

Machine-Level Programming III: Procedures

15-213/15-503: Introduction to Computer Systems

5th Lecture, May 21, 2025

Instructors:

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Reminder: Condition Codes

■ Single bit registers

- **CF** Carry Flag (for unsigned) **SF** Sign Flag (for signed)
- **ZF** Zero Flag **OF** Overflow Flag (for signed)

■ jX and SetX instructions

jX	Condition	Description
jmp	1	Unconditional
je	ZF	Equal / Zero
jne	$\sim ZF$	Not Equal / Not Zero
js	SF	Negative
jns	$\sim SF$	Nonnegative
jg	$\sim (SF \wedge OF) \ \& \ \sim ZF$	Greater (Signed)
jge	$\sim (SF \wedge OF)$	Greater or Equal (Signed)
jl	$(SF \wedge OF)$	Less (Signed)
jle	$(SF \wedge OF) \mid ZF$	Less or Equal (Signed)
ja	$\sim CF \ \& \ \sim ZF$	Above (unsigned)
jb	CF	Below (unsigned)

SetX	Condition	Description
sete	ZF	Equal / Zero
setne	$\sim ZF$	Not Equal / Not Zero
sets	SF	Negative
setns	$\sim SF$	Nonnegative
setg	$\sim (SF \wedge OF) \ \& \ \sim ZF$	Greater (Signed)
setge	$\sim (SF \wedge OF)$	Greater or Equal (Signed)
setl	$(SF \wedge OF)$	Less (Signed)
setle	$(SF \wedge OF) \mid ZF$	Less or Equal (Signed)
seta	$\sim CF \ \& \ \sim ZF$	Above (unsigned)
setb	CF	Below (unsigned)

Machine Level Programming – Control

■ C Control

- if-then-else
- do-while
- while, for
- switch

■ Assembler Control

- Conditional jump
- Conditional move
- Indirect jump (via jump tables)
- Compiler generates code sequence to implement more complex control

■ Standard Techniques

- Loops converted to do-while or jump-to-middle form
- Large switch statements use jump tables
- Sparse switch statements may use decision trees (if-elseif-elseif-else)

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

■ Mechanisms all implemented with machine instructions

■ x86-64 implementation of a procedure uses only those mechanisms required

```
P (...) {  
    •  
    •  
    y = Q(x);  
    print(y)  
    •  
}
```

```
int Q(int i)  
{  
    int t = 3*i;  
    int v[10];  
    •  
    •  
    return v[t];  
}
```

Mechanisms in Procedures

■ Passing control

- To beginning of procedure code
- Back to return point

■ Passing data

- Procedure arguments
- Return value

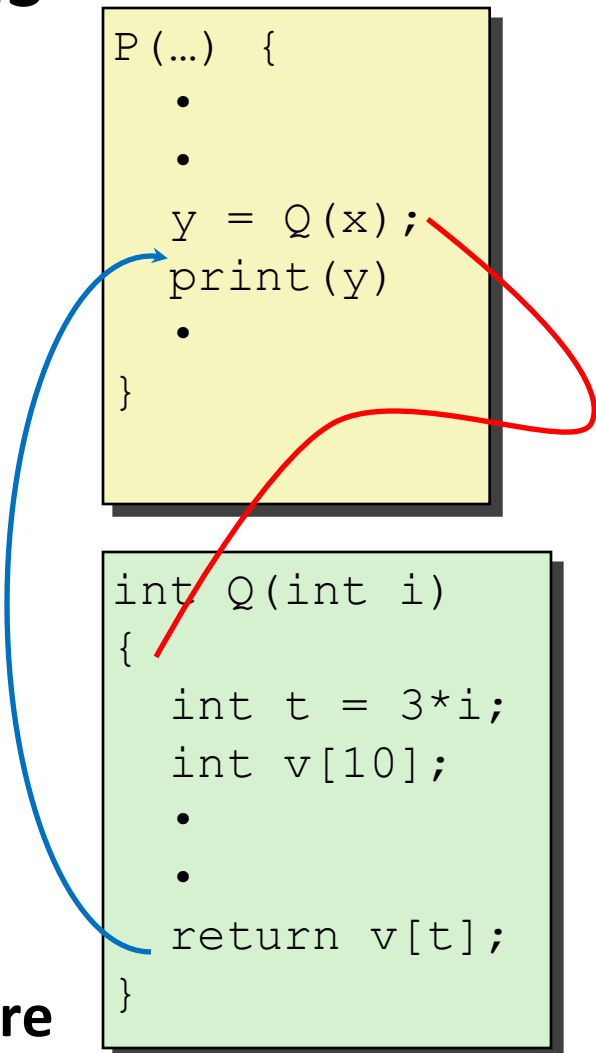
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    •  
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    •  
    •  
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Mechanisms in Procedures

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    •  
    •  
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Mechanisms in Procedures

■ Passing control

- To beginning of procedure code
- Back to return point

■ Passing data

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■ Memory management

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    •  
    •  
    y = Q(x);  
    print(y)  
    •  
}
```

```
int Q(int i)  
{  
    int t = 3*i;  
    int v[10];  
    •  
    •  
    return v[t];  
}
```

Mechanisms in Procedures

```
P ( ) {
```

Machine instructions implement the mechanisms, but the choices are determined by designers. These choices make up the **Application Binary Interface (ABI)**.

- Deallocate upon return
- **Mechanisms all implemented with machine instructions**
- **x86-64 implementation of a procedure uses only those mechanisms required**

