Machine-Level Programming III: Procedures

COMP402127: Introduction to Computer Systems
https://xjtu-ics.github.io/

Danfeng Shan
Xi'an Jiaotong University

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

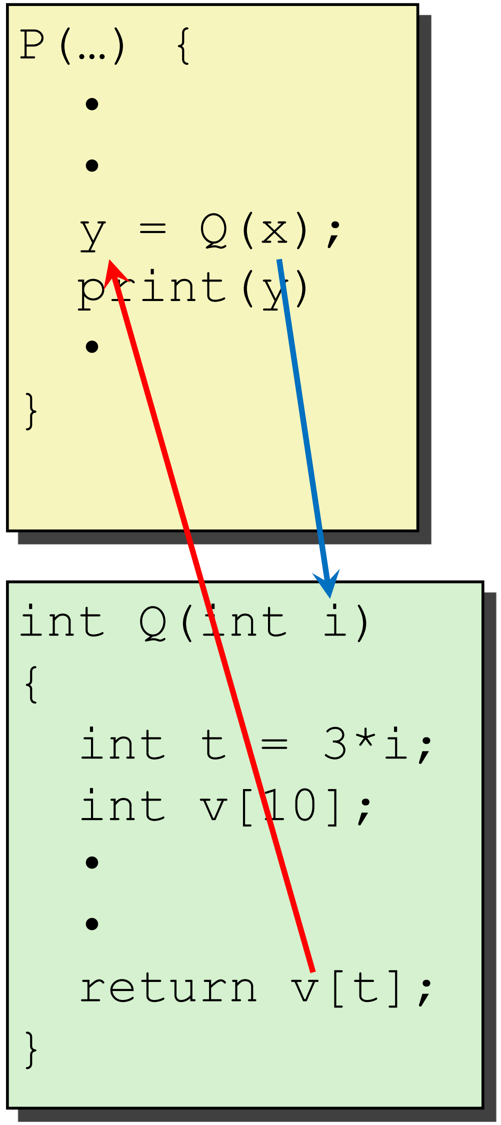
Passing control
- To beginning of procedure code
- Back to return point

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



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

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

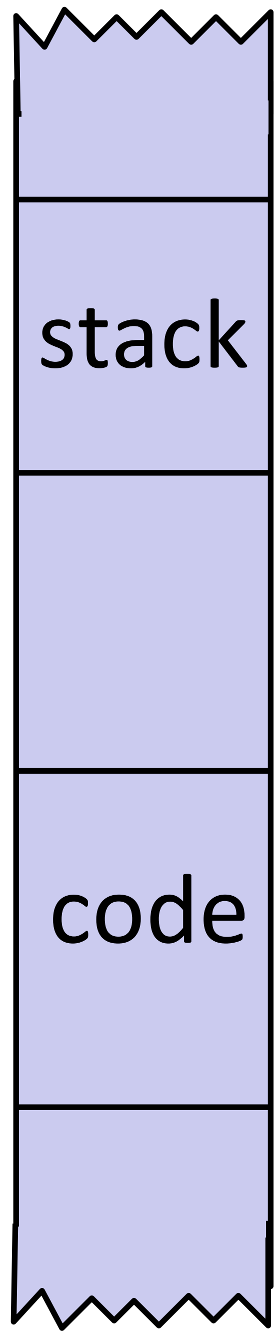
```
P(…) {
  int v[10];
  •
  •
  return v[t];
}
```

Today

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

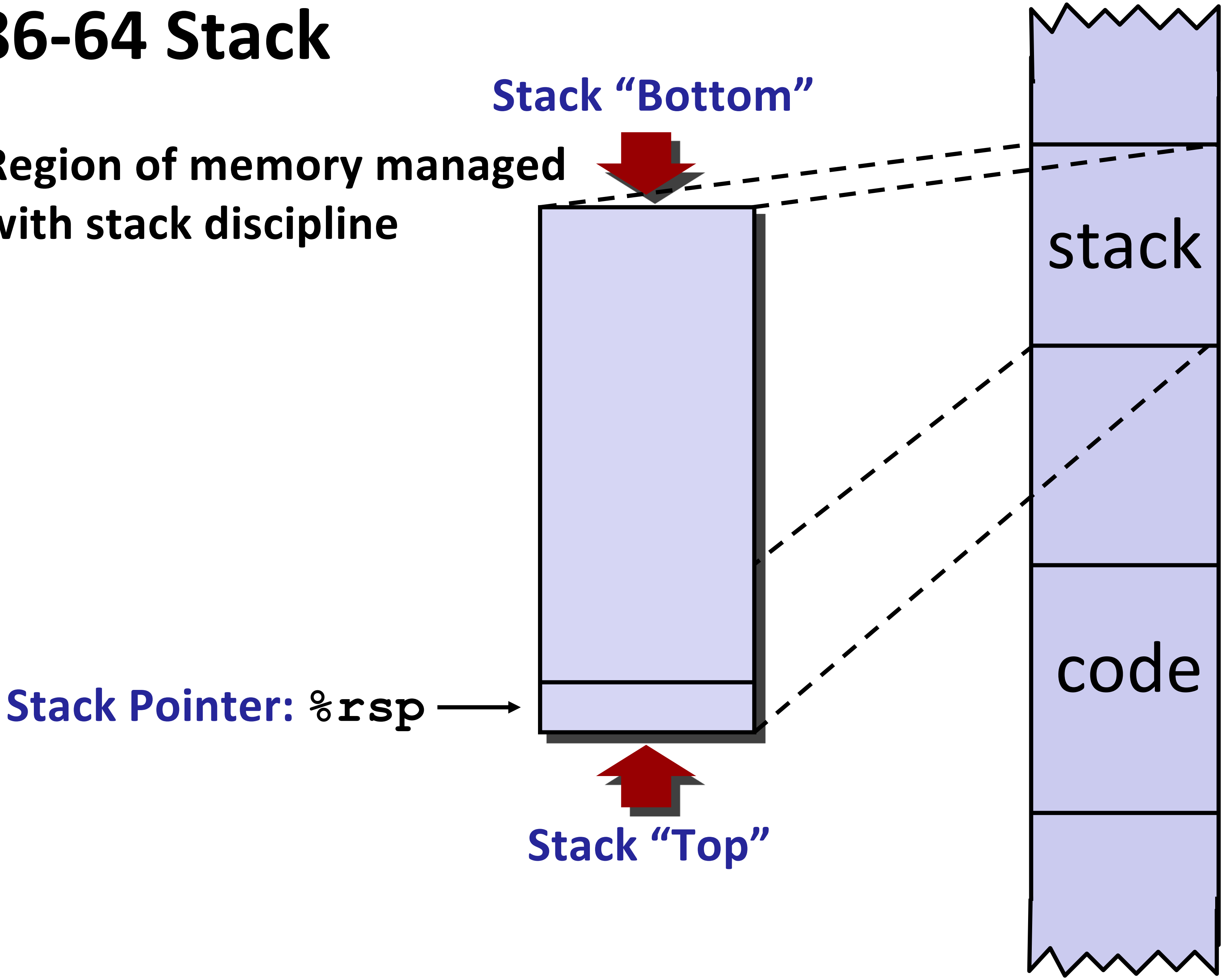
x86-64 Stack

- **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

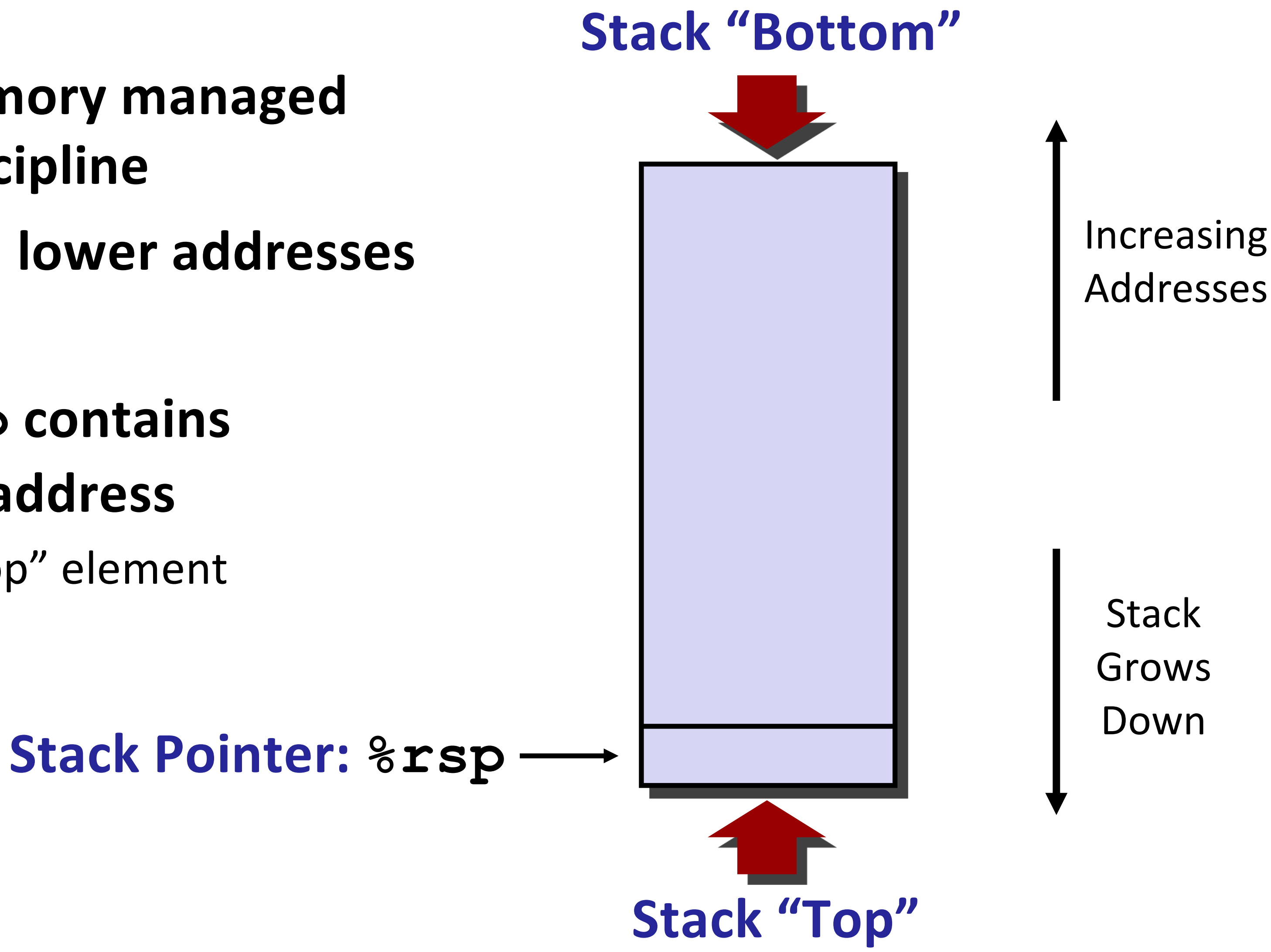
- Region of memory managed with stack discipline



