The Stack & Procedures

CSE 351 Spring 2021

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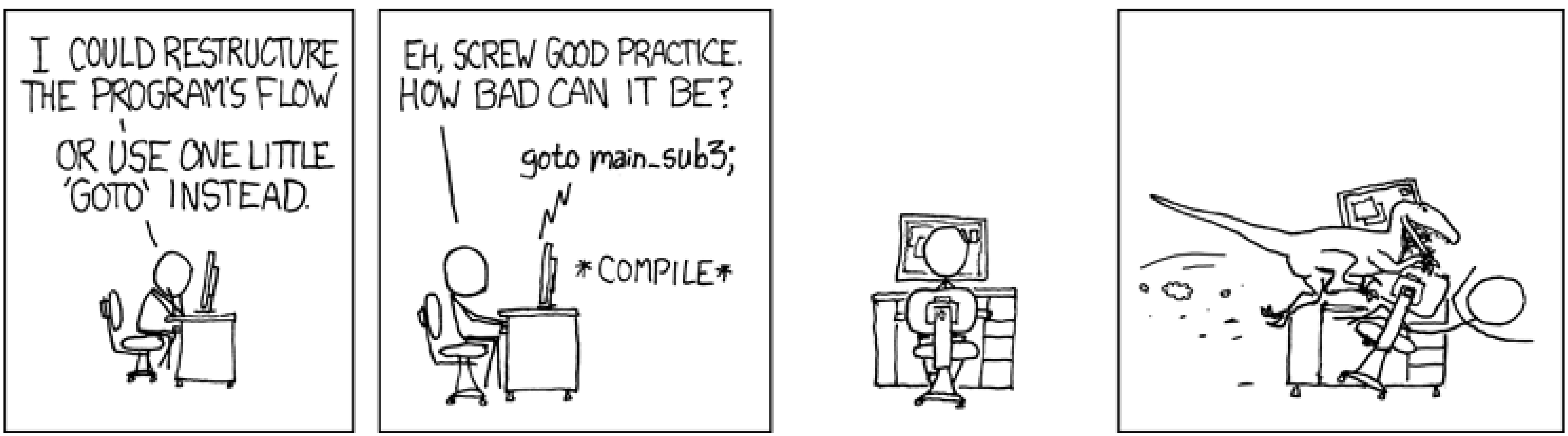


http://xkcd.com/571/

Administrivia

- Unit Summary #1 due this Friday (4/23) on Gradescope
  - 3 Tasks – separate submission for each task
- Lab 2 (x86-64) due next Friday (4/30)
  - Learn to read x86-64 assembly and use GDB
  - Optional GDB Tutorial on Ed Lessons
- **Questions Docs**: Use @uw google account to access!!
  - https://tinyurl.com/CSE351-21sp-Questions

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:

