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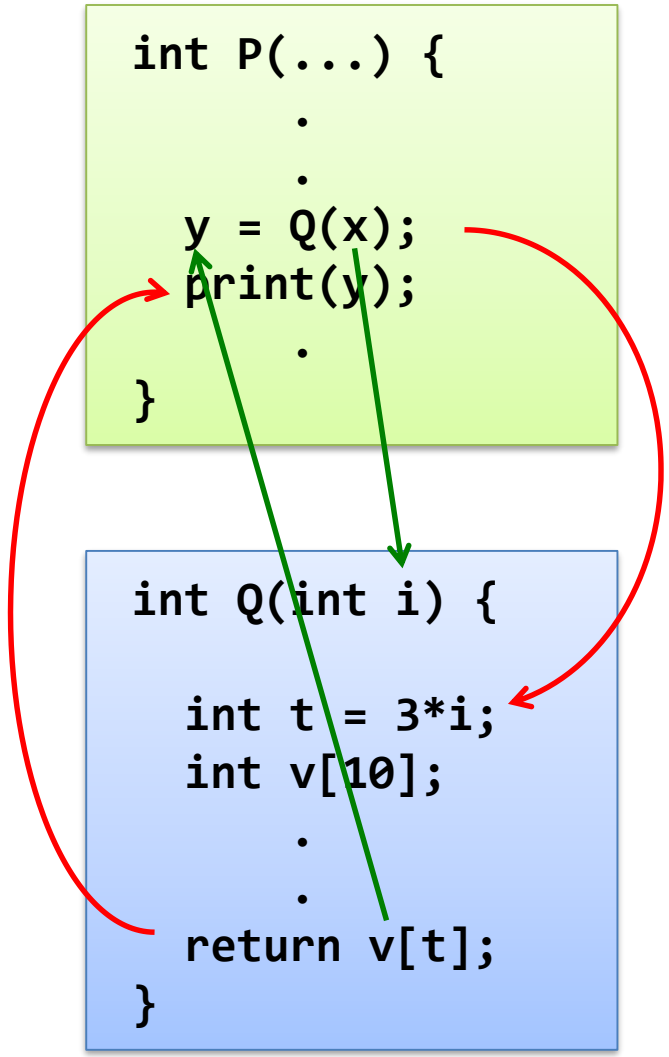
Spring 2019

