

The Stack & Procedures

CSE 351 Spring 2019

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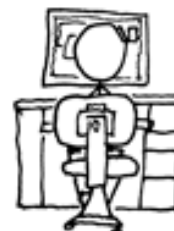
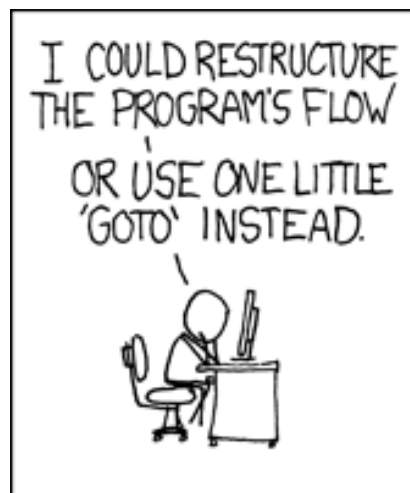
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Administrivia

- ❖ Homework 2 due TONIGHT Wednesday (4/24)
- ❖ Lab 2 (x86-64) due Wednesday (5/01)
 - Ideally want to finish well before the midterm
- ❖ Homework 3, coming soon
 - On midterm material, but due after the midterm
- ❖ Section tomorrow on Assembly and GDB
 - Bring your laptops!
- ❖ **Midterm** (Fri 5/03, 4:30-5:30pm in KNE 130)

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

- Memory & data
- Integers & floats
- x86 assembly
- Procedures & stacks**
- Executables
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

