The Stack & Procedures (aka Function)

CSE 351 Autumn 2024

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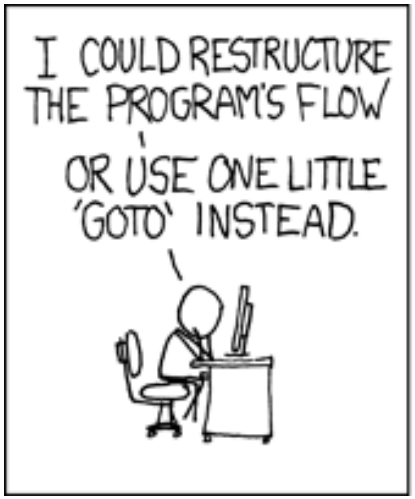
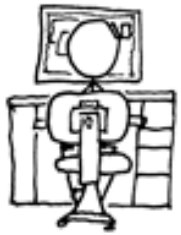




http://xkcd.com/571/

Relevant Course Information

- HW9 due TONIGHT, Friday (10/18) @ 11:59 pm
- Lab 2 (x86-64) due next Friday (10/25)
  - GDB Demo Video on Ed!
  - Learn to read x86-64 assembly and use GDB
  - See GDB Tutorial and Phase 1 walkthrough in Section 4!
- HW10 due Monday (10/21) @ 11:59 pm

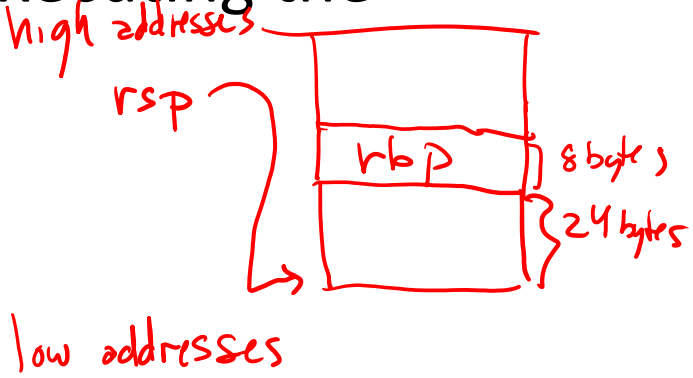
Reading Review

- 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
```



rsp = rsp - 0x18

32 bytes

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

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

rdi rsi rdx

rsp

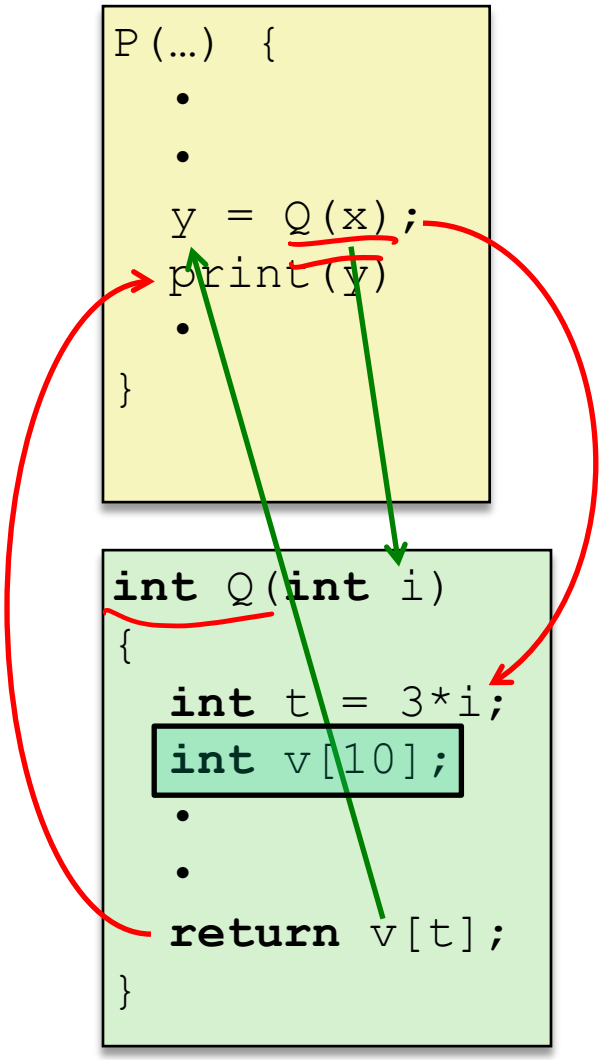
rax

rip

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

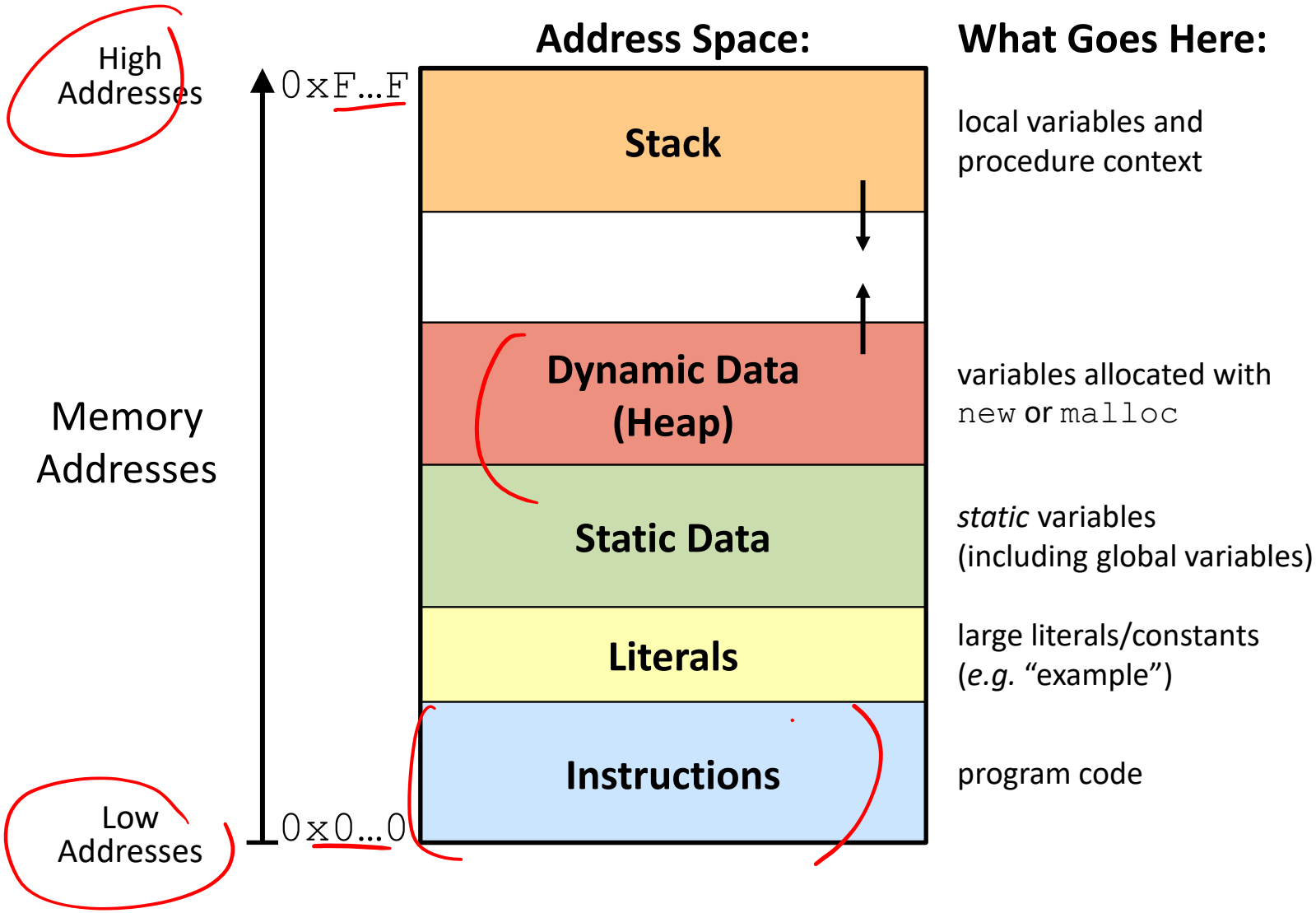
❖ All implemented with machine instructions!
