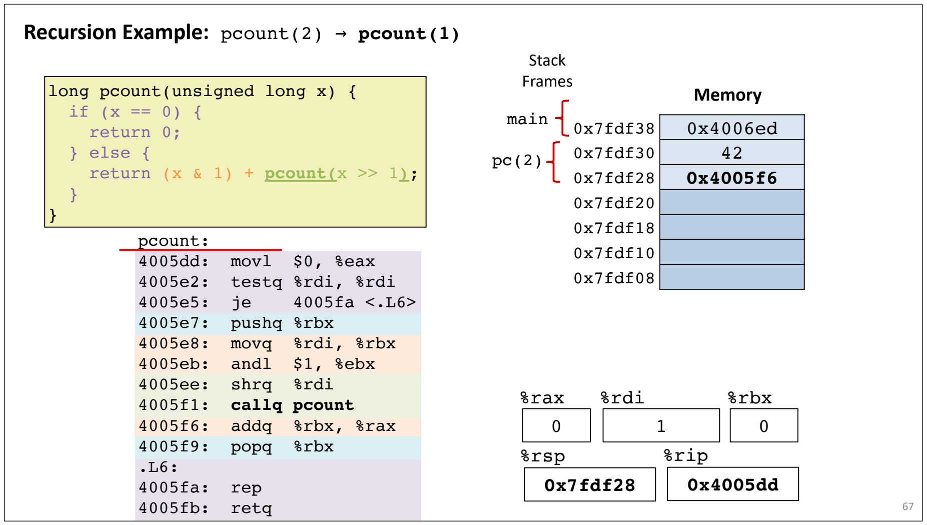
```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

| Stack Frames | | Memory |
|---|---|---|
| main | 0x7fdf38 | 0x4006ed |
| pc(2) | 0x7fdf30 | 42 |
| | 0x7fdf28 | |
| | 0x7fdf20 | |
| | 0x7fdf18 | |
| | 0x7fdf10 | |
| | 0x7fdf08 | |

| %rax | %rdi | %rbx |
|---|---|---|
| 0 | **1** | **0** |

| %rsp | %rip |
|---|---|
| 0x7fdf30 | 0x4005f1 |

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



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

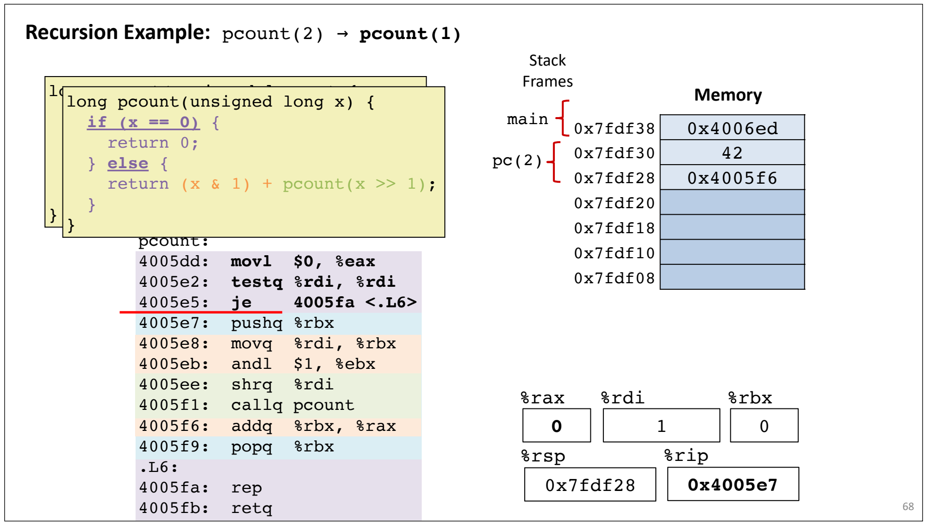
```
pcount:
4005dd:  movl   $0, %eax
4005e2:  testq  %rdi, %rdi
4005e5:  je     4005fa <.L6>
4005e7:  pushq  %rbx
4005e8:  movq   %rdi, %rbx
4005eb:  andl   $1, %ebx
4005ee:  shrq   %rdi
4005f1:  callq  pcount
4005f6:  addq   %rbx, %rax
4005f9:  popq   %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