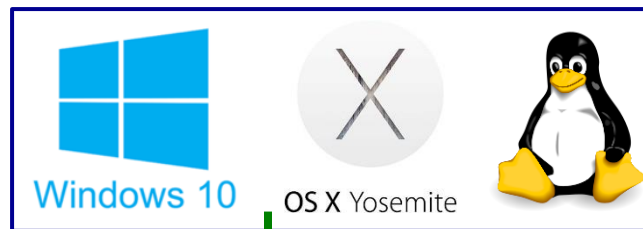
Assembly language:

```
get_mpg:
    pushq    %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

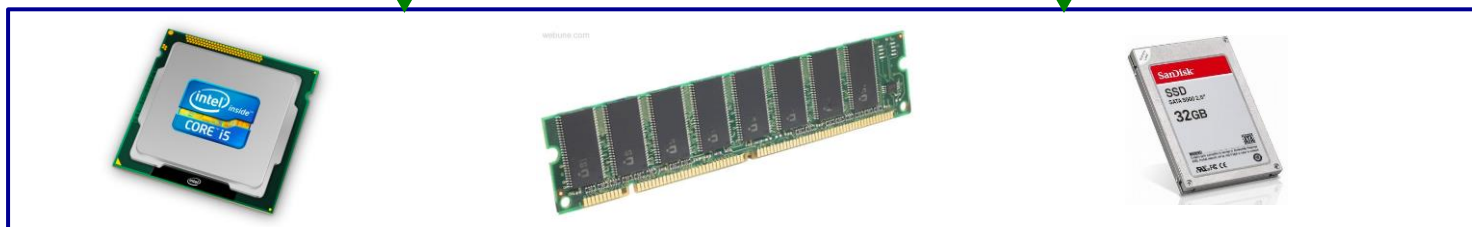
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

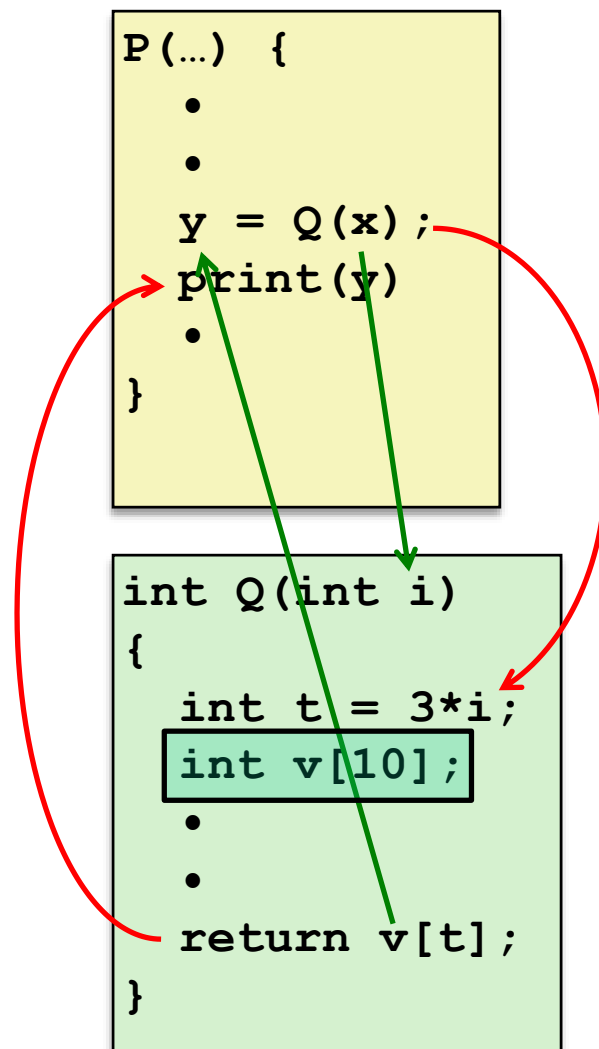


Computer system:



Mechanisms required for *procedures*

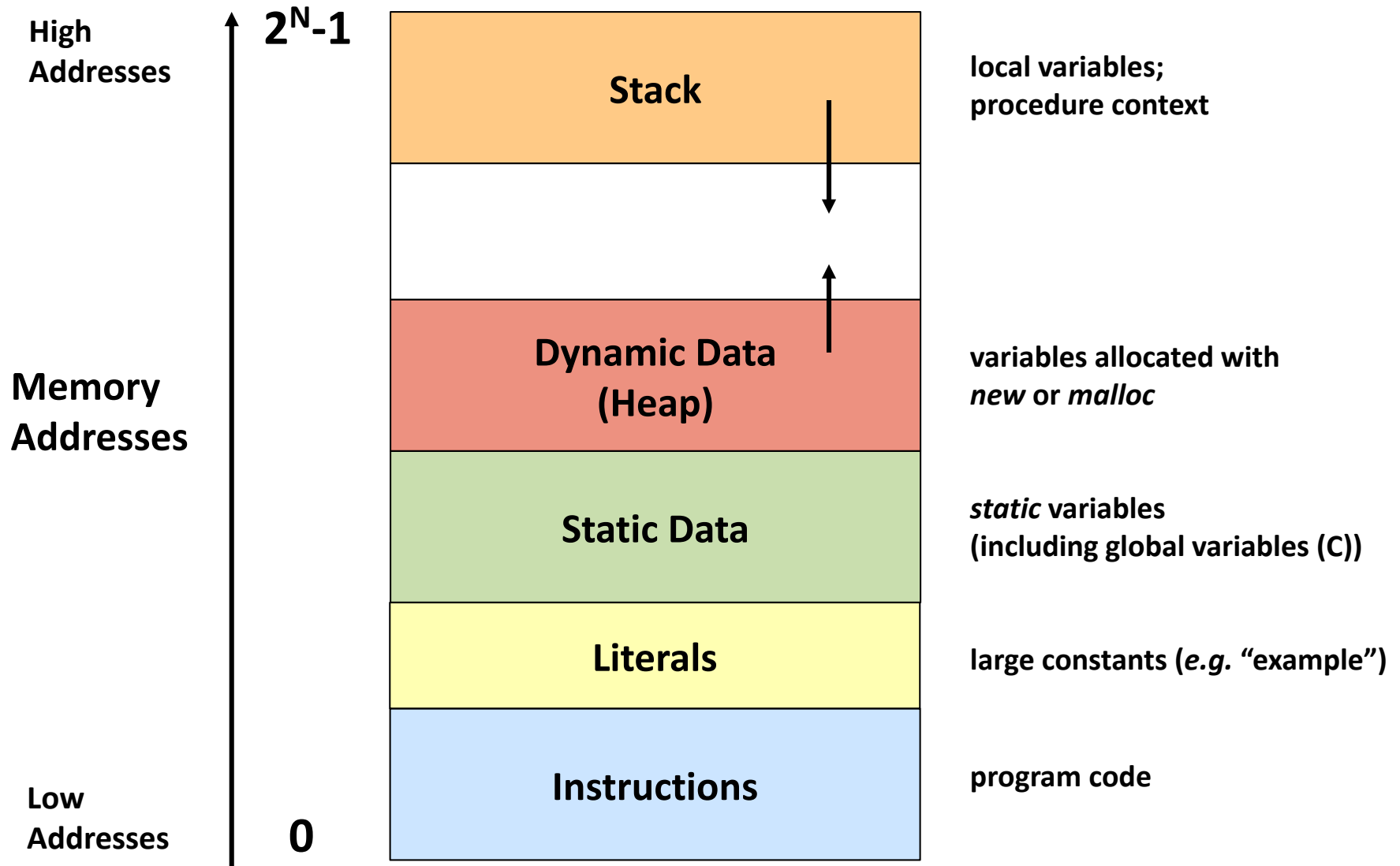
- 1) Passing control
 - To beginning of procedure code
 - Back to return point
 - 2) Passing data
 - Procedure arguments
 - Return value
 - 3) Memory management
 - Allocate during procedure execution
 - Deallocate upon return
- ❖ All implemented with machine instructions!
- An x86-64 procedure uses only those mechanisms required for that procedure



Procedures

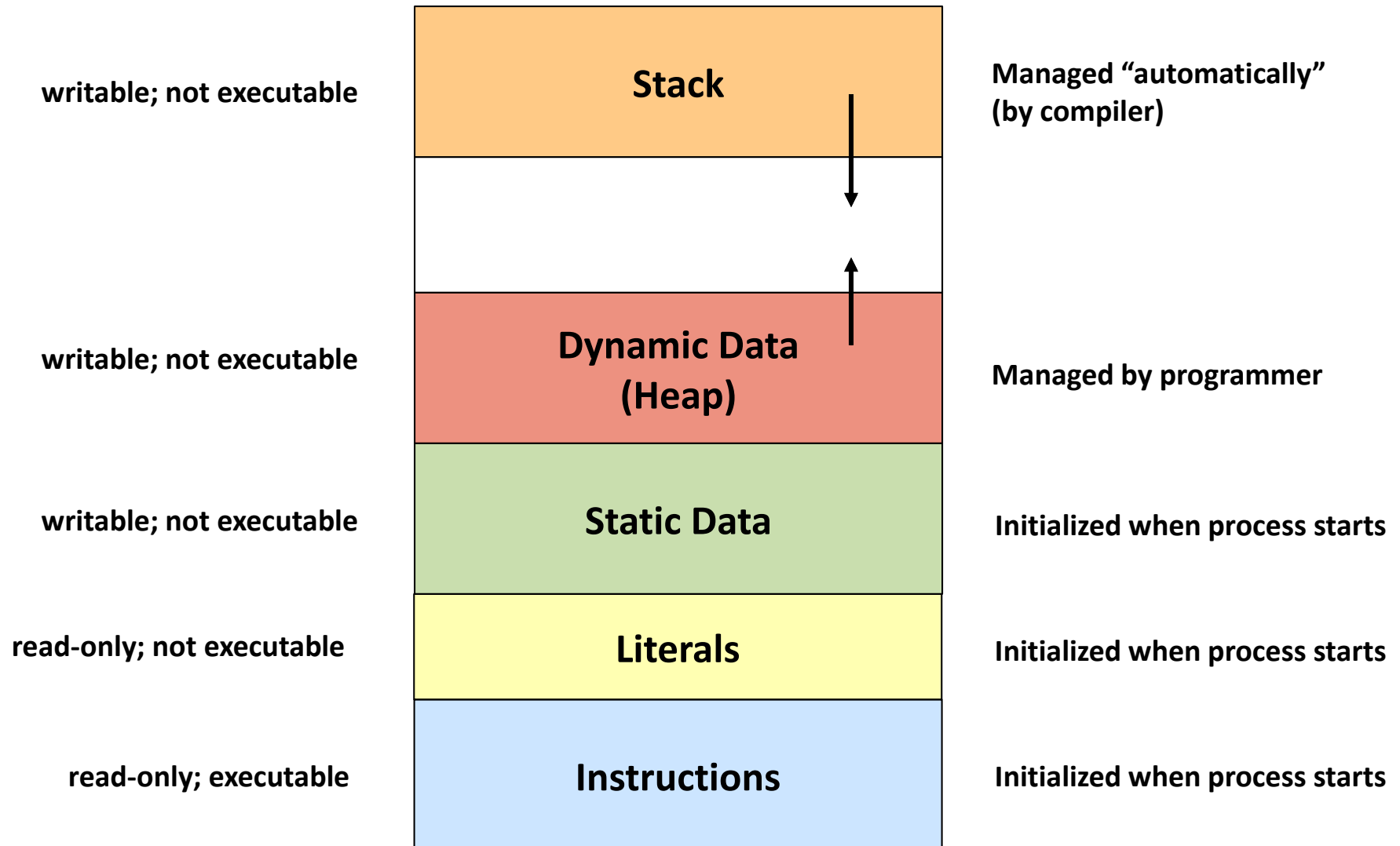
- ❖ **Stack Structure**
- ❖ Calling Conventions
 - Passing control
 - Passing data
 - Managing local data
- ❖ Register Saving Conventions
- ❖ Illustration of Recursion

Simplified Memory Layout



Memory Permissions

segmentation faults?



x86-64 Stack

- ❖ Region of memory managed with stack “discipline”
 - Grows toward lower addresses
 - Customarily shown “upside-down”
- ❖ Register $\%rsp$ contains *lowest* stack address
 - $\%rsp$ = address of *top* element, the most-recently-pushed item that is not-yet-popped

Stack Pointer: $\%rsp$ →

Stack “Bottom”



Stack “Top”

High
Addresses

↑
Increasing
Addresses

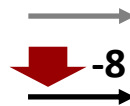
↓
Stack Grows
Down

Low
Addresses
0x00...00

x86-64 Stack: Push

- ❖ `pushq src`
 - Fetch operand at `src`
 - `Src` can be reg, memory, immediate
 - **Decrement** `%rsp` by 8
 - Store value at address given by `%rsp`
- ❖ Example:
 - `pushq %rcx`
 - Adjust `%rsp` and store contents of `%rcx` on the stack

Stack Pointer: `%rsp`



Stack "Bottom"



Stack "Top"

High
Addresses

↑
Increasing
Addresses
|

|
Stack Grows
Down
↓

Low
Addresses
0x00...00

x86-64 Stack: Pop

- ❖ `popq dst`
 - Load value at address given by `%rsp`
 - Store value at `dst`
 - **Increment** `%rsp` by 8
- ❖ Example:
 - `popq %rcx`
 - Stores contents of top of stack into `%rcx` and adjust `%rsp`

Stack Pointer: `%rsp`



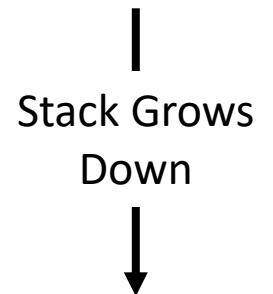
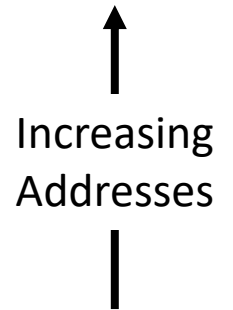
Stack "Bottom"



Stack "Top"

Those bits are still there;
we're just not using them.

High
Addresses

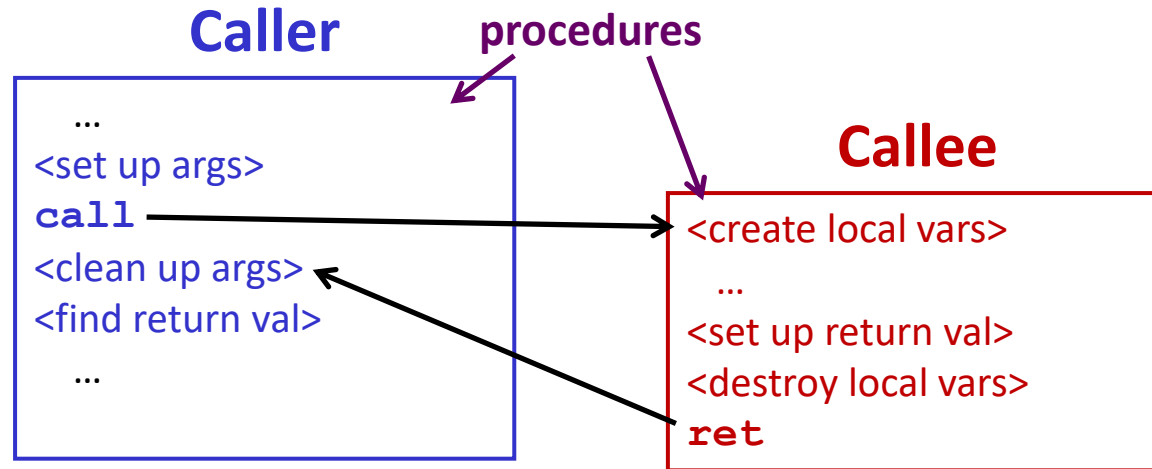


Low
Addresses
0x00...00

Procedures

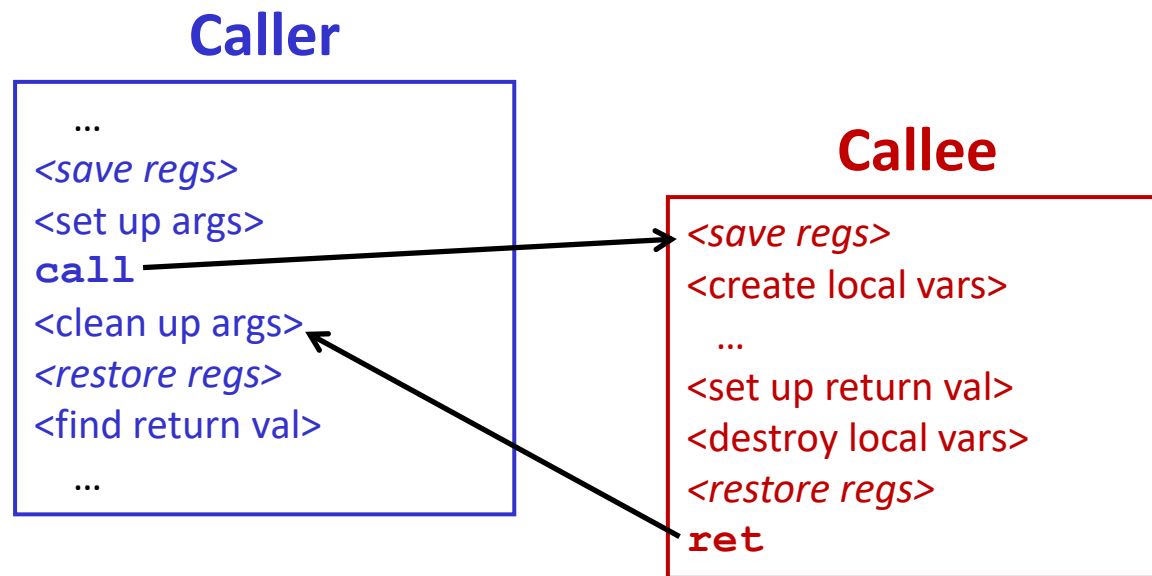
- ❖ Stack Structure
- ❖ **Calling Conventions**
 - **Passing control**
 - Passing data
 - Managing local data
- ❖ Register Saving Conventions
- ❖ Illustration of Recursion

Procedure Call Overview



- ❖ **Callee** must know where to find args
- ❖ **Callee** must know where to find *return address*
- ❖ **Caller** must know where to find *return value*
- ❖ **Caller** and **Callee** run on same CPU, so use the same registers
 - How do we deal with register reuse?
- ❖ Unneeded steps can be skipped (e.g. no arguments)

Procedure Call Overview



- ❖ The *convention* of where to leave/find things is called the calling convention (or procedure call linkage)
 - Details vary between systems
 - We will see the convention for x86-64/Linux in detail
 - What could happen if our program didn't follow these conventions?

Code Example (Preview)

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

Compiler Explorer:

<https://godbolt.org/g/cKKDZn>

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

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

