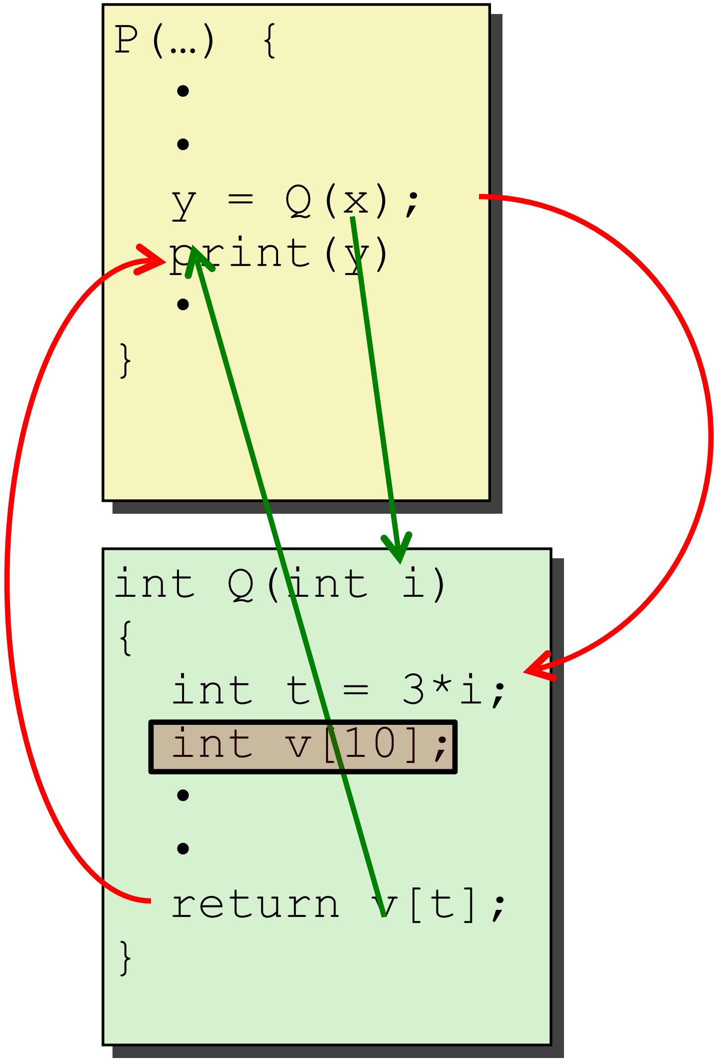
Procedures

+ Mechanisms in Procedures

- **Passing control**
  - To beginning of procedure code
  - Back to return point
- **Passing data**
  - Procedure arguments
  - Return value
- **Memory management**
  - Allocate during procedure execution
  - Deallocate upon return
- **Mechanisms all implemented with machine instructions**
- **x86-64 implementation of a procedure uses only those mechanisms required**

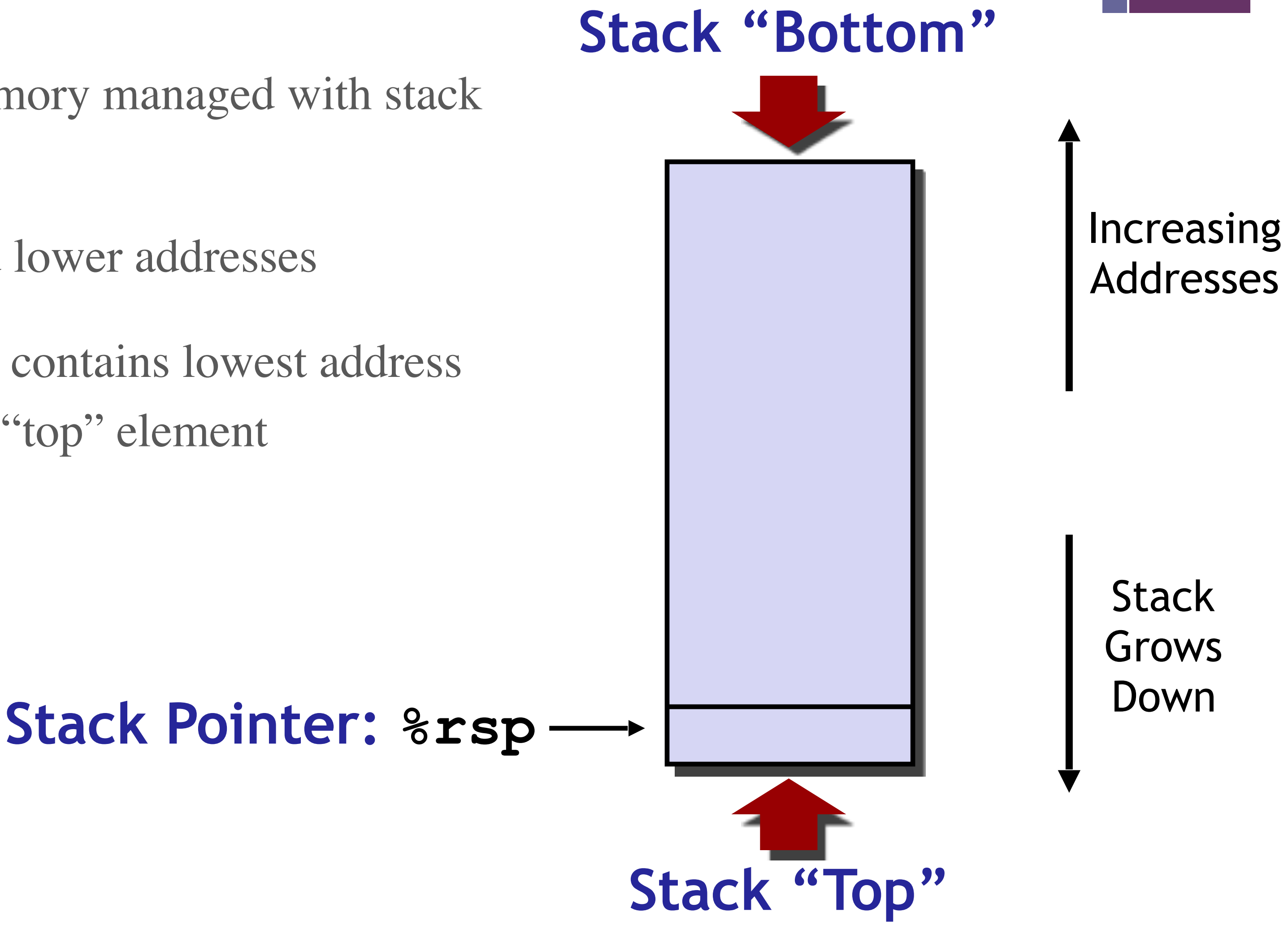


```
P(…) {
  •
  •
  y = Q(x);
  print(y)
  •
}
```

```
int Q(int i)
{
  int t = 3*i;
  int v[10];
  •
  •
  return v[t];
}
```

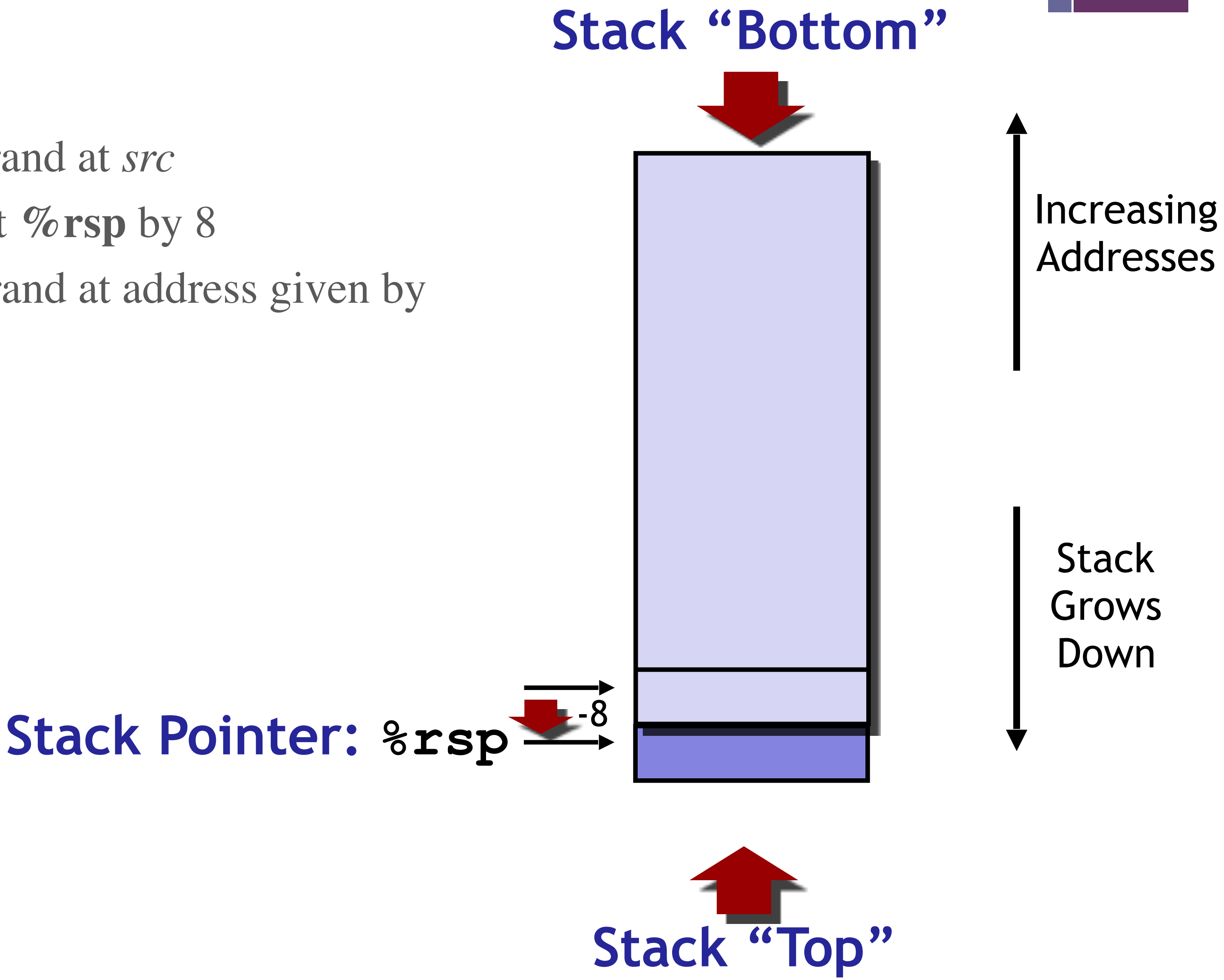
+ x86-64 Stack

- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register %rsp contains lowest address
  - address of “top” element



