The Stack & Procedures

CSE 351 Summer 2020

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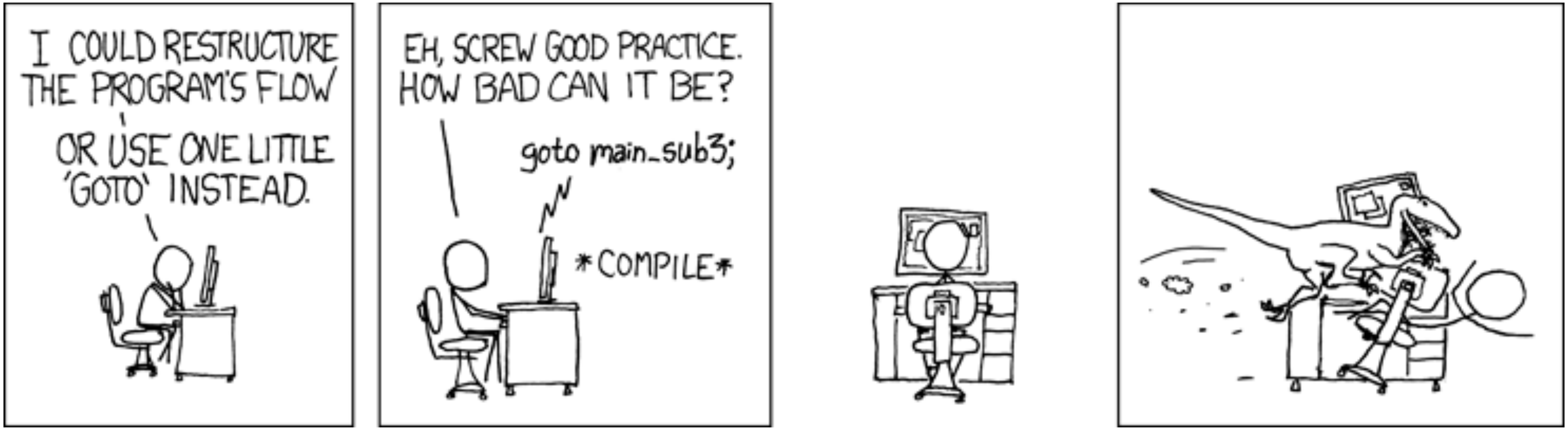


http://xkcd.com/571/

Administrivia

- Questions doc: https://tinyurl.com/CSE351-7-15
- Unit Summary 1 due Friday (7/17) – 11:59pm
  - Can still use late days until 7/20
- Mid-quarter Survey due Friday (7/17) – 11:59pm
  - Submit via Canvas!
- hw8, hw9, hw10 now due Monday (7/20) – 10:30am
  - hw11 also due Monday (7/20)
  - See course schedule for original/suggested deadlines
- Lab 2 due Wednesday (7/22)
  - GDB Tutorial on Gradescope walks through first phase

Administrivia

- No midterm or final! But the midterm and final cheat sheets could be useful throughout the course
  - Can find them at the exams page of the course website
  - https://courses.cs.washington.edu/courses/cse351/20su/exams/

- These ***do not*** mimic a good unit summary
  - Too much like a cheat sheet (lots of listed facts w/out much organization and summary)
  - See unit summary spec for more details and good/bad examples of unit summaries

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

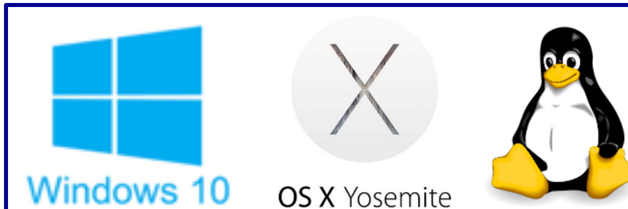
Assembly language:

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

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:



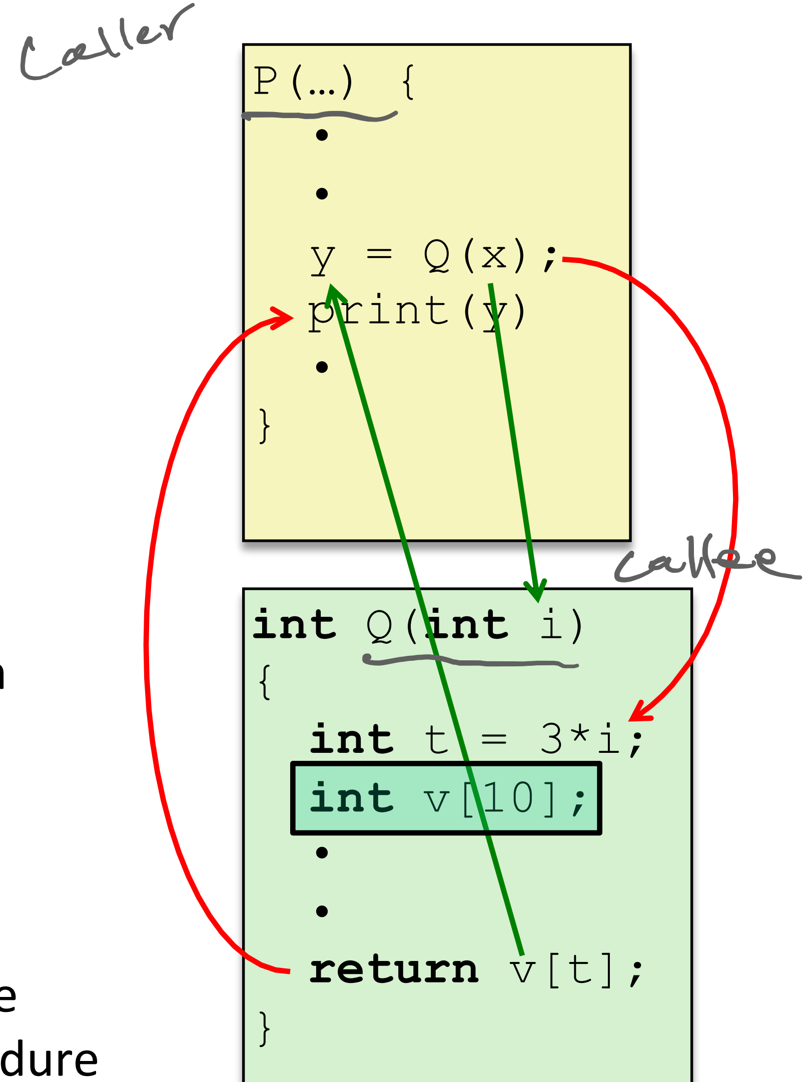
Computer system:

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

Mechanisms required for *procedures*

1) Passing control
   - To beginning of procedure code
   - Back to return point
2) Passing data
   - Procedure arguments
   - Return value
3) Memory management
   - Allocate during procedure execution
   - Deallocate upon return

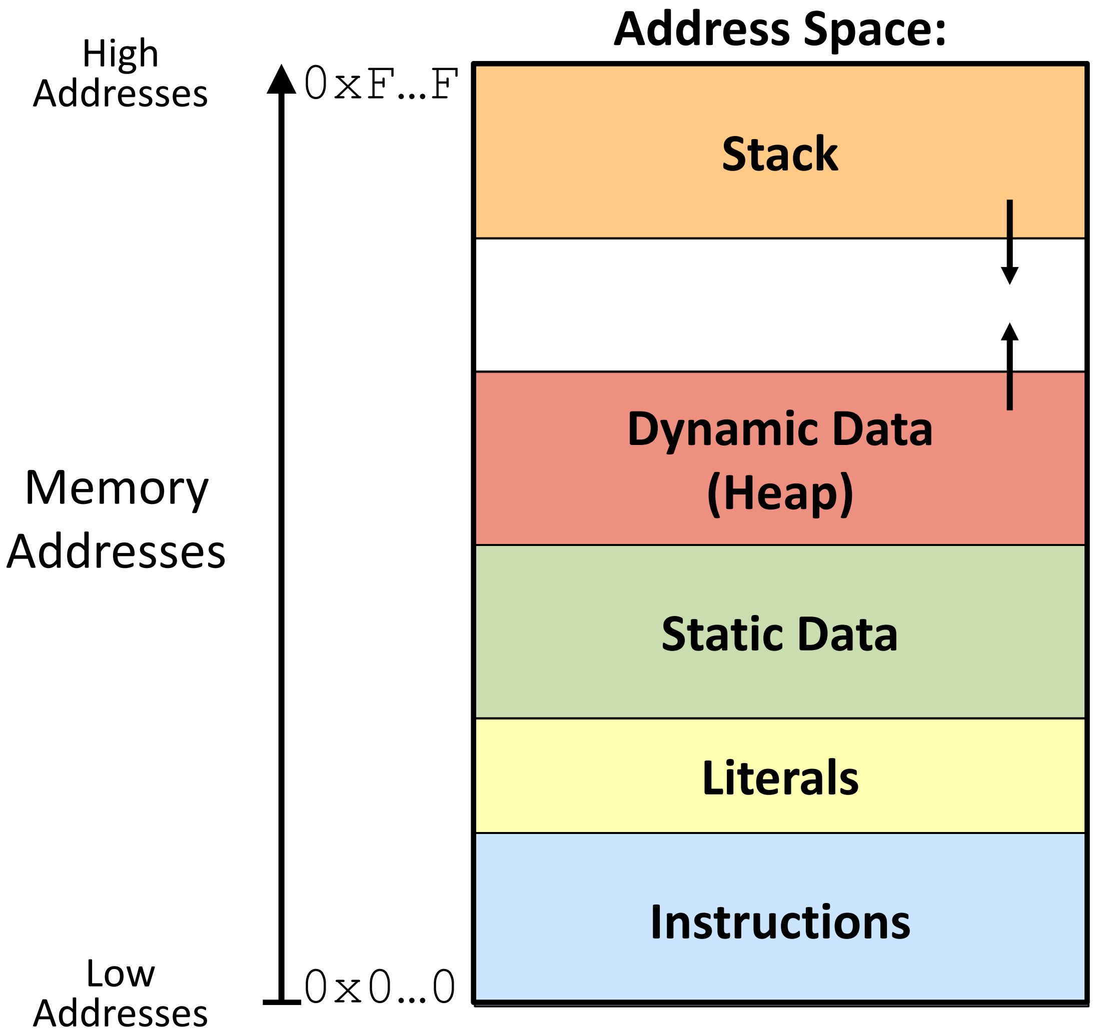
- All implemented with machine instructions!
  - An x86-64 procedure uses only those mechanisms required for that procedure



