Machine-Level Programming III: Procedures

COMP400727: Introduction to Computer Systems

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Reminder: Condition Codes

Single bit registers

CF Carry Flag (for unsigned) **SF** Sign Flag (for signed)

ZF Zero Flag **OF** Overflow Flag (for signed)

jX and SetX isntructions

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

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

Machine Level Programming – Control

C Control

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

Assembler Control

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

Standard Techniques

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

Mechanisms in Procedures

Passing control

- To beginning of procedure code
- Back to return point

Passing data

- Procedure arguments
- Return value

Memory management

- Allocate during procedure execution
- Deallocate upon return

Mechanisms all implemented with machine instructions

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

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

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

Mechanisms in

Passing control

To beginning of procedure code

Back to return point

Passing data

Procedure arguments

Return value

Memory management

Allocate during procedure exec

Deallocate upon return

Mechanisms all implemente machine instructions

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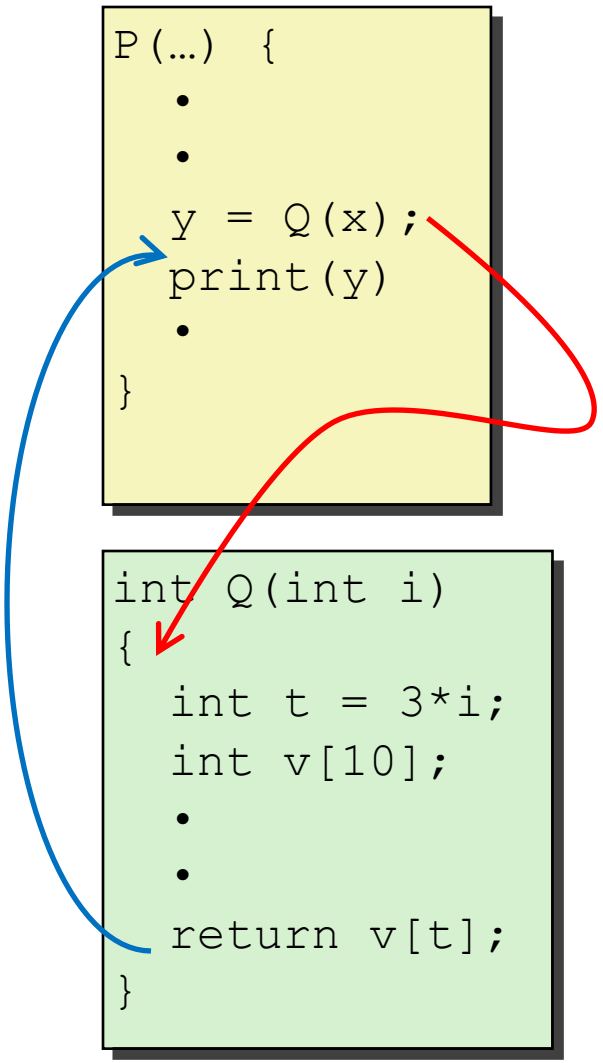

Mechanisms in Procedures

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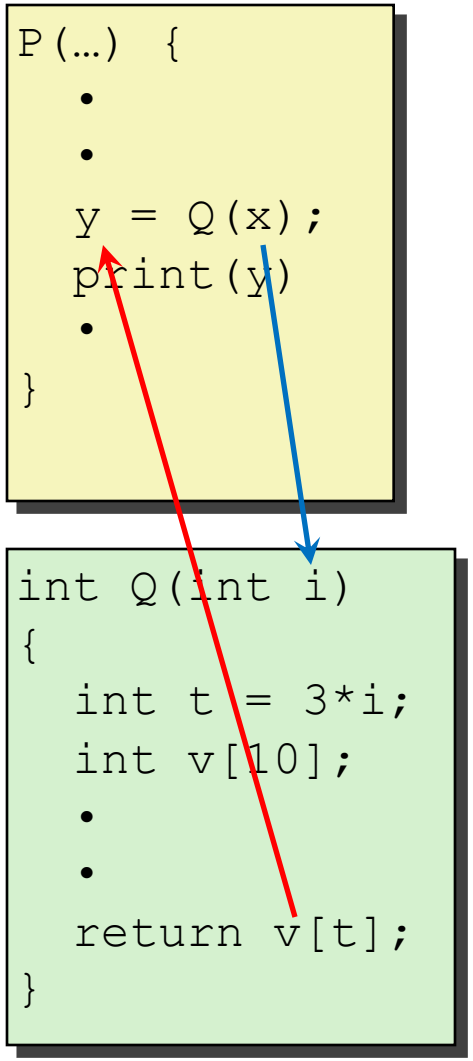

Mechanisms in Procedures

Passing control

- To beginning of procedure code
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Passing data

- Procedure arguments
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Memory management

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

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

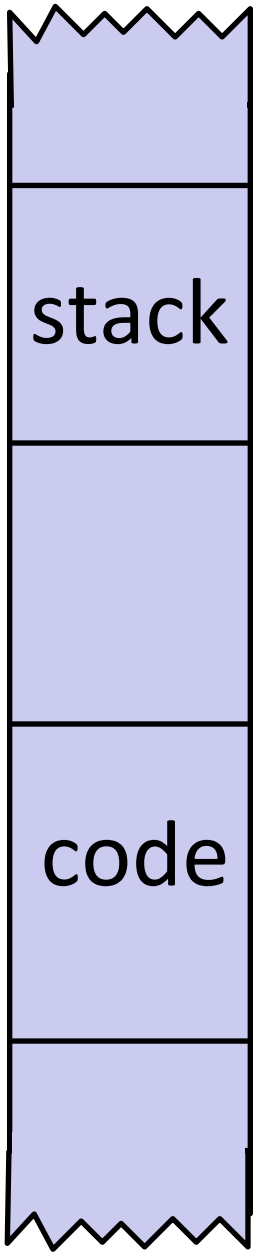
Today

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

x86-64 Stack 内存分段，每一段是Stack

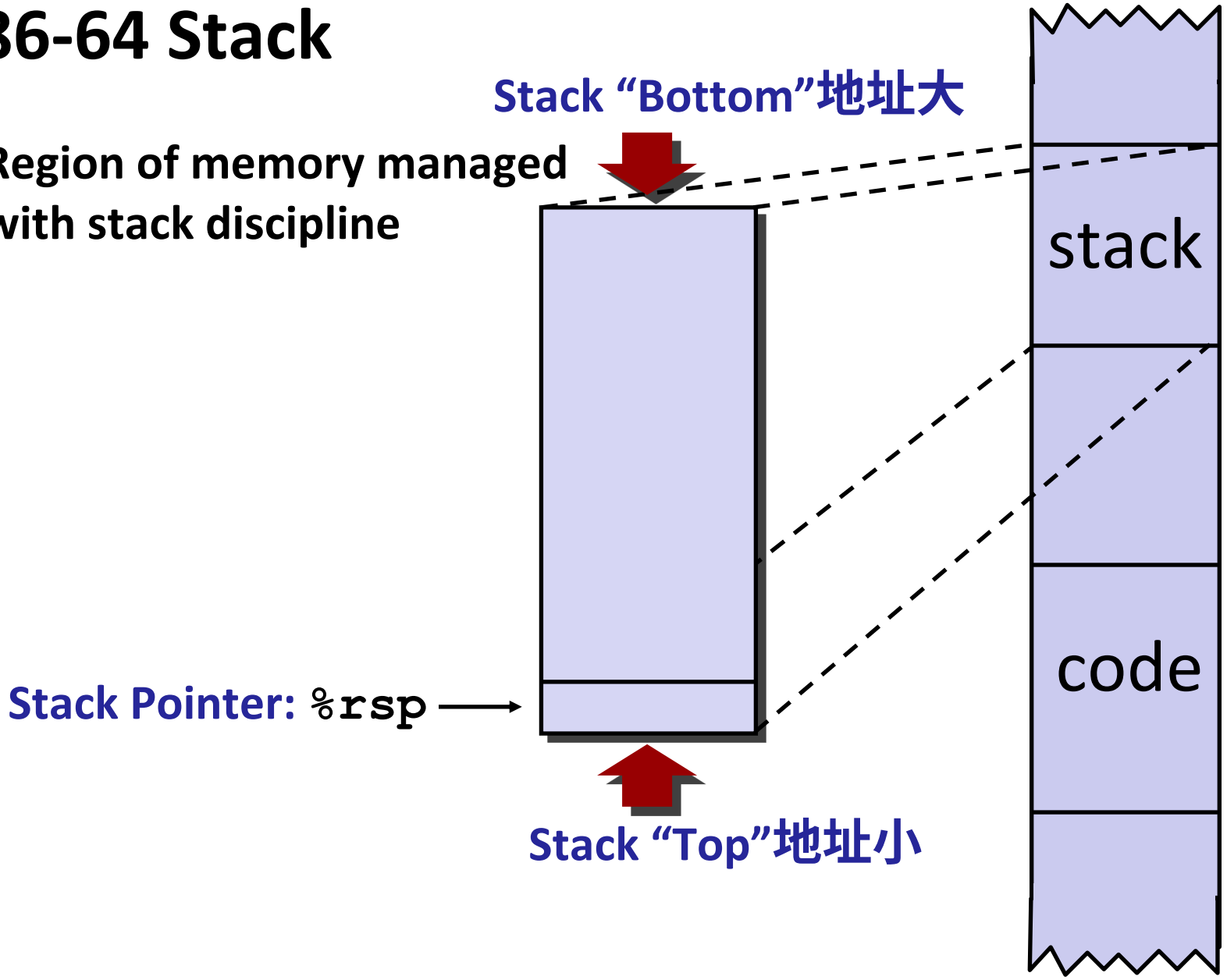
Region of memory managed with stack discipline

