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

https://cs.wellesley.edu/~cs240/

x86: Procedures and the Call Stack

Outline

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

Why procedures?

Why functions? Why methods?

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

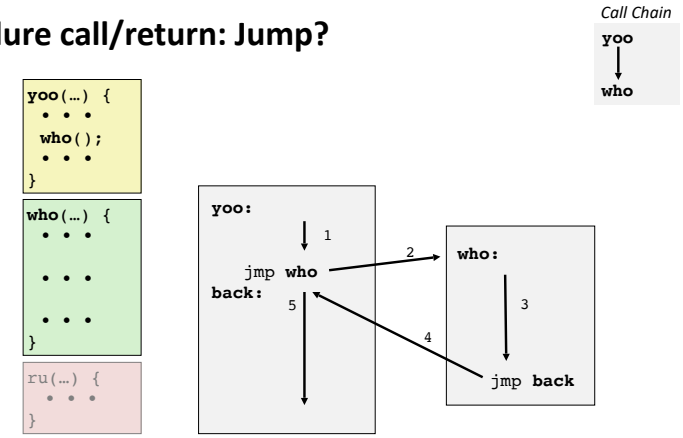
Answer: procedural abstraction

Implementing procedures

Have we already seen how this is done?

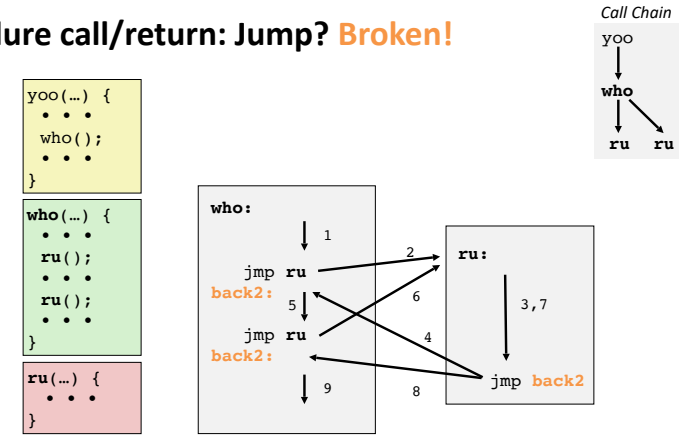
1. How does a caller pass arguments to a procedure? ✓
2. How does a caller receive a return value from a procedure? ✓
3. How does a procedure know where to return (what code to execute next when done)? ??
4. Where does a procedure store local variables? ✓?
5. How do procedures share limited registers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

Procedure call/return: Jump?



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

Procedure call/return: Jump? Broken!



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

Broken: needs to track context.

Implementing procedures

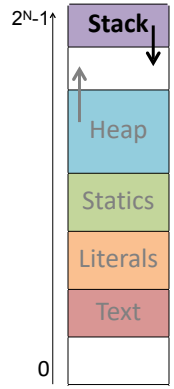
requires **separate storage *per call!***
(not just per procedure)

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? ??

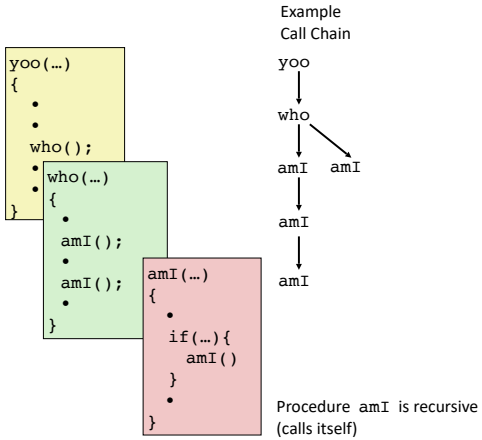
Memory Layout

reminder



Perm	Contents	Managed by	Initialized
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

