# Machine-Level Programming III: Procedures

COMP400727: Introduction to Computer Systems

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# Mechanisms in Procedures

**Passing control** 控制权转移

- To beginning of procedure code
- Back to return point

**Passing data** 传参

- Procedure arguments
- Return value

**Memory management** 内存分配

- 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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**Passing data**

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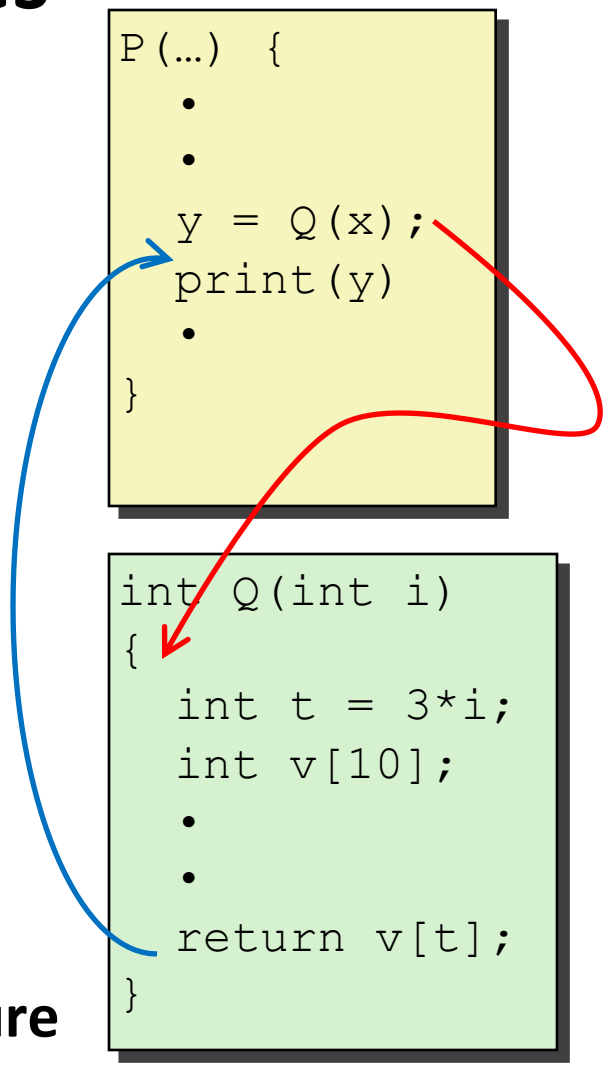

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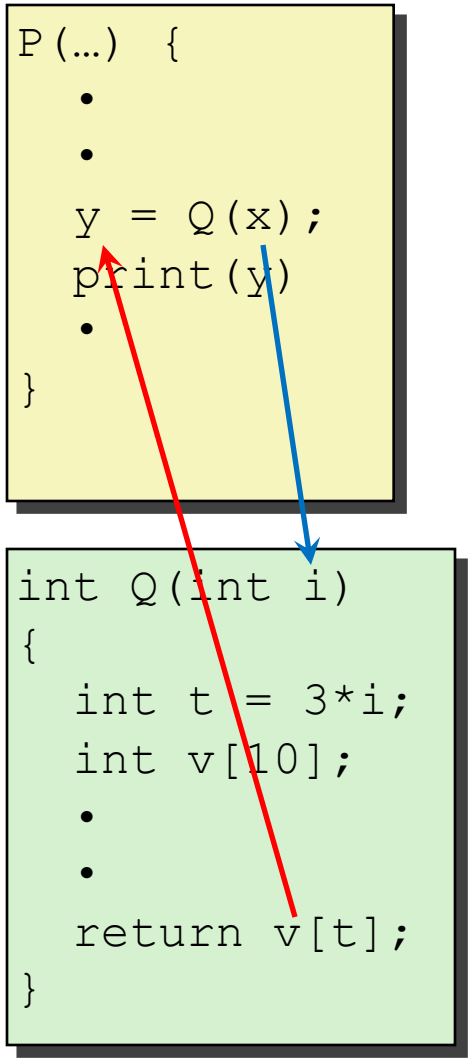

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   •
   •
   return v[t];
}
```

# Mechanisms in Procedures

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**