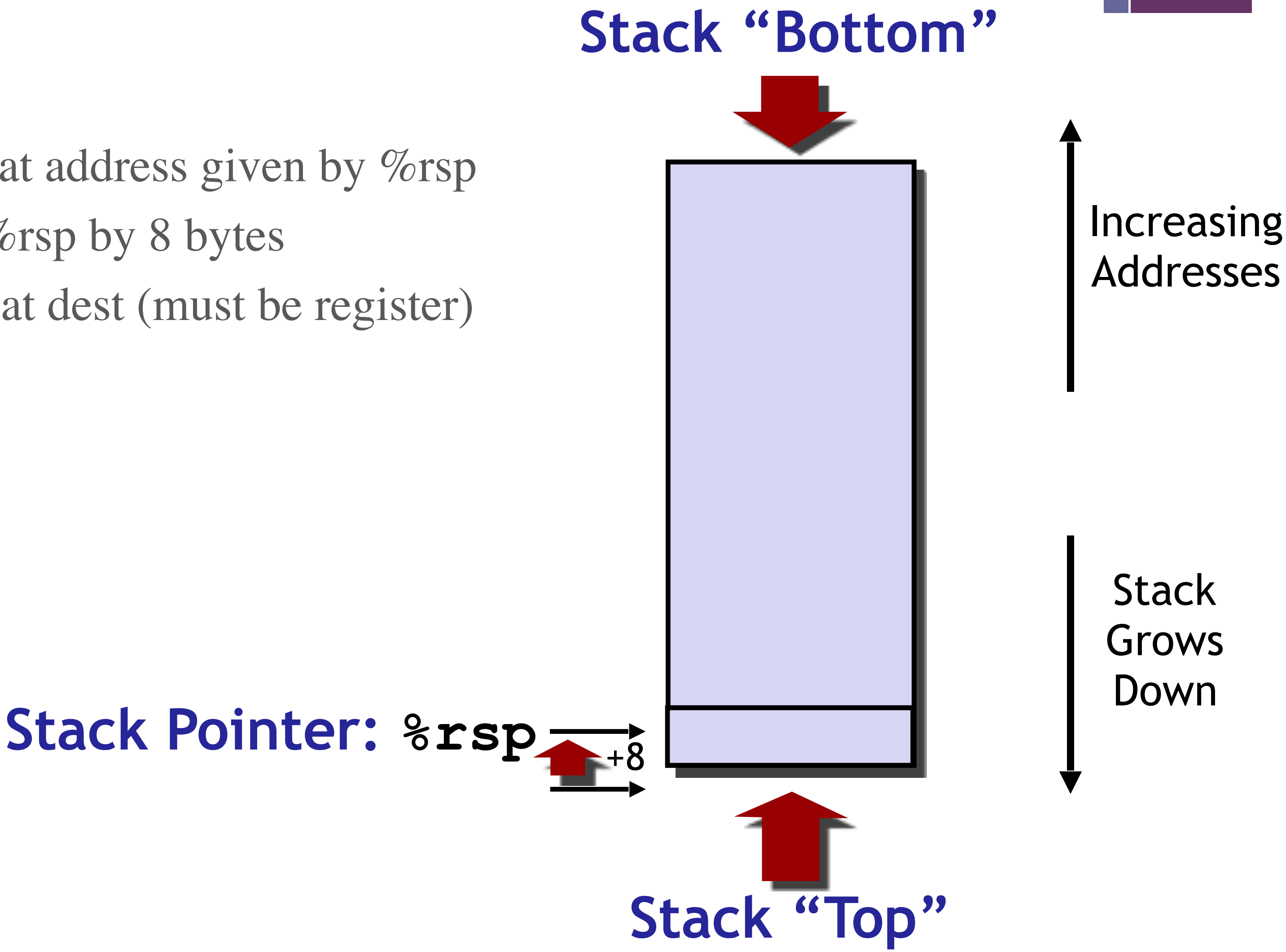
+ x86-64 Stack: Push

- **`pushq`** *src*
  - Fetch operand at *src*
  - Decrement %**rsp** by 8
  - Write operand at address given by %**rsp**



+ x86-64 Stack: Pop

- `popq` *dest*
  - Read value at address given by %rsp
  - Increment %rsp by 8 bytes
  - Store value at dest (must be register)



+

Passing Control

Code Examples

```
void multstore (long x, long y, long *dest){
    long t = mult2(x, y);
    *dest = t;
}
```

```
0000000000400540 <multstore>:
  400540: push   %rbx              # Save %rbx
  400541: mov    %rdx,%rbx         # Save dest
  400544: callq  400550 <mult2> # mult2(x,y)
  400549: mov    %rax,(%rbx)       # Save at dest
  40054c: pop    %rbx              # Restore %rbx
  40054d: retq                     # Return
```

```
long mult2(long a, long b){
  long s = a * b;
  return s;
}
```

