The Stack & Procedures

CSE 351 Summer 2019

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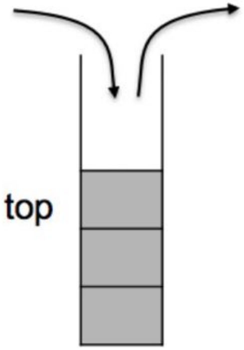
corn



stack

popcorn

Administrivia

- Homework 2 due TONIGHT Wednesday (7/17)
- Lab 2 (x86-64) due Monday (7/22)
- Homework 3, coming soon
  - On midterm material, but due after the midterm
- Section tomorrow on Assembly and GDB
  - Bring your laptops!
- **Midterm** (Fri 7/26, 10:50-11:50am)
  - You are allowed one double-sided, *handwritten* 8.5x11" sheet of notes
  - Find a study group! Look at past exams!
  - Review session: Wednesday, 7/24, 4-6pm, location TBD

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();
```

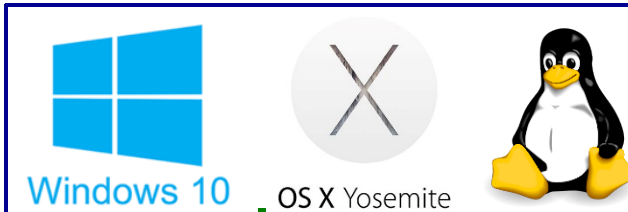
Assembly language:

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

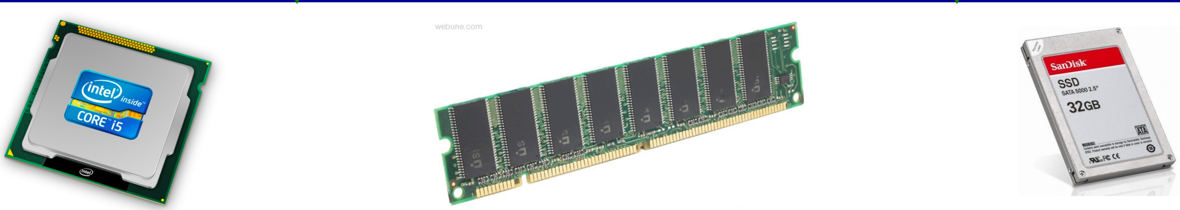
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:



Computer system:

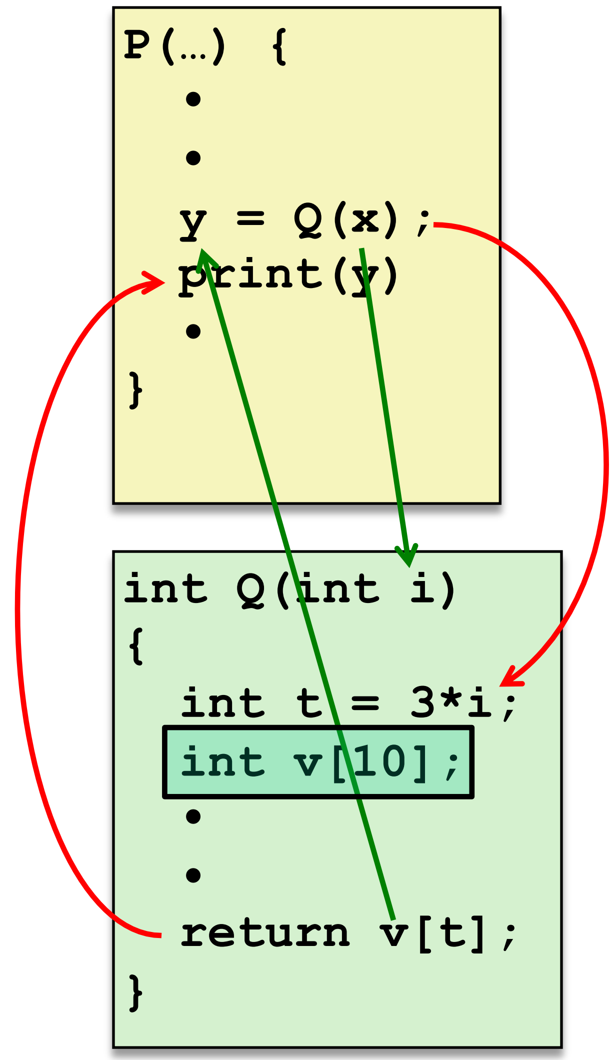


- Memory & data
- Integers & floats
- x86 assembly
- **Procedures & stacks**
- Executables
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

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
   - De-allocate upon return

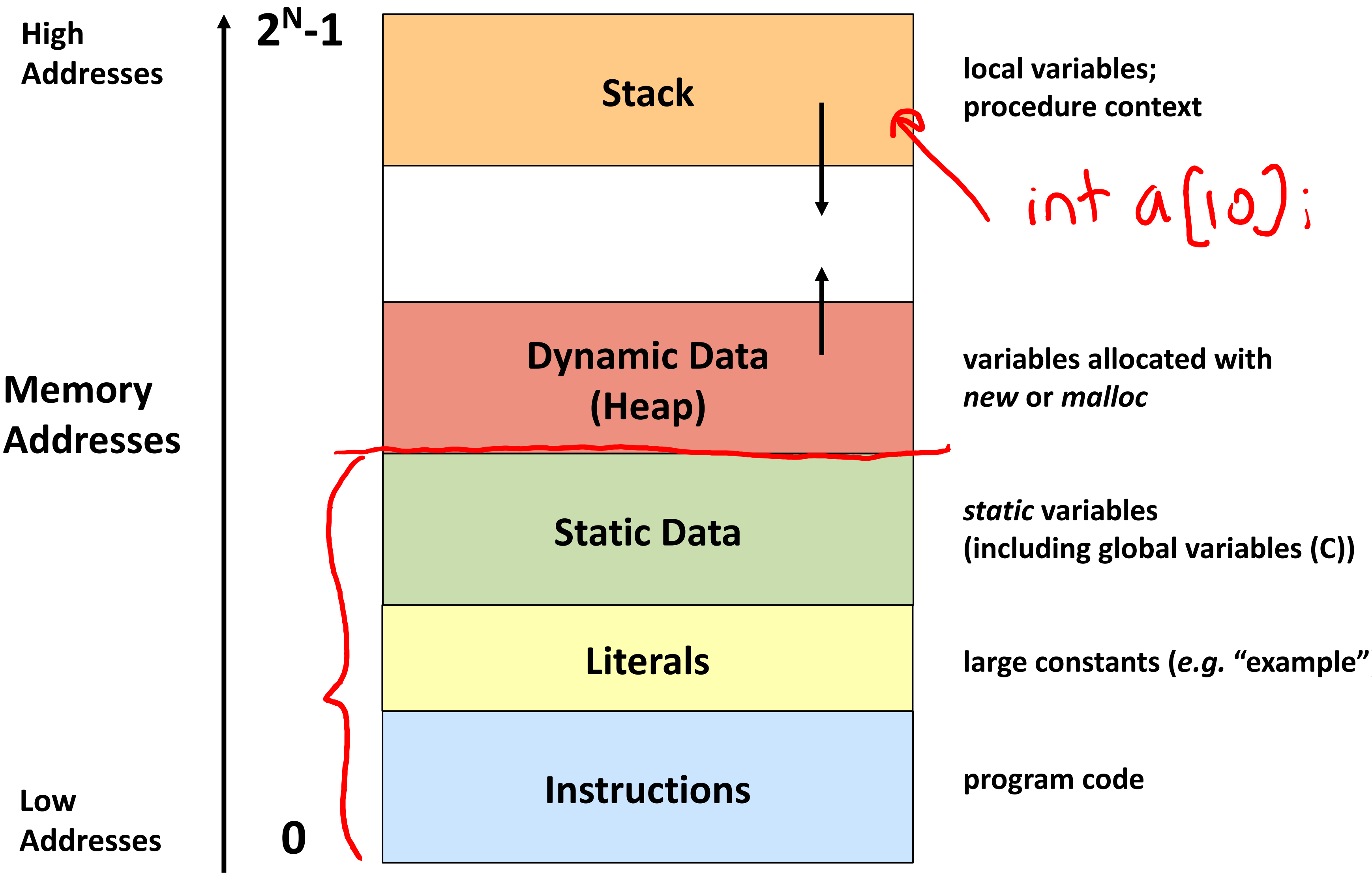
- All implemented with machine instructions!
  - An x86-64 procedure uses only those mechanisms required for that procedure