- 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



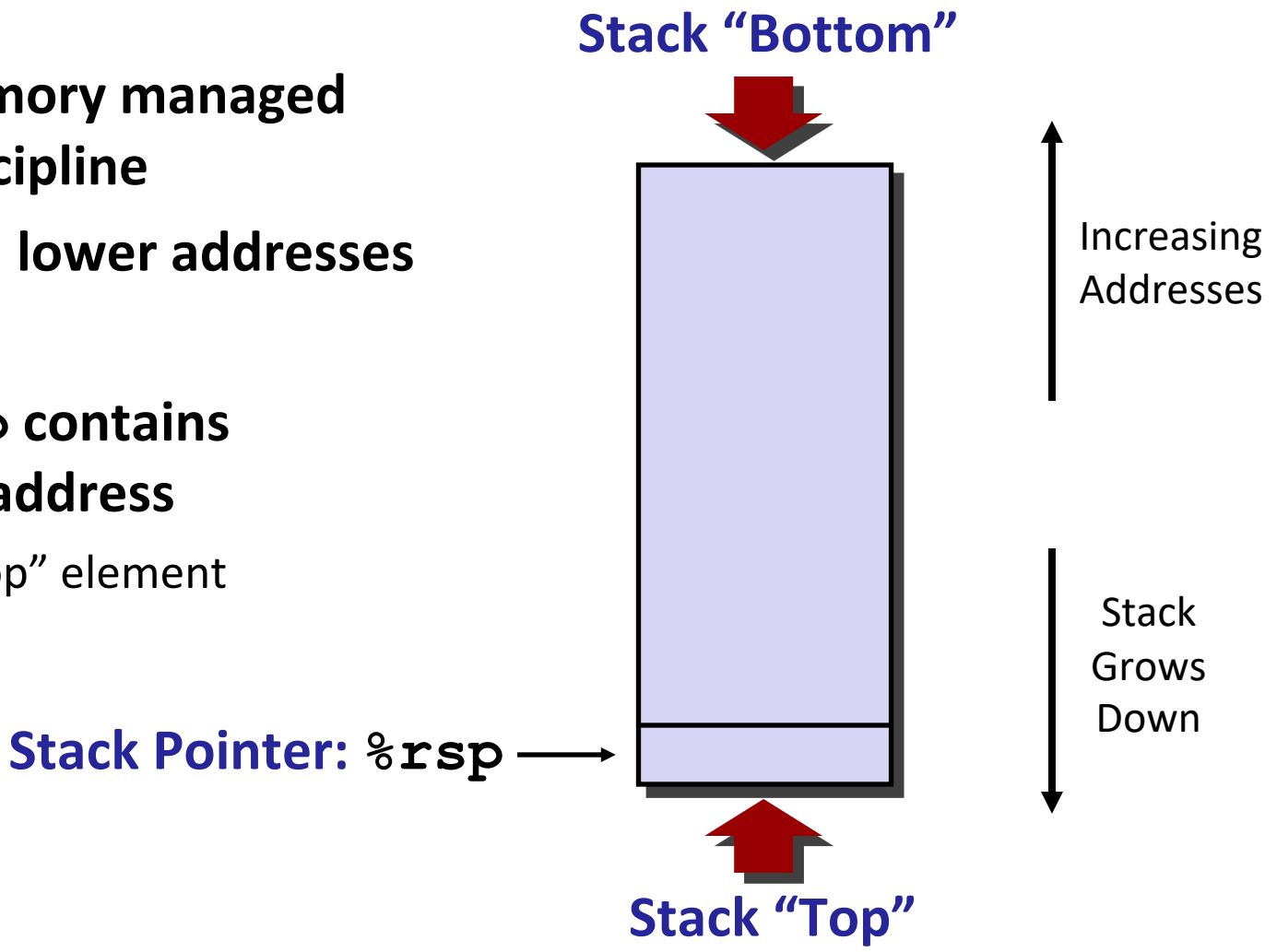
x86-64 Stack

Region of memory managed with stack discipline

Grows toward lower addresses

Register `%rsp` contains lowest stack address

address of "top" element



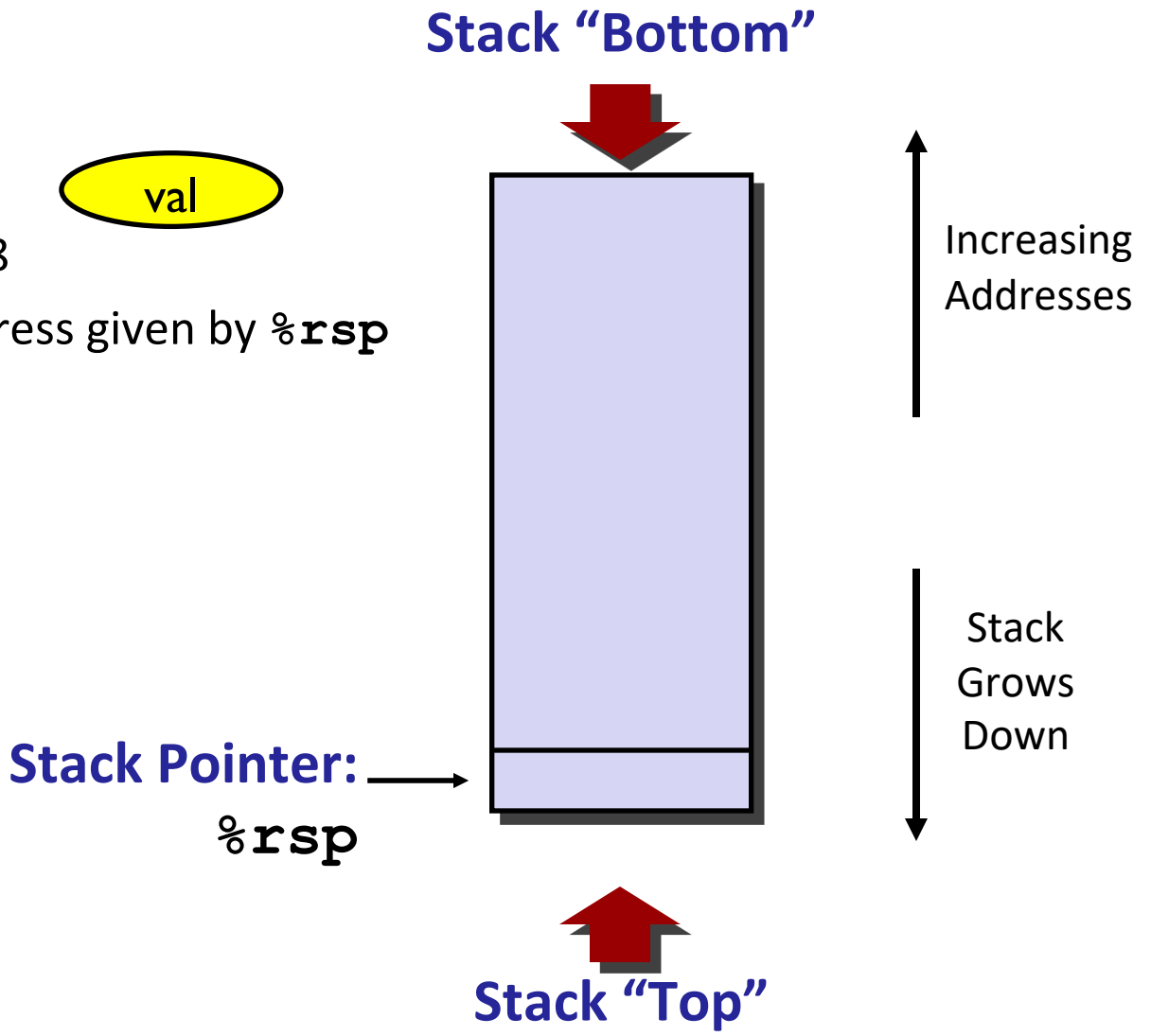
x86-64 Stack: Push

`pushq` *Src*

Fetch operand at *Src*

Decrement `%rsp` by 8

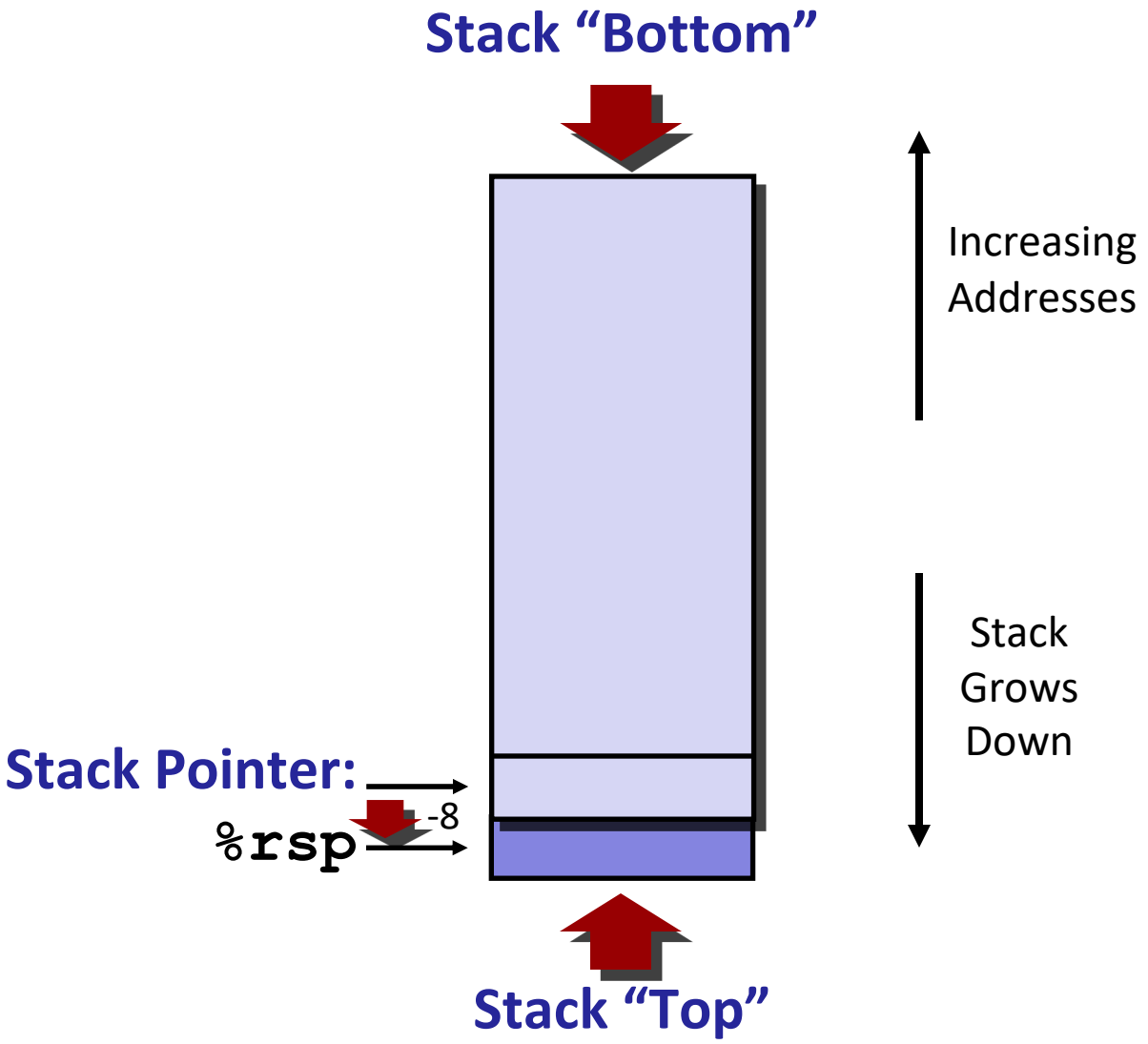
Write operand at address given by `%rsp`



x86-64 Stack: Push

`pushq` *Src*

- Fetch opera
- Decrement
- Write opera



x86-64 Stack: Pop

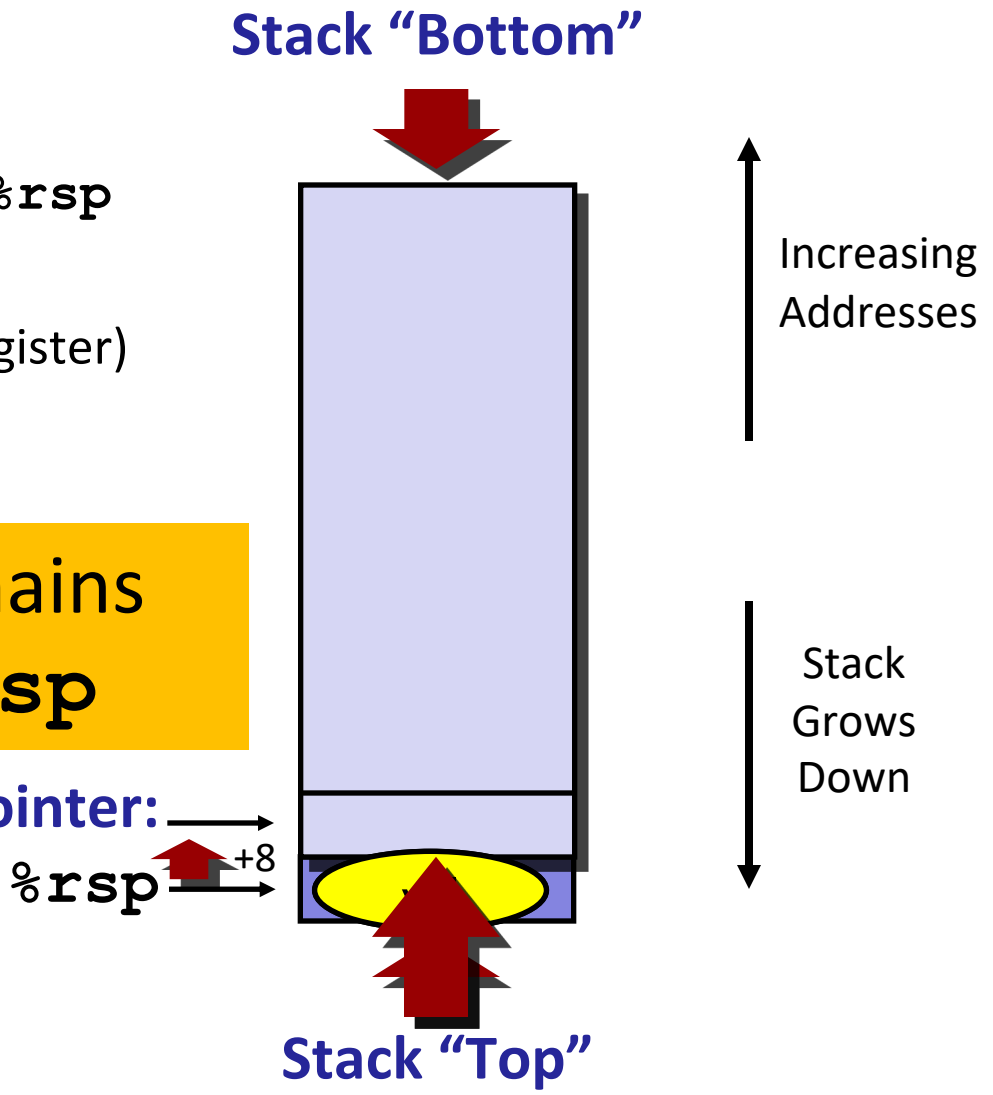
`popq` ***Dest***

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)(调用函数)
  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

