

Machine-Level Programming III: Procedures

15-213/18-213: Introduction to Computer Systems
7th Lecture, September 20, 2016

Instructor:

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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

■ 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

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int Q(int i)  
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  •  
  return v[t];  
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Mechanisms in Procedures

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    •  
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```

```
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

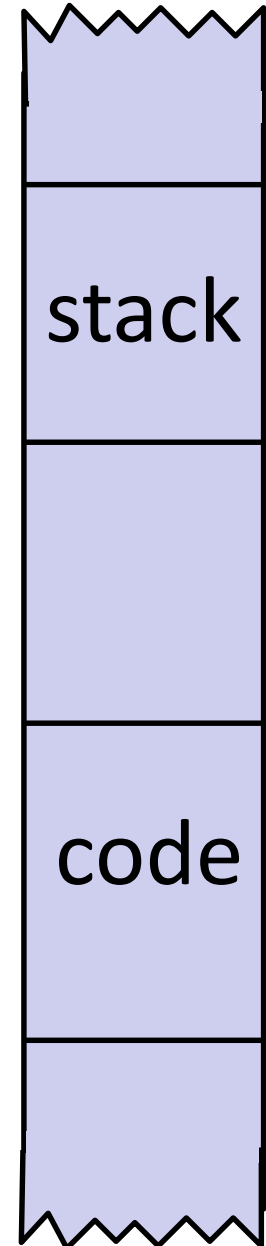
■ Procedures

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

x86-64 Stack

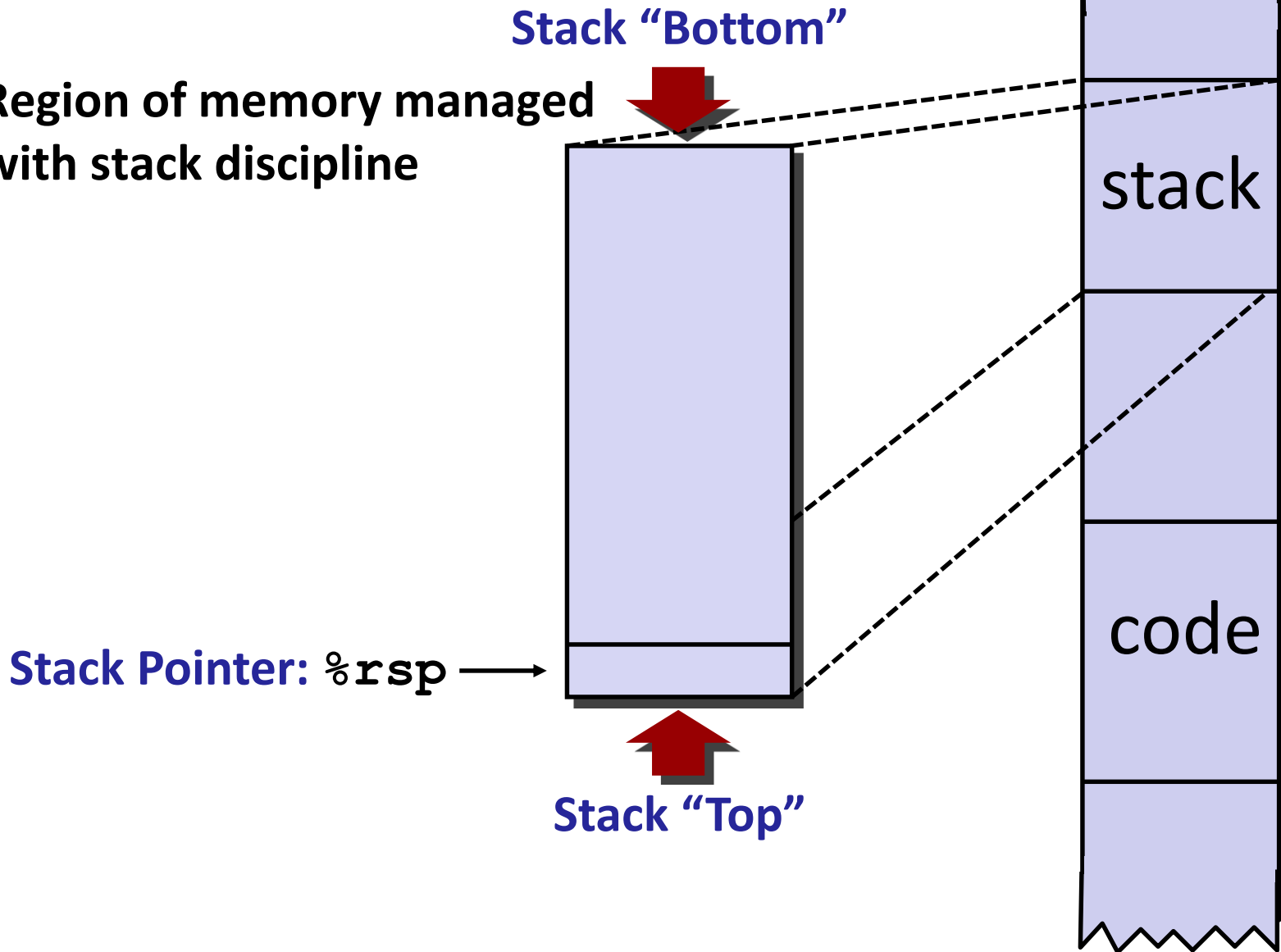
- **Region of memory managed with stack discipline**

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



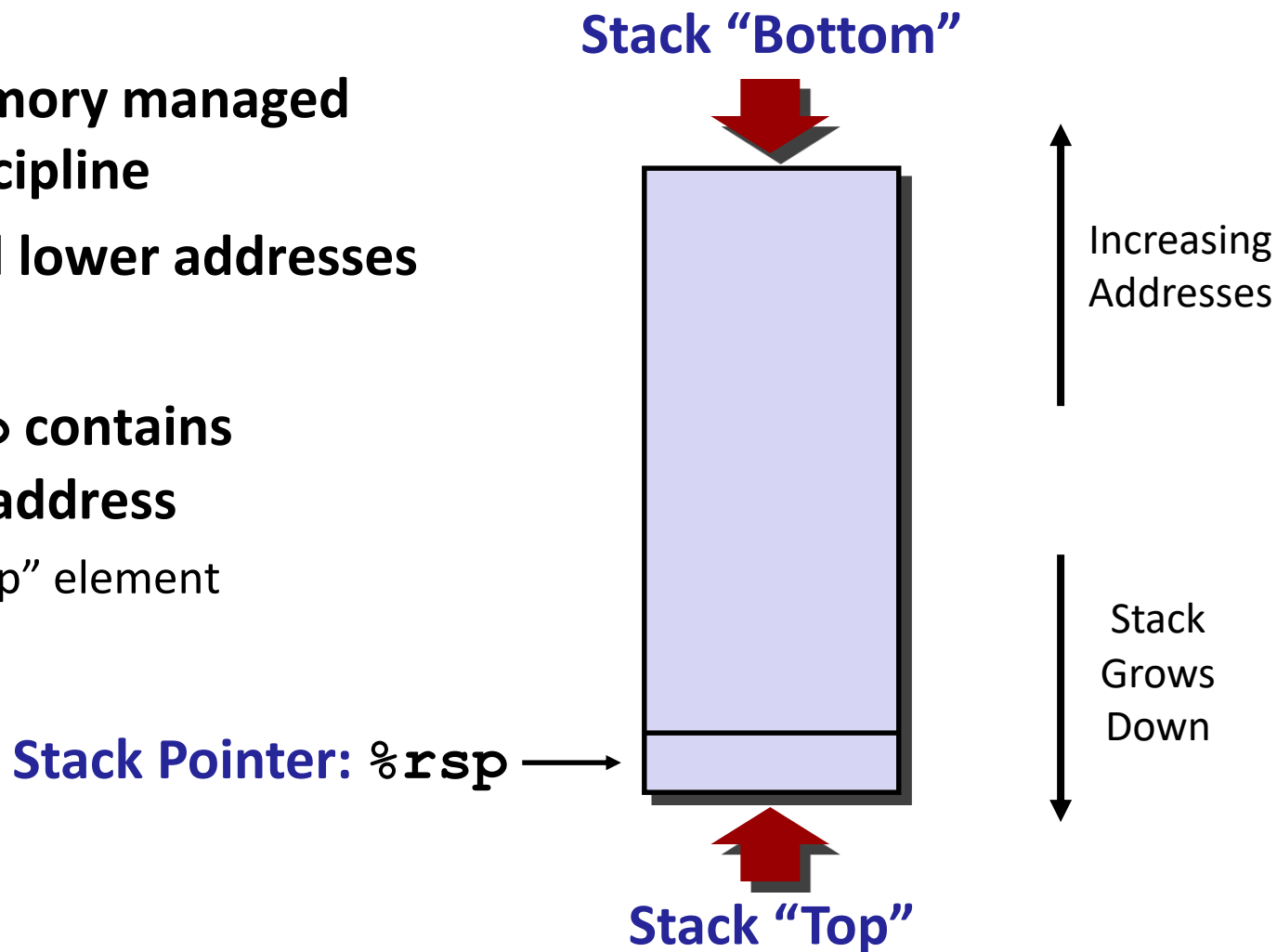
x86-64 Stack

- Region of memory managed with stack discipline



x86-64 Stack

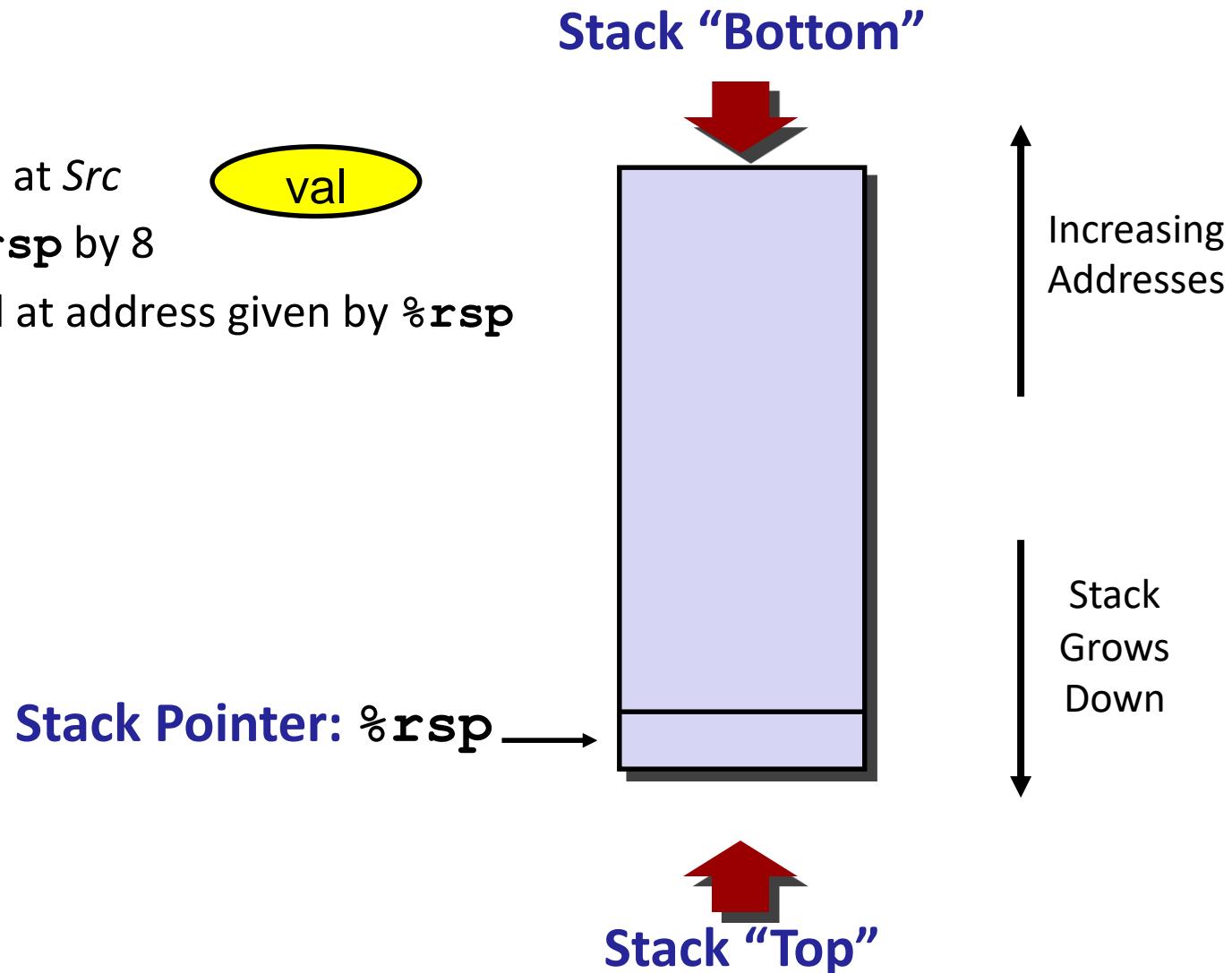
- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register `%rsp` contains lowest stack address