Assembly III: Procedures

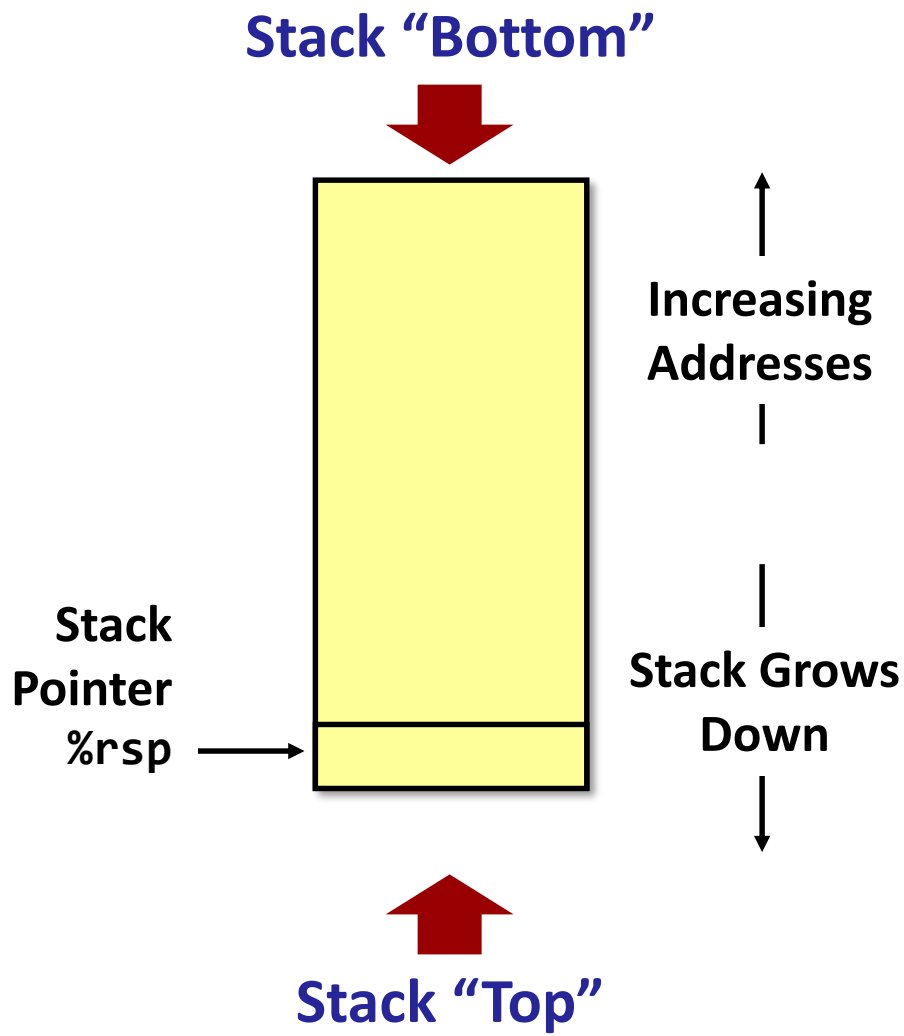
Mechanisms in Procedures

- 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



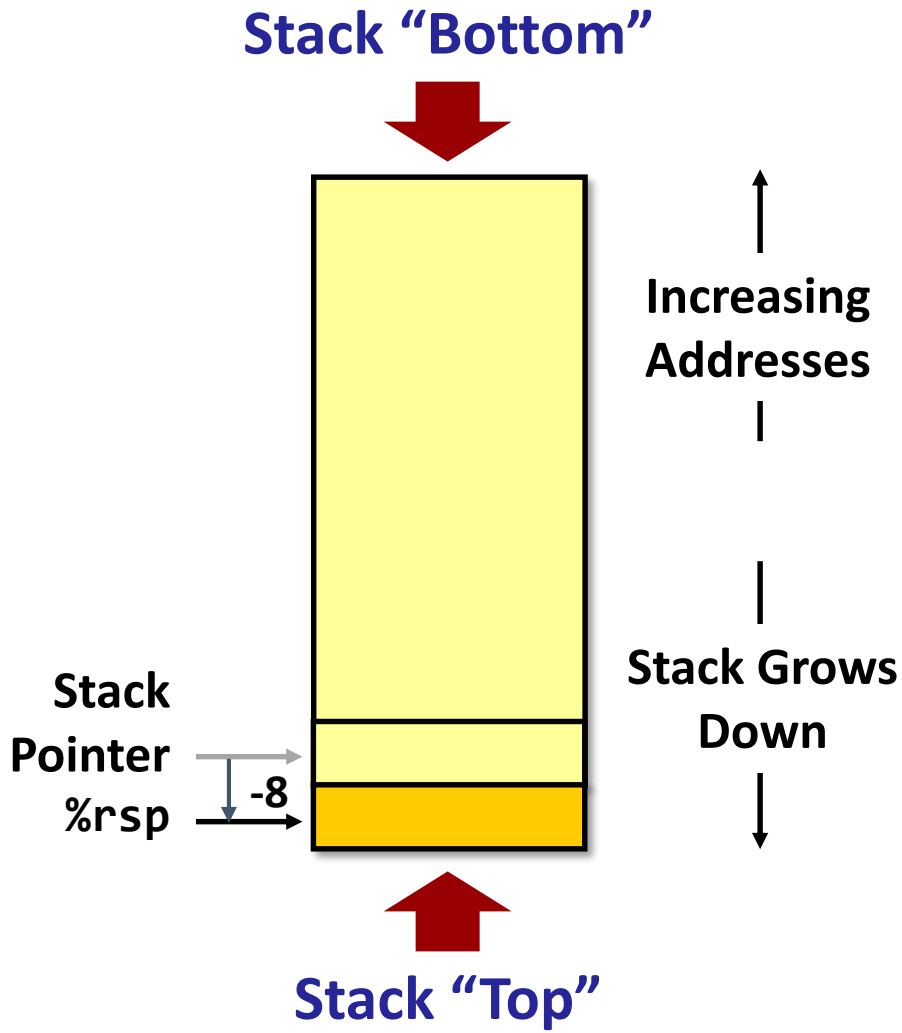
x86-64 Stack

- 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



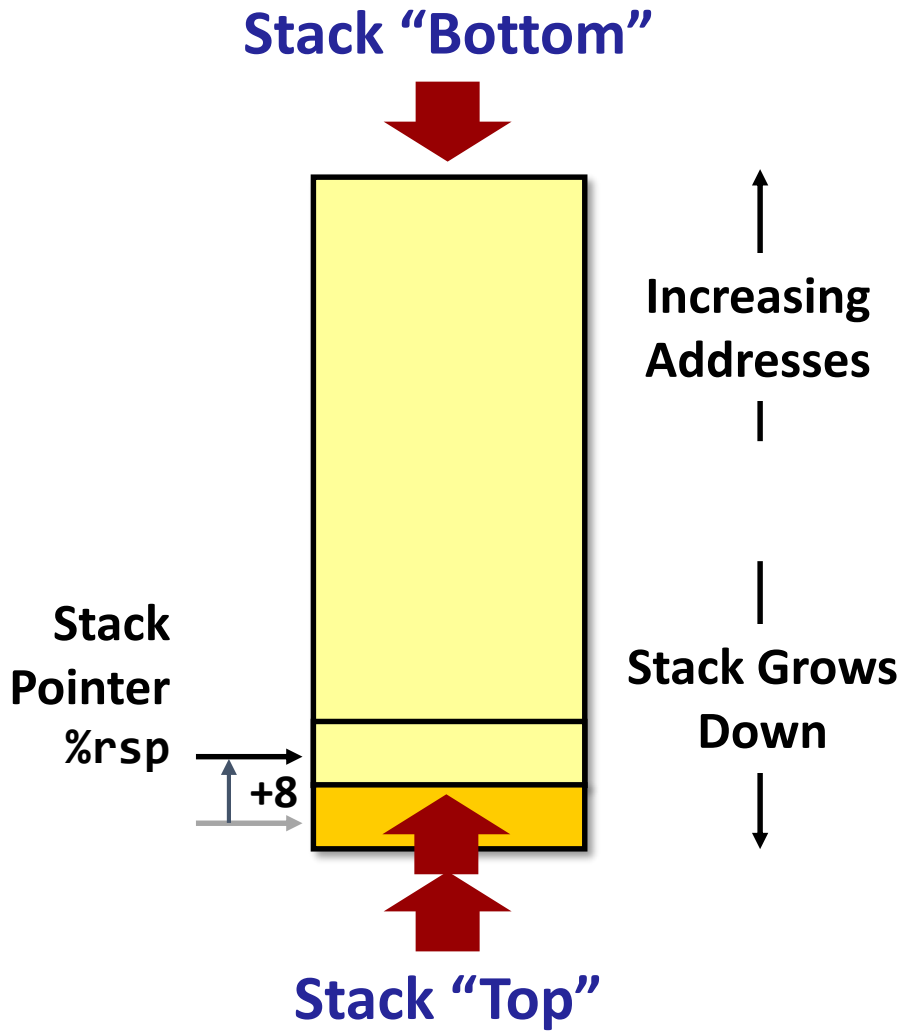
x86-64 Stack: Push

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



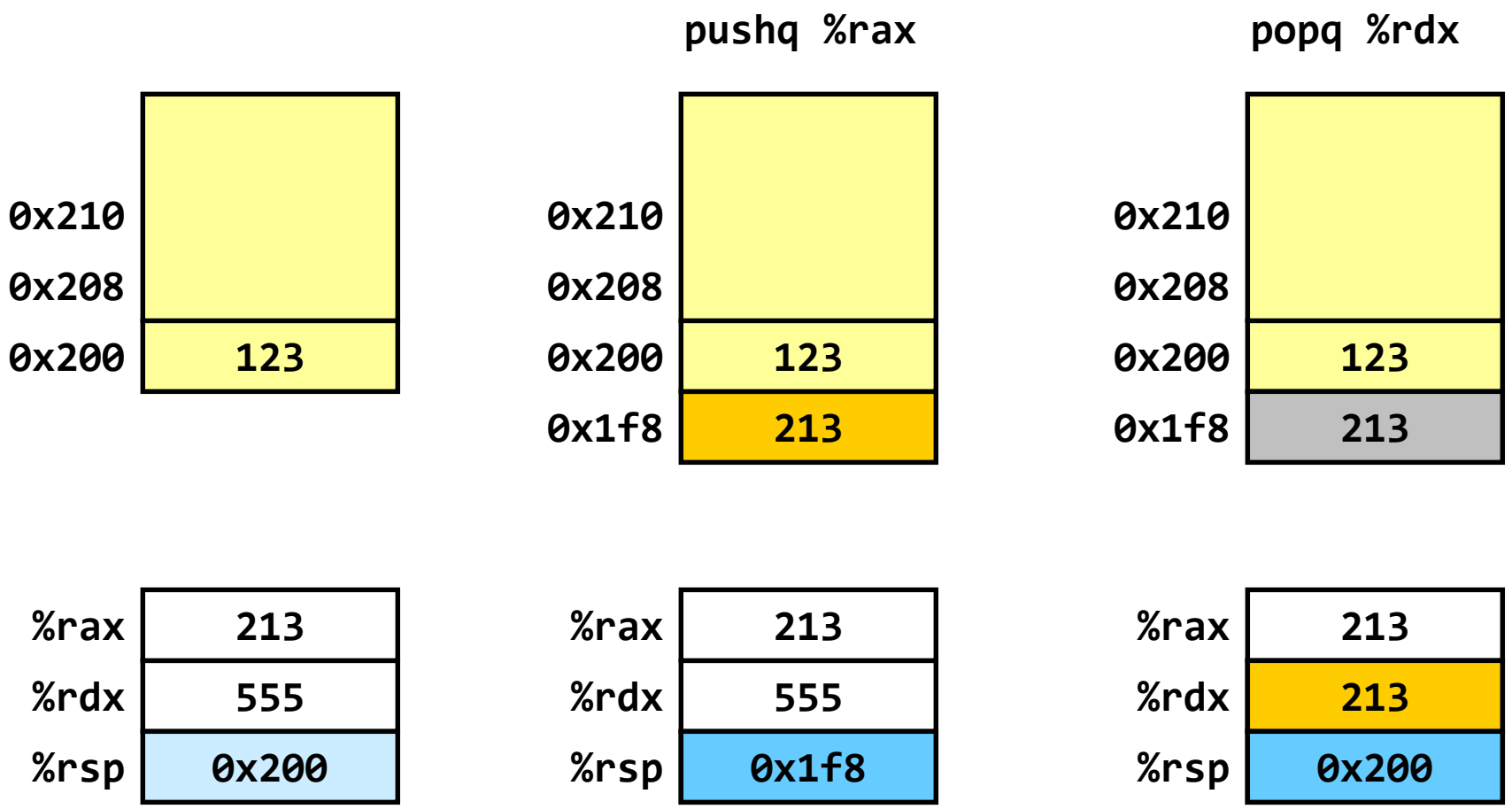
x86-64 Stack: Pop

- **`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

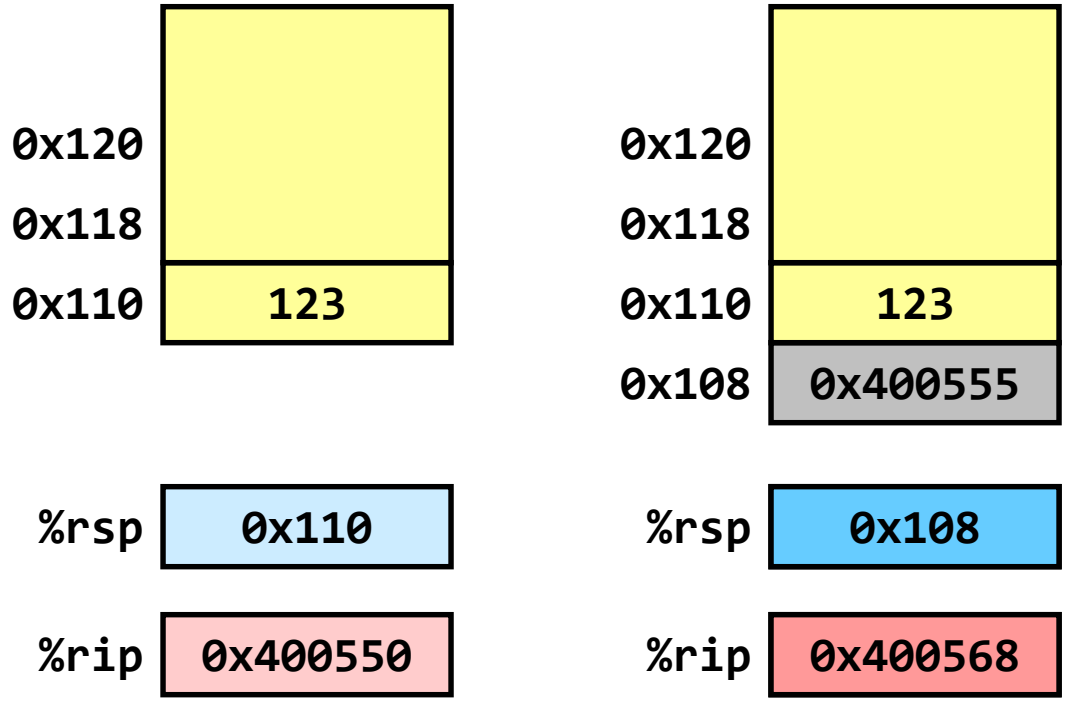
```
0000000000400546 <main>:
  400546:       48 8d 64 24 f8          lea    -0x8(%rsp),%rsp
  40054b:       bf 0a 00 00 00          mov    $0xa,%edi
  400550:       e8 13 00 00 00          callq  400568 <fact>
  400555:       48 89 c7                mov    %rax,%rdi
  400558:       e8 21 00 00 00          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

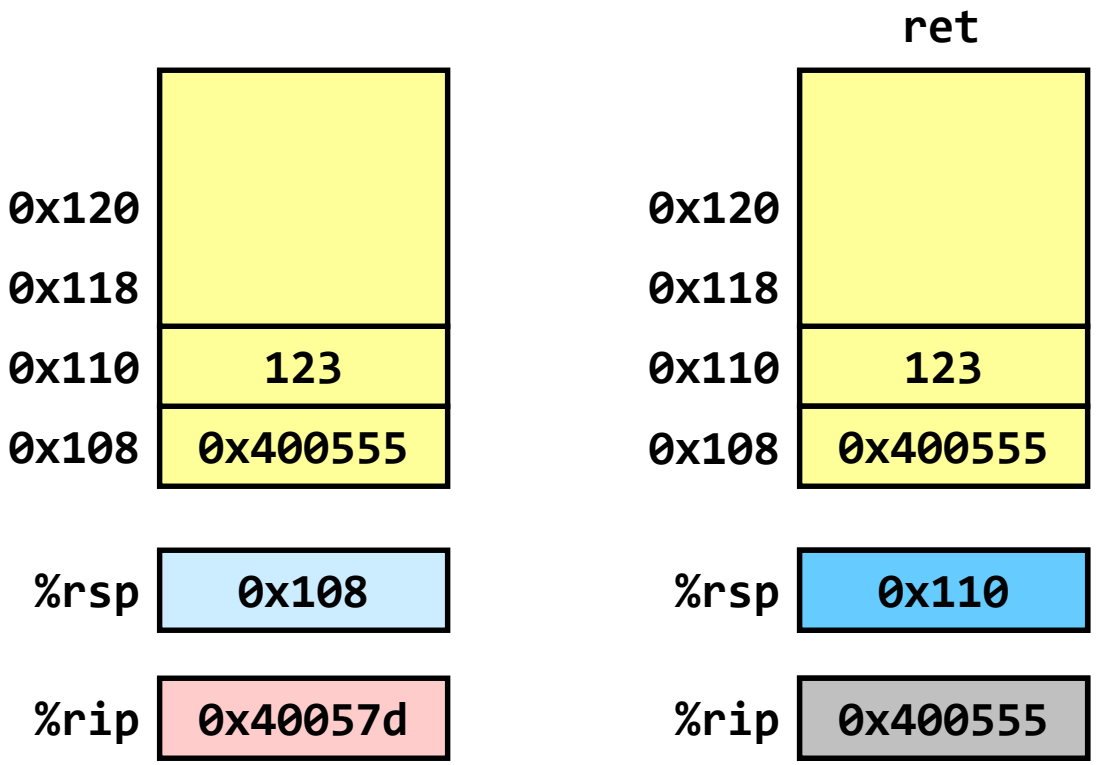
callq 400568



%rip is program counter

Procedure Return Example

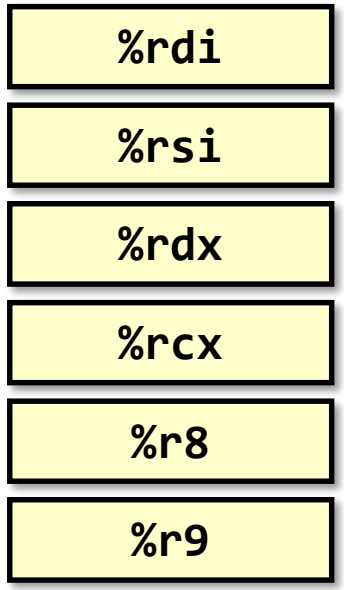
```
40057d:      c3                retq
```



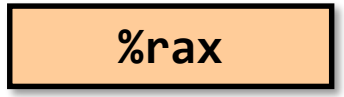
%rip is program counter

Passing Arguments

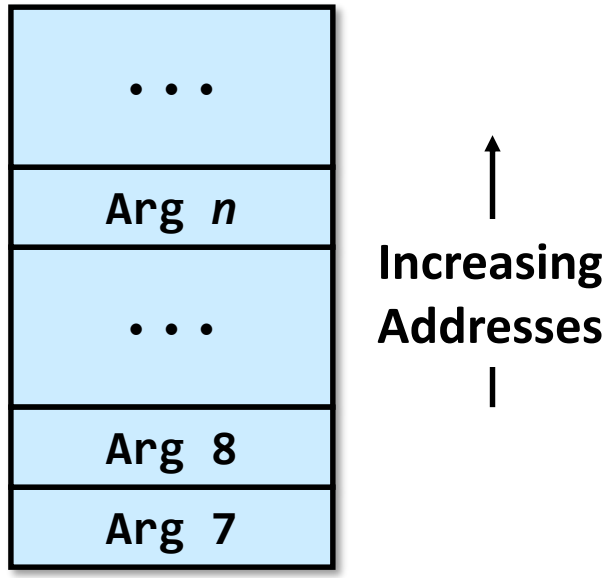
- First 6 arguments:
  - *"Diane's silk dress costs $89"*



- Return value



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

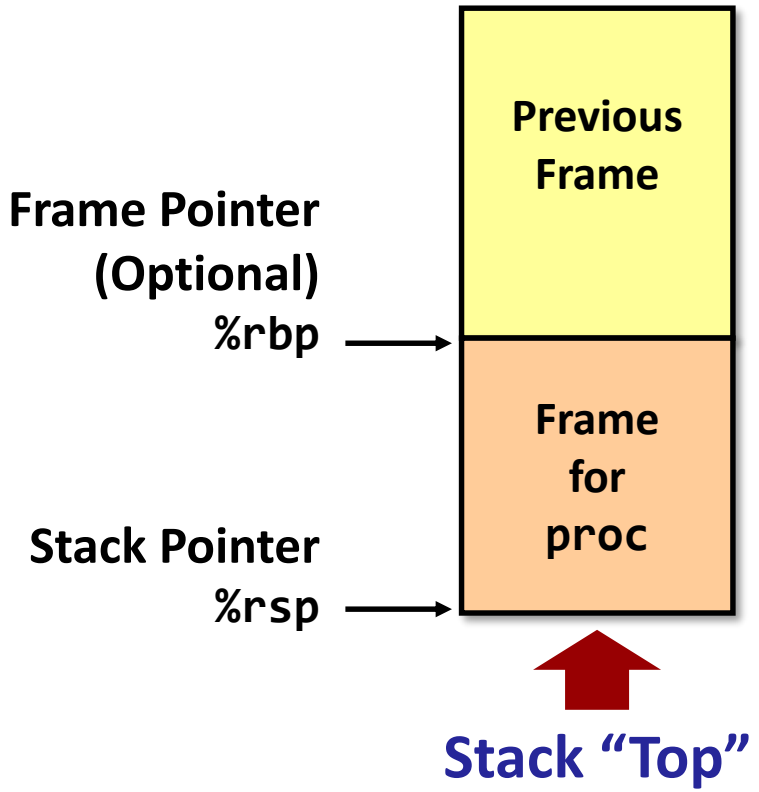


Stack-based Languages

- 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)

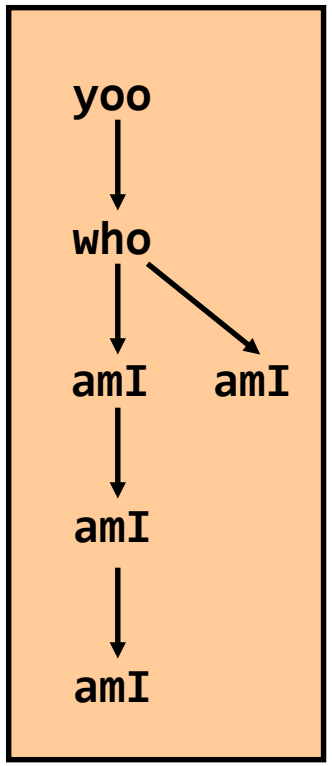
Code Structure

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

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

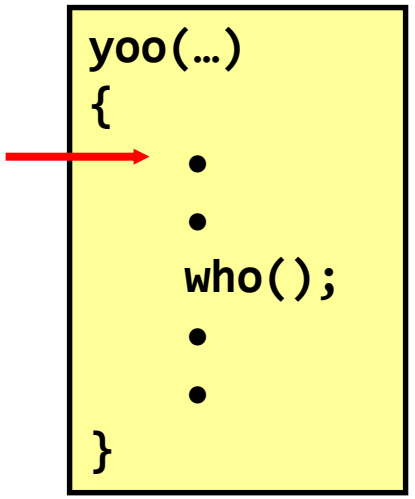
```
amI(…)
{
        •
        •
    amI();
        •
        •
}
```

Call Chain



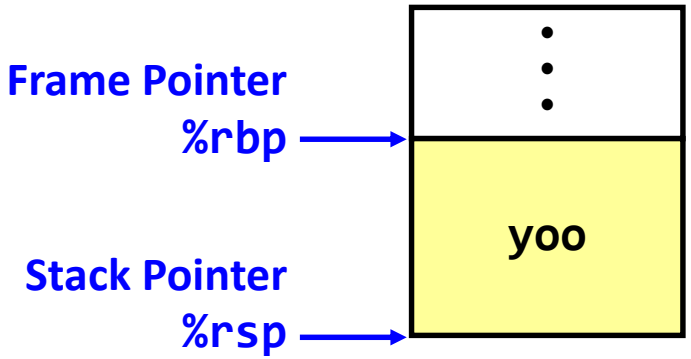
- Procedure **amI** recursive

Stack Frames: Example (2)

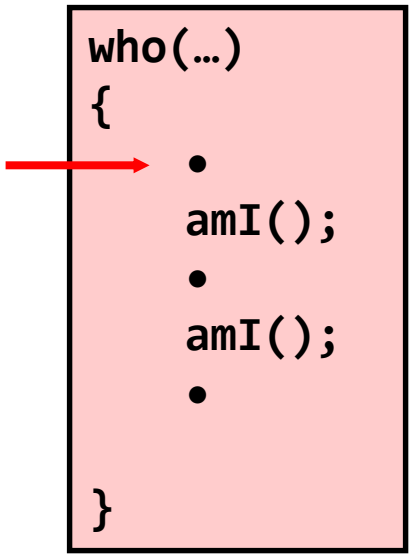


Call Chain