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax  # a
  400553:  imul   %rsi,%rax  # a * b
  400557:  retq              # return
```

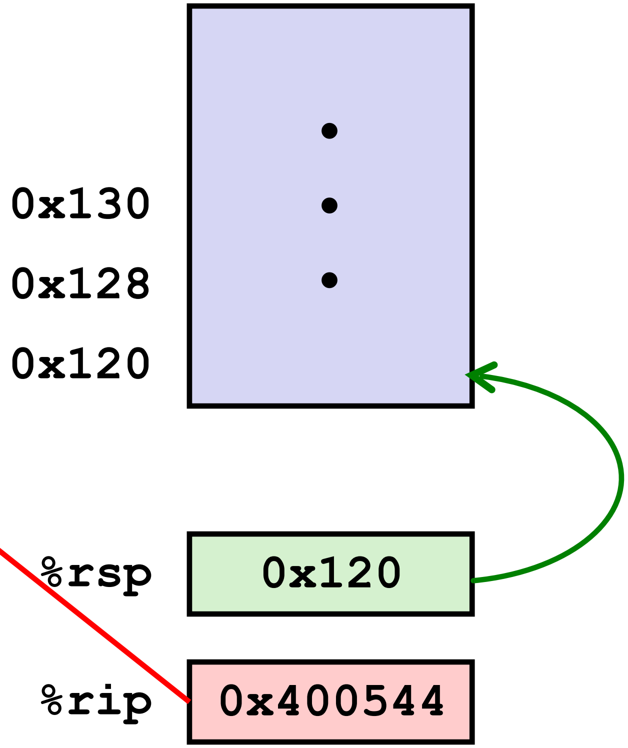
+ Procedure Control Flow

- Use stack to support procedure call and return
- **Procedure `call` with label**
  - Pushes ***return address*** on stack
    - Address of the next instruction right after call
  - Jumps to ***label***
- **Procedure return: `ret`**
  - Pops ***return address*** from stack
  - Jumps to ***return address***

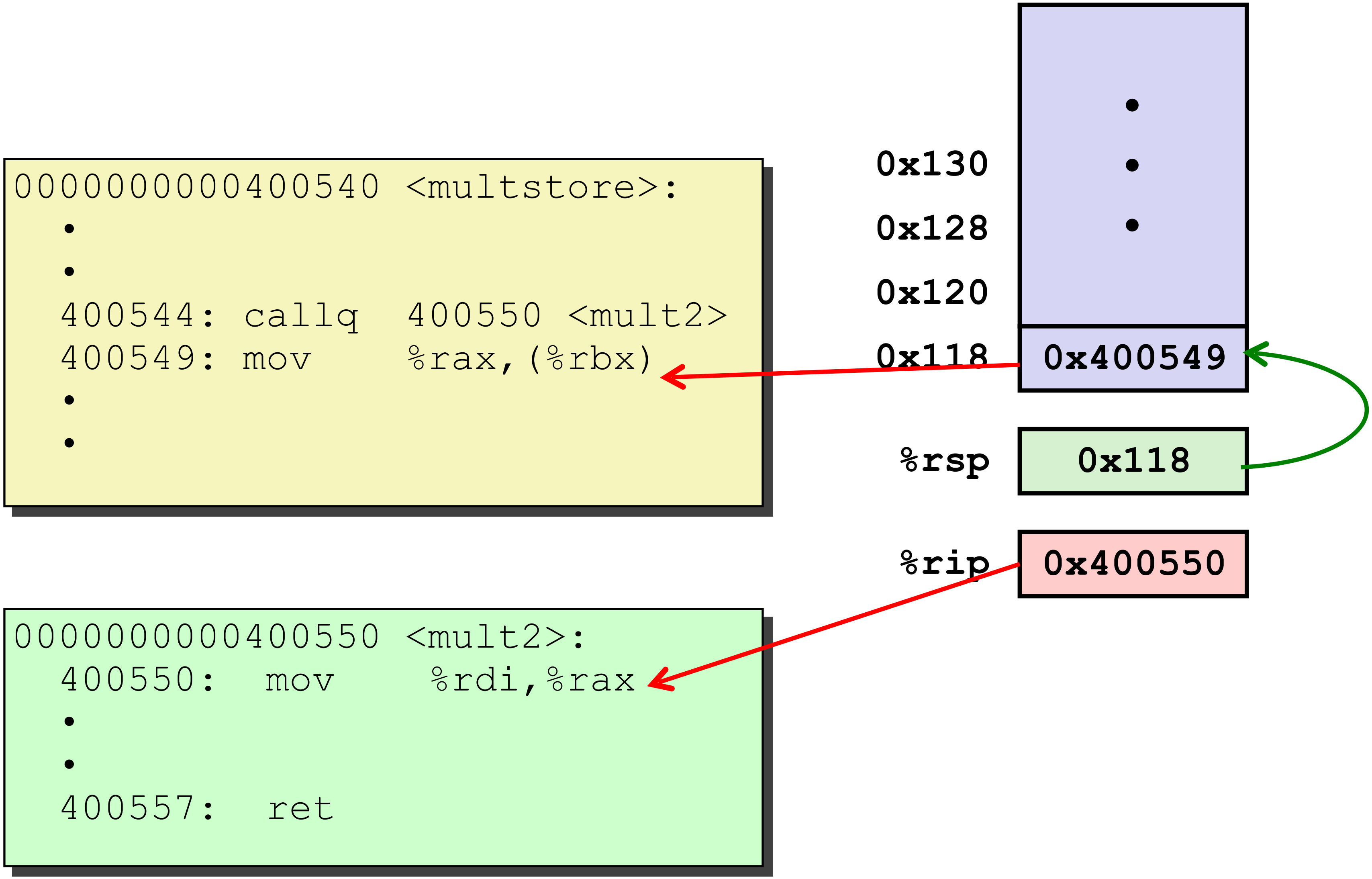
Control Flow Example #1

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

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



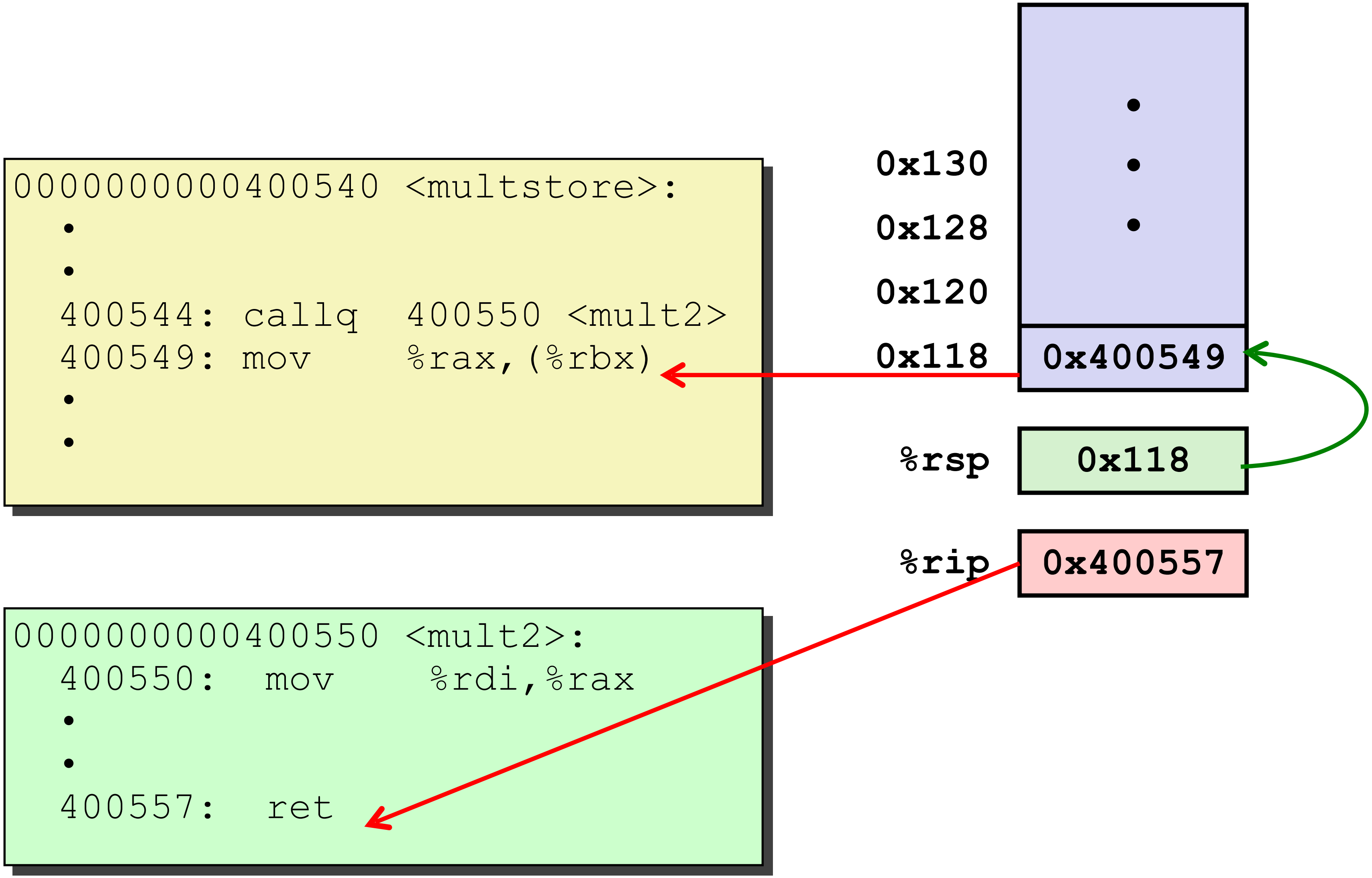
Control Flow Example #2



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

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

Control Flow Example #3



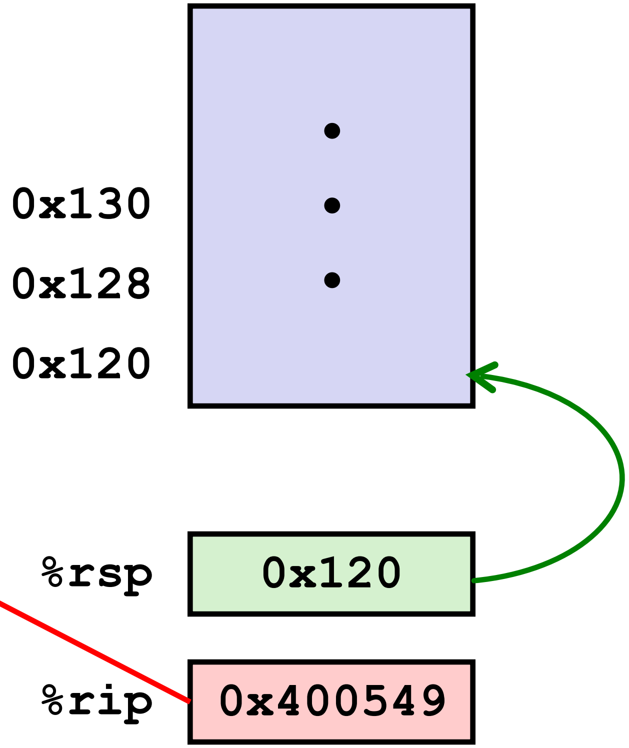
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

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

Control Flow Example #4

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

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



Passing Data

+ Procedure Data Flow

Registers

First 6 arguments

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

Return value

`%rax`

Stack

• • •

Arg *n*

• • •

Arg 8

Arg 7

- Only allocate stack space when needed

+ Data Flow Examples

```
void multstore (long x, long y, long *dest){
    long t = mult2(x, y);
    *dest = t;
}
```

```
0000000000400540 <multstore>:
  # x in %rdi, y in %rsi, dest in %rdx
  • • •
  400541: mov    %rdx,%rbx         # Save dest
  400544: callq  400550 <mult2>    # mult2(x,y)
  # t in %rax
  400549: mov    %rax,(%rbx)       # Save at dest
  • • •
```

