The Stack & Procedures

CSE 351 Autumn 2021

Instructor:

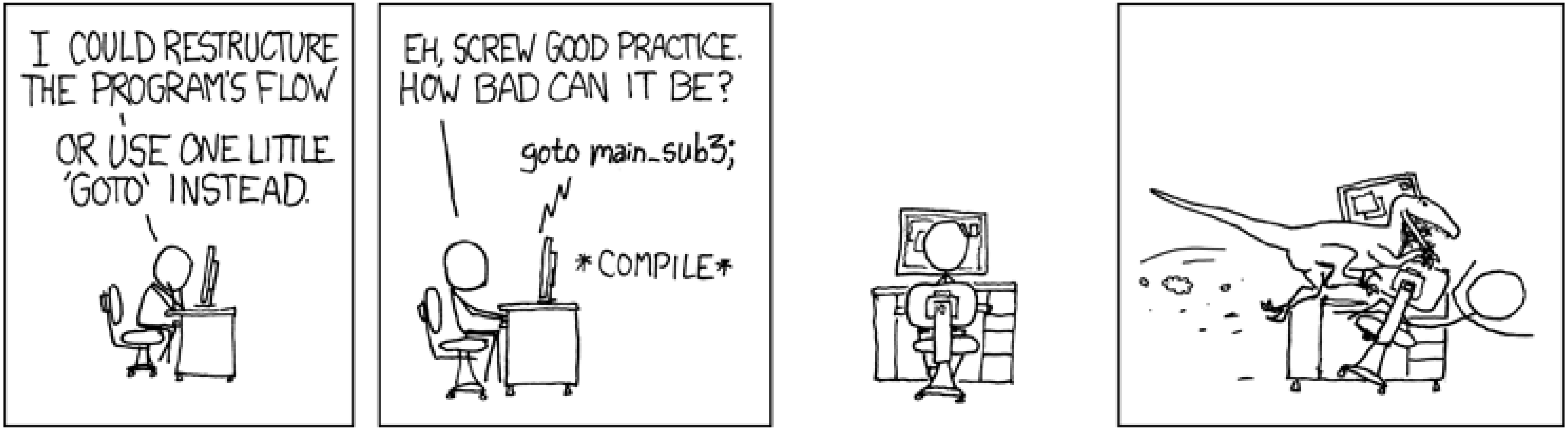
Justin Hsia

Teaching Assistants:

Allie Pfleger
Atharva Deodhar
Francesca Wang
Joy Dang
Monty Nitschke

Anirudh Kumar
Celeste Zeng
Hamsa Shankar
Julia Wang
Morel Fotsing

Assaf Vayner
Dominick Ta
Isabella Nguyen
Maggie Jiang
Sanjana Chintalapati


I COULD RESTRUCTURE THE PROGRAM'S FLOW OR USE ONE LITTLE 'GOTO' INSTEAD.
EH, SCREW GOOD PRACTICE. HOW BAD CAN IT BE?
goto main_sub3;
COMPILE

http://xkcd.com/571/

Relevant Course Information

- Lab 2 due next Friday (10/29)
  - Can start in earnest after today's lecture!
  - See GDB Tutorial and Phase 1 walkthrough in Section 4 Lesson
- Midterm (take home, 11/3–11/5)
  - Make notes and use the midterm reference sheet
  - Form study groups and look at past exams!

x86 Control Flow

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

```
long switch_ex
   (long x, long y, long z)
{
    long w = 1;
    switch (x) {
        case 1:
            w = y*z; break;
        case 2:
            w = y/z;
        /* Fall Through */
        case 3:
            w += z;  break;
        case 5:
        case 6:
            w -= z;  break;
        case 7:
            w = y%z; break;
        default:
            w = 2;
    }
    return w;
}
```

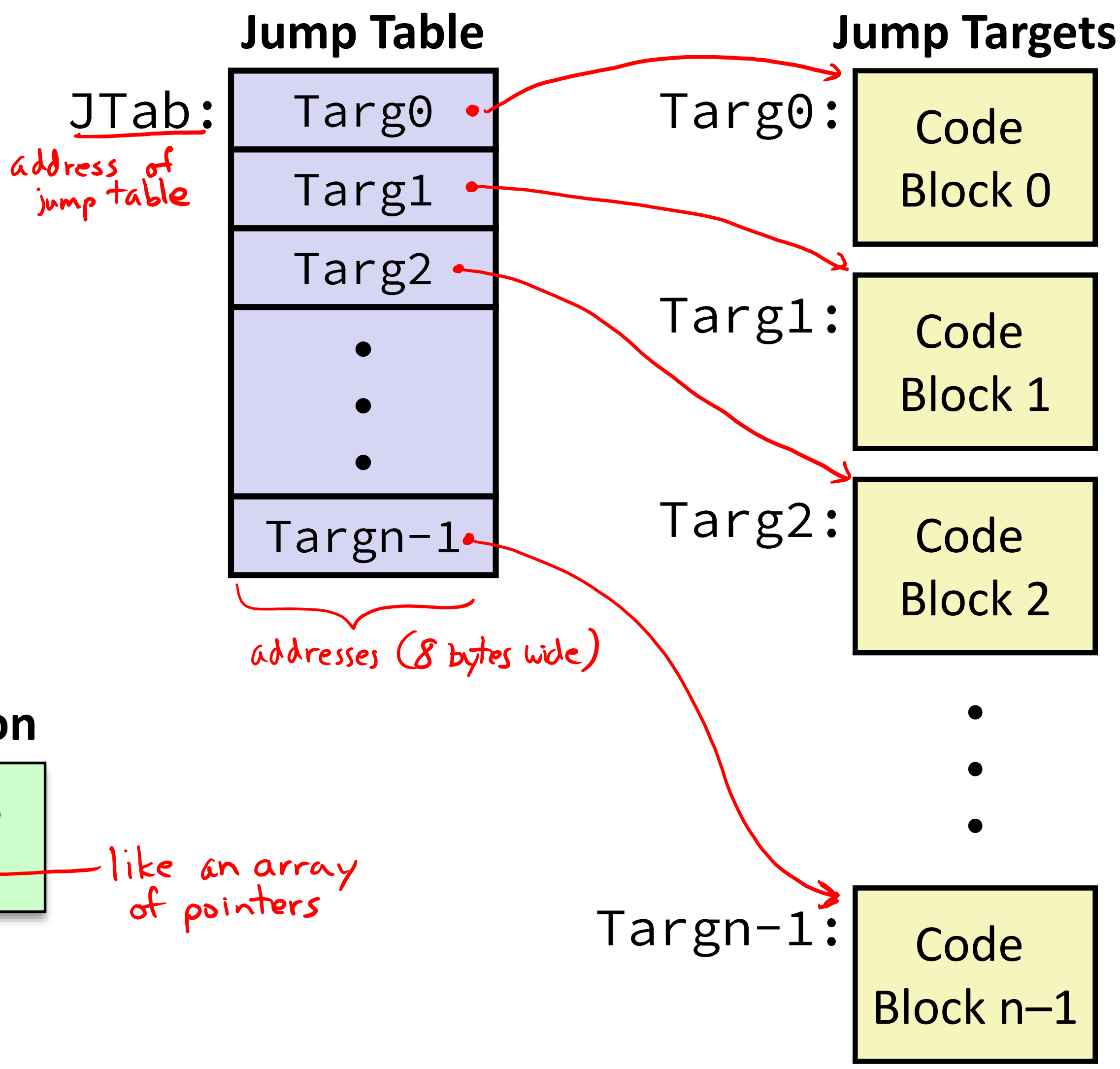
Switch Statement Example

- Multiple case labels
  - Here: 5 & 6
- Fall through cases
  - Here: 2
- Missing cases
  - Here: 4 ???
- Implemented with:
  - *Jump table*
  - *Indirect jump instruction*

Jump Table Structure

Switch Form

```
switch (x) {
  case val_0:
     Block 0
  case val_1:
     Block 1
     • • •
  case val_n-1:
     Block n–1
}
```



Approximate Translation

```
target = JTab[x];
goto target;
```

like an array of pointers

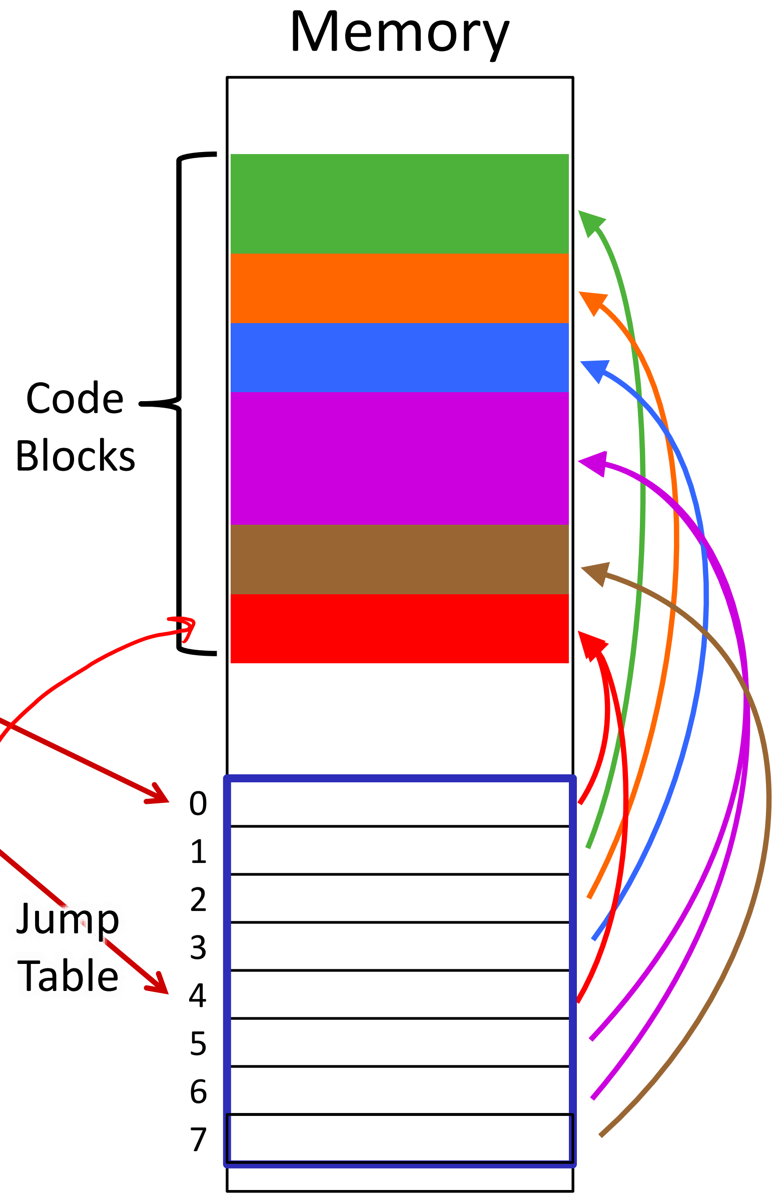
Jump Table Structure

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

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

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

where?