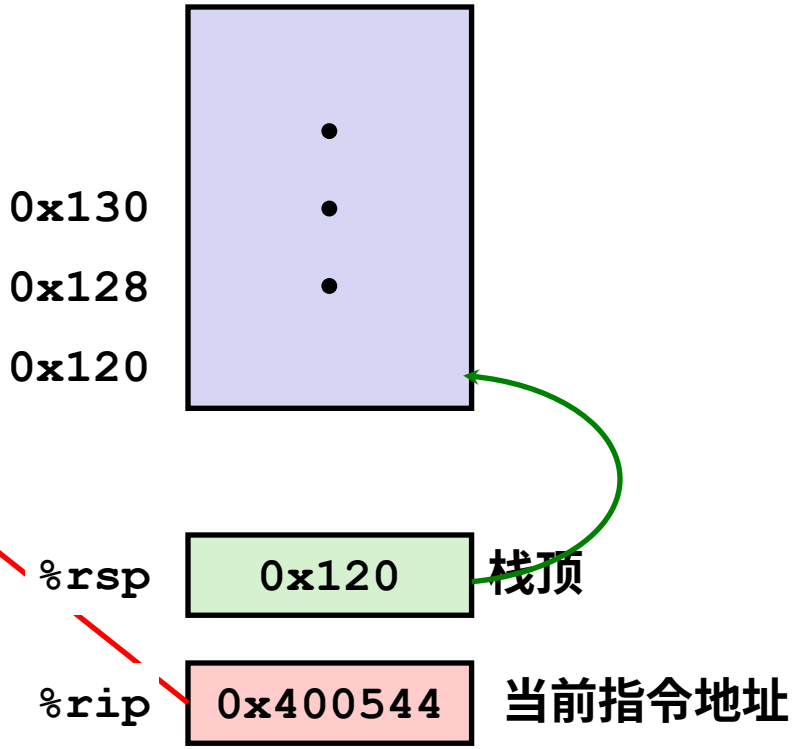
These instructions are sometimes printed with a `q` suffix

- 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)
  •
  •
```

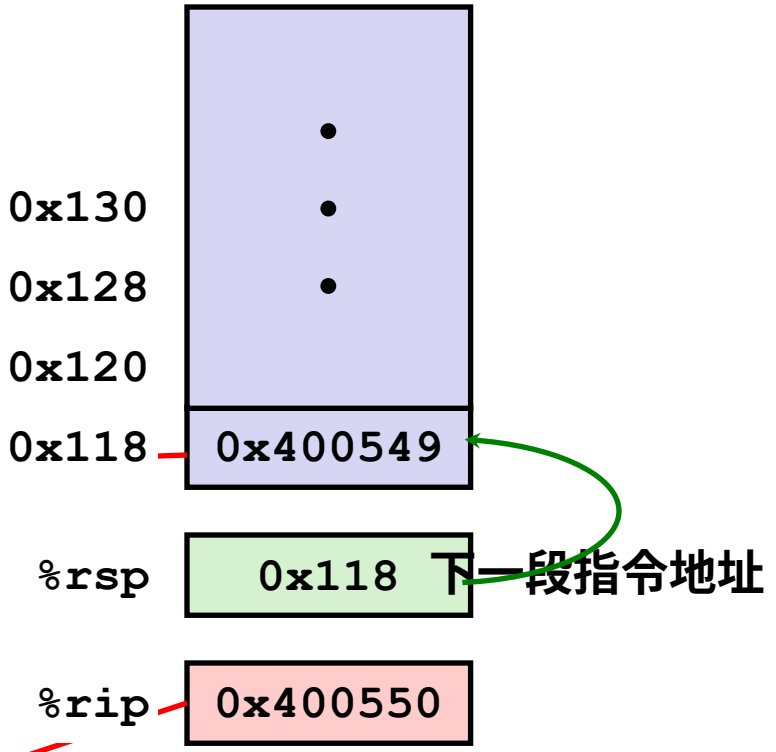
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  ret
```



Control Flow Example #2

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

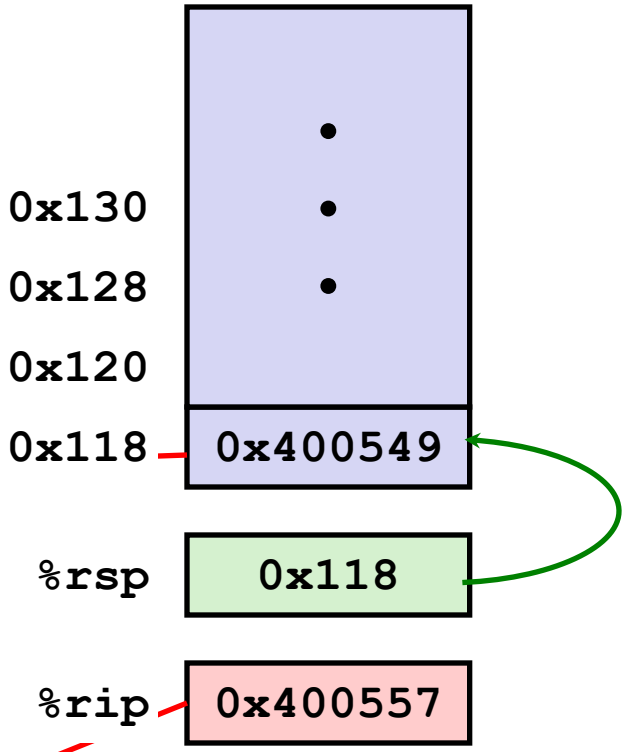
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  ret
```



Control Flow Example #3

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

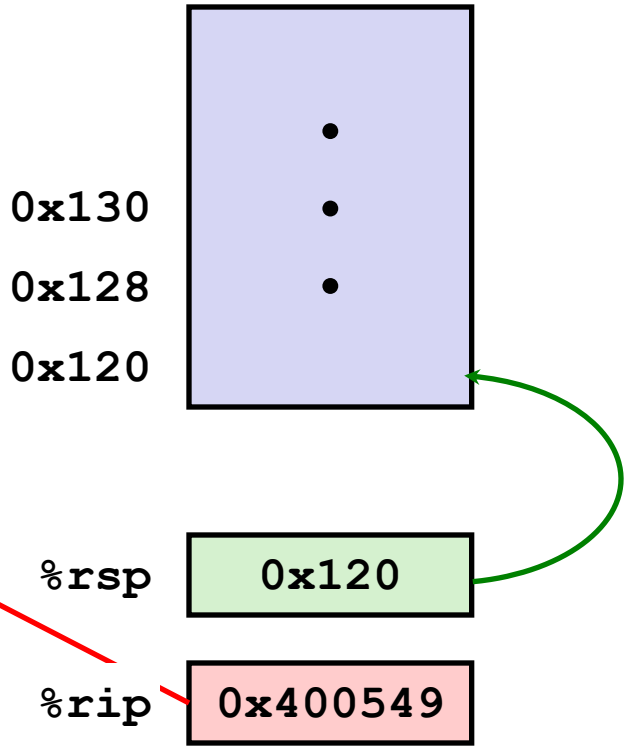
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  ret
```



Control Flow Example #4

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

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



Today

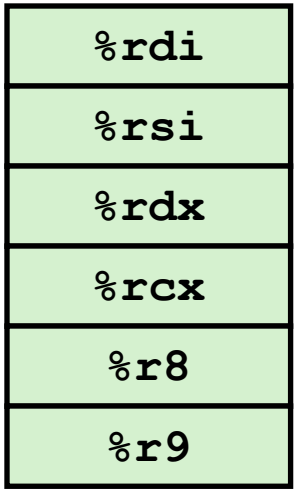
Procedures

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

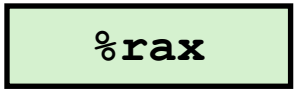
Procedure Data Flow

Registers

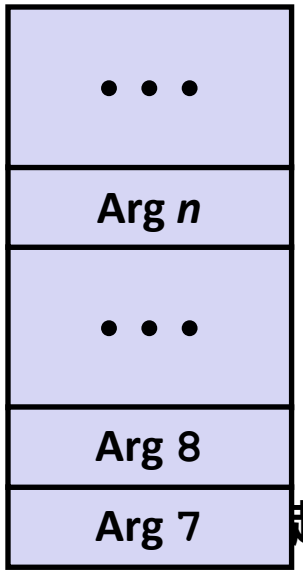
First 6 arguments



Return value



Stack



超出的参数存在栈

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 假设参数如此存在寄存器中
  •••
  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(递归)

- 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

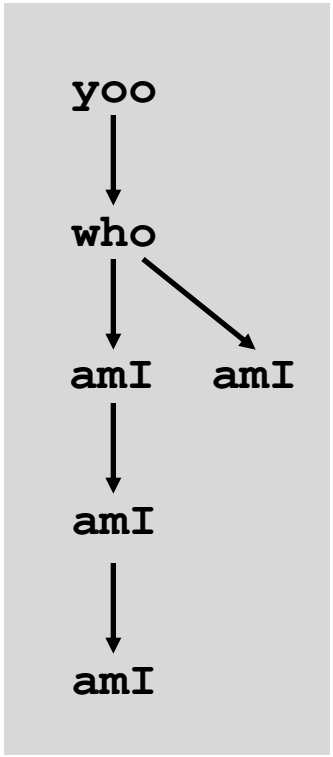
Call Chain Example

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

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

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

Example Call Chain



Procedure `amI()` is recursive

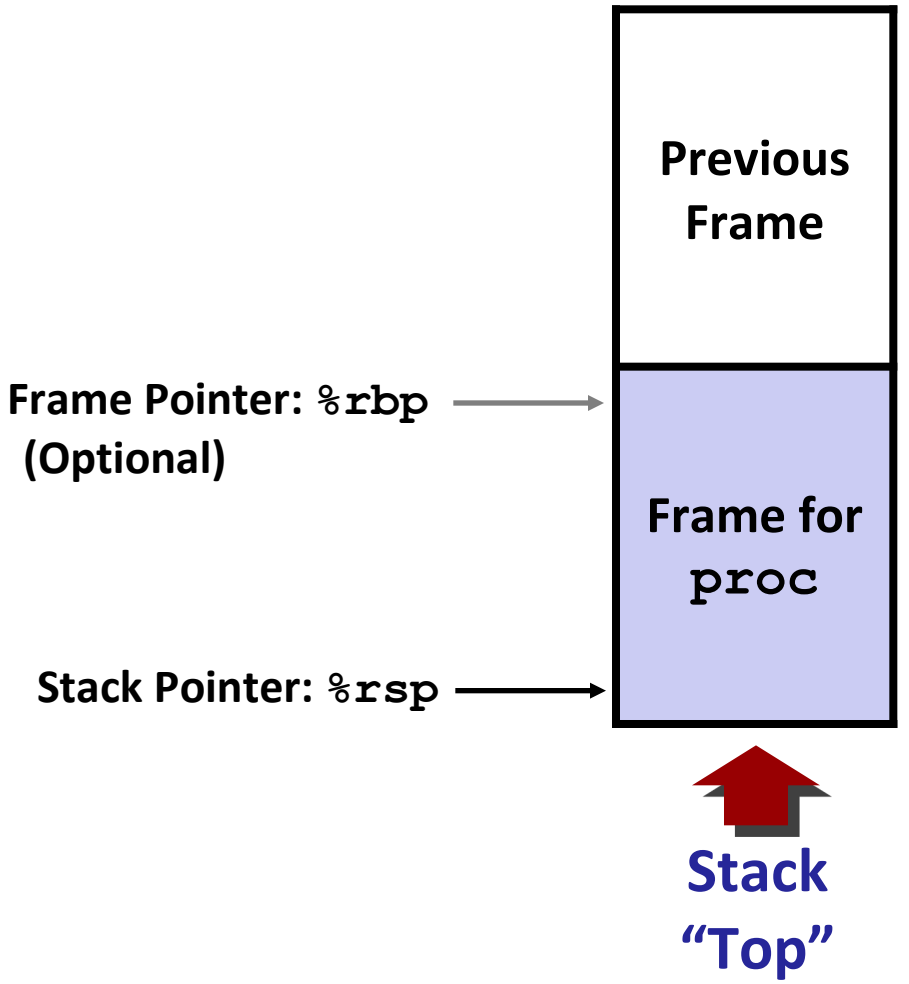
Stack Frames

Contents

Return information

Local storage (if needed)

Temporary space (if needed)