```
P(…) {
  int v[10];
  •
  •
  return v[t];
}
```

# Today

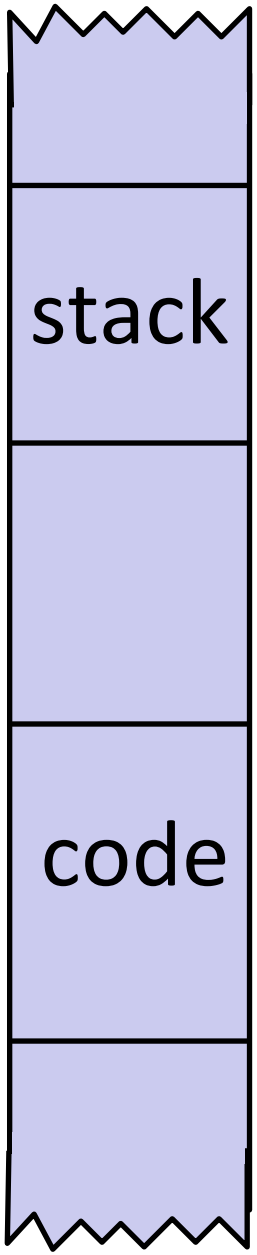
## Procedures

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

# x86-64 Stack

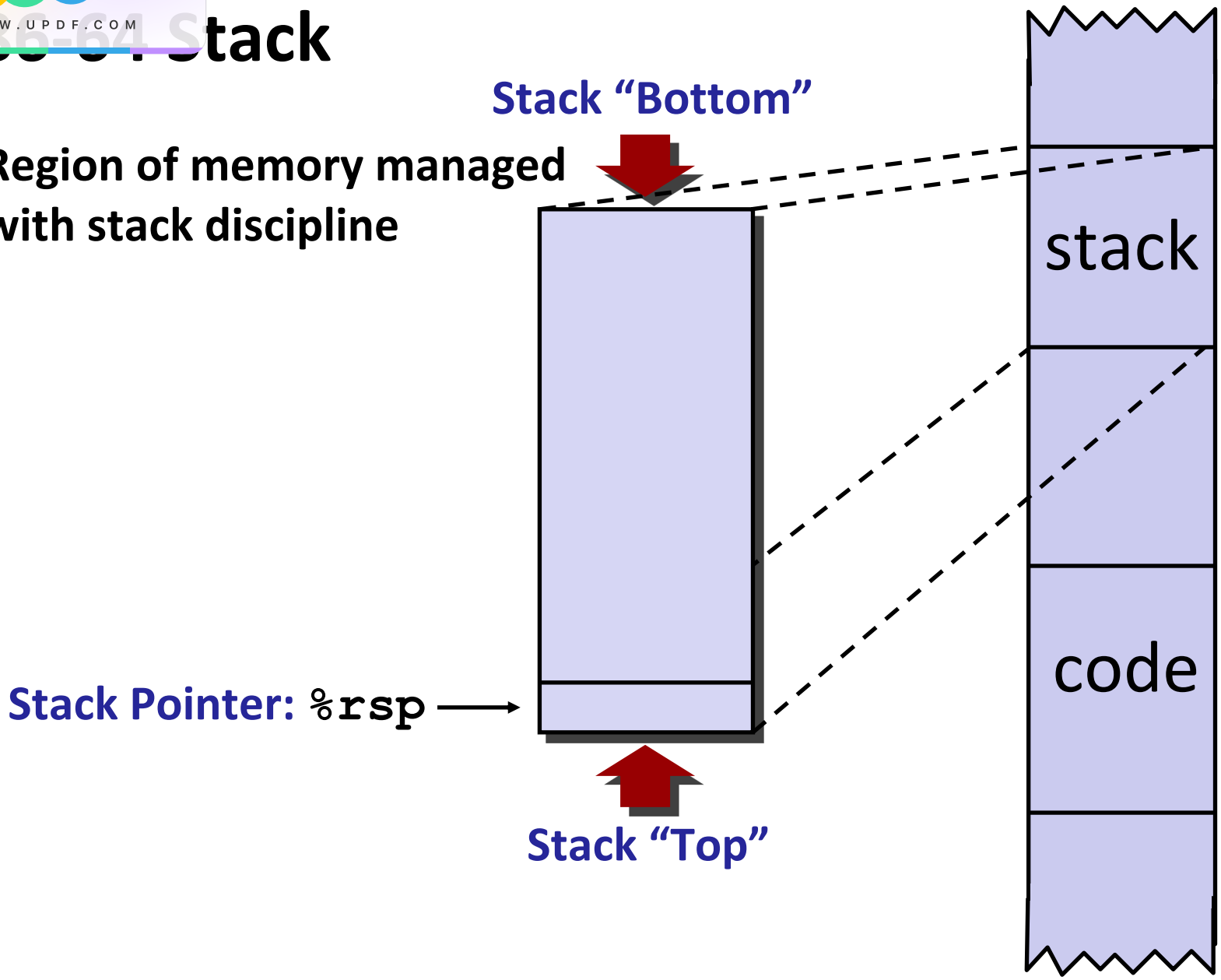
**Region of memory managed with stack discipline**

- 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



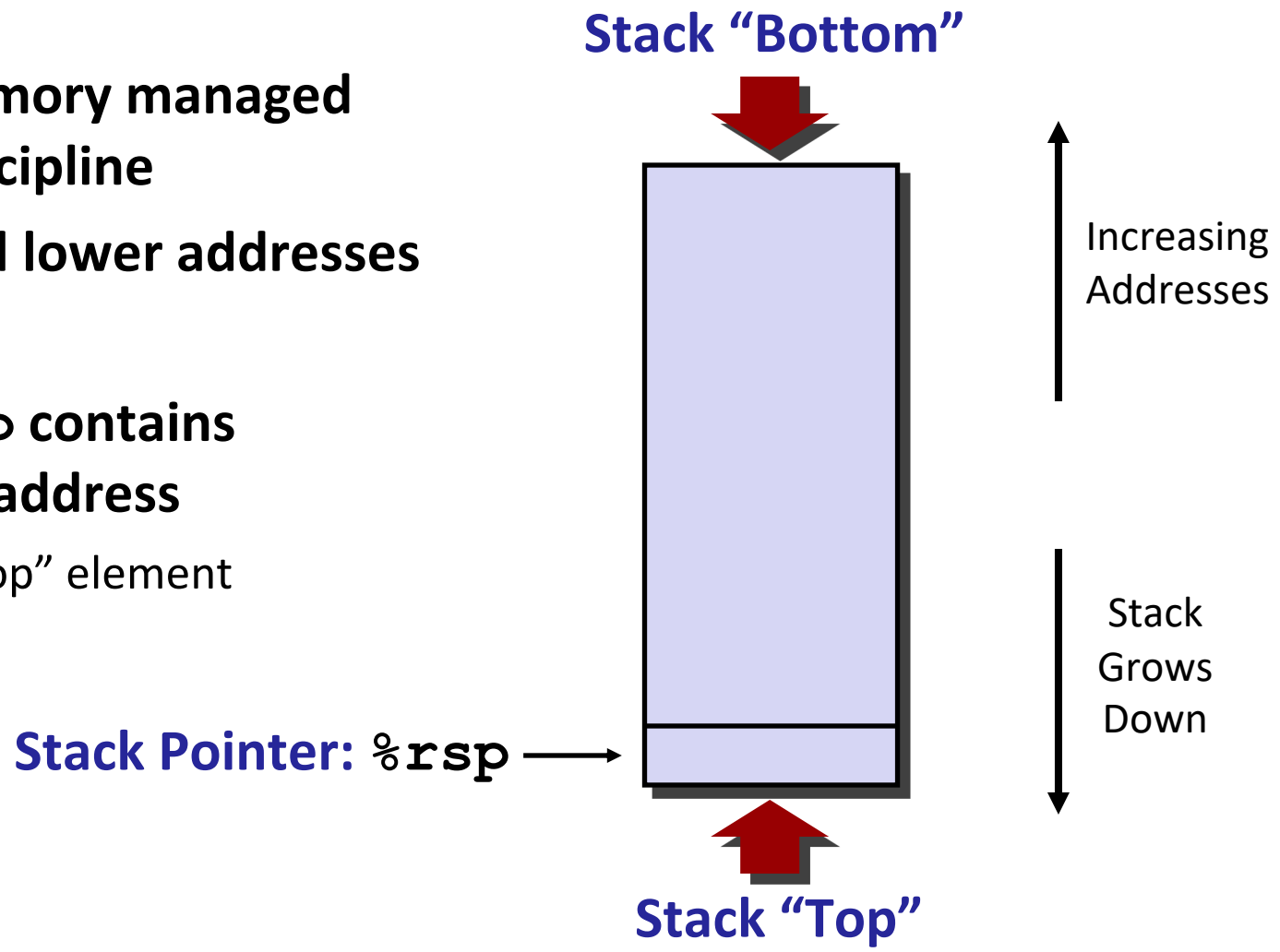
# x86-64 Stack

**Region of memory managed with stack discipline**

**Grows toward lower addresses**

**Register `%rsp` contains lowest stack address**

address of "top" element



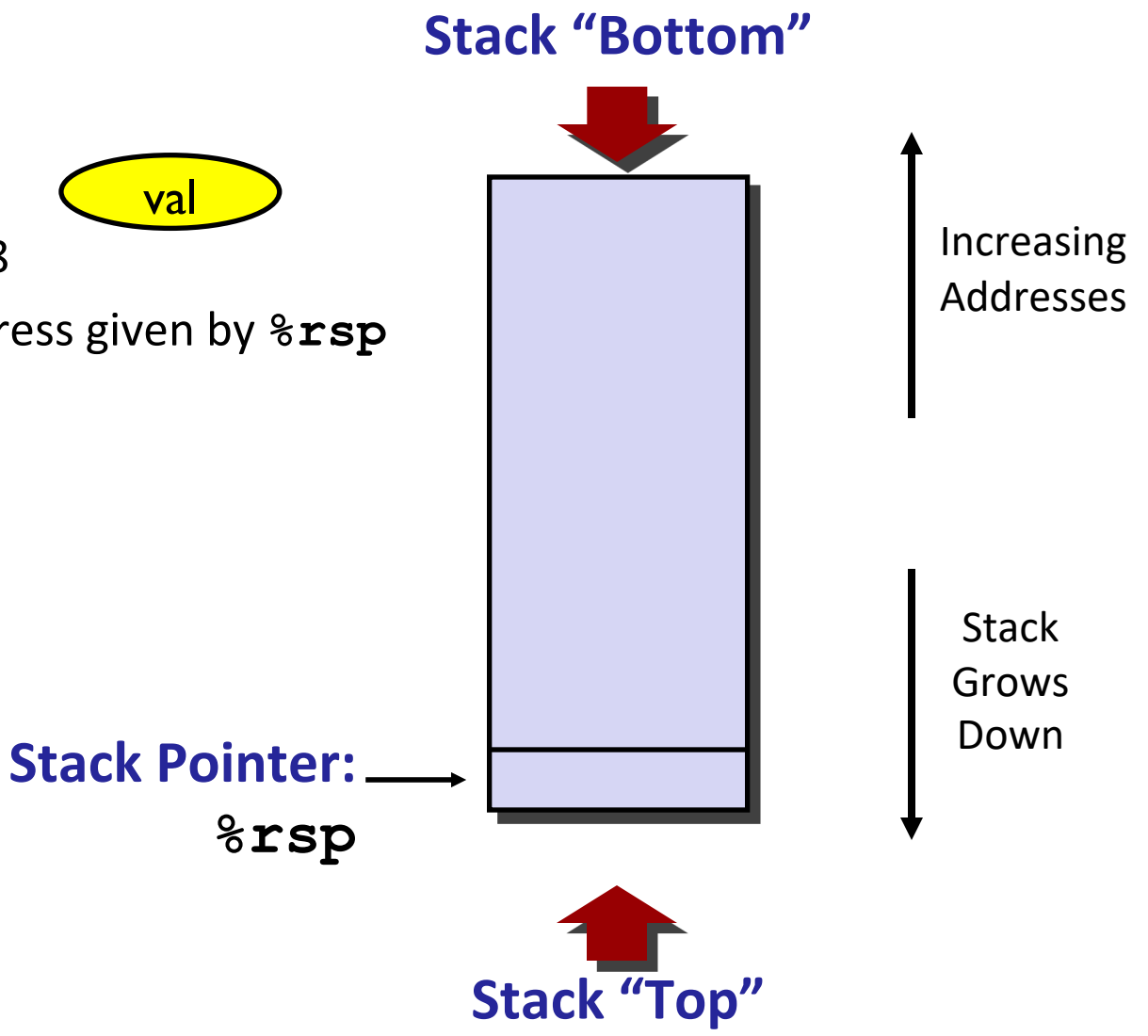
# x86-64 Stack: Push

**`pushq` *Src***

Fetch operand at *Src*

Decrement **`%rsp`** by 8

Write operand at address given by **`%rsp`**



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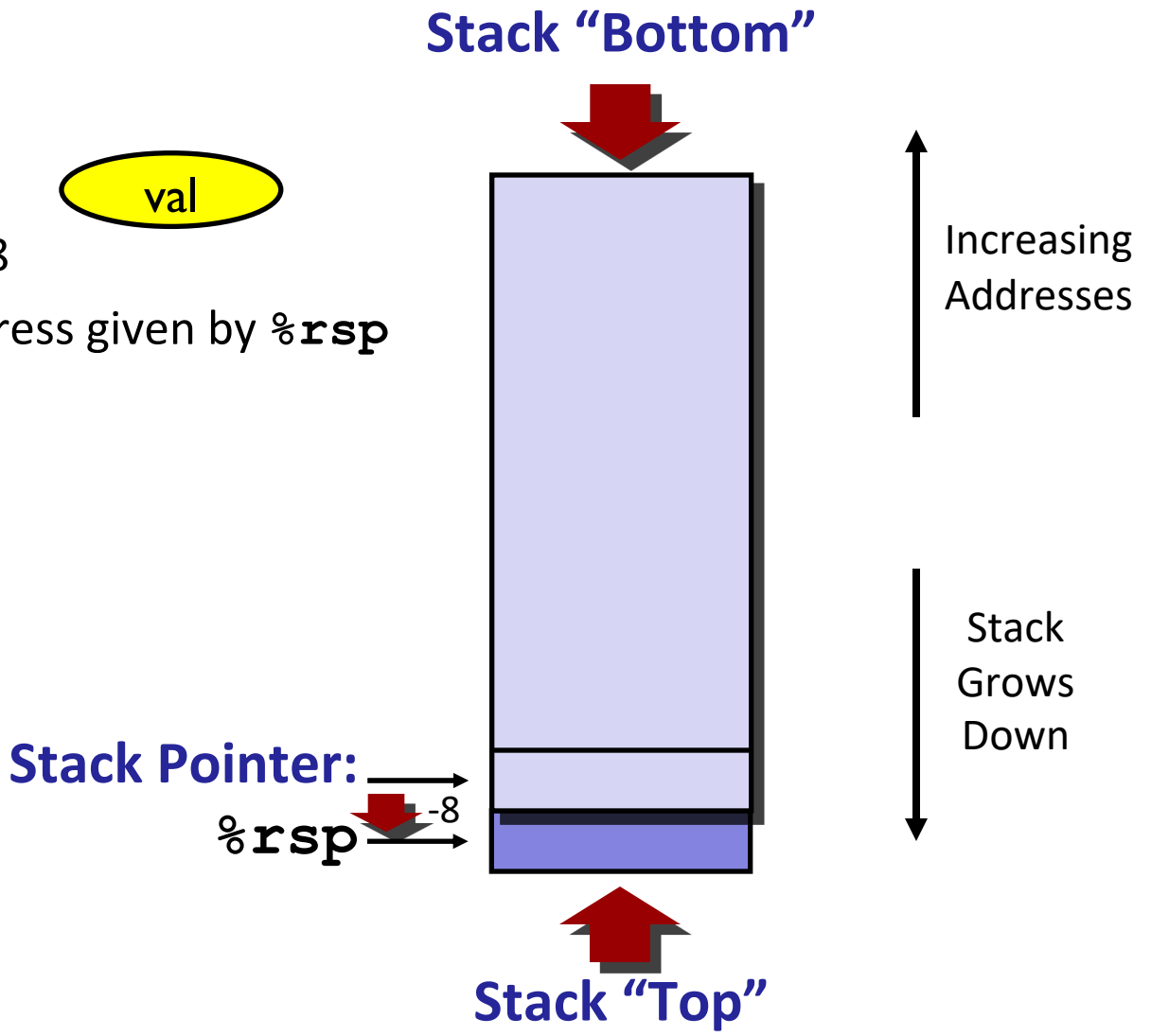
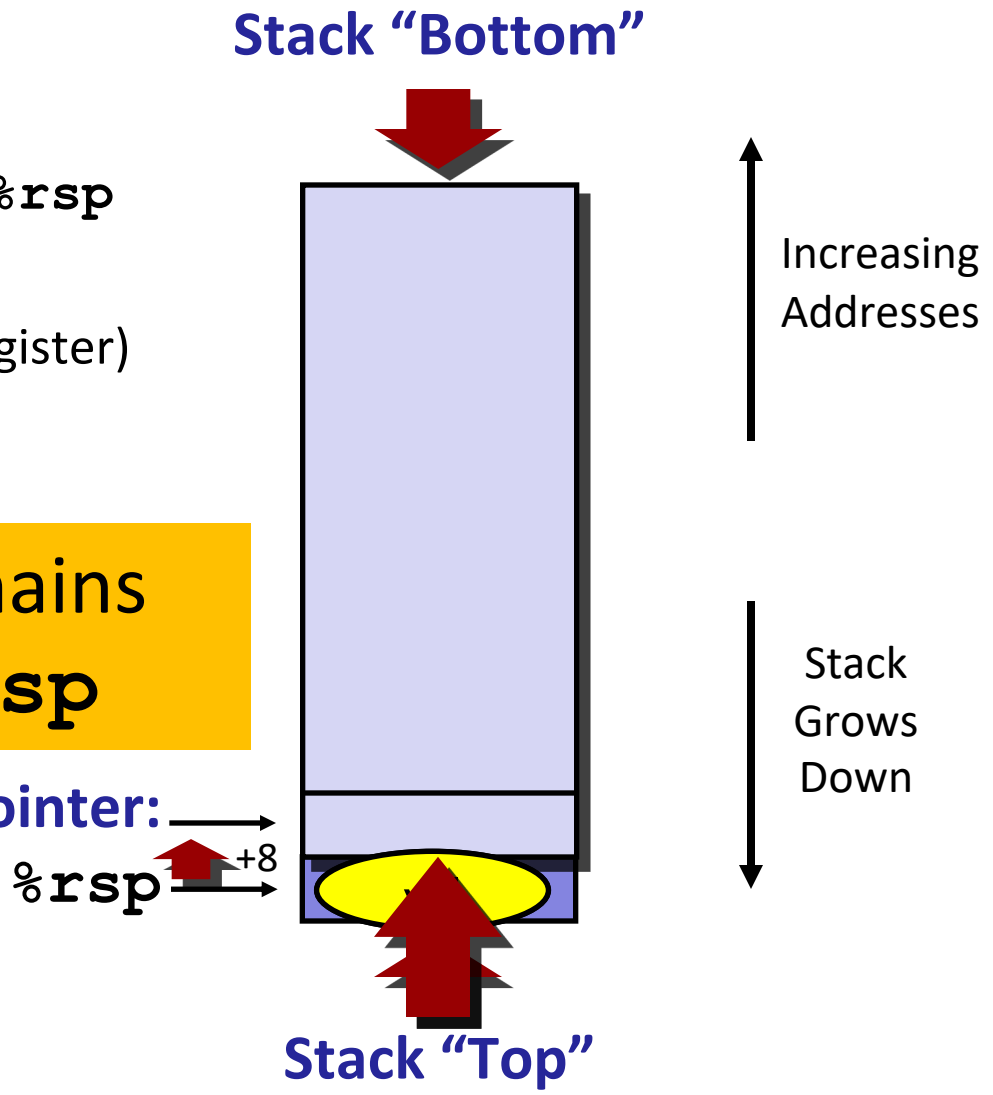


# x86-64 Stack: Pop

**`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`**



# Today

## Procedures

- Stack Structure
- Calling Conventions
  - **Passing control**
  - Passing data
  - Managing local data
- If we have time: 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: 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;
}
```

```
0000000000400550 <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

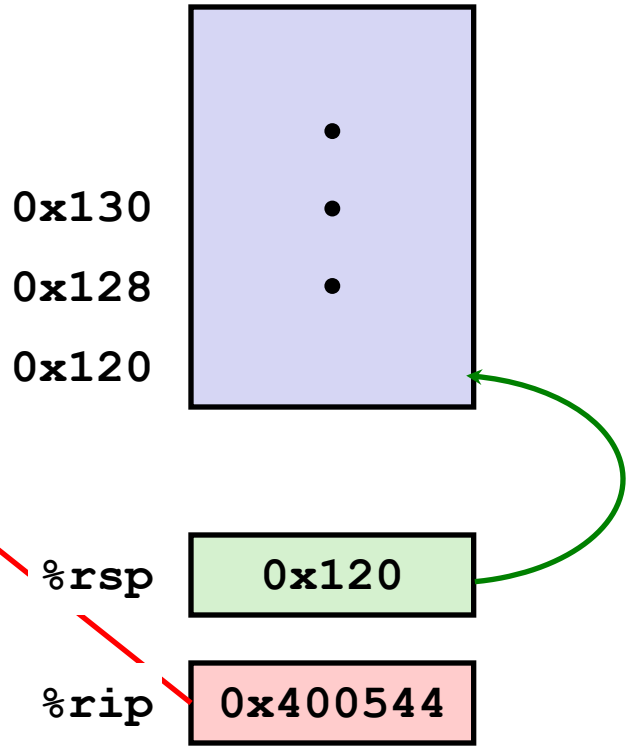
**These instructions are sometimes printed with a `q` suffix**

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

# Control Flow Example #1

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

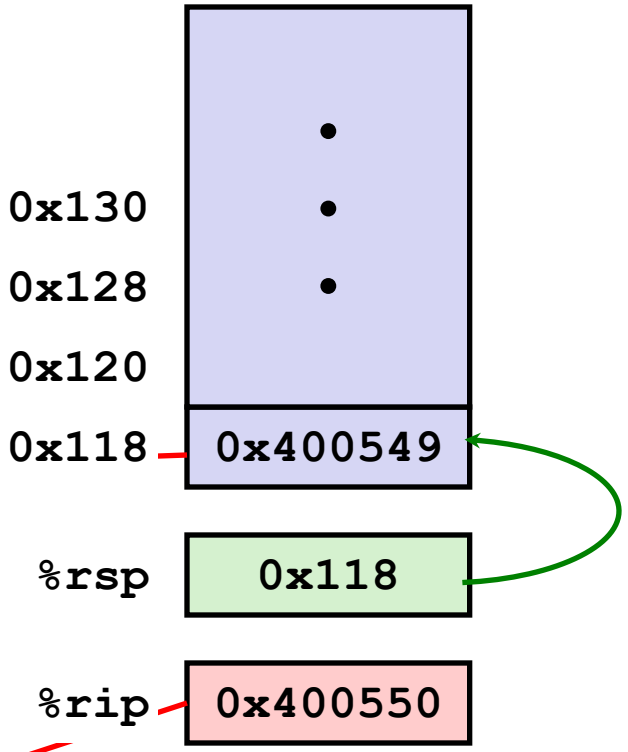
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  ret
```