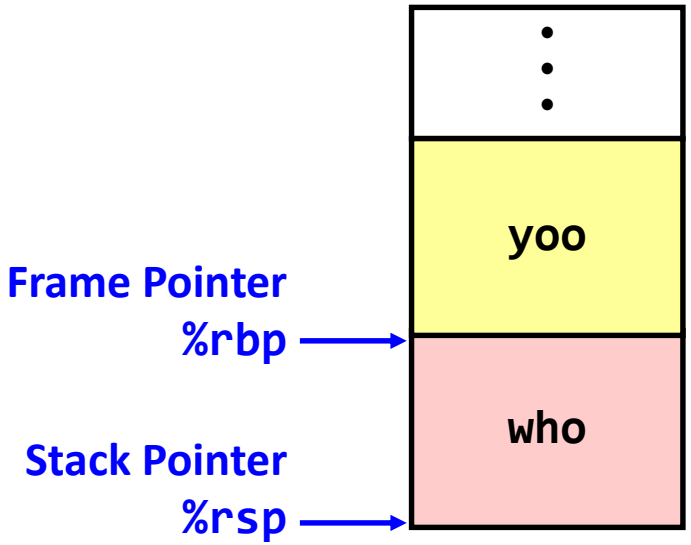
yoo



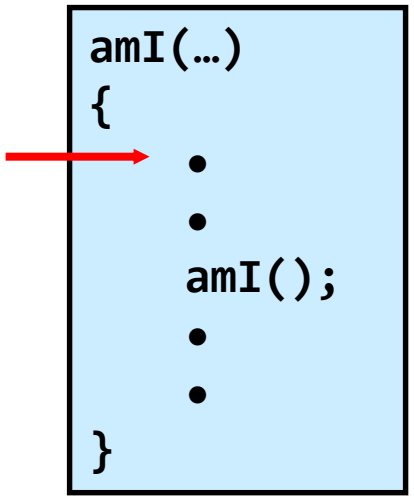
Stack Frames: Example (3)



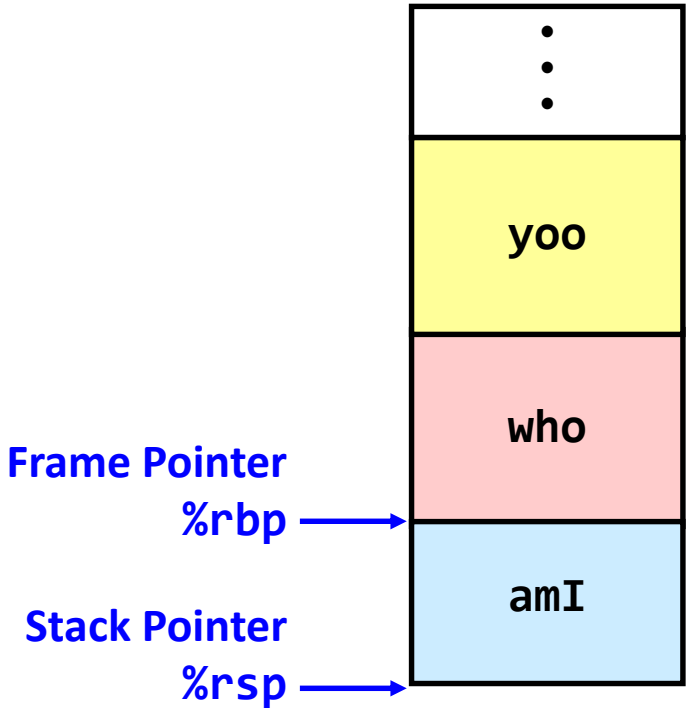
Call Chain



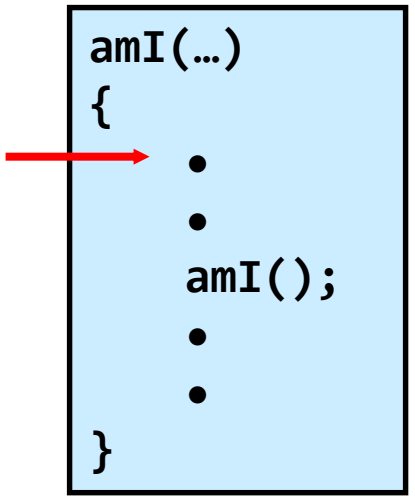
Stack Frames: Example (4)



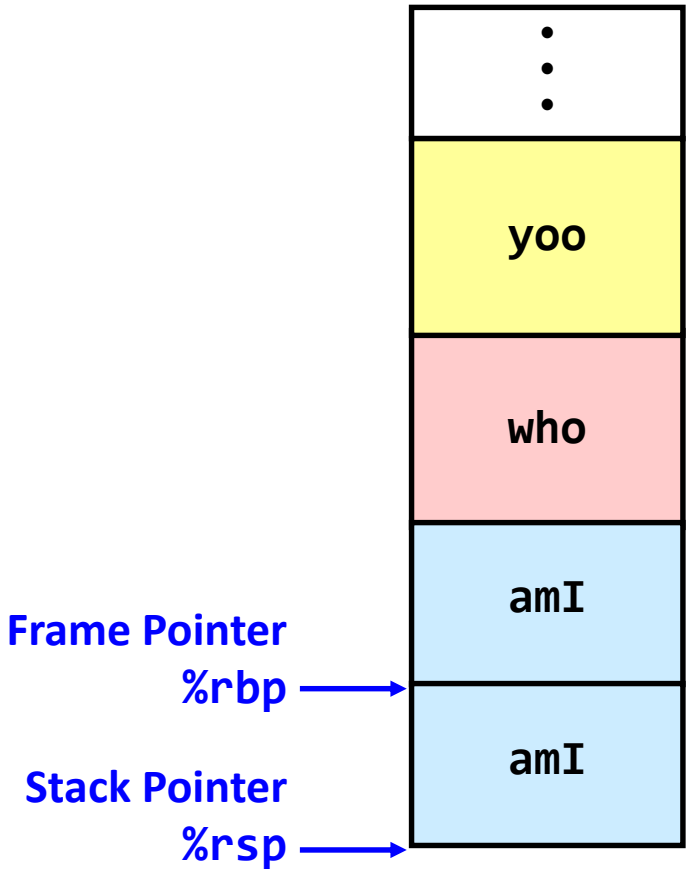
Call Chain



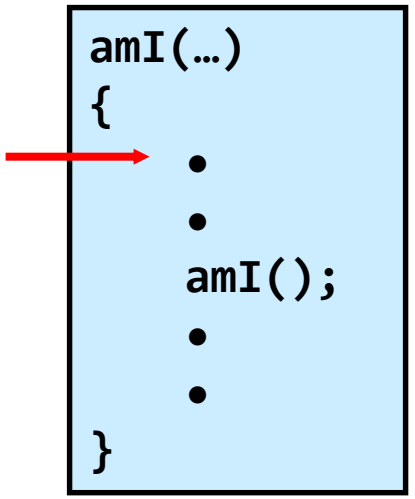
Stack Frames: Example (5)



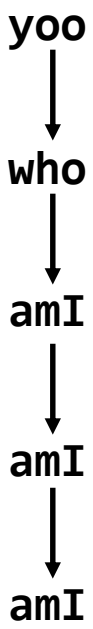
Call Chain

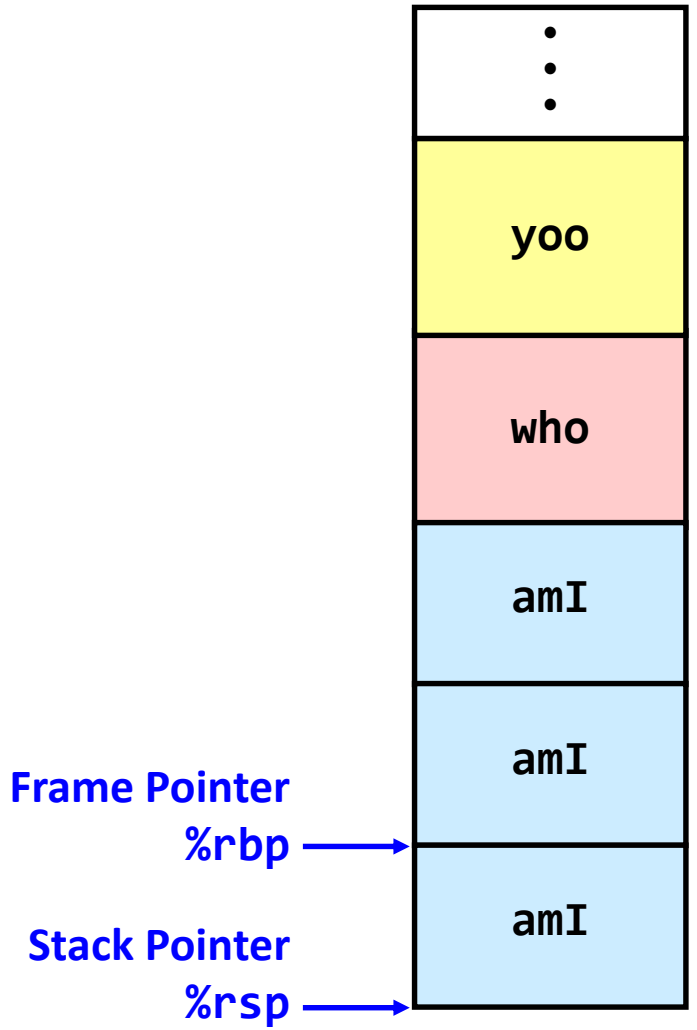


Stack Frames: Example (6)

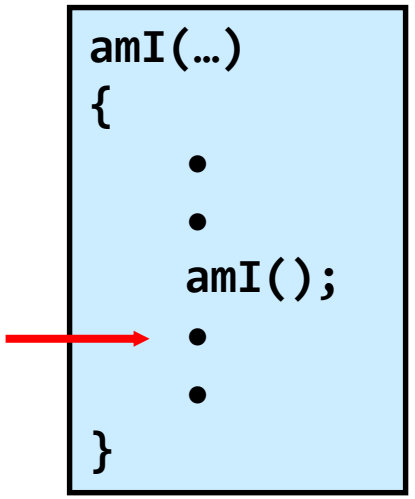


Call Chain

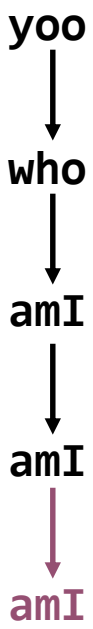


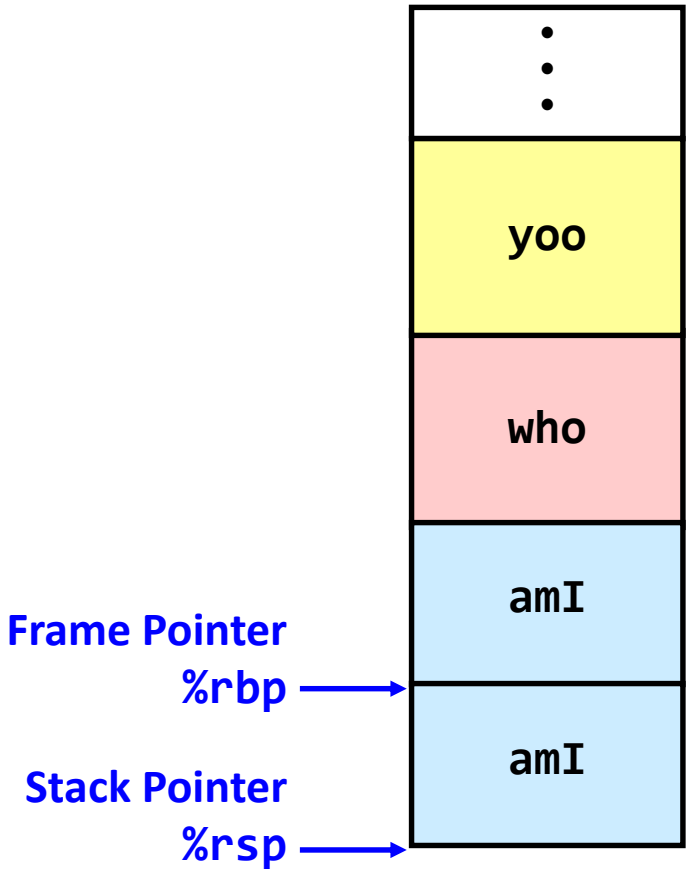


Stack Frames: Example (7)

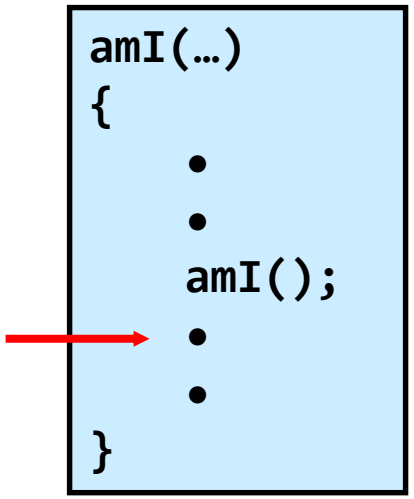


Call Chain

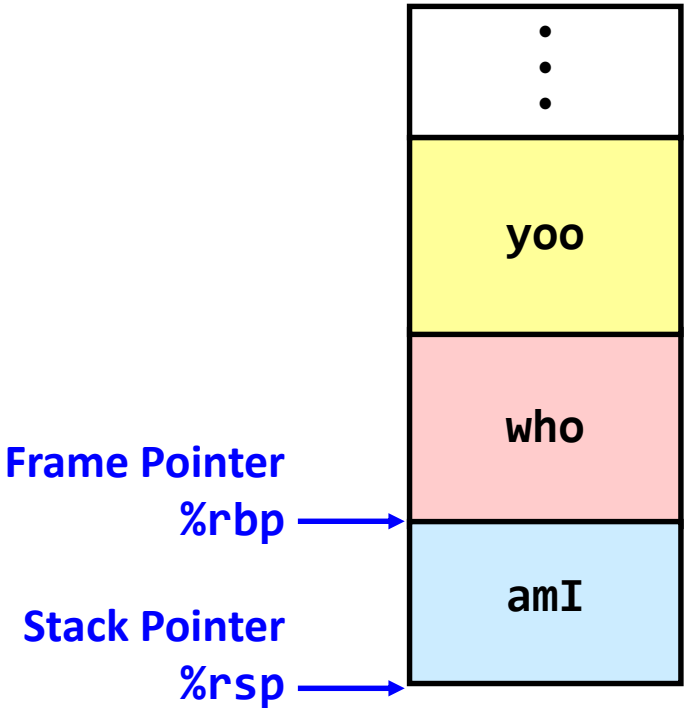




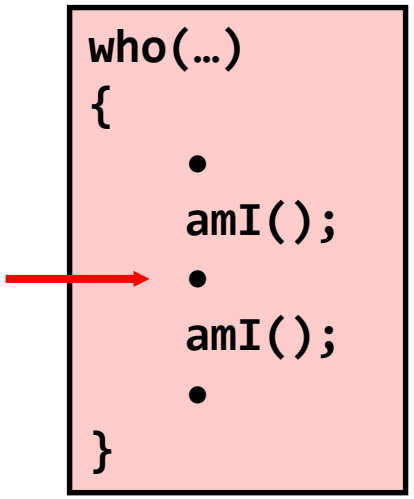
Stack Frames: Example (8)



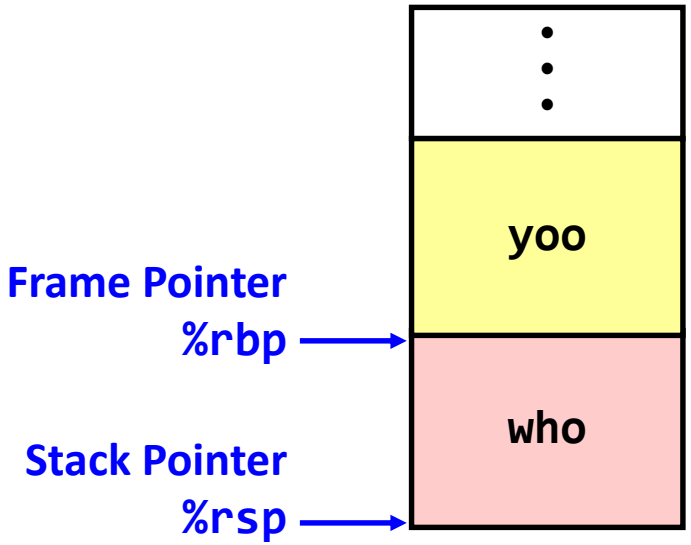
Call Chain



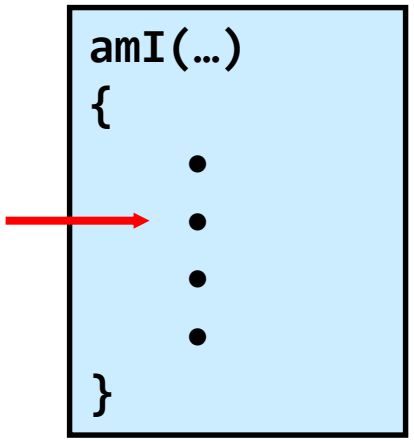
Stack Frames: Example (9)



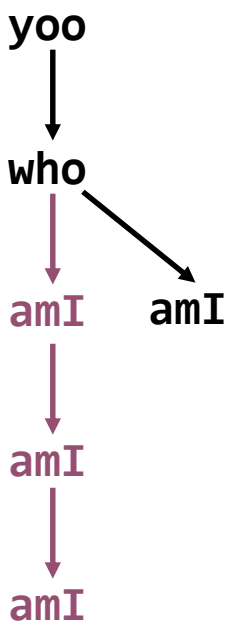
Call Chain

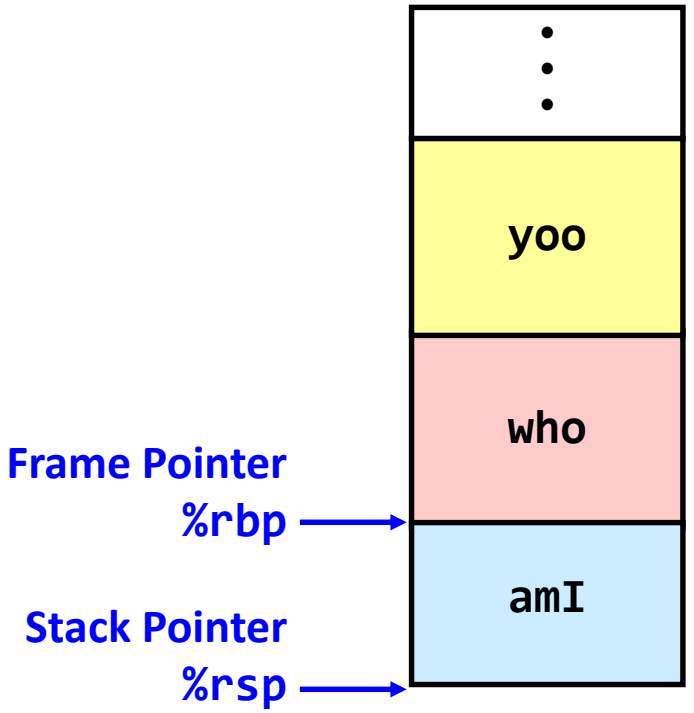


Stack Frames: Example (10)

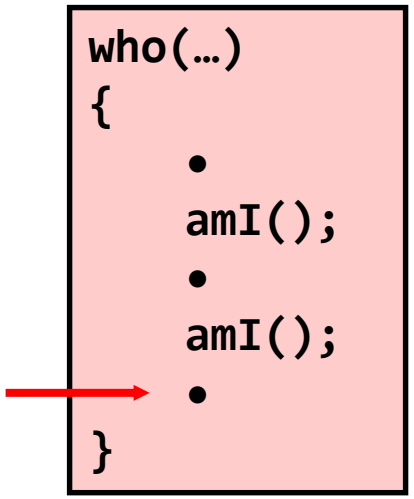


Call Chain

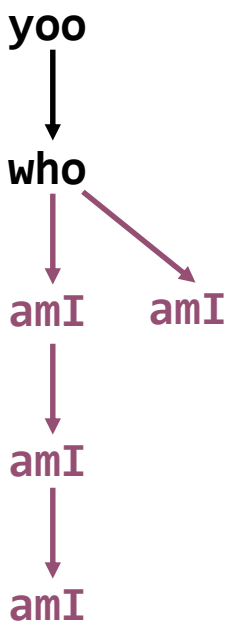


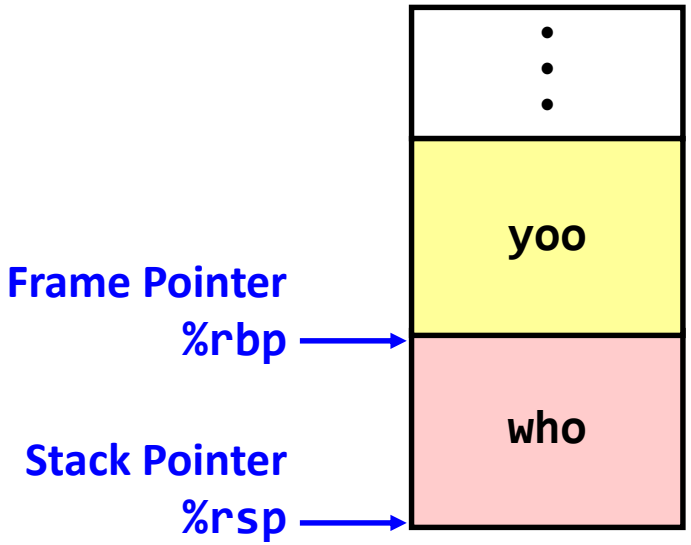


Stack Frames: Example (11)

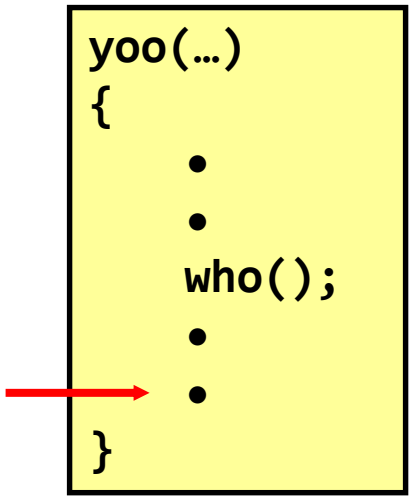


Call Chain

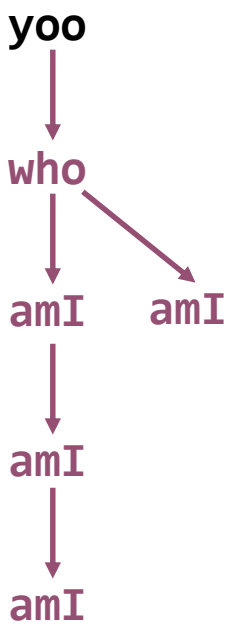


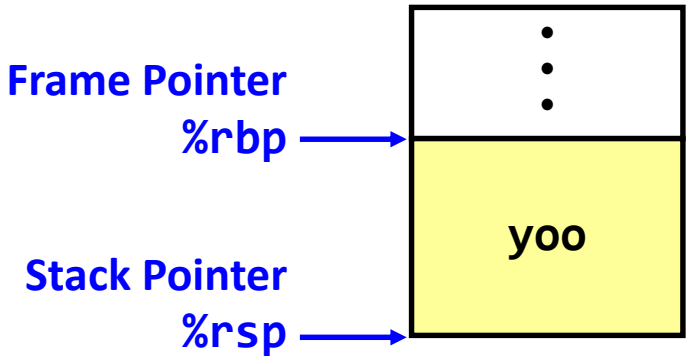


Stack Frames: Example (12)



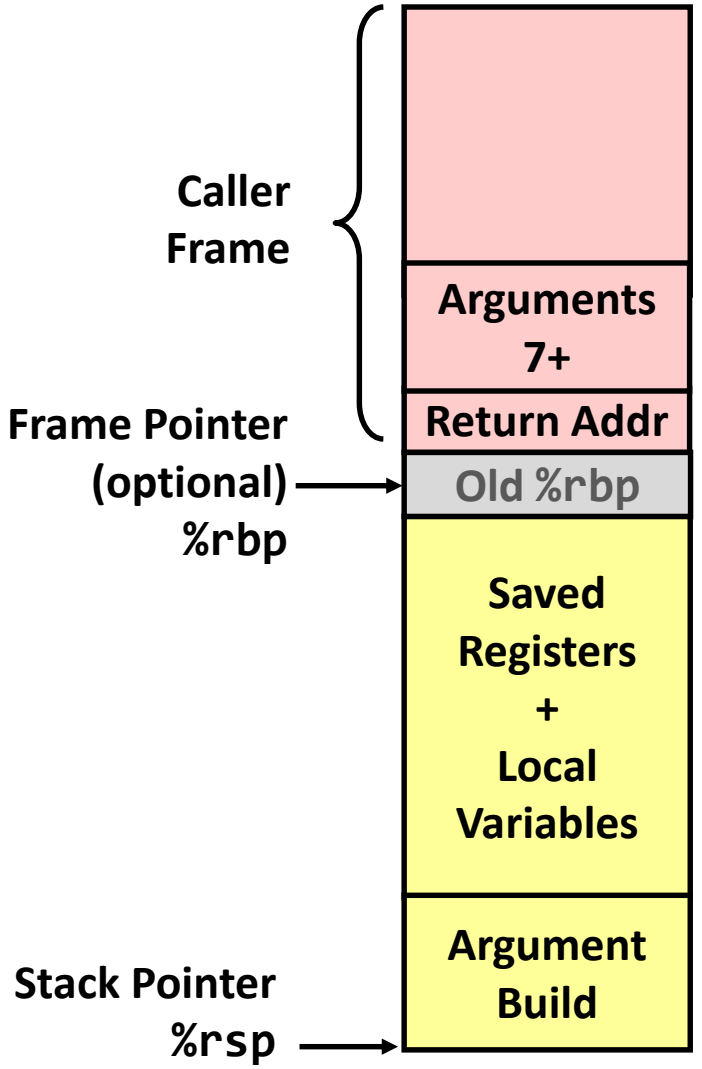
Call Chain





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()**

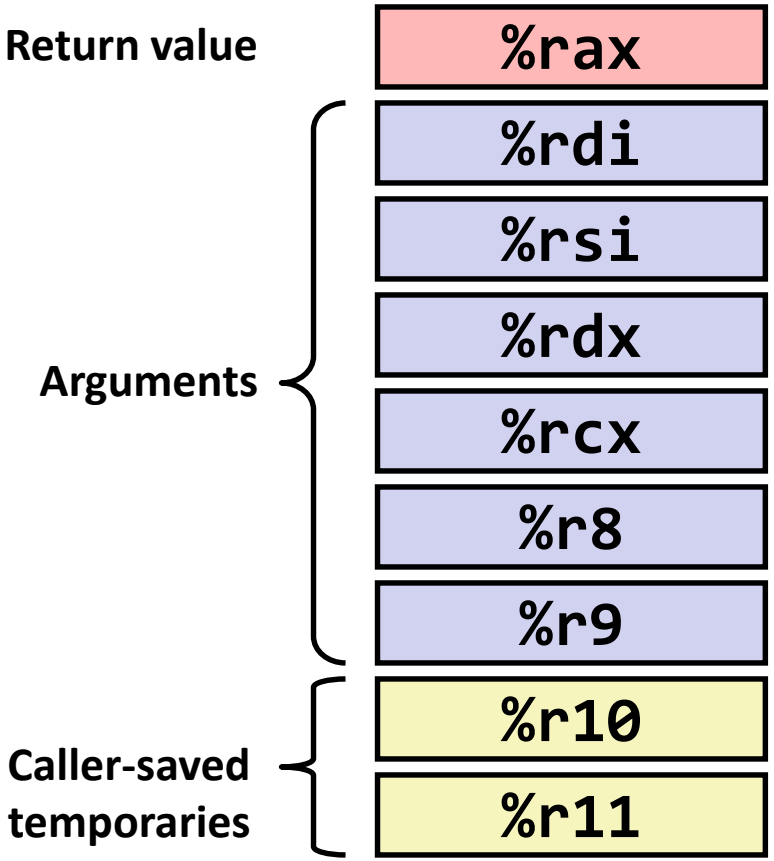
Register Saving Conventions

- "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

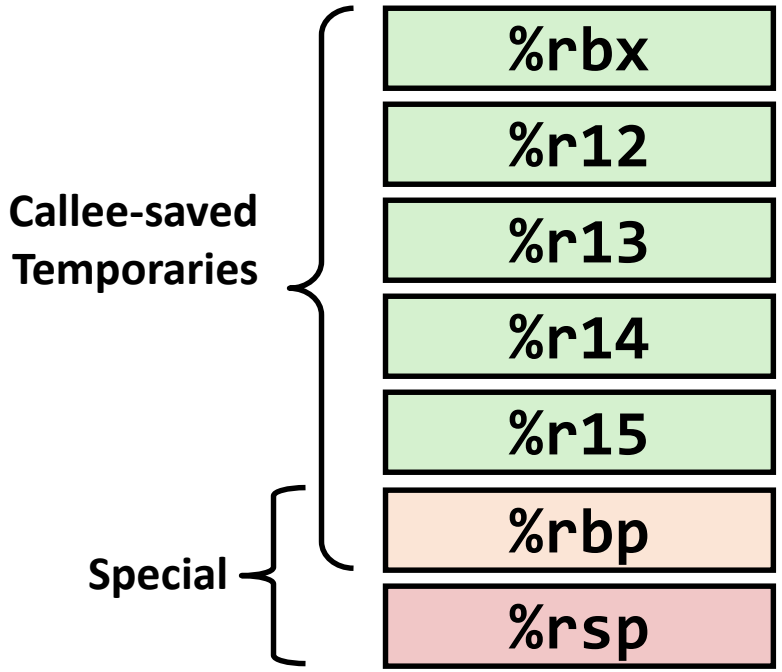
x86-64/Linux Register Usage (1)

- **`%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



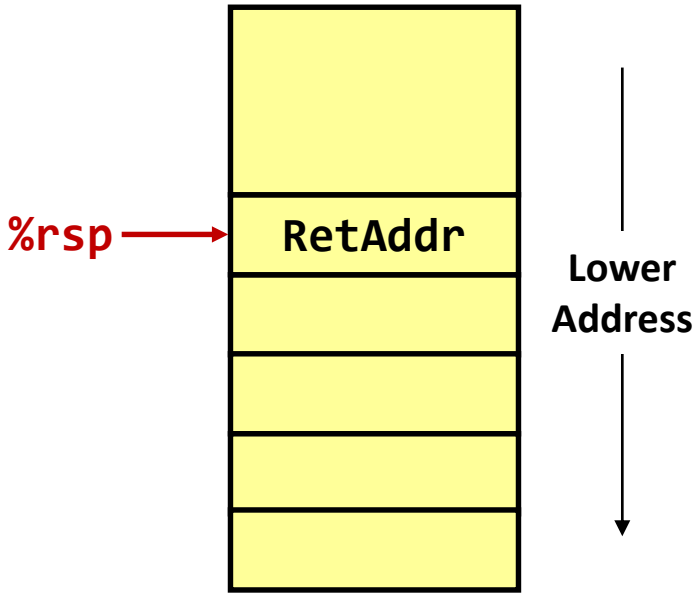
Recursive Factorial: rfact

- 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
```