   - An x86-64 procedure uses only those mechanisms required for that procedure



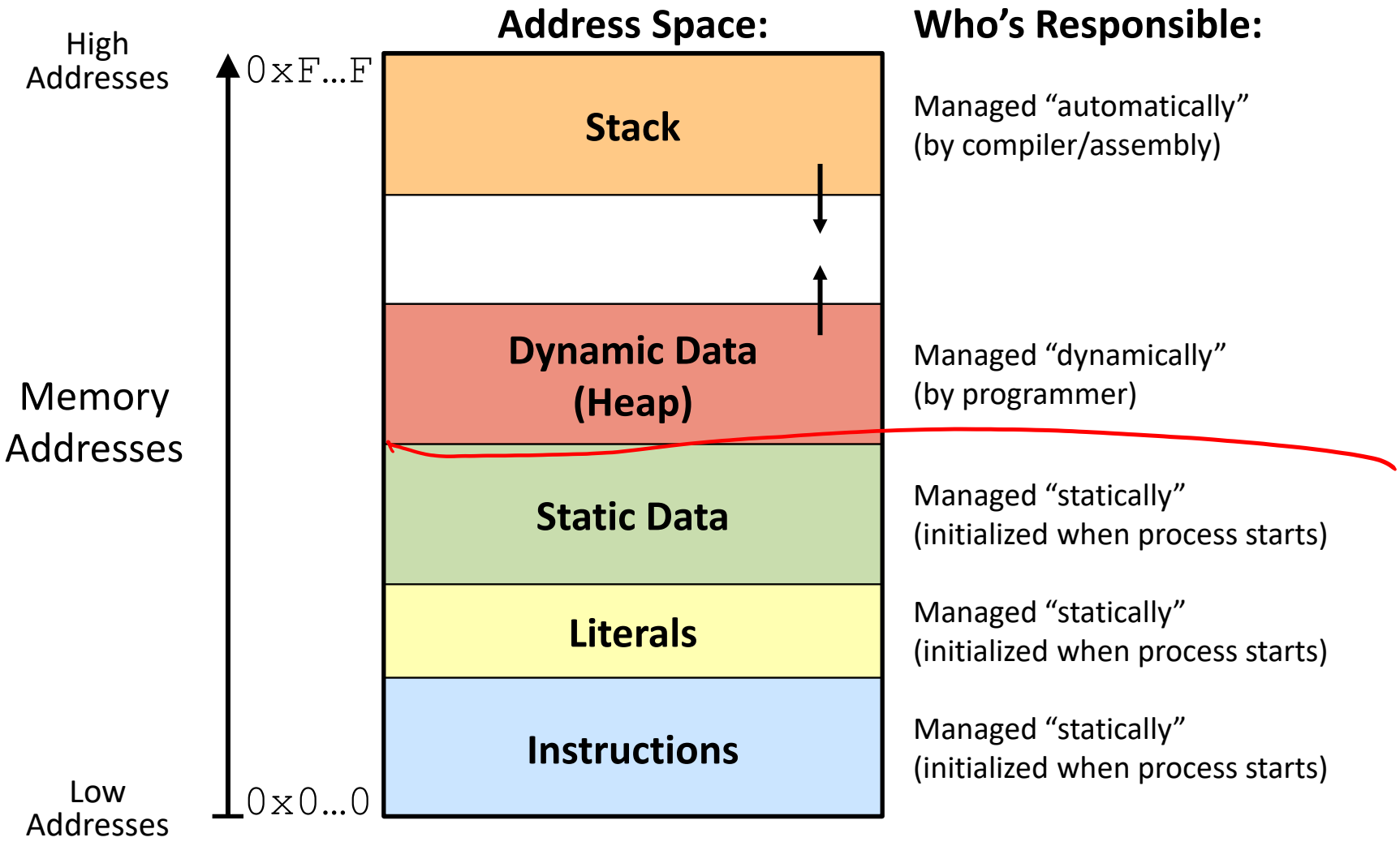
Procedures

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

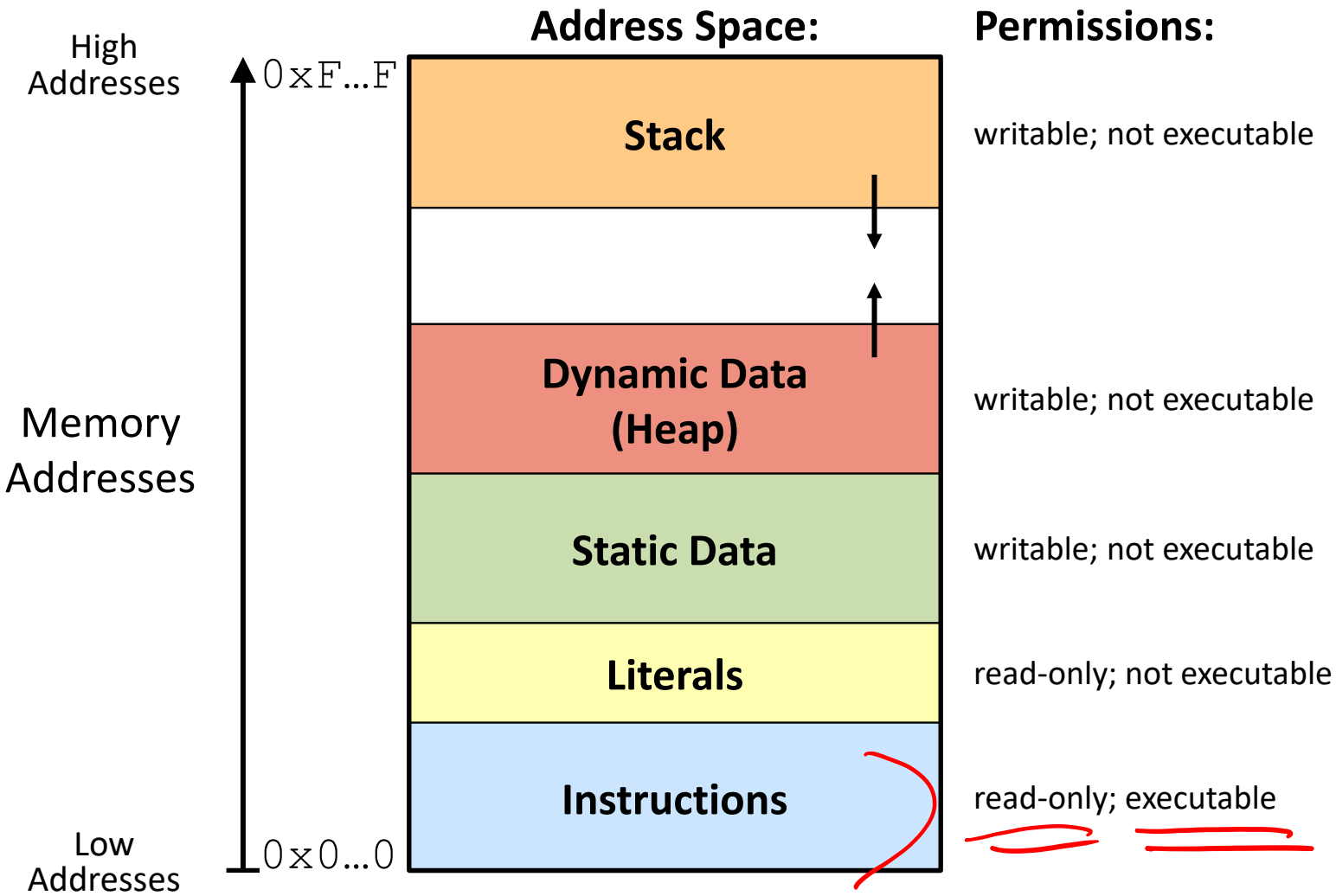
Simplified Memory Layout (Review)



Memory Management



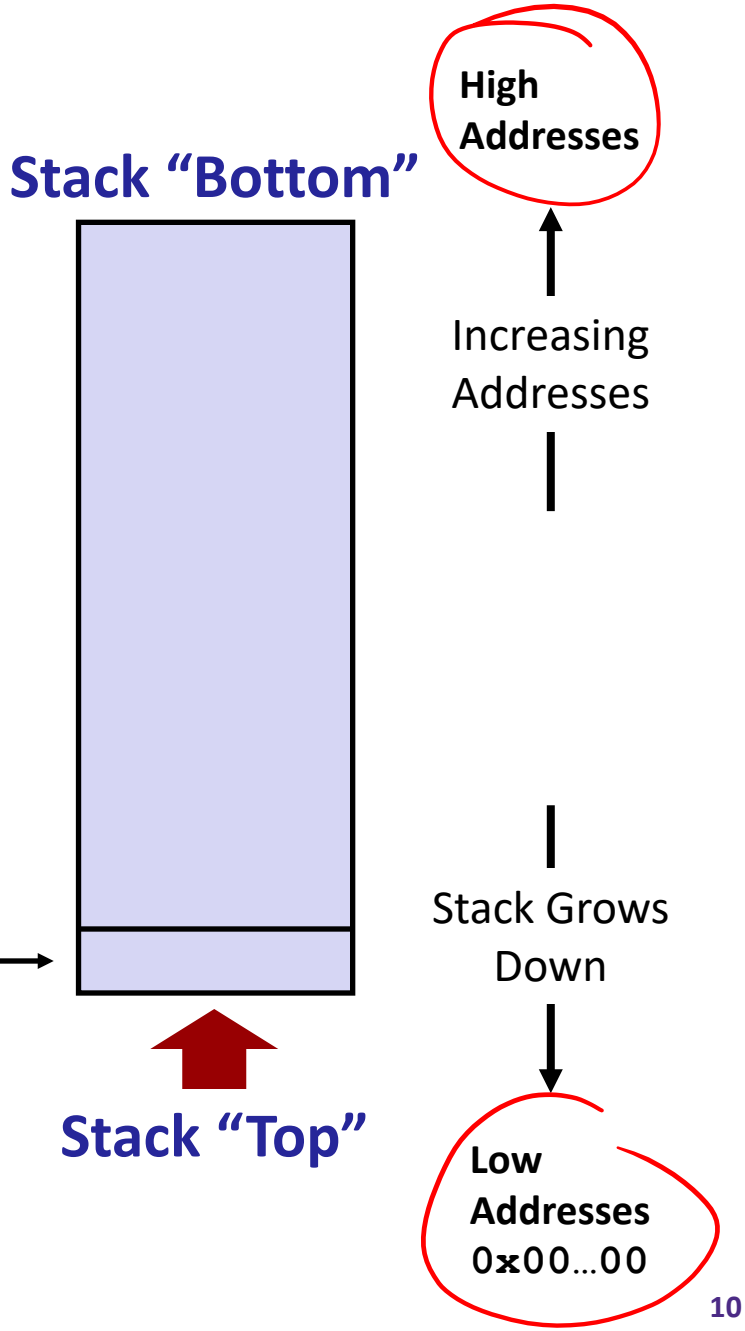
Memory Permissions



- Segmentation faults: impermissible memory access

x86-64 Stack (Review)

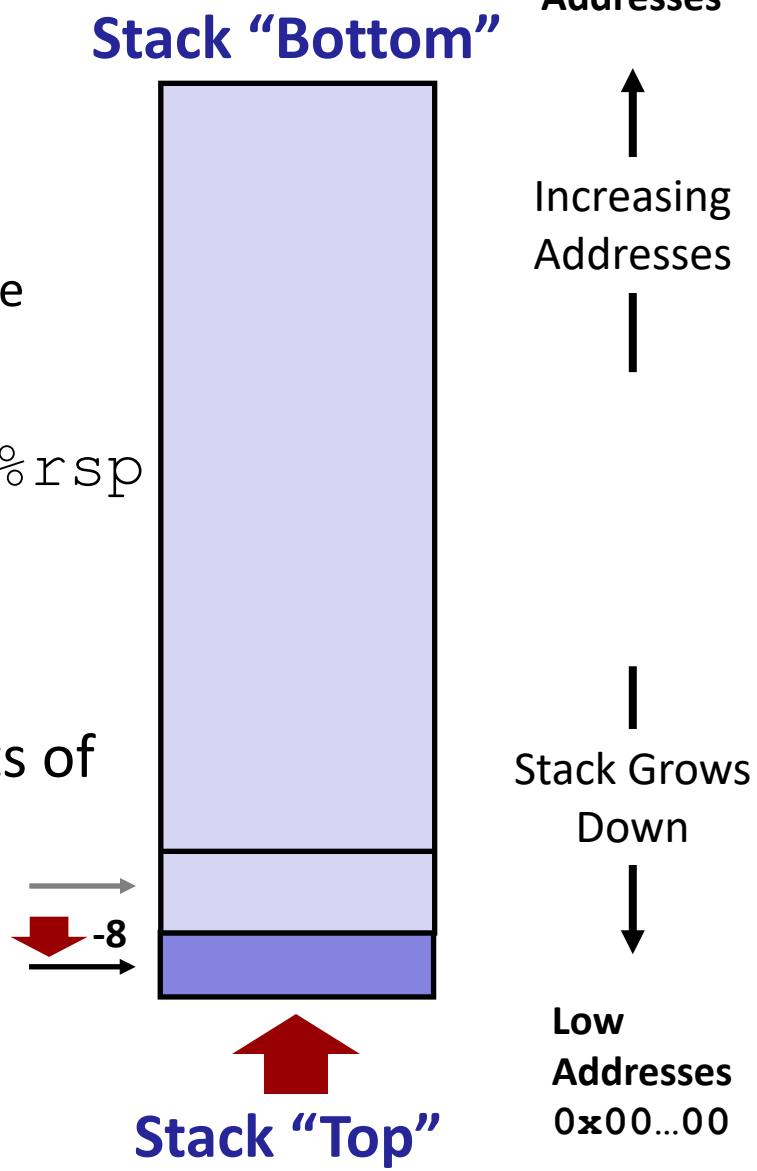
- Region of memory managed with stack "discipline"
  - Grows toward lower addresses
  - Customarily shown "upside-down"
- Register `%rsp` contains *lowest* stack address
  - `%rsp` = address of *top* element, the most-recently-pushed item that is not-yet-popped



LIFO

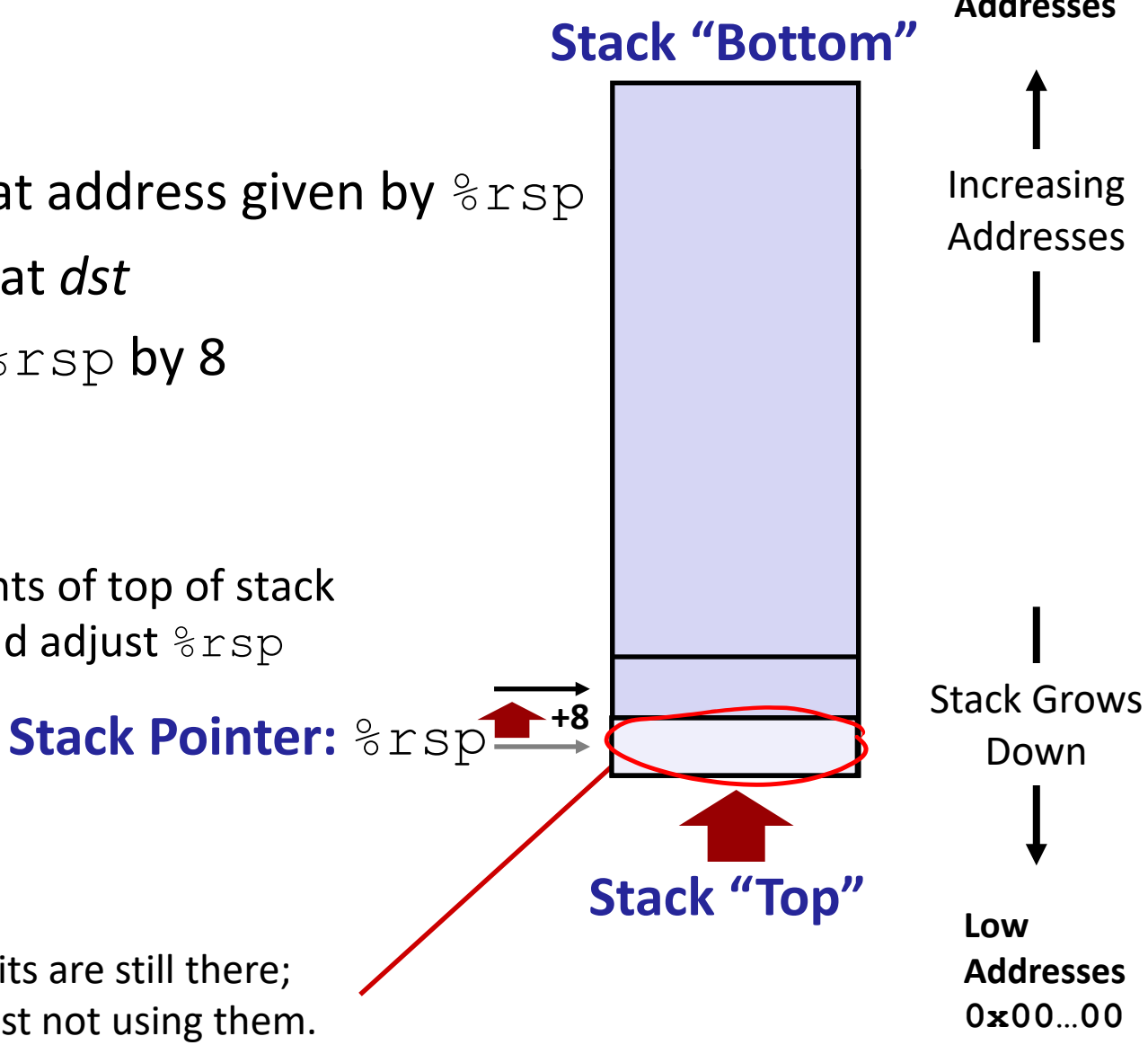
x86-64 Stack: Push (Review)

- `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)

