Assembly III: Procedures

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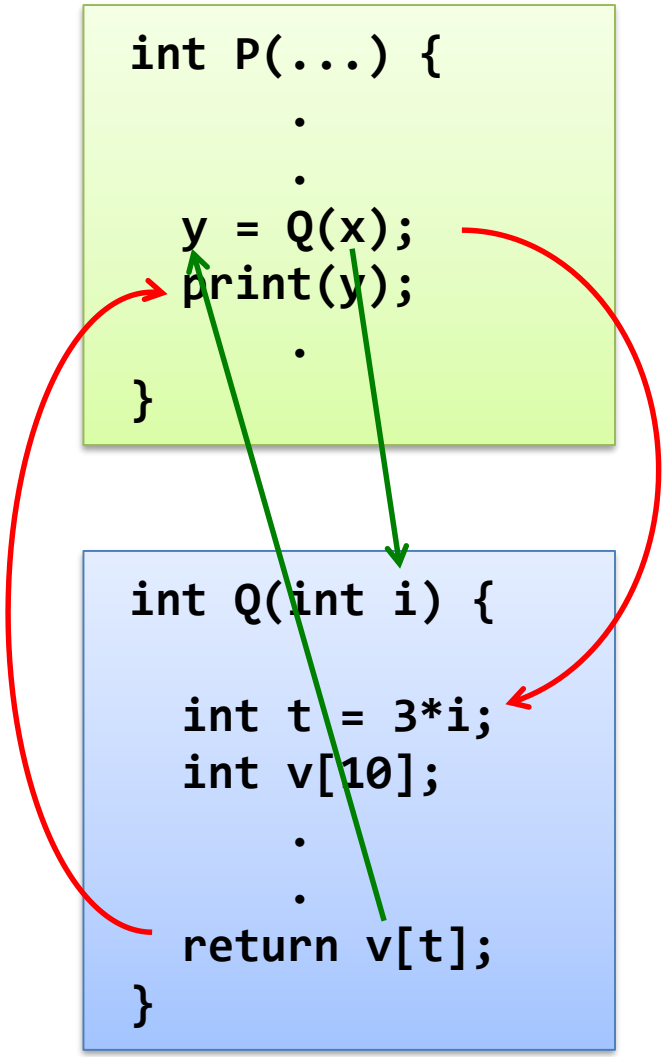
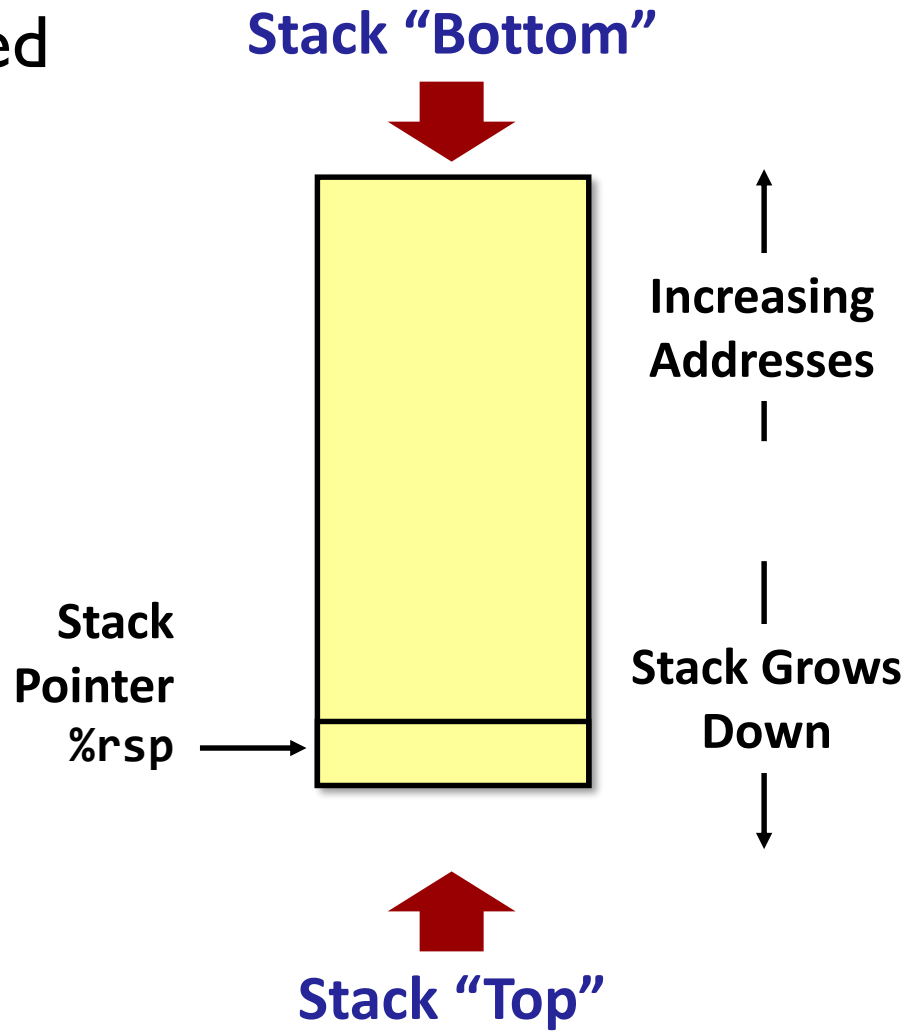
Mechanisms in Procedures

- Passing control
  - To beginning of procedure code
  - Back to return point
- Passing data
  - Procedure arguments
  - Return value
- Memory management
  - Allocate during procedure execution
  - Deallocate upon return
- All implemented with machine instructions



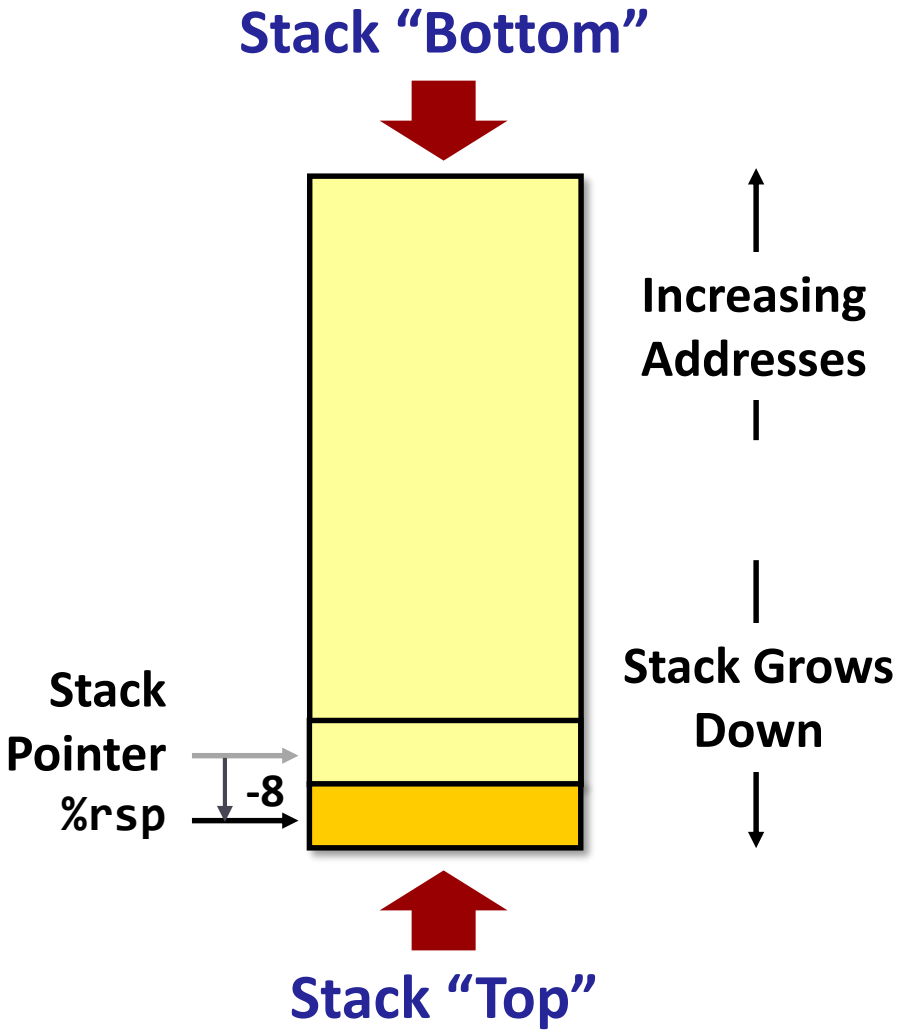
x86-64 Stack

- Region of memory managed with stack discipline
  - Last-In, First-Out (LIFO)
  - Push & Pop
- Grows toward lower addresses
- Register **`%rsp`** contains lowest stack address
  - Address of "top" element



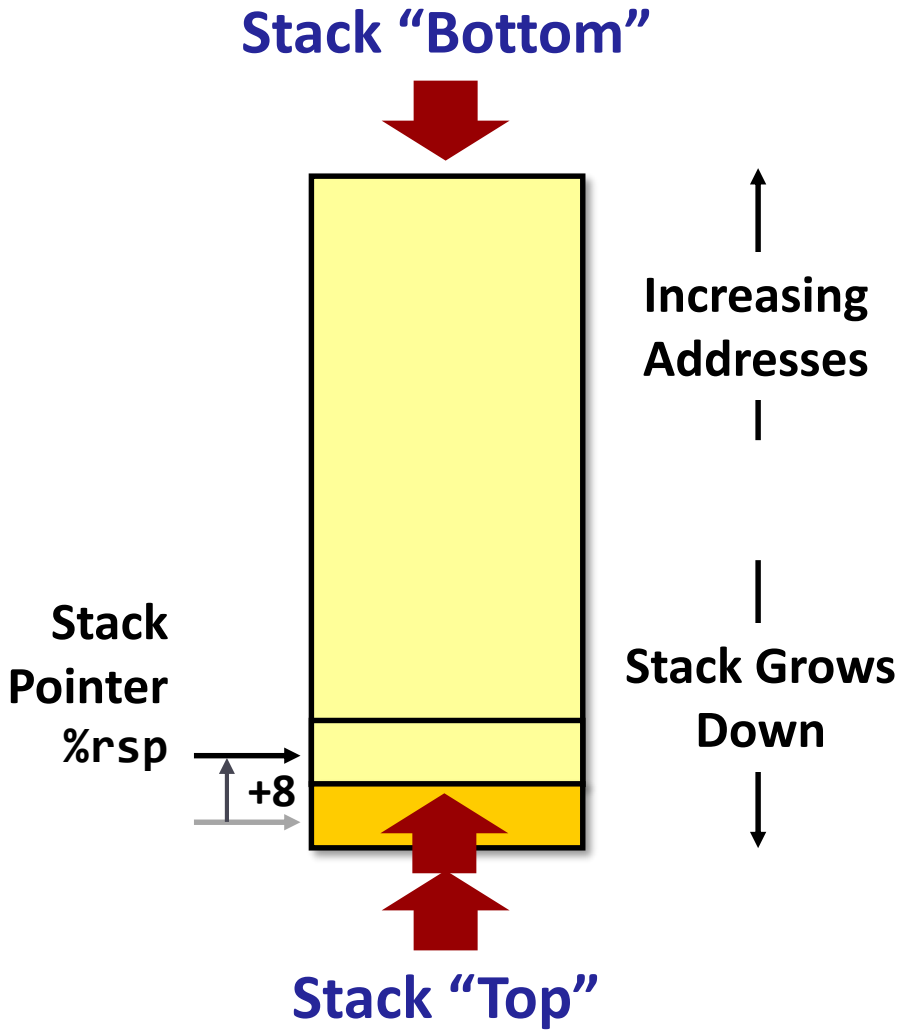
x86-64 Stack: Push

- **`pushq` *`Src`***
  - Fetch operand at ***`Src`***
  - Decrement **`%rsp`** by 8
  - Write operand at address given by **`%rsp`**