Procedures

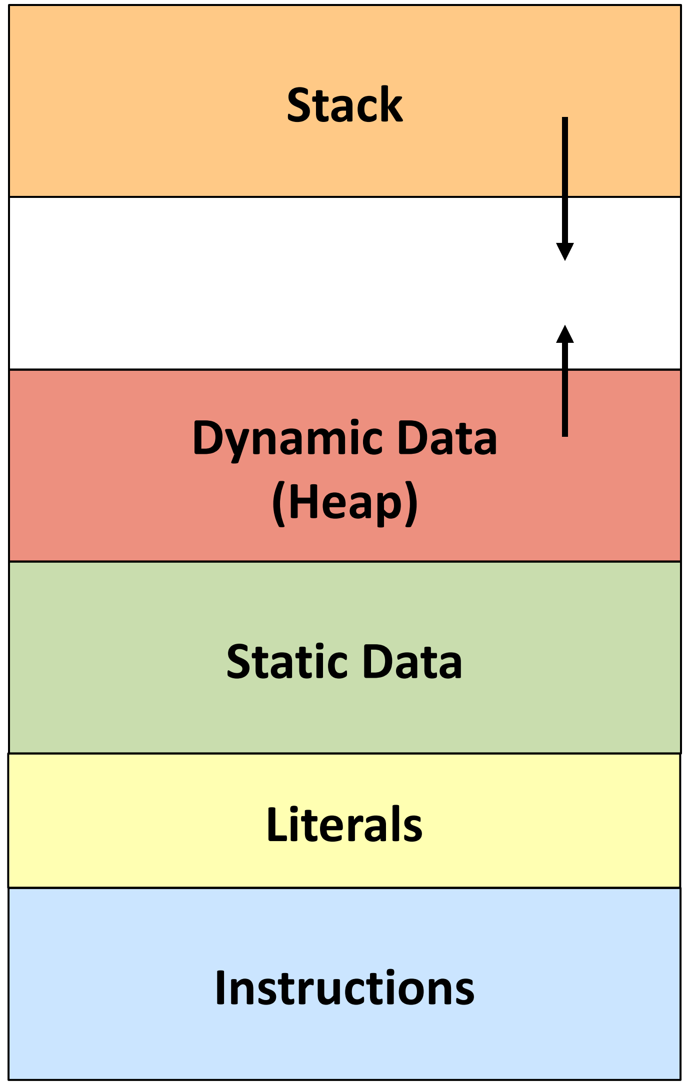
- **Stack Structure**
- Calling Conventions
  - Passing control
  - Passing data
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

Simplified Memory Layout



segmentation faults?

Memory Permissions



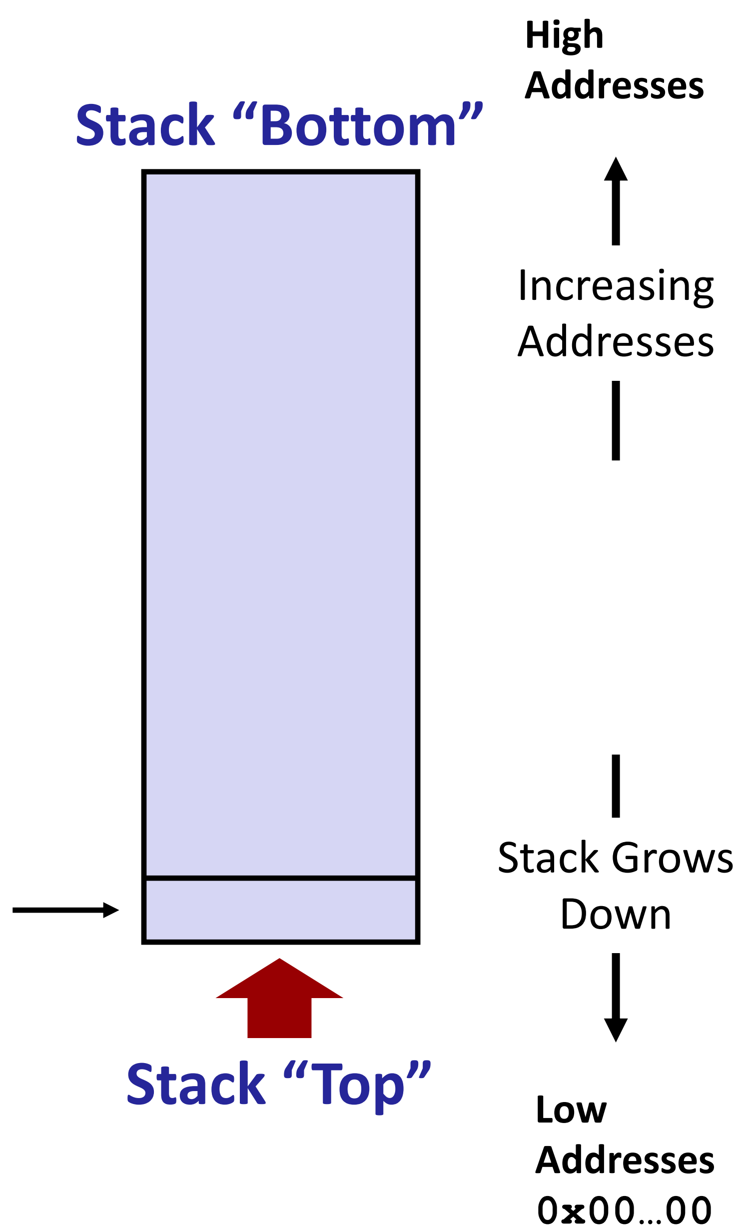
writable; not executable	Stack	Managed "automatically" (by compiler)
writable; not executable	Dynamic Data (Heap)	Managed by programmer
writable; not executable	Static Data	Initialized when process starts
read-only; not executable	Literals	Initialized when process starts
read-only; executable	Instructions	Initialized when process starts

x86-64 Stack

- Region of memory managed with stack "discipline"
  - Grows toward lower addresses
  - Customarily shown "upside-down"

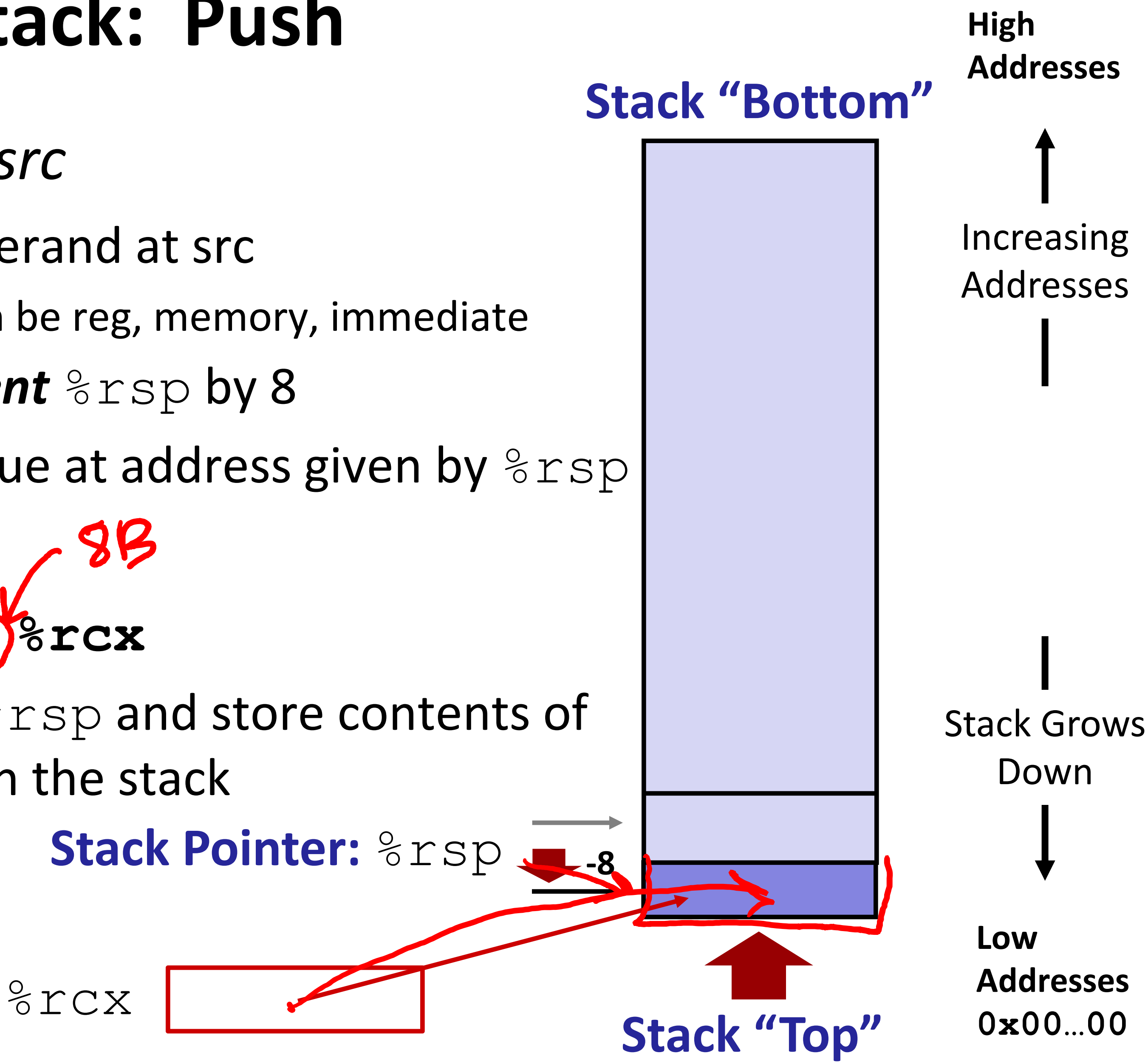
- Register `%rsp` contains *lowest* stack address
  - `%rsp` = address of *top* element, the most-recently-pushed item that is not-yet-popped

Stack Pointer: `%rsp`



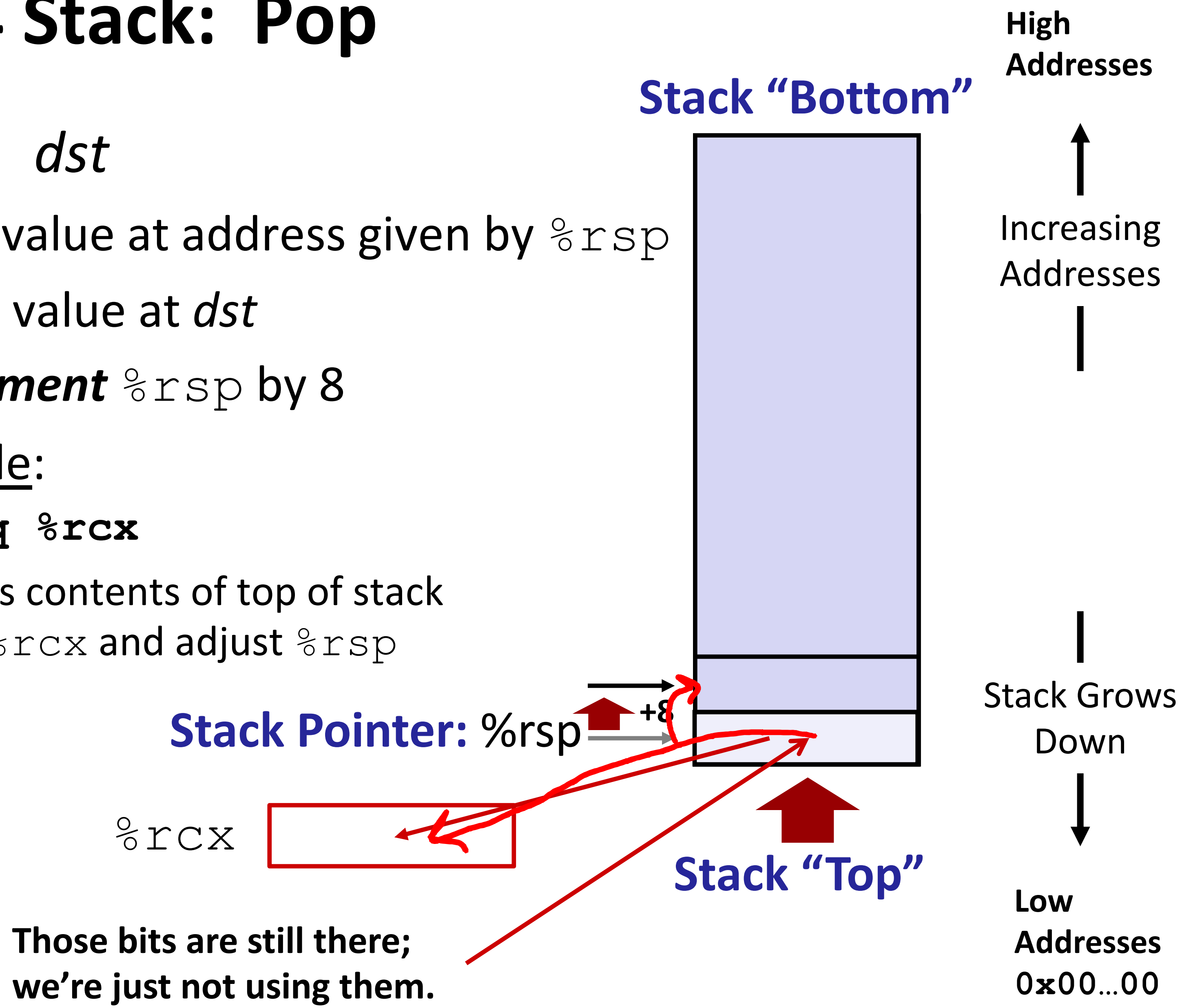
x86-64 Stack: Push

- `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



x86-64 Stack: Pop

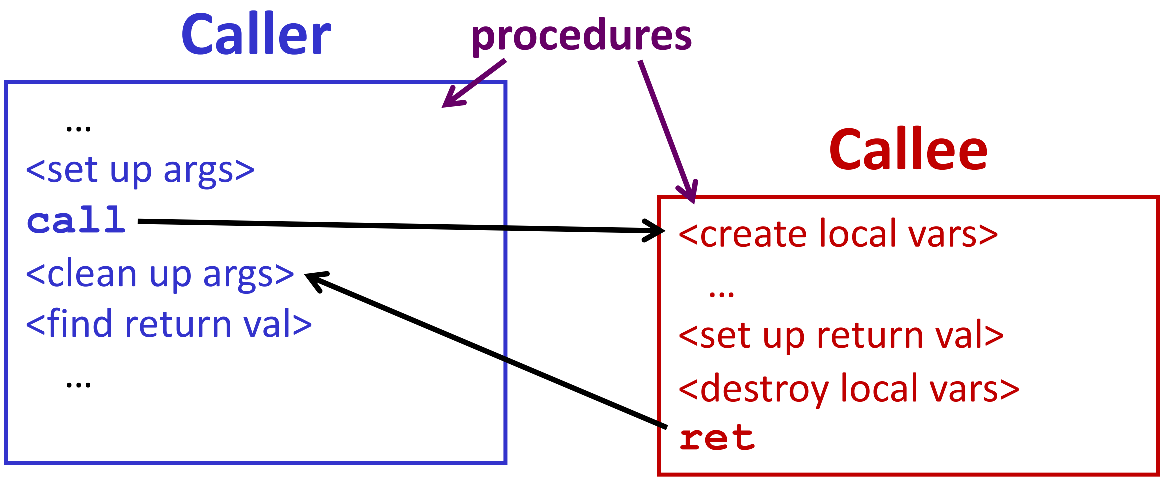
- `popq` *dst*
  - Load value at address given by `%rsp`
  - Store value at *dst*
  - ***Increment*** `%rsp` by 8
- <u>Example</u>:
  - **`popq %rcx`**
  - Stores contents of top of stack into `%rcx` and adjust `%rsp`



Procedures

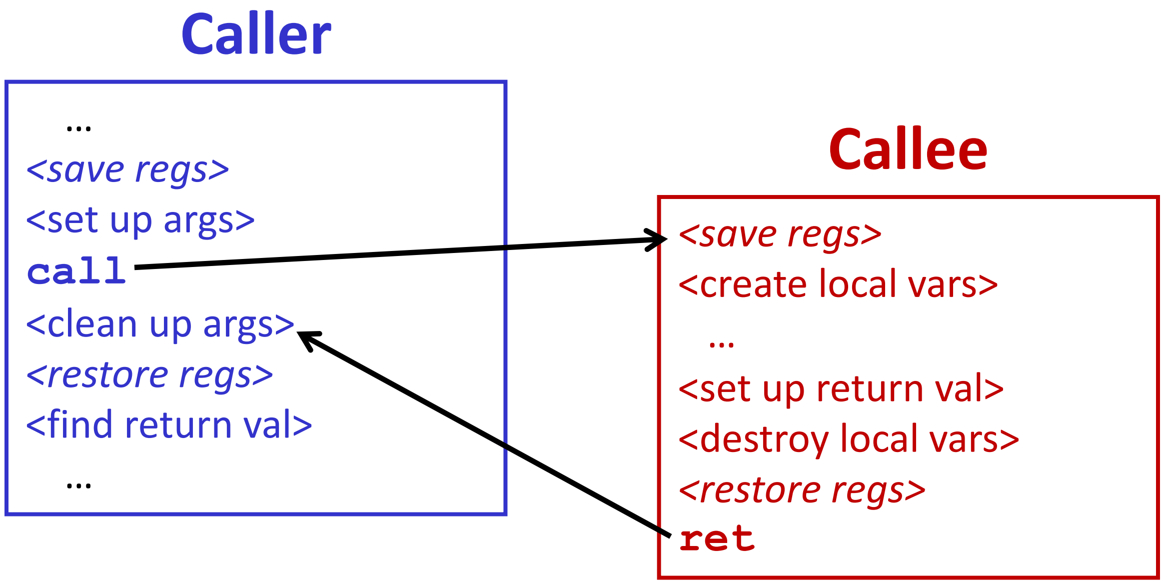
- Stack Structure
- **Calling Conventions**
  - **Passing control**
  - Passing data
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

Procedure Call Overview



- **Callee** must know where to find args
- **Callee** must know where to find *return <u>address</u>*
- **Caller** must know where to find *return <u>value</u>*
- **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`**

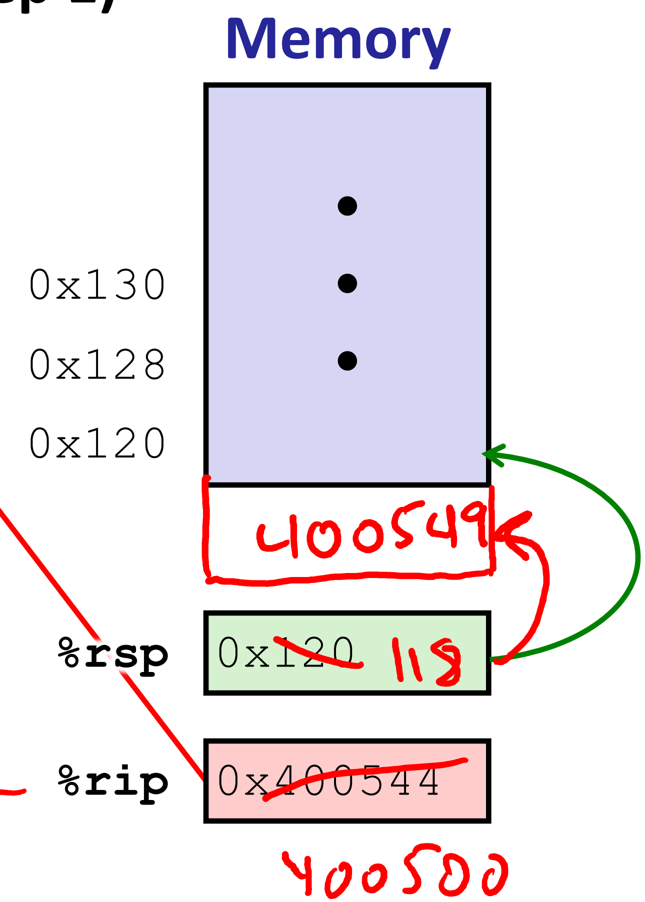
next instruction happens to be a move, but could be anything

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

Procedure Call Example (step 1)

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

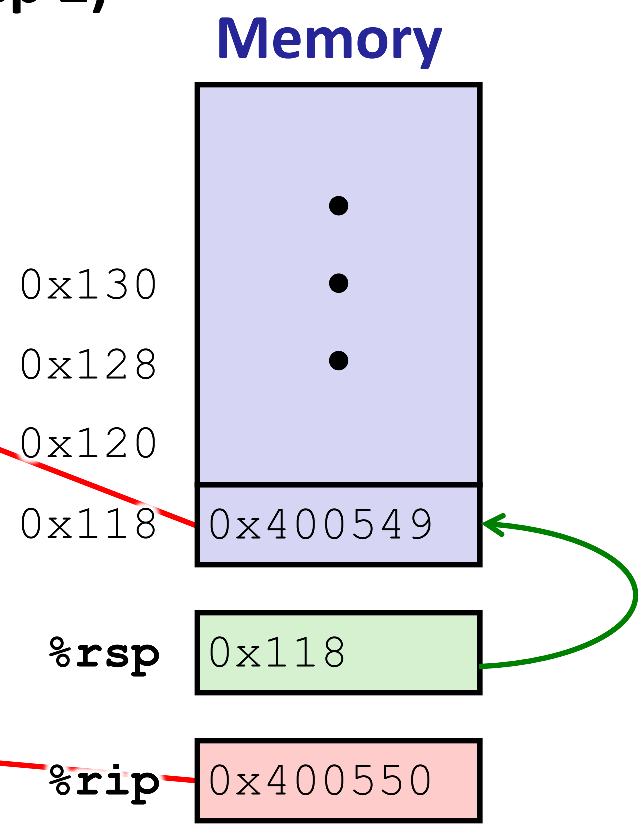
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



Procedure Call Example (step 2)

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

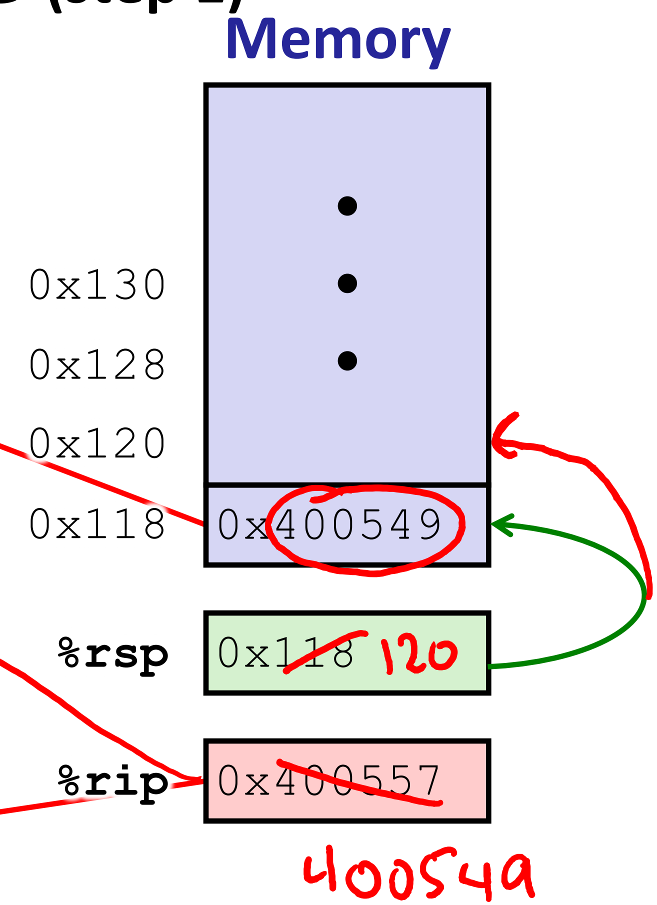
```
0000000000400550 <mult2>:
   400550:  movq    %rdi,%rax
   •
   •
   400557:  ret
```



Procedure Return Example (step 1)

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

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

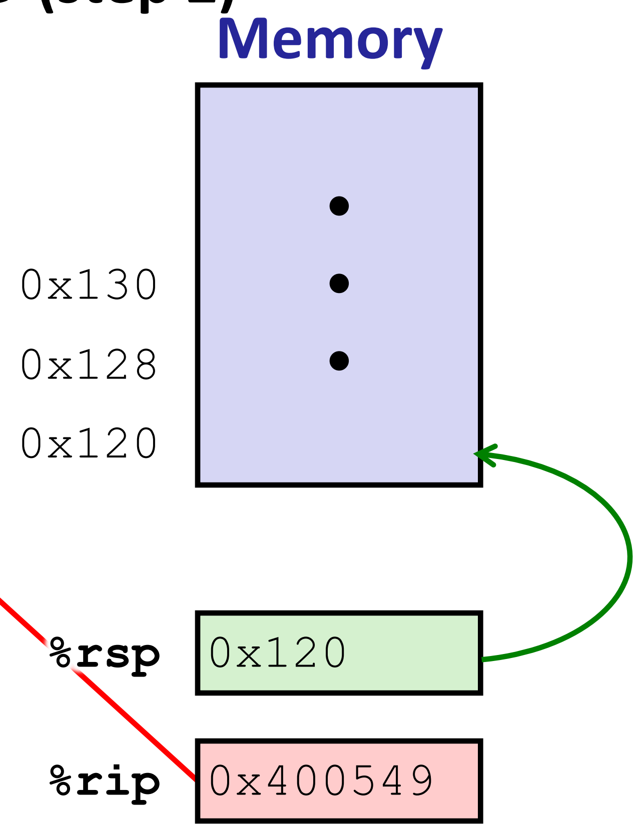


pop %rip

Procedure <u>Return</u> Example (step 2)