```
0000000000400550 <mult2>:
400550: movq   %rdi,%rax     # a
400553: imulq  %rsi,%rax     # a * b
400557: ret                                # Return
```

Procedure Control Flow

- ❖ Use stack to support procedure call and return
- ❖ **Procedure call:** `call label`
 - 1) Push return address on stack (*why? which address?*)
 - 2) Jump to *label*

Procedure Control Flow

- ❖ Use stack to support procedure call and return
- ❖ **Procedure call:** `call label`
 - 1) Push return address on stack (*why? which address?*)
 - 2) Jump to *label*
- ❖ Return address:
 - Address of instruction immediately after `call` instruction
 - Example from disassembly:

```
400544: call    400550 <mult2>
400549: movq   %rax, (%rbx)
```

Return address = **0x400549**

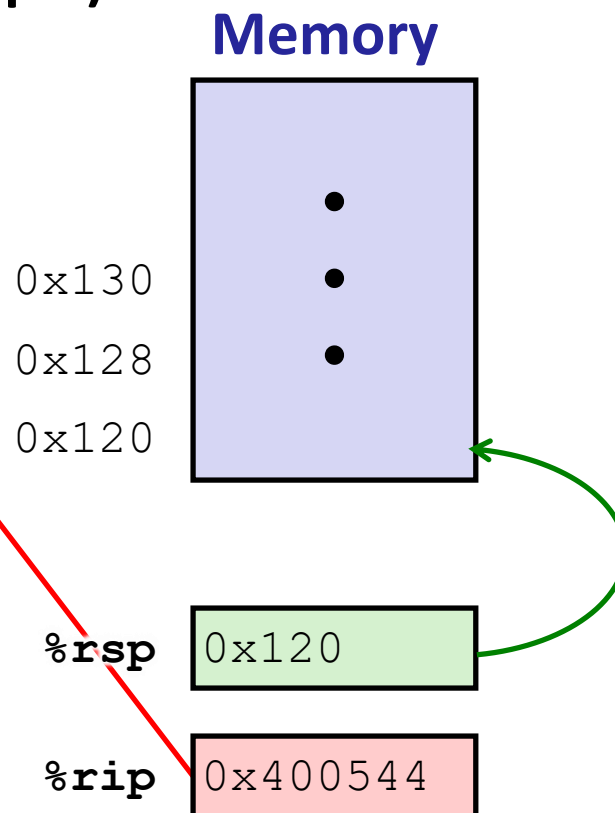
- ❖ **Procedure return:** `ret`
 - 1) Pop return address from stack
 - 2) Jump to address

next instruction happens to be a move, but could be anything

Procedure Call Example (step 1)

```
0000000000400540 <multstore>:  
.  
.  
400544: call    400550 <mult2>  
400549: movq   %rax, (%rbx)  
.  
.
```

```
0000000000400550 <mult2>:  
400550: movq   %rdi, %rax  
.  
.  
400557: ret
```



Procedure Call Example (step 2)

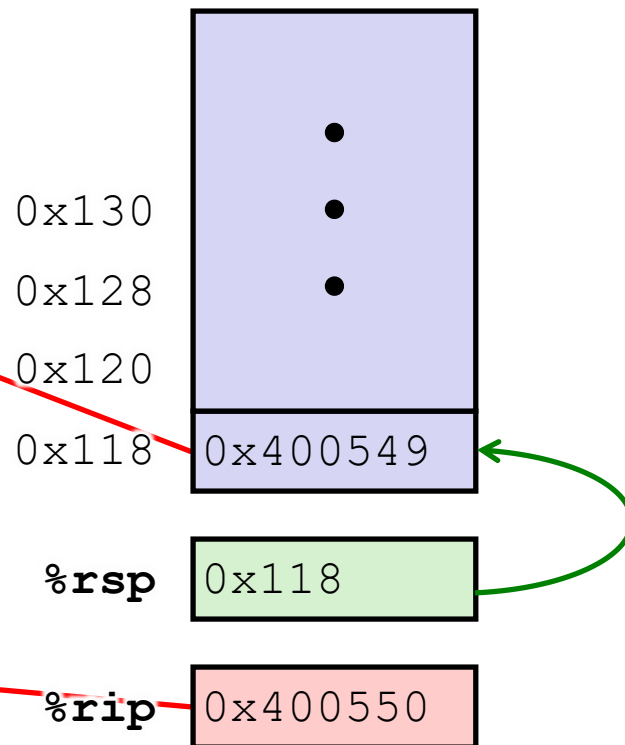
```

0000000000400540 <multstore>:
.
.
400544: call    400550 <mult2>
400549: movq   %rax, (%rbx)
.
.
    
```

```

0000000000400550 <mult2>:
400550: movq   %rdi, %rax
.
.
400557: ret
    
```

Memory



Procedure Return Example (step 1)

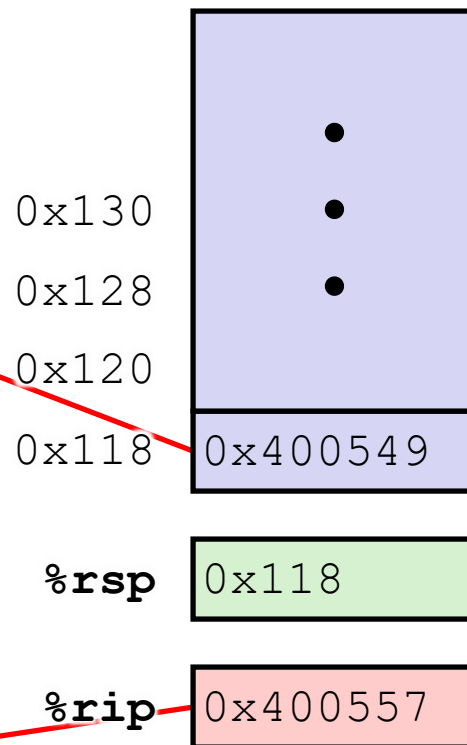
```

0000000000400540 <multstore>:
.
.
400544: call    400550 <mult2>
400549: movq   %rax, (%rbx)
.
.
    