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

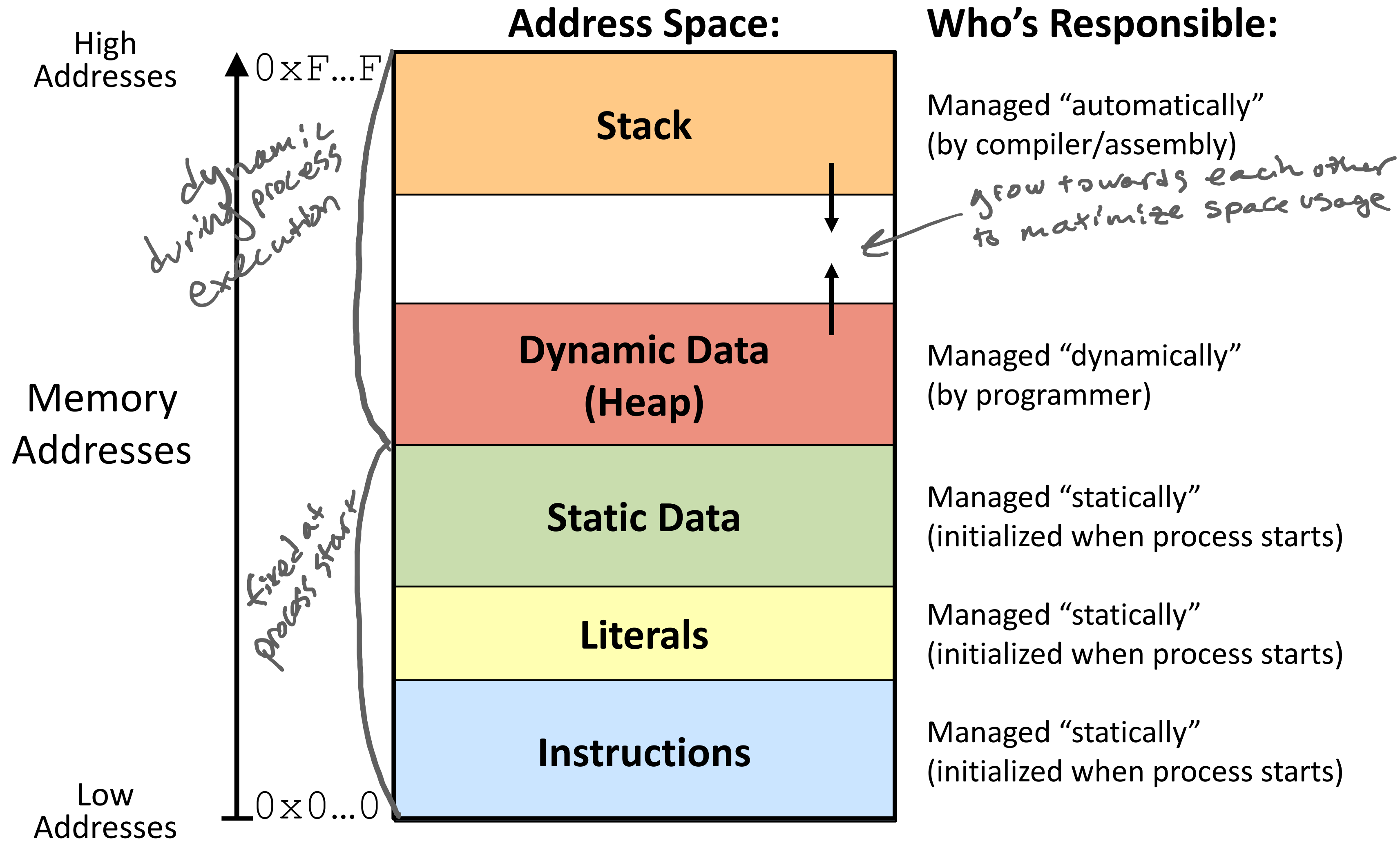
variables allocated with `new` or `malloc`

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)

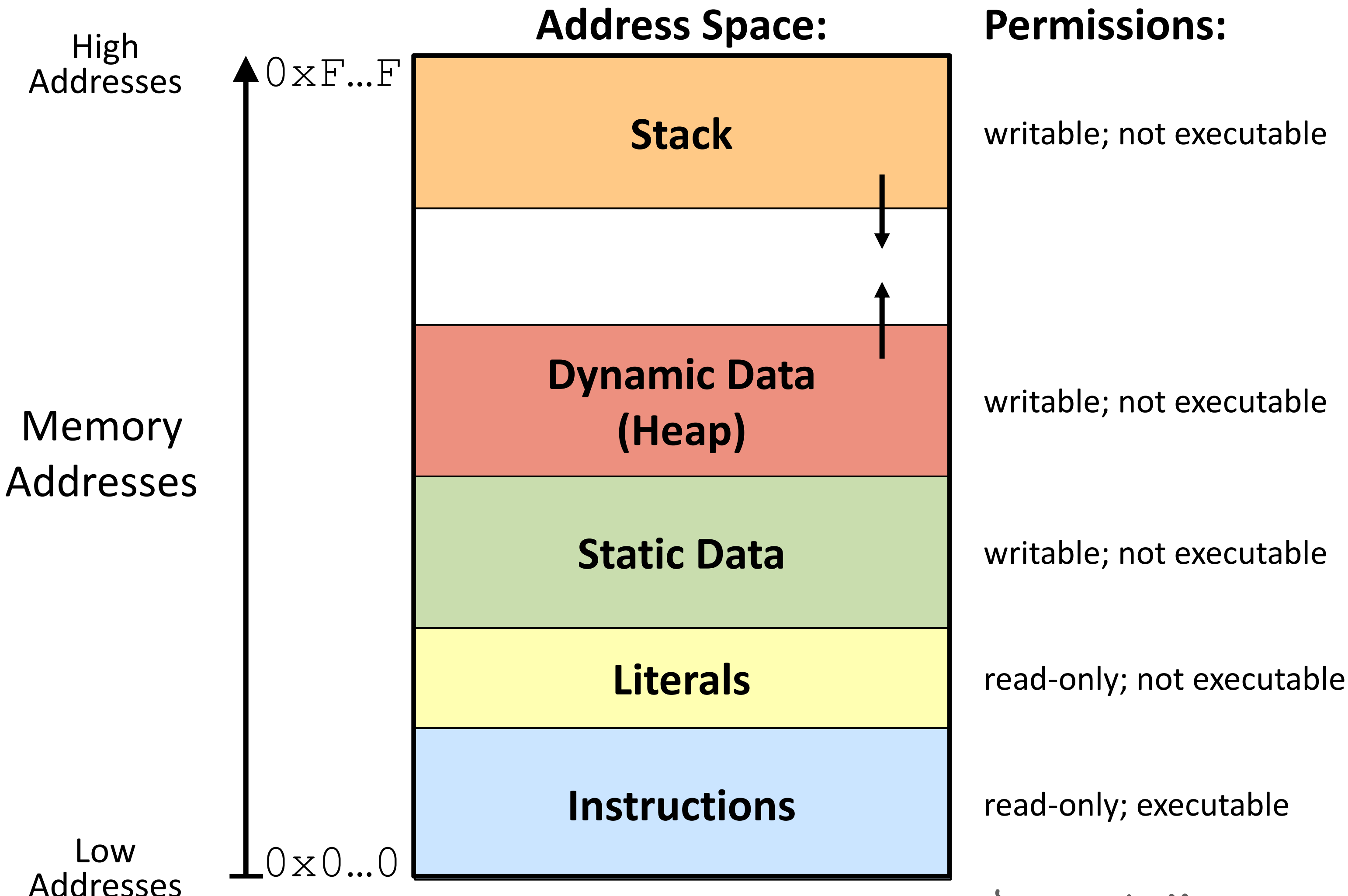
Managed "statically" (initialized when process starts)

Managed "statically" (initialized when process starts)

Managed "statically" (initialized when process starts)

Memory Permissions

Determined by the OS
Enforced by hardware (CPU/mmu)

