The Stack & Procedures

CSE 351 Summer 2022

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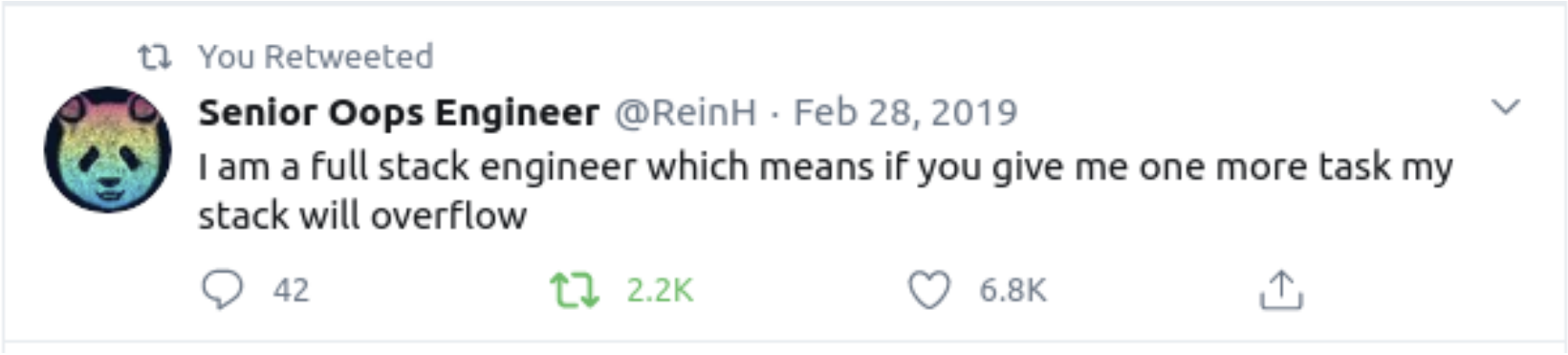


Relevant Course Information

- Lab 2 due next Friday (2/4)
  - Can start in earnest after today's lecture!
  - GDB tutorial and phase 1 walkthrough in section tomorrow
- Midterm (take home, 2/9—2/11)
  - Make notes and use the midterm reference sheet
  - Form study groups and look at past exams!
  - Socio-technical content **is** fair game
- We're looking forward to seeing you back in person next week!
  - I'll send out an announcement with more details soon

x86 Control Flow

- Condition codes
- Conditional and unconditional branches
- Loops
- **Switches**

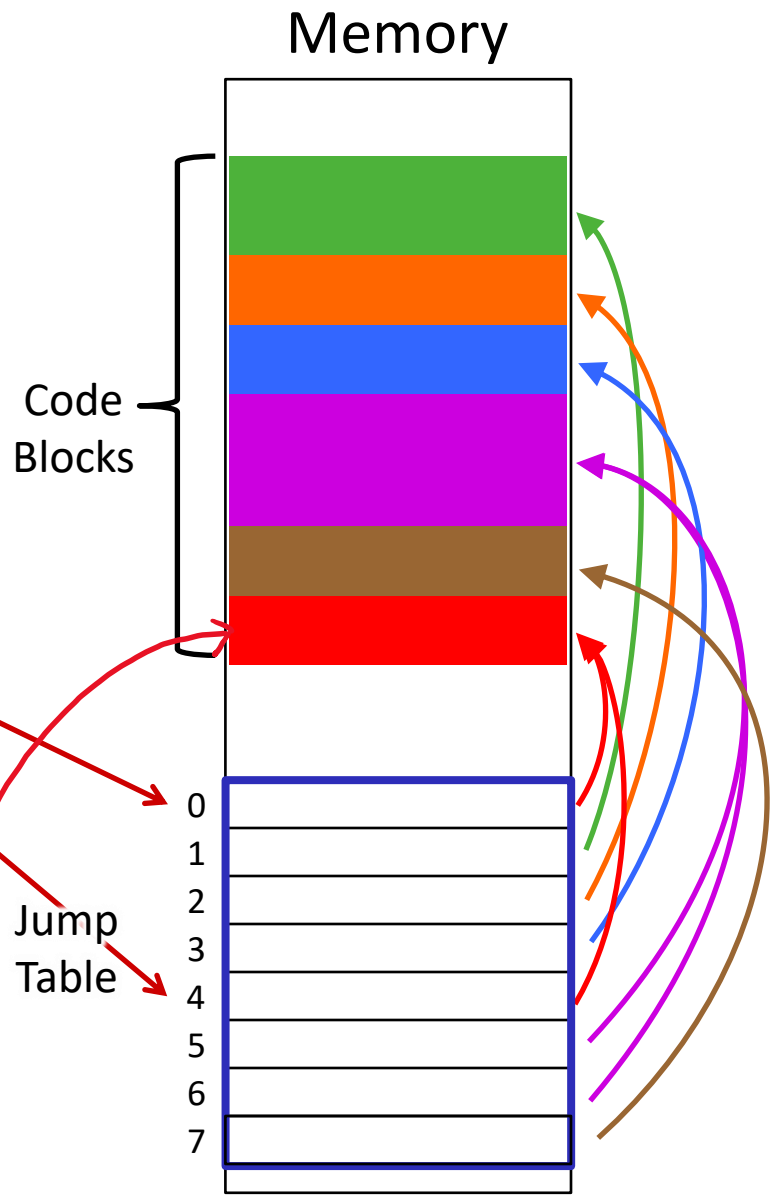
Jump Table Structure

C code:

```
switch (x) {
  case 1: <code> break;
  case 2: <code>
  case 3: <code> break;
  case 5:
  case 6: <code> break;
  case 7: <code> break;
  default: <code>
}
```

Use the jump table when x ≤ 7:

```
if (x <= 7)
  target = JTab[x];
  goto target;
else
  goto default;
```



Switch Statement Example

```
long switch_ex(long x, long y, long z)
{
    long w = 1;
    switch (x) {
      . . .
    }
    return w;
}
```

where?

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rdx	3rd argument (z)
%rax	return value

Note compiler chose to not initialize w

Take a look!
https://godbolt.org/z/Y9Kerb

```
switch_ex:
    movq    %rdx, %rcx
    cmpq    $7, %rdi        # x:7
    ja      .L9             # default
    jmp     *.L4(,%rdi,8)   # jump table
```

jump to default case if x>7 (unsigned)

ja jump **a**bove – unsigned > catches negative default cases

-1 > 7U → jump to default

Switch Statement Example

```
long switch_ex(long x, long y, long z)
{
    long w = 1;
    switch (x) {
      . . .
    }
    return w;
}
```

```
switch_ex:
    movq    %rdx, %rcx
    cmpq    $7, %rdi        # x:7
    ja      .L9             # default
    jmp     *.L4(,%rdi,8)   # jump table
```

Indirect jump

D + Ri * S

addr of jtab

x

size of (void *)

following data is a "quad word" = 8 bytes

Jump table

```
.section    .rodata
  .align 8
.L4:
  .quad     .L9     # x = 0
  .quad     .L8     # x = 1
  .quad     .L7     # x = 2
  .quad     .L10    # x = 3
  .quad     .L9     # x = 4
  .quad     .L5     # x = 5
  .quad     .L5     # x = 6
  .quad     .L3     # x = 7
```

address

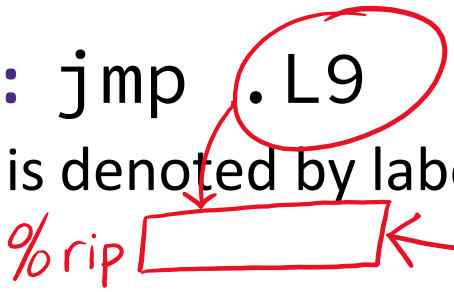
Assembly Setup Explanation

- Table Structure
  - Each target requires 8 bytes (address)
  - Base address at `.L4`

Jump table

```
.section    .rodata
  .align 8
.L4:
  .quad    .L9    # x = 0
  .quad    .L8    # x = 1
  .quad    .L7    # x = 2
  .quad    .L10   # x = 3
  .quad    .L9    # x = 4
  .quad    .L5    # x = 5
  .quad    .L5    # x = 6
  .quad    .L3    # x = 7
```

- **Direct jump:** `jmp .L9`
  - Jump target is denoted by label `.L9`

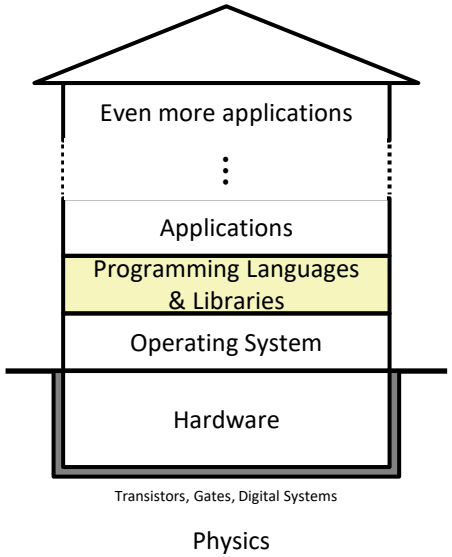


- **Indirect jump:** `jmp *.L4(,%rdi,8)`
  - Start of jump table: `.L4`
  - Must scale by factor of 8 (addresses are 8 bytes)
  - Fetch target from effective address `.L4 + x*8`
    - Only for $0 \le x \le 7$

Mem[D+Reg[Ri]*S]

The Hardware/Software Interface

- 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?

Reading Review

- Terminology:
  - Stack, Heap, Static Data, Literals, Code
  - Stack pointer (`%rsp`), `push`, `pop`
  - Caller, callee, return address, `call`, `ret`
    - Return value: `%rax`
    - Arguments: `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9`
  - Stack frames and stack discipline

- Questions from the Reading?