```
long mult2(long a, long b){
  long s = a * b;
  return s;
}
```

```
0000000000400550 <mult2>:
  # a in %rdi, b in %rsi
  400550:  mov     %rdi,%rax   # a
  400553:  imul    %rsi,%rax   # a * b
  # s in %rax
  400557:  ret                 # return
```

+

Managing Local Data

+ Stack Frames

- **Functions have “instantiations”**
  - Every function call is a distinct execution with distinct data.
  - Need some place to store state of each instantiation
    - Arguments
    - Local variables
    - Return pointer (next instruction in caller)

- **Stack allocated in *frames***
  - State for single procedure instantiation
  - Moreover, an allocation of memory holding all the data for some function call.

- **Recursion**
  - Supported by this idea of *instantiation* and *stack discipline*.

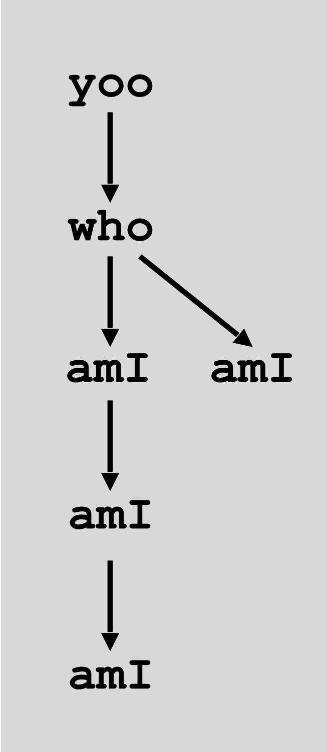
+ Call Chain Example

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

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

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

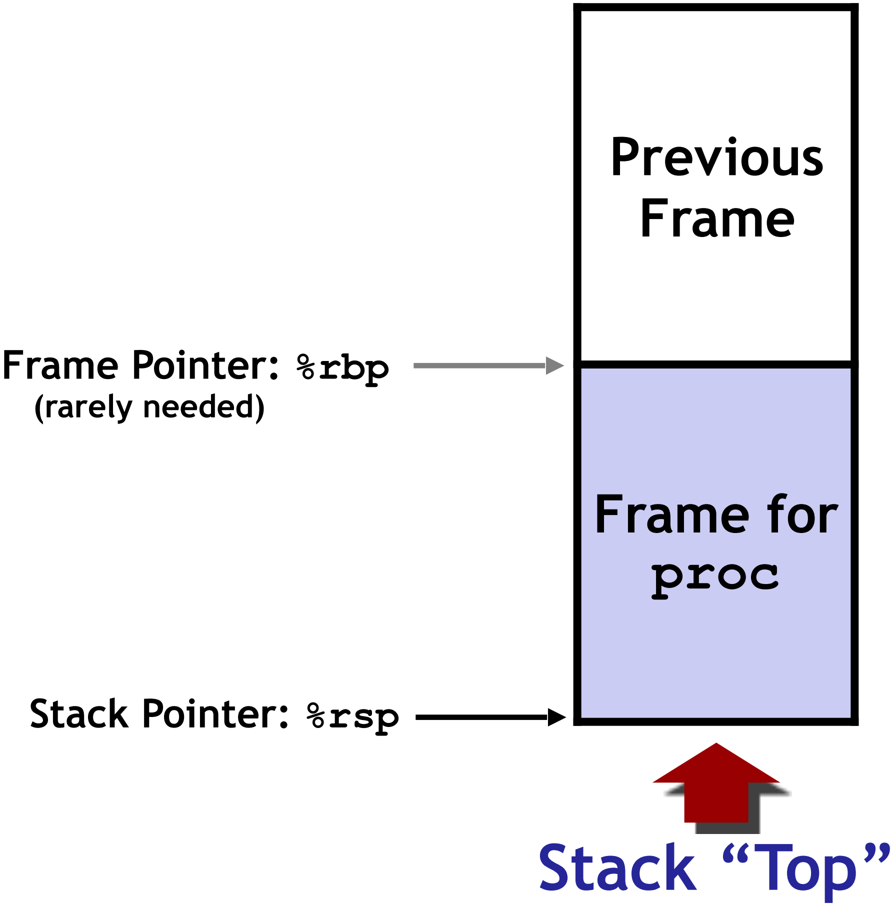
Example Call Chain



Procedure `amI()` is recursive

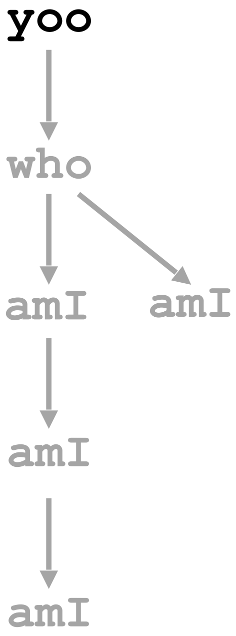
+ Stack Frames

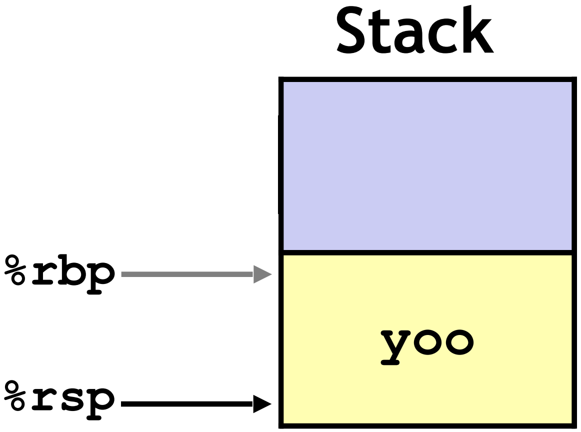
- **Contents**
  - Return information
  - Local storage (if needed)
- **Management**
  - Space allocated on procedure call
    - push by **`call`** instruction
  - Space deallocated on return
    - pop by **`ret`** instruction



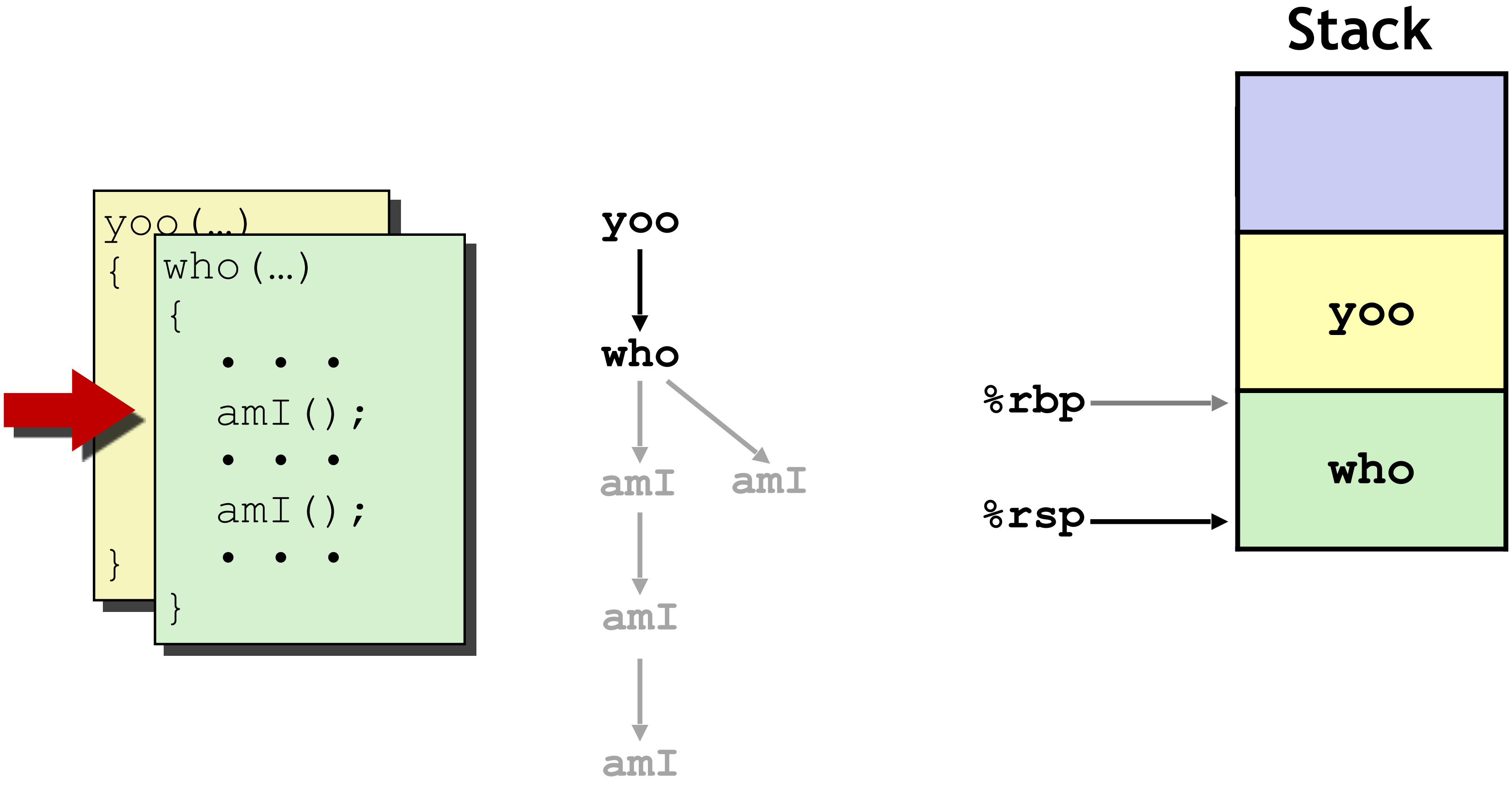
Example

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





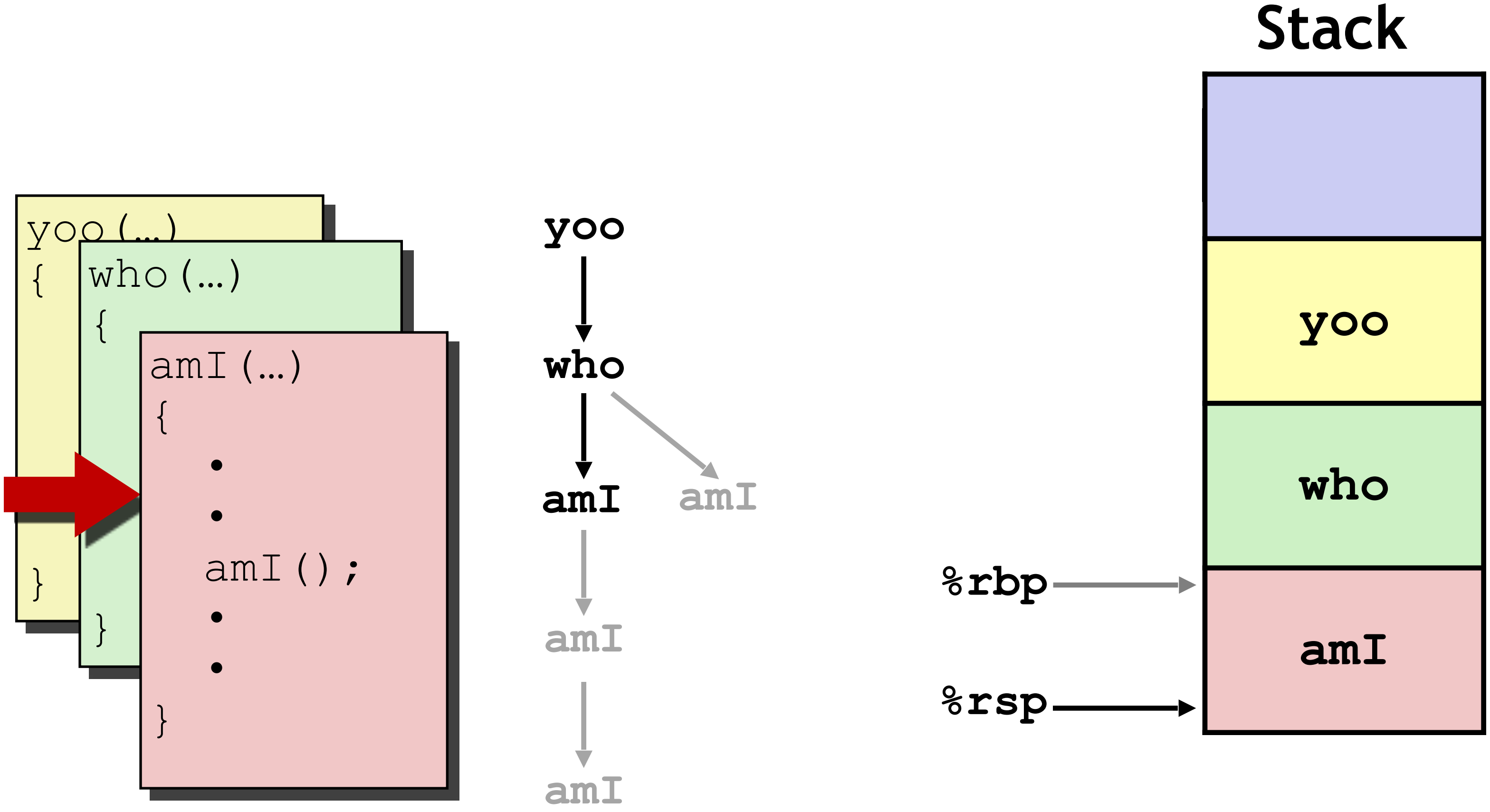
Example