x86-64 Stack

- Region of memory managed with stack discipline
- Grows toward lower addresses

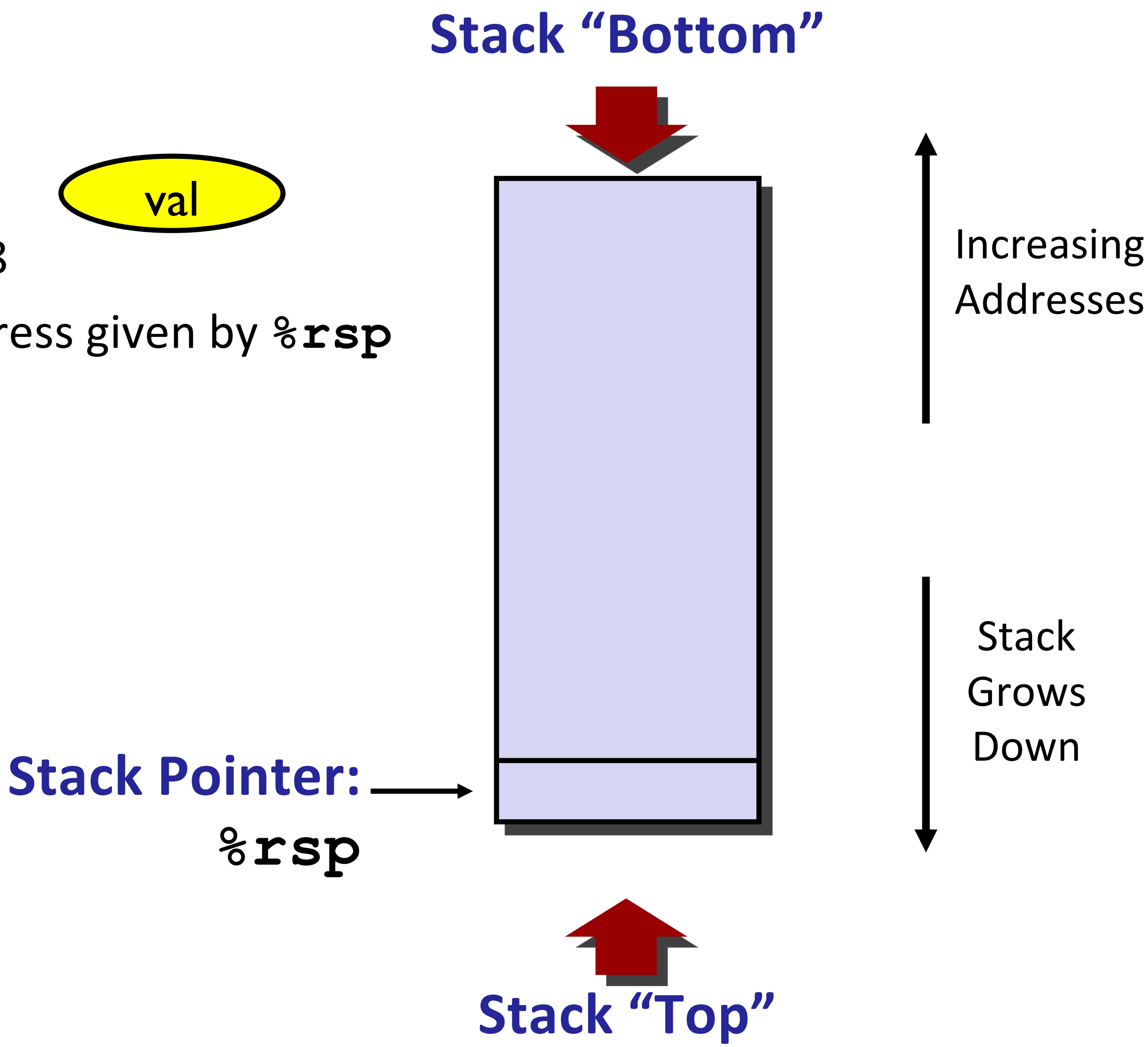
- Register `%rsp` contains lowest stack address
  - address of "top" element



x86-64 Stack: Push

`pushq` *Src*

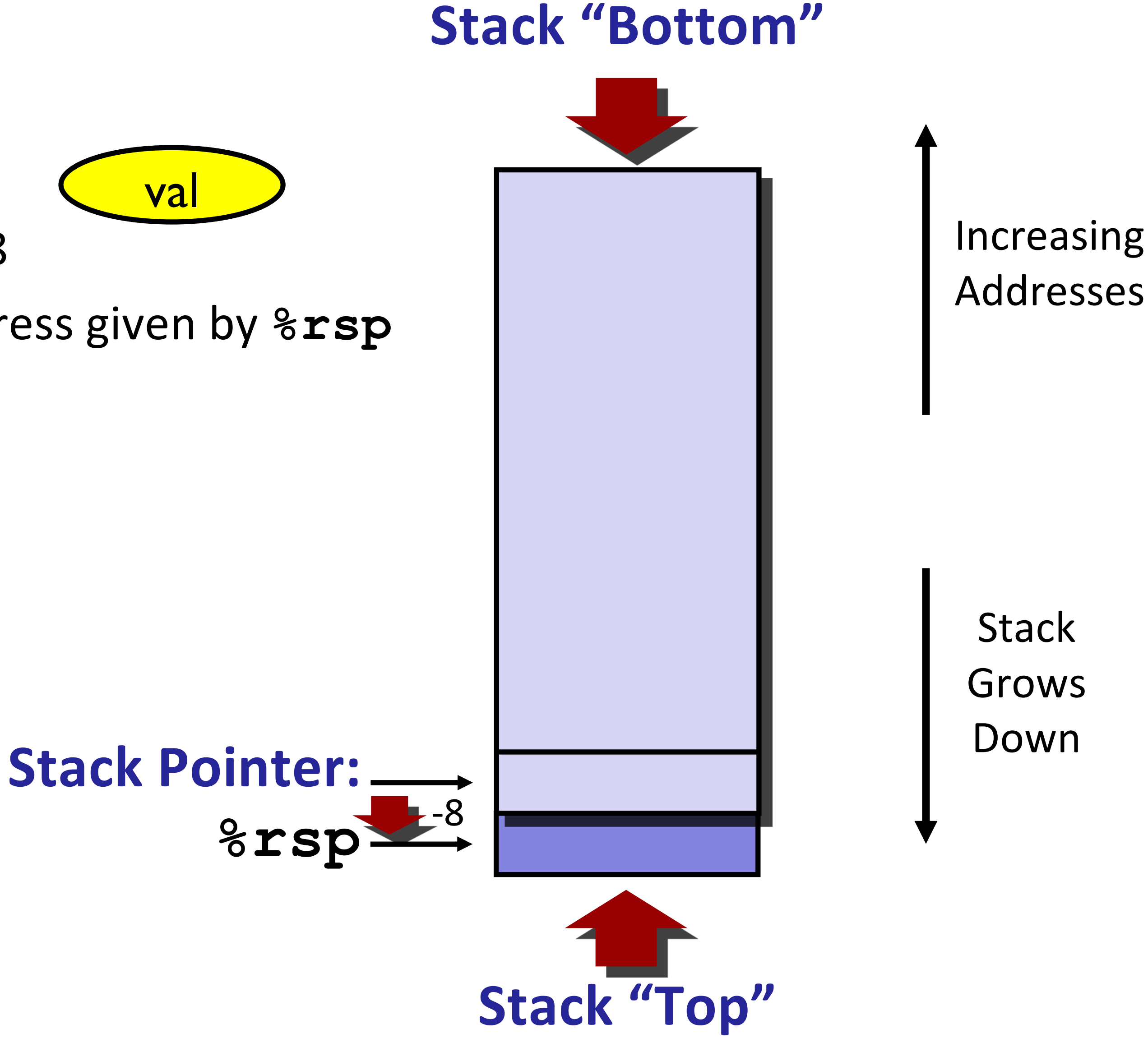
- Fetch operand at *Src*
- Decrement **`%rsp`** by 8
- Write operand at address given by **`%rsp`**



x86-64 Stack: Push

`pushq` *Src*

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

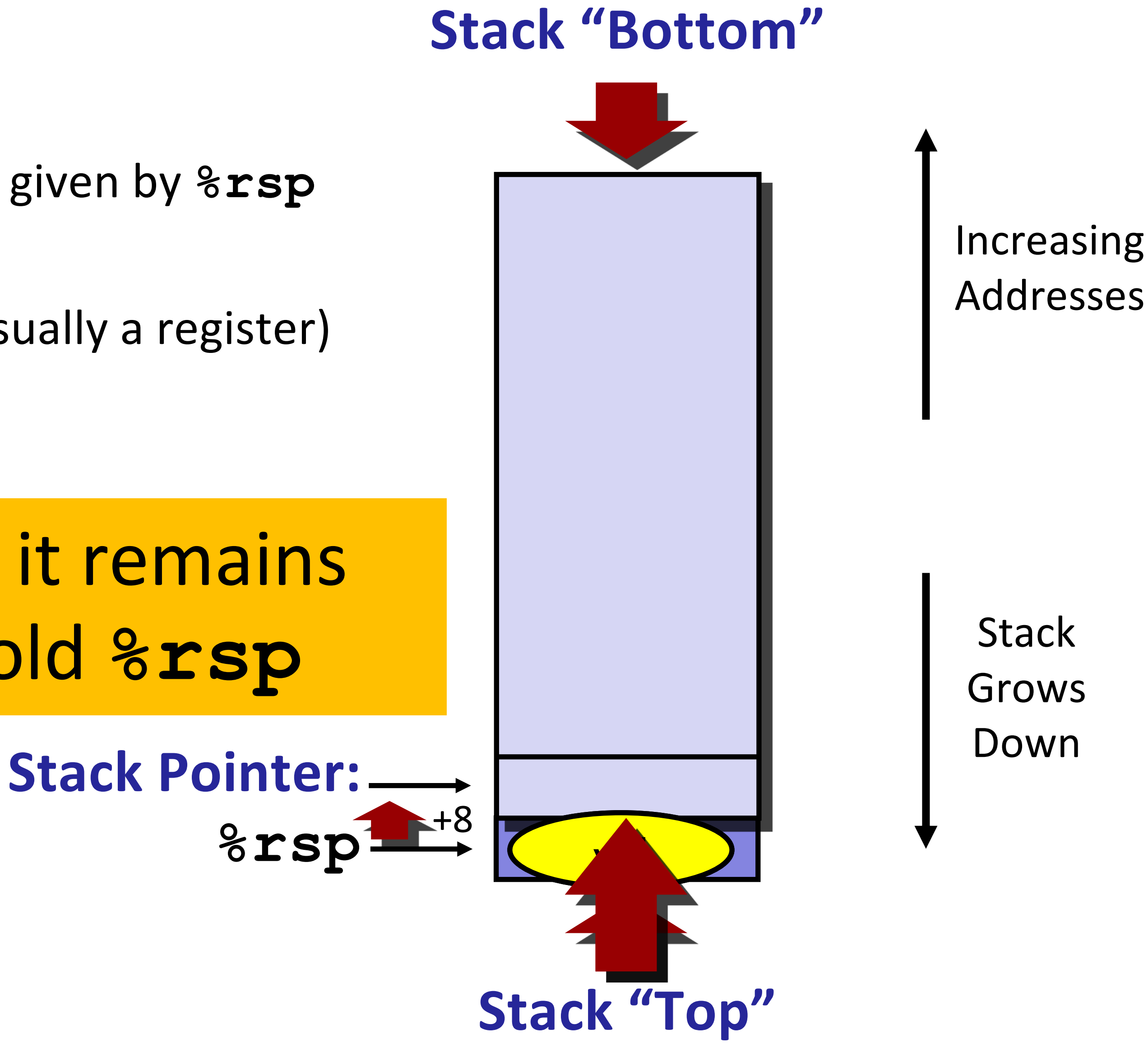


x86-64 Stack: Pop

`popq` ***Dest***

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

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



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

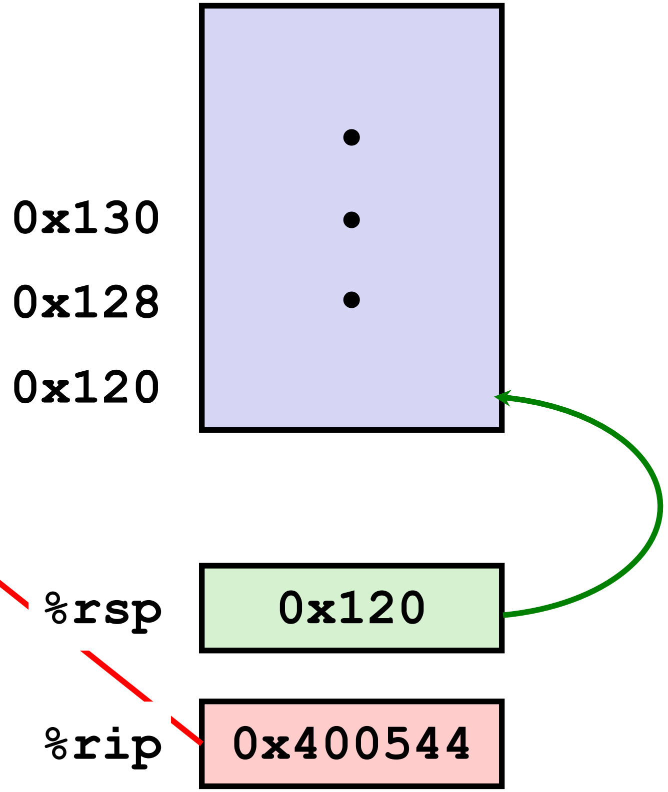
- **Use stack to support procedure call and return**
- **Procedure call: `call label`**
  - Push return address on stack
  - Jump to ***label***
- **Return address:**
  - Address of the next instruction right after call
  - Example from disassembly
- **Procedure return: `ret`**
  - Pop address from stack
  - 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)
  •
  •
```

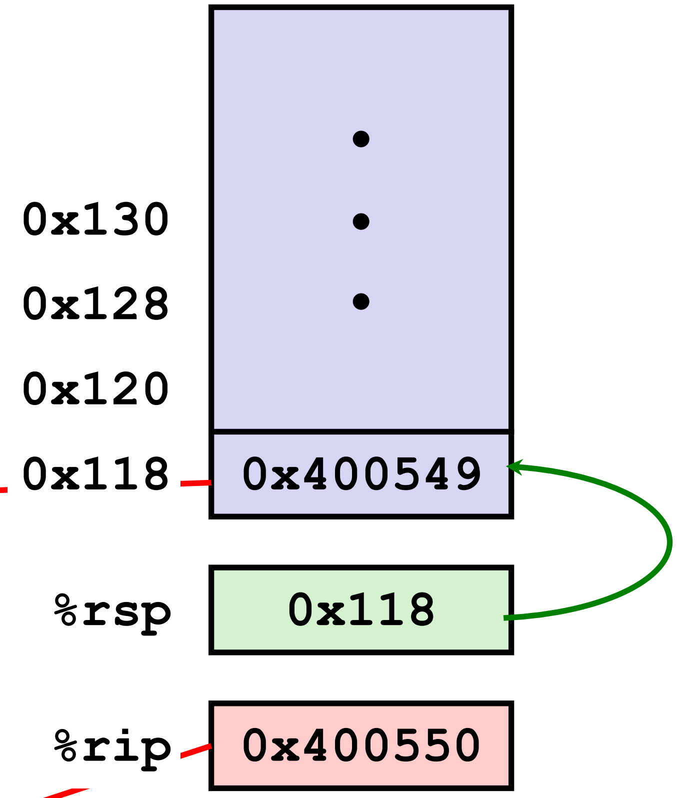
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  ret
```



