

Machine-Level Programming III: Procedures

Introduction to Computer Systems
6th Lecture, Sep. 26, 2024

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Objectives

- Basic functionality of the pairs: push / pop and call / ret
- Students should be able to identify the different components of a stack (return address, arguments, saved registers, local variables)
- Explain the difference between callee and caller save registers
- Explain how a stack permits functions to be called recursively / re-entrant

Today

■ Procedures

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

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

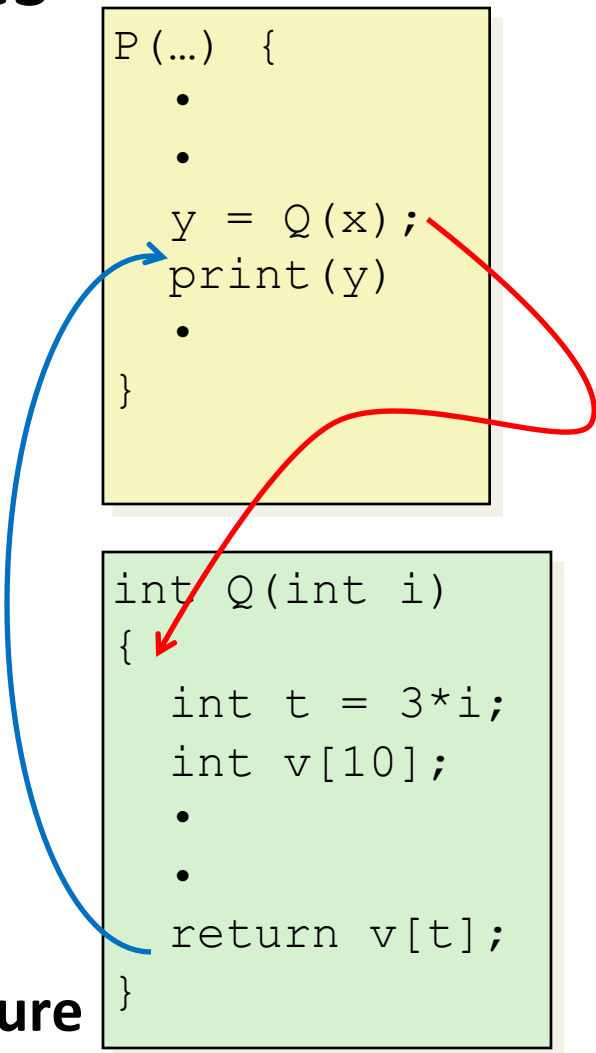
■ Memory management

- 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

■ 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

■ 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

```
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

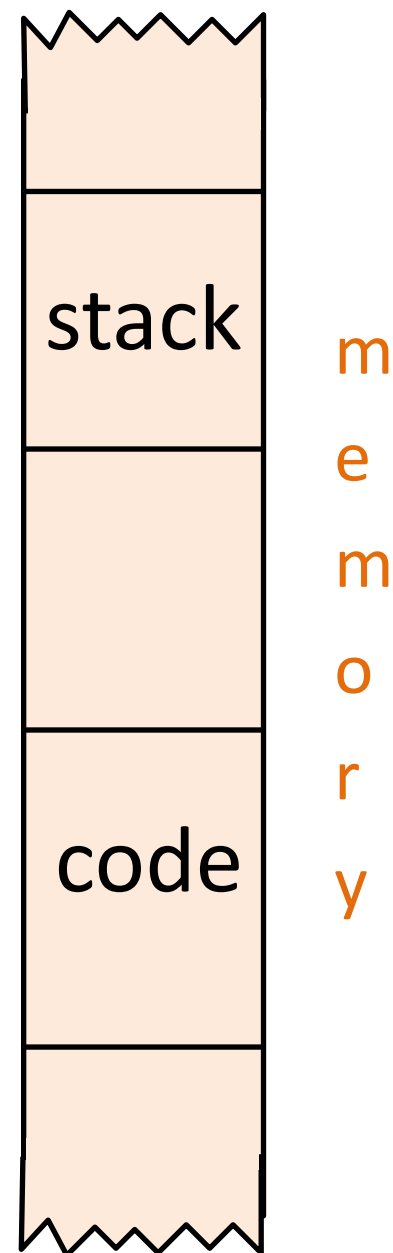
■ Procedures

- Mechanisms
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 - Managing local data
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x86-64 Stack

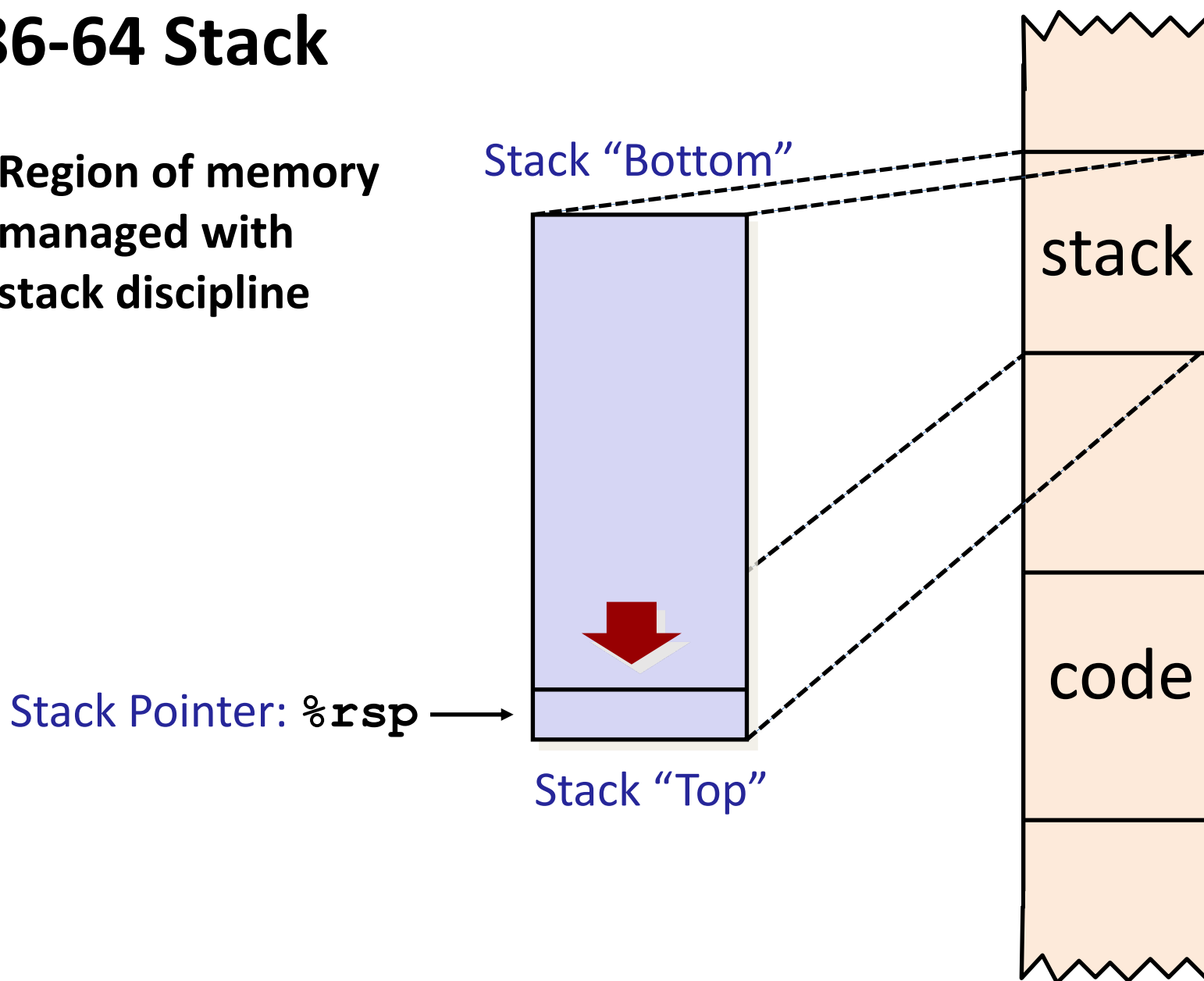
■ Region of memory managed with stack discipline

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