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

a b

jump to default case if x>7 (unsigned)

Note compiler chose to not initialize w

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

jump above – unsigned > catches negative default cases

-1 > 7U → jump to default case

Switch Statement Example

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

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

following data is a "quad word" = 8 bytes

```
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 jump table

x

sizeof (void*)

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`

%rip

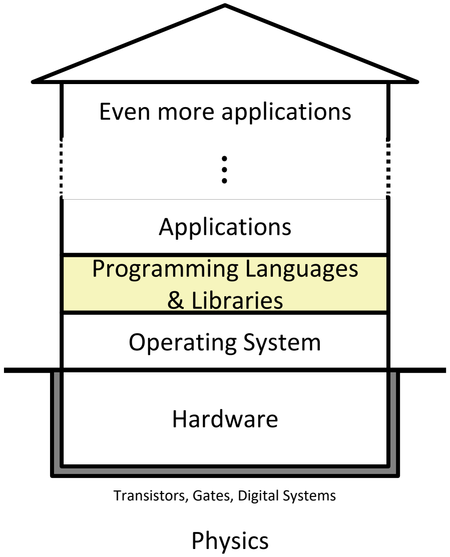
- **Indirect jump:** `jmp *.L4(,%rdi,8)`

Mem[D+ Reg[Ri]*S]

  - 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 ≤ x ≤ 7

The Hardware/Software Interface

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


Even more applications
⋮
Applications
Programming Languages & Libraries
Operating System
Hardware
Transistors, Gates, Digital Systems
Physics

- 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?

add to stack

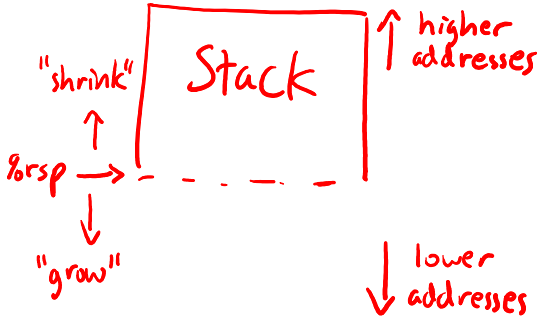
8B