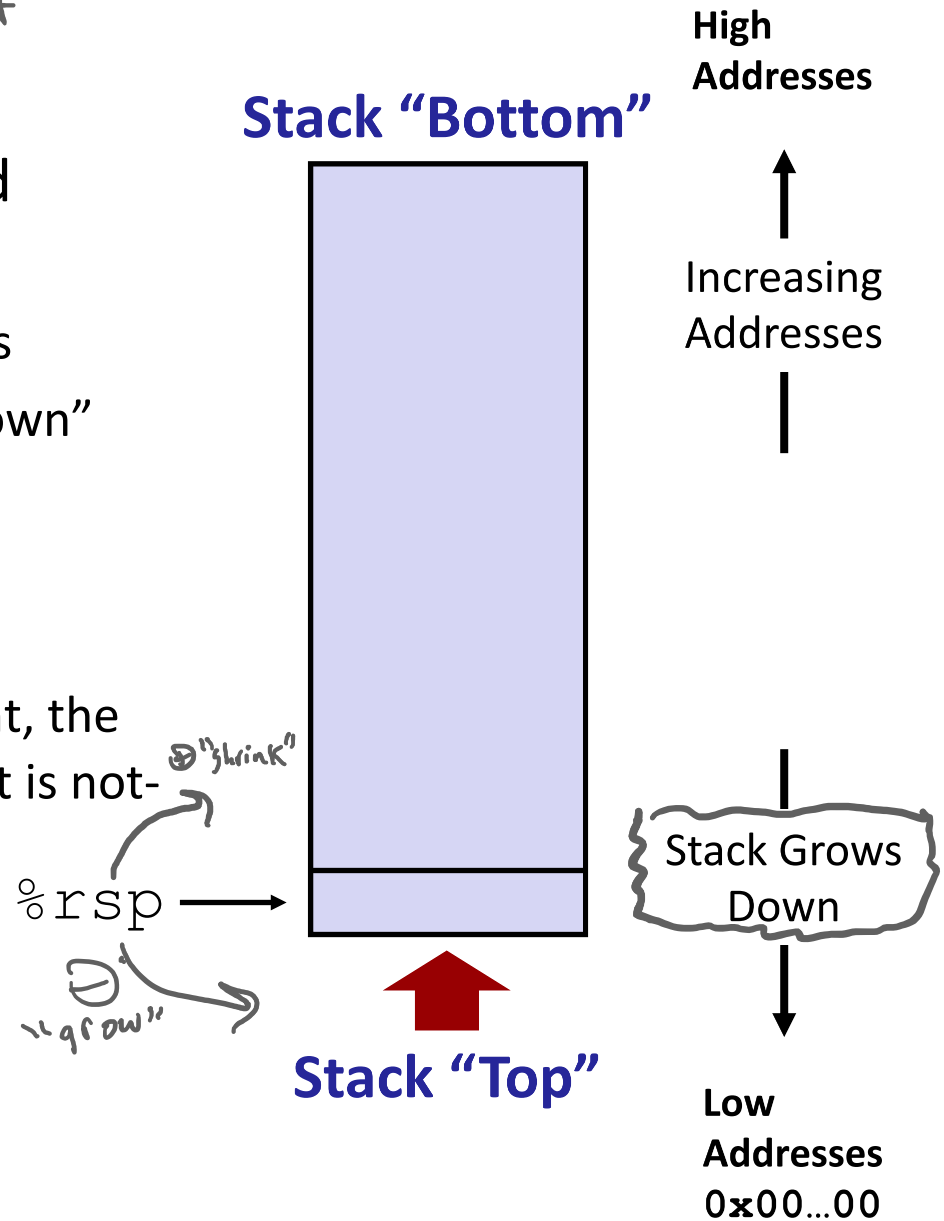


- Segmentation faults? accessing memory in a way that is not allowed

x86-64 Stack

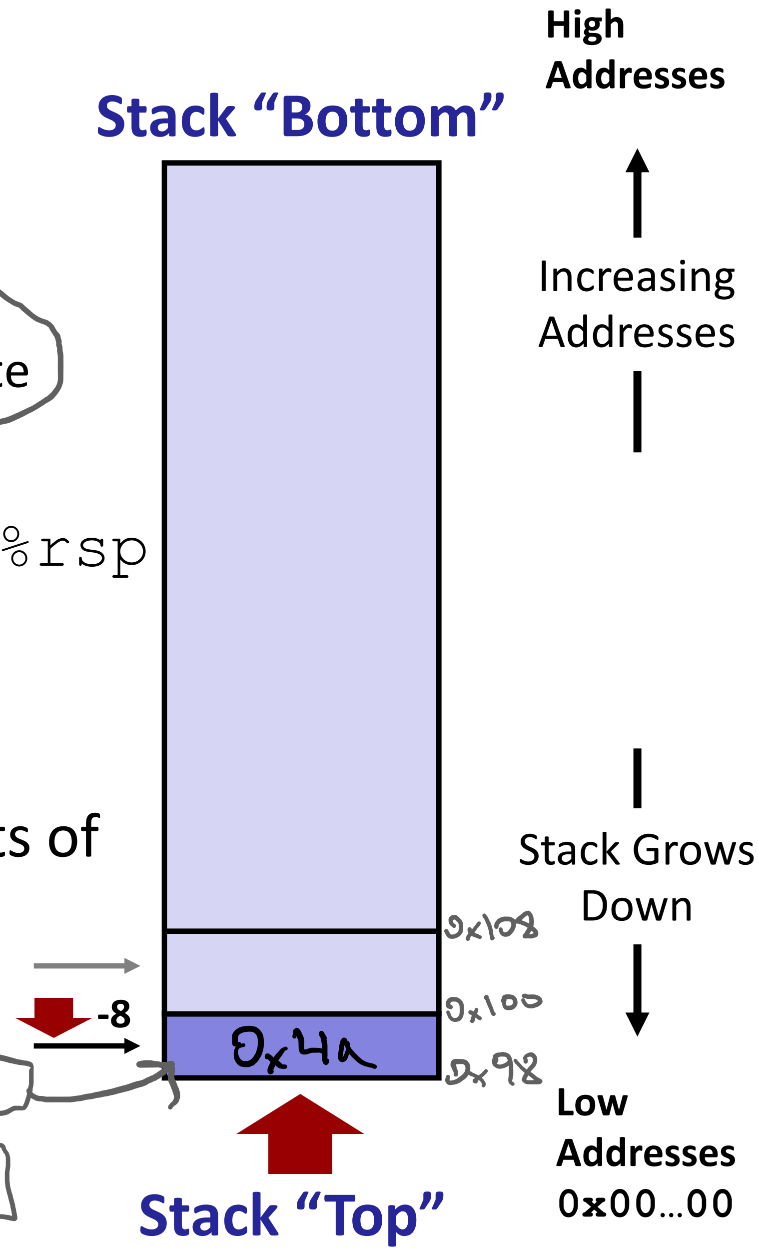
Last in First out

- 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

- `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

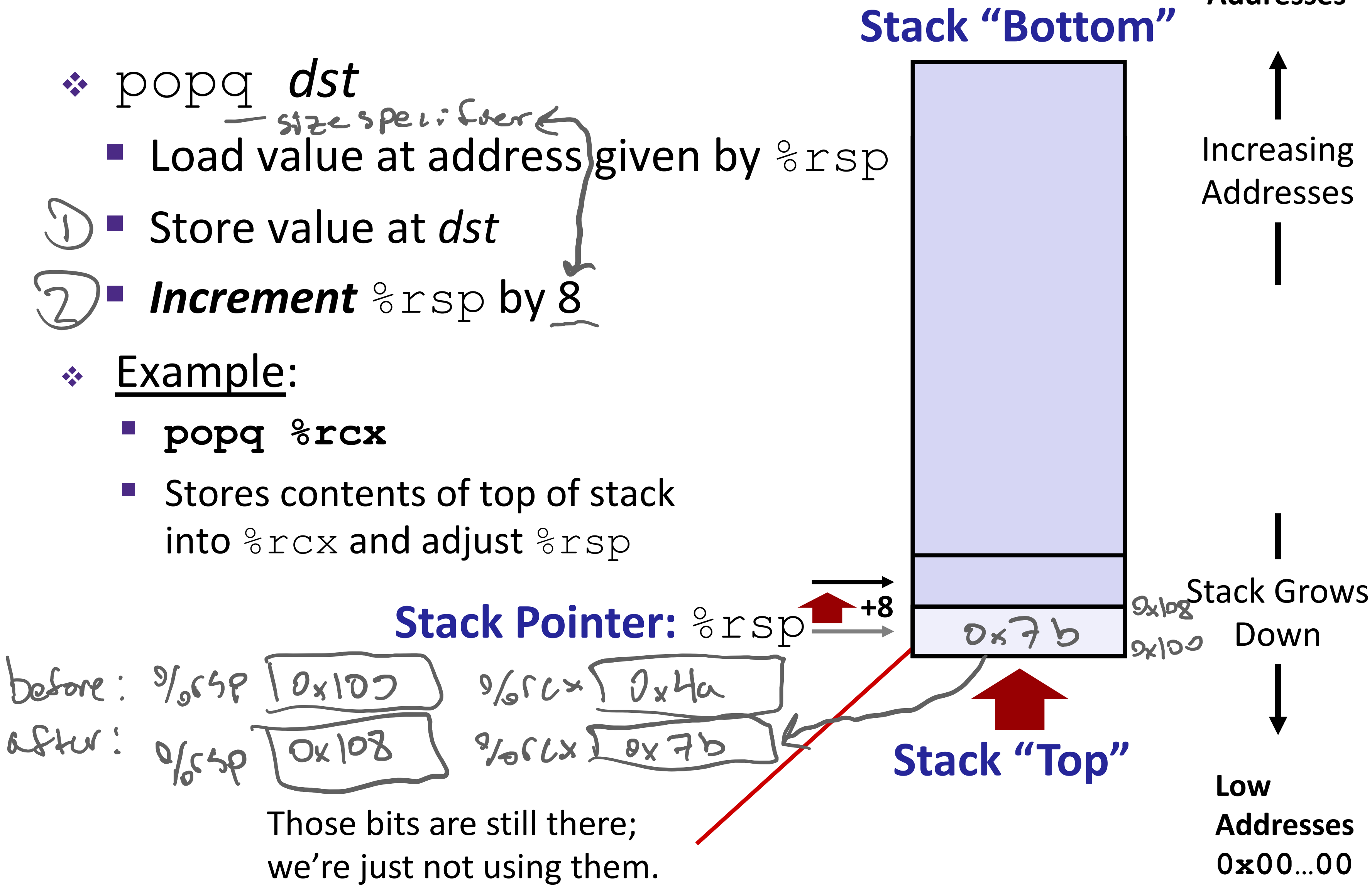


before: %rsp 0x100 %rcx 0x4a

after: %rsp 0x98 %rcx 0x4a

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`

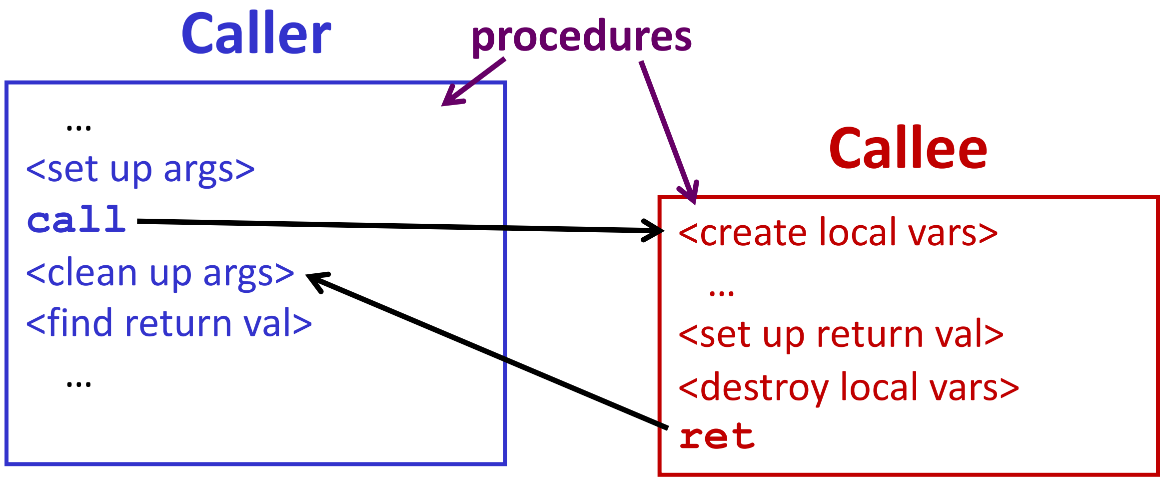


Those bits are still there; we're just not using them.