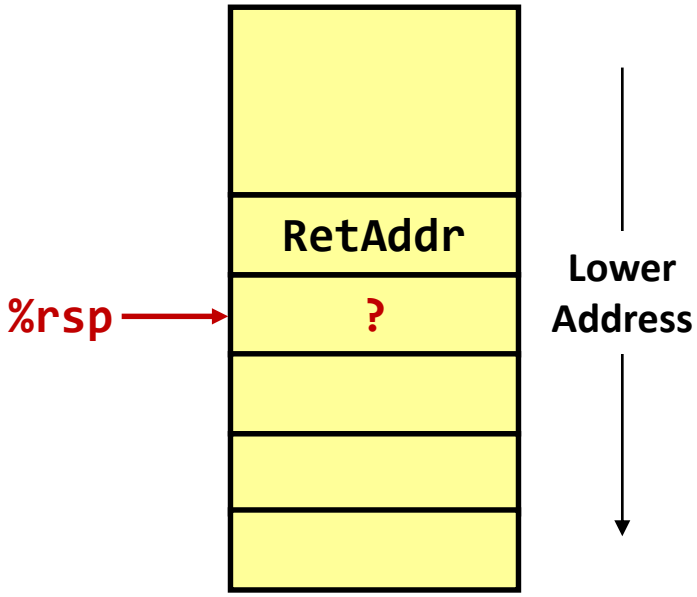
Example: rfact(3)