Management

Space allocated when enter procedure

"Set-up" code

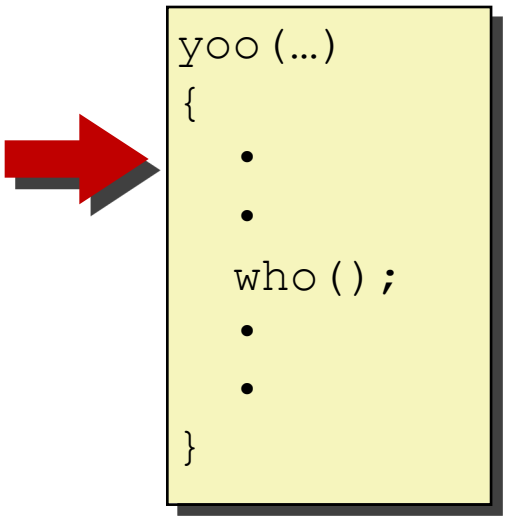
Includes push by **`call`** instruction

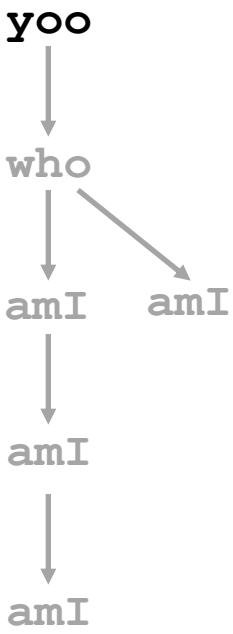
Deallocated when return

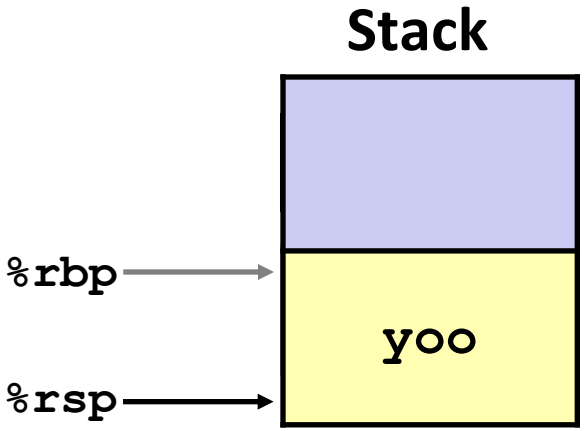
"Finish" code

Includes pop by **`ret`** instruction

1







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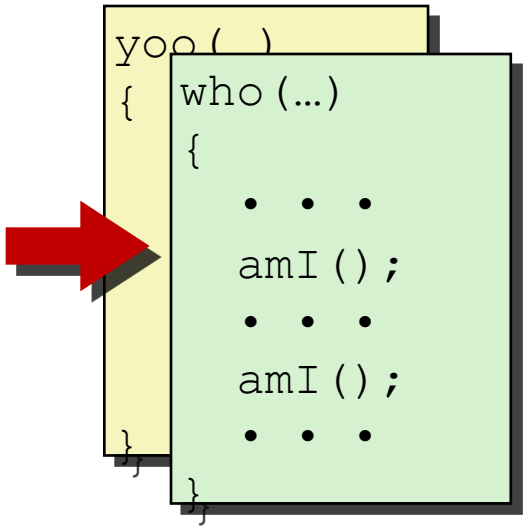

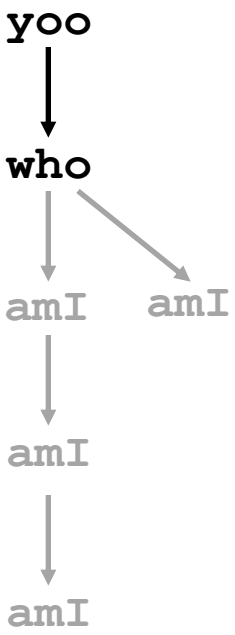

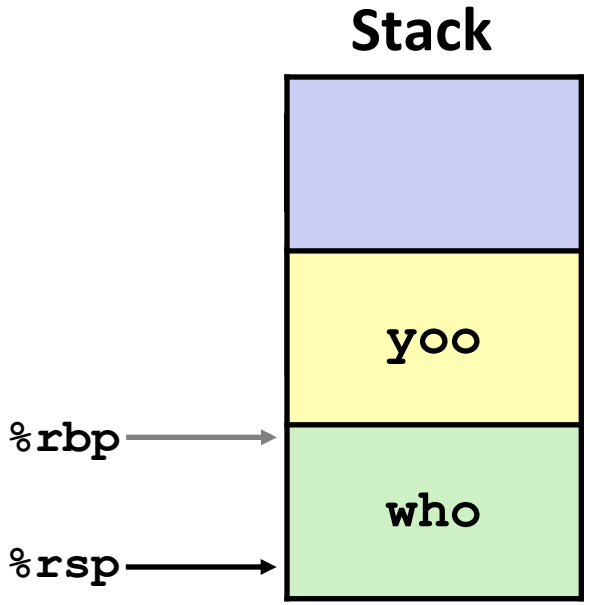

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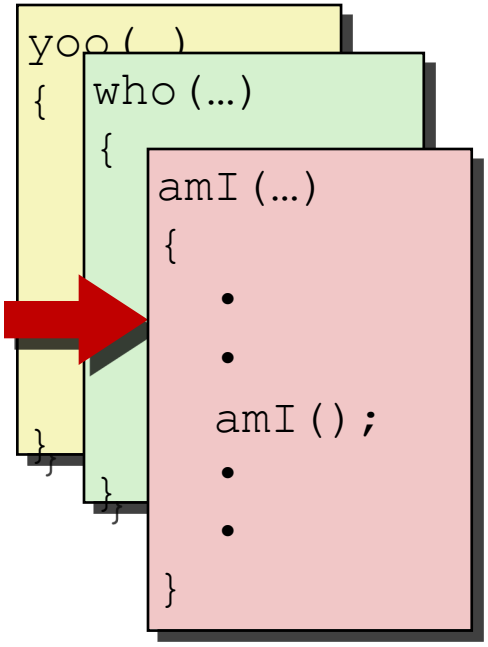
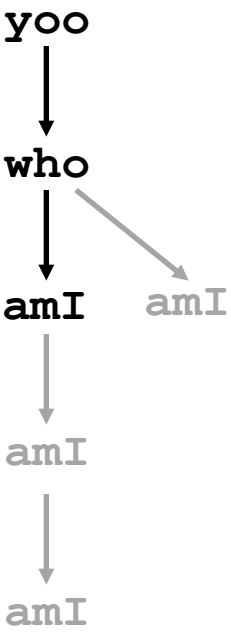
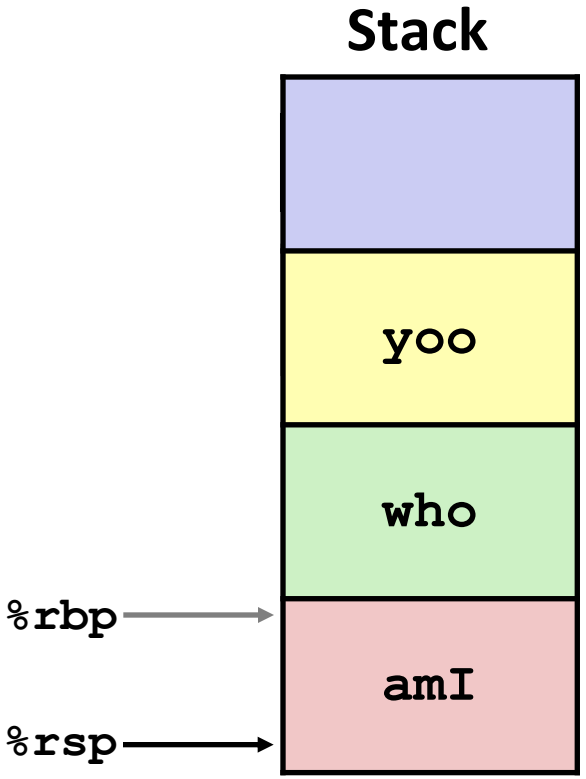
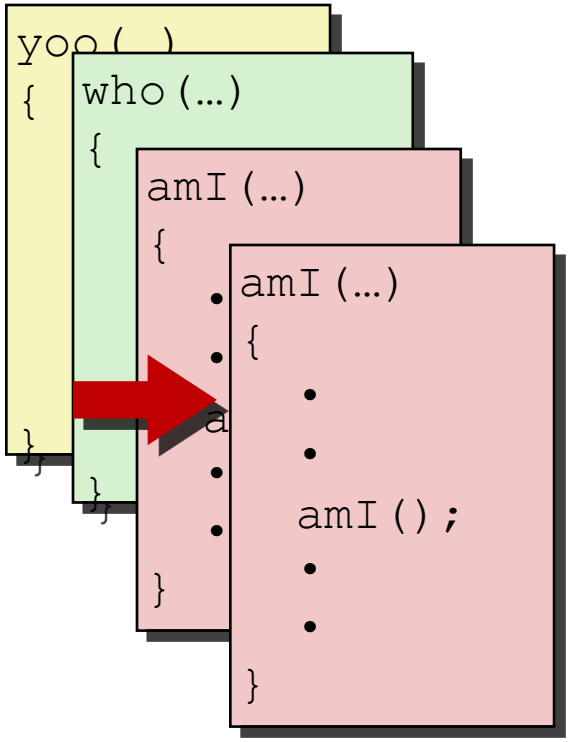
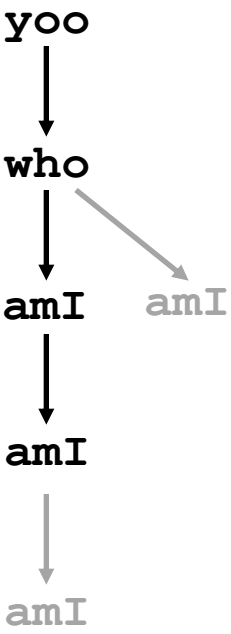