```
pushq %rbp            # grow 8 B
subq  $0x18, %rsp     # grow 24 B
```

lower address

0x18 = 24

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, and %rdx

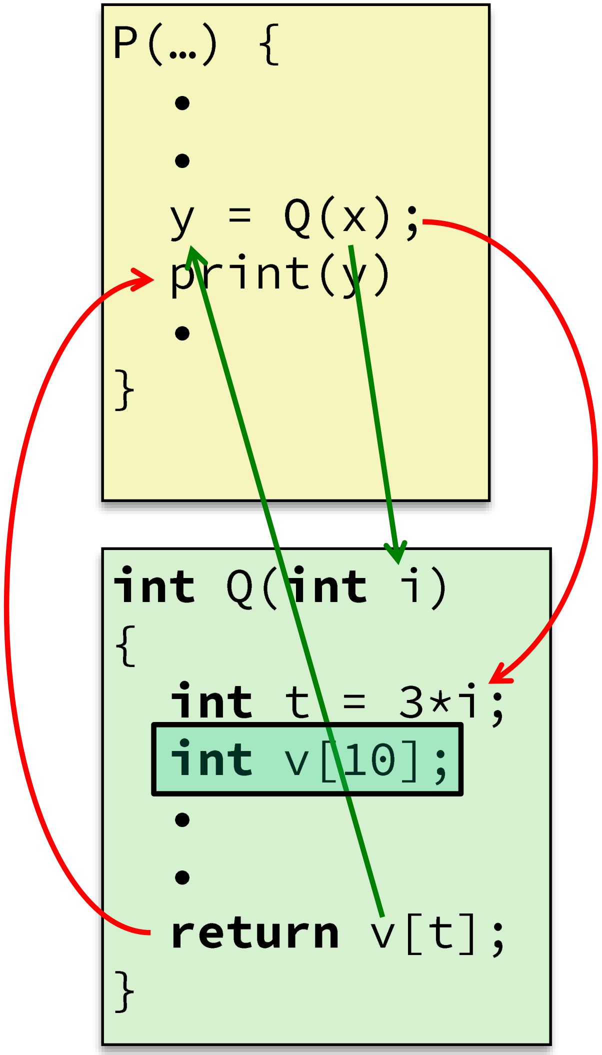
%rsp changed by call & ret

%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
   - Deallocate upon return

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



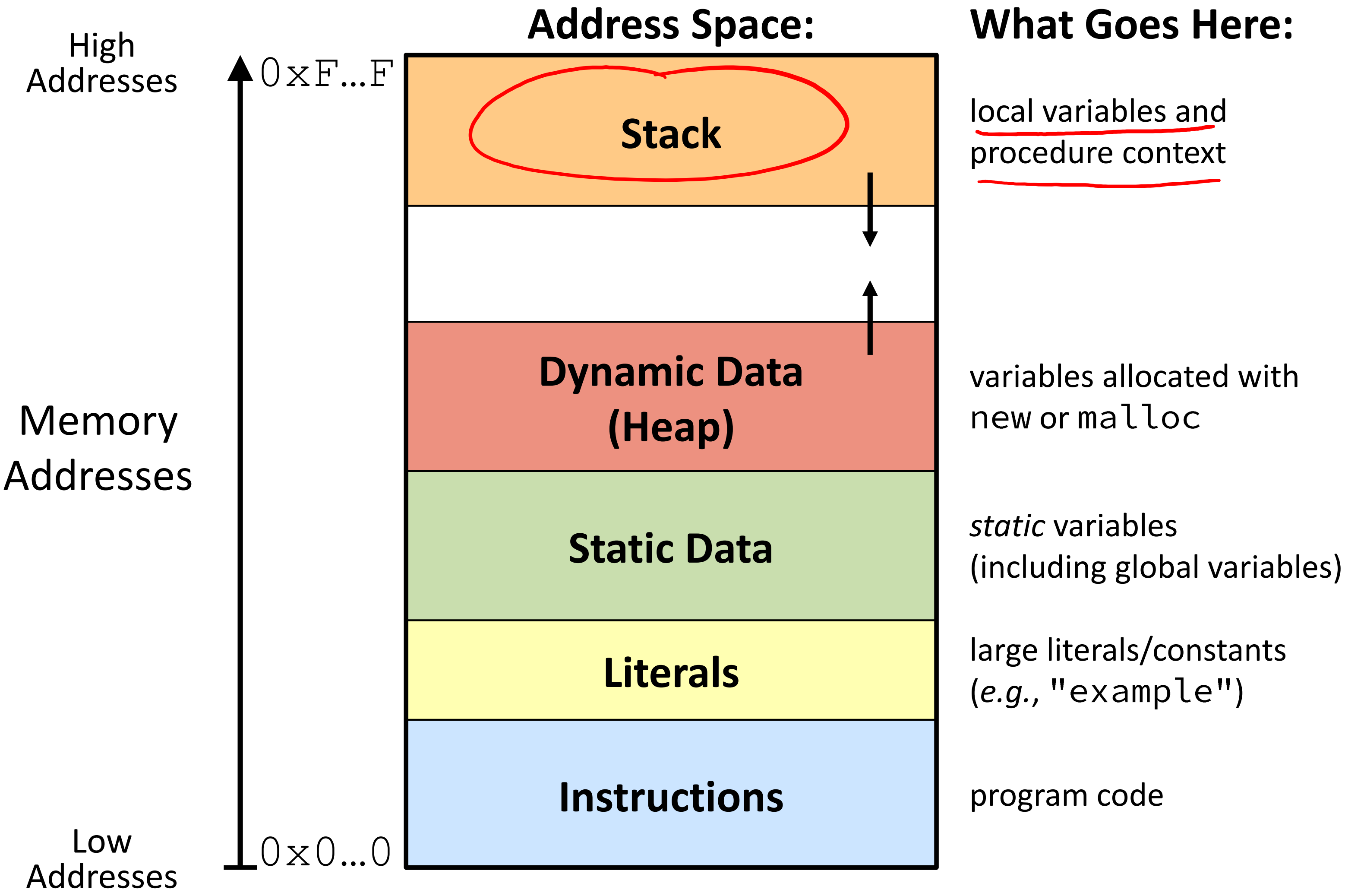
```
P(…) {
  •
  •
  y = Q(x);
  print(y)
  •
}
```

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

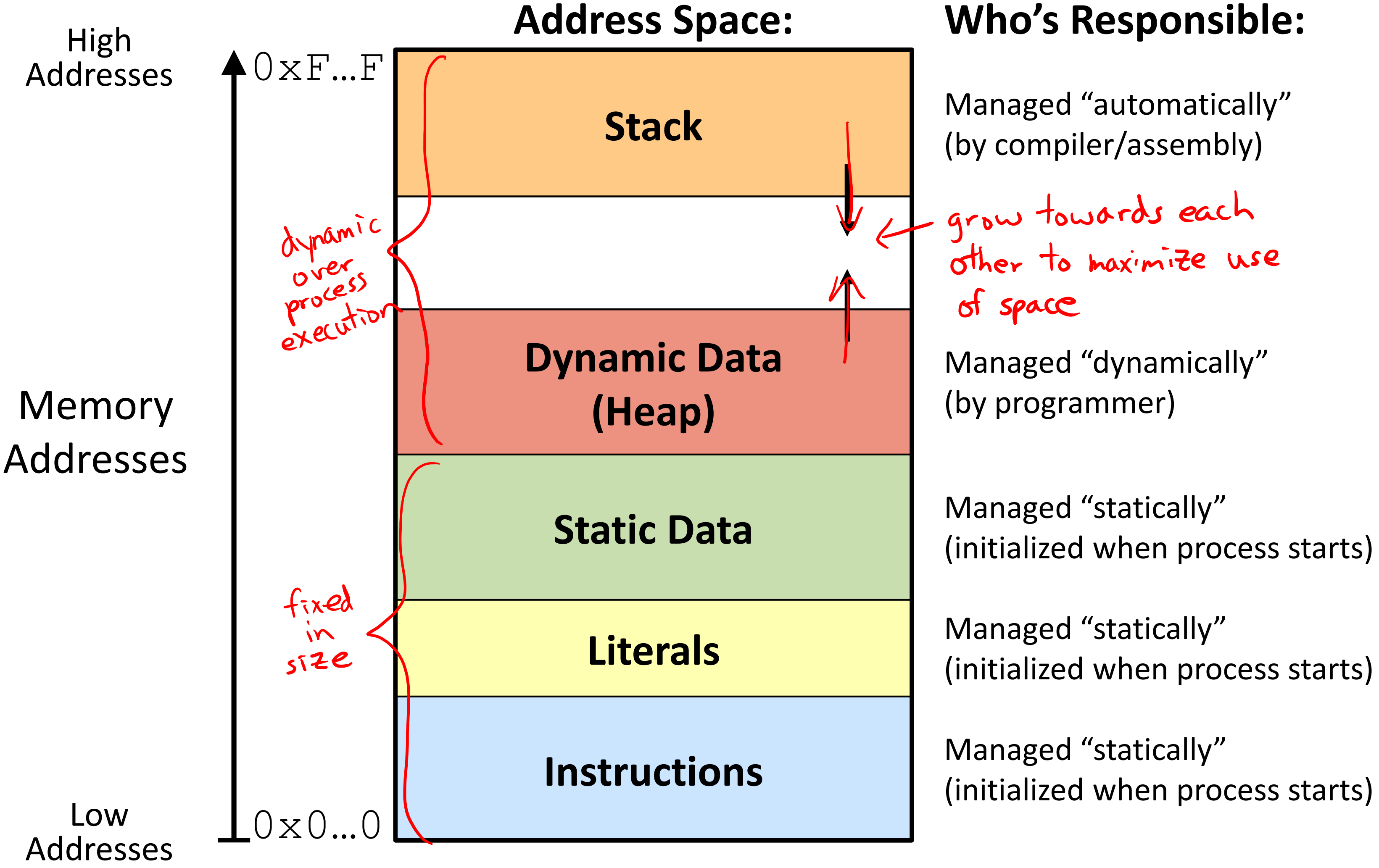
Procedures

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

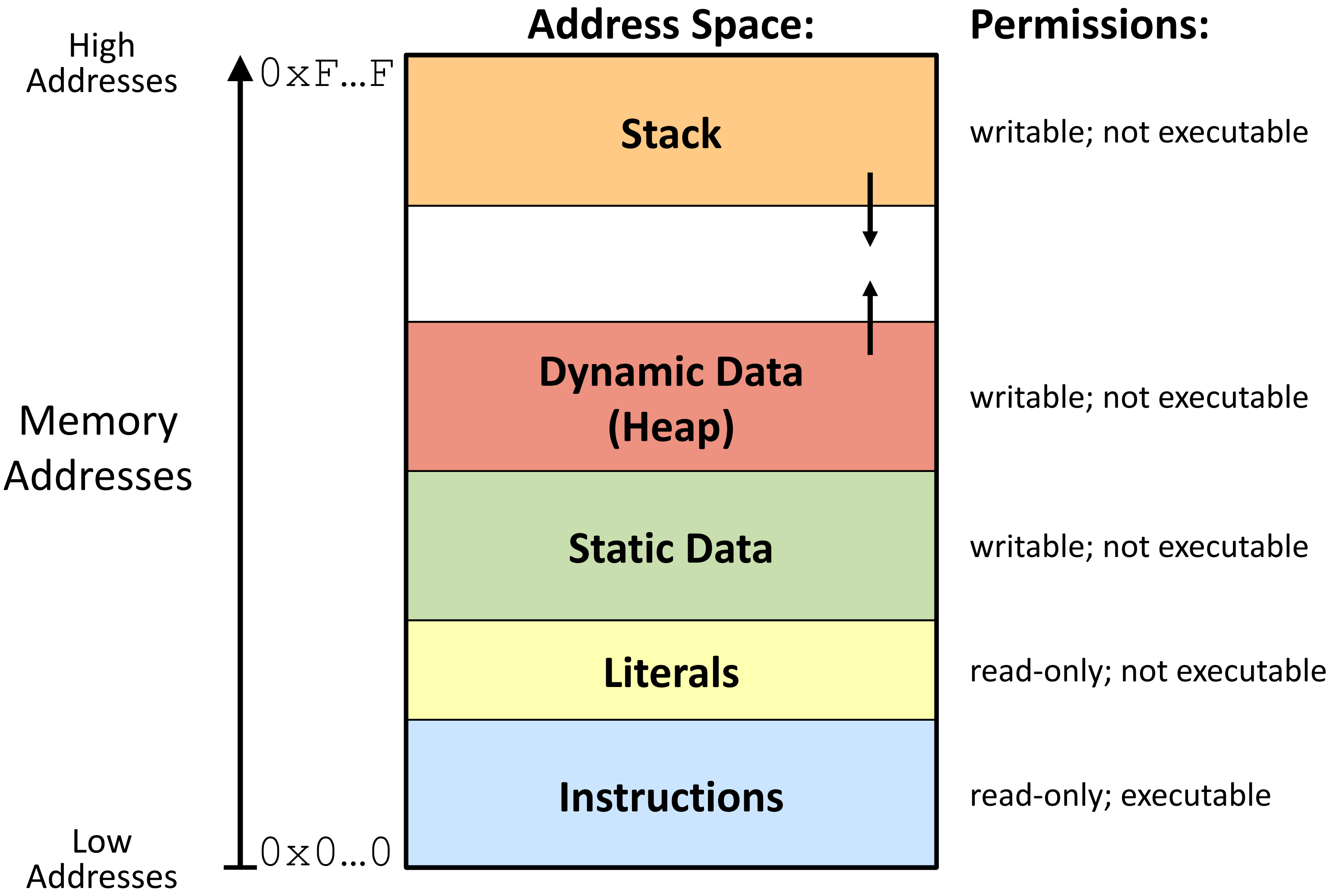
Simplified Memory Layout (Review)


Address Space:
What Goes Here:
High Addresses
0xF…F
Stack
local variables and procedure context
Dynamic Data (Heap)
variables allocated with new or malloc
Memory Addresses
Static Data
static variables (including global variables)
Literals
large literals/constants (e.g., "example")
Instructions
program code
Low Addresses
0x0…0

Memory Management


Address Space:
Who's Responsible:
High Addresses
0xF…F
Stack
Managed "automatically" (by compiler/assembly)
grow towards each other to maximize use of space
dynamic over process execution
Memory Addresses
Dynamic Data (Heap)
Managed "dynamically" (by programmer)
Static Data
Managed "statically" (initialized when process starts)
fixed in size
Literals
Managed "statically" (initialized when process starts)
Instructions
Managed "statically" (initialized when process starts)
Low Addresses
0x0…0

Memory Permissions



High Addresses

0xF…F

Memory Addresses

Low Addresses

0x0…0

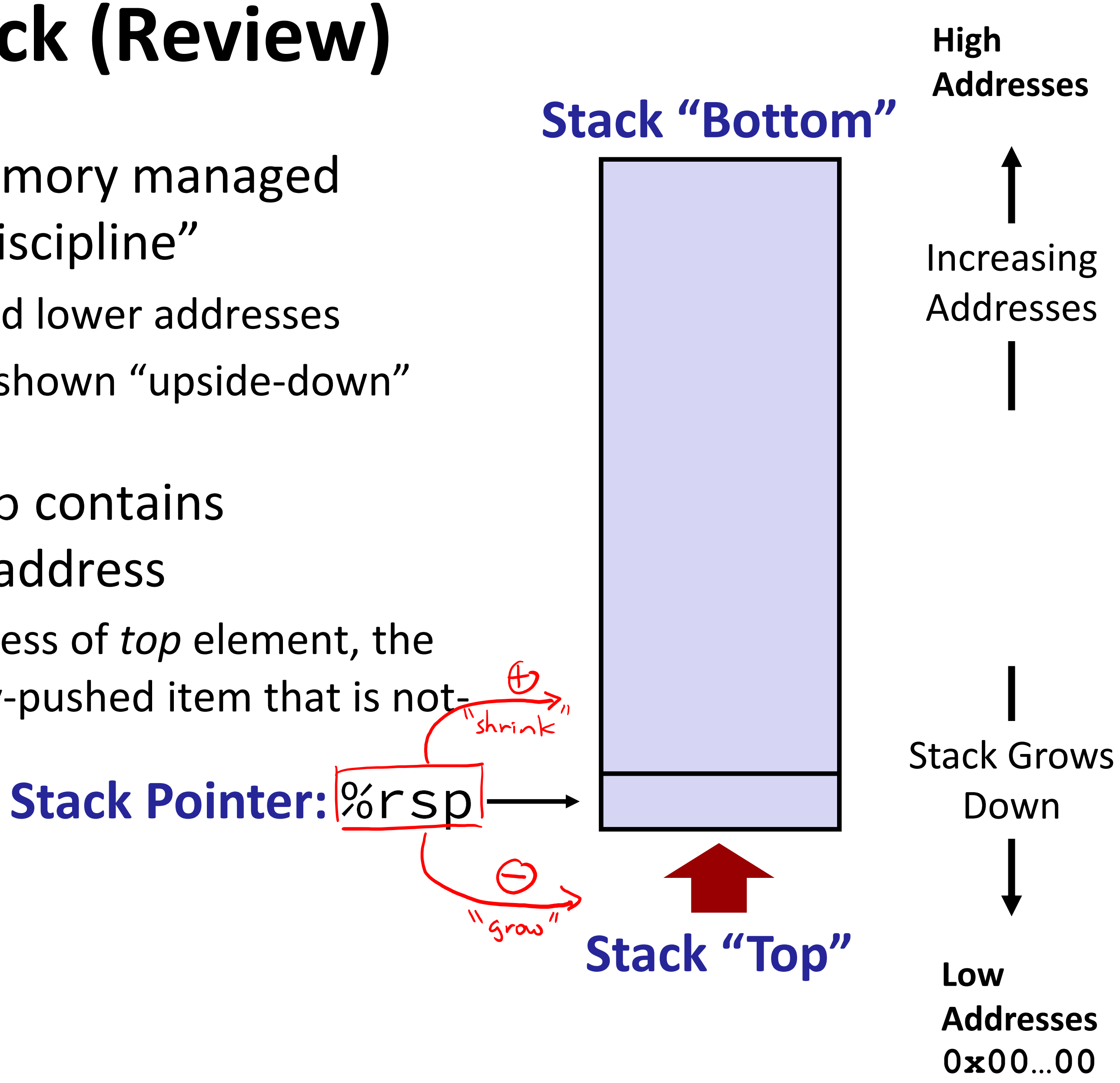
Address Space:	Permissions:
Stack	writable; not executable
Dynamic Data (Heap)	writable; not executable
Static Data	writable; not executable
Literals	read-only; not executable
Instructions	read-only; executable

- Segmentation fault: impermissible memory access

Last In, First Out (LIFO)

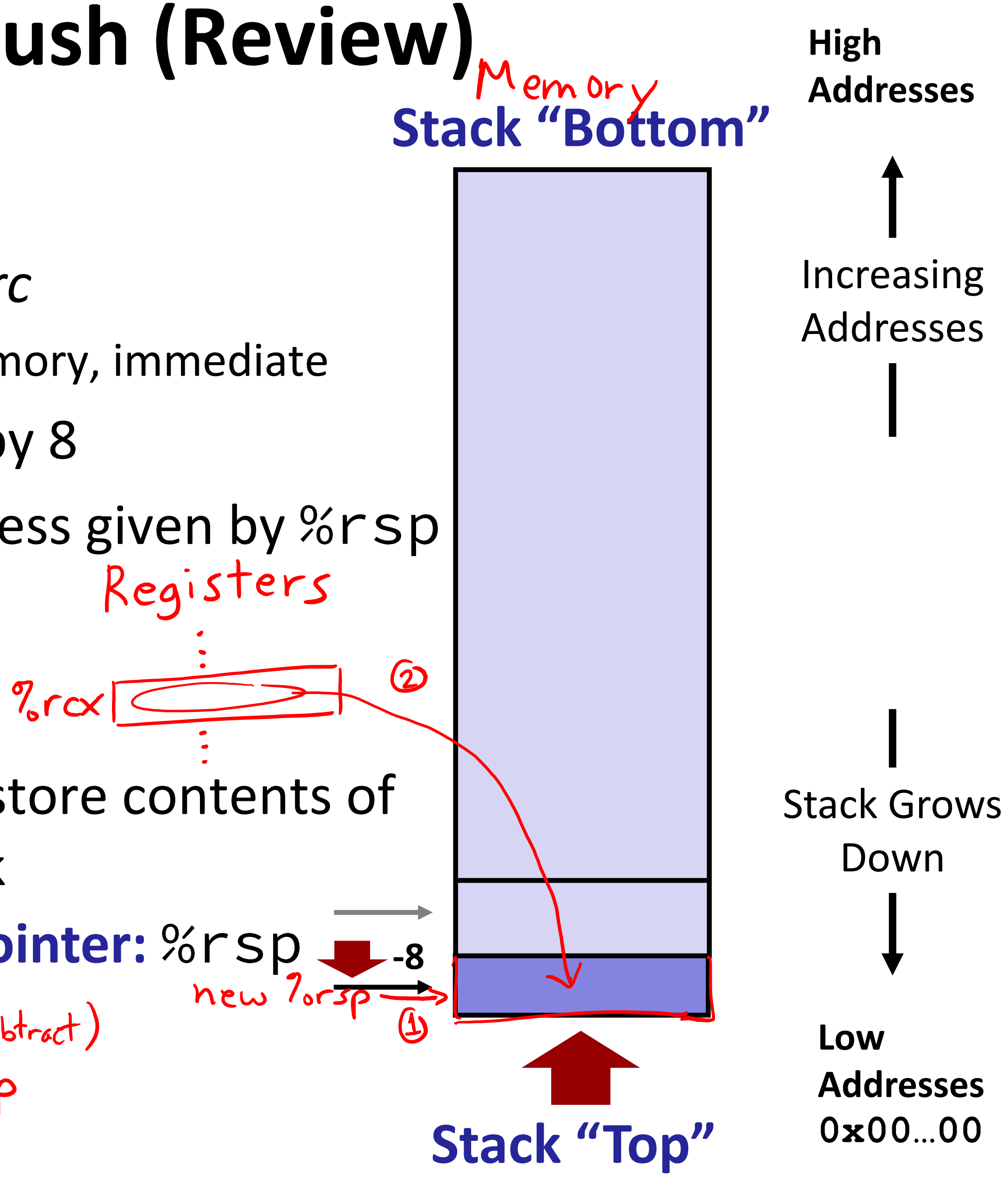
x86-64 Stack (Review)

- 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

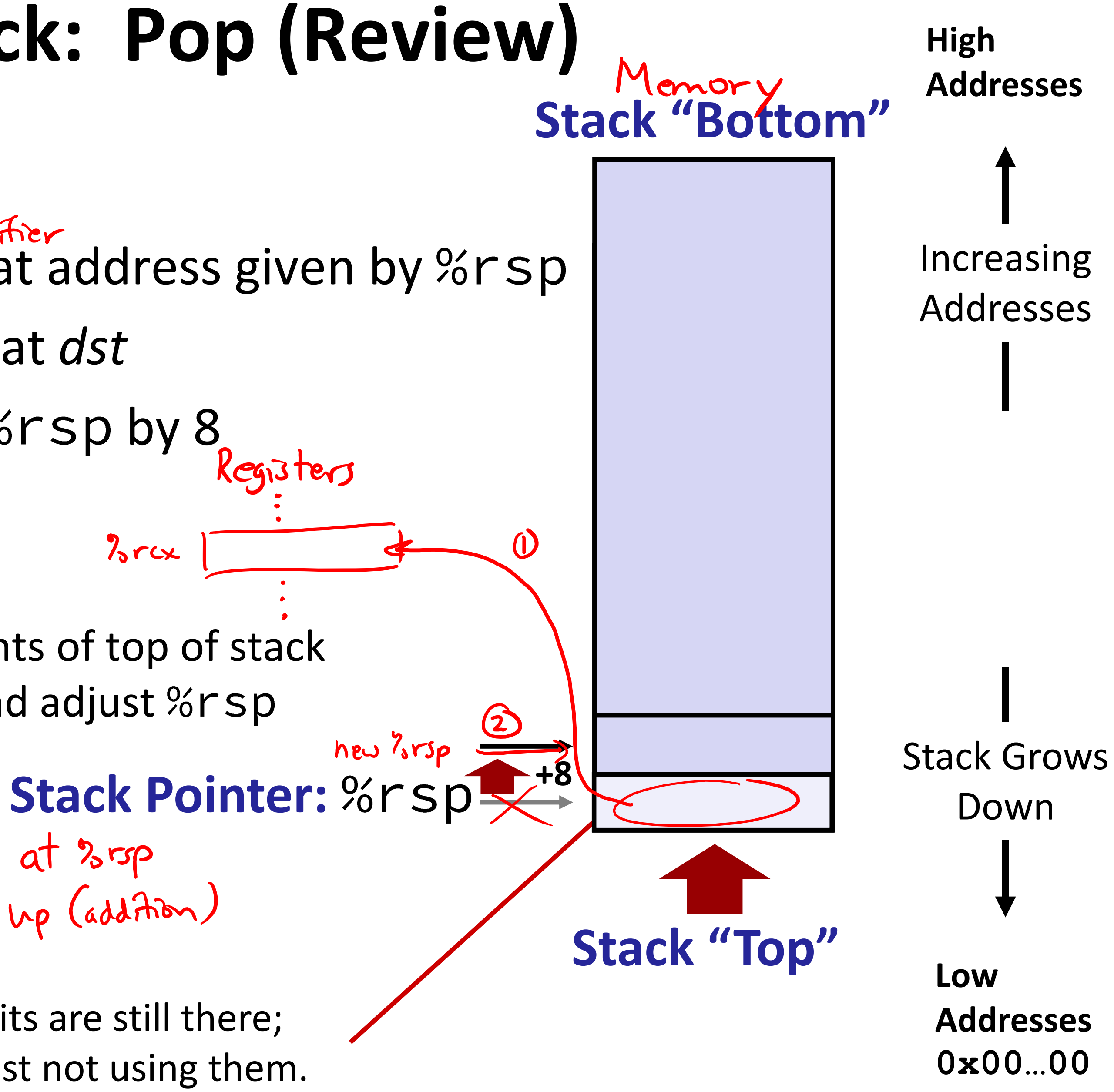


① move %rsp down (subtract)

② store src at %rsp

x86-64 Stack: Pop (Review)

- popq *dst*
  ↳ size specifier
  - 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`



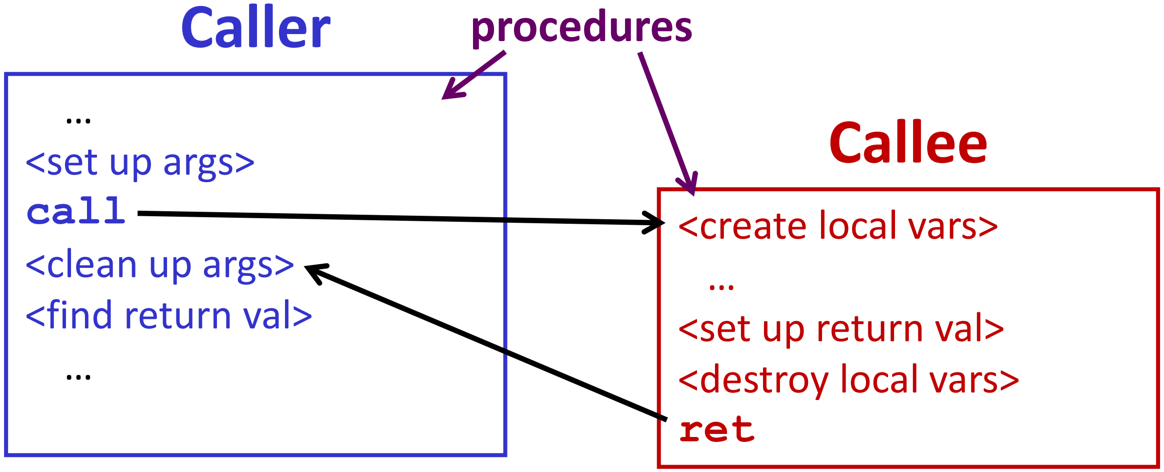
① read out data at %rsp
② move %rsp up (addition)

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

Procedures

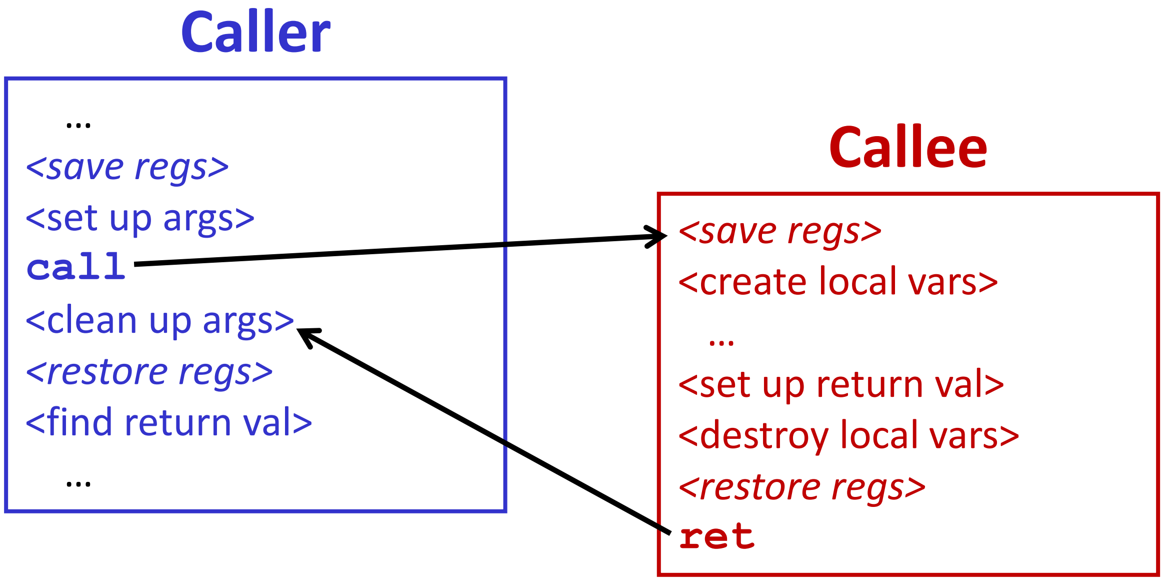
- Stack Structure
- **Calling Conventions**
  - **Passing control**
  - Passing data
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

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
```