| Stack Frames | | Memory |
|---|---|---|
| main | 0x7fdf38 | 0x4006ed |
| pc(2) | 0x7fdf30 | 42 |
| | 0x7fdf28 | **0x4005f6** |
| | 0x7fdf20 | |
| | 0x7fdf18 | |
| | 0x7fdf10 | |
| | 0x7fdf08 | |

| %rax | %rdi | %rbx |
|---|---|---|
| 0 | 1 | 0 |

| %rsp | %rip |
|---|---|
| **0x7fdf28** | **0x4005dd** |

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



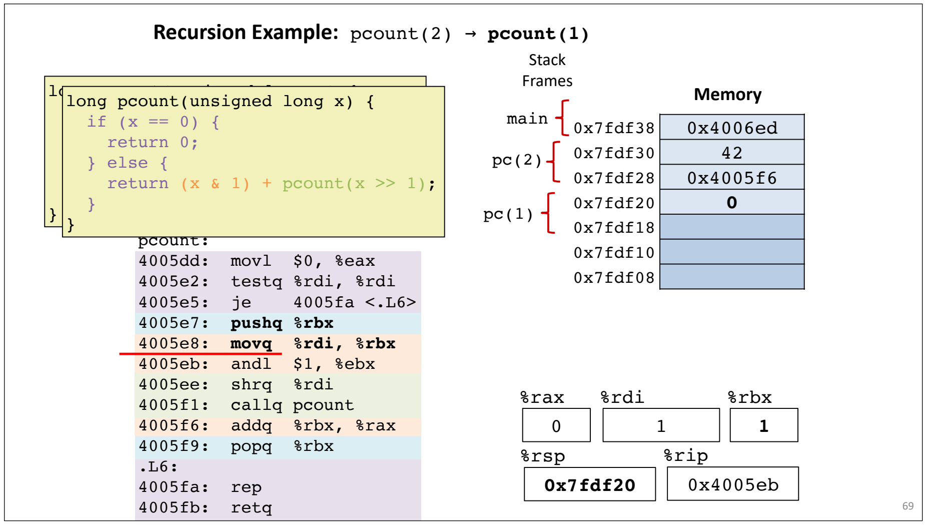
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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
```

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

| %rax | %rdi | %rbx |
|---|---|---|
| **0** | 1 | 0 |

| %rsp | %rip |
|---|---|
| 0x7fdf28 | **0x4005e7** |



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

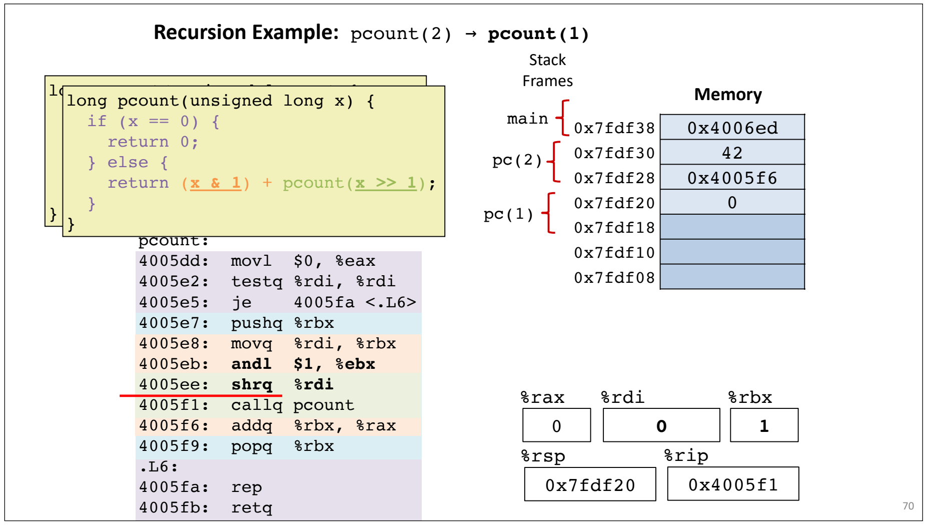
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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 |
|---|---|---|
| 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)**

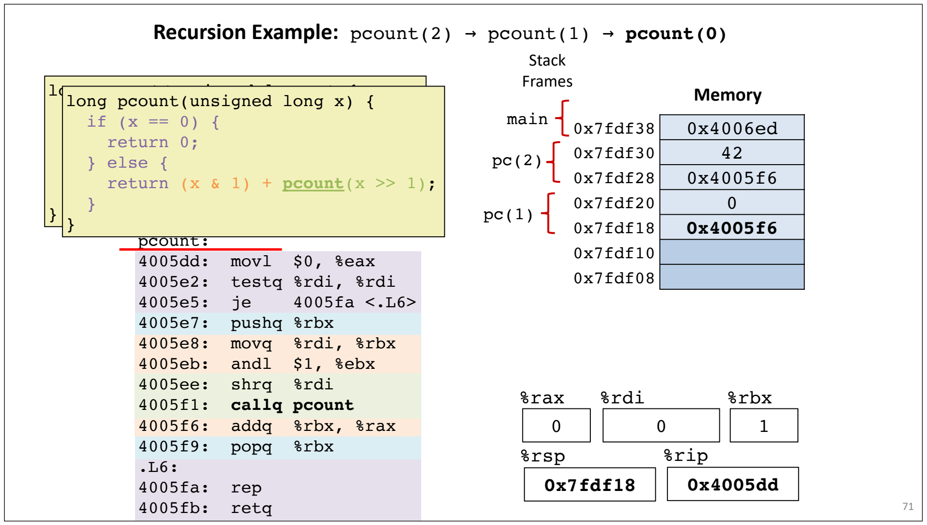
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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
```