```
yoo(…)
{

}
```

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

Example

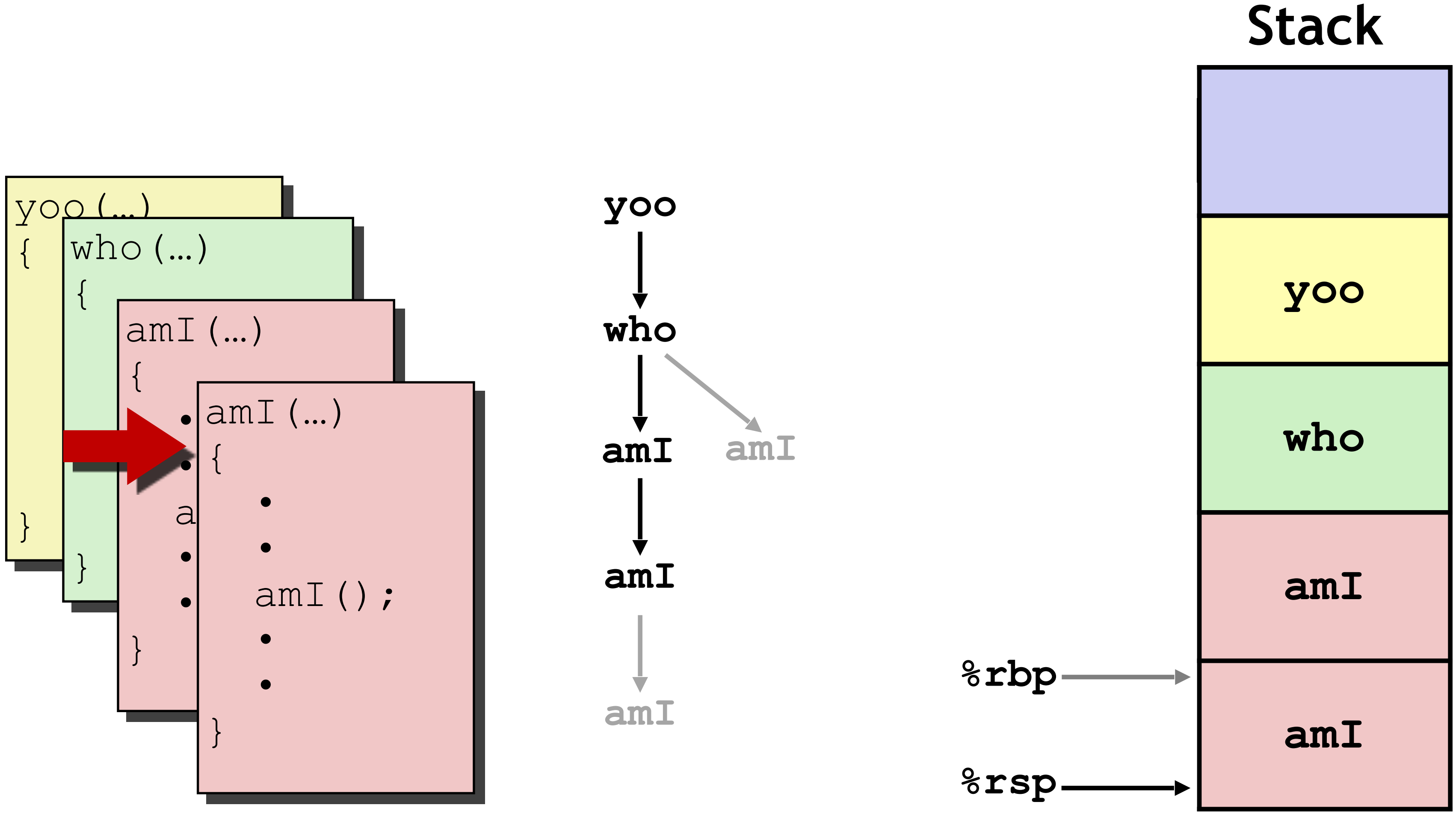


