The Hardware/Software Interface

Procedures I

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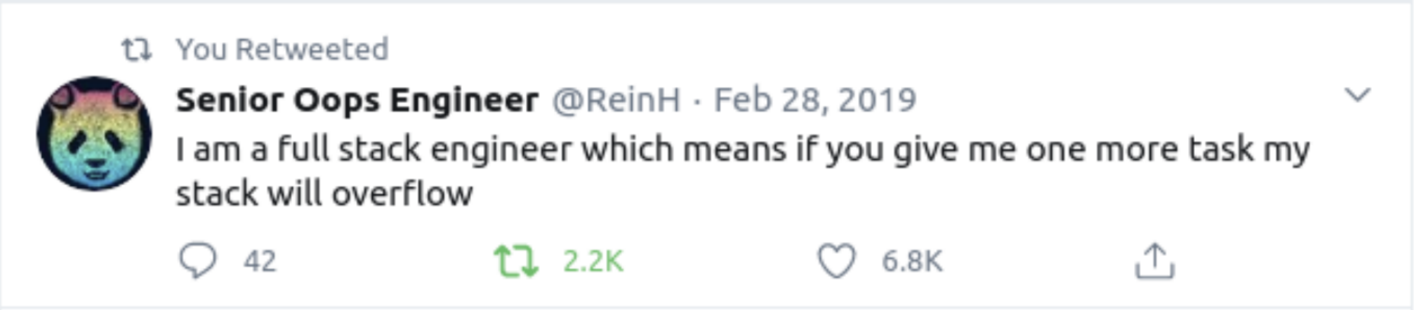


Relevant Course Information

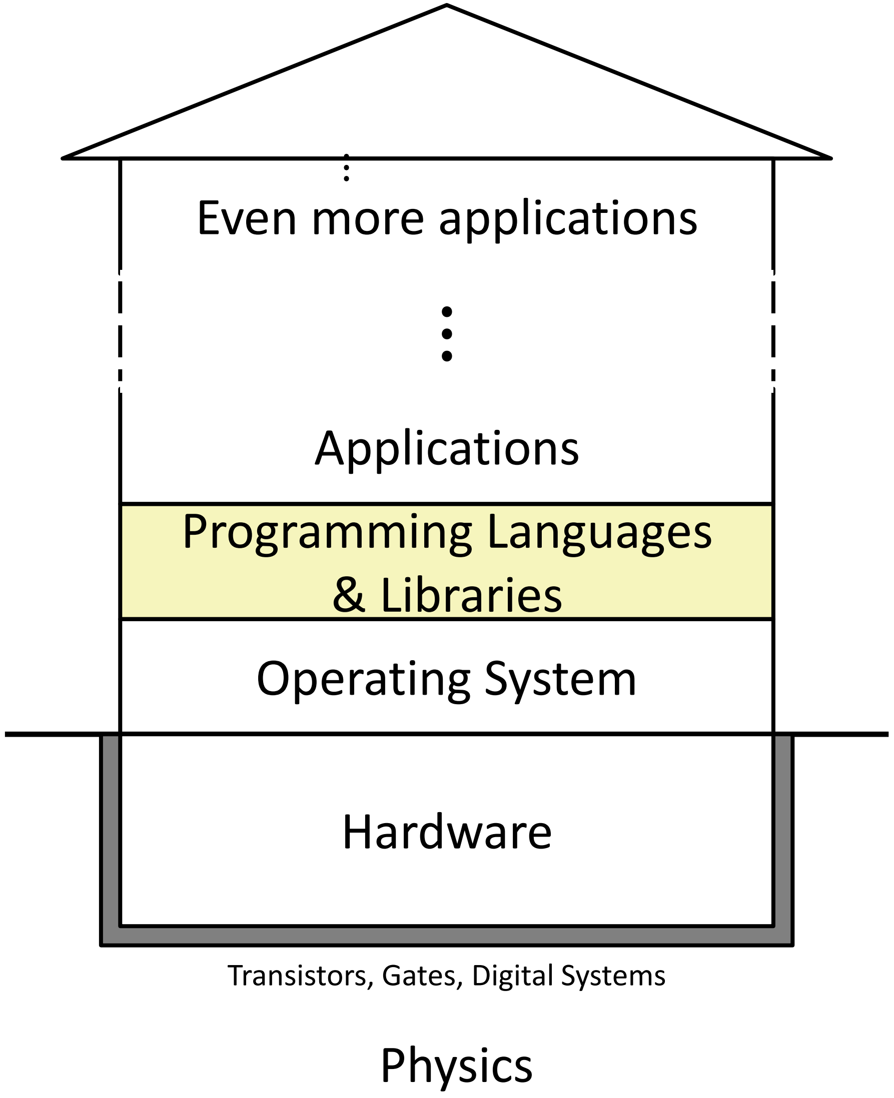
- Lab 2 due next Friday (10/24)
  - Can start in earnest after today's lecture!
  - See GDB Tutorial Lesson and and Phase 1 walkthrough in Section 4 Lesson

- Midterm: 10/27, 5:30 pm in ARC 147, CSE2 G20, SIG 134
  - You will be provided a fresh midterm reference sheet
  - You get 1 *handwritten*, double-sided cheat sheet (letter-size)
  - Form study groups and look at past exams!

House of Computing Check-In

- Topic Group 2: **Programs**
  - x86-64 Assembly, **Procedures**, **Stacks**, Executables

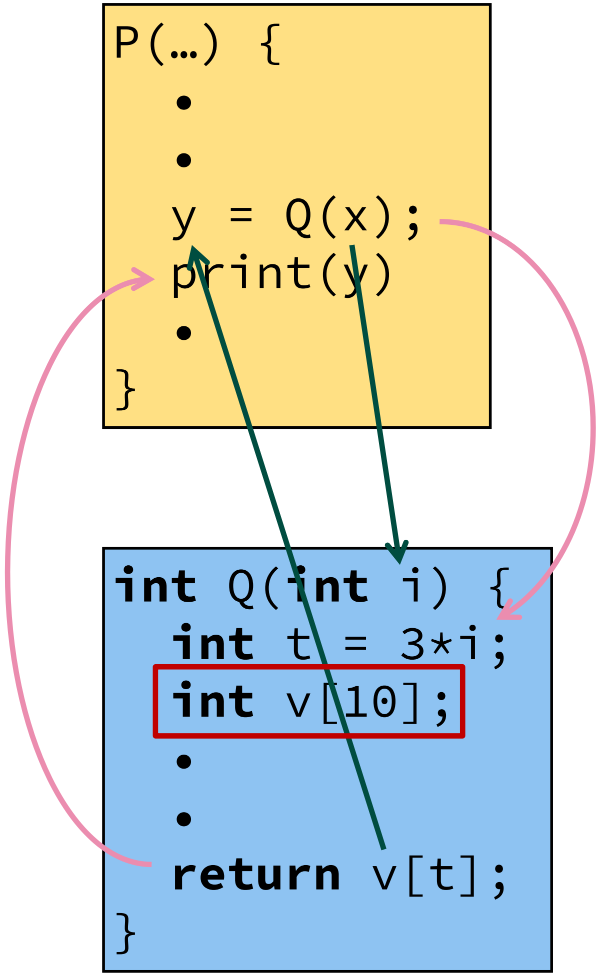
- How are programs created and executed on a CPU?
  - How does your source code become something that your computer understands?
  - How does the CPU organize and manipulate local data?



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

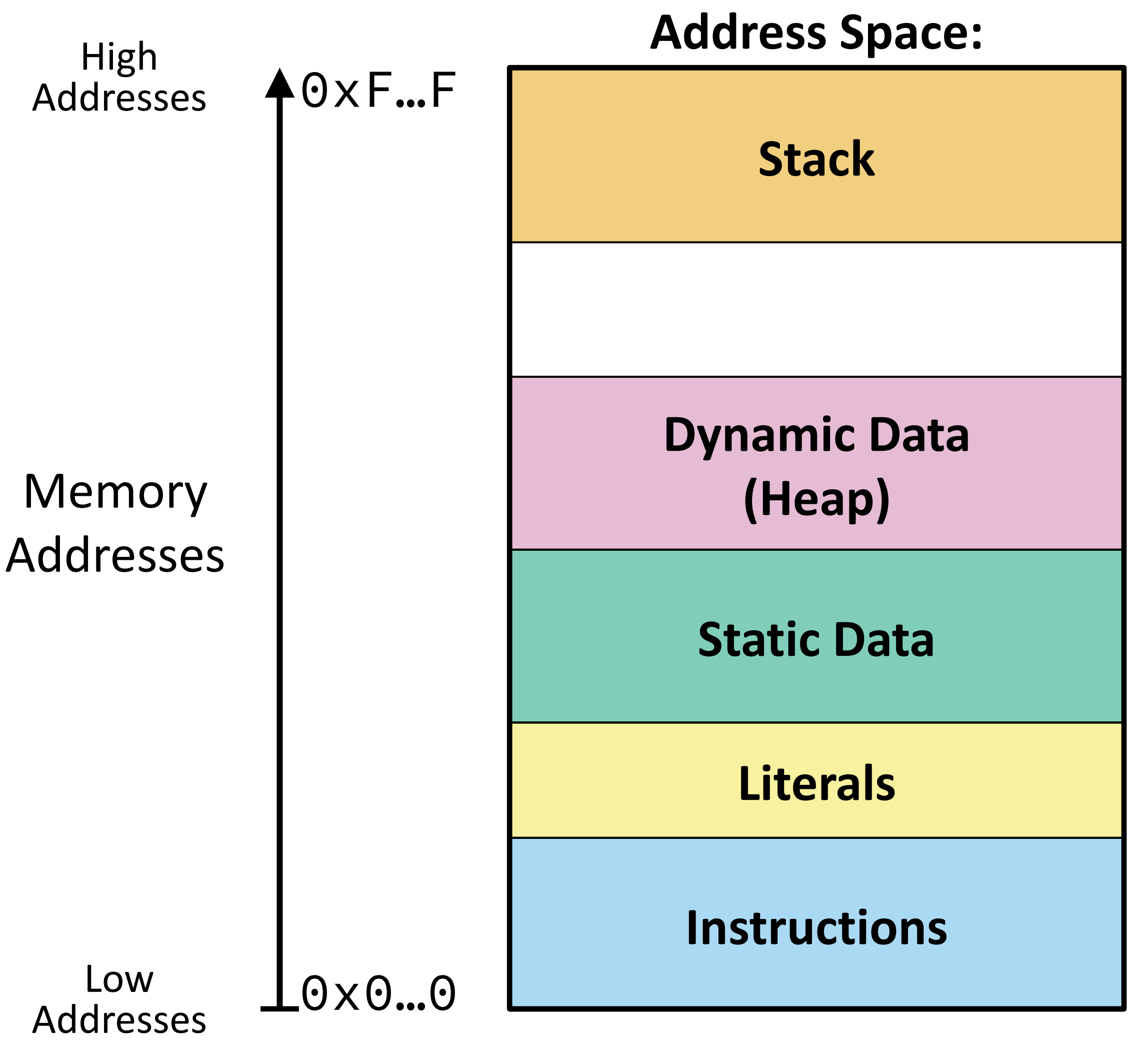
- All implemented with machine instructions!
  - An x86-64 procedure uses only those mechanisms required for that procedure



Lecture Outline (1/4)

- **Memory Layout**
- Stack Manipulation
- x86-64 Procedure Calling Conventions
- Stack Frames

Simplified Memory Layout (Review)



What Goes Here:

Local variables and procedure context

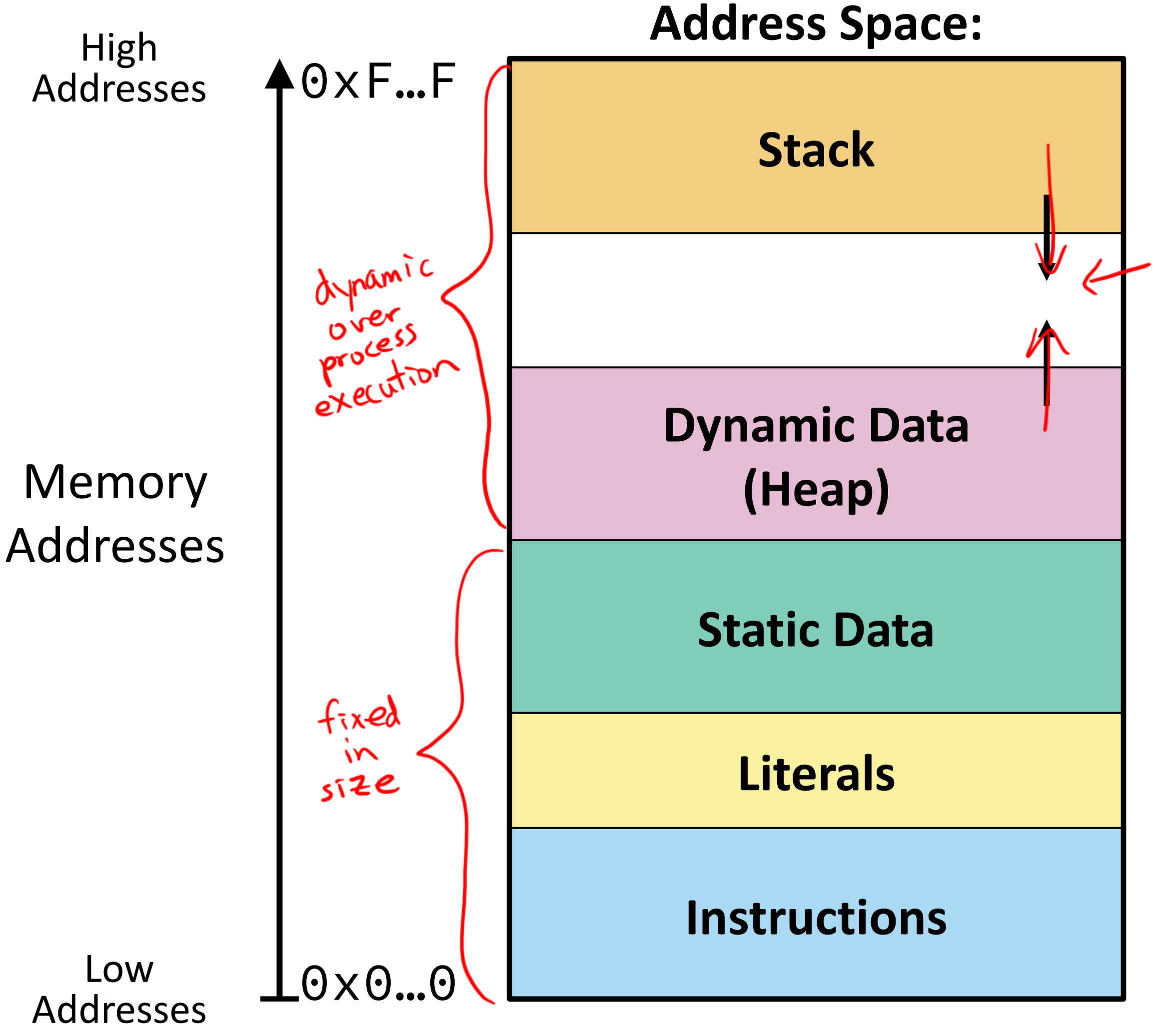
Variables allocated with new or `malloc`

