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

Why procedures?

Why functions? Why methods?

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

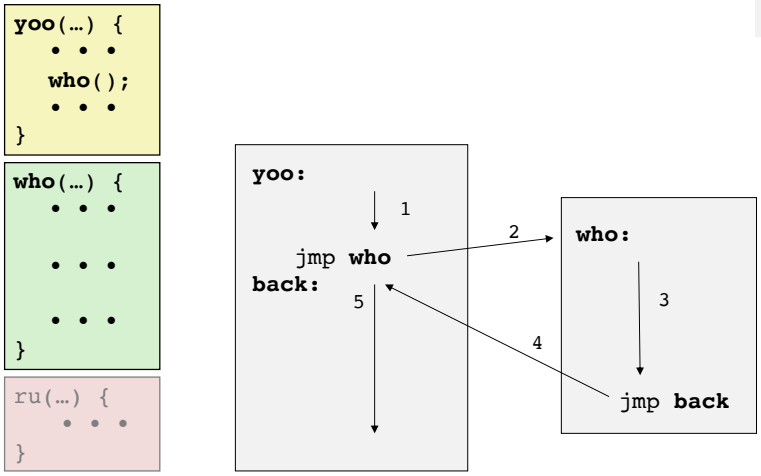
Procedural Abstraction

Implementing procedures

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

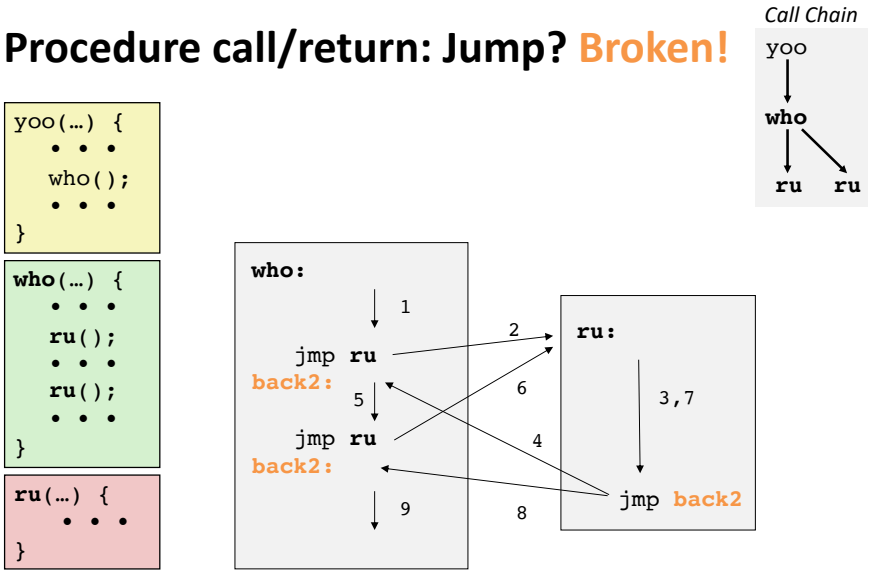
Procedure call/return: Jump?

Call Chain



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.

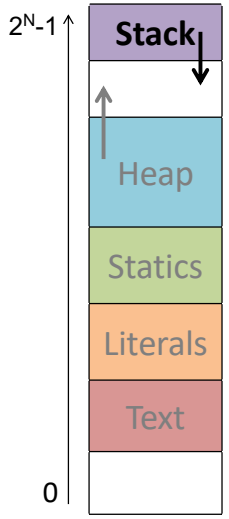
Implementing procedures

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

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

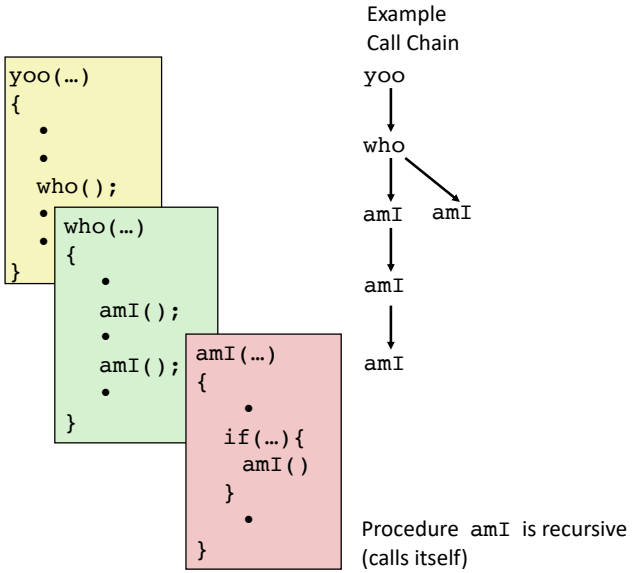
Memory Layout

reminder



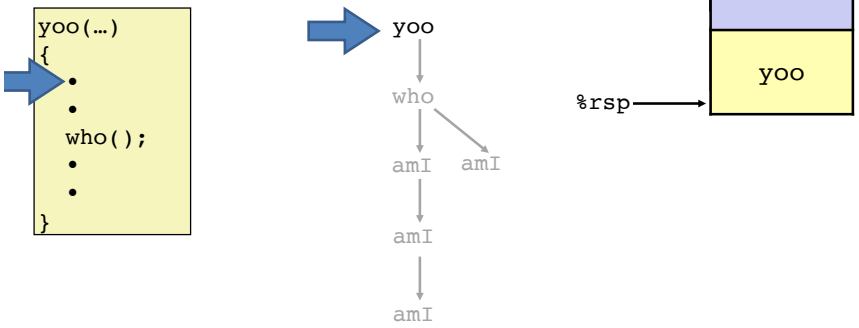
Perm	Contents	Managed by	Initialized
RW	**Procedure context**	**Compiler**	**Run-time**
RW	Dynamic data structures	Programmer, malloc/free, new/GC	Run-time
RW	Global variables/ static data structures	Compiler/ Assembler/Linker	Startup
R	String literals	Compiler/ Assembler/Linker	Startup
X	Instructions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

Call stack tracks context

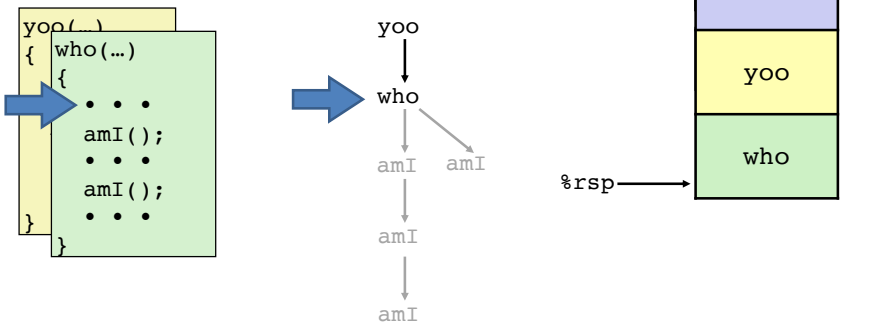


Procedure `amI` is recursive (calls itself)