- `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`



Procedures

- Stack Structure
- **Calling Conventions**
  - **Passing control**
  - Passing data
  - Managing local data
- Register Saving Conventions
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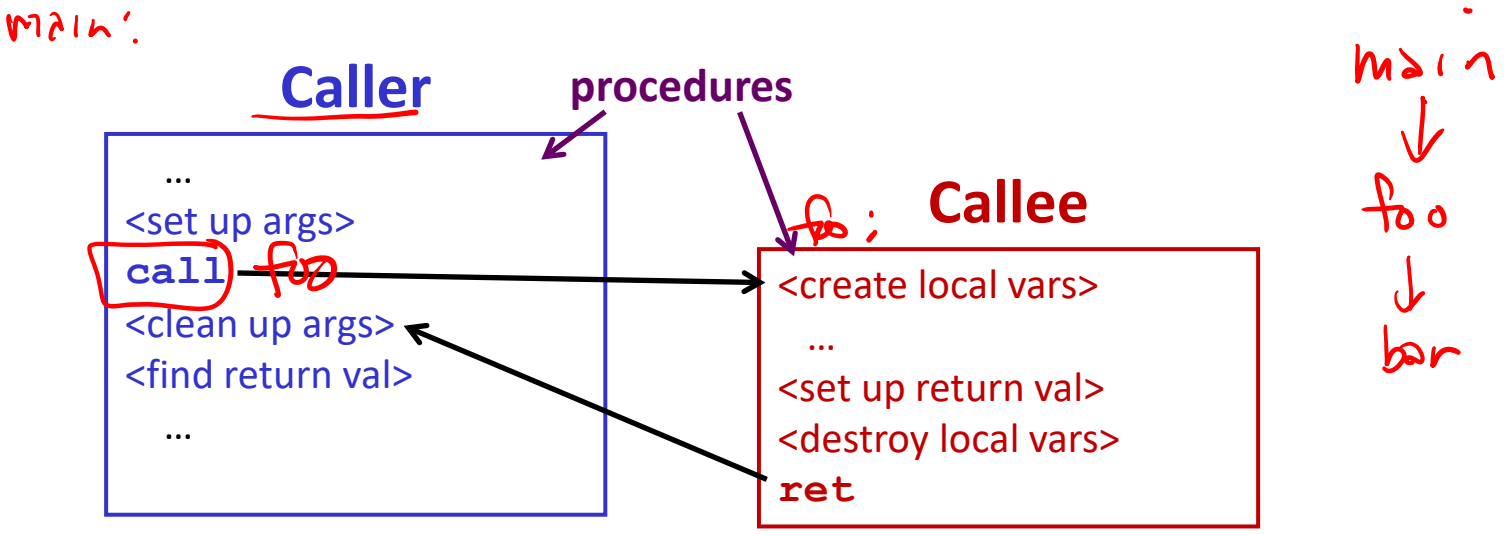
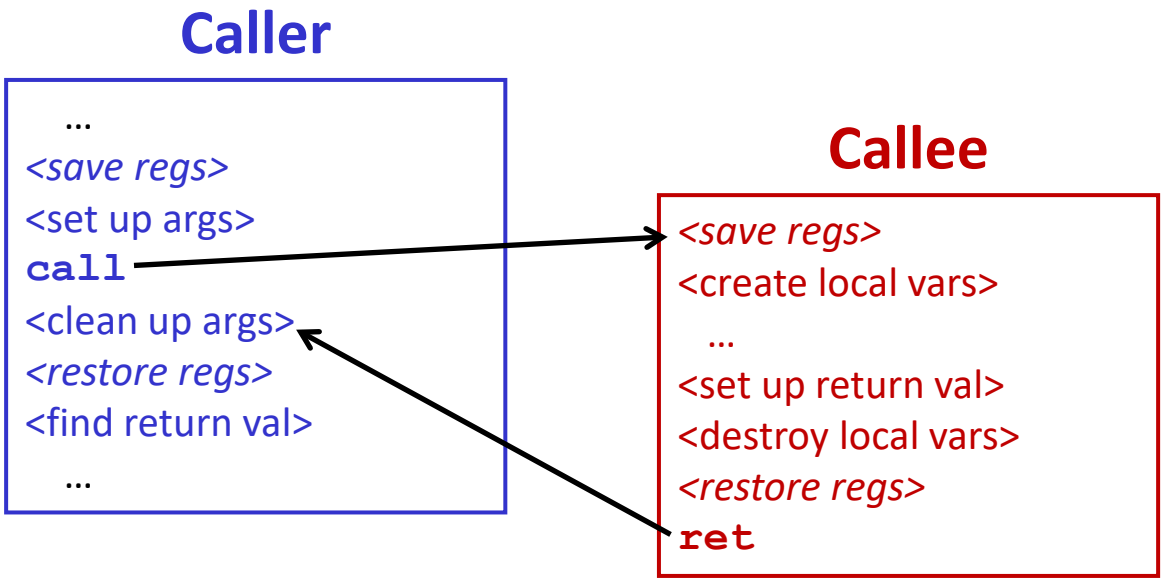
Procedure Call Overview



- **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 Calling Convention



- 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 (Review)

- 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 (Review)

- 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**

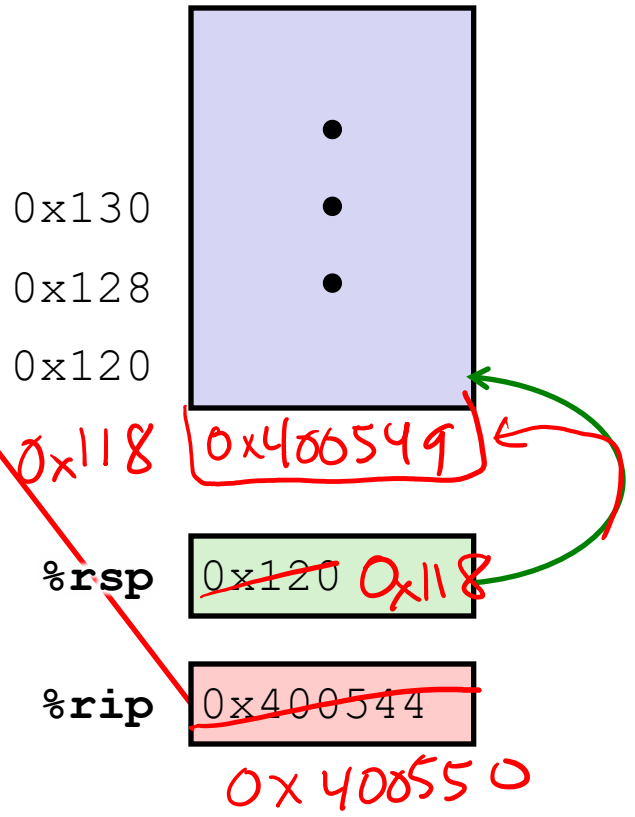
next instruction happens to be a move, but could be anything

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

Procedure Call Example (step 1)

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