Review Questions

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

```
pushq %rbp
subq  $0x18, %rsp
```

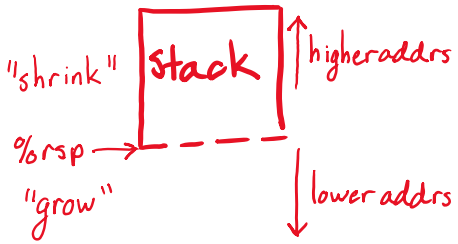
add to stack → pushq 8B %rbp

lower addr → subq $0x18 = 24, %rsp

#grow 8 B

#grow 24B

grow by 32 B



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

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

return value in %rax

arguments in %rdi, %rsi, %rdx

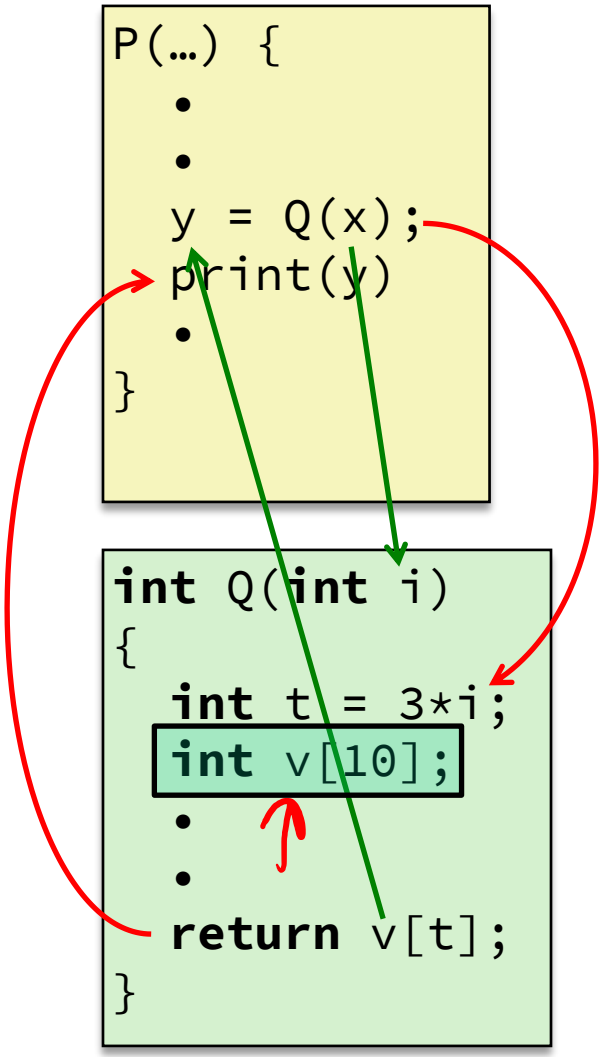
%rsp changed by call and ret

%rip changed while executing instructions

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

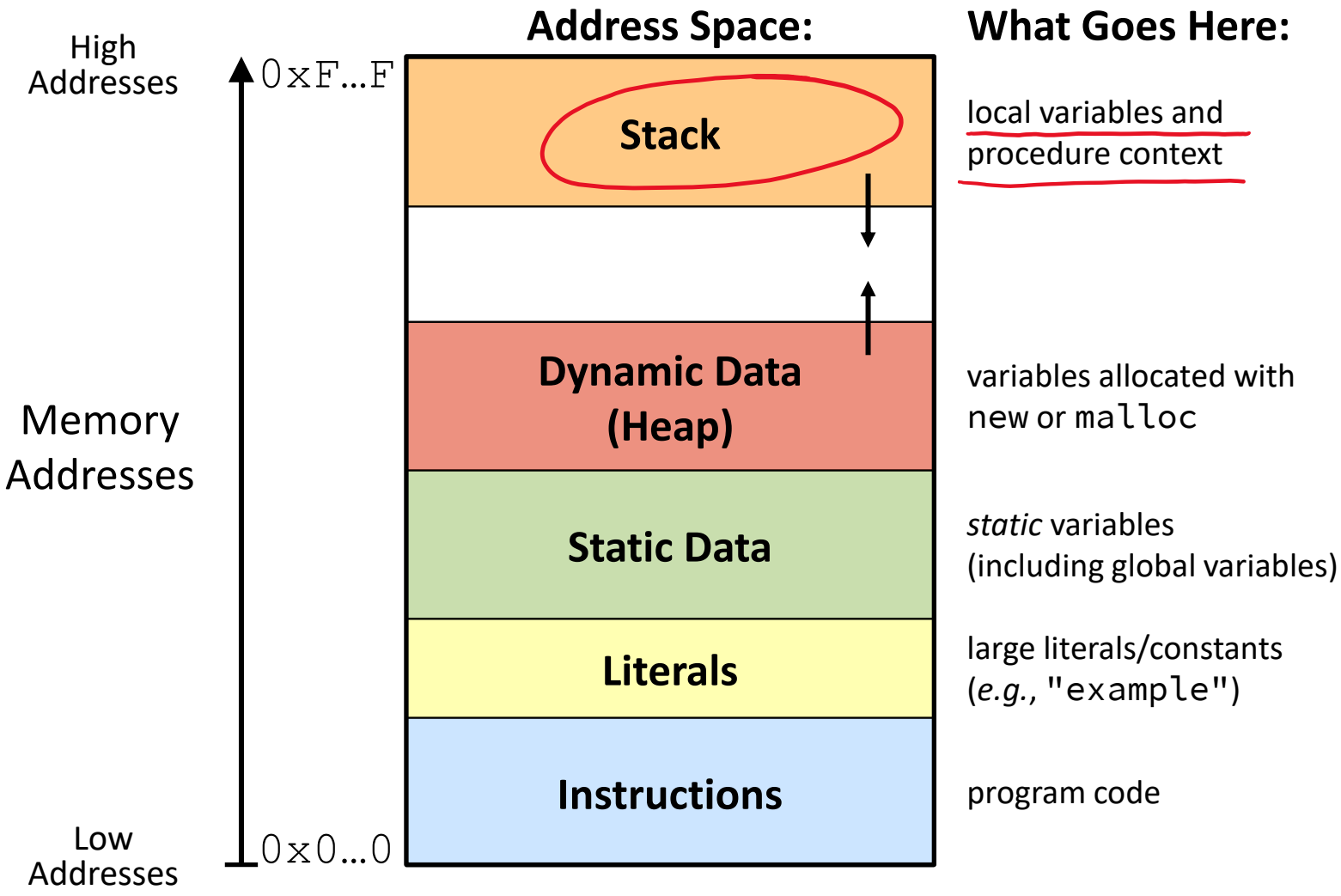
❖ All implemented with machine instructions!
   - An x86-64 procedure uses only those mechanisms required for that procedure



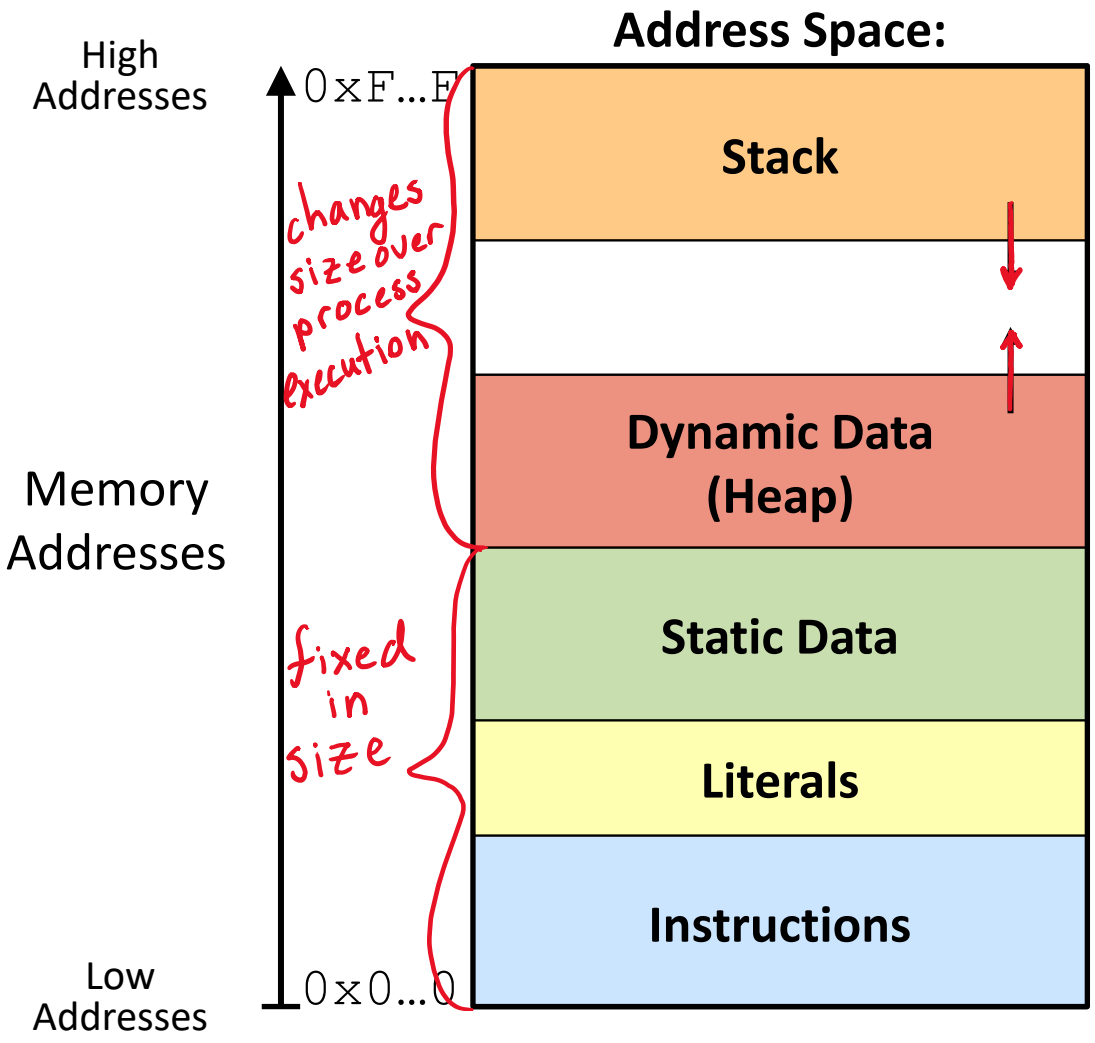
Procedures

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

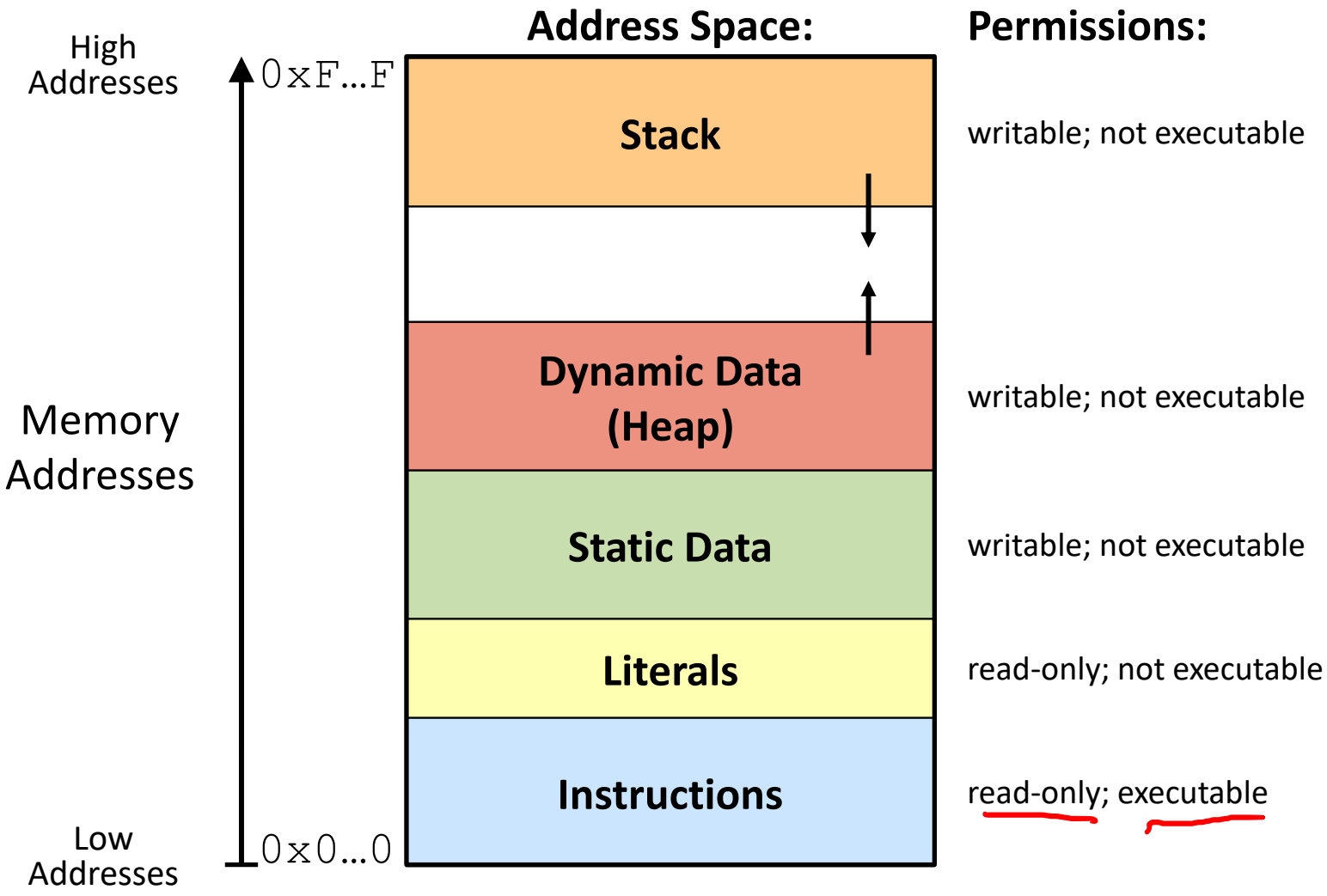
Simplified Memory Layout (Review)