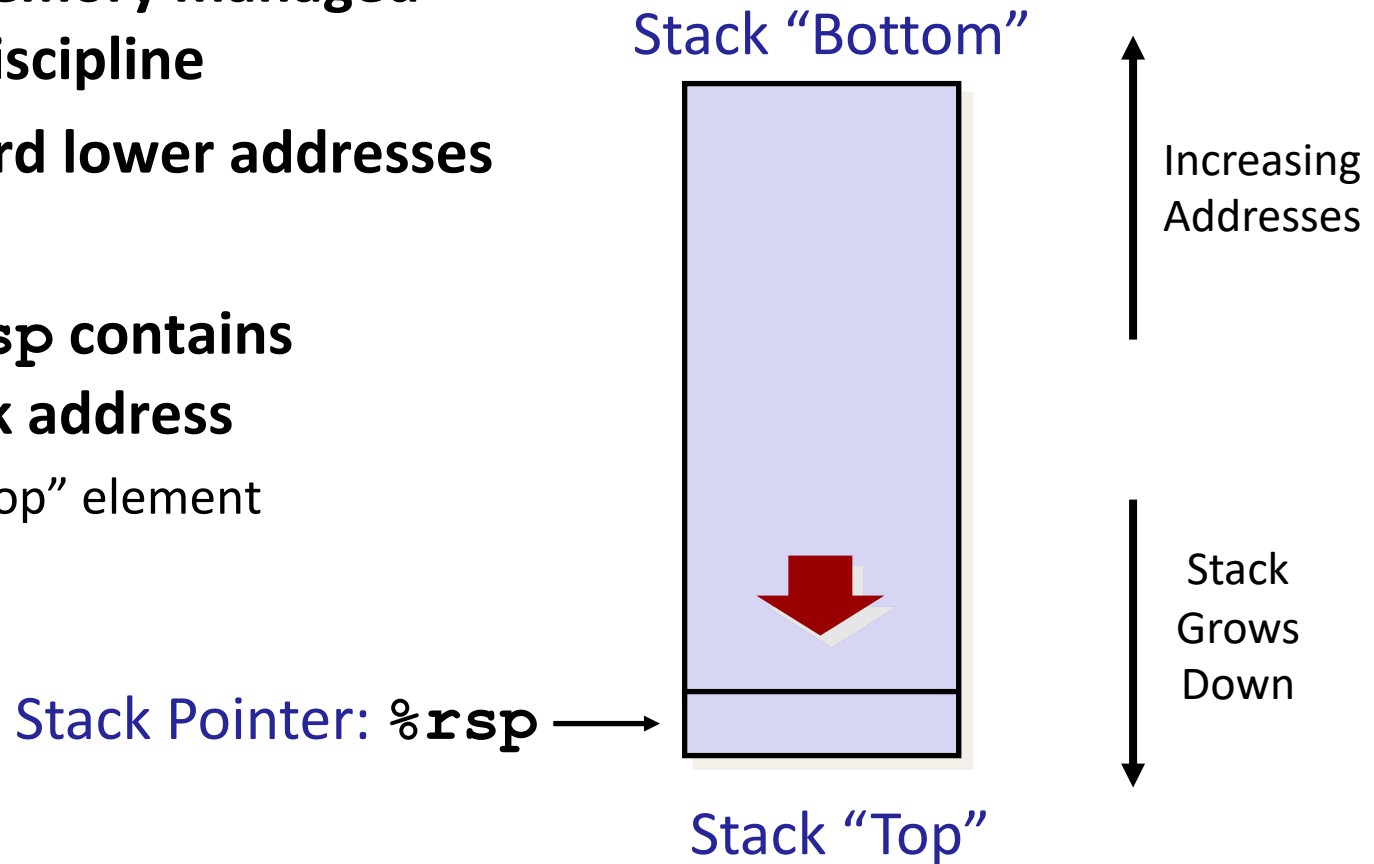
x86-64 Stack

- Region of memory managed with stack discipline



x86-64 Stack

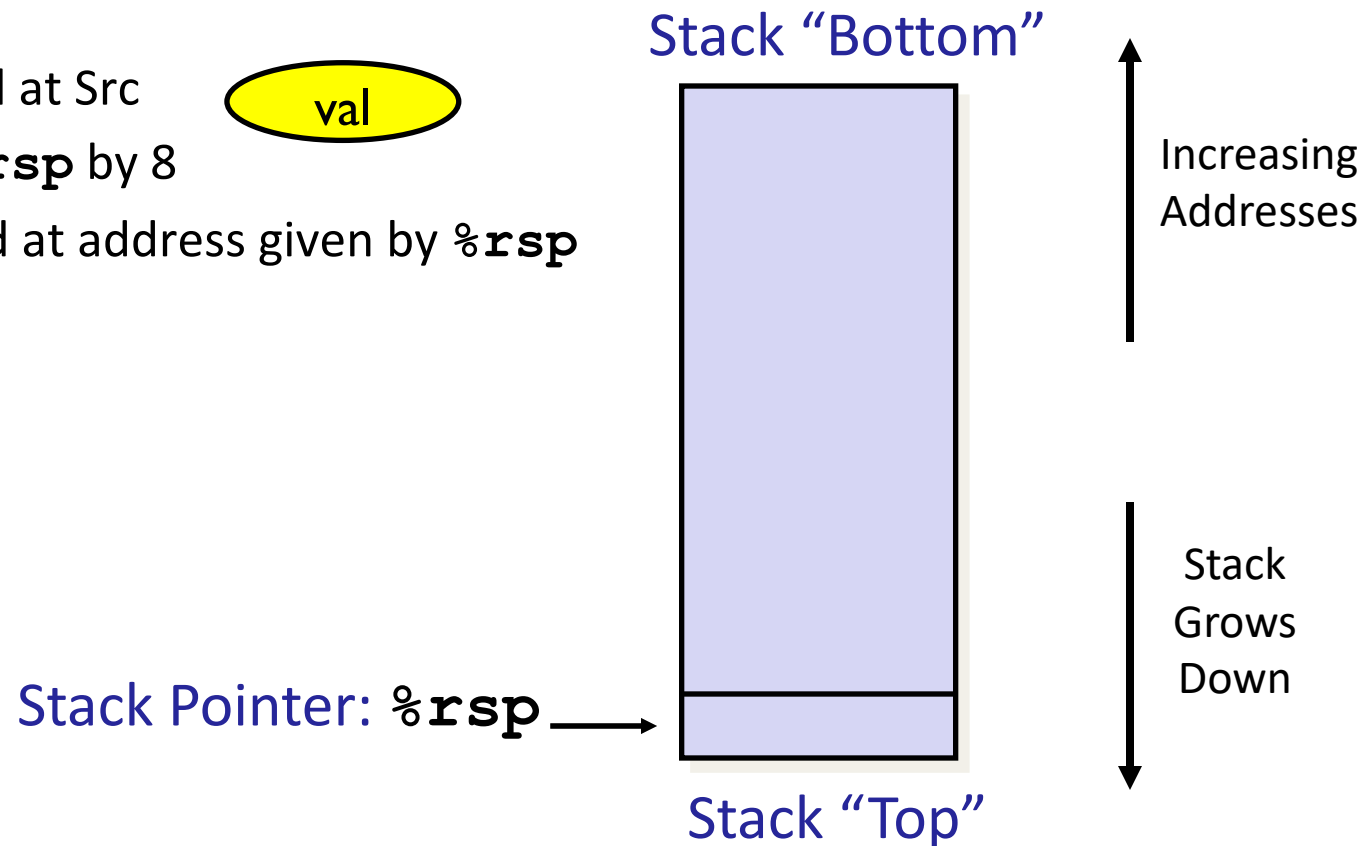
- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register `%rsp` contains lowest stack address
 - address of “top” element



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**

val

Stack “Bottom”

Stack Pointer: `%rsp`

-8

Stack “Top”

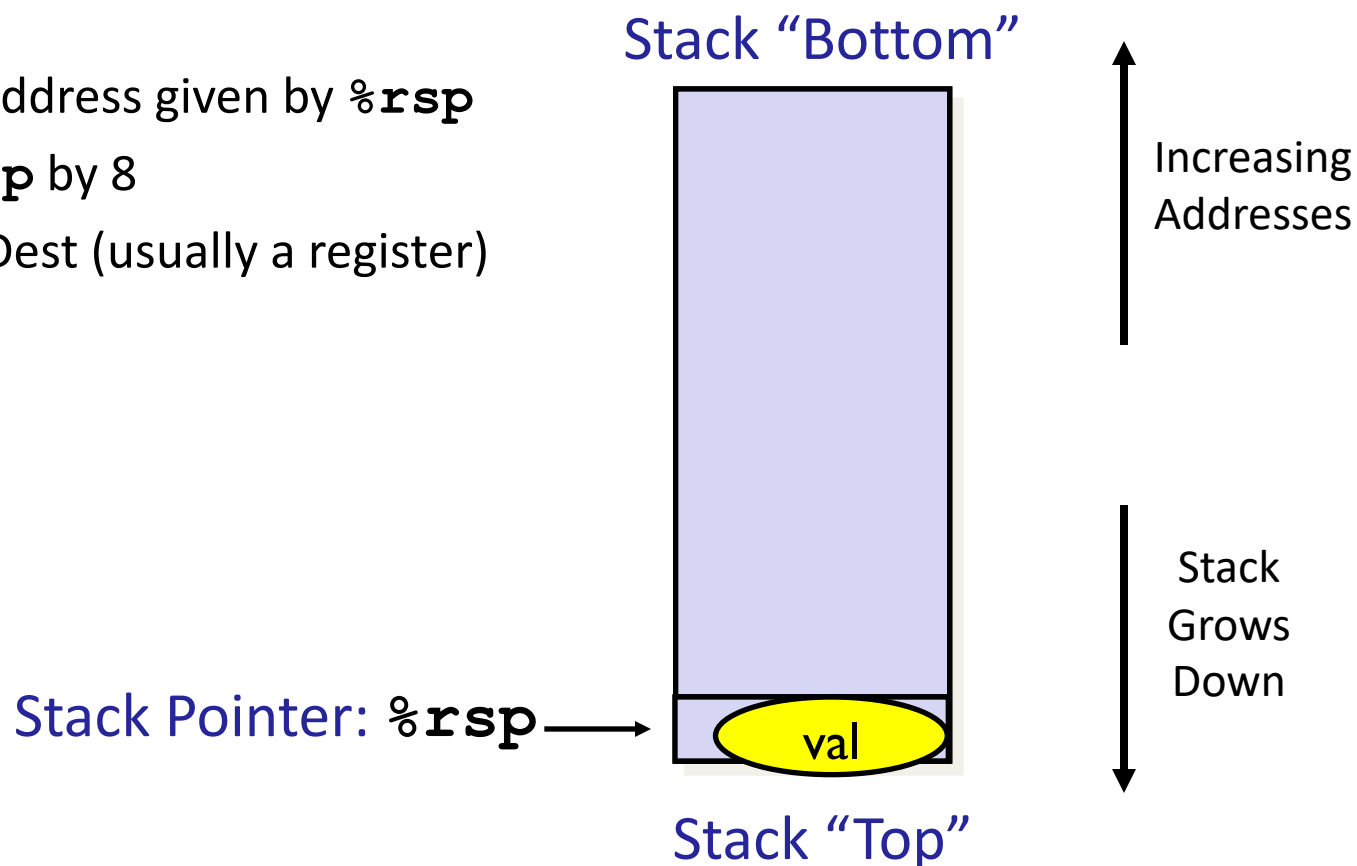
Increasing Addresses

Stack Grows Down

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`

+8

Stack “Bottom”



Stack “Top”

Increasing
Addresses

Stack
Grows
Down

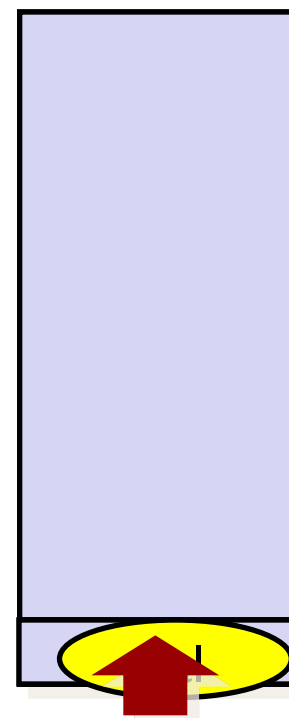
x86-64 Stack: Pop

■ `popq Dest`

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

Stack Pointer: `%rsp` →

Stack “Bottom”



Increasing
Addresses

Stack
Grows
Down

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

Today

■ Procedures

- Mechanisms
- 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;
}
```

```
00000000000400540 <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;
}
```

```
00000000000400550 <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

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

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

0x130

0x128

0x120

%rsp

%rip

0x120

0x400544

Control Flow Example #2