```

```

0000000000400550 <mult2>:
400550: movq   %rdi,%rax
.
.
400557: ret
    
```

Memory



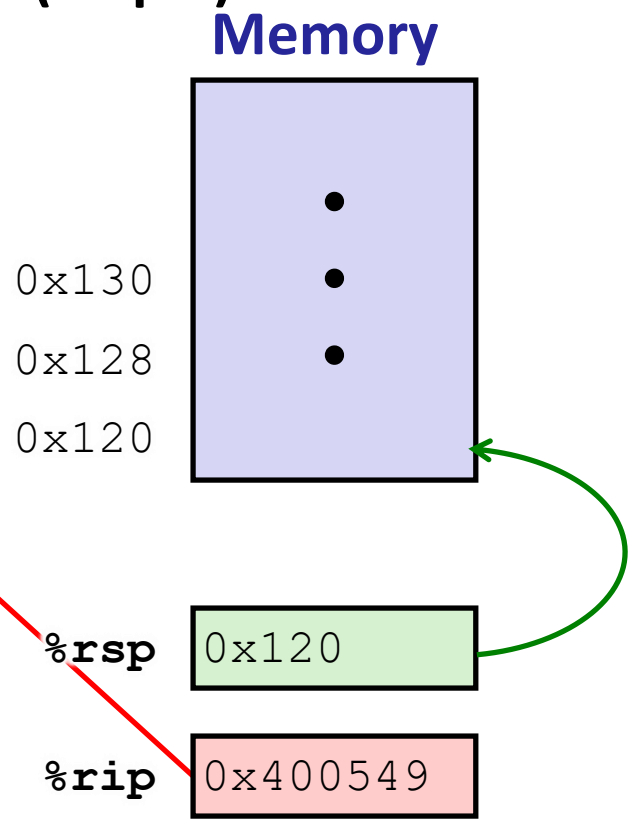
Procedure Return Example (step 2)

```

0000000000400540 <multstore>:
.
.
400544: call    400550 <mult2>
400549: movq   %rax, (%rbx)
.
.
    
```

```

0000000000400550 <mult2>:
400550: movq   %rdi, %rax
.
.
400557: ret
    
```



Procedures

- ❖ Stack Structure
- ❖ **Calling Conventions**
 - Passing control
 - **Passing data**
 - Managing local data
- ❖ Register Saving Conventions
- ❖ Illustration of Recursion

Procedure Data Flow

Registers (**NOT** in Memory)

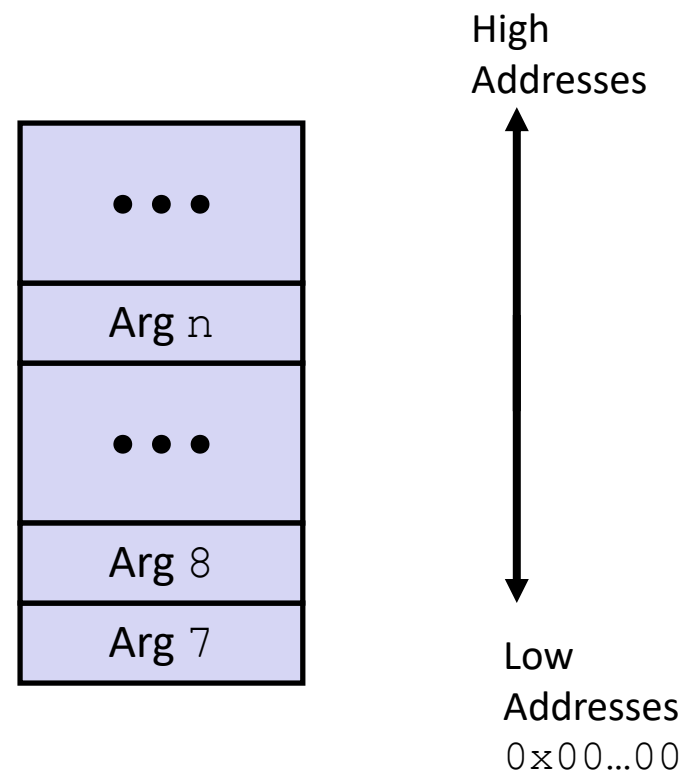
- ❖ First 6 arguments

<code>%rdi</code>	<i><u>D</u>iane's</i>
<code>%rsi</code>	<i><u>S</u>ilk</i>
<code>%rdx</code>	<i><u>D</u>ress</i>
<code>%rcx</code>	<i><u>C</u>osts</i>
<code>%r8</code>	<i><u>\$</u>8 <u>9</u></i>
<code>%r9</code>	

- ❖ Return value

<code>%rax</code>

Stack (**M**emory)



- Only allocate stack space when needed

x86-64 Return Values

- ❖ By convention, values returned by procedures are placed in `%rax`
 - Choice of `%rax` is arbitrary
- 1) **Caller** must make sure to save the contents of `%rax` before calling a **callee** that returns a value
 - Part of register-saving convention
- 2) **Callee** places return value into `%rax`
 - Any type that can fit in 8 bytes – integer, float, pointer, etc.
 - For return values greater than 8 bytes, best to return a *pointer* to them
- 3) Upon return, **caller** finds the return value in `%rax`

Data Flow Examples

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

```
00000000000400540 <multstore>:
    # x in %rdi, y in %rsi, dest in %rdx
    ...
400541: movq    %rdx,%rbx    # Save dest
400544: call   400550 <mult2> # mult2(x,y)
    # t in %rax
400549: movq    %rax,(%rbx)  # Save at dest
    ...
```

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