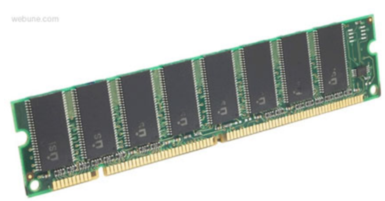
```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

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

Review Questions

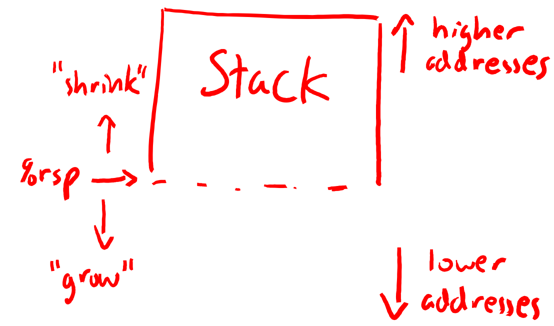
- How does the stack change after executing the following instructions?

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

add to stack — 8B — # grow 8 B

lower address — 0x18 = 24 — # grow 24 B

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

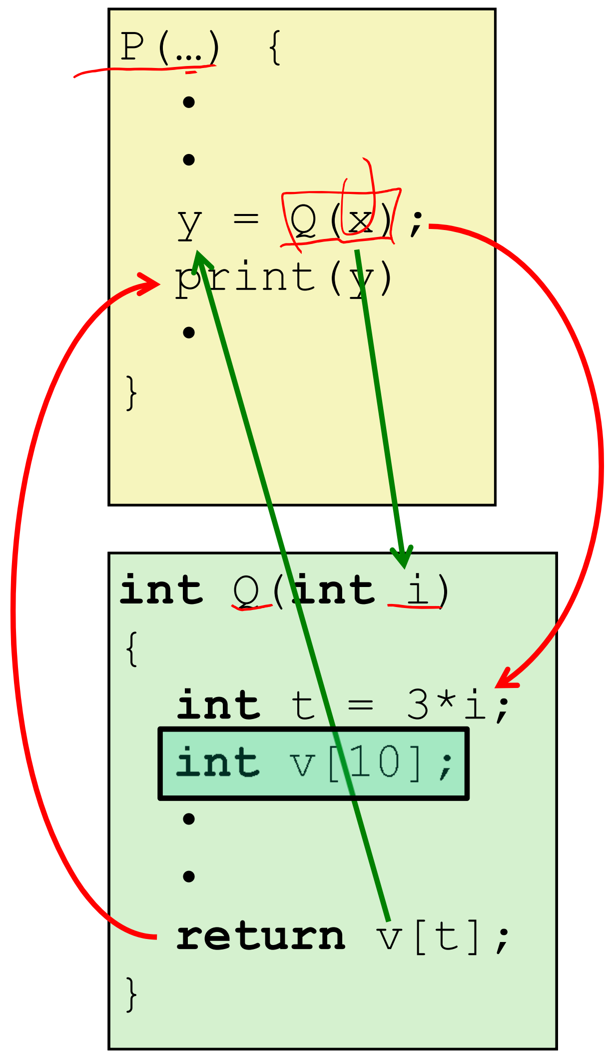
%rsp changed by call & ret

%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

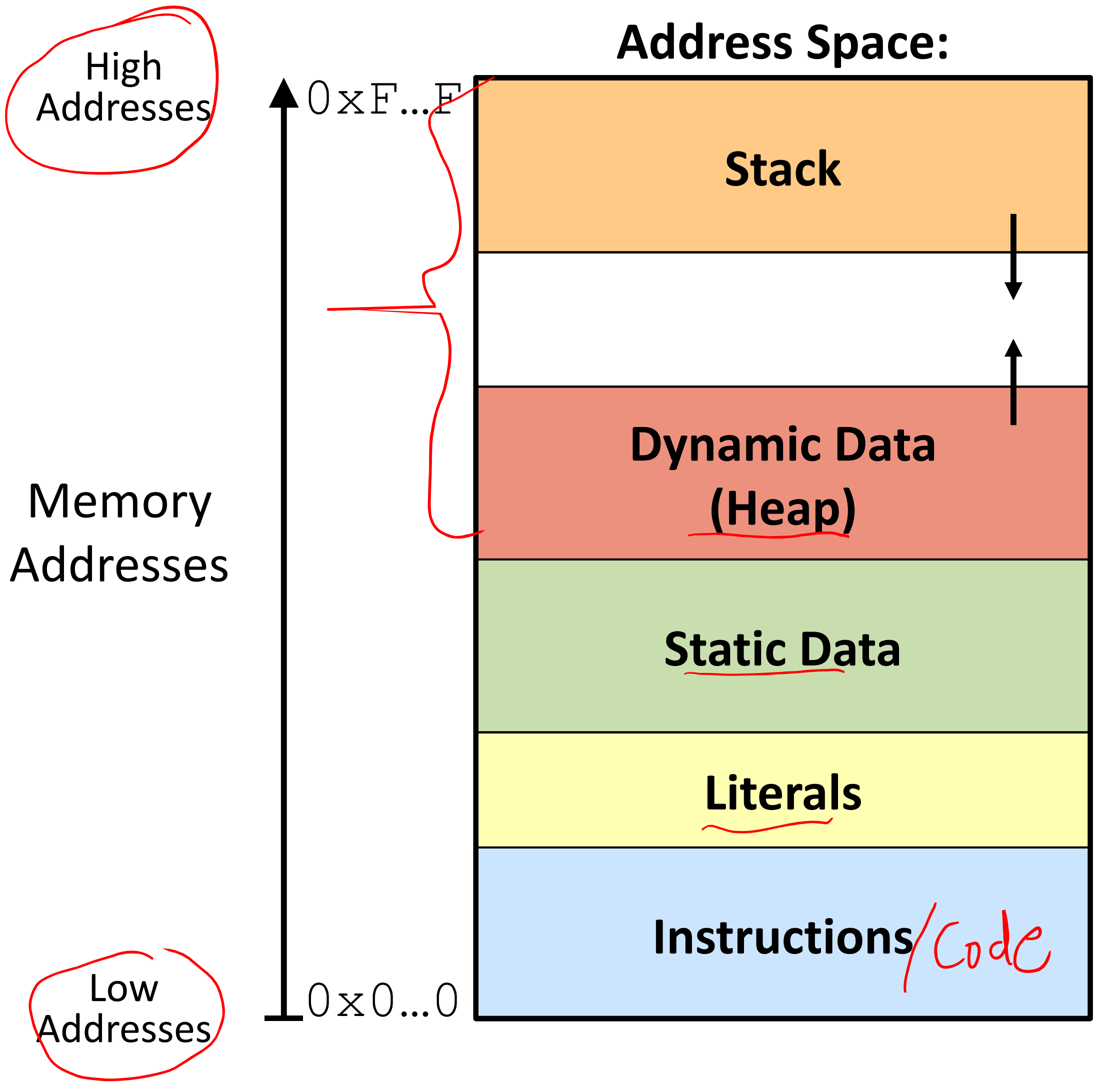
- All implemented with machine instructions!
  - An x86-64 procedure uses only those mechanisms required for that procedure



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

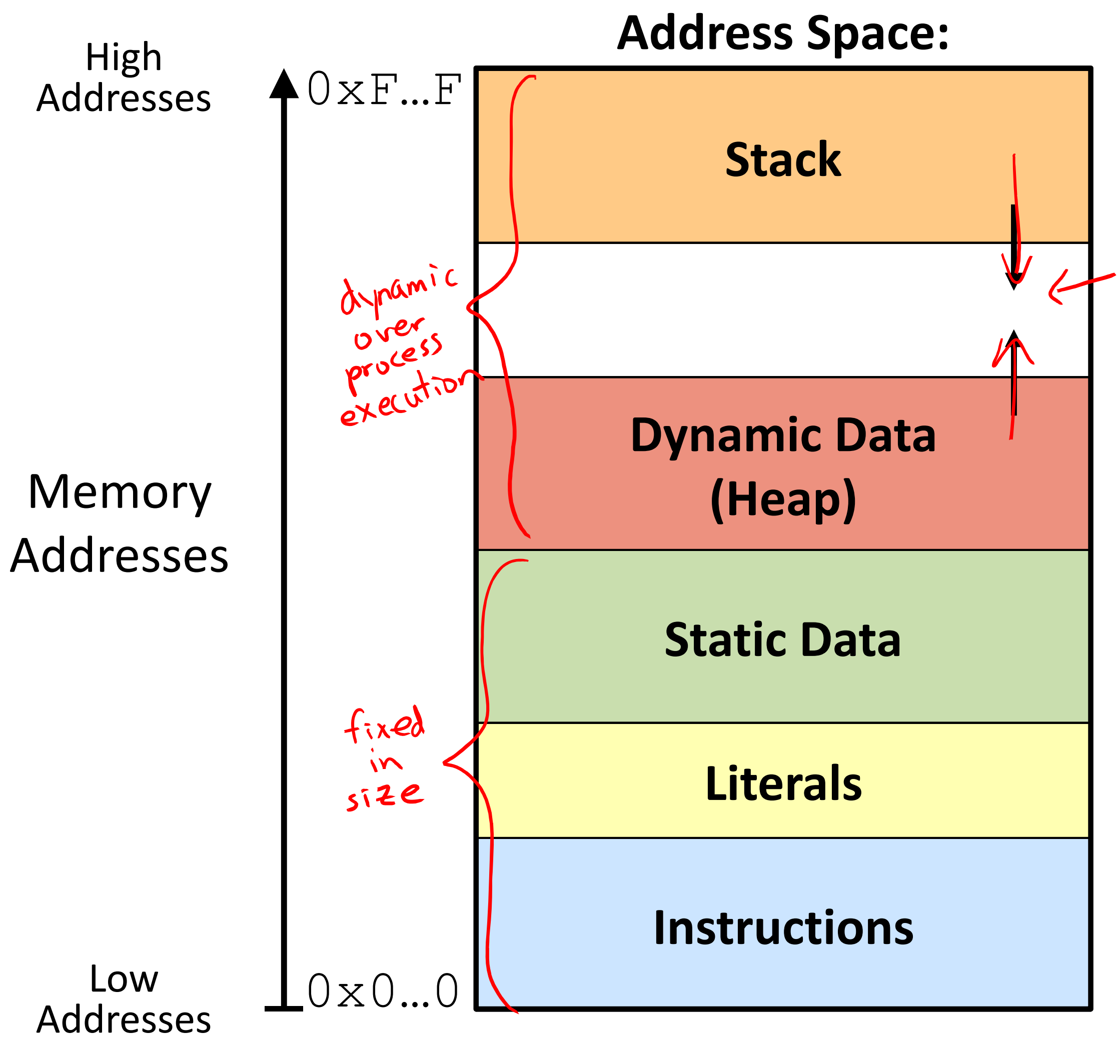
variables allocated with `new` or `malloc`

static variables (including global variables)

large literals/constants (*e.g.* “example”)

program code

Memory Management



Who's Responsible:

Managed "automatically" (by compiler/assembly)

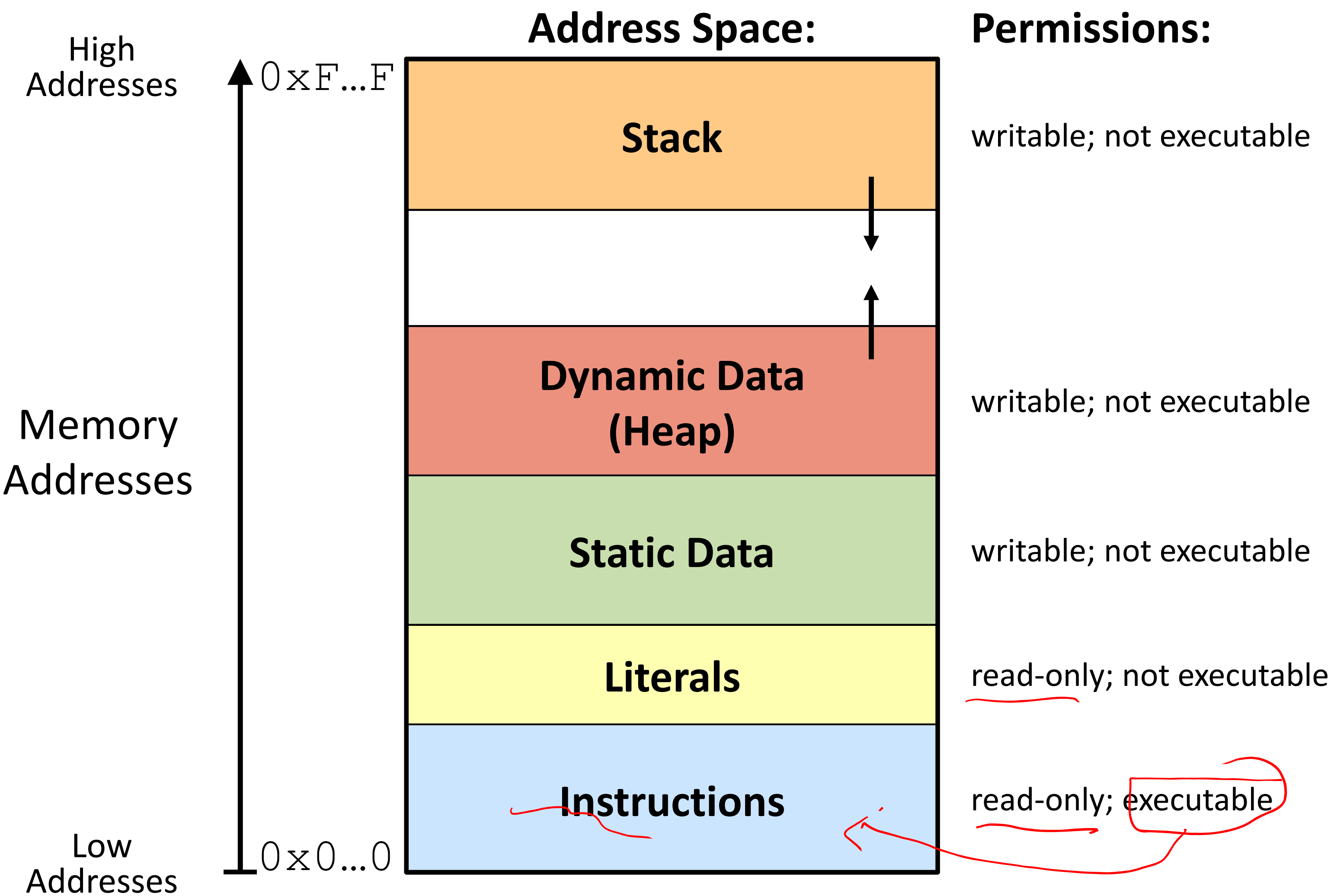
Managed "dynamically" (by programmer)

Managed "statically" (initialized when process starts)

Managed "statically" (initialized when process starts)

Managed "statically" (initialized when process starts)

Memory Permissions

