The Stack & Procedures

CSE 351 Winter 2021

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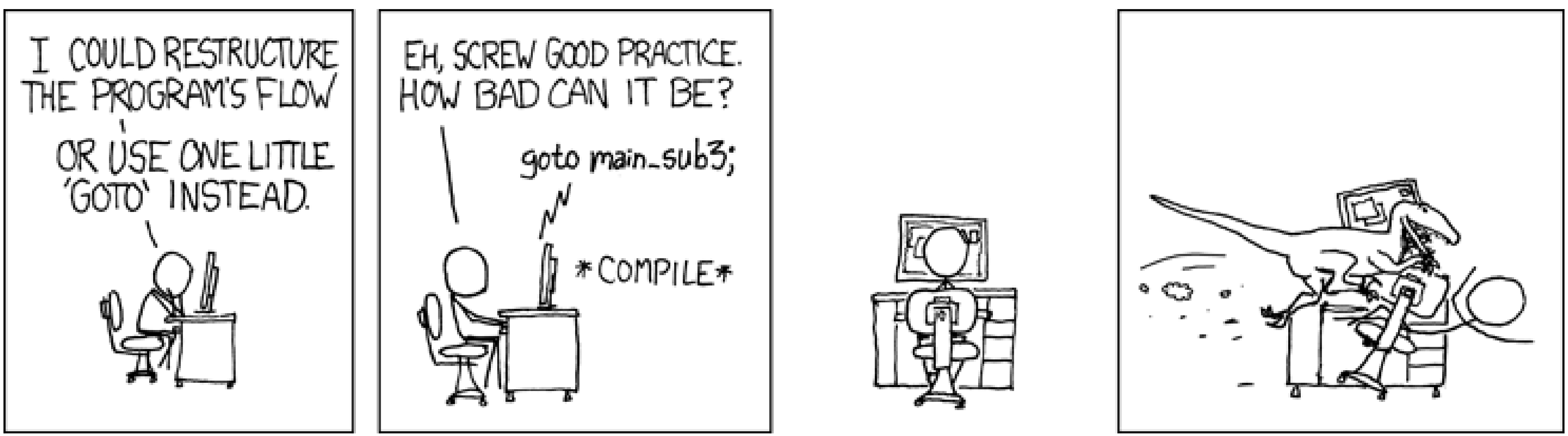


http://xkcd.com/571/

Administrivia

- Study Guide 1 due tonight
- Lab 2 due next Friday (2/5)
- hw10 due Monday, hw11 due Wednesday

x86 Control Flow

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

Switch Statement Example

```
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;
}
```

- 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
}
```

Jump Table

```
JTab: Targ0
      Targ1
      Targ2
      •
      •
      •
      Targn-1
```

Jump Targets

```
Targ0:   Code Block 0
Targ1:   Code Block 1
Targ2:   Code Block 2
•
•
•
Targn-1: Code Block n–1
```

Approximate Translation

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

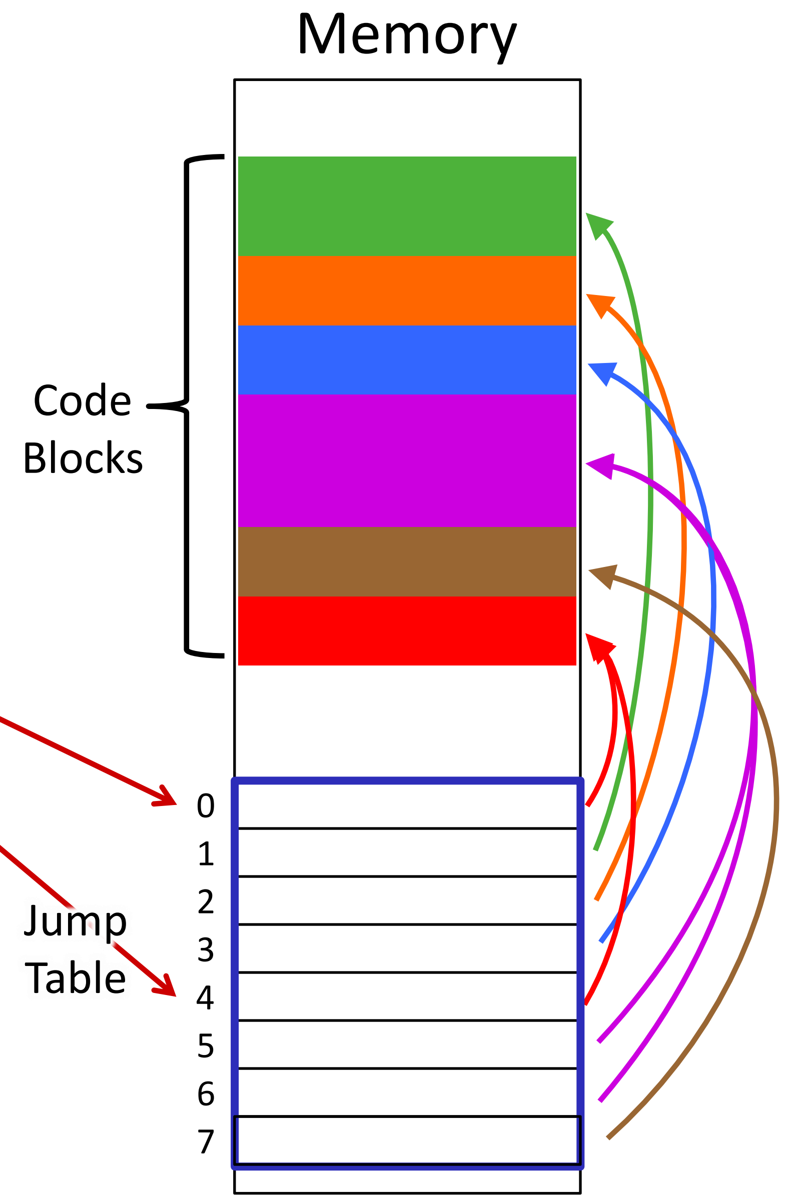
Jump Table Structure

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;
}
```

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

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

Take a look!

https://godbolt.org/z/Y9Kerb

jump above – unsigned > catches negative default cases

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(Rb, Ri, S) *(.L4 + x*8)

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
```

jump table

8 bytes

Assembly Setup Explanation

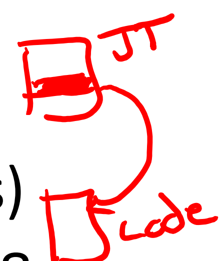
- Table Structure
  - Each target requires 8 bytes (address)
  - Base address at `.L4`

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 $0 \le x \le 7$



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:

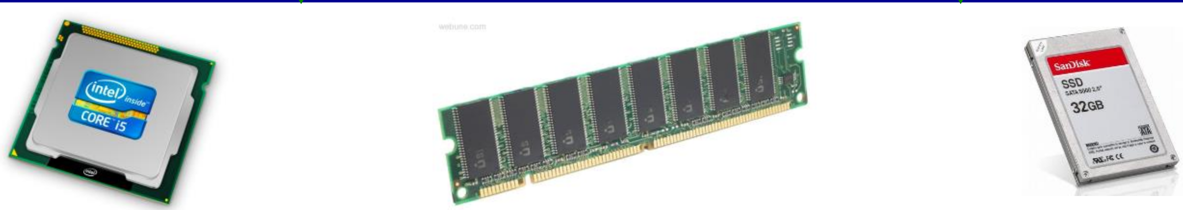
```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 10

OS X Yosemite

Computer system:



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

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?
  - remember to post to Ed!

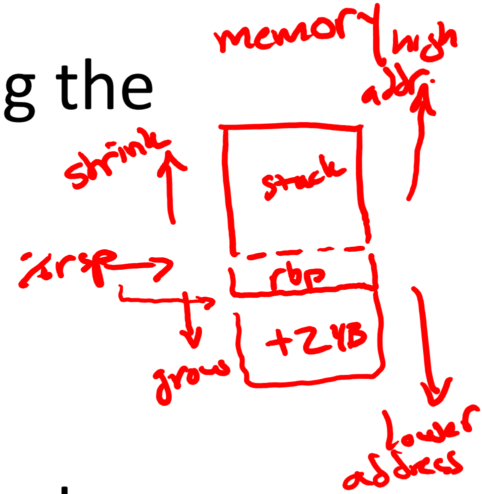
Review Questions

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

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

grow by 32B

24B



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

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

rax rdi rsi rdx

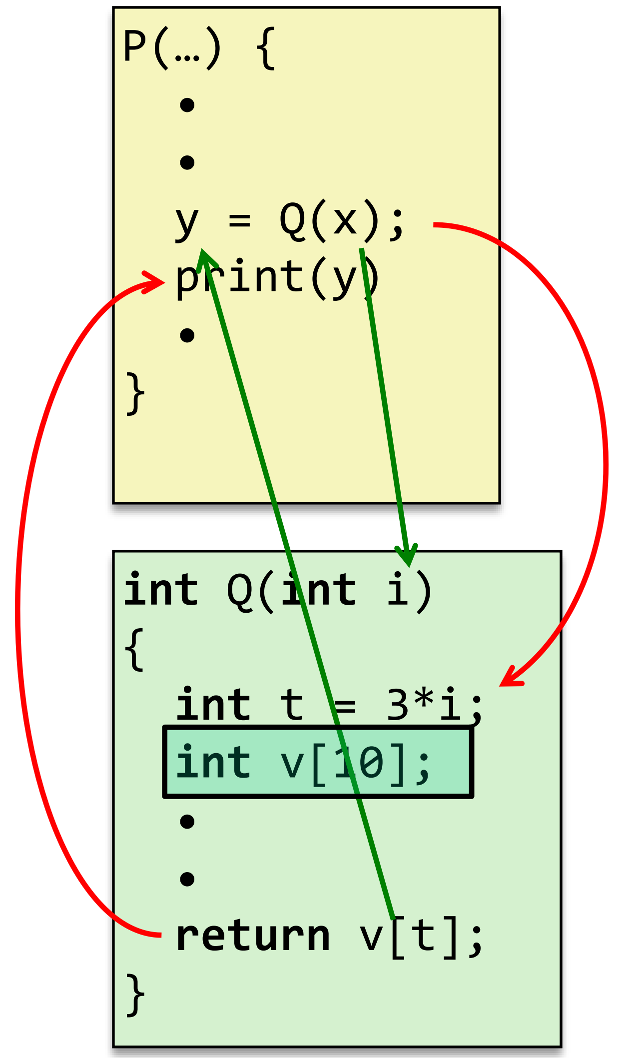
%rip → execute instrs.