yoo( )
{
who(…)
{
amI(…)
{
•
•
amI();
•
•
}
}
}

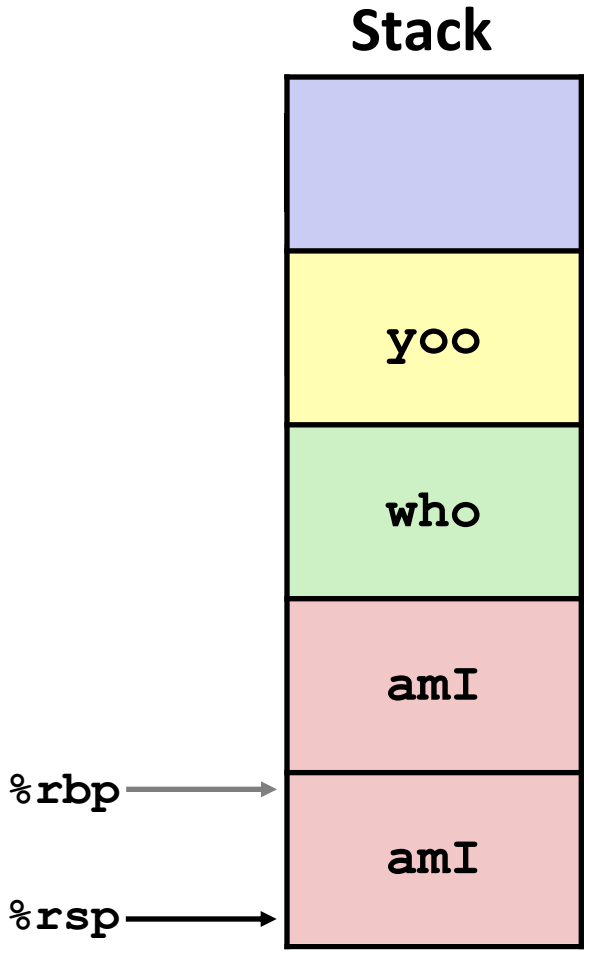

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
%rbp
%rsp

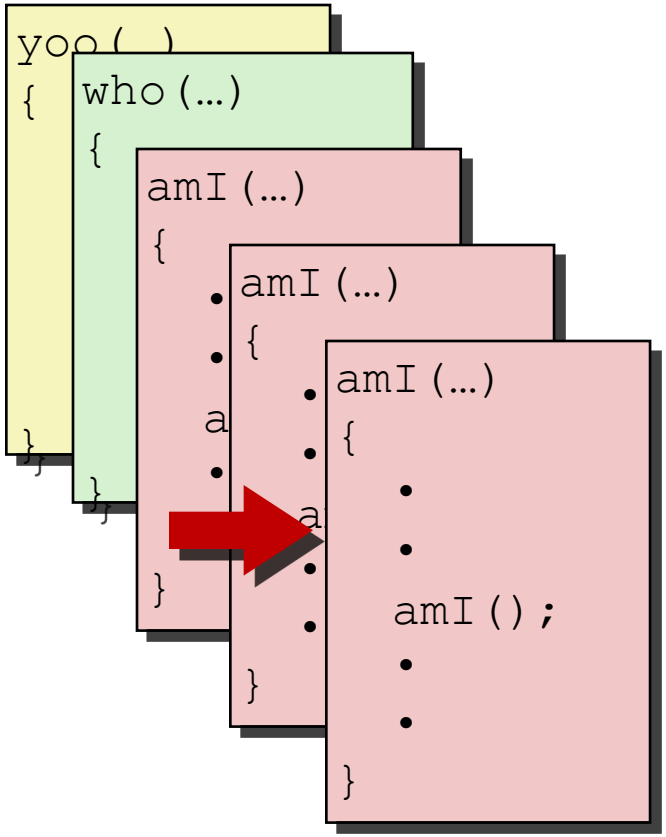
4

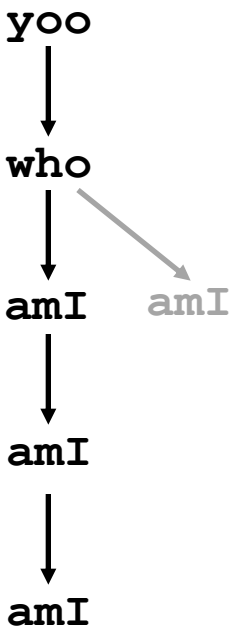

yoo( )
{
who(…)
{
amI(…)
{
amI(…)
{
amI();
}
}
}
}

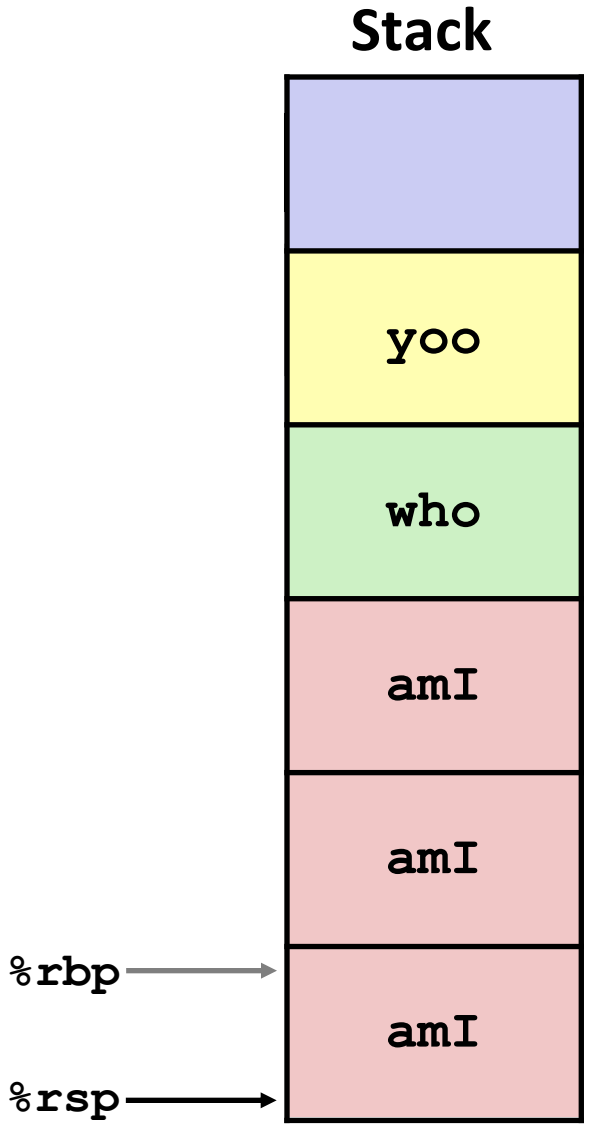

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
%rbp
%rsp

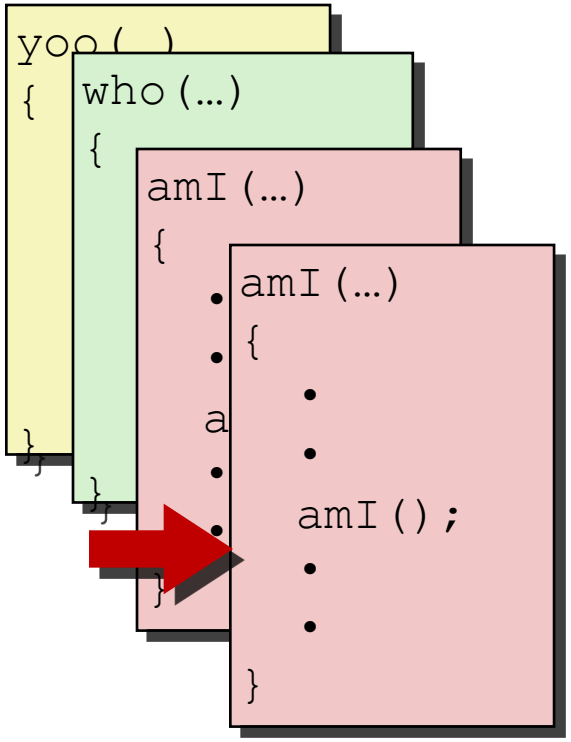
5


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


yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
amI
%rbp
%rsp

6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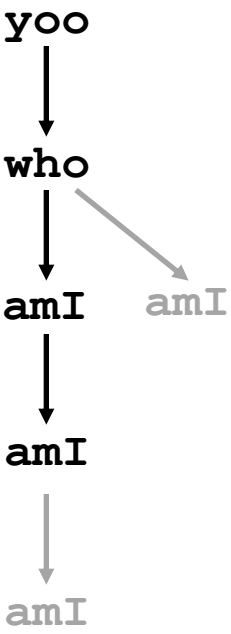
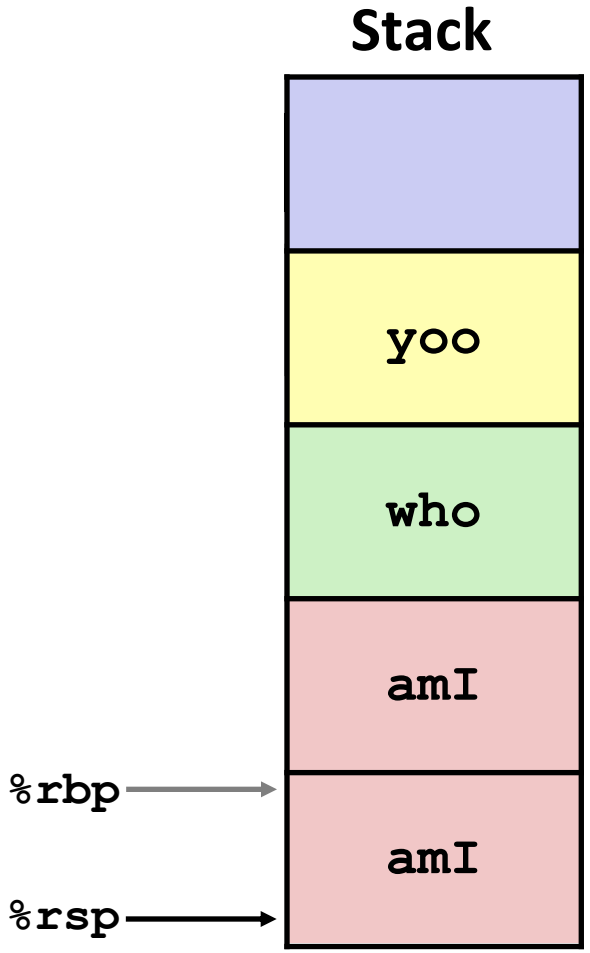
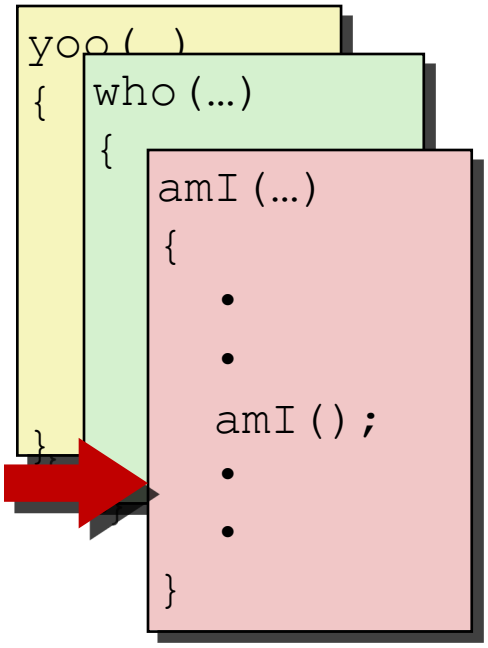
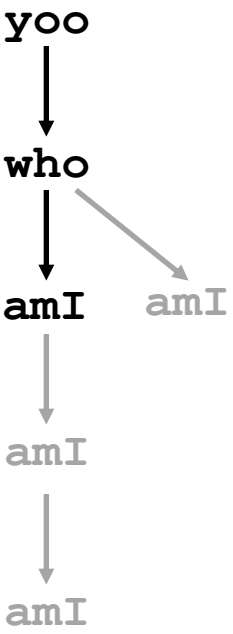
{
who(…)
{
amI(…)
{
amI(…)
{
amI();
}