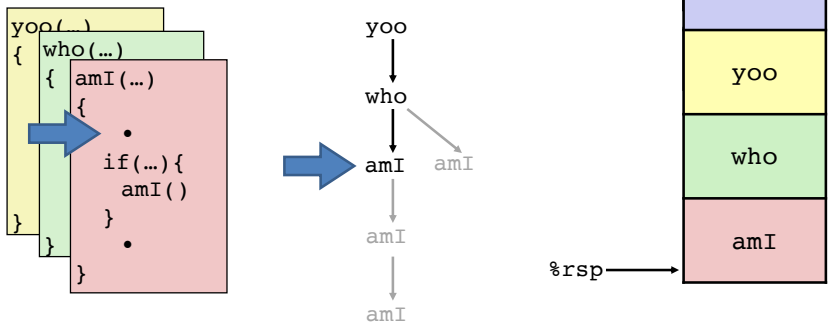
Call stack tracks context



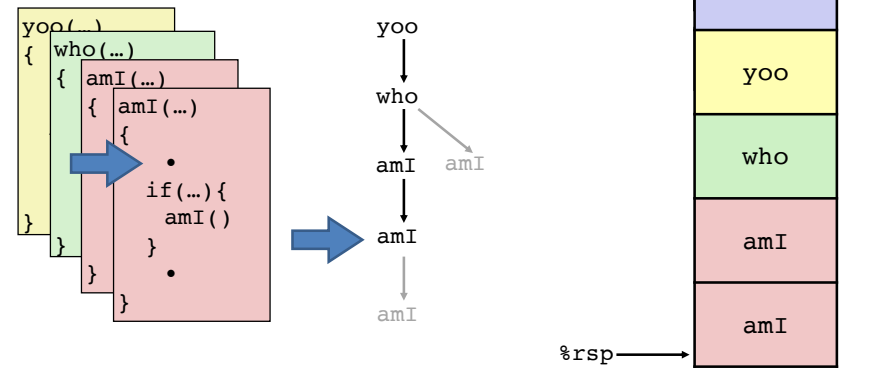
Call stack tracks context



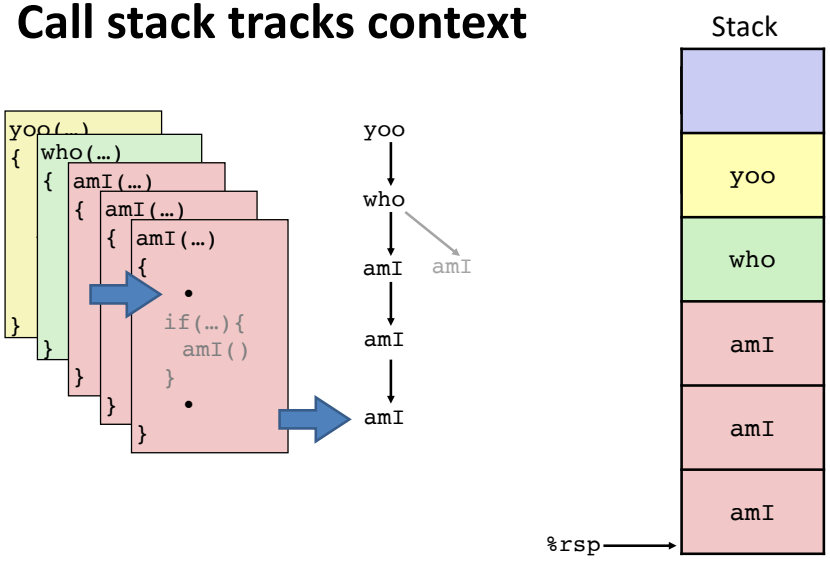
Call stack tracks context



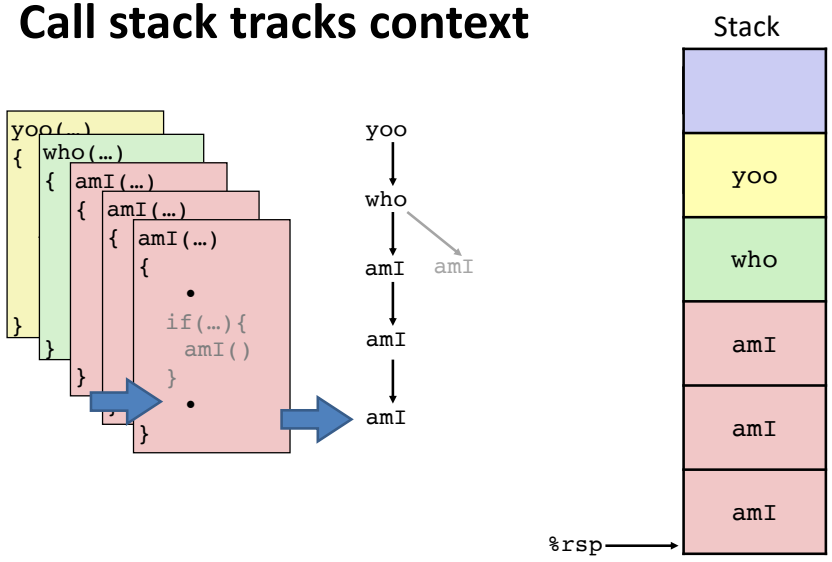
Call stack tracks context



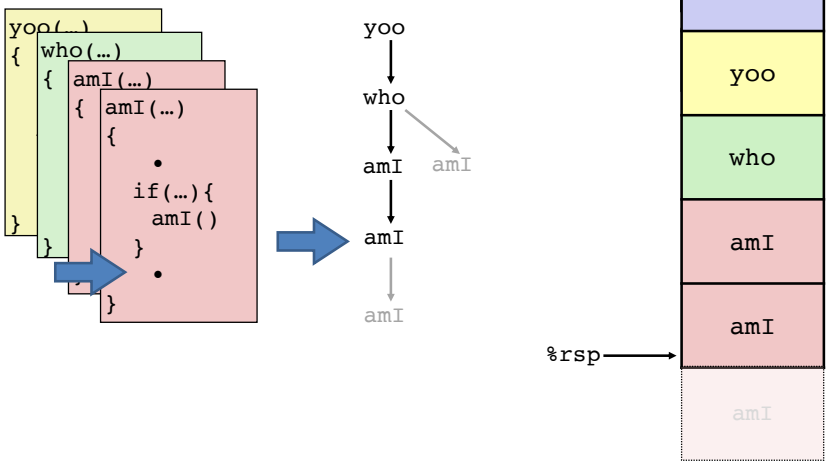
Call stack tracks context



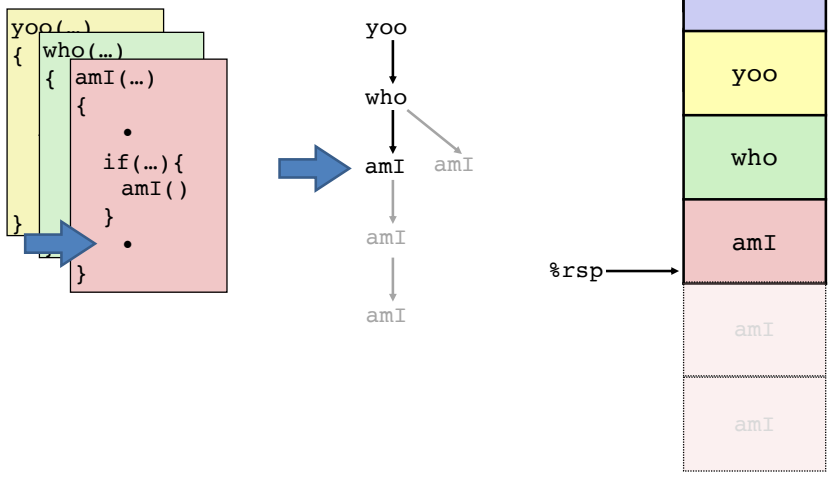
Call stack tracks context



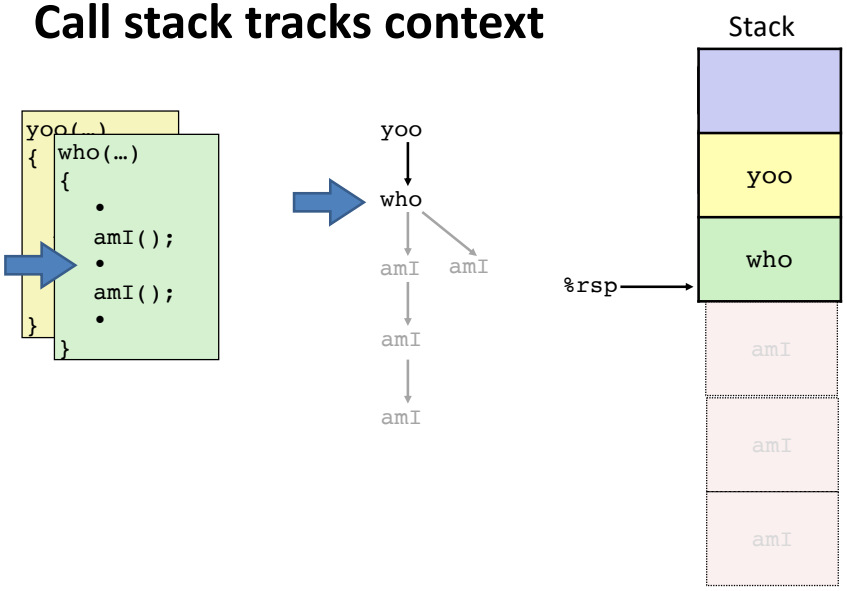
Call stack tracks context



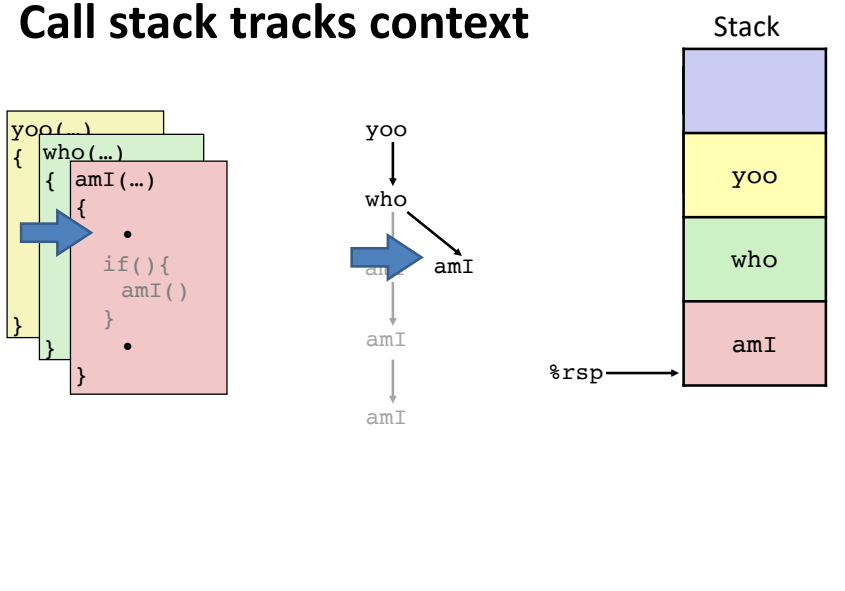
Call stack tracks context



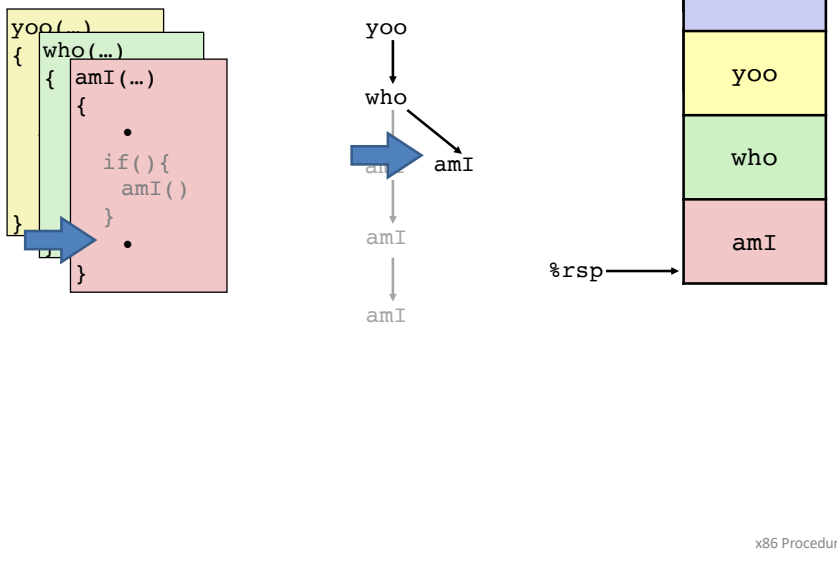
Call stack tracks context



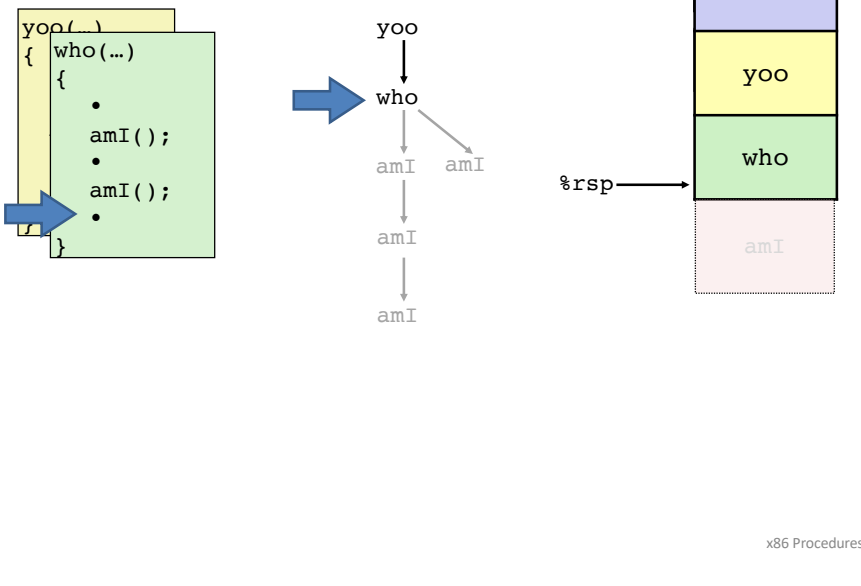
Call stack tracks context



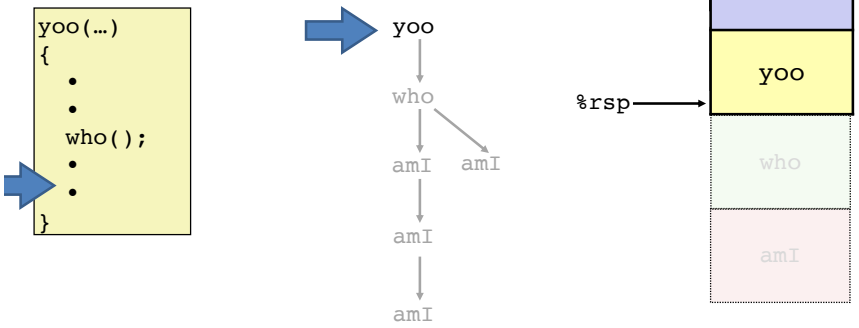
Call stack tracks context



Call stack tracks context



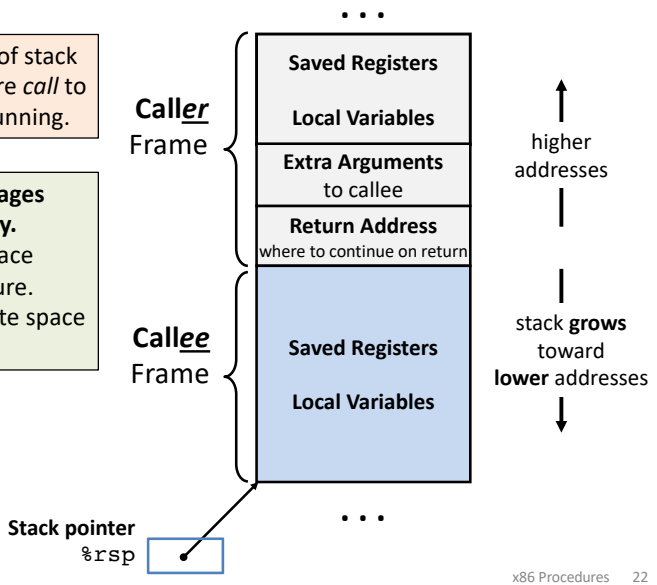
Call stack tracks context



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`

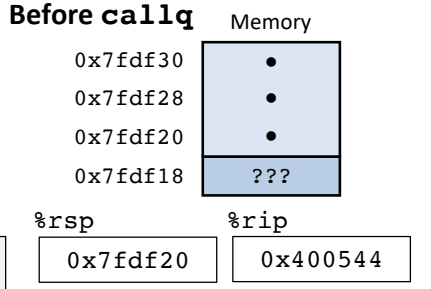
1. Pop return address from stack
2. Jump to return address

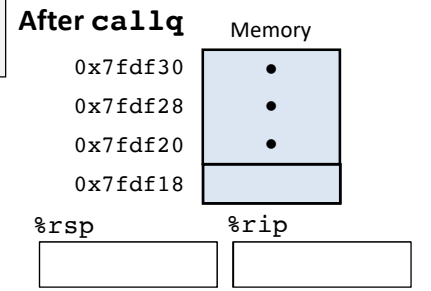
Call example

```
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*





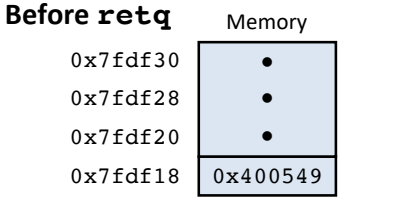
Return example