%rsp → procedure call

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

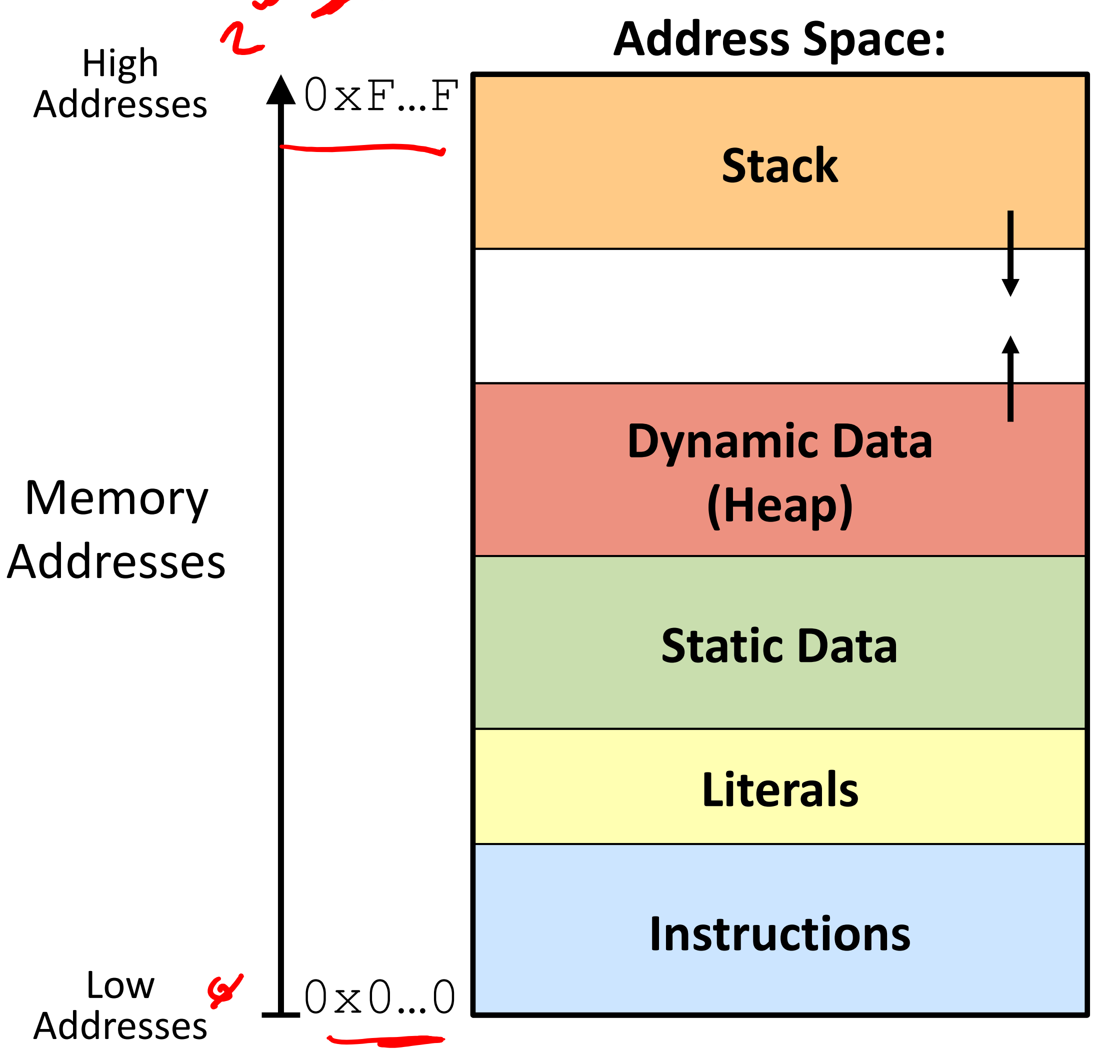
- All implemented with machine instructions!
  - An x86-64 procedure uses only those mechanisms required for that procedure



Procedures

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

Simplified Memory Layout



What Goes Here:

local variables and procedure context

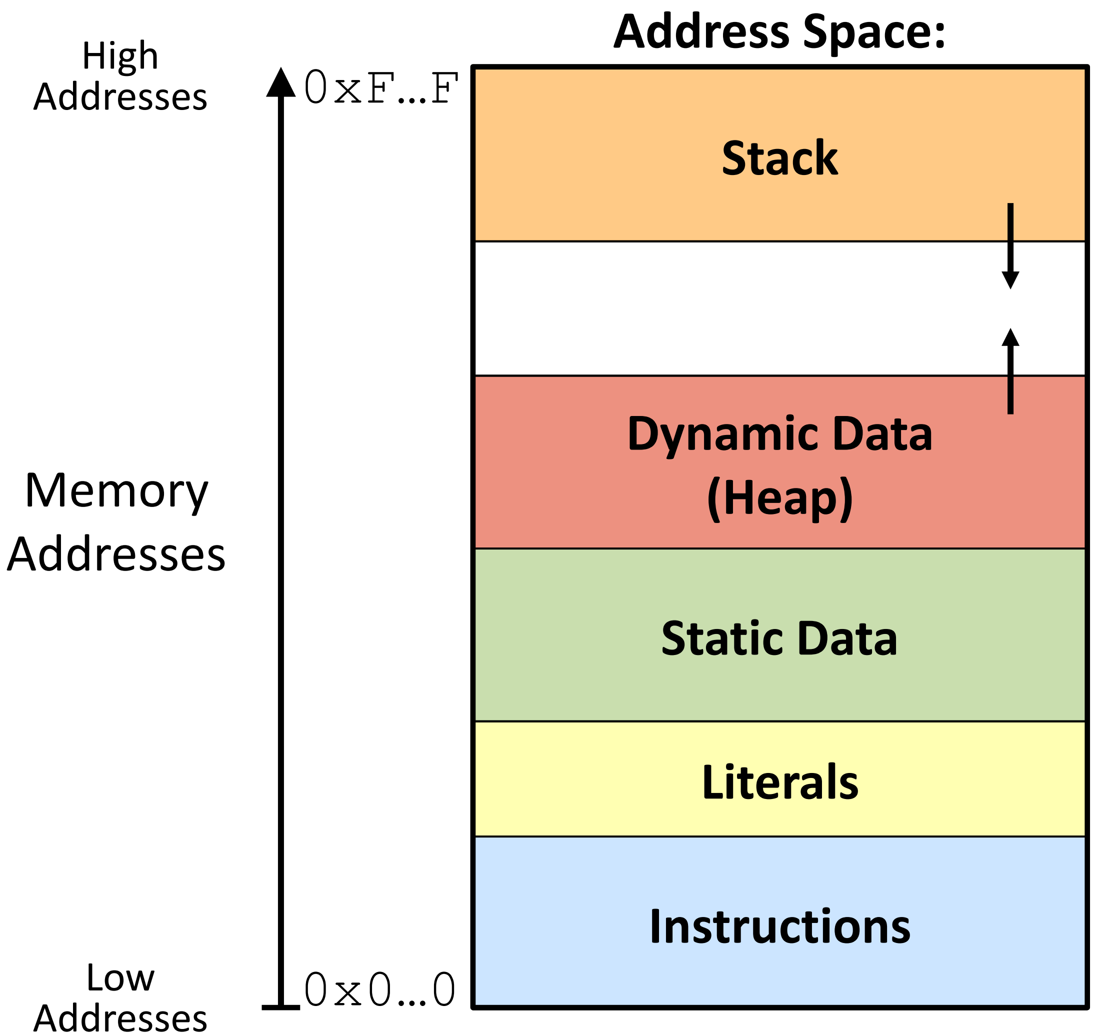
variables allocated with new or `malloc`

static variables (including global variables)

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

program code

Memory Management



Who's Responsible:

Managed "automatically"
(by compiler/assembly)

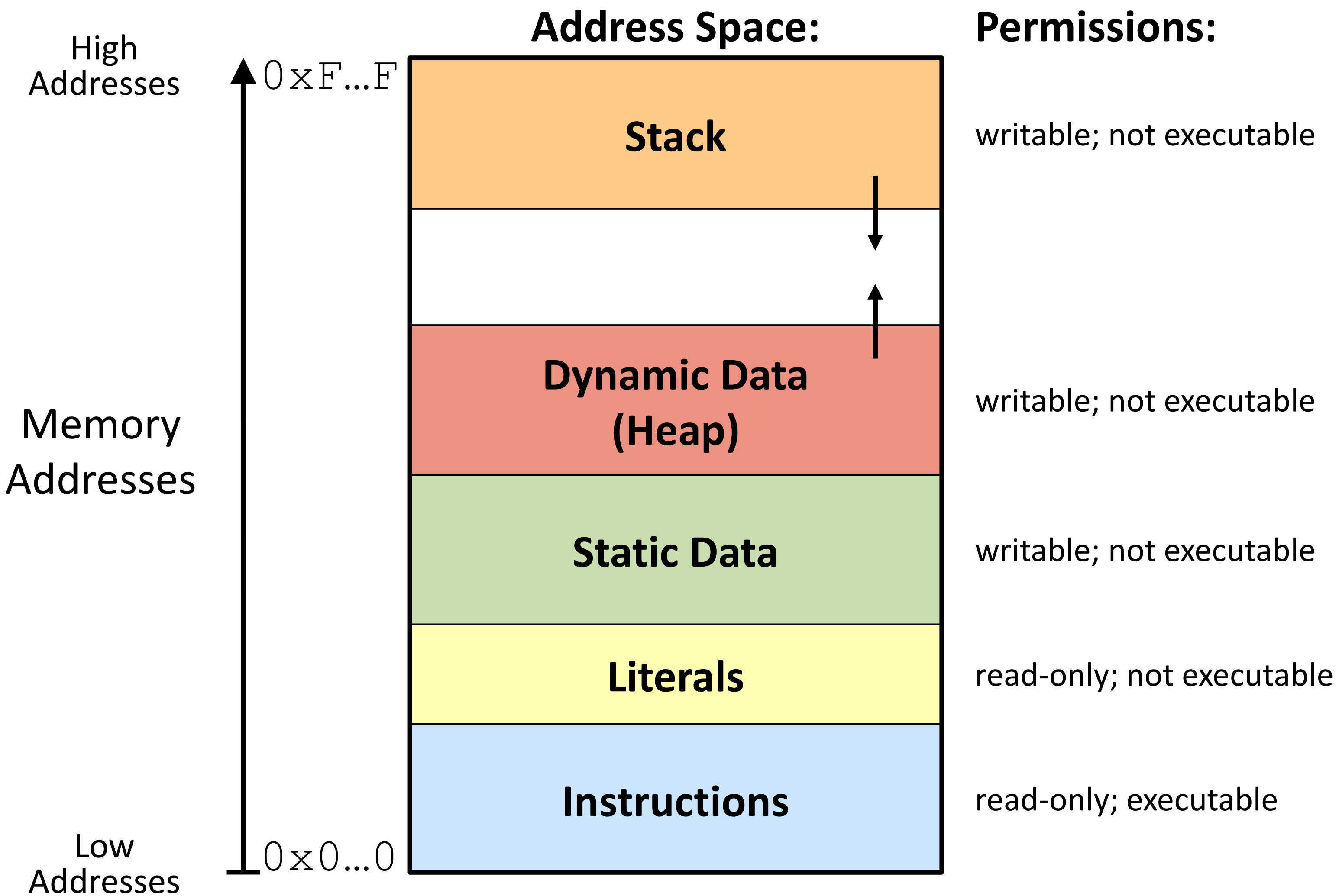
Managed "dynamically"
(by programmer)