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

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



Procedures

- Stack Structure
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Procedure Data Flow

Registers (NOT in Memory)

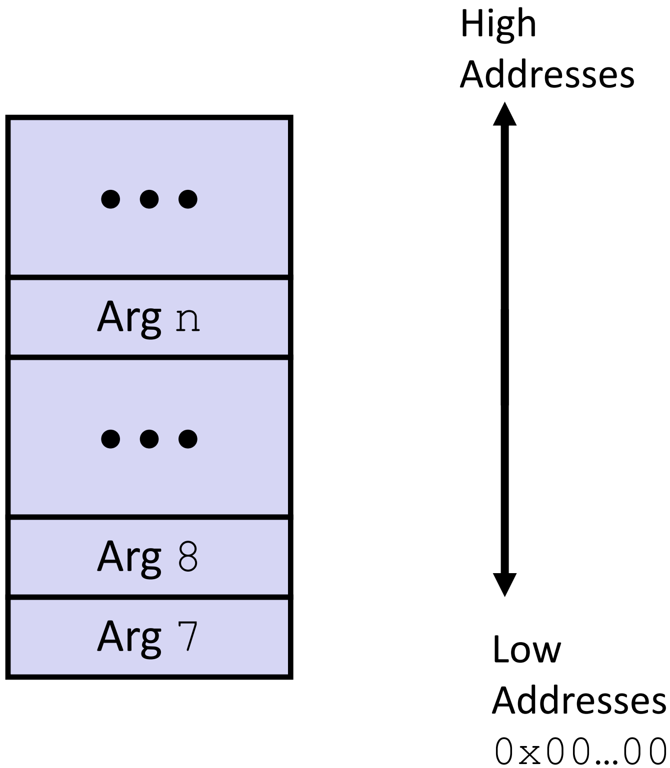
- First 6 arguments

Register	Mnemonic
`%rdi`	***D**iane's*
`%rsi`	***S**ilk*
`%rdx`	***D**ress*
`%rcx`	***C**osts*
`%r8`	*$**8**
`%r9`	***9***

- Return value

`%rax`

Stack (Memory)



- 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;
}
```

```
0000000000400540 <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;
}
```

```
0000000000400550 <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
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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

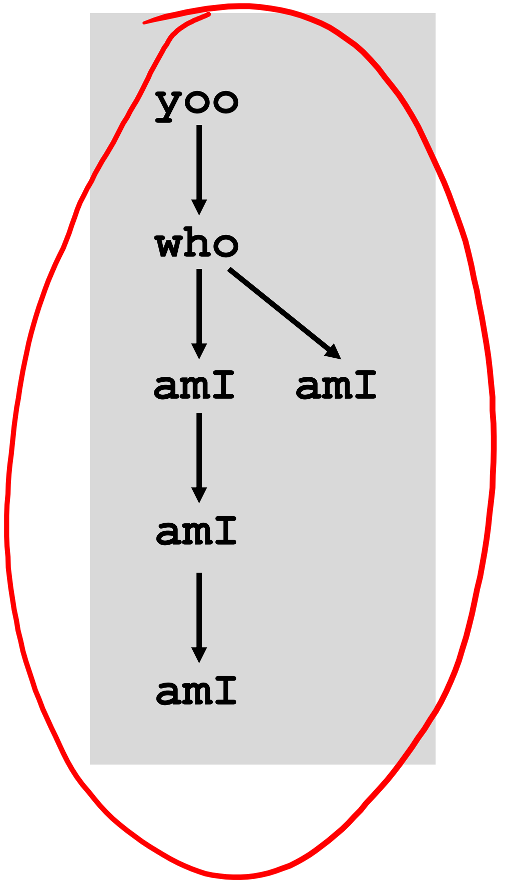
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

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

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

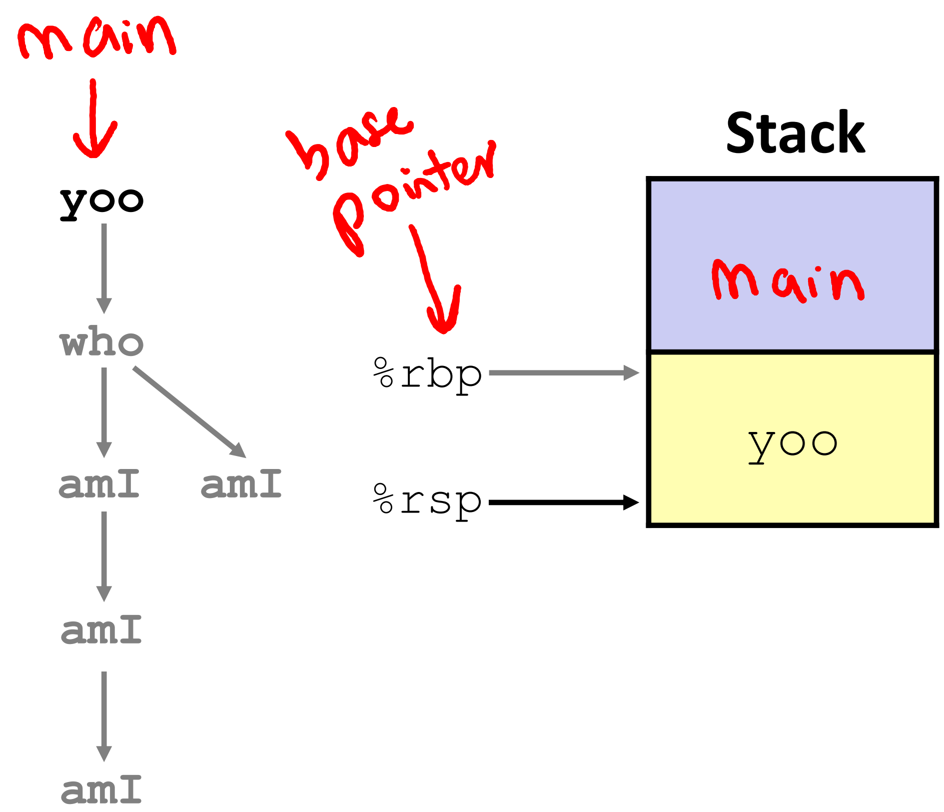
Procedure amI is recursive
(calls itself)

Example
Call Chain

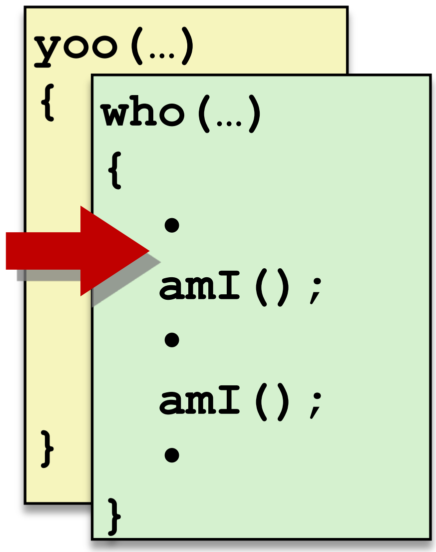


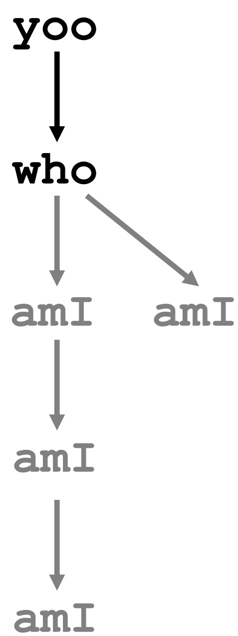
1) Call to yoo

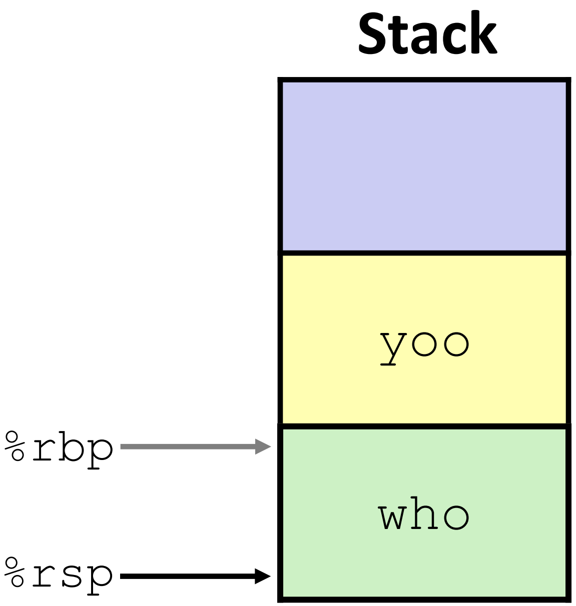
```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```