# Control Flow Example #2

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

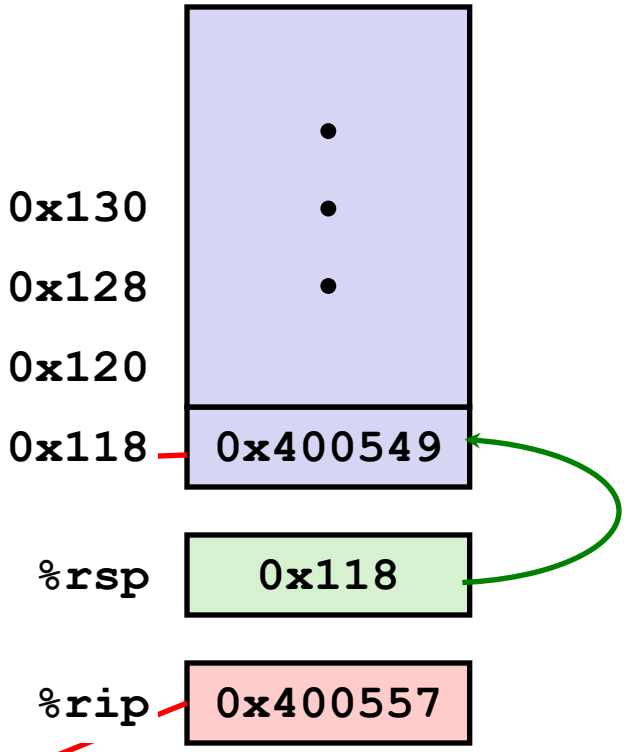
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  ret
```



# Control Flow Example #3

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

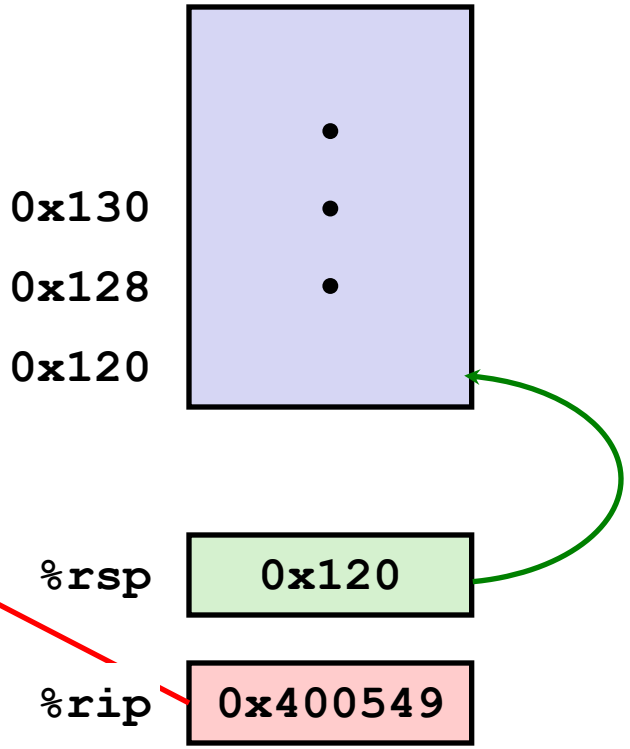
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  ret
```



# Control Flow Example #4

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

```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  ret
```



# Today

## Procedures

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

# Procedure Data Flow

## Registers

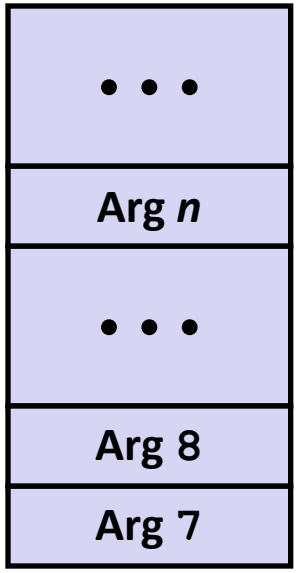
### First 6 arguments

| %rdi |
| --- |
| %rsi |
| %rdx |
| %rcx |
| %r8 |
| %r9 |

### Return value

| %rax |
| --- |

## 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
```

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## Procedures

- Stack Structure
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  - **Managing local data**
- 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

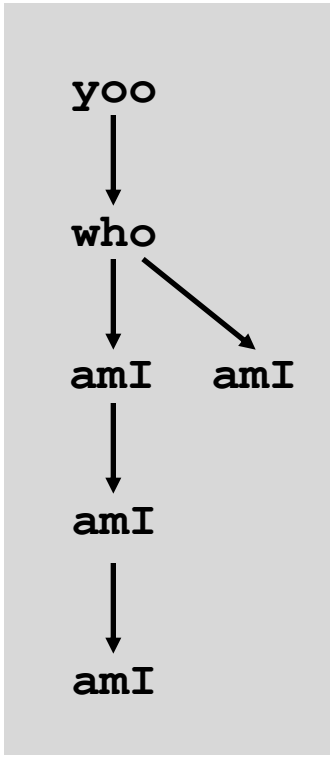
```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```

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

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

**Procedure `amI()` is recursive**

**Example Call Chain**



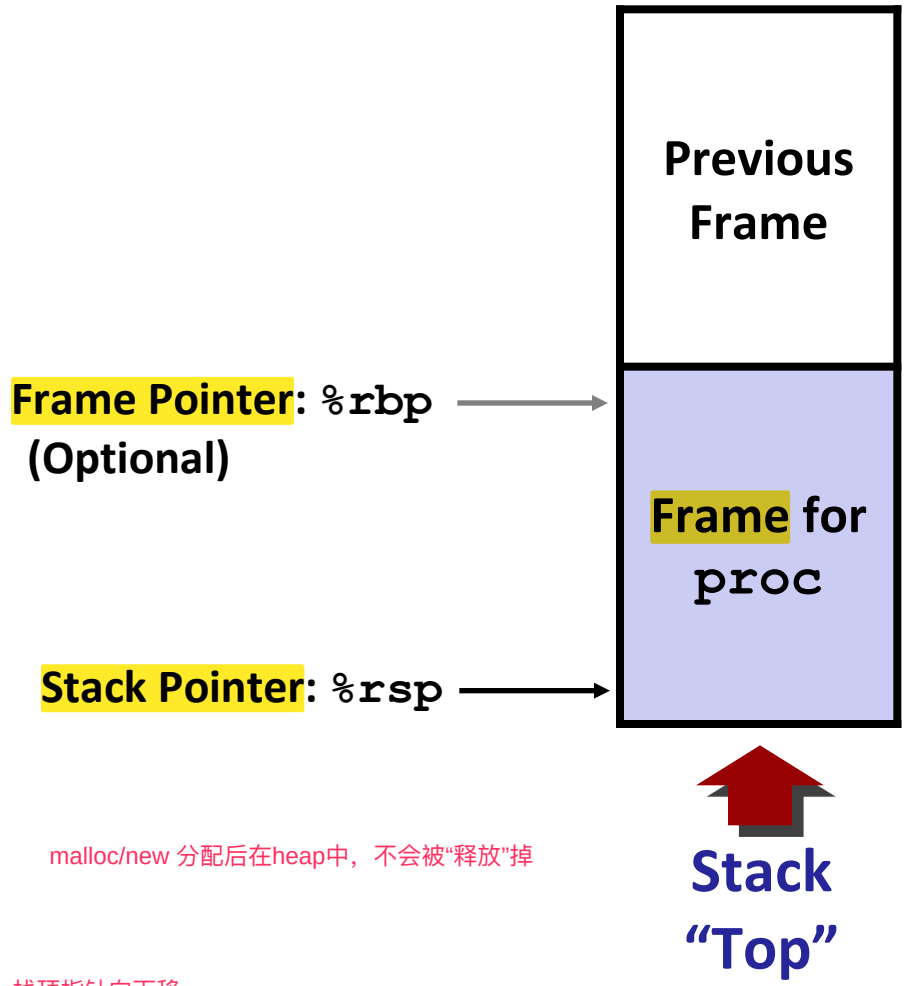
# Stack Frames

## Contents

Return information

Local storage (if needed)

Temporary space (if needed)