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

| %rax | %rdi | %rbx |
|---|---|---|
| 0 | **0** | **1** |

| %rsp | %rip |
|---|---|
| 0x7fdf20 | 0x4005f1 |



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

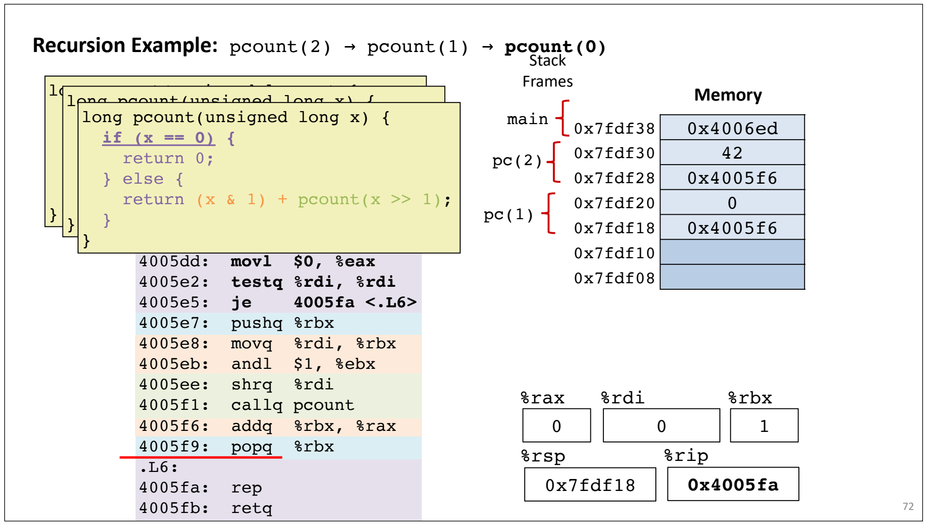
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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
```

| 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** | **0x4005dd** |



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

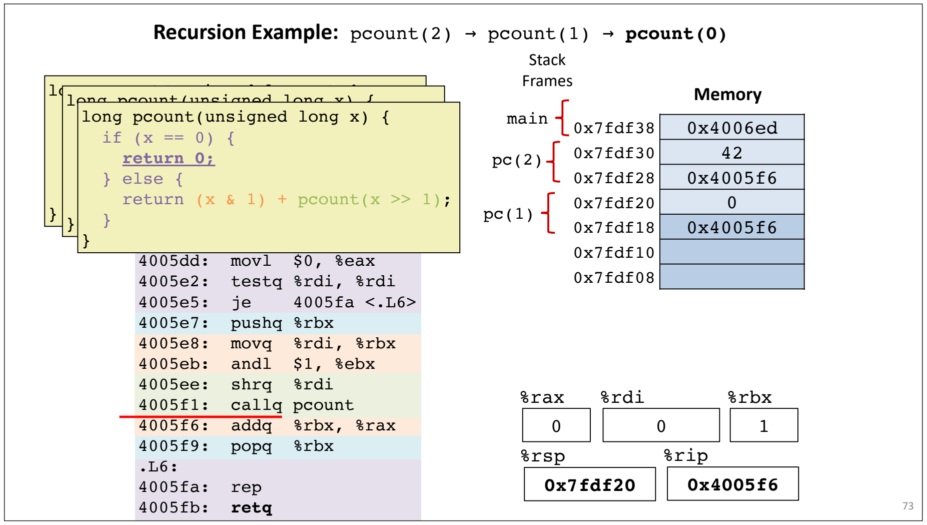
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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);
  }
}
```