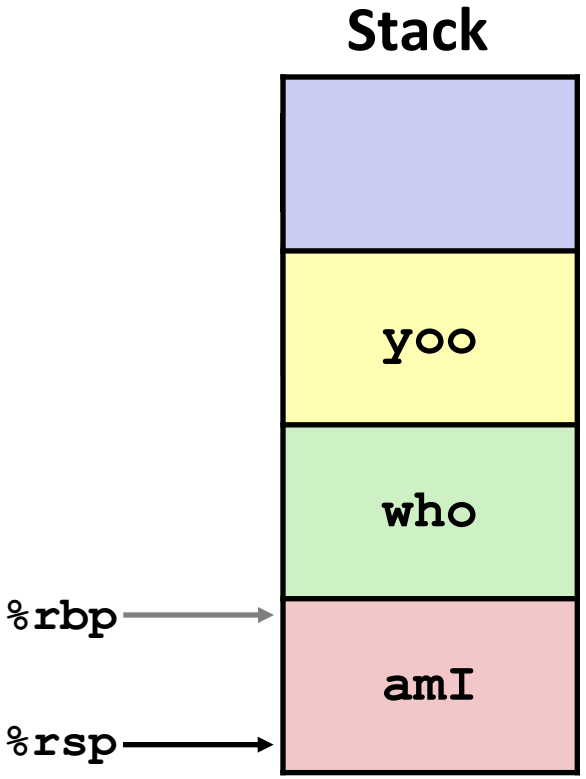

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
%rbp
%rsp

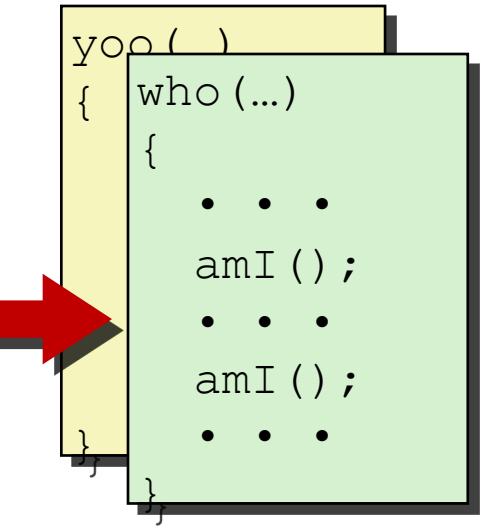
7

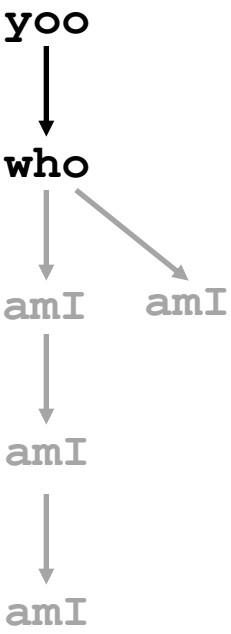

yoo( )
{
who(…)
{
amI(…)
{
•
•
amI();
•
•
}

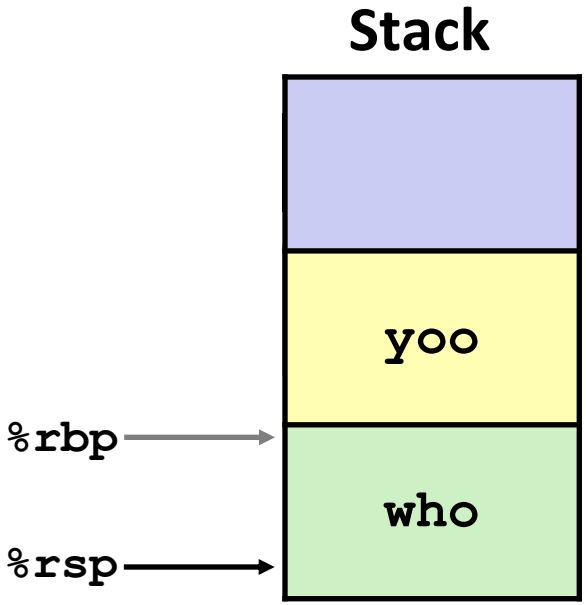

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
%rbp
%rsp

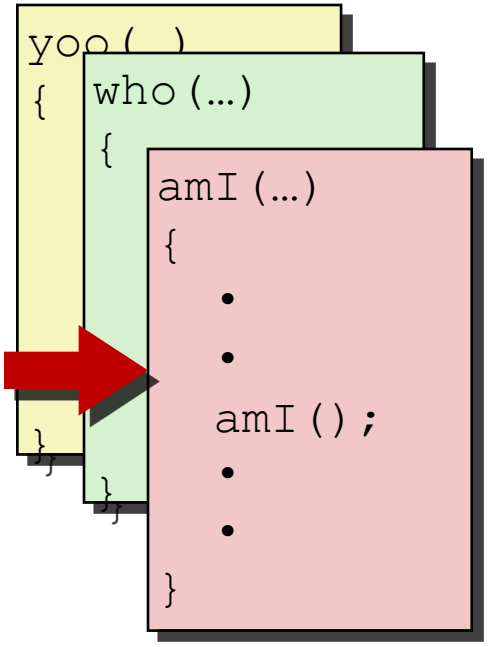
8

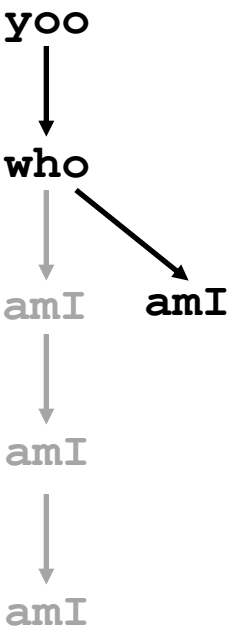


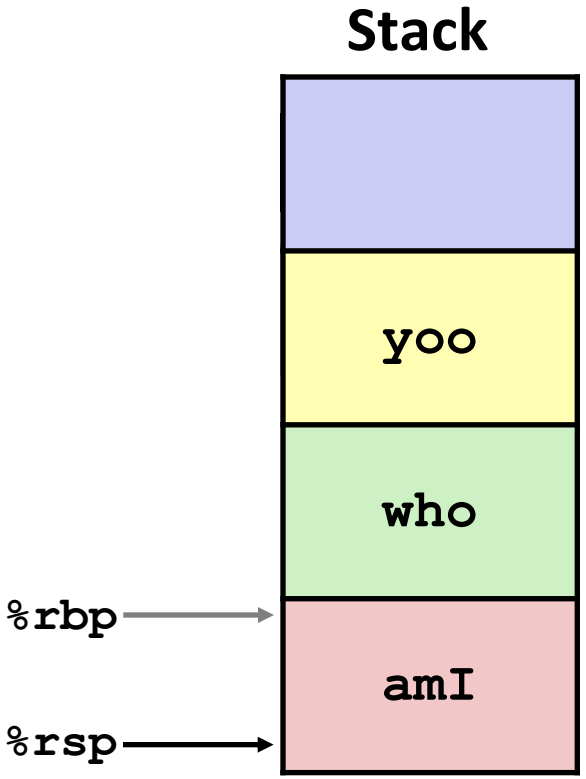




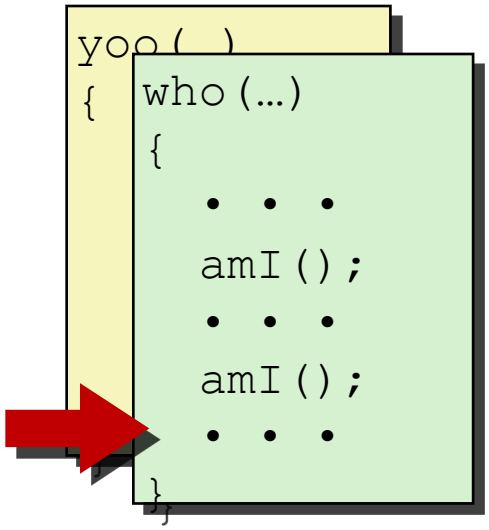
9

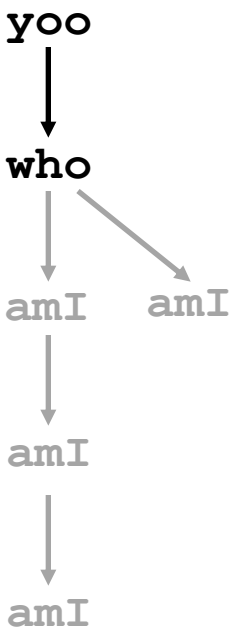

yoo( )
{
who(…)
{
amI(…)
{
•
•
amI();
•
•
}
}
}

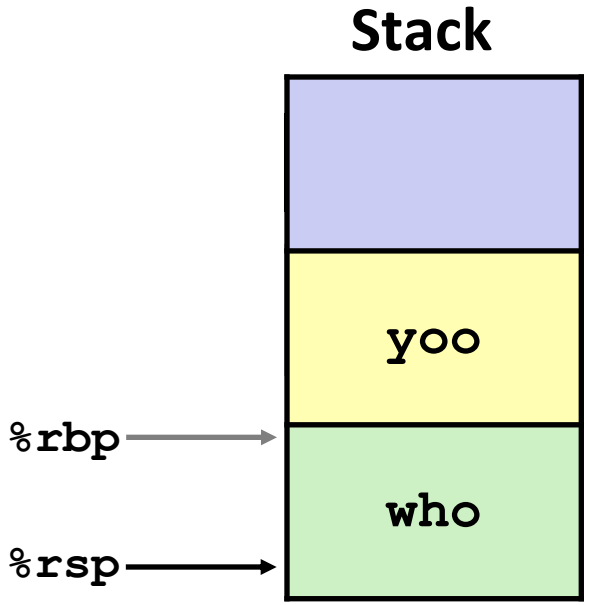

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
%rbp
%rsp

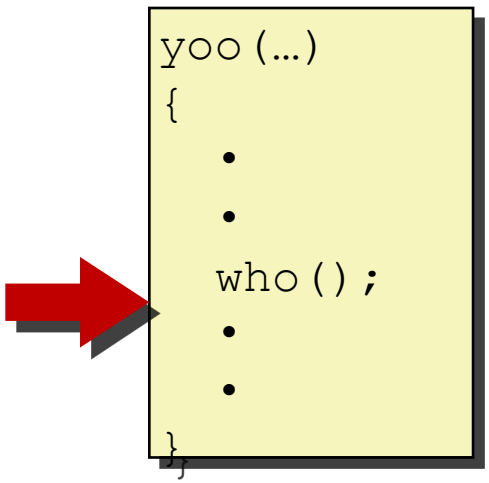
10

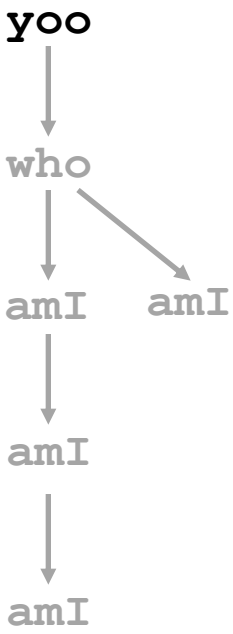


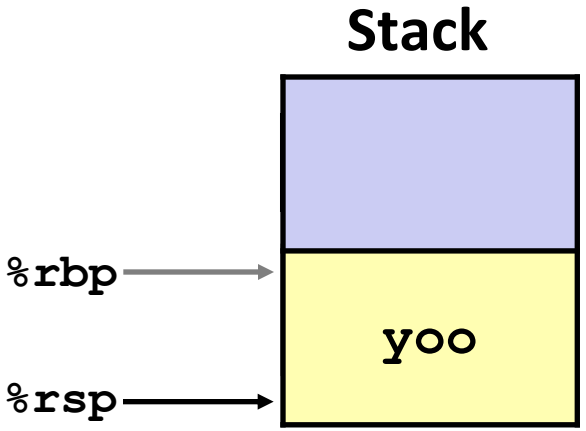




1







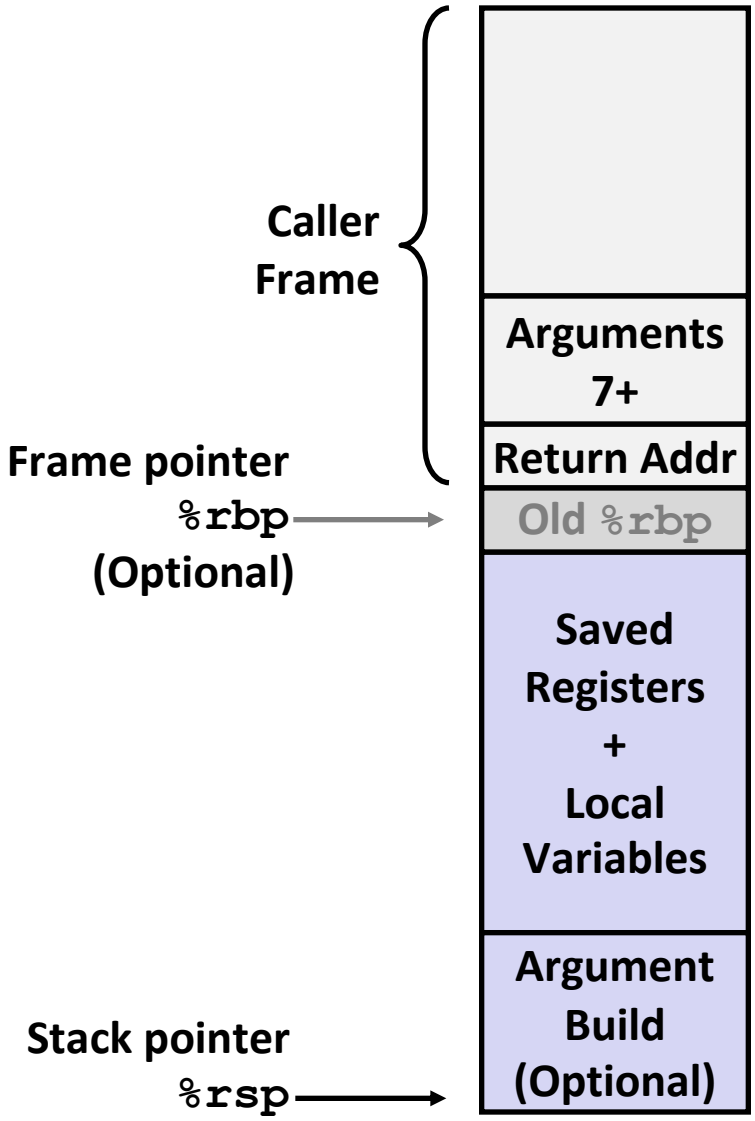
x86-64/Linux Stack Frame

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`

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

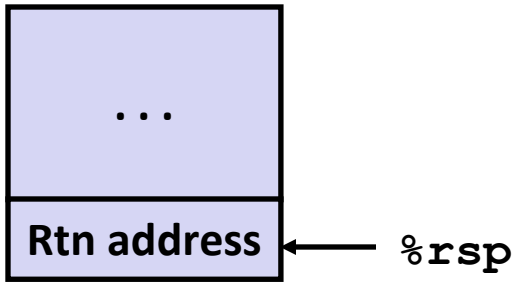
```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```

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

Example: Calling `incr` #1

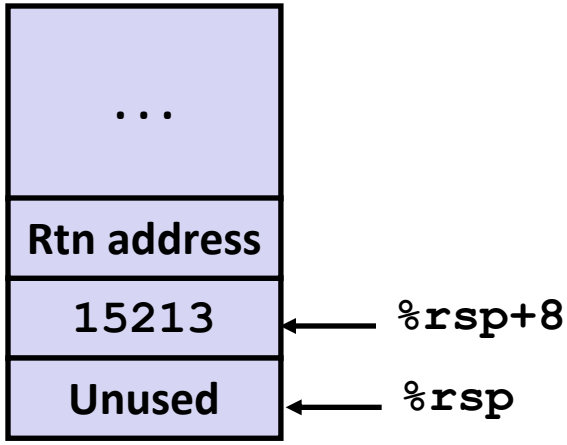
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

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

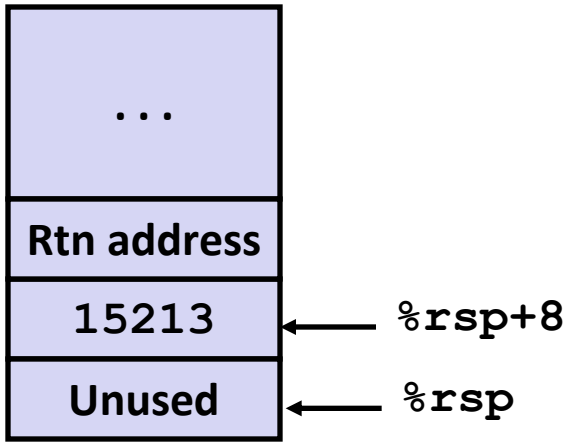


Example: Calling `incr` #2

```
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

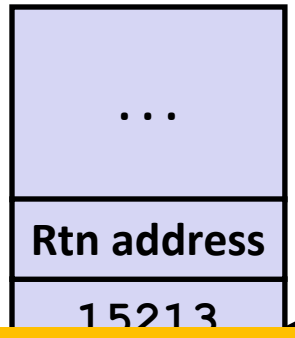


Register	Use(s)
%rdi	&v1
%rsi	3000

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.