```
int v[10];  
.  
.  
return v[t];  
}
```

Today

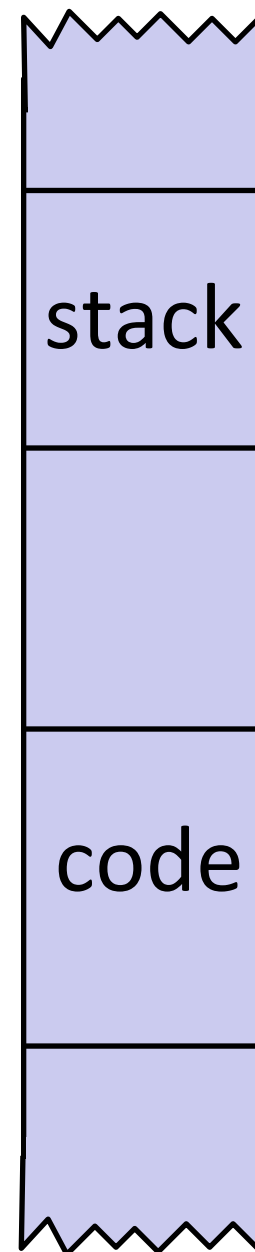
■ Procedures

- **Stack Structure**
- **Calling Conventions**
 - Passing control
 - Passing data
 - Managing local data
- **Activity**
- If we have time: illustration of recursion

x86-64 Stack

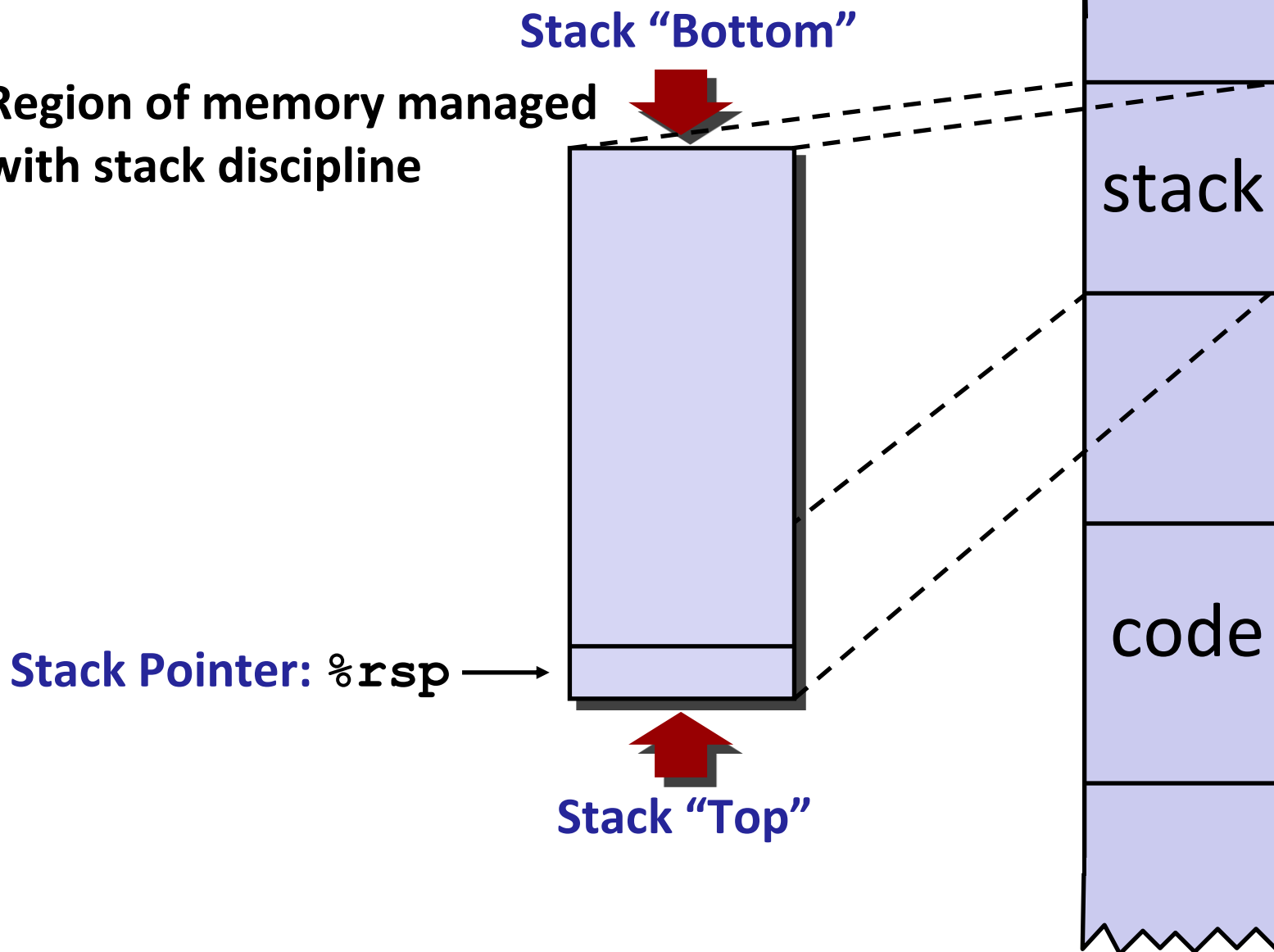
■ Region of memory managed with stack discipline

- Memory viewed as array of bytes.
- Different regions have different purposes.
- (Like ABI, a policy decision)



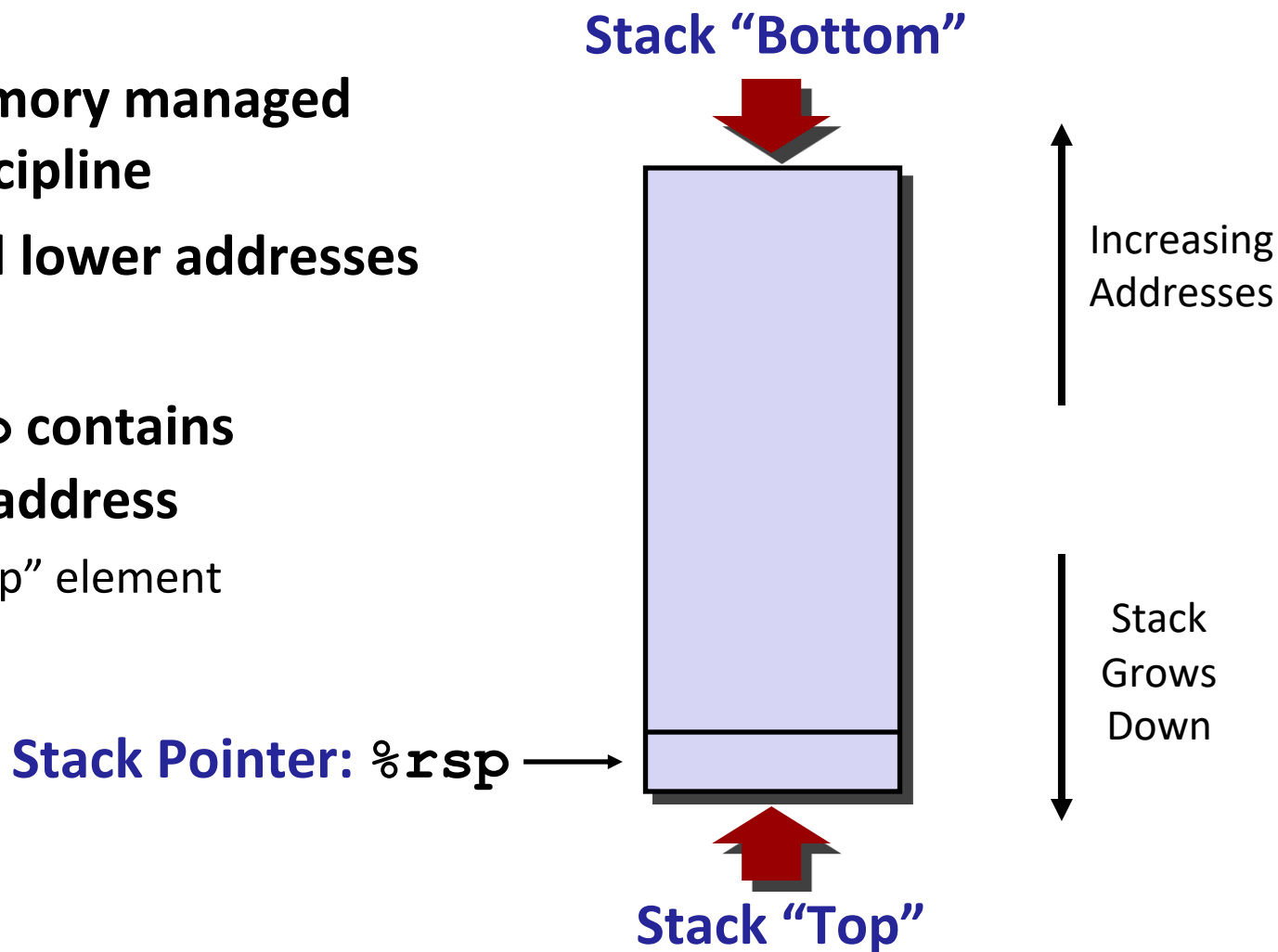
x86-64 Stack

- Region of memory managed with stack discipline



x86-64 Stack

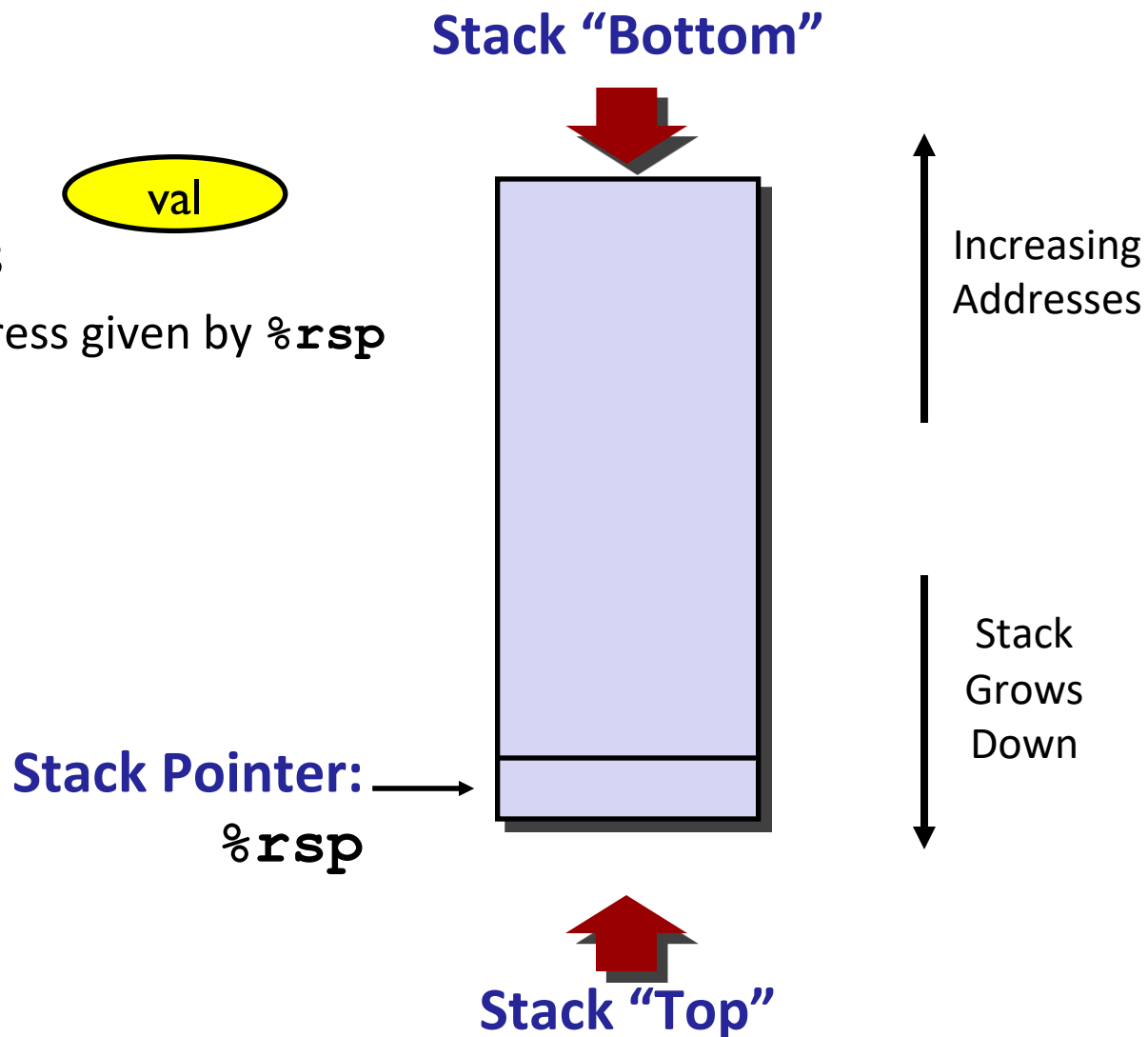
- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register `%rsp` contains lowest stack address
 - address of “top” element



x86-64 Stack: Push

■ `pushq Src`

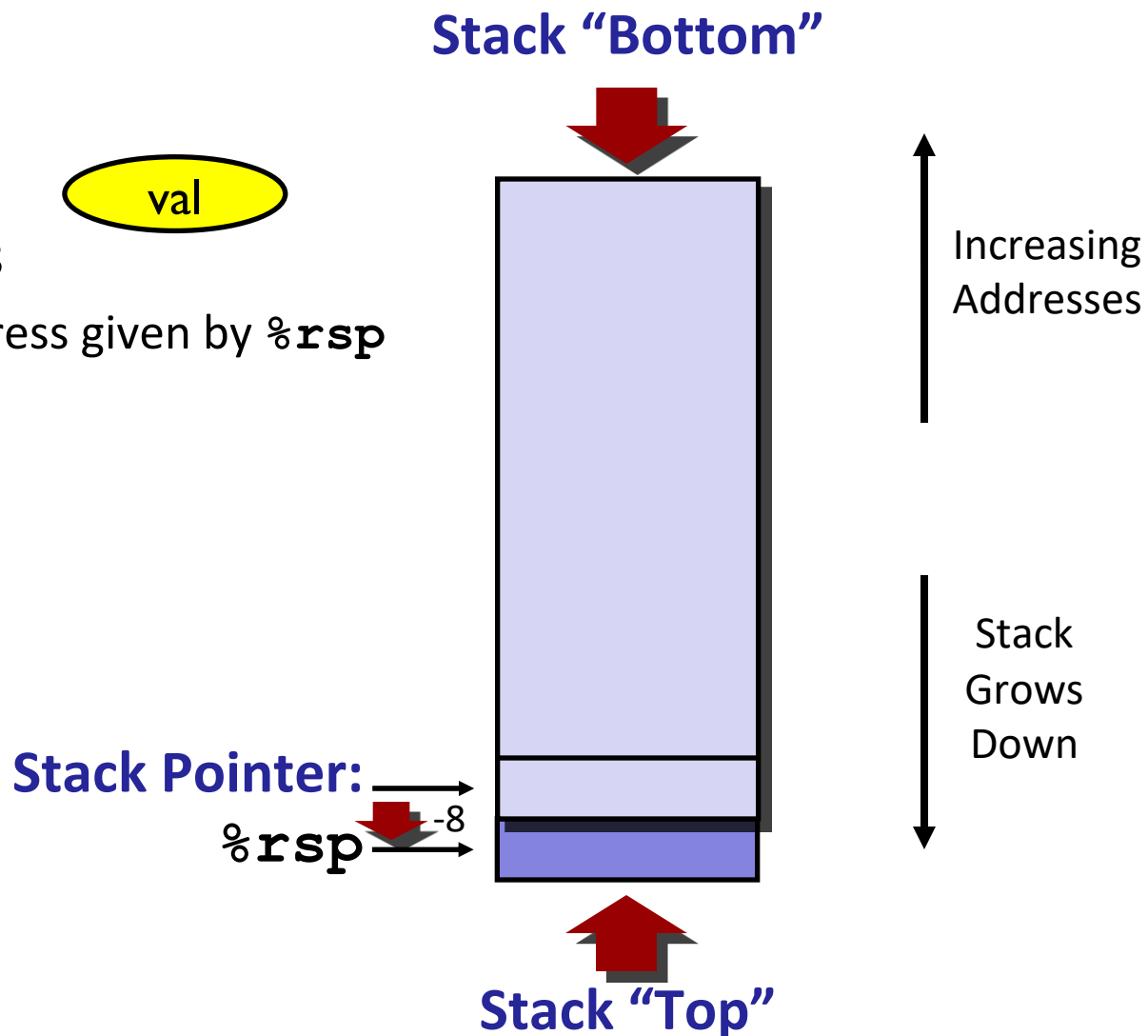
- Fetch operand at *Src*
- Decrement `%rsp` by 8
- Write operand at address given by `%rsp`



x86-64 Stack: 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` (usually a register)

Value is **copied**; it remains in memory at old `%rsp`

Stack Pointer:

`%rsp`



Stack "Bottom"



Increasing
Addresses



Stack
Grows
Down



Stack "Top"



Today

■ Procedures

- Stack Structure
- Calling Conventions
 - **Passing control**
 - Passing data
 - Managing local data
- Activity
- If we have time: illustration of recursion

Code Examples

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