these are 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?*) → ① move %rsp down → ② store ret addr at %rsp
  2) Jump to ***`label`*** → ③ label → %rip

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?*) → ① move %rsp down → ② store ret addr at %rsp
  2) Jump to ***label*** → 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**

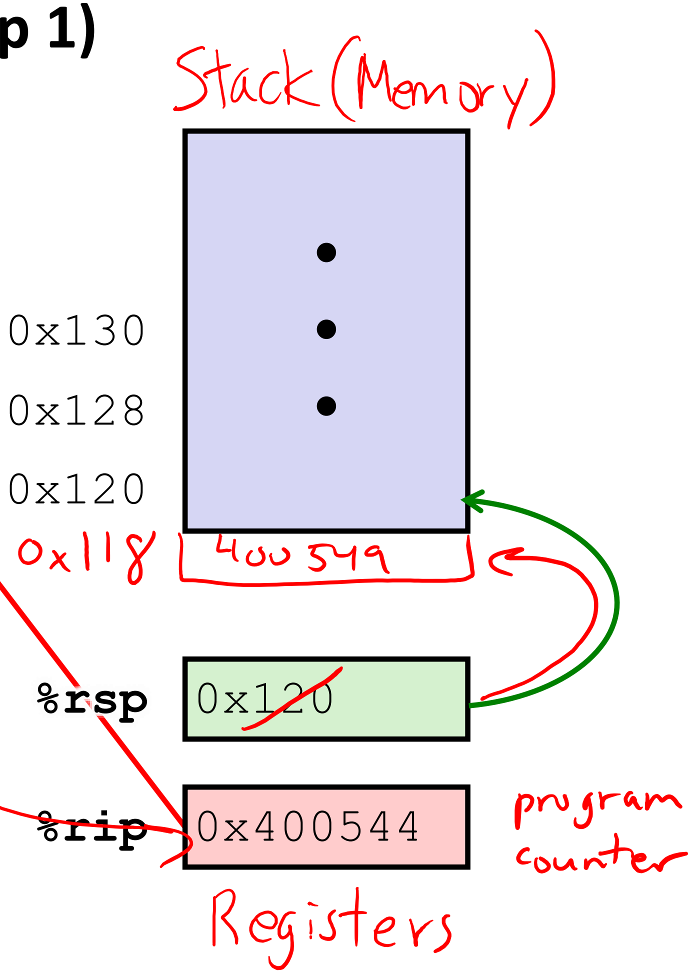
next instruction happens to be a move, but could be anything

- Procedure return: `ret` (special pop)
  1) Pop return address from stack ① read ret addr at %rsp into %rip
  2) Jump to address ② move %rsp up

Procedure Call Example (step 1)

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

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



Stack (Memory)