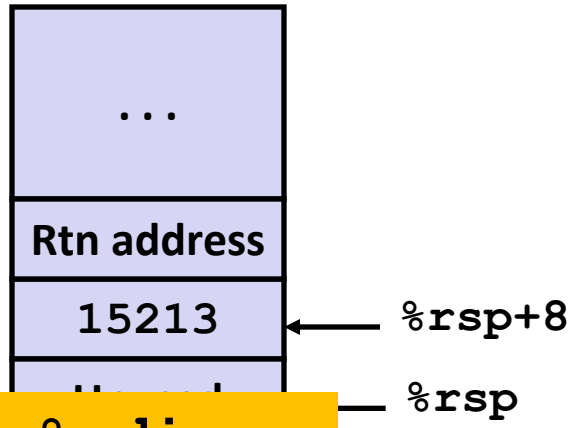
```
ca
    movl    $3000, %esi
    leaq    8(%rsp), %rdi
    call    incr
    addq    8(%rsp), %rax
    addq    $16, %rsp
    ret
```

%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
  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!

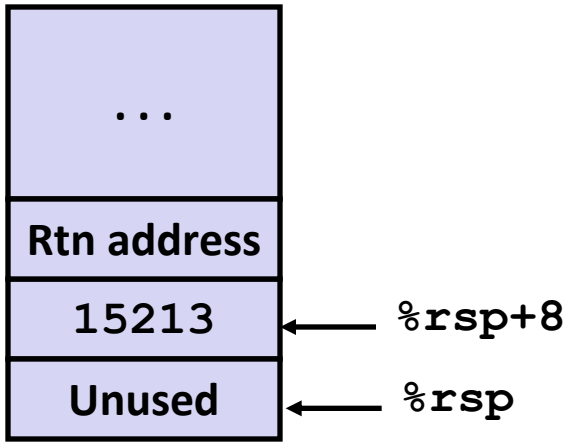
se(s)	
	v1
%rsi	3000

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



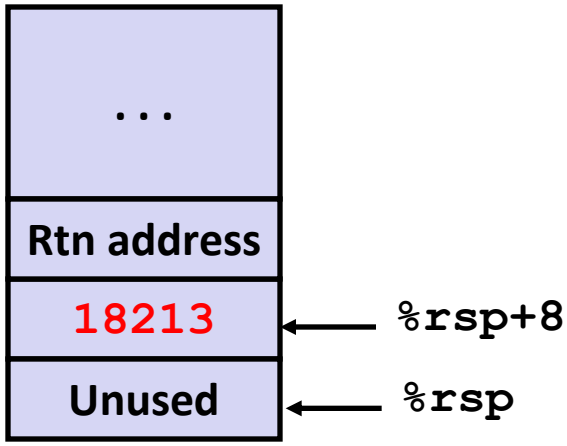
Register	Use(s)
%rdi	&v1
%rsi	3000

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

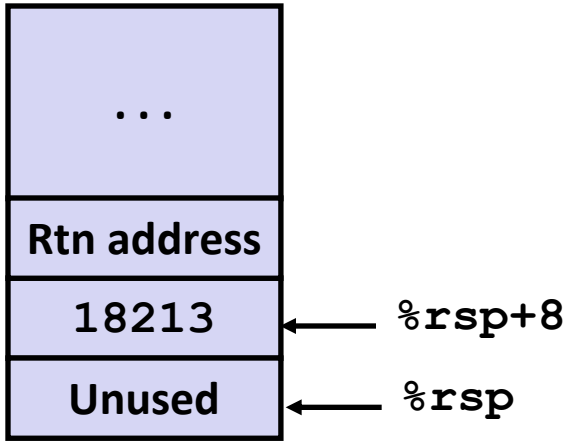


Register	Use(s)
%rdi	&v1
%rsi	3000

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
```

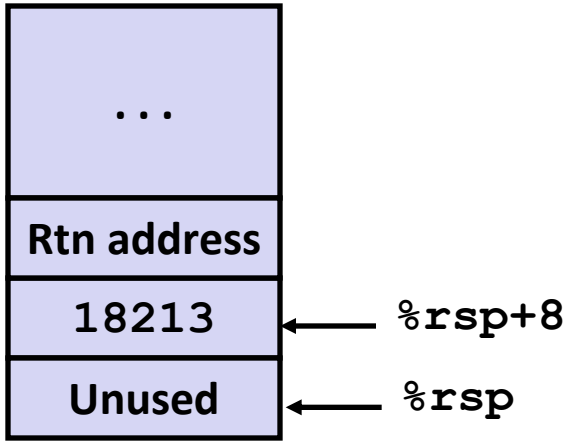
Register	Use(s)
%rax	Return value

Example: Calling `incr` #5a

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

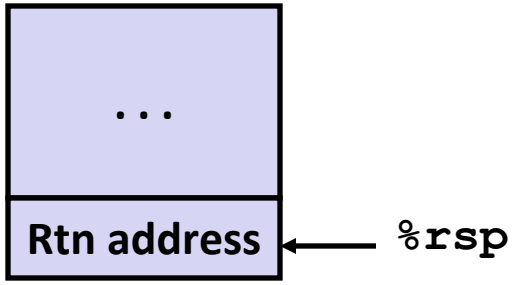
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure



Register	Use(s)
%rax	Return value

Updated Stack Structure

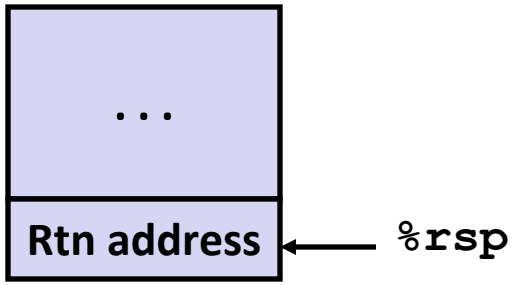


Example: Calling `incr` #5b

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

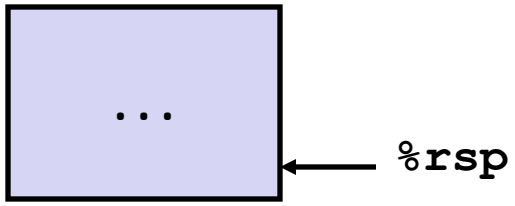
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Updated Stack Structure



Register	Use(s)
%rax	Return value

Final Stack Structure



Register Saving Conventions

When procedure `yoo` calls `who`:

`yoo` is the ***caller***

`who` is the ***callee***

Can register be used for temporary storage?

```
yoo:
        • • •
    movq $15213, %rdx
    call who
    addq %rdx, %rax
        • • •
    ret
```