Managed "statically"
(initialized when process starts)

Managed "statically"
(initialized when process starts)

Managed "statically"
(initialized when process starts)

Memory Permissions

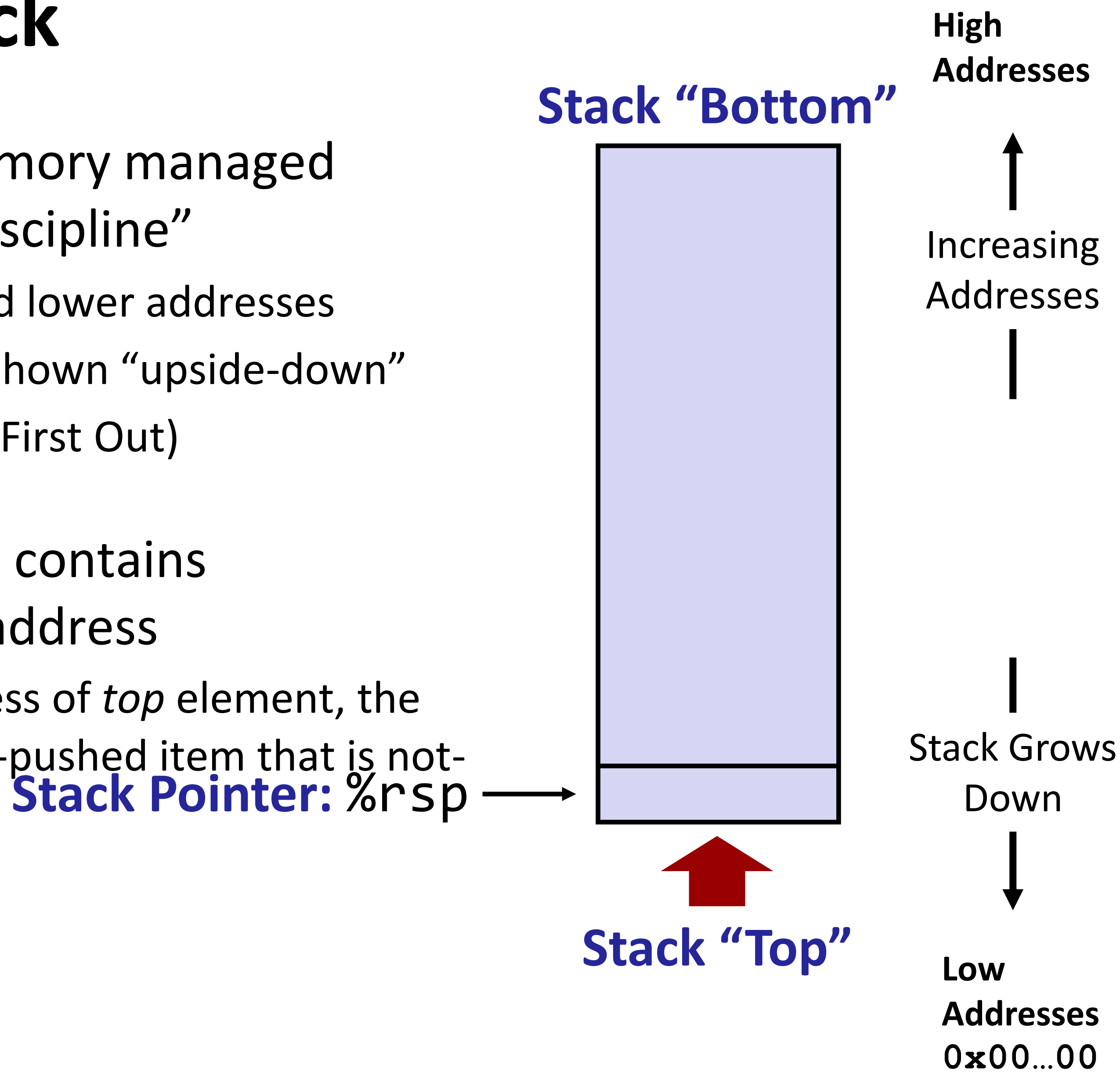


- Segmentation fault: impermissible memory access

x86-64 Stack

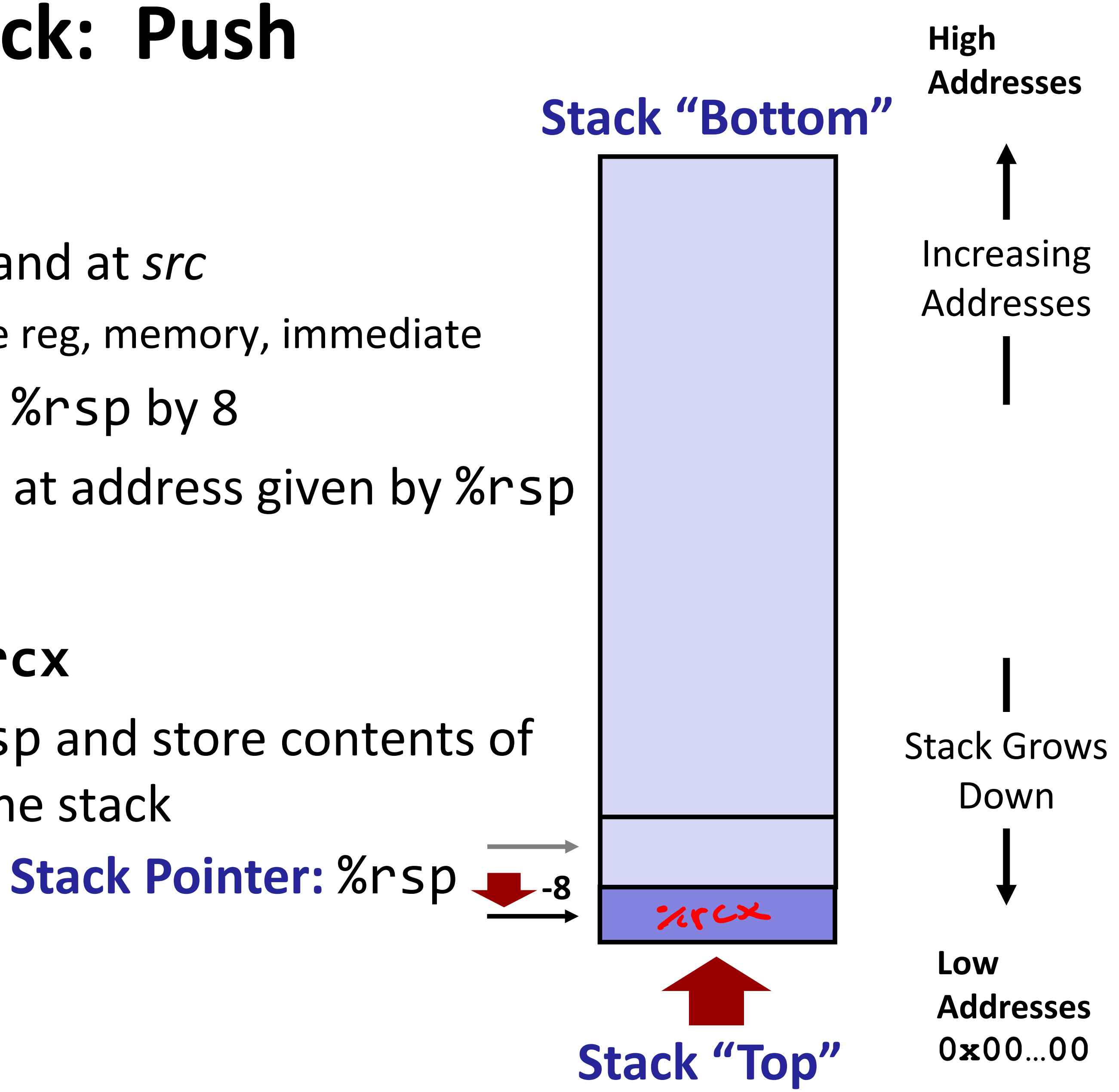
- Region of memory managed with stack "discipline"
  - Grows toward lower addresses
  - Customarily shown "upside-down"
  - LIFO (Last In, First Out)