0x130

0x128

0x120

0x118

400549

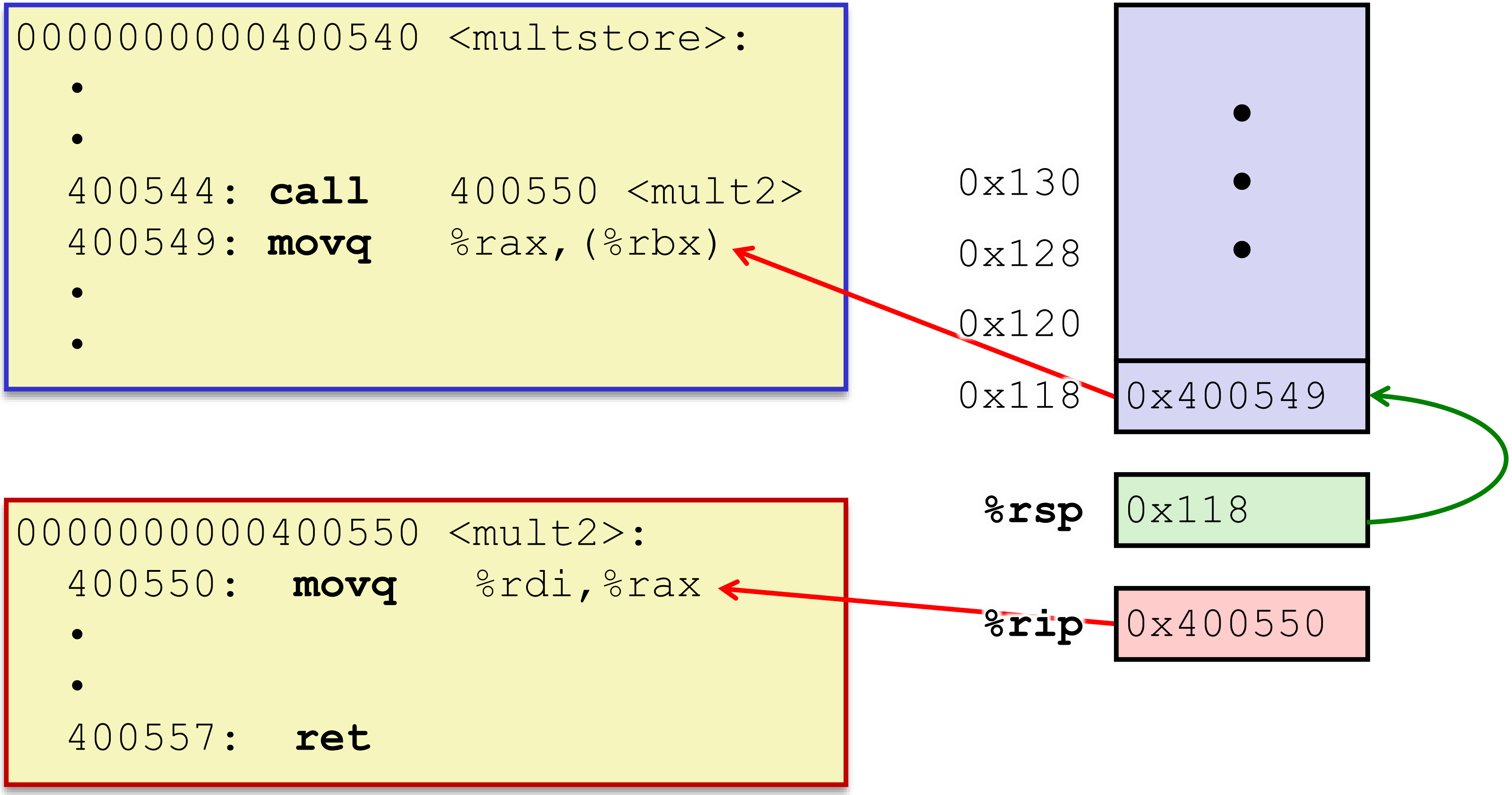
%rsp ~~0x120~~

%rip 0x400544

program counter

Registers

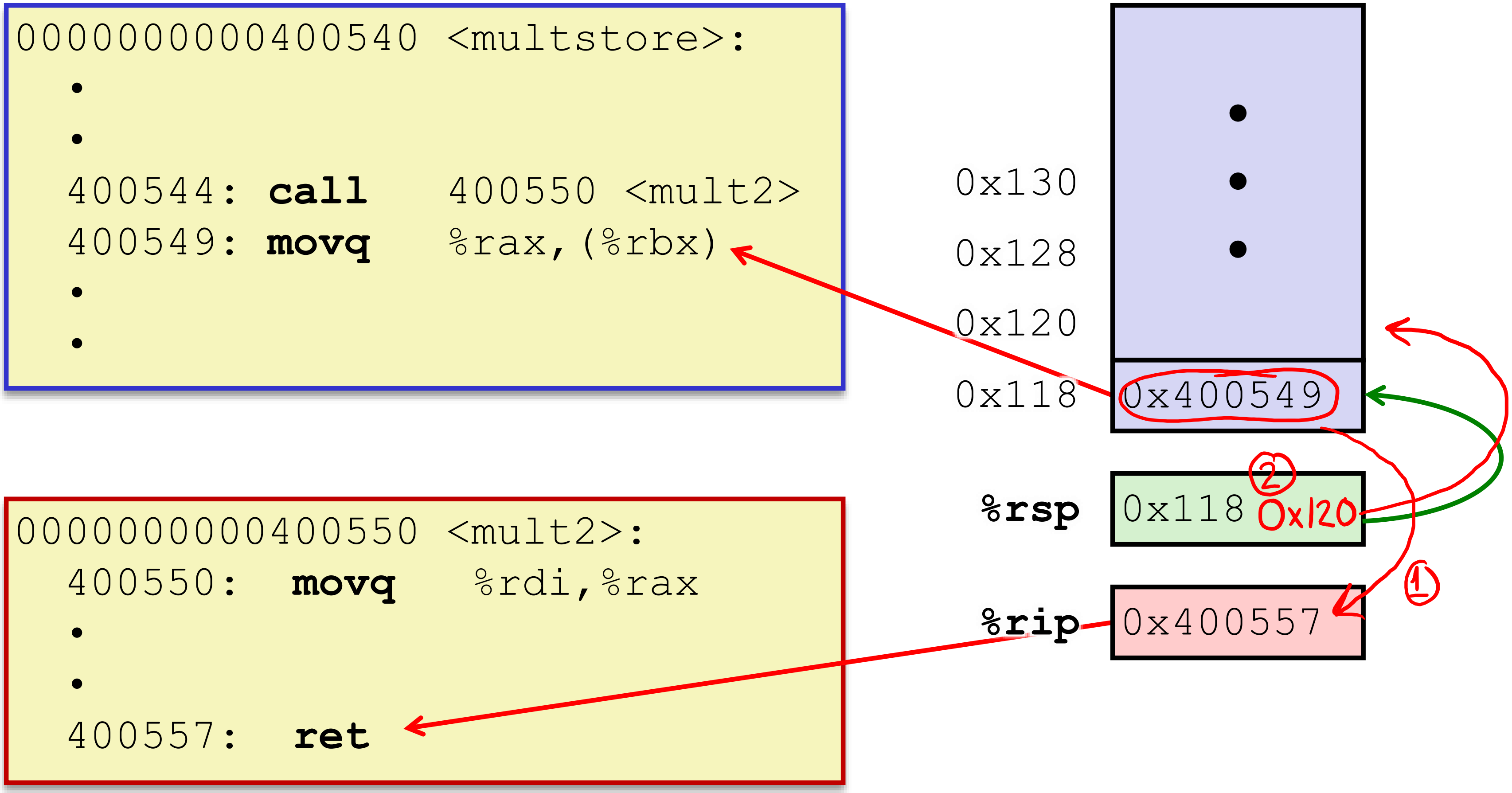
Procedure Call Example (step 2)



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

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

Procedure Return Example (step 1)