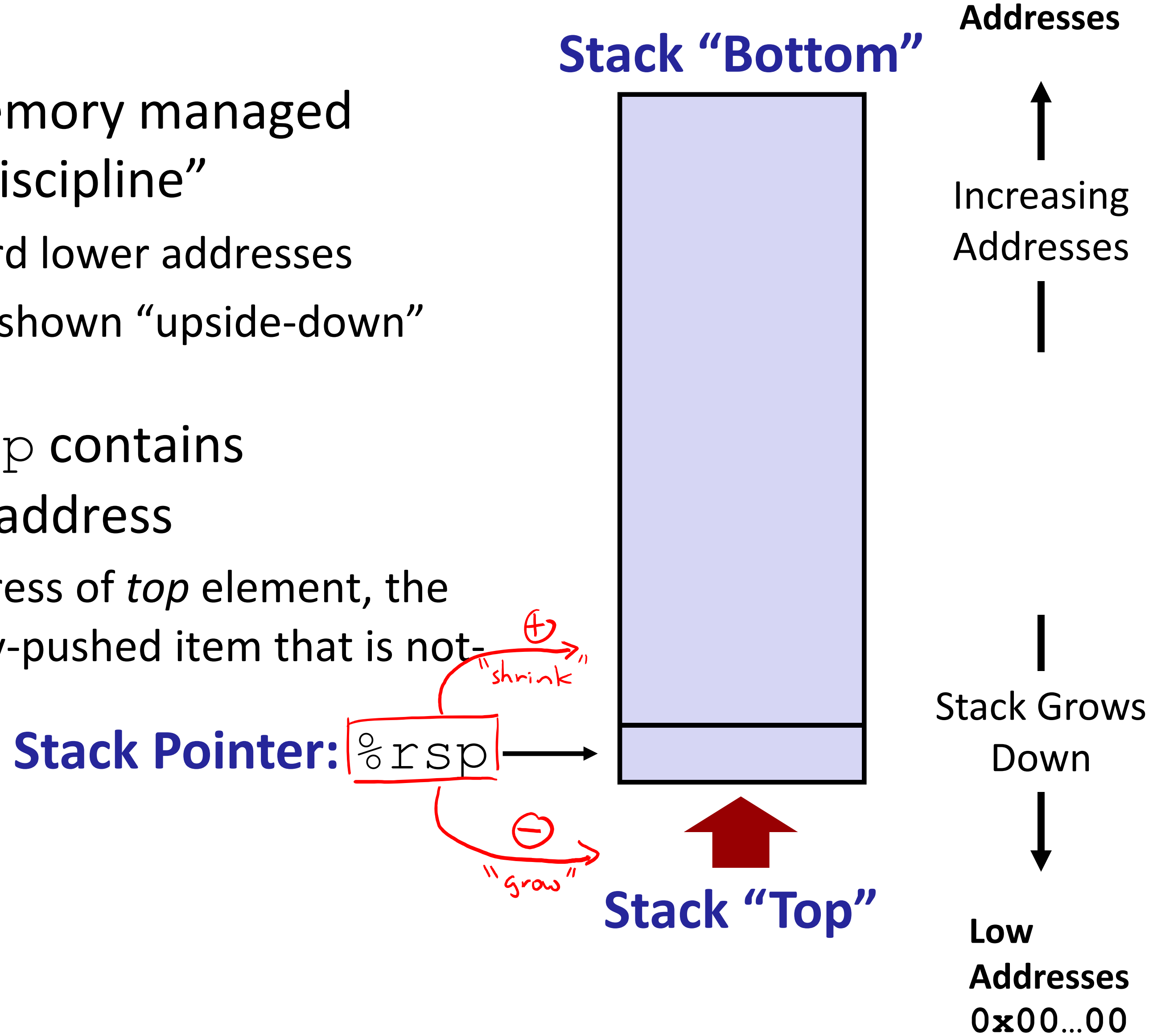


- Segmentation faults: impermissible memory access

x86-64 Stack

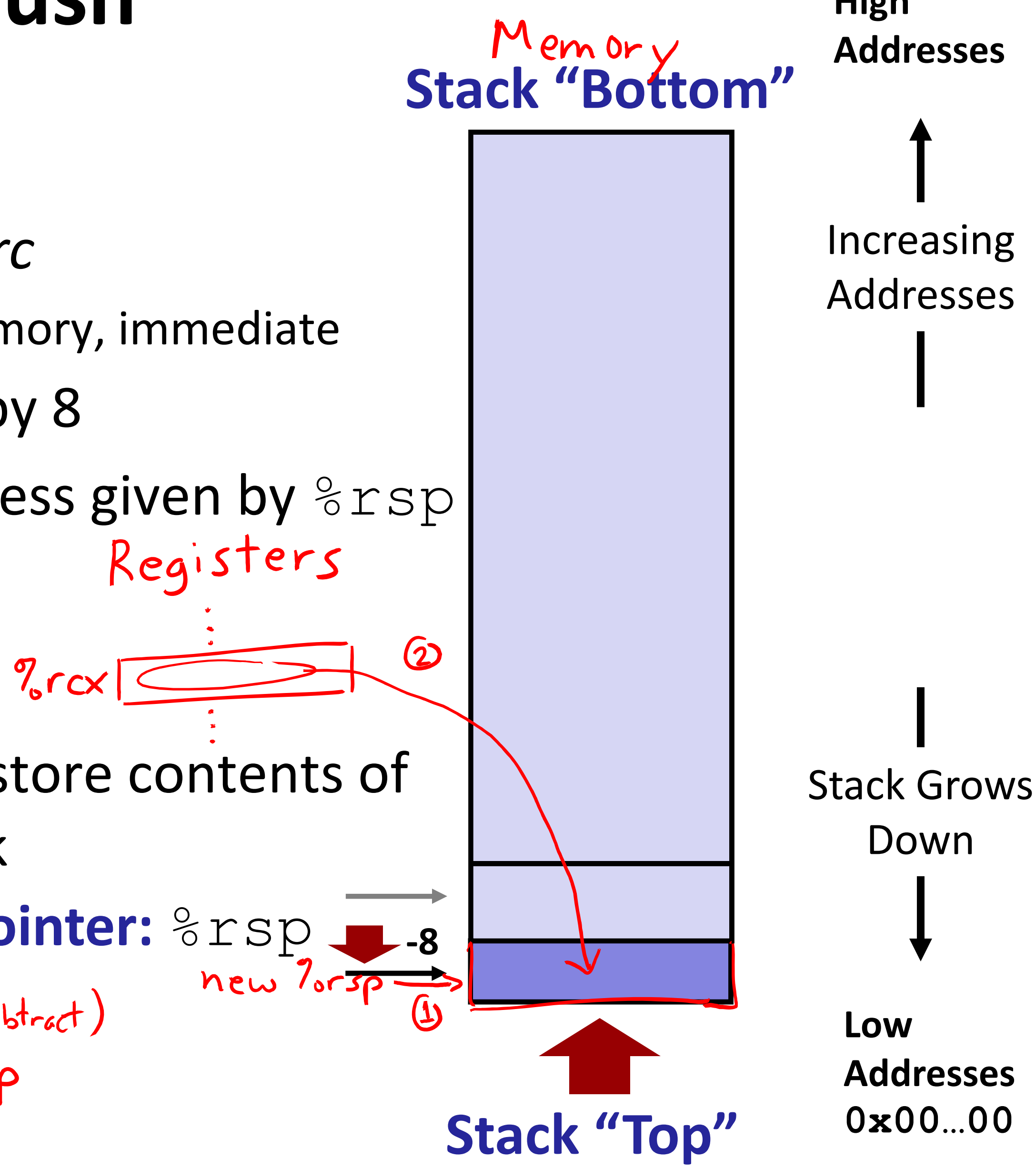
Last In, First Out (LIFO)

- 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*
  (size specifier)
  - 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

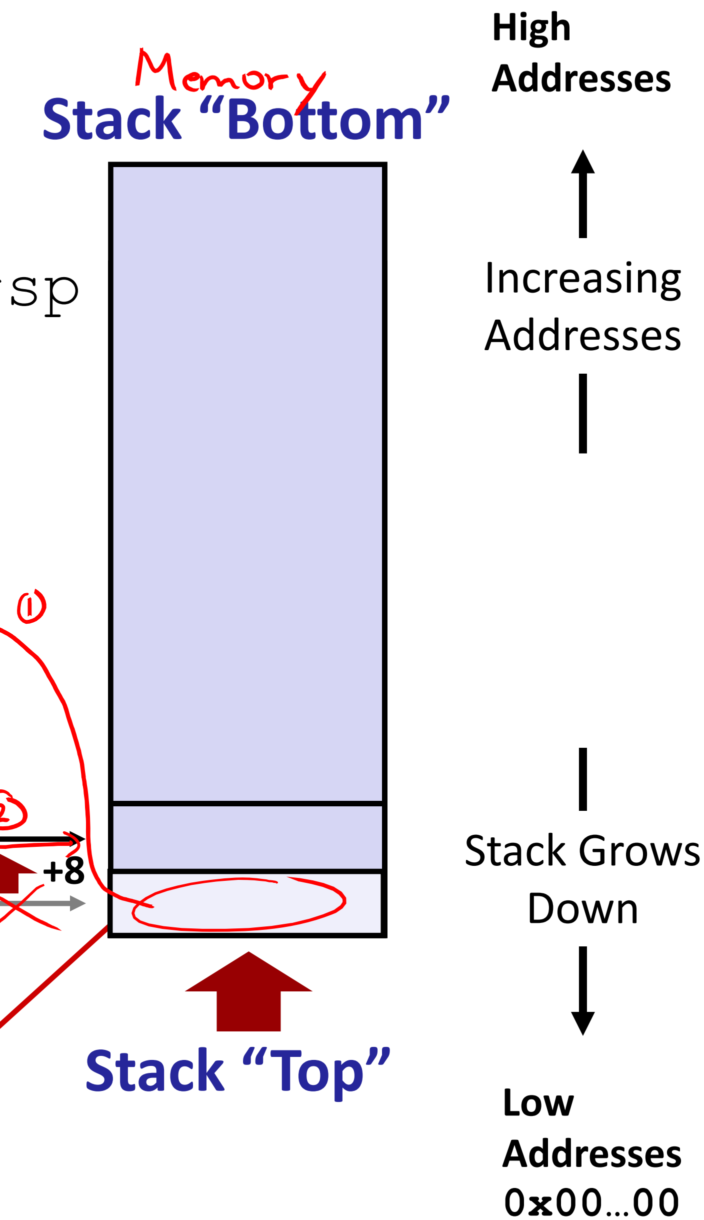


① move %rsp down (subtract)
② store src at %rsp

x86-64 Stack: Pop

- `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`

Stack Pointer: `%rsp` +8

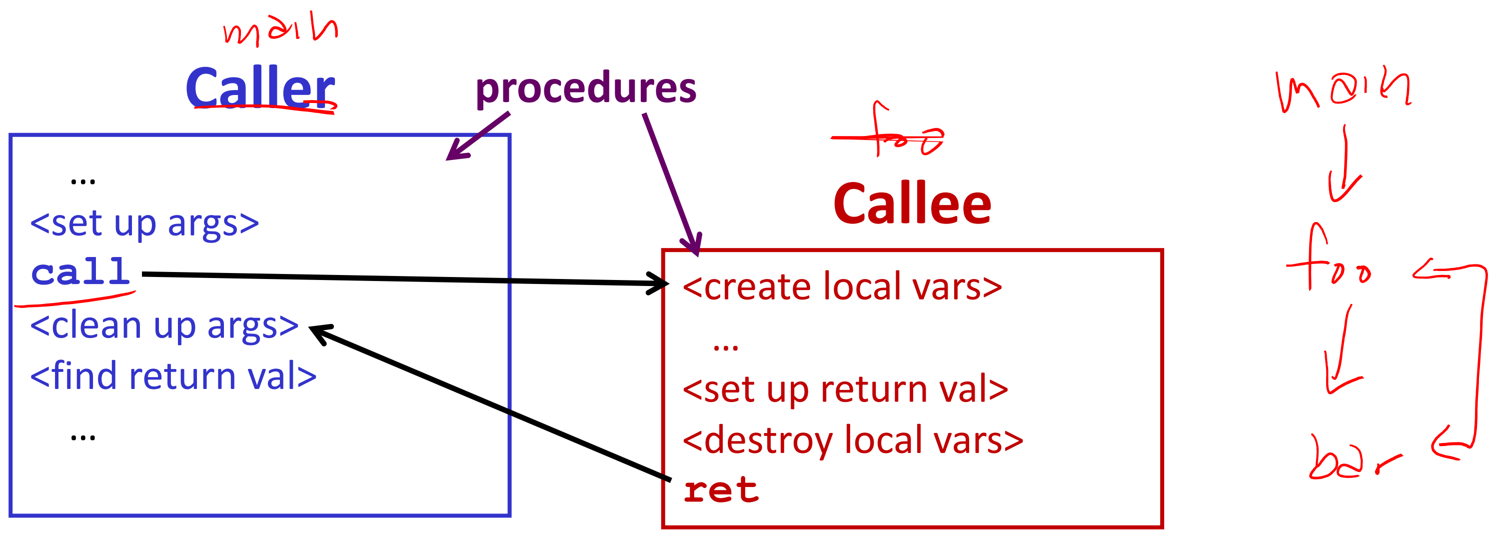


Those bits are still there; we're just not using them.

Procedures

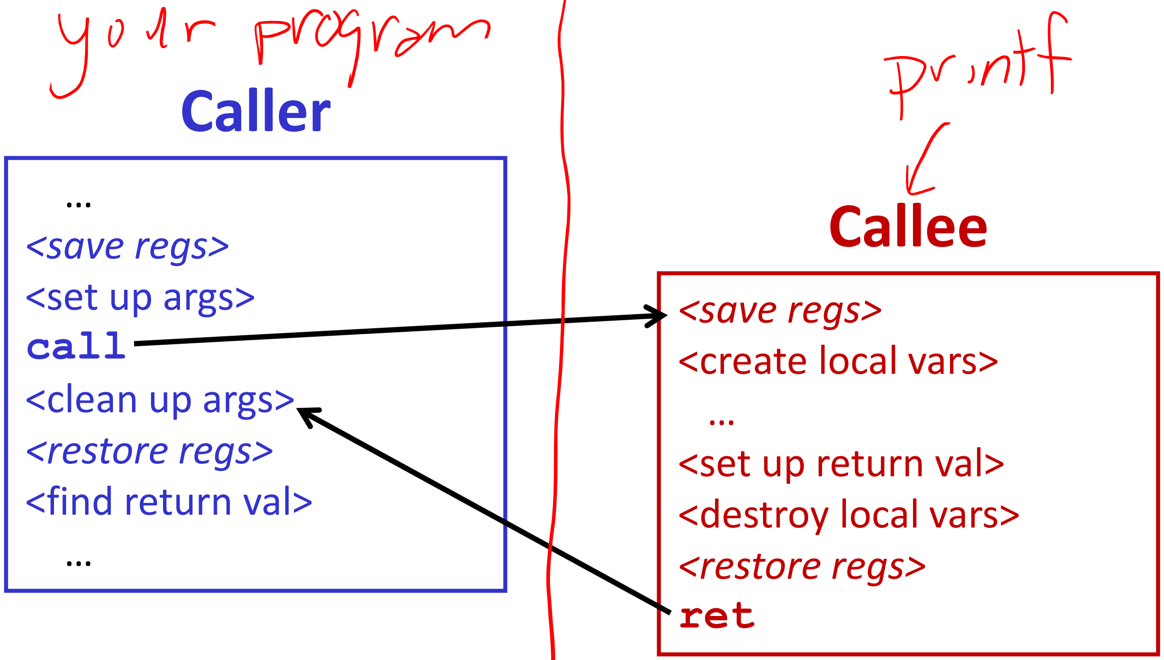
- Stack Structure
- **Calling Conventions**
  - **Passing control**
  - Passing data
  - Managing local data
- Register Saving Conventions
- Illustration of Recursion

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)

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

Caller

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

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

- 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

- 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`**

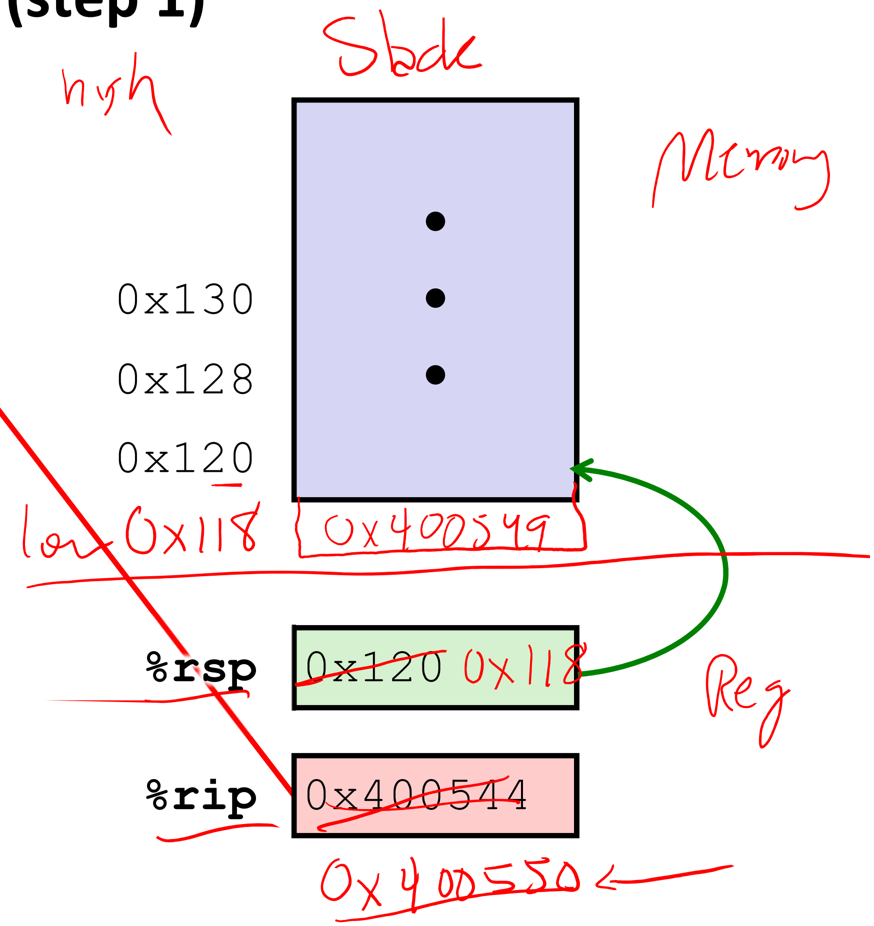
next instruction happens to be a move, but could be anything

- Procedure return: `ret` (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
```