Static variables (including global variables)

Immutable literals/constants (*e.g.*, `"example"`)

Program code

Memory Management



grow towards each other to maximize use of space

How Managed:

"Automatically" by compiler/assembly

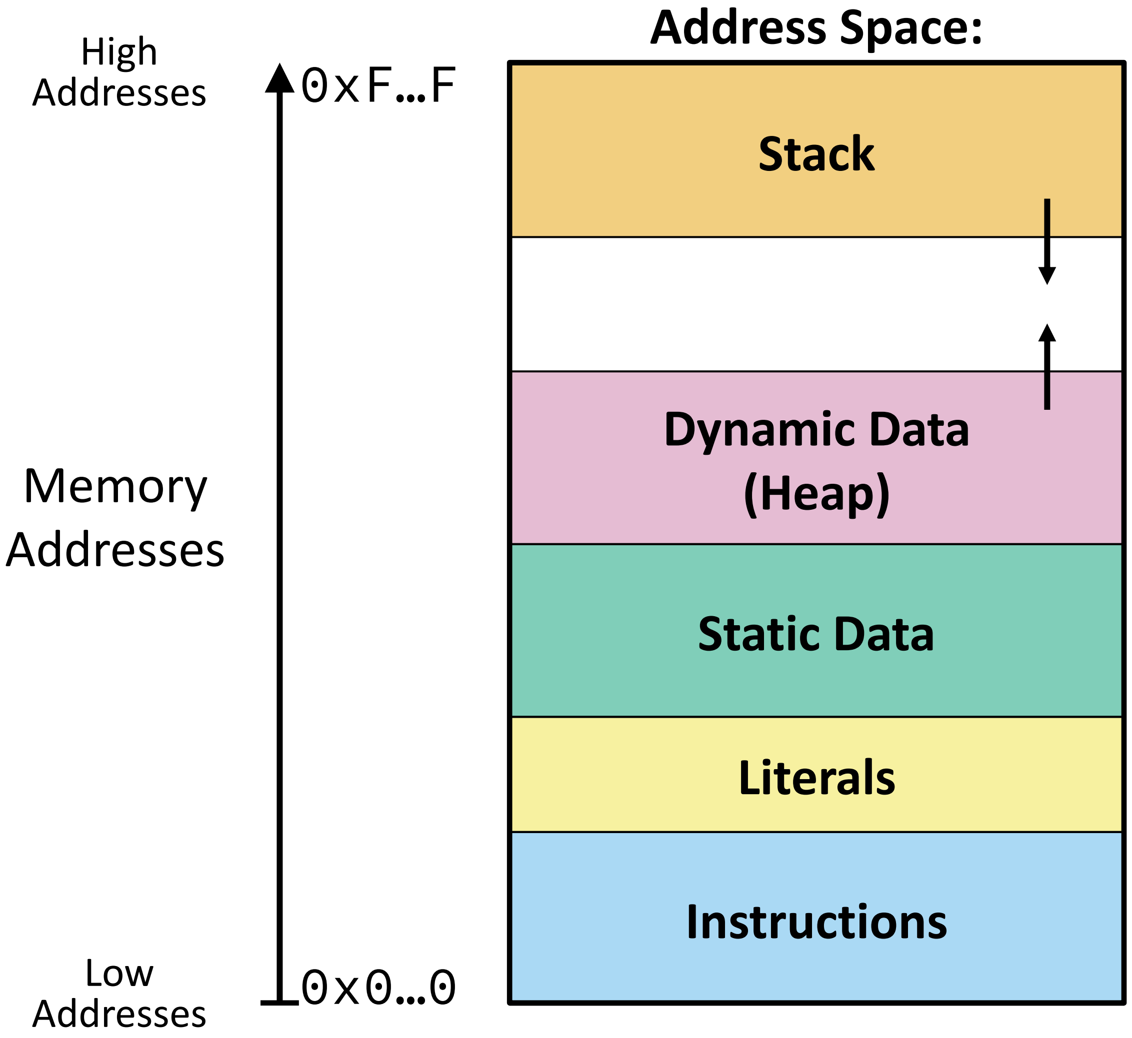
"Dynamically" by programmer

"Statically" at process start

"Statically" at process start

"Statically" at process start

Memory Permissions



Permissions:

Writable; not executable

Writable; not executable

Writable; not executable

Read-only; not executable

Read-only; executable

Segmentation fault: impermissible memory access!

Lecture Outline (2/4)

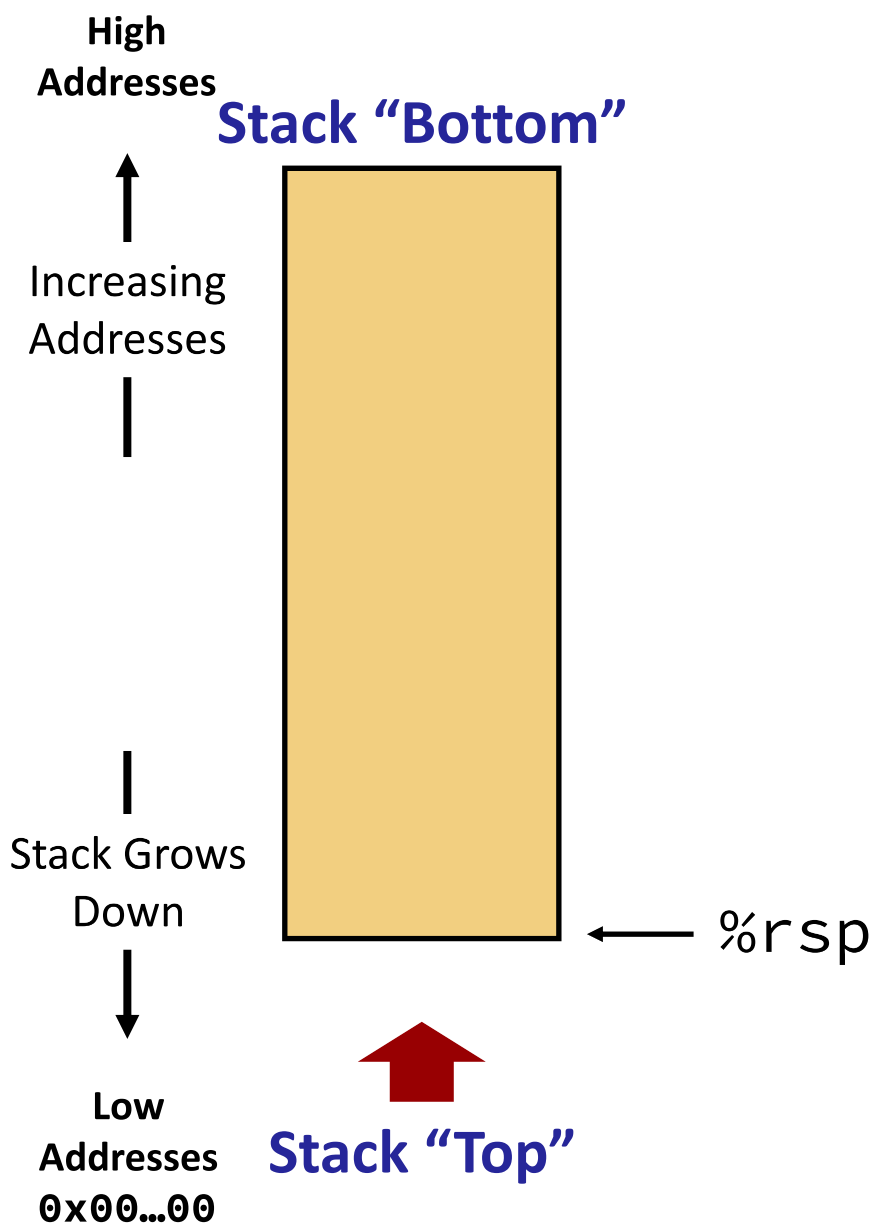
- Memory Layout
- **Stack Manipulation**
- x86-64 Procedure Calling Conventions
- Stack Frames

x86-64 Stack (Review)

Last In, First Out (LIFO)

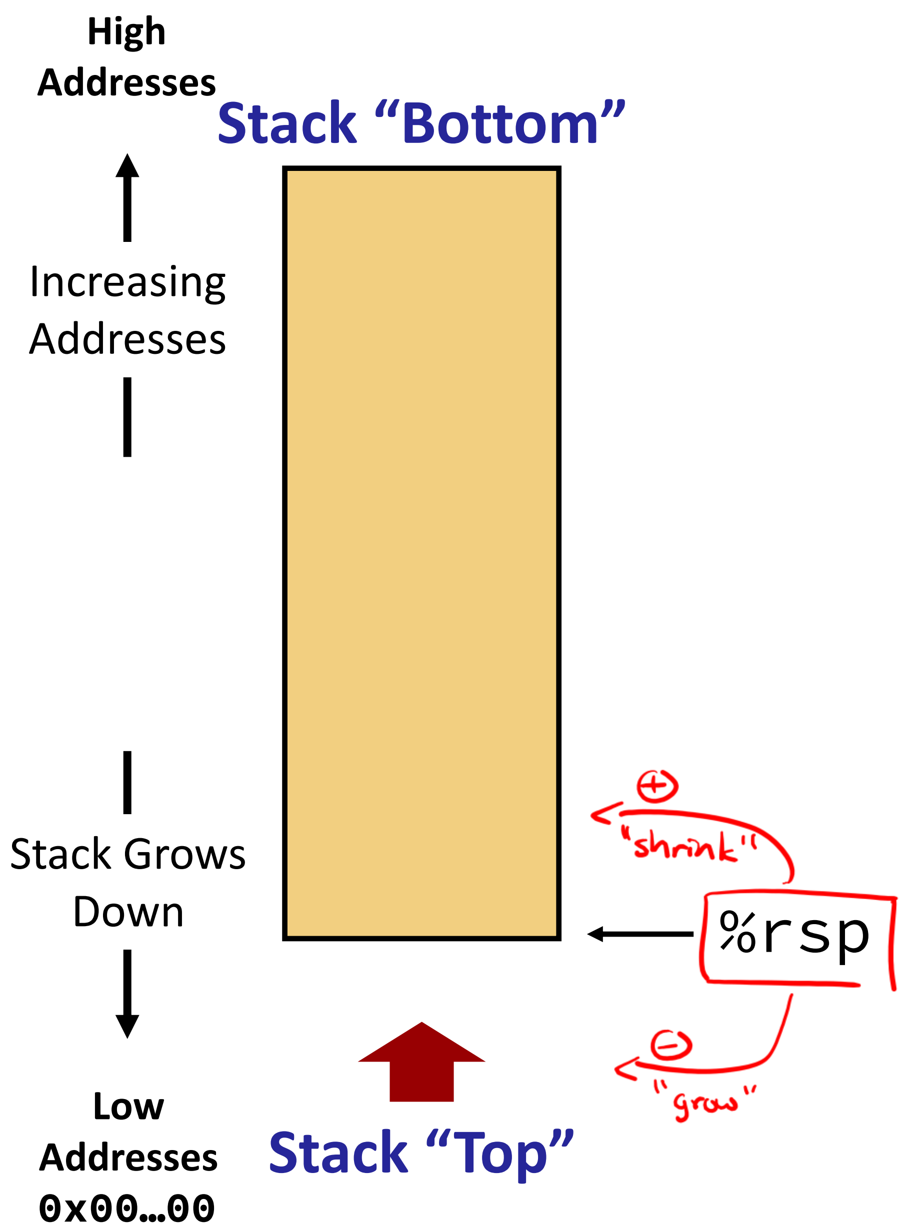
- Region of memory managed automatically via assembly instructions
  - Grows toward lower addresses
  - Customarily shown "upside-down"