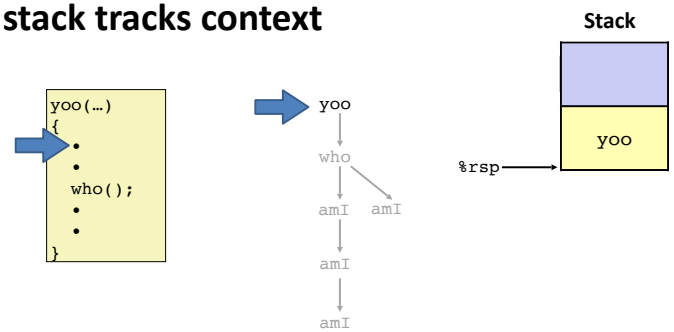
Call stack tracks context



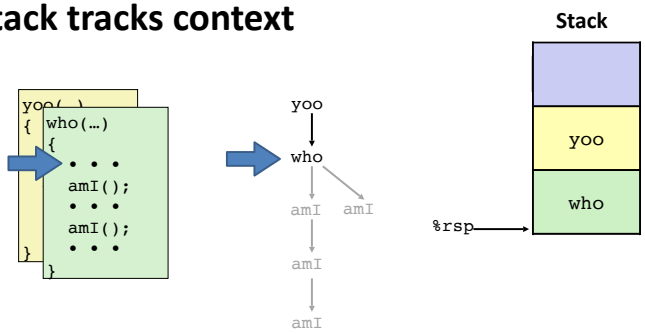
Example
Call Chain

Procedure `amI` is recursive
(calls itself)