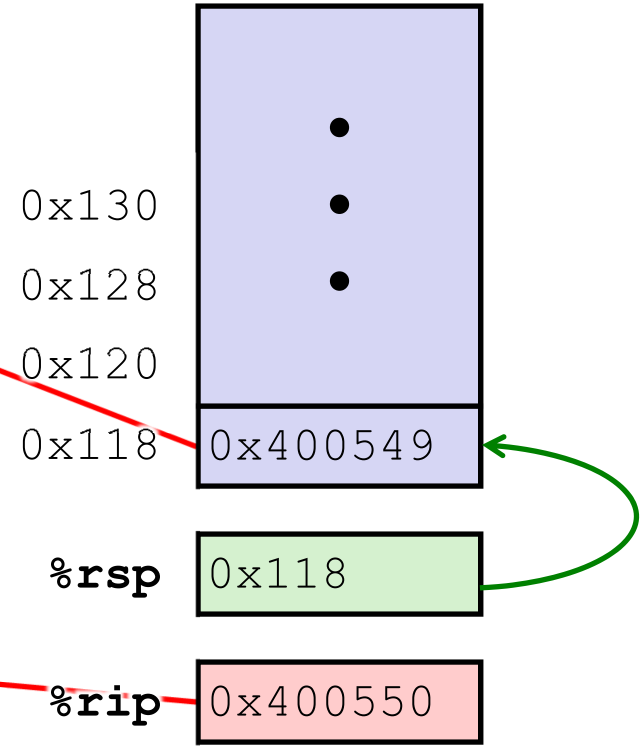


① push ret addr on stack
② jump to label

Procedure Call Example (step 2)

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

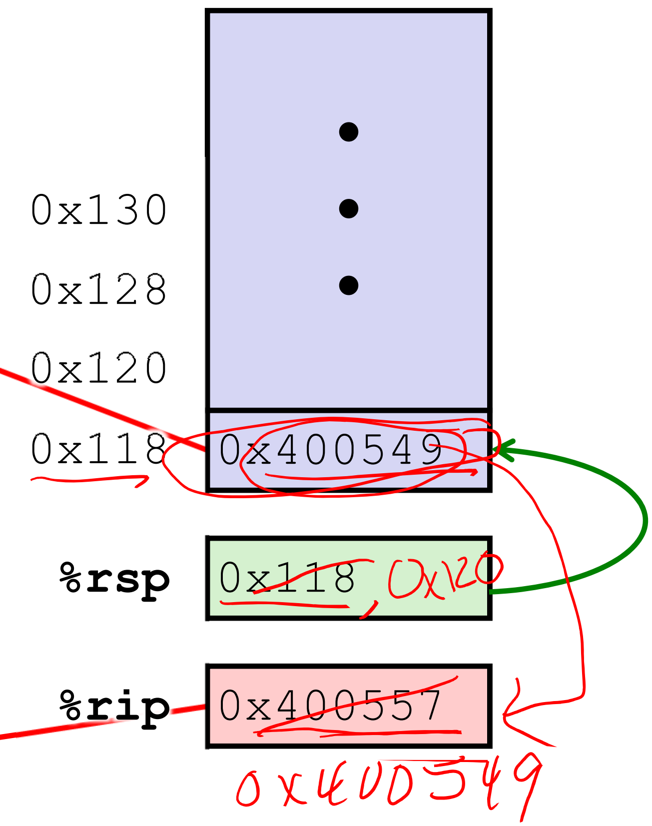
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



Procedure Return Example (step 1)

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

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

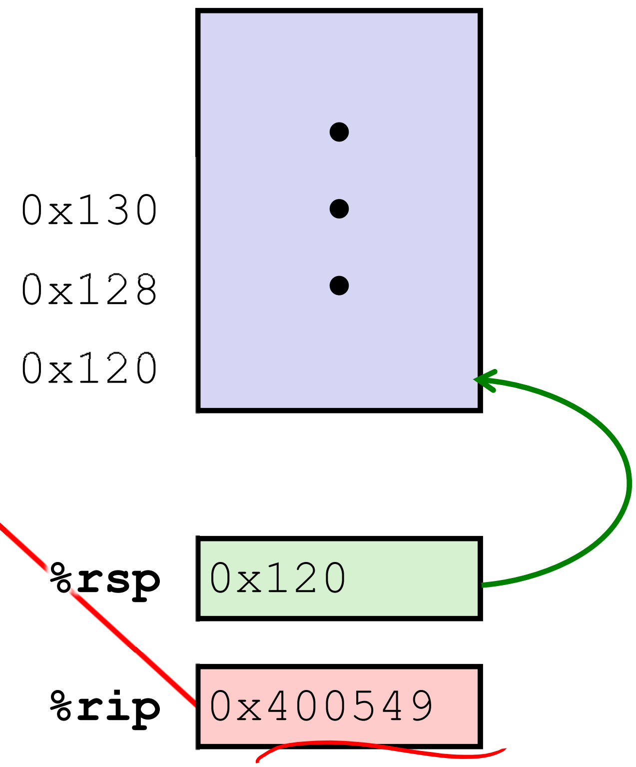


(1) pop ret addr off stack
(2) jump to ret addr

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
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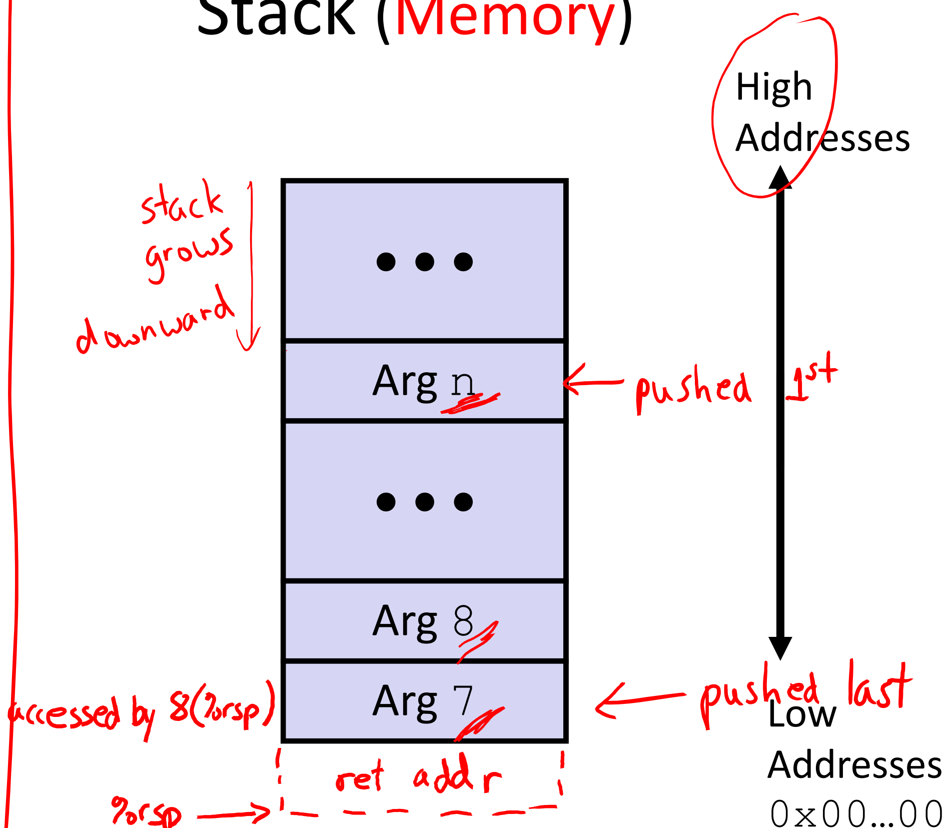
Procedure Data Flow