- Register `%rsp` is the ***stack pointer***
  - Contains the *lowest* stack address (*top* element)
  - Useful reference point – stack data accessed via nonnegative offsets
    - Example: `8(%rsp)` is 8 bytes from the top/end of the stack



x86-64 Stack: Add/Sub (Review)

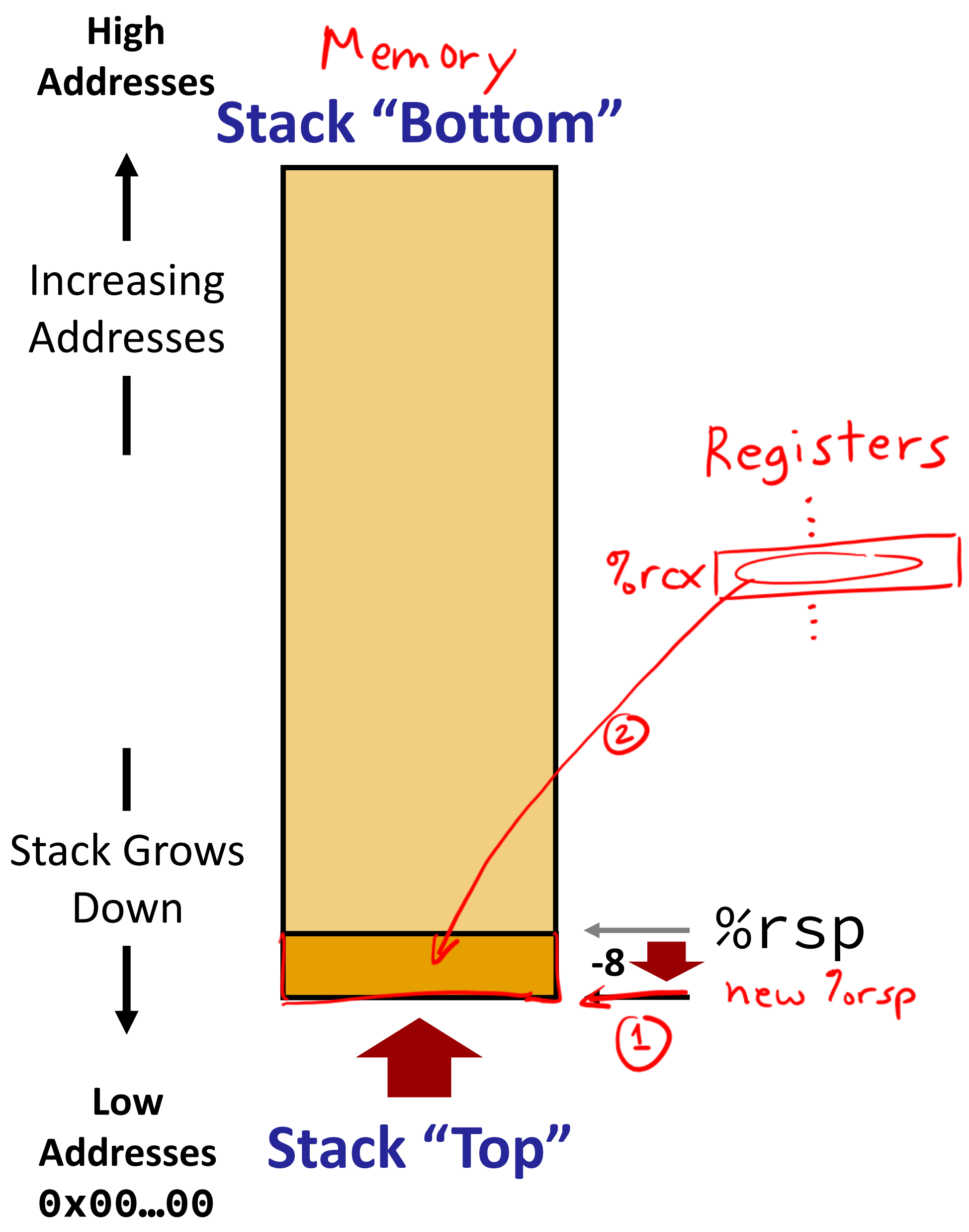
- The size of the stack can be directly manipulated
  - Remember which direction is grow/shrink
  - Example: **subq** `$8, %rsp`
- Doesn't change the data on the stack
  - Need specialized instructions to avoid separate instructions for (1) changing size and (2) manipulating data



x86-64 Stack: Push (Review)

- **push_** *src*
  size specifier
  1) *Decrement* `%rsp` by specified size
  2) Store *src* operand value at `%rsp`'s address
     - Operand can be Reg, Mem, or Imm

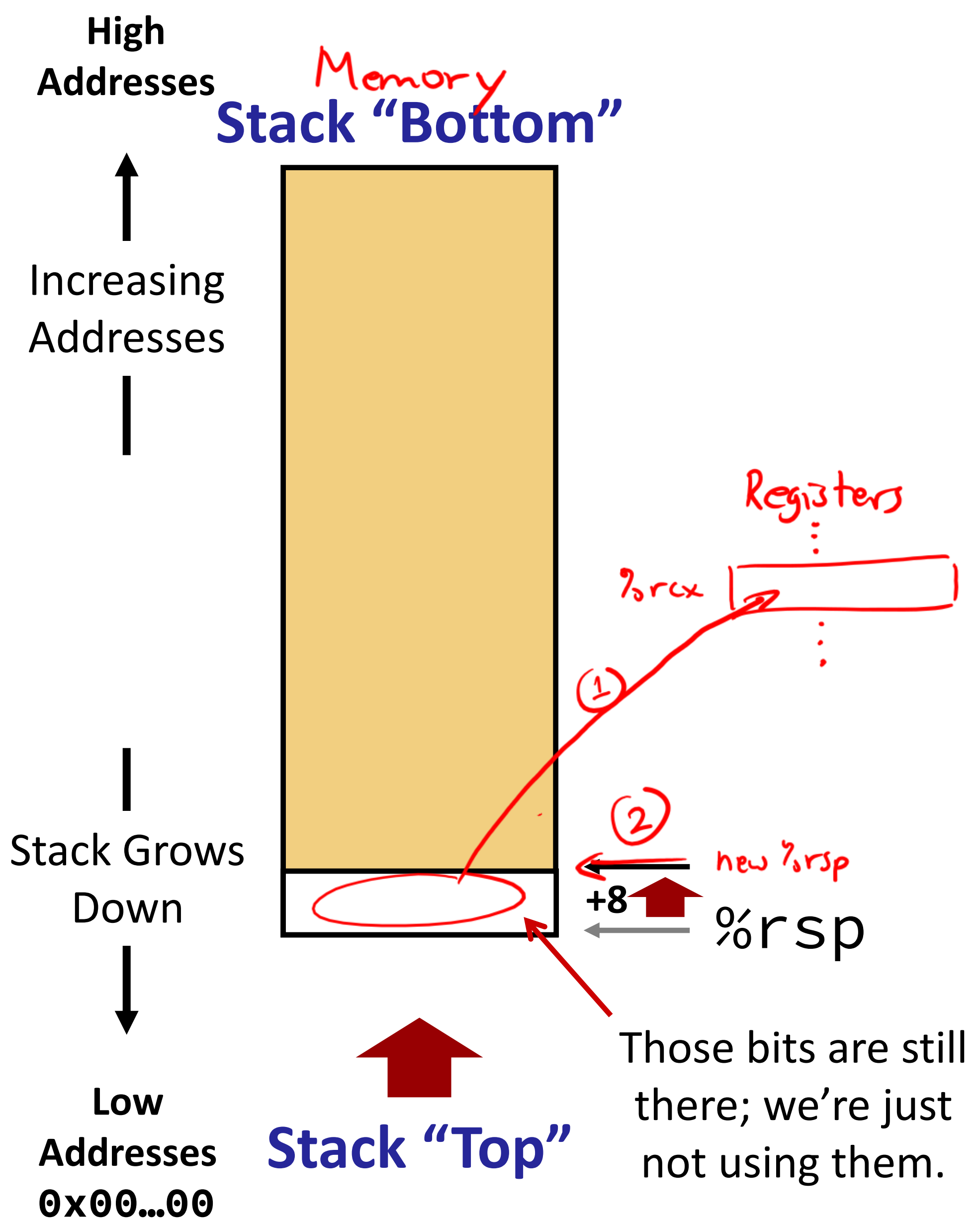
- Example: **pushq** `%rcx`
  - Decrement `%rsp` by 8 bytes
  - Store copy of `%rcx` on the stack



x86-64 Stack: Pop (Review)

- **pop_** *dst*
  size specifier
  1) Store value at address given by `%rsp` into *dst*
     - Operand can be Reg or Mem
  2) *Increment* `%rsp` by specified size

- Example: **popq** `%rcx`
  - Store copy of top 8 bytes of the stack into `%rcx`
  - Increment `%rsp` by 8 bytes

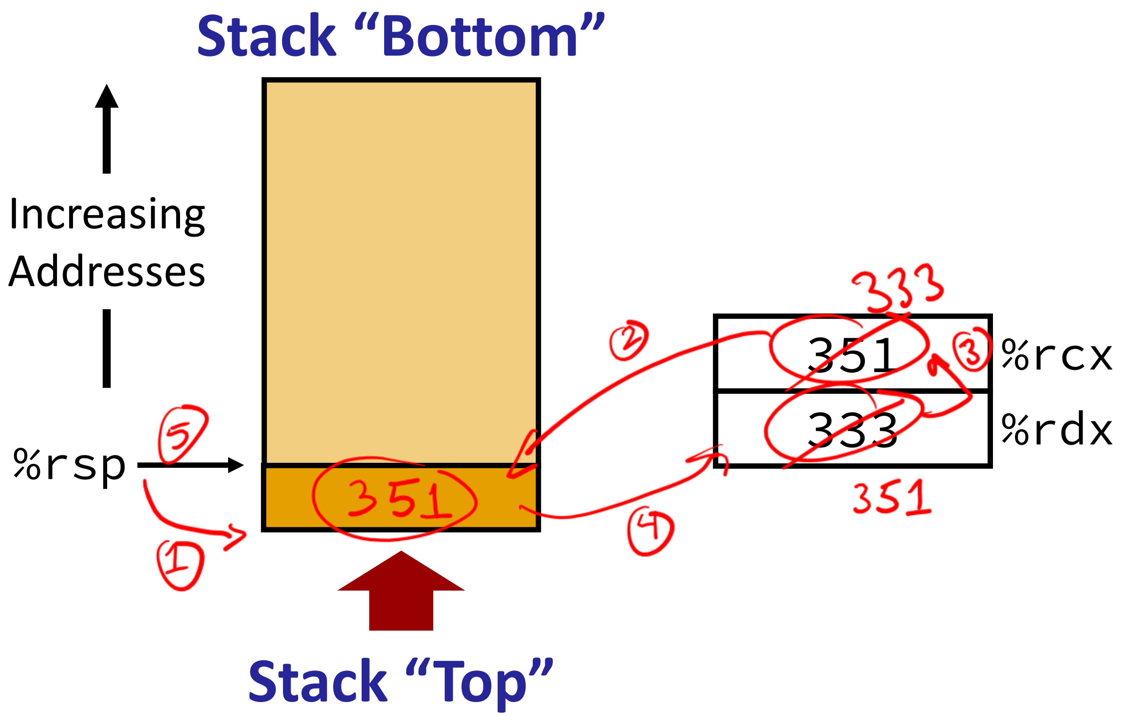


Stack Manipulation Example

- Using the stack for temporary space to swap `%rcx` and `%rdx`
  - Note: You wouldn't want to do this because memory is slower than registers

```
swap_stack1:
   1 subq $8, %rsp
   2 movq %rcx, (%rsp)
   3 movq %rdx, %rcx
   4 movq (%rsp), %rdx
   5 addq $8, %rsp
     ret
```

```
swap_stack2:
     pushq %rcx
     movq %rdx, %rcx
     popq %rdx
     ret
```



Polling Questions (1/3)

- How does the stack change after executing the following instructions?