```
00000000000400550 <mult2>:
    # a in %rdi, b in %rsi
400550: movq    %rdi,%rax    # a
400553: imulq   %rsi,%rax    # a * b
    # s in %rax
400557: ret                          # Return
```


Procedures

- ❖ Stack Structure
- ❖ **Calling Conventions**
 - Passing control
 - Passing data
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- ❖ Register Saving Conventions
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Stack-Based Languages

- ❖ Languages that support recursion
 - *e.g.* C, Java, most modern languages
 - Code must be re-entrant
 - Multiple simultaneous instantiations of single procedure
 - Need some place to store *state* of each instantiation
 - Arguments, local variables, return address
- ❖ Stack allocated in frames
 - State for a single procedure instantiation
- ❖ Stack discipline
 - State for a given procedure needed for a limited time
 - Starting from when it is called to when it returns
 - Callee always returns before caller does

Call Chain Example

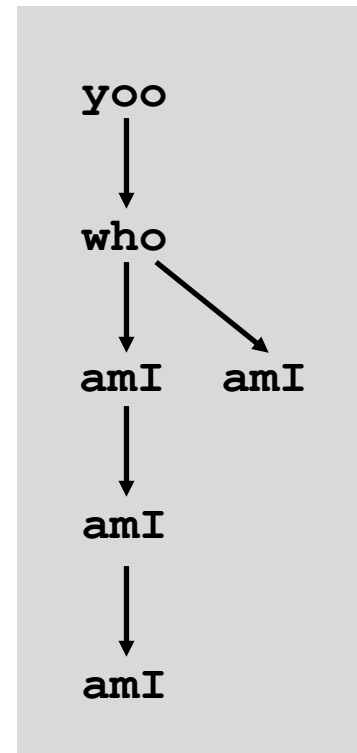