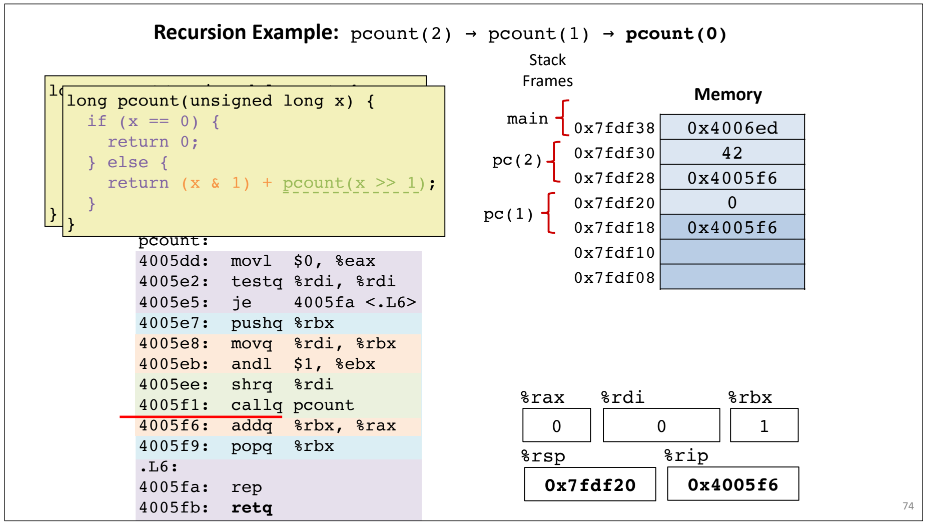
```
4005dd:  movl  $0, %eax
4005e2:  testq %rdi, %rdi
4005e5:  je    4005fa <.L6>
4005e7:  pushq %rbx
4005e8:  movq  %rdi, %rbx
4005eb:  andl  $1, %ebx
4005ee:  shrq  %rdi
4005f1:  callq pcount
4005f6:  addq  %rbx, %rax
4005f9:  popq  %rbx
.L6:
4005fa:  rep
4005fb:  retq
```

Stack Frames

| 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 |
|---|---|
| **0x7fdf20** | **0x4005f6** |



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

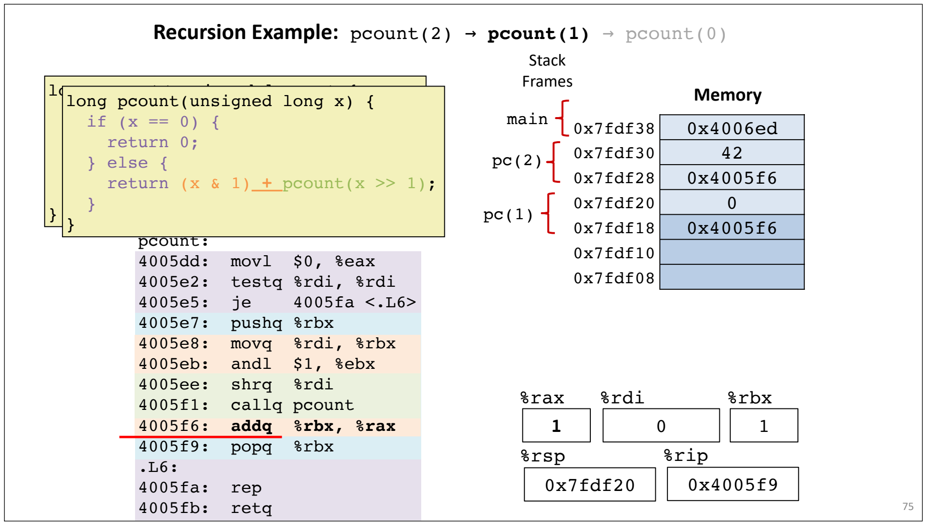
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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 |
|---|---|---|
| 0 | 0 | 1 |