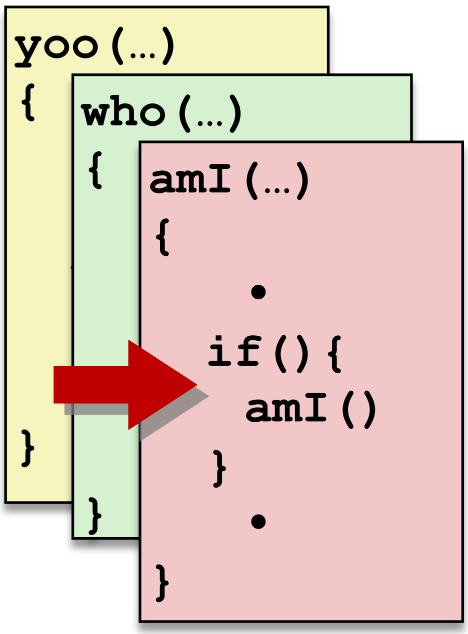
2) Call to who

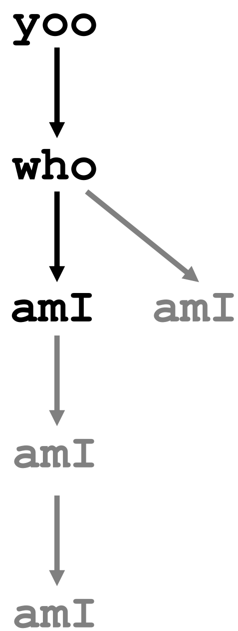


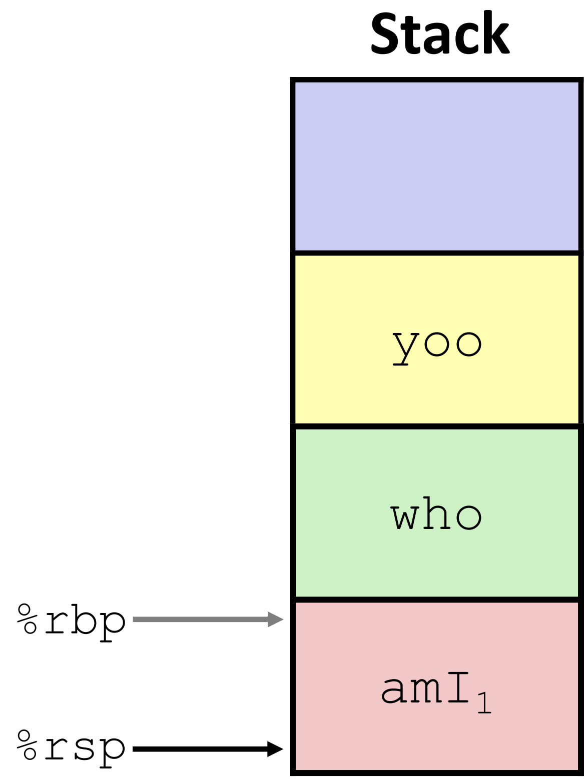




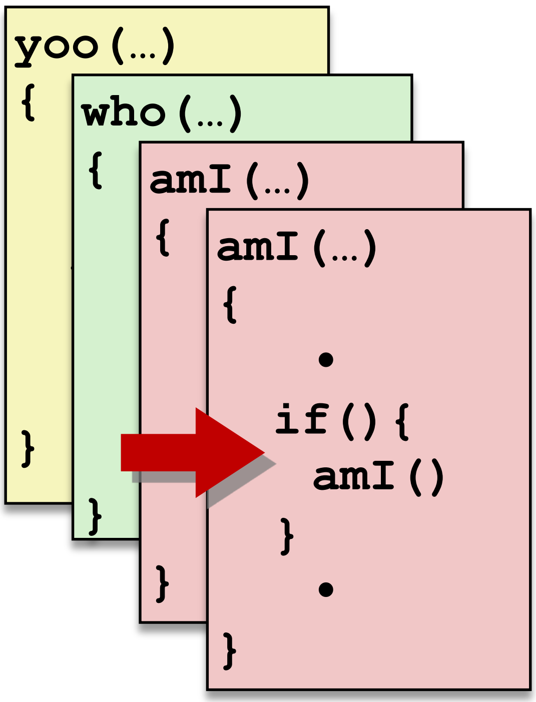
3) Call to amI (1)