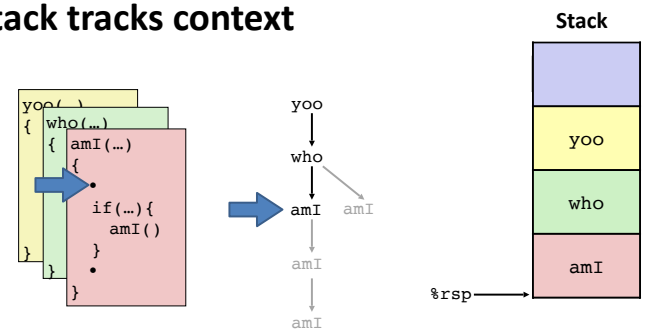
Call stack tracks context



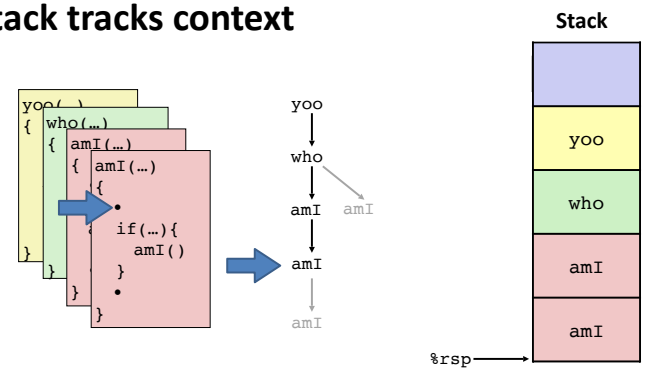
Call stack tracks context



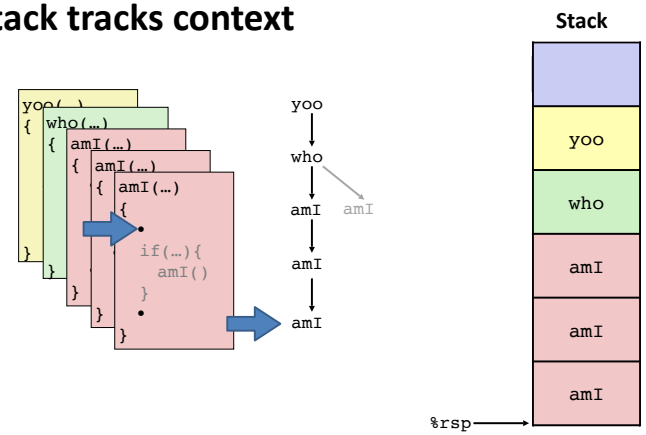
Call stack tracks context



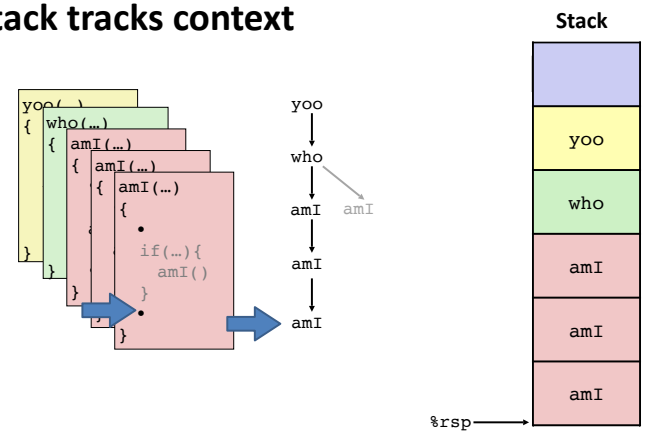
Call stack tracks context



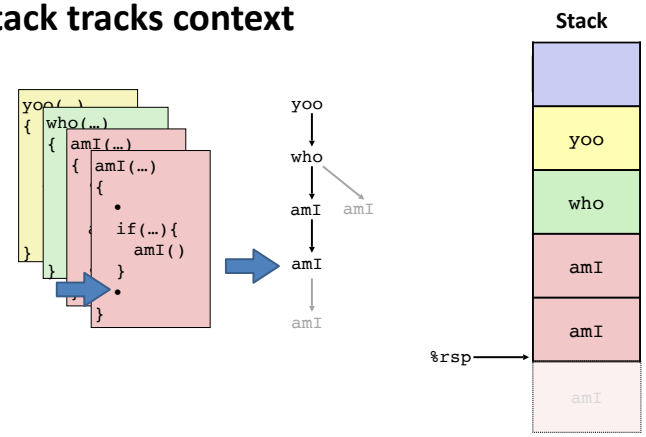
Call stack tracks context



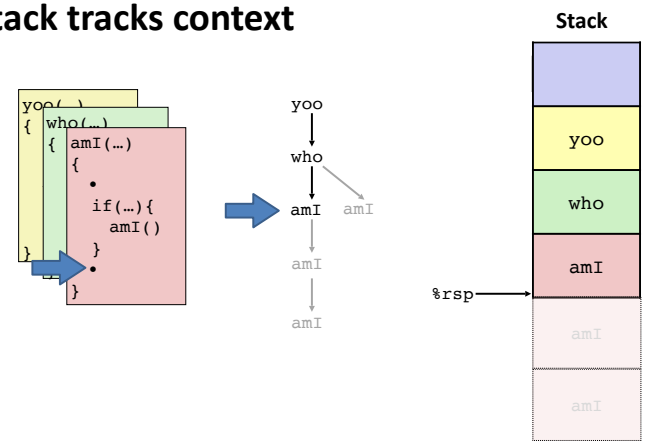
Call stack tracks context



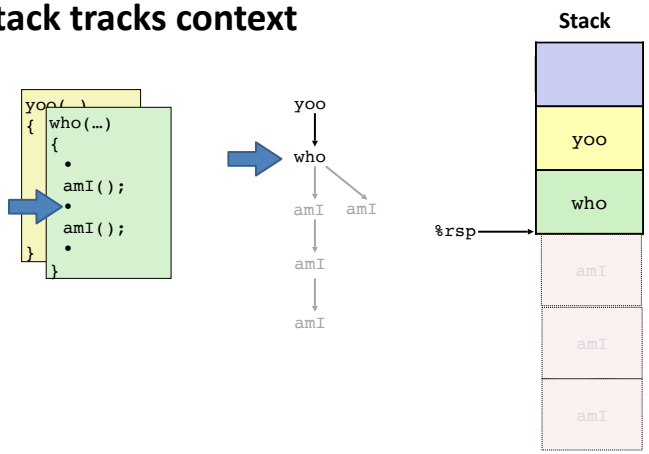
Call stack tracks context



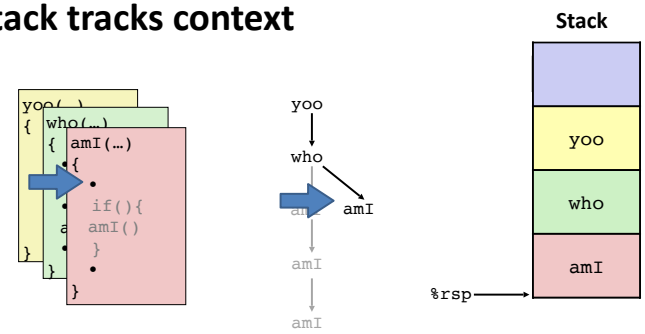
Call stack tracks context



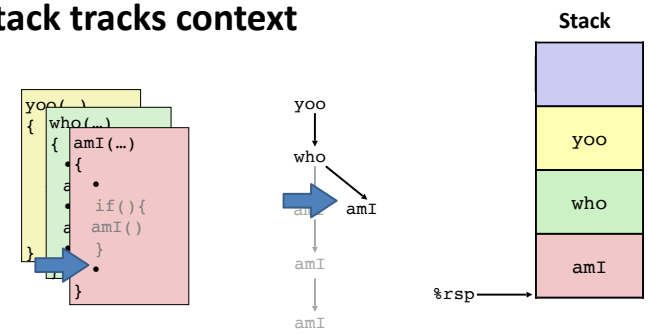
Call stack tracks context



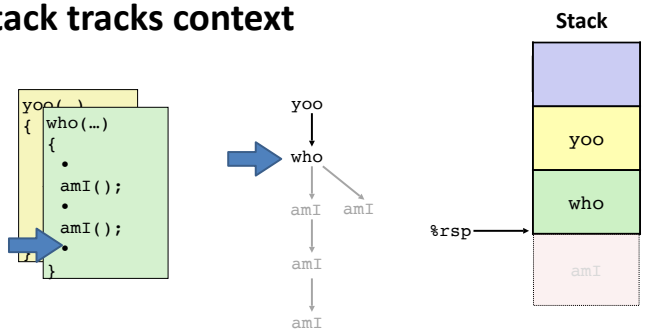
Call stack tracks context



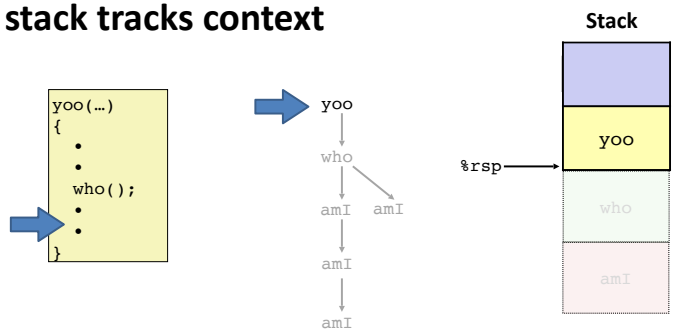
Call stack tracks context



Call stack tracks context



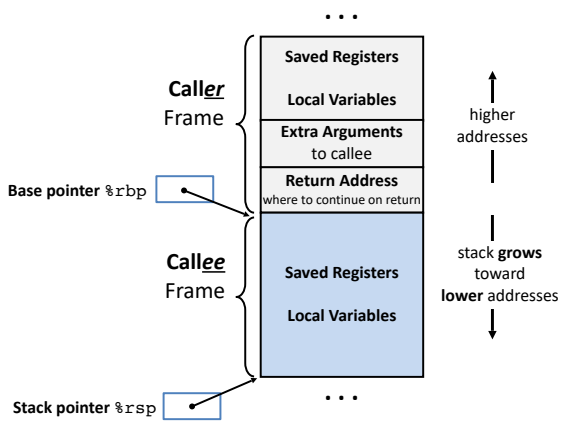
Call stack tracks context



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*

Before `callq`

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

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

%rsp	%rip
0x7fdf20	0x400544

After `callq`

Memory

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

%rsp	%rip
0x7fdf18	0x400550

Return example

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

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

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

Before `retq`

Memory

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