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)

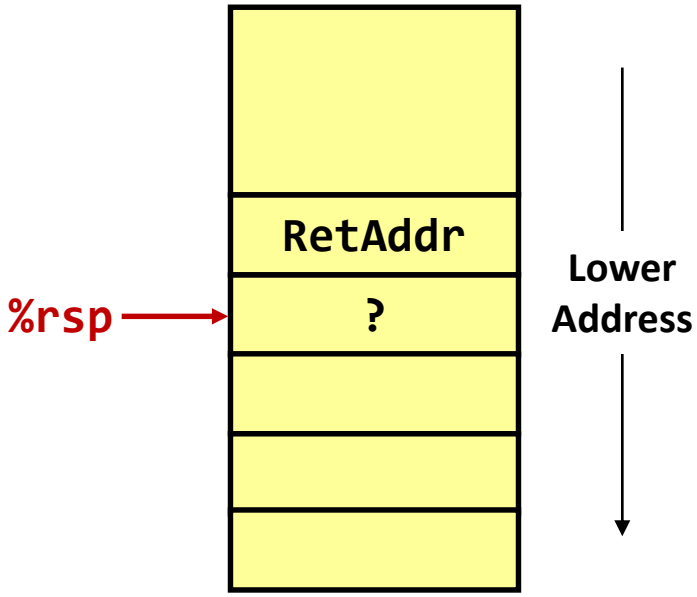


Registers	
%rdi	3
%rax	?
%rbx	?

%rip →

```
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
```

Example: rfact(3)

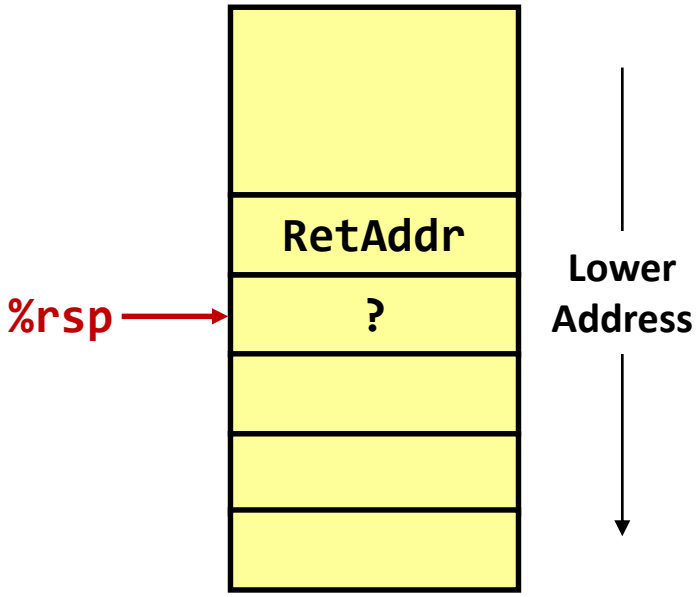


Registers	
%rdi	3
%rax	?
%rbx	3

%rip →

```
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
```

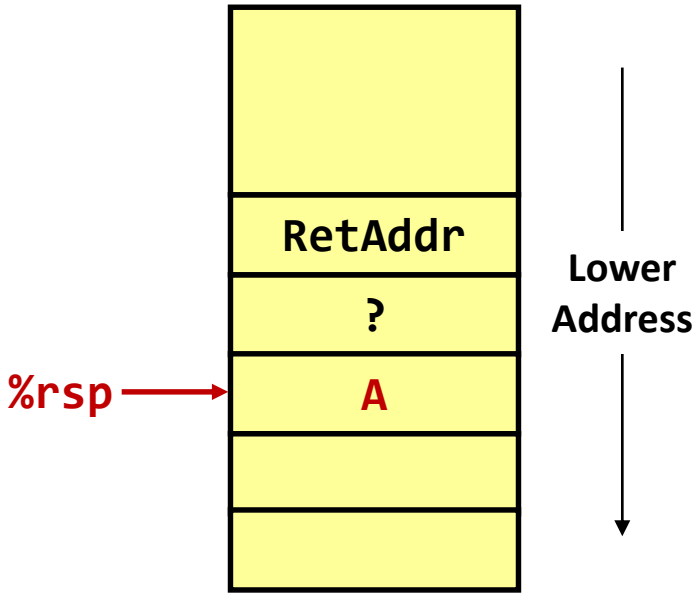
Example: rfact(3)



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
```

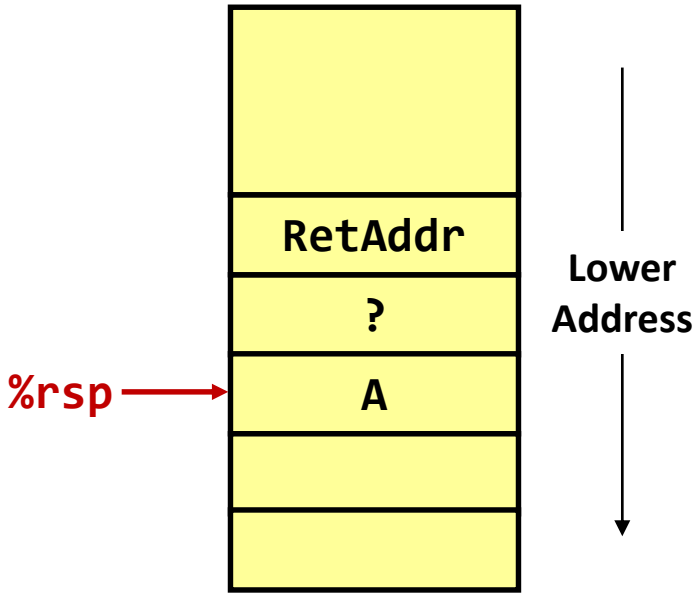
Example: rfact(3)



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
```

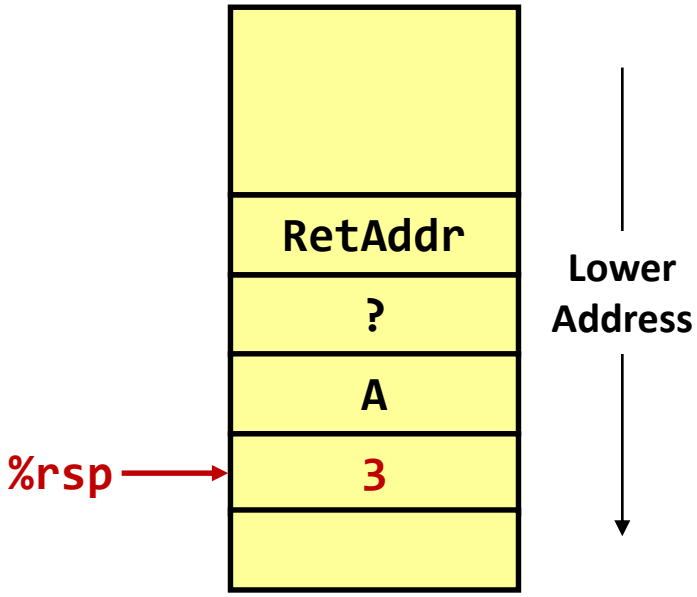
Example: rfact(3)