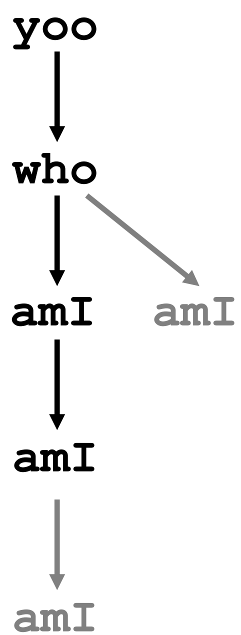


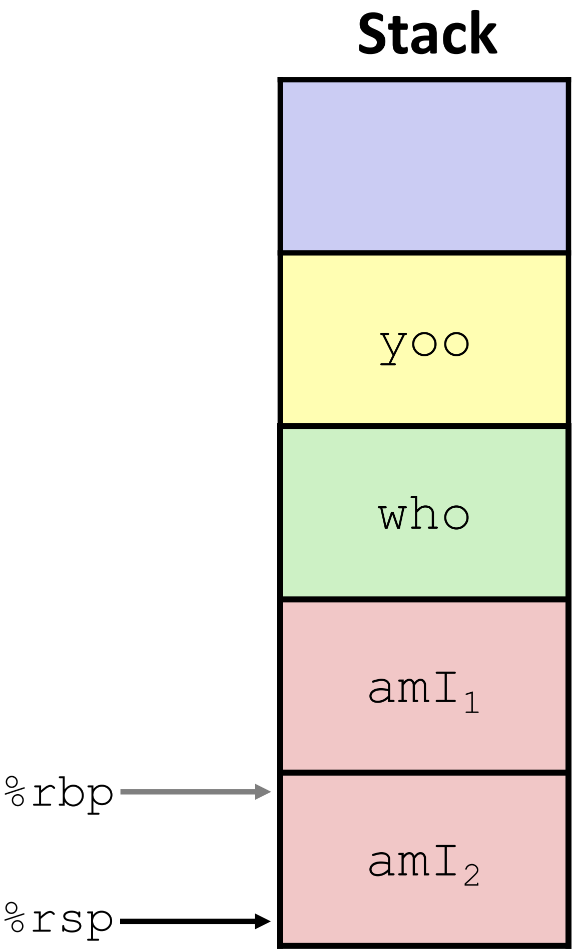




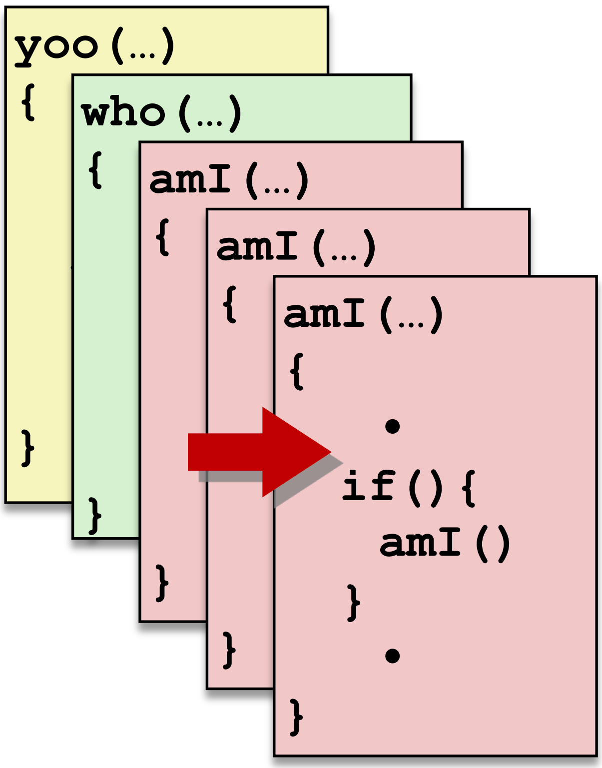
4) Recursive call to amI (2)

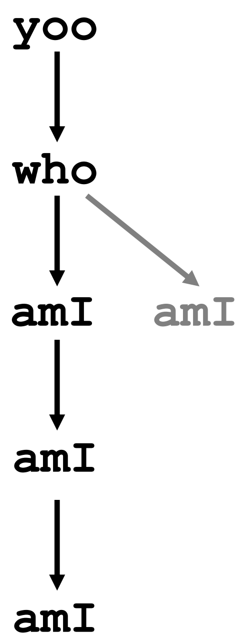


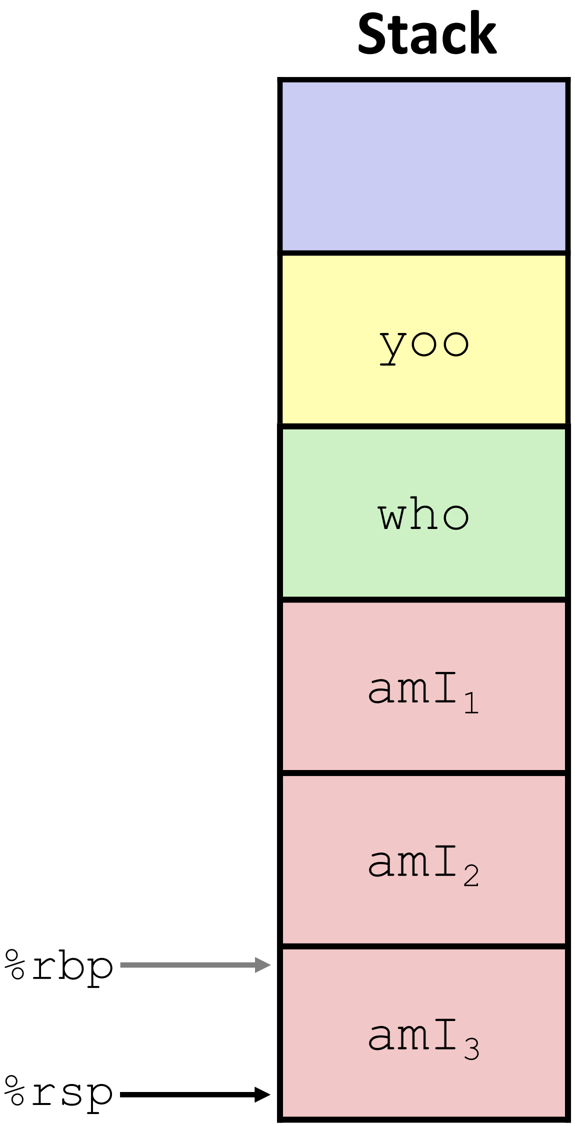




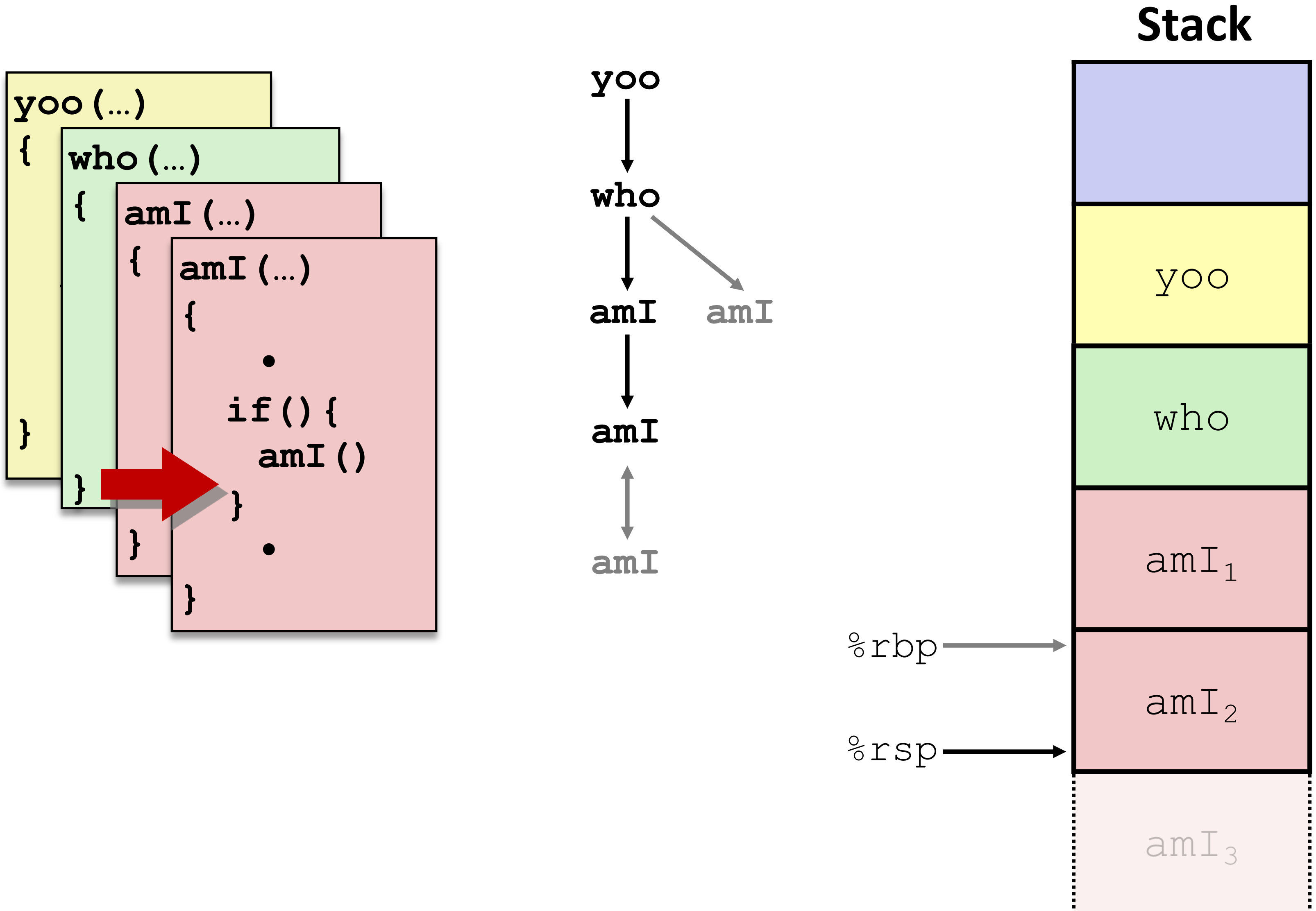
5) (another) Recursive call to `amI` (3)