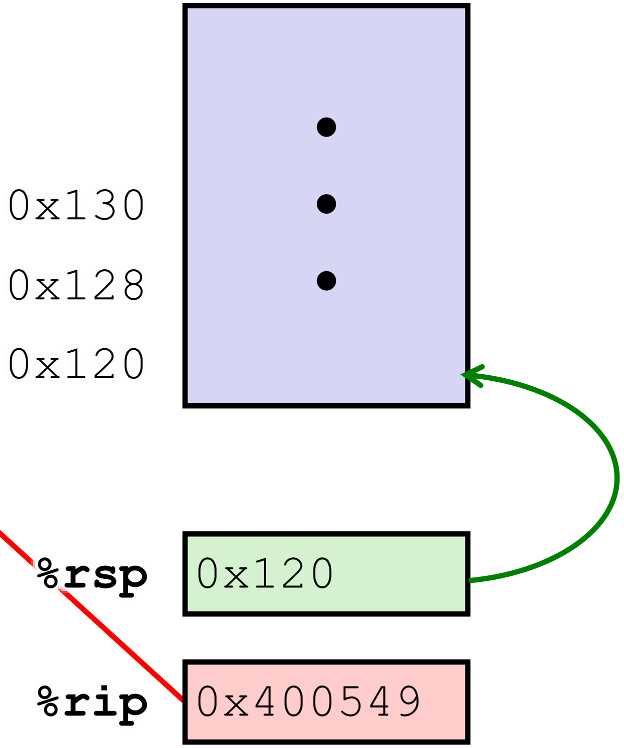
```
0000000000400540 <multstore>:
  •
  •
  400544: call    400550 <mult2>
  400549: movq    %rax,(%rbx)
  •
  •
```

```
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

(1) %rdi Diane's

(2) %rsi Silk

(3) %rdx Dress

(4) %rcx Costs

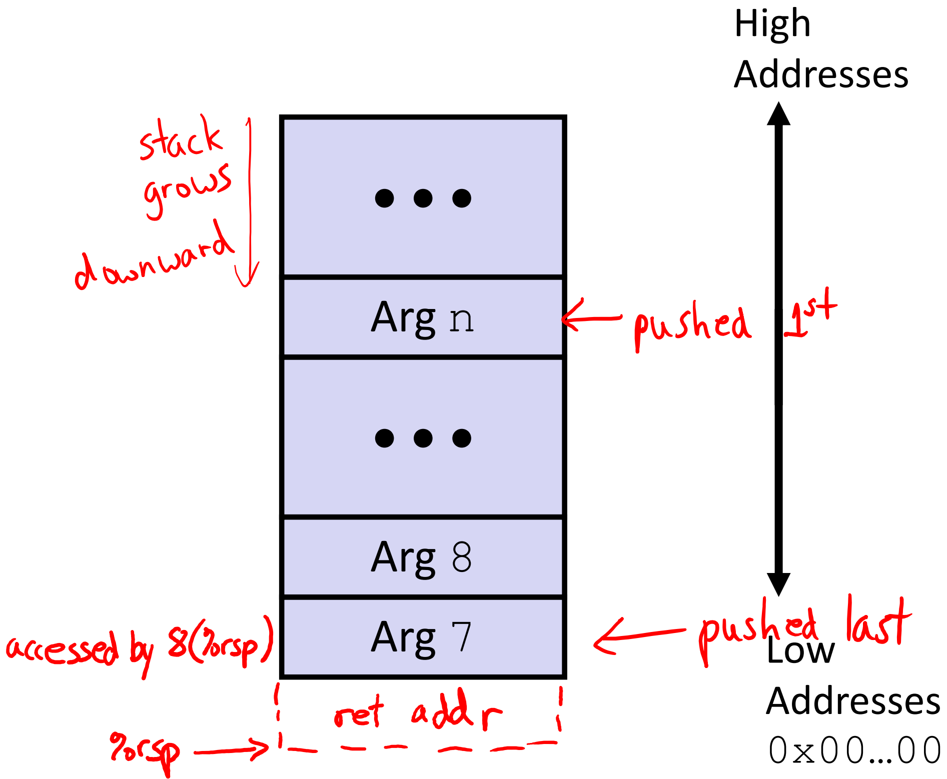
(5) %r8 $8

(6) %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

rdi rsi rdx

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

rdi rsi

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

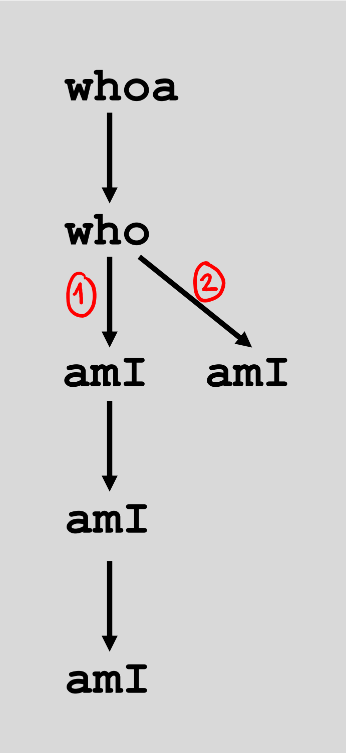
1st call recurses twice

2nd call doesn't recurse

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

based on condition

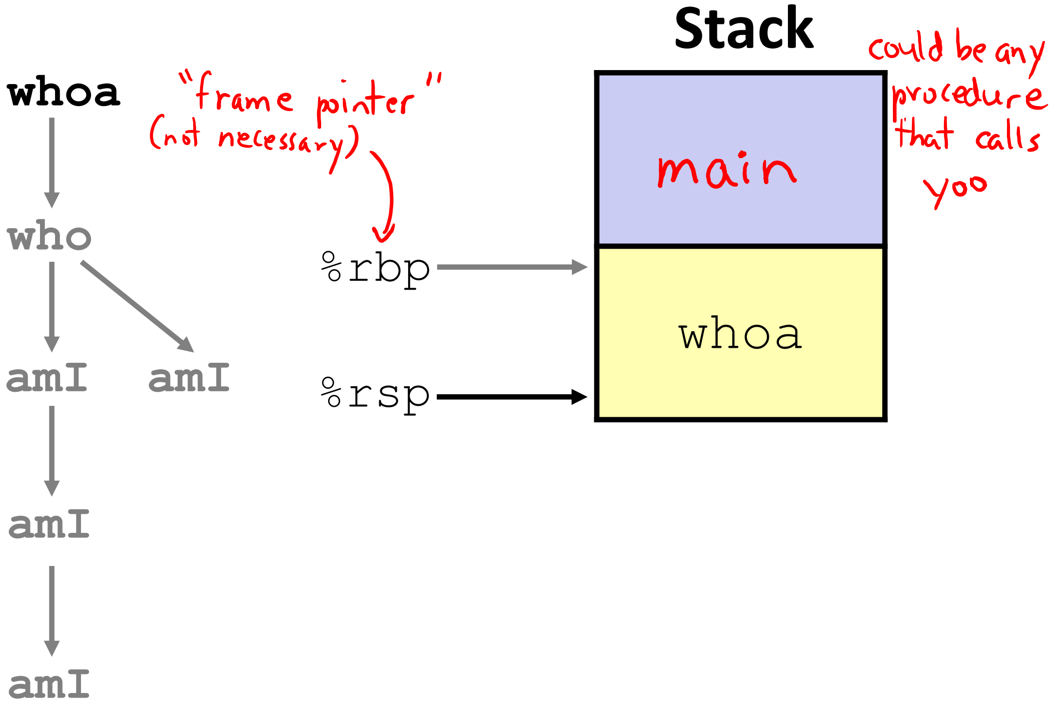
Example
Call Chain



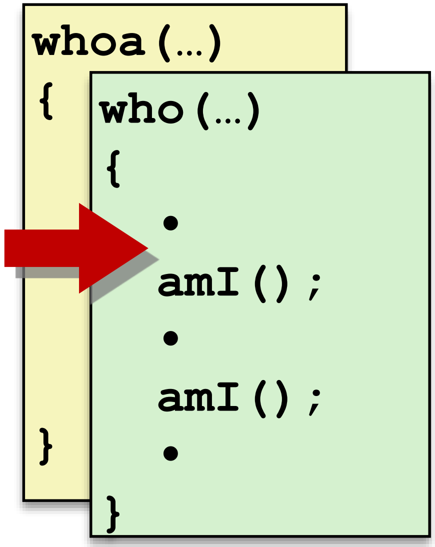
Procedure amI is recursive
(calls itself)

1) Call to whoa

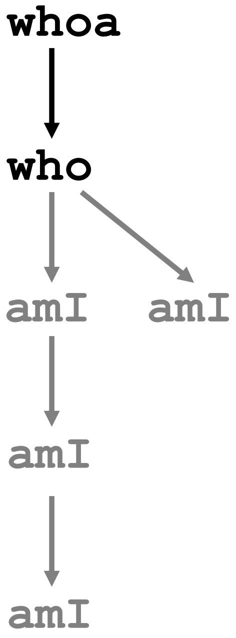
```
whoa(…)
{
   •
   •
   who();
   •
   •
}
```

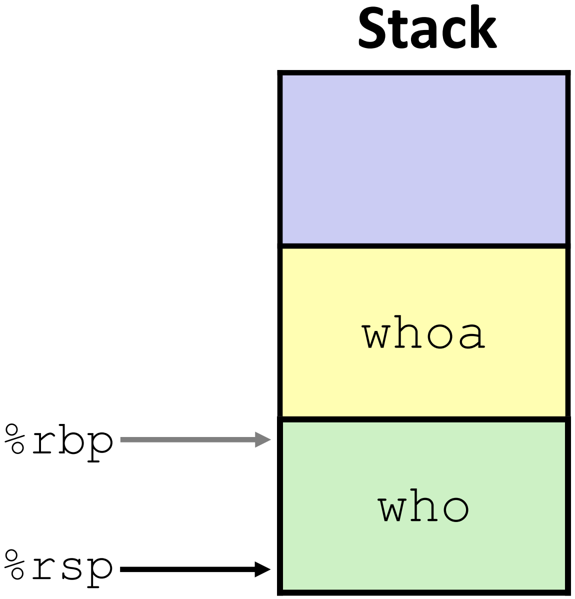


2) Call to who



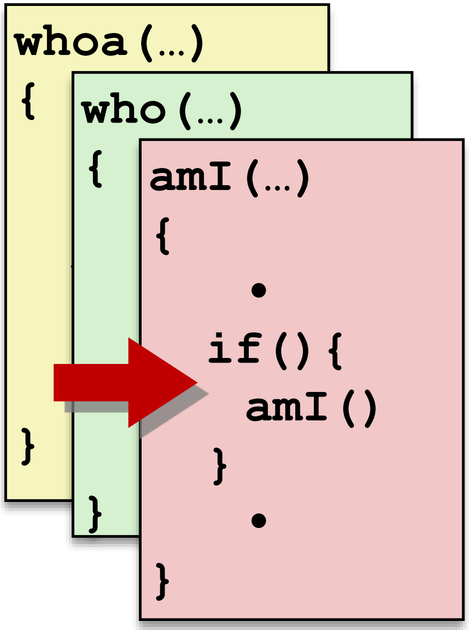
```
whoa(…)
{
    who(…)
    {
       •
       amI();
       •
       amI();
       •
    }
}
```



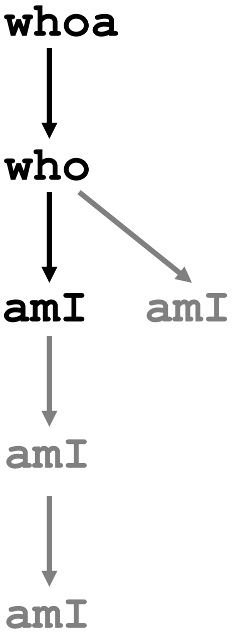


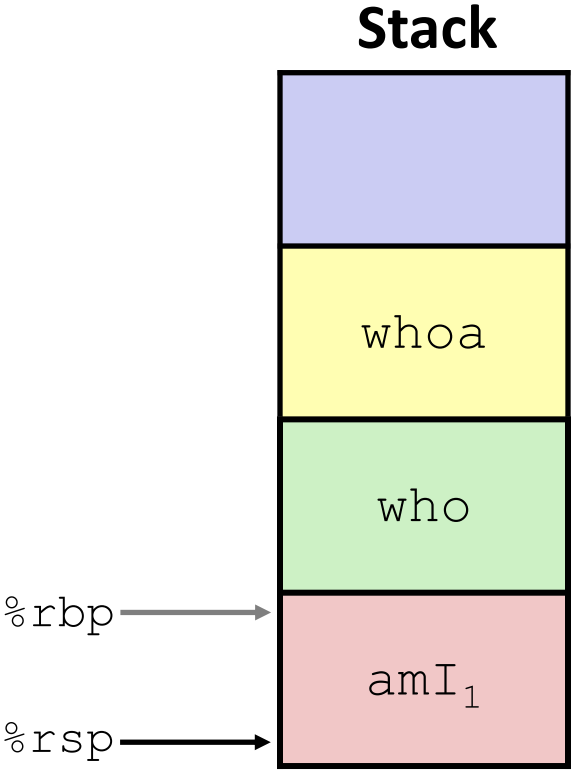
"create" frame
by manipulating %rsp

3) Call to amI (1)

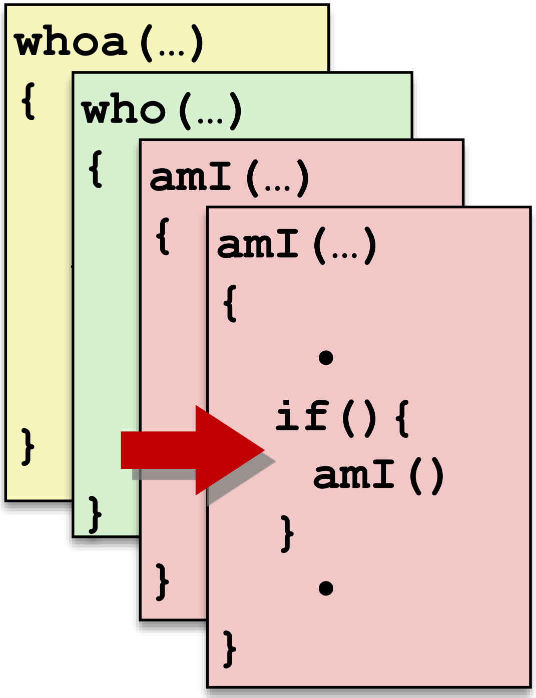


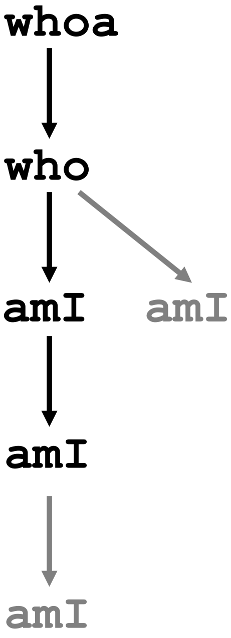
```
whoa(…)
{
}