Control Flow Example #2

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

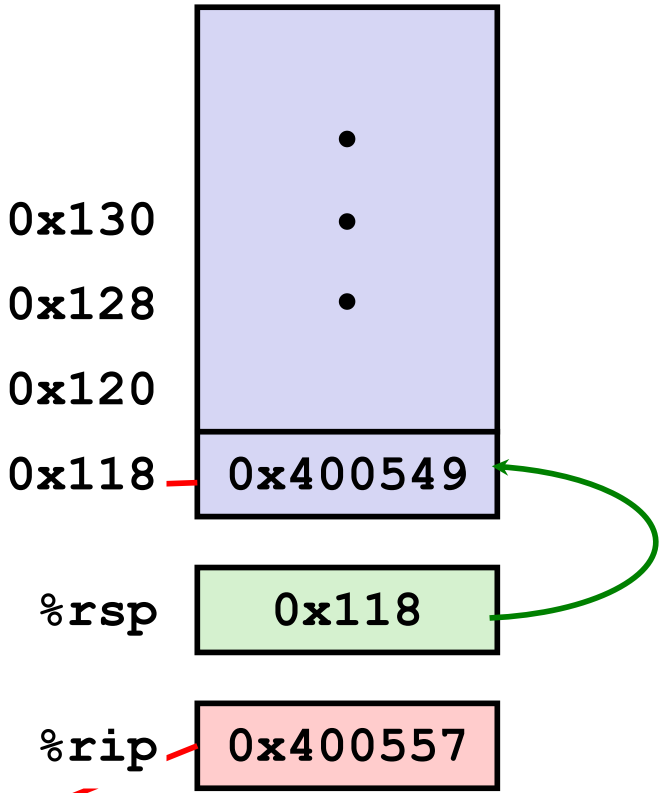
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  ret
```



Control Flow Example #3

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

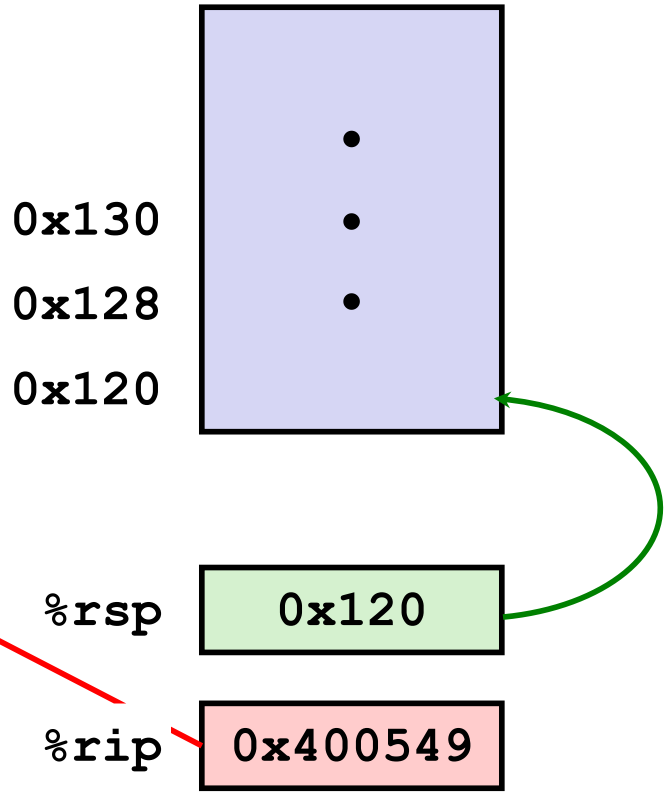
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  ret
```



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

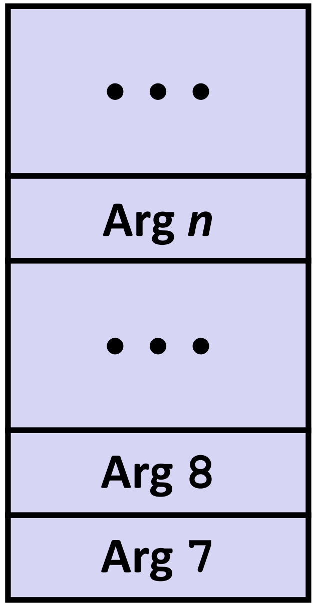
First 6 arguments

`%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
```

Today

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

Today

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

Call Chain Example

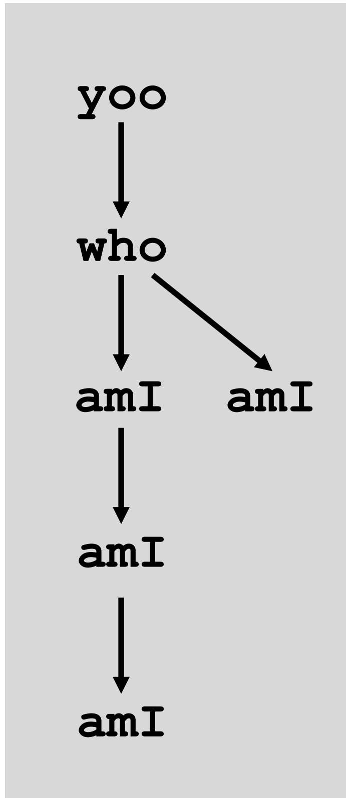
```
yoo(…)
{
  •
  •
  who();
  •
  •
}
```

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

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

Procedure amI() is recursive

Example Call Chain



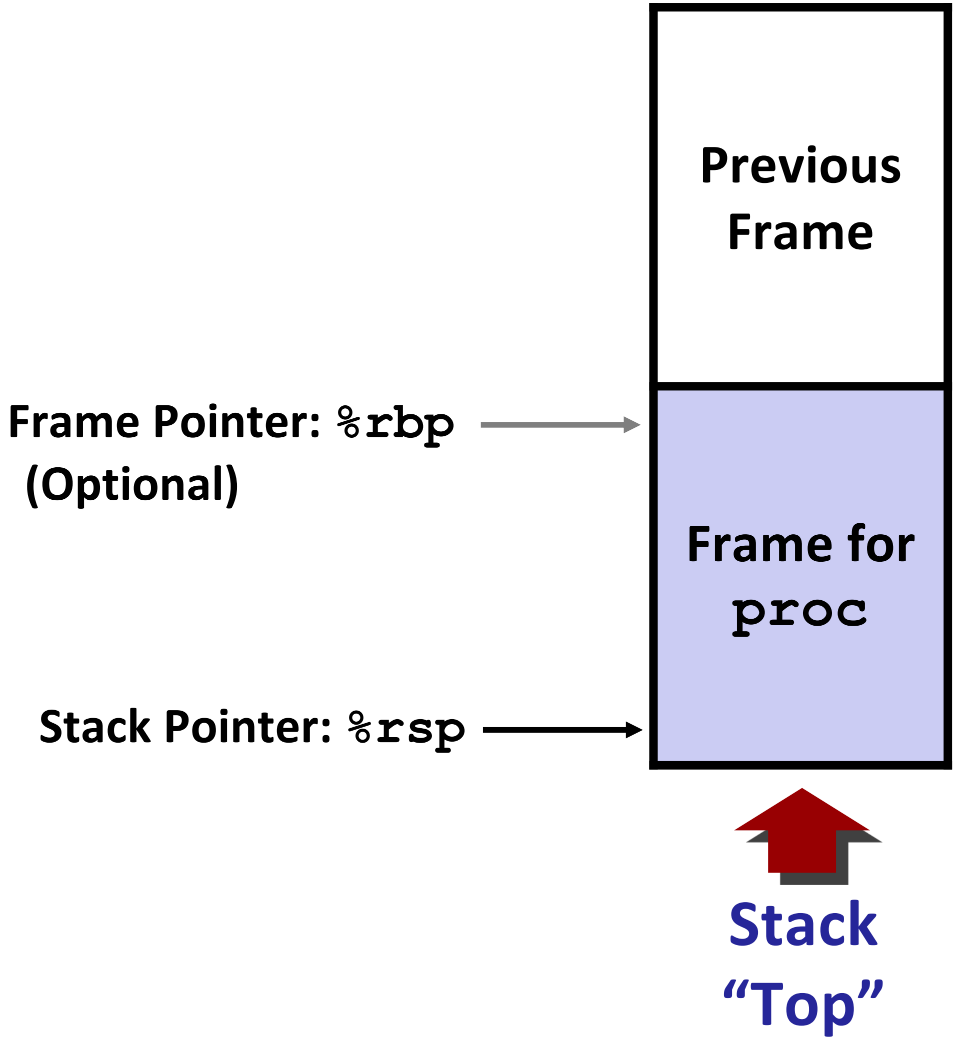
Stack Frames

Contents

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

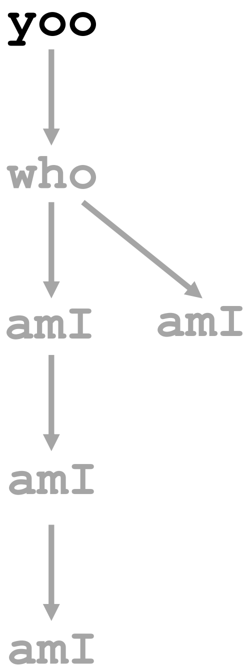
Management

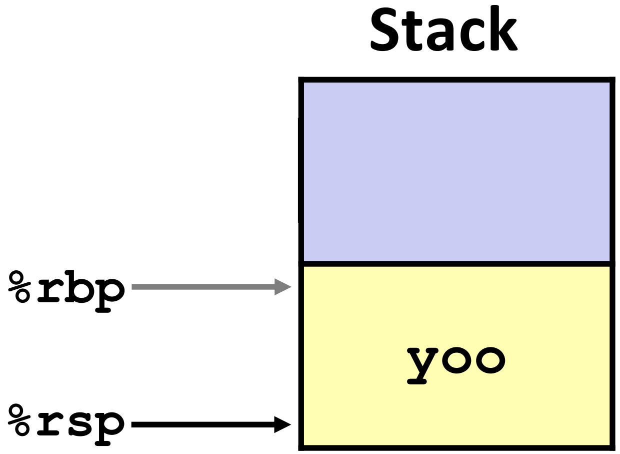
- Space allocated when enter procedure
  - "Set-up" code
  - Includes push by **`call`** instruction
- Deallocated when return
  - "Finish" code
  - Includes pop by **`ret`** instruction



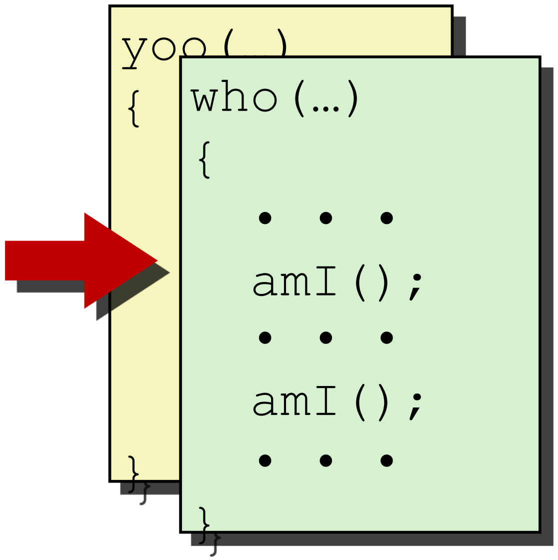
Example

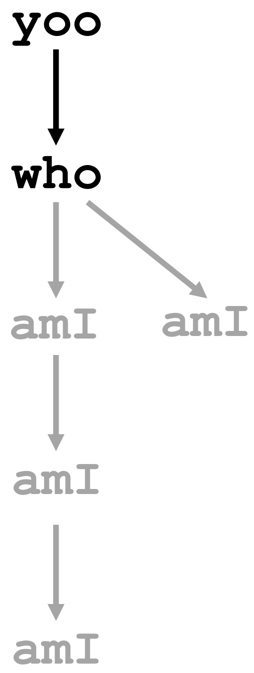
```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```