Registers (NOT in Memory)

- First 6 arguments
  1. `%rdi` — *Diane's*
  2. `%rsi` — *Silk*
  3. `%rdx` — *Dress*
  4. `%rcx` — *Costs*
  5. `%r8` — *$8 9*
  6. `%r9`
- 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
```

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

(will explain later)

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();
    •
}
```

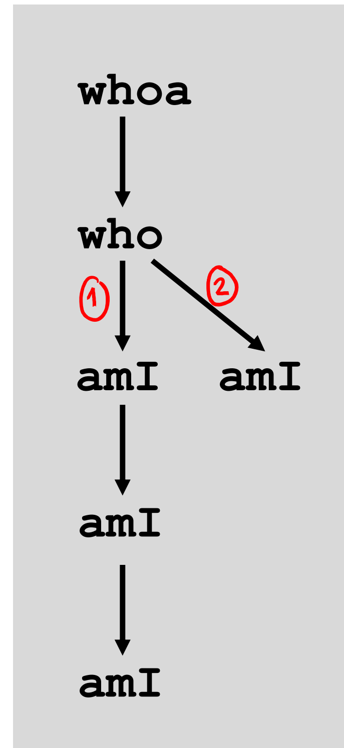
1st call recurses twice

2nd call doesn't recurse

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

based on condition

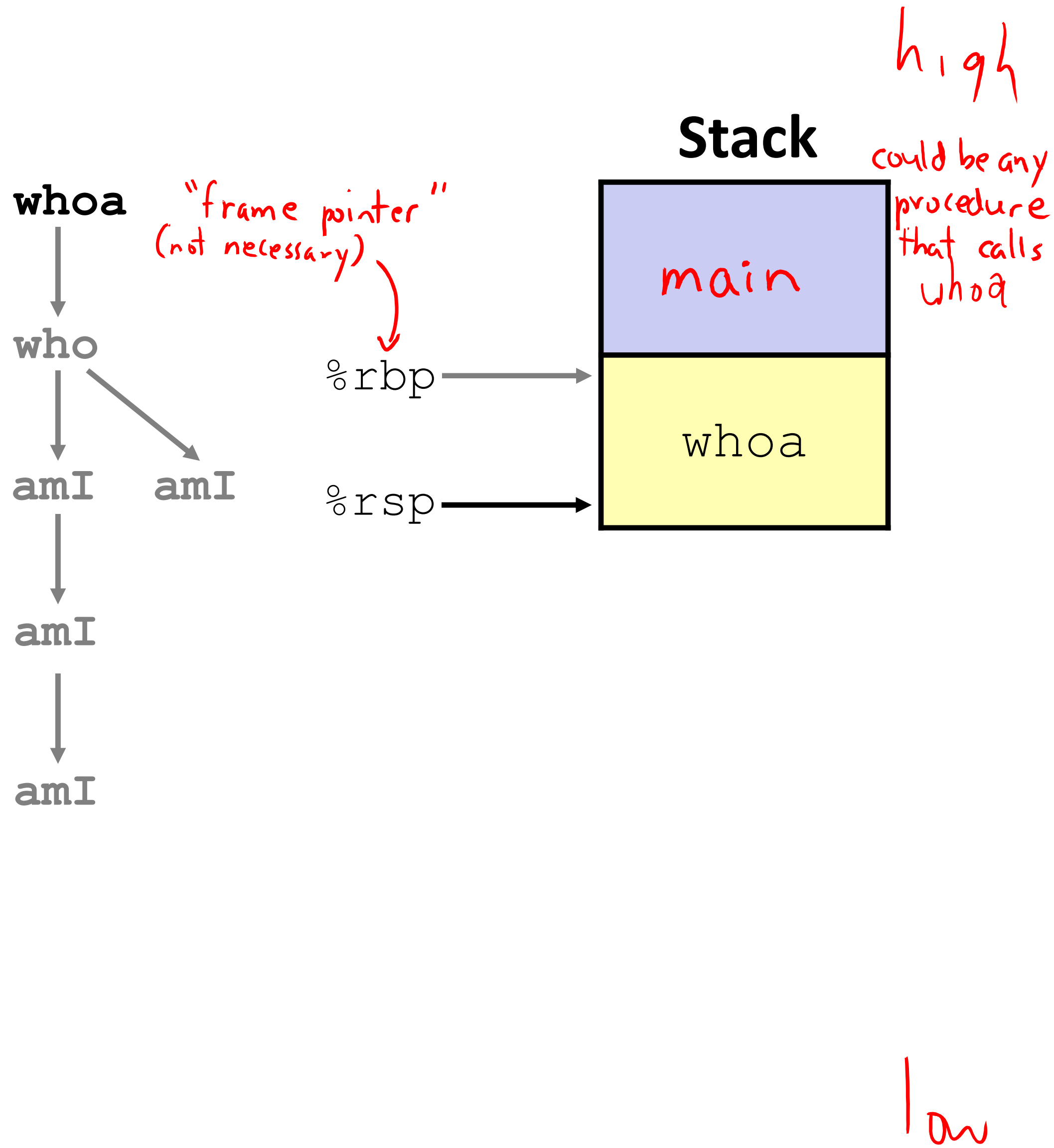
Example
Call Chain



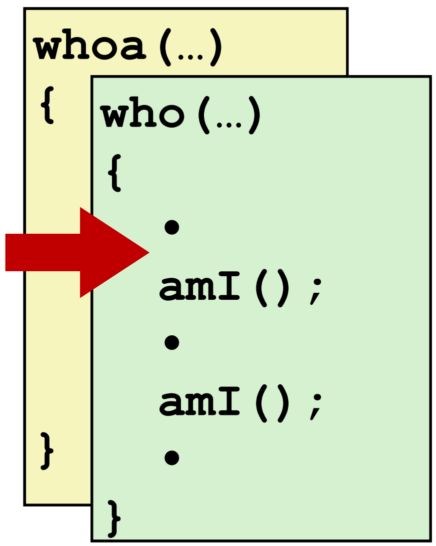
Procedure `amI` is recursive (calls itself)

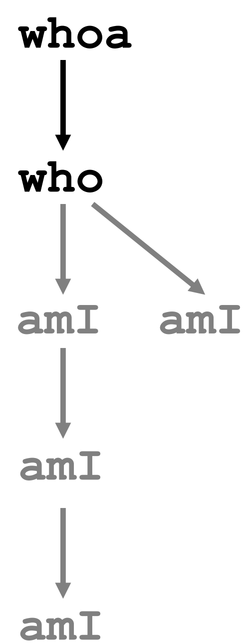
1) Call to whoa

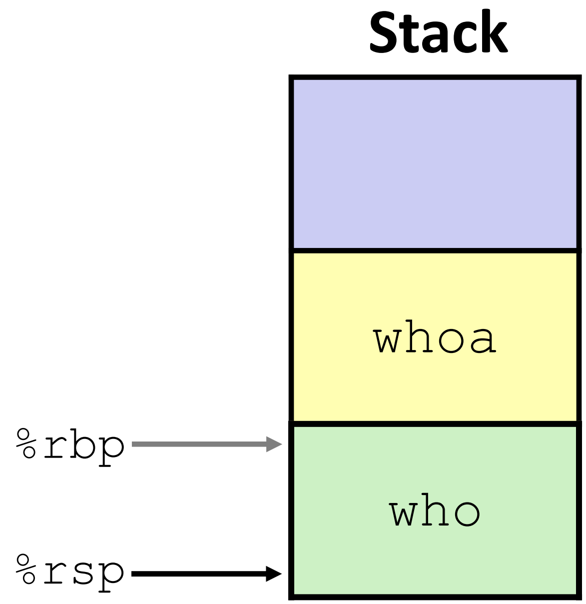
```
whoa(…)
{
    •
    •
    who();
    •
    •
}
```