%rsp	%rip
0x7fdf18	0x400557

Return example

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

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

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

Before `retq`

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**

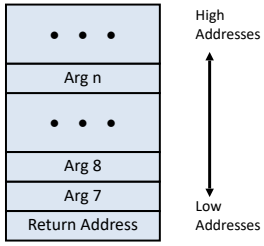
Arg 1	`%rdi`
Arg 2	`%rsi`
Arg 3	`%rdx`
Arg 4	`%rcx`
Arg 5	`%r8`
Arg 6	`%r9`

Diane's Silk Dress Costs $8 9

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

`%rax`

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



Procedure call / stack frame example

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

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

Passes address of local variable (in stack).

Uses memory through pointer.

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

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


Procedure call example (step 0)

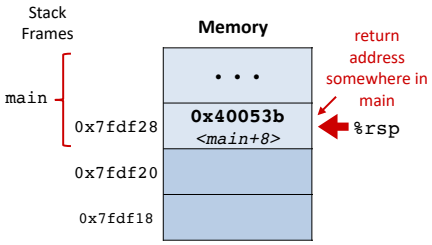
```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

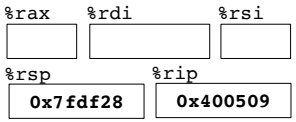
red line shows `%rip`

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

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

`main` called `step_up`





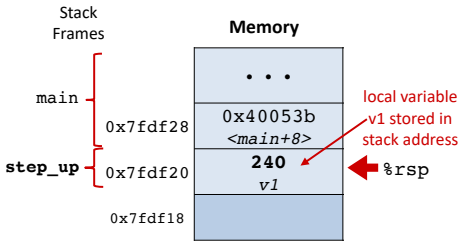
Procedure call example (step 1)

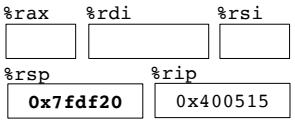
```
long step_up() {
    long v1 = 240;
    long v2 = increment(&v1, 61);
    return v1+v2;
}
```