```
00000000000400540 <multstore>:
```

•

•

```
400544: callq 400550 <mult2>
```

```
400549: mov    %rax, (%rbx) ←
```

•

•

```
00000000000400550 <mult2>:
```

```
400550: mov    %rdi,%rax ←
```

•

•

```
400557: retq
```

0x130

0x128

0x120

0x118

%rsp

%rip

0x400549

0x118

0x400550

Control Flow Example #3

```
00000000000400540 <multstore>:
```

•

•

```
400544: callq 400550 <mult2>
```

```
400549: mov    %rax, (%rbx) ←
```

•

•

```
00000000000400550 <mult2>:
```

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

•

•

```
400557: retq ←
```

0x130

•

0x128

•

•

0x120

0x118

0x400549

%rsp

0x118

%rip

0x400557

Control Flow Example #4

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

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

0x130

0x128

0x120

%rsp

0x120

%rip

0x400549

Today

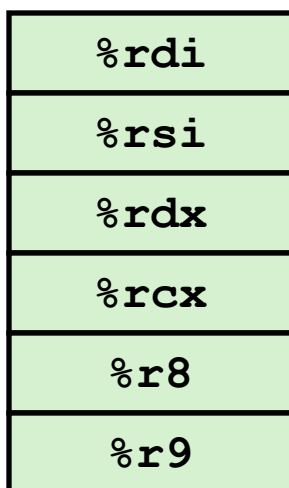
■ Procedures

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

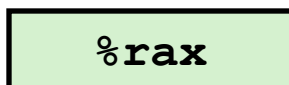
Procedure Data Flow

Registers

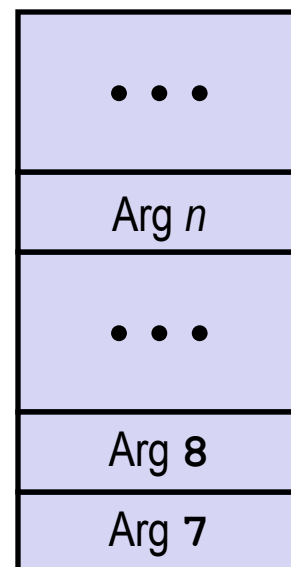
■ First 6 arguments



■ 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

- Mechanisms
- Stack Structure
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 - Passing control
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 - **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

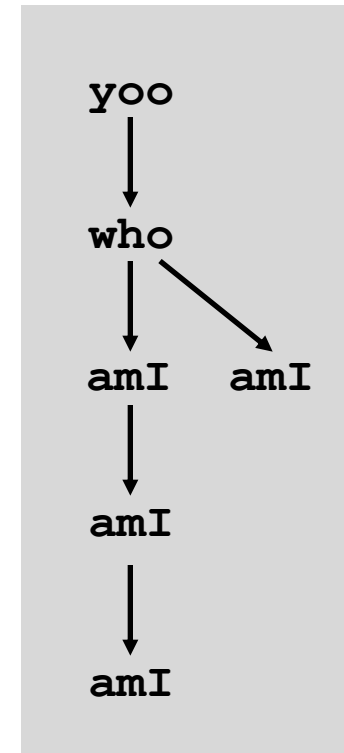
```
yoo (...)
{
  .
  .
  who ();
  .
  .
}
```

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

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

Procedure **amI ()** is recursive

Example
Call Chain



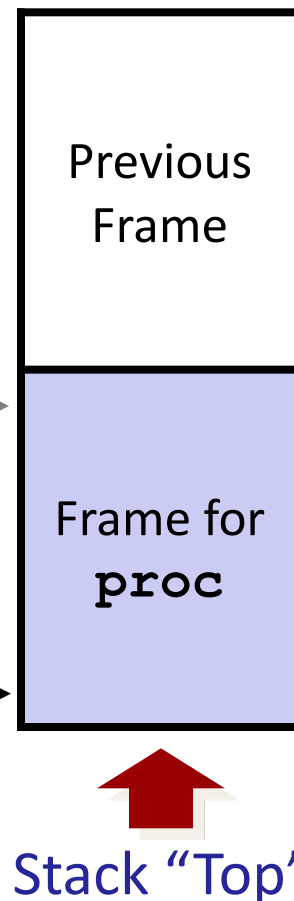
Stack Frames

■ Contents

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

Frame Pointer: `%rbp`
(Optional)


Stack Pointer: `%rsp`



■ Management

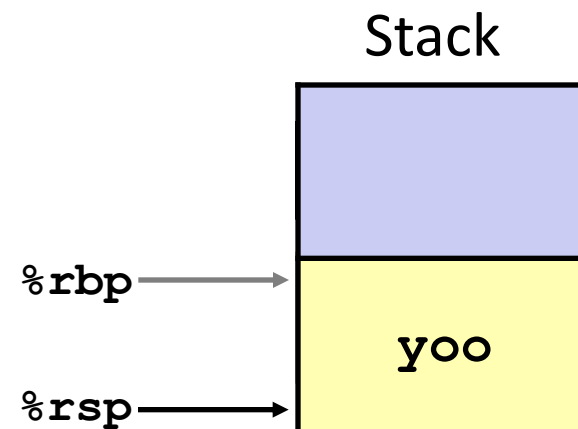
- Space allocated when enter procedure
 - “Set-up” code
 - Includes push by `call` instruction
- Deallocated when return
 - “Finish” code
 - Includes pop by `ret` instruction

Example

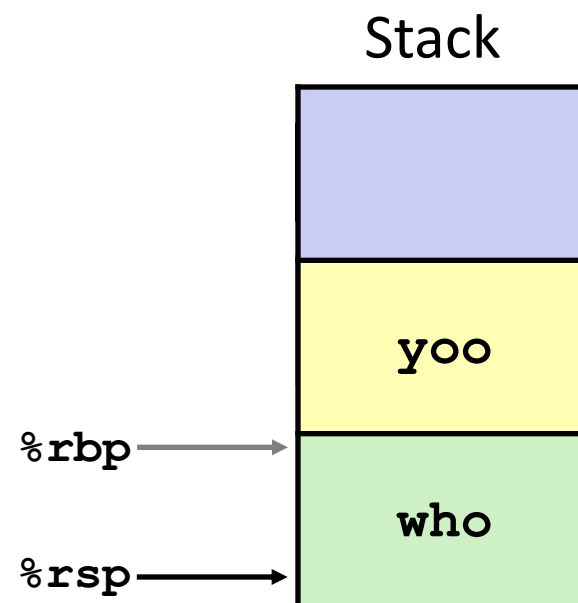
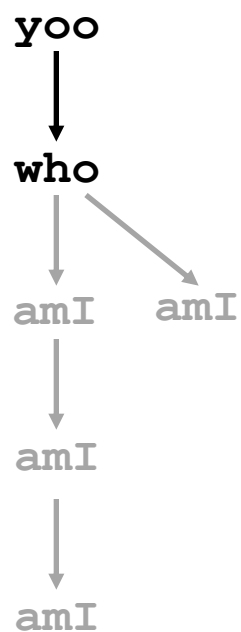
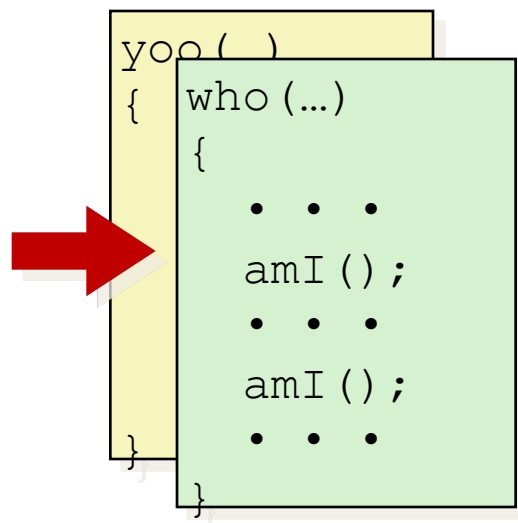