Memory Management



Memory Permissions

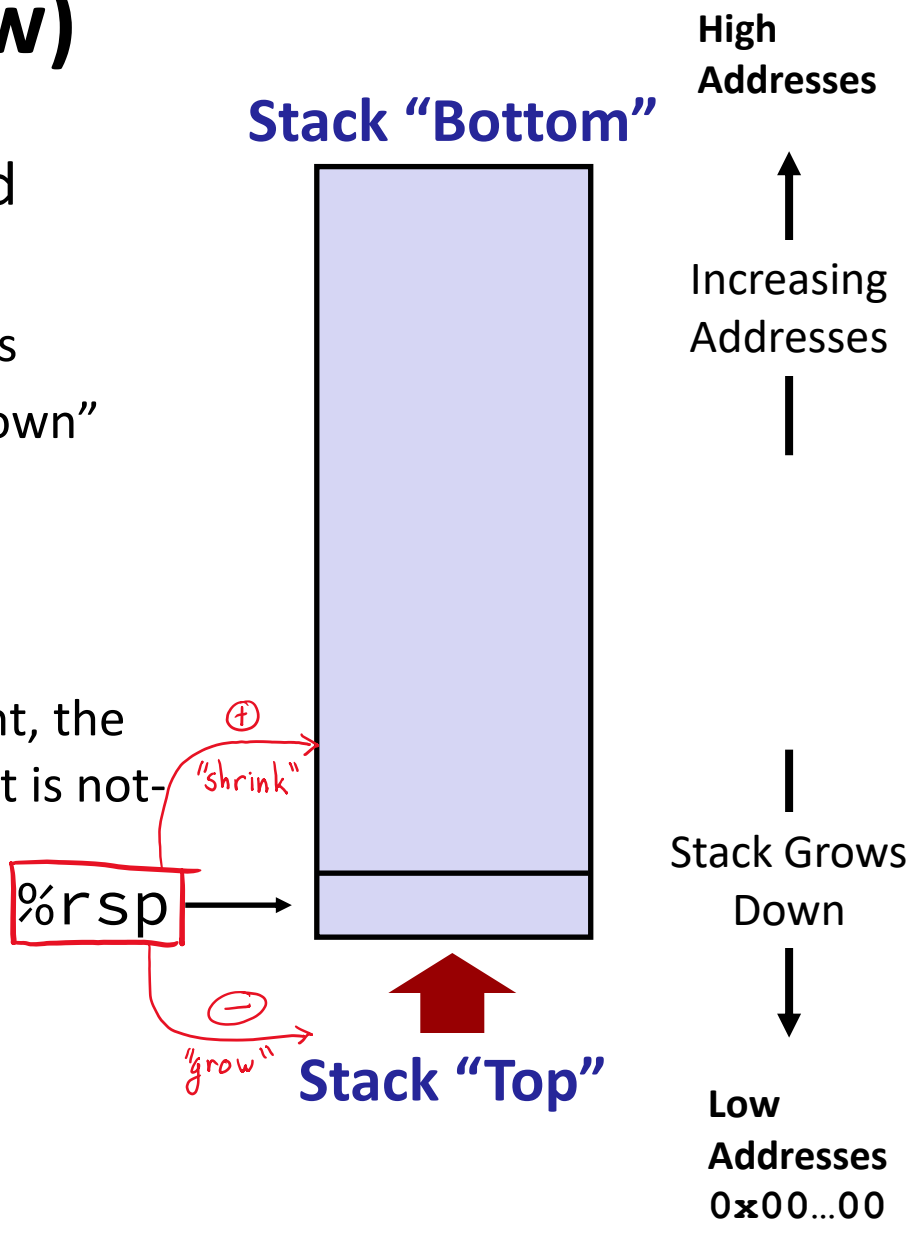


- Segmentation fault: impermissible memory access

Last In, First Out (LIFO)

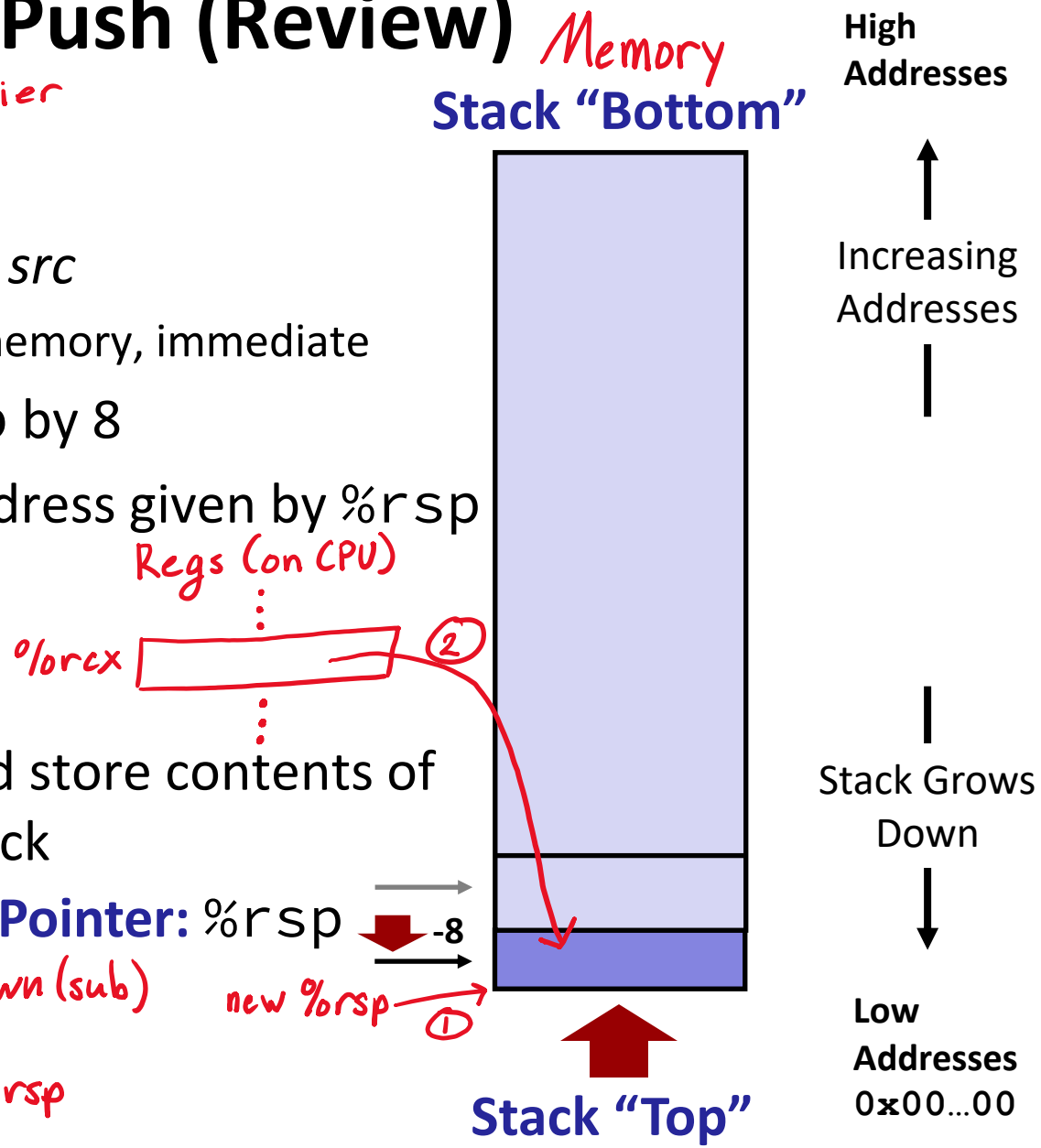
x86-64 Stack (Review)

- 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



x86-64 Stack: Push (Review)

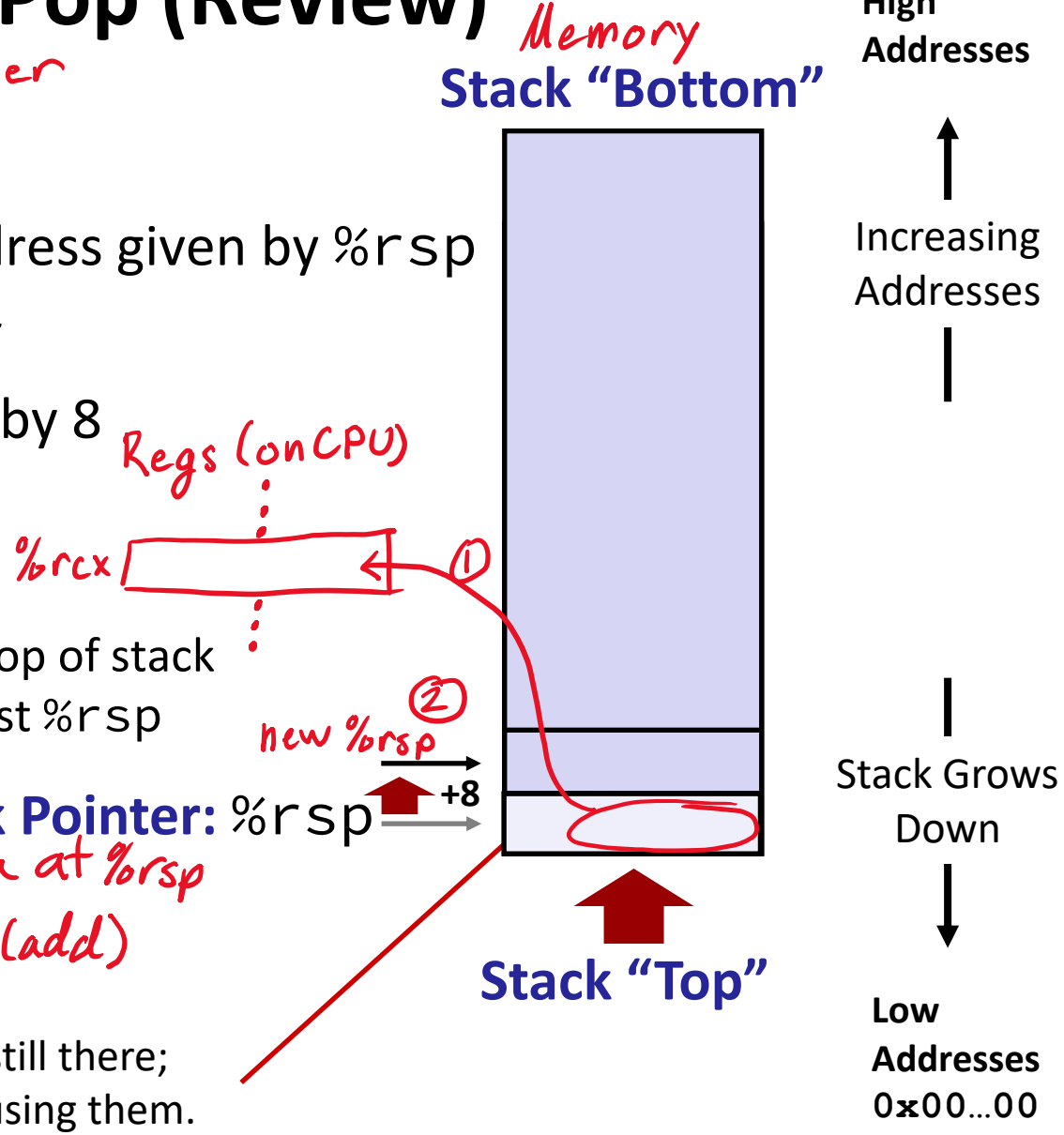
- `pushq` *src*
  - Fetch operand at *src*
    - *Src* can be reg, memory, immediate
  - ***Decrement*** `%rsp` by 8
  - Store value at address given by `%rsp`
- Example:
  - **`pushq %rcx`**
  - Adjust `%rsp` and store contents of `%rcx` on the stack