```
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
```

Allocate space for local vars





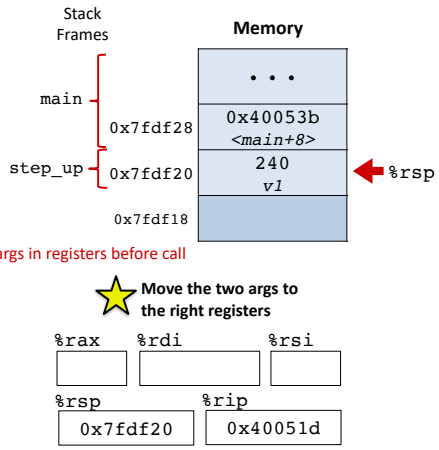
Procedure call example (step 2)

```
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

Move the two args to the right registers

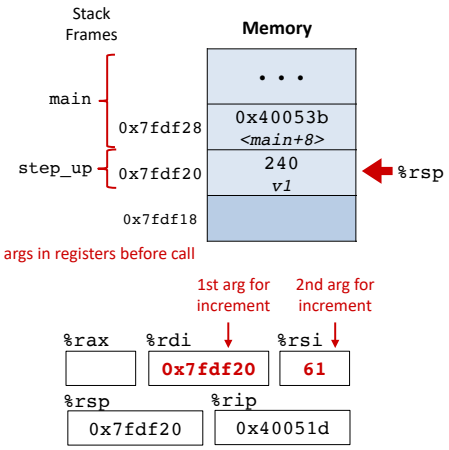
Procedure call example (step 2)

```
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

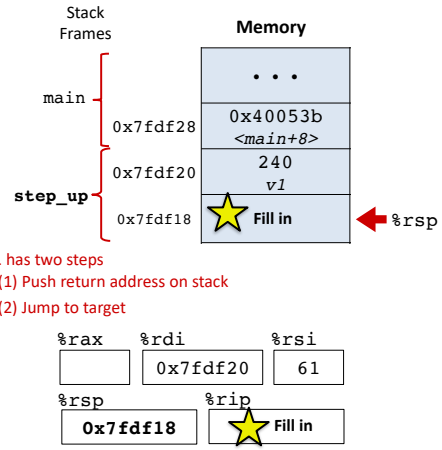
Procedure call example (step 3)

```
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 `increment`



`call` has two steps

(1) Push return address on stack

(2) Jump to target

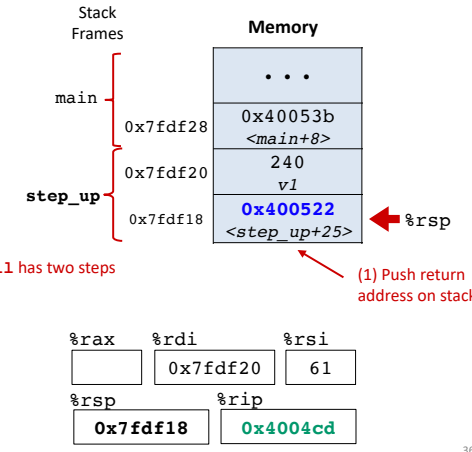
Procedure call example (step 3)

```
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 `increment`



`call` has two steps

(1) Push return address on stack

(2) Jump to target

Procedure call example (step 4)

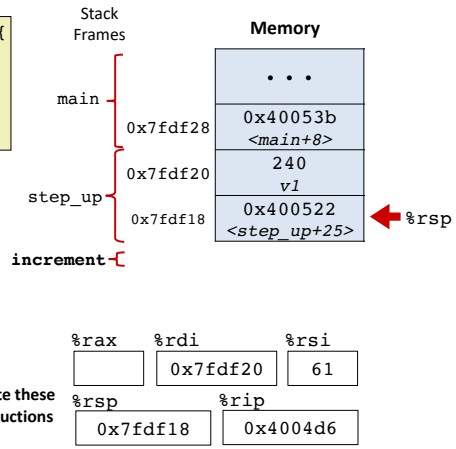
Run increment

```
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



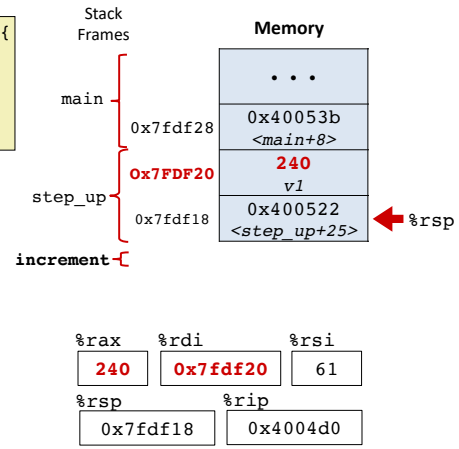
Procedure call example (step 4)