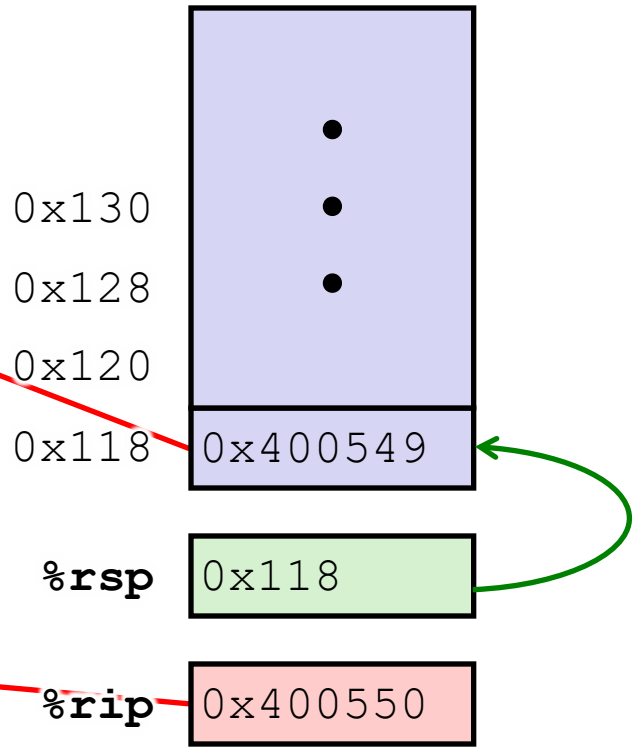
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



Procedure Call Example (step 2)

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

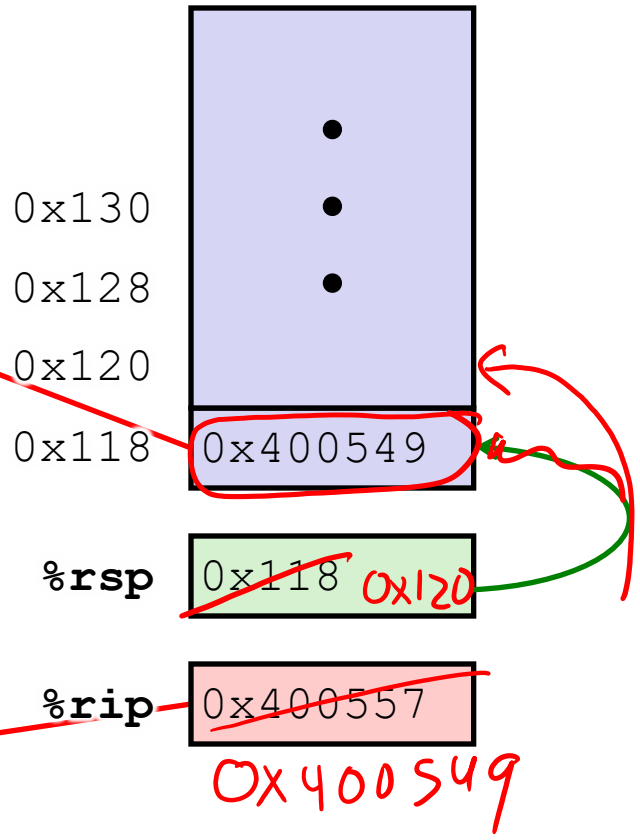
```
0000000000400550 <mult2>:
   400550:  movq   %rdi,%rax
   •
   •
   400557:  ret
```



Procedure Return Example (step 1)

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

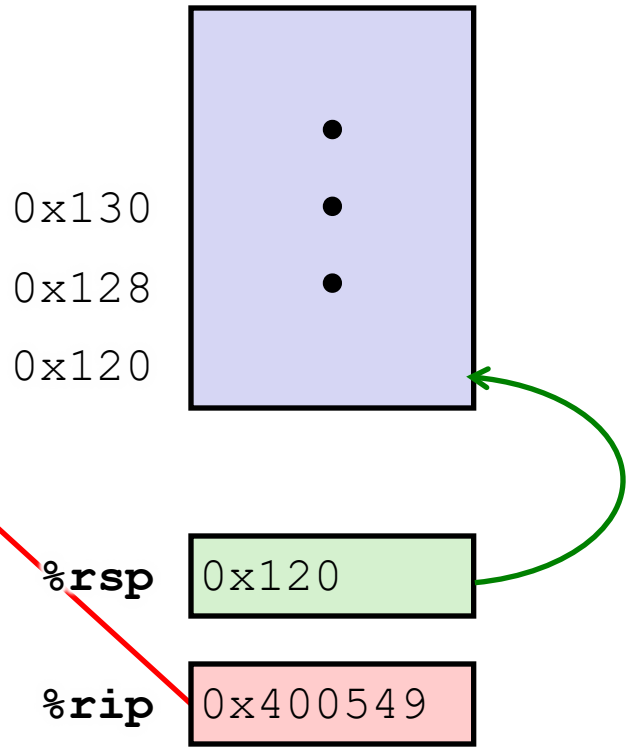
```
0000000000400550 <mult2>:
  400550:  movq   %rdi,%rax
  •
  •
  400557:  ret
```



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
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Procedure Data Flow (Review)

Registers (NOT in Memory)

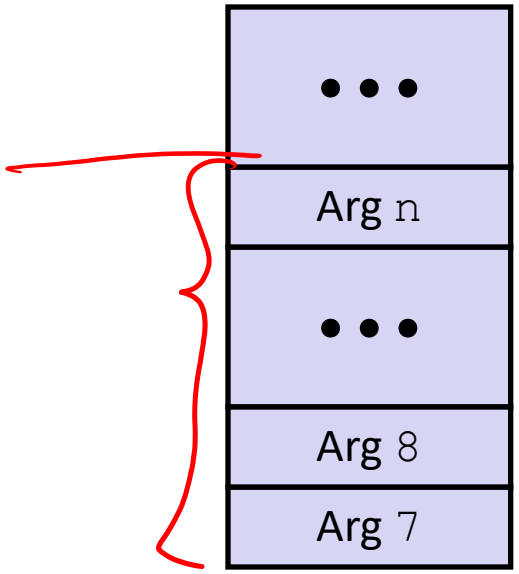
- First 6 arguments

%rdi	*Diane's*
%rsi	*Silk*
%rdx	*Dress*
%rcx	*Costs*
%r8	*$8*
%r9	*9*

- Return value

%rax

Stack (Memory)