```
yoo (...)  
{  
  •  
  •  
  who ();  
  •  
  •  
}
```

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

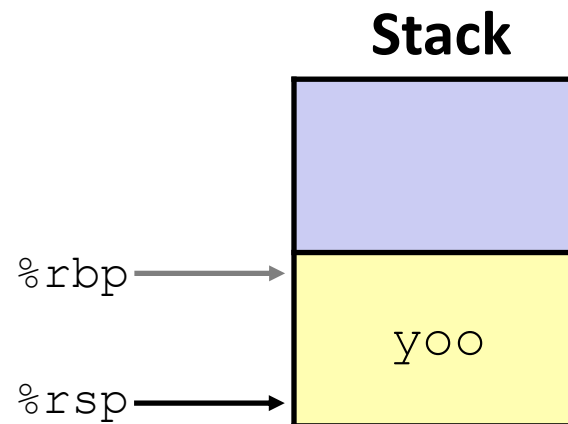
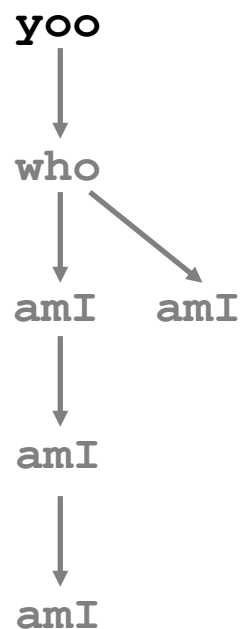
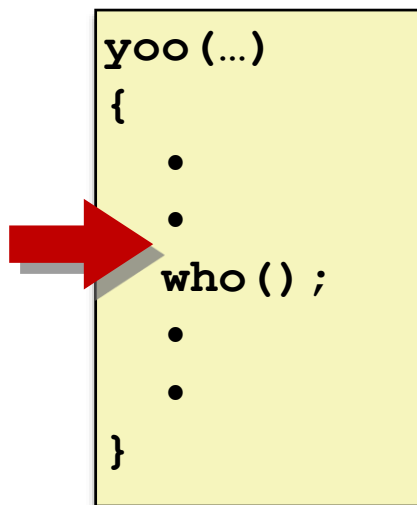
```
amI (...)  
{  
  •  
  if (...) {  
    amI ()  
  }  
  •  
}
```

Procedure `amI` is recursive
(calls itself)

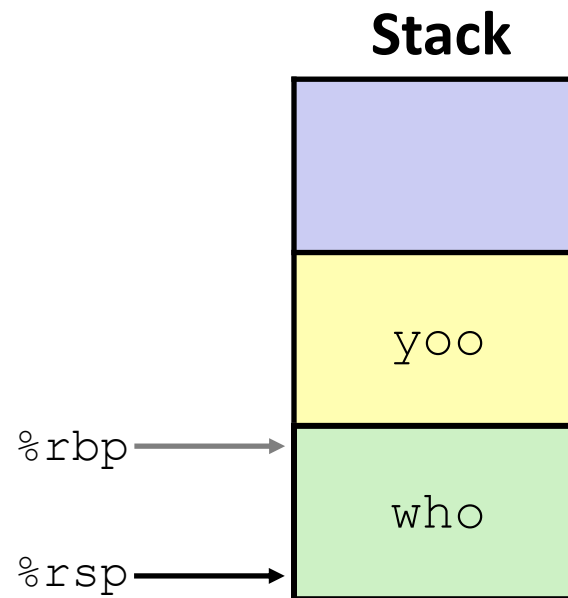
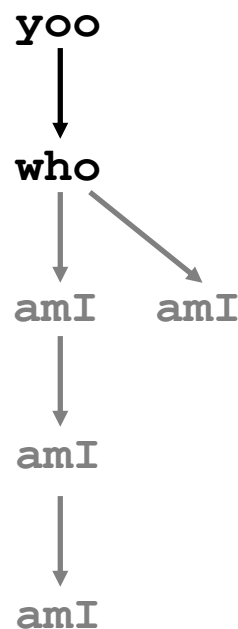
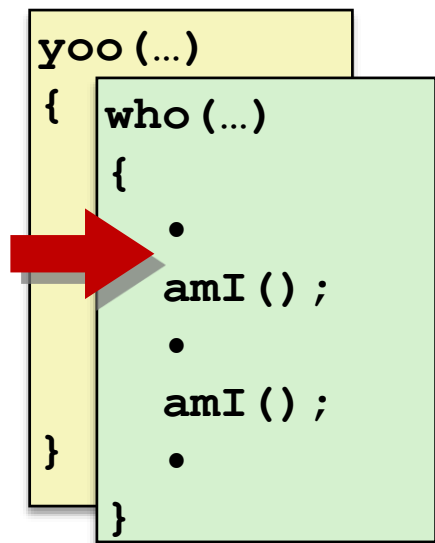
Example
Call Chain



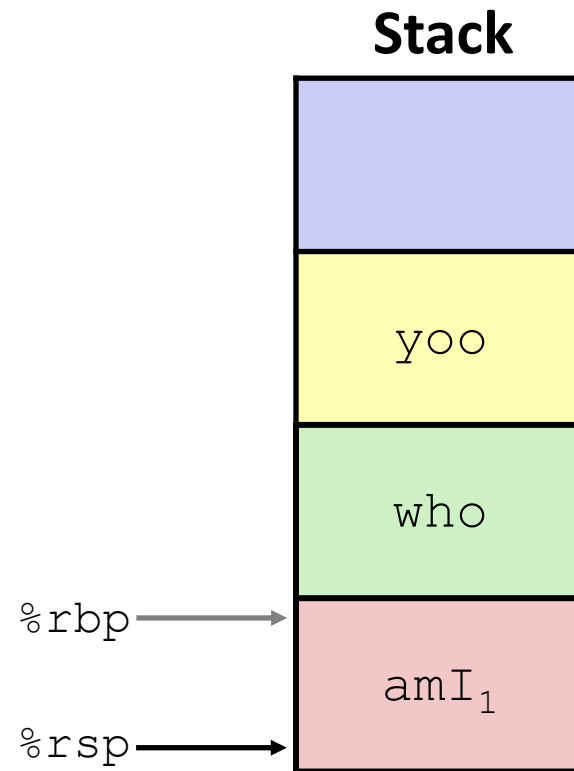
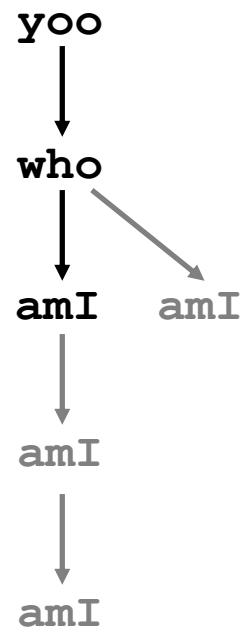
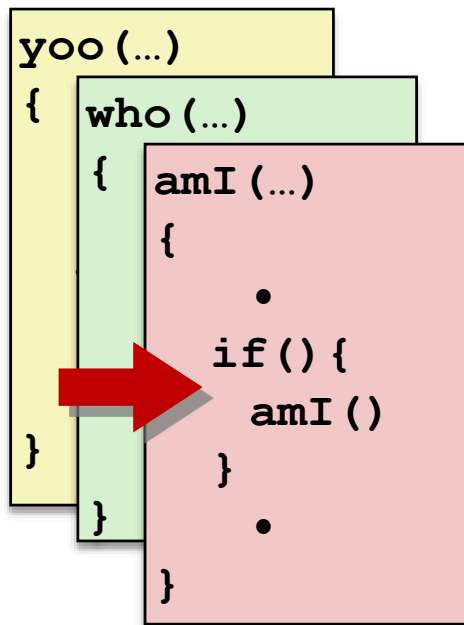
1) Call to yoo



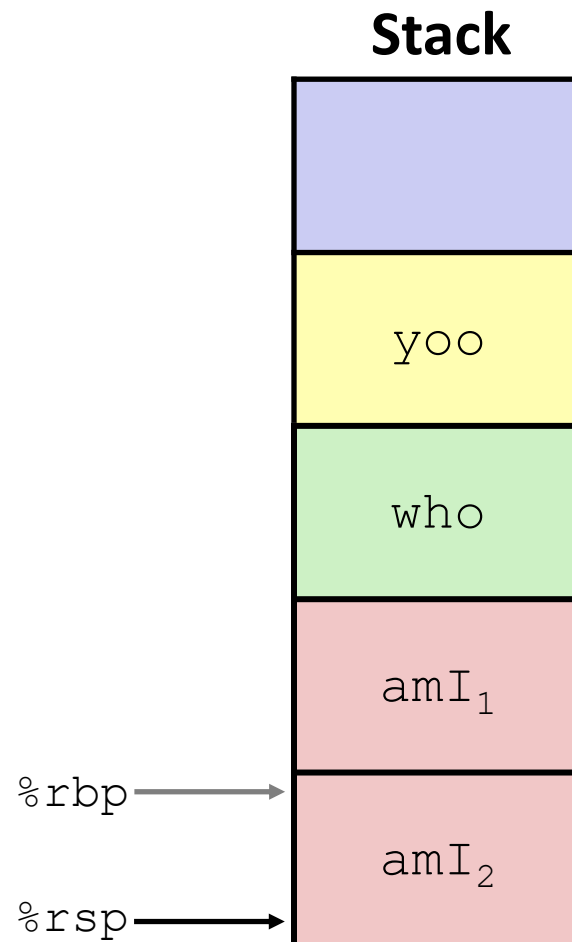
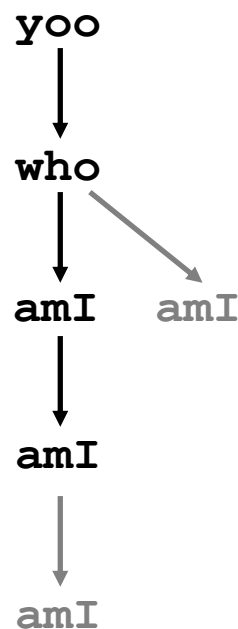
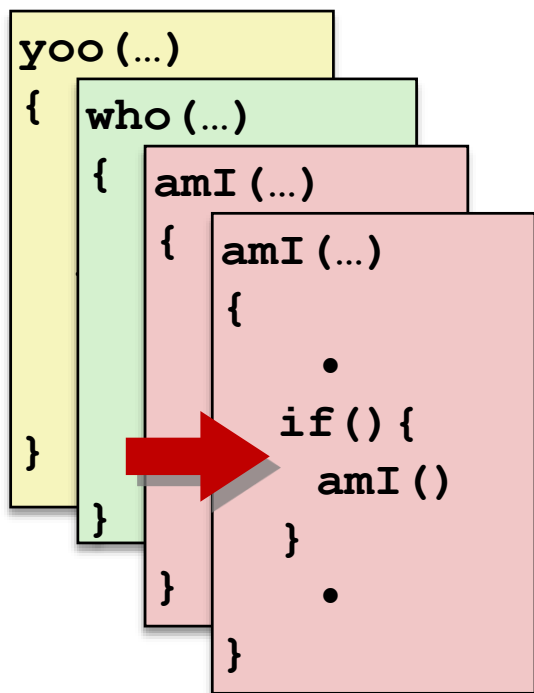
2) Call to who



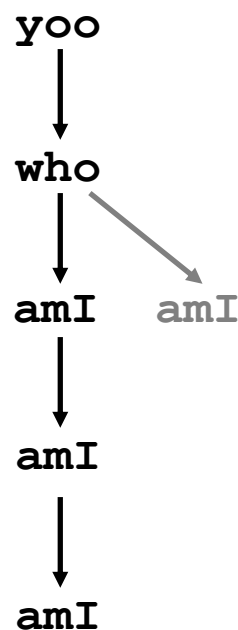
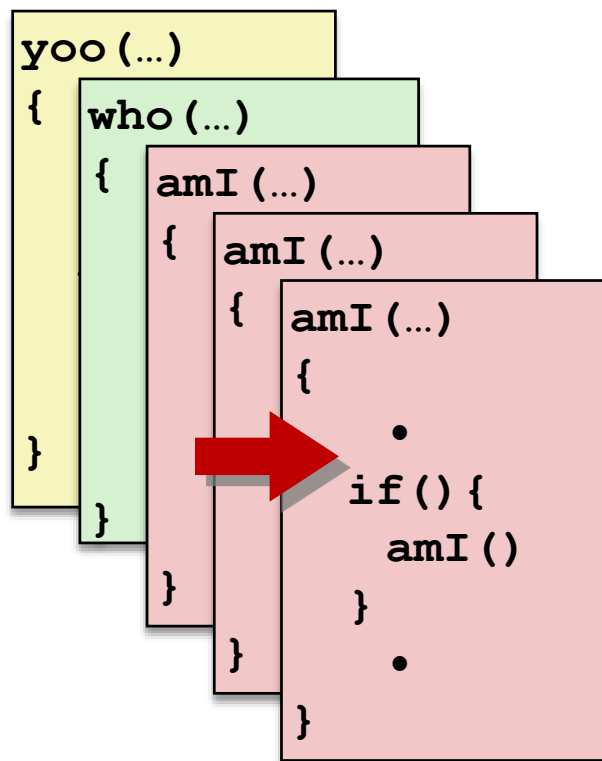
3) Call to amI (1)



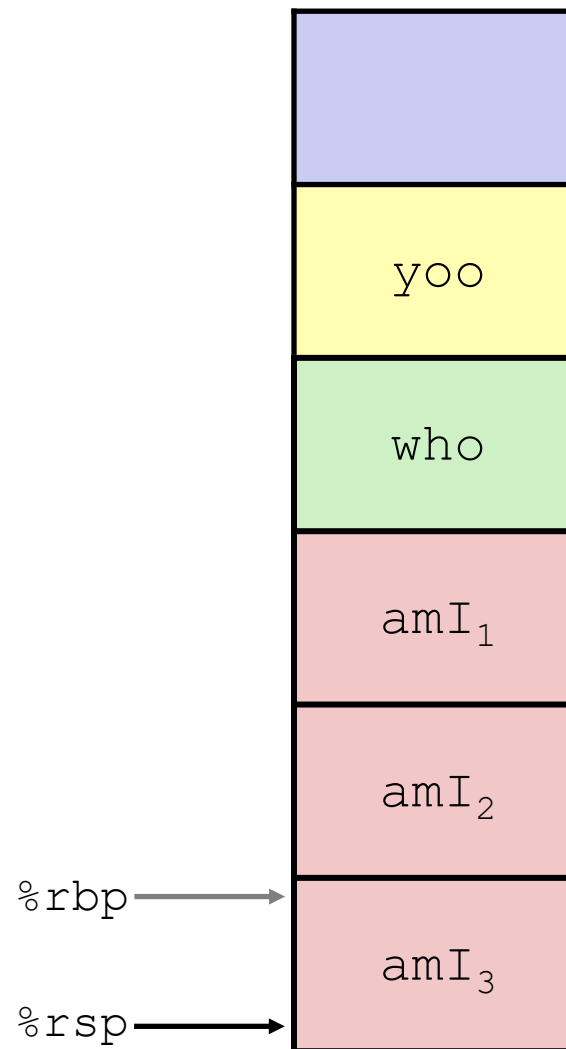
4) Recursive call to amI (2)



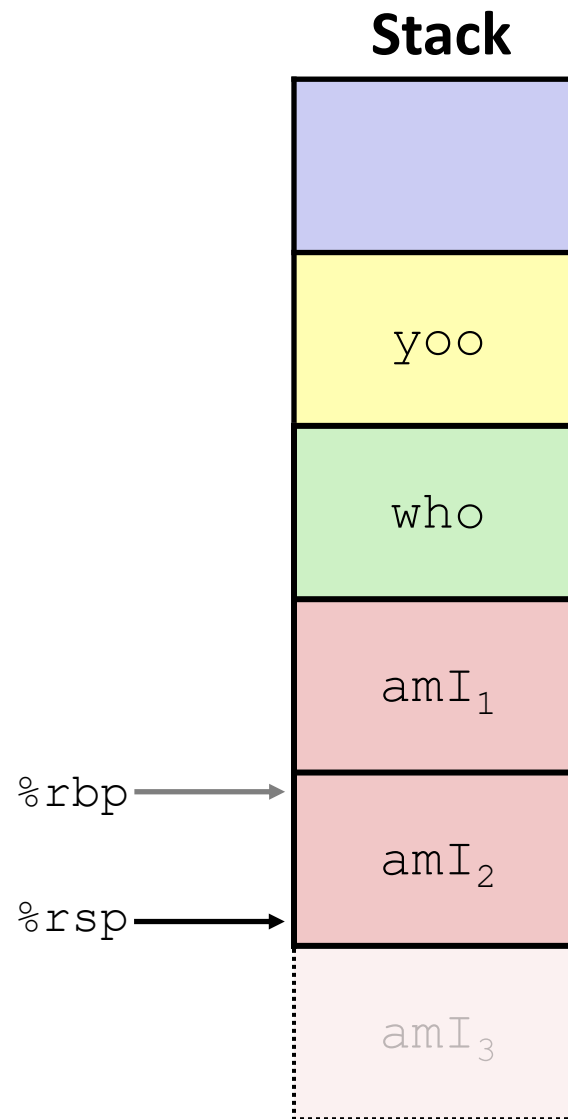