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
```



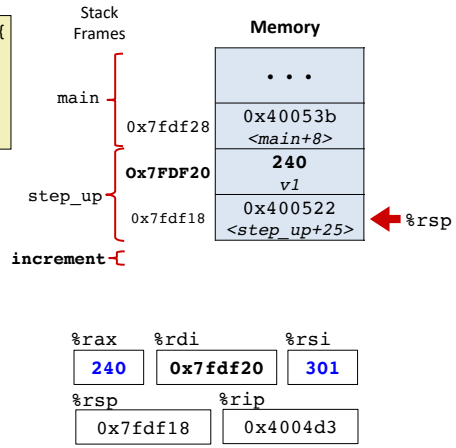
Procedure call example (step 4)

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
```



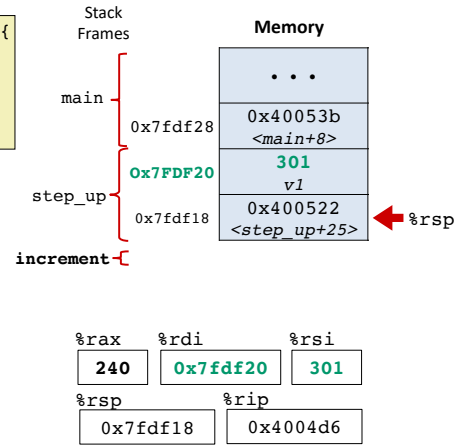
Procedure call example (step 4)

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)

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

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

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

Execute ret

Return from `increment` to `step_up`

Stack Frames		Memory
main		. . .
	0x7fdf28	0x40053b <main+8>
step_up	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 5a)

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

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

(2) jump to return address

ret has two steps

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

Return from `increment` to `step_up`

Stack Frames		Memory
main		. . .
	0x7fdf28	0x40053b <main+8>
step_up	7FDF20	301 v1
	0x7fdf18	0x400522 <step_up+25>

%rsp

(1) pop return address from stack

%rax	%rdi	%rsi
240	0x7fdf20	301

%rsp	%rip
0x7fdf20	0x400522

Procedure call example (step 6)

```
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
```

Prepare `step_up` result

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

%rsp

%rax	%rdi	%rsi
240	0x7fdf20	301

%rsp	%rip
0x7fdf20	0x400526

Procedure call example (step 6)

```
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
```

Prepare `step_up` result

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

%rsp

add

%rax	%rdi	%rsi
541	0x7fdf20	301

%rsp	%rip
0x7fdf20	0x400526

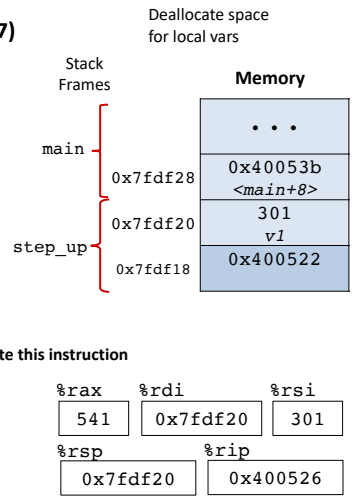
Procedure call example (step 7)

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

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

Execute this instruction

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

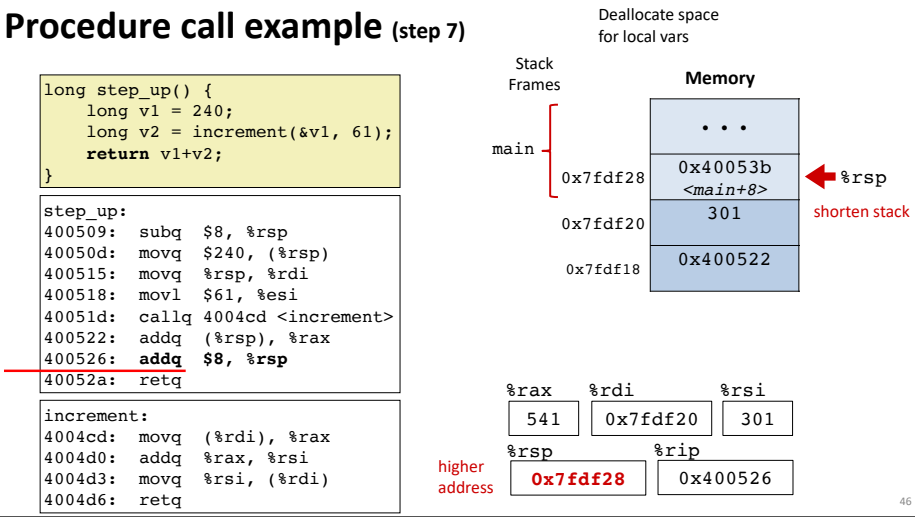


Procedure call example (step 7)