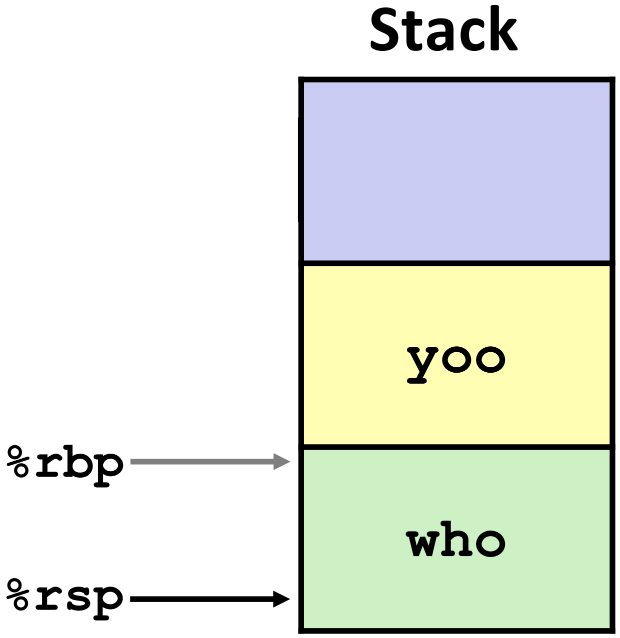




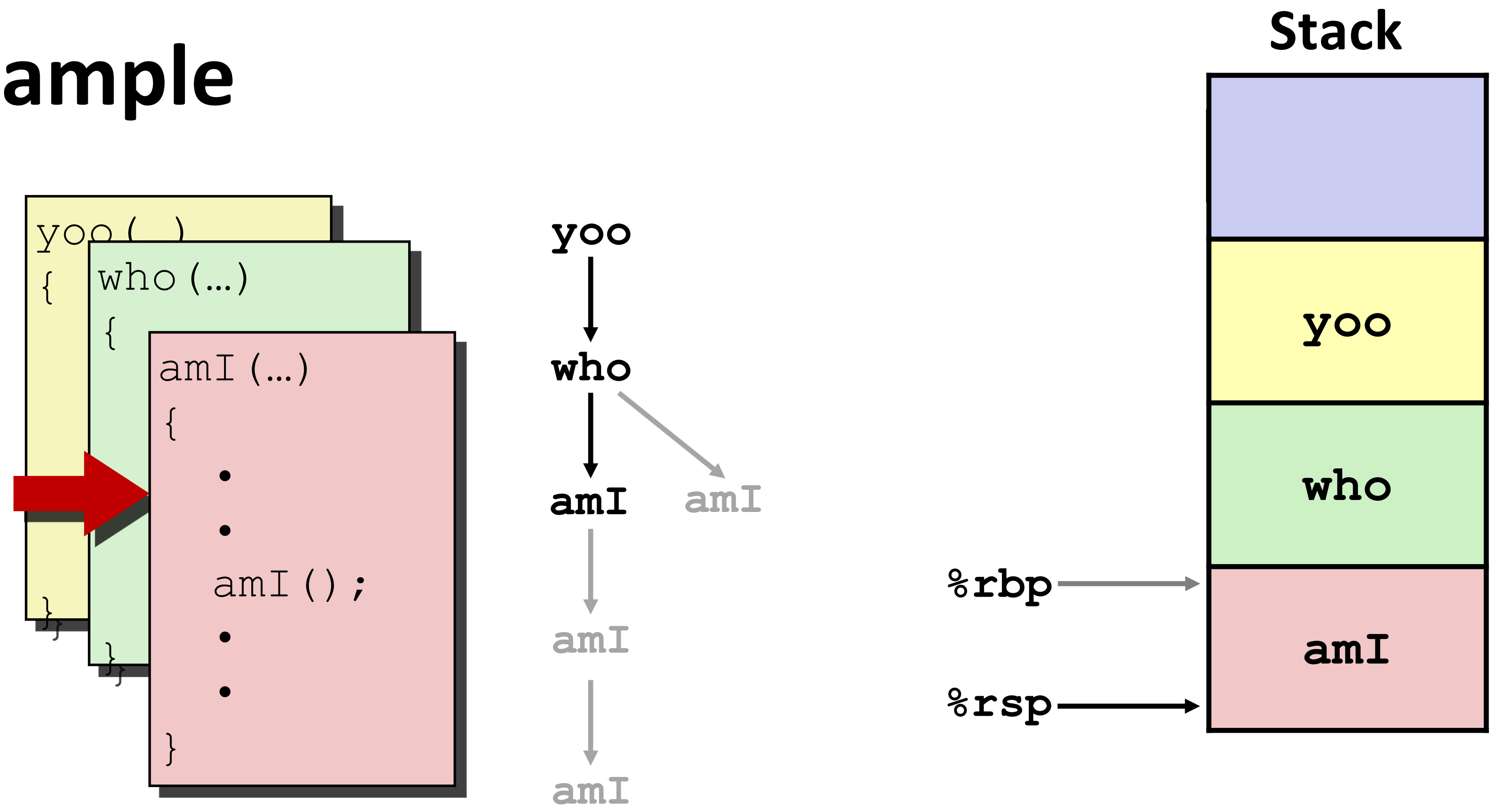
Example



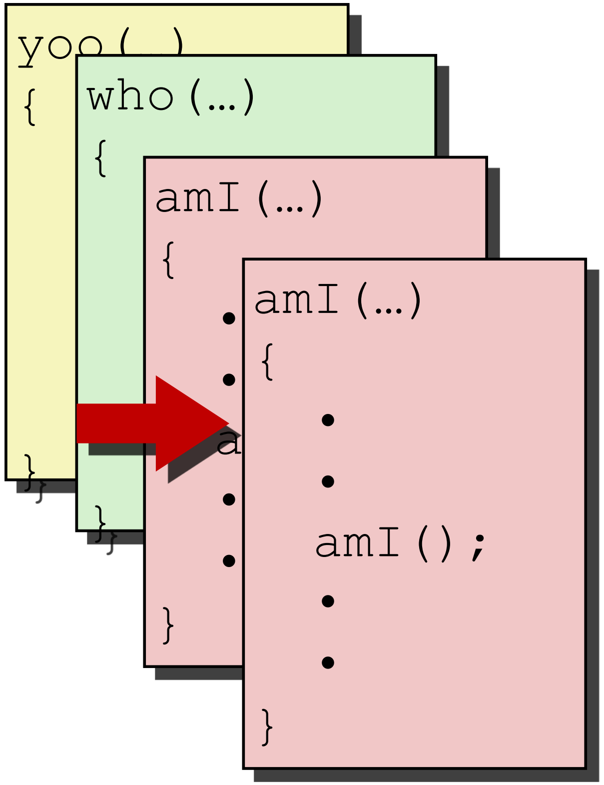




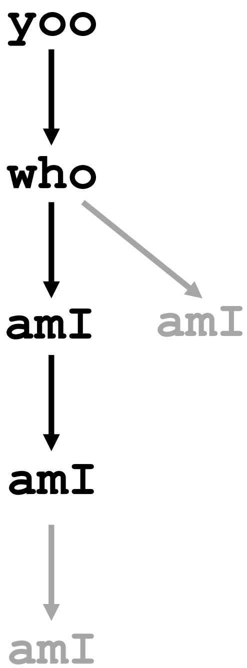
Example


yoo (…)
{
}
who (…)
{
}
amI (…)
{
•
•
amI ();
•
•
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
%rbp
%rsp