```
00000000000400540 <multstore>:
400540: push    %rbx                # Save %rbx
400541: mov     %rdx,%rbx           # Save dest
400544: call    400550 <mult2>      # mult2(x,y)
400549: mov     %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;
}
```

```
00000000000400550 <mult2>:
400550: mov     %rdi,%rax           # a
400553: imul    %rsi,%rax           # a * b
400557: ret                          # Return
```

Procedure Control Flow

■ Use stack to support procedure call and return

■ **Procedure call:** `call label`

- Push return address on stack
- Jump to *label*

■ **Return address:**

- Address of the next instruction right after call
- Example from disassembly

■ **Procedure return:** `ret`

- Pop address from stack
- Jump to address

These instructions are sometimes printed with a `q` suffix

- This is just to remind you that you're looking at 64-bit code

Control Flow Example #1

```
00000000000400540 <multstore>:
```

•
•
•

```
400544: call    400550 <mult2>
```

```
400549: mov     %rax, (%rbx)
```

•
•

```
00000000000400550 <mult2>:
```

```
400550: mov     %rdi, %rax
```

•
•

```
400557: ret
```

0x130

0x128

0x120

%rsp

%rip

0x120

0x400544

Control Flow Example #2

```
00000000000400540 <multstore>:
```

•
•
•
•
•

```
400544: call    400550 <mult2>
```

```
400549: mov     %rax, (%rbx) ←
```

0x130

0x128

0x120

0x118

0x400549

%rsp

0x118

%rip

0x400550

```
00000000000400550 <mult2>:
```

```
400550: mov     %rdi,%rax ←
```

•
•

```
400557: ret
```

Control Flow Example #3

```
00000000000400540 <multstore>:
```

•
•
•

```
400544: call    400550 <mult2>
```

```
400549: mov     %rax, (%rbx) ←
```

•
•

```
00000000000400550 <mult2>:
```

```
400550: mov     %rdi, %rax
```

•
•

```
400557: ret     ←
```

0x130

0x128

0x120

0x118

0x400549

%rsp

0x118

%rip

0x400557

Control Flow Example #4

```
00000000000400540 <multstore>:  
.  
.  
400544: call    400550 <mult2>  
400549: mov     %rax, (%rbx)  
.  
.
```

```
00000000000400550 <mult2>:  
400550: mov     %rdi, %rax  
.  
.  
400557: ret
```

0x130

0x128

0x120

%rsp

0x120

%rip

0x400549

Today

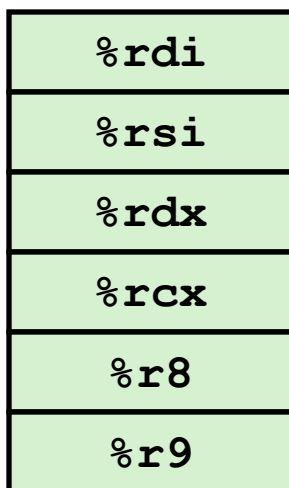
■ Procedures

- Stack Structure
- Calling Conventions
 - Passing control
 - **Passing data**
 - Managing local data
- Activity
- If we have time: illustration of recursion

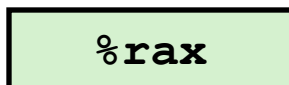
Procedure Data Flow

Registers

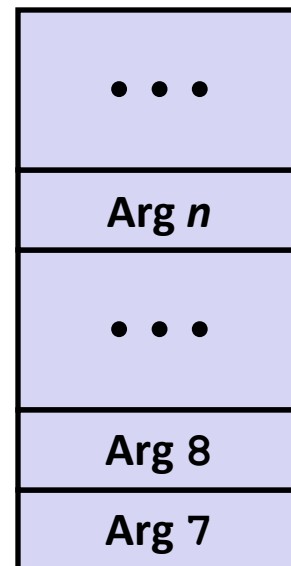
■ First 6 arguments



■ Return value



Stack



■ Only allocate stack space when needed

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: mov     %rdx,%rbx        # Save dest
400544: call    400550 <mult2>    # mult2(x,y)
    # t in %rax
400549: mov     %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:  mov     %rdi,%rax        # a
400553:  imul    %rsi,%rax        # a * b
    # s in %rax
400557:  ret                     # Return
```

Today

■ Procedures

- Stack Structure
- Calling Conventions
 - Passing control
 - Passing data
 - **Managing local data**
- Activity
- If we have time: illustration of recursion

Stack-Based Languages

■ Languages that support recursion

- e.g., 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 pointer

■ 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

Call Chain Example

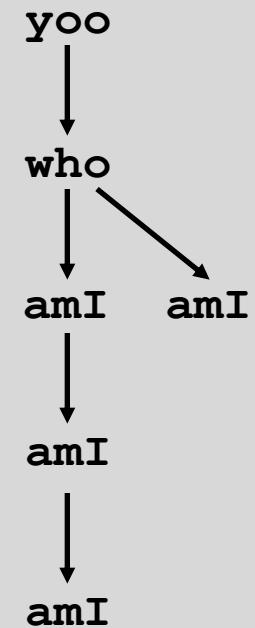
```
yoo (...)  
{  
  .  
  .  
  who ();  
  .  
  .  
}
```

```
who (...)  
{  
  . . .  
  amI ();  
  . . .  
  amI ();  
  . . .  
}
```

```
amI (...)  
{  
  .  
  .  
  amI ();  
  .  
  .  
}
```

Procedure `amI ()` is recursive

Example Call Chain



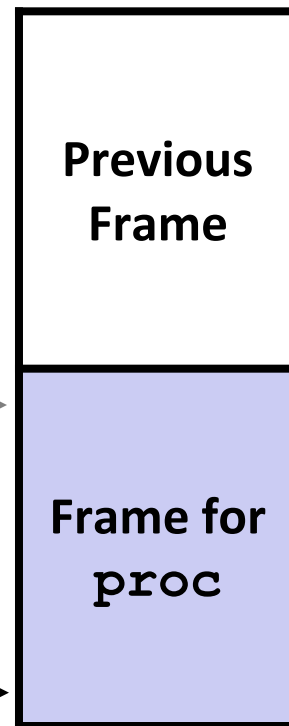
Stack Frames

■ Contents

- Return information
- Local storage (if needed)
- Temporary space (if needed)

Frame Pointer: `%rbp`
(Optional)

Stack Pointer: `%rsp`



■ Management

- Space allocated when enter procedure
 - “Set-up” code
 - Includes push by **call** instruction
- Deallocated when return
 - “Finish” code
 - Includes pop by **ret** instruction

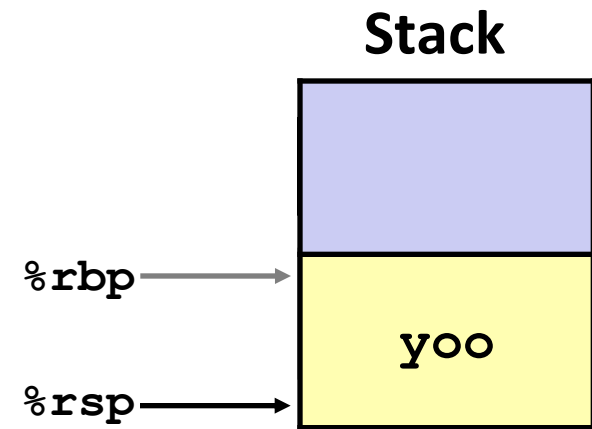

**Stack
“Top”**

Example

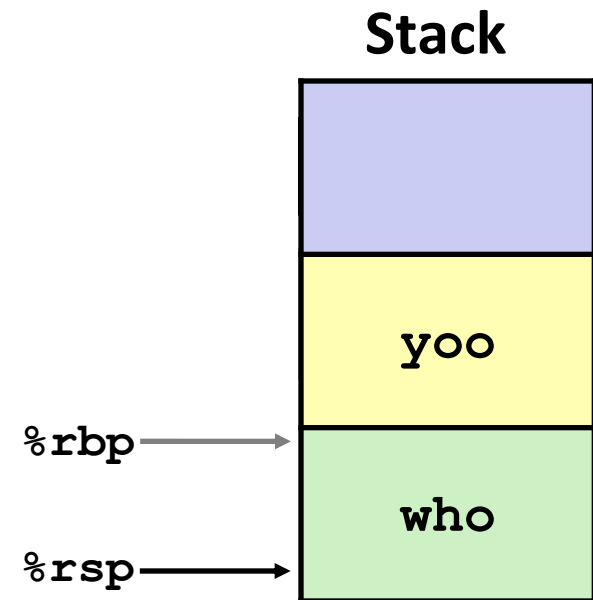
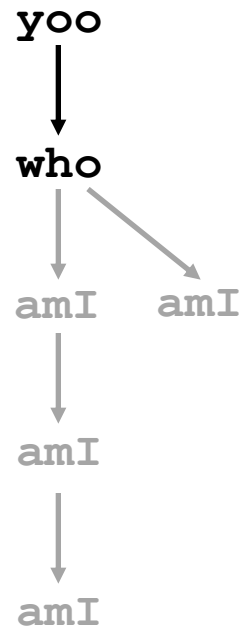
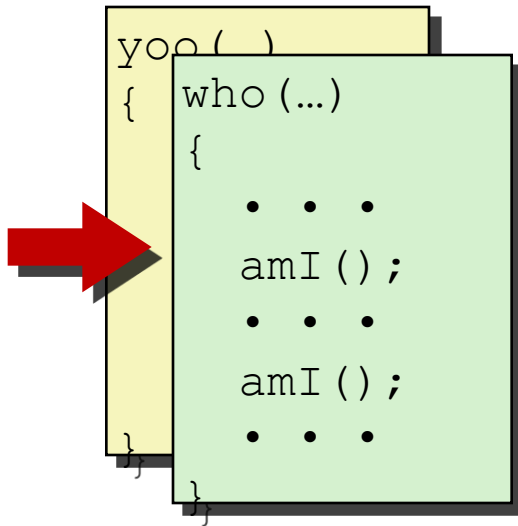


```
yoo (...)  
{  
  .  
  .  
  who ();  
  .  
  .  
}
```