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

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

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

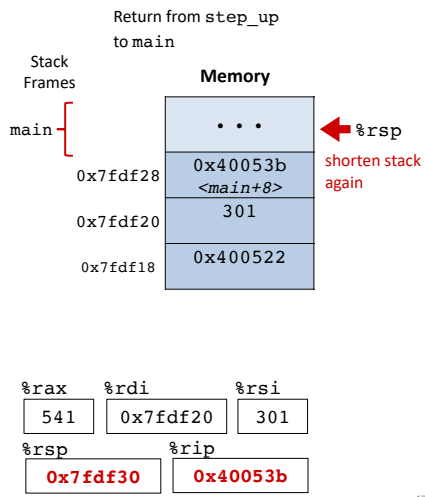


Procedure call example (step 8)

```
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
```



Implementing procedures

Have we now seen how this is done?

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

Register saving conventions

yoo calls who:
Caller ***Callee***

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

Will register contents still be there after a procedure call?

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

?

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

Conventions:

Caller Save

Callee Save

x86-64 register conventions

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

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

Callee-save example (step 0)

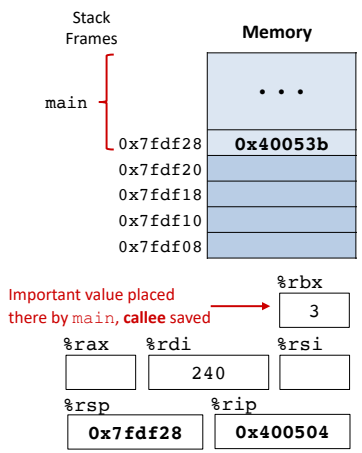
Similar function, but now takes an arg for the local variable

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

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

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

main called step_by(240)



Callee-save example (step 1)

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

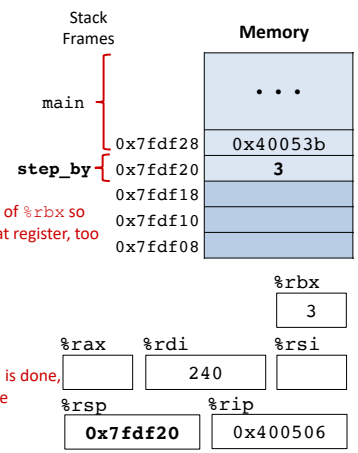
```
step_by:
400504:  pushq %rbx
400506:  movq  %rdi, %rbx
400509:  subq  $16, %rsp
40050d:  movq  %rdi, (%rsp)
400515:  movq  %rsp, %rdi
400518:  movl  $61, %esi
40051d:  callq 4004cd <increment>
400522:  addq  %rbx, %rax
400525:  addq  $16, %rsp
400529:  popq  %rbx
40052b:  retq
```

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

Once this function is done, restore saved value

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

Save register %rbx



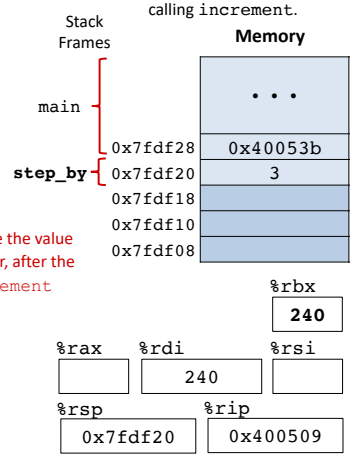
Callee-save example (step 2)

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

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

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

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



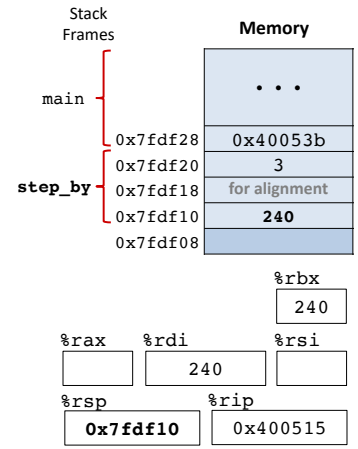
caller saved: %rax, %rdi, %rsi
callee saved: %rbx