x86-64 Stack: Pop (Review)

size specifier

- `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`



① read out data at %rsp

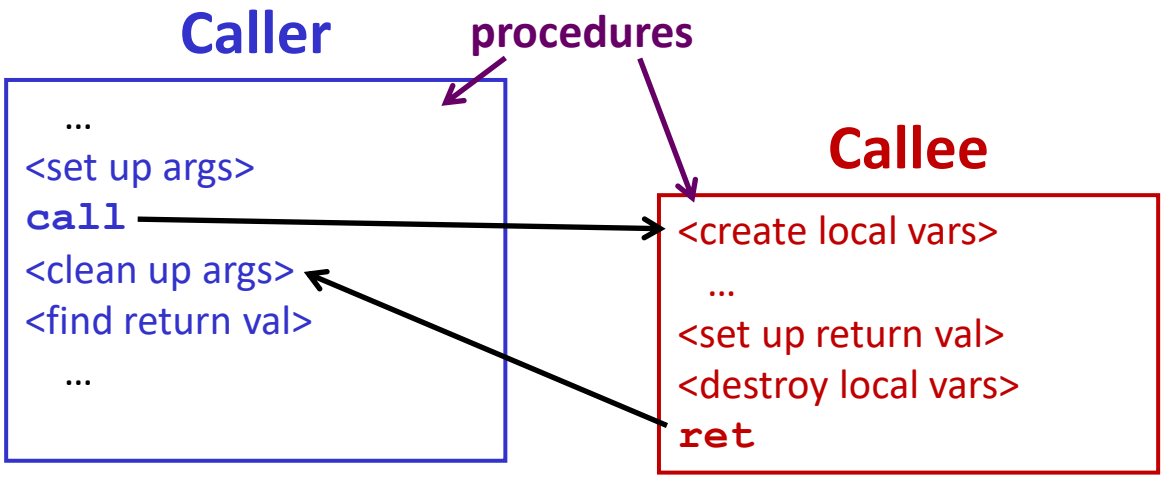
② move %rsp up (add)

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

Procedures

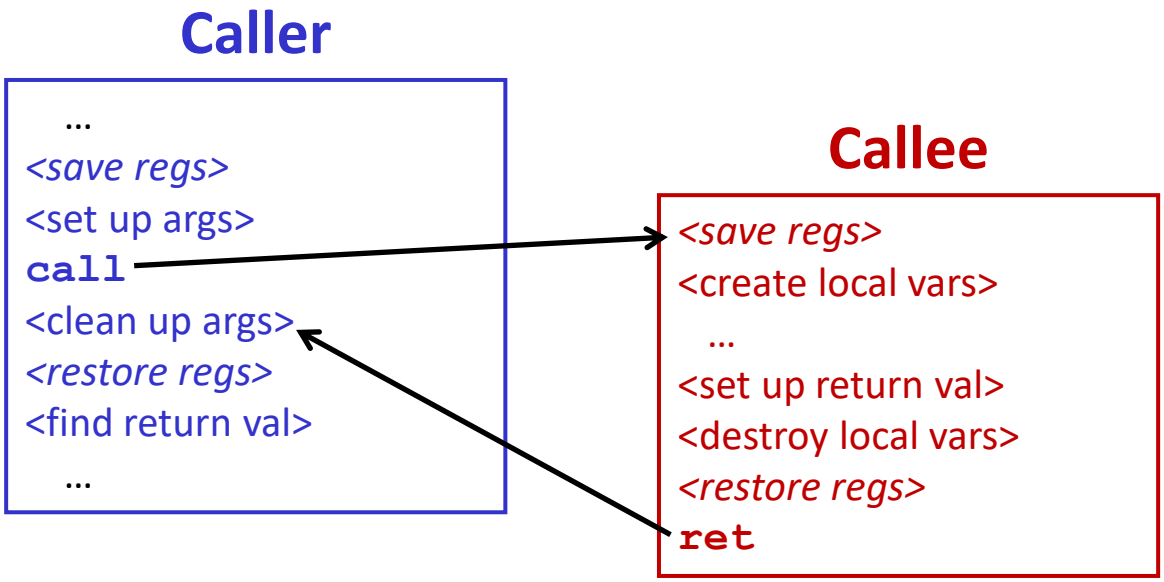
- Stack Structure
- **Calling Conventions**
  - **Passing control**
  - Passing data
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

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;
}
```

Caller

Compiler Explorer:
https://godbolt.org/z/ndro9E

executable disassembly

```
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
```

instruction addresses!

Callee

```
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 (Review)

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

① move %rsp down
② store retaddr at %rsp
③ label → %rip

- 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` (special pop)
  1) Pop return address from stack
  2) Jump to address

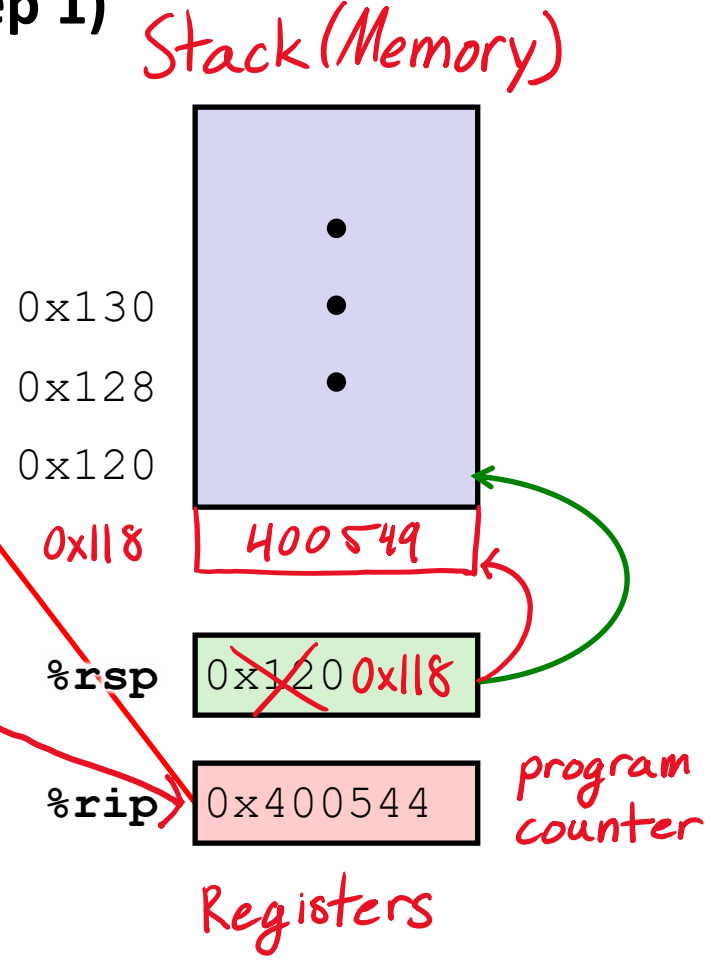
① read retaddr at %rsp into %rip
② move %rsp up