 - address of “top” element



x86-64 Stack: Push

■ `pushq Src`

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

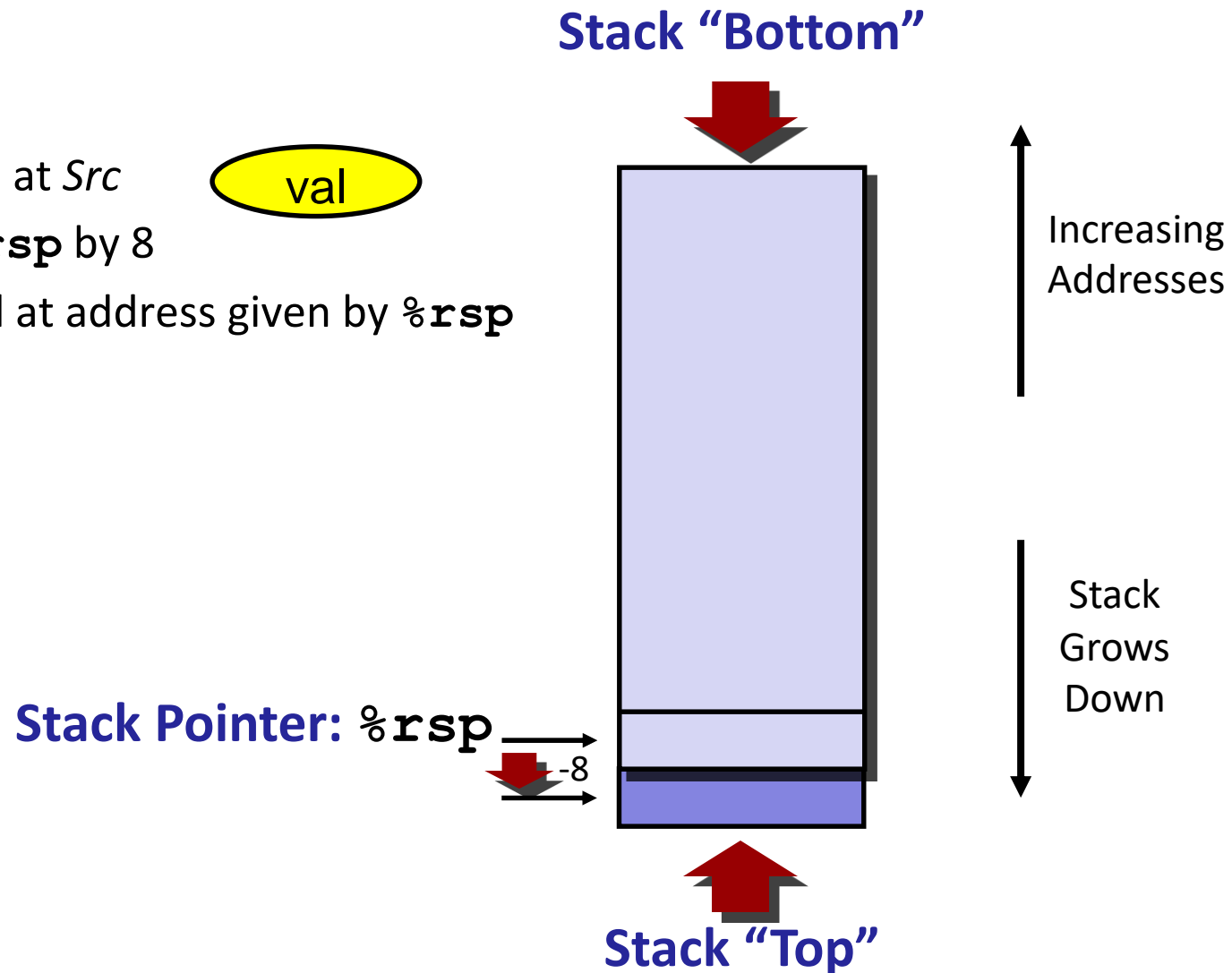


x86-64 Stack: Push

■ `pushq Src`

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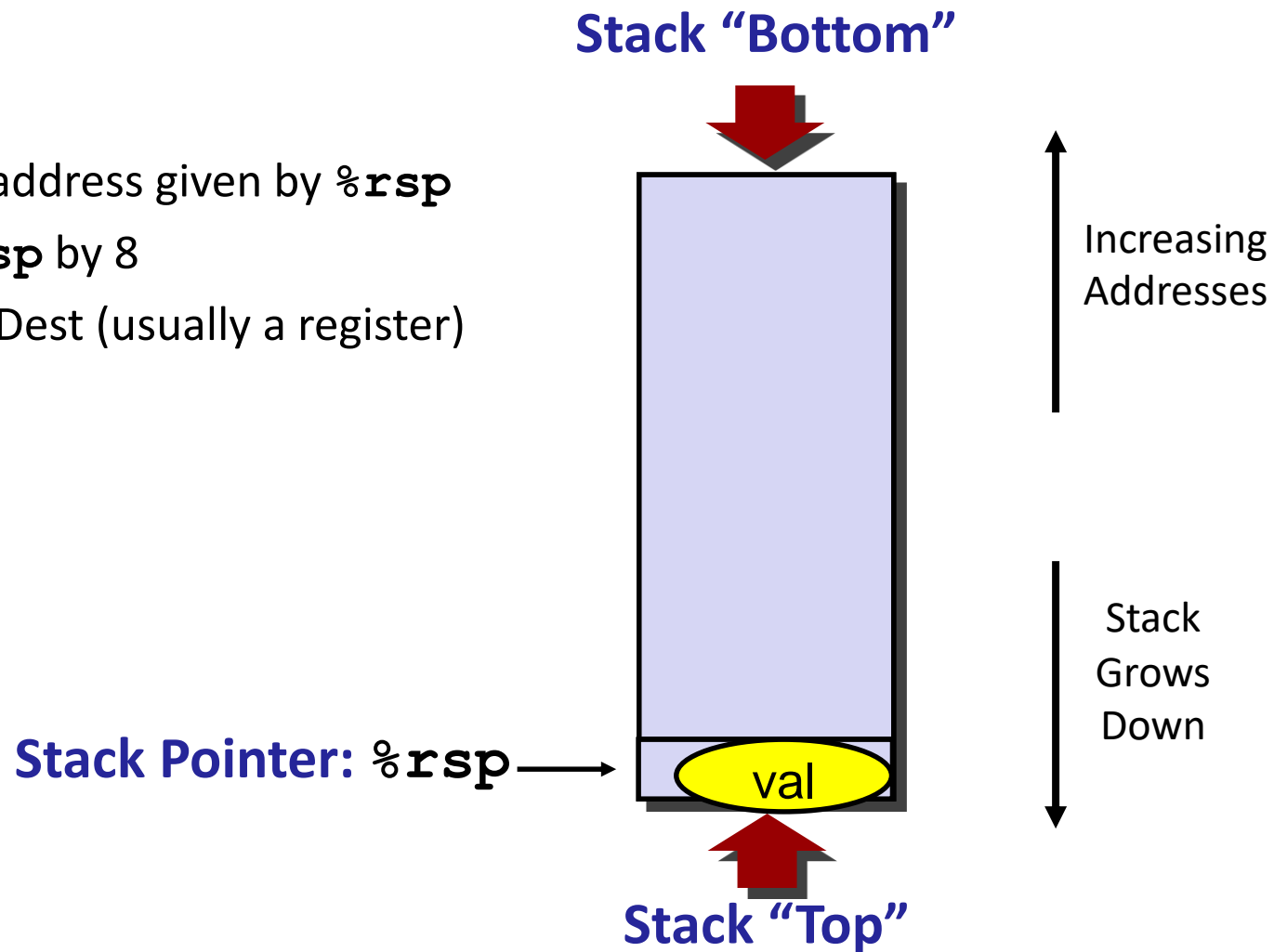
val



x86-64 Stack: Pop

■ `popq Dest`

- Read value at address given by `%rsp`
- Increment `%rsp` by 8
- Store value at `Dest` (usually a register)



x86-64 Stack: Pop

■ `popq Dest`

- Read value at address given by `%rsp`
- Increment `%rsp` by 8
- Store value at `Dest` (usually a register)

val

Stack Pointer: `%rsp` $\xrightarrow{+8}$

Stack "Bottom"



Increasing
Addresses

Stack
Grows
Down

Stack "Top"

x86-64 Stack: Pop

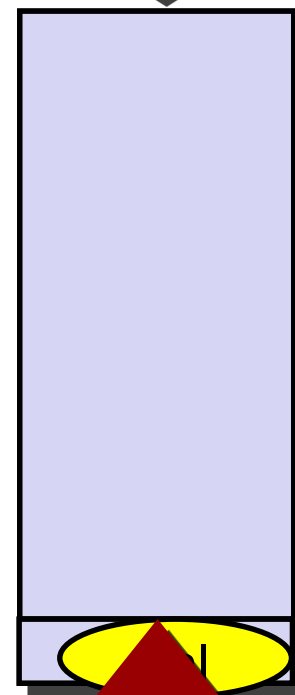
■ `popq Dest`

- Read value at address given by `%rsp`
- Increment `%rsp` by 8
- Store value at `Dest` (usually a register)

Stack Pointer: `%rsp` →

(The memory doesn't change,
only the value of `%rsp`)

Stack "Bottom"



Increasing
Addresses

Stack
Grows
Down

Stack "Top"

Today

■ Procedures

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

Code Examples

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