Procedures

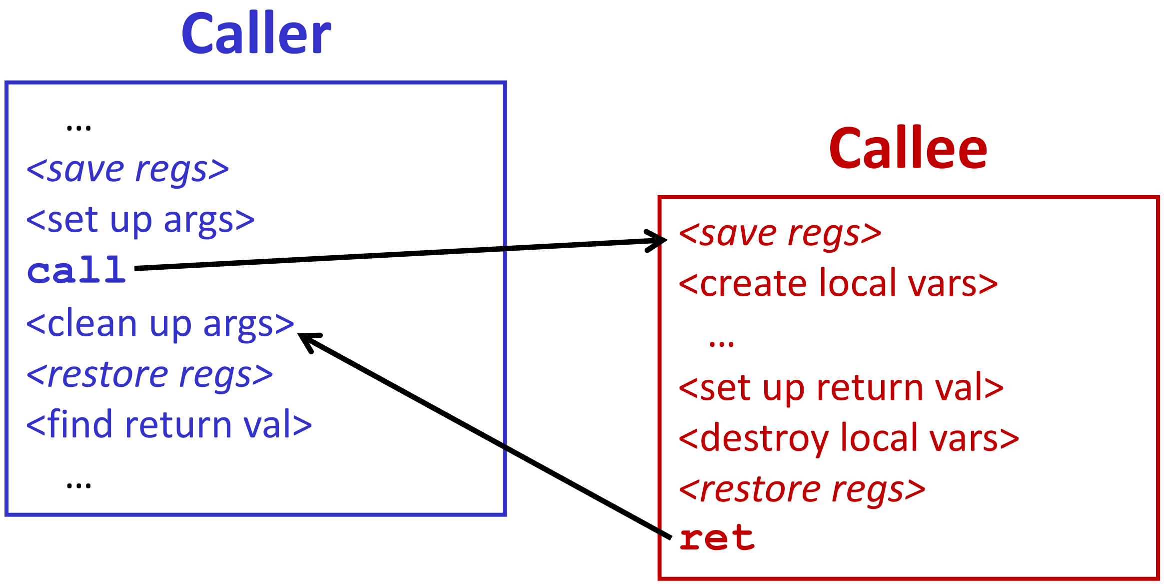
- Stack Structure
- **Calling Conventions**
  - **Passing control**
  - Passing data
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

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;
}
```

```
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
```

Compiler Explorer:
https://godbolt.org/z/nQ6KbZ

Caller

Callee

instruction addresses

```
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` (special push)
  1) Push return address on stack (*why? which address?*)
  2) Jump to ***label***

  ① move %rsp down
  ② store ret addr at rsp
  ③ move label to 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
  2) Jump to address

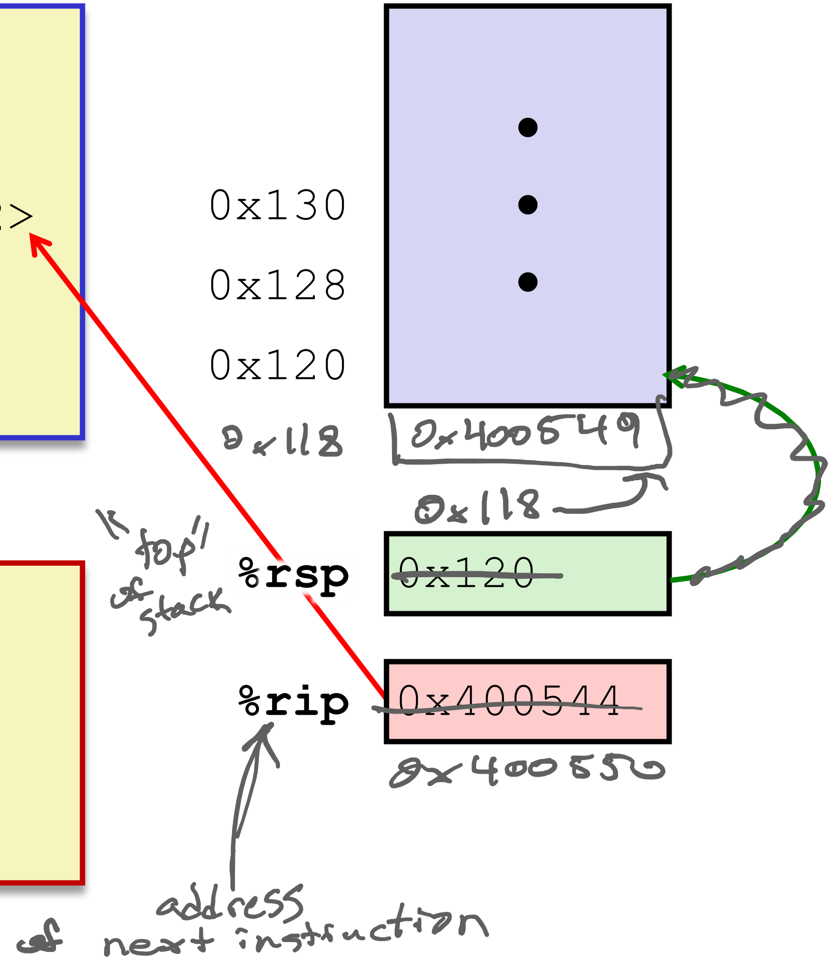
  ① read ret addr at rsp into rip
  ② move rsp up

jump to address = move address to %rip

Procedure Call Example (step 1)

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

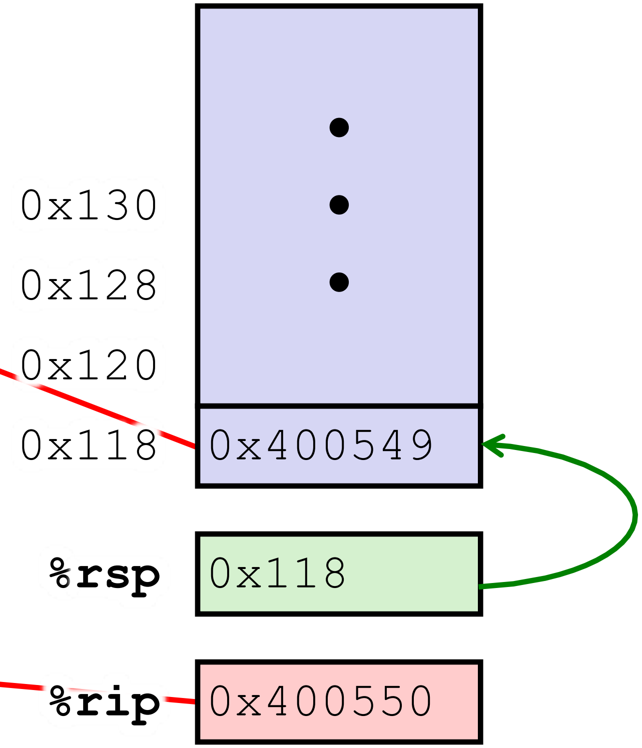
```
0000000000400550 <mult2>:
  400550:  movq    %rdi,%rax
  •
  •
  400557:  ret
```



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

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

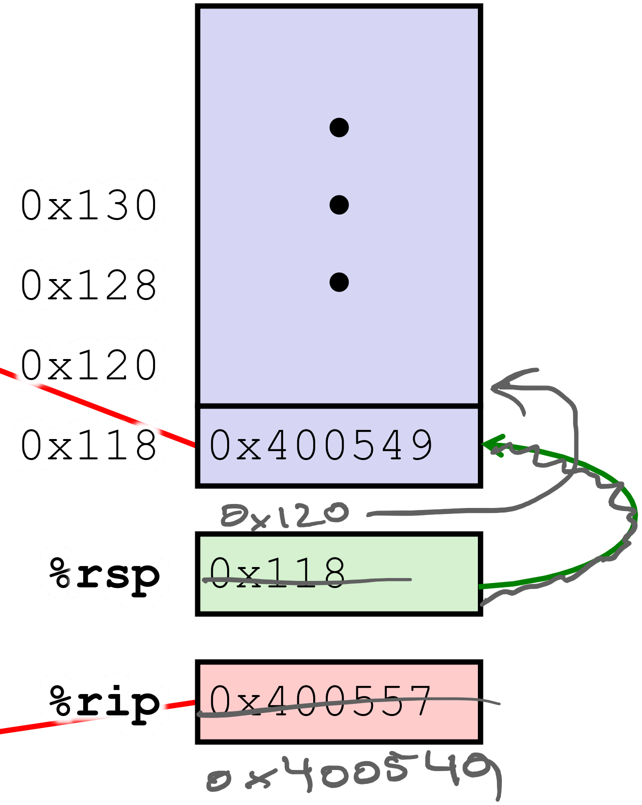
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



Procedure Return Example (step 1)

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

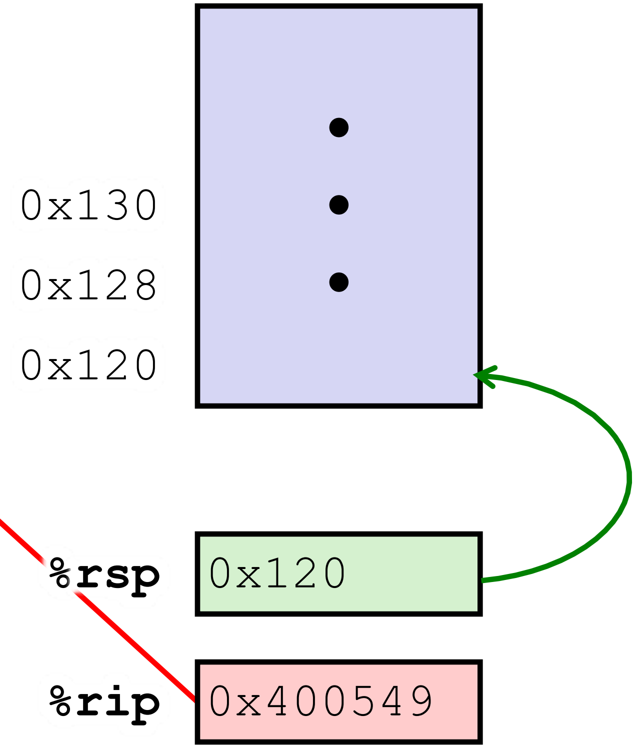
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



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**
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Procedure Data Flow

Registers (NOT in Memory)

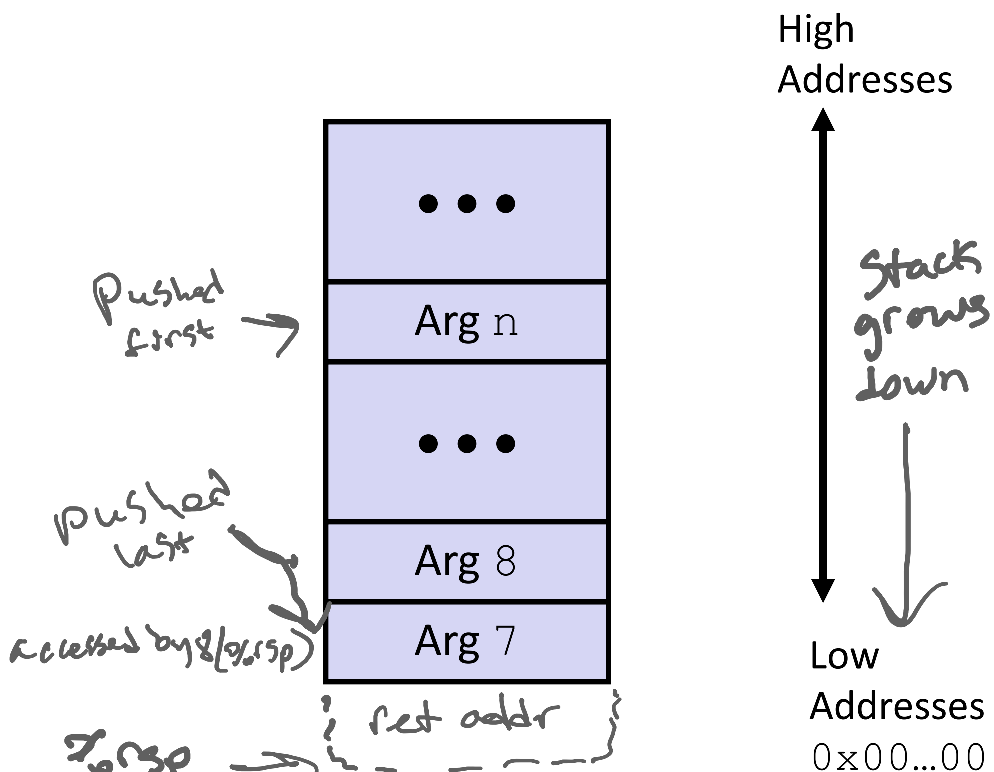
- First 6 arguments

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

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

no need to move args before calling mult2

```
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

can use returned val