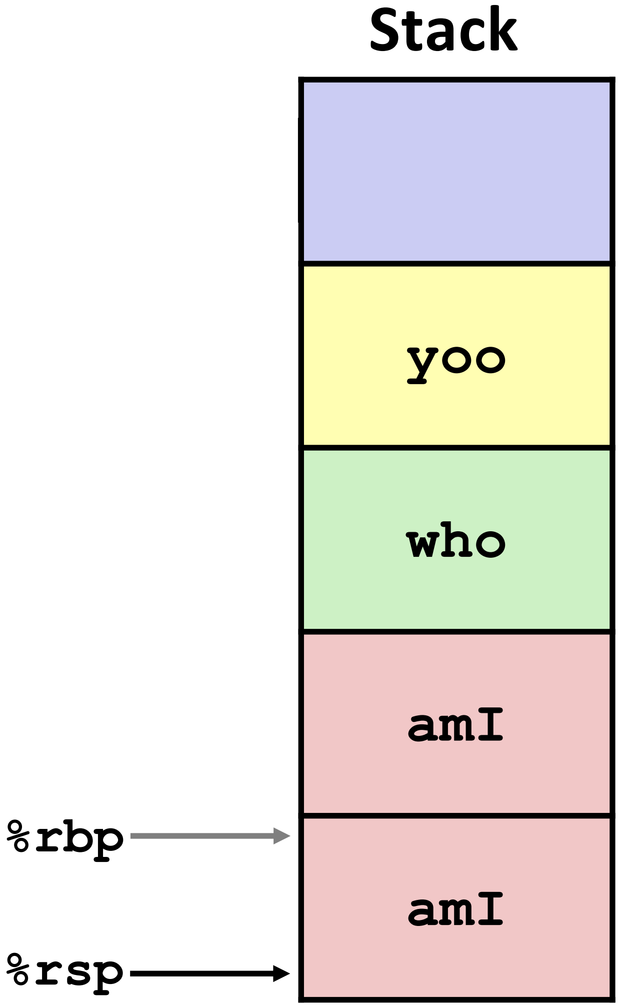
Example



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

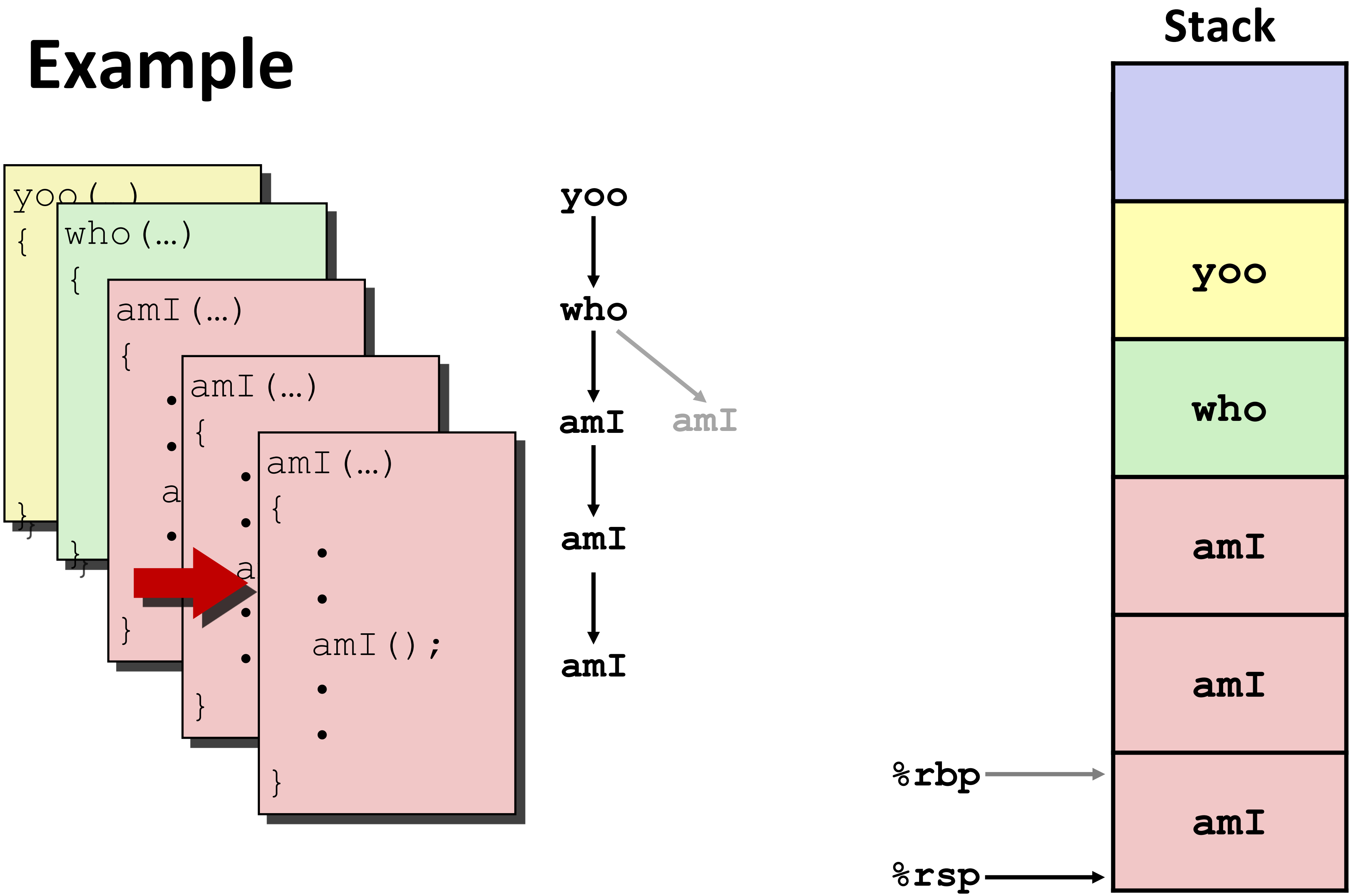


yoo
who
amI
amI
amI
amI

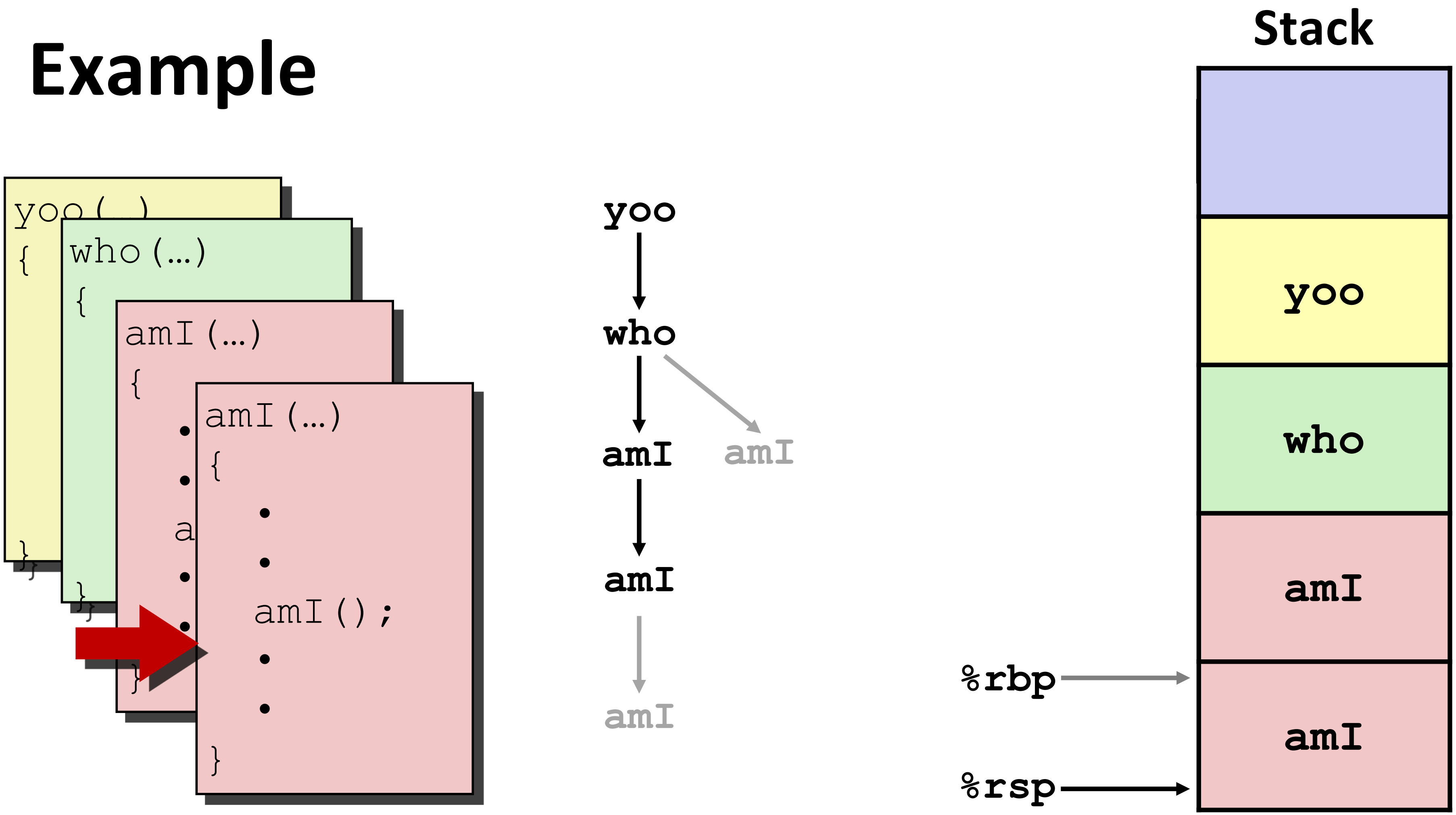


Stack
yoo
who
amI
amI
%rbp
%rsp

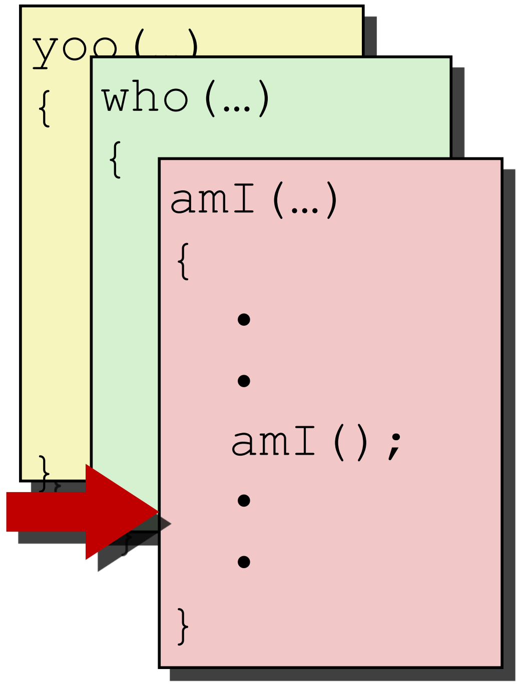
Example


yoo(…)
{
who(…)
{
amI(…)
{
amI(…)
{
amI(…)
{
amI();
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
amI
amI
%rbp
%rsp

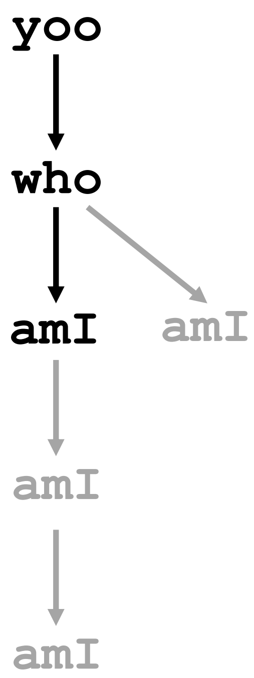
Example


yoo(…)
{
who(…)
{
amI(…)
{
a
amI(…)
{
amI();
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
amI
%rbp
%rsp