```
0000000000400540 <multstore>:
 400540: push    %rbx           # Save %rbx
 400541: mov     %rdx,%rbx     # Save dest
 400544: callq  400550 <mult2> # mult2(x,y)
 400549: mov     %rax,(%rbx)   # Save at dest
 40054c: pop     %rbx         # Restore %rbx
 40054d: retq                   # Return
```

```
long mult2(long a, long b)
{
    long s = a * b;
    return s;
}
```

```
0000000000400550 <mult2>:
 400550: mov     %rdi,%rax     # a
 400553: imul   %rsi,%rax     # a * b
 400557: retq                   # 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

Control Flow Example #1

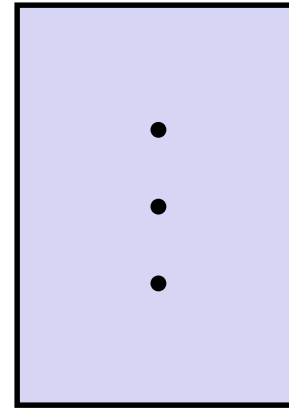
```
0000000000400540 <multstore>:  
.  
.  
400544: callq 400550 <mult2>  
400549: mov  %rax, (%rbx)  
.  
.
```

```
0000000000400550 <mult2>:  
400550: mov  %rdi,%rax  
.  
.  
400557: retq
```

0x130

0x128

0x120



%rsp

0x120

%rip

0x400544

Control Flow Example #2

```
0000000000400540 <multstore>:  
.  
.  
400544: callq 400550 <mult2>  
400549: mov  %rax, (%rbx) ←  
.  
.
```

```
0000000000400550 <mult2>:  
400550: mov  %rdi,%rax ←  
.  
.  
400557: retq
```

0x130

0x128

0x120

0x118

0x400549

%rsp

0x118

%rip

0x400550

Control Flow Example #3

```
0000000000400540 <multstore>:  
.  
.  
400544: callq 400550 <mult2>  
400549: mov  %rax, (%rbx) ←  
.  
.
```

```
0000000000400550 <mult2>:  
400550: mov  %rdi,%rax  
.  
.  
400557: retq ←
```

0x130

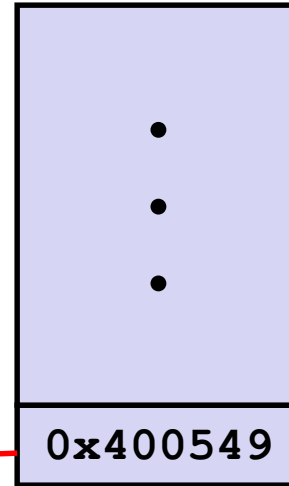
0x128

0x120

0x118

%rsp

%rip



0x400549

0x118

0x400557

Control Flow Example #4

```
0000000000400540 <multstore>:  
.  
.  
400544: callq 400550 <mult2>  
400549: mov  %rax, (%rbx)  
.  
.
```

```
0000000000400550 <mult2>:  
400550: mov  %rdi,%rax  
.  
.  
400557: retq
```

0x130

0x128

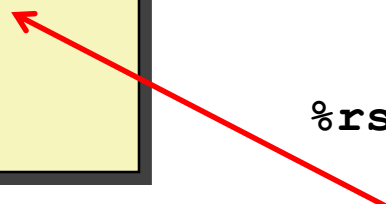
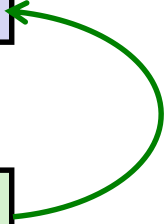
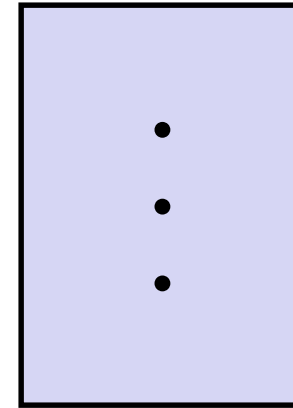
0x120

%rsp

0x120

%rip

0x400549



Today

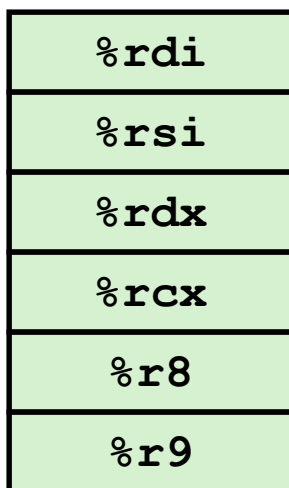
■ Procedures

- Stack Structure
- Calling Conventions
 - Passing control
 - **Passing data**
 - Managing local data
- Illustrations of Recursion & Pointers

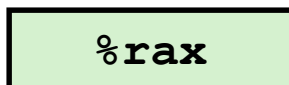
Procedure Data Flow

Registers

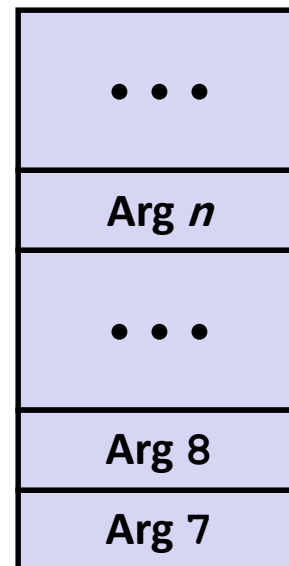
■ First 6 arguments



■ 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: callq  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: retq                               # Return
```

Today

■ Procedures

- Stack Structure
- Calling Conventions
 - Passing control
 - Passing data
 - **Managing local data**
- 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

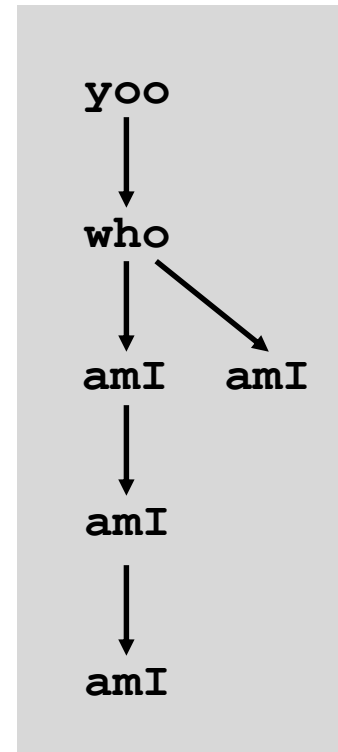
```
yoo (...)  
{  
  .  
  .  
  who ();  
  .  
  .  
}
```

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

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

Procedure amI () is recursive

Example Call Chain



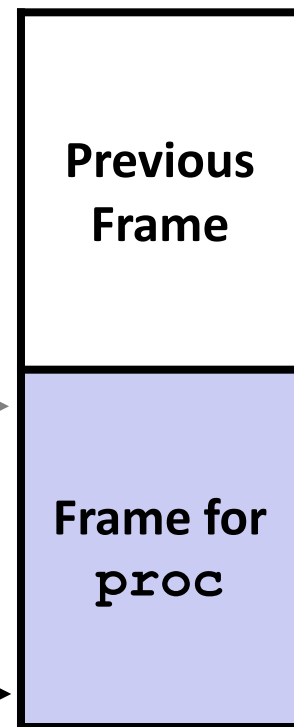
Stack Frames

■ Contents

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

Frame Pointer: `%rbp`
(Optional)

Stack Pointer: `%rsp`





Stack "Top"

■ Management

- Space allocated when enter procedure
 - "Set-up" code
 - Includes push by `call` instruction
- Deallocated when return
 - "Finish" code
 - Includes pop by `ret` instruction

Example

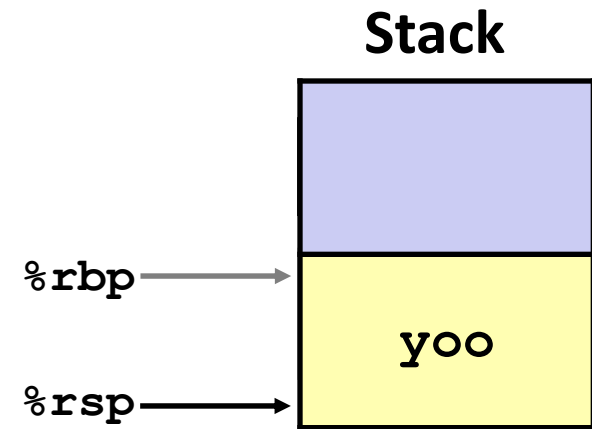


```

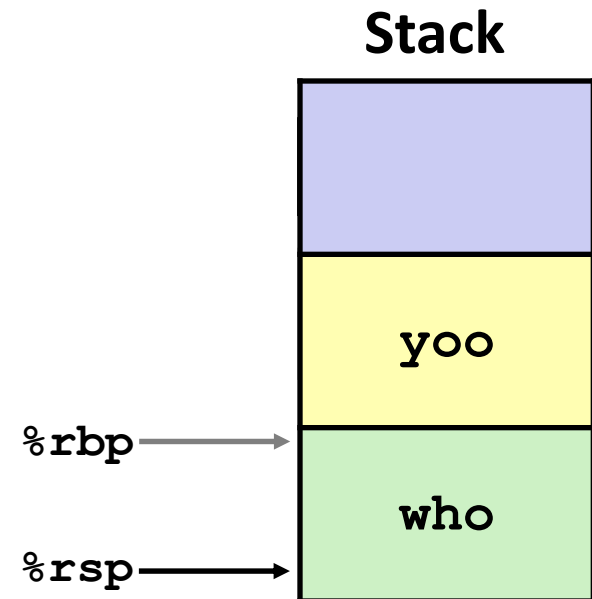
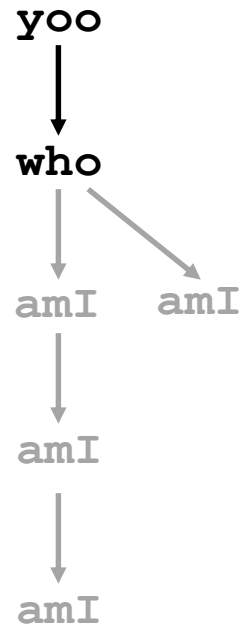
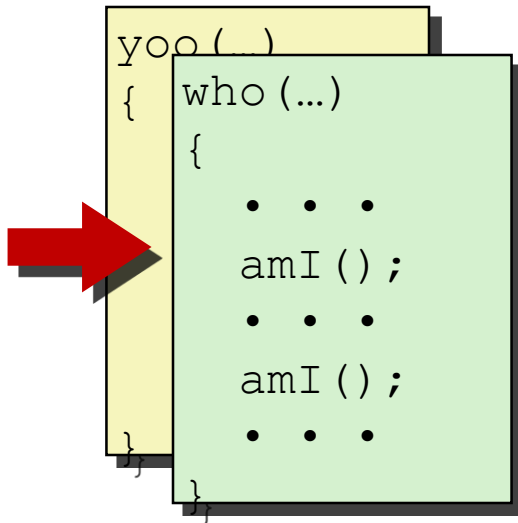
yoo (...)
{
    .
    .
    who ();
    .
    .
}
  
```