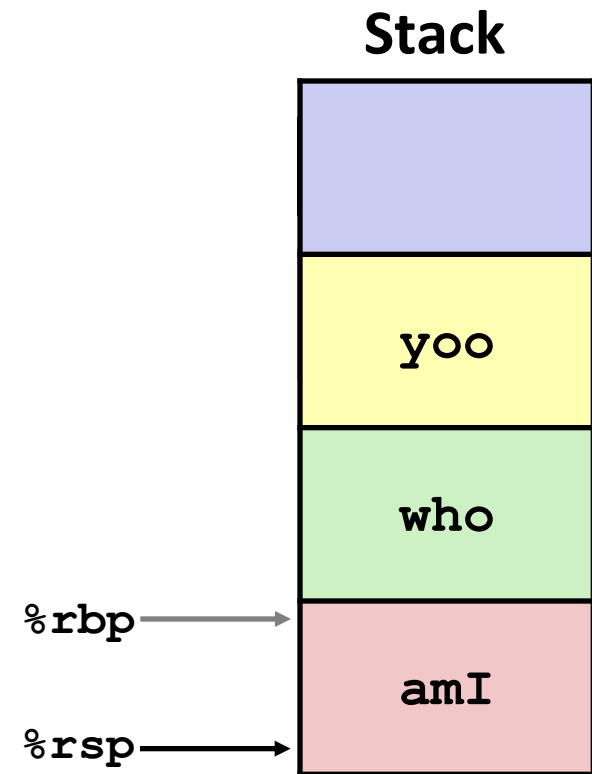
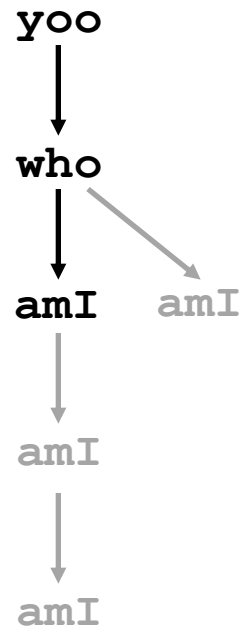
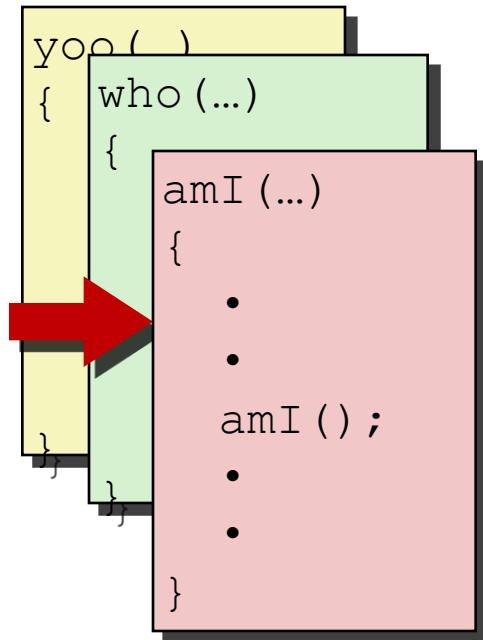
```
yoo  
  ↓  
who  
  ↓  ↘  
amI  amI  
  ↓  
amI  
  ↓  
amI
```



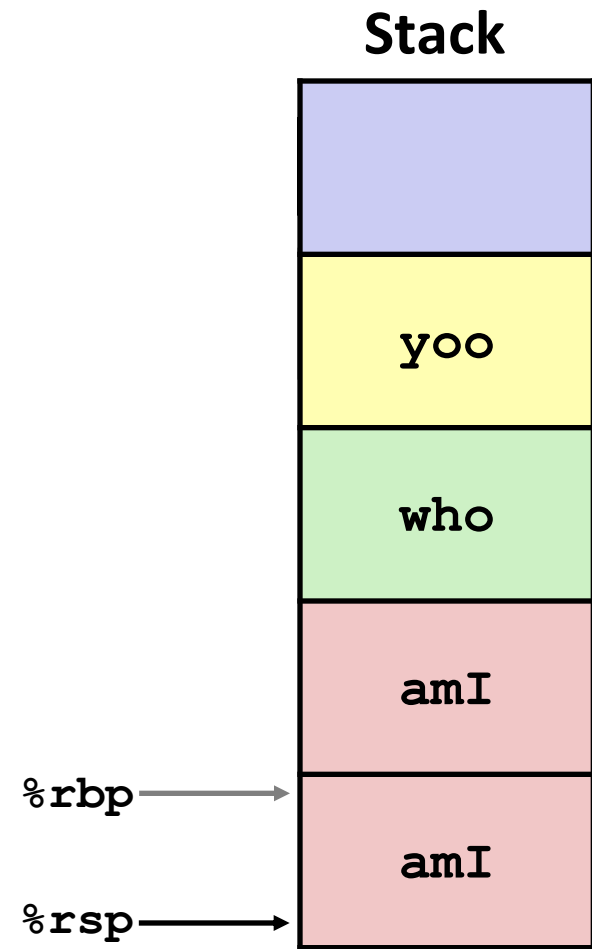
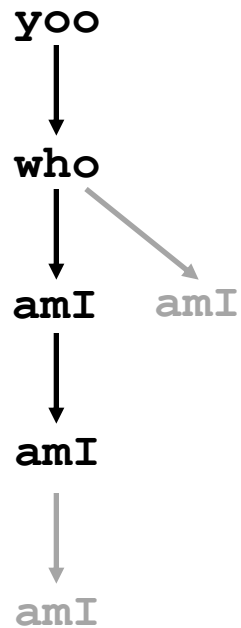
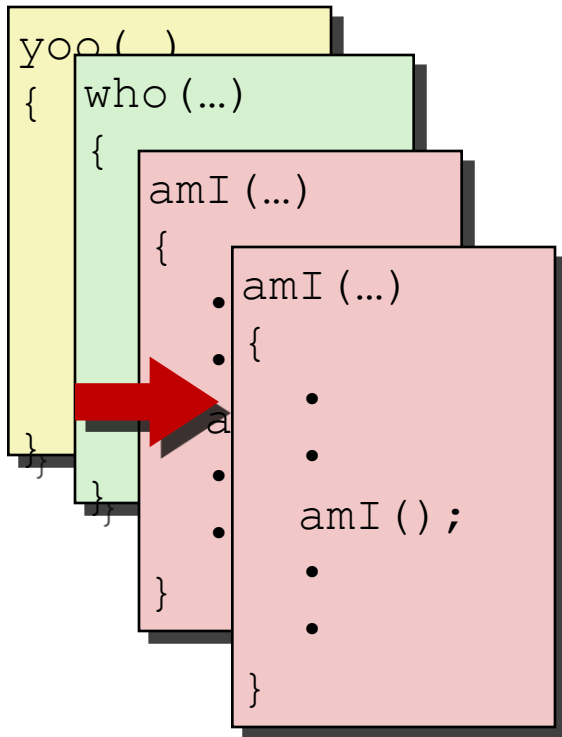
Example