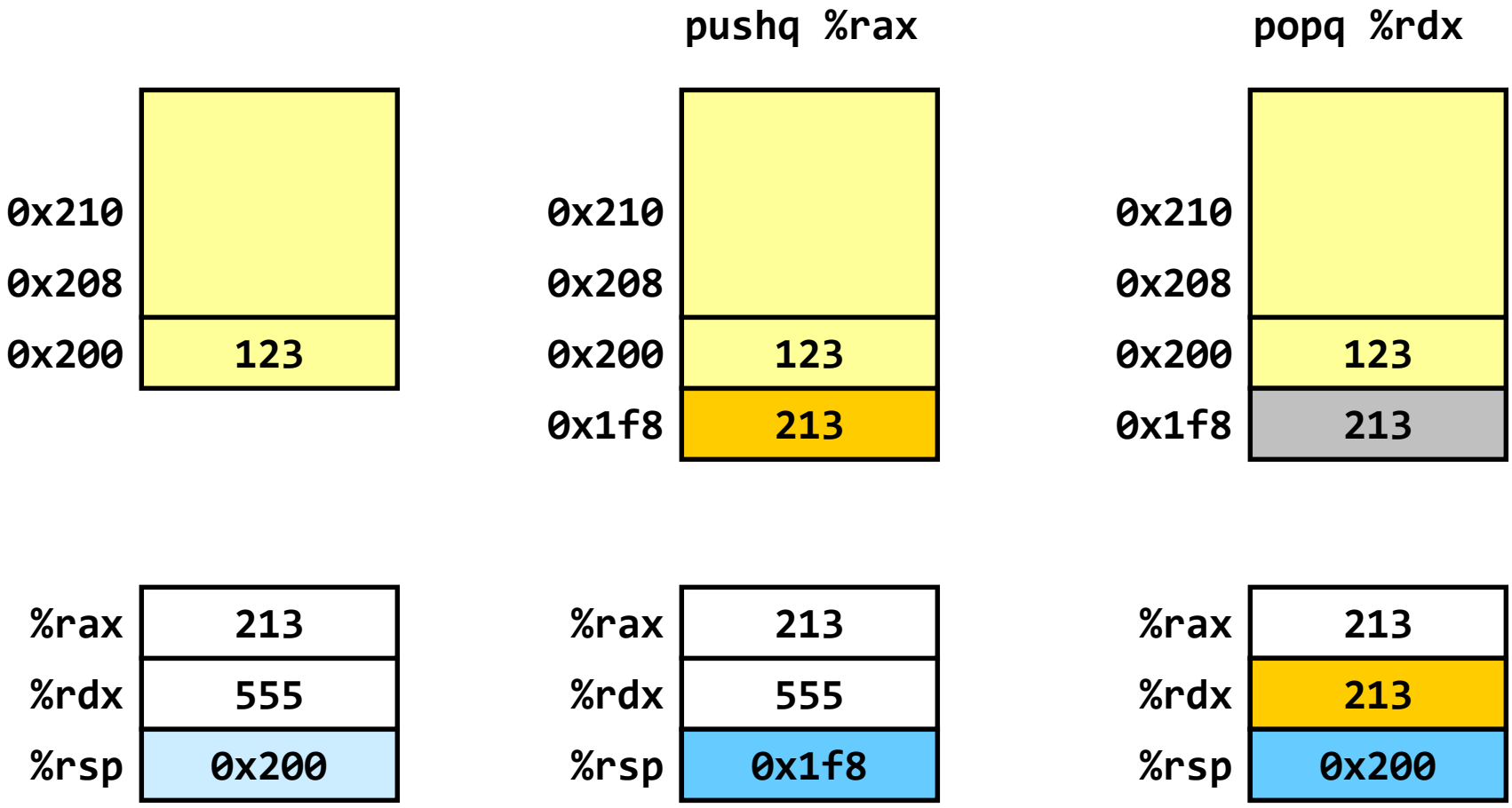
x86-64 Stack: Pop

- **`popq` *`Dest`***
  - Read value at address given by `%rsp`
  - Increment `%rsp` by 8
  - Store value at ***`Dest`*** (must be a register)



x86-64 Stack: Example

- Stack operation examples



Procedure Control Flow

- Use stack to support procedure call and return

- Procedure call: **`call`** ***`label`***
  - Push return address on stack
    - Address of the next instruction right after call
  - Jump to ***`label`***

- Procedure return: ***`ret`***
  - Pop address from stack
  - Jump to address

Example

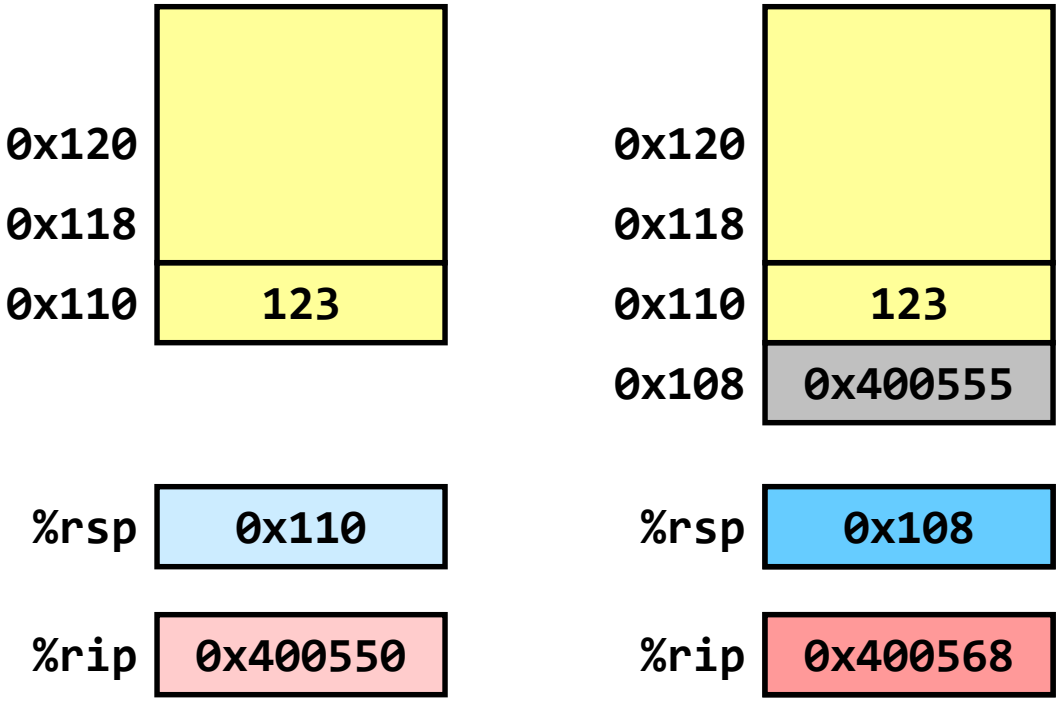
```
0000000000400546 <main>:
  400546:       48 8d 64 24 f8          lea    -0x8(%rsp),%rsp
  40054b:       bf 0a 00 00 00          mov    $0xa,%edi
  400550:       e8 13 00 00 00          callq  400568 <fact>
  400555:       48 89 c7                mov    %rax,%rdi
  400558:       e8 21 00 00 00          callq  40057e <print>
  40055d:       b8 00 00 00 00          mov    $0x0,%eax
  400562:       48 8d 64 24 08          lea    0x8(%rsp),%rsp
  400567:       c3                      retq

0000000000400568 <fact>:
  400568:       b8 01 00 00 00          mov    $0x1,%eax
  40056d:       eb 08                   jmp    400577 <fact+0xf>
  40056f:       48 0f af c7             imul   %rdi,%rax
  400573:       48 83 ef 01             sub    $0x1,%rdi
  400577:       48 83 ff 01             cmp    $0x1,%rdi
  40057b:       7f f2                   jg     40056f <fact+0x7>
  40057d:       c3                      retq
```

Procedure Call Example

```
400550:    e8 13 00 00 00        callq  400568 <fact>
400555:    48 89 c7              mov    %rax,%rdi
```

0x00400555
+0x00000013
=0x00400568

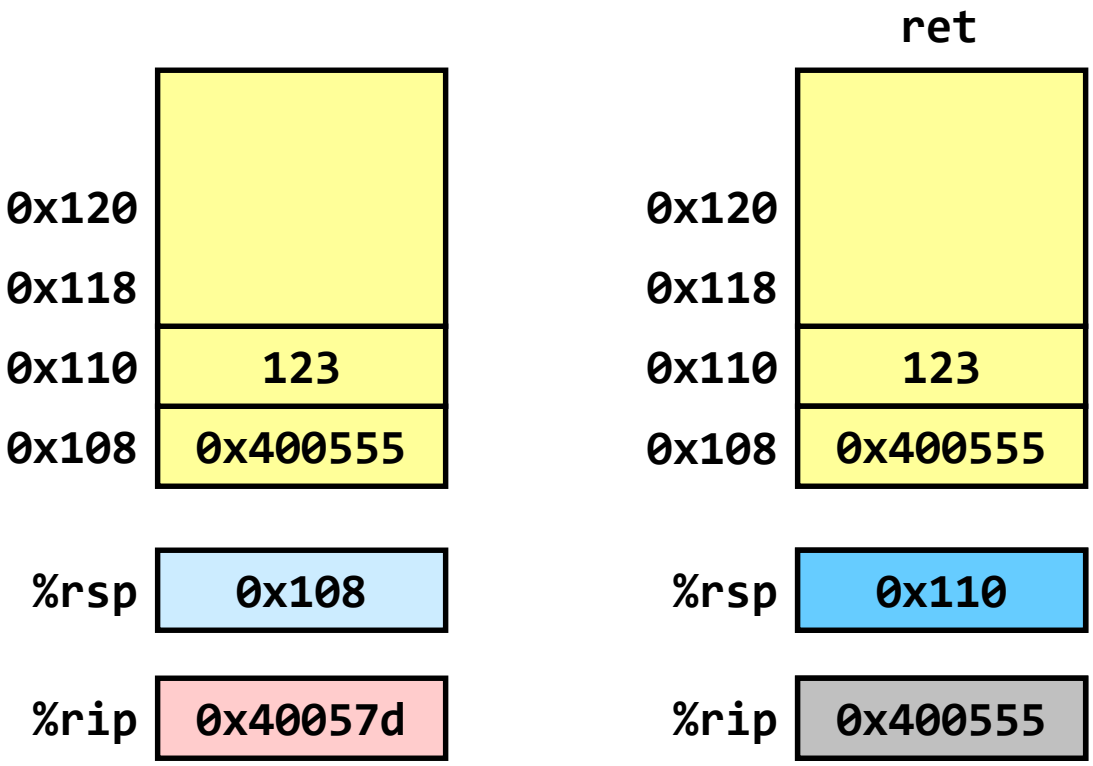
callq 400568



%rip is program counter

Procedure Return Example

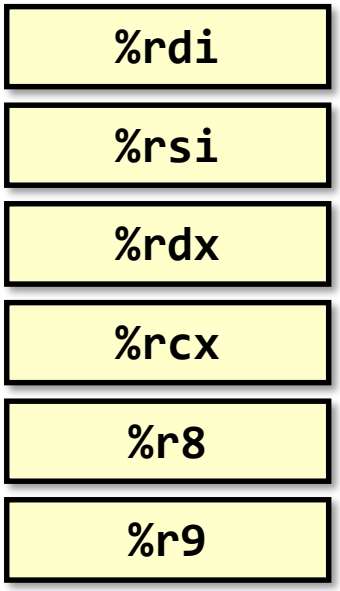
```
40057d:      c3                    retq
```