who(…)
{
}

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

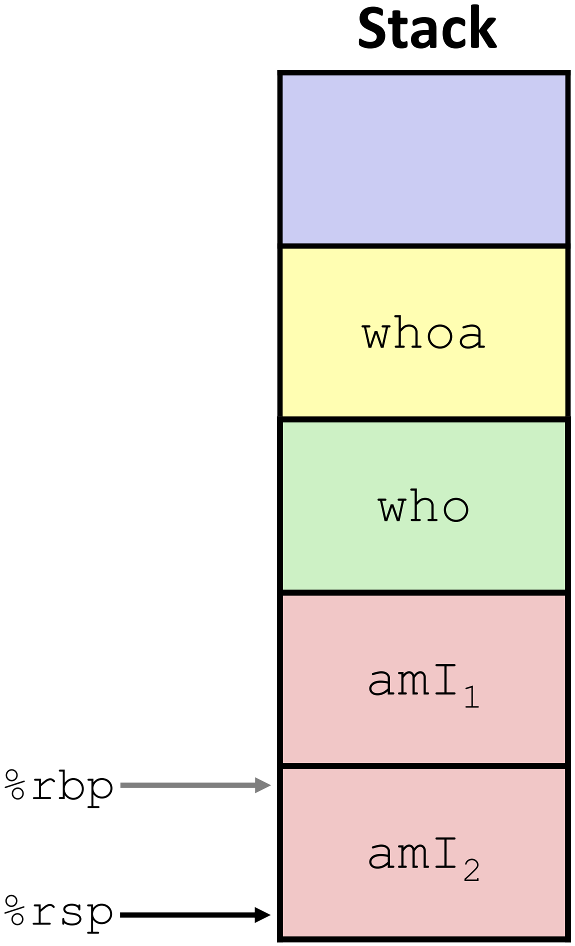




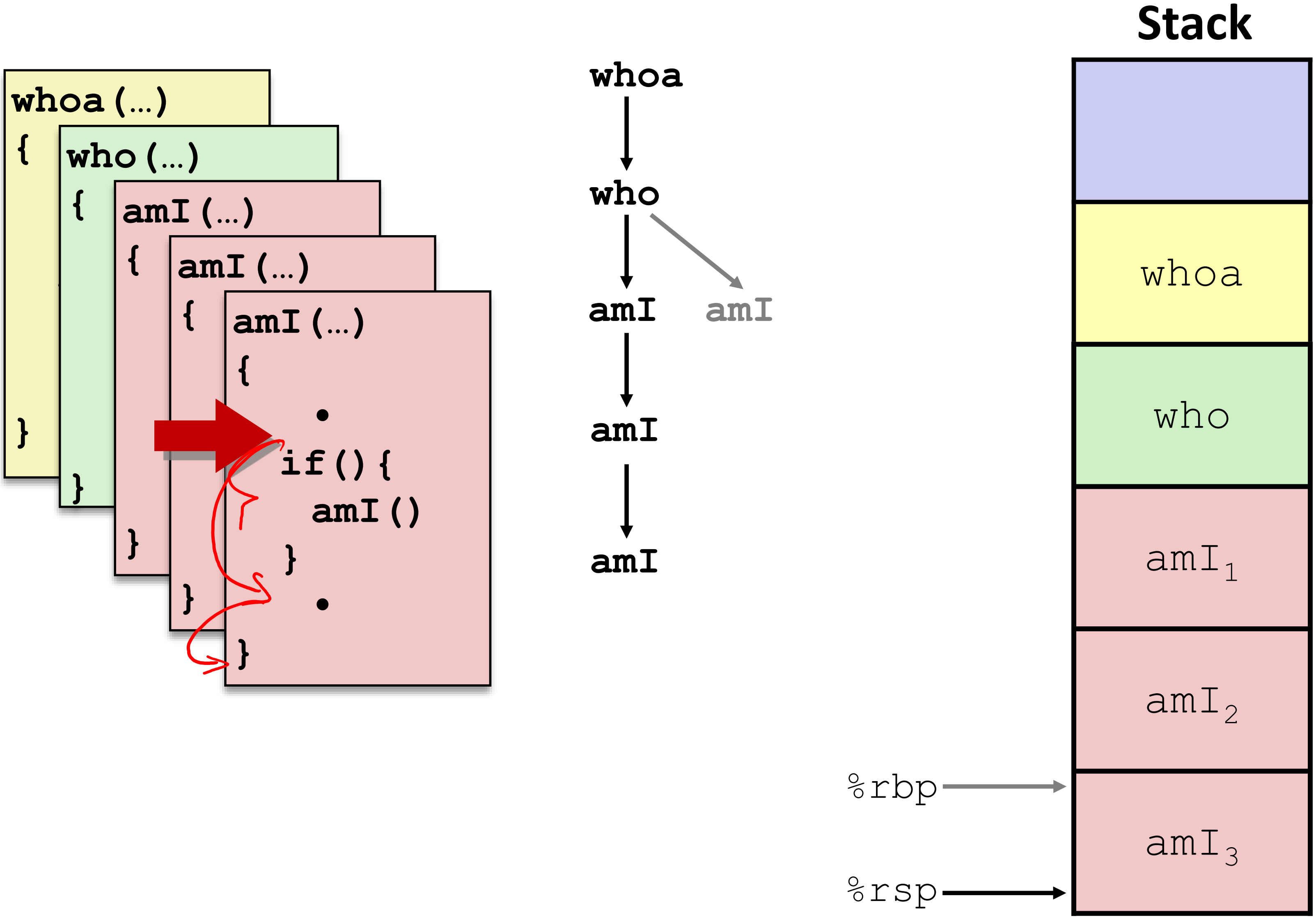
4) Recursive call to amI (2)


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

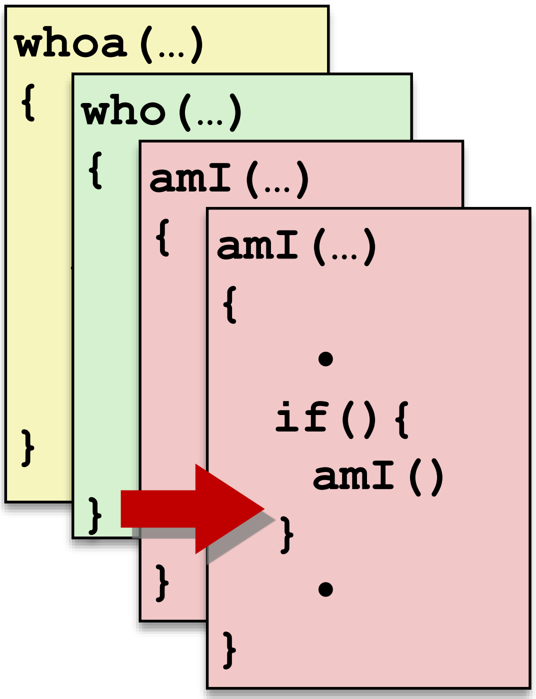




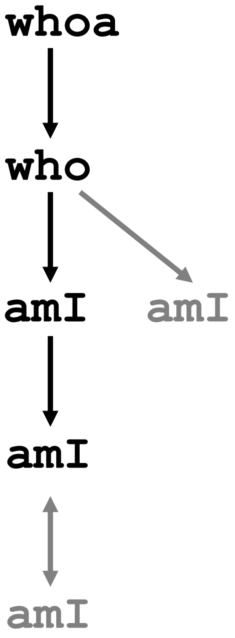
5) (another) Recursive call to amI (3)

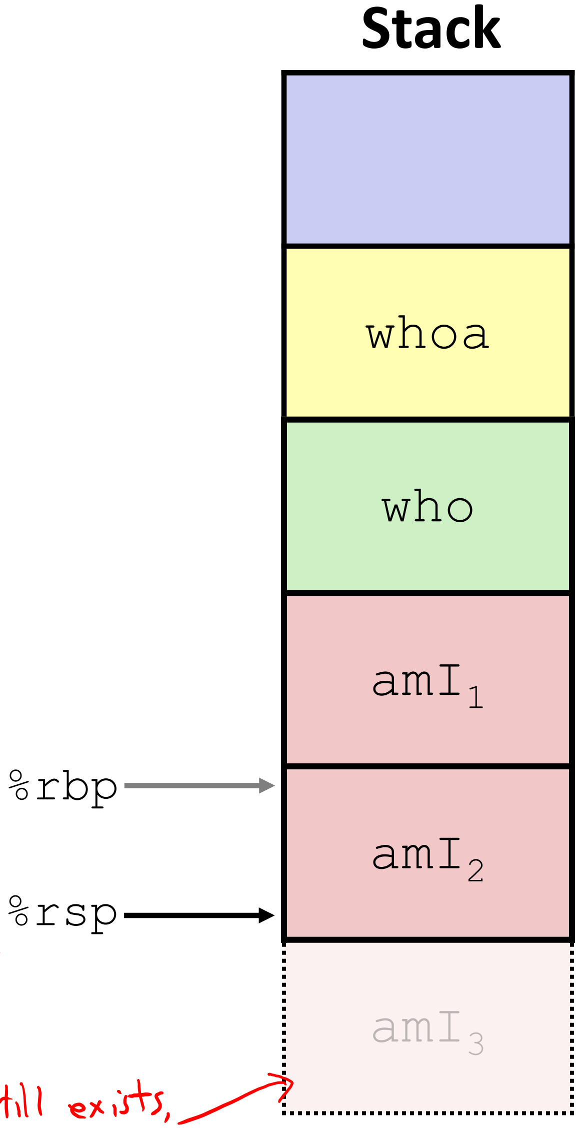


6) Return from (another) recursive call to amI



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

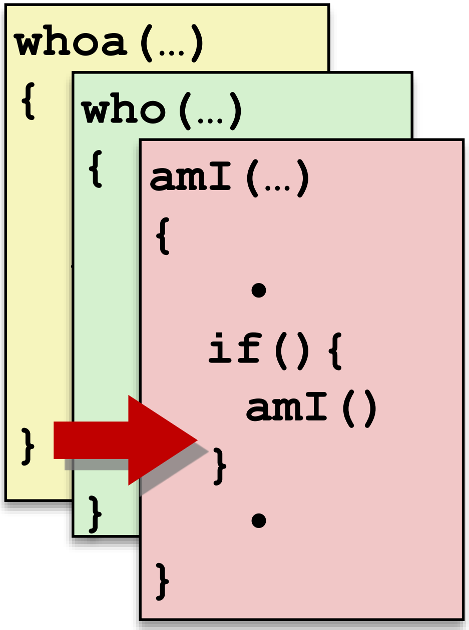




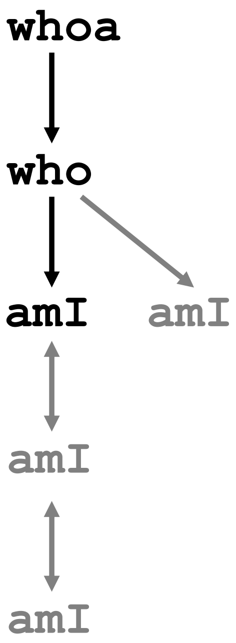
"deallocate" stack frame by moving %rsp back up

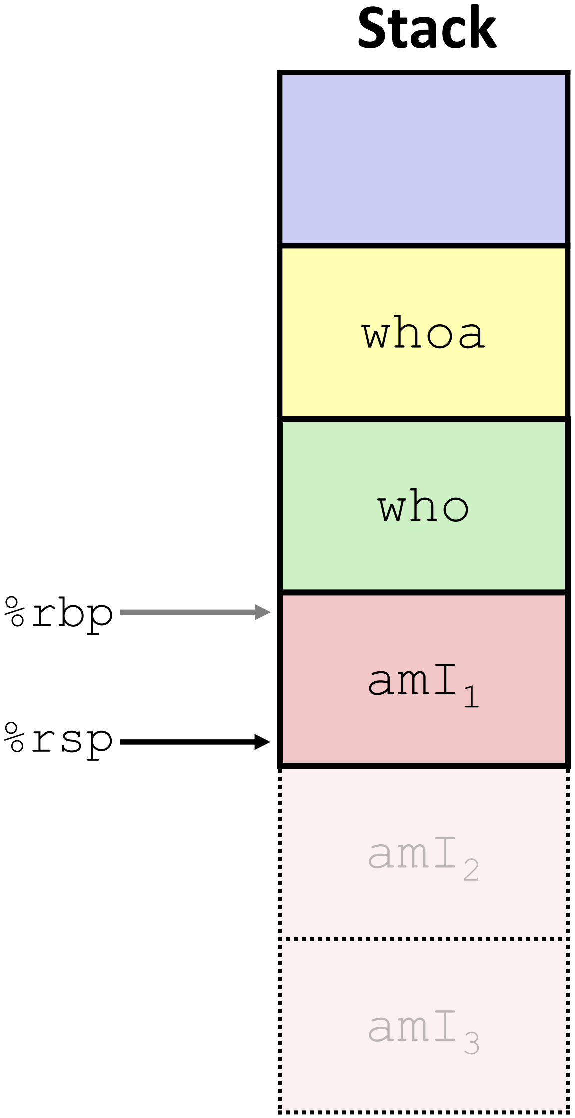
data still exists, but you shouldn't use it

7) Return from recursive call to amI



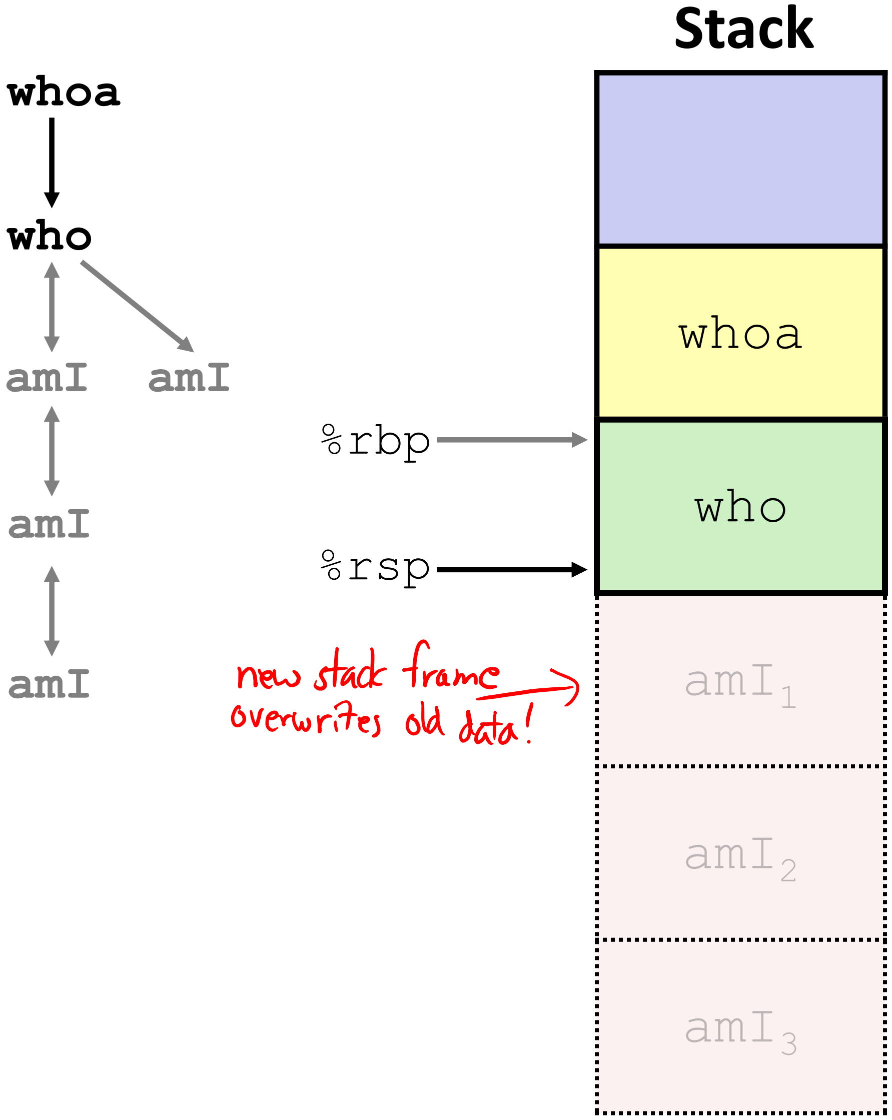
```
whoa(…)
{
  who(…)
  {
    amI(…)
    {
      •
      if(){
        amI()
      }
      •
    }
  }
}
```