```
yoo(…)
{

}
```

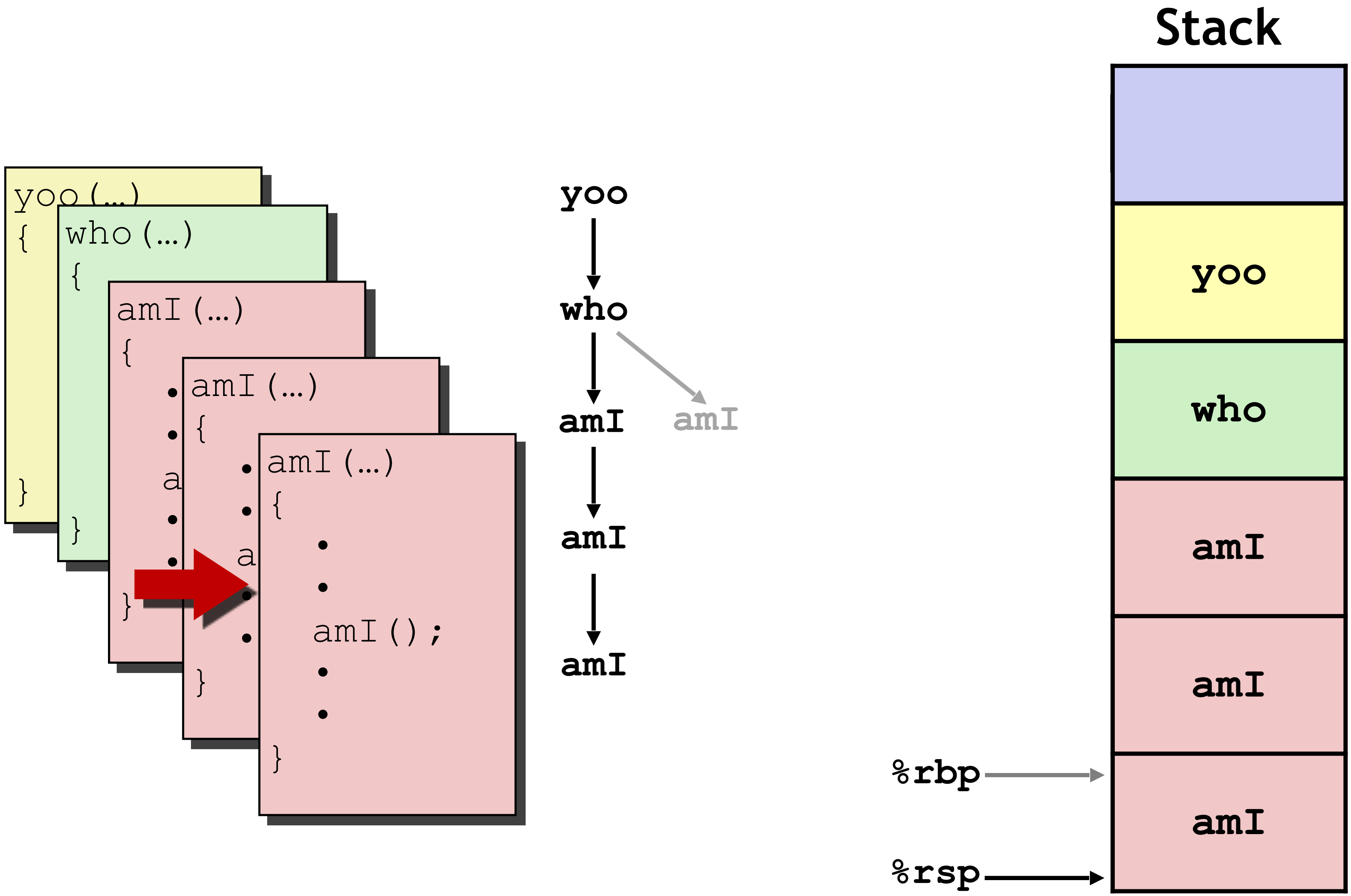
```
who(…)
{

}
```

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

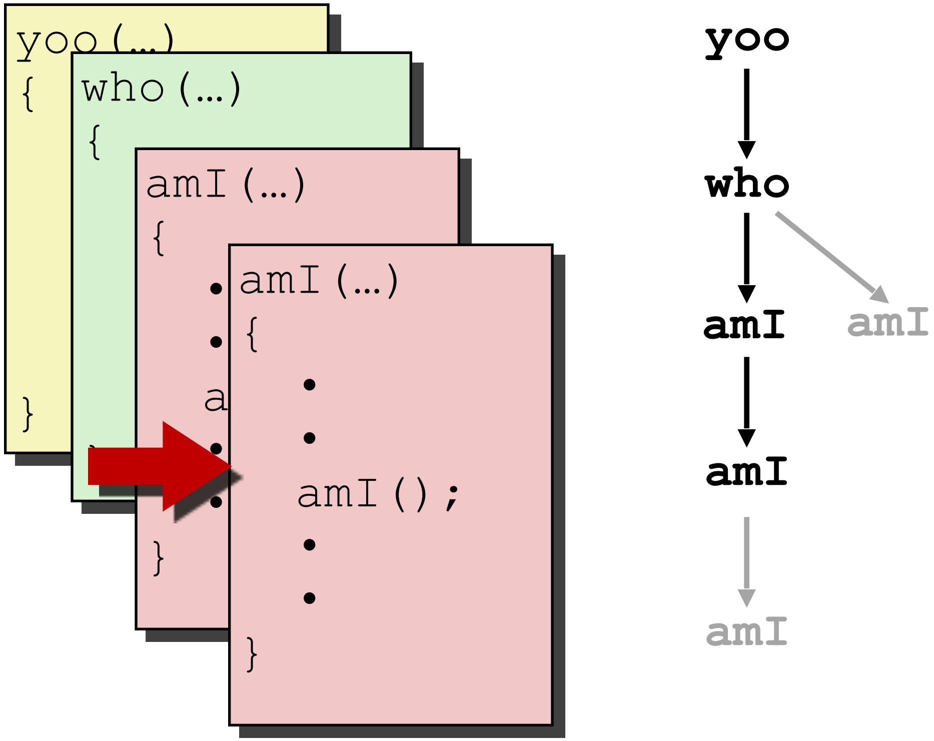
Example

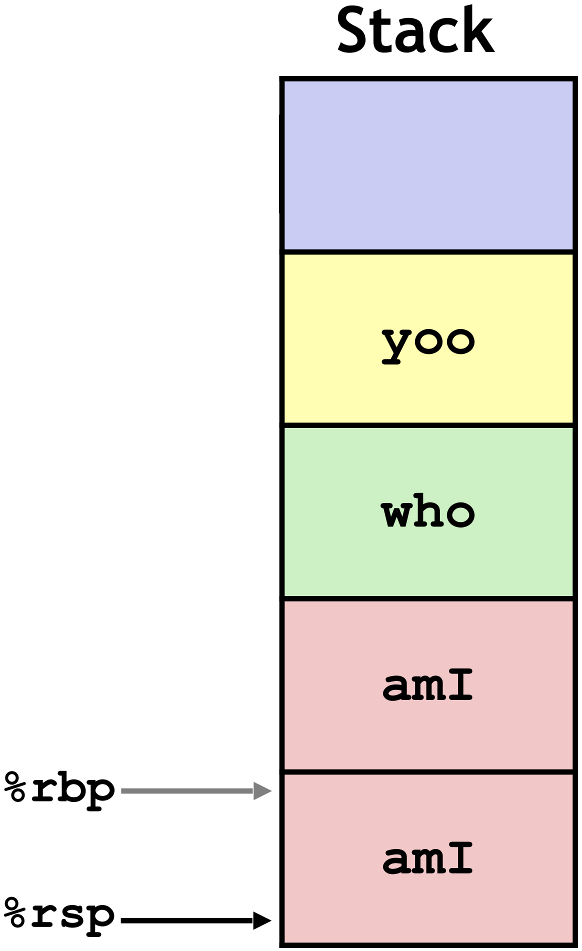

yoo (…)
{
}
who (…)
{
}
amI (…)
{
•
•
a
•
•
}
amI (…)
{
•
•
amI();
•
•
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
amI
%rbp
%rsp

+ Example

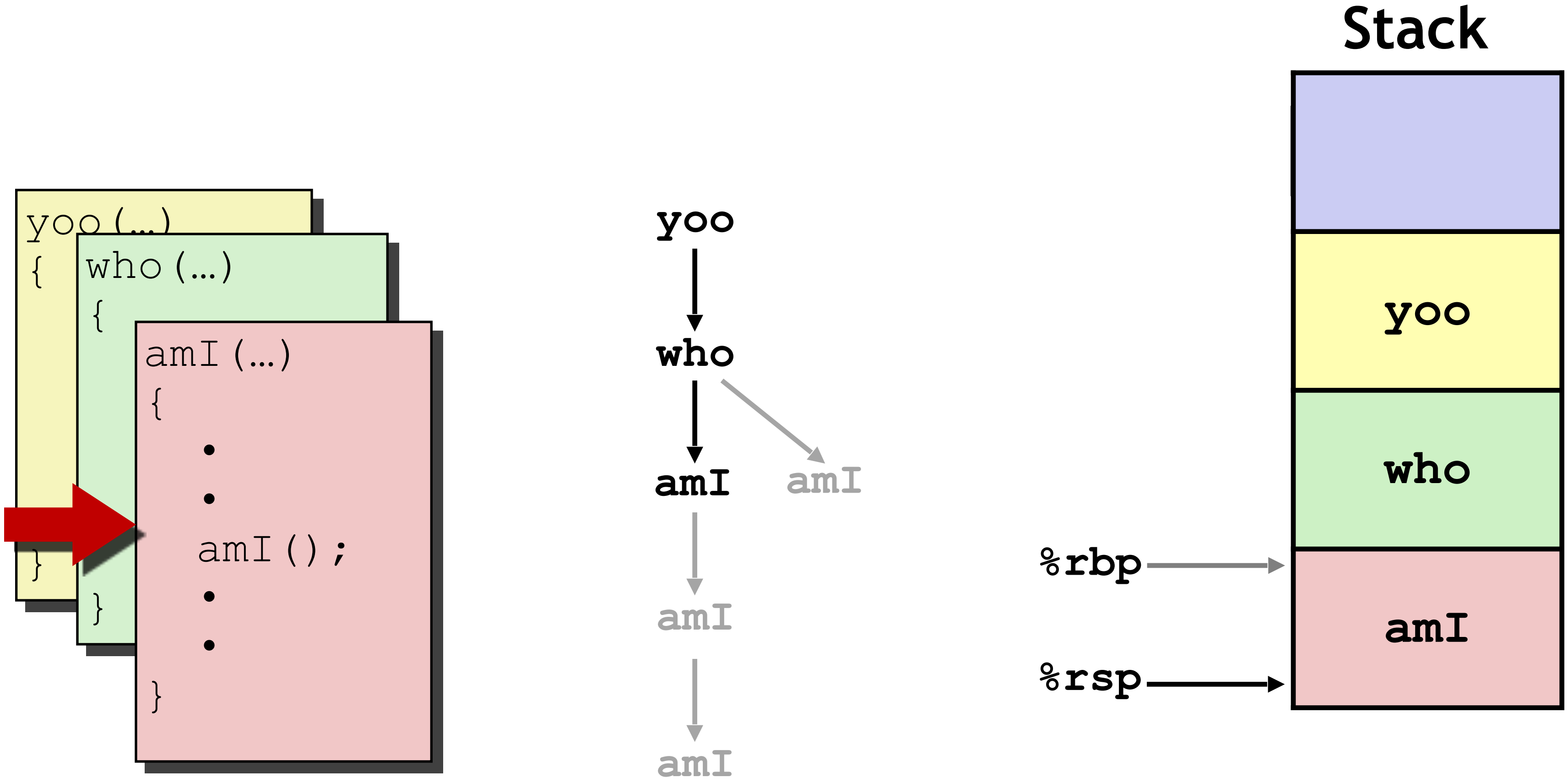

yoo (…)
{
}
who (…)
{
}
amI (…)
{
•
•
a
•
•
}
amI (…)
{
•
•
a
•
•
}
amI (…)
{
•
•
amI ();
•
•
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
amI
amI
%rbp
%rsp

+ Example

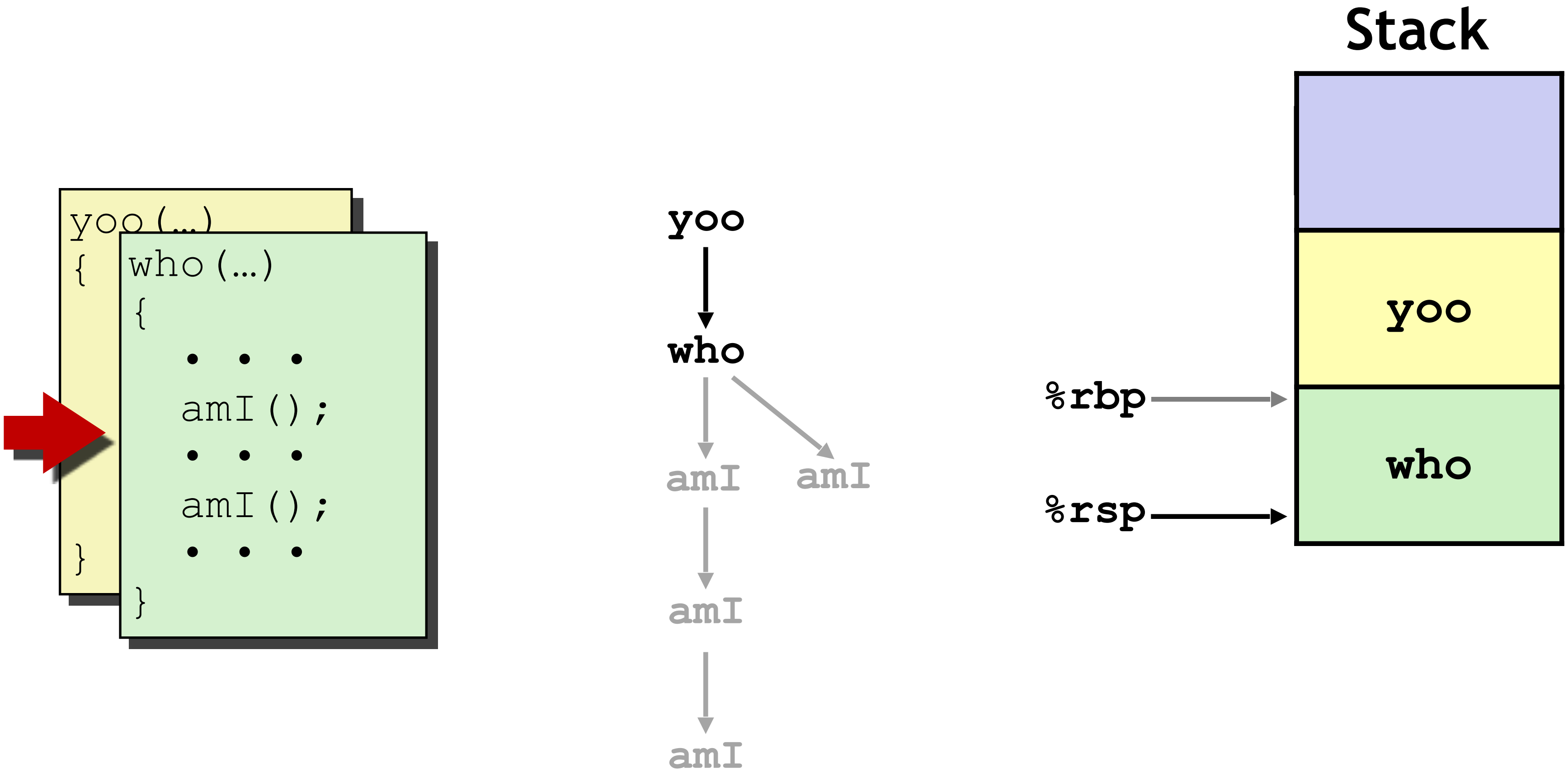

yoo(…)
{
}
who(…)
{
amI(…)
{
•
•
a
•
•
}
amI(…)
{
•
•
amI();
•
•
}
yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
%rbp
%rsp

Example


yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
amI();
•
•
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
%rbp
%rsp

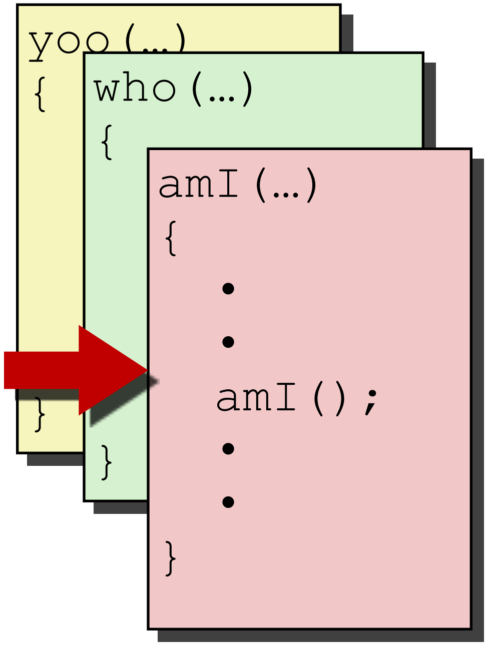
Example

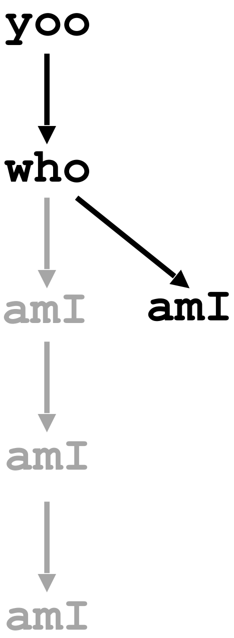


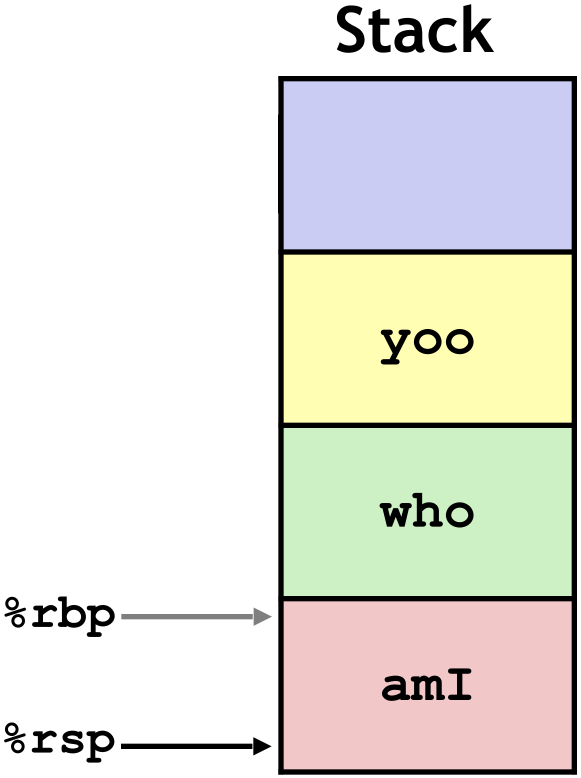
```
yoo(…)
{