```
yoo (...)  
{  
  .  
  .  
  who ();  
  .  
  .  
}
```

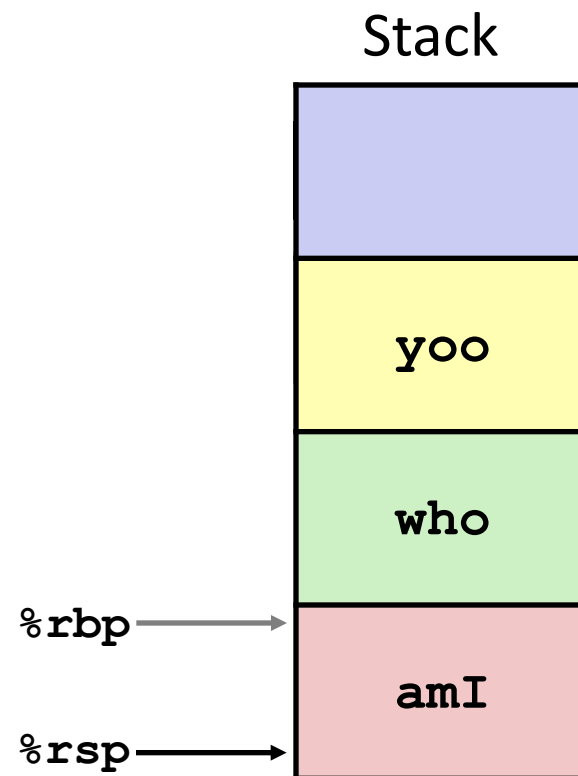
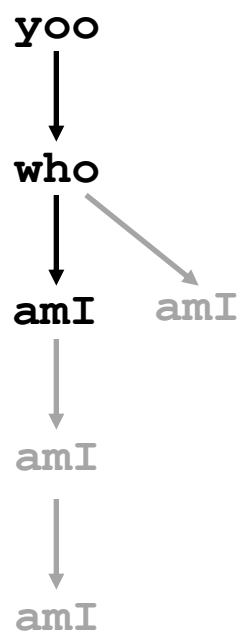
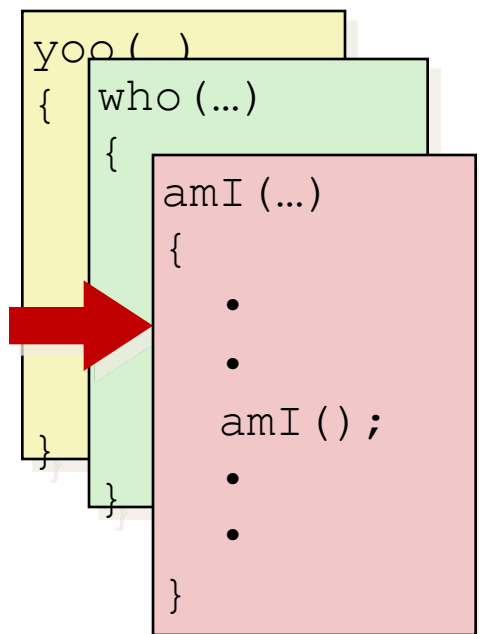
```
yoo  
  ↓  
who  
  ↓  ↘  
amI  amI  
  ↓  
amI  
  ↓  
amI
```



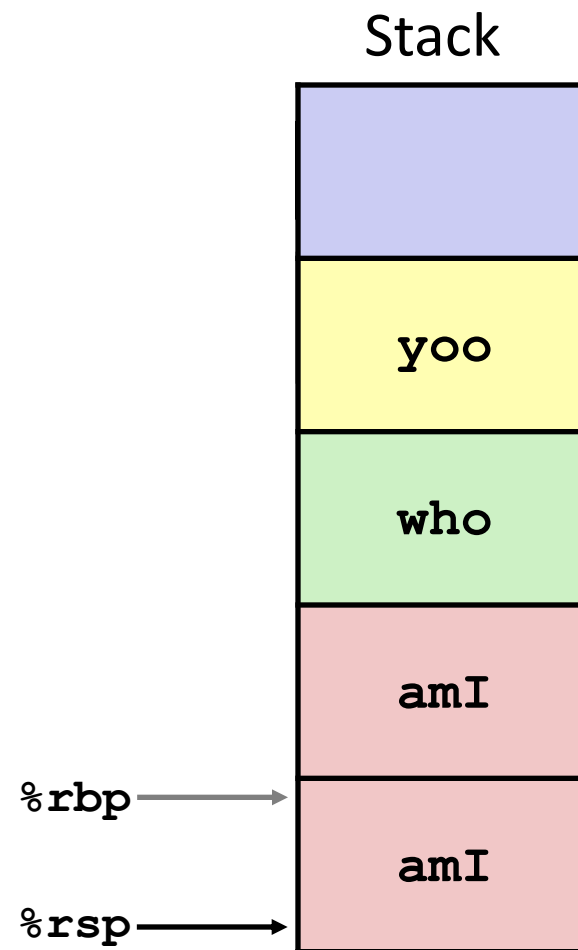
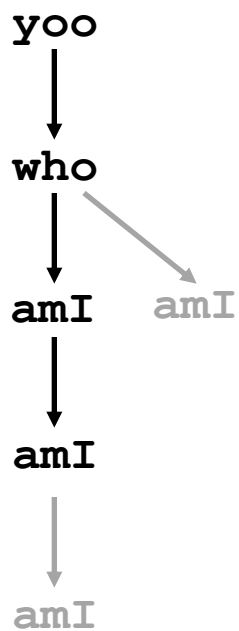
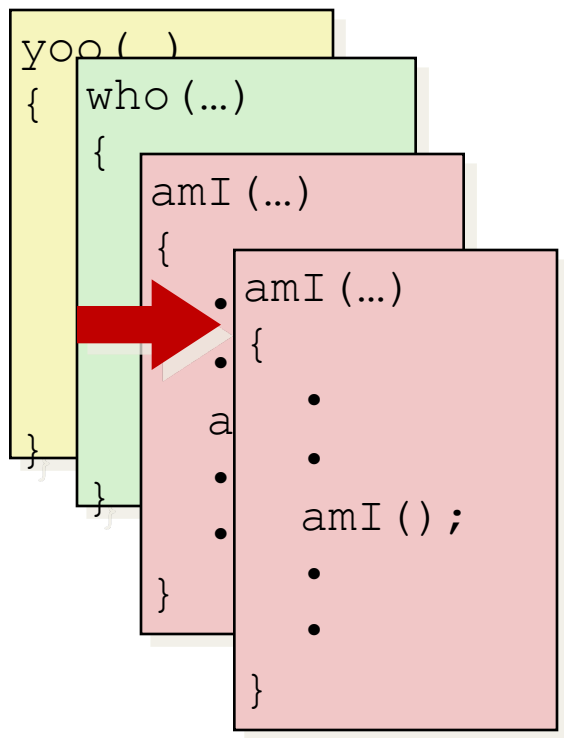
Example



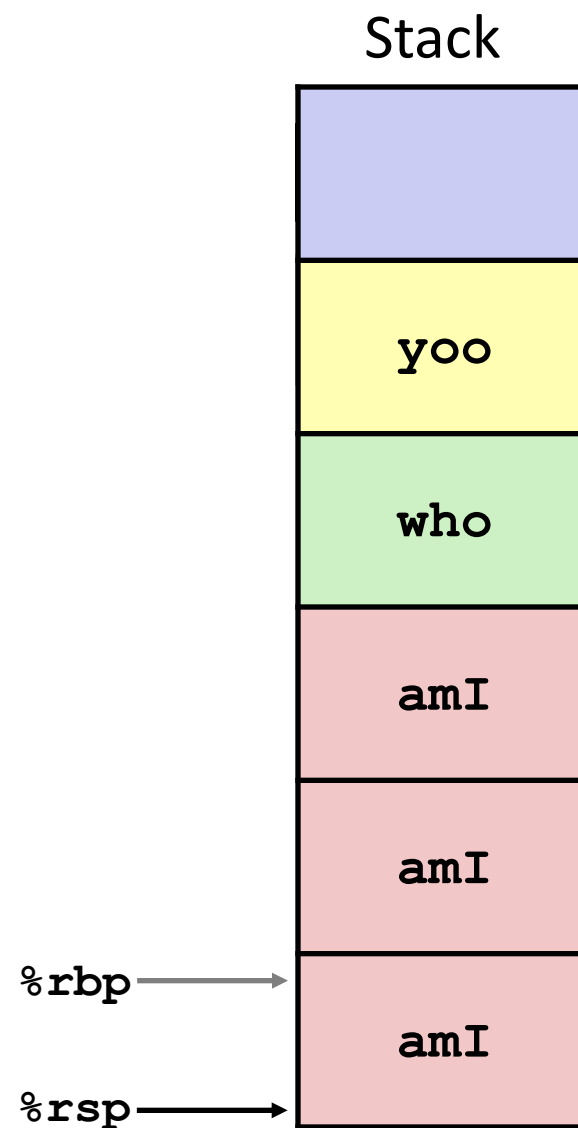
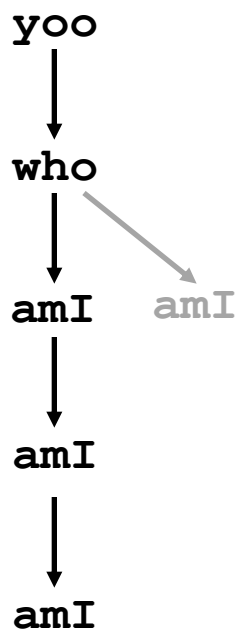
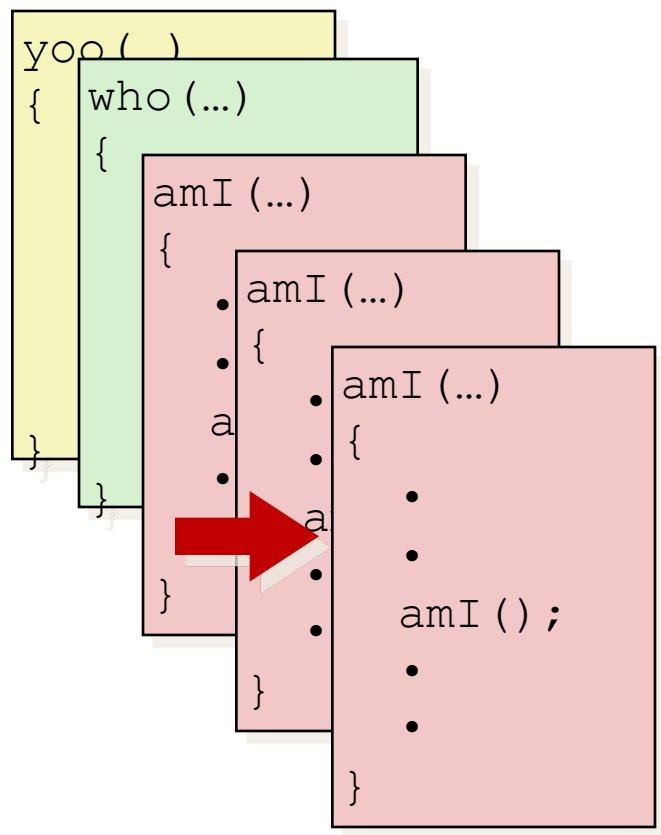
Example



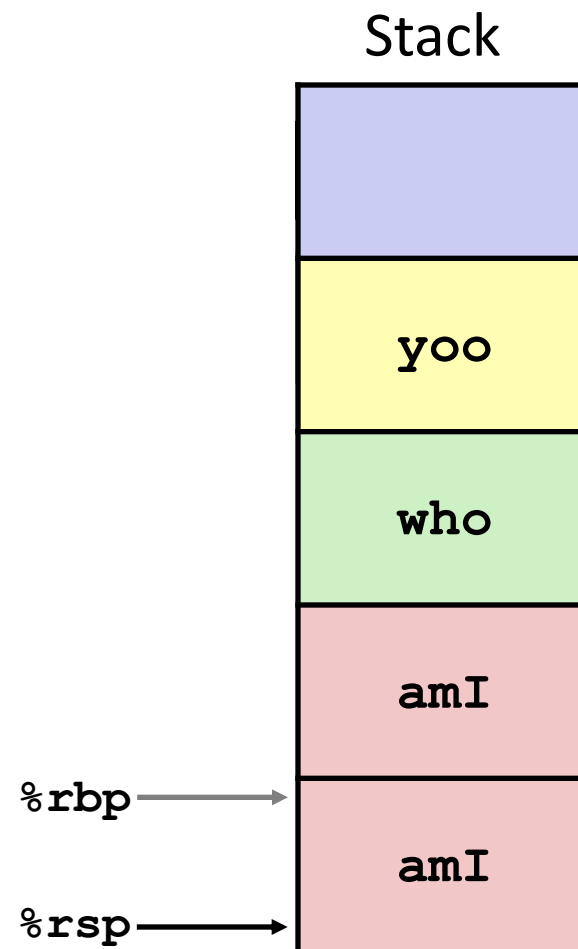
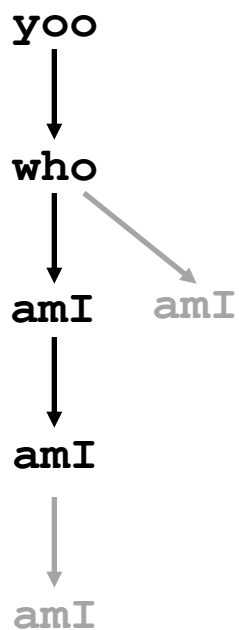
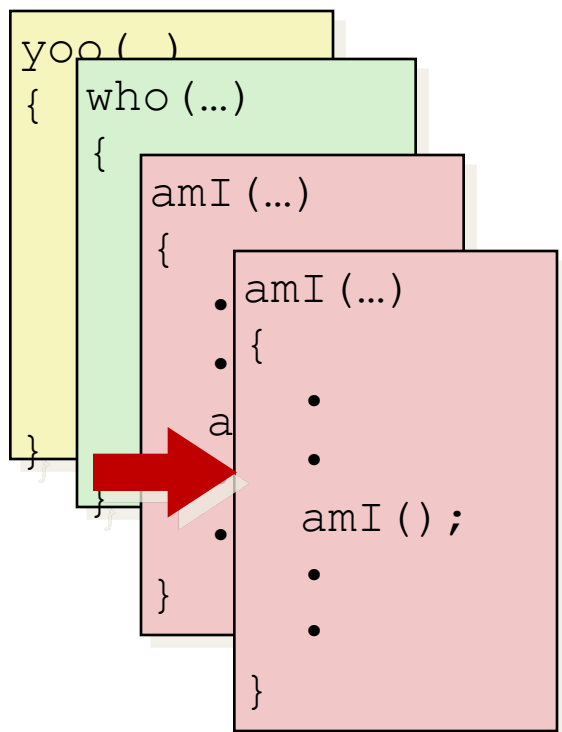
Example



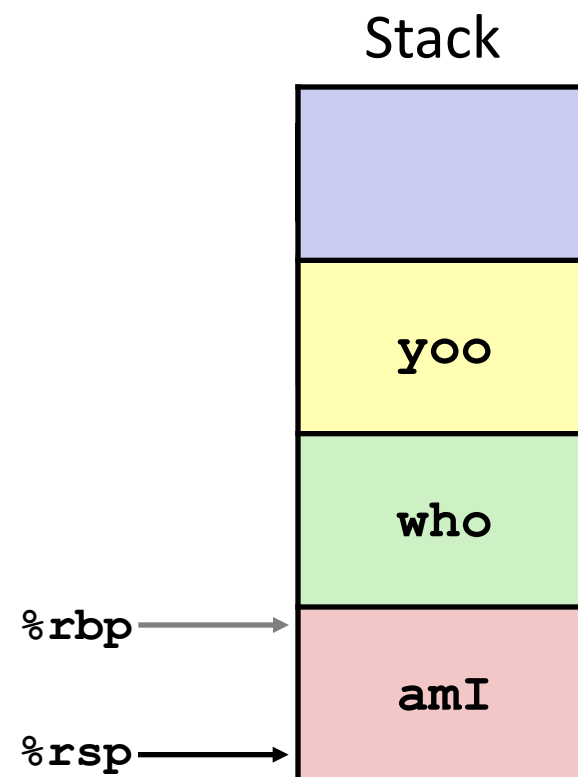
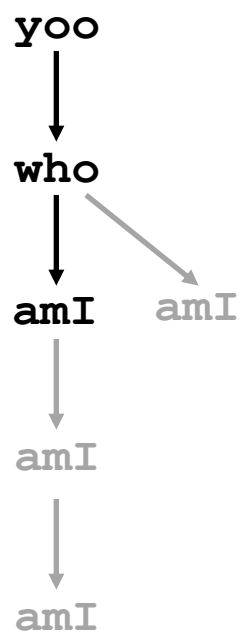