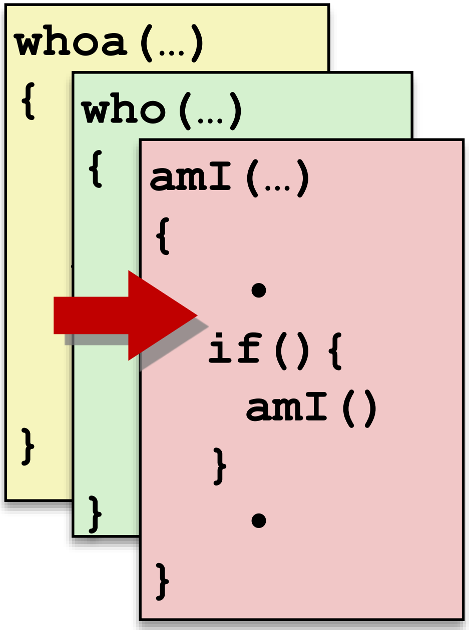
8) Return from call to amI

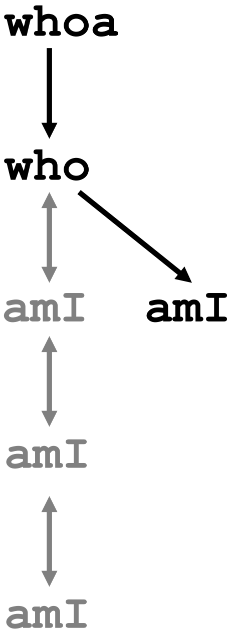
```
whoa(…)
{
        who(…)
        {
          •
          amI();
          •
          amI();
          •
        }
}
```

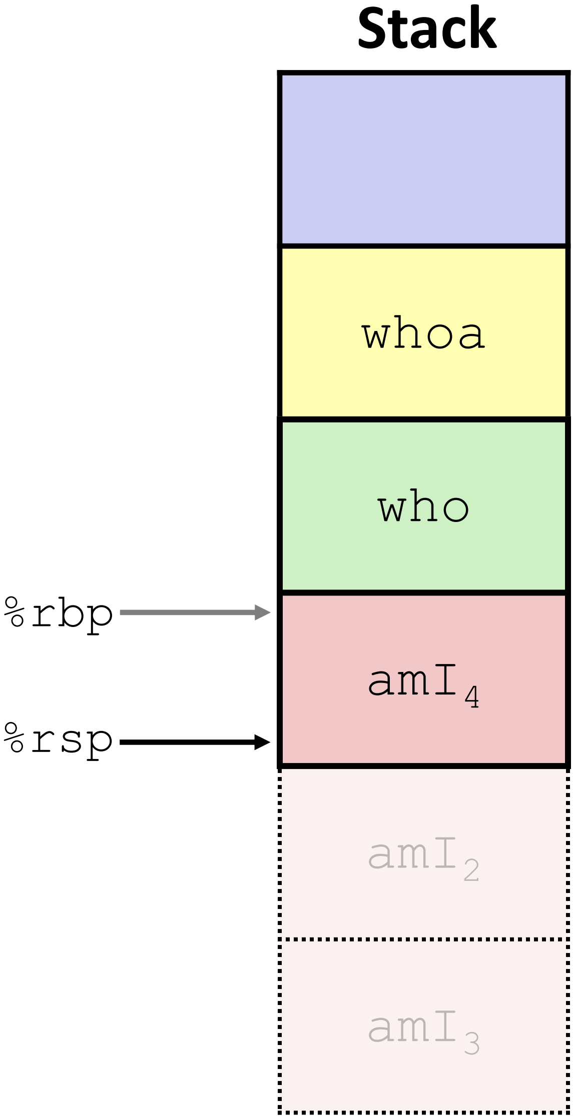


new stack frame overwrites old data!

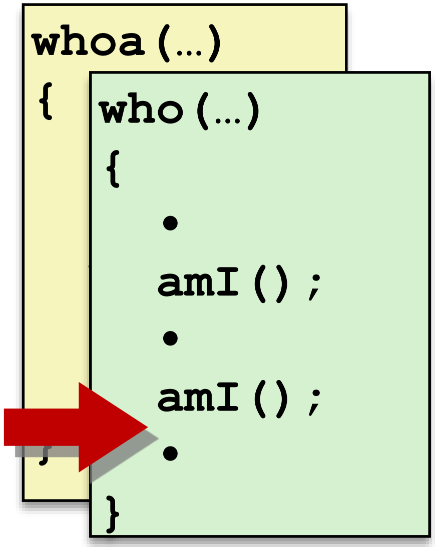
9) (second) Call to amI (4)



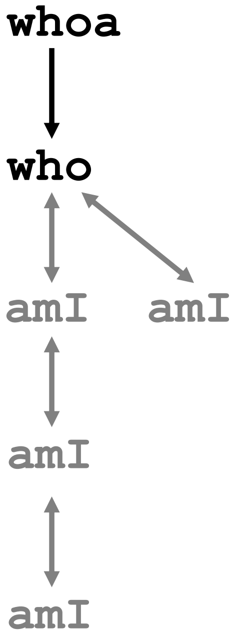


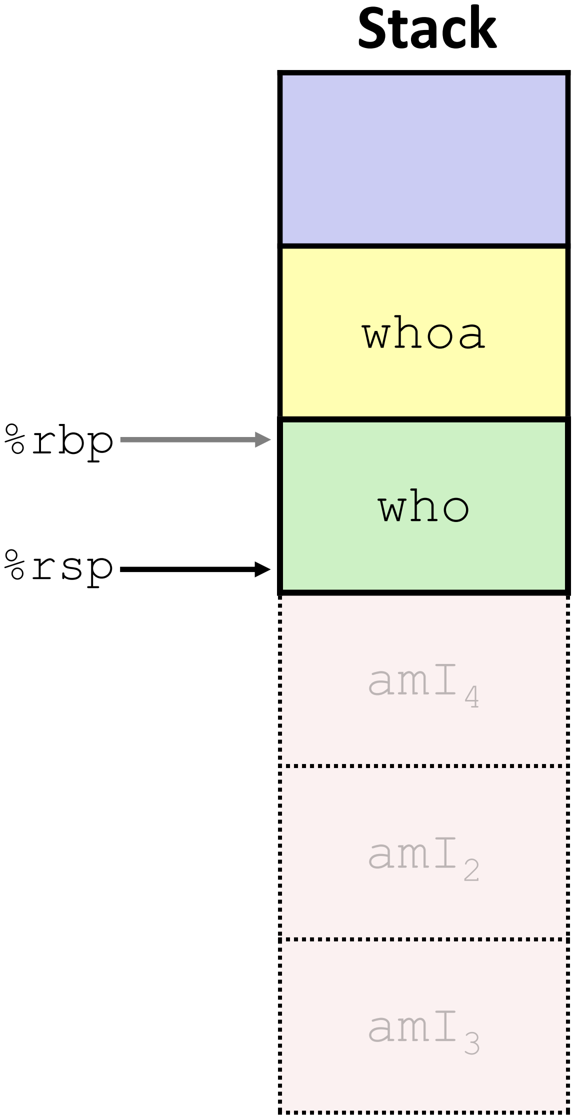


10) Return from (second) call to amI



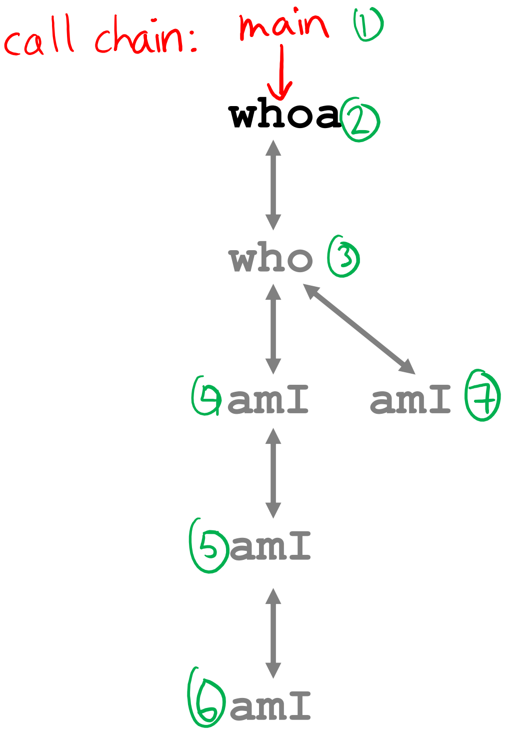
```
whoa(…)
{
   who(…)
   {
      •
      amI();
      •
      amI();
      •
   }
}
```

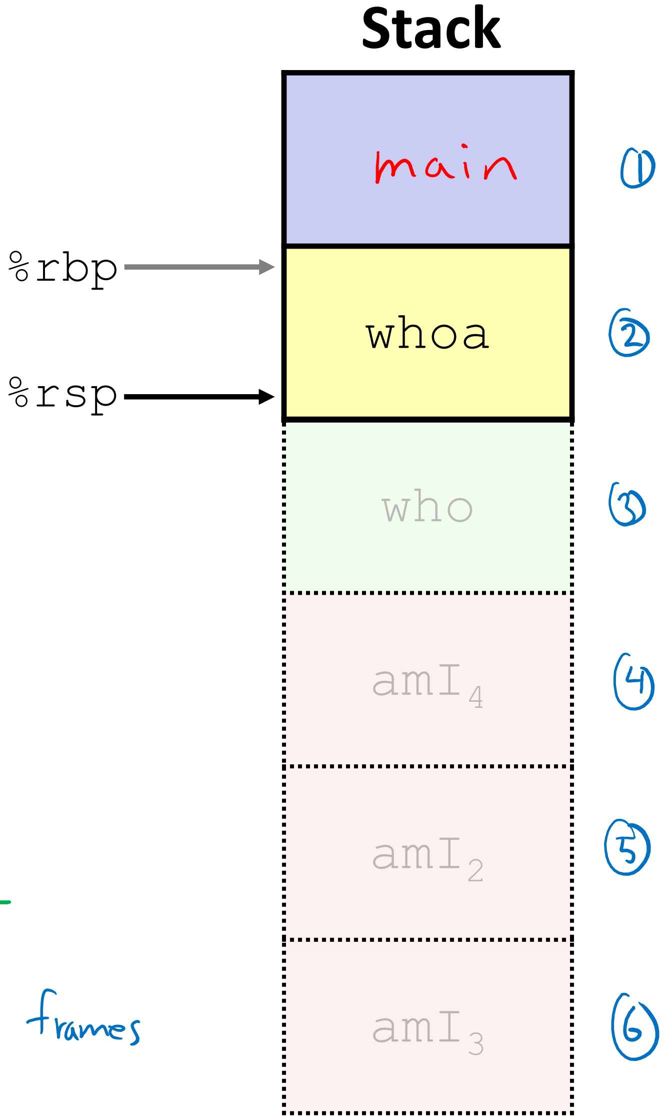




11) Return from call to who

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





total stack frames created: 7

maximum stack depth: 6 frames