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

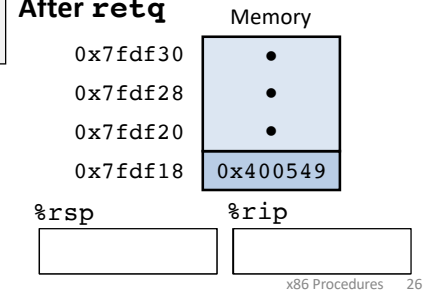
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```

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

Before `retq`



After `retq`



Procedure data flow conventions

First 6 arguments:
passed in **registers**

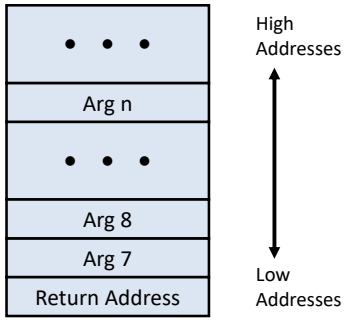
Arg 1	%rdi
Arg 2	%rsi
Arg 3	%rdx
Arg 4	%rcx
Arg 5	%r8
Arg 6	%r9

Diane's Silk Dress Costs $8 9

Return value:
passed in `%rax`

%rax

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



Allocate stack space for arguments only when needed.

`callq` puzzle

optional

```
    callq next
next:
    popq %rax
```

What gets stored into %rax?

Why is there no `ret` instruction corresponding to the `call`?

What does this code do? (Hint: unusual use of `call`.)

Procedure data flow puzzle

ex

C function body:

```
_____ huh(_____ _, _____ _, _____ _, _____ _) {
    *p = d;
    return x - c;
}
```

Translated to x86 assembly:

```
huh:
  movsbl %dl,  %edx
  movl   %edx, (%rsi)
  movswl %di,  %edi
  subl   %edi, %ecx
  movl   %ecx, %eax
  retq
```

Reverse engineer the x86 `huh` procedure and the body of the C `huh` function to fill blanks in the C `huh` function header with:
- the parameter types / order; and
- the return type.

`movsbl` = **move** **s**ign-extending a **b**yte to a **l**ong (4-byte)
`movswl` = **move** **s**ign-extending a **w**ord (2-byte) to a **l**ong (4-byte)

Procedure data flow puzzle

ex

C function body:

```
int  huh(short c, int* p, char d, int  x) {
    *p = d;
    return x - c;
}
```

Translated to x86 assembly:

```
huh:
  movsbl %dl,  %edx
  movl   %edx, (%rsi)
  movswl %di,  %edi
  subl   %edi, %ecx
  movl   %ecx, %eax
  retq
```

Reverse engineer the x86 `huh` procedure and the body of the C `huh` function to fill blanks in the C `huh` function header with:

- the parameter types / order; and
- the return type.

`movsbl` = **mov**e **s**ign-extending a **b**yte to a **l**ong (4-byte)
`movswl` = **mov**e **s**ign-extending a **w**ord (2-byte) to a **l**ong (4-byte)

Procedure call / stack frame example

```
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
```

Passes address of local variable (in stack).

Uses memory through pointer.

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

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

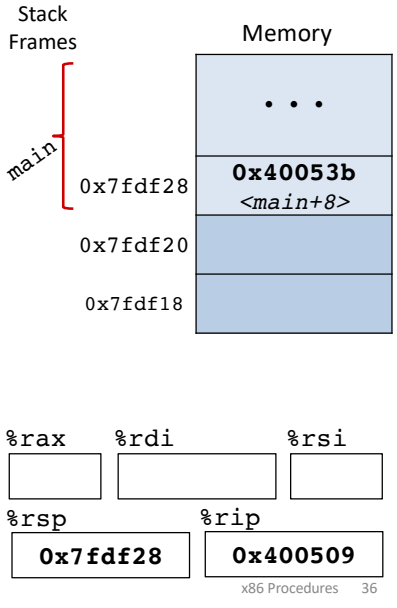

Procedure call example (step 0)

`main` called `step_up`