High Addresses

Low Addresses 0x00…00

- 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**
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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

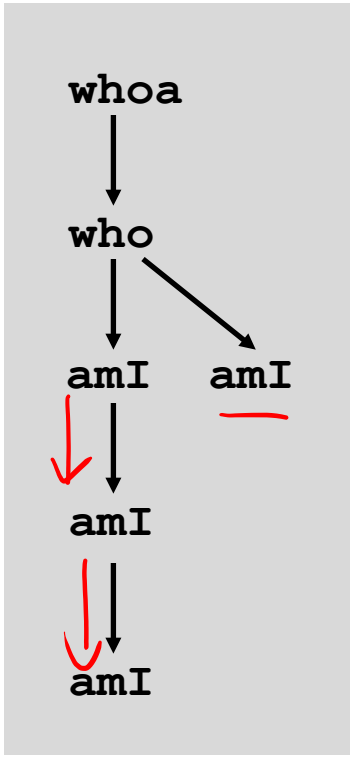
```
whoa(…)
{
  •
  •
  who();
  •
  •
}
```

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

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

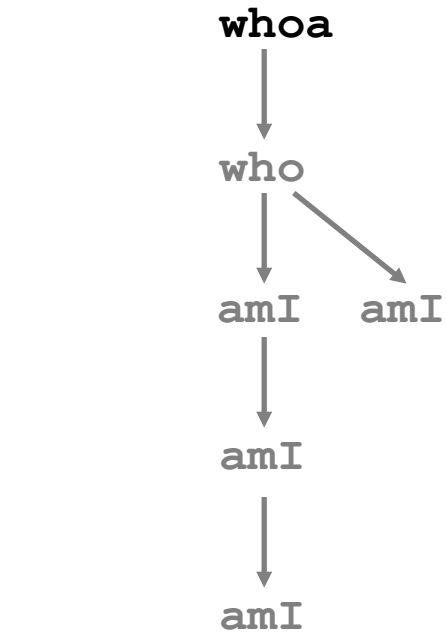
Procedure `amI` is recursive (calls itself)

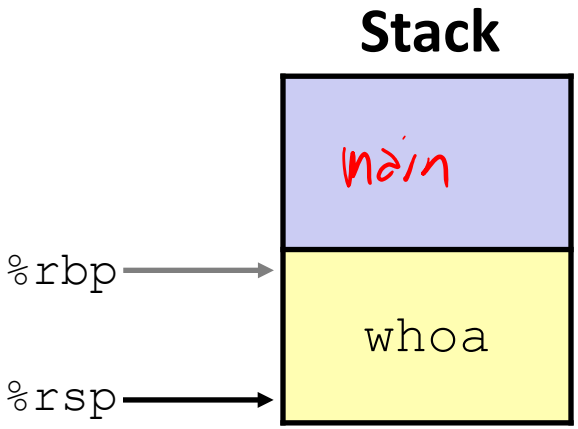
Example Call Chain



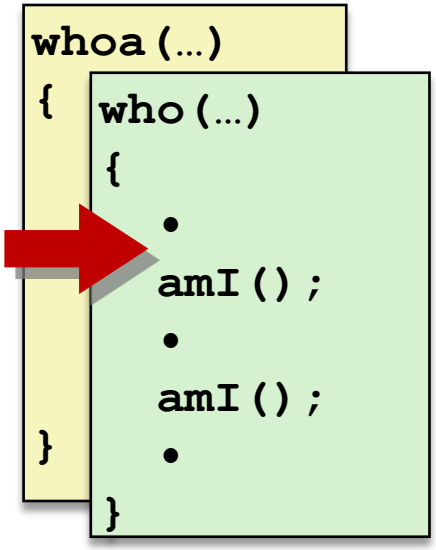
1) Call to whoa

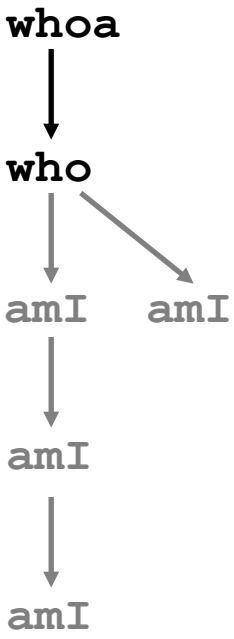
```
whoa(...)
{
    •
    •
    who();
    •
    •
}
```

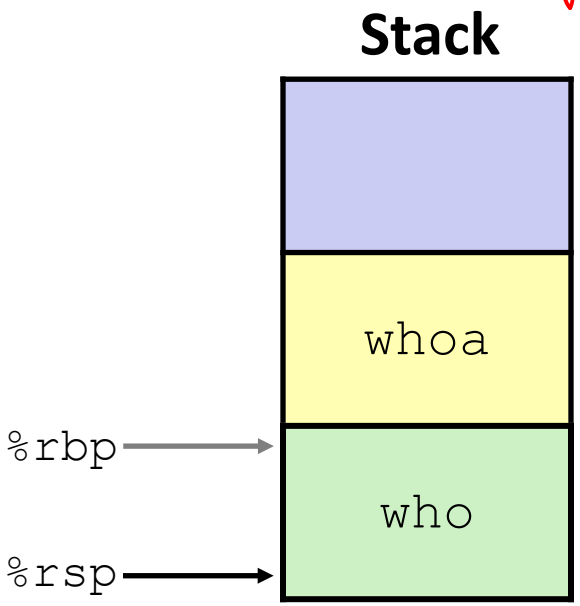




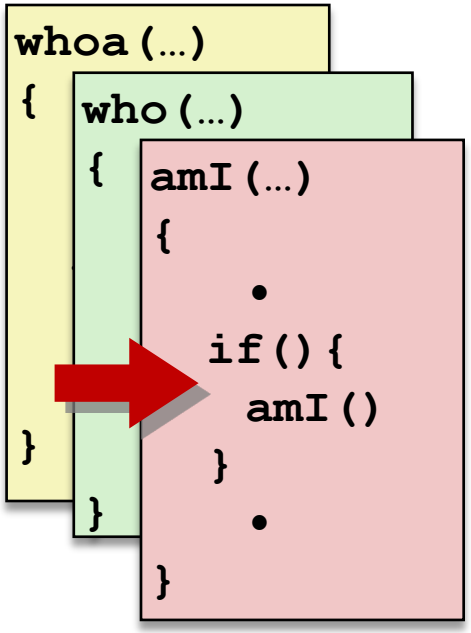
2) Call to who

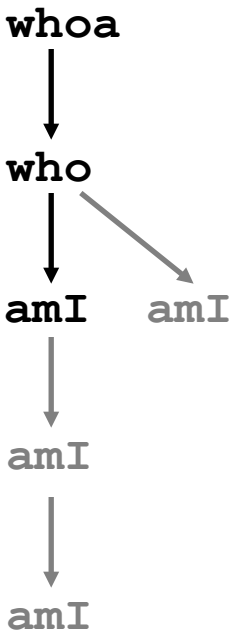

whoa(...)
{
who(...)