add to stack

8B

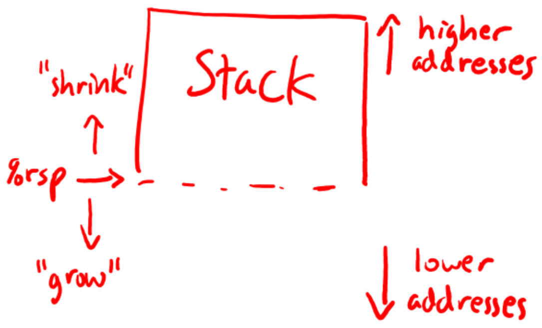
```
pushq  %rbp            # grow 8 B
```

lower address

```
subq   $0x18, %rsp     # grow 24 B
```

0x18 = 24

grow by 32 B

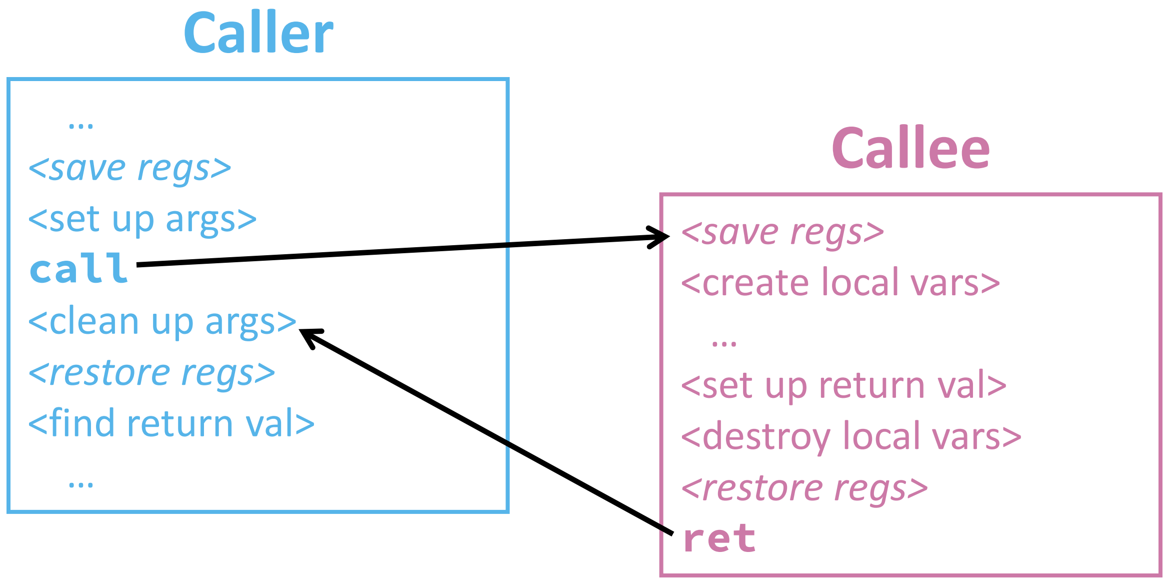


Lecture Outline (3/4)

- Memory Layout
- Stack Manipulation
- **x86-64 Procedure Calling Conventions**
- Stack Frames

Calling Conventions (Review)

- Set of rules to guarantee that procedures can pass *control* and *data* to one another (*i.e.*, where to leave and find things)
  - Goal is to allow register and memory reuse without losing/corrupting data
  - The procedure doing the calling is the ***caller***
  - The procedure being called is the ***callee***



Code Example: Preview

Compiler Explorer: https://godbolt.org/z/TYG6x44Gs

executable disassembly

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

Caller

```
000000000040110e <multstore>:
  40110e: push   %rbx              # save %rbx
  40110f: movq   %rdx,%rbx         # save dst
  401112: call   401106 <mult2>    # mult2(x,y)
  401117: movq   %rax,(%rbx)       # save at dst
  40111a: pop    %rbx              # restore %rbx
  40111b: ret                      # return
```

these are instruction addresses

Callee

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

```
0000000000401106 <mult2>:
  401106:  movq   %rdi,%rax   # a
  401109:  imulq  %rsi,%rax   # a * b
  40110d:  ret                # return
```

Procedures: Passing Control (Review)

- *Return address* indicates how to return to the Caller
  - Callee can be invoked from multiple places in code
  - Which address?

```
401112: call   401106 <mult2>
401117: movq   %rax,(%rbx)
```

next instruction could be anything

- Address of instruction immediately *after* the `call` instruction (**`0x401117`**)

- **`call`** `label` – pass control to Callee (special push)
  1) Automatically push the return address onto the stack
  2) Update the program counter (`%rip`) to the address of the specified label

① move %rsp down
② store ret addr at %rsp

- **`ret`** – return control to Caller (special pop)
  1) Automatically pop the return address off of the stack and then
  2) Update the program counter (`%rip`) to the popped address

① read ret addr at %rsp into %rip
② move %rsp up

Procedure Call Example (Step 1)

```
0000000000040110e <multstore>:
  •
  •
  401112: call    401106 <mult2>
  401117: movq    %rax,(%rbx)
  •
  •
```

```
0000000000401106 <mult2>:
  401106:   movq   %rdi,%rax
  •
  •
  40110d:   ret
```

2

3

Stack
(Memory)

0x130	•
0x128	•
0x120	•
	0x401117

1

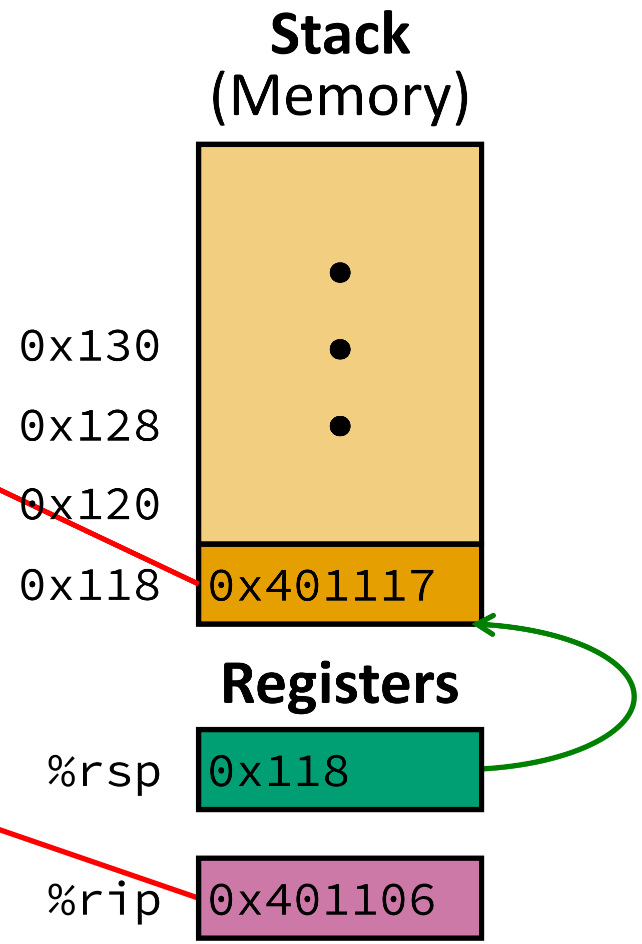
Registers

%rsp	~~0x120~~ 118
%rip	~~0x401112~~ 0x401106

Procedure Call Example (Step 2)

```
0000000000040110e <multstore>:
  •
  •
  401112: call   401106 <mult2>
  401117: movq   %rax,(%rbx)
  •
  •
```

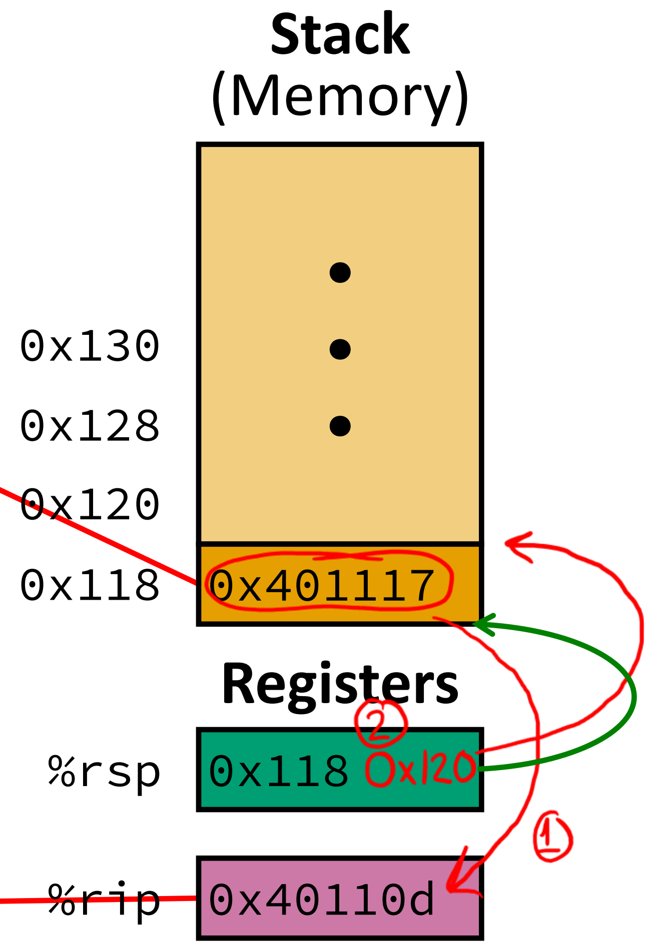
```
0000000000401106 <mult2>:
  401106:  movq   %rdi,%rax
  •
  •
  40110d:  ret
```



Procedure Return Example (Step 1)

```
0000000000040110e <multstore>:
  •
  •
  401112: call   401106 <mult2>
  401117: movq   %rax,(%rbx)
  •
  •
```

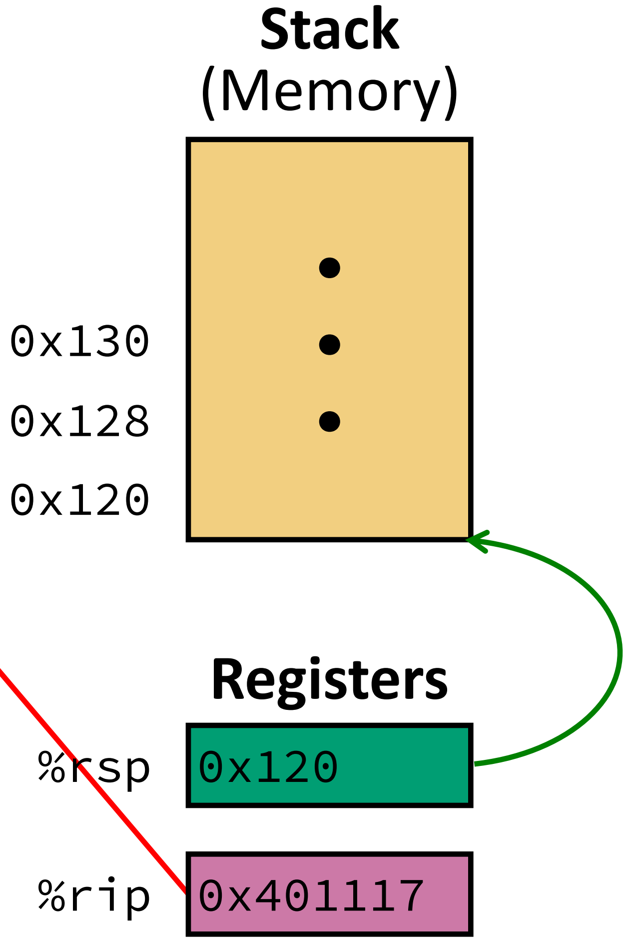
```
0000000000401106 <mult2>:
  401106:  movq   %rdi,%rax
  •
  •
  40110d:  ret
```



Procedure Return Example (Step 2)

```
000000000040110e <multstore>:
  •
  •
  401112: call   401106 <mult2>
  401117: movq   %rax,(%rbx)
  •
  •
```

```
0000000000401106 <mult2>:
  401106:  movq   %rdi,%rax
  •
  •
  40110d:  ret
```



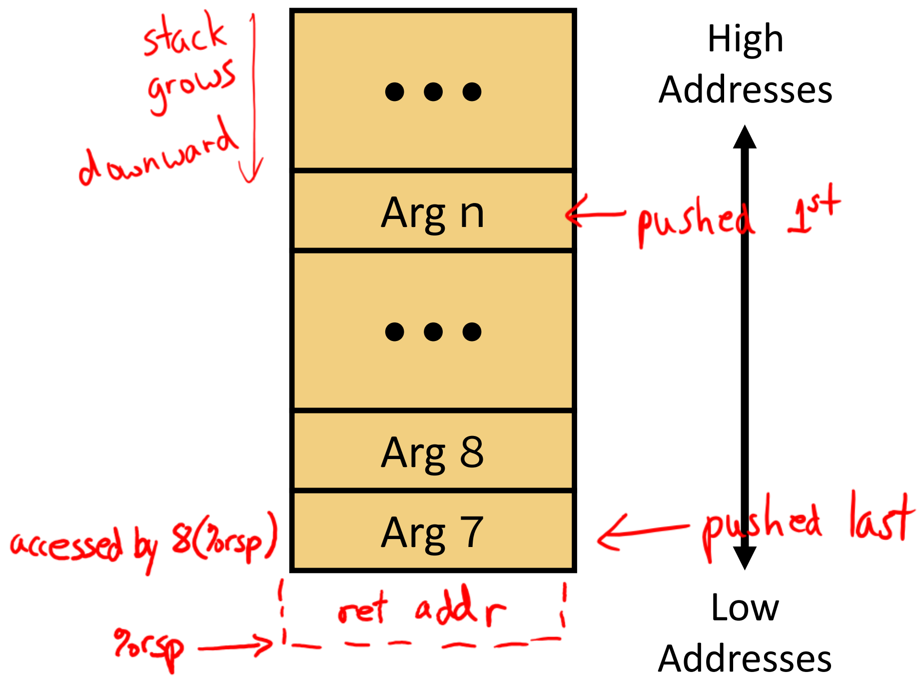
Procedures: Passing Data (Review)

- Registers (NOT in Memory)
  - First 6 arguments:

1	%rdi	Diane's
2	%rsi	Silk
3	%rdx	Dress
4	%rcx	Costs
5	%r8	$8
6	%r9	9

  - Return value: %rax
    - Return pointer for anything >8 bytes wide
    - Caller can directly use `%rax` after return

- Stack (Memory)
  - Only allocate memory if needed



Code Example: Passing Data

lined up nicely so we didn't have to manipulate arguments

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

rdi rsi rdx

rdi rsi

```
0000000000040110e <multstore>:
  # x in %rdi, y in %rsi, dst in %rdx
    • • •
  40110f: movq   %rdx,%rbx        # "save" dst
  401112: call   401106 <mult2> # mult2(x,y)
  # t in %rax
  401117: movq   %rax,(%rbx)     # save at dst
    • • •
```

will explain later

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

```
0000000000401106 <mult2>:
  # a in %rdi, b in %rsi
  401106:  movq   %rdi,%rax   # a
  401109:  imulq  %rsi,%rax   # a * b
  # s in %rax
  40110d:  ret                # return
```

Polling Questions (2/3)

- For the following function, which registers do we know *must* be used?

```
void* memset(void* ptr, int value, size_t num);
```

return value in $\boxed{\%rax}$

arguments in $\boxed{\%rdi, \%rsi, \text{and } \%rdx}$

$\boxed{\%rsp}$ changed by call & ret

$\boxed{\%rip}$ changed while executing instructions

Lecture Outline (4/4)

- Memory Layout
- Stack Manipulation
- x86-64 Procedure Calling Conventions
- **Stack Frames**

Stack Organization (Review)

- Enables multiple instantiations of a procedure to be "running" simultaneously
  - Need some place to store *state* of each instantiation
  - This makes recursion possible!