```
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
```



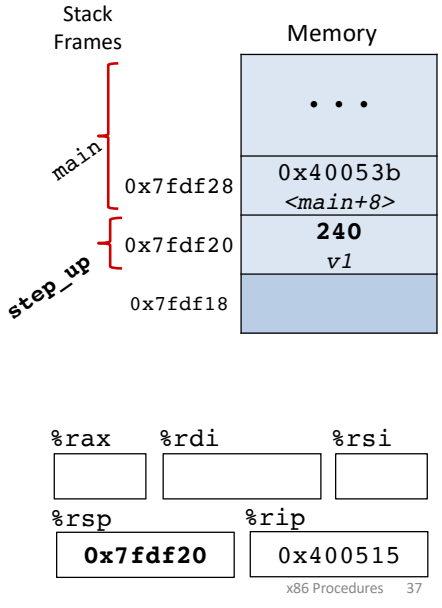
Procedure call example (step 1)

Allocate space for local vars

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

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

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



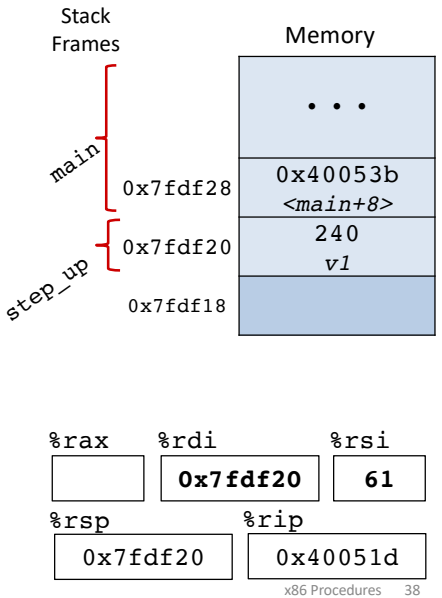
Procedure call example (step 2)

Set up args for call to `increment`

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

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

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



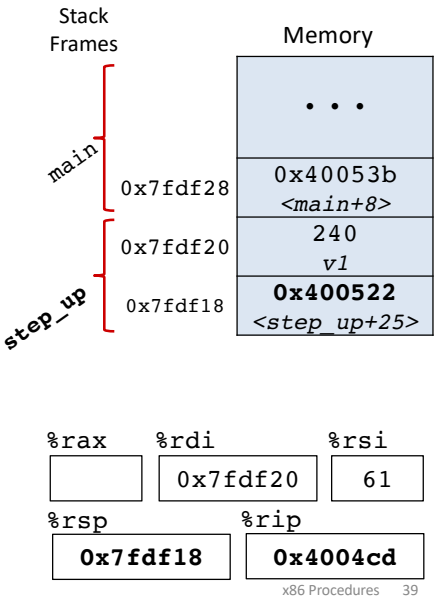
Procedure call example (step 3)

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
```



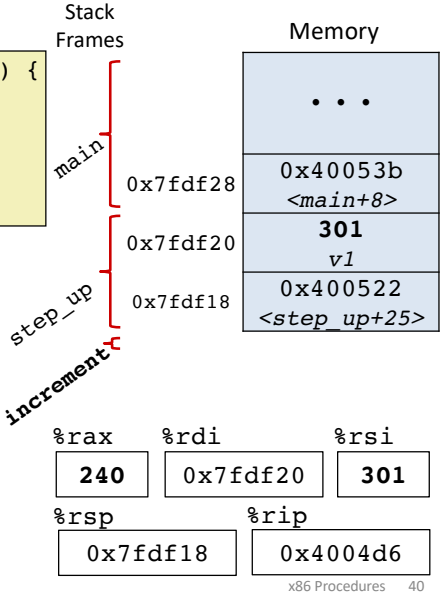
Procedure call example (step 4)

Run `increment`

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

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

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



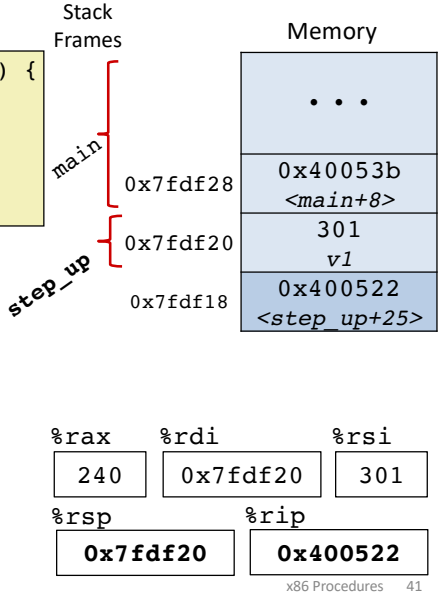
Procedure call example (step 5a)

Return from `increment` to `step_up`

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

```
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
```



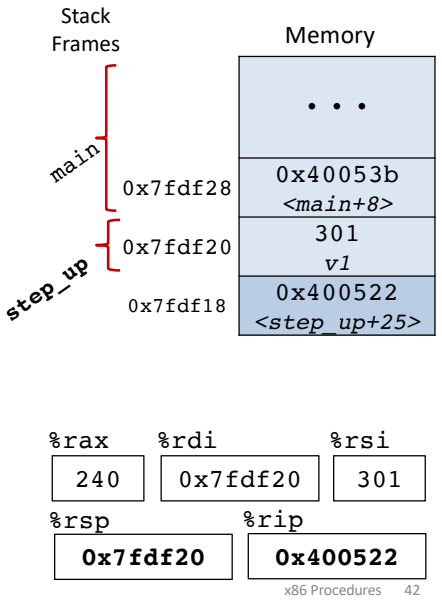
Procedure call example (step 5b)

Return from `increment` to `step_up`

```
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
```



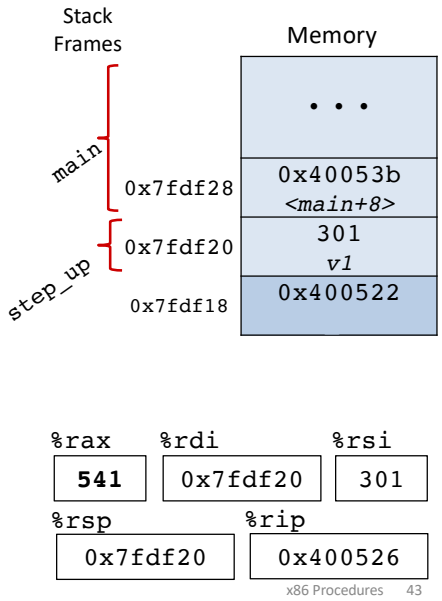
Procedure call example (step 6)

Prepare `step_up` result

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

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

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



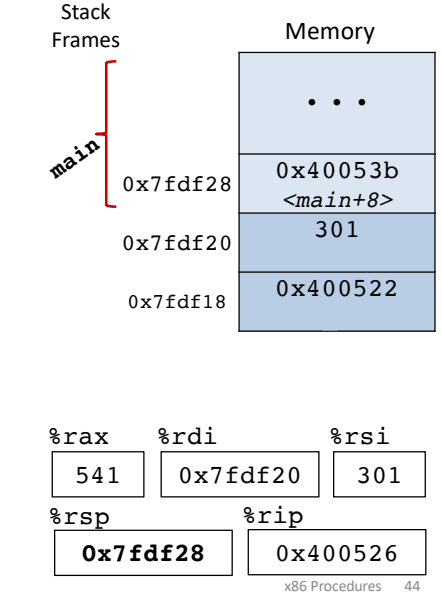
Procedure call example (step 7)