{
•
amI();
•
amI();
•
}
}

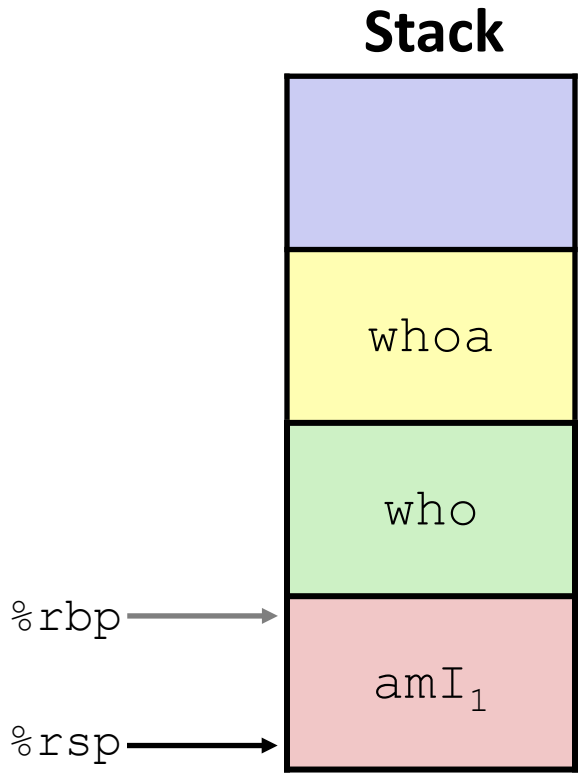

whoa
who
amI
amI
amI
amI


Stack
whoa
%rbp
who
%rsp

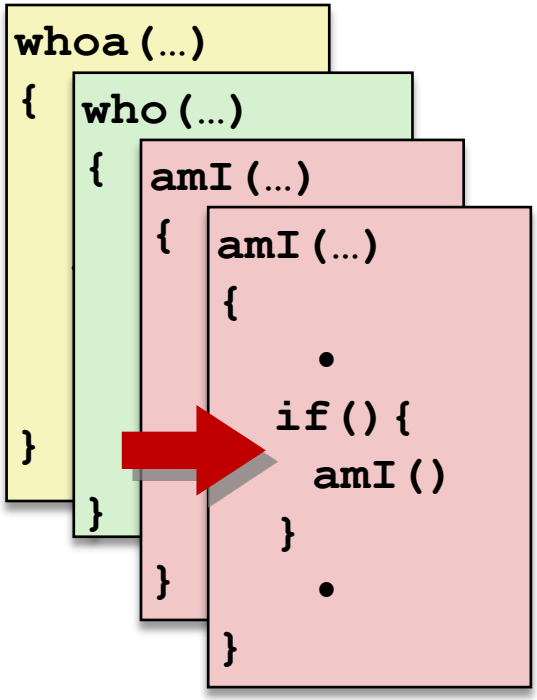
3) Call to amI (1)

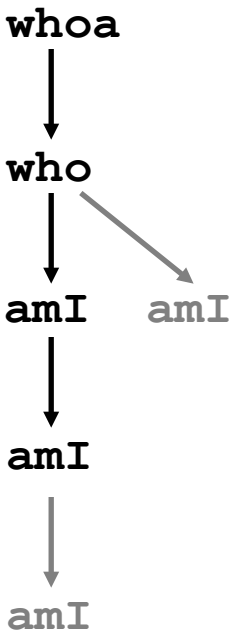


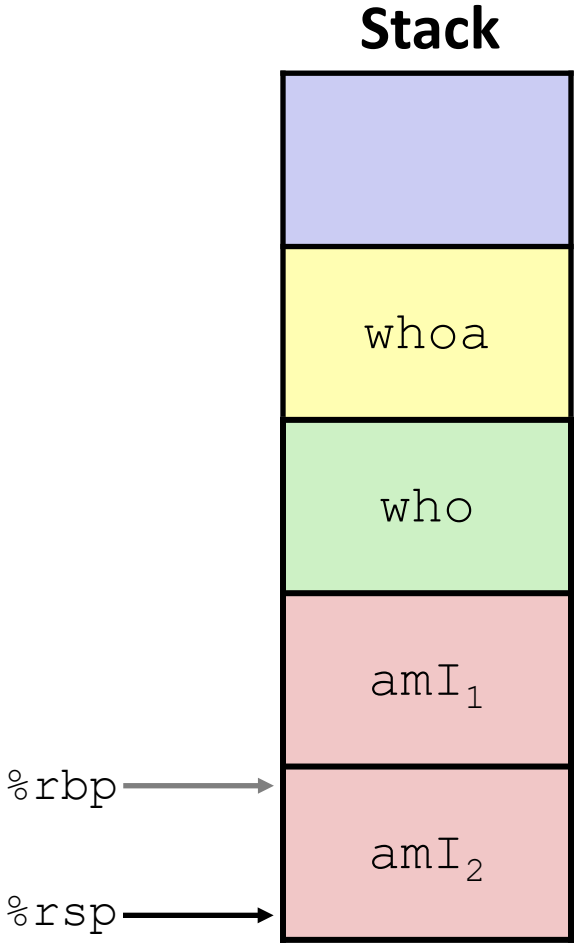




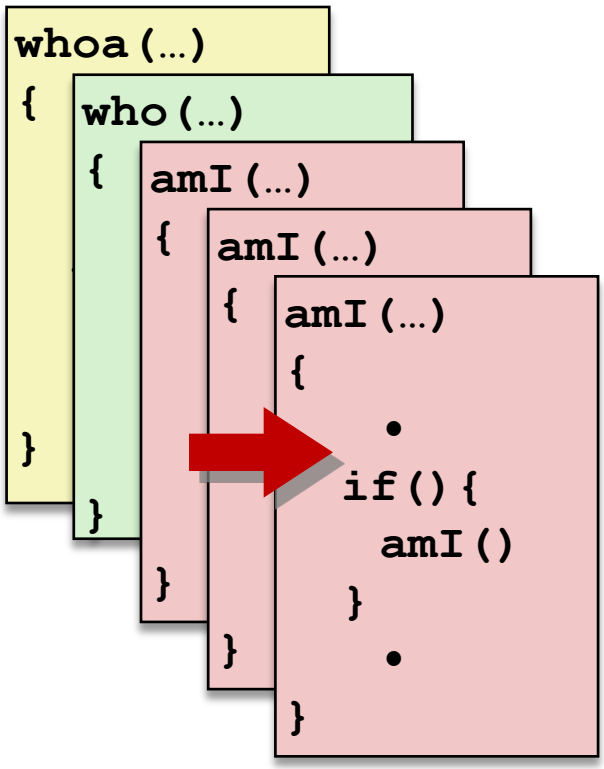
4) Recursive call to amI (2)

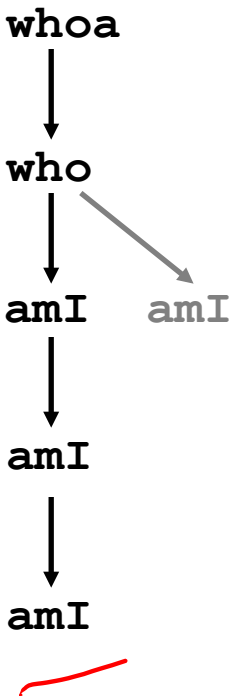


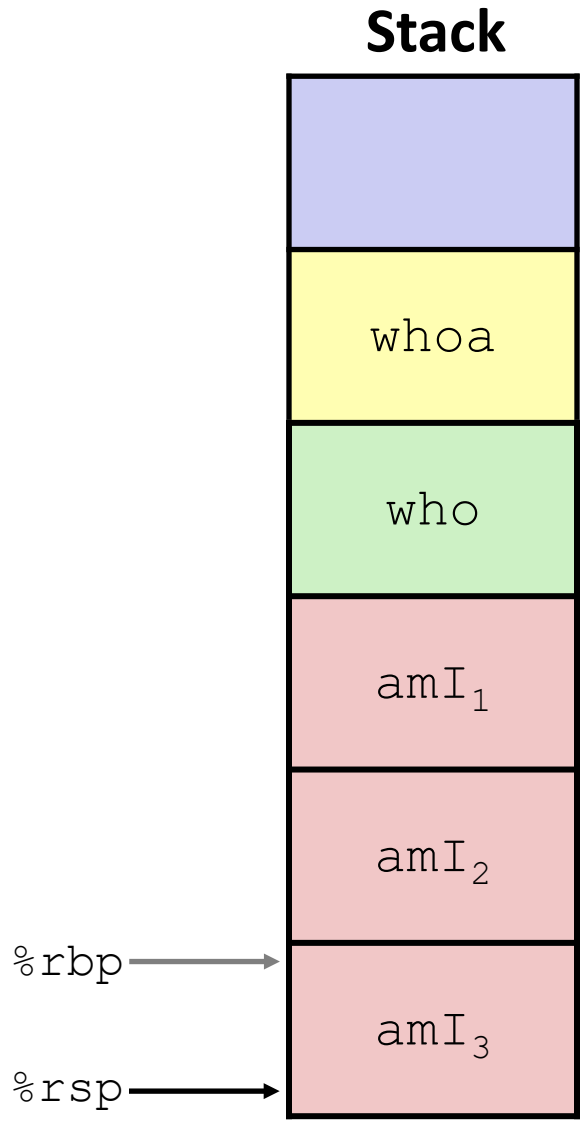




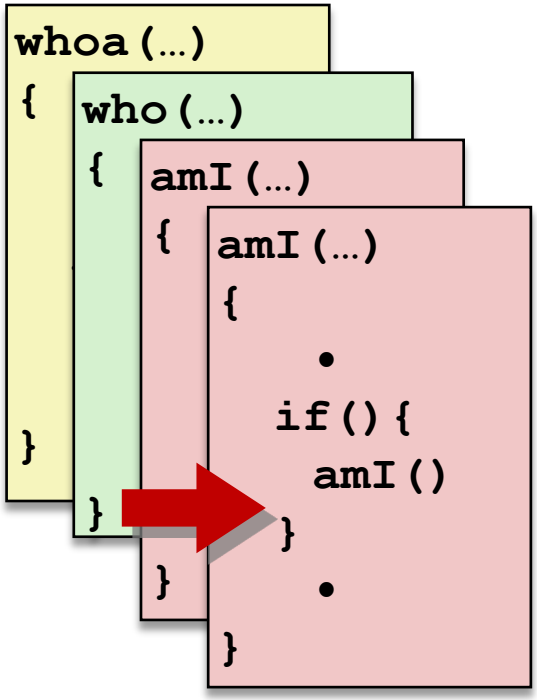
5) (another) Recursive call to amI (3)