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



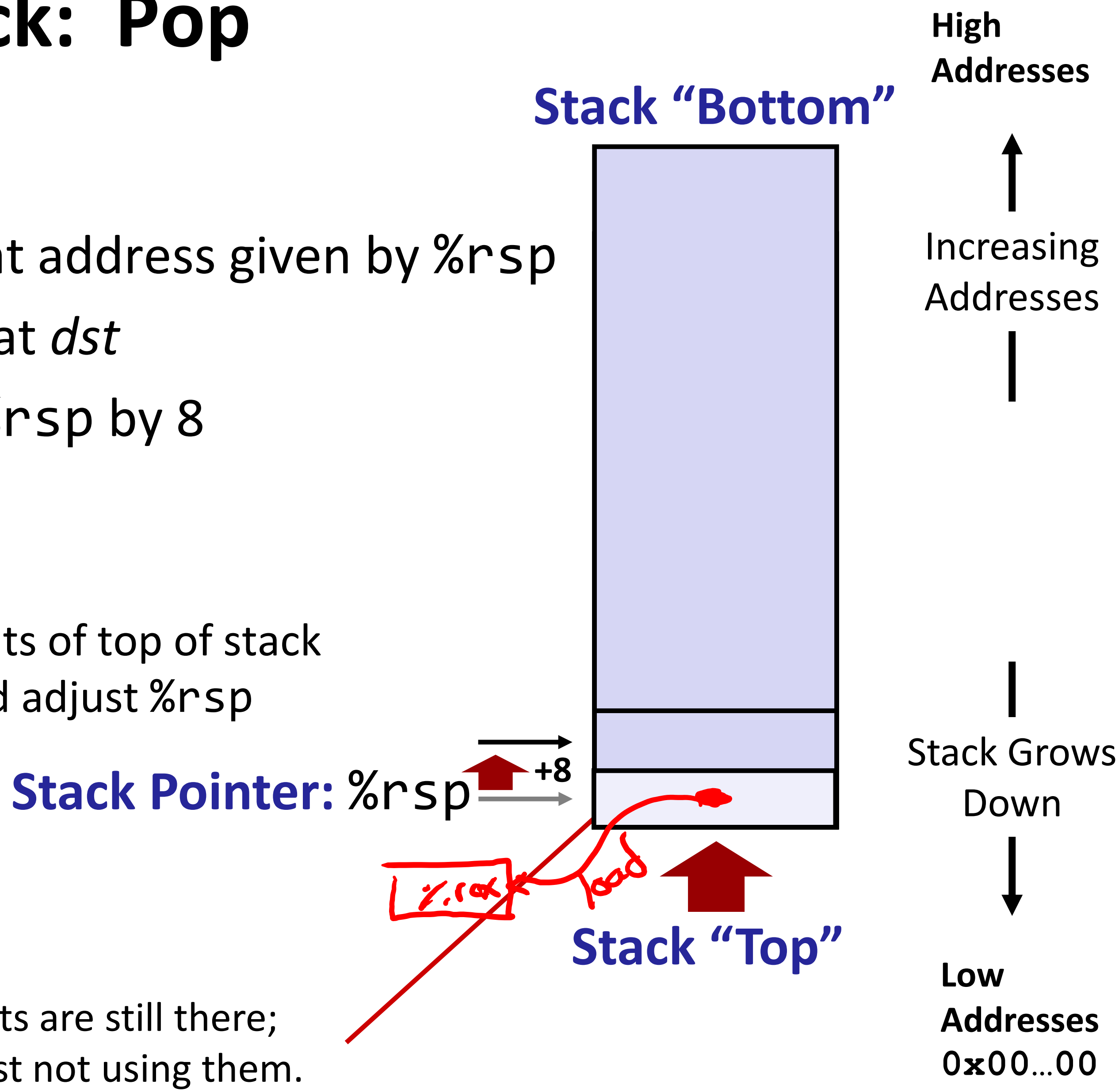
x86-64 Stack: Push

- pushq *src*
  - Fetch operand at *src*
    - *Src* can be reg, memory, immediate
  - ① ***Decrement*** `%rsp` by 8
  - ② 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
- Example:
  - **popq %rcx**
  - Stores contents of top of stack into %rcx and adjust %rsp

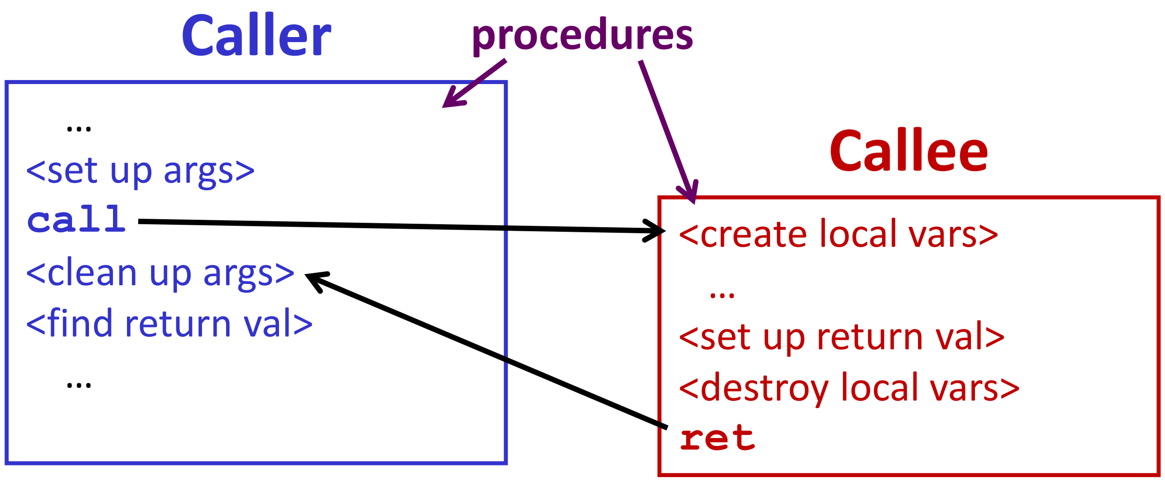


Those bits are still there; we're just not using them.

Procedures

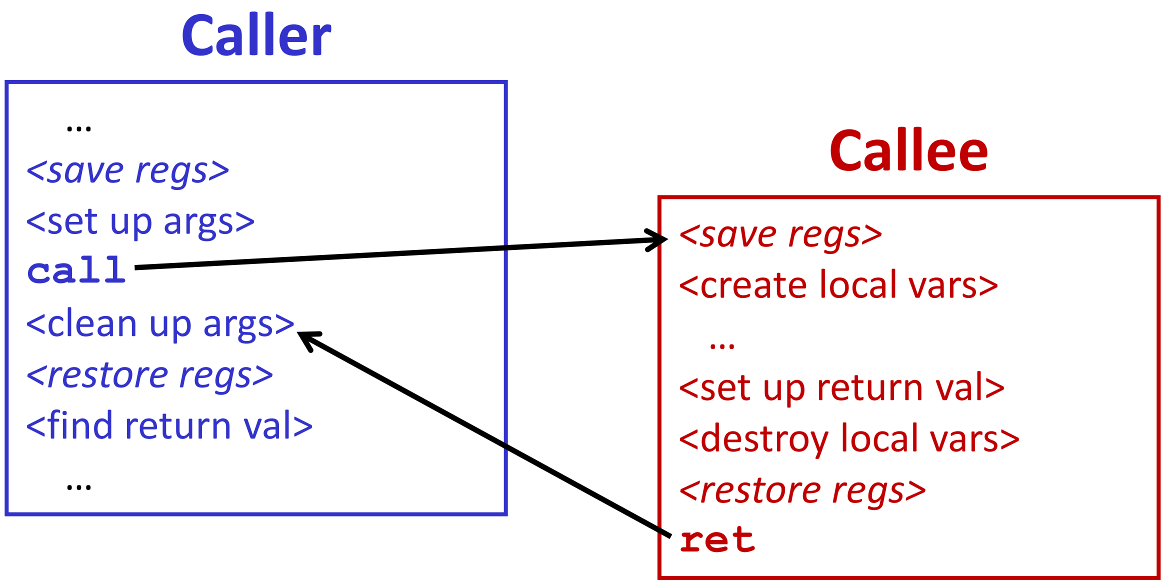
- Stack Structure
- **Calling Conventions**
  - **Passing control**
  - Passing data
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

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;
}
```

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

```
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`**

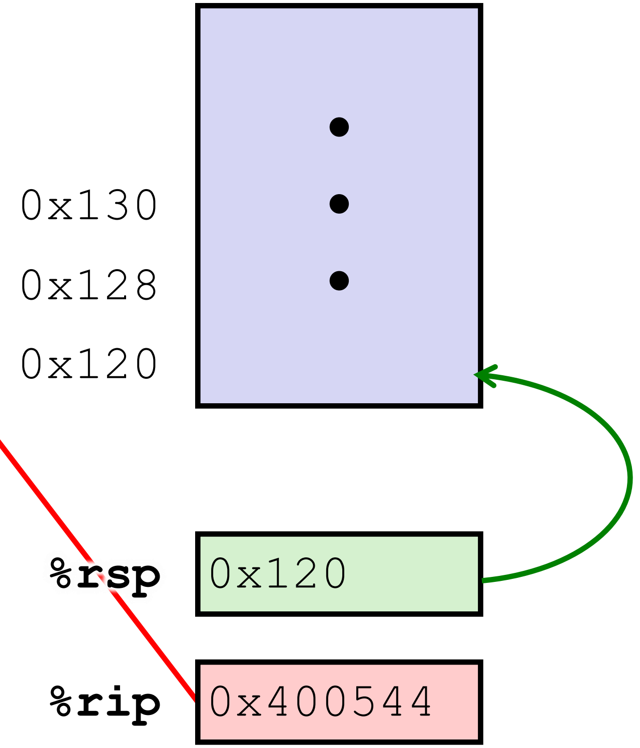
next instruction happens to be a move, but could be anything

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

Procedure <u>Call</u> Example (step 1)