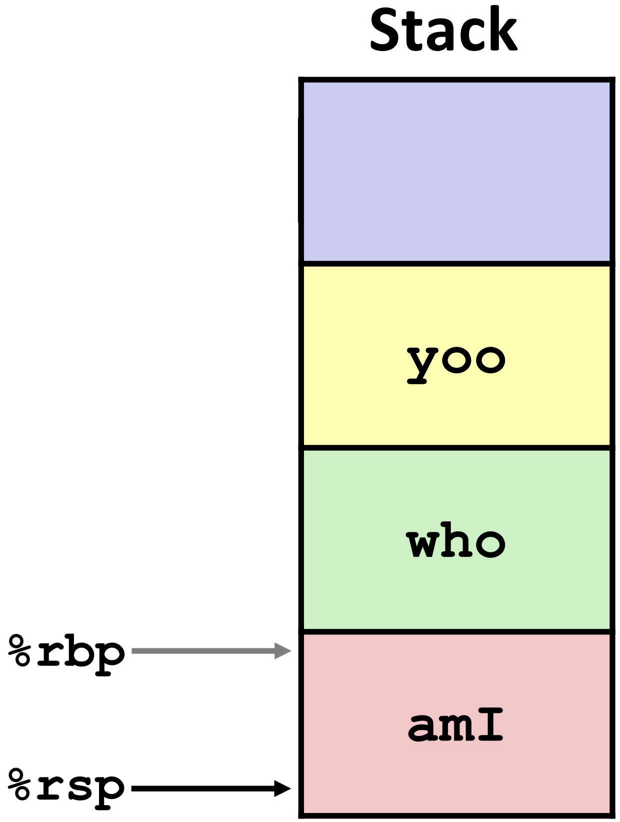
Example



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

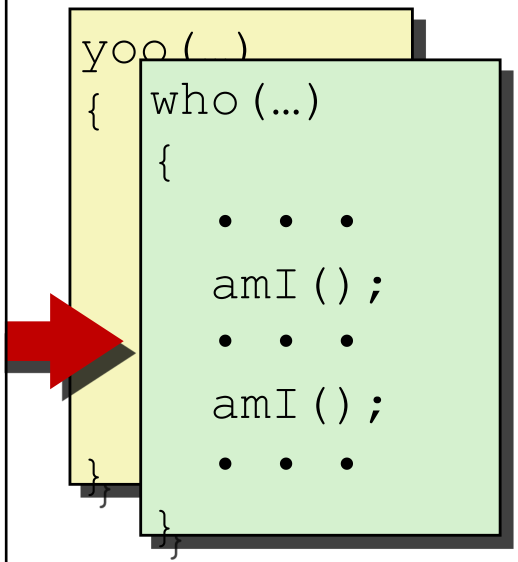


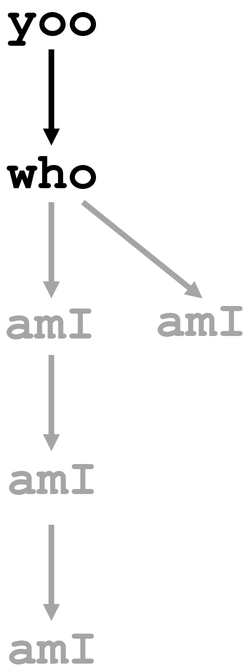
yoo
who
amI
amI
amI
amI

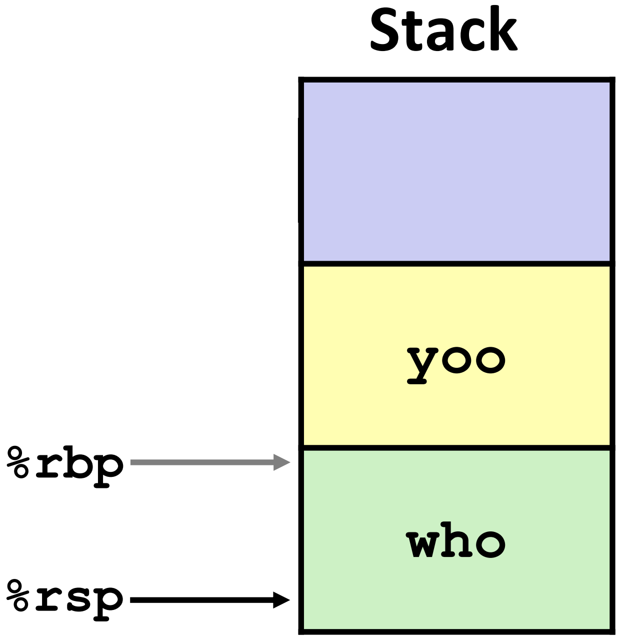


Stack
yoo
who
amI
%rbp
%rsp

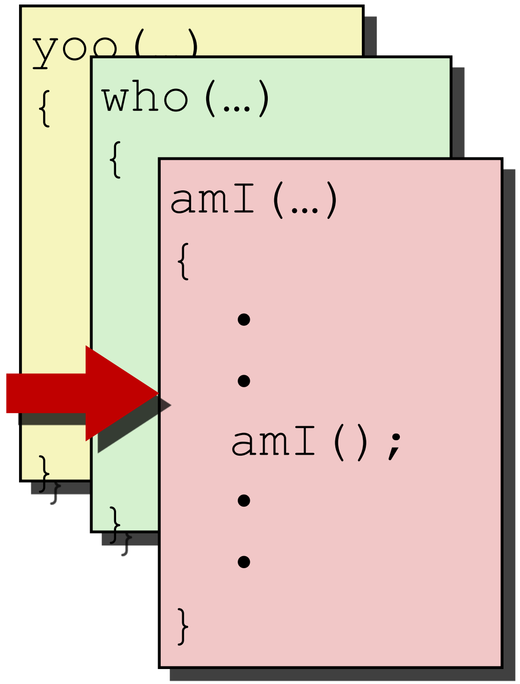
Example

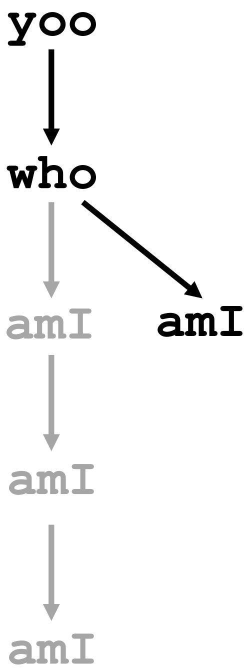


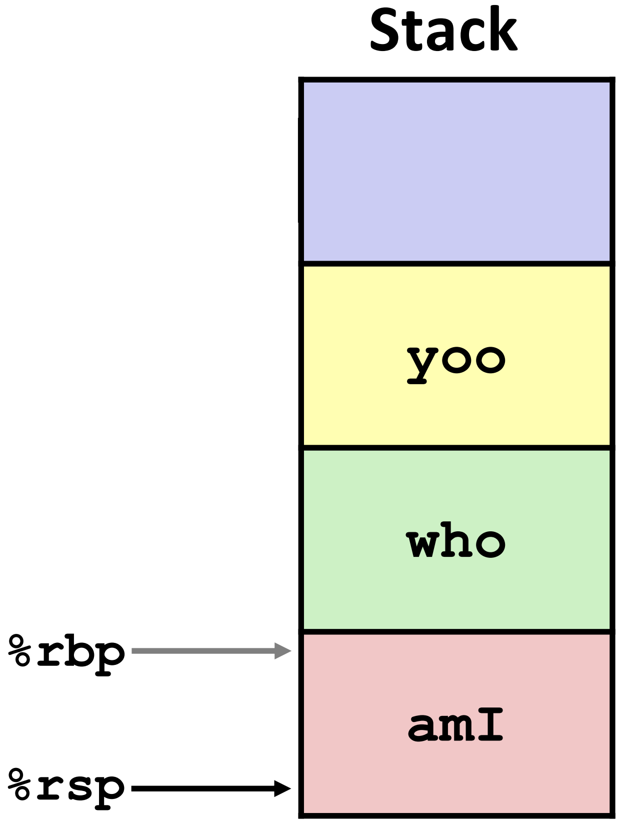




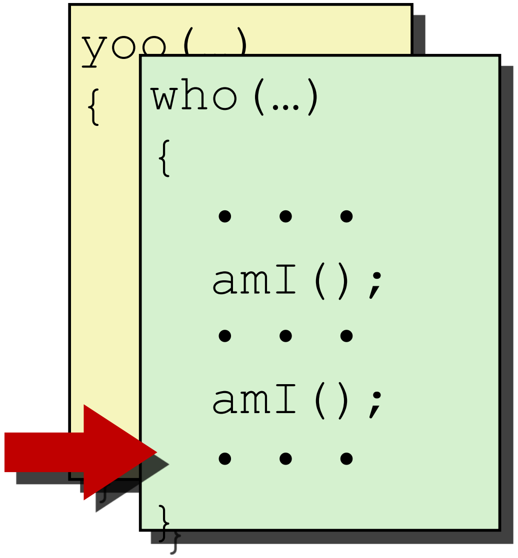
Example

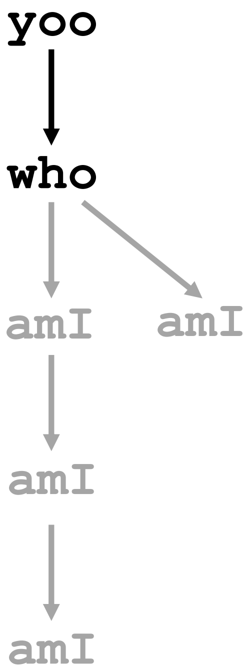

yoo(…)
{
who(…)
{
amI(…)
{
•
•
amI();
•
•
}
}
}

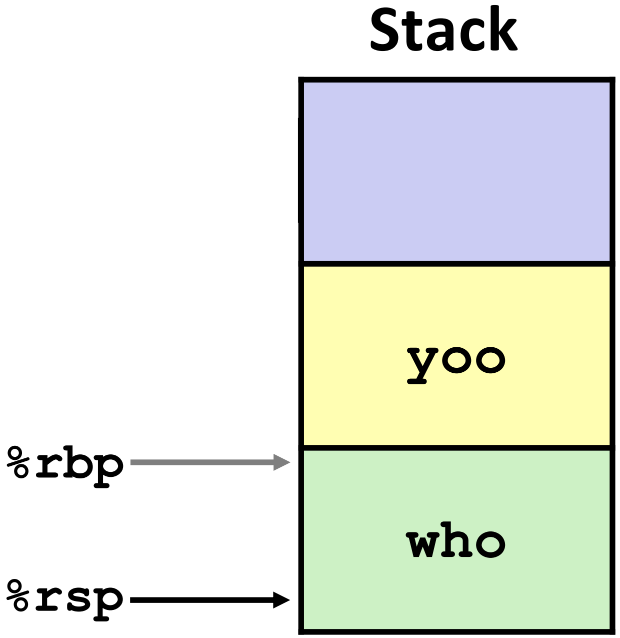

yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
%rbp
%rsp

Example

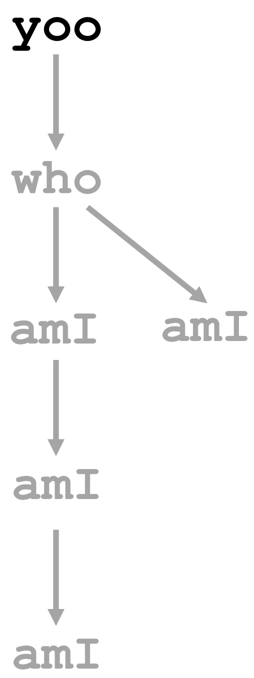


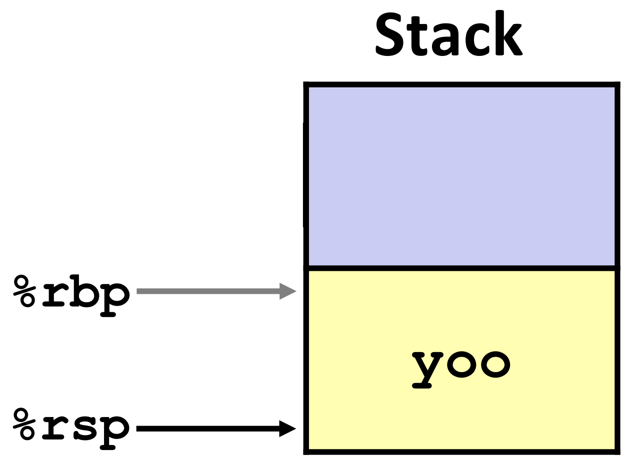




Example

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





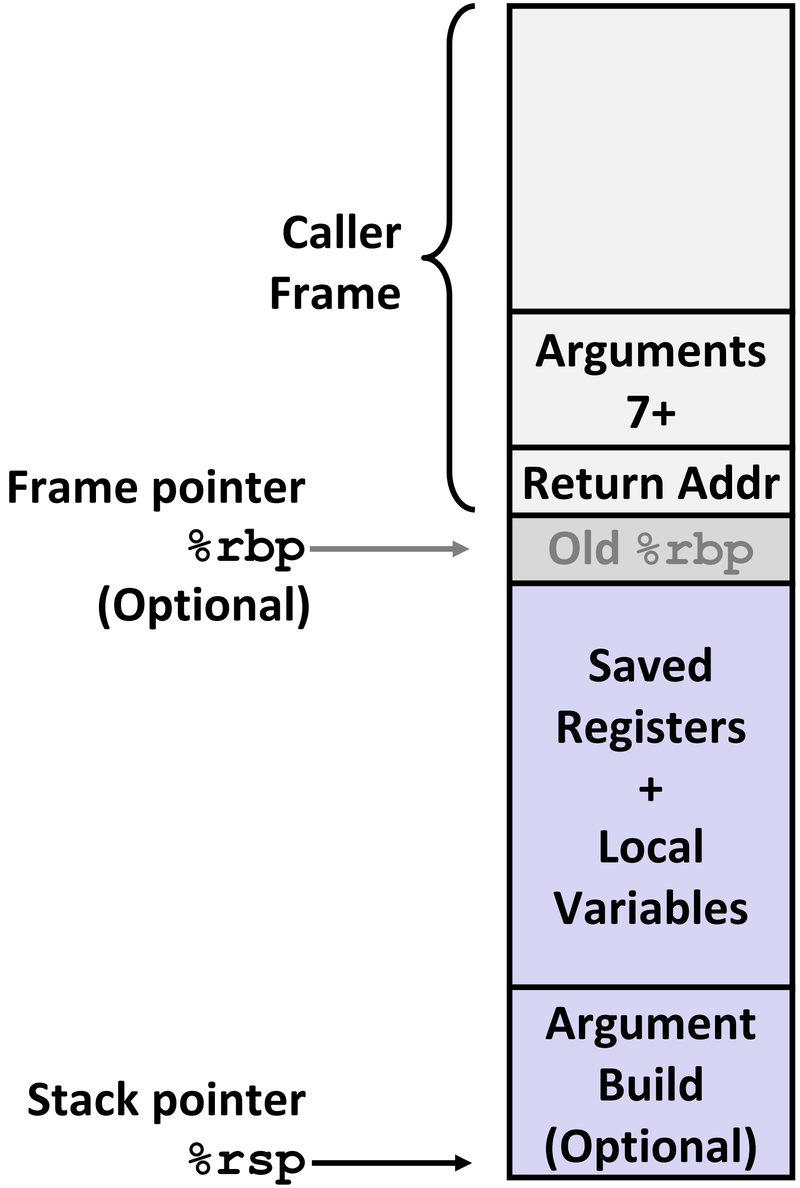
x86-64/Linux Stack Frame

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;
}
```

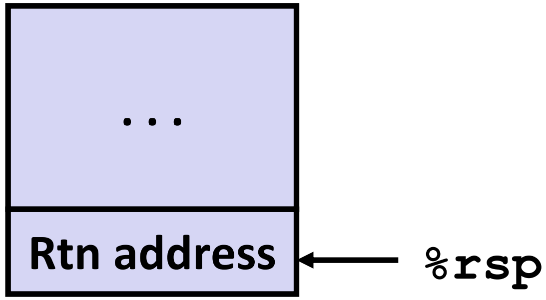
```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```

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

Example: Calling `incr` #1

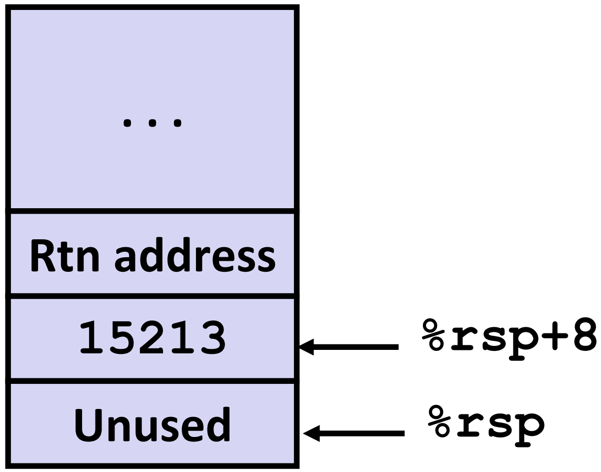
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