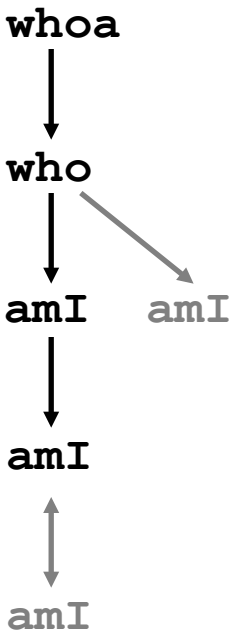


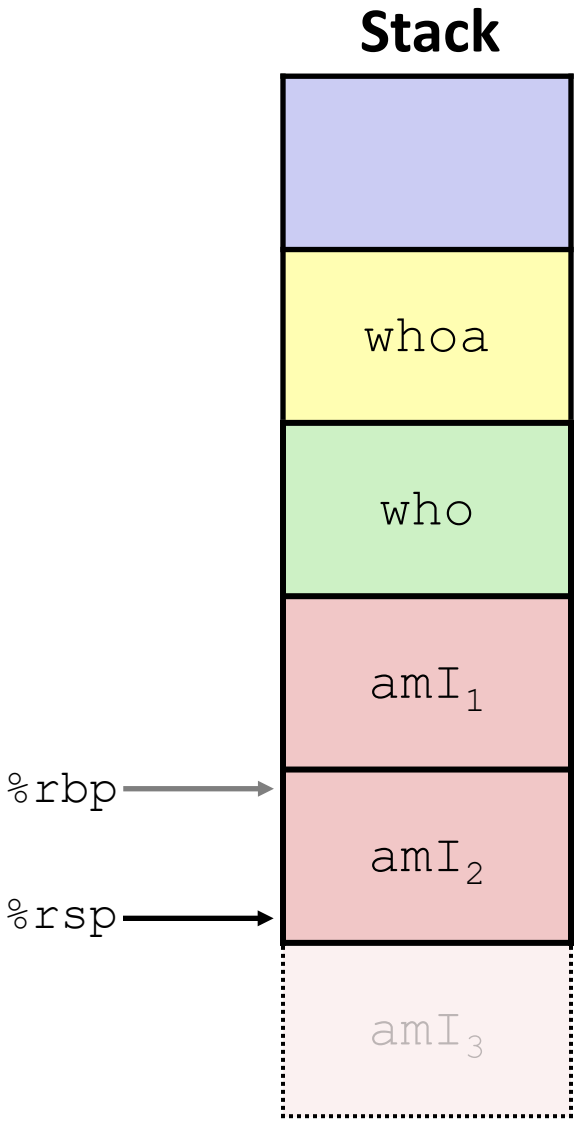




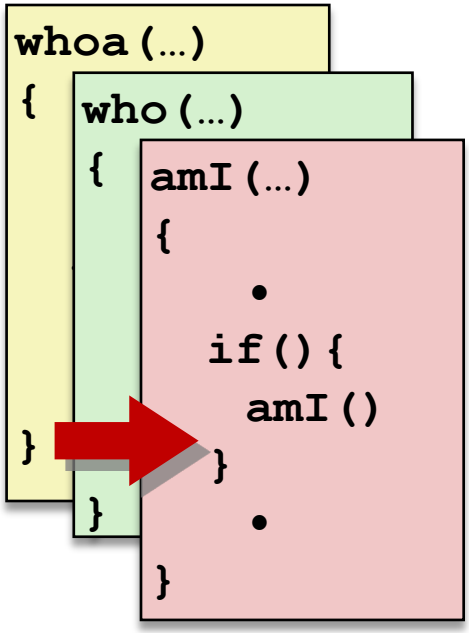
6) Return from (another) recursive call to amI

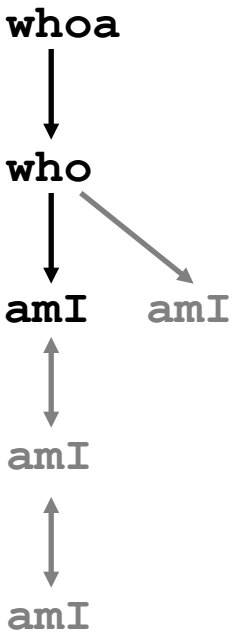


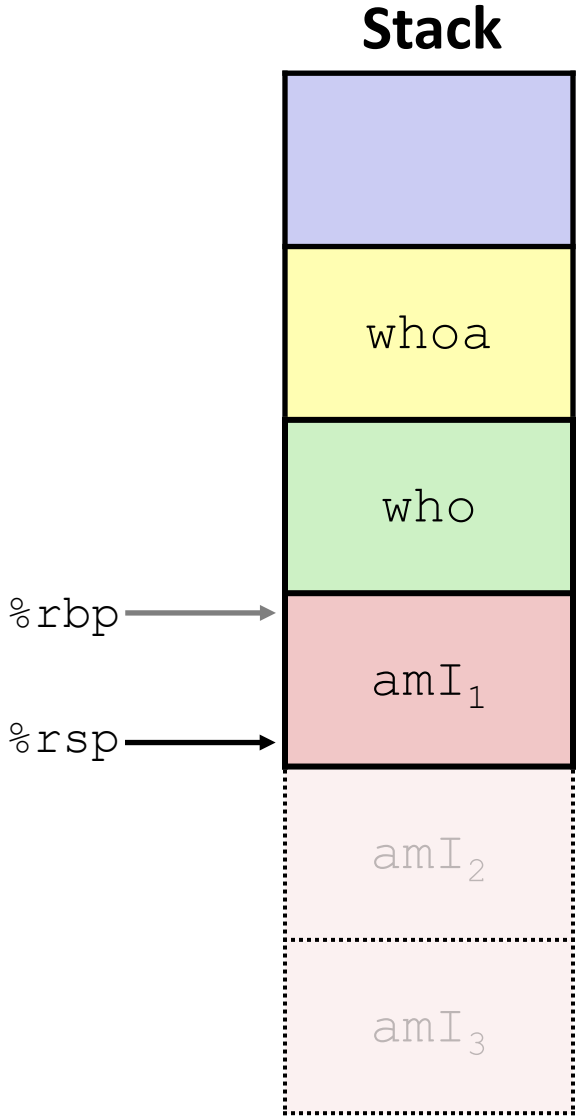




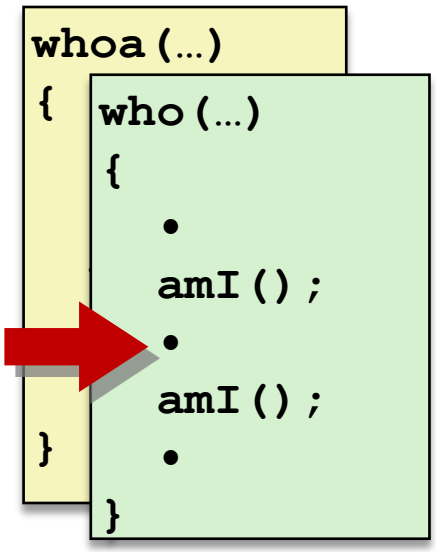
7) Return from recursive call to amI

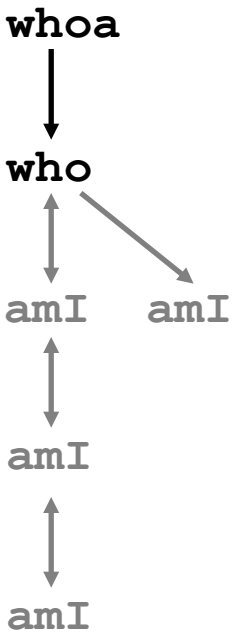


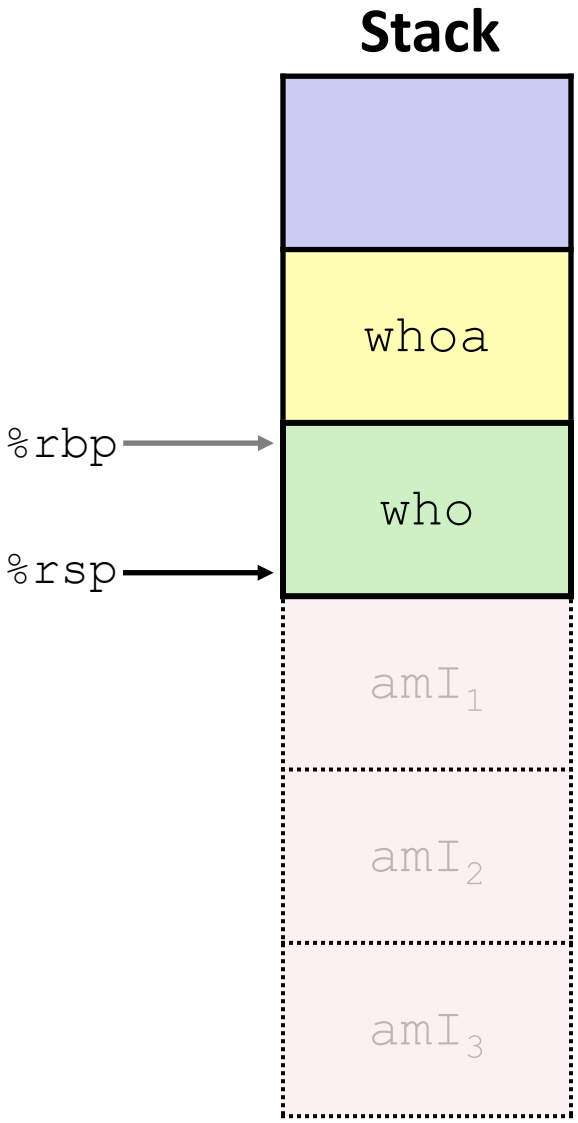




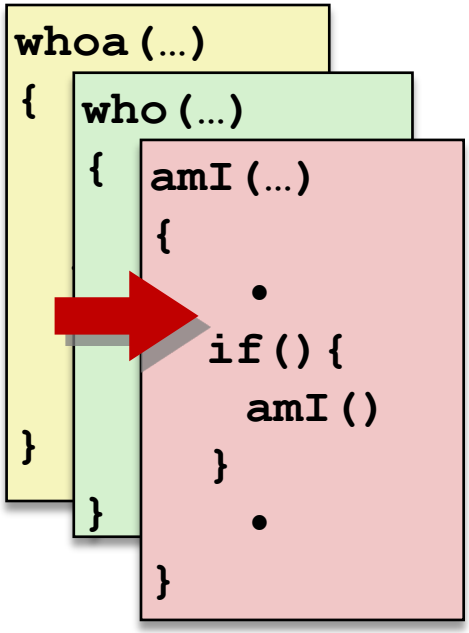
8) Return from call to amI