Deallocate space for local vars

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

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

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



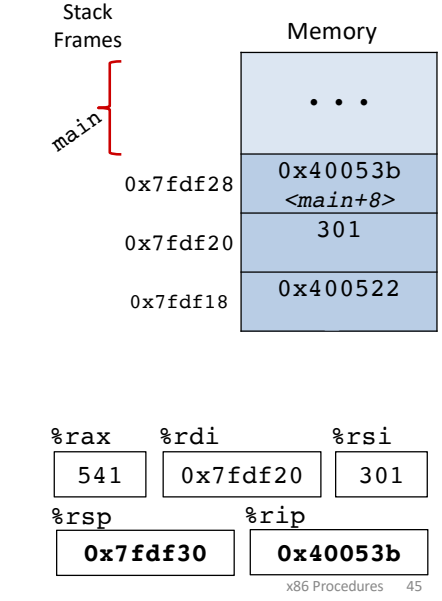
Procedure call example (step 8)

Return from `step_up` to `main`

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

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

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



Implementing procedures

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

Register saving conventions

yoo calls who:

Caller ***Callee***

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

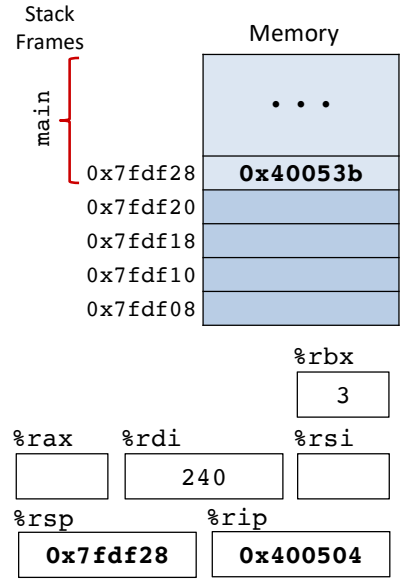
%rax	Return value – Caller saved	%r8	Argument #5 – Caller saved
%rbx	**Callee** saved	%r9	Argument #6 – Caller saved
%rcx	Argument #4 – Caller saved	%r10	Caller saved
%rdx	Argument #3 – Caller saved	%r11	Caller Saved
%rsi	Argument #2 – Caller saved	%r12	**Callee** saved
%rdi	Argument #1 – Caller saved	%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)`

```
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
```

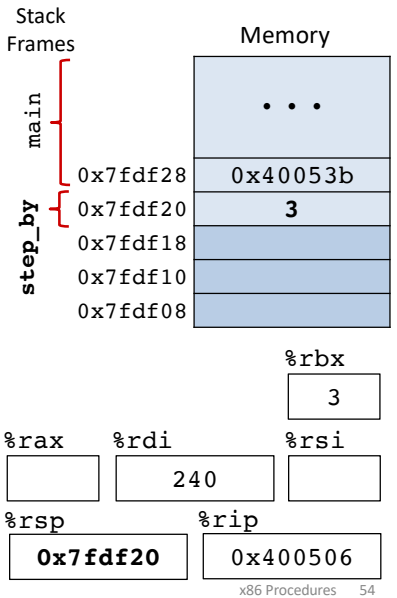


Callee-save example (step 1)

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
```

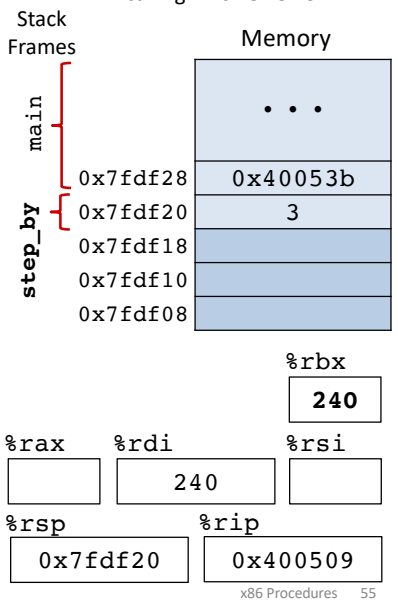


Callee-save example (step 2)

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
```

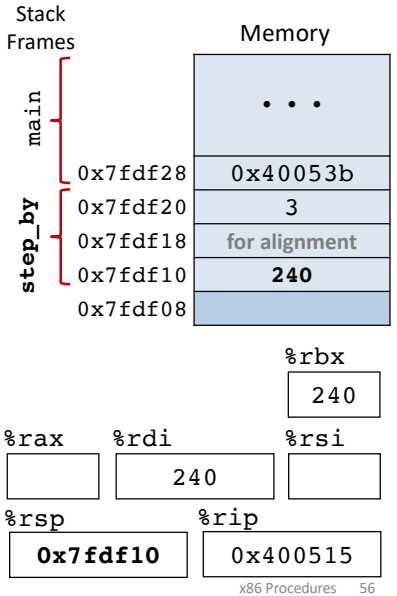


Callee-save example (step 3)

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
```

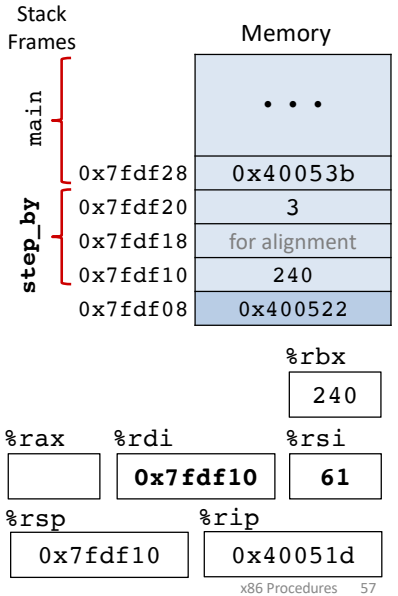


Callee-save example (step 4)

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
```

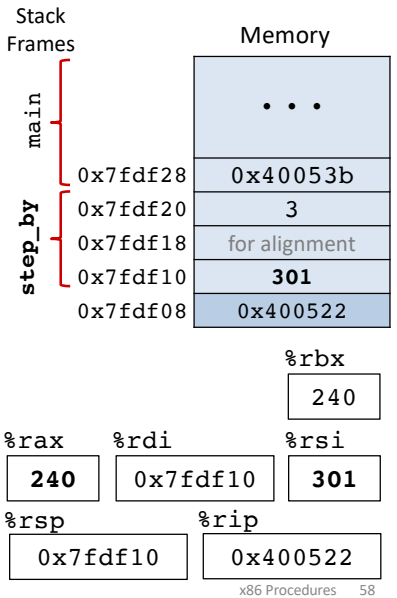


Callee-save example (step 5)