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)
   •
   •
```

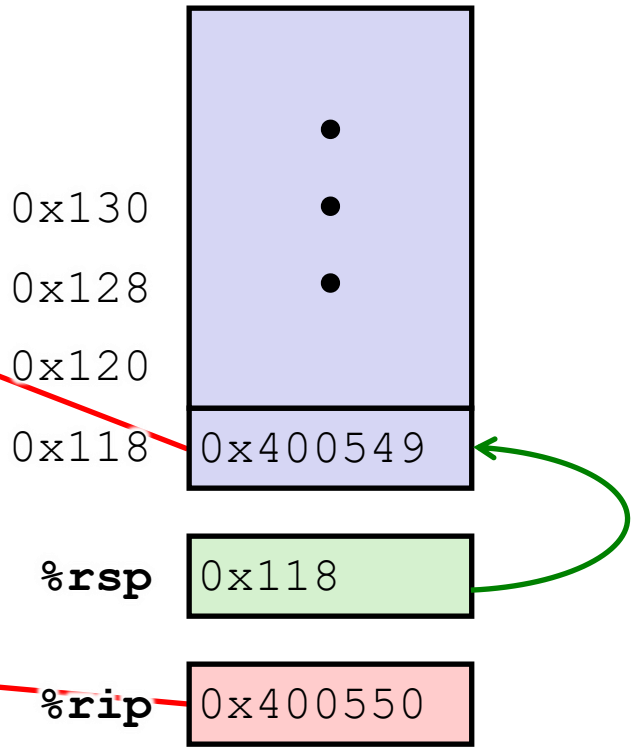
```
0000000000400550 <mult2>:
   400550:  movq   %rdi,%rax
   •
   •
   400557:  ret
```



Procedure Call Example (step 2)

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

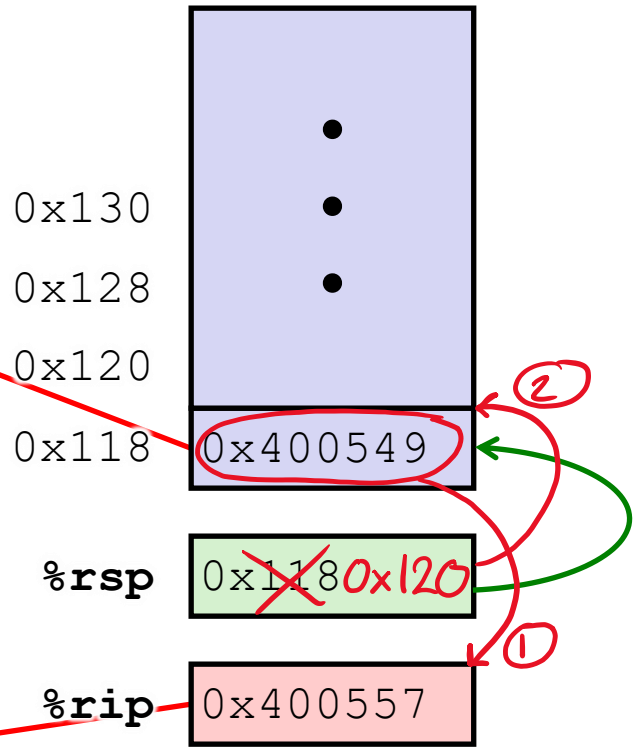
```
0000000000400550 <mult2>:
   400550:  movq   %rdi,%rax
   •
   •
   400557:  ret
```



Procedure Return Example (step 1)

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

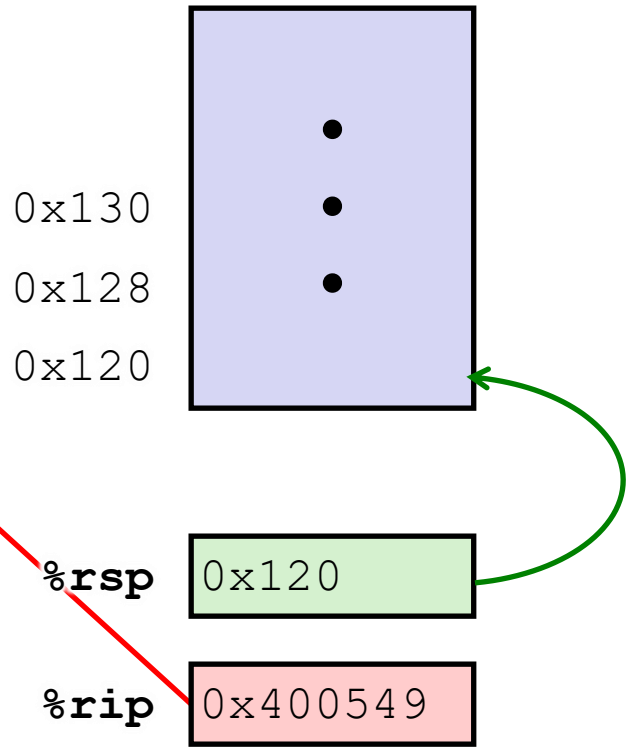
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



Procedure Return Example (step 2)

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

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



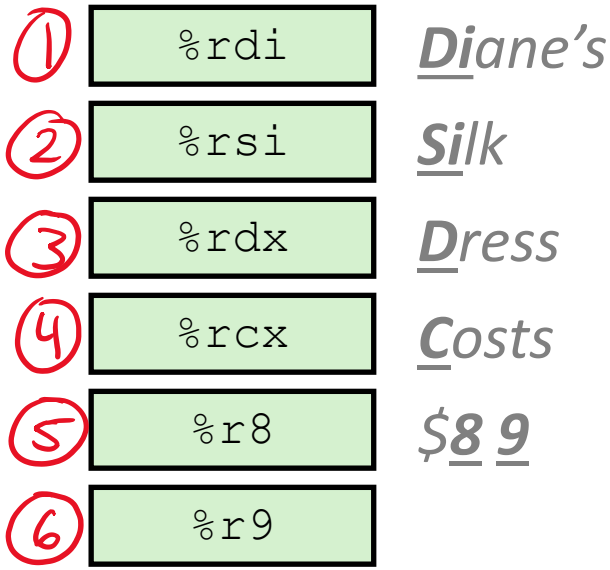
Procedures

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

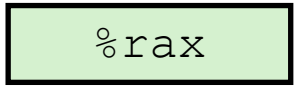
Procedure Data Flow (Review)

Registers (NOT in Memory)

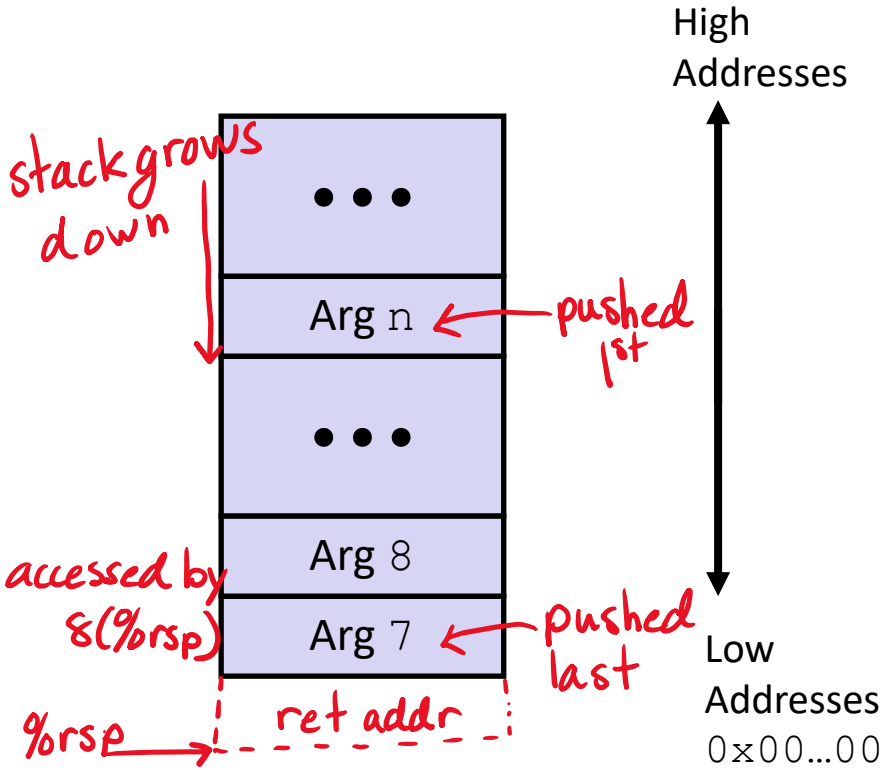
- First 6 arguments



- Return value



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;
}
```

rdi rsi rdx

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

```
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
    •••
```

(will explain later)

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

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

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

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

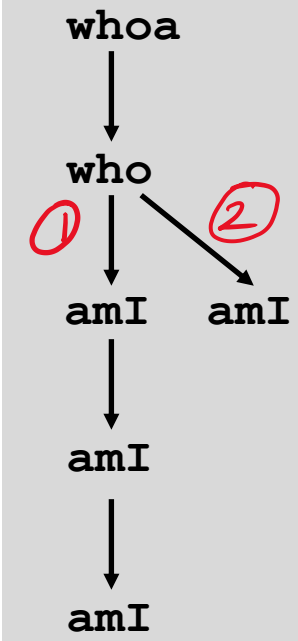
1st call recurses twice

2nd call doesn't recurse

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

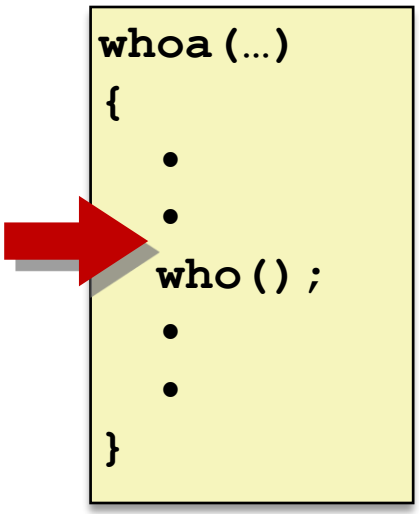
based on some condition

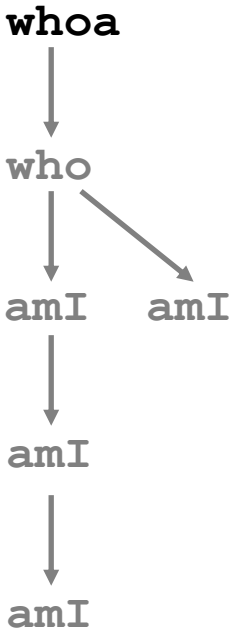
Example Call Chain

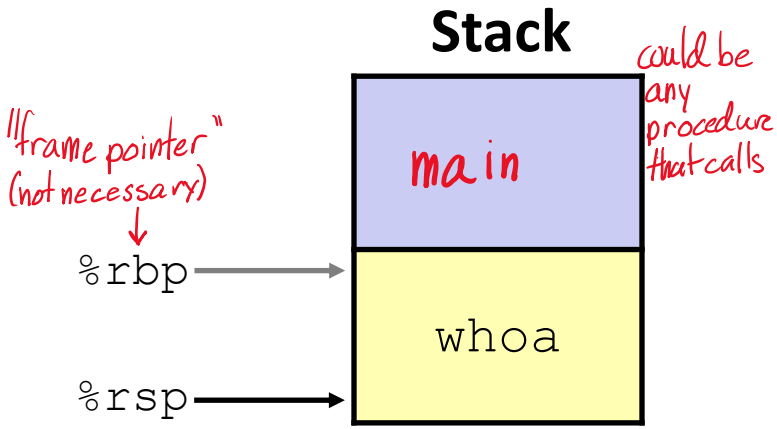


Procedure `amI` is recursive (calls itself)