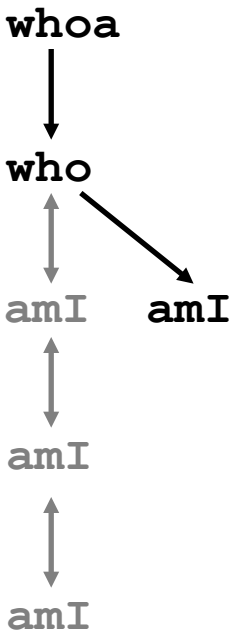


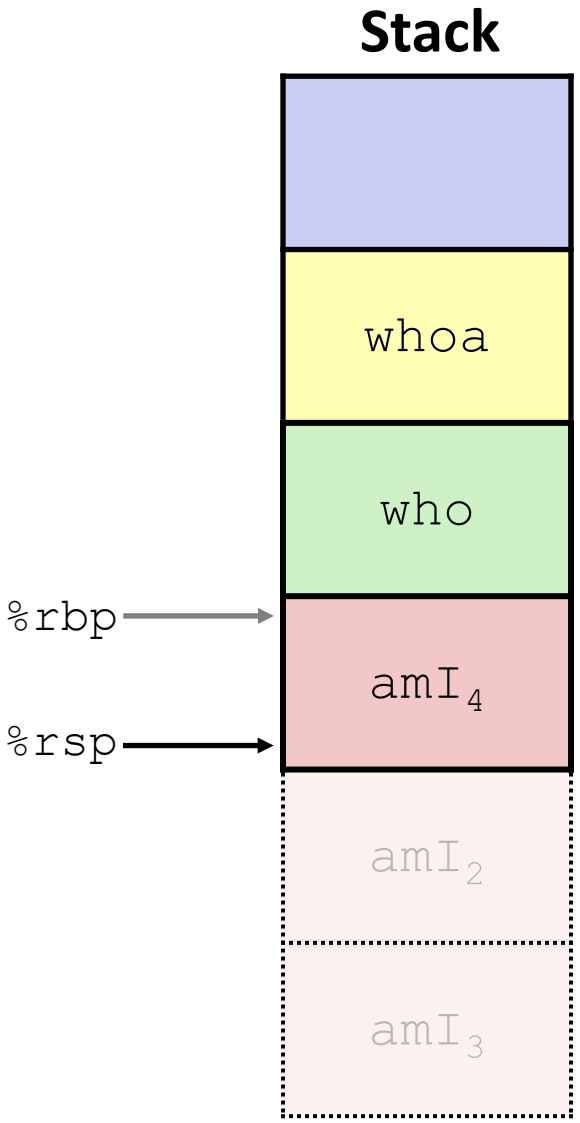




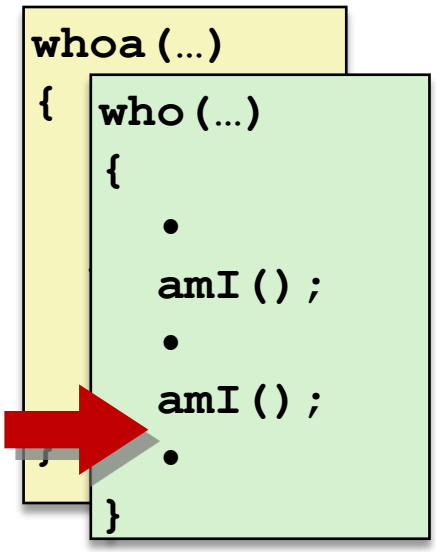
9) (second) Call to amI (4)

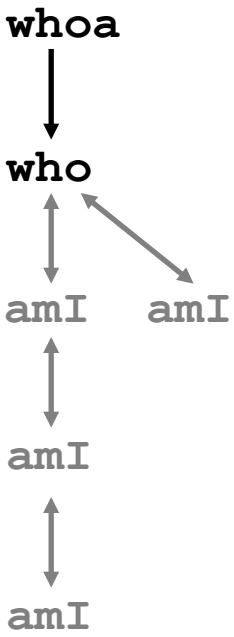


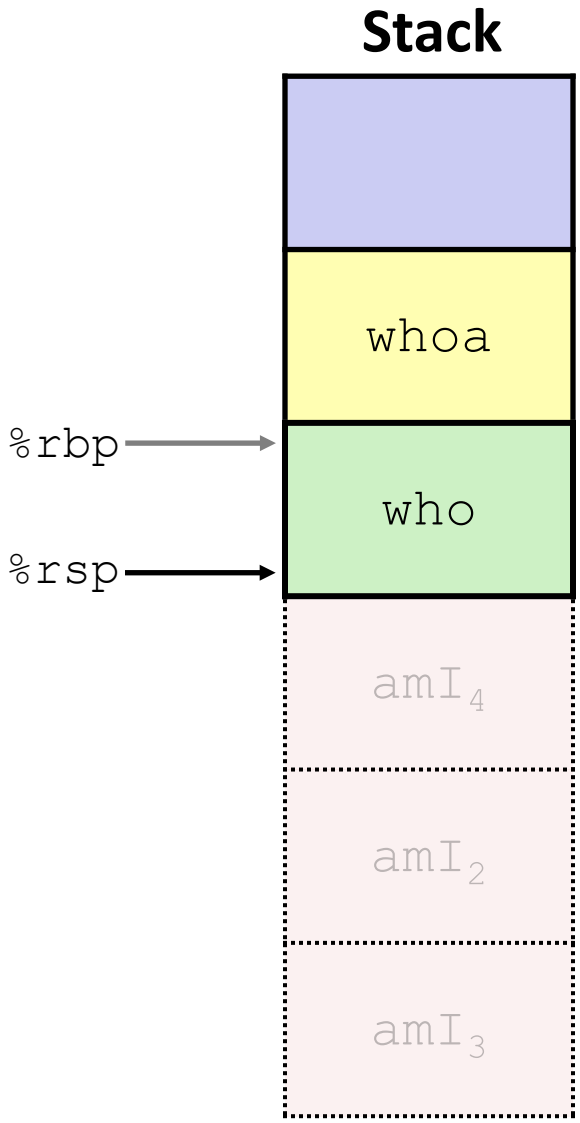




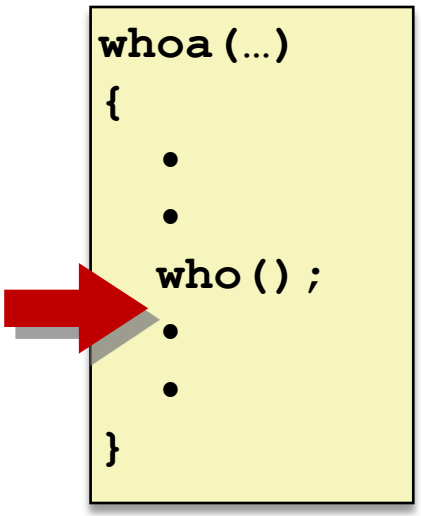
10) Return from (second) call to amI

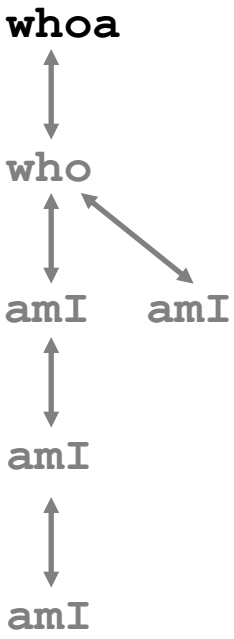


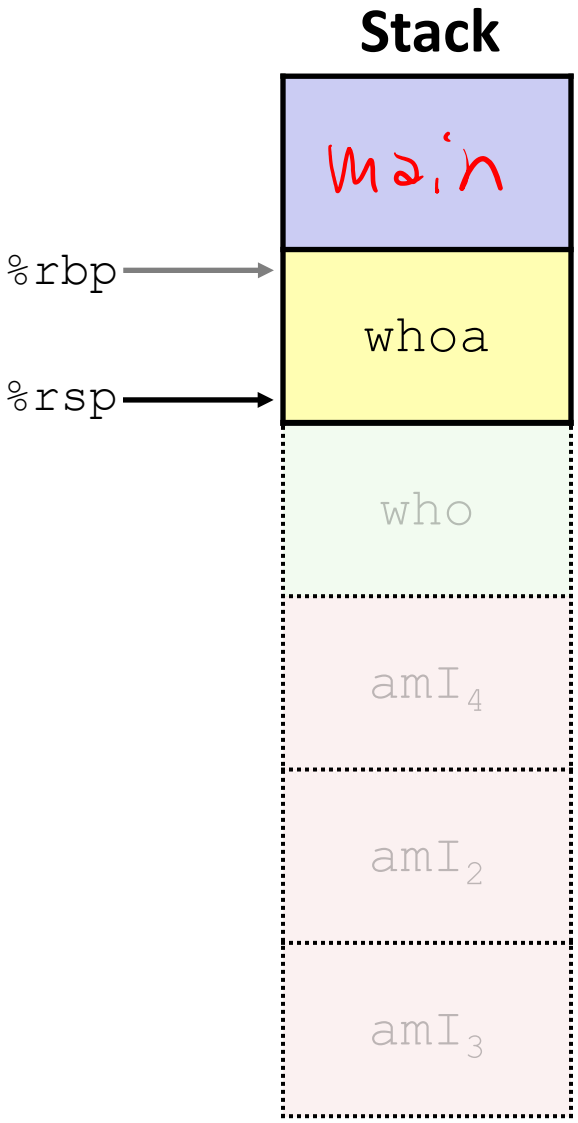




11) Return from call to who







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)