```
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
```

ret val

Procedures

- Stack Structure
- **Calling Conventions**
  - Passing control
  - Passing data
  - **Managing local data**
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Stack-Based Languages

- Languages that support recursion
  - *e.g.* C, Java, most modern languages
  - Code must be *re-entrant*
    - Multiple simultaneous instantiations of single procedure
  - Need some place to store *state* of each instantiation
    - Arguments, local variables, return address
- Stack allocated in *frames*
  - State for a single procedure instantiation
- Stack discipline
  - State for a given procedure needed for a limited time
    - Starting from when it is called to when it returns
  - Callee always returns before caller does

Call Chain Example

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

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

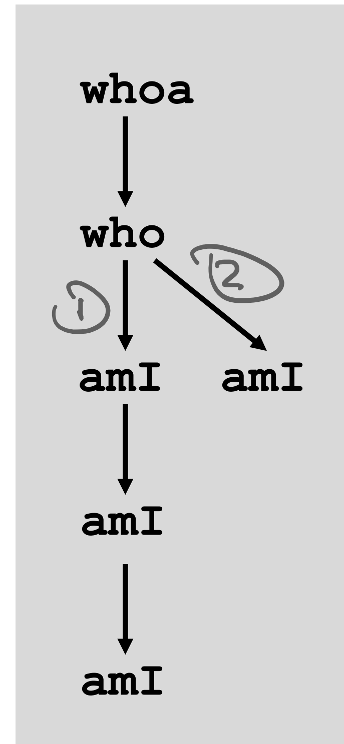
Will recurse twice (for this example)

Won't recurse (for this example)

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

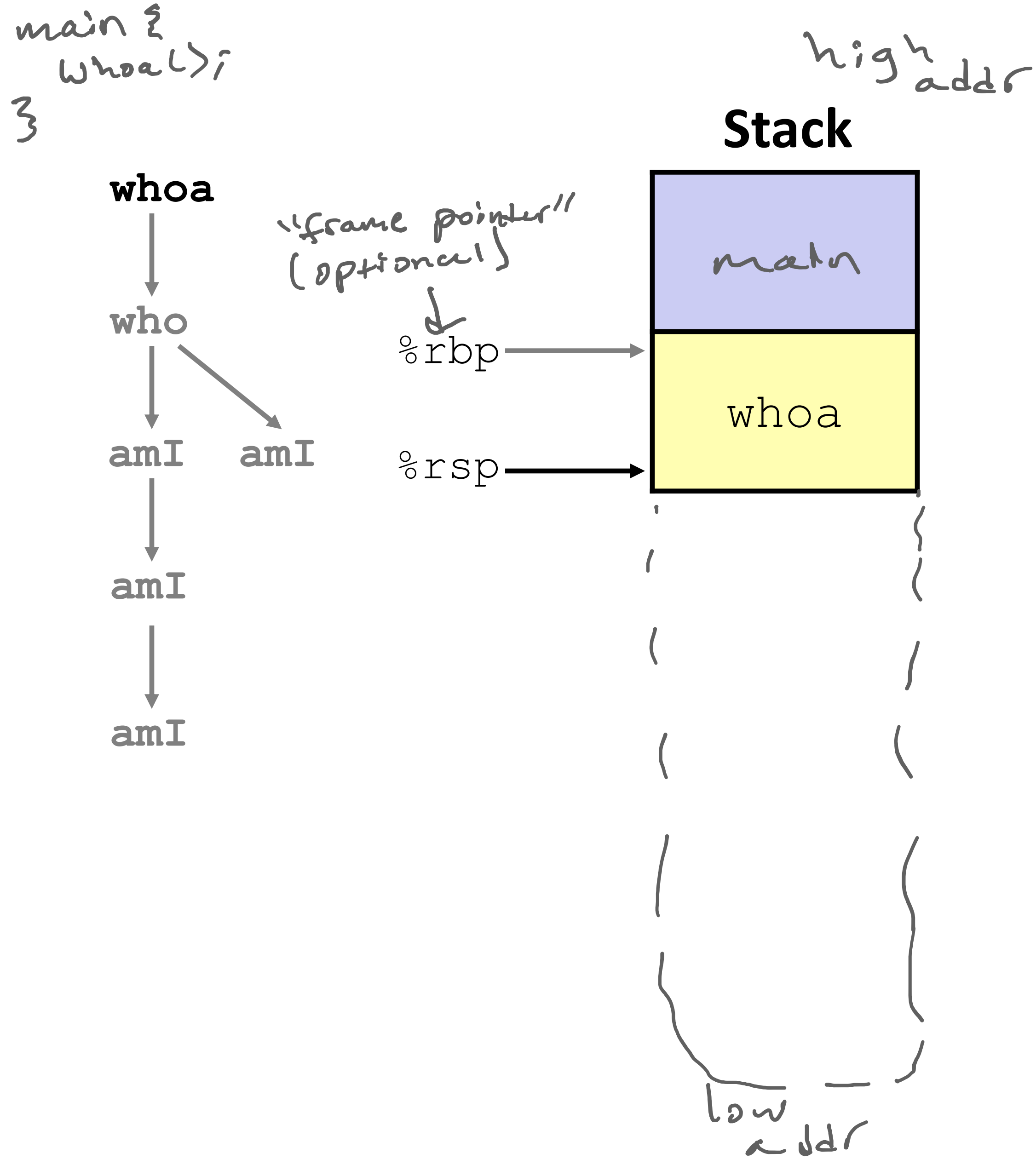
Procedure amI is recursive (calls itself)

Example Call Chain

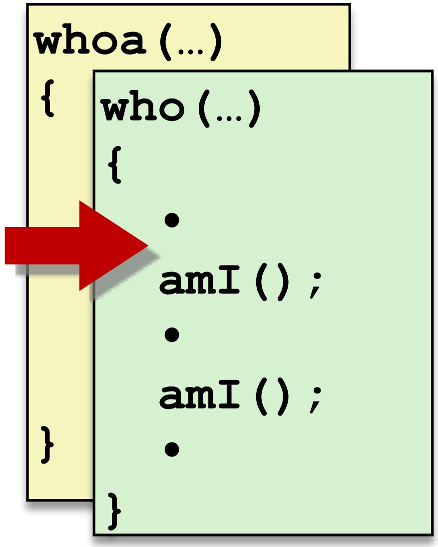


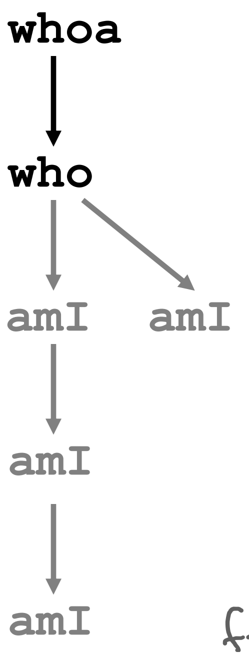
1) Call to whoa

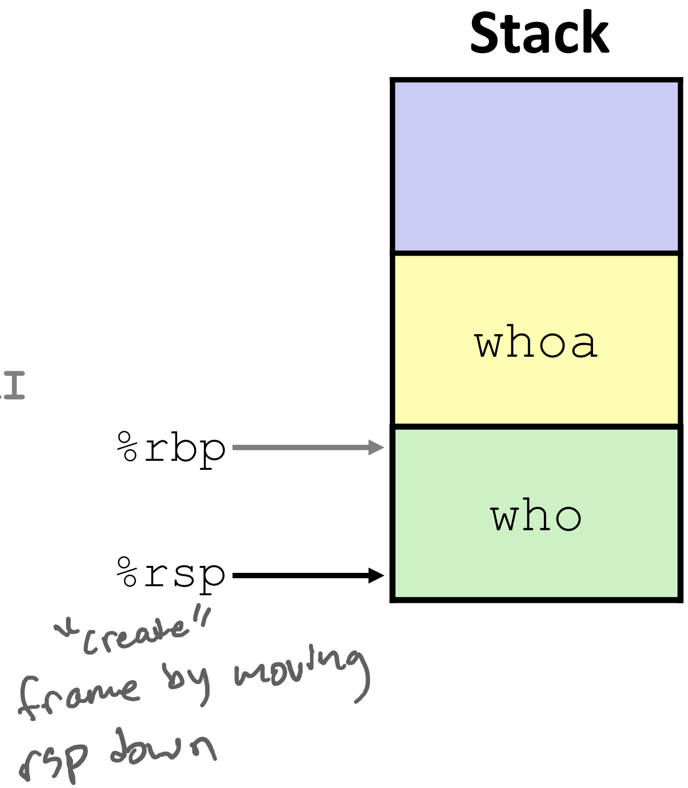
```
whoa(…)
{
    •
    •
    who();
    •
    •
}
```



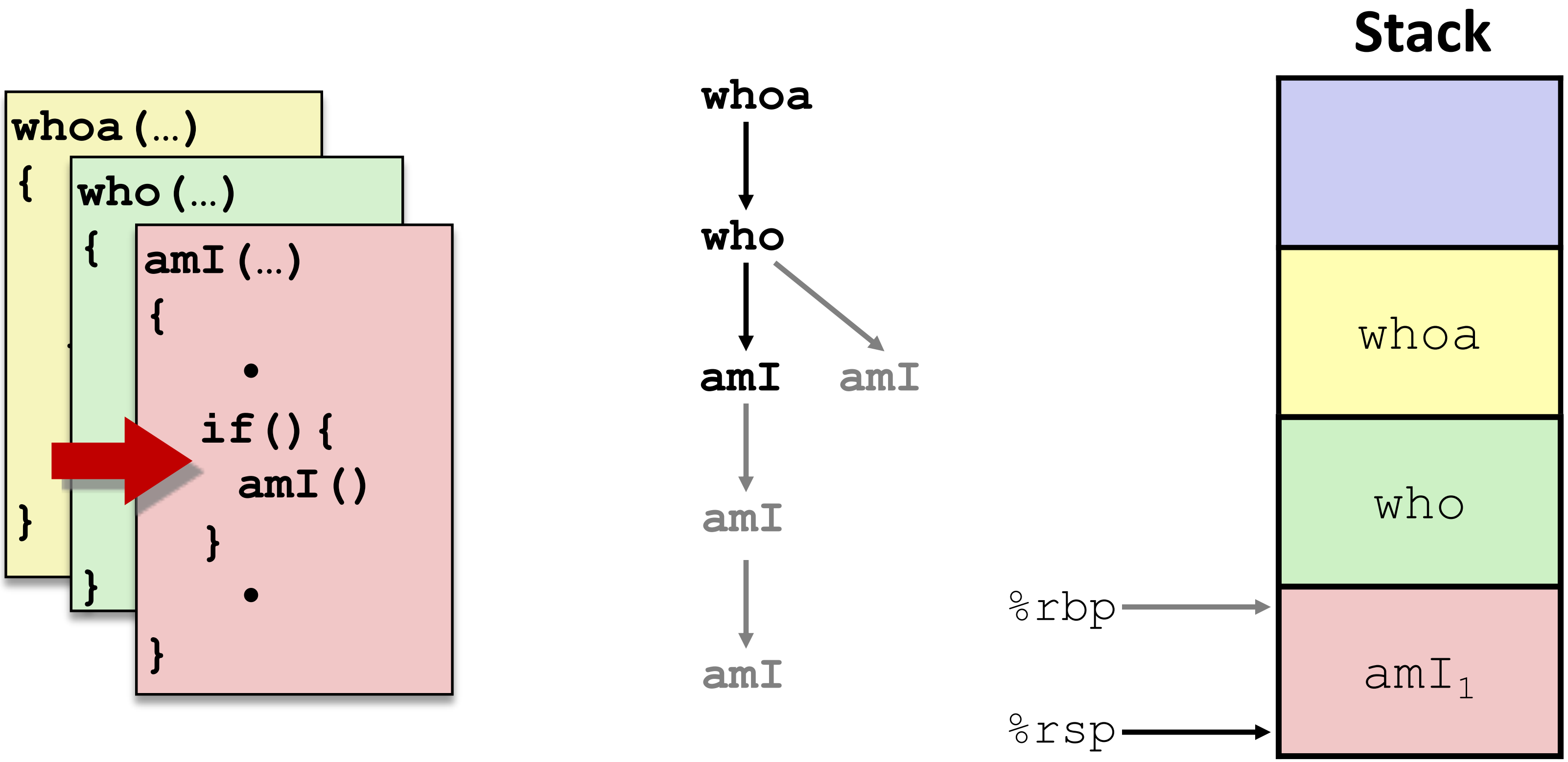
2) Call to who


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

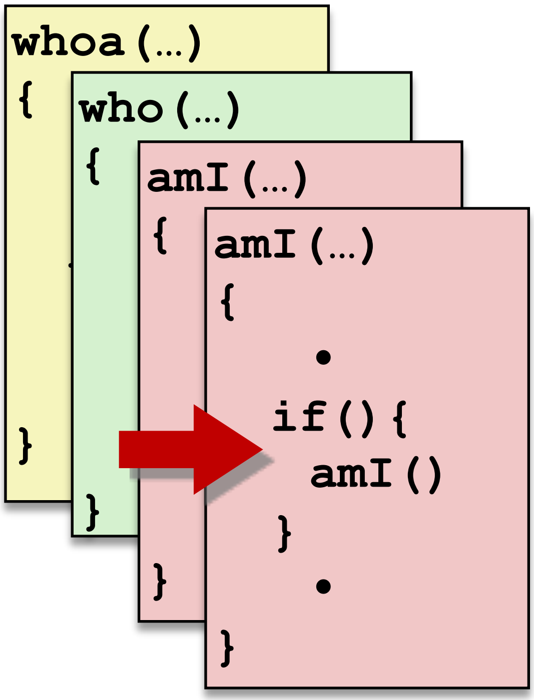

whoa
who
amI
amI
amI
amI

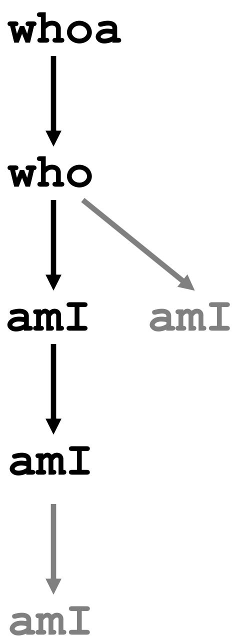

Stack
whoa
who
%rbp
%rsp
"create" frame by moving rsp down

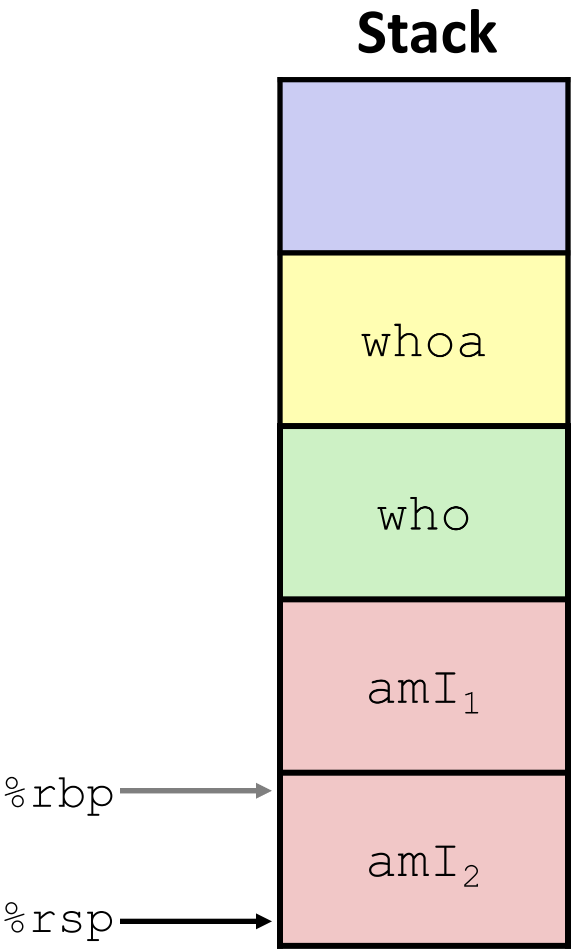
3) Call to amI (1)