## Management

Space allocated when enter procedure

malloc/new 分配后在heap中，不会被"释放"掉

"Set-up" code

开启函数 => 需要内存时：栈顶指针向下移

Includes push by **`call`** instruction

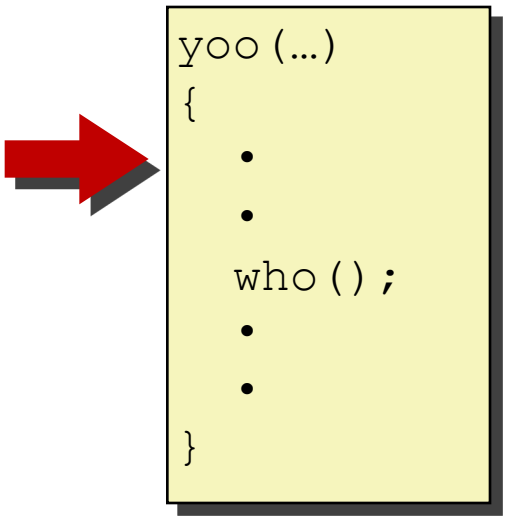
Deallocated when return

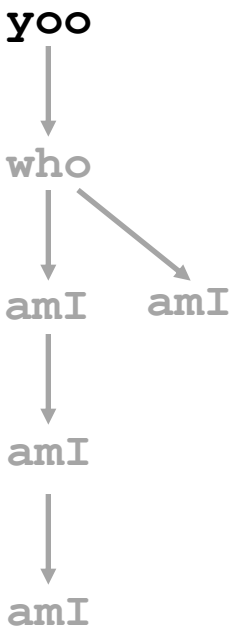
"Finish" code

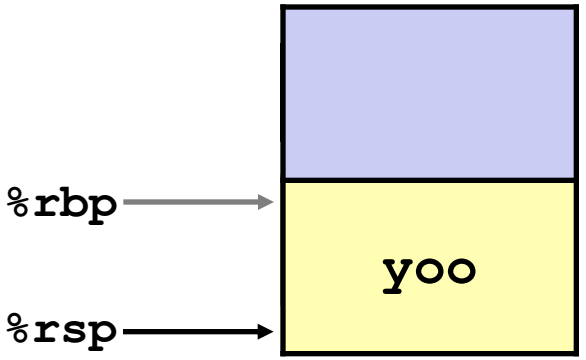
关闭函数 => 不需要内存时：栈顶指针向上移

Includes pop by **`ret`** instruction

# Example



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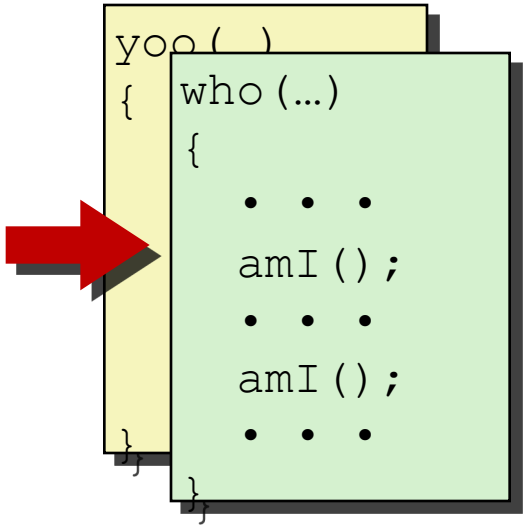


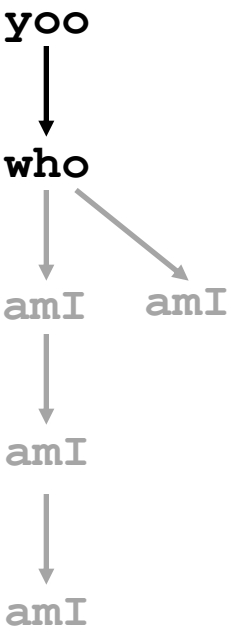


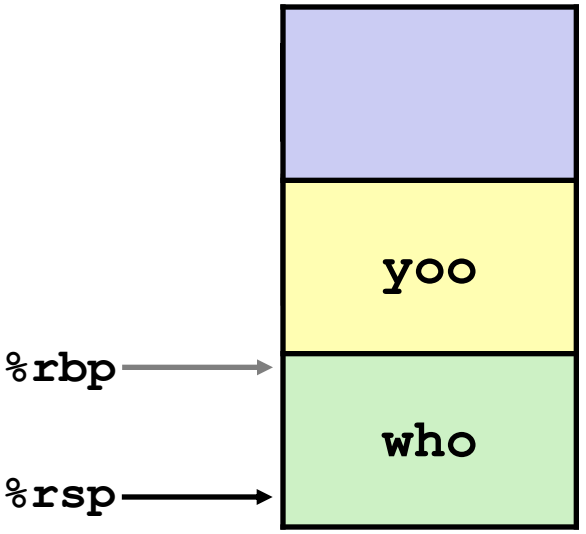

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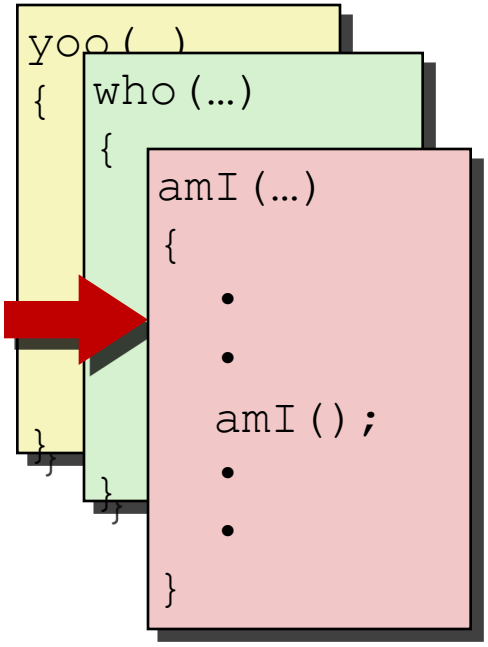


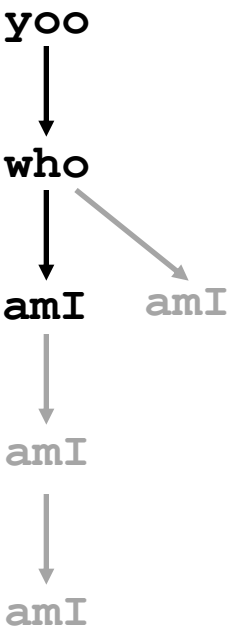


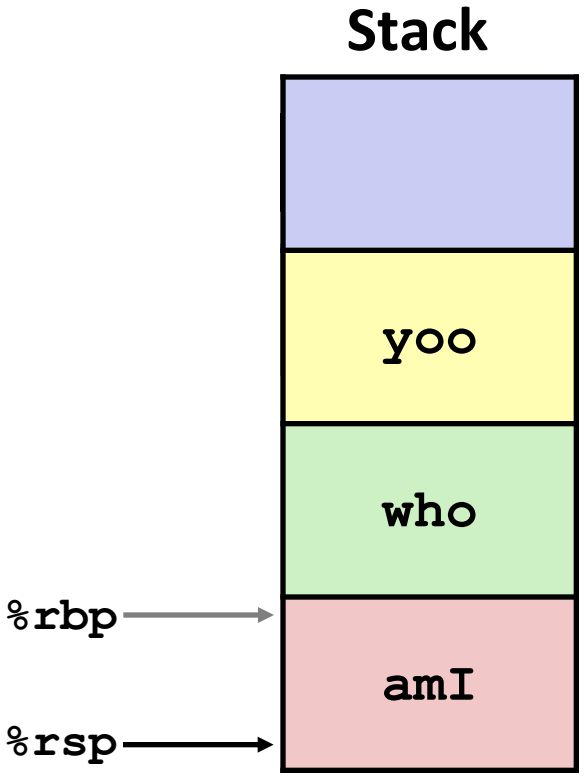

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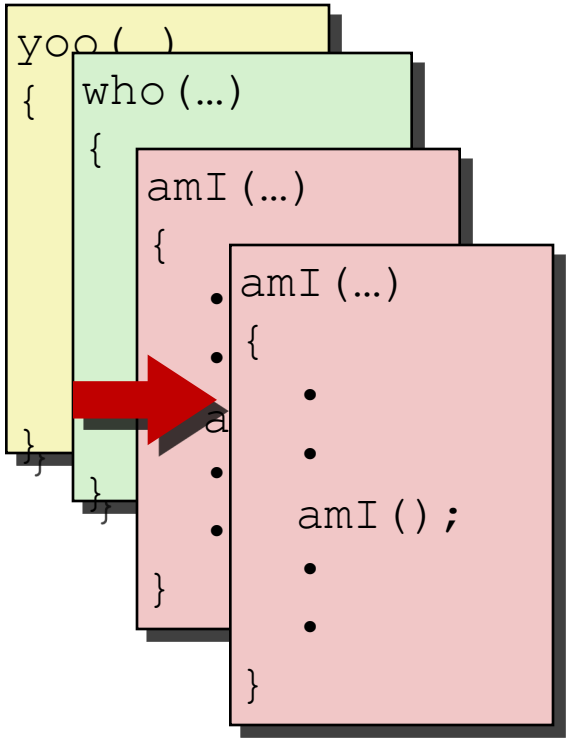


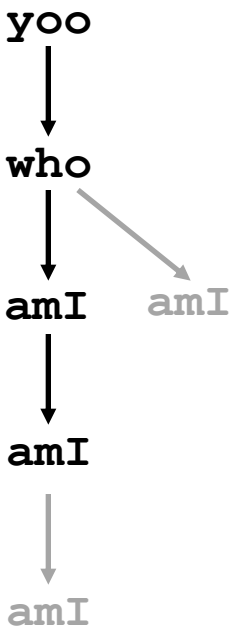


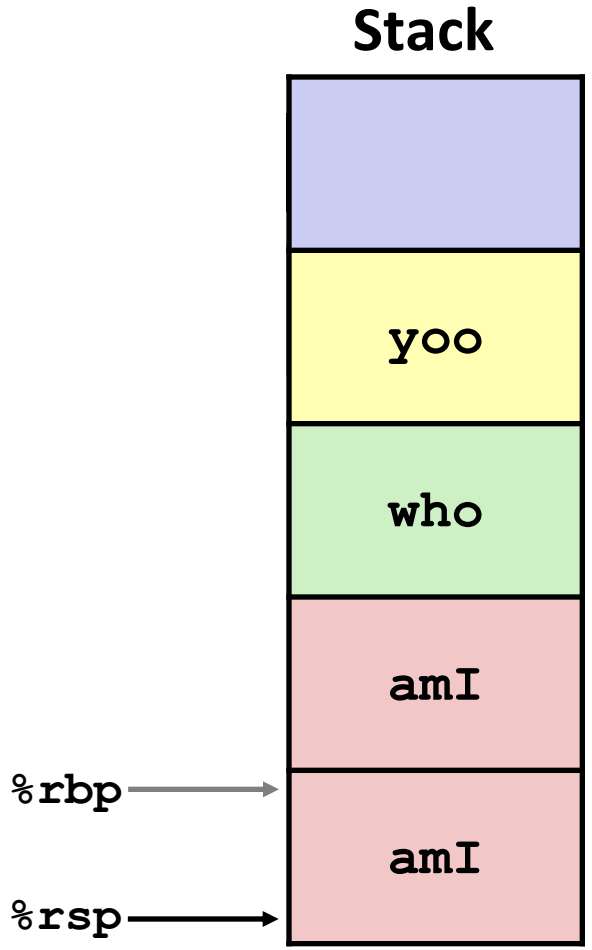

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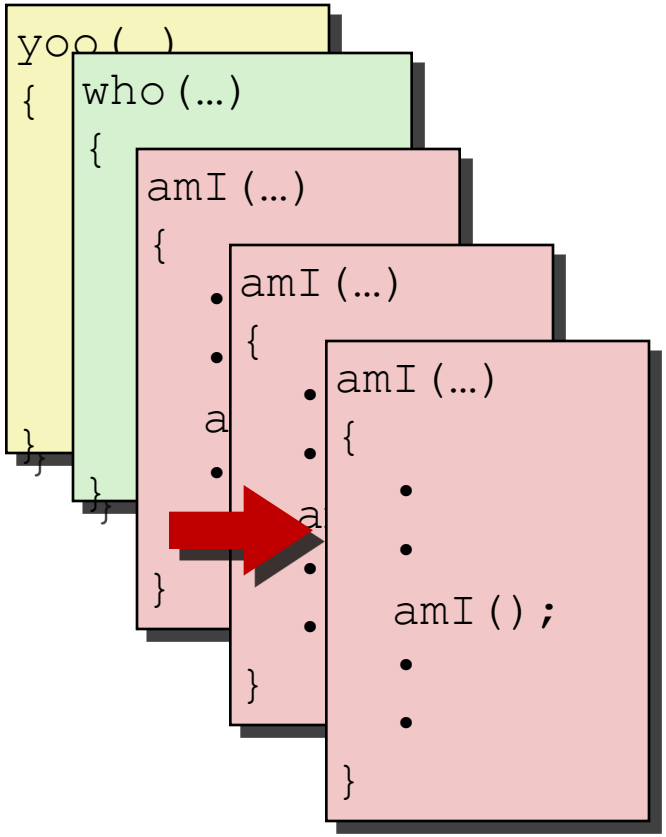