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
```

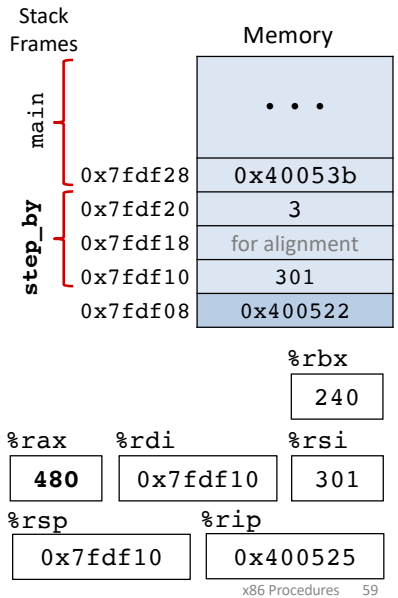


Callee-save example (step 6)

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
```

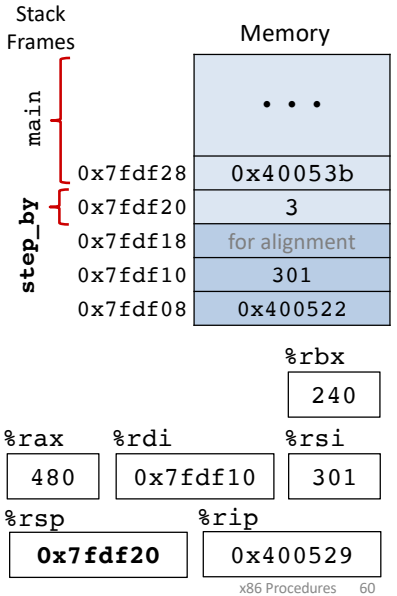


Callee-save example (step 7)

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
```

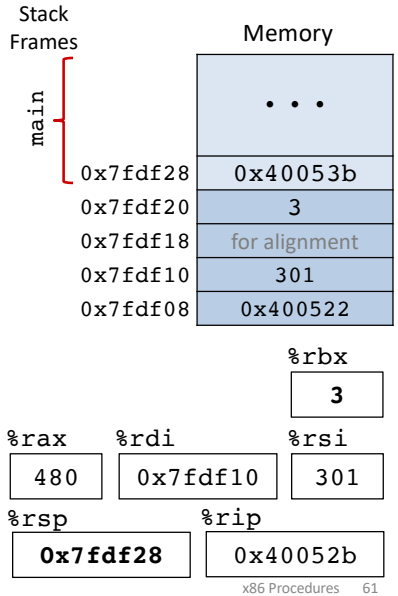


Callee-save example (step 8)

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
```



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
0	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	

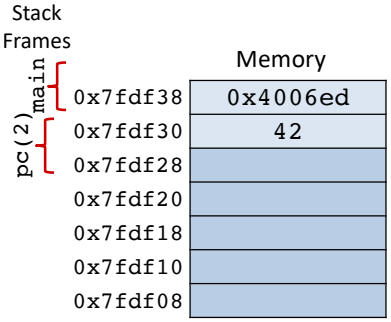
%rax	%rdi	%rbx
0	2	2

%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
```



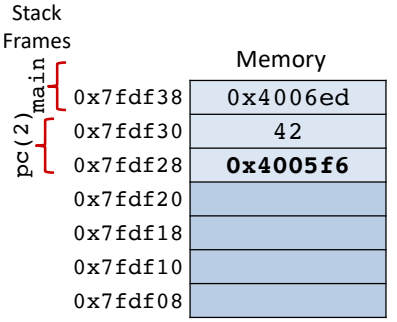
%rax	%rdi	%rbx
0	**1**	**0**

%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
```



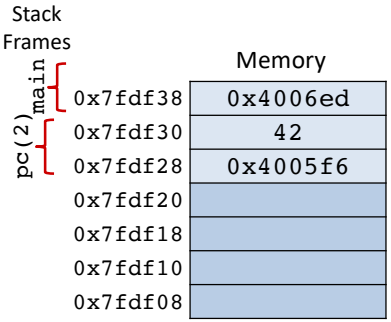
%rax	%rdi	%rbx
0	1	0

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

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

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

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



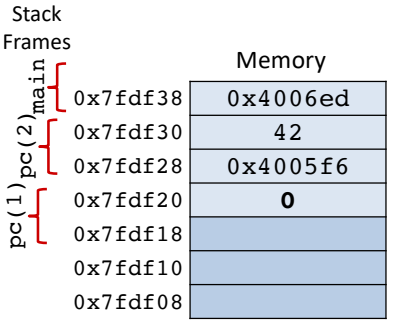
%rax	%rdi	%rbx
0	1	0

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

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

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

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



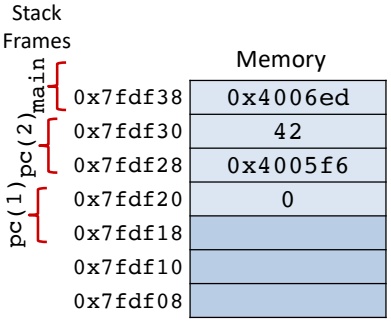
%rax	%rdi	%rbx
0	1	**1**

%rsp	%rip
0x7fdf20	0x4005eb

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

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

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



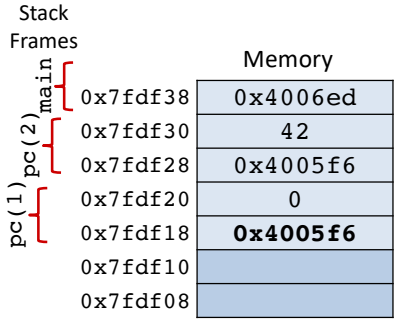
%rax	%rdi	%rbx
0	**0**	**1**

%rsp	%rip
0x7fdf20	0x4005f1

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

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

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



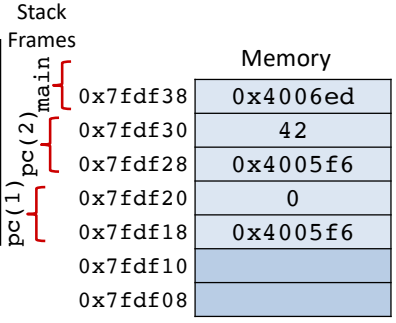
%rax	%rdi	%rbx
0	0	1

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

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

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

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



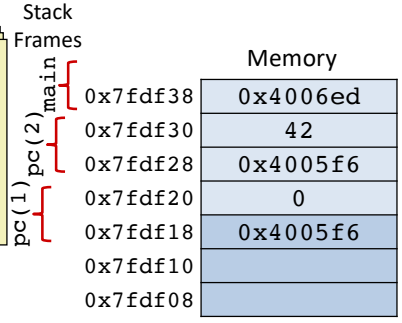
%rax	%rdi	%rbx
0	0	1

%rsp	%rip
0x7fdf18	**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
```



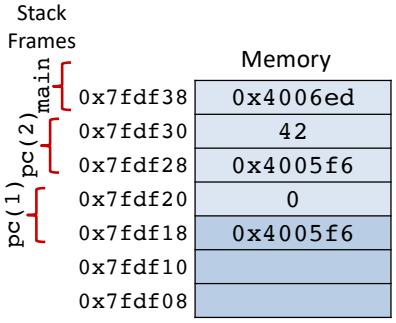
%rax	%rdi	%rbx
0	0	1

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

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

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

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



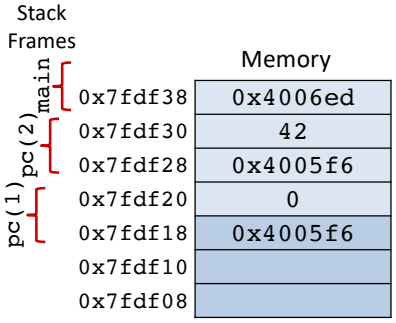
%rax	%rdi	%rbx
0	0	1

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

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

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

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



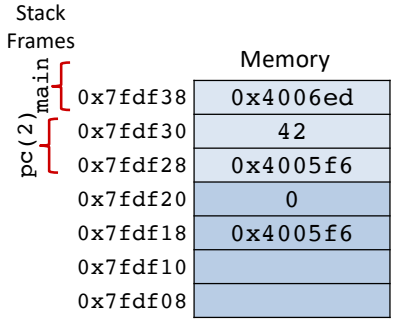
%rax	%rdi	%rbx
1	0	1

%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
```