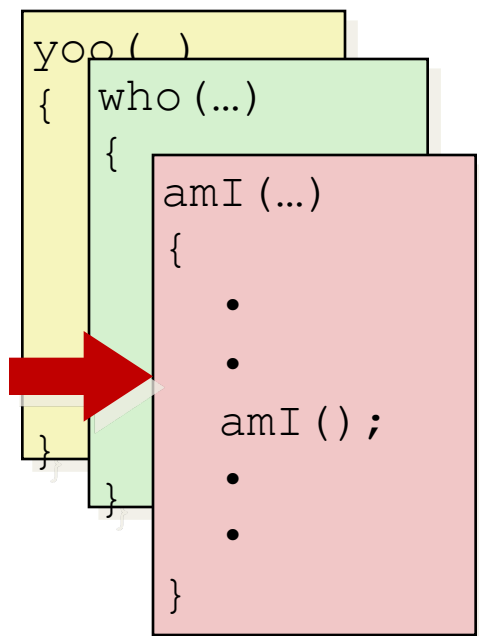
Example



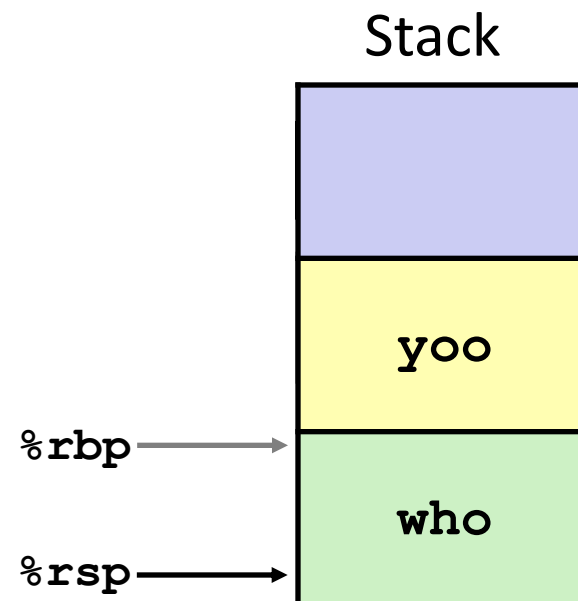
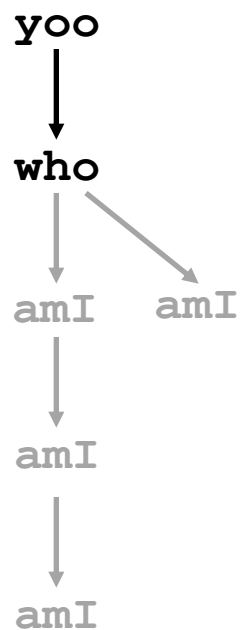
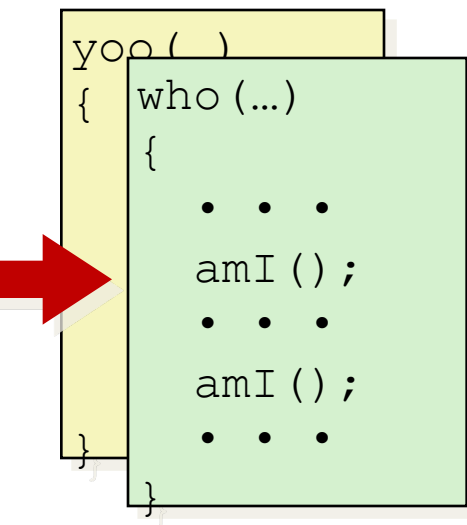
Example



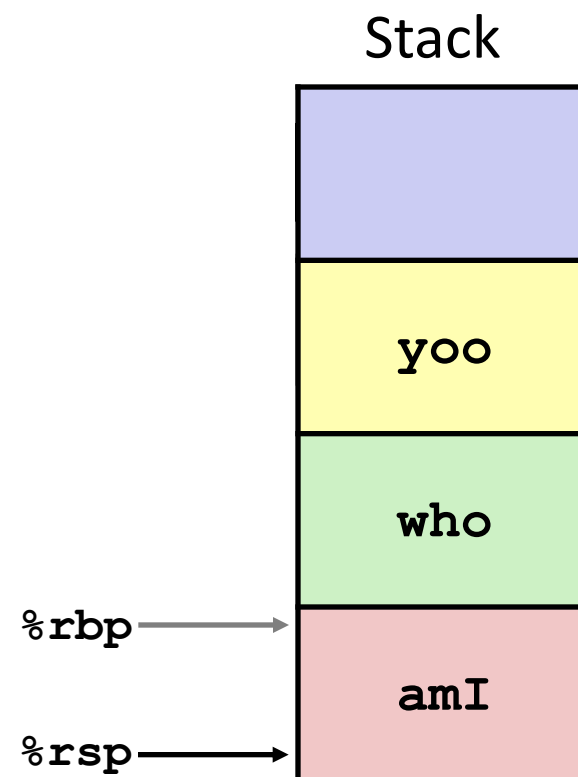
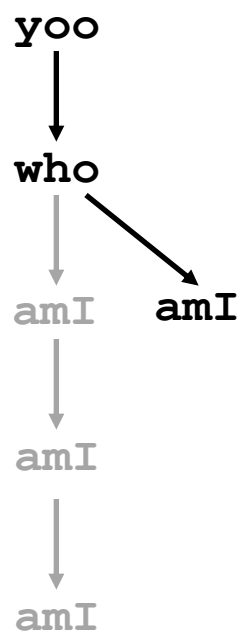
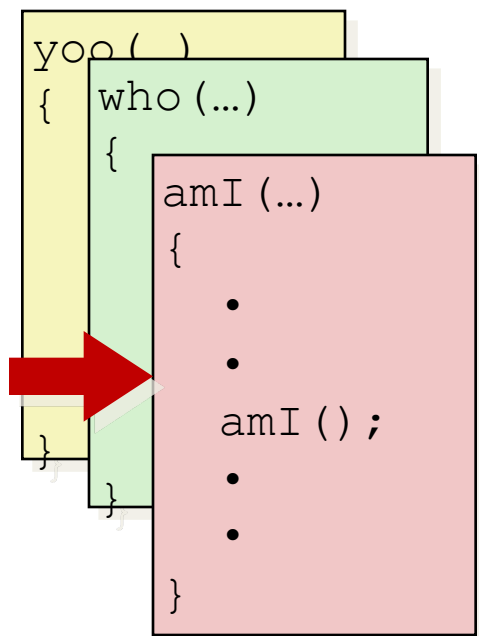
Example



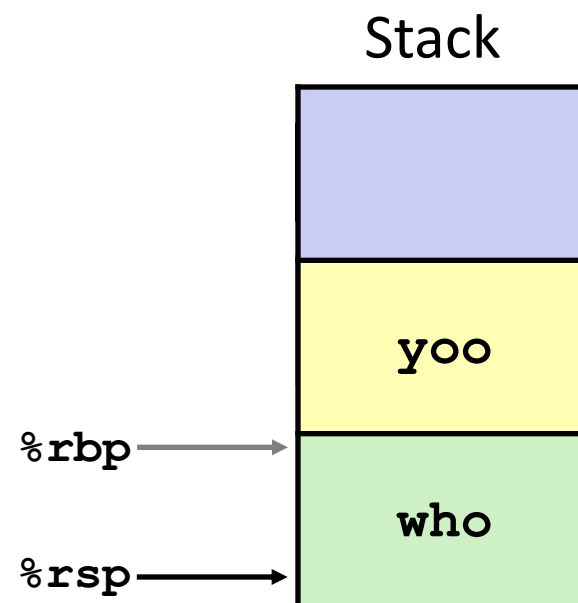
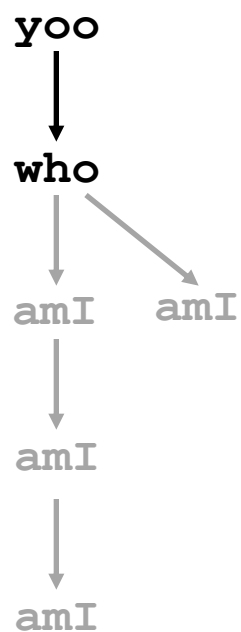
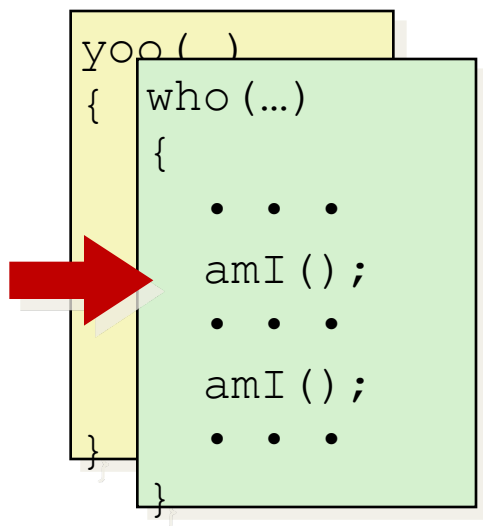
Example



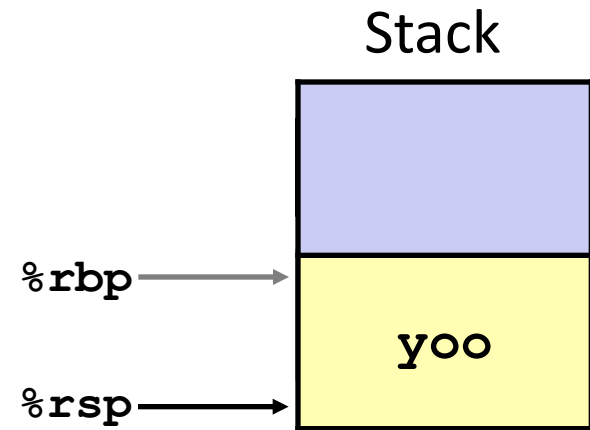
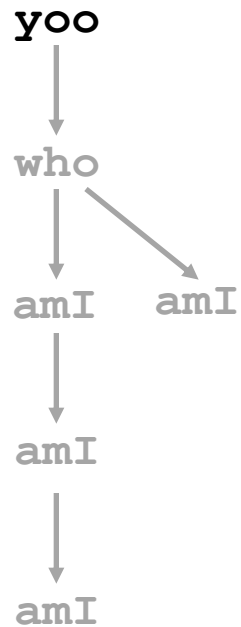
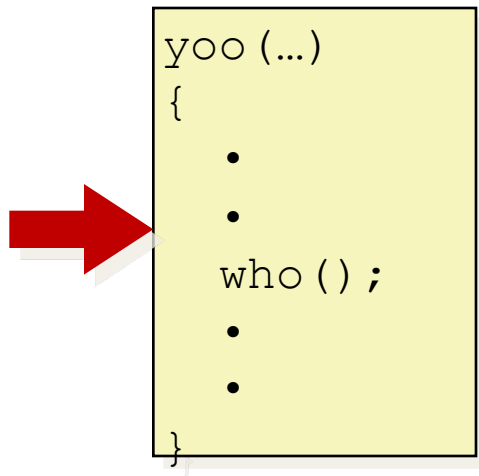
Example



Example



Example



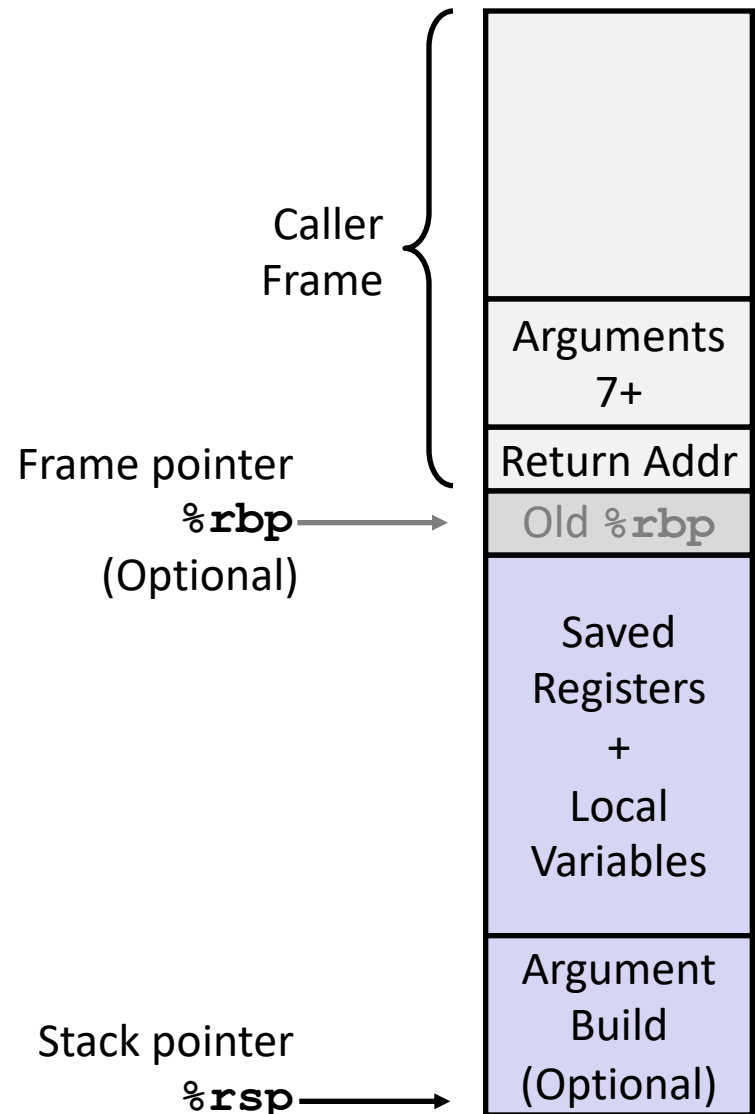
x86-64/Linux Stack Frame

■ 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;
}
```