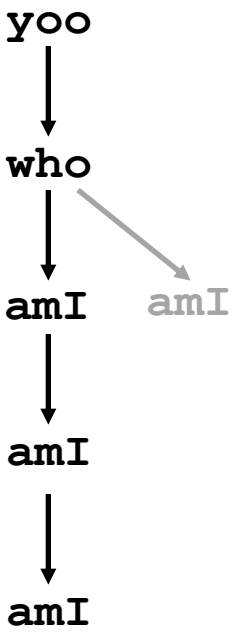


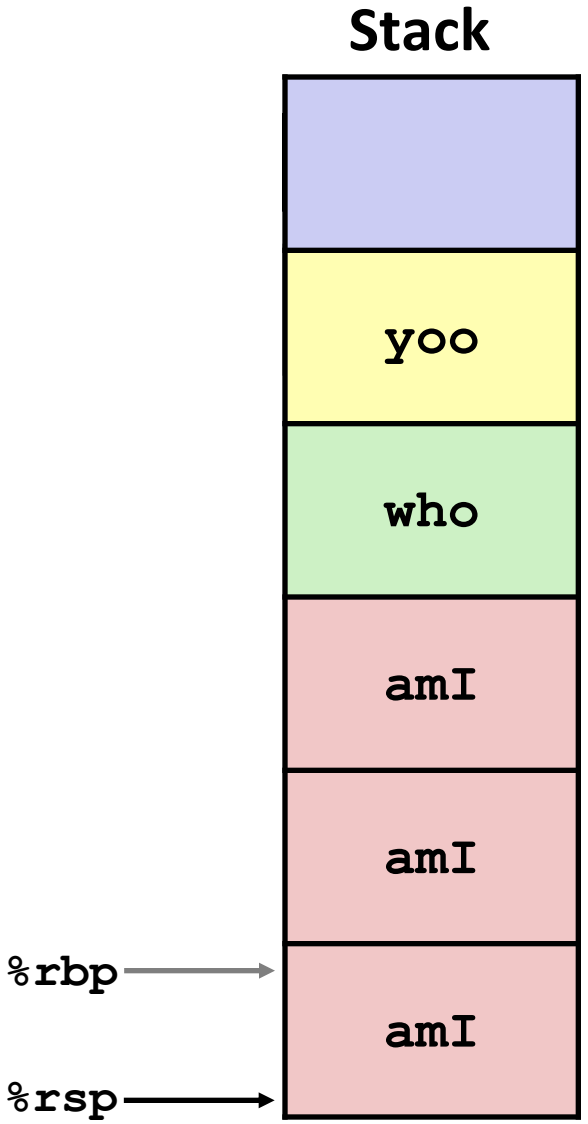

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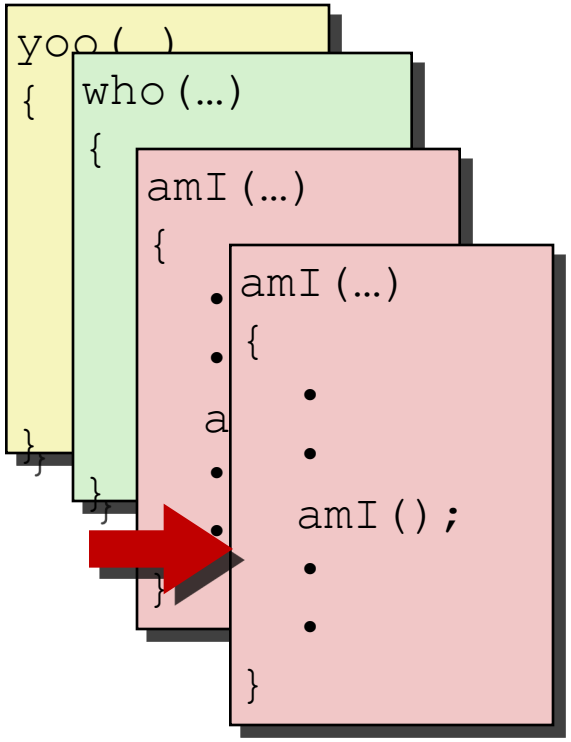


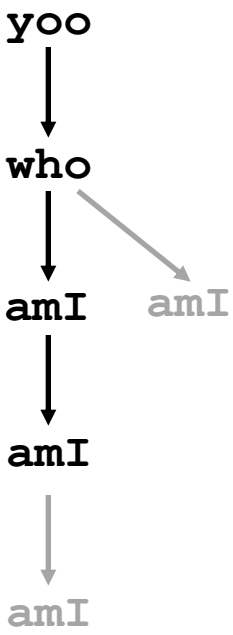


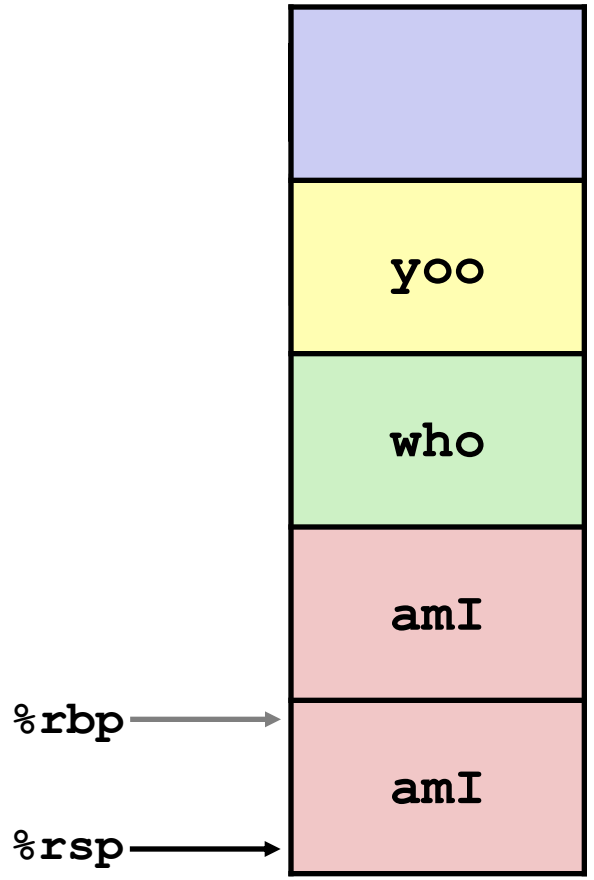

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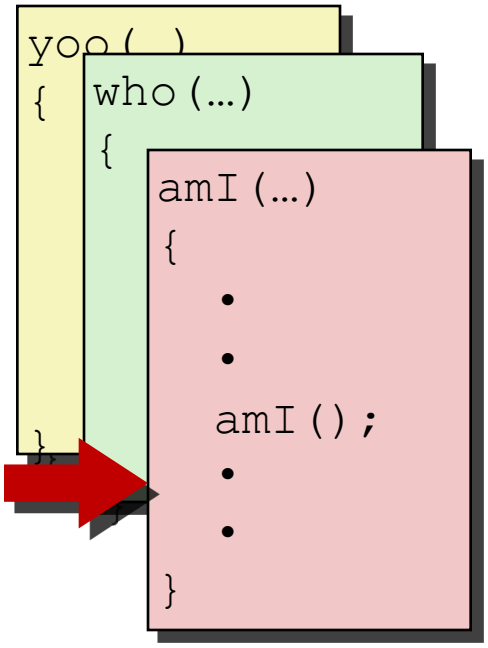


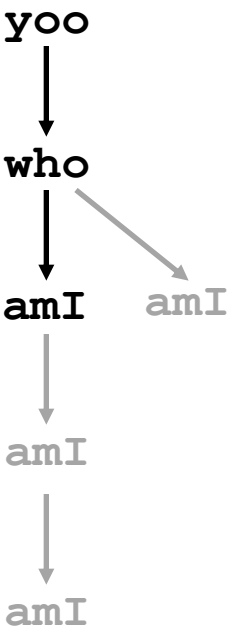


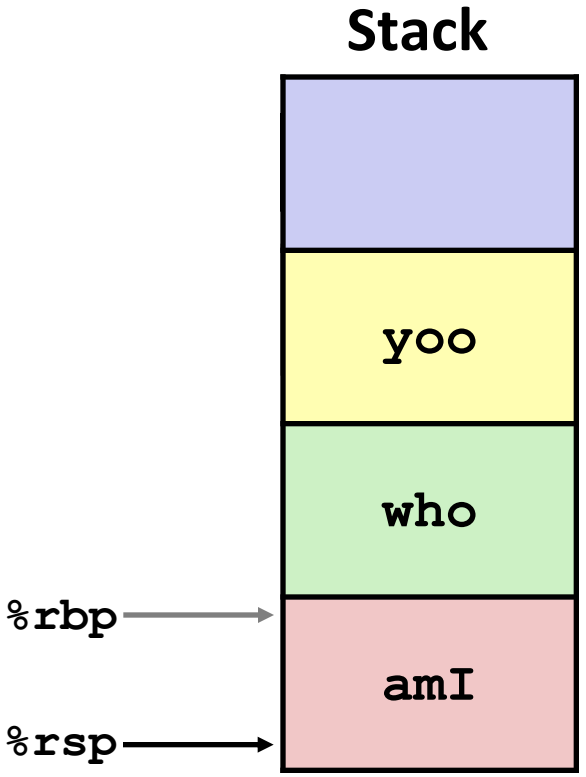

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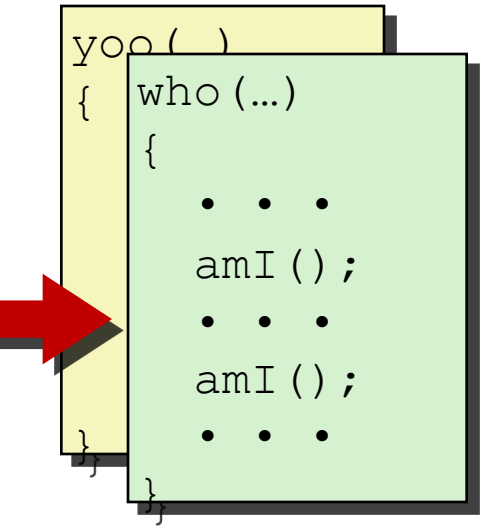
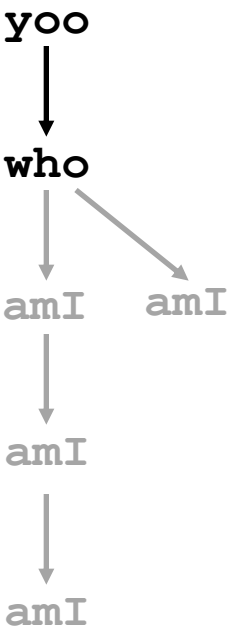
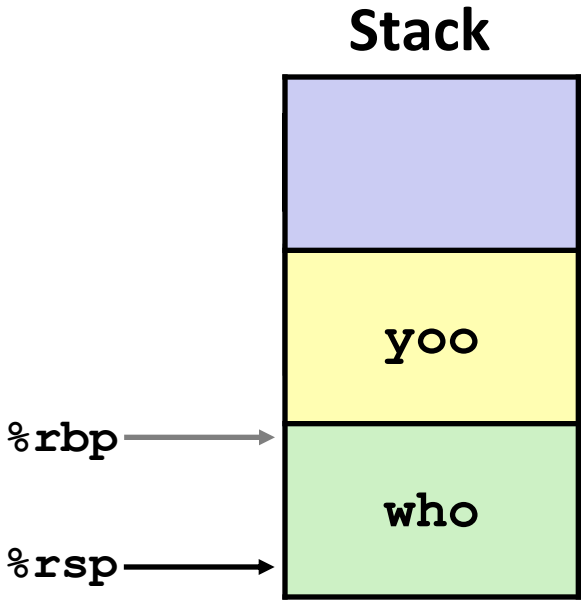
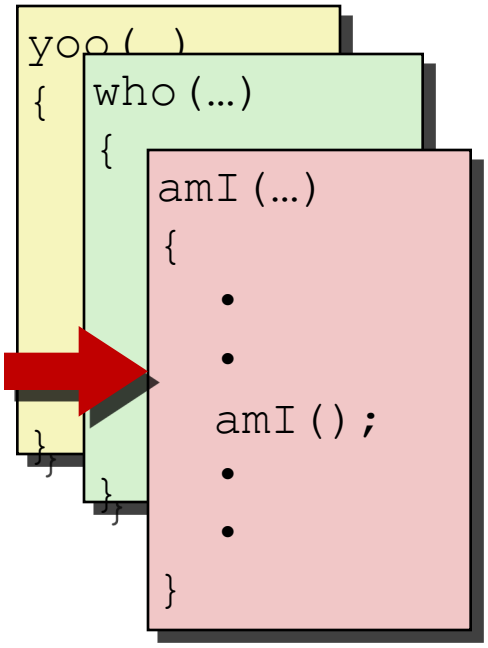
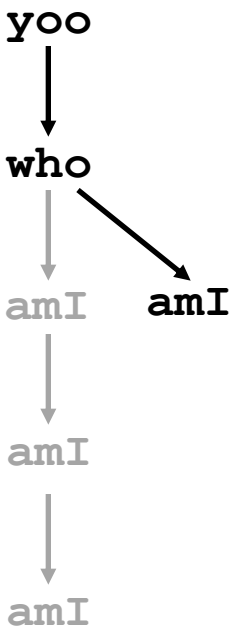