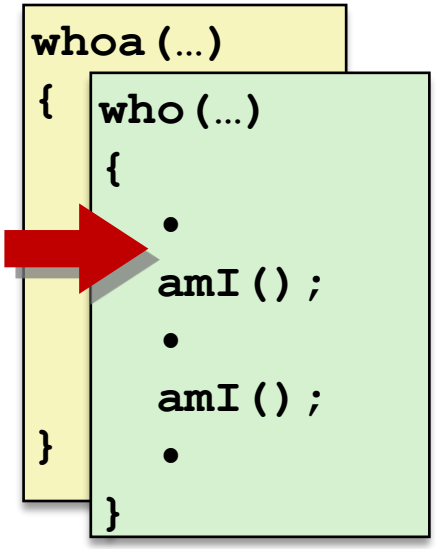
1) Call to whoa

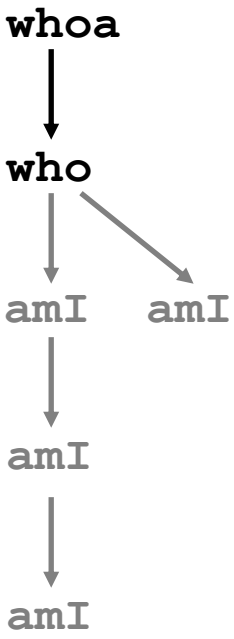


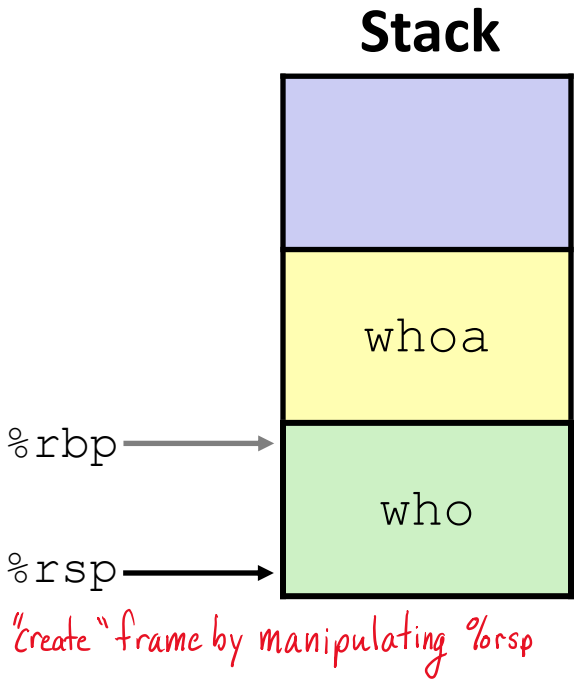




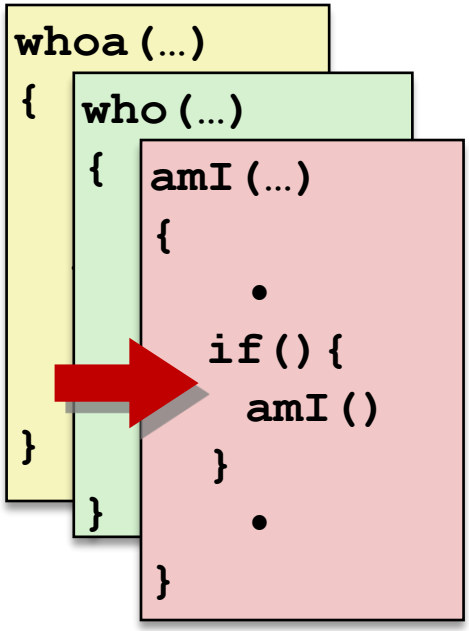
2) Call to who

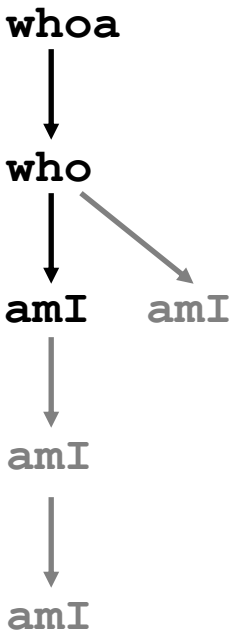

whoa(...)
{
who(...)
{
•
amI();
•
amI();
•
}
}

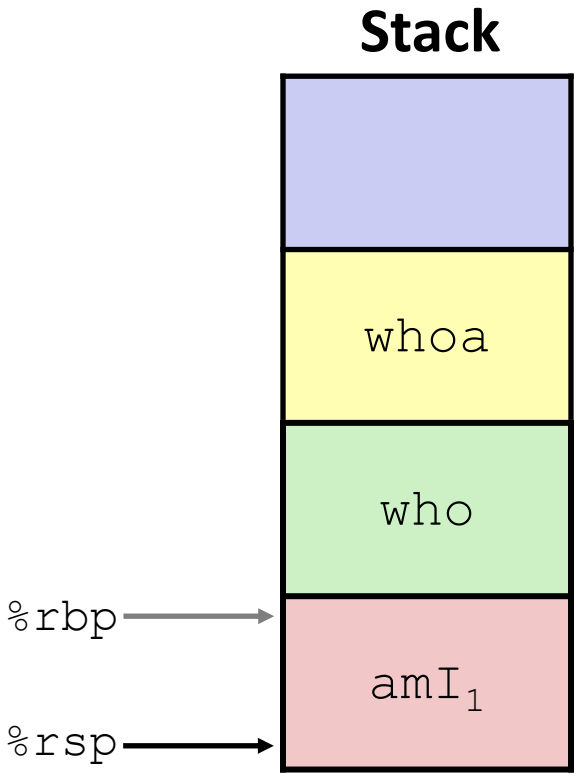

whoa
who
amI
amI
amI
amI


Stack
whoa
who
%rbp
%rsp
"create" frame by manipulating %rsp

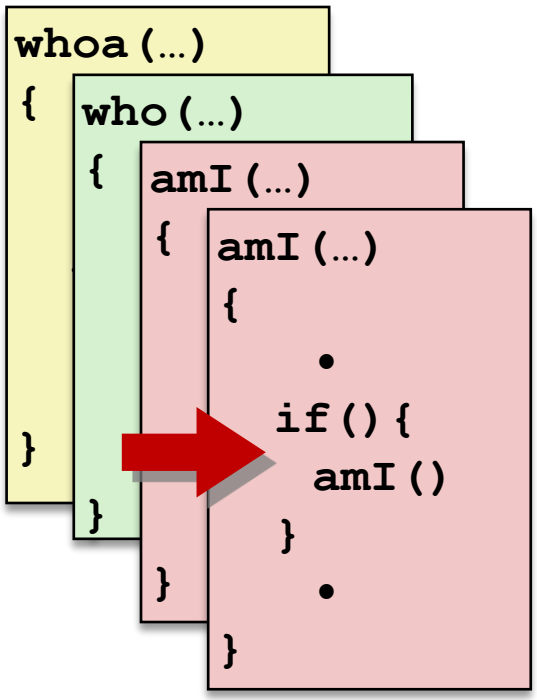
3) Call to amI (1)

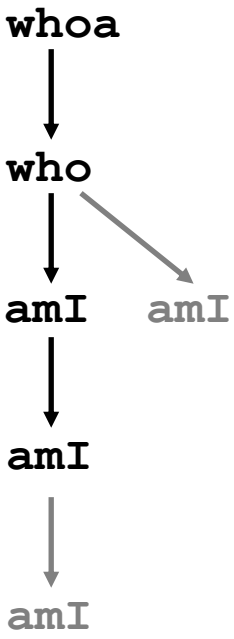


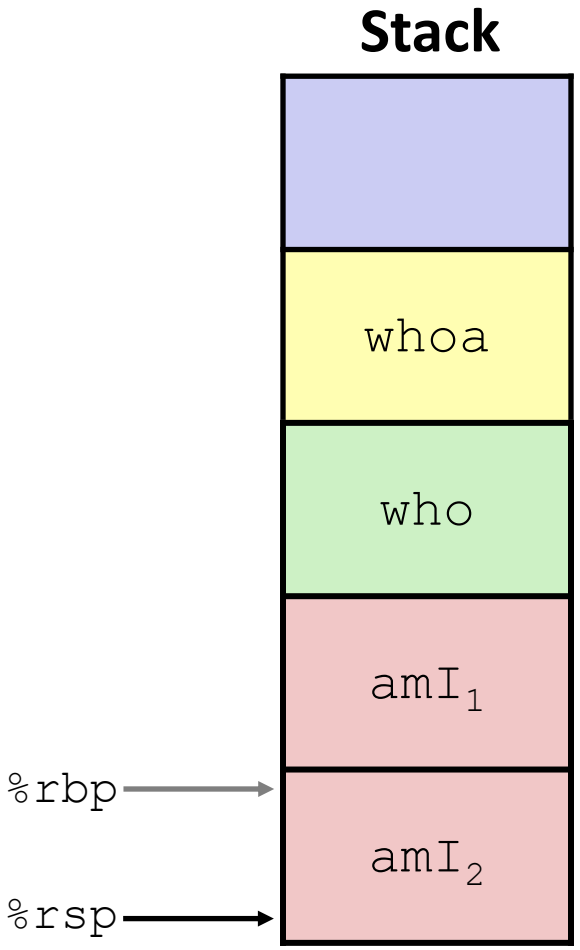




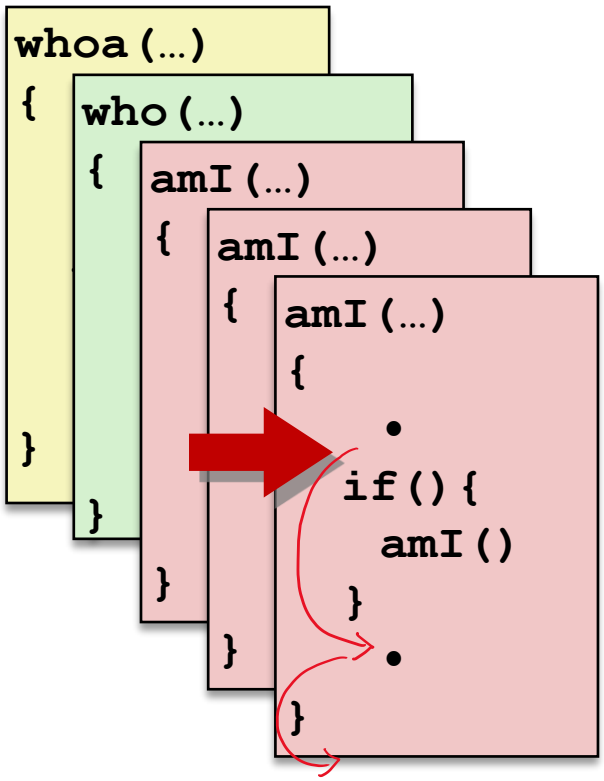
4) Recursive call to amI (2)

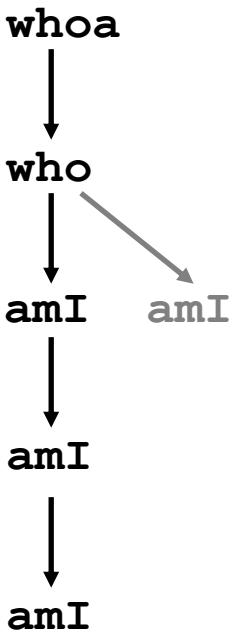


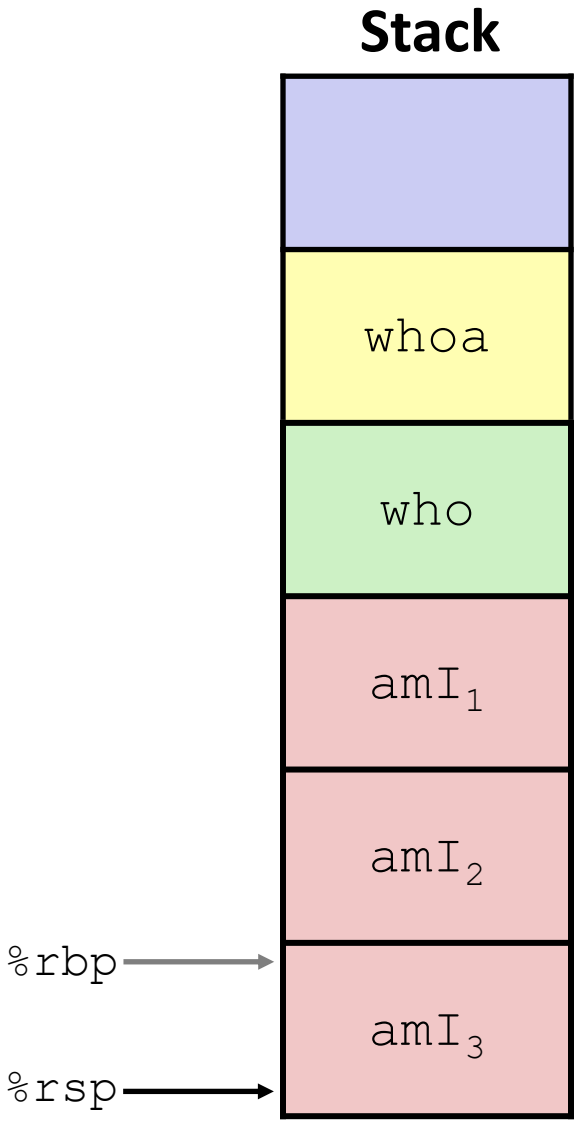




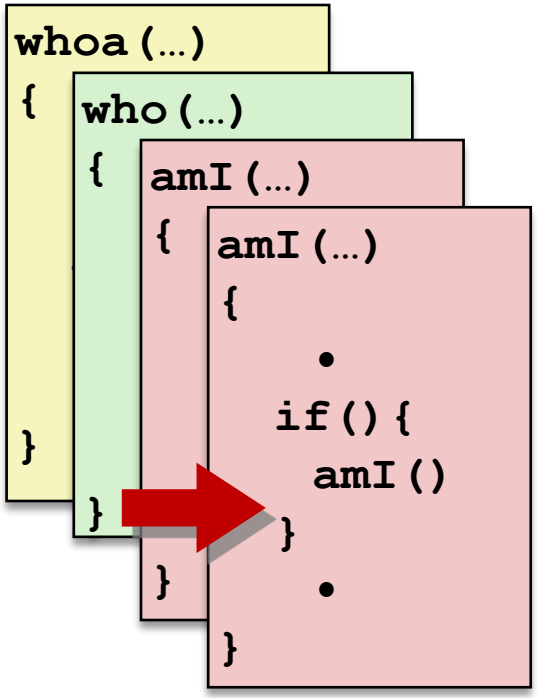
5) (another) Recursive call to amI (3)