- ***Stack discipline*** – how do we prevent bad things from happening?
  - Observation #1: State for a given procedure only needed for a limited time
  - Observation #2: Callee always returns before Caller does

- Stack organized in conceptual units called *stack frames*
  - Each stack frame contains the state for a single procedure instantiation

Stack Frames Example

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

```
who(…)
{
    •
  ①amI();
    •
  ②amI();
    •
}
```

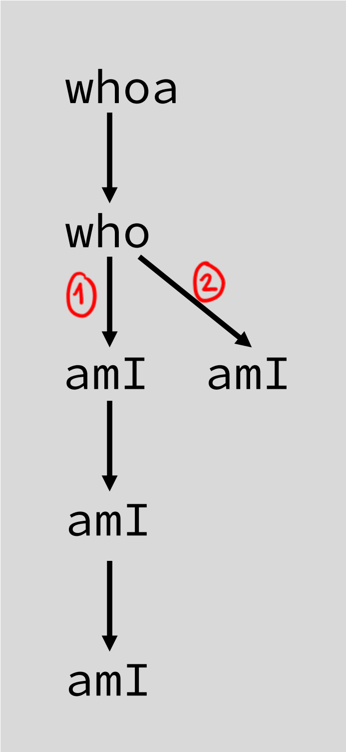
1st call recurses twice

2nd call doesn't recurse

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

based on condition

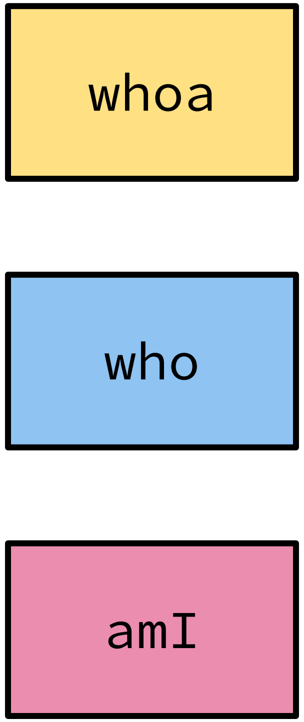
Example
Call Chain



Procedure amI is conditionally recursive (calls itself)

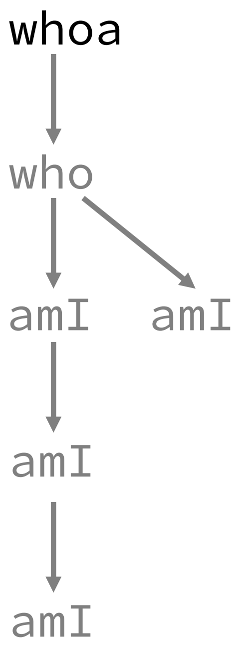
Stack Frame Management

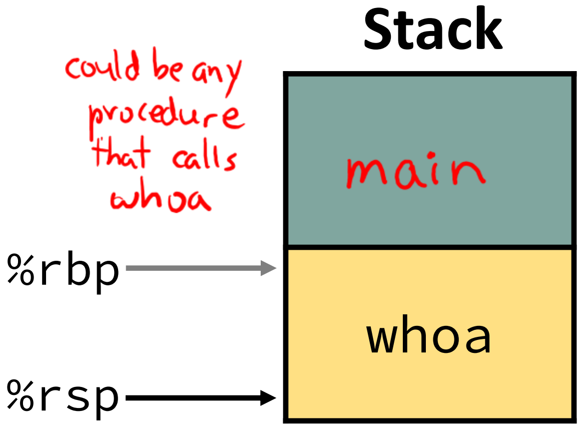
- Contents
  - All necessary local context – we'll see details later
  - Size will vary based on procedure specifics
    - Showing same size in this example, but not usually the case
- Management
  - Space gets allocated as procedure executes
  - Space must get deallocated by the time it returns
- Reference points
  - Stack pointer (`%rsp`) indicates the top of the stack and current frame
  - *Frame pointer* (`%rbp`) may indicate the "start"/"bottom" of current frame
    - Less commonly used this way in x86-64



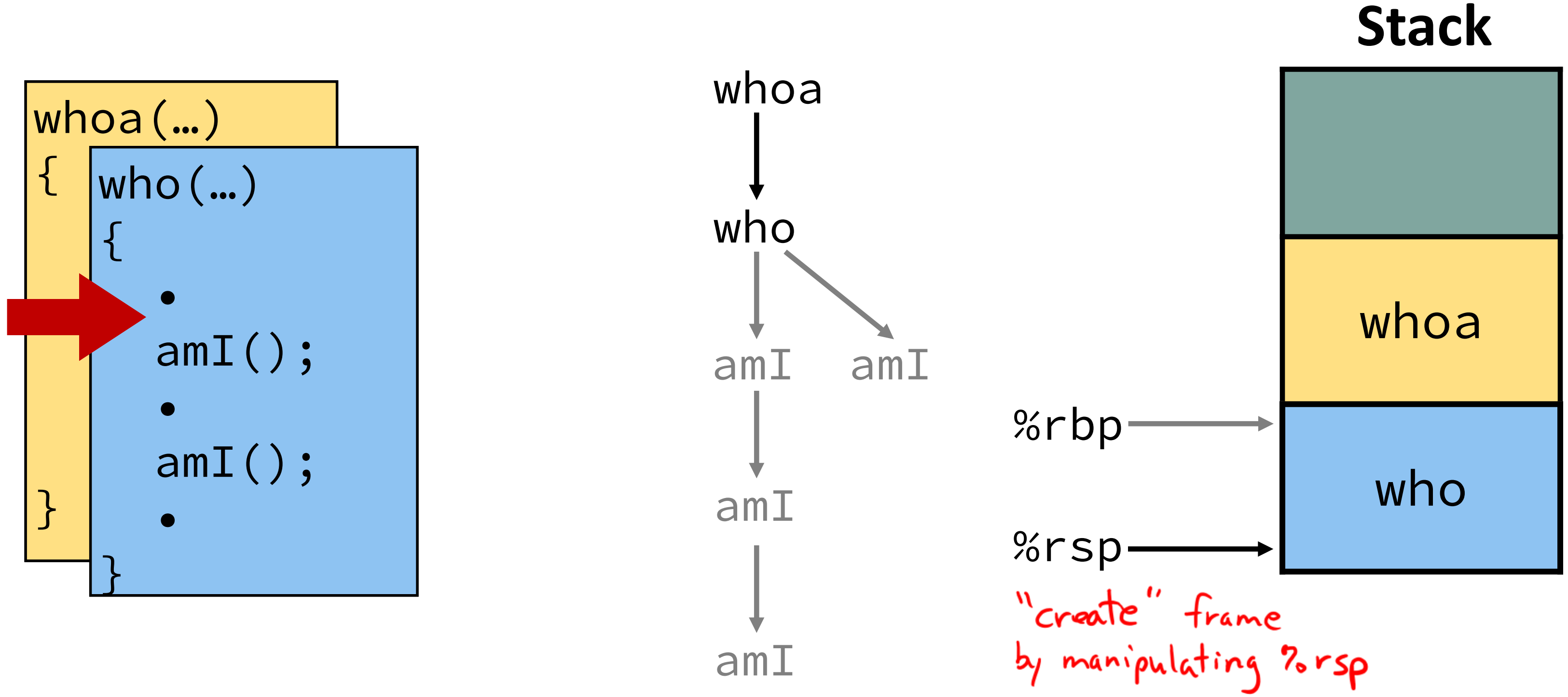
1) Call to whoa

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

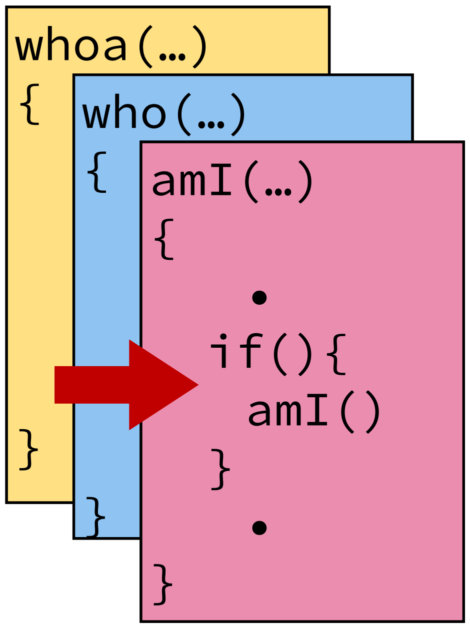


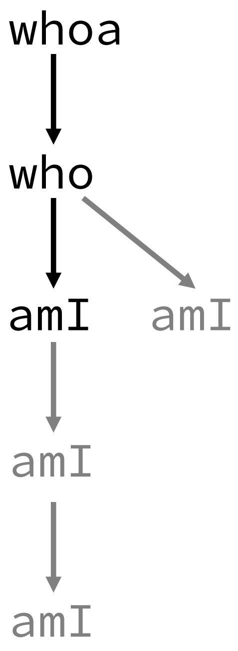


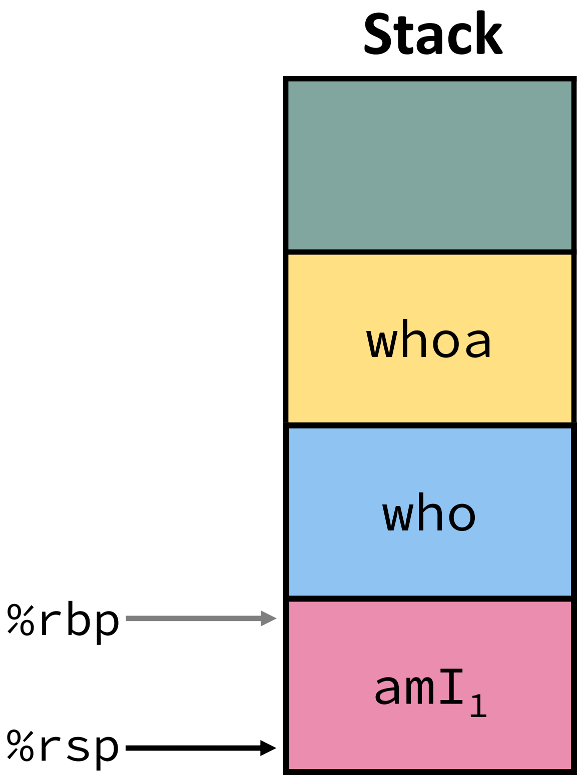
2) Call to who


whoa(…)
{
}
who(…)
{
•
amI();
•
amI();
•
}
whoa
who
amI
amI
amI
amI
Stack
whoa
who
%rbp
%rsp
"create" frame
by manipulating %rsp

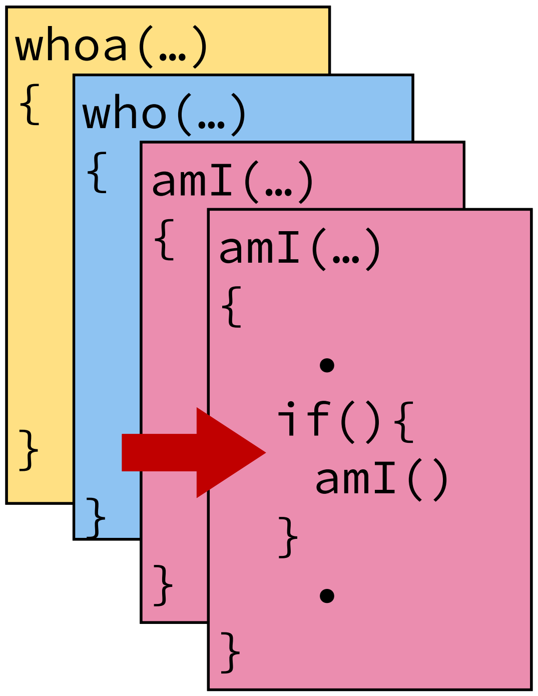
3) Call to `amI` (1st)