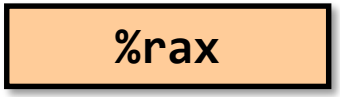
%rip is program counter

Passing Arguments

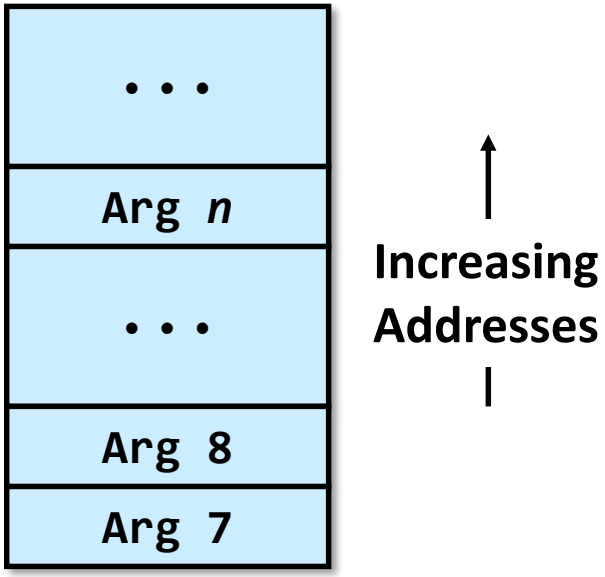
- First 6 arguments:
  - *"Diane's silk dress costs $89"*



- Return value



- Remaining arguments:
  - Push the rest on the stack in reverse order
  - Only allocate stack space when needed

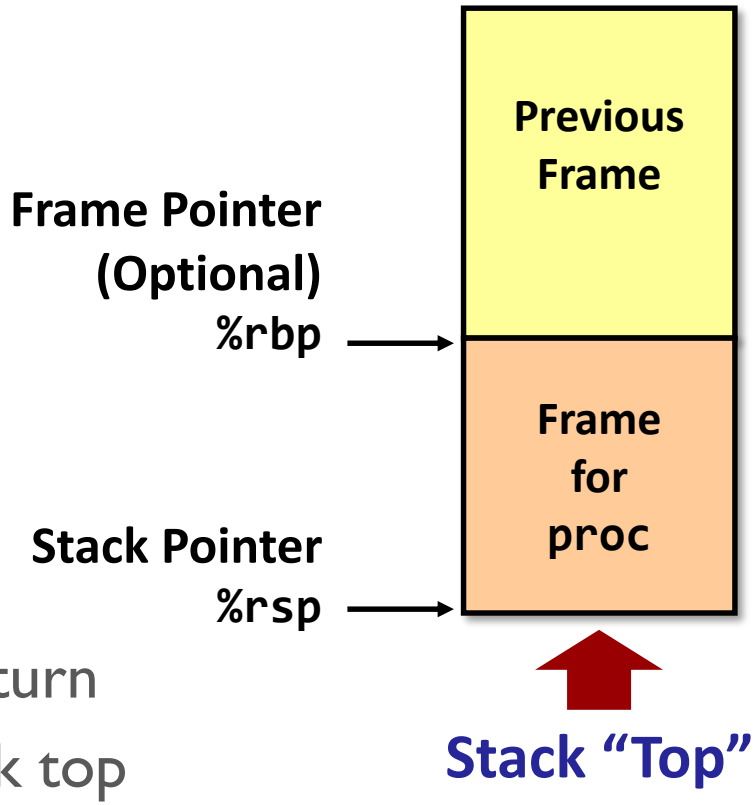


Stack-based Languages

- Languages that support recursion (e.g. C, C++, Pascal, Java)
  - Code must be "Reentrant"
    - Multiple simultaneous instantiations of single procedure
  - Need some place to store state of each instantiation
    - Arguments, local variables, return address
- Stack discipline
  - State for given procedure needed for limited time
    - From when called to when return
  - Callee returns before caller does
- Stack allocated in *frames*
  - State for single procedure instantiation

Stack Frame

- Contents
  - Return information
  - Arguments
  - Local variables & temp space
- Management
  - "Set-up" code: space allocated when enter procedure
  - "Finish" code: deallocate when return
  - Stack pointer **`%rsp`** indicates stack top
  - Optional frame pointer **`%rbp`** indicates start of current frame



Stack Frames: Example (1)

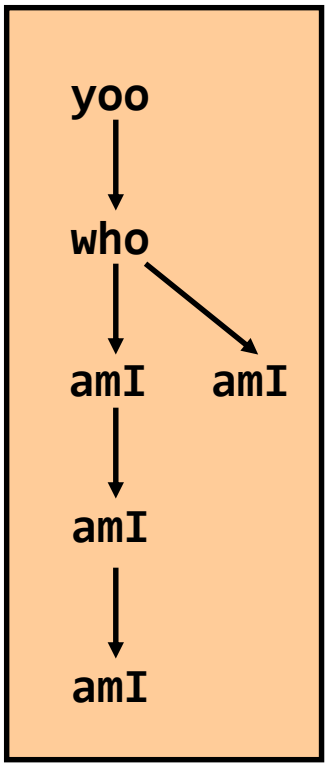
Code Structure

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

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

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

Call Chain



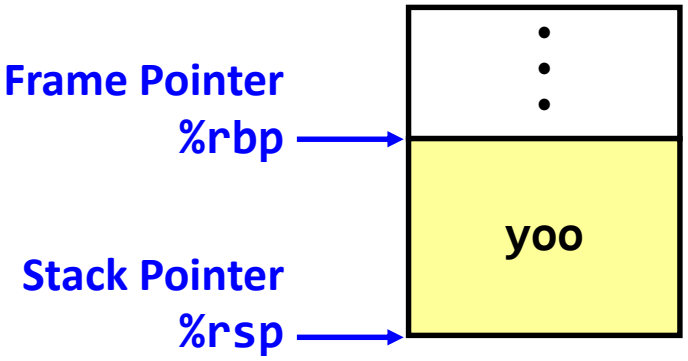
- Procedure **amI** recursive

Stack Frames: Example (2)

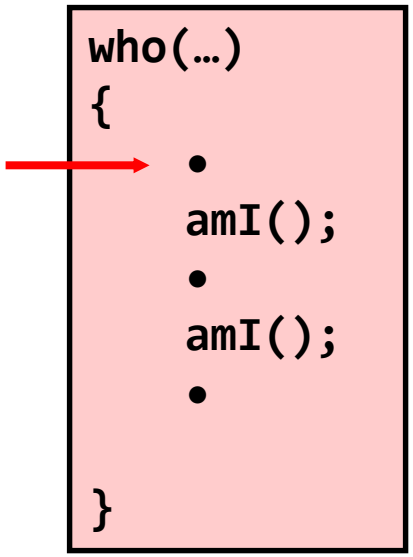
```
yoo(…)
{
    •
    •
    who();
    •
    •
}
```

Call Chain

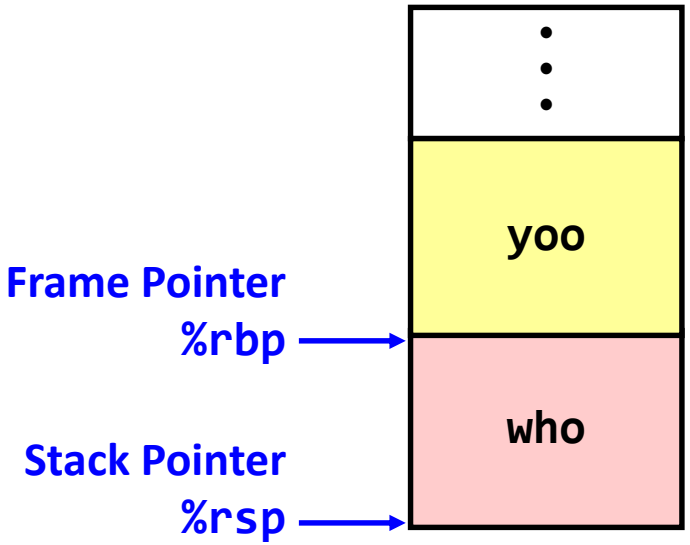
yoo



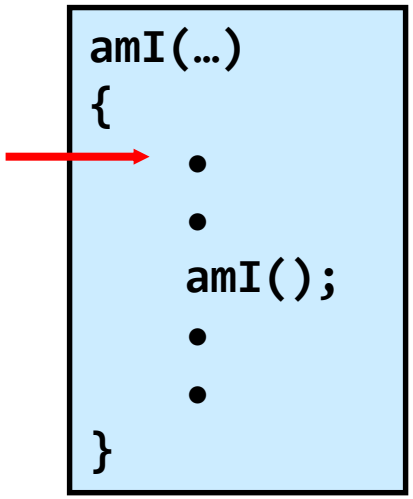
Stack Frames: Example (3)



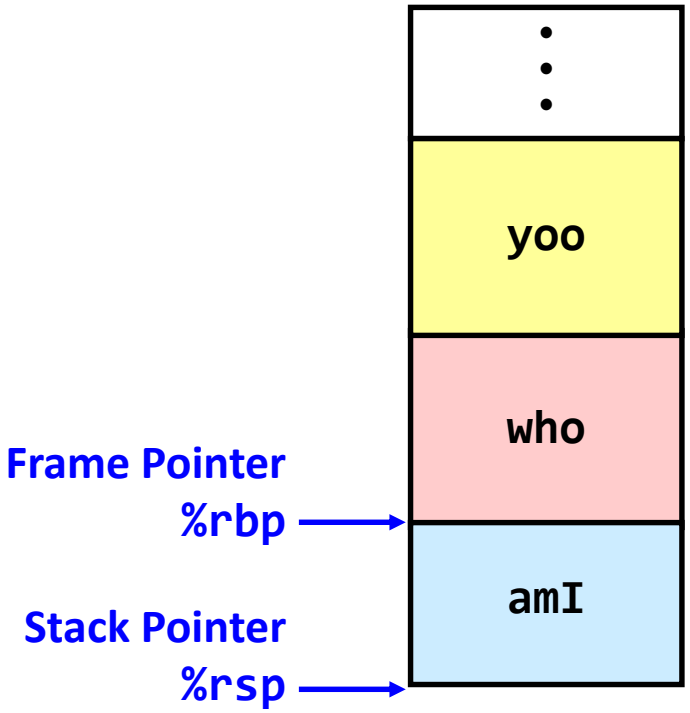
Call Chain



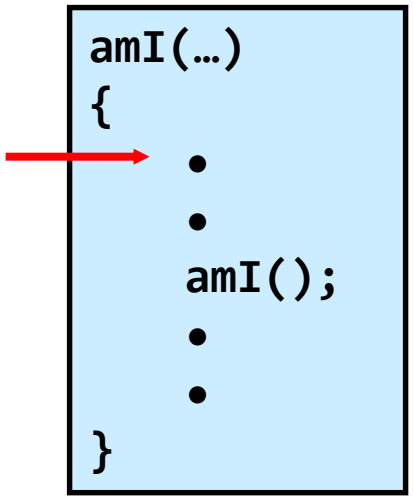
Stack Frames: Example (4)