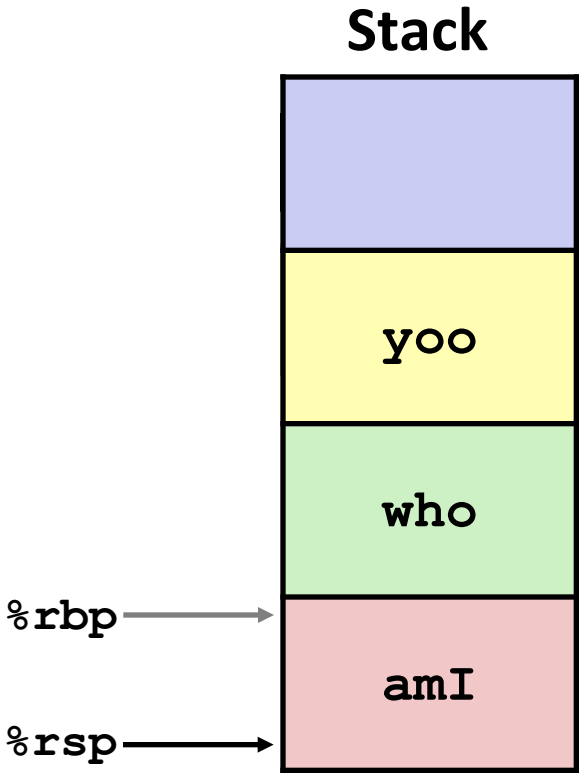



# Example

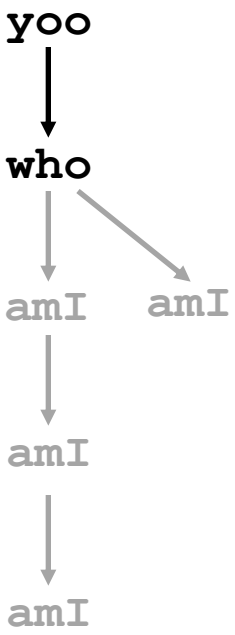


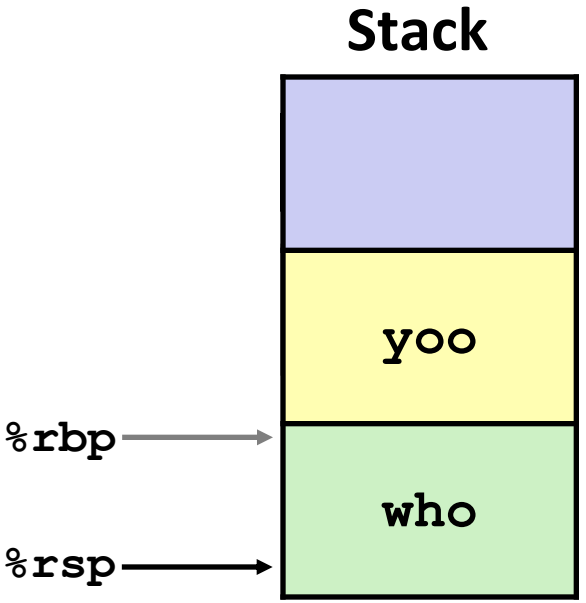



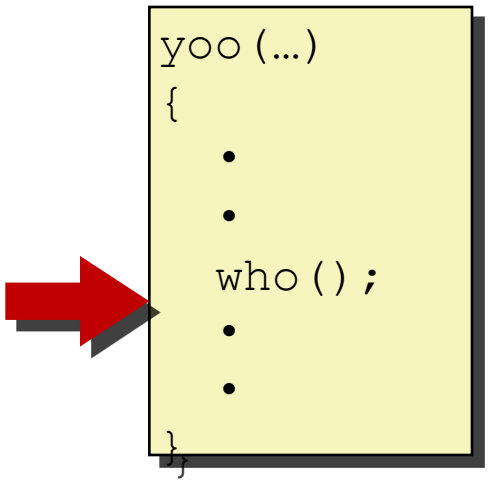
# Example

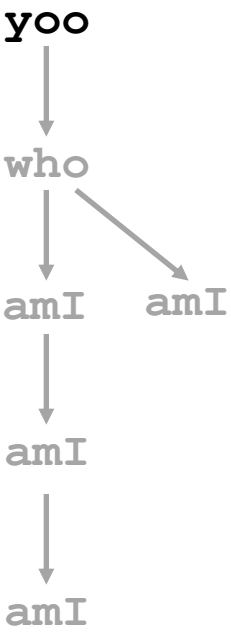
```
yoo( )
{
    who(…)
    {
       • • •
       amI();
       • • •
       amI();
       • • •
    }
```

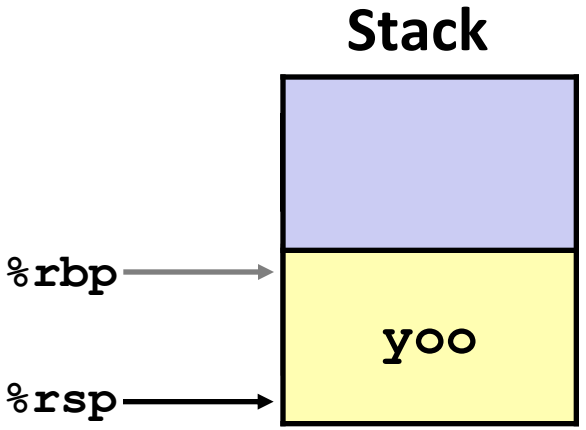


# Example



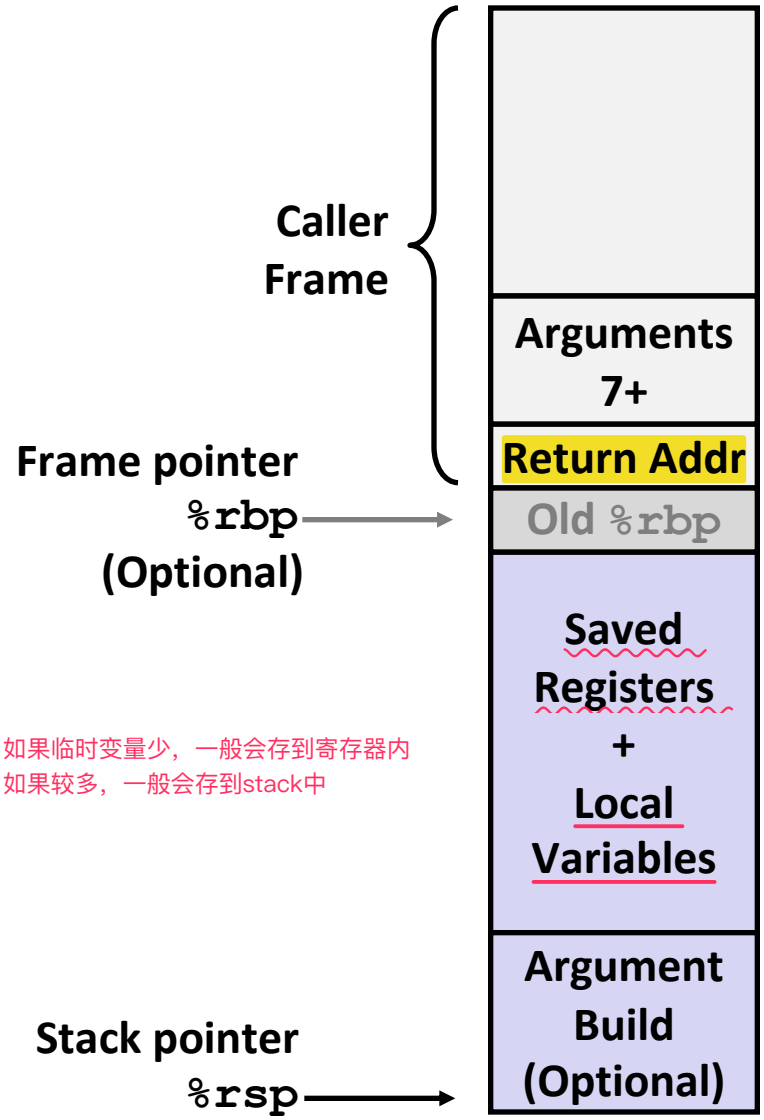
# x86-64 Linux Stack Frame

## Caller Stack Frame

- Arguments for this call
- Return address
  - Pushed by `call` instruction

## Current Stack Frame

- Old frame pointer (optional)
- Saved register context
- Local variables
  If can't keep in registers
- "Argument build:"
  Parameters for function about to call



# Example: incr

%rdi

```
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
```

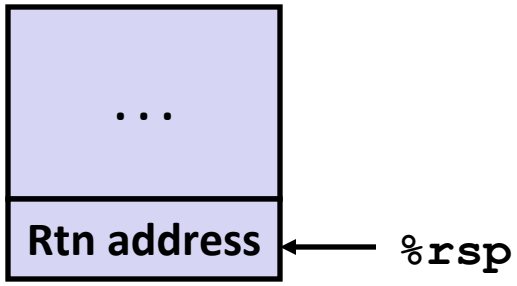
| Register | Use(s) |
|---|---|
| %rdi | Argument p |
| %rsi | Argument val, y |
| %rax | x, Return value |

# Example: Calling `incr` #1

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

此处v1不能存在寄存器中，因为这样没法取址

## 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
```

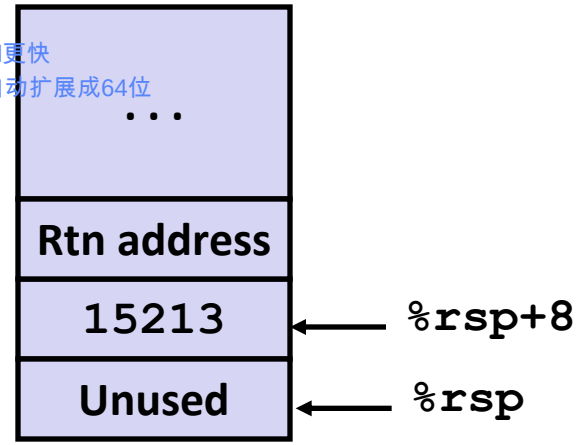
调用函数

内存对齐

32bytes已经够用
1）同等情况下，使用movl更快
2）32位会在64位机器中自动扩展成64位

结束函数调用

## Resulting Stack Structure

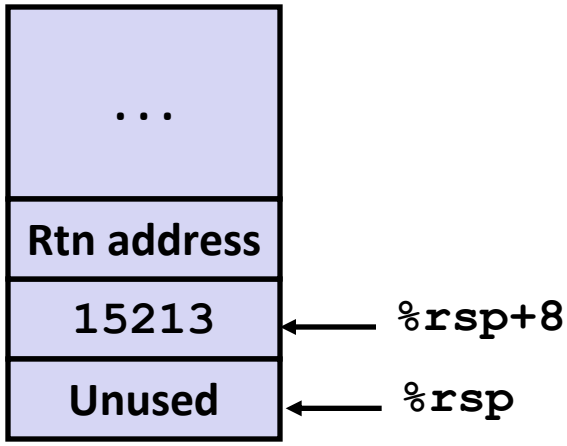


# Example: Calling `incr` #2