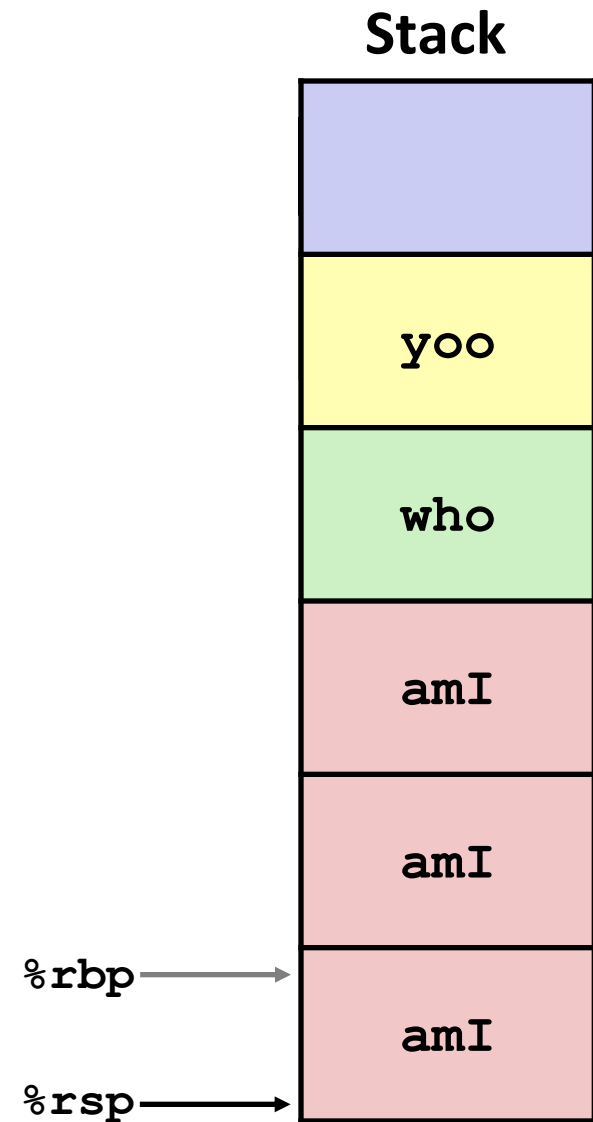
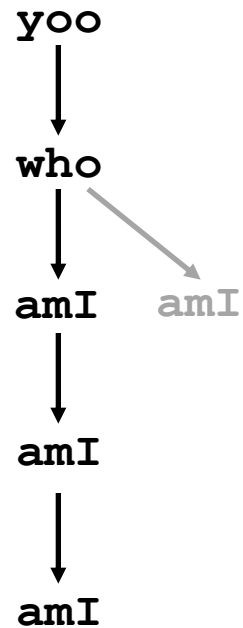
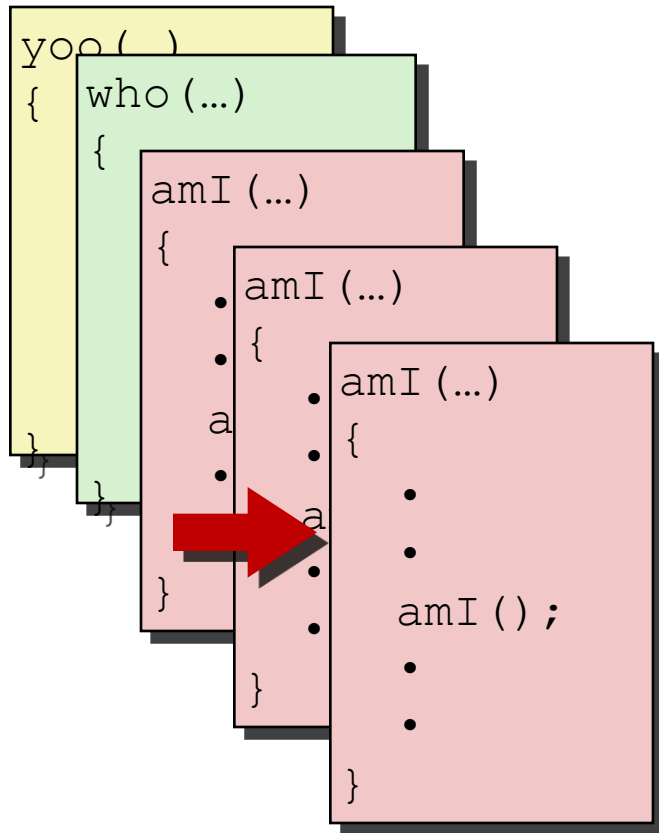
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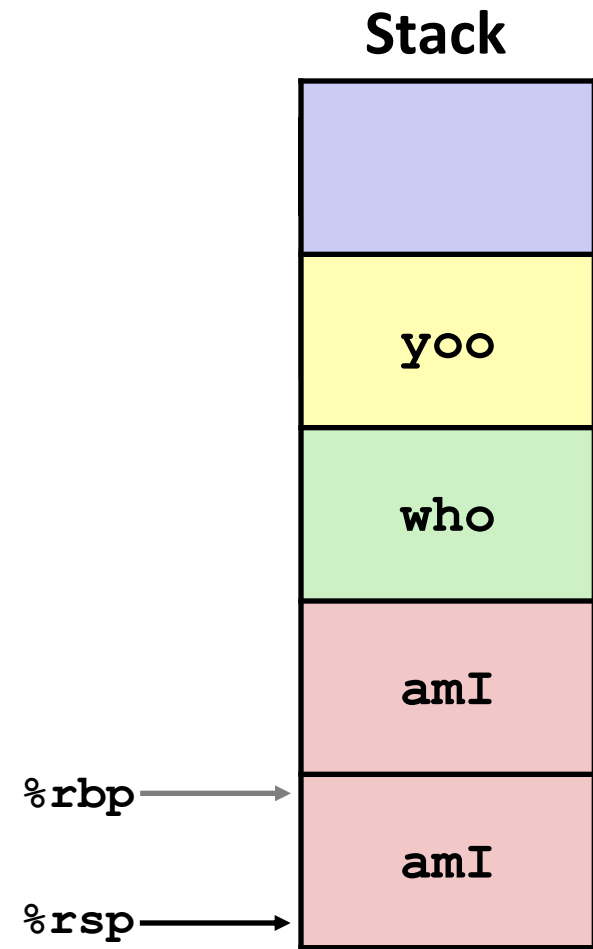
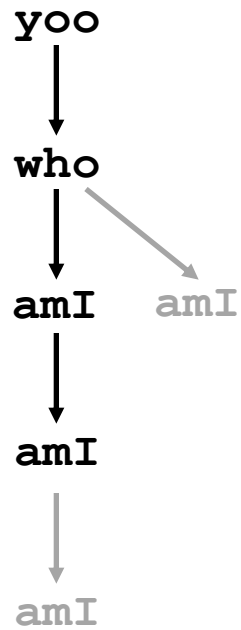
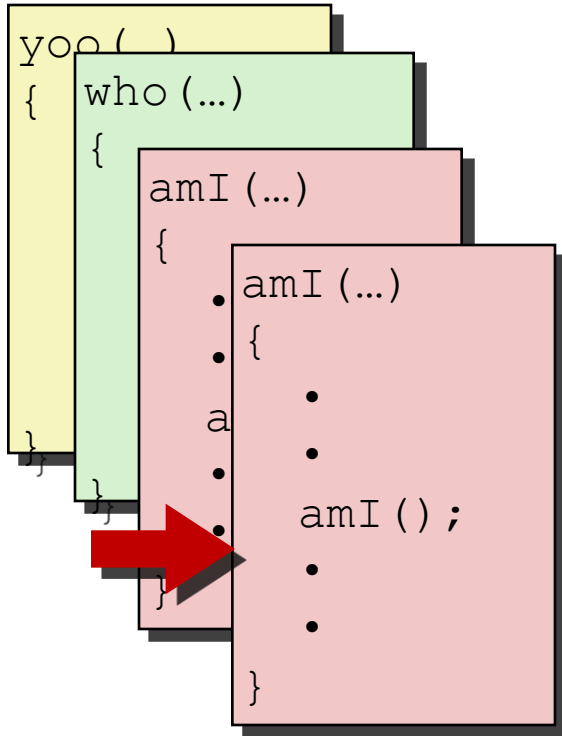
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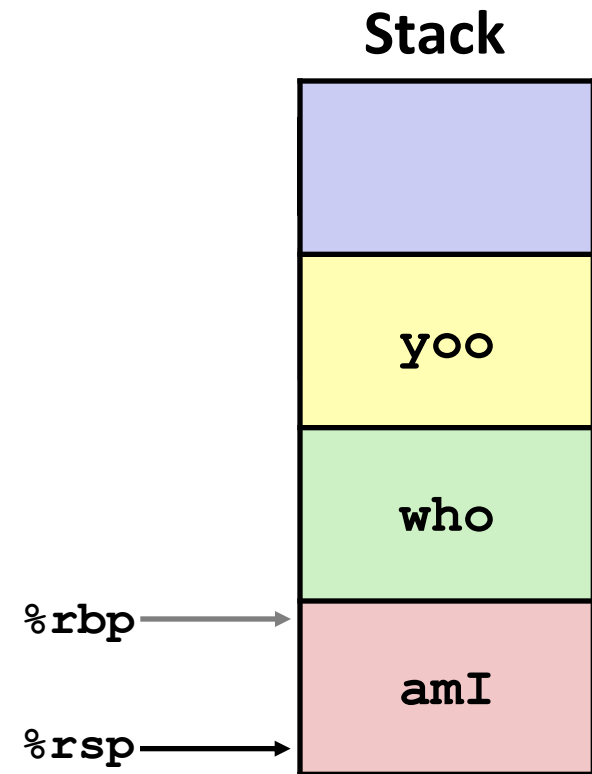
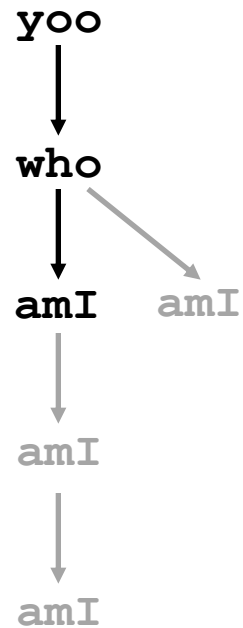
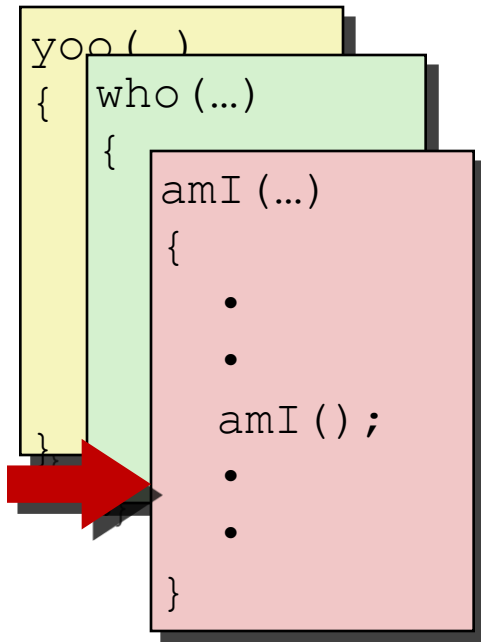
Example



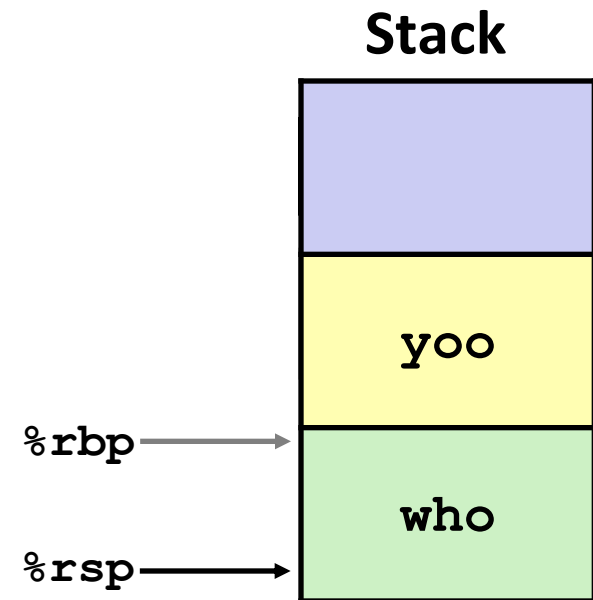
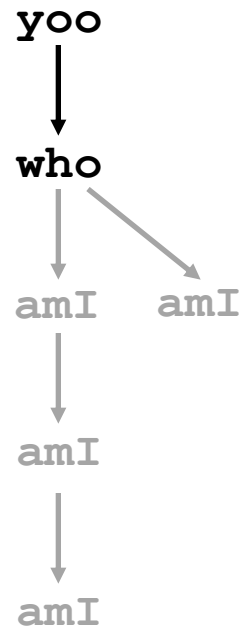
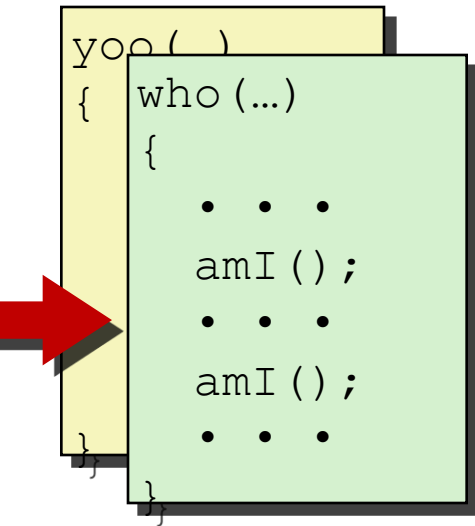
Example



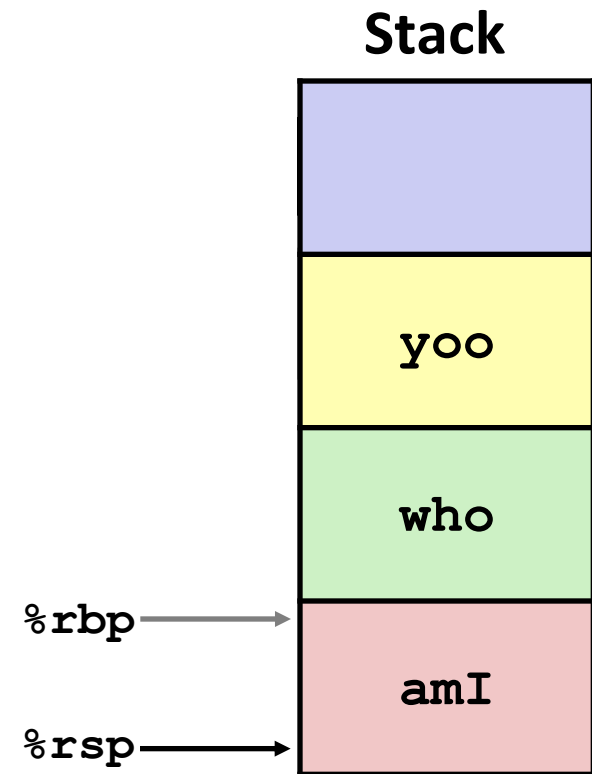
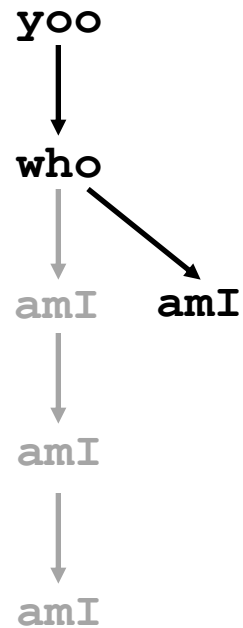
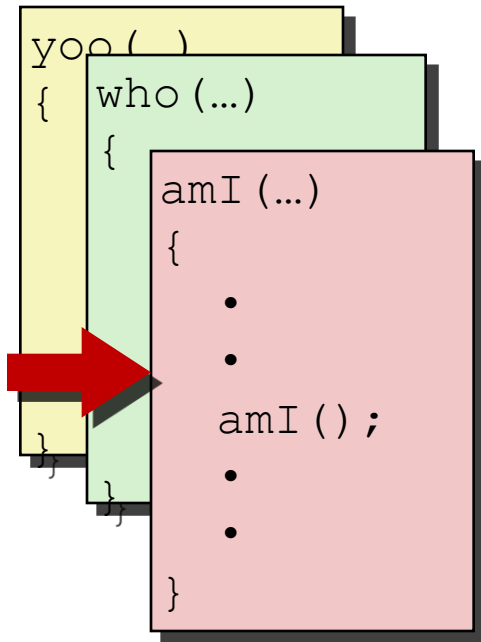
Example