Call Chain

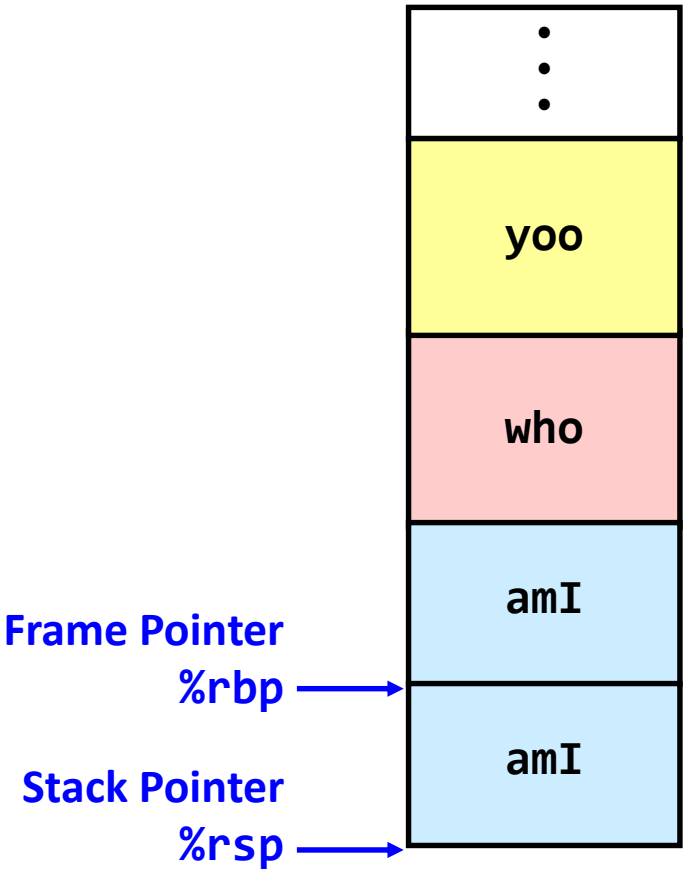


Stack Frames: Example (5)



Call Chain

yoo
who
amI
amI

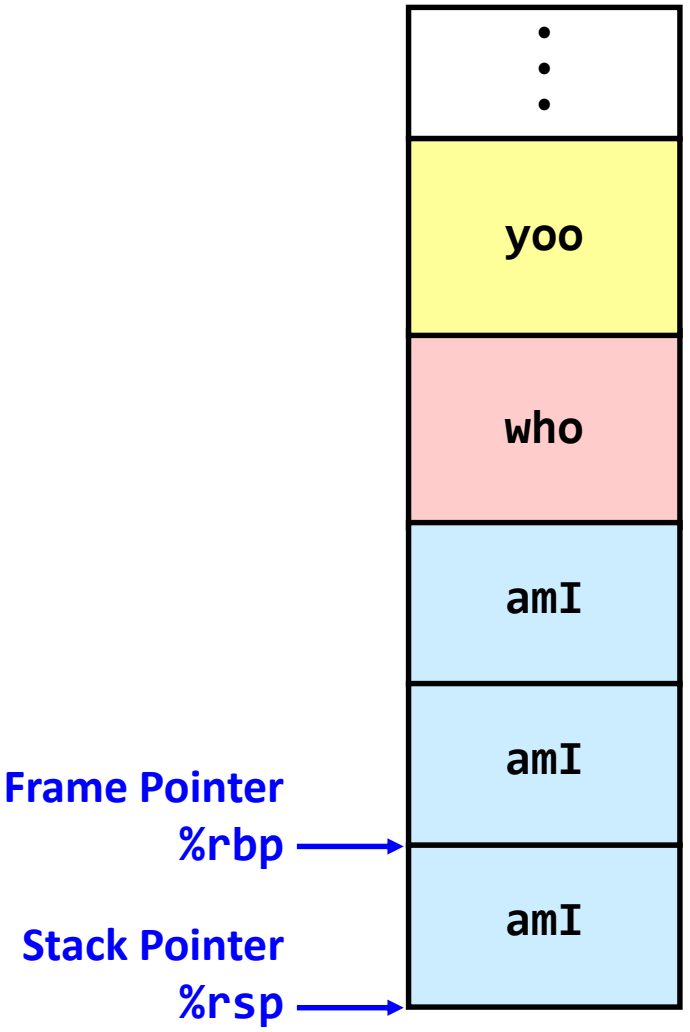


Stack Frames: Example (6)

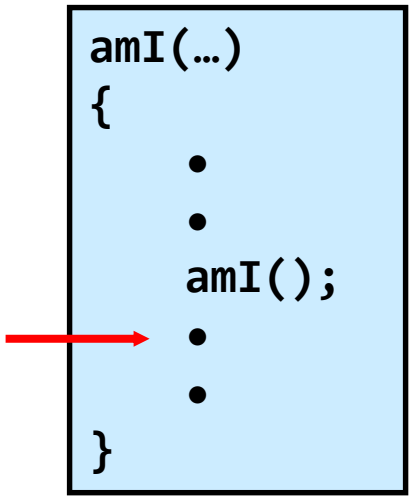
```
amI(…)
{
    •
    •
    amI();
    •
    •
}
```

Call Chain

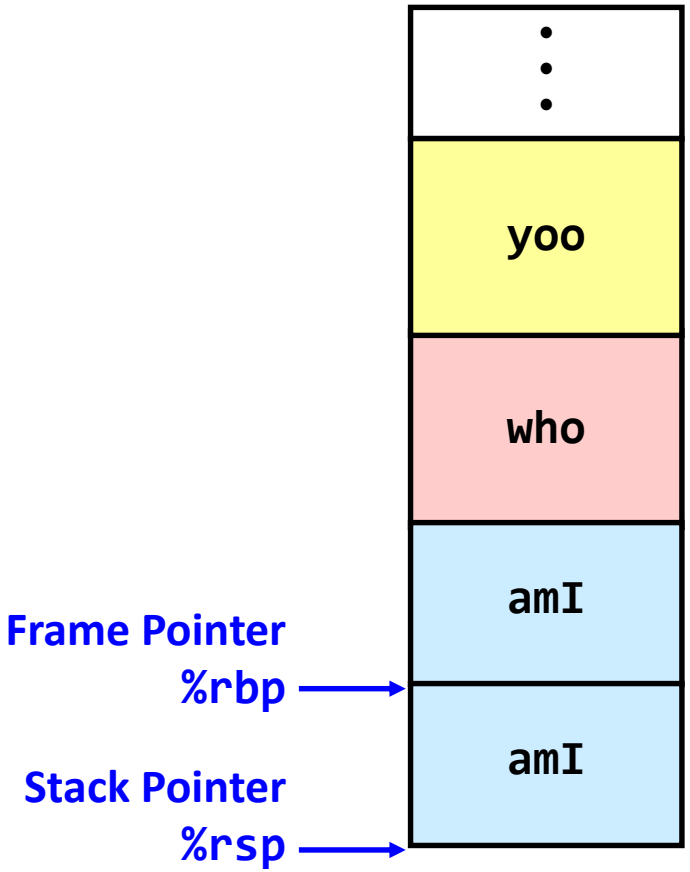
yoo
↓
who
↓
amI
↓
amI
↓
amI



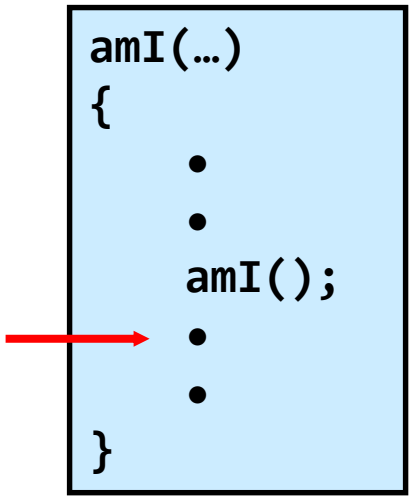
Stack Frames: Example (7)



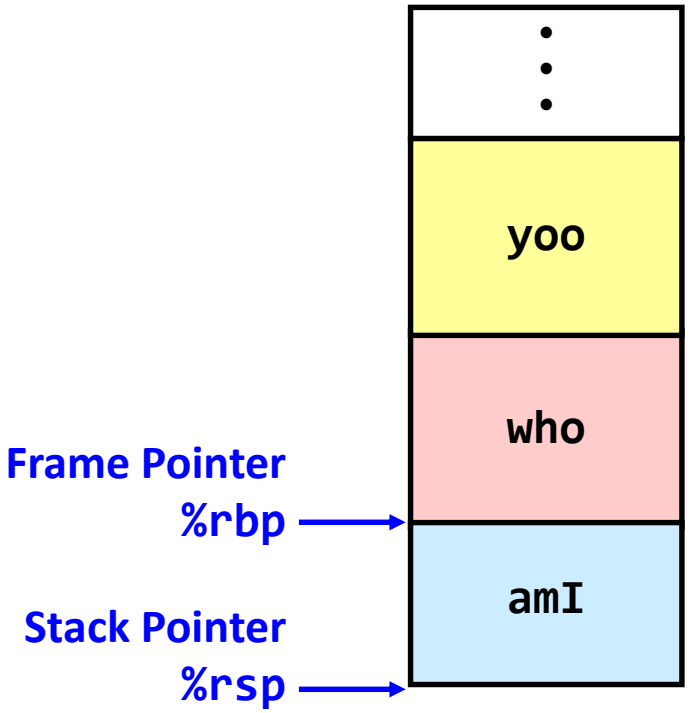
Call Chain



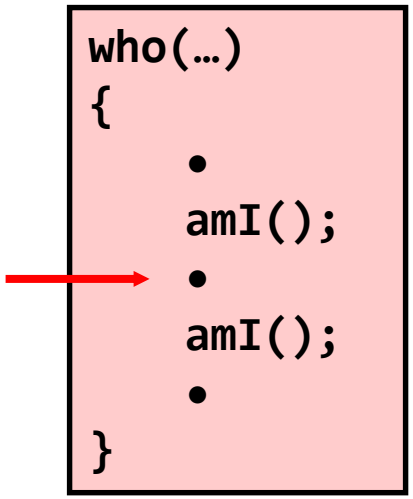
Stack Frames: Example (8)



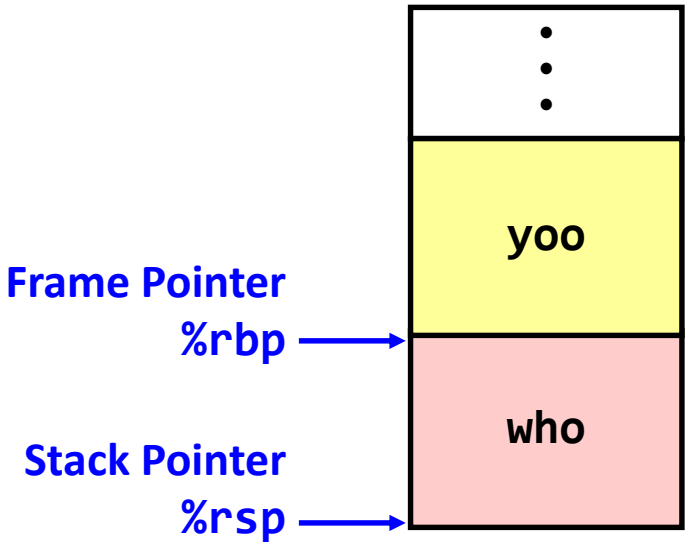
Call Chain



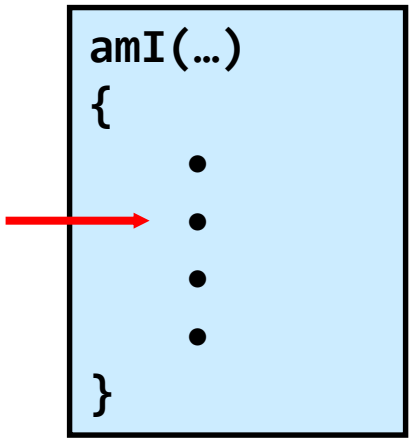
Stack Frames: Example (9)