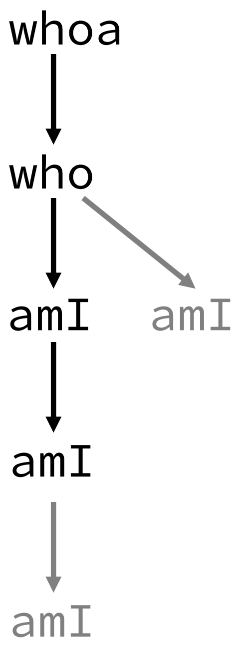


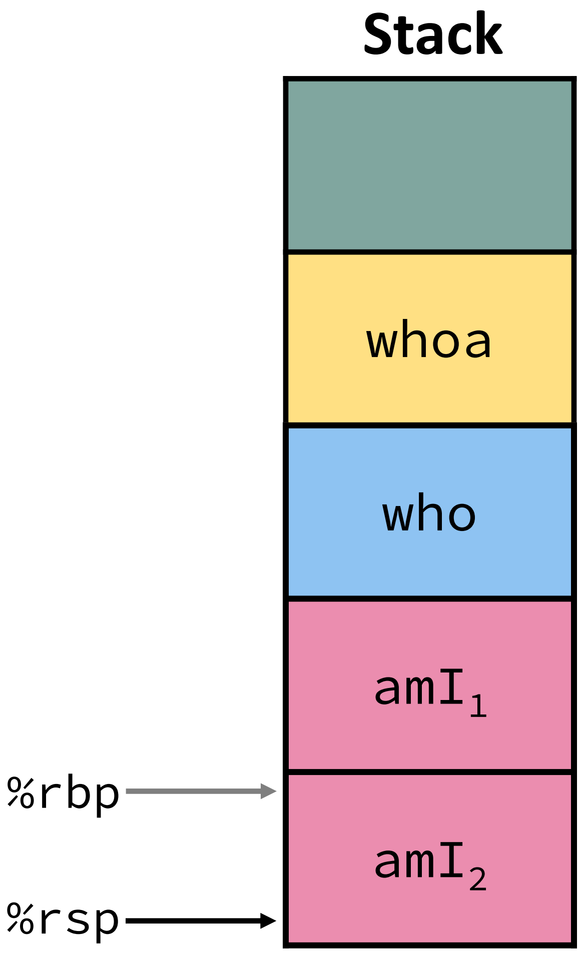




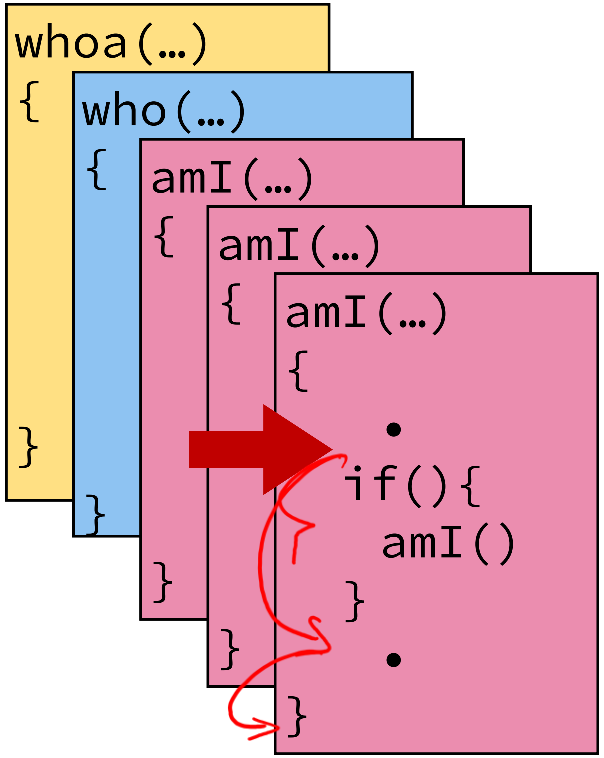
4) Recursive call to `amI` (2nd)

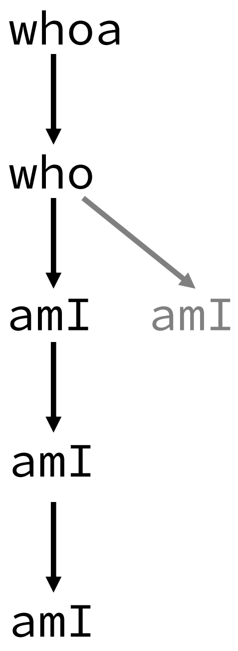


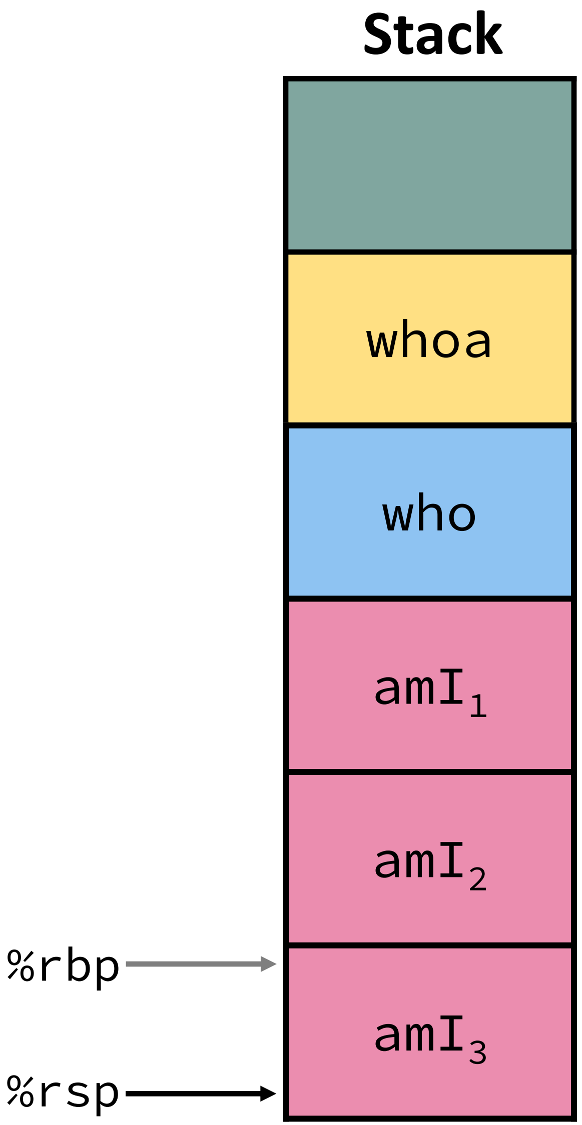




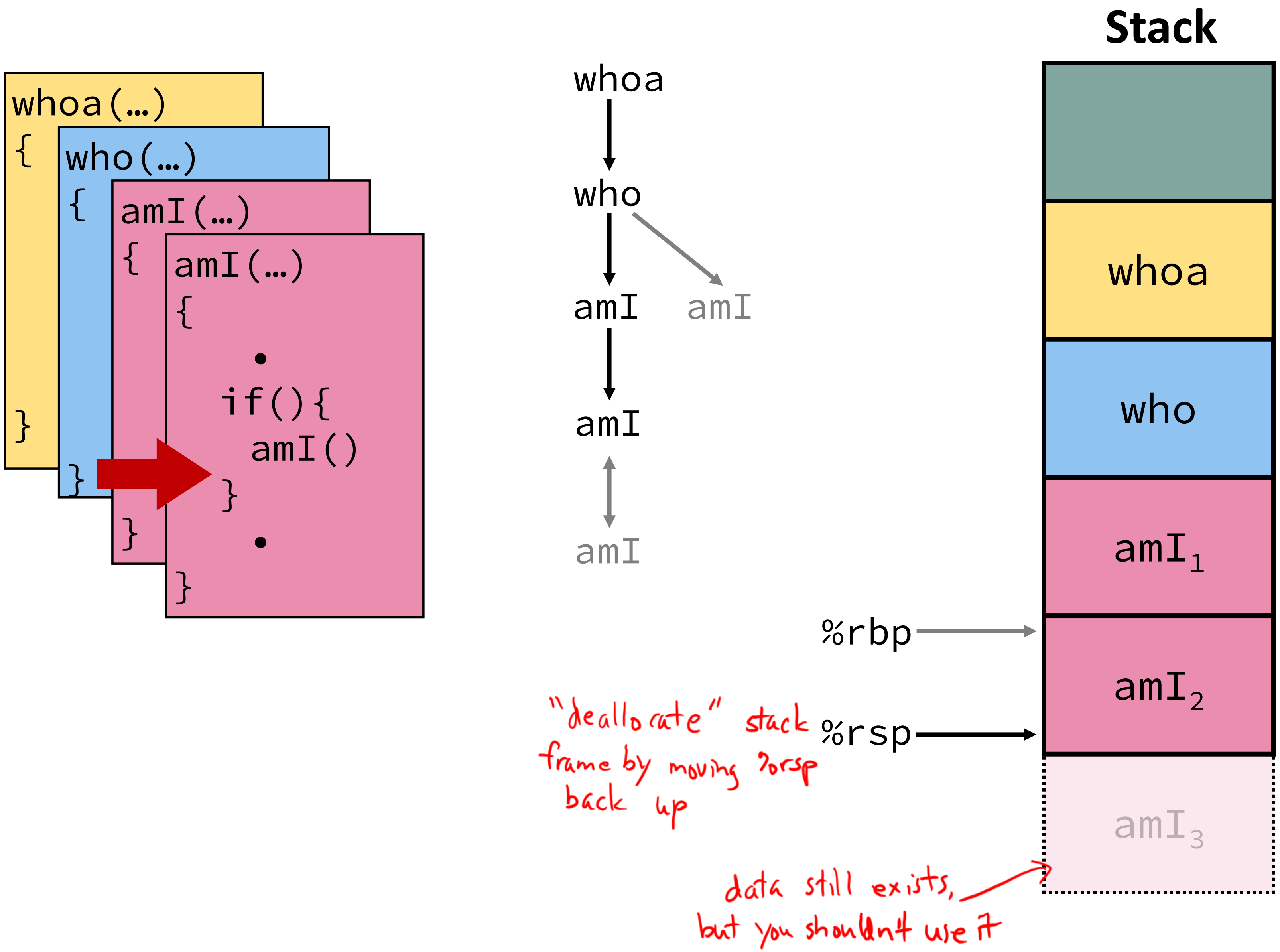
5) Another recursive call to `amI` (3^{rd})