| %rsp | %rip |
|---|---|
| **0x7fdf20** | **0x4005f6** |



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

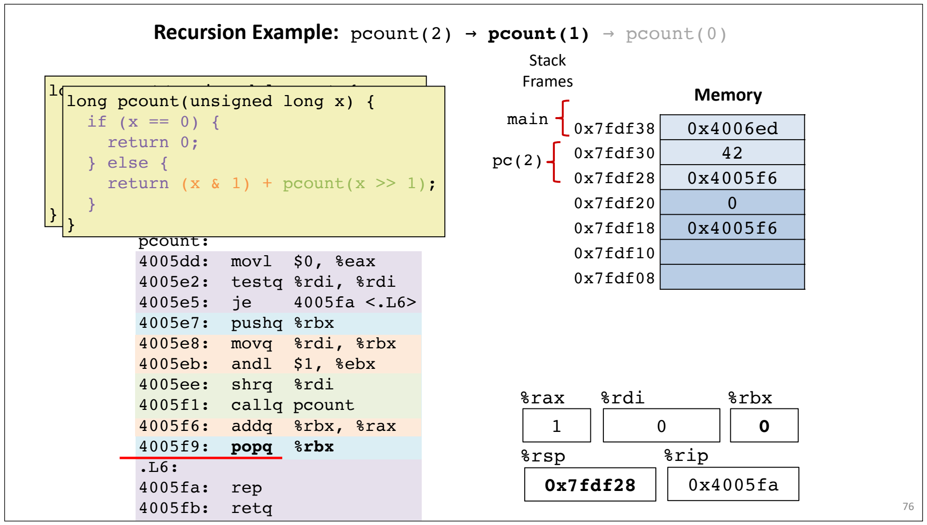
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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)

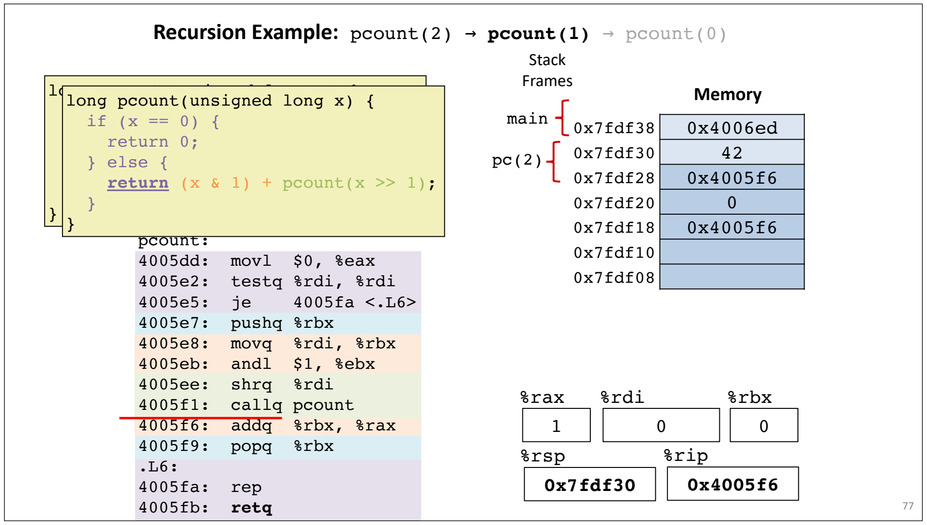
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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)

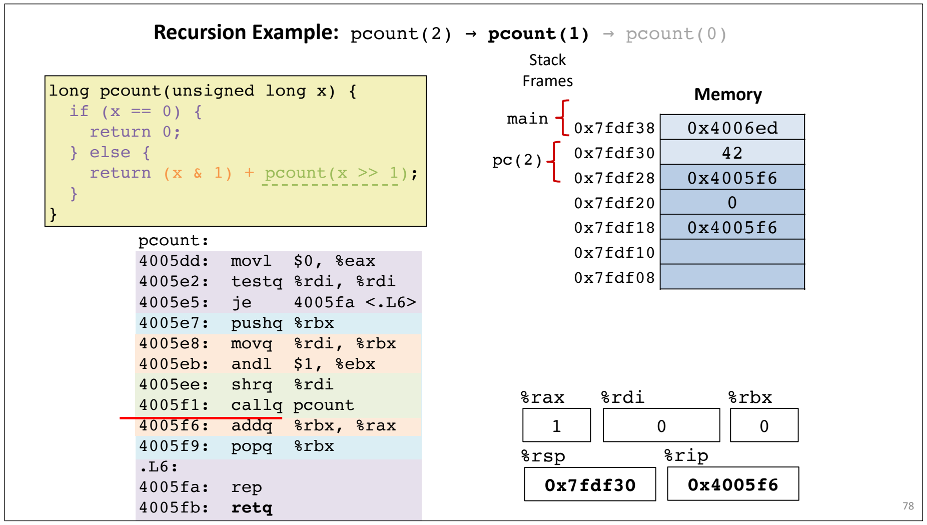
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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)