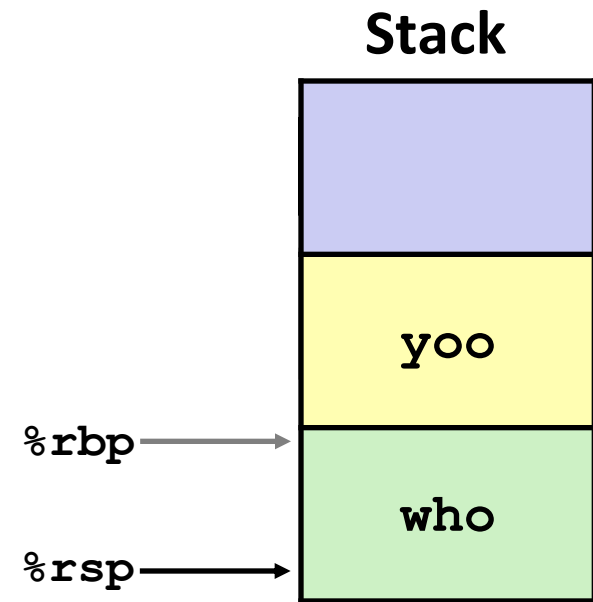
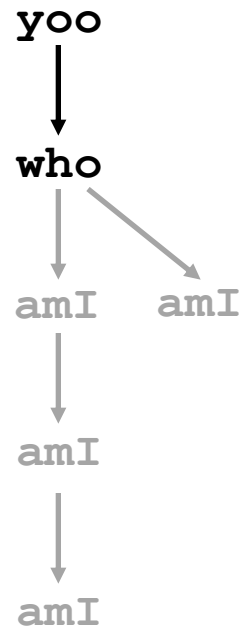
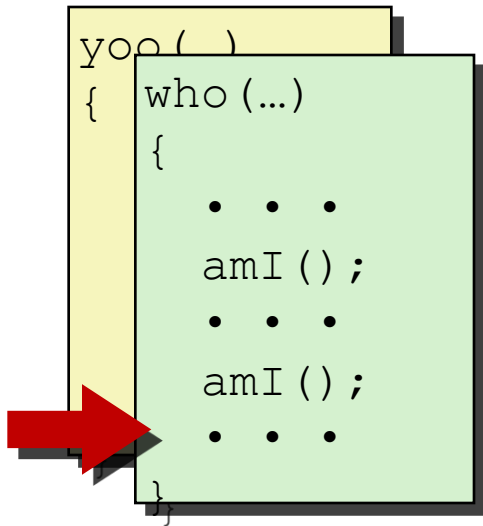
Example



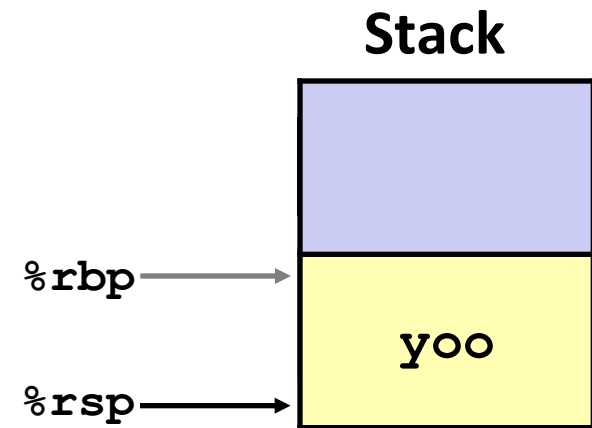
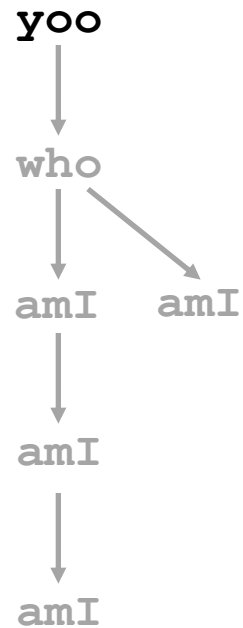
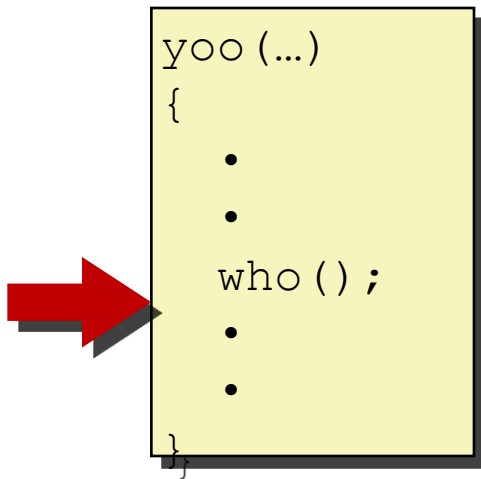
Example



Example



Example



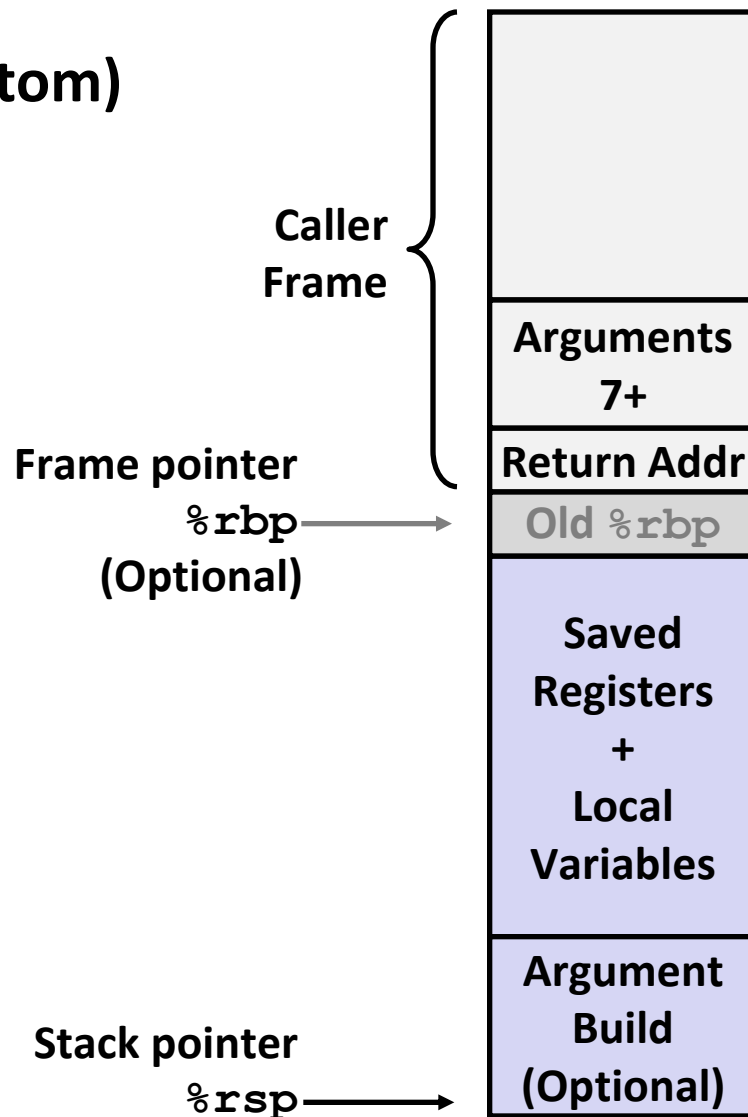
x86-64/Linux Stack Frame

■ 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



Example: `incr`

```
long incr(long *p, long val) {  
    long x = *p;  
    long y = x + val;  
    *p = y;  
    return x;  
}
```

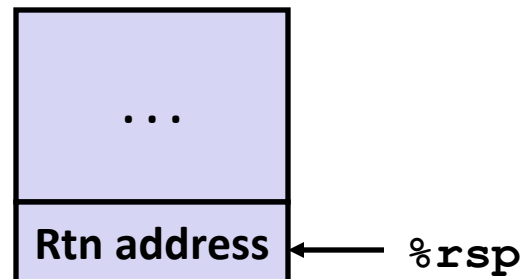
```
incr:  
    movq    (%rdi), %rax  
    addq    %rax, %rsi  
    movq    %rsi, (%rdi)  
    ret
```

Register	Use(s)
%rdi	Argument <code>p</code>
%rsi	Argument <code>val</code> , <code>y</code>
%rax	<code>x</code> , Return value

Example: Calling `incr` #1

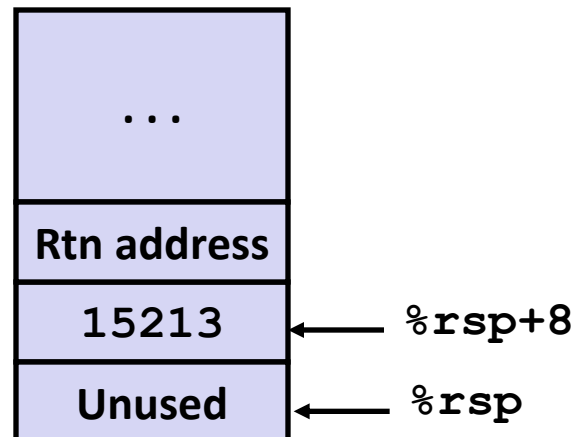
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