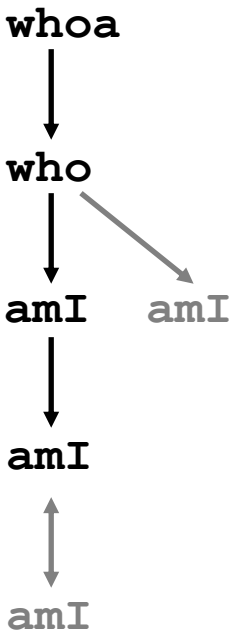


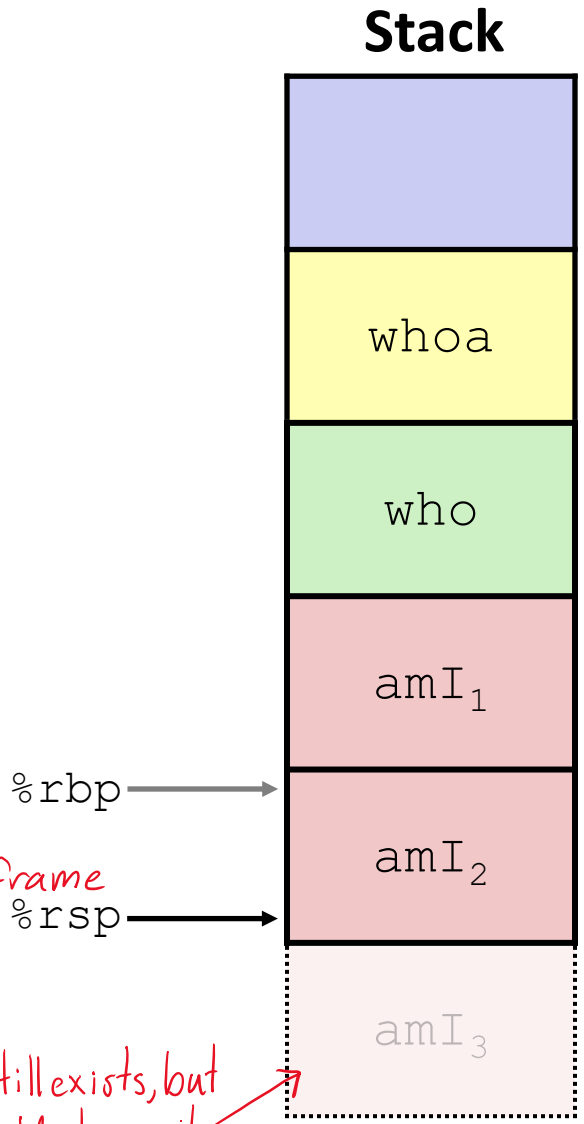




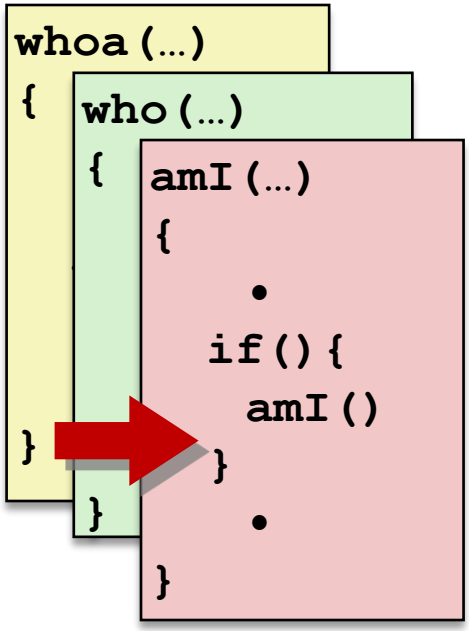
6) Return from (another) recursive call to amI