```

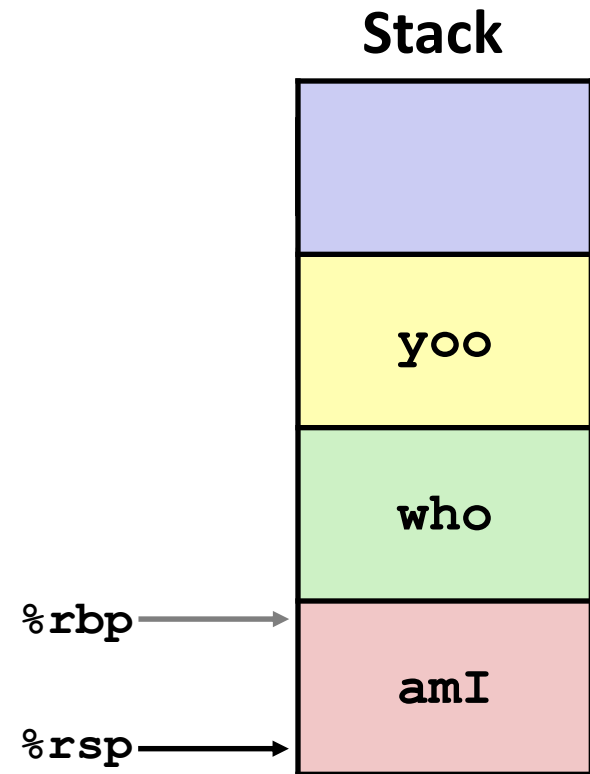
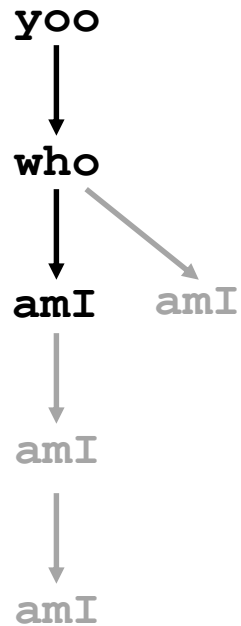
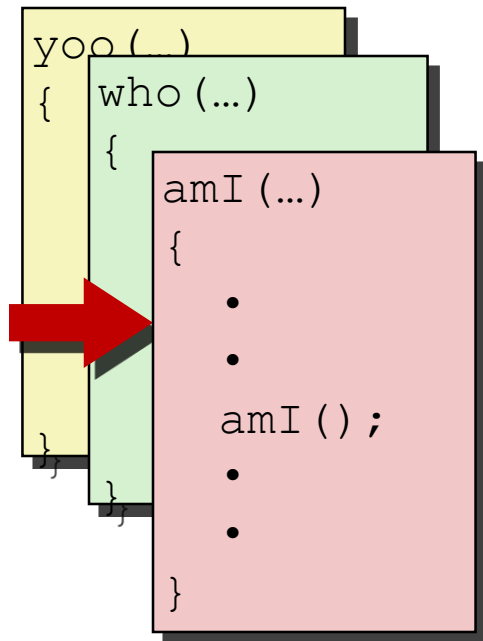
yoo
  |
  v
who
  |  \
  v   v
amI  amI
  |
  v
amI
  |
  v
amI
  
```



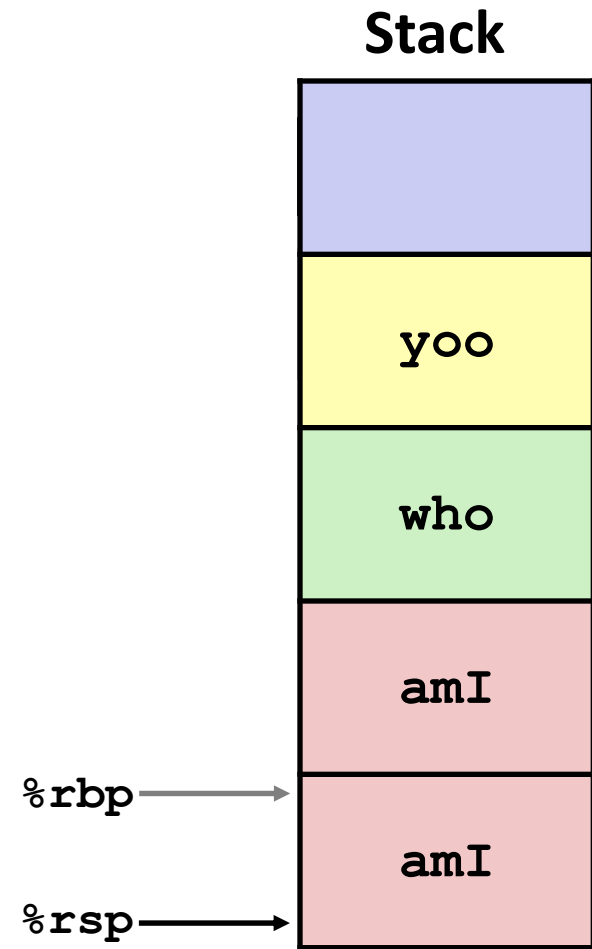
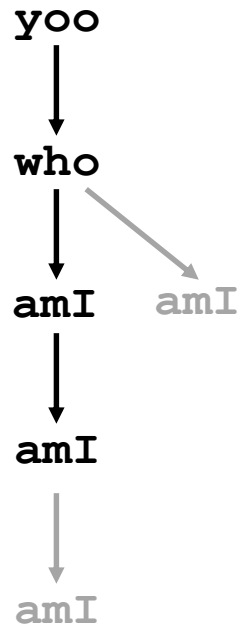
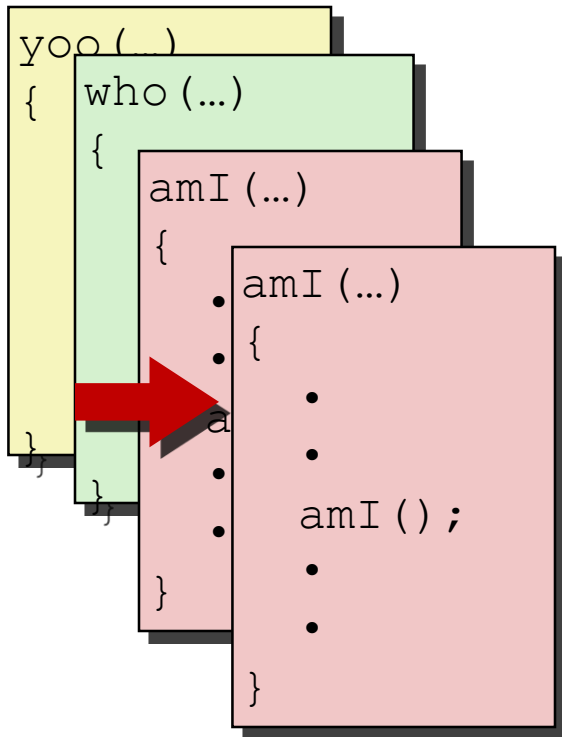
Example



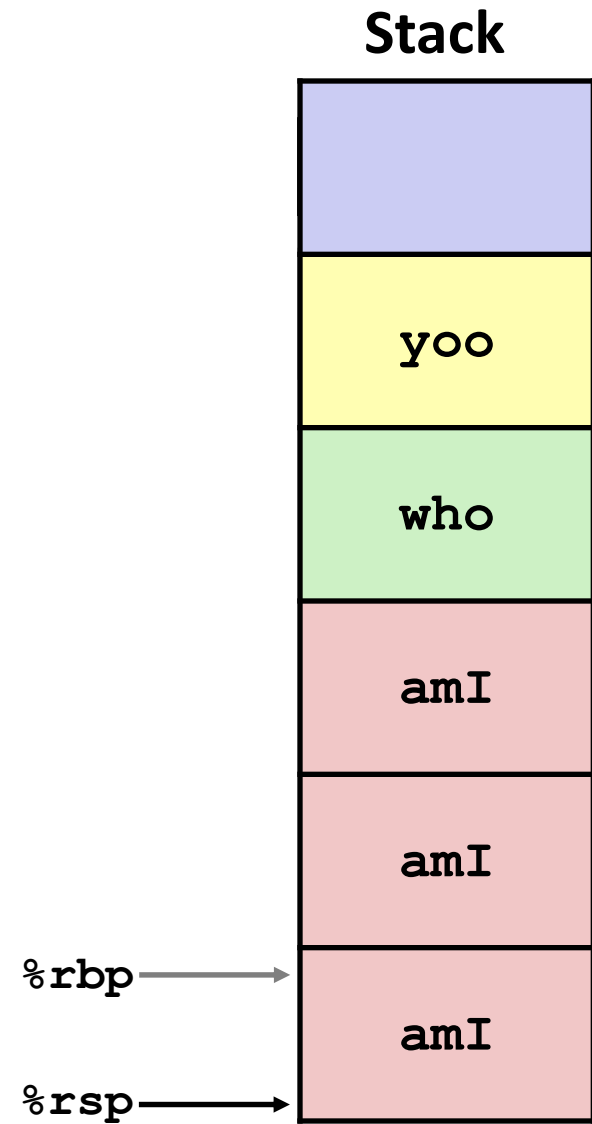
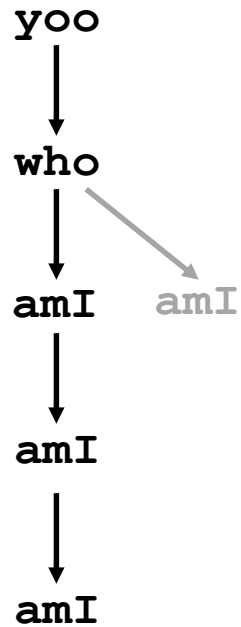
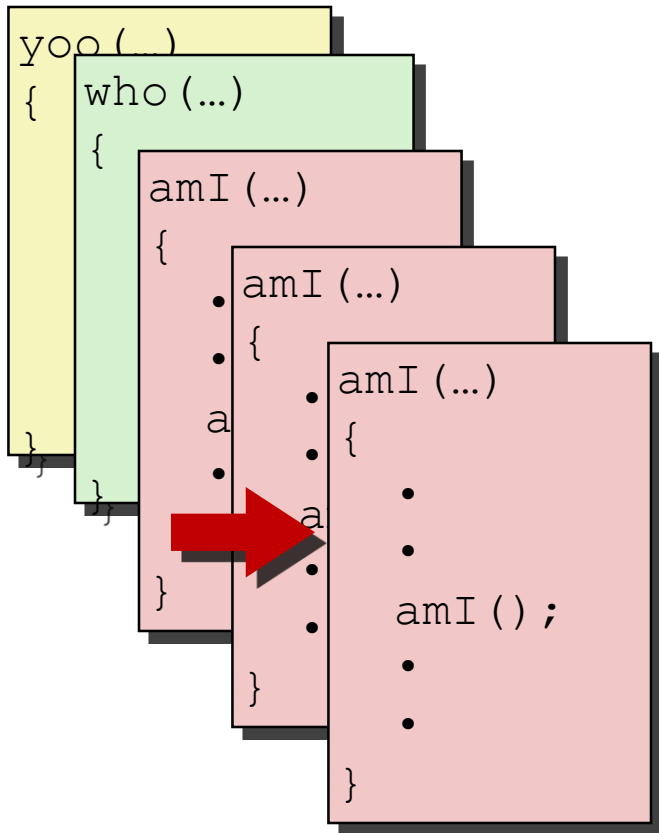
Example



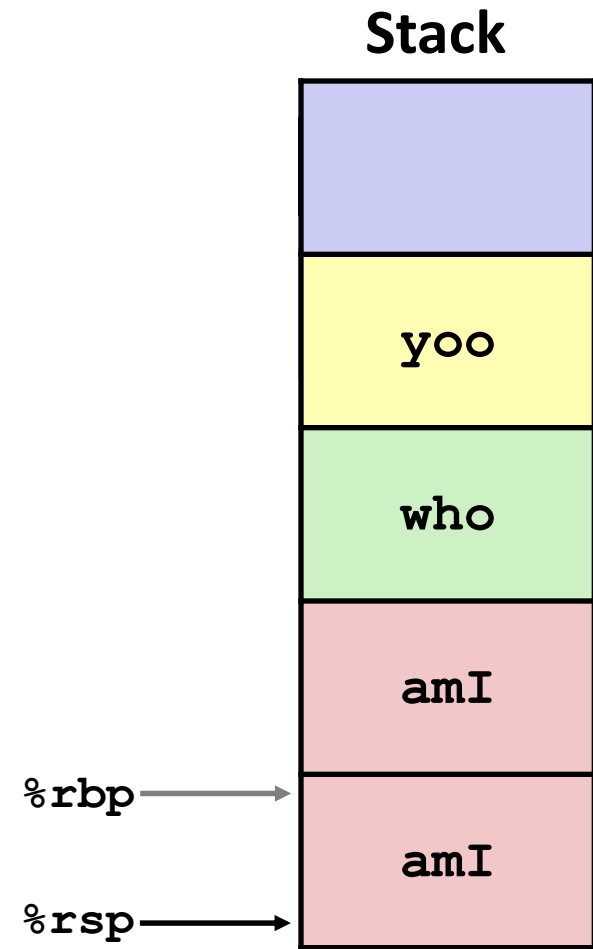
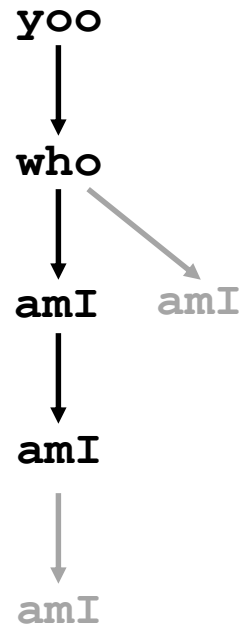
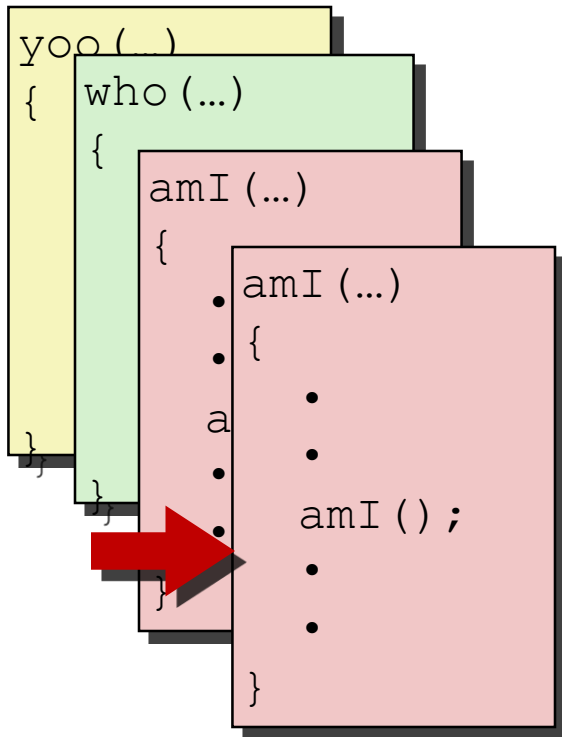