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)

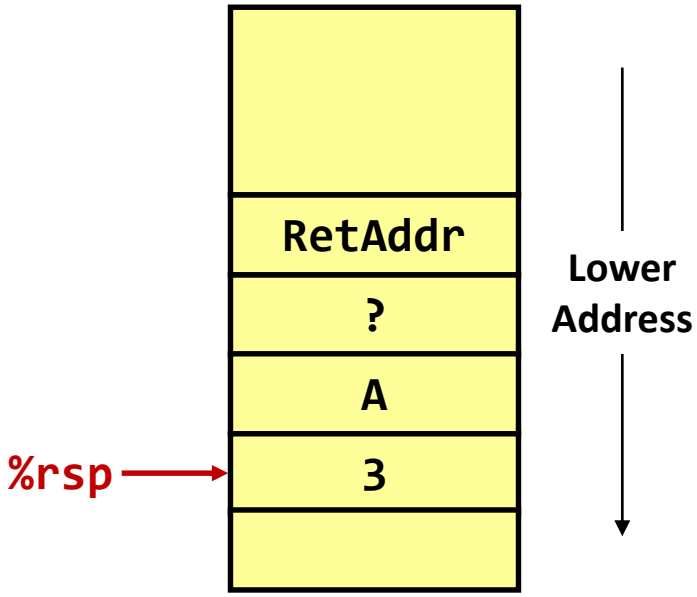


Registers	
%rdi	2
%rax	?
%rbx	3

%rip →

```
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
```

Example: rfact(3)

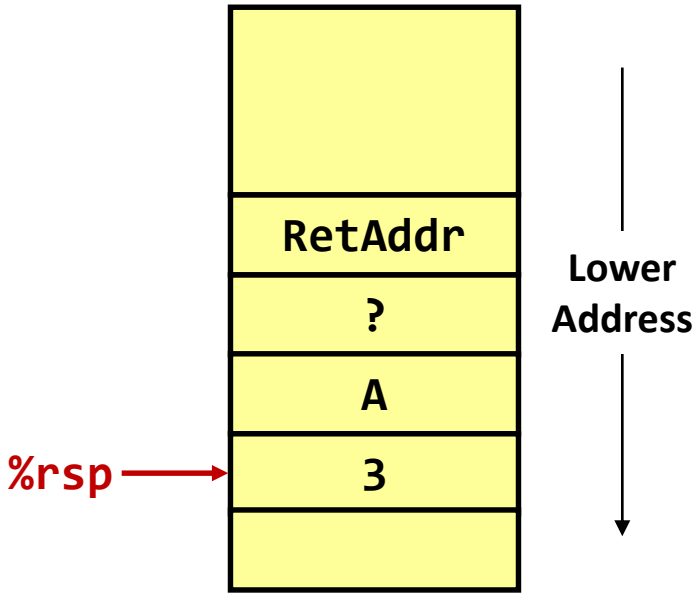


Registers	
%rdi	2
%rax	?
%rbx	2

```
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 →

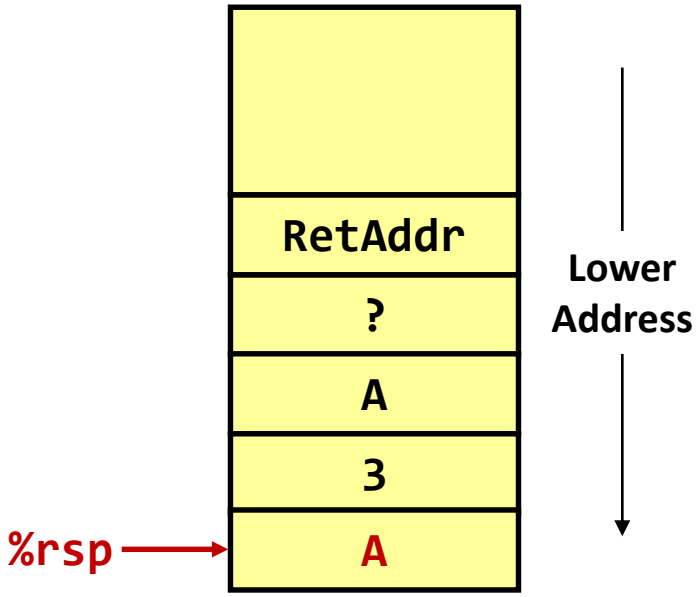
Example: rfact(3)



Registers	
%rdi	1
%rax	?
%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
```

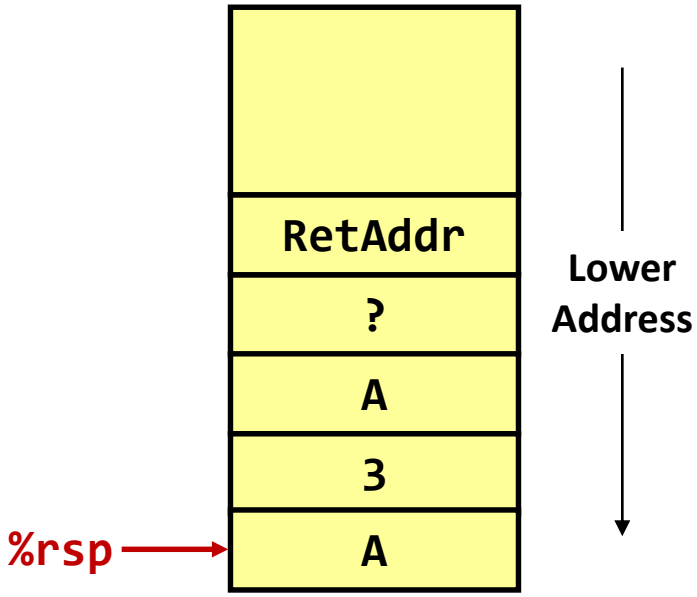
Example: rfact(3)



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
```

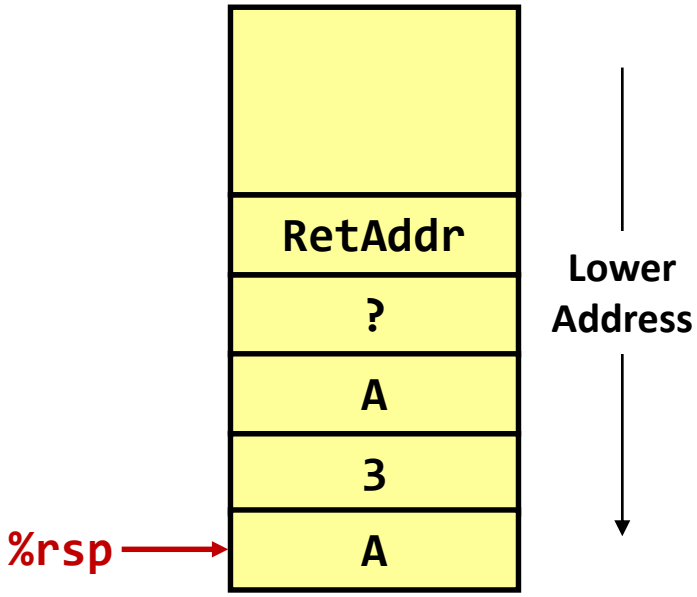
Example: rfact(3)



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)

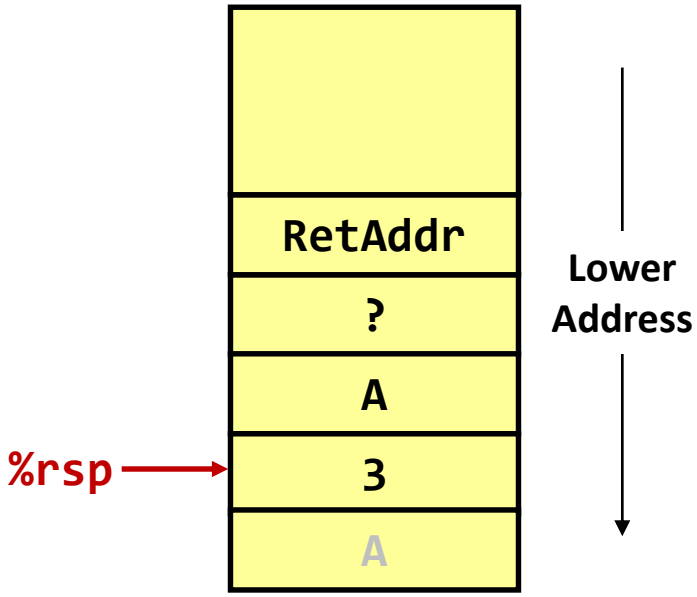


Registers	
%rdi	1
%rax	1
%rbx	2

```
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)

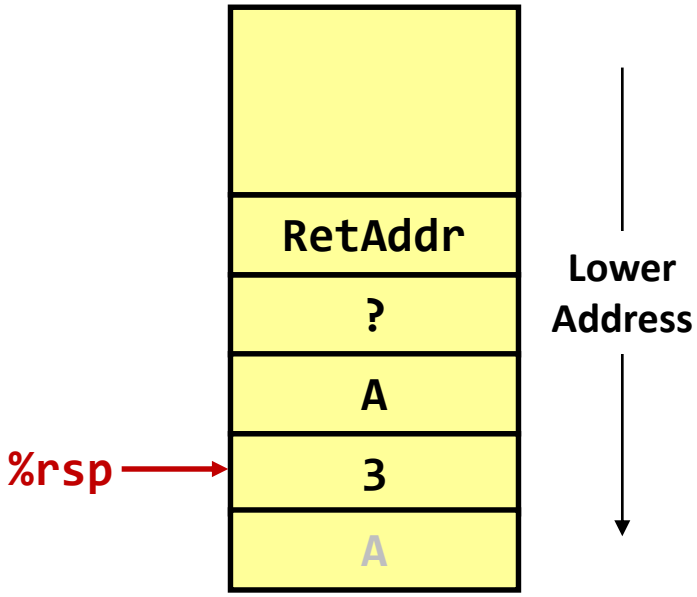


Registers	
%rdi	1
%rax	1
%rbx	2

```
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)

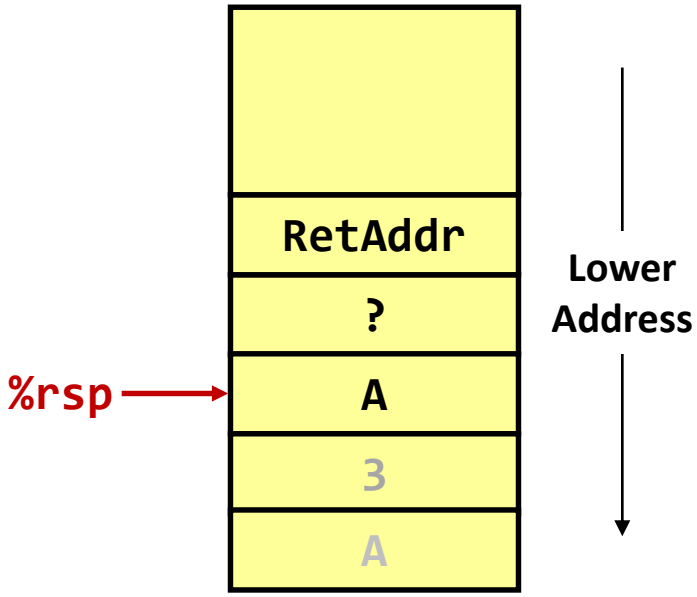


Registers	
%rdi	1
%rax	2
%rbx	2

```
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:

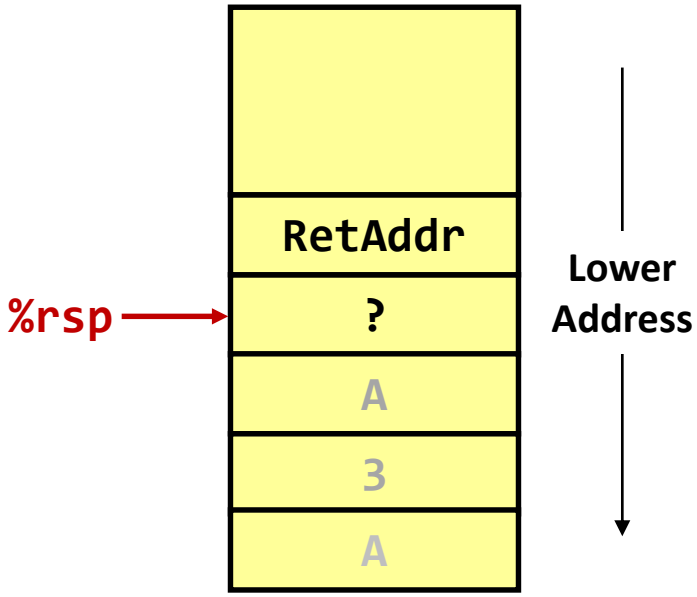
Example: rfact(3)