}
```

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

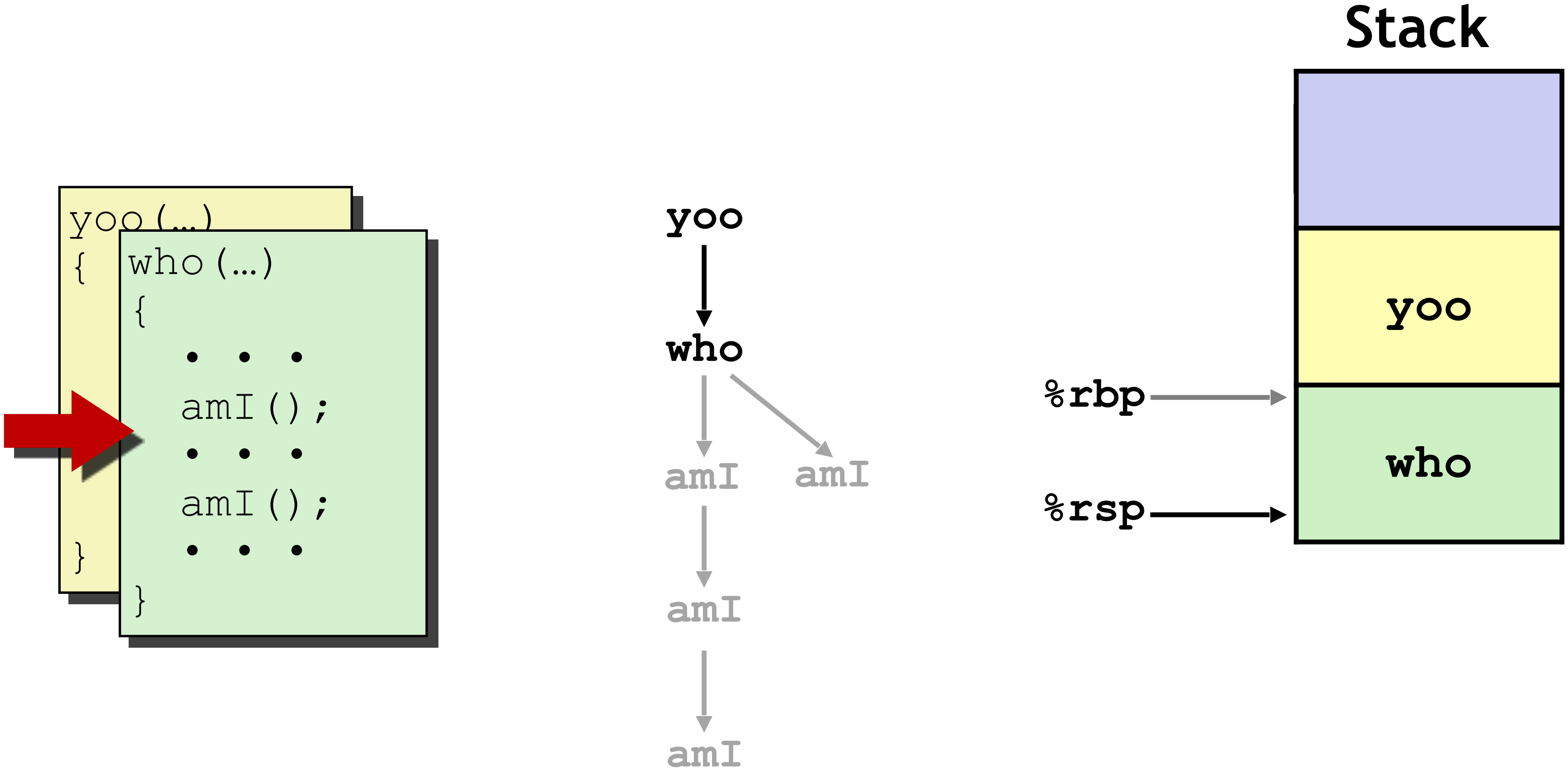
+ Example


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


yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
%rbp
%rsp

Example

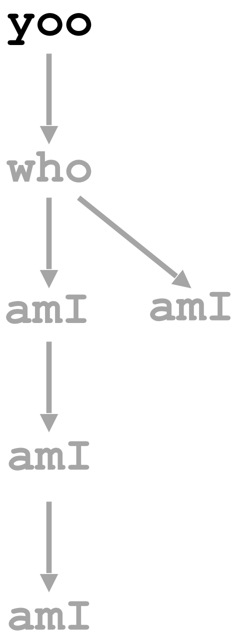


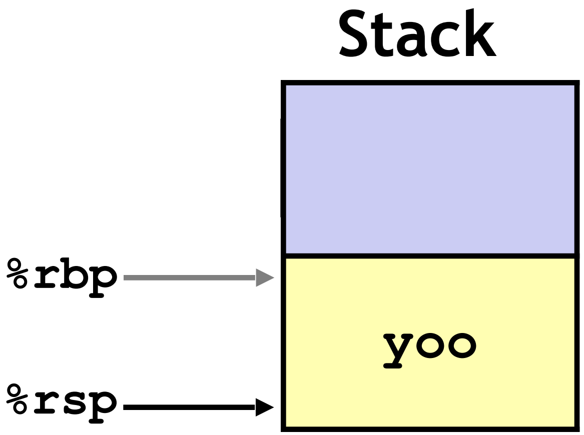
```
yoo(…)
{
        }
```

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

+ Example

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

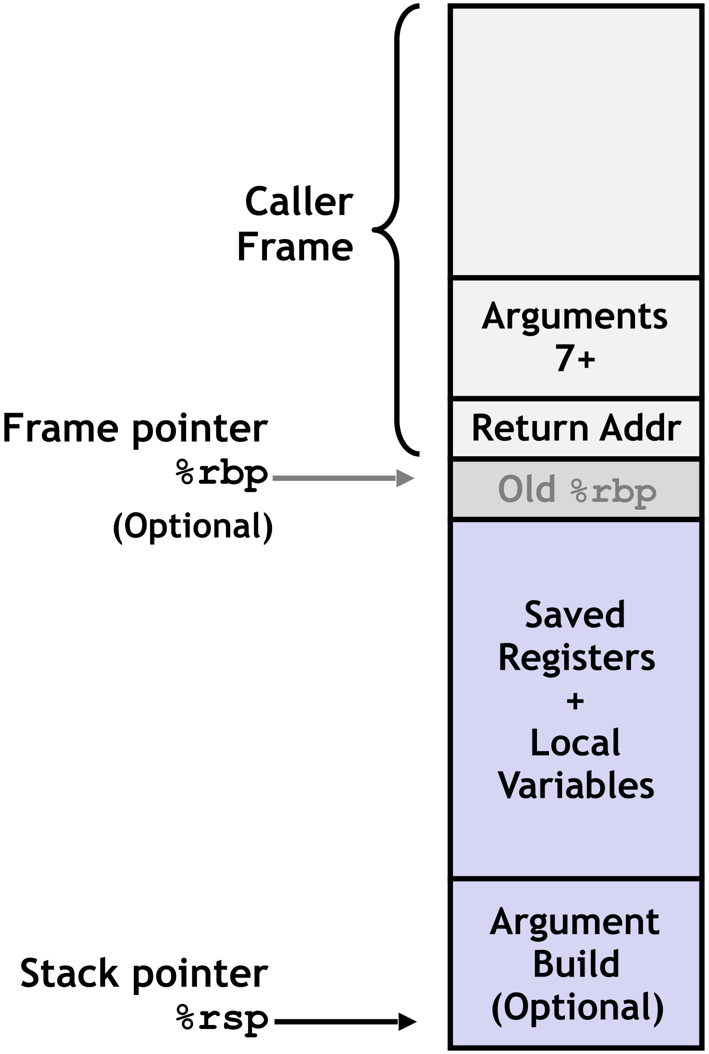




+ x86-64/Linux Stack Frame

- **Current Stack Frame ('Top' to 'Bottom')**
  - *"Argument build"*
    Parameters for function about to call
  - *Local variables*
    If can't keep in registers
  - *Old frame pointer* (optional)

- **Caller Stack Frame**
  - Return address
    - Pushed by `call` instruction
  - Arguments for this call



Caller Frame
Arguments 7+
Return Addr
Frame pointer %rbp (Optional)
Old %rbp
Saved Registers + Local Variables
Argument Build (Optional)
Stack pointer %rsp

+

Managing Local Data

Register Saving Conventions

- When procedure yoo calls who:
  - `yoo()` is the *caller*
  - `who()` is the *callee*
- Can register be used for temporary storage?