Example



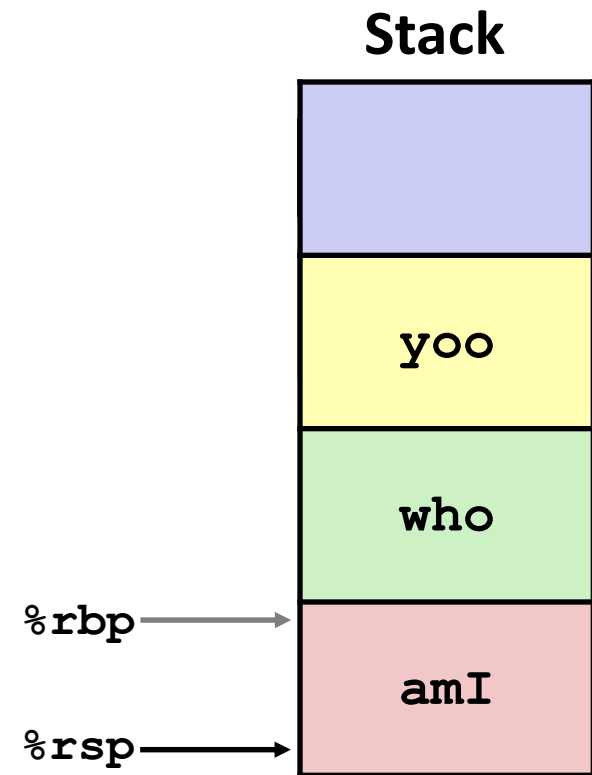
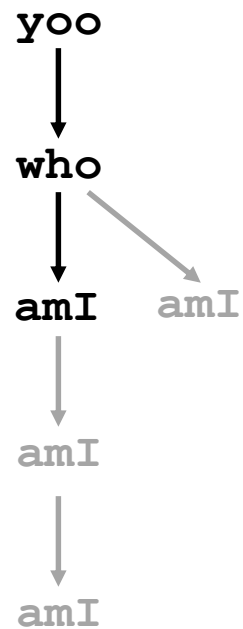
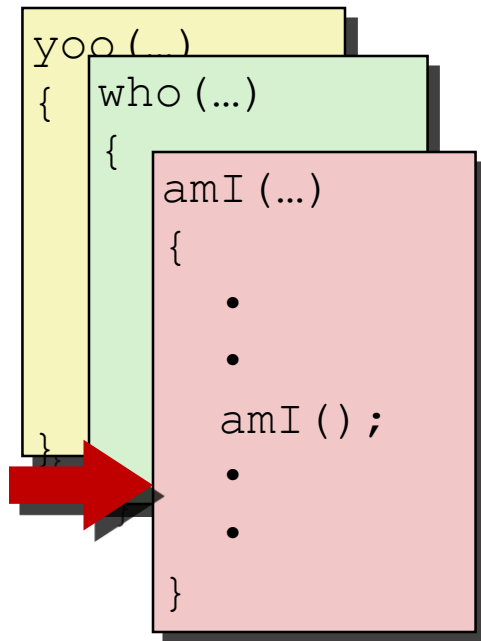
Example



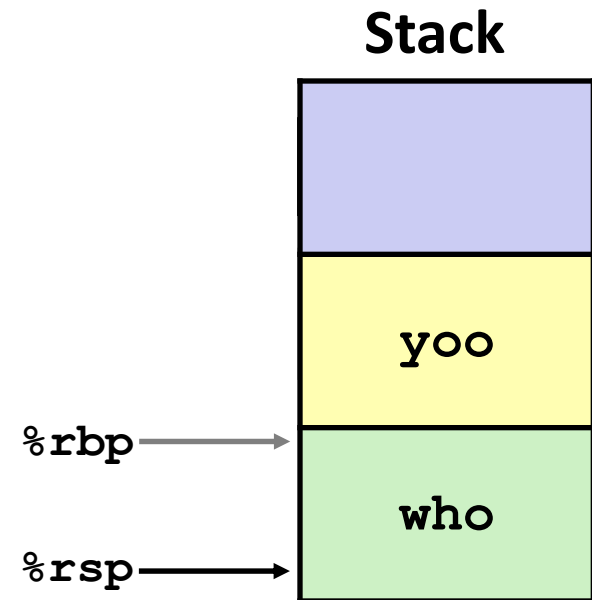
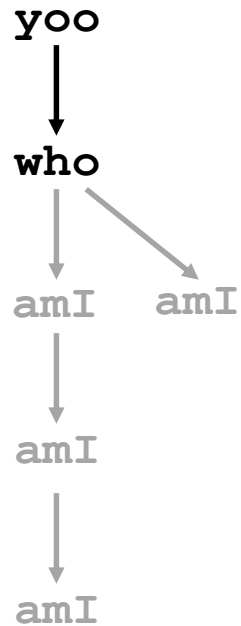
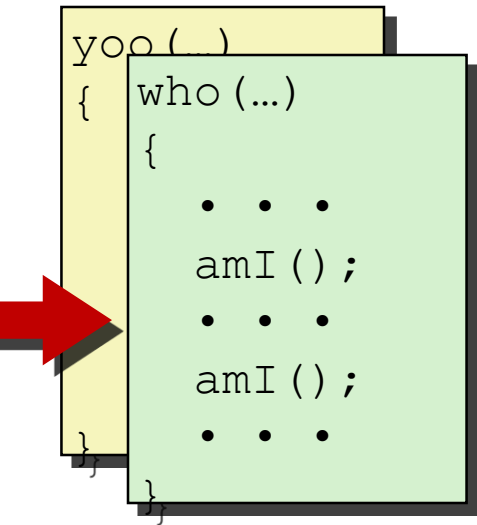
Example



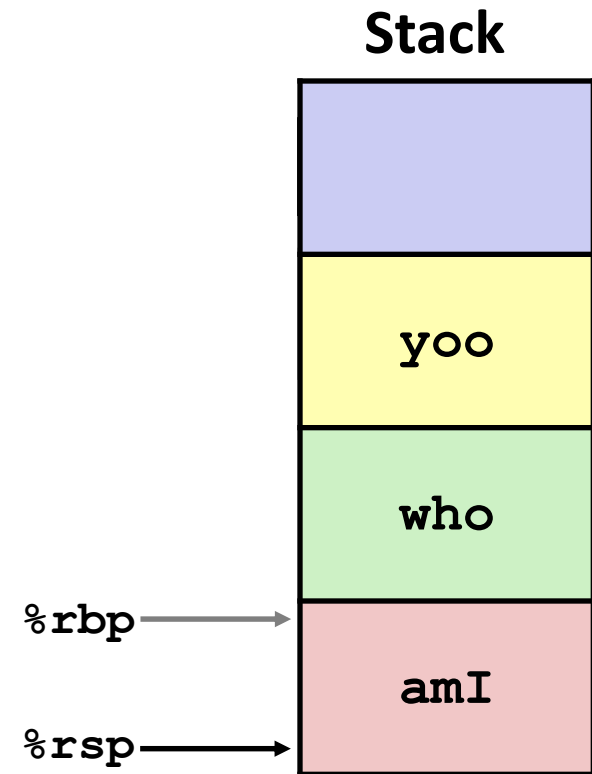
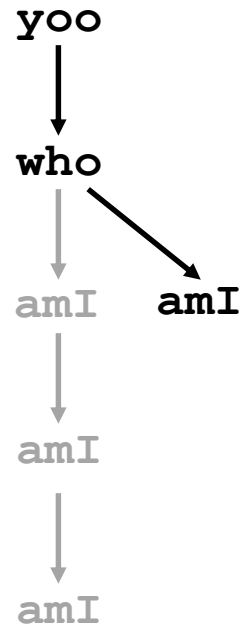
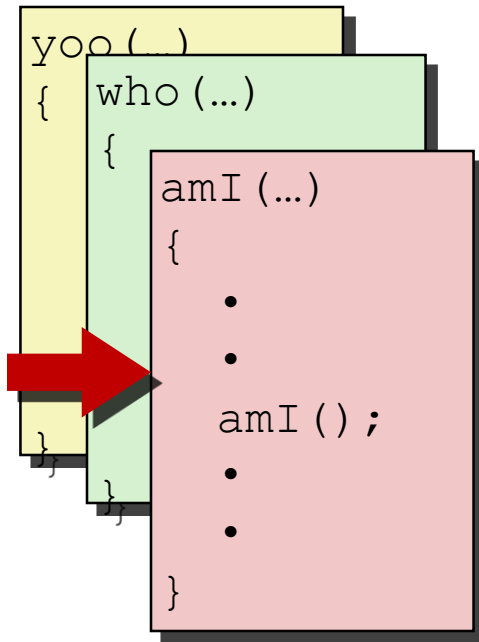
Example



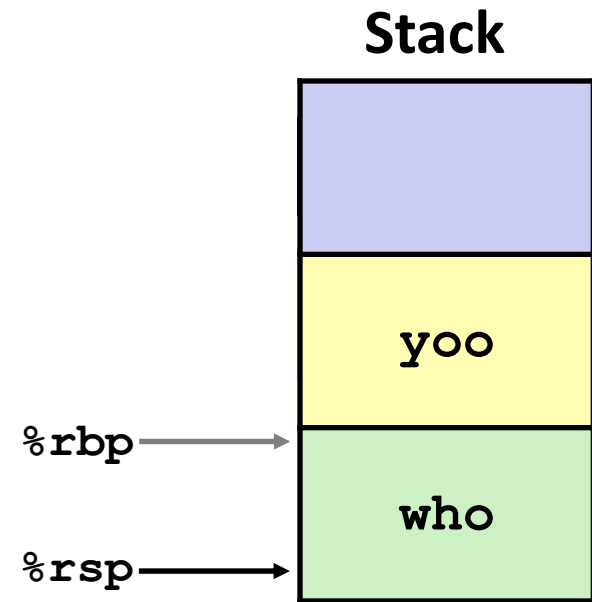
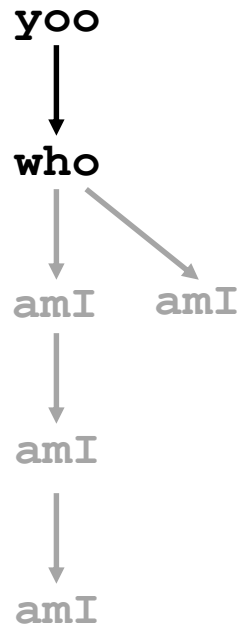
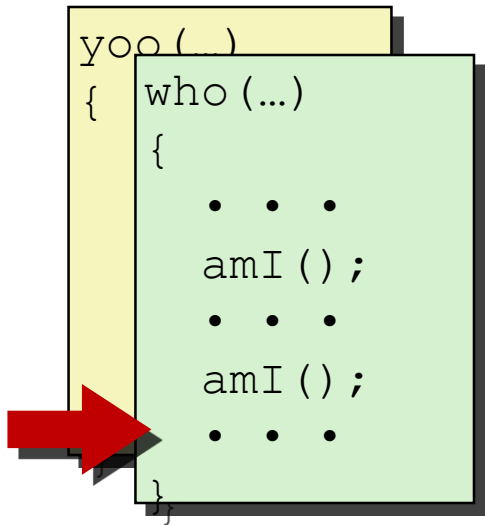
Example



Example



Example




Example