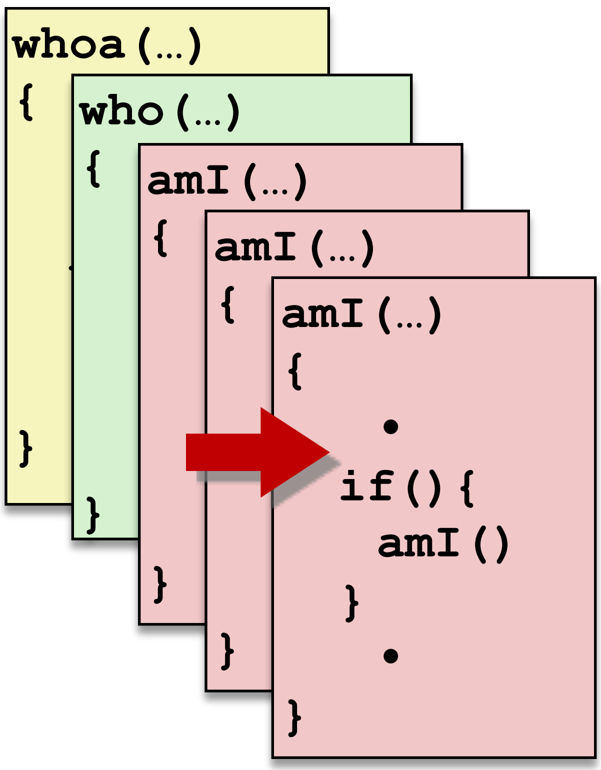
4) Recursive call to amI (2)

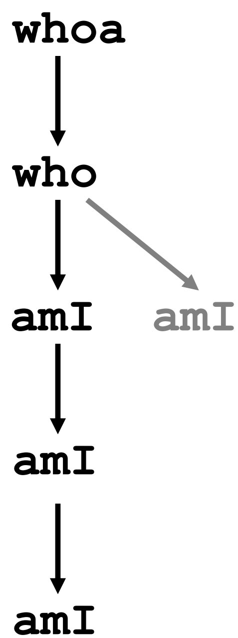




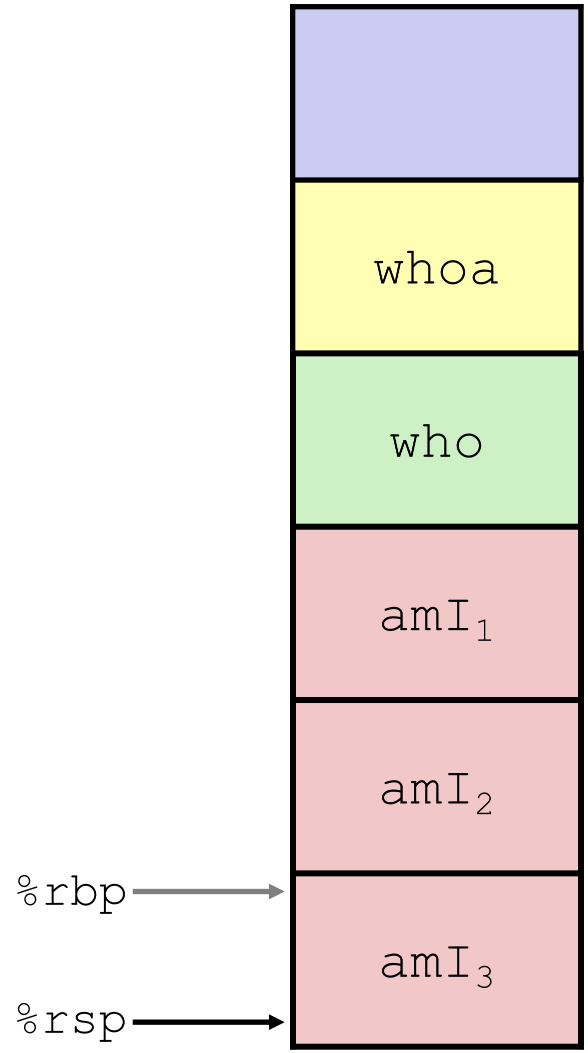


5) (another) Recursive call to amI (3)

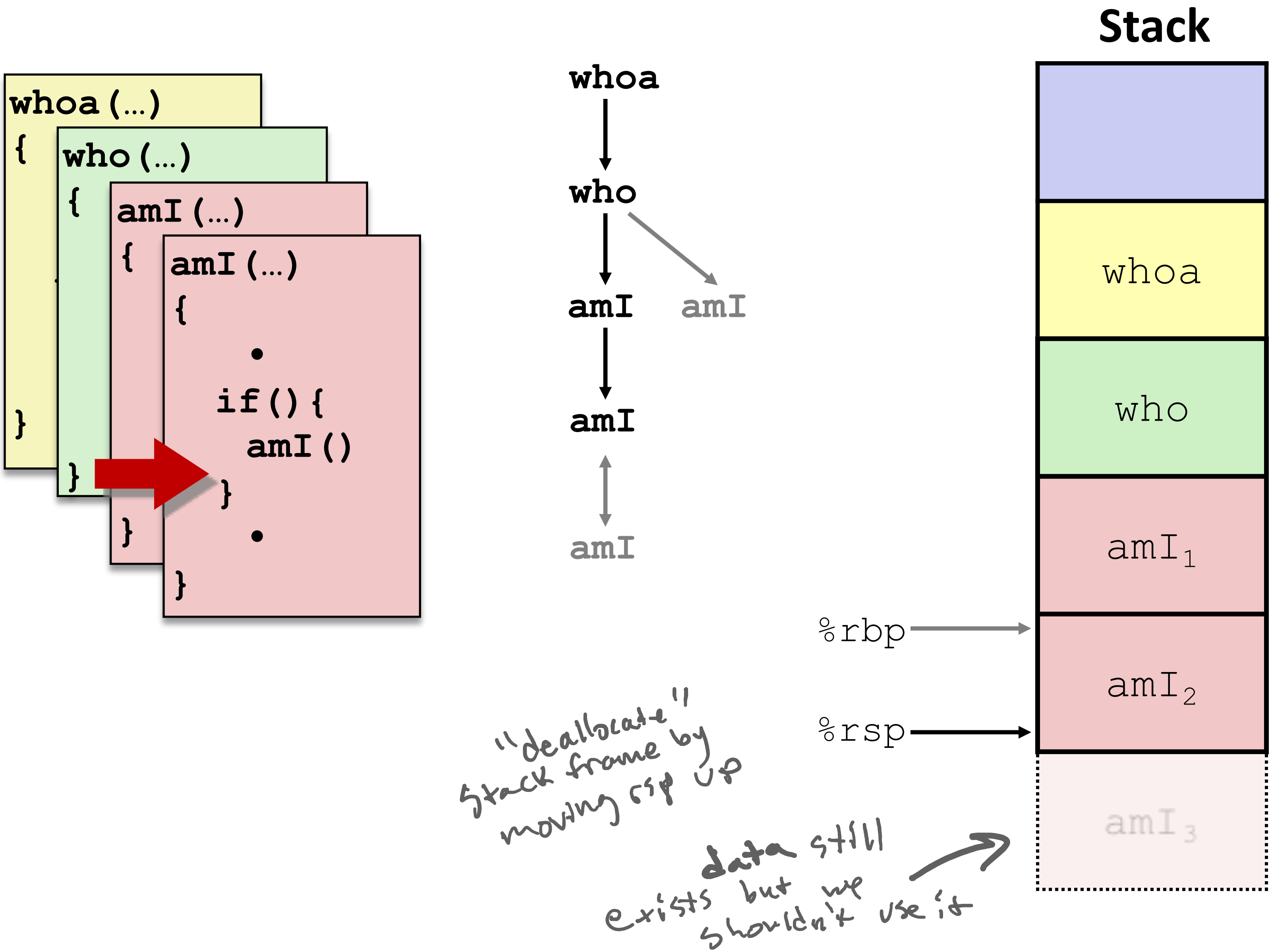




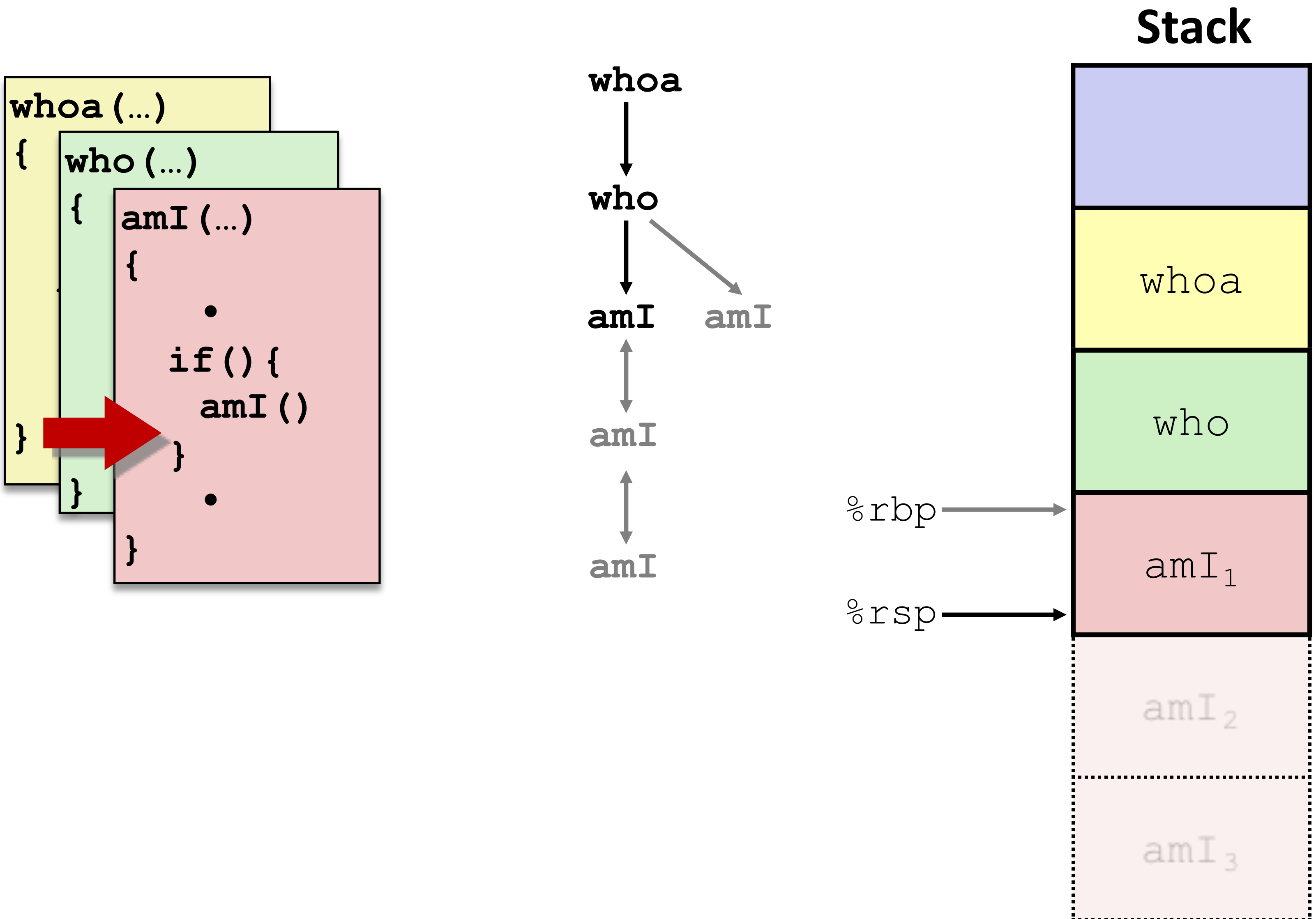
Stack



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

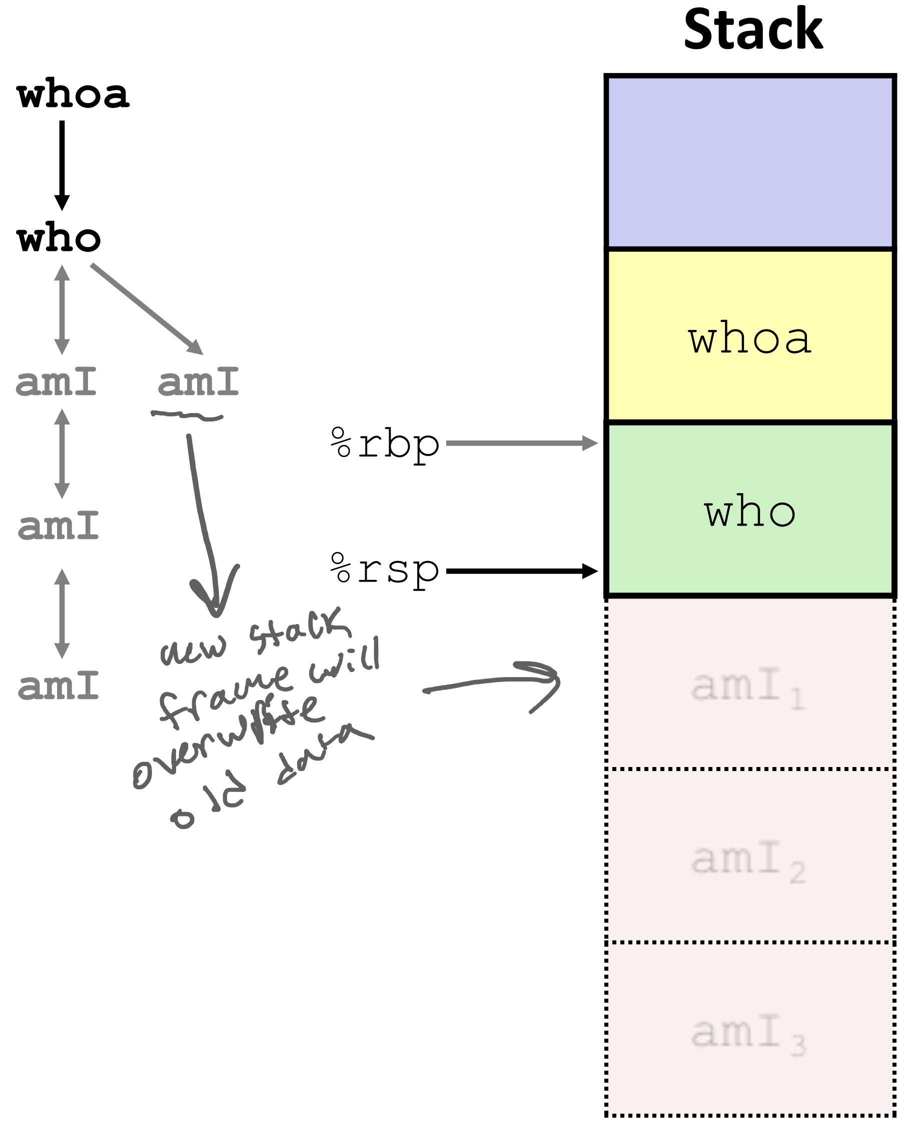


7) Return from recursive call to amI

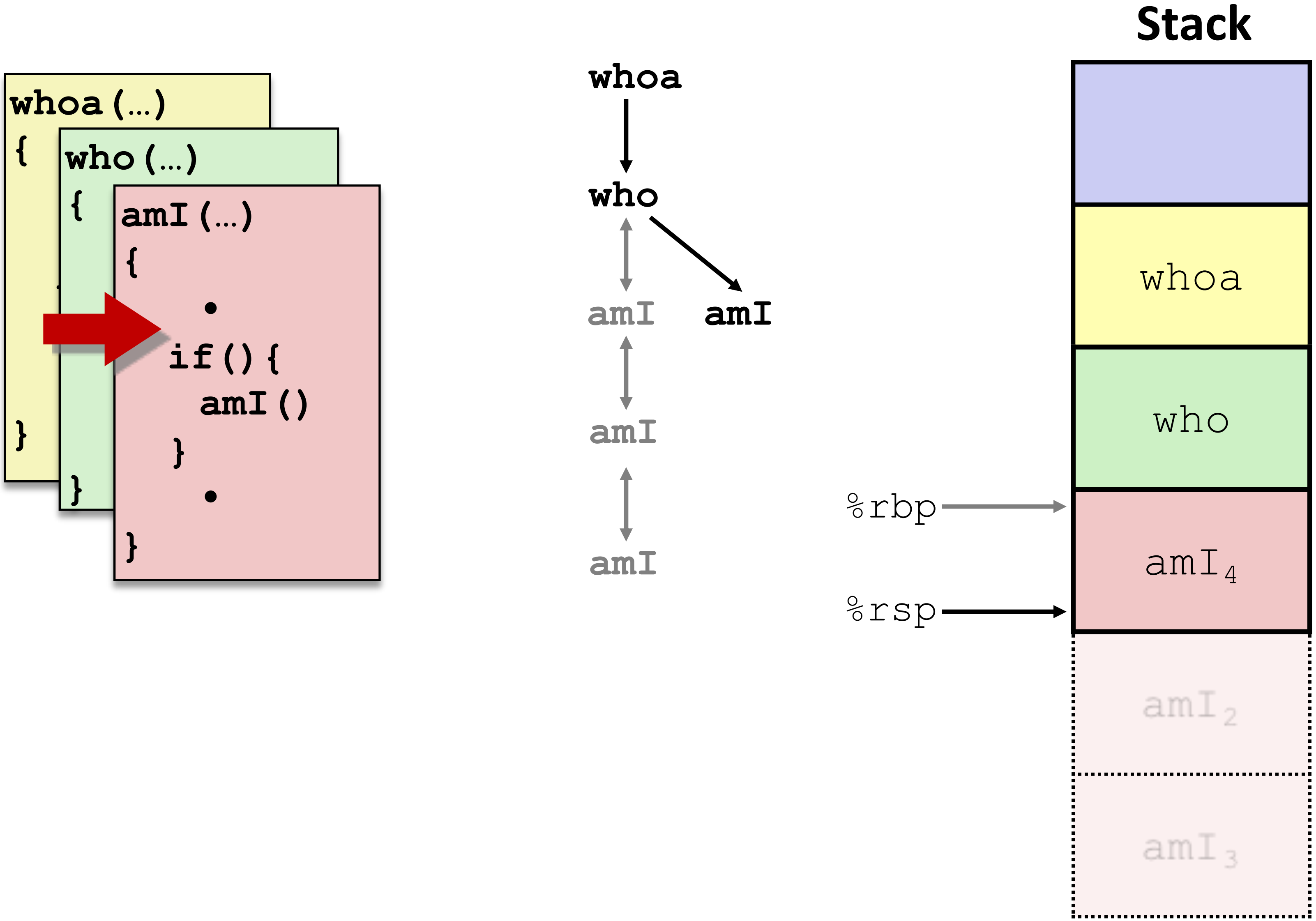


8) Return from call to amI

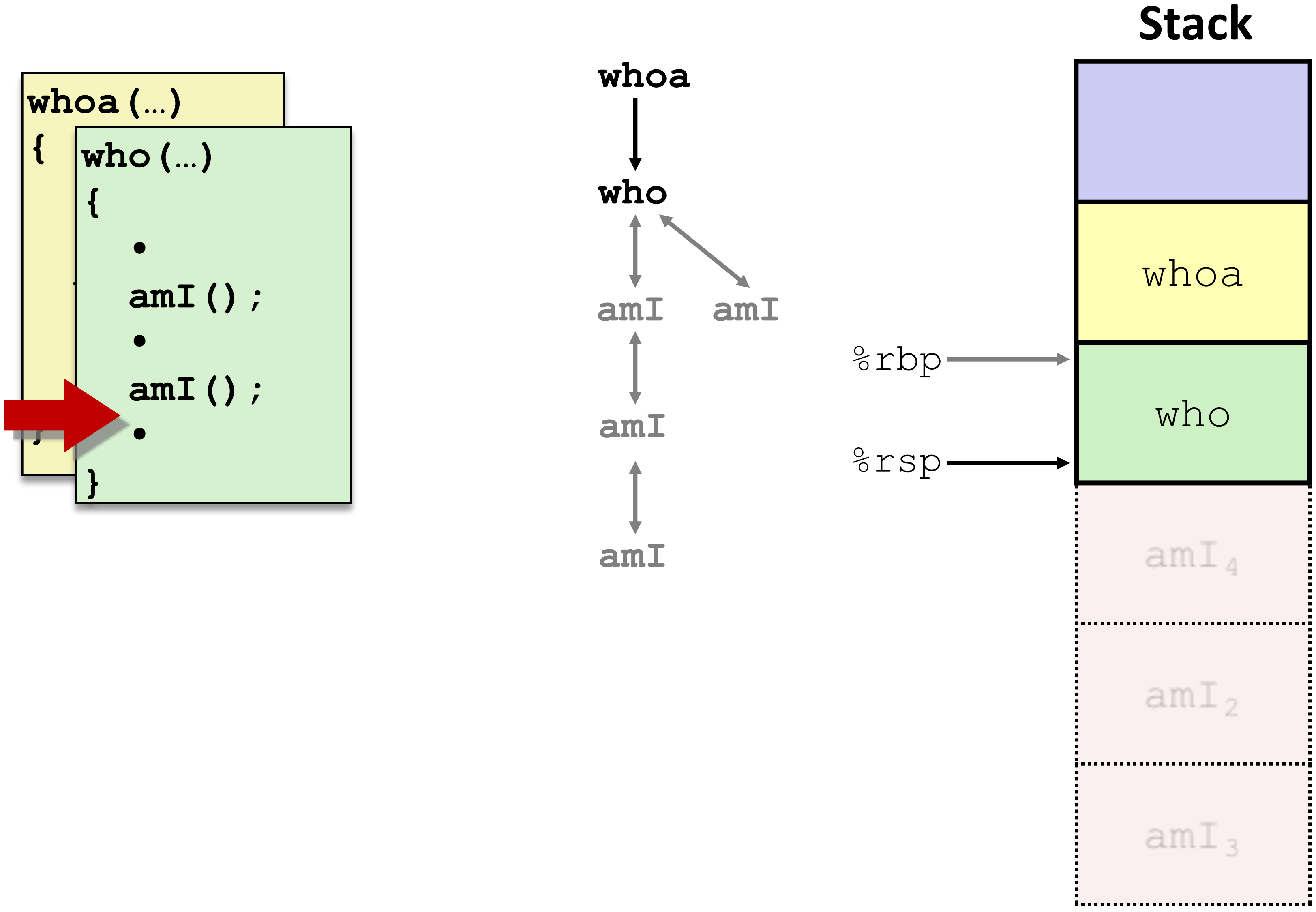
```
whoa(…)
{
  who(…)
  {
    •
    amI();
    •
    amI();
    •
  }
}
```



9) (second) Call to amI (4)

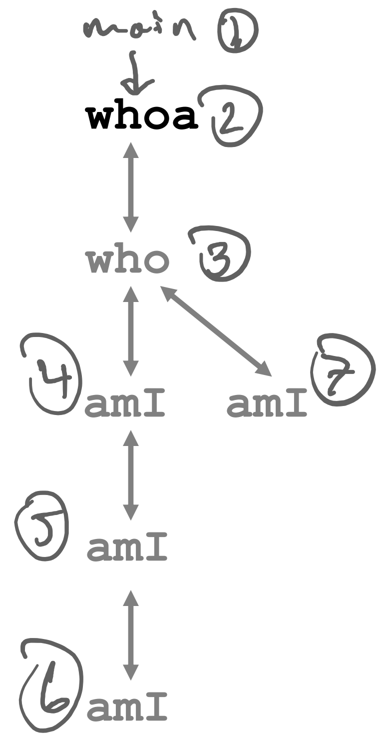


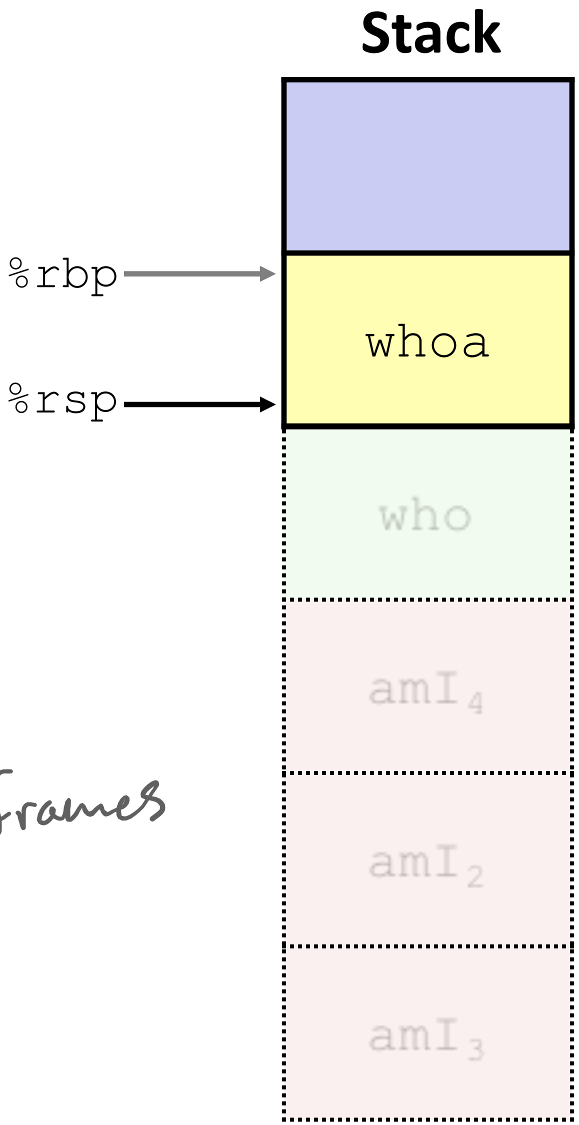
10) Return from (second) call to `amI`



11) Return from call to who

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





Total stack frames created: 7 frames

max stack depth: 6 frames

Polling Question [Proc I – a]

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

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

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

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

Will start here on Friday

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

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

x86-64/Linux Stack Frame

- Caller's Stack Frame
  - Extra arguments (if > 6 args) for this call
- Current/Callee Stack Frame
  - Return address
    - Pushed by `call` instruction
  - Old frame pointer (optional)
  - Saved register context (when reusing registers)
  - Local variables (If can't be kept in registers)
  - "Argument build" area (If callee needs to call another function - parameters for function about to call, if needed)