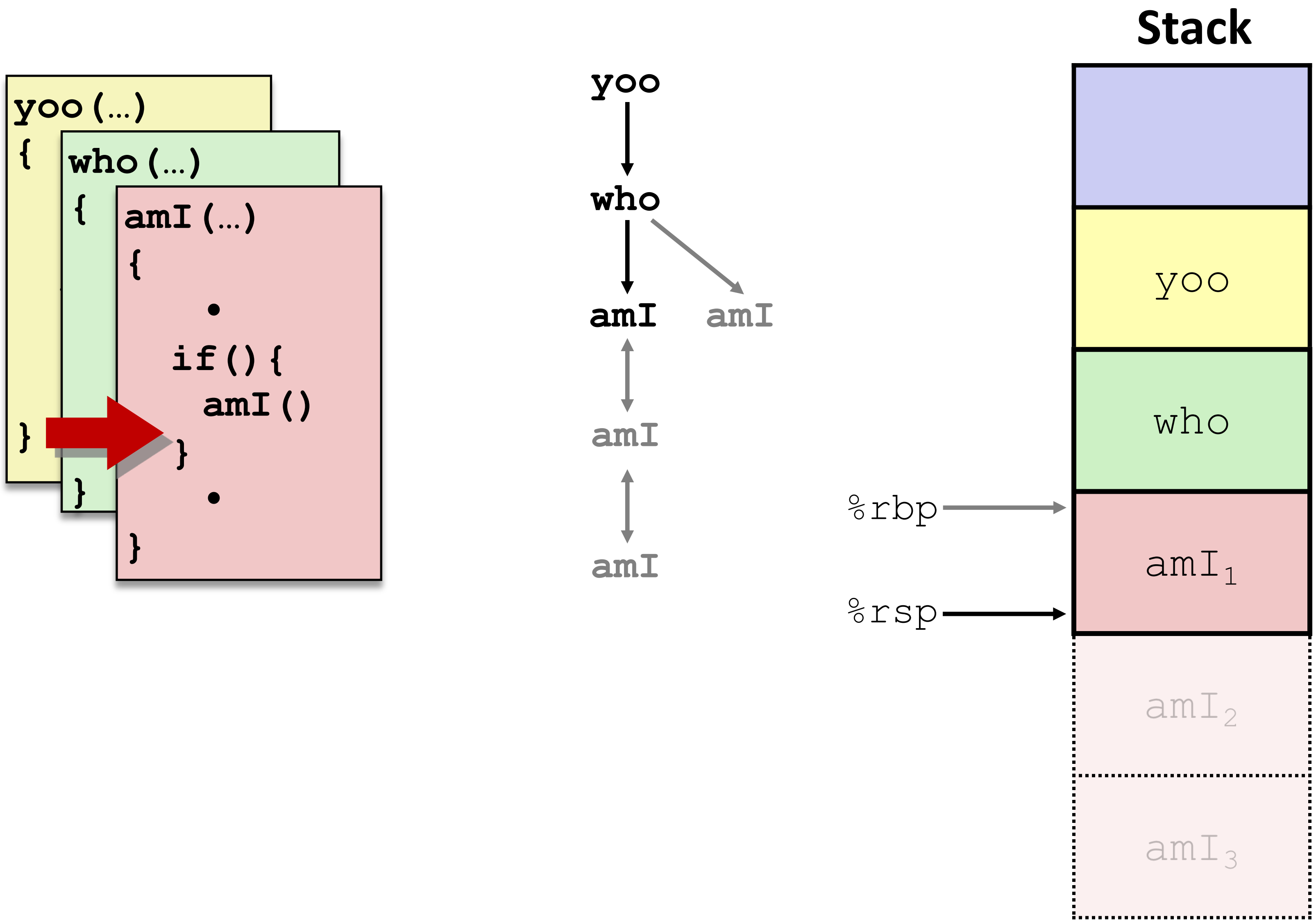




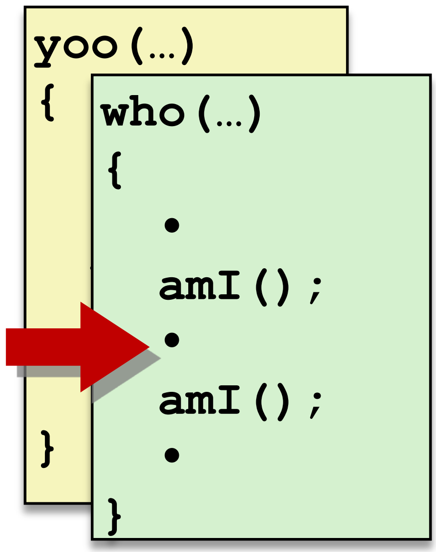
6) Return from (another) recursive call to amI