2) Call to who

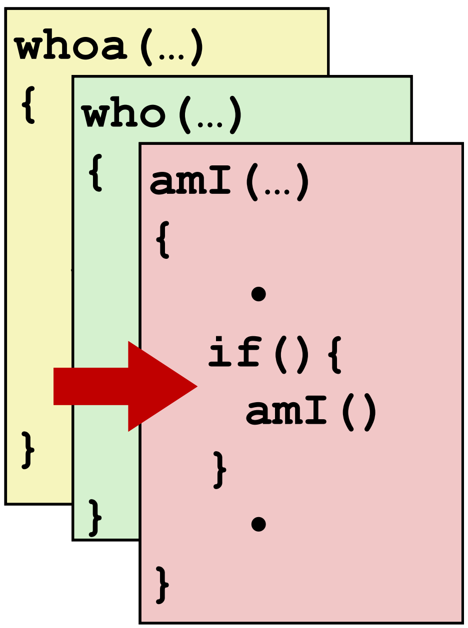


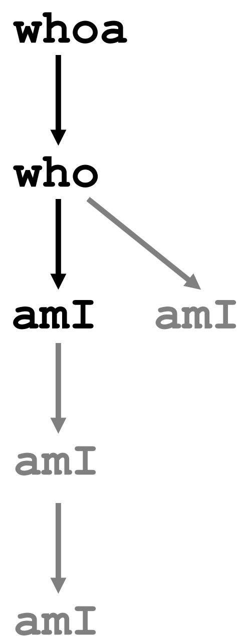


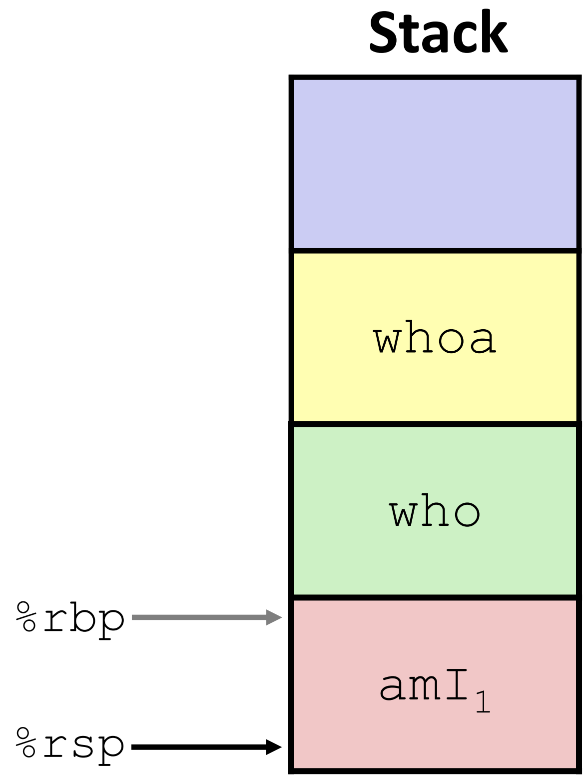


"create" frame
by manipulating %rsp

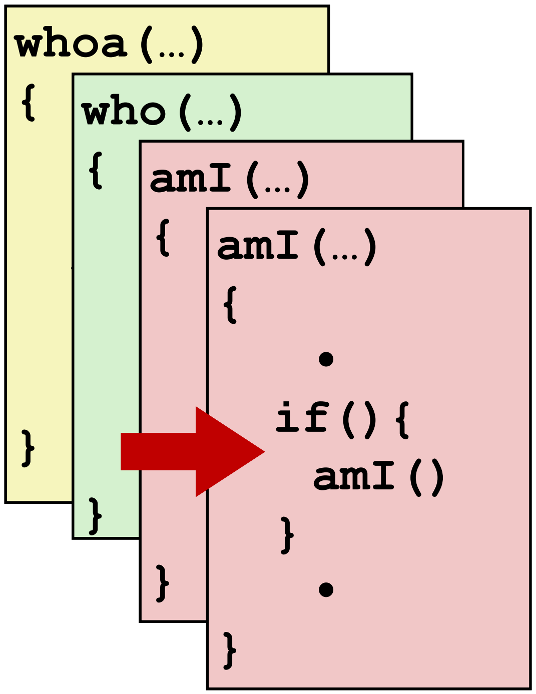
3) Call to amI (1)

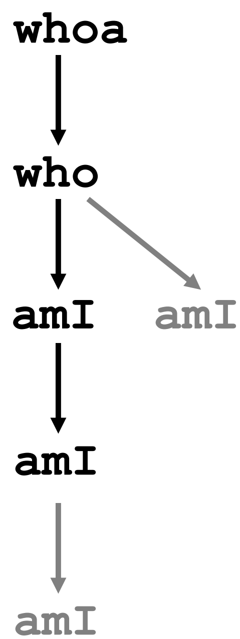


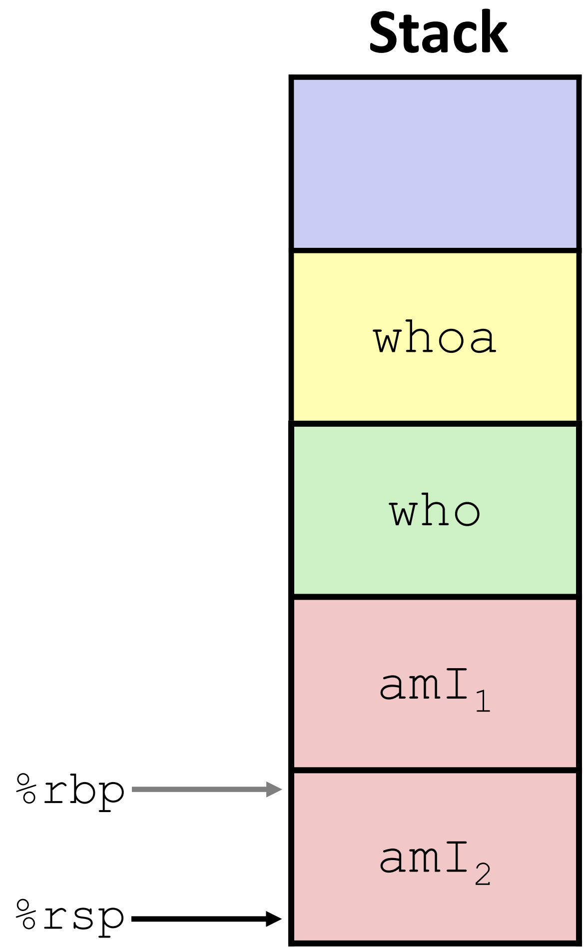




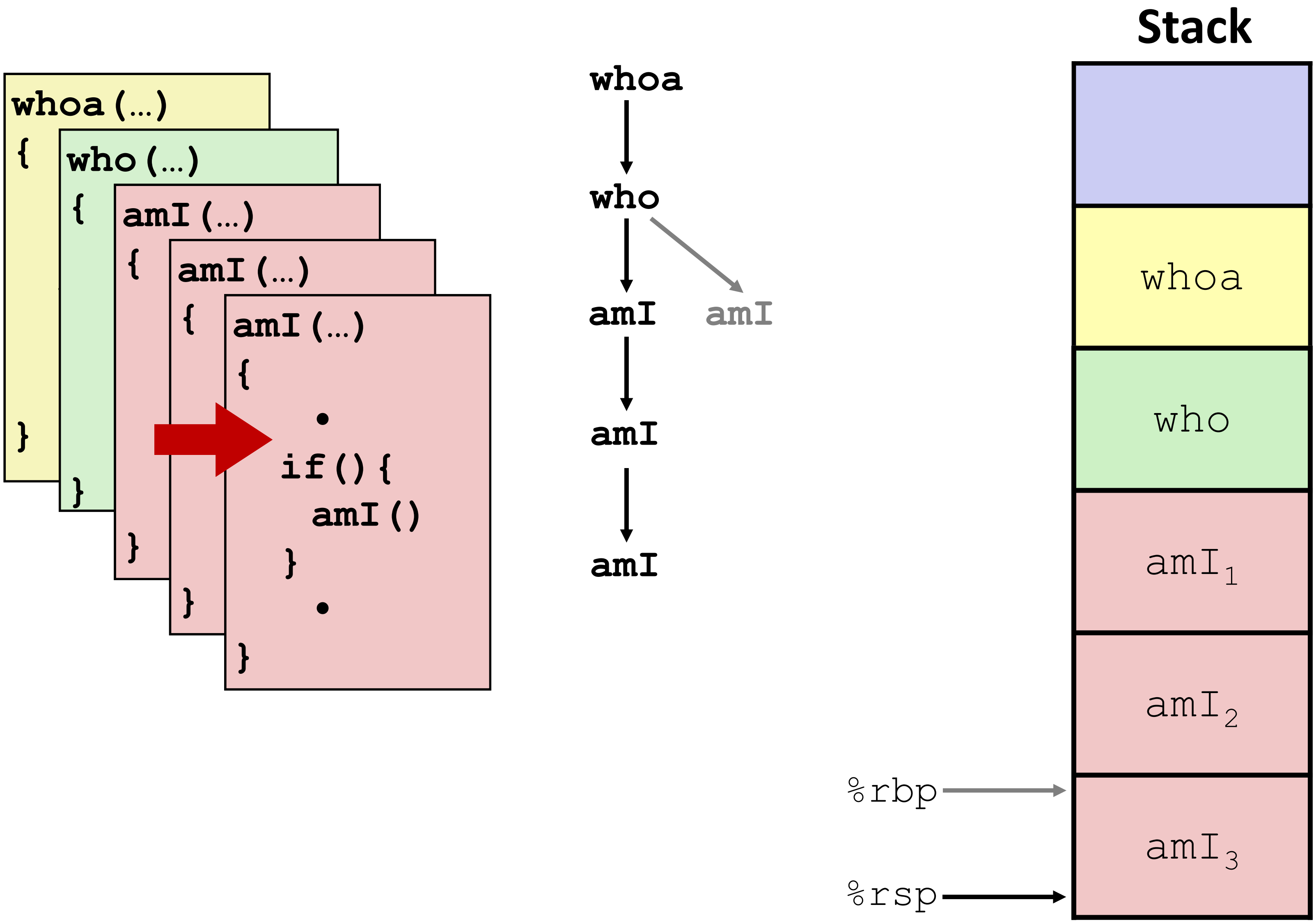
4) Recursive call to amI (2)