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:
%rip popq  %rbx
    ret
```

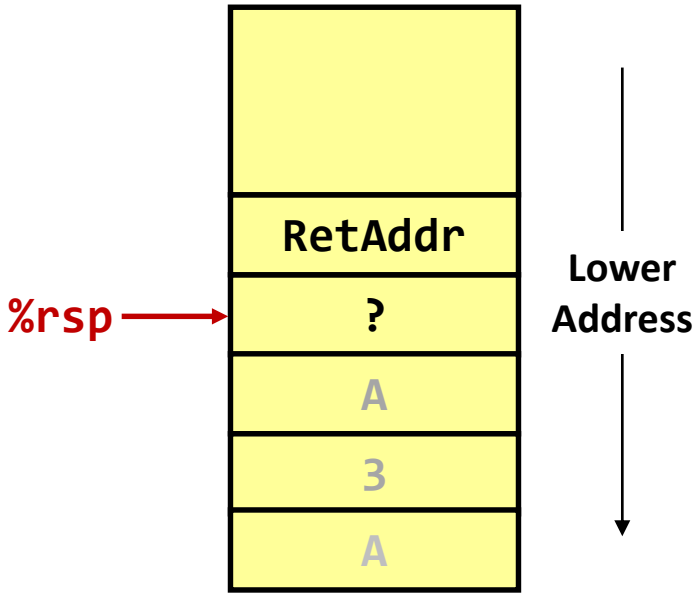
Example: rfact(3)



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
```

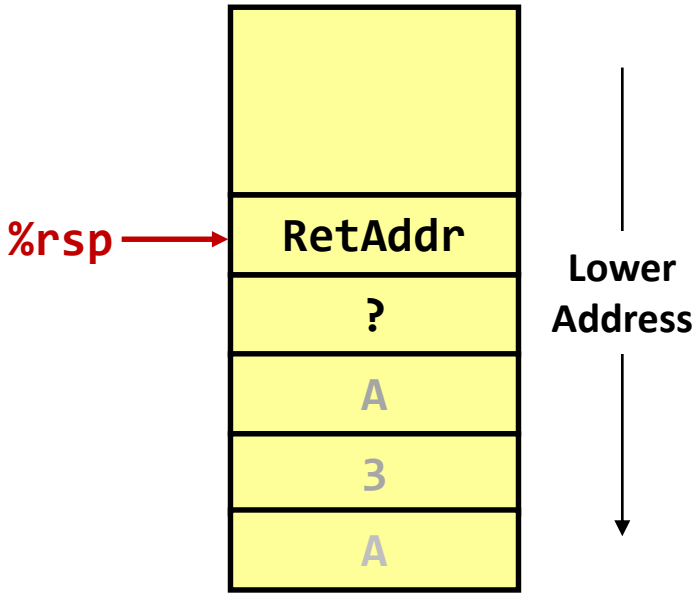
Example: rfact(3)



Registers	
%rdi	1
%rax	6
%rbx	3

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

Example: rfact(3)

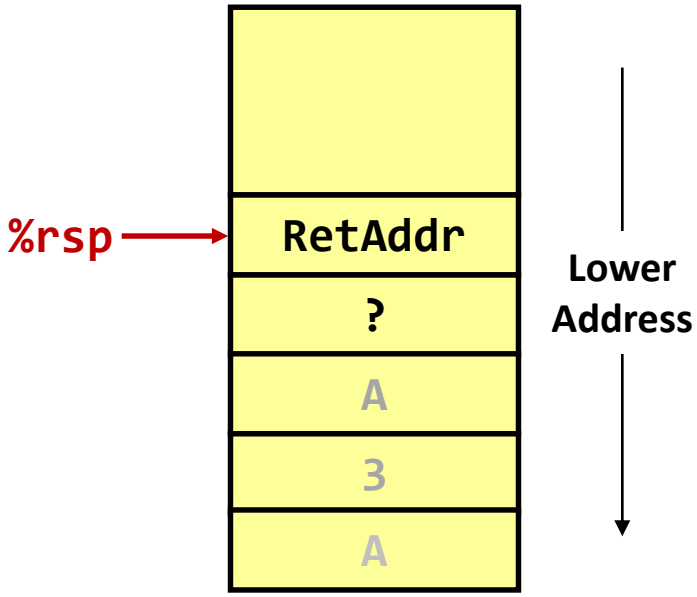


Registers	
%rdi	1
%rax	6
%rbx	?

```
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

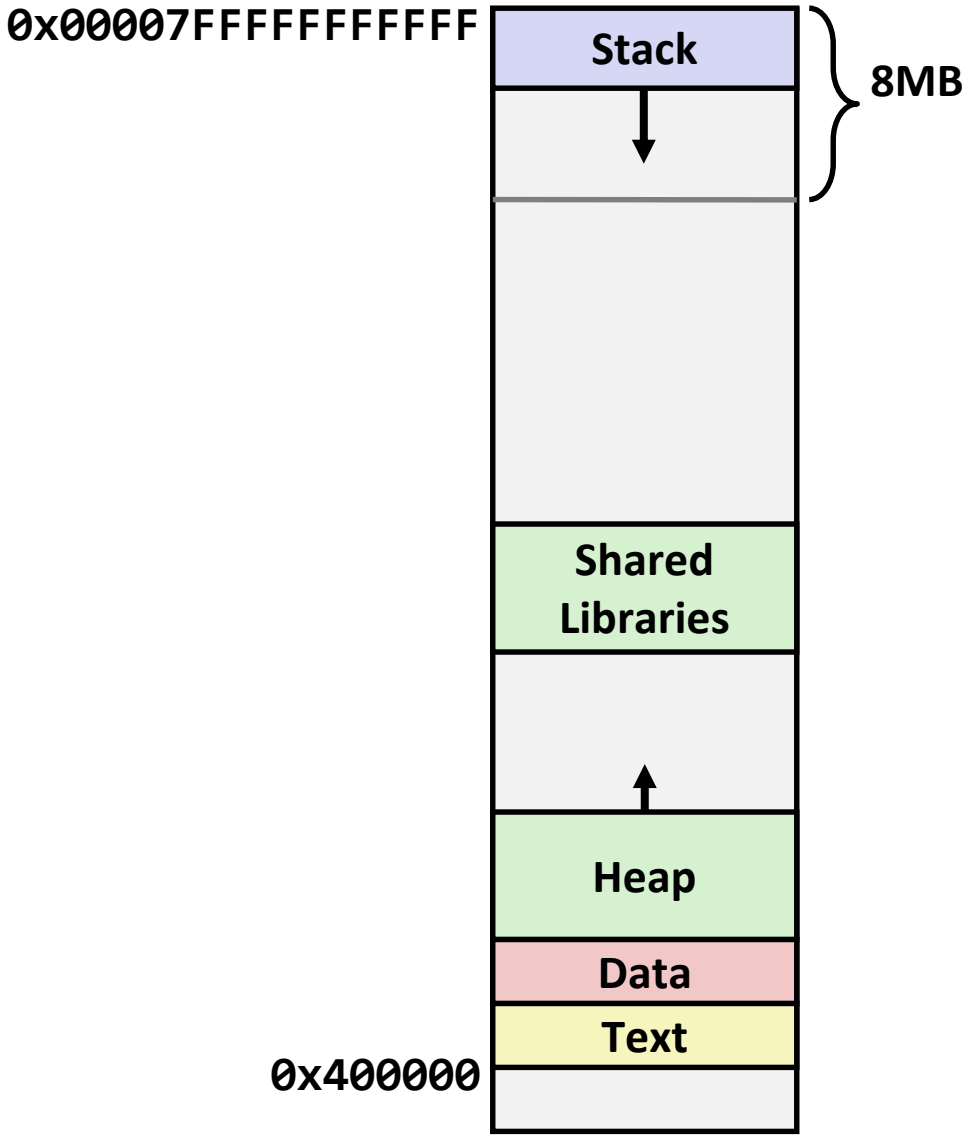
Summary

- 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

Buffer Overflow

x86-64/Linux Memory Layout

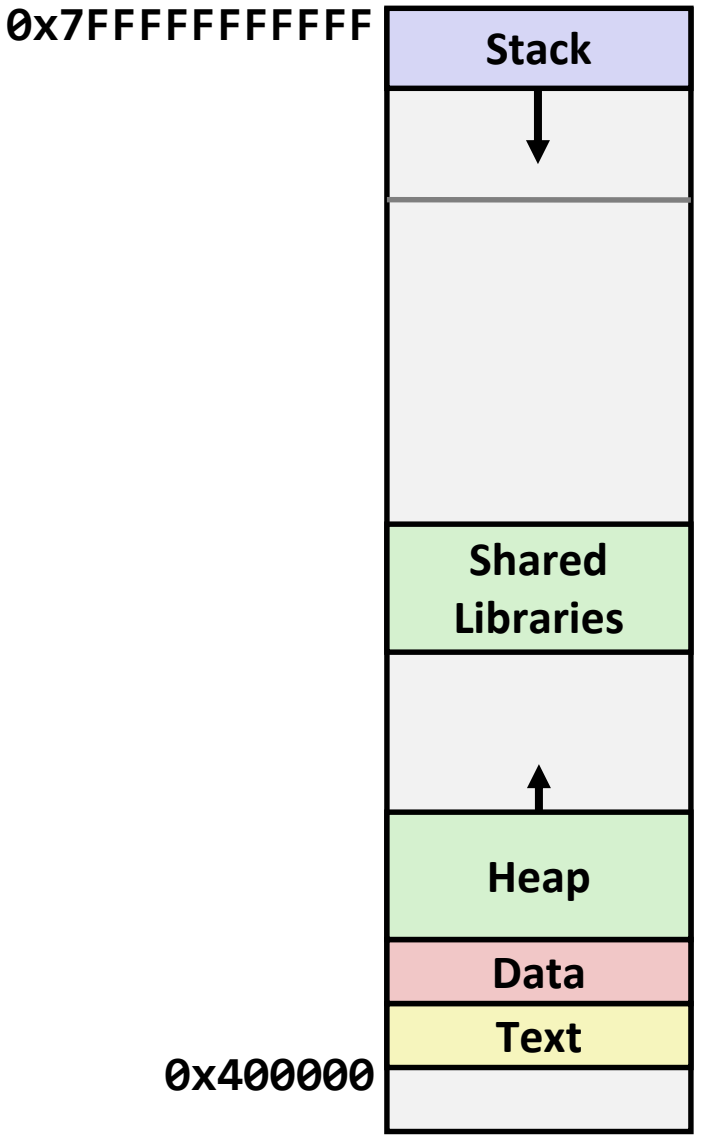
- Stack
  - Runtime stack (8MB limit)
- Heap
  - Dynamically allocated as needed
  - When call `malloc()`, `calloc()`, `new()`
- Data
  - Statically allocated data
  - e.g. global vars, static vars, string constants
- Text / Shared libraries
  - Executable machine instructions
  - Read-only



x86-64 Addresses Example

```
#include <stdio.h>
#include <stdlib.h>

int g = 1;
int main(void) {
  char *p = malloc(100);
  printf("main() = %p\n", main);
  printf("&g = %p\n", &g);
  printf("&p = %p\n", &p);
  printf("p = %p\n", p);
}
```

```
$ gcc -Og -g mem.c
$ ./a.out
main() = 0x4005f6
&g = 0x601048
&p = 0x7fff07b94b70
p = 0x1ece010
```



Vulnerable Buffer Code

```
/* Echo Line */
void echo()
{
    // Way too small!
    char buf[4];
    gets(buf);
    puts(buf);
}

int main()
{
    printf("Type: ");
    echo();
    return 0;
}
```

```
$ ./bufdemo
Type:012
012

$ ./bufdemo
Type: 0123456789012345678901
0123456789012345678901

$ ./bufdemo
Type: 01234567890123456789012
Segmentation fault (core dumped)
```

String Library Code

- Implementation of Unix function **`gets()`**
  - No way to specify limit on number of characters to read

```
char *gets(char *dest) {   // Get string from stdin
    int c = getc();
    char *p = dest;
    while (c != EOF && c != '\n') {
        *p++ = c;
        c = getc();
    }
    *p = '\0';
    return dest;
}
```

  - Similar problems with other Unix functions
    - **`strcpy`**: copies string of arbitrary length
    - **`scanf`** / **`fscanf`** / **`sscanf`**, given **`%s`** conversion specification

Buffer Overflow Disassembly

- **`echo()`**:

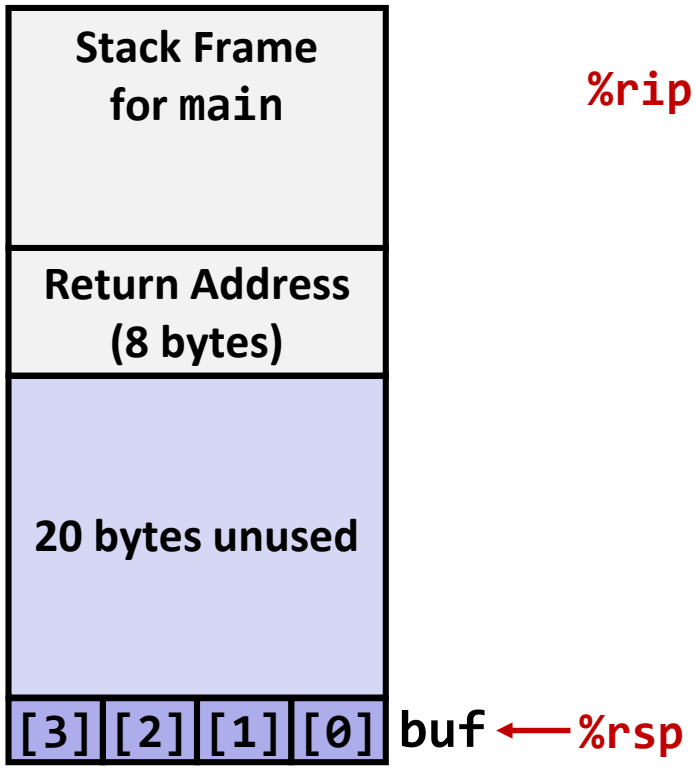
```
0000000004006cf <echo>:
 4006cf:   48 83 ec 18              sub    $0x18,%rsp
 4006d3:   48 89 e7                 mov    %rsp,%rdi
 4006d6:   e8 a5 ff ff ff           callq  400680 <gets>
 4006db:   48 89 e7                 mov    %rsp,%rdi
 4006de:   e8 3d fe ff ff           callq  400520 <puts@plt>
 4006e3:   48 83 c4 18              add    $0x18,%rsp
 4006e7:   c3                       retq
```

- **`main()`**:

```
           ...
 4006ec:   b8 00 00 00 00           mov    $0x0,%eax
 4006f1:   e8 d9 ff ff ff           callq  4006cf <echo>
 4006f6:   48 83 c4 08              add    $0x8,%rsp
           ...
```

Buffer Overflow (1)

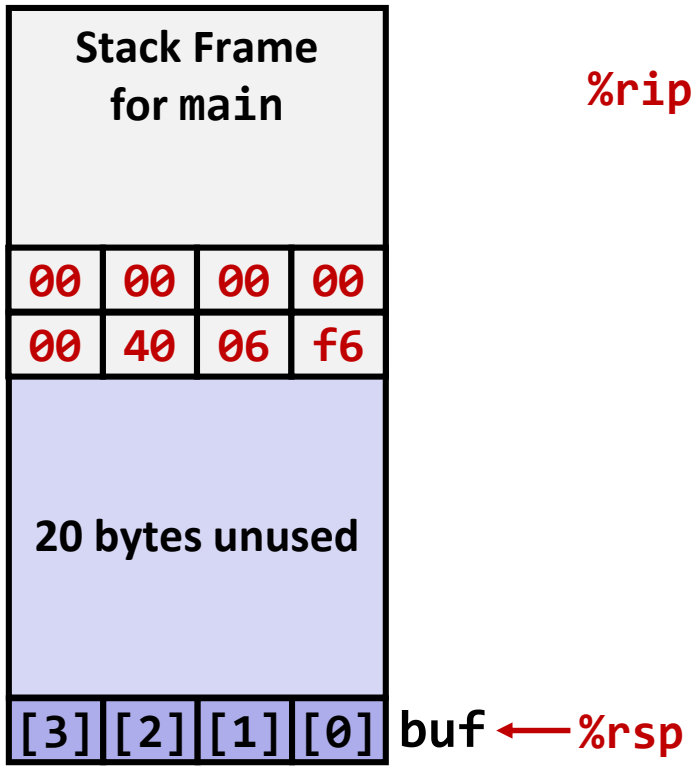
- Before call to **`gets()`**




```
%rip →
echo:
   4006cf:  sub    $0x18,%rsp
   4006d3:  mov    %rsp,%rdi
   4006d6:  callq  400680 <gets>
   4006db:  mov    %rsp,%rdi
   4006de:  callq  400520 <puts@plt>
   4006e3:  add    $0x18,%rsp
   4006e7:  retq

main:
            ...
   4006ec:  mov    $0x0,%eax
   4006f1:  callq  4006cf <echo>
   4006f6:  add    $0x8,%rsp
            ...
```

Buffer Overflow (2)

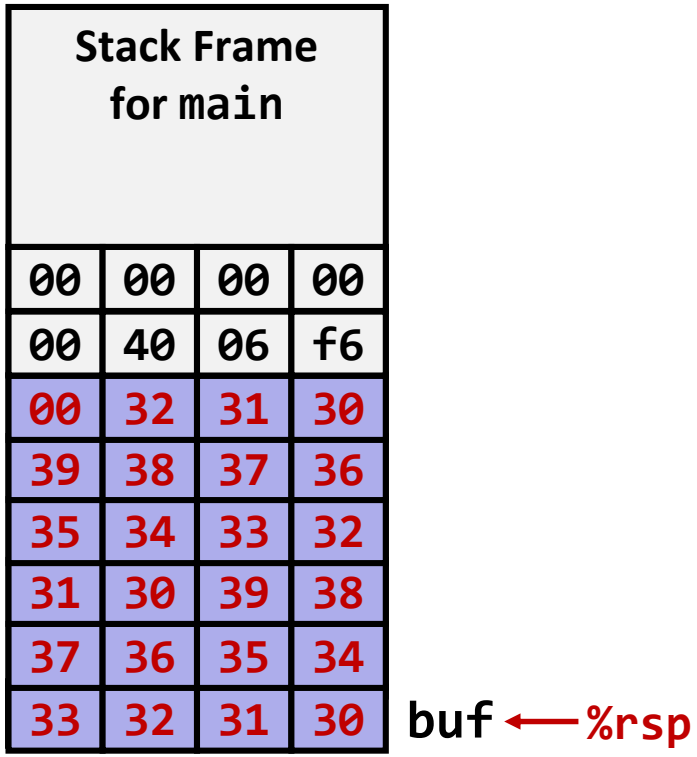
- Before call to **`gets()`**




```
%rip →
echo:
   4006cf:  sub    $0x18,%rsp
   4006d3:  mov    %rsp,%rdi
   4006d6:  callq  400680 <gets>
   4006db:  mov    %rsp,%rdi
   4006de:  callq  400520 <puts@plt>
   4006e3:  add    $0x18,%rsp
   4006e7:  retq

main:
            ...
   4006ec:  mov    $0x0,%eax
   4006f1:  callq  4006cf <echo>
   4006f6:  add    $0x8,%rsp
            ...
```

Buffer Overflow (3)

- Overflowed buffer, but did not corrupt state

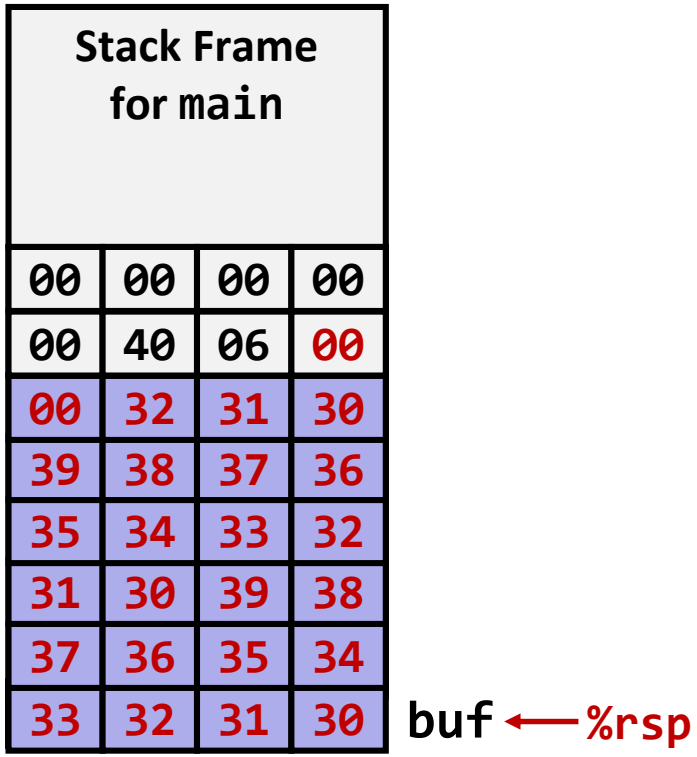



```
echo:
  4006cf:  sub    $0x18,%rsp
  4006d3:  mov    %rsp,%rdi
  4006d6:  callq  400680 <gets>
  4006db:  mov    %rsp,%rdi
  4006de:  callq  400520 <puts@plt>
  4006e3:  add    $0x18,%rsp
  4006e7:  retq
```

```
$ ./bufdemo
Type: 012345678901234567890123
012345678901234567890123
```

Buffer Overflow (4)

- Overflowed buffer, and corrupted return pointer

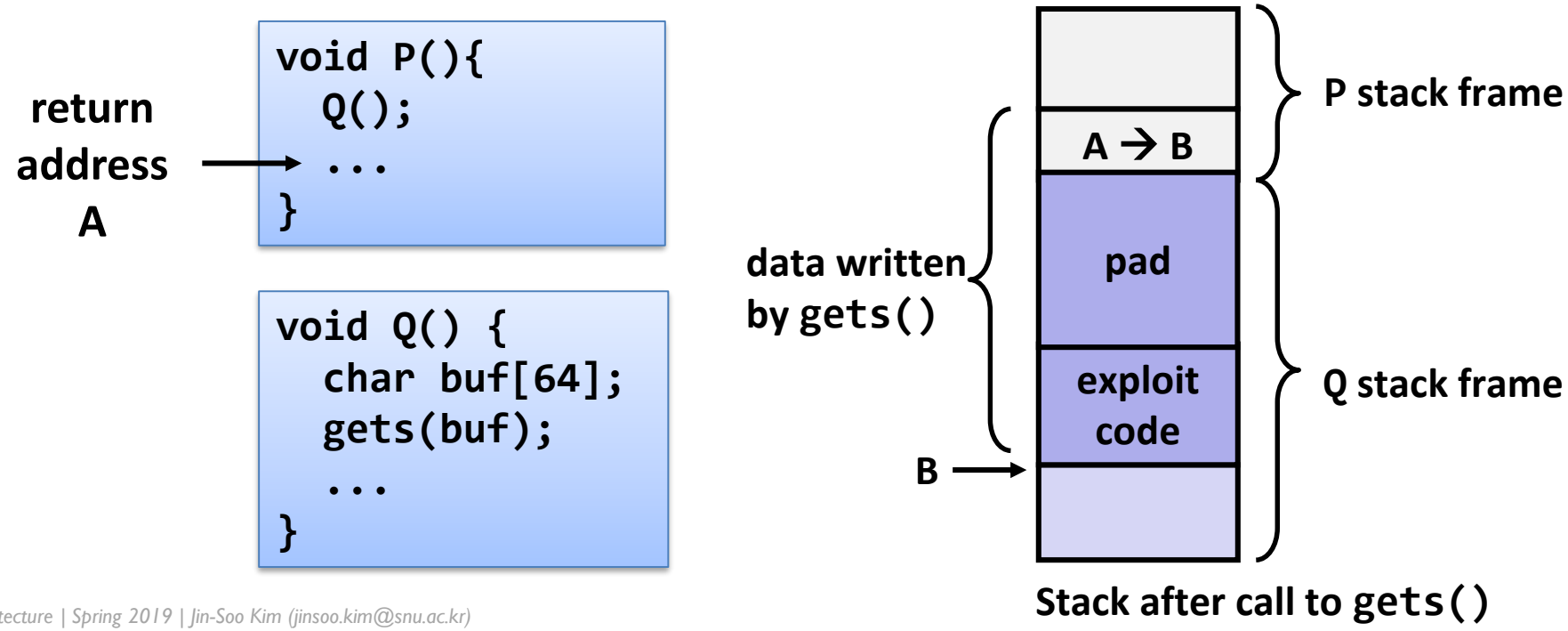



```
echo:
  4006cf:  sub    $0x18,%rsp
  4006d3:  mov    %rsp,%rdi
  4006d6:  callq  400680 <gets>
  4006db:  mov    %rsp,%rdi
  4006de:  callq  400520 <puts@plt>
  4006e3:  add    $0x18,%rsp
  4006e7:  retq
```

```
$ ./bufdemo
Type: 01234567890123456789012
Segmentation fault (core dumped)
```

Buffer Overflow Attack

- Malicious use of buffer overflow
  - Input string contains byte representation of executable code
  - Overwrite return address **A** with address of buffer **B**
  - When **P()** executes **ret**, will jump to exploit code



Exploits Using Buffer Overflows

- Buffer overflow bugs can allow remote machines to execute arbitrary code on victim machines
- Distressingly common in real programs
  - Programmers keep making the same mistakes ☹
  - Recent measures make these attacks much more difficult

Avoiding Buffer Overflow

- Use library routines that limit string lengths
  - `fgets()` instead of `gets()`
  - `strncpy()` instead of `strcpy()`
  - Don't use `scanf()` with `%s` conversion specification
    - Use `fgets()` to read the string
    - Or use `%ns` where `n` is a suitable integer

```
/* Echo Line */
void echo()
{
    char buf[4];  /* Way too small! */
    fgets(buf, 4, stdin);
    puts(buf);
}
```

System-Level Protections

- Randomized stack offsets
  - At start of program, allocate random amount of space on stack
  - Makes it difficult for hacker to predict beginning of inserted code

- Executable space protection
  - Mark certain areas of memory as non-executable (e.g. stack)
  - Requires hardware assistance:
    x86-64 added explicit "execute" permission

Stack Canaries

- Idea
  - Place special value ("canary") on stack just beyond buffer
  - Check for corruption before exiting function
- GCC implementation
  - `-fstack-protector` (now the default)

```
$ ./bufdemo                              bufdemo with -fstack-protector
Type:01234567
01234567
$ ./bufdemo
Type: 012345678
012345678
*** stack smashing detected ***: ./bufdemo terminated
Aborted (core dumped)
```

Summary

- Memory layout
  - OS/machine dependent (including kernel version)
  - Basic partitioning:
    stack, data, text, heap, shared libraries found in most machines

- Avoiding buffer overflow vulnerability
  - Important to use library routines that limit string lengths

- Working with strange code
  - Important to analyze nonstandard cases
    - e.g. What happens when stack corrupted due to buffer overflow?
  - Helps to step through with GDB