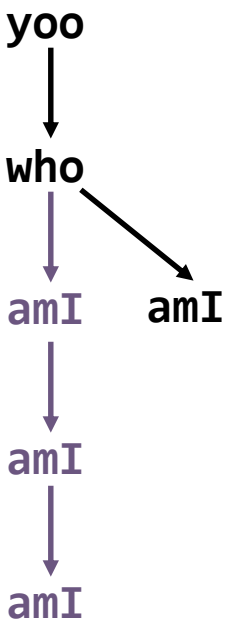
Call Chain

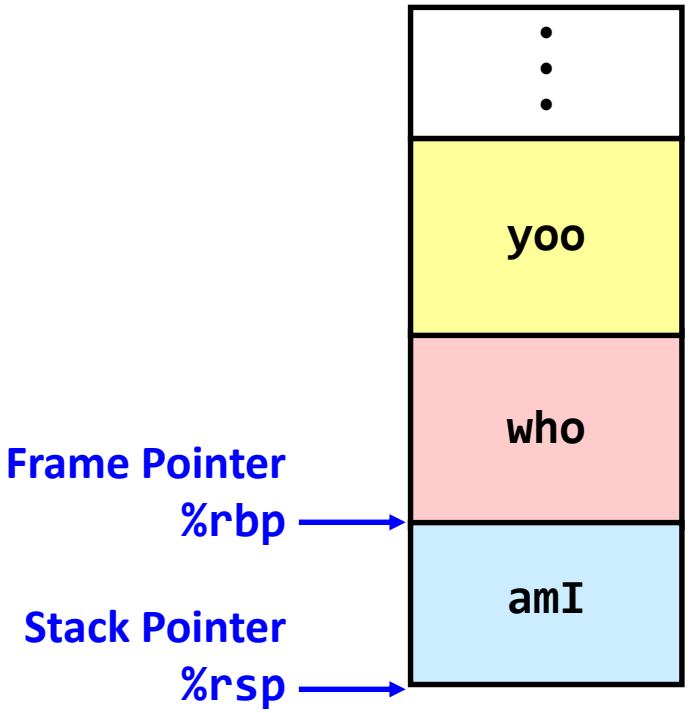


Stack Frames: Example (10)

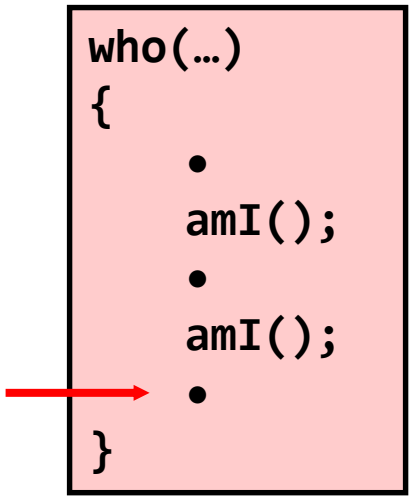


Call Chain

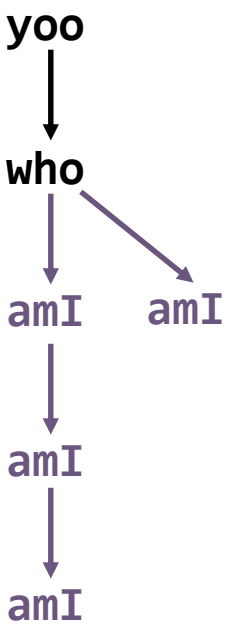


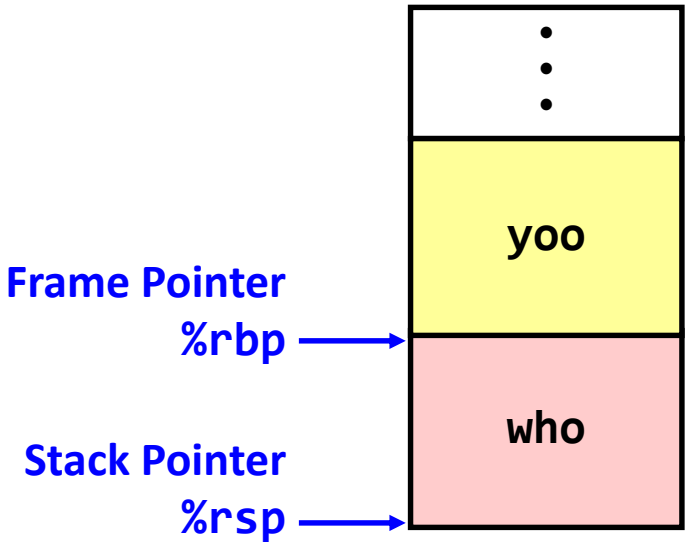


Stack Frames: Example (11)

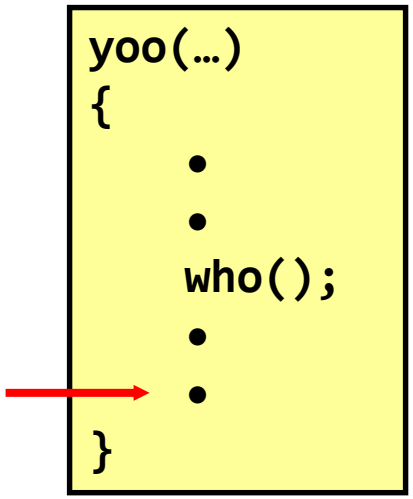


Call Chain

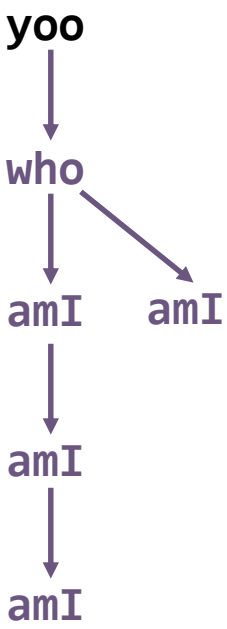


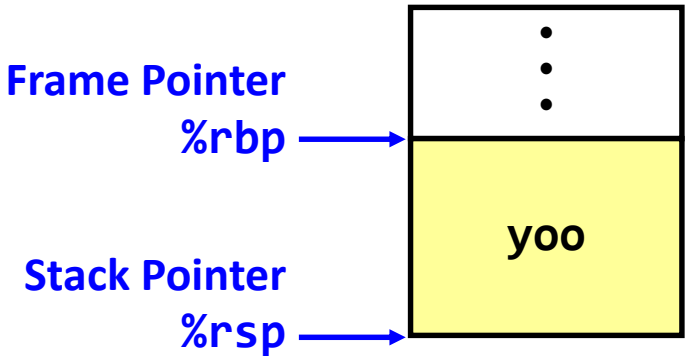


Stack Frames: Example (12)



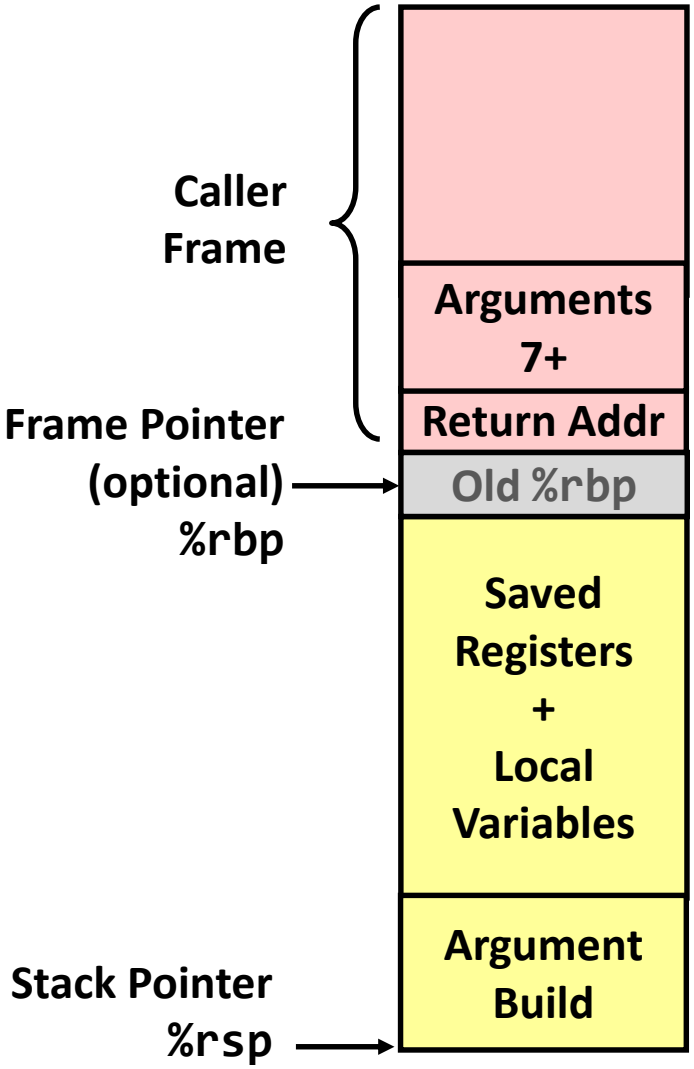
Call Chain





x86-64/Linux Stack Frame

- Current stack frame ("Top" to Bottom)
  - "Argument build:" Parameters for function about to call
  - Local variables
    - if can't keep in registers
  - Saved register context
  - Old frame pointer (optional)
- Caller stack frame
  - Return address
    - Pushed by `call` instruction
  - Arguments for this call



Revisiting Swap

```
long v1 = 1111;
long v2 = 2222;

void swap (long *xp, long *yp)
{
    long t = *xp;
    *xp = *yp;
    *yp = t;
}

int main (void)
{
     swap (&v1, &v2);
          ...
}
```

```
v2:
    .quad    2222
    ...
v1:
    .quad    1111
    ...
swap:
    movq     (%rdi), %rax
    movq     (%rsi), %rdx
    movq     %rdx, (%rdi)
    movq     %rax, (%rsi)
    ret

main:
    ...
    movq     $v2, %rsi
    movq     $v1, %rdi
    call     swap
    ...
    ret
```

Register Saving Problem

- When procedure **yoo()** calls **who()**:
  - **yoo()** is the caller, **who()** is the callee
- Can register be used for temporary storage?

```
yoo:
    . . .
    movq $15213, %rdx
    call who
    addq %rdx, %rax
    . . .
    ret
```

```
who:
    . . .
    subq $91125, %rdx
    . . .
    ret
```