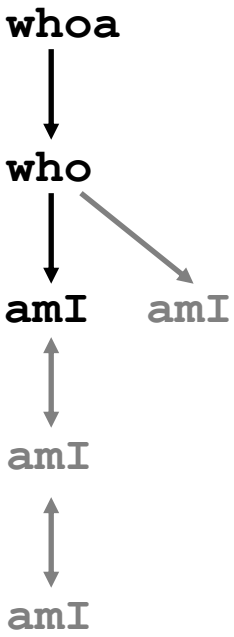


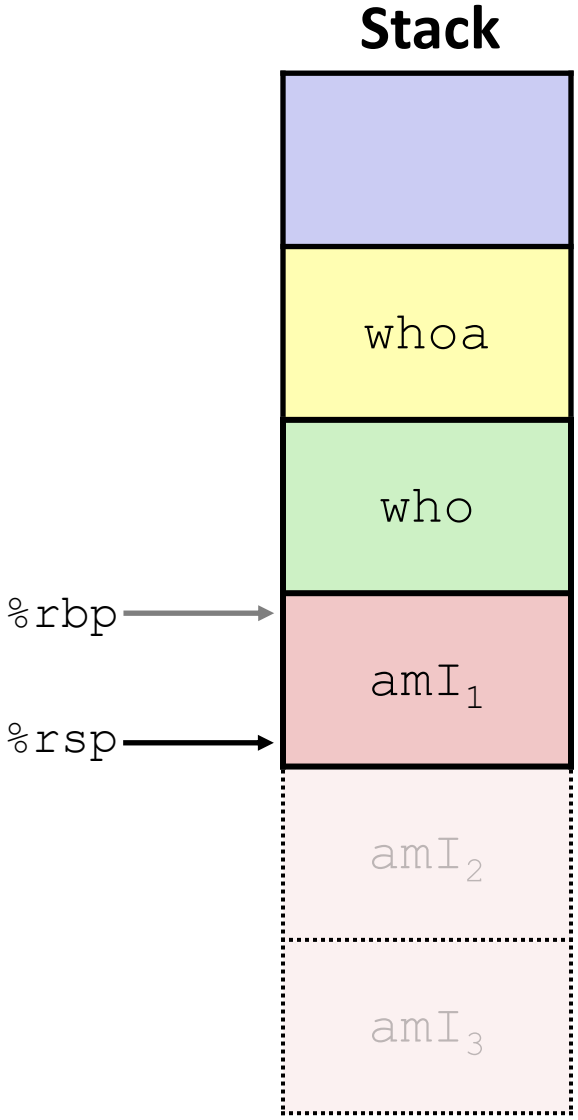




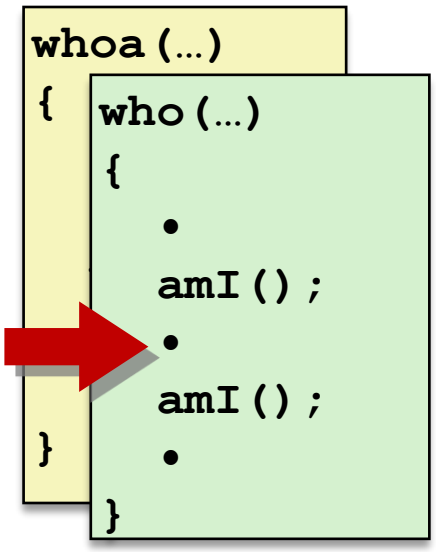
7) Return from recursive call to amI

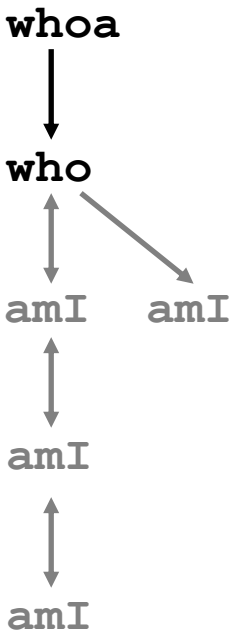


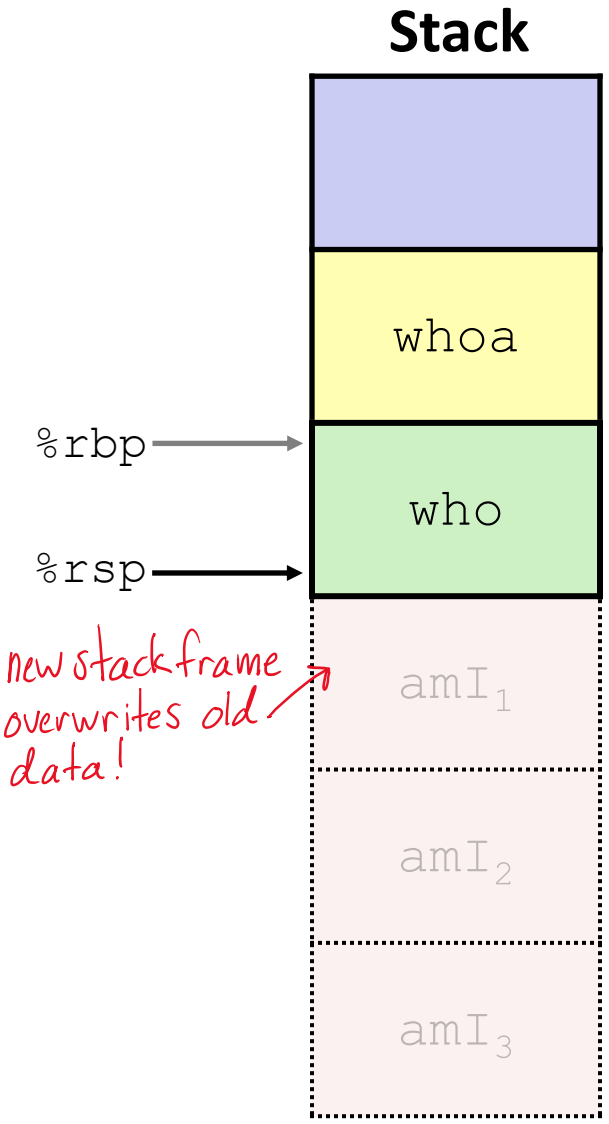




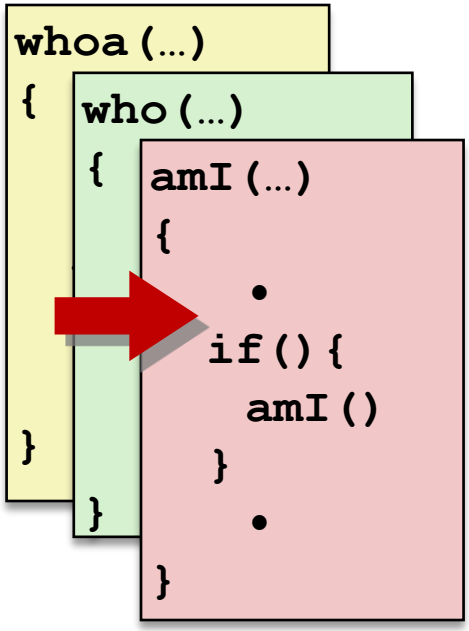
8) Return from call to amI

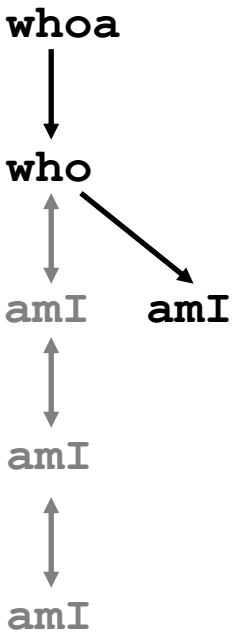


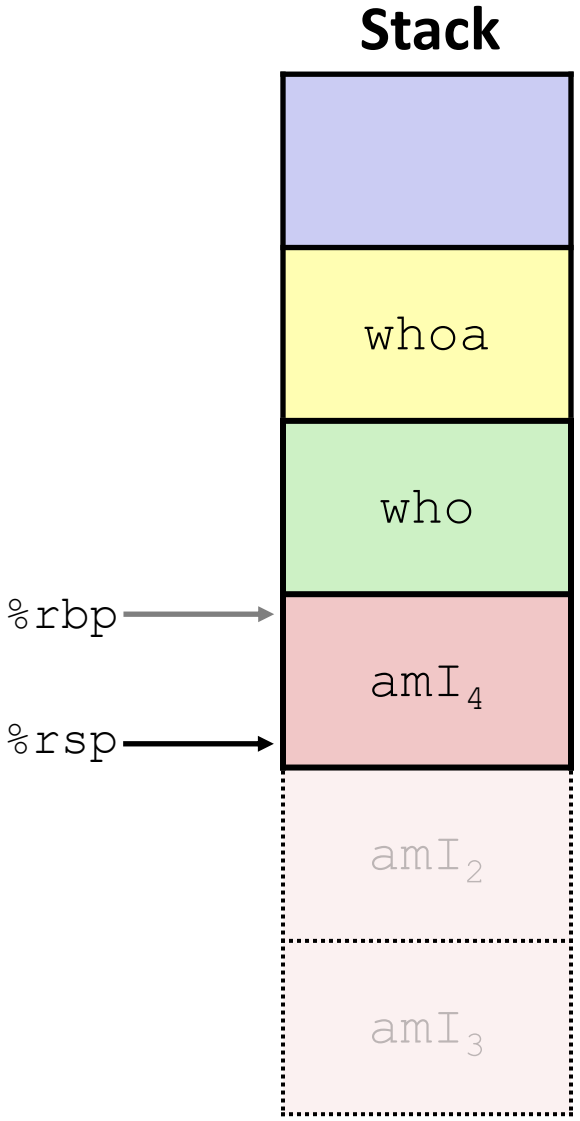




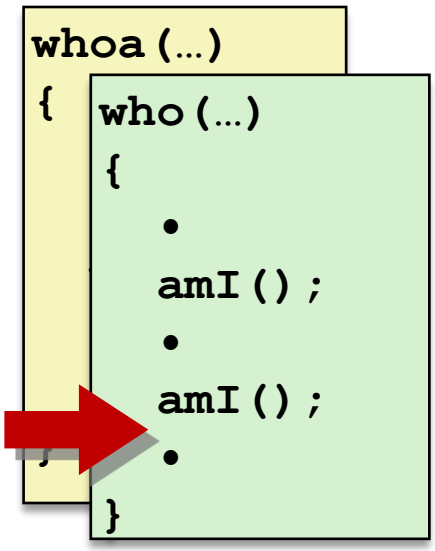
9) (second) Call to amI (4)

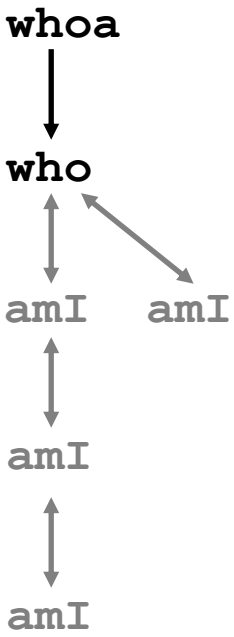


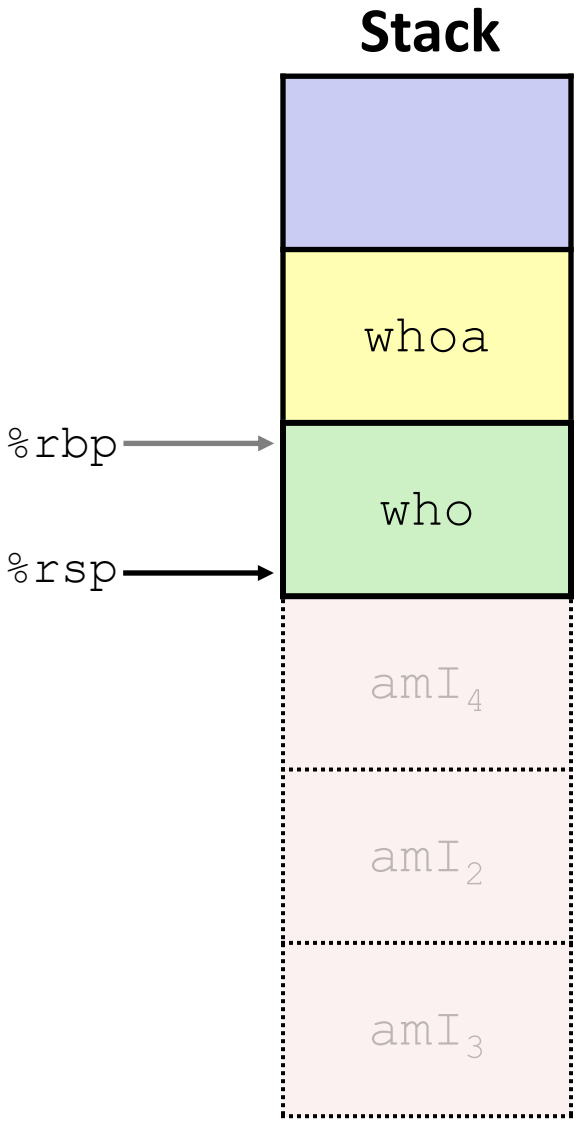




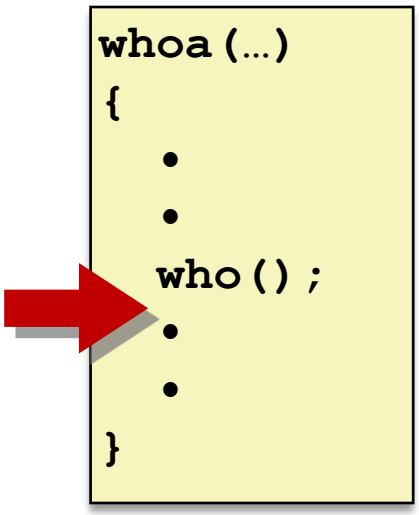
10) Return from (second) call to amI

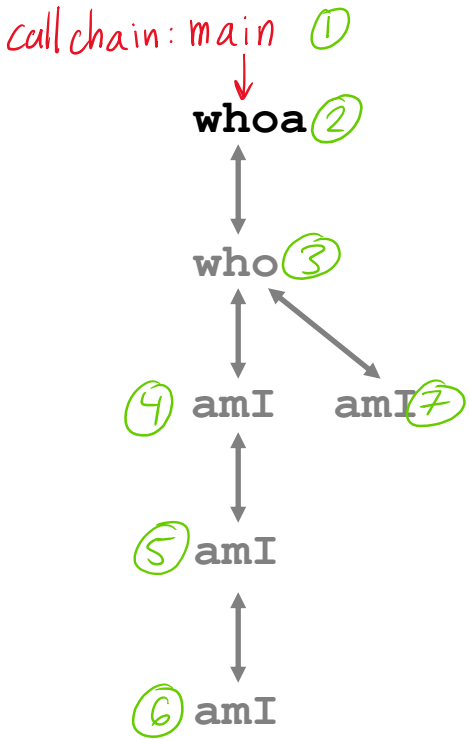


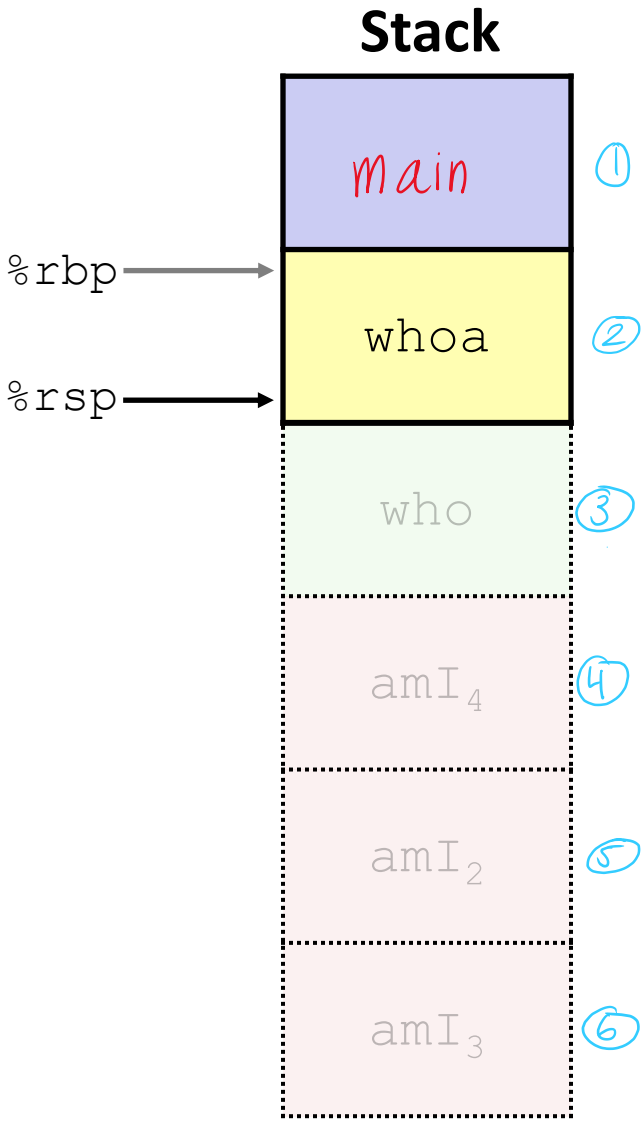




11) Return from call to who







total stack frames created: 7

maximum stack depth: 6