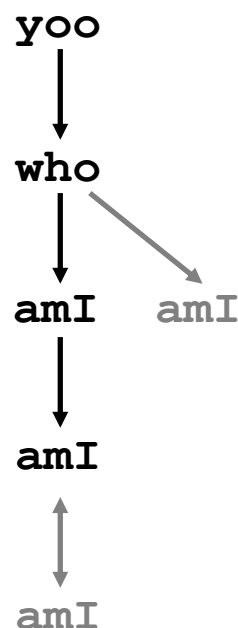
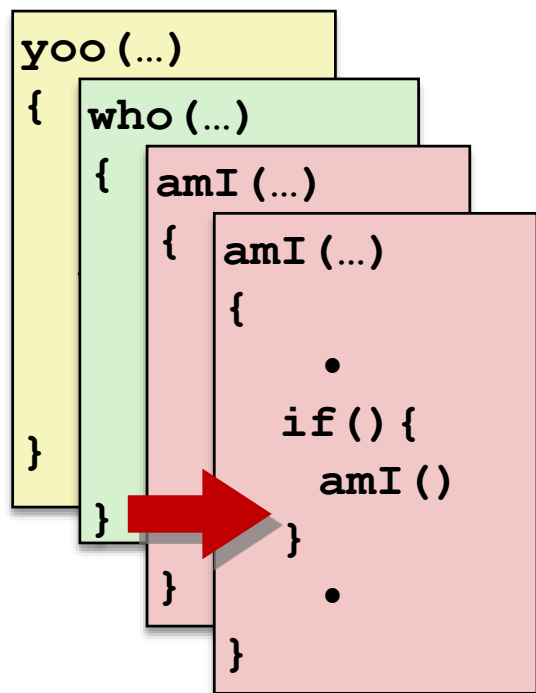
5) (another) Recursive call to amI (3)



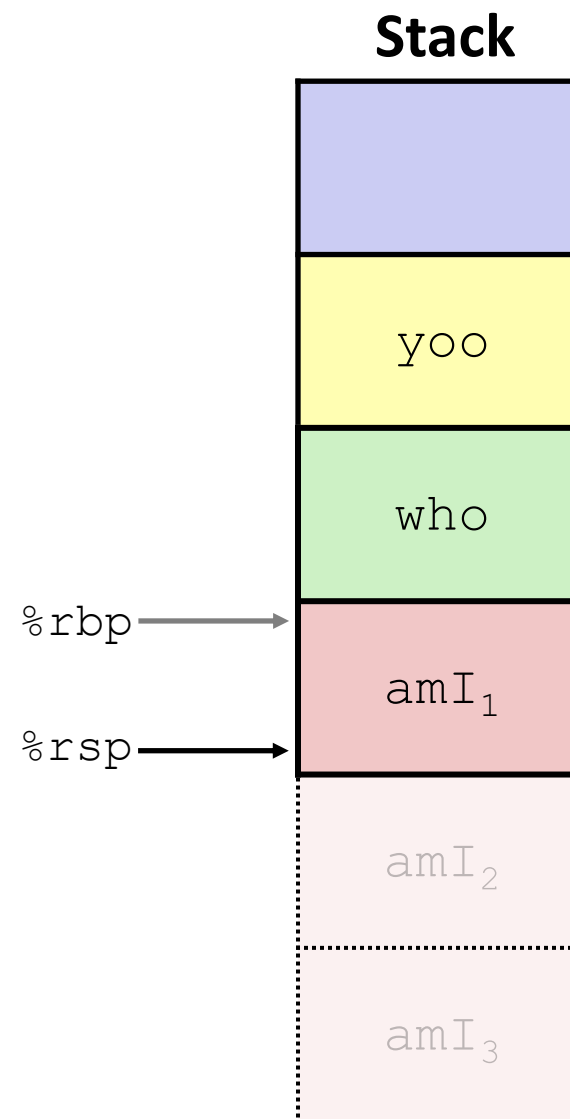
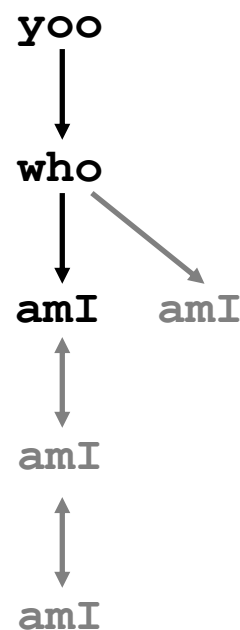
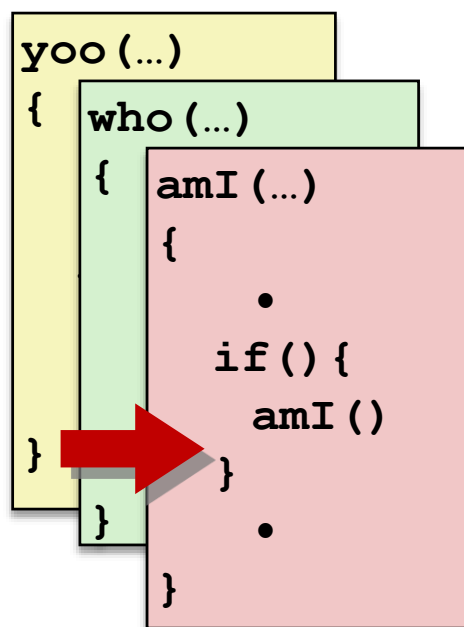
Stack



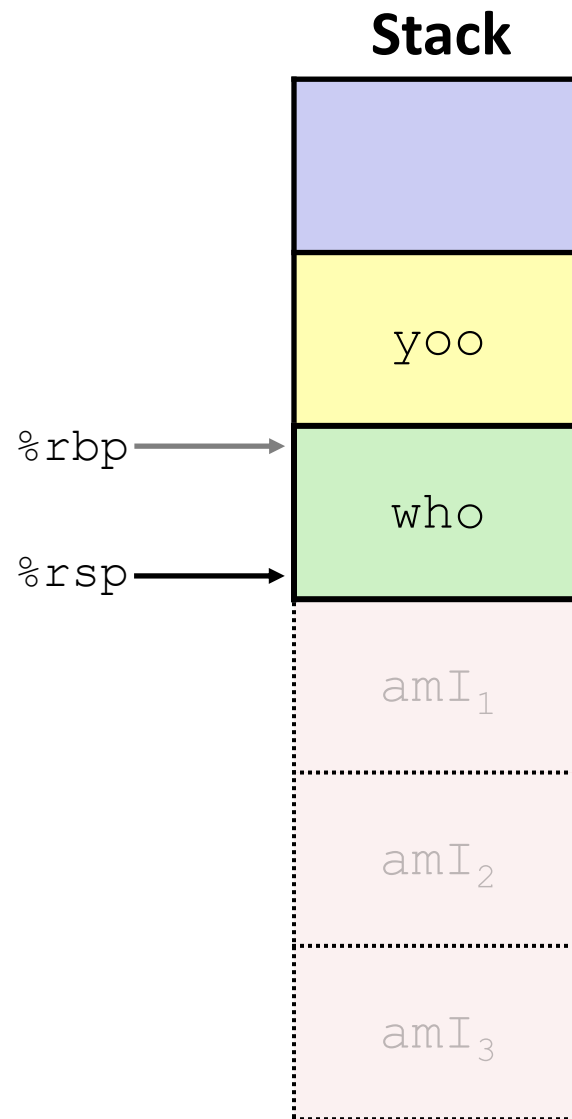
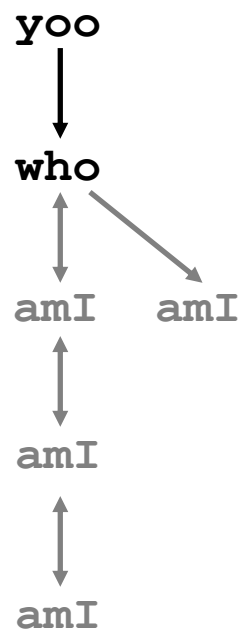
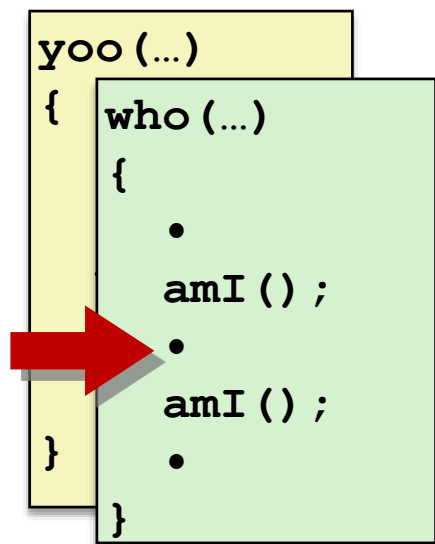
6) Return from (another) recursive call to amI



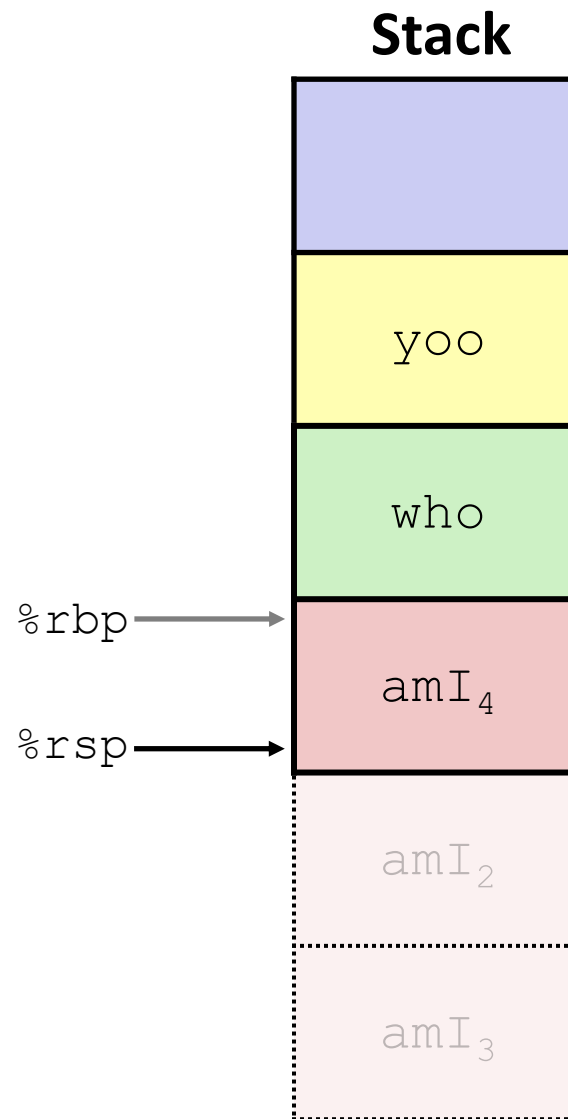
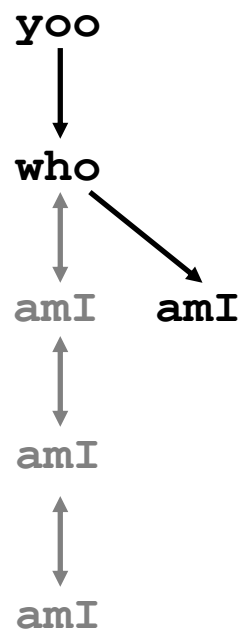
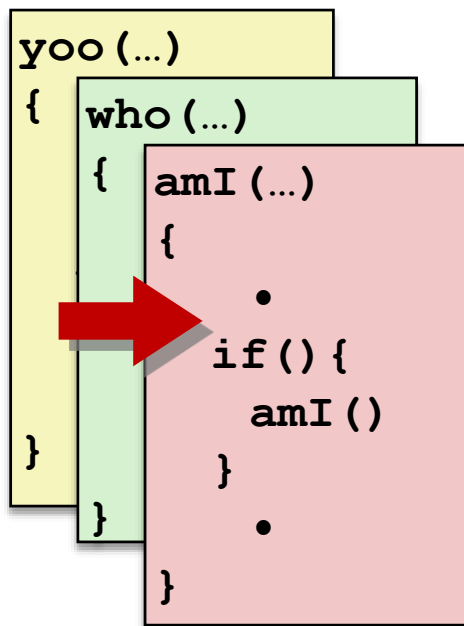
7) Return from recursive call to amI



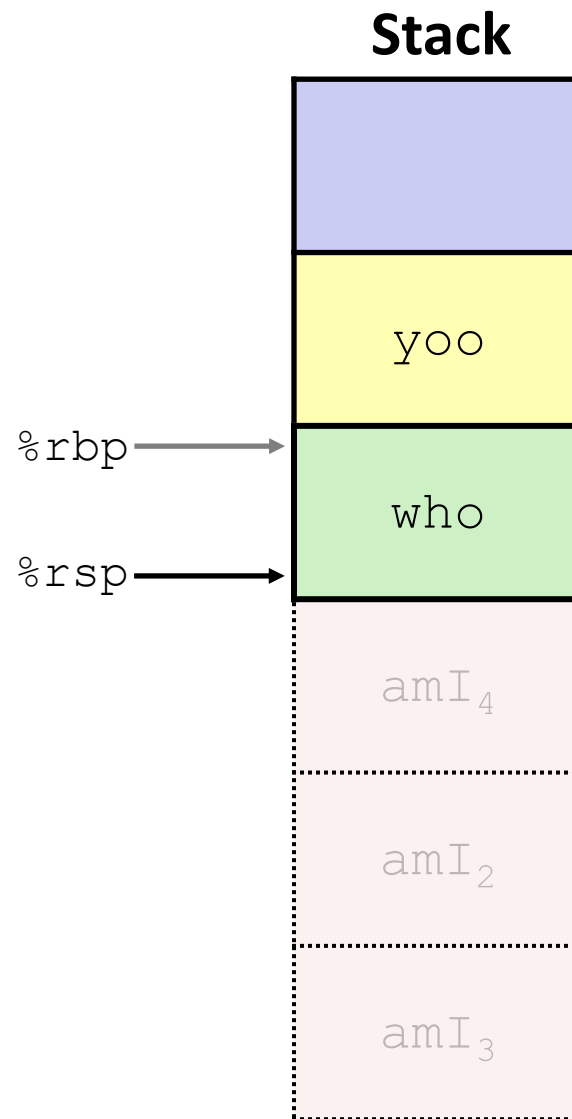
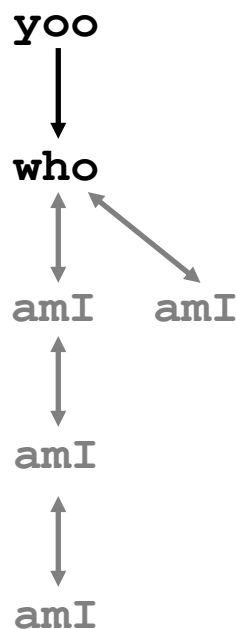
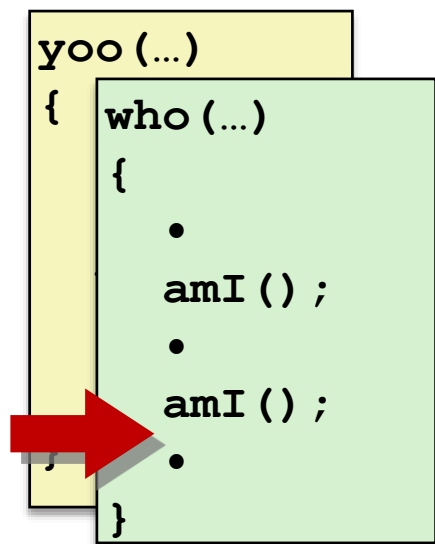
8) Return from call to amI



9) (second) Call to amI (4)




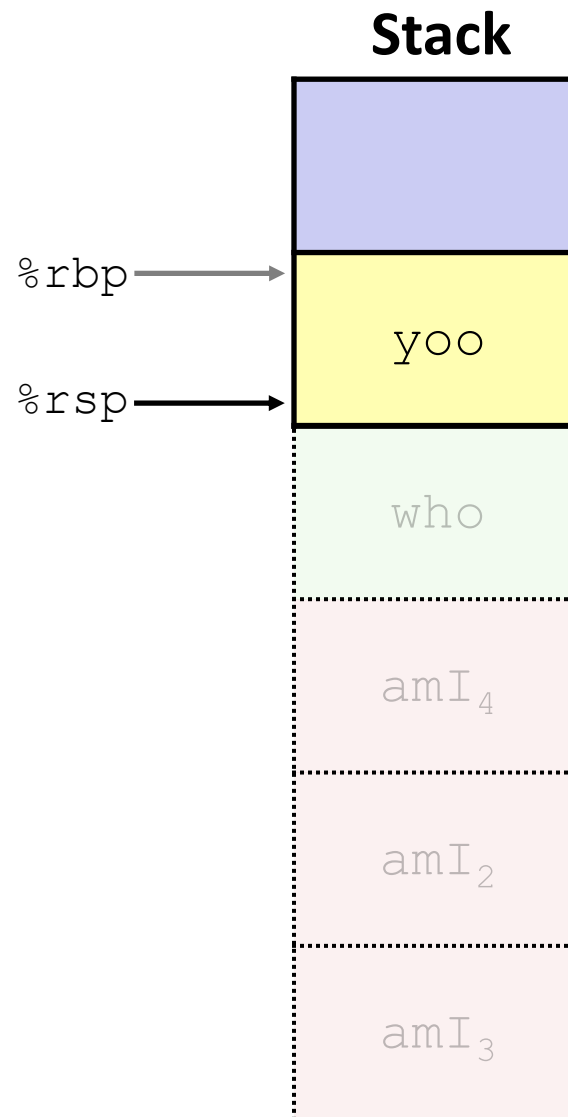
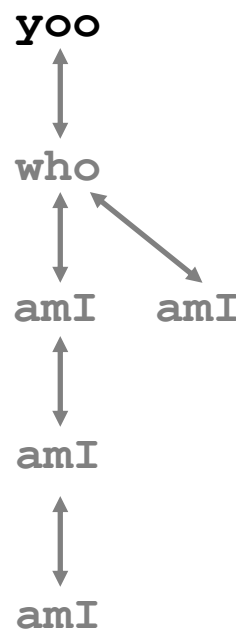
10) Return from (second) call to amI



11) Return from call to who

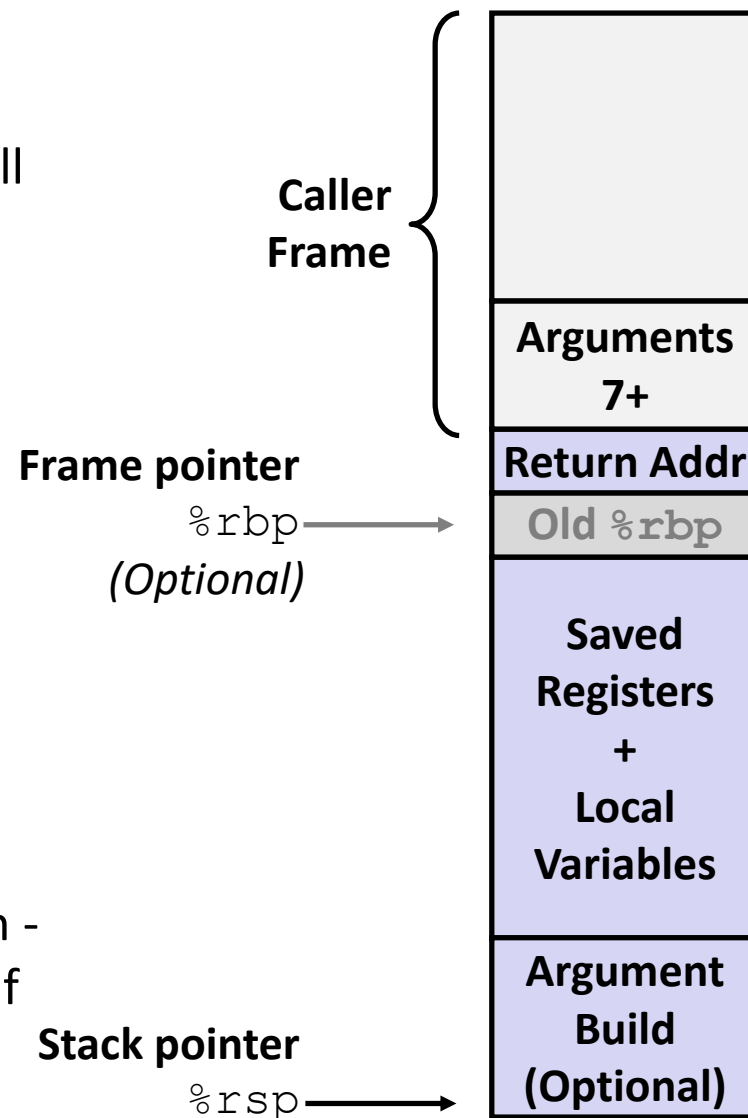
```

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

x86-64/Linux Stack Frame

- ❖ **Caller's Stack Frame**
 - Extra arguments (if > 6 args) for this call
- ❖ **Current/Callee Stack Frame**
 - Return address
 - Pushed by `call` instruction
 - Old frame pointer (optional)
 - Saved register context (when reusing registers)
 - Local variables (If can't be kept in registers)
 - "Argument build" area (If callee needs to call another function - parameters for function about to call, if needed)



Peer Instruction Question

Vote only on 3rd question at
<http://pollev.com/rea>

- ❖ Answer the following questions about when `main()` is run (assume `x` and `y` stored on the Stack):

```
int main() {
    int i, x = 0;
    for(i = 0; i < 3; i++)
        x = randSum(x);
    printf("x = %d\n", x);
    return 0;
}
```

```
int randSum(int n) {
    int y = rand() % 20;
    return n + y;
}
```

- *Higher/larger address:* `x` or `y`?
- How many total stack frames are *created*?
- What is the maximum *depth* (# of frames) of the Stack?

A. 1 B. 2 C. 3 D. 4