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

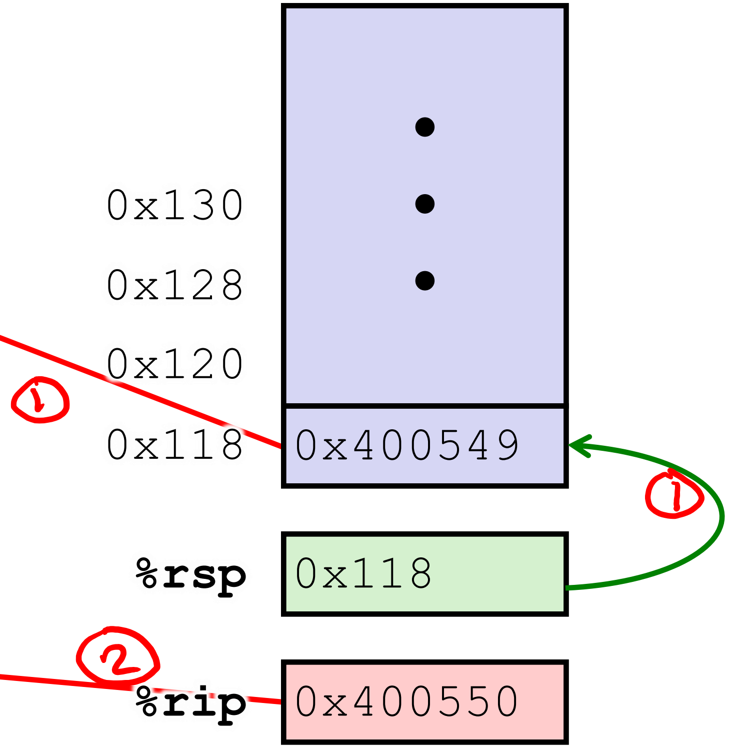
```
0000000000400550 <mult2>:
  400550:  movq    %rdi,%rax
  •
  •
  400557:  ret
```



Procedure Call Example (step 2)

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

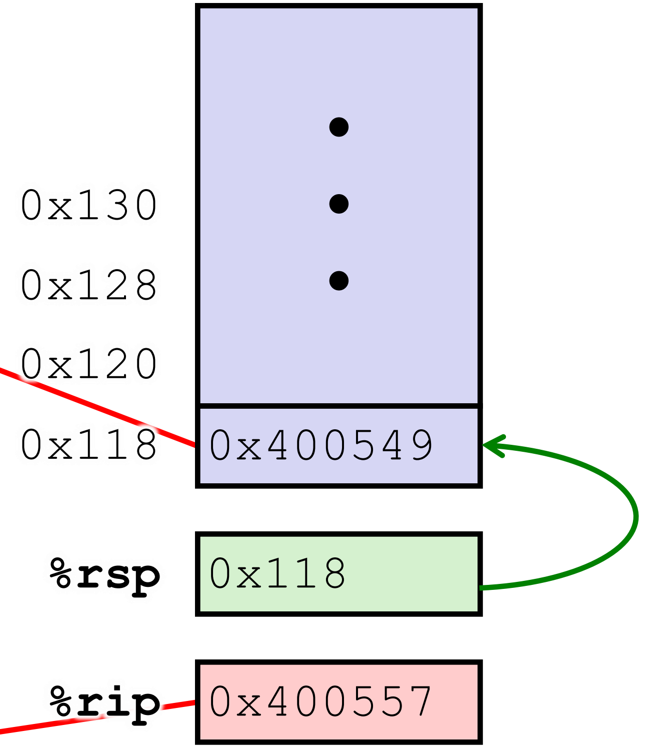
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



Procedure Return Example (step 1)

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

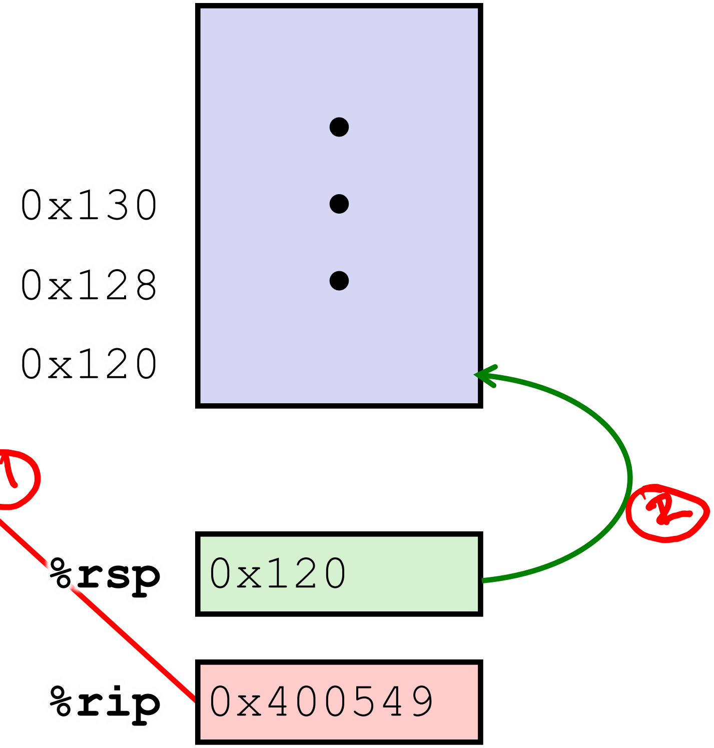
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



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**
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Procedure Data Flow

Registers (NOT in Memory)

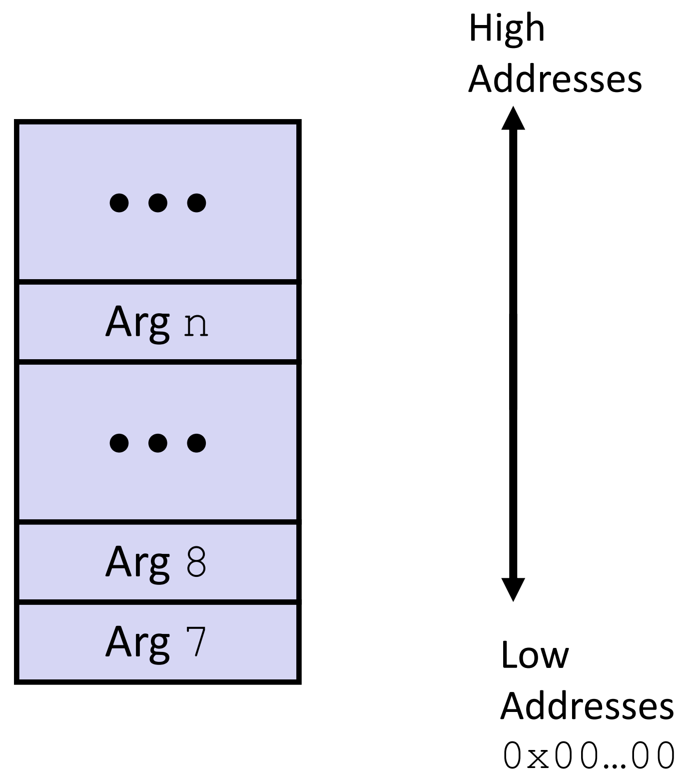
- First 6 arguments

`%rdi`	*Diane's*
`%rsi`	*Silk*
`%rdx`	*Dress*
`%rcx`	*Costs*
`%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
- **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

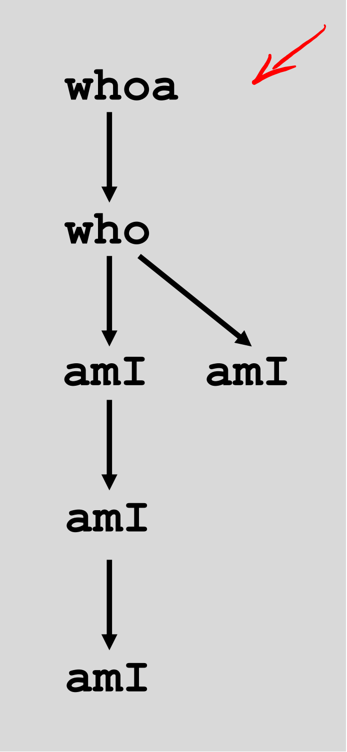
```
whoa(…)
{
    •
    •
    who();
    •
    •
}
```

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

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

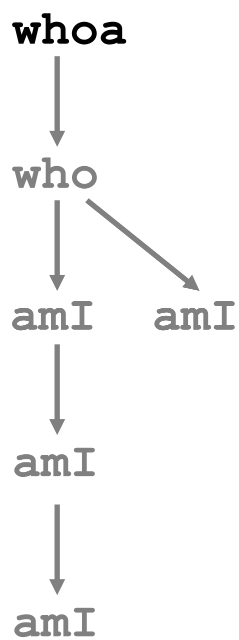
Procedure `amI` is recursive (calls itself)

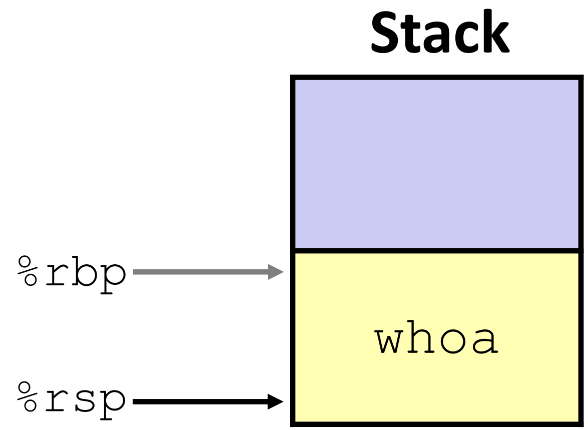
Example Call Chain



1) Call to ~~yoo~~ who

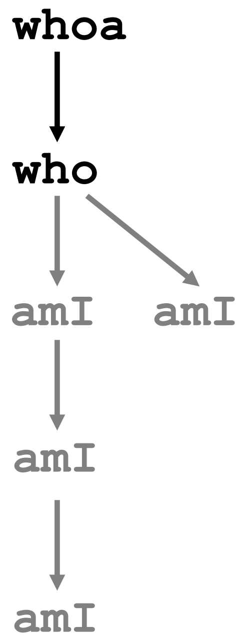
```
whoa(…)
{
   •
   •
   who();
   •
   •
}
```