```
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**

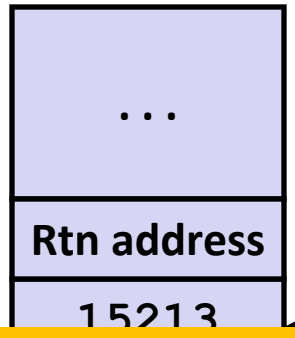



| Register | Use(s) |
|---|---|
| %rdi | &v1 |
| %rsi | 3000 |

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

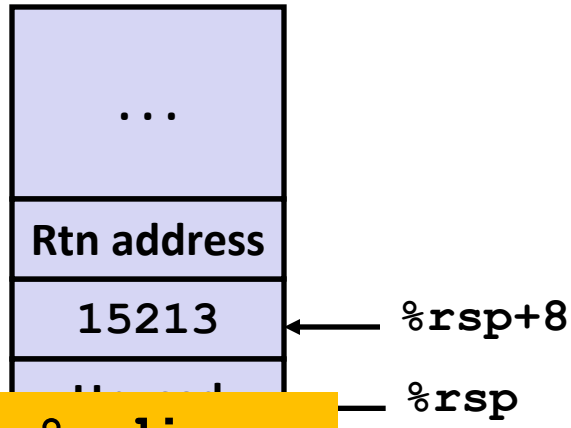
```
ca
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

| | |
|---|---|
| %rdi | &v1 |
| %rsi | 3000 |

# Example: Calling `incr` #2

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

Stack Structure




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

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

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

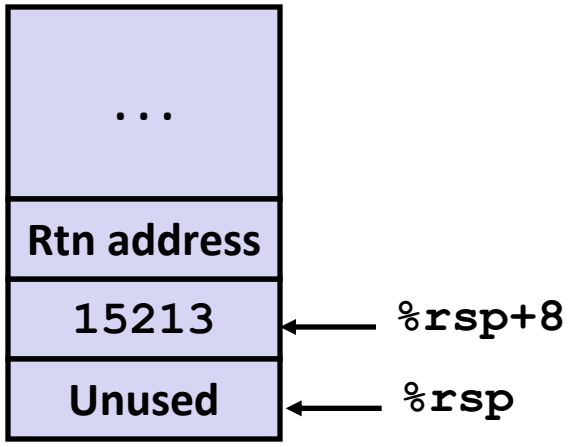
| se(s) | |
|---|---|
| | v1 |
| %rsi | 3000 |

# 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



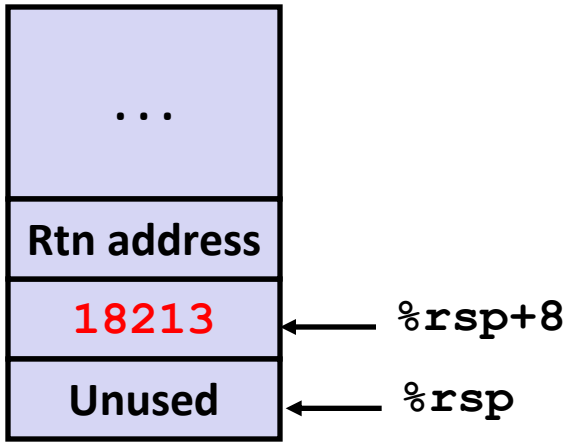

| Register | Use(s) |
|---|---|
| %rdi | &v1 |
| %rsi | 3000 |

# 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

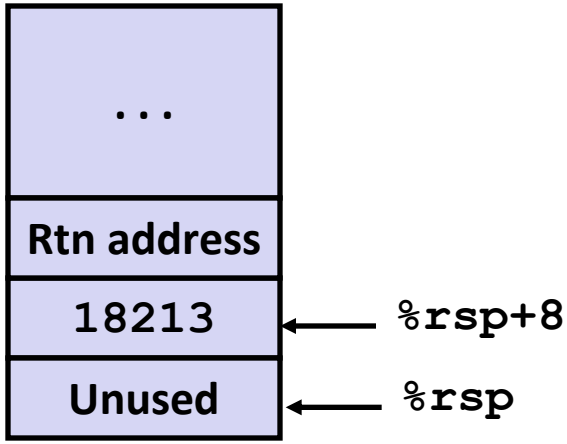



| Register | Use(s) |
|---|---|
| %rdi | &v1 |
| %rsi | 3000 |

# Example: Calling `incr` #4

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

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
```

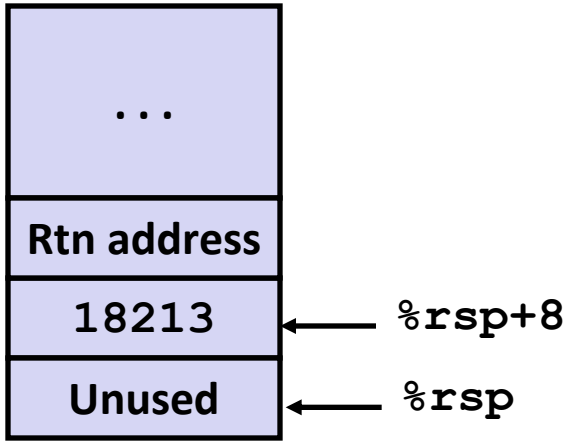
| Register | Use(s) |
|---|---|
| %rax | Return value |

# Example: Calling `incr` #5a

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

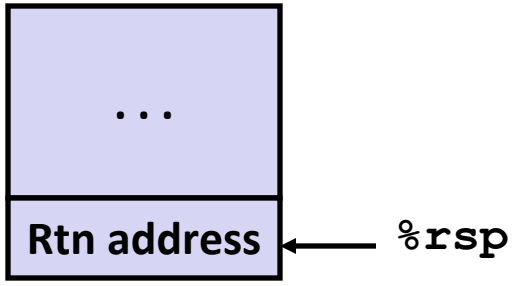
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

**Stack Structure**




| Register | Use(s) |
|---|---|
| %rax | Return value |

**Updated Stack Structure**

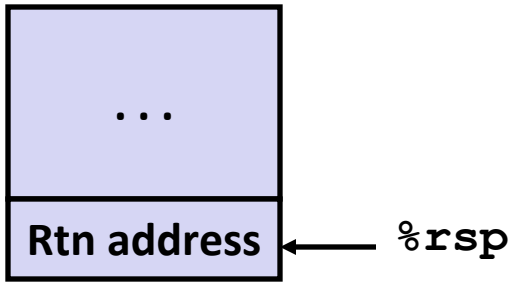


# Example: Calling `incr` #5b

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

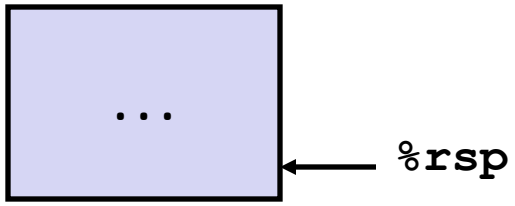
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

**Updated Stack Structure**




| Register | Use(s) |
|---|---|
| %rax | Return value |

**Final Stack Structure**



# Register Saving Conventions

**When procedure `yoo` calls `who`:**

`yoo` is the ***caller*** 调用函数者

`who` is the ***callee*** 被调用函数者

**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**

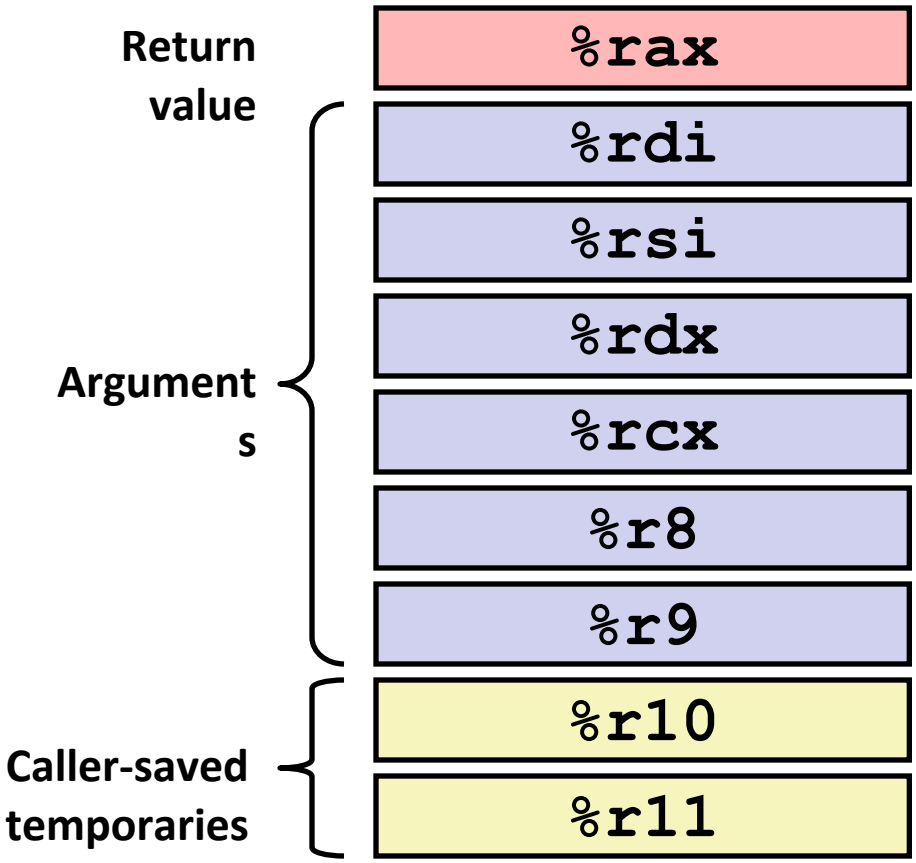
- Return value
- Also caller-saved
- Can be modified by procedure

**%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**

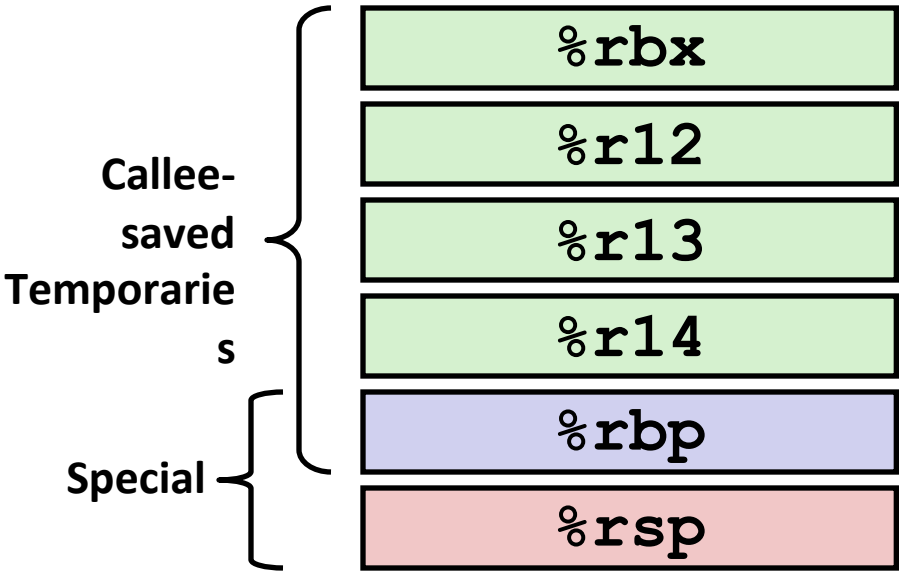
- Callee-saved
- Callee must save & restore

**%rbp**

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

**%rsp**

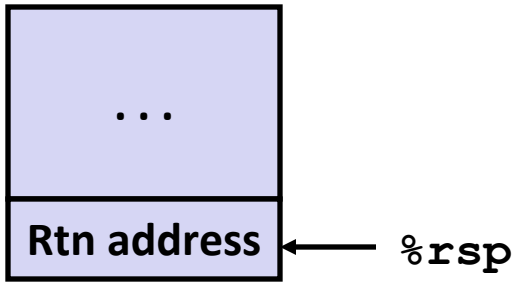
- Special form of callee save
- Restored to original value upon exit from procedure