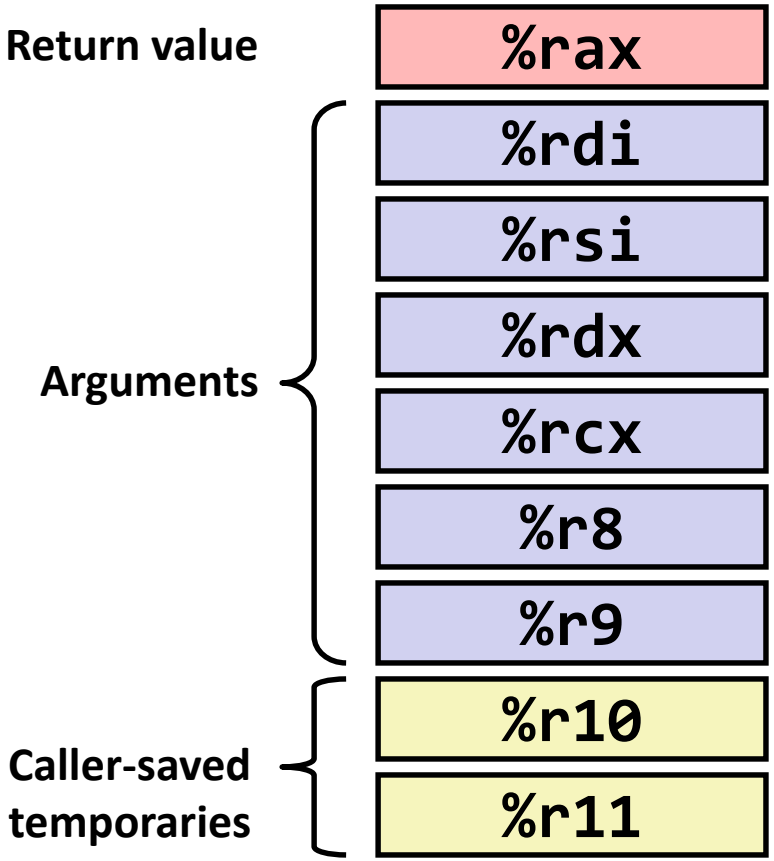
  - Contents of register **%rdx** overwritten by **who()**

Register Saving Conventions

- "Caller saved" registers
  - Caller saves temporary values in its frame before the call
  - Contents of these registers can be modified as a result of procedure call
  - x86-64: %rax, %rdi, %rsi, %rdx, %rcx, %r8, %r9, %r10, %r11
- "Callee saved" registers
  - Callee saves temporary values in its frame before using
  - Callee restores them before returning to caller
  - The contents of these registers are preserved across a procedure call
  - x86-64: %rbx, %r12, %r13, %r14, %r15, %rbp

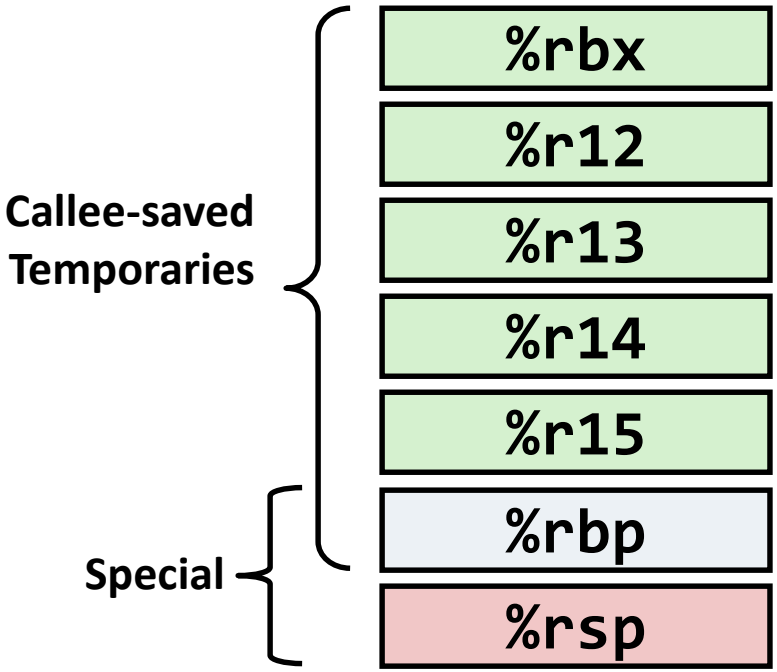
x86-64/Linux Register Usage (1)

- **`%rax`**
  - Return value
  - Also caller-saved
  - Can be modified by procedure
- **`%rdi`, …, `%r9`**
  - Arguments
  - Also caller-saved
  - Can be modified by procedure
- **`%r10`, `%r11`**
  - Caller-saved
  - Can be modified by procedure



x86-64/Linux Register Usage (2)

- **`%rbx`, `%r12`, `%r13`, `%r14`, `%r15`**
  - Callee-saved
  - Callee must save & restore
- **`%rbp`**
  - Callee-saved
  - Callee must save & restore
  - May be used as frame pointer
- **`%rsp`**
  - Special from of callee save
  - Restored to original value upon exit from procedure



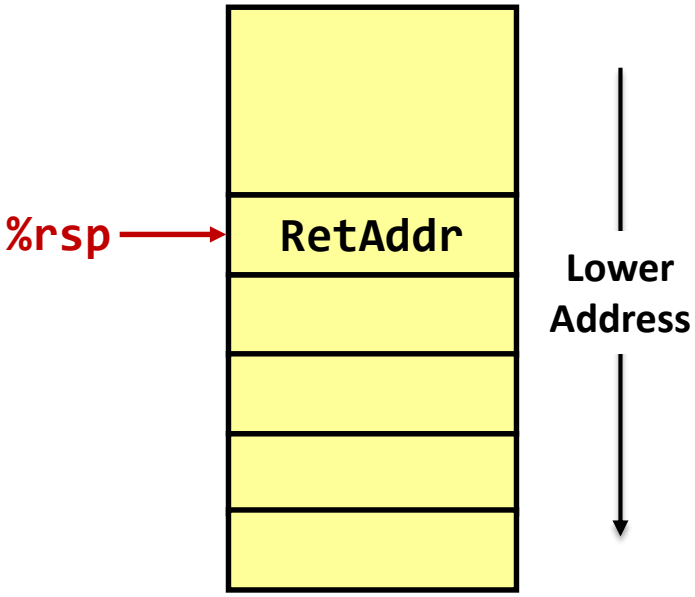
Recursive Factorial: rfact

- Registers
  - %rax used without first saving
  - %rbx used, but save at beginning & restore at end

```
long rfact(long x)
{
    long rval;
    if (x <= 1)
      return 1;
    rval = rfact(x-1);
    return rval * x;
}
```

```
rfact:
    cmpq    $1, %rdi
    jle     .L3
    pushq   %rbx
    movq    %rdi, %rbx
    leaq    -1(%rdi), %rdi
    call    rfact
    imulq   %rbx, %rax
    jmp     .L2
.L3:
    movl    $1, %eax
    ret
.L2:
    popq    %rbx
    ret
```

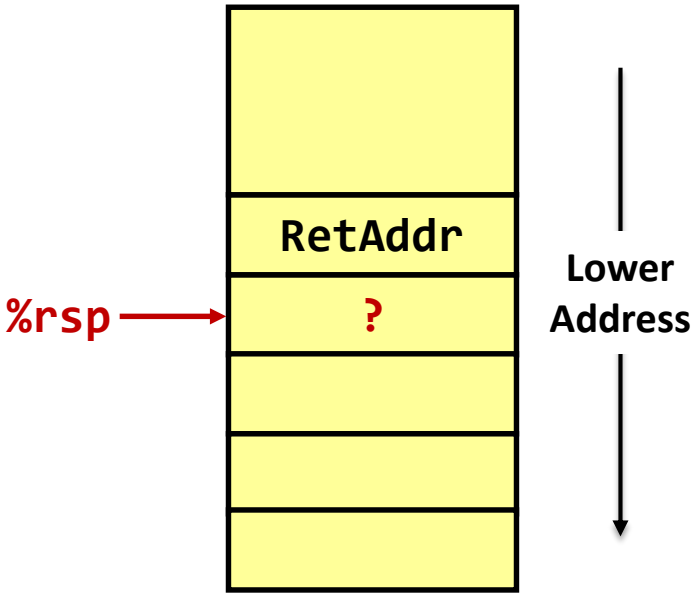
Example: rfact(3)



Registers	
%rdi	3
%rax	?
%rbx	?

```
rfact:
%rip → cmpq   $1, %rdi
       jle    .L3
       pushq  %rbx
       movq   %rdi, %rbx
       leaq   -1(%rdi), %rdi
       call   rfact
A:     imulq  %rbx, %rax
       jmp    .L2
.L3:
       movl   $1, %eax
       ret
.L2:
       popq   %rbx
       ret
```

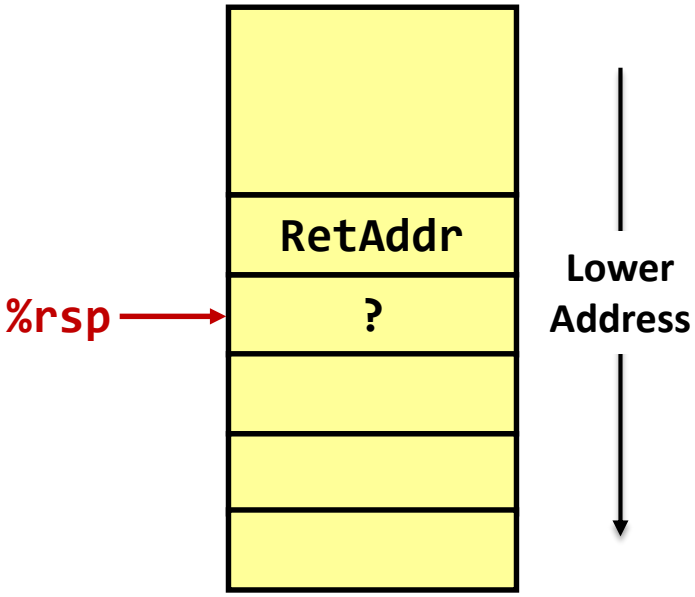
Example: rfact(3)



Registers	
%rdi	3
%rax	?
%rbx	?

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
%rip→ pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

Example: rfact(3)

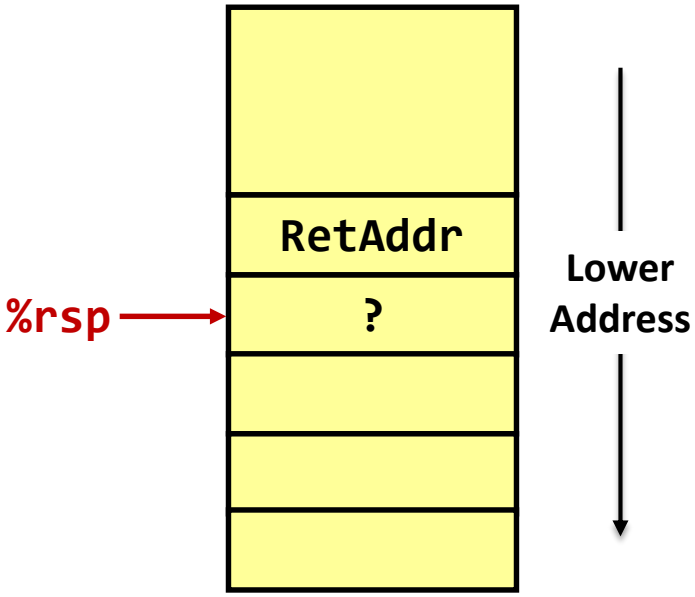


Registers	
%rdi	3
%rax	?
%rbx	3

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

%rip →

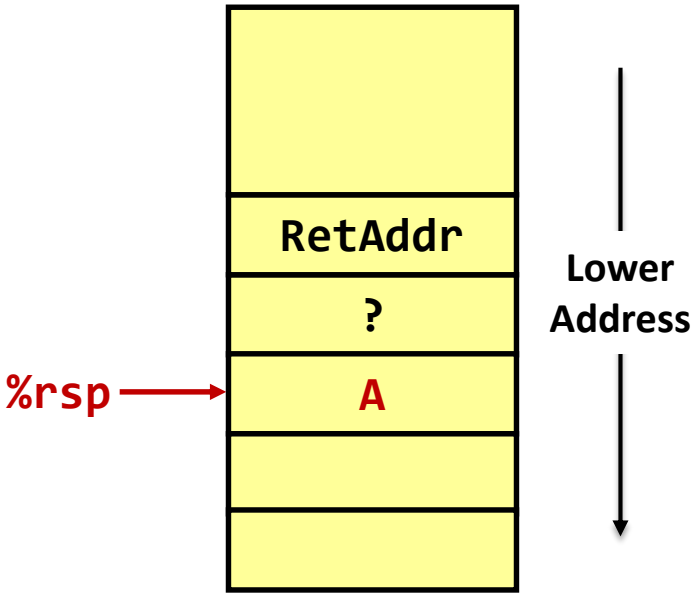
Example: rfact(3)