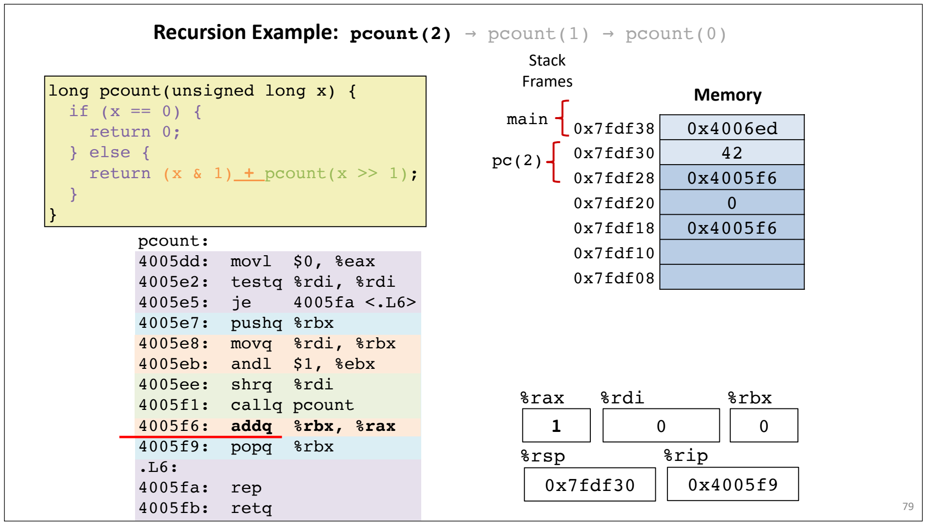
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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)

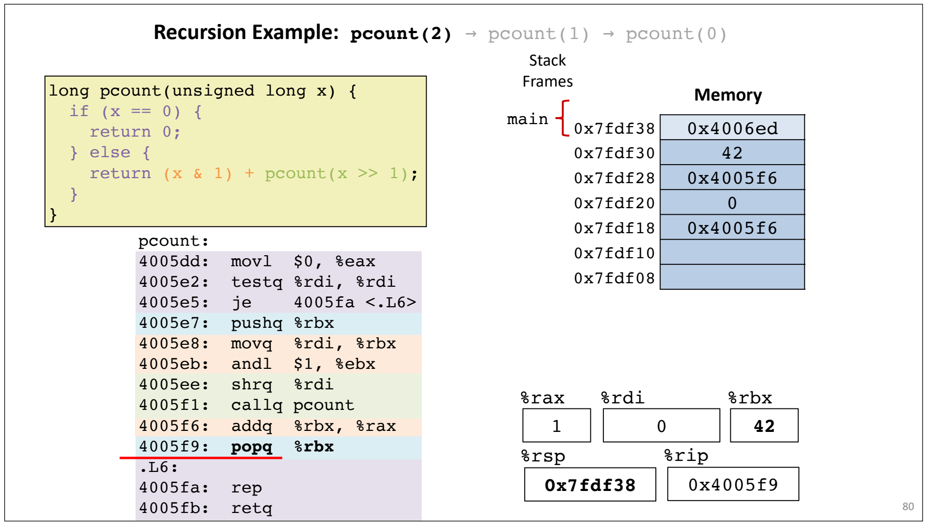
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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)