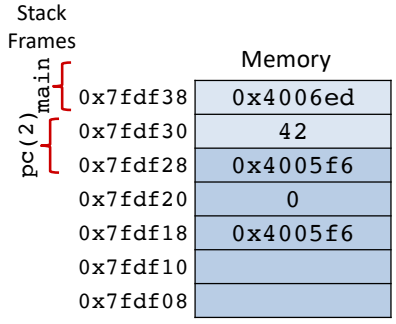
%rax	%rdi	%rbx
1	0	**0**

%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
```



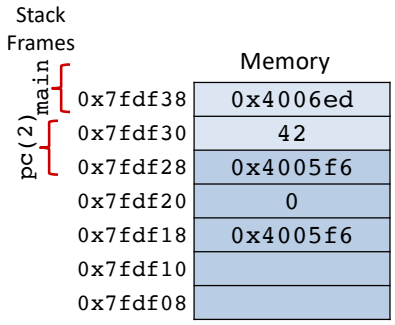
%rax	%rdi	%rbx
1	0	0

%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
```



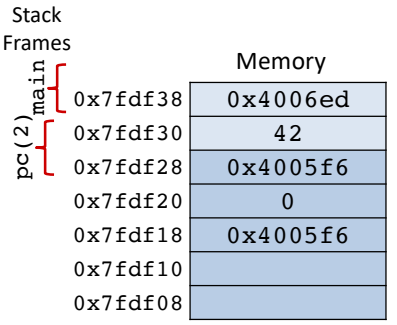
%rax	%rdi	%rbx
1	0	0

%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
```



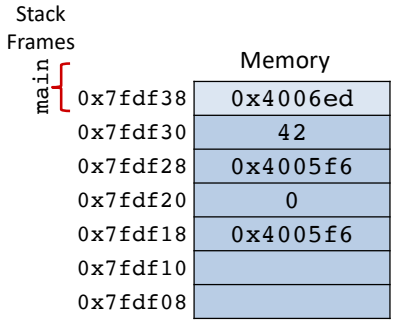
%rax	%rdi	%rbx
1	0	0

%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
```



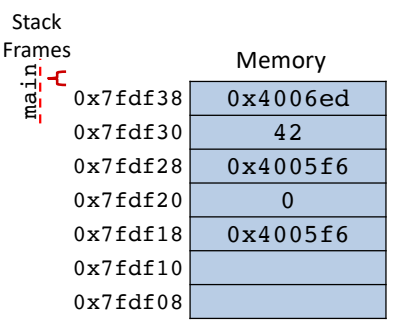
%rax	%rdi	%rbx
1	0	**42**

%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
```



%rax	%rdi	%rbx
1	0	42

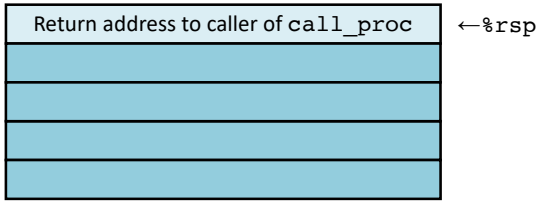
%rsp	%rip
0x7fdf40	**0x4006ed**

Stack storage example (1)

optional

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

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

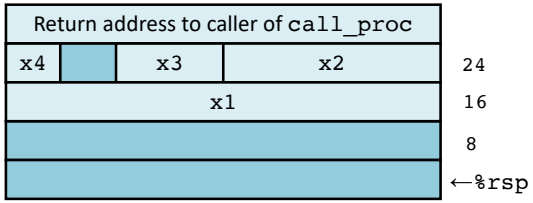


Stack storage example (2) Allocate local vars

optional

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

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

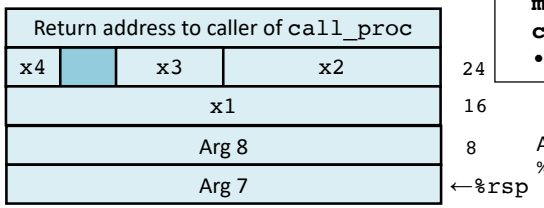


Stack storage example (3) setup args to proc

optional

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

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



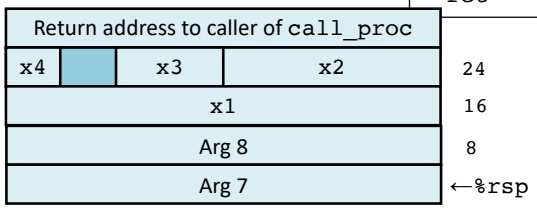
Arguments passed in (in order):
%rdi, %rsi, %rdx, %rcx, %r8, %r9

Stack storage example (4) after call to proc

optional

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

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



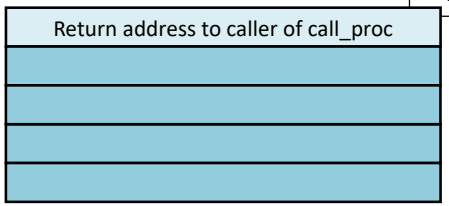
Stack storage example

optional

(5) deallocate local vars

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

```
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
```



←%rsp

Procedure Summary

call, ret, push, pop

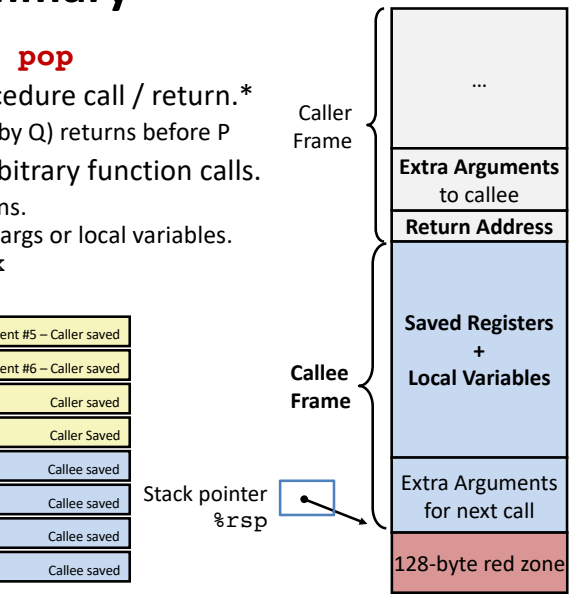
Stack discipline fits procedure call / return.*

- 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



*Take CS 251 to learn about languages where a simple stack does not suffice.