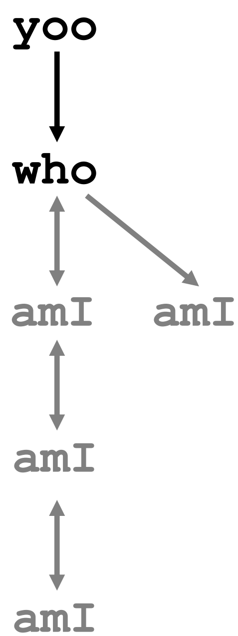


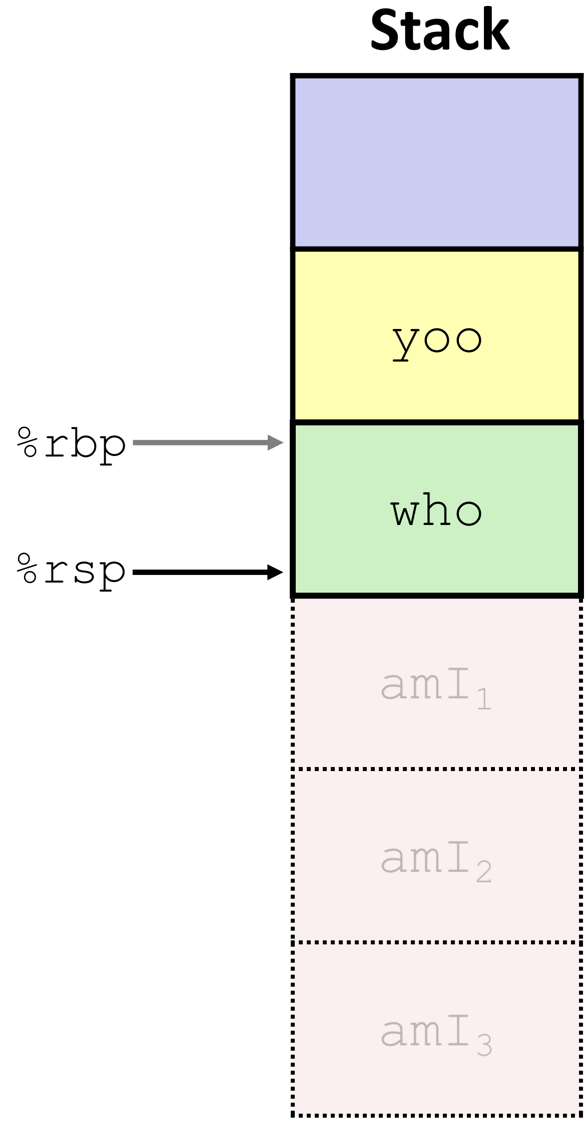
7) Return from recursive call to `amI`



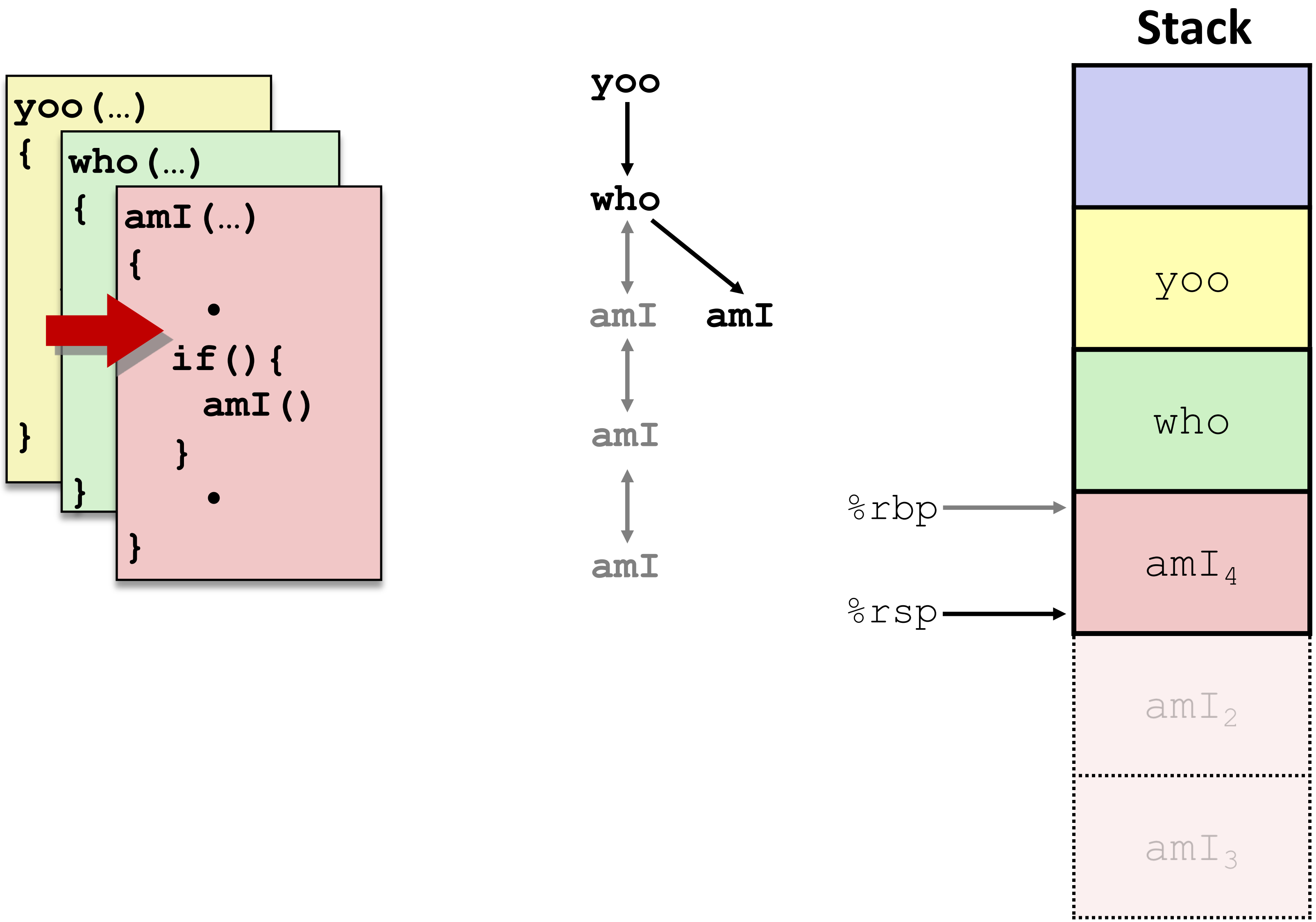
8) Return from call to `amI`



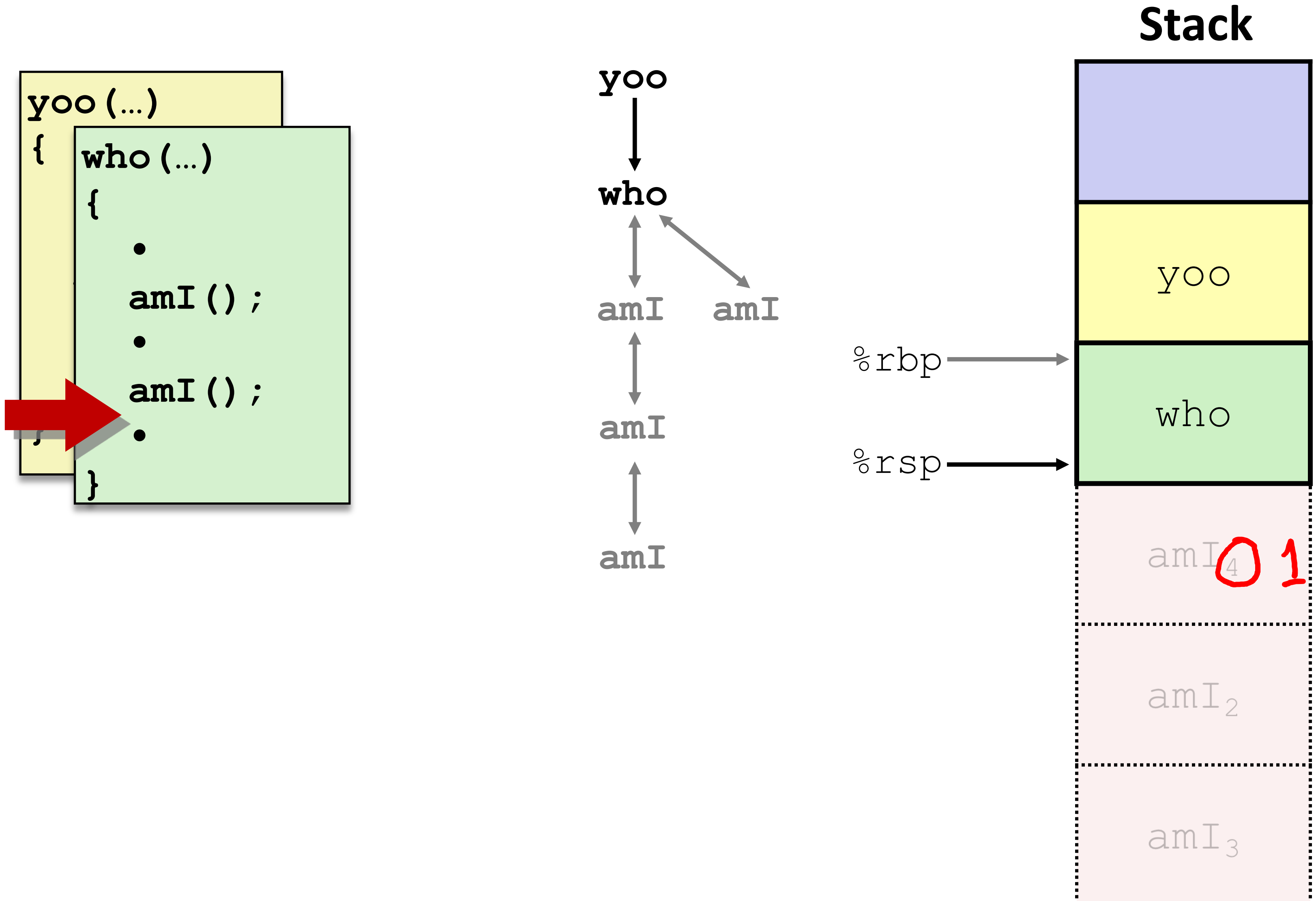




9) (second) Call to amI (4)

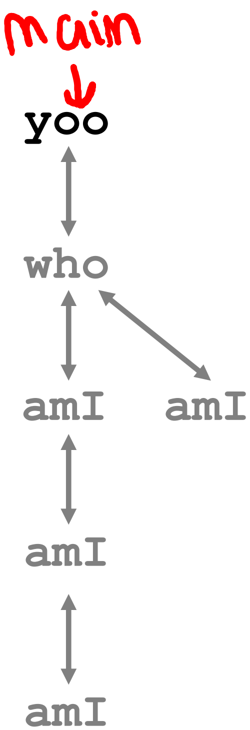


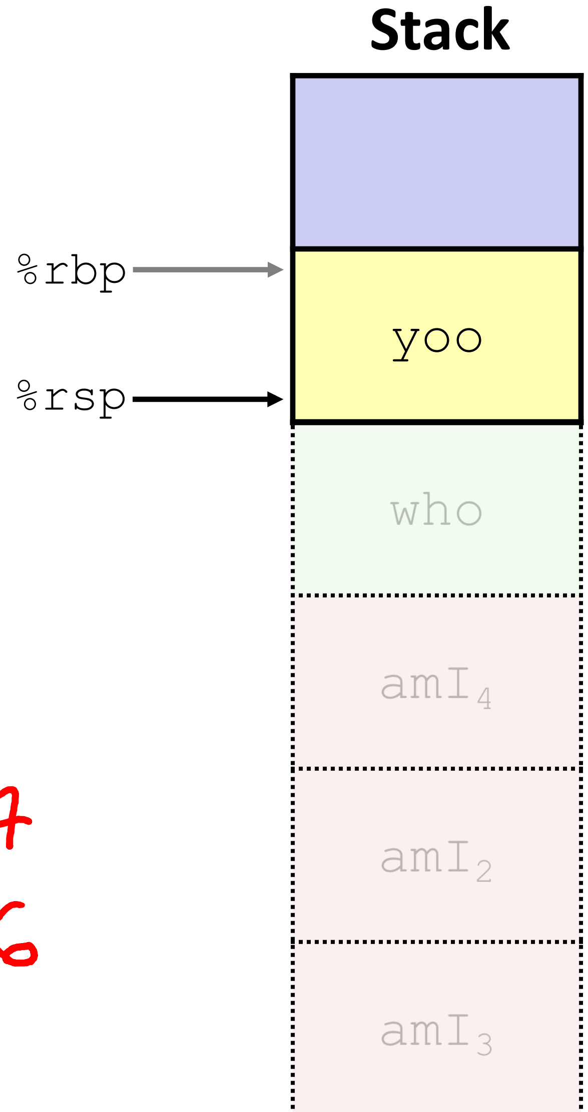
10) Return from (second) call to amI



11) Return from call to who

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



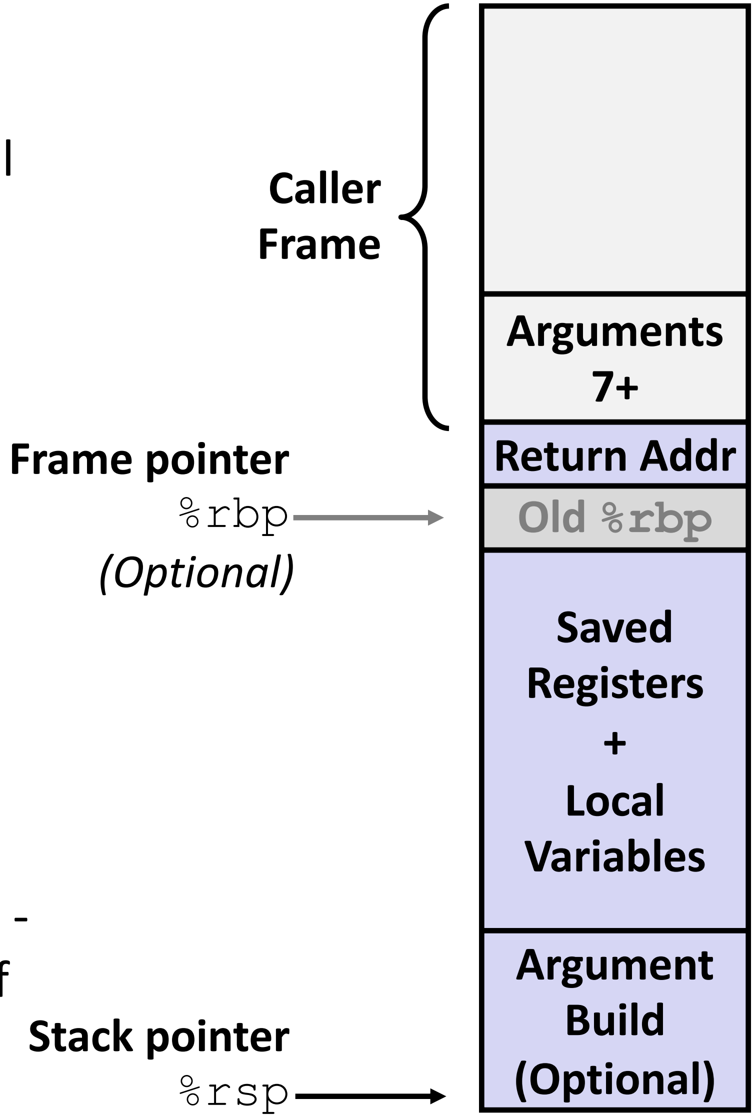


total frames: 7

max depth: 6

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

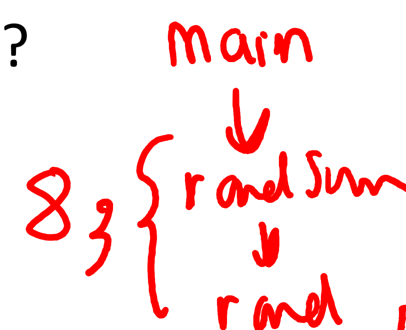
Vote only on 3rd question at http://pollev.com/wolfson

- 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