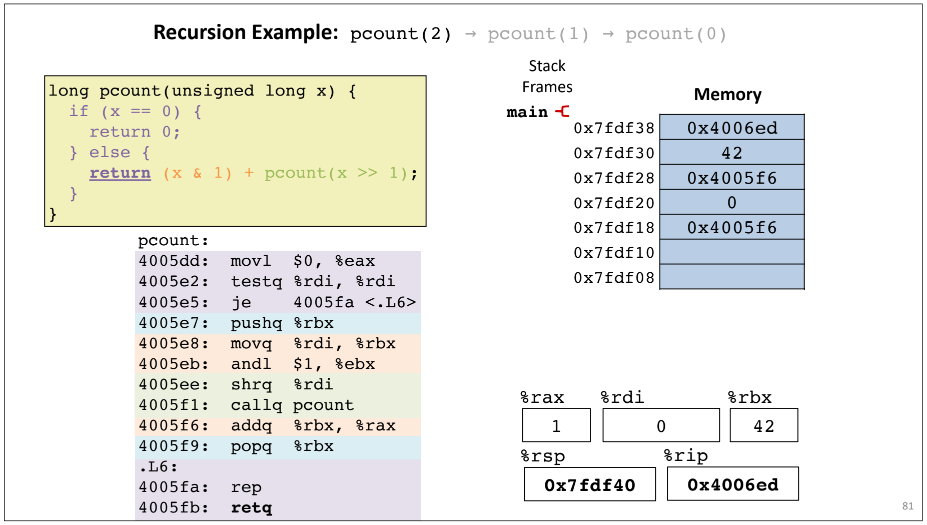
```
long pcount(unsigned long x) {
  if (x == 0) {
    return 0;
  } else {
    return (x & 1) + pcount(x >> 1);
  }
}
```

```
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
```

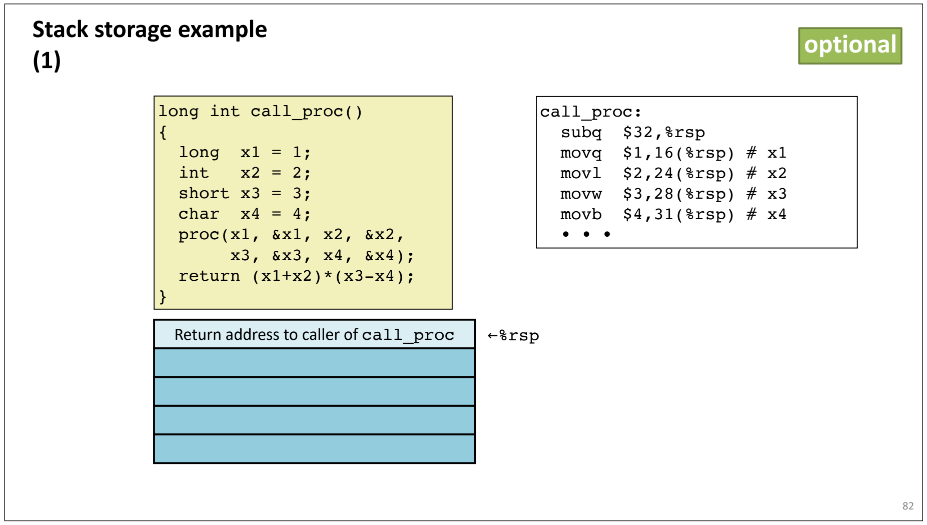
Stack Frames

main

| | Memory |
|---|---|
| 0x7fdf38 | 0x4006ed |
| 0x7fdf30 | 42 |
| 0x7fdf28 | 0x4005f6 |
| 0x7fdf20 | 0 |
| 0x7fdf18 | 0x4005f6 |
| 0x7fdf10 | |
| 0x7fdf08 | |

| %rax | %rdi | %rbx |
|---|---|---|
| 1 | 0 | 42 |

| %rsp | %rip |
|---|---|
| 0x7fdf40 | 0x4006ed |



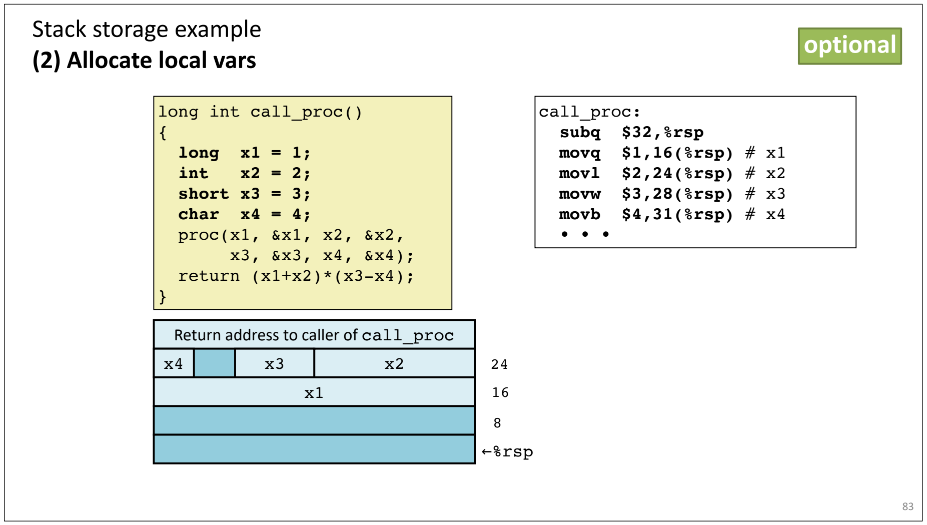
## Stack storage example (1)