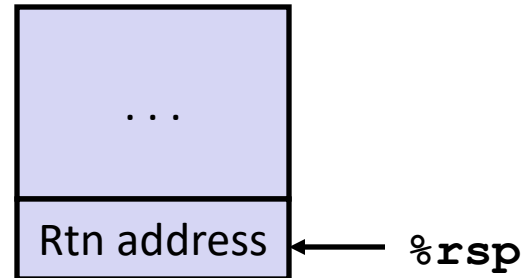
```
incr:
    movq    (%rdi), %rax
    addq    %rax, %rsi
    movq    %rsi, (%rdi)
    ret
```

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

Example: Calling `incr` #1

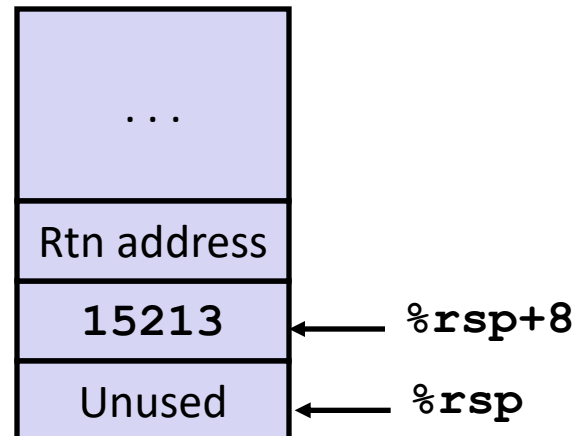
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

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

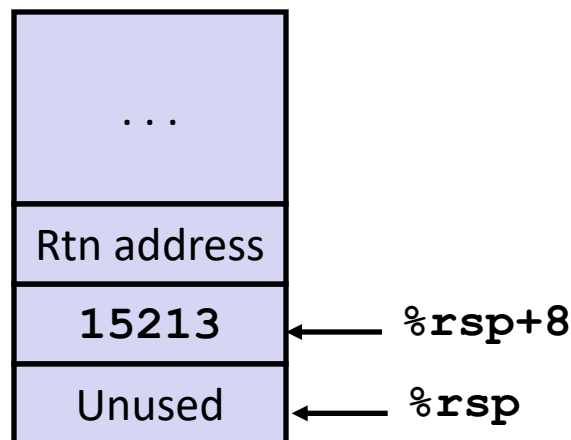


Example: Calling `incr` #2

```
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

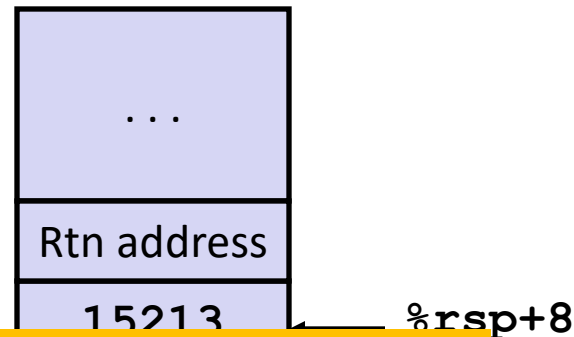


Register	Use(s)
<code>%rdi</code>	<code>&v1</code>
<code>%rsi</code>	3000

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`

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

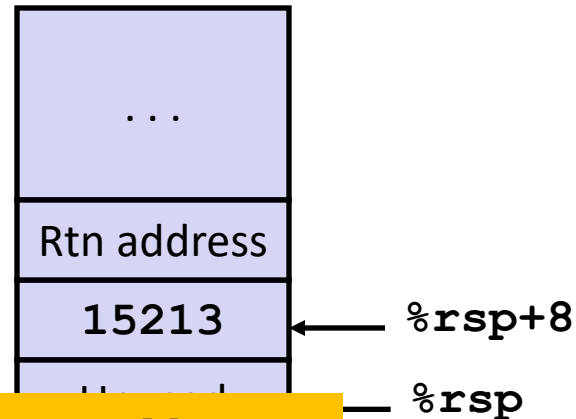
```
call_incr:
    subq    $8, %rsp
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