Registers	
%rdi	2
%rax	?
%rbx	3

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
%rip→ leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

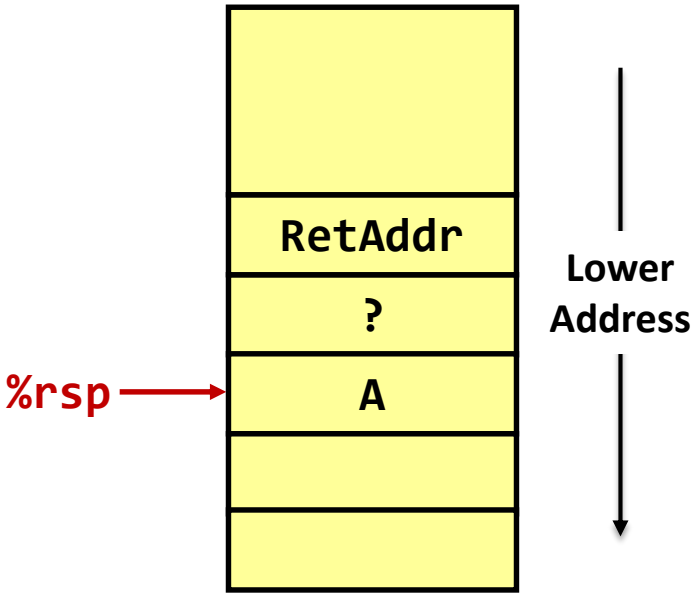
Example: rfact(3)



Registers	
%rdi	2
%rax	?
%rbx	3

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
%rip→ call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

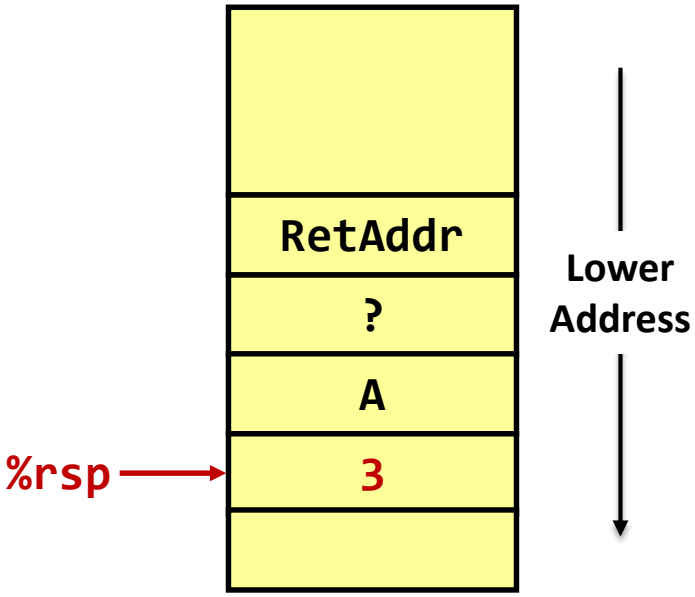
Example: rfact(3)



Registers	
%rdi	2
%rax	?
%rbx	3

```
rfact:
%rip → cmpq   $1, %rdi
       jle    .L3
       pushq  %rbx
       movq   %rdi, %rbx
       leaq   -1(%rdi), %rdi
       call   rfact
A:     imulq  %rbx, %rax
       jmp    .L2
.L3:
       movl   $1, %eax
       ret
.L2:
       popq   %rbx
       ret
```

Example: rfact(3)

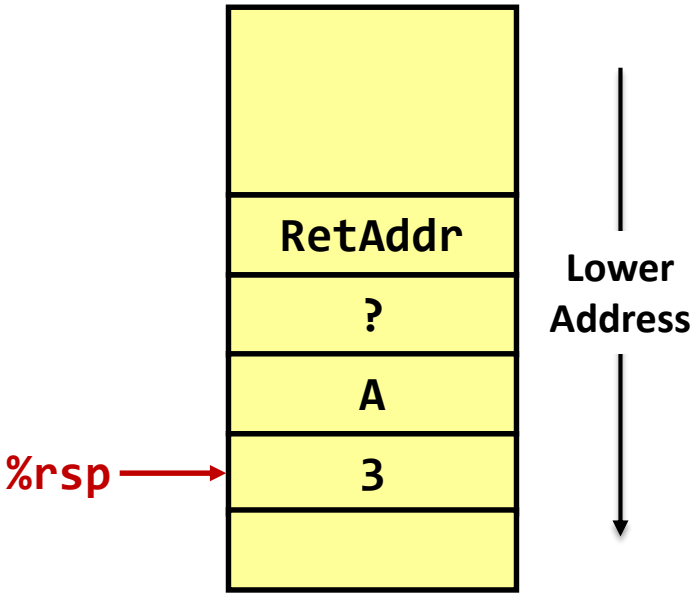


Registers	
%rdi	2
%rax	?
%rbx	3

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

%rip →

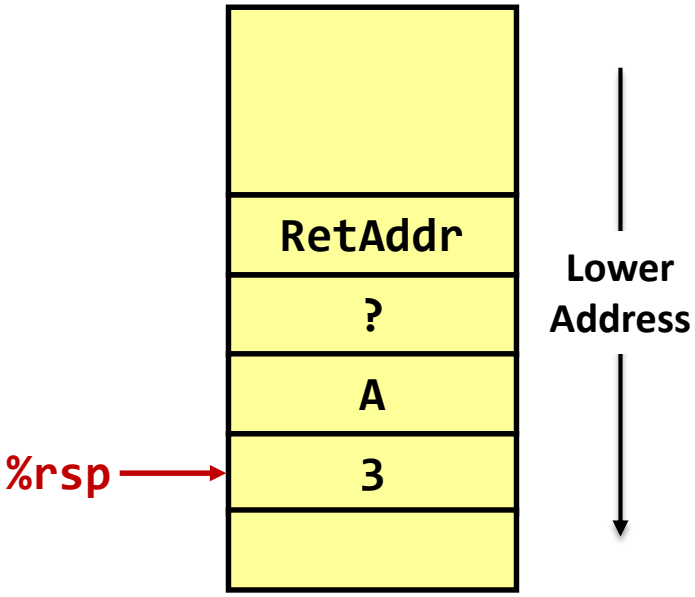
Example: rfact(3)



Registers	
%rdi	2
%rax	?
%rbx	2

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
%rip→ movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

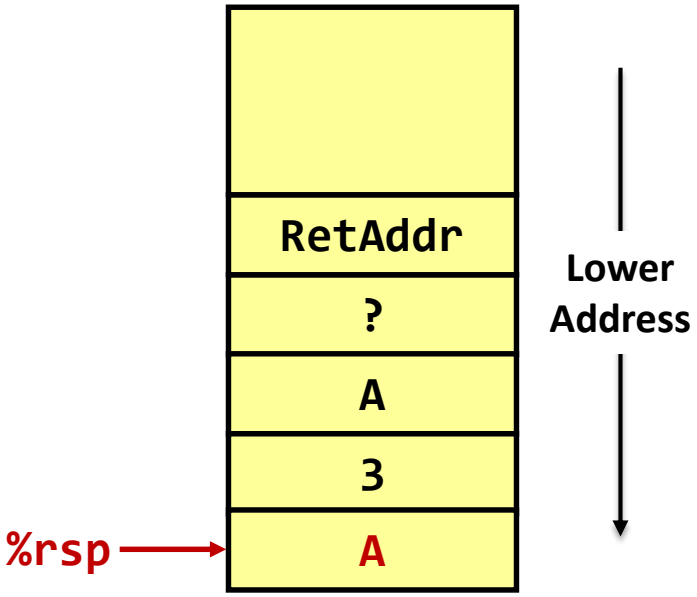
Example: rfact(3)



Registers	
%rdi	1
%rax	?
%rbx	2

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
%rip→ leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

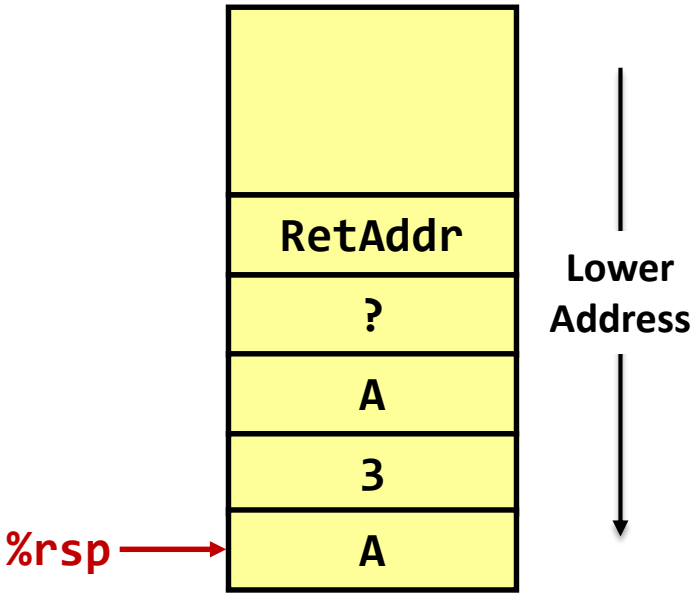
Example: rfact(3)



Registers	
%rdi	1
%rax	?
%rbx	2

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
%rip→ call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

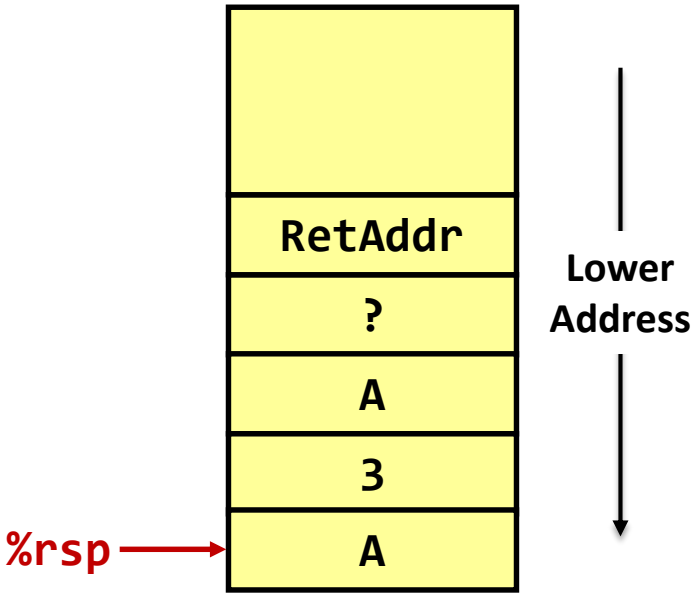
Example: rfact(3)



Registers	
%rdi	1
%rax	?
%rbx	2

```
rfact:
%rip → cmpq   $1, %rdi
       jle    .L3
       pushq  %rbx
       movq   %rdi, %rbx
       leaq   -1(%rdi), %rdi
       call   rfact
A:     imulq  %rbx, %rax
       jmp    .L2
.L3:
       movl   $1, %eax
       ret
.L2:
       popq   %rbx
       ret
```