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
```

Set up stack frame
Initialize v1



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

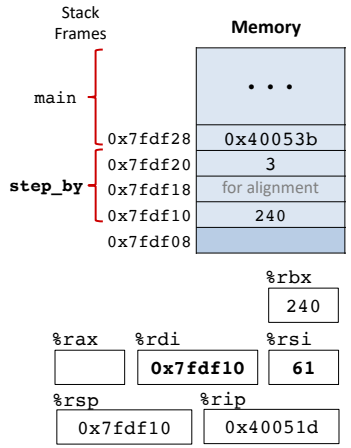
caller saved: %rax, %rdi, %rsi
callee saved: %rbx

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
```

Set up arguments



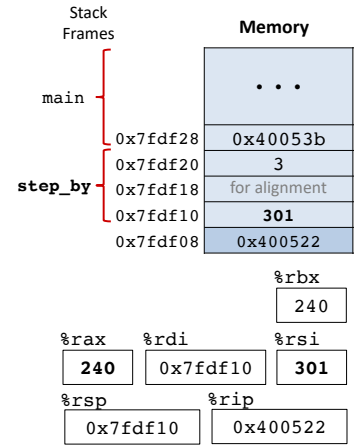
caller saved: %rax, %rdi, %rsi
callee saved: %rbx

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
```

Call, execute, and return from increment



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

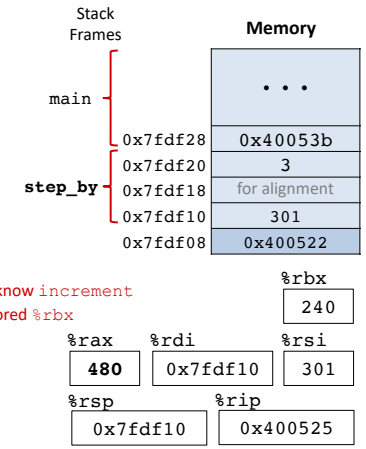
Callee-save example (step 6)

```
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`

Prepare return value



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

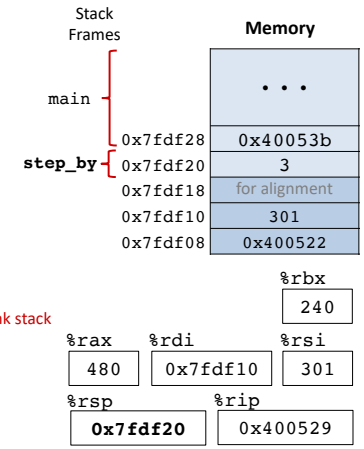
Callee-save example (step 7)

```
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

Clean up stack frame



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

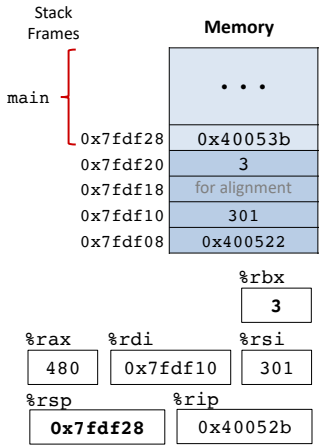
Callee-save example (step 8)

```
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`

Restore register `%rbx`
Ready to return



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

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
```

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

		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

		Memory
main	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

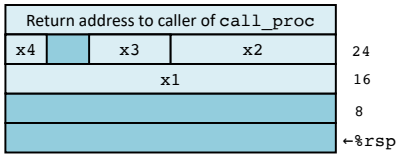
←%rsp

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
  • • •
```

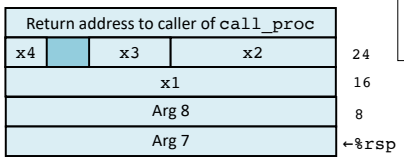


Stack storage example
(3) setup args to proc

optional

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

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



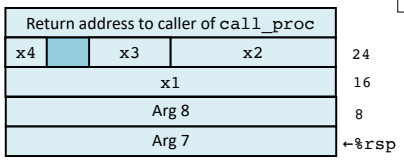
Arguments passed in (in order):
`%rdi, %rsi, %rdx, %rcx, %r8, %r9`

Stack storage example
(4) after call to proc

optional

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

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

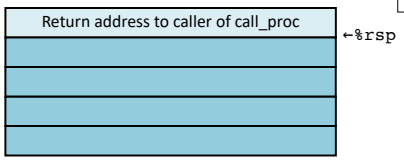


Stack storage example
(5) deallocate local vars

optional

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

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



Procedure Summary

`call, ret, push, pop`

Stack discipline fits procedure call / return.*

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

Conventions support arbitrary function calls.

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

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

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