```
who:
        • • •
        subq $18213, %rdx
        • • •
    ret
```

Contents of register `%rdx` overwritten by `who`

This could be trouble → something should be done!

Need some coordination

Register Saving Conventions

When procedure `yoo` calls `who`:

`yoo` is the ***caller***

`who` is the ***callee***

Can register be used for temporary storage?

Conventions

"Caller Saved" (aka "Call-Clobbered")调用者

Caller saves temporary values in its frame before the call

"Callee Saved" (aka "Call-Preserved")被调用

Callee saves temporary values in its frame before using

Callee restores them before returning to caller

x86-64 Linux Register Usage #1

`%rax`

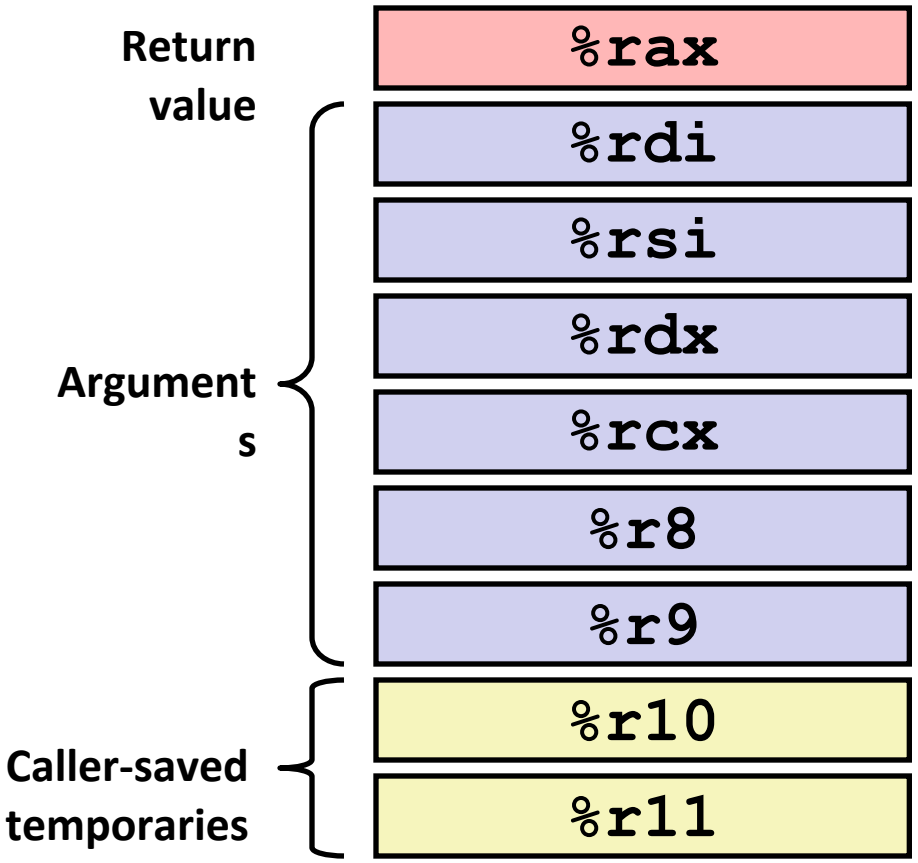
- Return value
- Also caller-saved
- Can be modified by procedure

`%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`

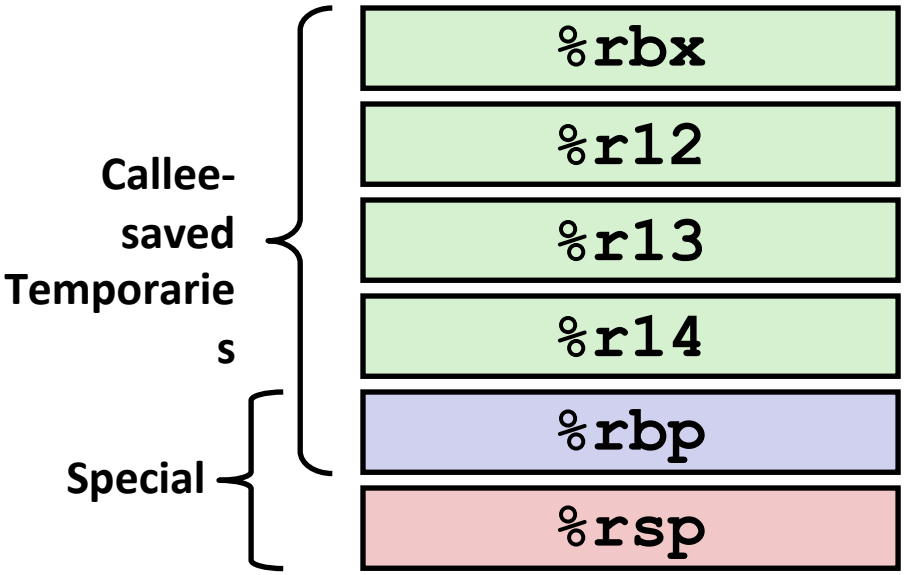
- Callee-saved
- Callee must save & restore

`%rbp`

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

`%rsp`

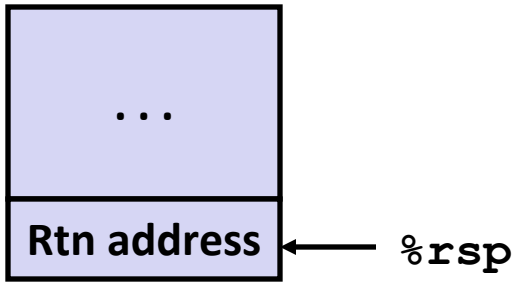
- Special form of callee save
- Restored to original value upon exit from procedure



Callee-Saved Example #1

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

Initial Stack Structure



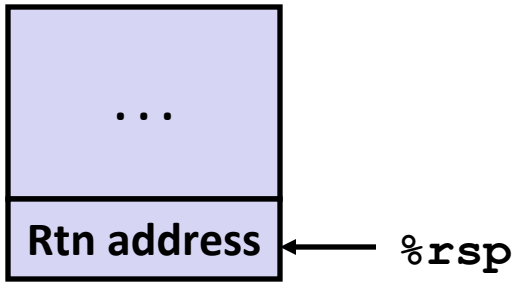
- X comes in register **`%rdi`**.
- We need **`%rdi`** for the call to incr.
- Where should be put x, so we can use it after the call to incr?

Callee-Saved Example #2

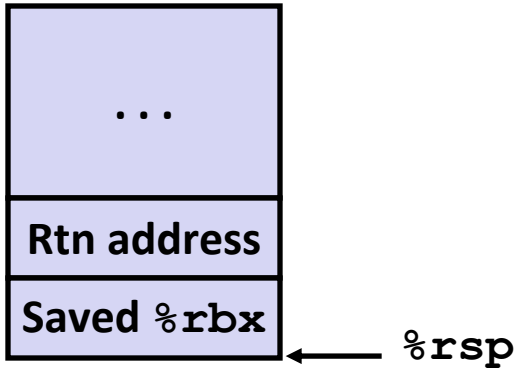
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

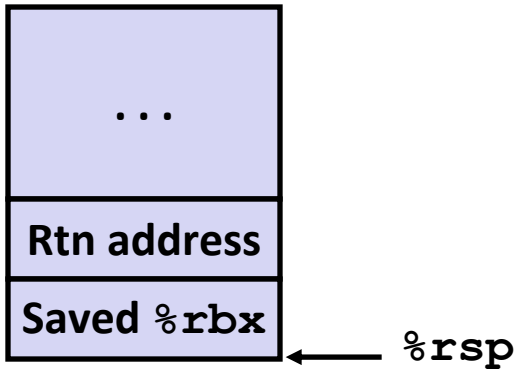


Callee-Saved Example #3

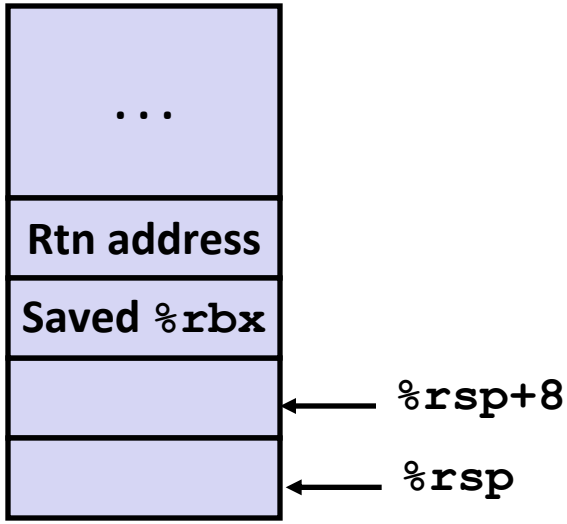
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

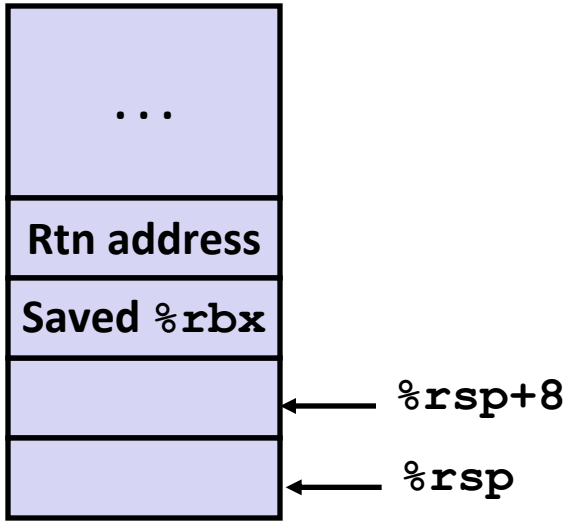


Callee-Saved Example #4

```
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



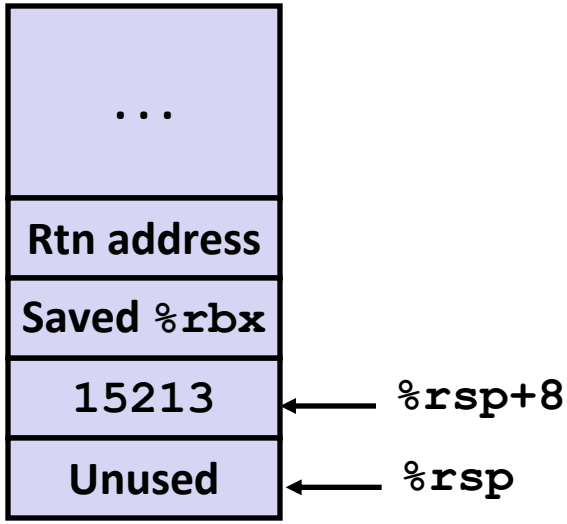
- X saved in **%rbx**.
- A callee saved register.

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



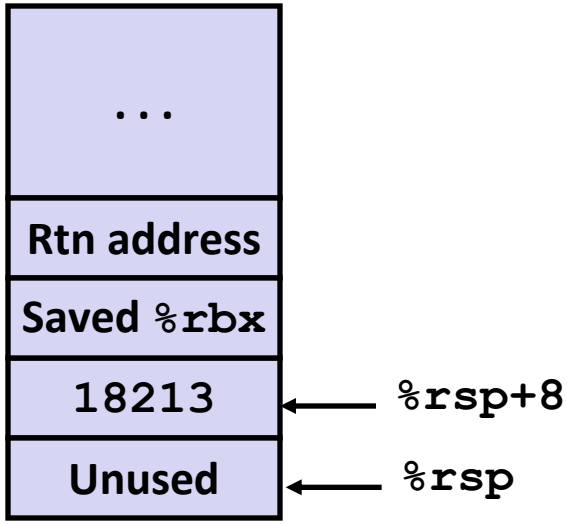
- X saved in **%rbx**.
- A callee saved register.

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



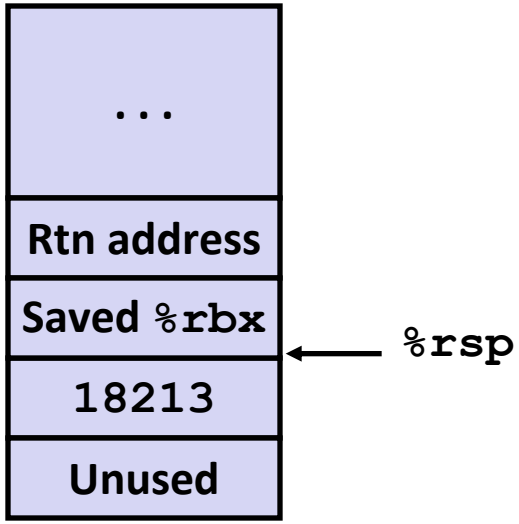
- X Is safe in **%rbx**
- Return result in **%rax**

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



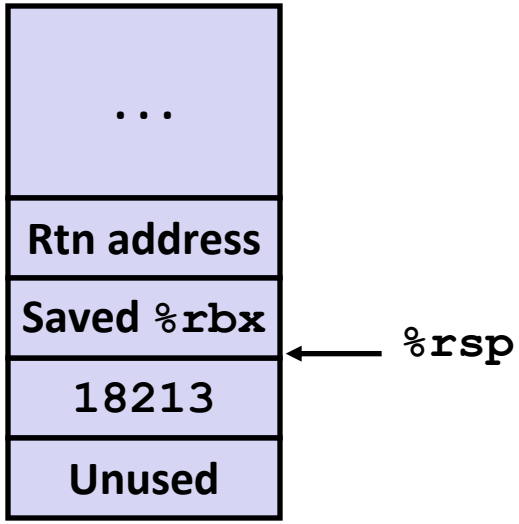
- Return result in **%rax**

Callee-Saved Example #8

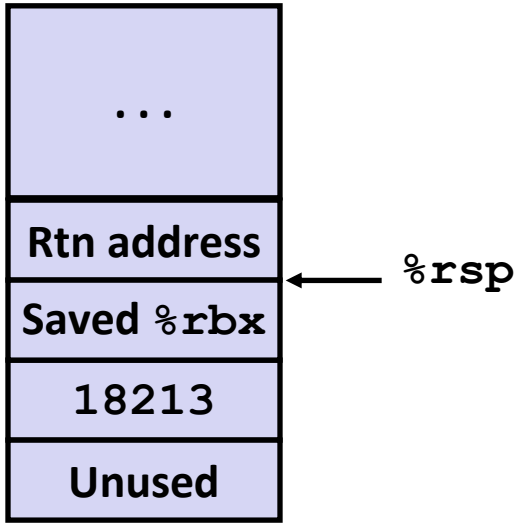
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

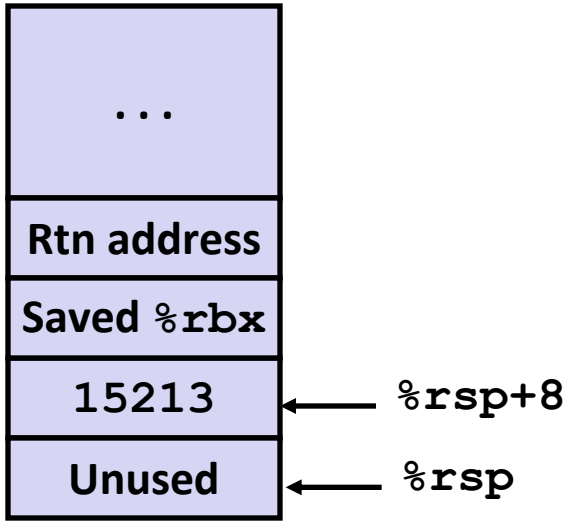


Callee-Saved Example #2

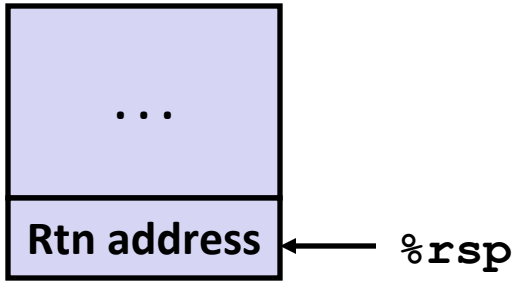
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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)
    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
```

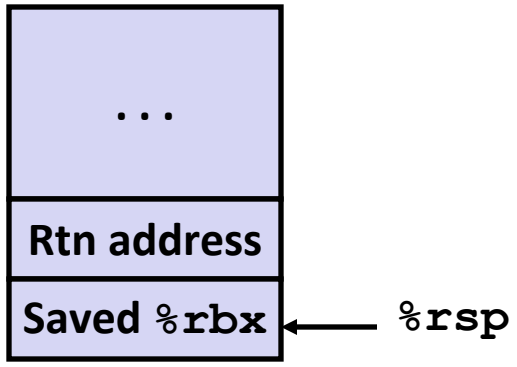
Register	Use(s)	Type
%rdi	x	Argument
%rax	Return value	Return value

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
```

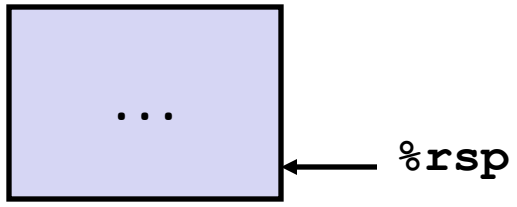
Register	Use(s)	Type
%rbx	x & 1	Callee-saved
%rax	Return value	

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