Example: rfact(3)

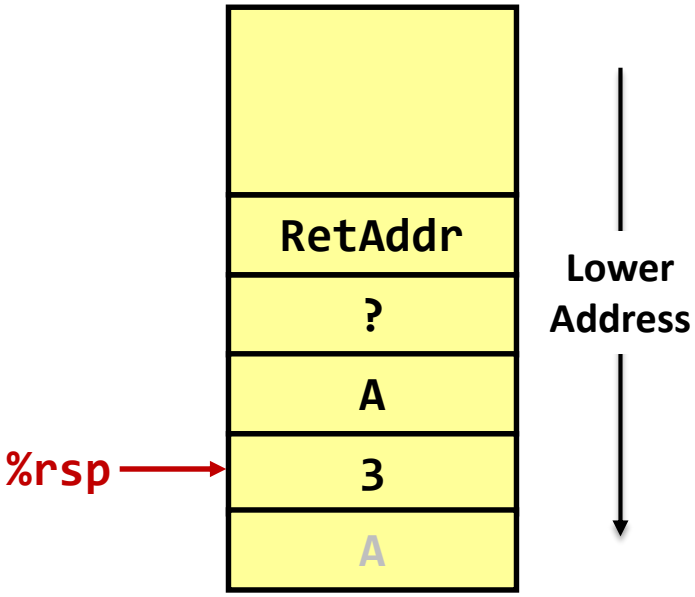


Registers	
%rdi	1
%rax	1
%rbx	2

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

%rip →

Example: rfact(3)

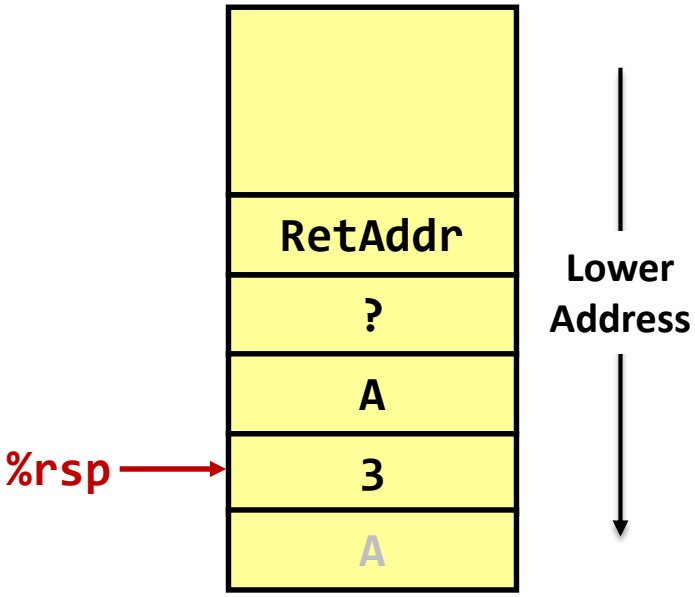


Registers	
%rdi	1
%rax	1
%rbx	2

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

%rip → A:

Example: rfact(3)

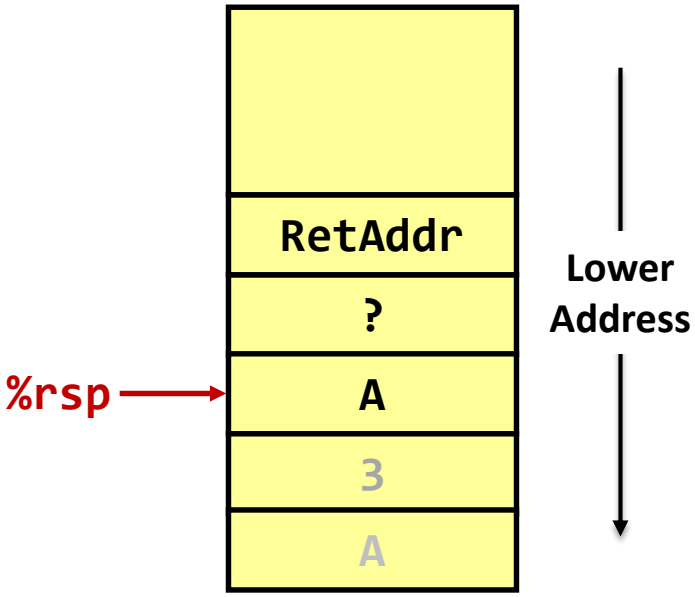


Registers	
%rdi	1
%rax	2
%rbx	2

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

%rip → A:

Example: rfact(3)

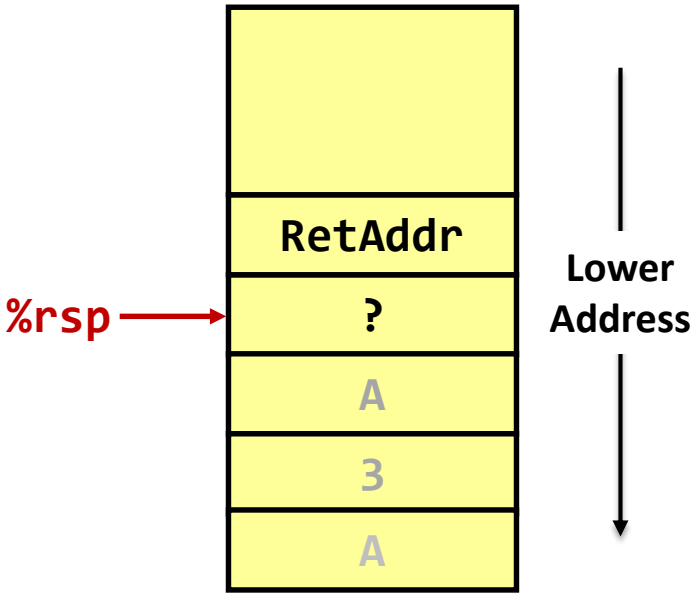


Registers	
%rdi	1
%rax	2
%rbx	3

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

%rip →

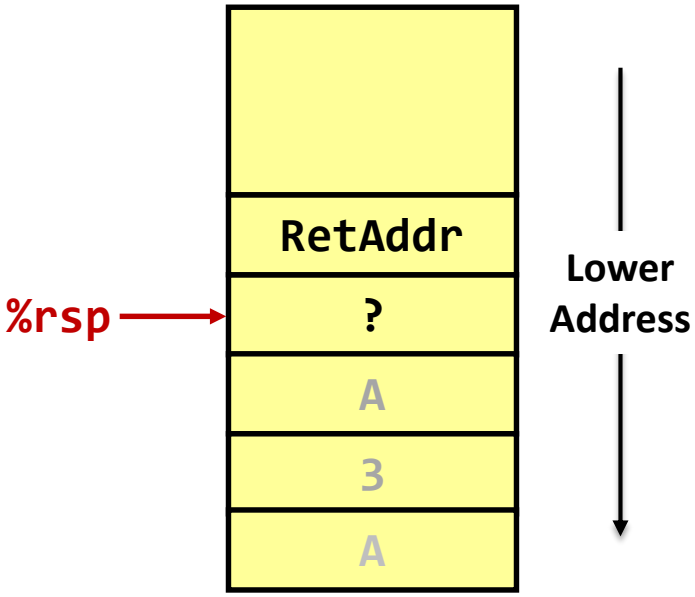
Example: rfact(3)



Registers	
%rdi	1
%rax	2
%rbx	3

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
%rip A: imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

Example: rfact(3)

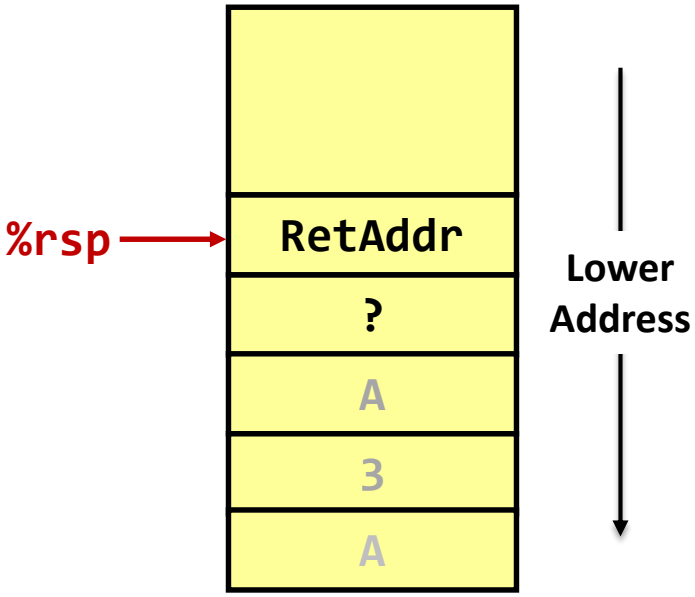


Registers	
%rdi	1
%rax	6
%rbx	3

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

%rip → A:

Example: rfact(3)

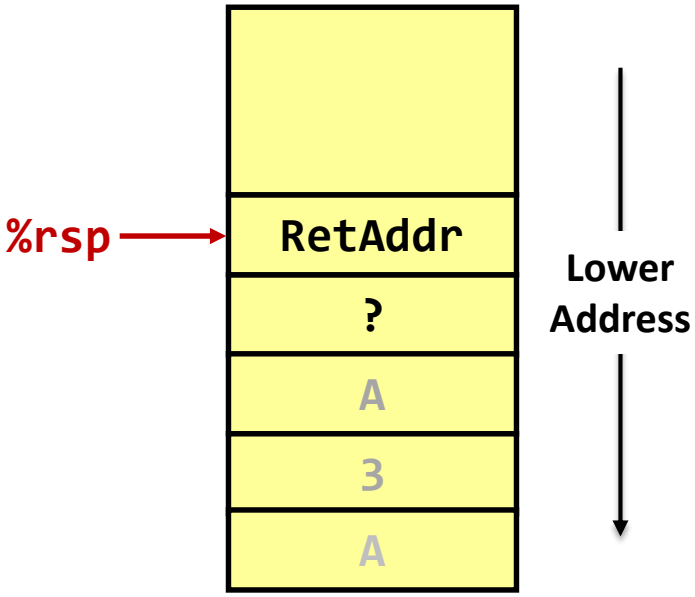


Registers	
%rdi	1
%rax	6
%rbx	?

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

%rip →

Example: rfact(3)



Registers	
%rdi	1
%rax	6
%rbx	?

```
rfact:
    cmpq   $1, %rdi
    jle    .L3
    pushq  %rbx
    movq   %rdi, %rbx
    leaq   -1(%rdi), %rdi
    call   rfact
A:  imulq  %rbx, %rax
    jmp    .L2
.L3:
    movl   $1, %eax
    ret
.L2:
    popq   %rbx
    ret
```

%rip →

Observations about Recursion

- Handled without special consideration
  - Stack frames mean each function call has private storage
    - Saved registers + local variables
    - Saved return address
  - Register saving conventions prevent one function call from corrupting another's data
    - Unless the C code explicitly does so (e.g. buffer overflow)
  - Stack discipline follows call / return pattern
    - If P calls Q, then Q returns before P
    - Last-In, First-Out
- Also works for mutual recursion
  - P calls Q; Q calls P

Summary

- Stack is the right data structure for procedure call / return
  - Private storage for each instance of procedure call
  - Recursion handled by normal calling conventions
- Mechanisms
  - Call, ret, push, pop, etc. instructions
  - Registers for passing arguments and return value
  - Stack memory
- Policies
  - Register usage (caller / callee save, `%rbp` & `%rsp`)
  - Stack frame organization