# 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

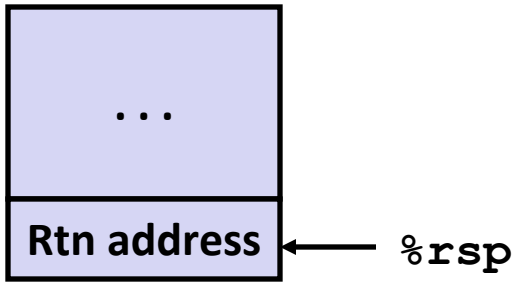
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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
```

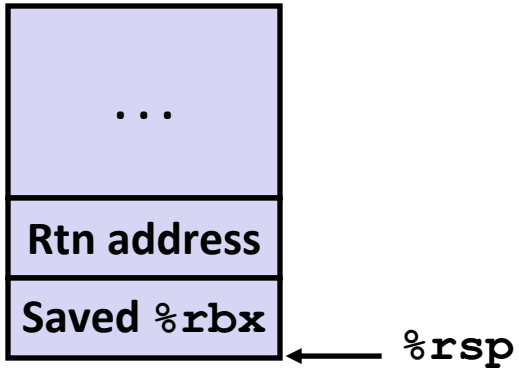
事实上是寄存器内原值的push，而不是“寄存器”的物理push

跟pushq同理

Initial Stack Structure




Resulting Stack Structure

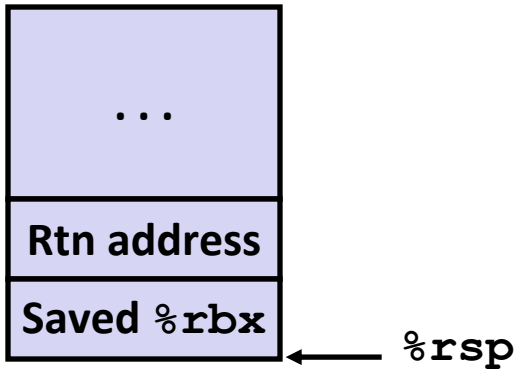


# Callee-Saved Example #3

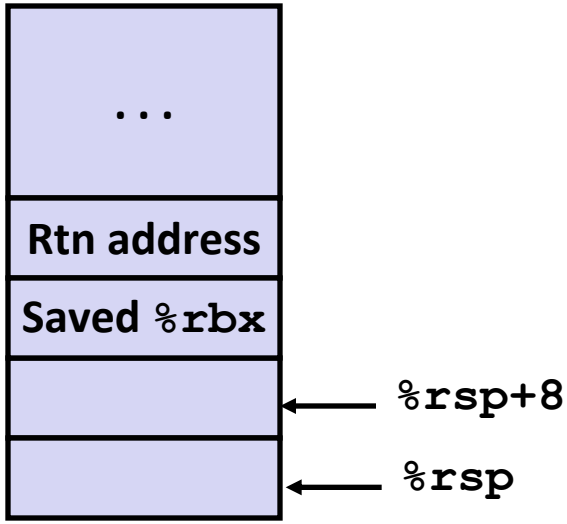
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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**

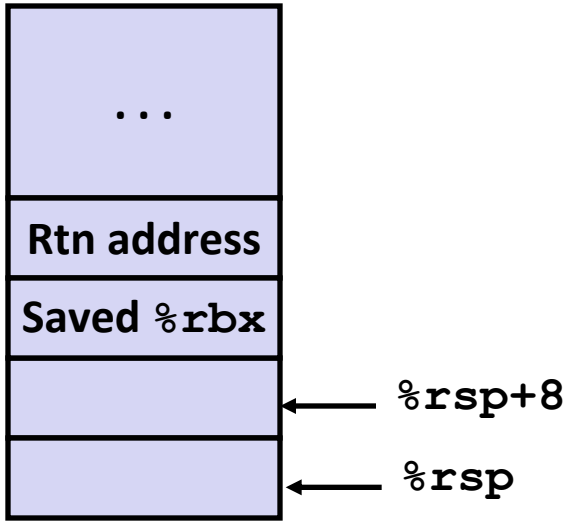


# Callee-Saved Example #4

```
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



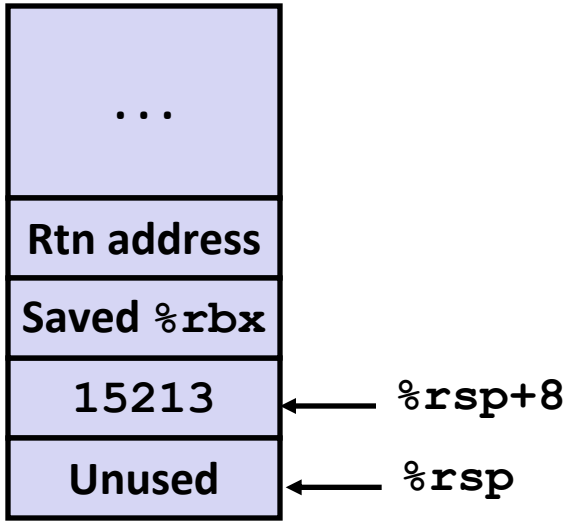

- X saved in **%rbx**.
- A callee saved register.

# 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



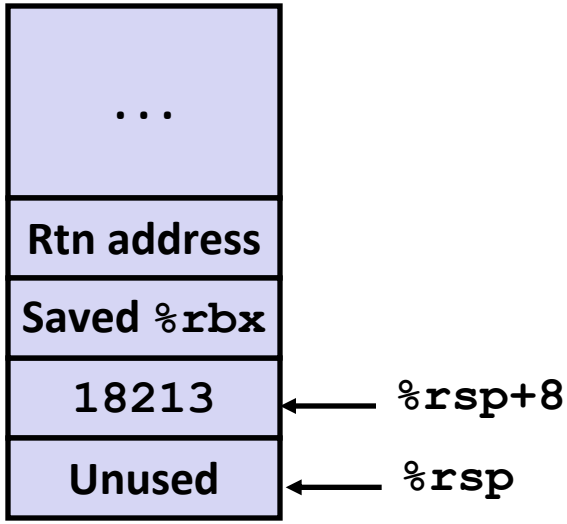

- X saved in **%rbx**.
- A callee saved register.

# 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



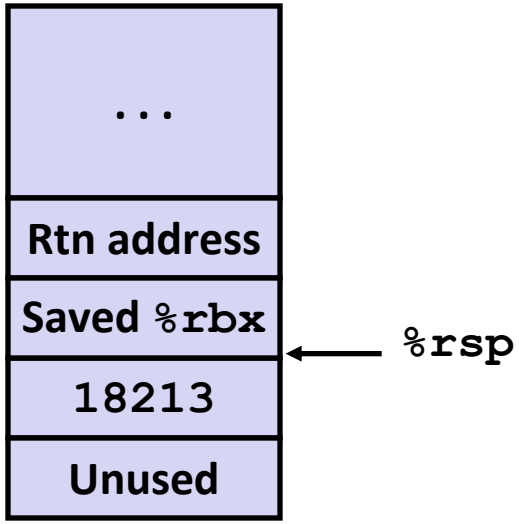

- X Is safe in **%rbx**
- Return result in **%rax**

# 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



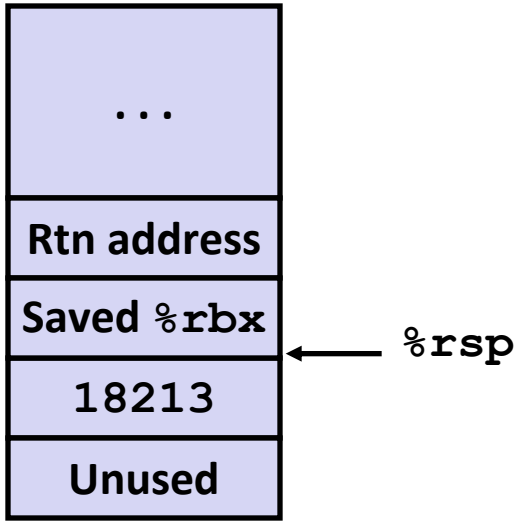

- Return result in **%rax**

# Callee-Saved Example #8

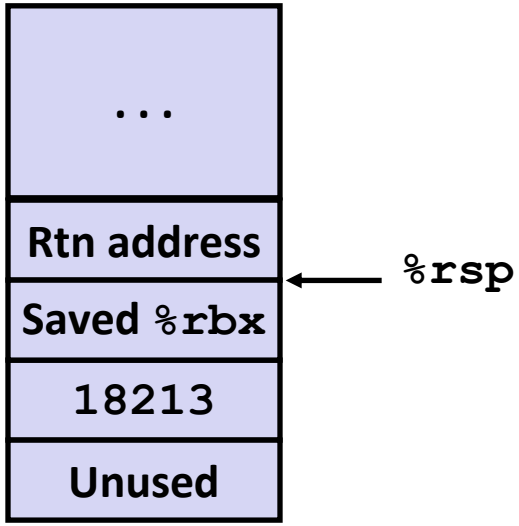
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

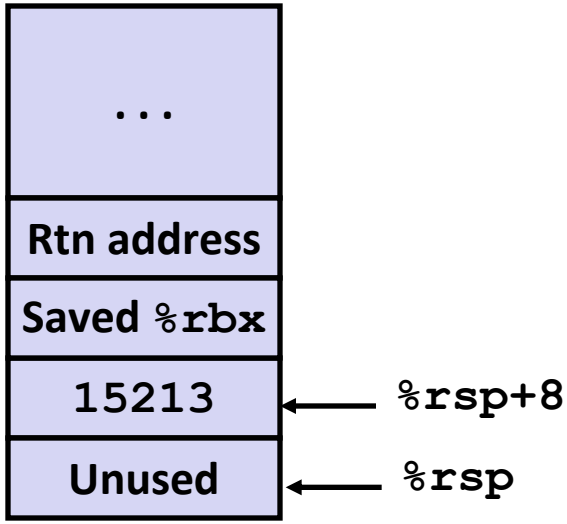


# Callee-Saved Example #2

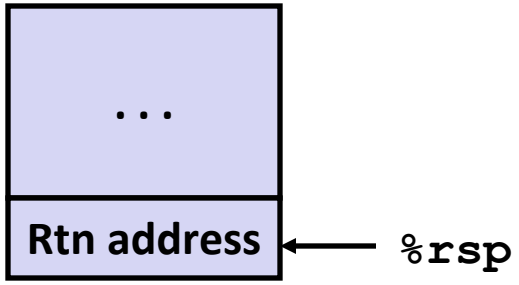
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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
```

**Resulting Stack Structure**




**Pre-return 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) 递归出口，否则会 stackoverflow
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

LSB：The Least Significant Bit
MSB: The Most Significant Bit

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi   test：X 本身
  je      .L6
  pushq   %rbx         callee-saved
  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
```

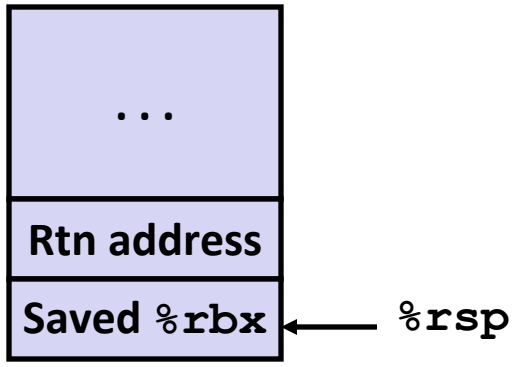
| Register | Use(s) | Type |
|---|---|---|
| %rdi | x | Argument |
| %rax | Return value | Return value |

# 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
```

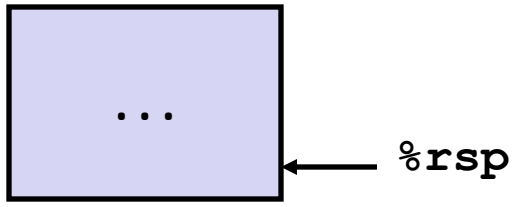
| Register | Use(s) | Type |
|---|---|---|
| %rbx | x & 1 | Callee-saved |
| %rax | Return value | |

# 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 called-saved & callee-saved

- 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**