```

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

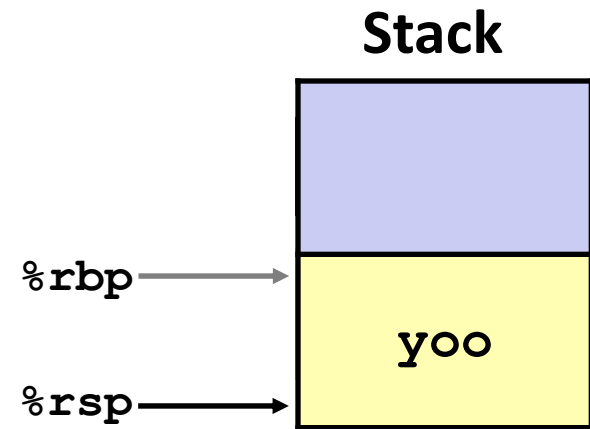
```



```

yoo
  ↓
who
  ↓  ↘
amI  amI
  ↓
amI
  ↓
amI

```



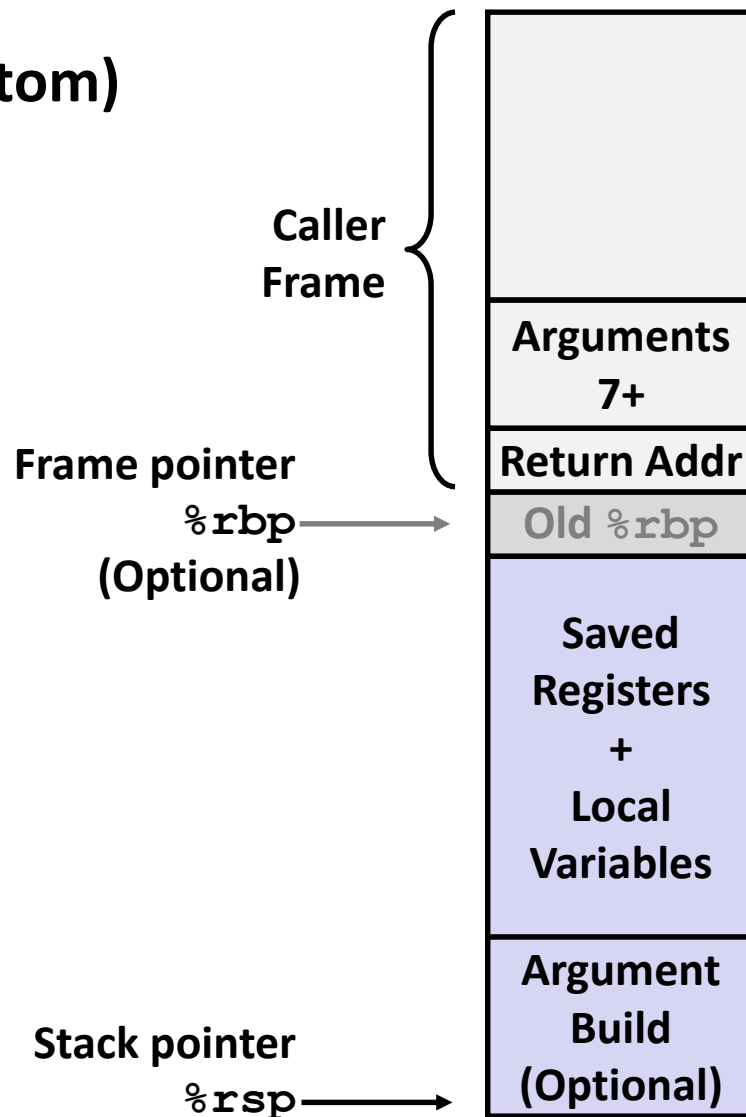
x86-64/Linux Stack Frame

■ 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
```

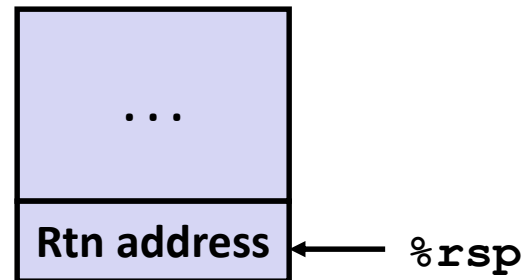
| Register | Use(s) |
|-------------------|--|
| <code>%rdi</code> | Argument <code>p</code> |
| <code>%rsi</code> | Argument <code>val</code> , <code>y</code> |
| <code>%rax</code> | <code>x</code> , Return value |

Example: Calling `incr` #1

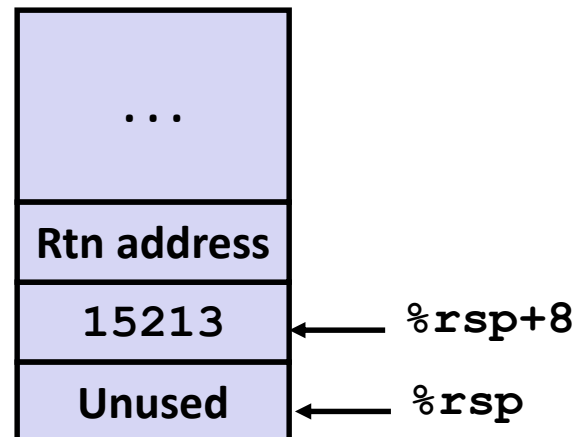
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
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
```

Initial Stack Structure



Resulting Stack Structure

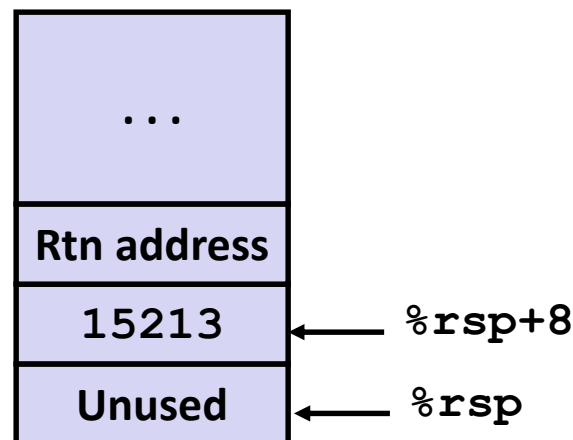


Example: Calling `incr` #2

```
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

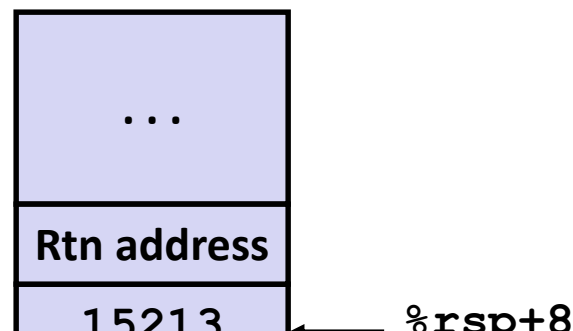


| Register | Use(s) |
|----------|--------|
| %rdi | &v1 |
| %rsi | 3000 |

Example: Calling `incr` #2

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

Stack Structure



Aside 1: `movl $3000, %esi`

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

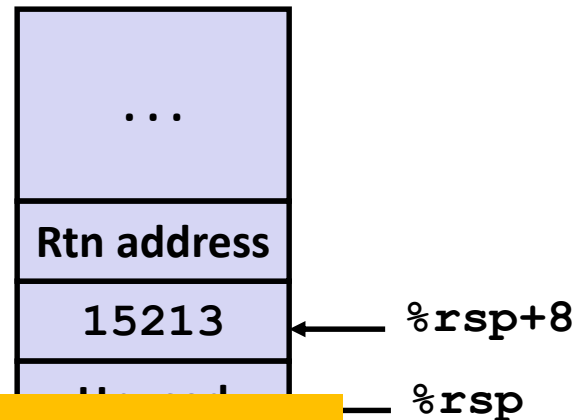
```
movl    $3000, %esi
leaq   8(%rsp), %rdi
call   incr
addq   8(%rsp), %rax
addq   $16, %rsp
ret
```

| | |
|-------------------|----------------------|
| <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 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
```

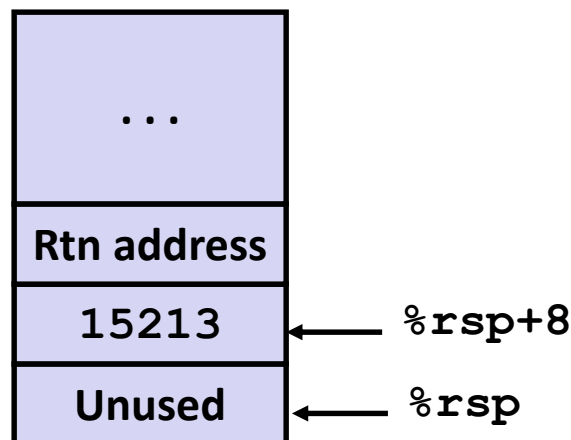
| | use(s) |
|-------------------|-----------------|
| <code>%rdi</code> | <code>v1</code> |
| <code>%rsi</code> | 3000 |

Example: Calling `incr` #2

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