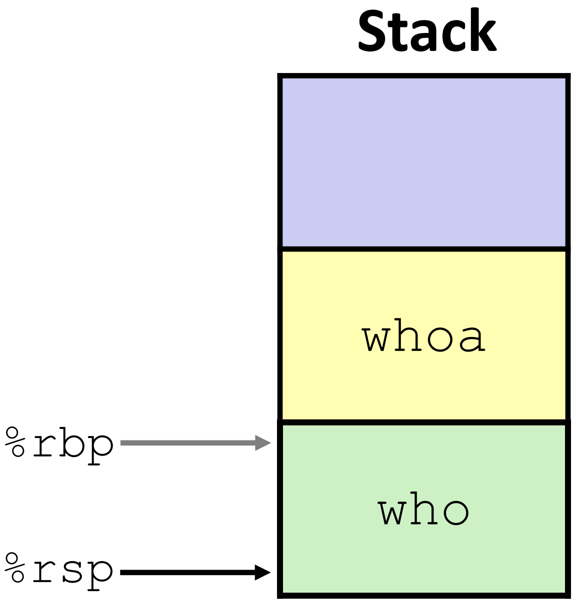




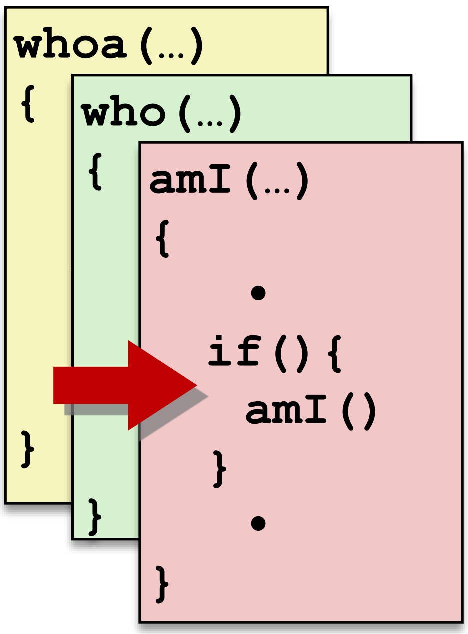
2) Call to who

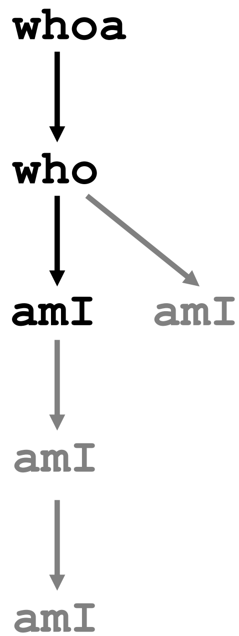
```
whoa(…)
{
  who(…)
  {
    •
    amI();
    •
    amI();
    •
  }
}
```



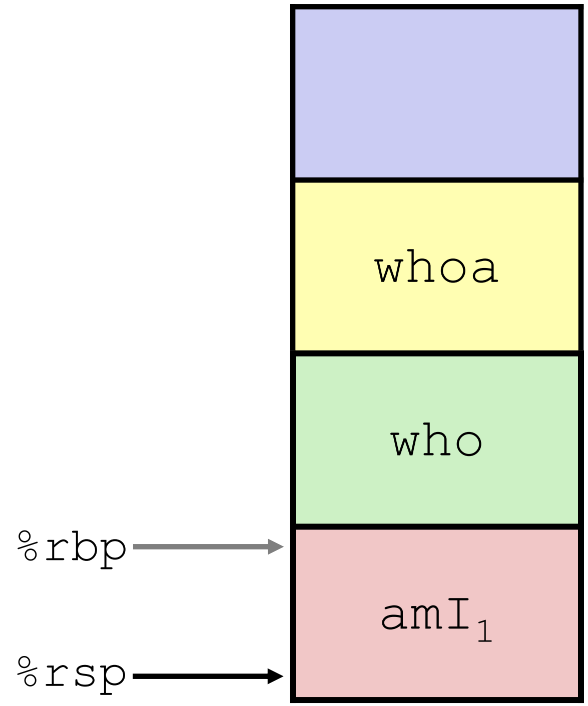


3) Call to amI (1)

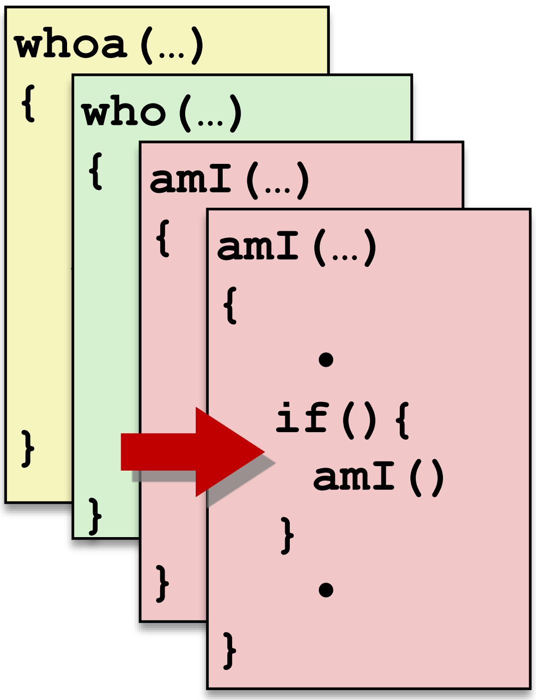


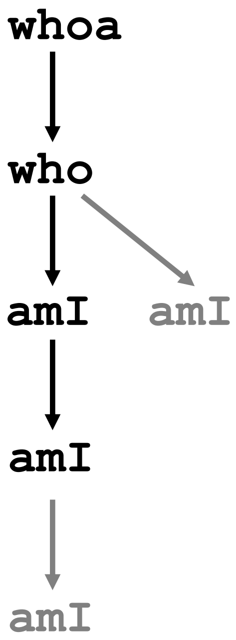


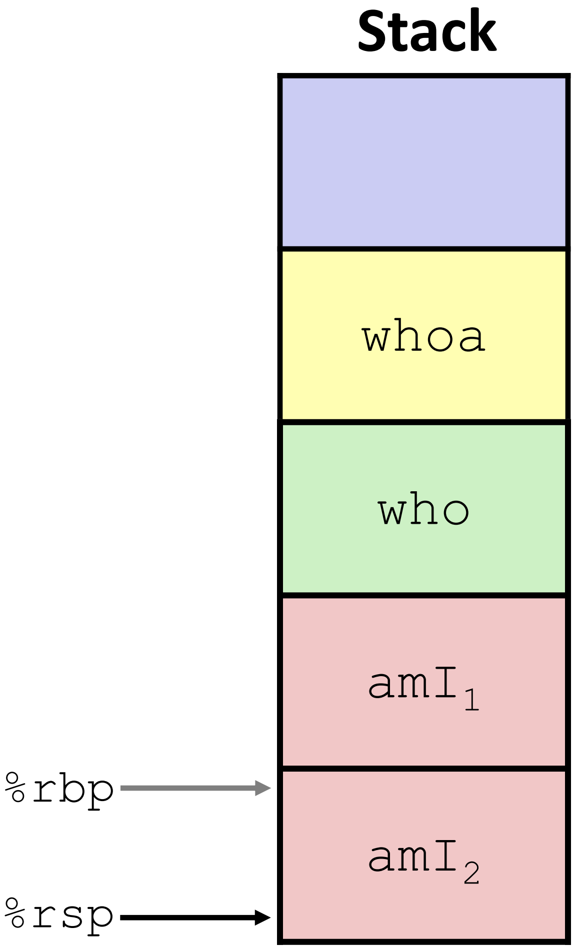
Stack



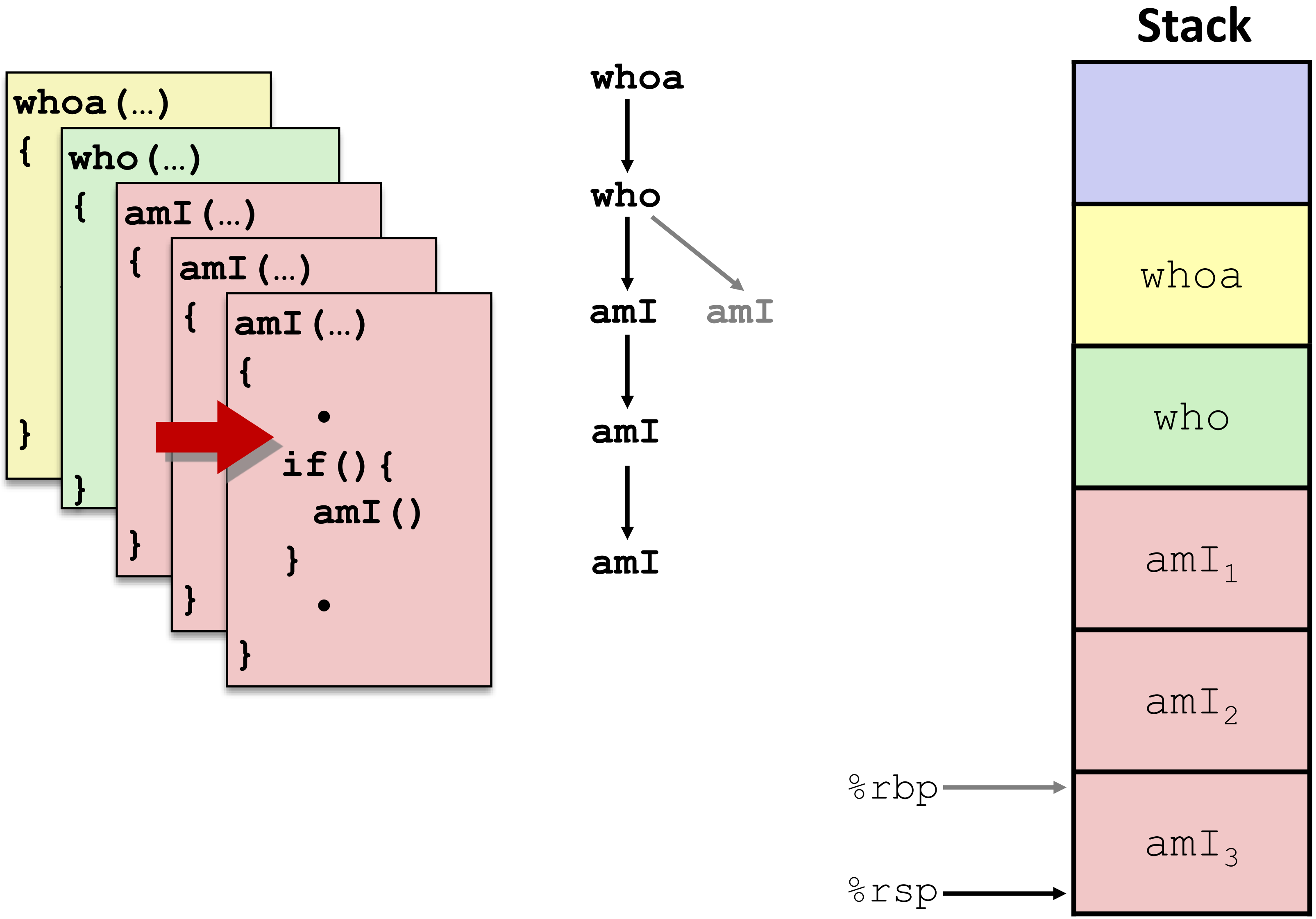
4) Recursive call to amI (2)