%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
```

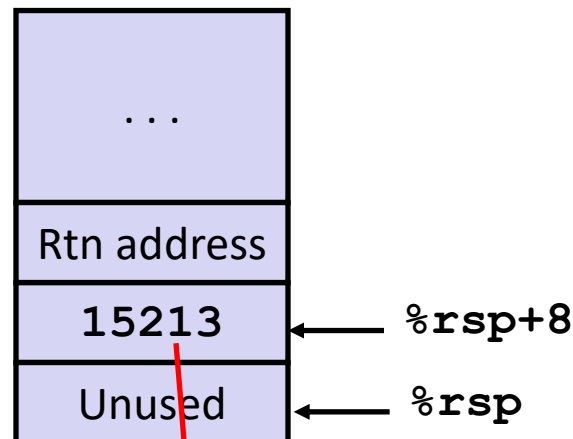
Case(s)	
return	v1
%rsi	3000

Example: Calling `incr` #3a

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)
%rdi	&v1
%rsi	3000

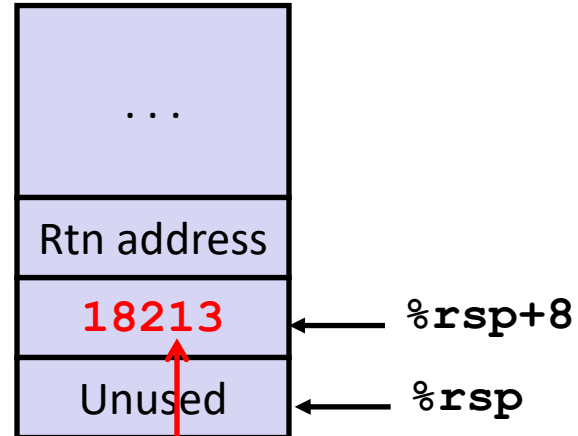
```
long incr(long *p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

Example: Calling `incr` #3b

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
```



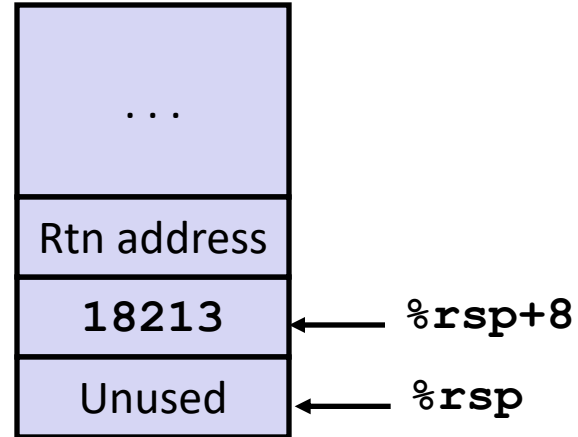
Register	Use(s)
<code>%rdi</code>	<code>&v1</code>
<code>%rsi</code>	3000

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

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
```

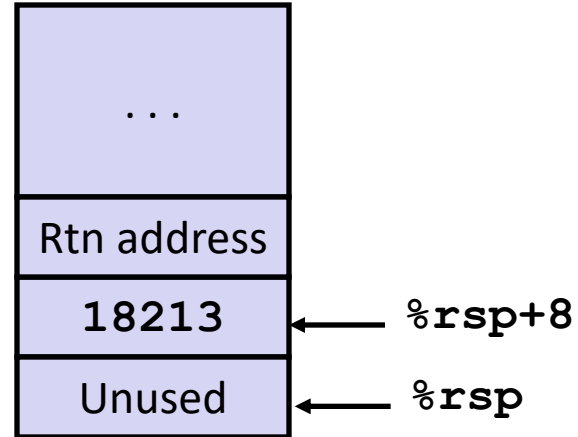
Register	Use(s)
<code>%rax</code>	Return value, 15213

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

Example: Calling `incr` #5a

Stack Structure

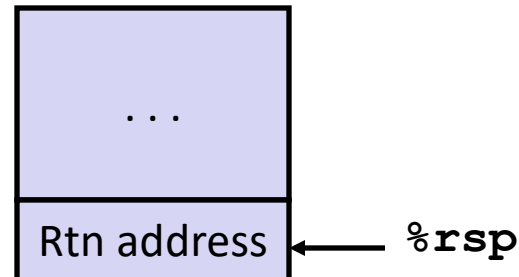
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```



```
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)
%rax	Return value

Updated Stack Structure

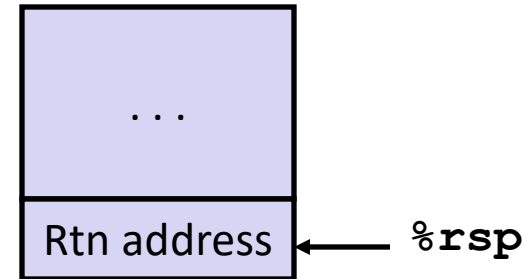


Example: Calling `incr` #5b

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

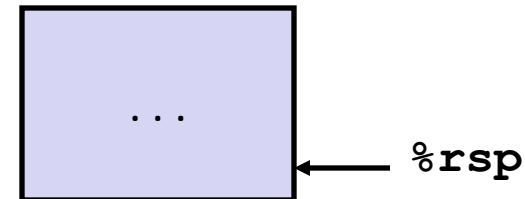
```
call_incr:
    subq    $16, %rsp
    movq    $15213, 8(%rsp)
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

Updated Stack Structure



Register	Use(s)
%rax	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

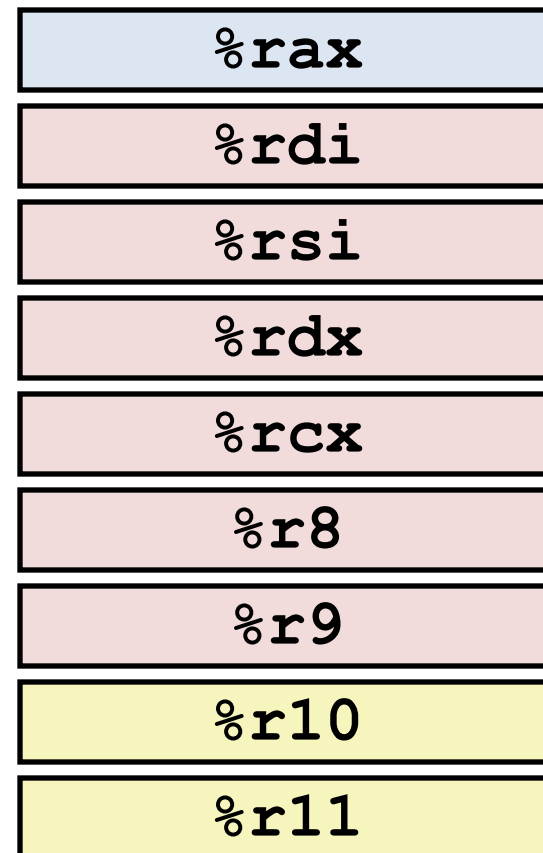
■ **%r10, %r11**

- Caller-saved
- Can be modified by procedure

Return value

Arguments

Caller-saved
temporaries



x86-64 Linux Register Usage #2

■ **%rbx, %r12, %r13, %r14**

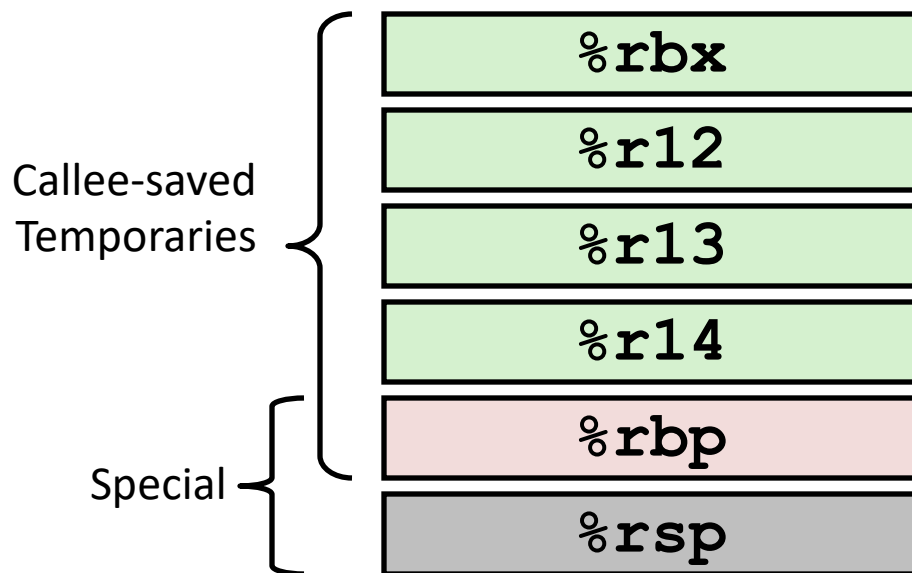
- Callee-saved
- Callee must save & restore

■ **%rbp**

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

■ **%rsp**

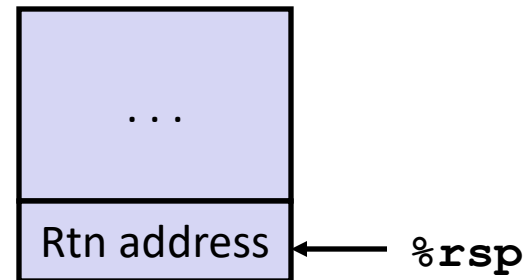
- Special form of callee save
- Restored to original value upon exit from procedure



Callee-Saved Example #1

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

Initial Stack Structure



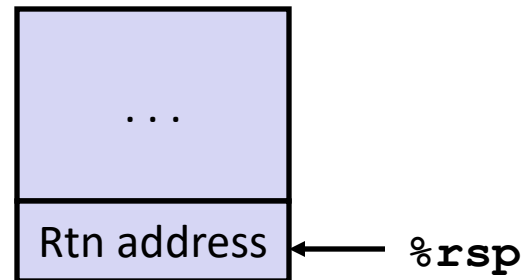
- **x** comes in register **%rdi**.
- We need **%rdi** for the call to **incr**.
- Where should be put **x**, so we can use it after the call to **incr**?