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

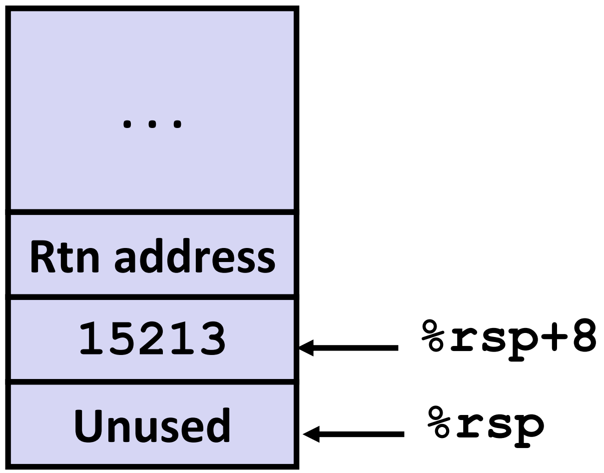


Example: Calling `incr` #2

```
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

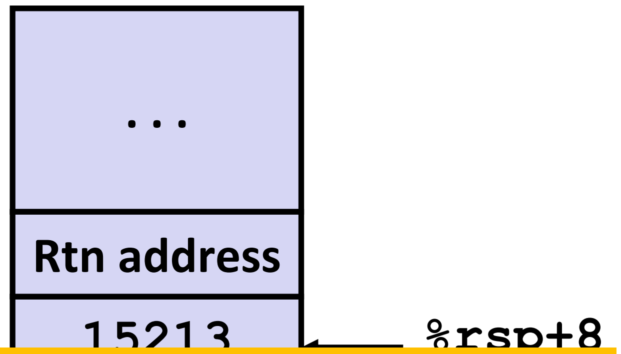


Register	Use(s)
%rdi	&v1
%rsi	3000

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.

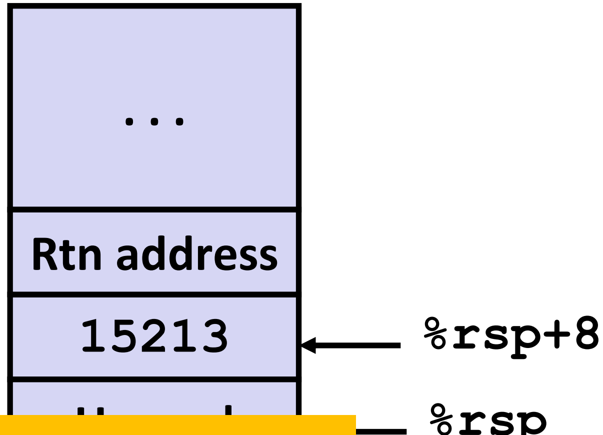
```
ca
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

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

	se(s)
	v1
%rsi	3000

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

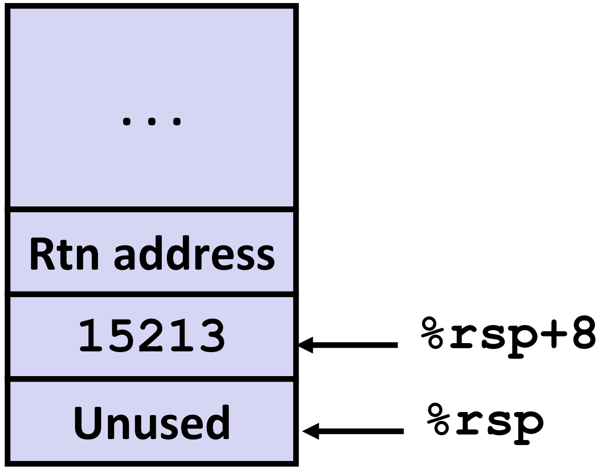
- Computes %rsp+8
- Actually, used for what it is meant!

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



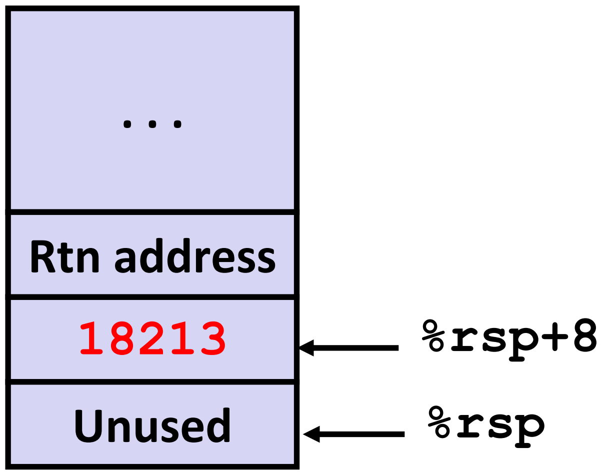
Register	Use(s)
%rdi	&v1
%rsi	3000

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



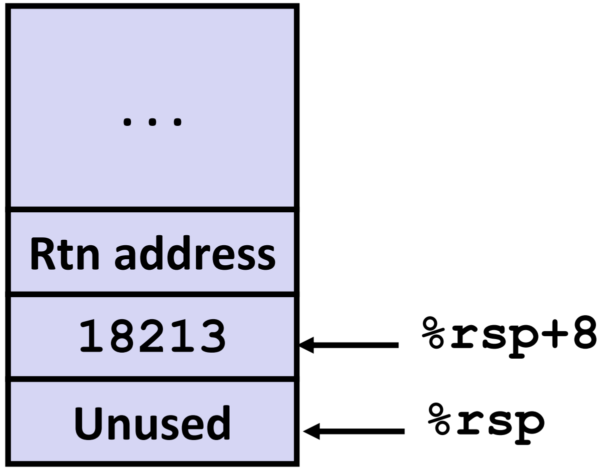
Register	Use(s)
%rdi	&v1
%rsi	3000

Example: Calling `incr` #4

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

```
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



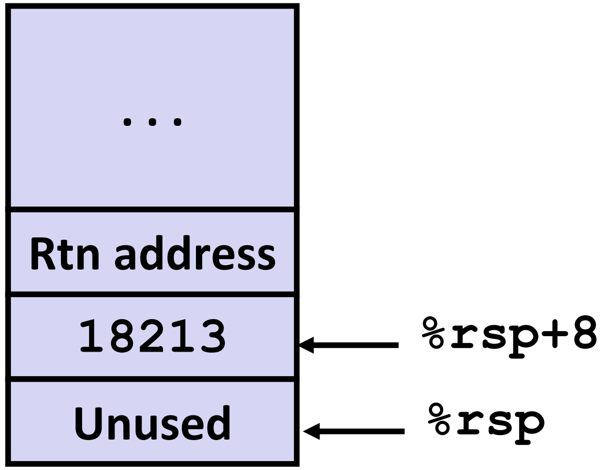
Register	Use(s)
`%rax`	Return value

Example: Calling `incr` #5a

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

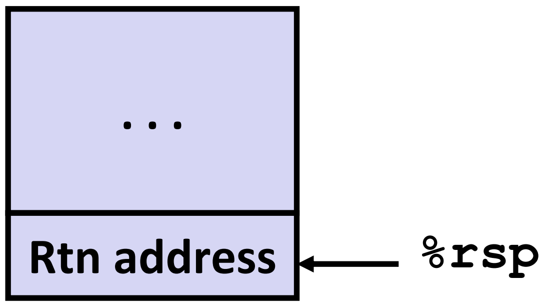
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure



Register	Use(s)
%rax	Return value

Updated Stack Structure

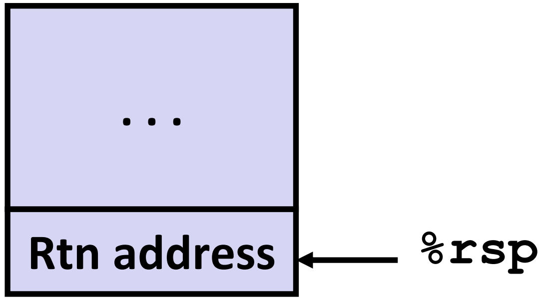


Example: Calling `incr` #5b

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

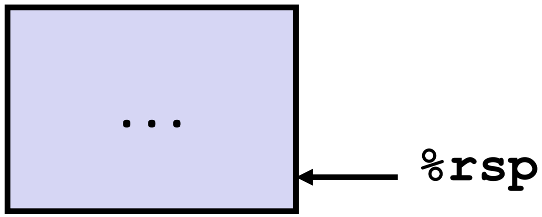
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

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
```

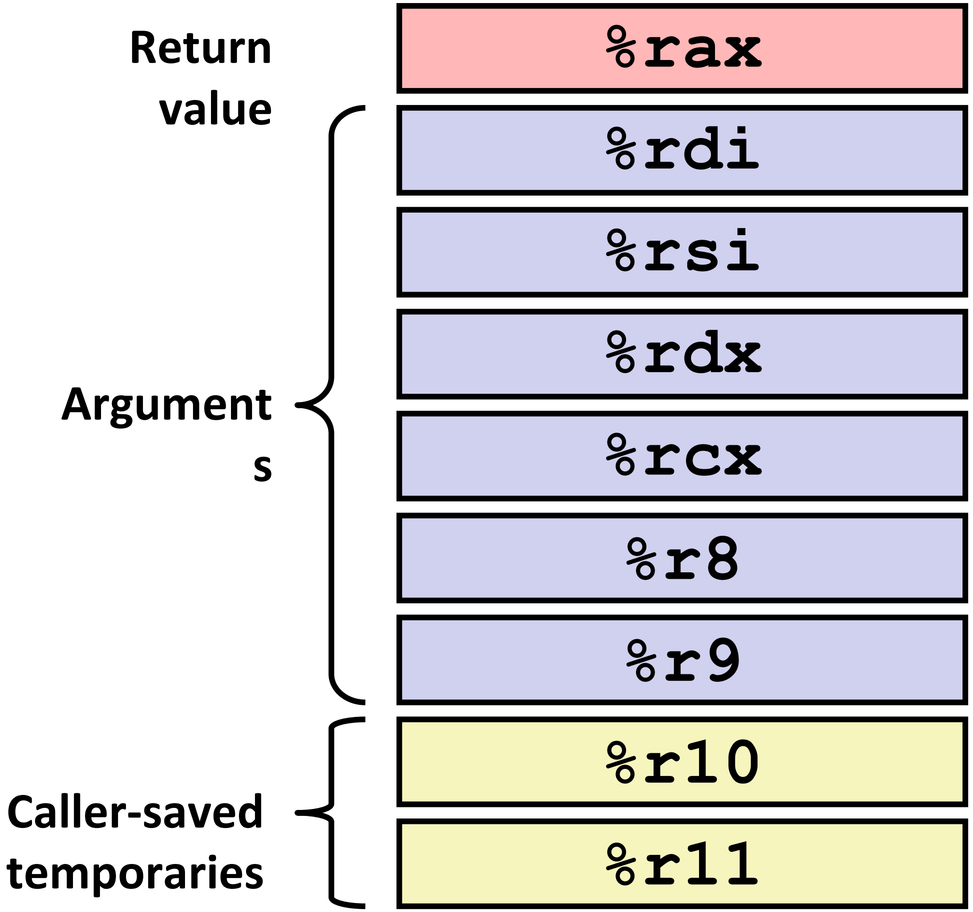
- Contents of register `%rdx` overwritten by `who`
- This could be trouble → something should be done!
  - Need some coordination

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")***
    - 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`

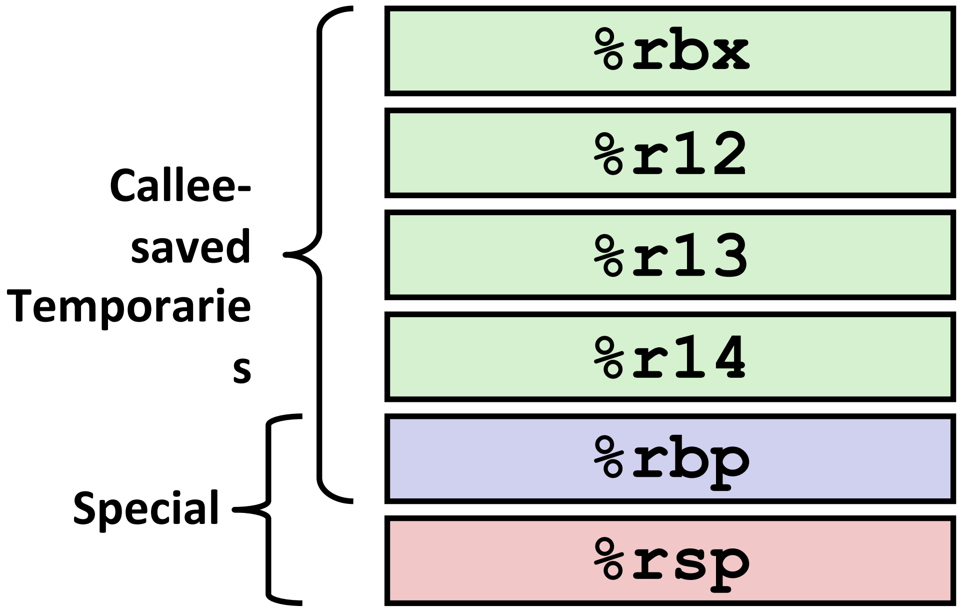
- Callee-saved
- Callee must save & restore

`%rbp`

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

`%rsp`

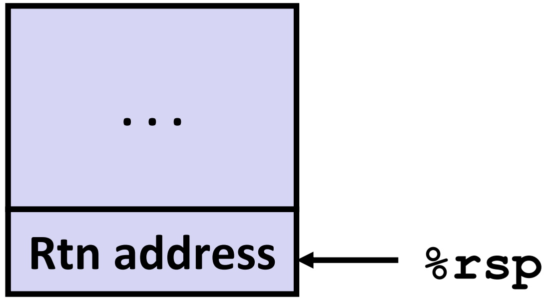
- Special form of callee save
- Restored to original value upon exit from procedure



Callee-Saved Example #1

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

Initial Stack Structure



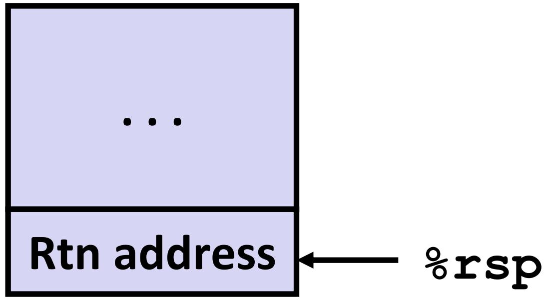
- X comes in register **%rdi**.
- We need **%rdi** for the call to incr.
- Where should be put x, so we can use it after the call to incr?