```
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



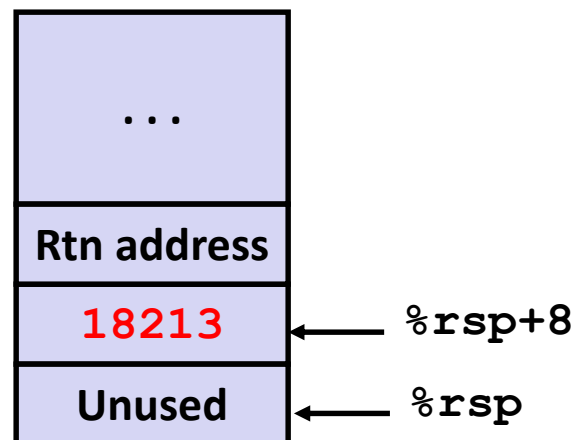
| Register | Use(s) |
|-------------------|----------------------|
| <code>%rdi</code> | <code>&v1</code> |
| <code>%rsi</code> | 3000 |

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



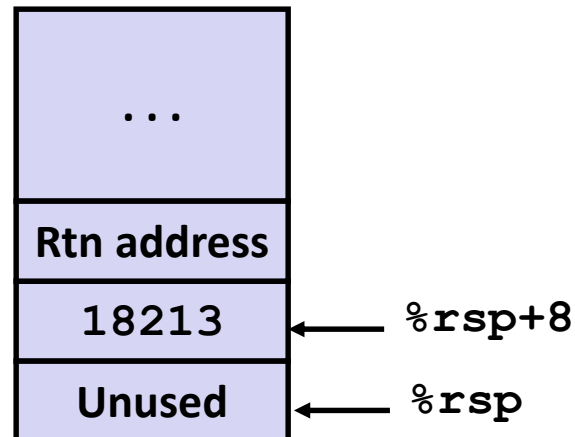
| Register | Use(s) |
|----------|--------|
| %rdi | &v1 |
| %rsi | 3000 |

Example: Calling `incr` #4

```
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



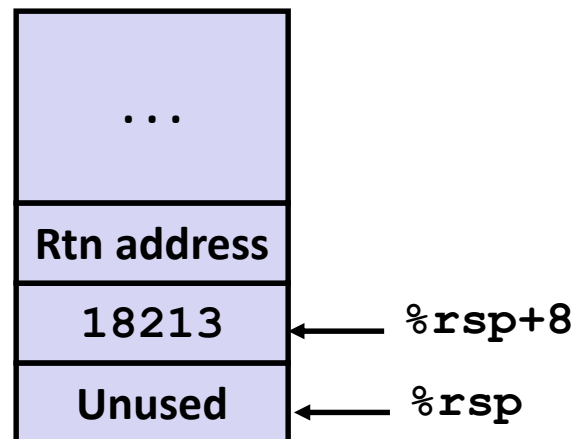
| Register | Use(s) |
|-------------------|--------------|
| <code>%rax</code> | Return value |

Example: Calling `incr` #5a

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

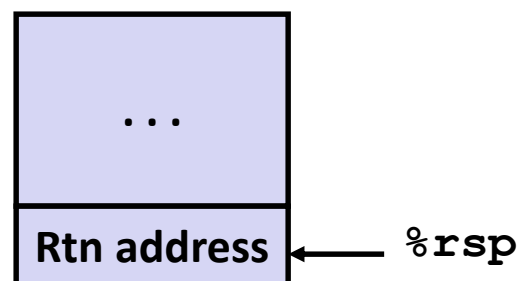
```
call_incr:
    subq    $16, %rsp
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

Stack Structure



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

Updated Stack Structure

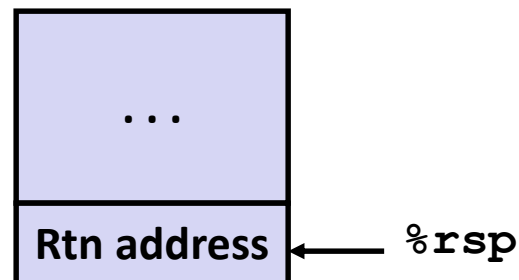


Example: Calling `incr` #5b

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

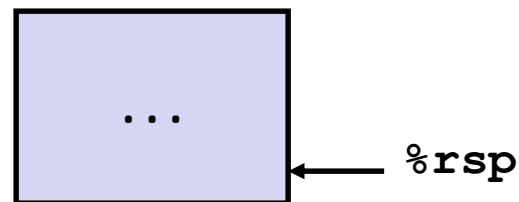
```
call_incr:
    subq    $16, %rsp
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

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”*
 - Caller saves temporary values in its frame before the call
 - *“Callee Saved”*
 - Callee saves temporary values in its frame before using
 - Callee restores them before returning to caller

x86-64 Linux Register Usage #1

■ **%rax**

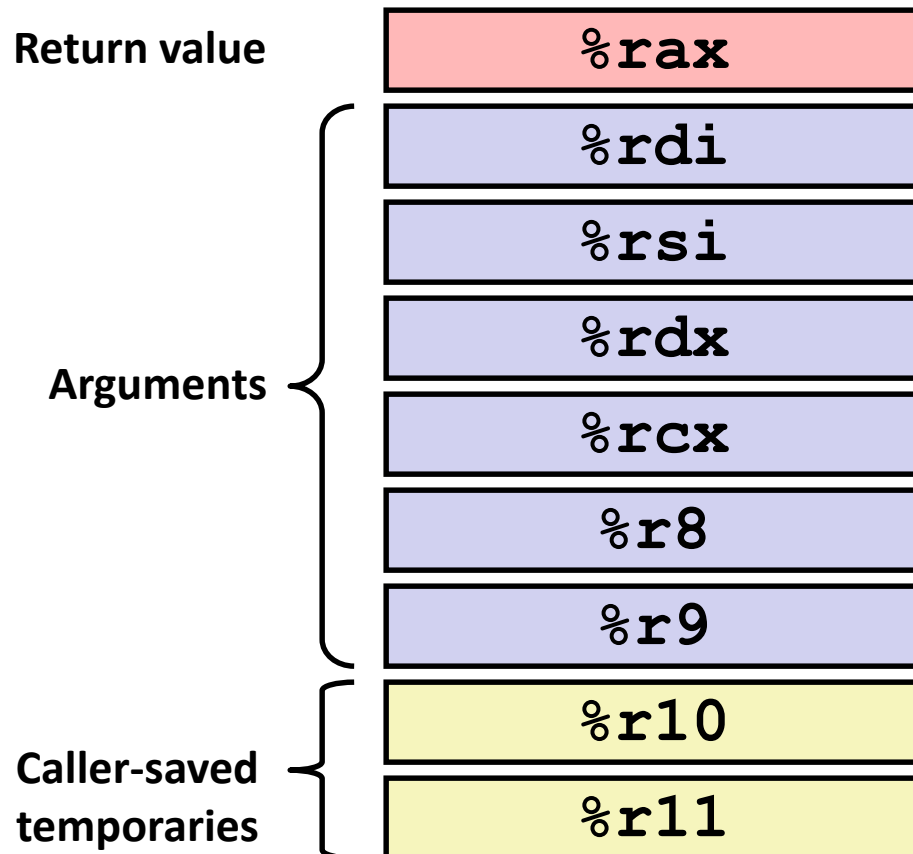
- Return value
- Also caller-saved
- Can be modified by procedure

■ **%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`

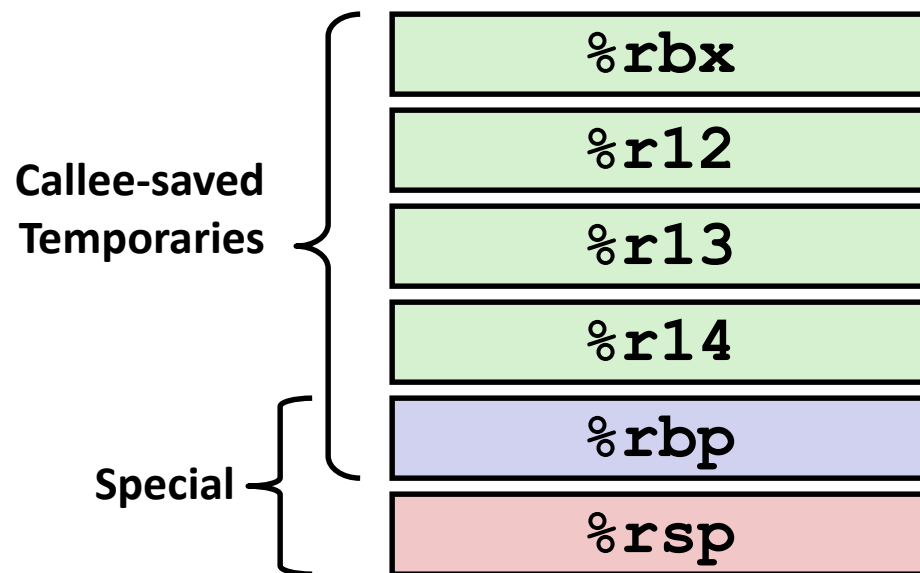
- Callee-saved
- Callee must save & restore

■ `%rbp`

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

■ `%rsp`

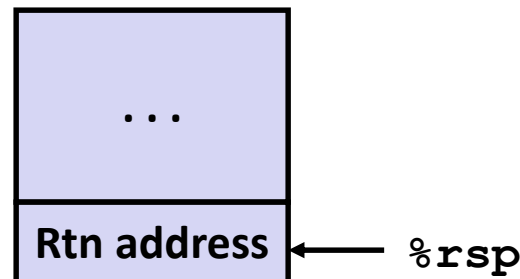
- Special form of callee save
- Restored to original value upon exit from procedure



Callee-Saved Example #1