Initial Stack Structure



```
call_incr:
    subq    $16, %rsp
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

Resulting Stack Structure

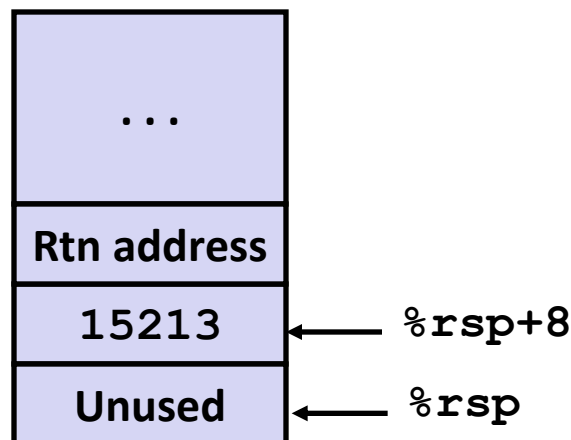


Example: Calling `incr` #2

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
call_incr:
    subq    $16, %rsp
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

Stack Structure

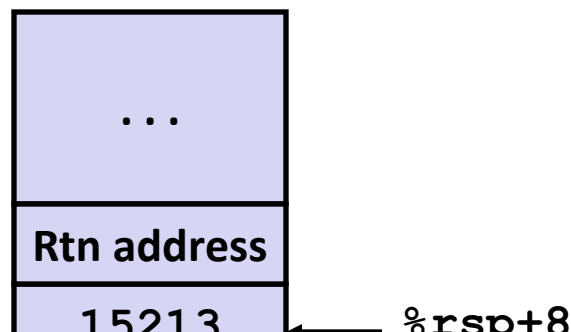


Register	Use(s)
<code>%rdi</code>	<code>&v1</code>
<code>%rsi</code>	3000

Example: Calling `incr` #2

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

Stack Structure



Aside 1: `movl $3000, %esi`

- Remember, `movl` -> %exx zeros out high order 32 bits.
- Why use `movl` instead of `movq`? 1 byte shorter.

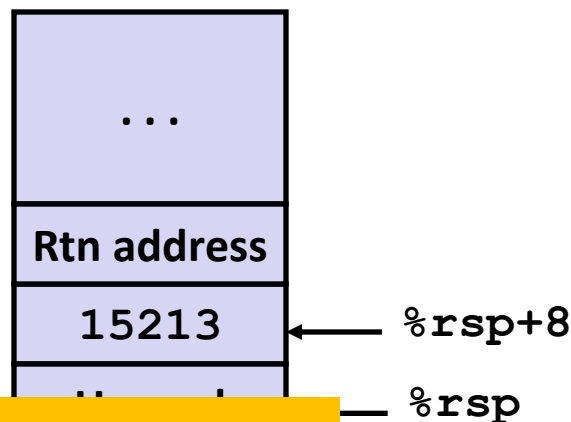
```
movl    $3000, %esi
leaq    8(%rsp), %rdi
call    incr
addq    8(%rsp), %rax
addq    $16, %rsp
ret
```

%rdi	&v1
%rsi	3000

Example: Calling `incr` #2

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

Stack Structure



Aside 2: `leaq 8(%rsp), %rdi`

- Computes `%rsp+8`
- Actually, used for what it is meant!

```
leaq    8(%rsp), %rdi
call    incr
addq    8(%rsp), %rax
addq    $16, %rsp
ret
```

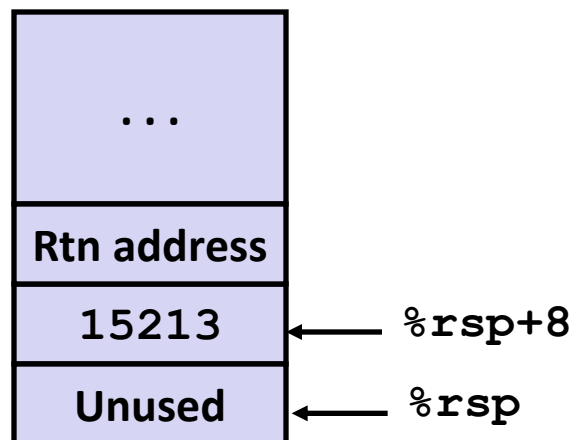
Register(s)	
<code>%rdi</code>	<code>v1</code>
<code>%rsi</code>	3000

Example: Calling `incr` #2

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
call_incr:
    subq    $16, %rsp
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

Stack Structure



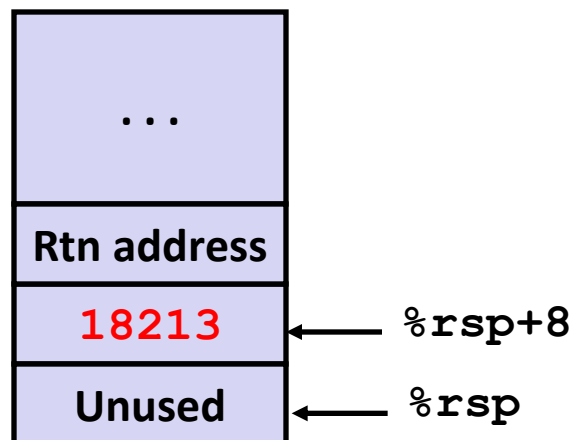
Register	Use(s)
<code>%rdi</code>	<code>&v1</code>
<code>%rsi</code>	3000

Example: Calling `incr` #3

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
call_incr:
    subq    $16, %rsp
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

Stack Structure

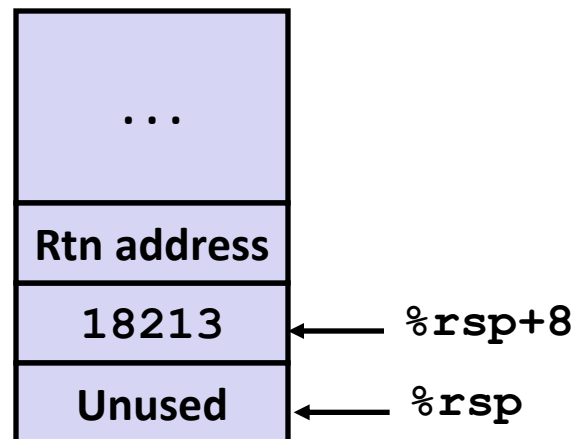


Register	Use(s)
<code>%rdi</code>	<code>&v1</code>
<code>%rsi</code>	3000

Example: Calling `incr` #4

Stack Structure

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```



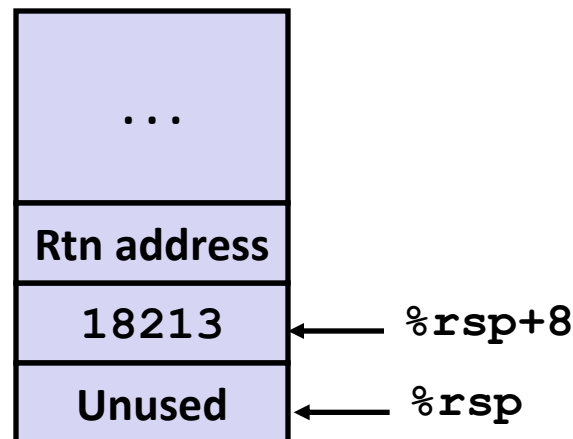
```
call_incr:
    subq    $16, %rsp
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

Register	Use(s)
%rax	Return value

Example: Calling `incr` #5a

Stack Structure

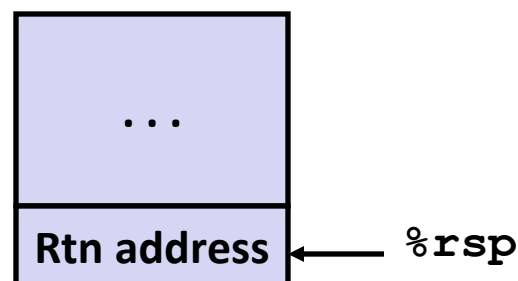
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```



```
call_incr:
    subq    $16, %rsp
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

Register	Use(s)
<code>%rax</code>	Return value

Updated Stack Structure

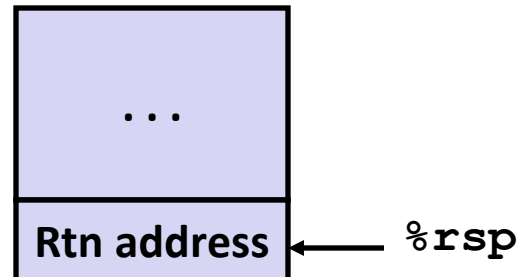


Example: Calling `incr` #5b

```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

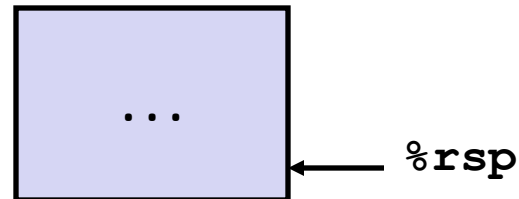
```
call_incr:
    subq    $16, %rsp
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

Updated Stack Structure



Register	Use(s)
<code>%rax</code>	Return value

Final Stack Structure



Register Saving Conventions

■ 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 $18213, %rdx  
    . . .  
    ret
```

- Contents of register `%rdx` overwritten by `who`
- This could be trouble → something should be done!
 - Need some coordination

Register Saving Conventions

■ When procedure *yoo* calls *who*:

- *yoo* is the *caller*
- *who* is the *callee*

■ Can register be used for temporary storage?

■ Conventions

- *“Caller Saved” (aka “Call-Clobbered”)*
 - Caller saves temporary values in its frame before the call
- *“Callee Saved” (aka “Call-Preserved”)*
 - Callee saves temporary values in its frame before using
 - Callee restores them before returning to caller

x86-64 Linux Register Usage #1

■ **%rax**

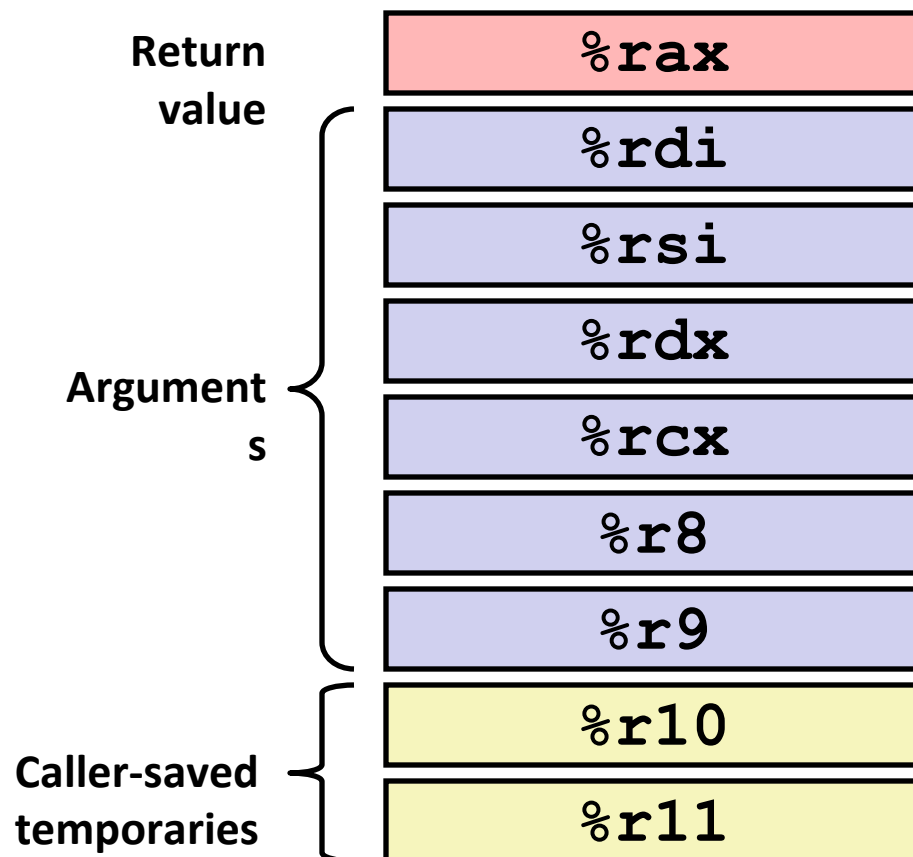
- Return value
- Also caller-saved
- Can be modified by procedure