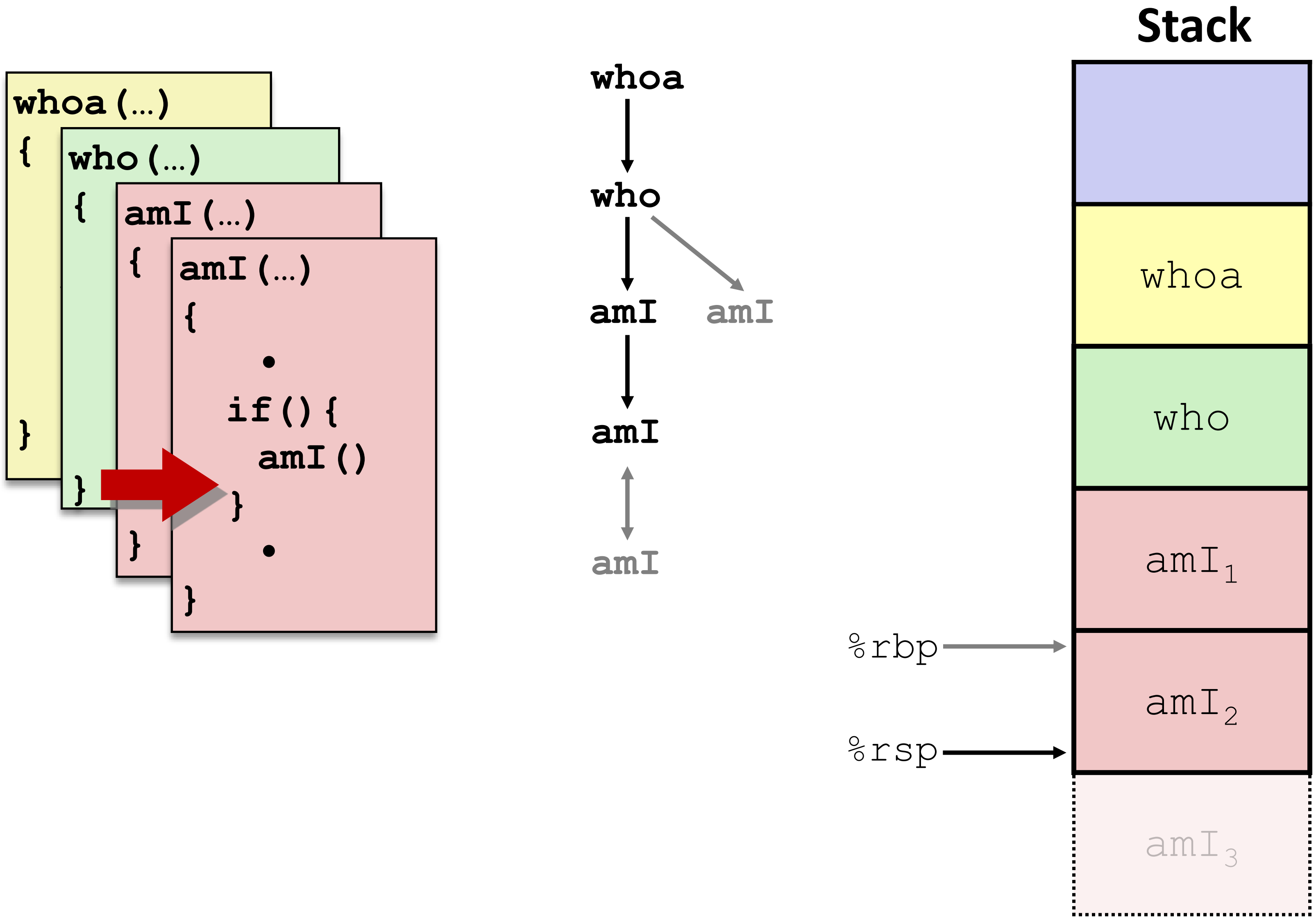




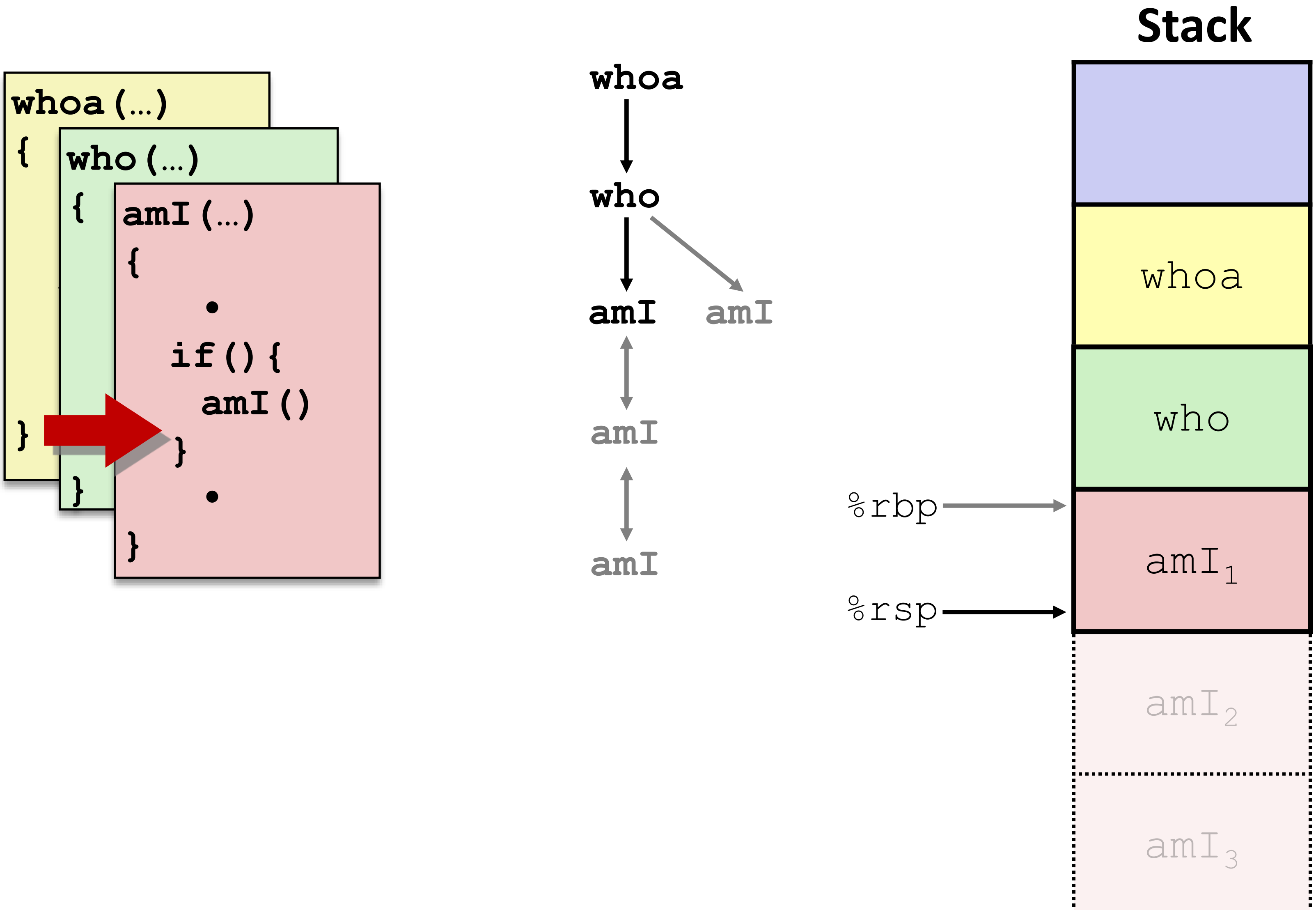
5) (another) Recursive call to amI (3)



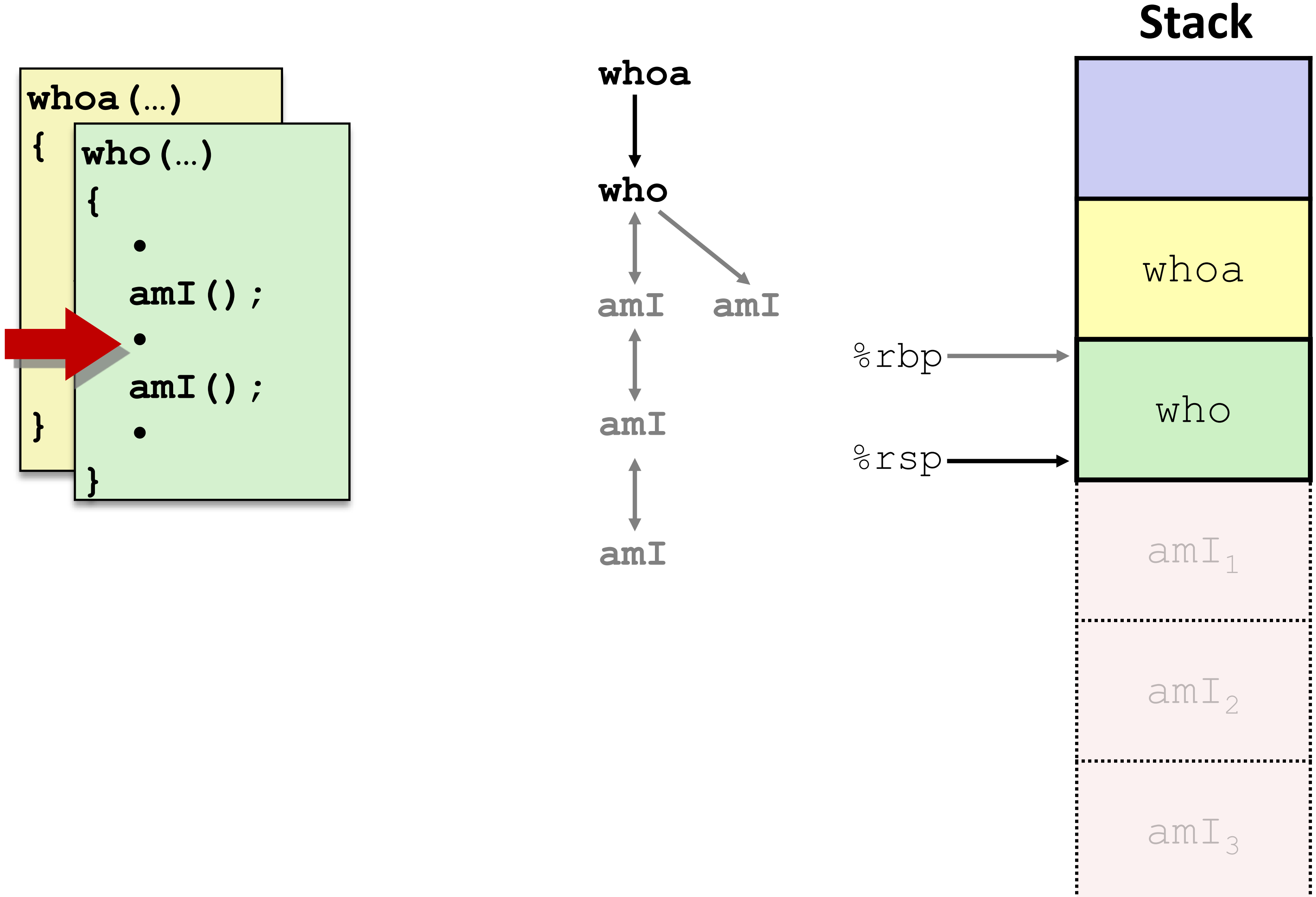
6) Return from (another) recursive call to amI