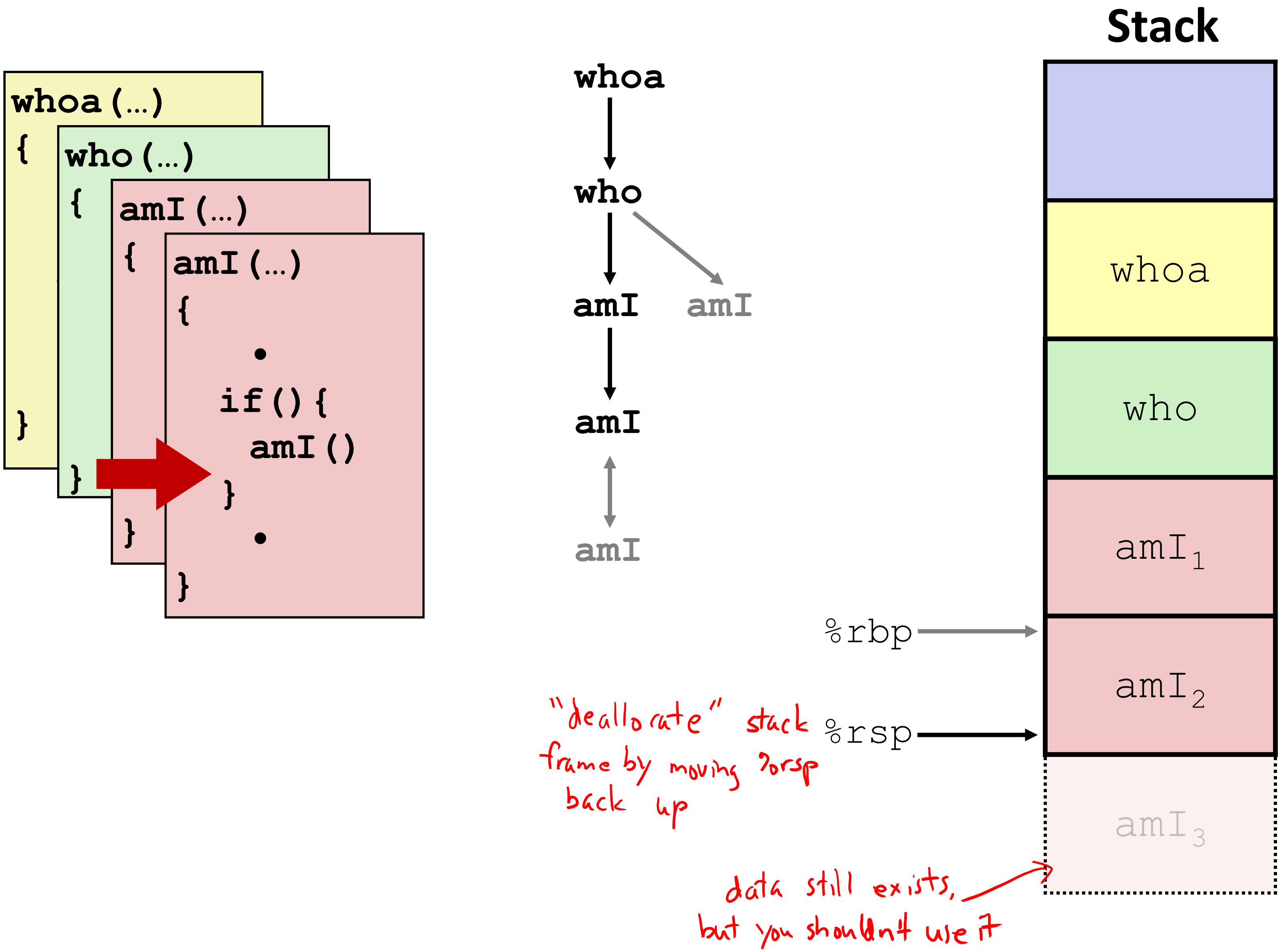




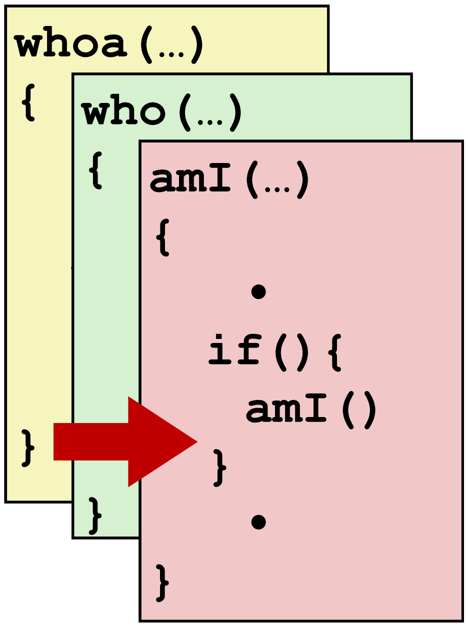
5) (another) Recursive call to amI (3)

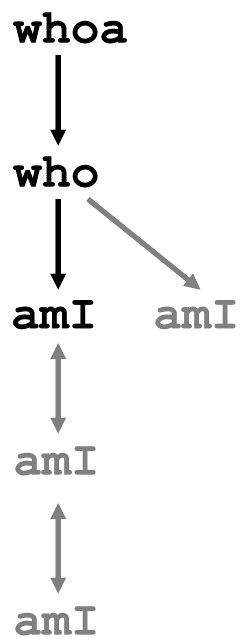


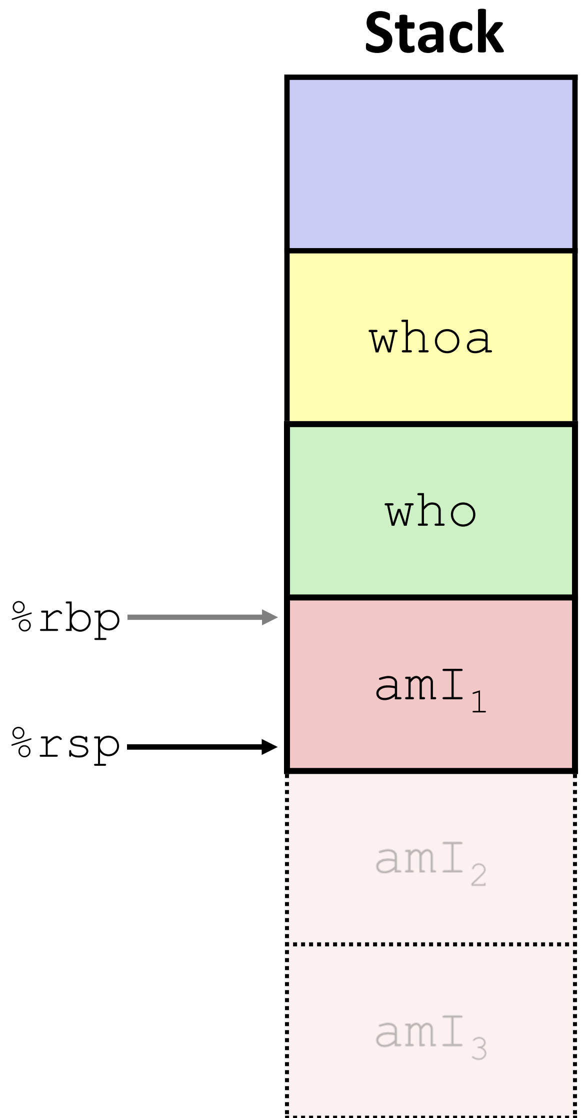
6) Return from (another) recursive call to amI