■ **%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**

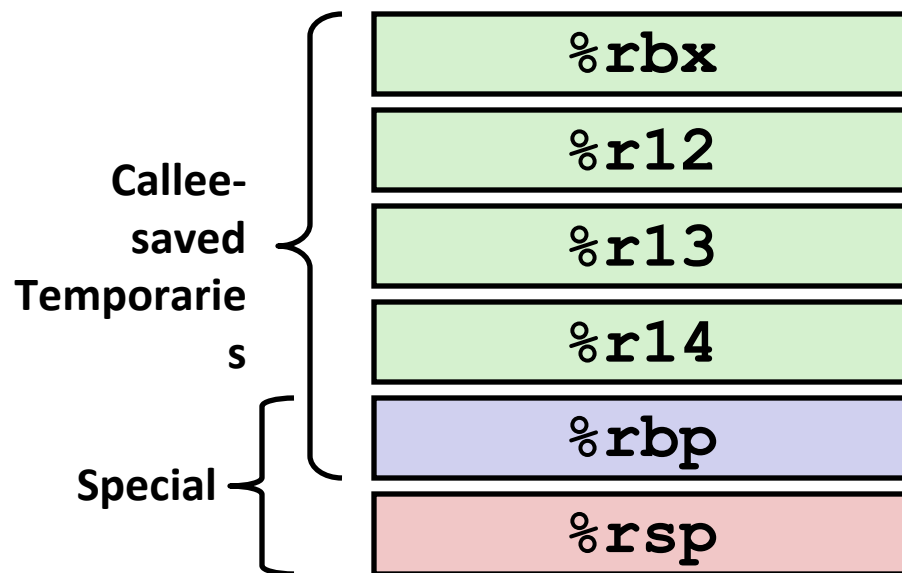
- Callee-saved
- Callee must save & restore

■ **%rbp**

- Callee-saved
- Callee must save & restore
- May be used as frame pointer
- Can mix & match

■ **%rsp**

- Special form of callee save
- Restored to original value upon exit from procedure



Activity Time!

<http://www.cs.cmu.edu/~213/activities/machine-procedures.pdf>

Quiz

<https://canvas.cmu.edu/courses/47415/quizzes/143243>

Today

■ Procedures

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

Recursive Function

```
/* Recursive popcount */  
long pcount_r(unsigned long x) {  
    if (x == 0)  
        return 0;  
    else  
        return (x & 1)  
            + pcount_r(x >> 1);  
}
```

```
pcount_r:  
    movl    $0, %eax  
    testq   %rdi, %rdi  
    je      .L6  
    pushq   %rbx  
    movq    %rdi, %rbx  
    andl    $1, %ebx  
    shrq    %rdi  
    call    pcount_r  
    addq    %rbx, %rax  
    popq    %rbx  
.L6:  
    rep; ret
```

Recursive Function Terminal Case

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
    if (x == 0)
        return 0;
    else
        return (x & 1)
            + pcount_r(x >> 1);
}
```

```
pcount_r:
    movl    $0, %eax
    testq   %rdi, %rdi
    je      .L6
    pushq   %rbx
    movq    %rdi, %rbx
    andl    $1, %ebx
    shrq    %rdi
    call    pcount_r
    addq    %rbx, %rax
    popq    %rbx
.L6:
    rep; ret
```

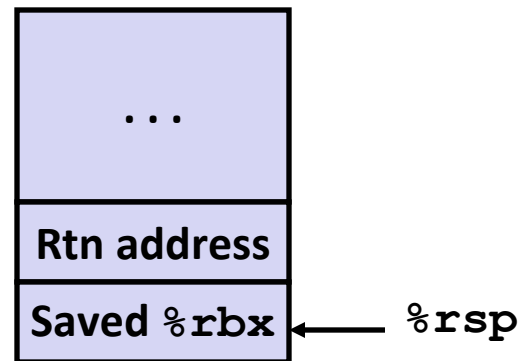
Register	Use(s)	Type
%rdi	x	Argument
%rax	Return value	Return value

Recursive Function Register Save

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
    if (x == 0)
        return 0;
    else
        return (x & 1)
            + pcount_r(x >> 1);
}
```

```
pcount_r:
    movl    $0, %eax
    testq   %rdi, %rdi
    je      .L6
    pushq   %rbx
    movq    %rdi, %rbx
    andl    $1, %ebx
    shrq    %rdi
    call    pcount_r
    addq    %rbx, %rax
    popq    %rbx
.L6:
    rep; ret
```

Register	Use(s)	Type
%rdi	x	Argument



Recursive Function Call Setup

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
    if (x == 0)
        return 0;
    else
        return (x & 1)
            + pcount_r(x >> 1);
}
```

```
pcount_r:
    movl    $0, %eax
    testq   %rdi, %rdi
    je      .L6
    pushq   %rbx
    movq    %rdi, %rbx
    andl    $1, %ebx
    shrq    %rdi
    call    pcount_r
    addq    %rbx, %rax
    popq    %rbx
.L6:
    rep; ret
```

Register	Use(s)	Type
%rdi	x >> 1	Rec. argument
%rbx	x & 1	Callee-saved

Recursive Function Call

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
    if (x == 0)
        return 0;
    else
        return (x & 1)
            + pcount_r(x >> 1);
}
```

```
pcount_r:
    movl    $0, %eax
    testq   %rdi, %rdi
    je      .L6
    pushq   %rbx
    movq    %rdi, %rbx
    andl    $1, %ebx
    shrq    %rdi
    call    pcount_r
    addq    %rbx, %rax
    popq    %rbx
.L6:
    rep; ret
```

Register	Use(s)	Type
%rbx	x & 1	Callee-saved
%rax	Recursive call return value	

Recursive Function Result

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
    if (x == 0)
        return 0;
    else
        return (x & 1)
            + pcount_r(x >> 1);
}
```

```
pcount_r:
    movl    $0, %eax
    testq   %rdi, %rdi
    je      .L6
    pushq   %rbx
    movq    %rdi, %rbx
    andl    $1, %ebx
    shrq    %rdi
    call    pcount_r
    addq    %rbx, %rax
    popq    %rbx
.L6:
    rep; ret
```

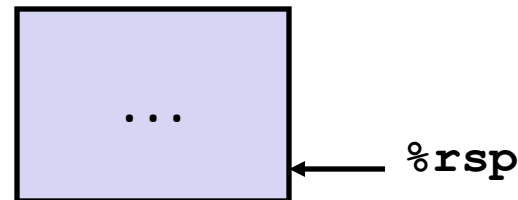
Register	Use(s)	Type
%rbx	x & 1	Callee-saved
%rax	Return value	

Recursive Function Completion

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
    if (x == 0)
        return 0;
    else
        return (x & 1)
            + pcount_r(x >> 1);
}
```

```
pcount_r:
    movl    $0, %eax
    testq   %rdi, %rdi
    je      .L6
    pushq   %rbx
    movq    %rdi, %rbx
    andl    $1, %ebx
    shrq    %rdi
    call    pcount_r
    addq    %rbx, %rax
    popq    %rbx
.L6:
    rep; ret
```

Register	Use(s)	Type
%rax	Return value	Return value



Observations About Recursion

■ Handled Without Special Consideration

- Stack frames mean that each function call has private storage
 - Saved registers & local variables
 - Saved return pointer
- Register saving conventions prevent one function call from corrupting another's data
 - Unless the C code explicitly does so (e.g., buffer overflow in Lecture 9)
- 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

x86-64 Procedure Summary

■ Important Points

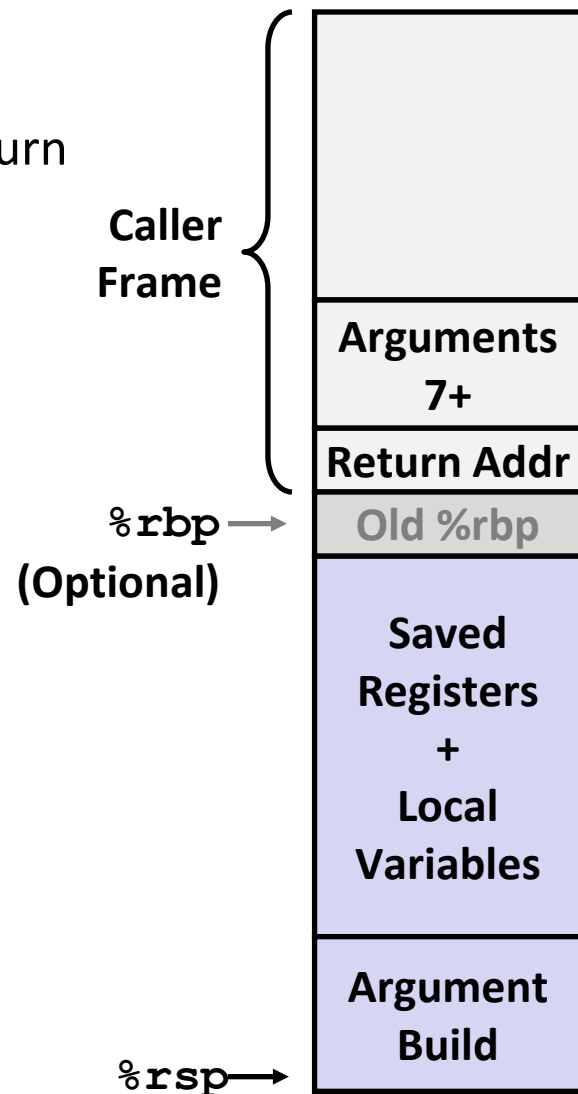
- Stack is the right data structure for procedure call/return
 - If P calls Q, then Q returns before P

■ Recursion (& mutual recursion) handled by normal calling conventions

- Can safely store values in local stack frame and in callee-saved registers
- Put function arguments at top of stack
- Result return in **%rax**

■ Pointers are addresses of values

- On stack or global



Bonus Content: Tail Recursive

■ Recursive functions can be “tail recursive”

- There is no computation after the function call
- Many compilers / languages can optimize these functions

```
long popcount_t(unsigned long x,  
                long s)  
{  
    if (x == 0) return s;  
    long b = x & 1UL;  
    return popcount_t(x >>1,  
                      s + b);  
}
```

```
popcount_t:  
    movq    %rsi, %rax  
    testq   %rdi, %rdi  
    je      .L18  
.L15:  
    movq    %rdi, %rdx  
    andl    $1, %edx  
    addq    %rdx, %rax  
    shrq    %rdi  
    jne     .L15  
.L18:  
    ret
```