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
  • • •
```

| Return address to caller of `call_proc` | ←%rsp |
|---|---|
| | |
| | |
| | |
| | |



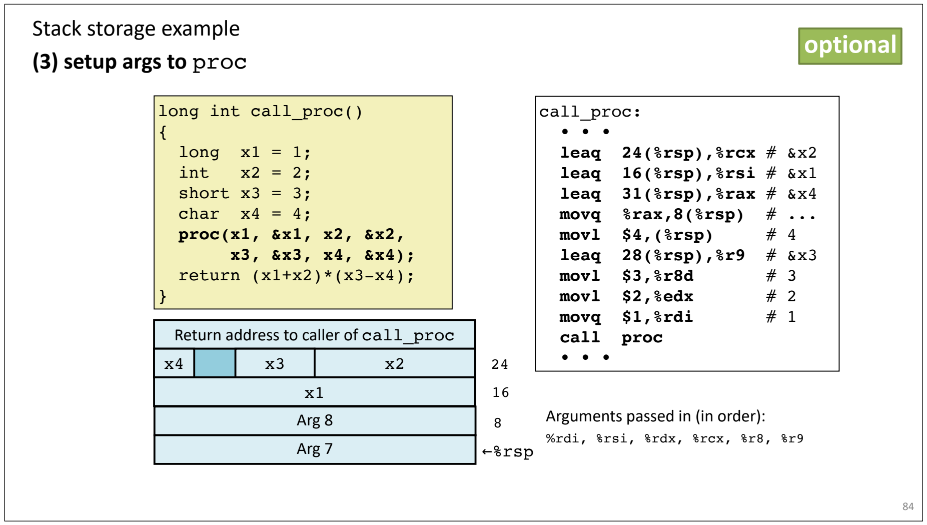
## Stack storage example (2) Allocate local vars

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
  • • •
```

| 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`

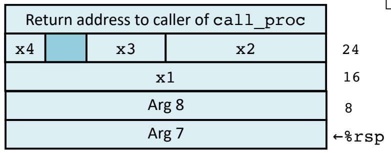
Stack storage example

**(4) after call to `proc`**

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
```



Return address to caller of `call_proc`

x4 | | x3 | x2 — 24

x1 — 16

Arg 8 — 8

Arg 7 — ←%rsp

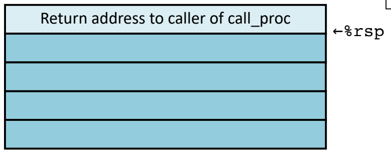
Stack storage example

**(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
```



Return address to caller of call_proc ←%rsp

# Procedure Summary

**`call, ret, push, pop`**

Stack discipline fits procedure call / return.*

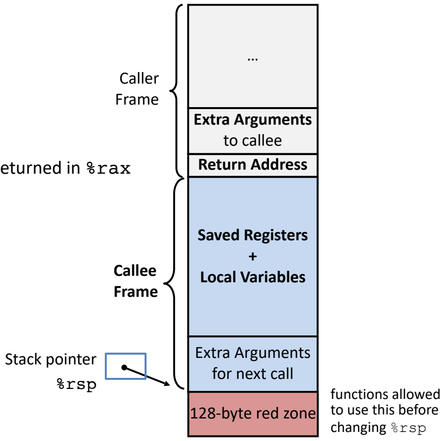
If P calls Q: Q (and calls by Q) returns before P

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 | **%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 |



Caller Frame

…

**Extra Arguments** to callee

**Return Address**

**Callee Frame**

**Saved Registers + Local Variables**

Extra Arguments for next call

128-byte red zone

Stack pointer `%rsp`

functions allowed to use this before changing `%rsp`