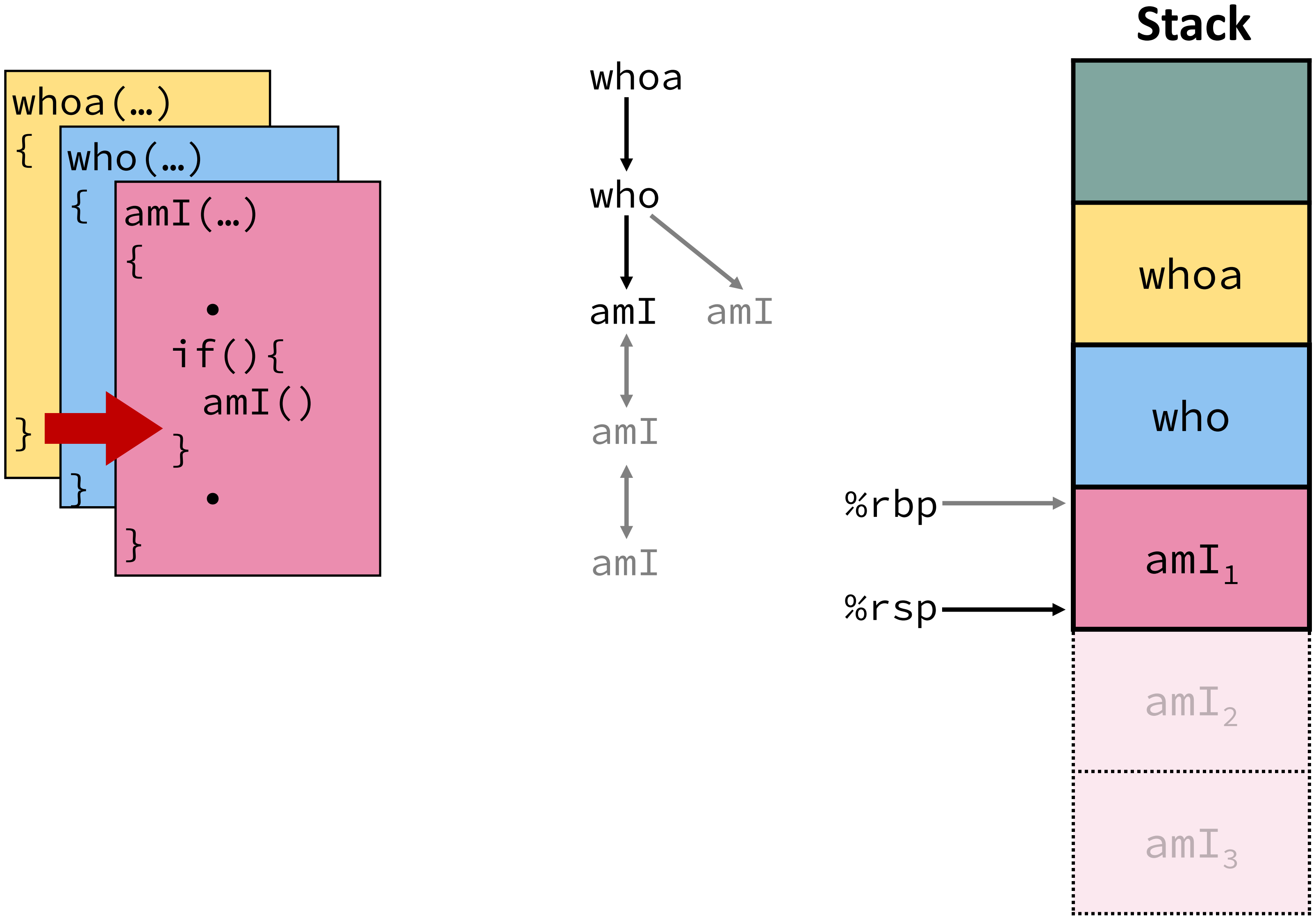




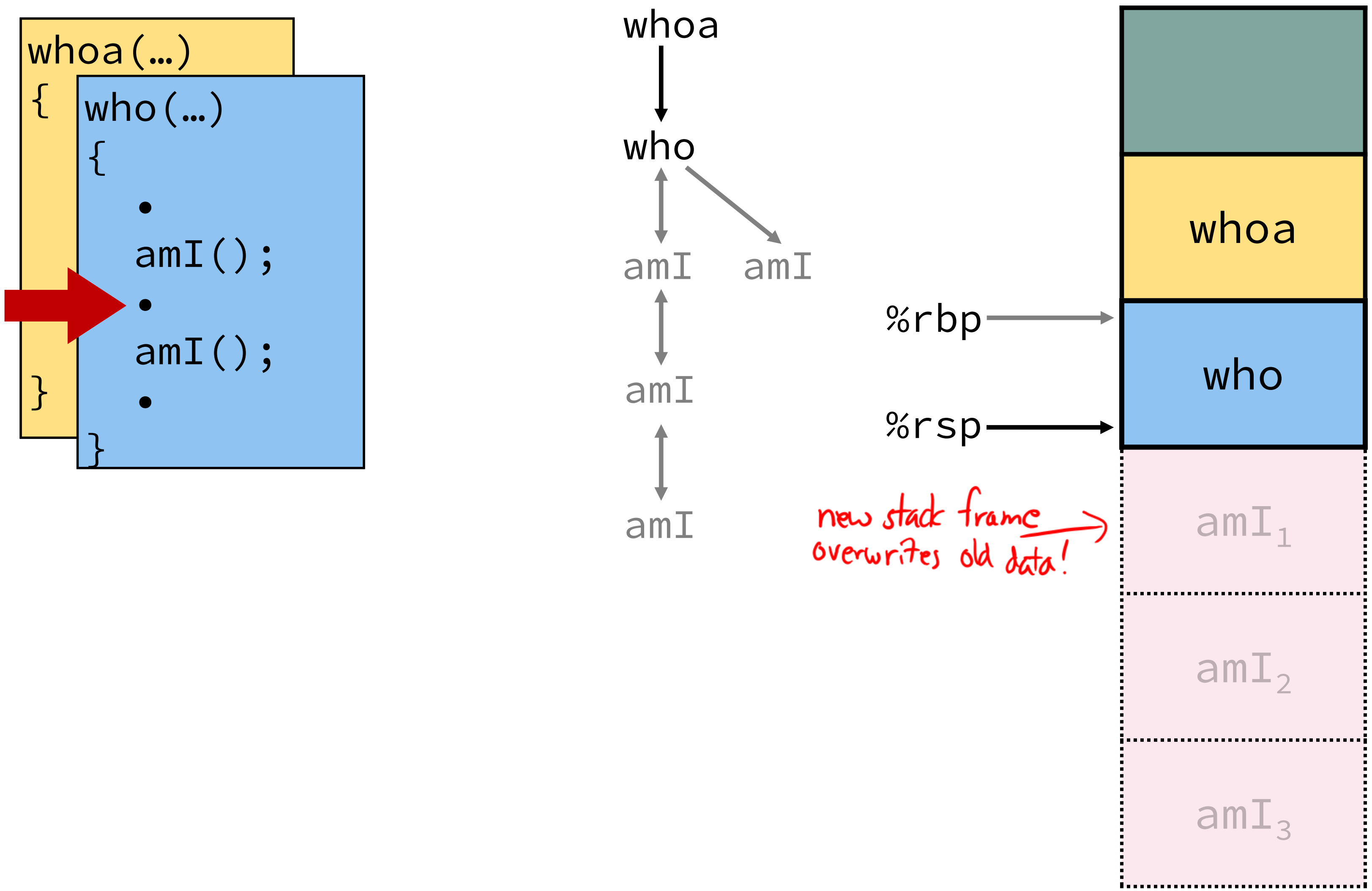
6) Return from another recursive call to `amI` (3rd)



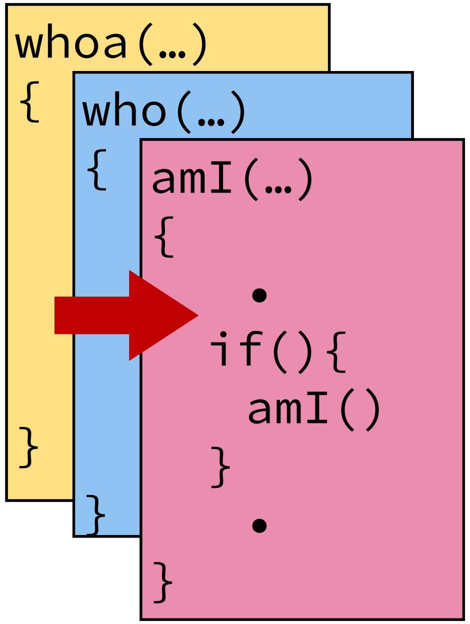
7) Return from recursive call to `amI` (2^{nd})

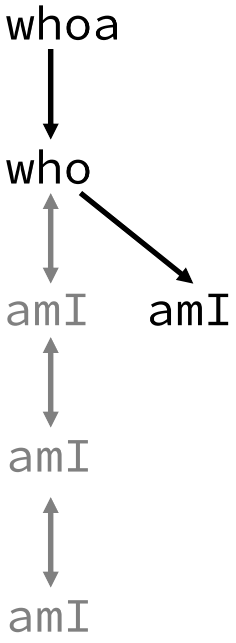


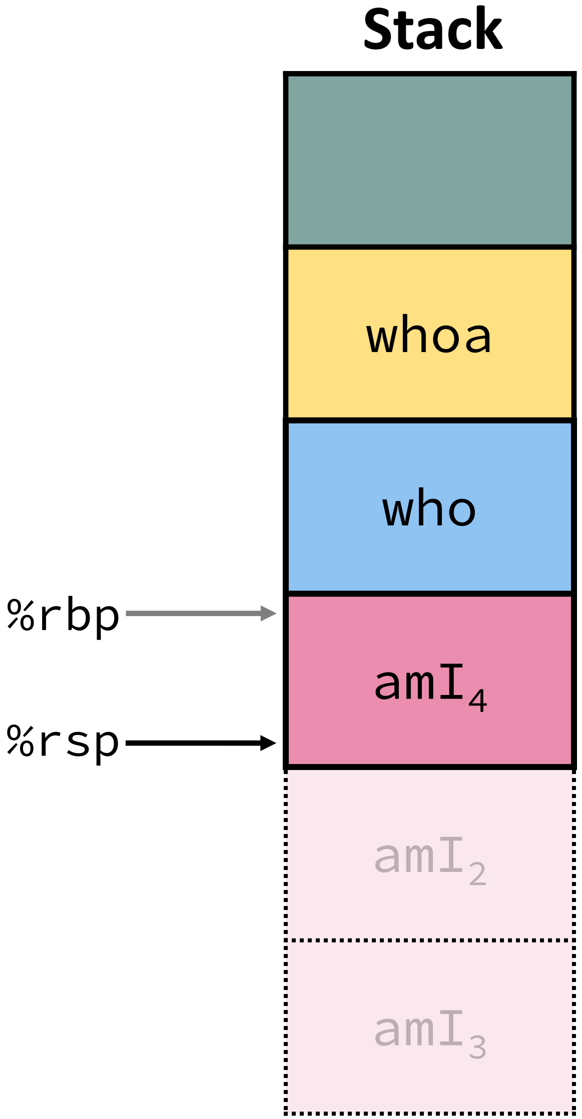
8) Return from call to `amI` (1^{st})



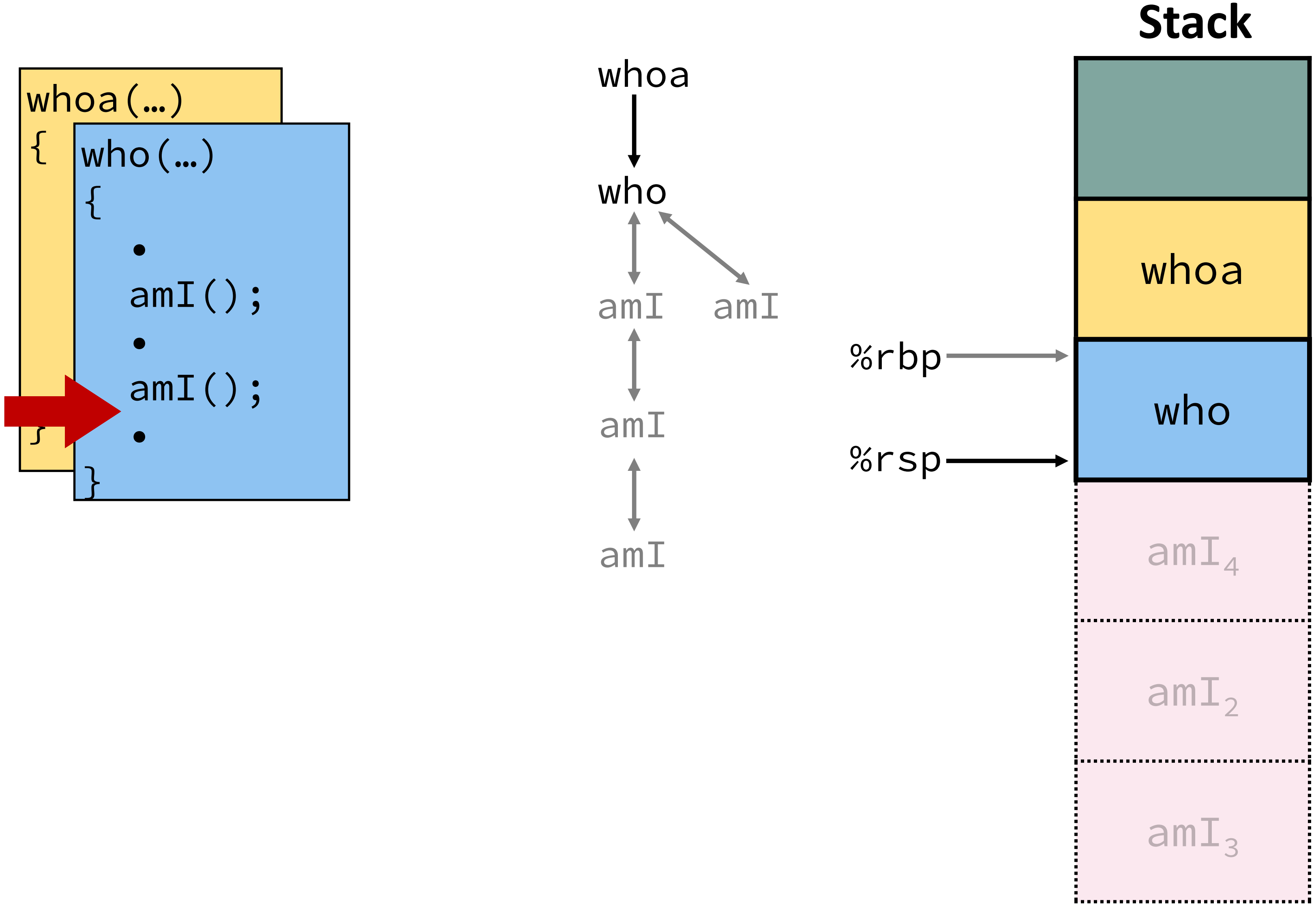
9) Second call to `amI` (4th)





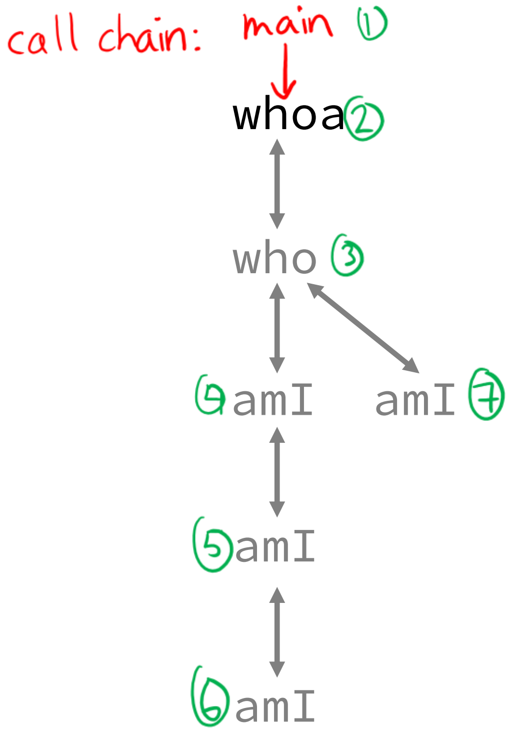


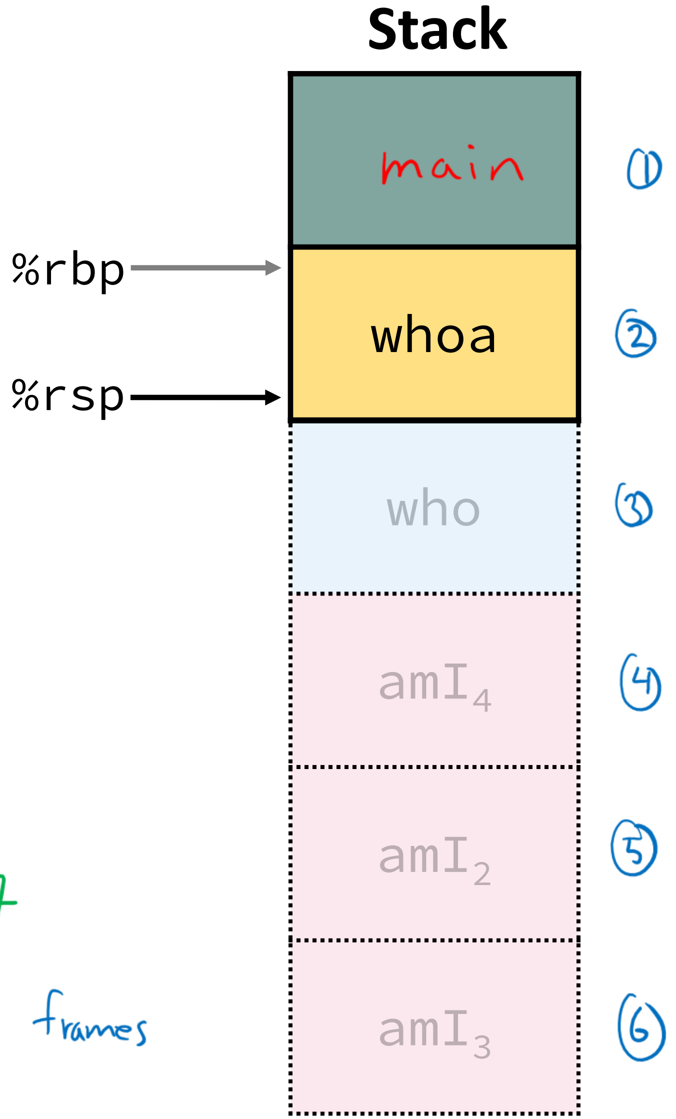
10) Return from second call to `amI` (4^{th})