Callee-Saved Example #2

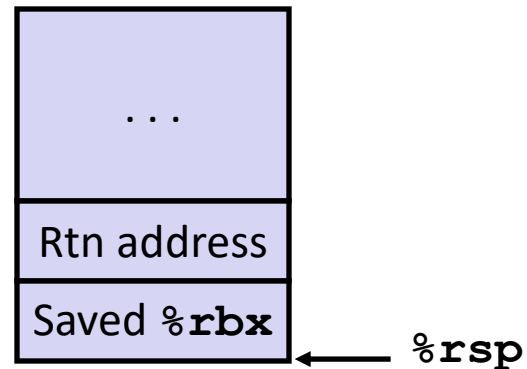
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

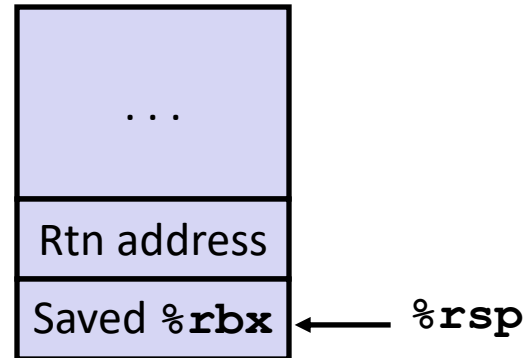


Callee-Saved Example #3

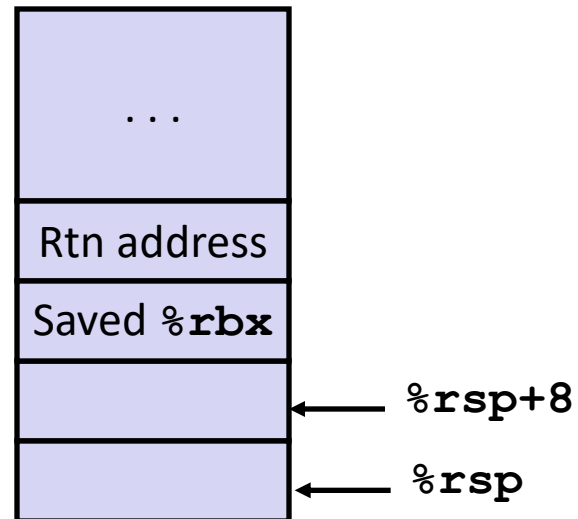
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

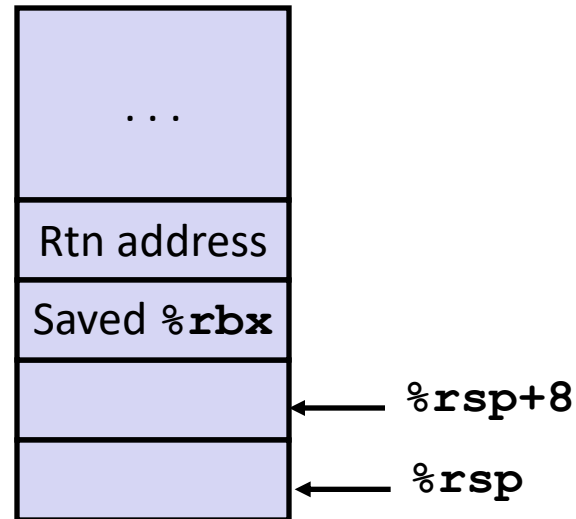


Callee-Saved Example #4

```
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



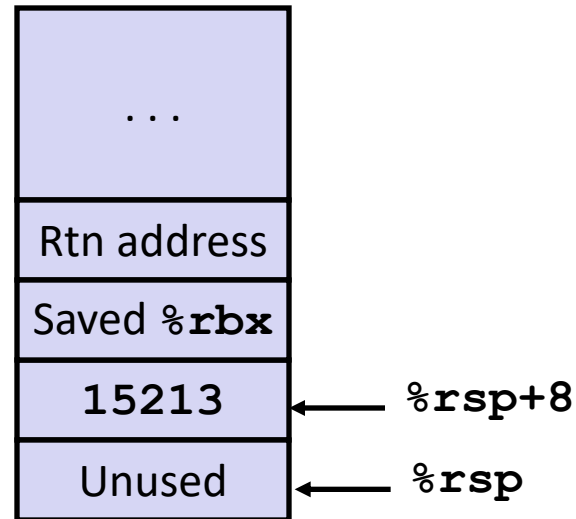
- **x** is saved in **%rbx**,
a callee saved register

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



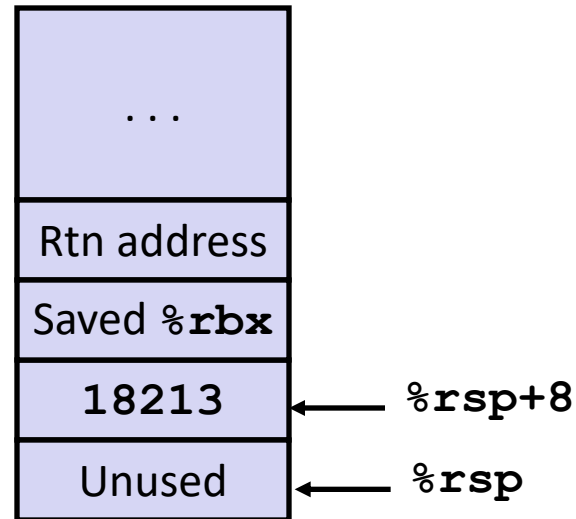
- **x** is saved in **%rbx**,
a callee saved register

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



Upon return from `incr`:

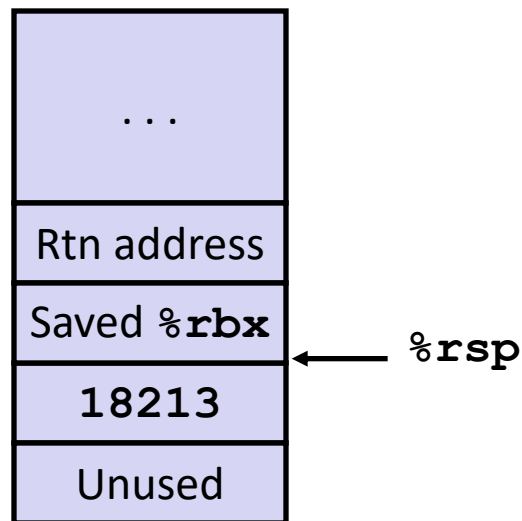
- `x` safe in `%rbx`
- Return val `v2` in `%rax`
- Compute `x+v2`:
`addq %rbx, %rax`

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



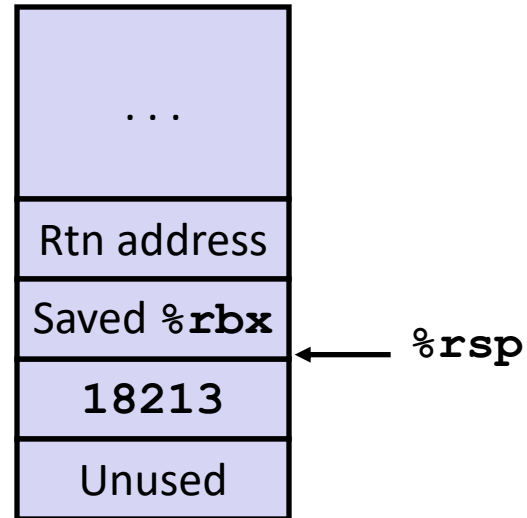
- Return result in **%rax**

Callee-Saved Example #8

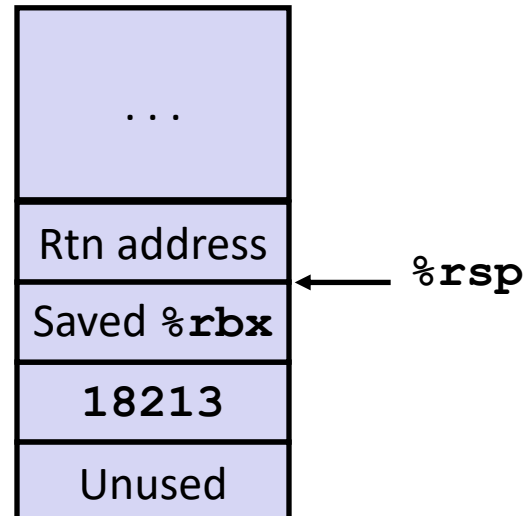
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

- Mechanisms
- 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 # (by 1)
    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 # (by 1)
    call    pcount_r
    addq    %rbx, %rax
    popq    %rbx
.L6:
    rep; ret
```

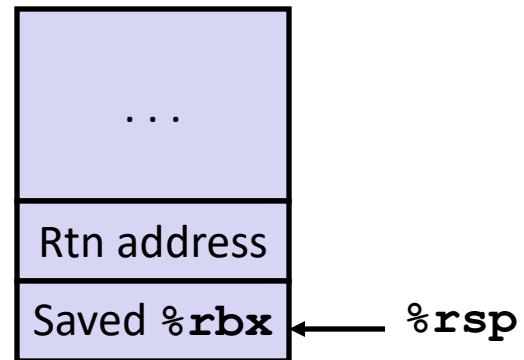
Register	Use(s)	Type
%rdi	x	Argument
%rax	Return value	Return value

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 # (by 1)
    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 # (by 1)
    call    pcount_r
    addq    %rbx, %rax
    popq    %rbx
.L6:
    rep; ret
```

Register	Use(s)	Type
%rdi	x >> 1	Recursive 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 # (by 1)
    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 # (by 1)
    call    pcount_r
    addq    %rbx, %rax
    popq    %rbx
.L6:
    rep; ret
```

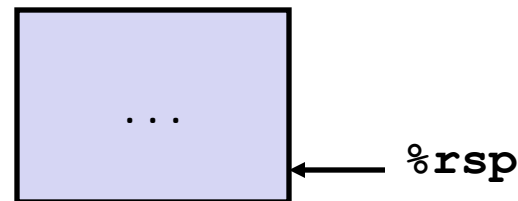
Register	Use(s)	Type
%rbx	x & 1	Callee-saved
%rax	Return value	

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 # (by 1)
    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