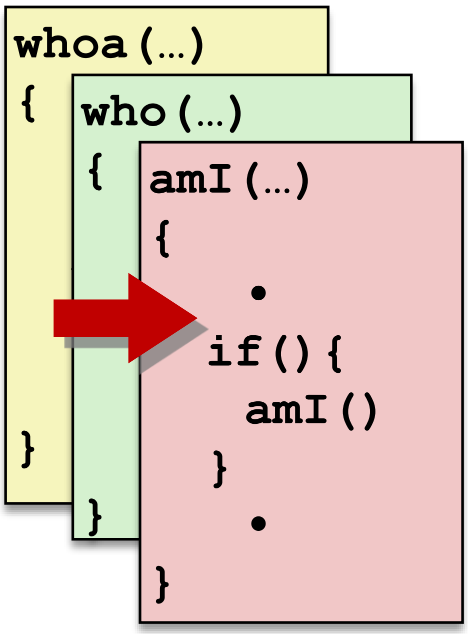
7) Return from recursive call to amI

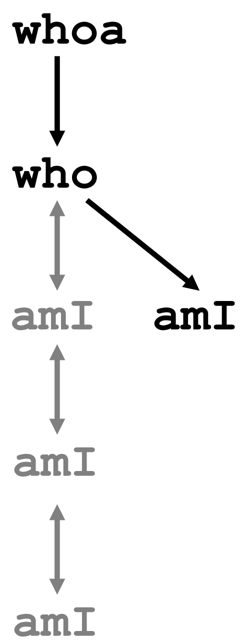


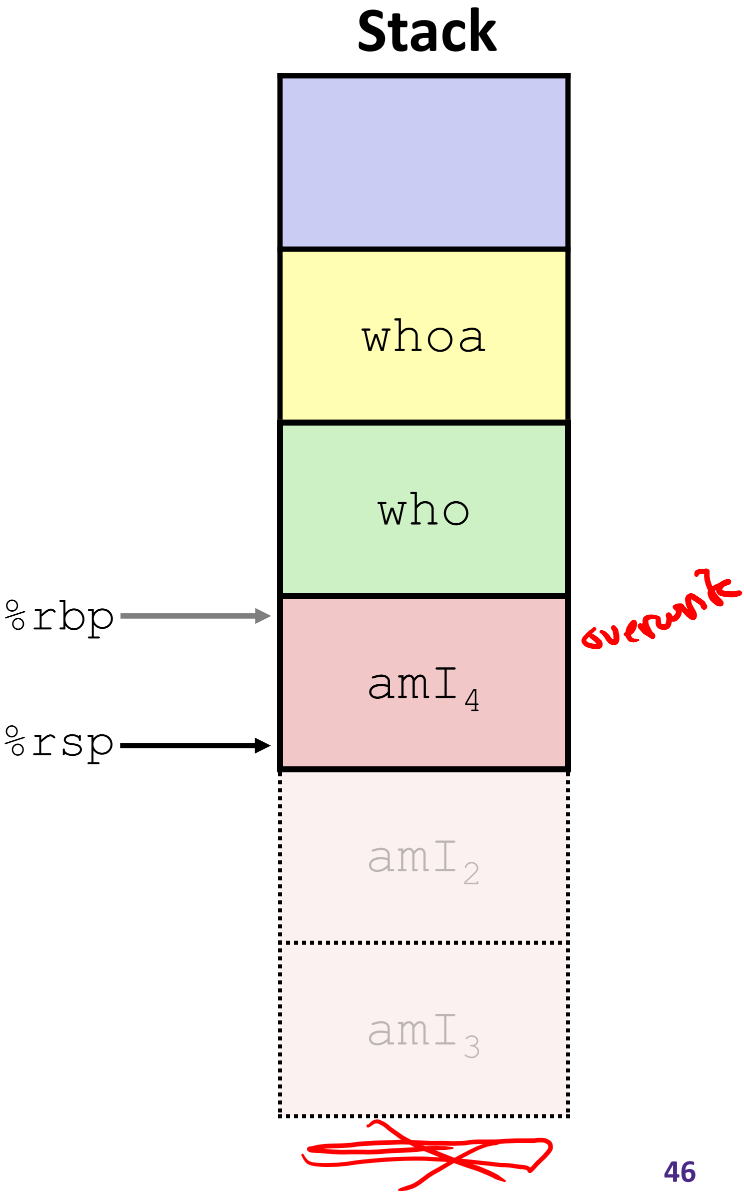
8) Return from call to amI



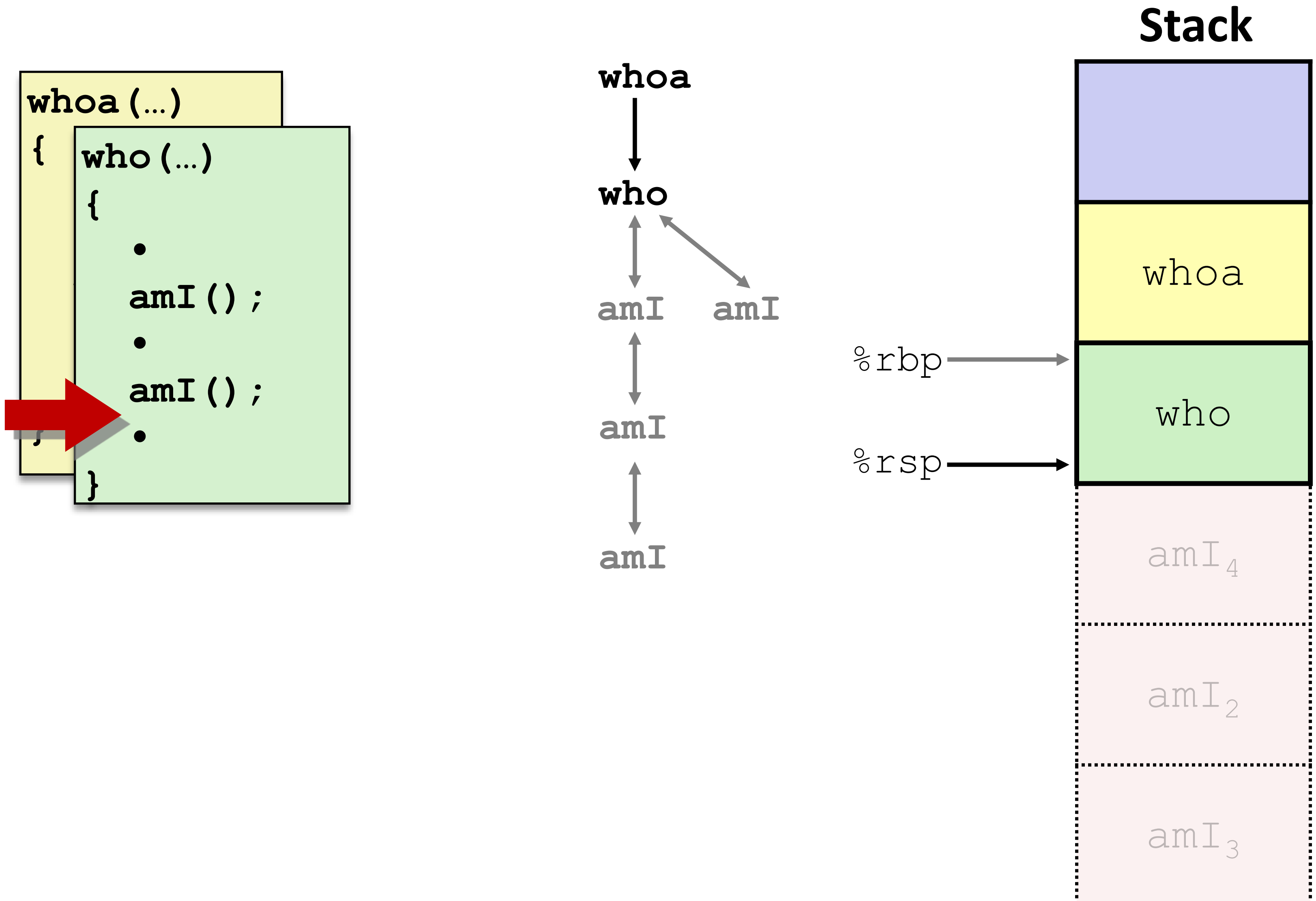
9) (second) Call to `amI` (4)







10) Return from (second) call to amI



11) Return from call to who

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