```
yoo:
    • • •
    movq $15213, %rdx
    call who
    addq %rdx, %rax
    • • •
    ret
```

```
who:
    • • •
    subq $18213, %rdx
    • • •
    ret
```

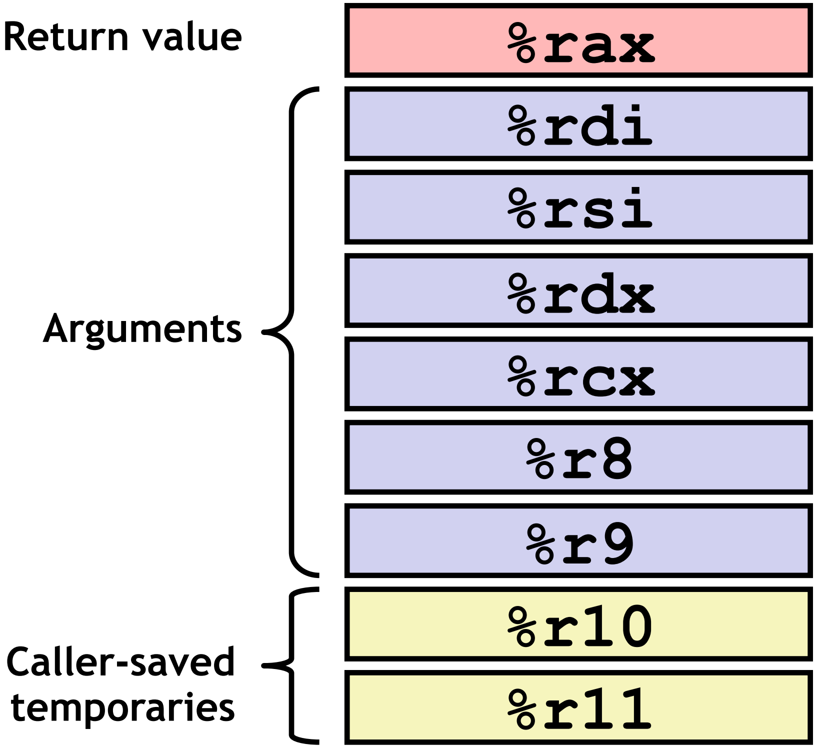
  - Contents of register **%rdx** overwritten by **who**
  - Machine-Level programmer needs to solve for this.

+ Register Saving Conventions

- When procedure yoo calls who:
  - `yoo()` is the ***caller***
  - `who()` is the ***callee***
- Can register be used for temporary storage?
- **Conventions**
  - *"Caller Saved"*
    - Caller saves temporary values in its frame before the call
  - *"Callee Saved"*
    - Callee saves temporary values in its frame before using
    - Callee restores them before returning to caller

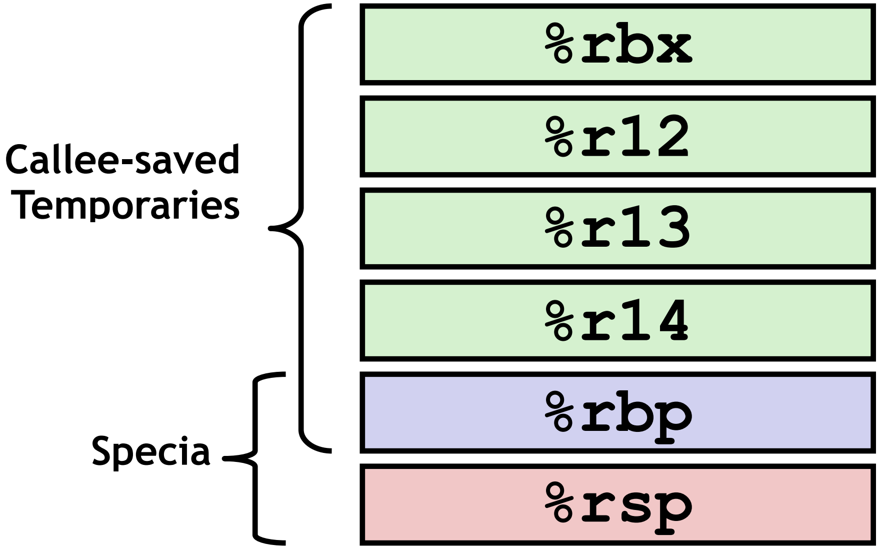
+ x86-64 Linux Caller-saved Registers

- `%rax`
  - Return value
  - Also caller-saved
  - Can be modified by procedure
- `%rdi, ..., %r9`
  - Arguments
  - Also caller-saved
  - Can be modified by procedure
- `%r10, %r11`
  - Caller-saved
  - Can be modified by procedure



+ x86-64 Linux Callee-saved Registers

- **`%rbx, %r12, %r13, %r14`**
  - Callee-saved
  - Callee must save & restore
- **`%rbp`**
  - Callee-saved
  - Callee must save & restore
  - May be used as frame pointer
- **`%rsp`**
  - Special form of callee save
  - Restored to original value upon exit from procedure



Callee-Saved Example

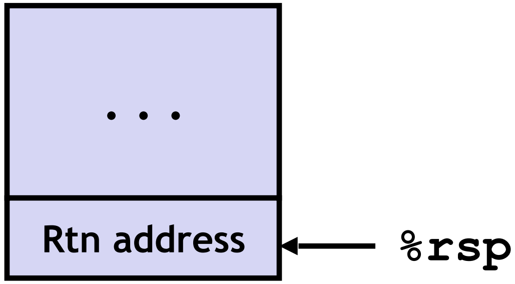
```
long incr(long *p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
long call_incr(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
call_incr:
  pushq    %rbx             # callee-saved
  subq     $8, %rsp         # allocate
  movq     %rdi, %rbx       # caller-saved
  movq     $15213, (%rsp)   # “push”
  movq     $3000, %rsi
  leaq     (%rsp), %rdi
  call     incr
  addq     %rbx, %rax
  addq     $8, %rsp
  popq     %rbx
  ret
```

call_incr’s stack

Initial Stack

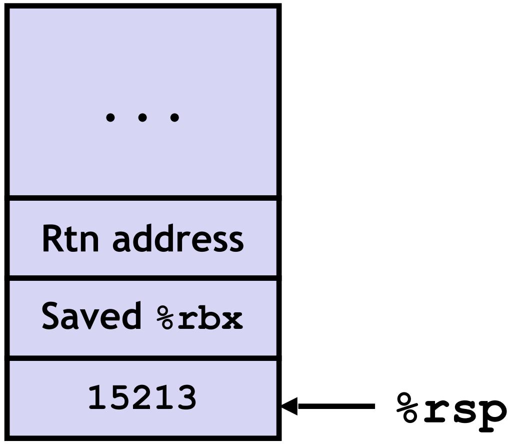


. . .

Rtn address

%rsp

Resulting Stack



. . .

Rtn address

Saved %rbx

15213

%rsp

+ Callee-Saved Example *con't*

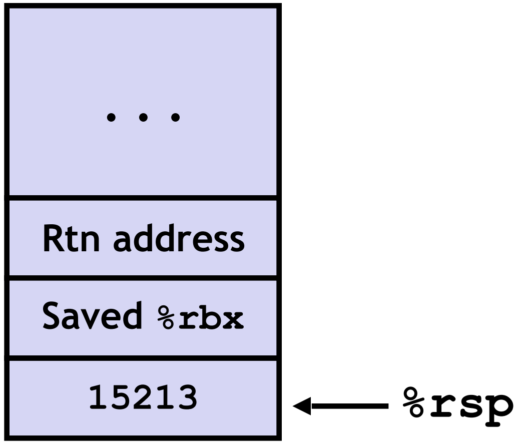
```
long incr(long *p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
long call_incr(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

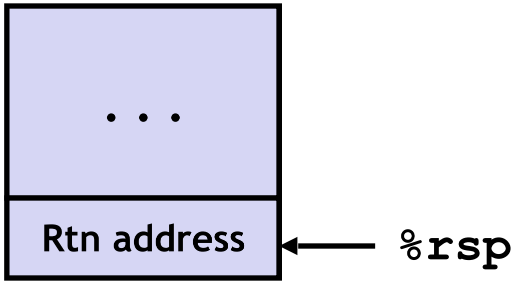
```
call_incr:
  pushq    %rbx             # callee-saved
  subq     $8, %rsp         # allocate
  movq     %rdi, %rbx       # caller-saved
  movq     $15213, (%rsp)   # "push"
  movq     $3000, %rsi
  leaq     (%rsp), %rdi
  call     incr
  addq     %rbx, %rax
  addq     $8, %rsp         # deallocate
  popq     %rbx             # restore %rbx
  ret
```

call_incr's stack

Resulting Stack



Pre-return Stack



. . .
Rtn address
%rsp