```
long call_incr2(long x) {  
    long v1 = 15213;  
    long v2 = incr(&v1, 3000);  
    return x+v2;  
}
```

Initial Stack Structure



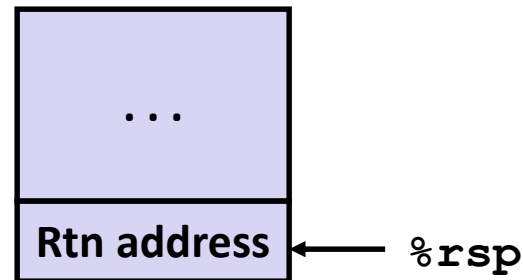
- X comes in register `%rdi`.
- We need `%rdi` for the call to `incr`.
- Where should be put `x`, so we can use it after the call to `incr`?

Callee-Saved Example #2

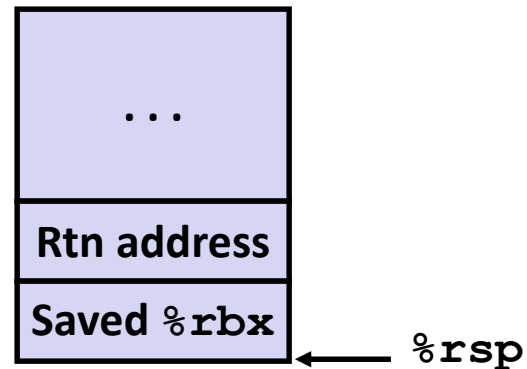
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
call_incr2:
    pushq    %rbx
    subq    $16, %rsp
    movq    %rdi, %rbx
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    %rbx, %rax
    addq    $16, %rsp
    popq    %rbx
    ret
```

Initial Stack Structure



Resulting Stack Structure

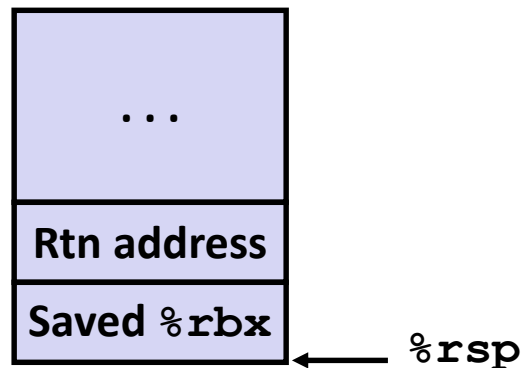


Callee-Saved Example #3

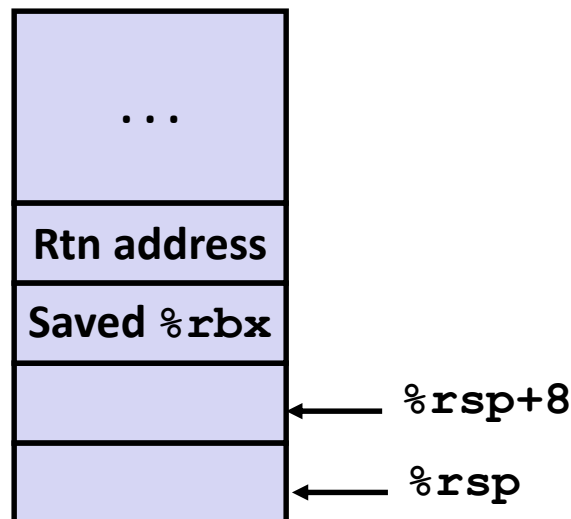
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
call_incr2:
    pushq    %rbx
    subq     $16, %rsp
    movq     %rdi, %rbx
    movq     $15213, 8(%rsp)
    movl     $3000, %esi
    leaq     8(%rsp), %rdi
    call     incr
    addq     %rbx, %rax
    addq     $16, %rsp
    popq     %rbx
    ret
```

Initial Stack Structure



Resulting Stack Structure

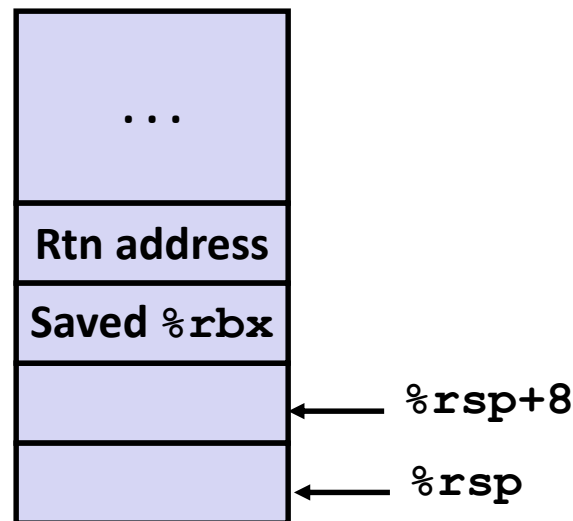


Callee-Saved Example #4

```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
call_incr2:
    pushq    %rbx
    subq    $16, %rsp
    movq    %rdi, %rbx
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    %rbx, %rax
    addq    $16, %rsp
    popq    %rbx
    ret
```

Stack Structure



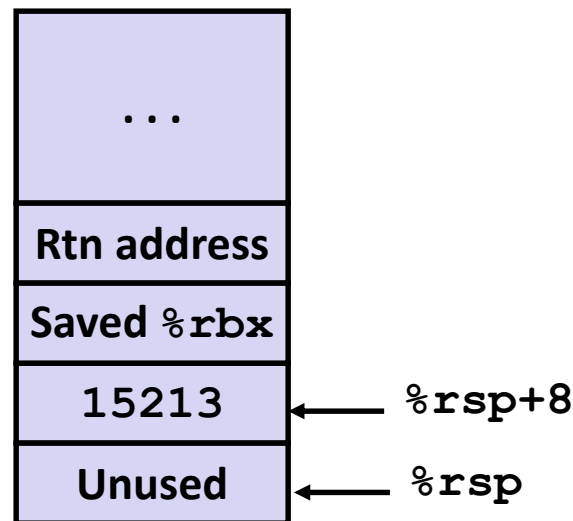
- X saved in `%rbx`.
- A callee saved register.

Callee-Saved Example #5

```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
call_incr2:
    pushq    %rbx
    subq    $16, %rsp
    movq    %rdi, %rbx
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    %rbx, %rax
    addq    $16, %rsp
    popq    %rbx
    ret
```

Stack Structure



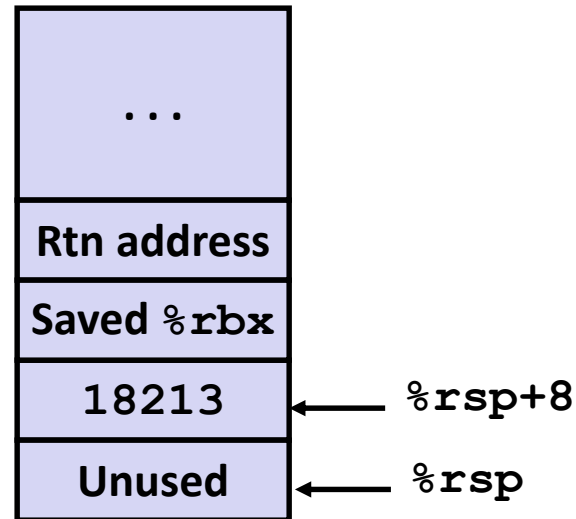
- X saved in **%rbx**.
- A callee saved register.

Callee-Saved Example #6

```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
call_incr2:
    pushq    %rbx
    subq    $16, %rsp
    movq    %rdi, %rbx
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    %rbx, %rax
    addq    $16, %rsp
    popq    %rbx
    ret
```

Stack Structure



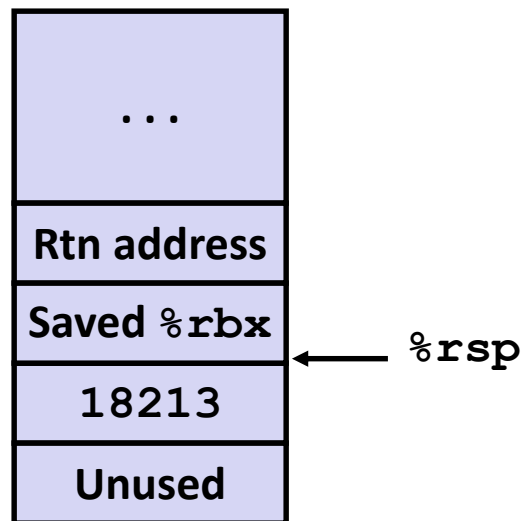
- X is safe in **%rbx**
- Return result in **%rax**

Callee-Saved Example #7

```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
call_incr2:
    pushq    %rbx
    subq    $16, %rsp
    movq    %rdi, %rbx
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    %rbx, %rax
    addq    $16, %rsp
    popq    %rbx
    ret
```

Stack Structure



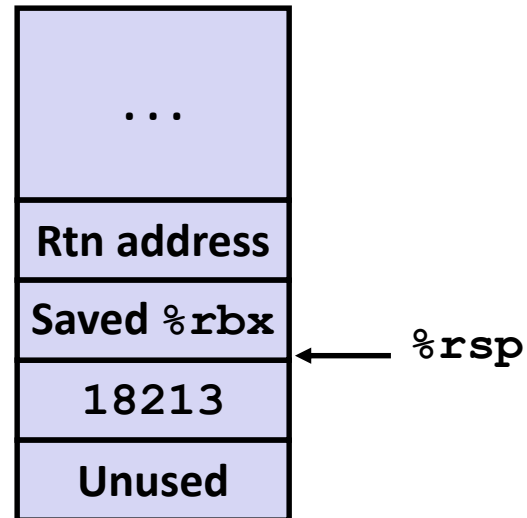
- Return result in **%rax**

Callee-Saved Example #8

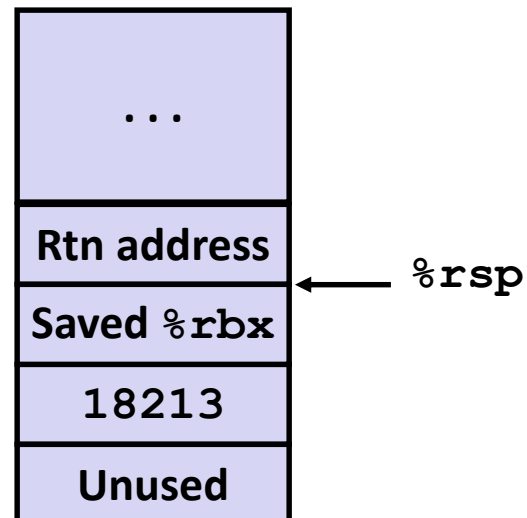
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
call_incr2:
    pushq    %rbx
    subq    $16, %rsp
    movq    %rdi, %rbx
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    %rbx, %rax
    addq    $16, %rsp
    popq    %rbx
    ret
```

Initial Stack Structure



final Stack Structure



Today

■ Procedures

- Stack Structure
- Calling Conventions
 - Passing control
 - Passing data
 - Managing local data
- **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);
}

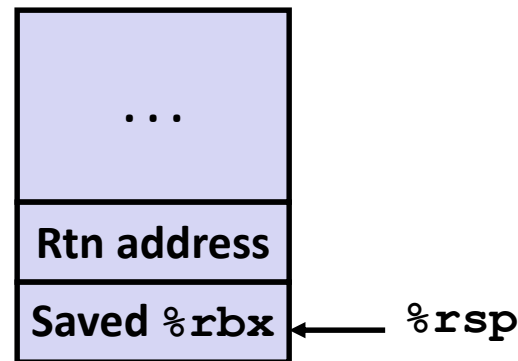
```

```

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);
}

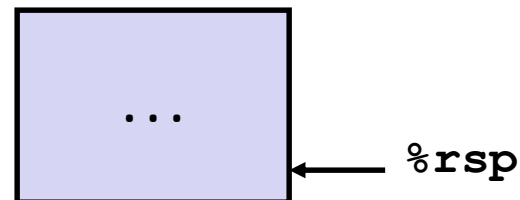
```

```

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