11) Return from call to who

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





total stack frames created: 7

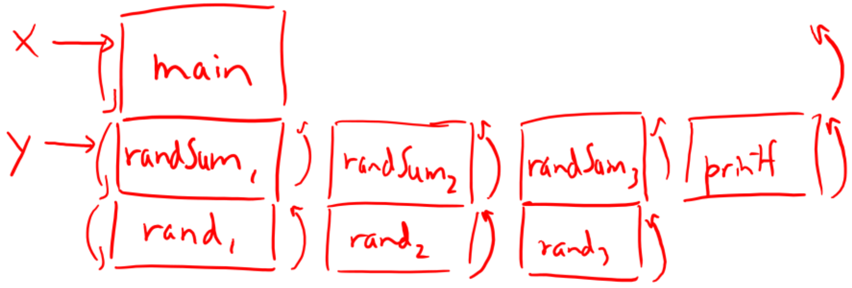
maximum stack depth: 6 frames

Polling Questions (3/3)

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

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

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



  - *Higher/larger address*: x or y?
  - How many total stack frames are *created*? 8
  - What is the maximum *depth* (# of frames) of the Stack?

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

Aside: Stack Overflow

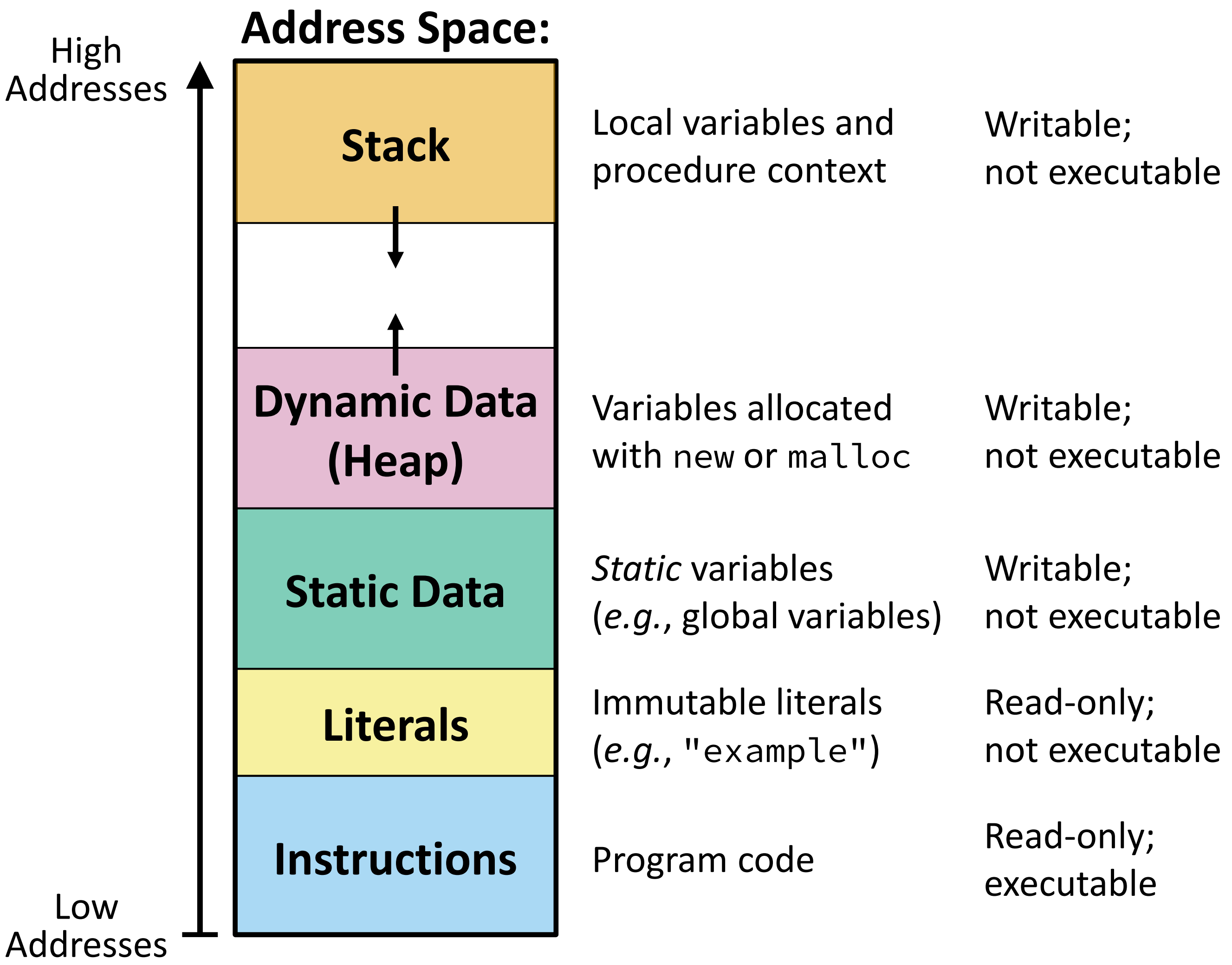
- When the stack pointer exceeds the stack bounds (segmentation fault)
  - In theory: when it collides with the Heap
  - In x86-64 Linux, when it exceeds 8 MiB limit

- Causes?
  - Infinite/deep recursion
  - Very large local variables

- Fixes?
  - Use iterative solution, compiler tail-call optimization
  - Allocate large variables elsewhere (more on the Heap later this quarter)

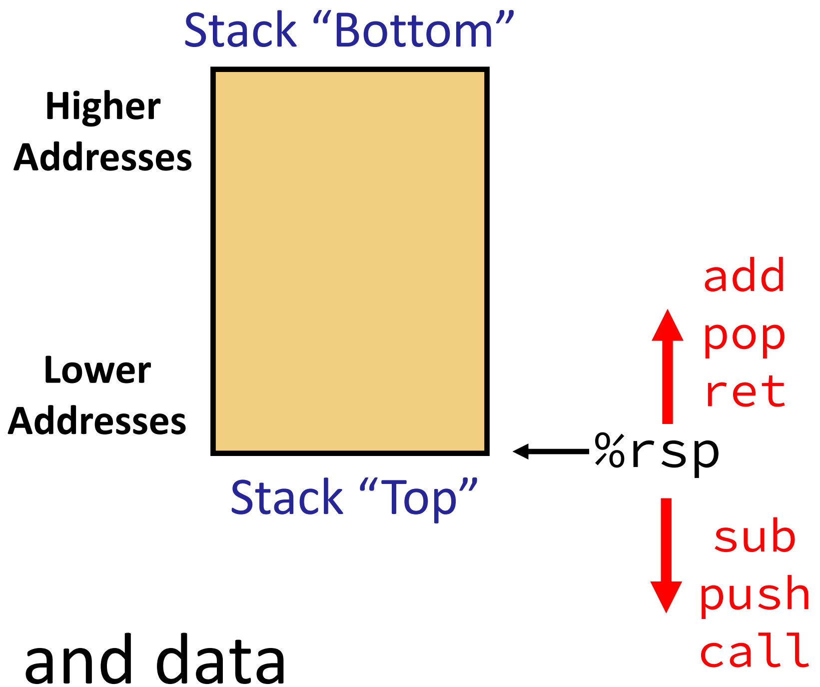
Summary (1/3)

- Memory is organized into 5 segments based on data declaration and lifetime
  - Goals: maximize use of space, manage data differently, apply separate permissions
- A **segmentation fault** is caused by an impermissible memory access



Summary (2/3)

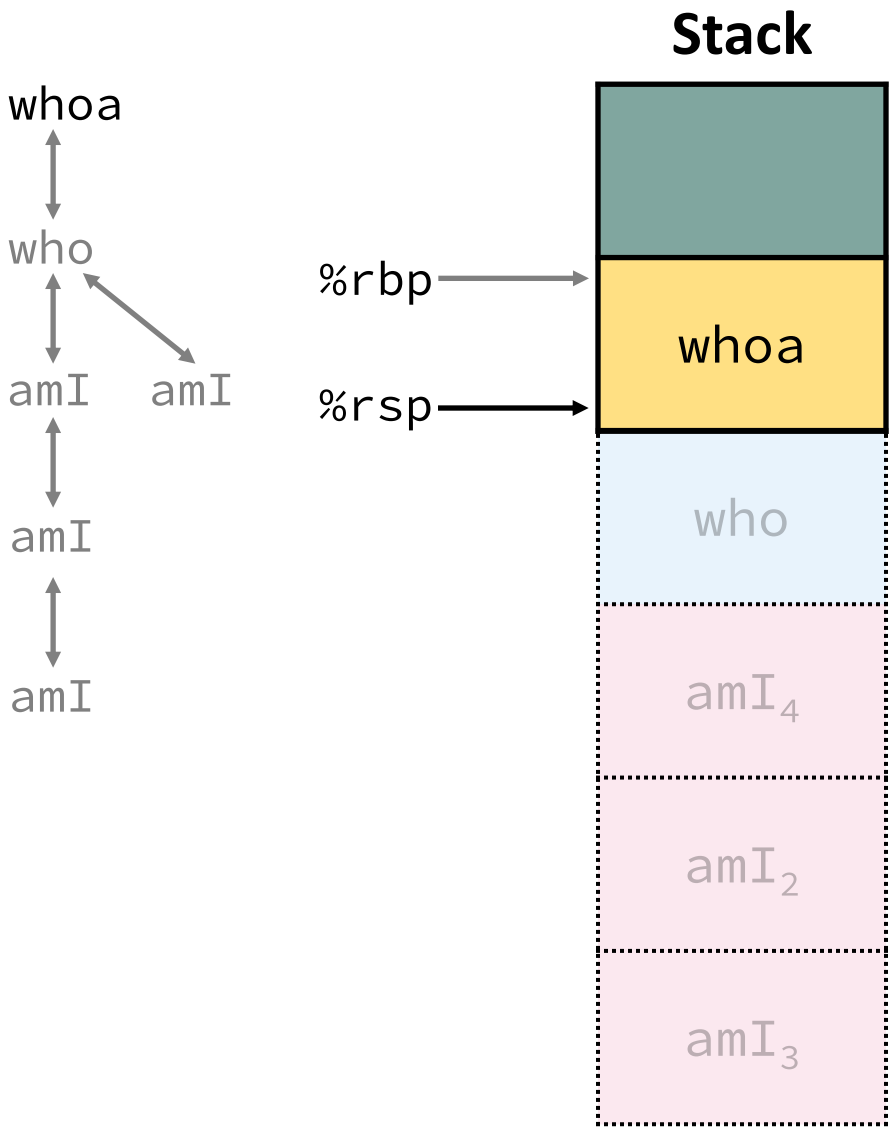
- **The Stack** is the memory segment with the highest addresses and grows downward
  - Stack "top" (lowest address) is defined by the value of the stack pointer (`%rsp`)
  - Can manipulate using `add`, `sub`, `push`, and `pop`



- Procedure calling conventions for passing control and data
  - `call` and `ret` pass control using `%rip` and a return address on the stack
  - Return value: `%rax`, Arguments: `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9`, Stack

Summary (3/3)

- Stack organized into **stack frames** that hold a procedure instance's data
  - Size will vary based on procedure specifics
  - Space gets allocated as procedure executes, deallocated by the time it returns



Bonus: x86-64 Linux Memory Layout

This is extra (non-testable) material

- Stack
  - Runtime stack has 8 MiB limit
- Heap
  - Dynamically allocated as needed
  - `malloc()`, `calloc()`, `new`, …
- Statically allocated data (Data)
  - Read-only: string literals
  - Read/write: global arrays and variables
- Code / Shared Libraries
  - Executable machine instructions
  - Read-only