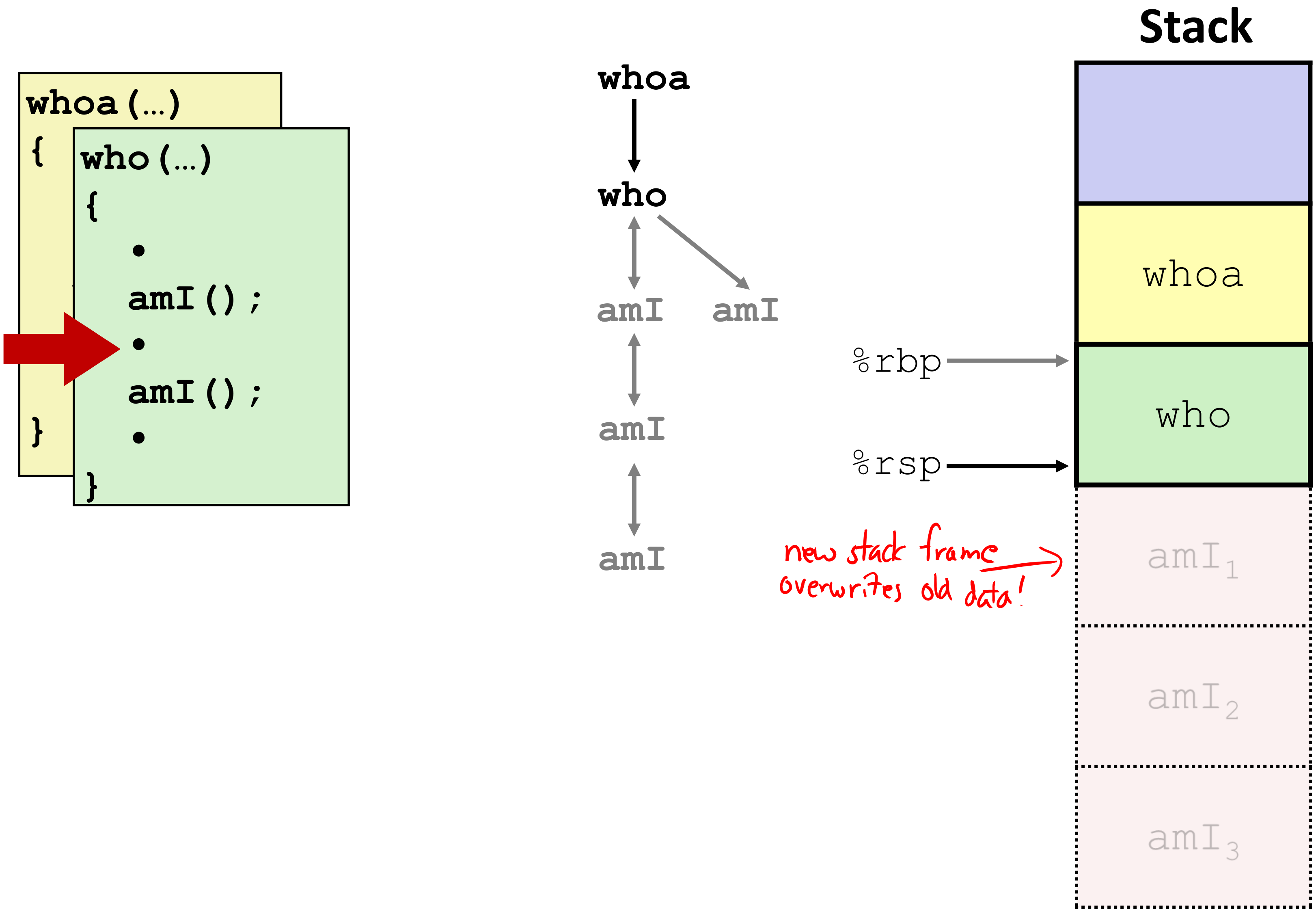
7) Return from recursive call to amI



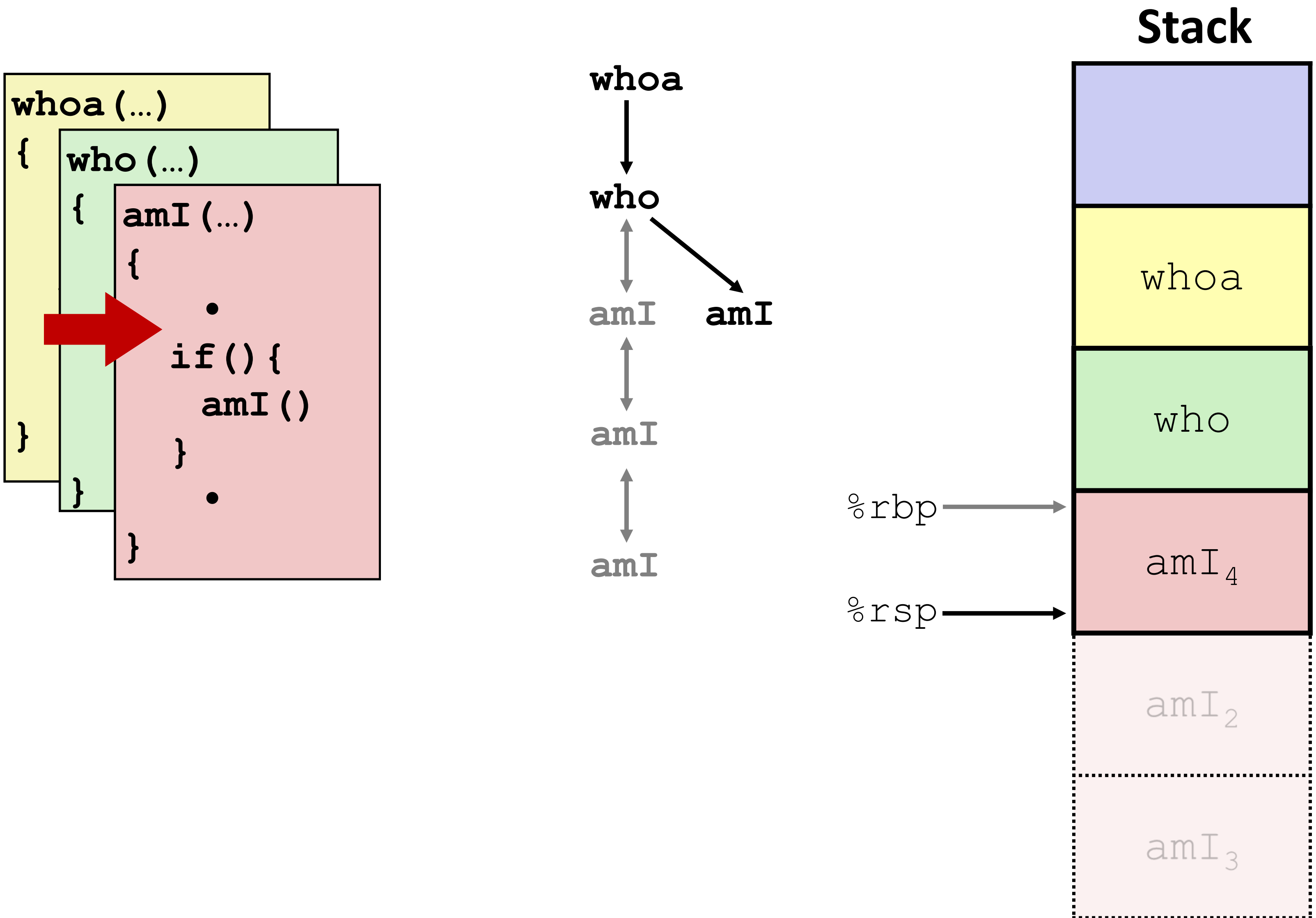




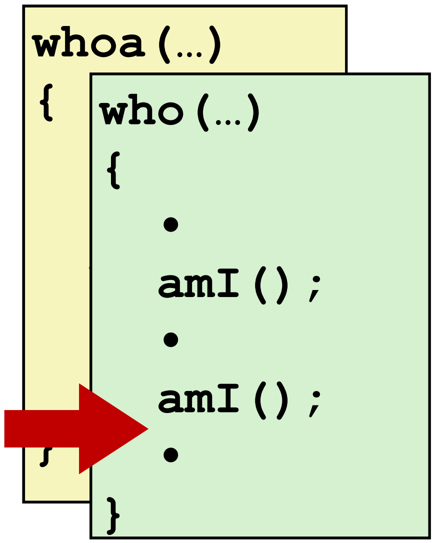
8) Return from call to amI

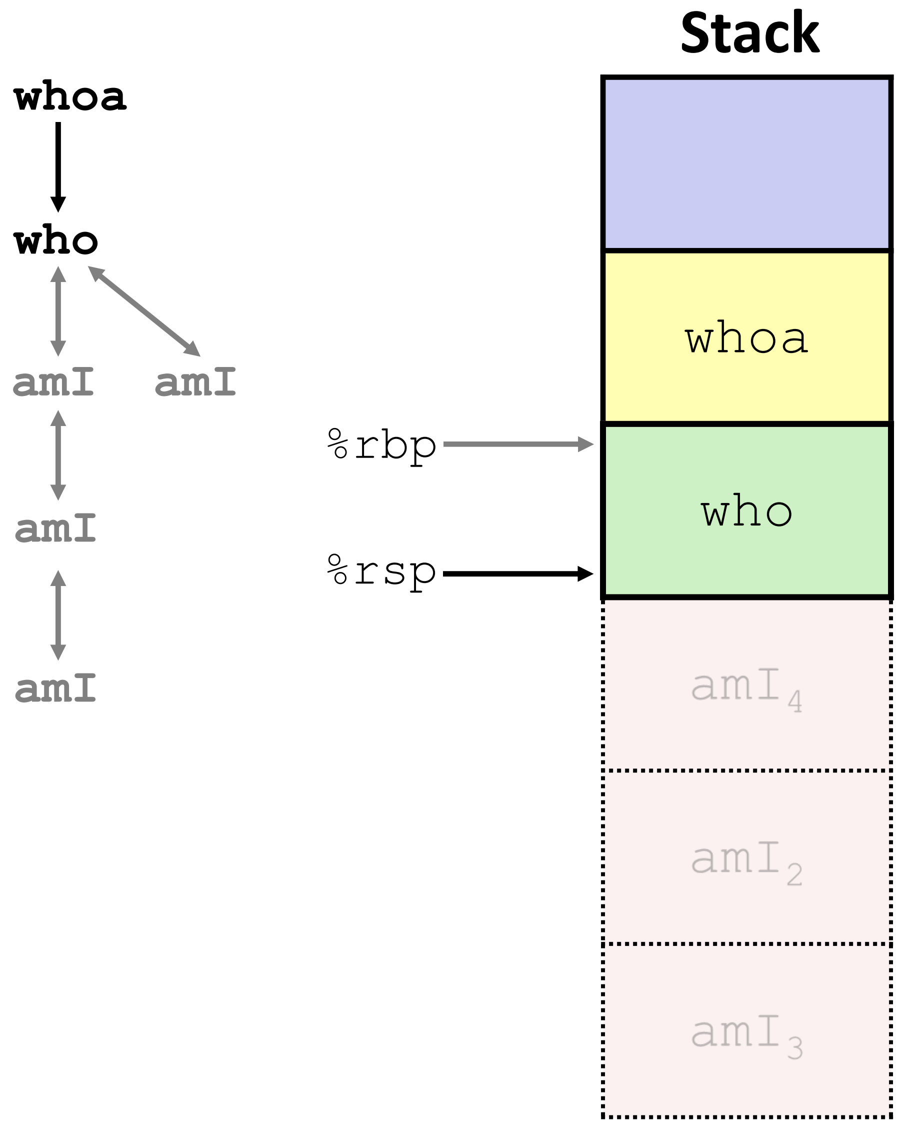


9) (second) Call to amI (4)



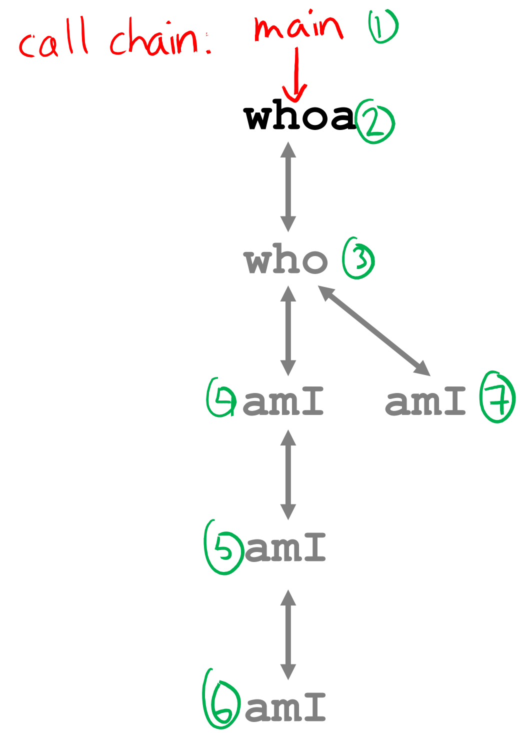
10) Return from (second) call to amI

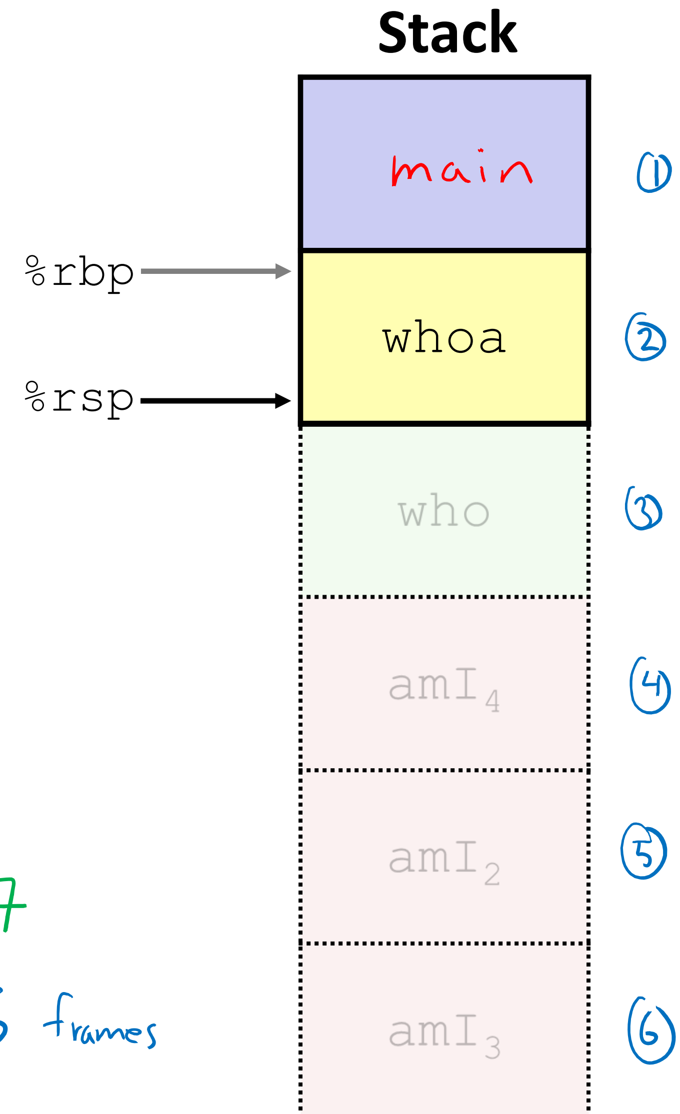




11) Return from call to who

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





total stack frames created: 7

maximum stack depth: 6 frames

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)