Callee-Saved Example #2

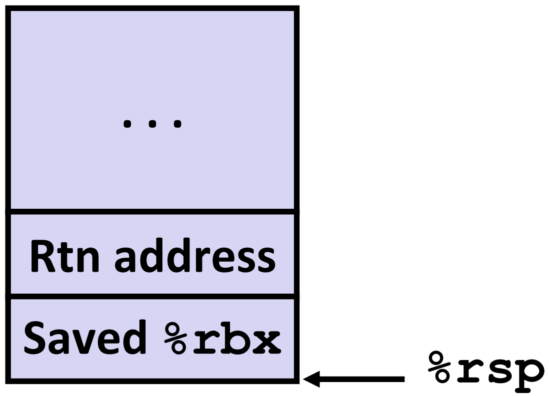
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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
```

Initial Stack Structure



Resulting Stack Structure

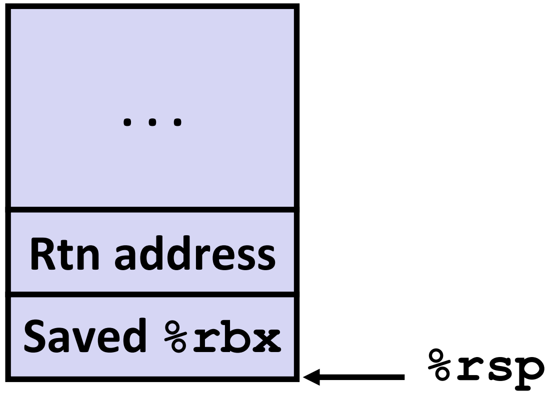


Callee-Saved Example #3

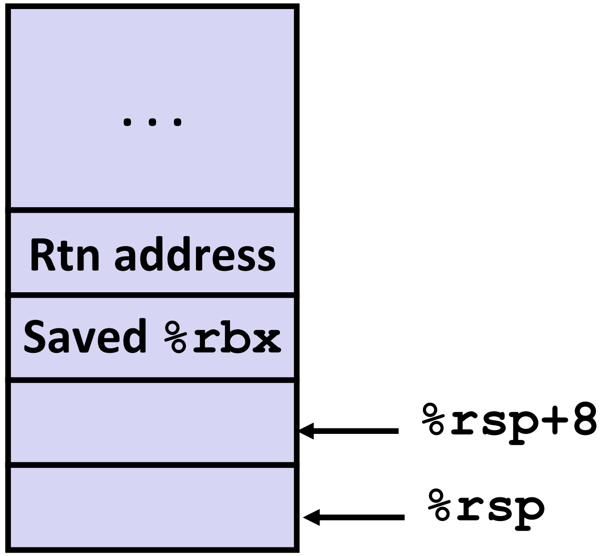
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

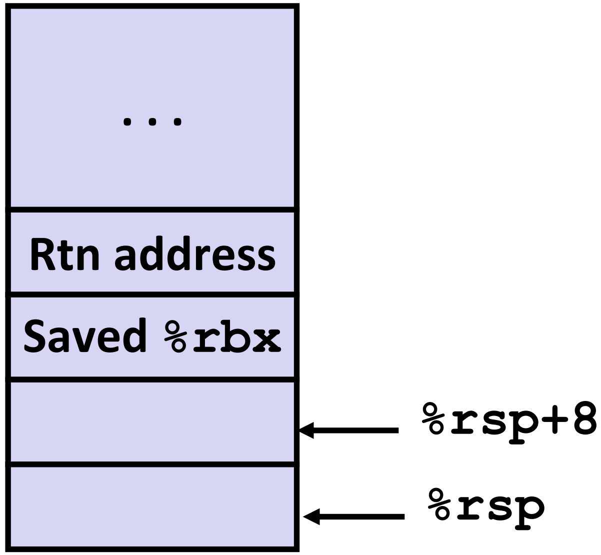


Callee-Saved Example #4

```
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



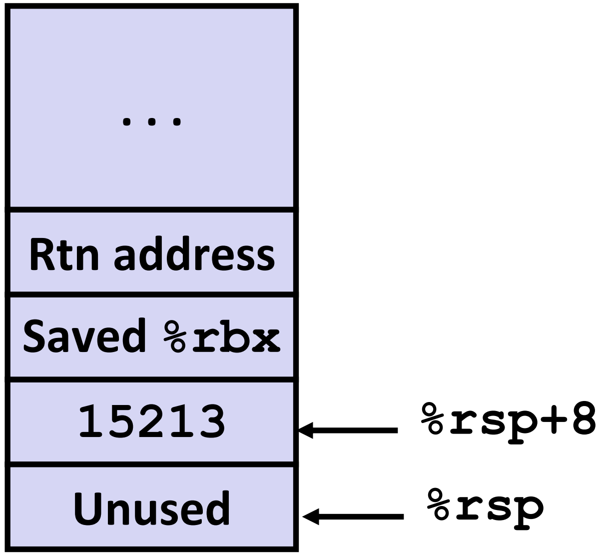
- X saved in **%rbx**.
- A callee saved register.

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



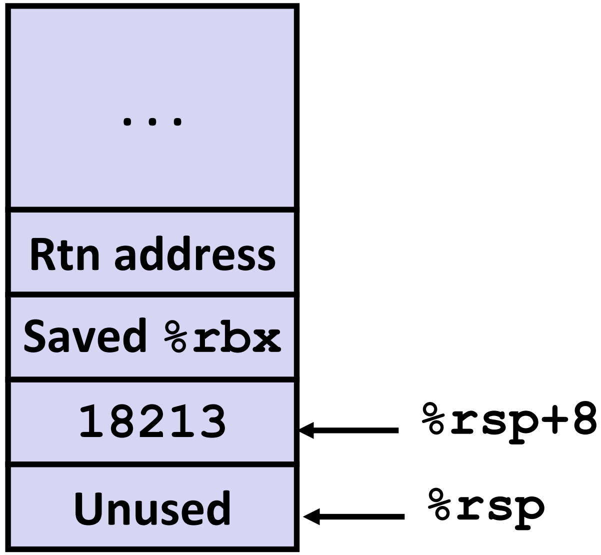
- X saved in **%rbx**.
- A callee saved register.

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



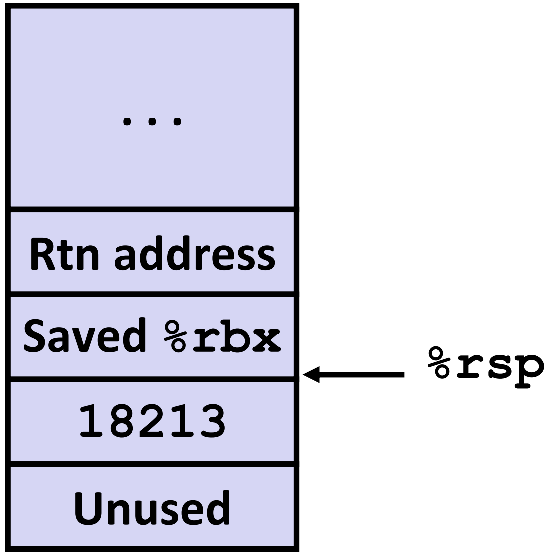
- X Is safe in **%rbx**
- Return result in **%rax**

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



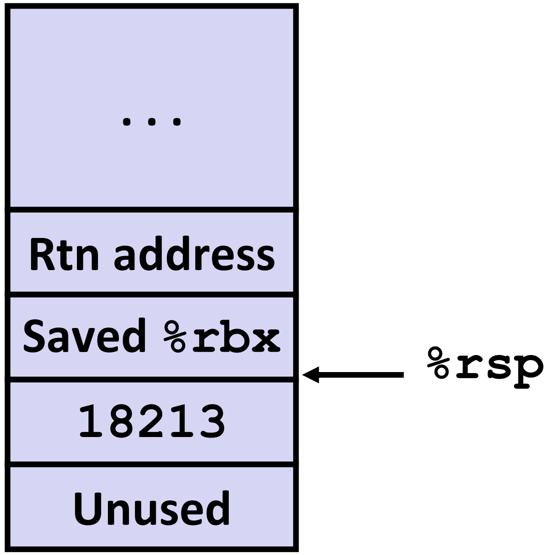
- Return result in **%rax**

Callee-Saved Example #8

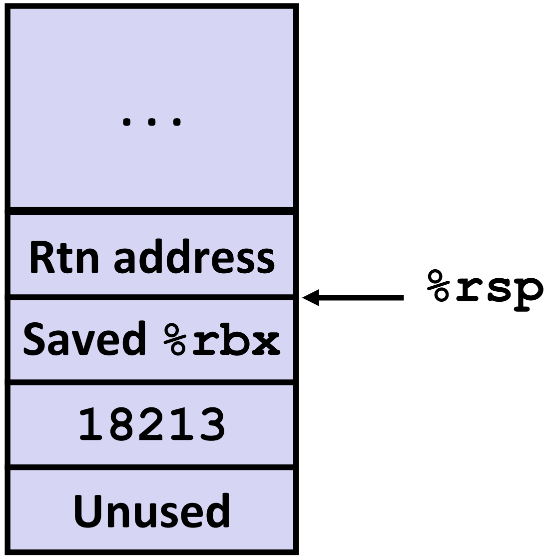
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

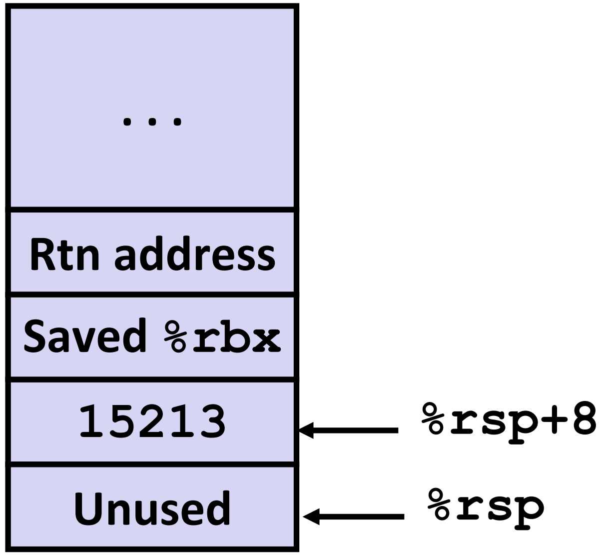


Callee-Saved Example #2

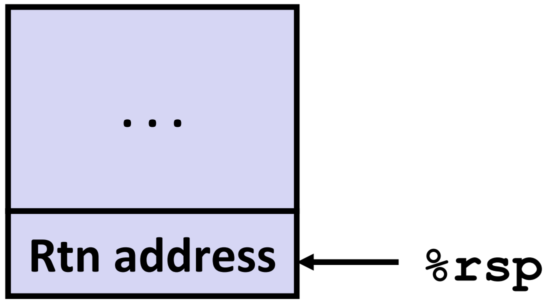
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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
```

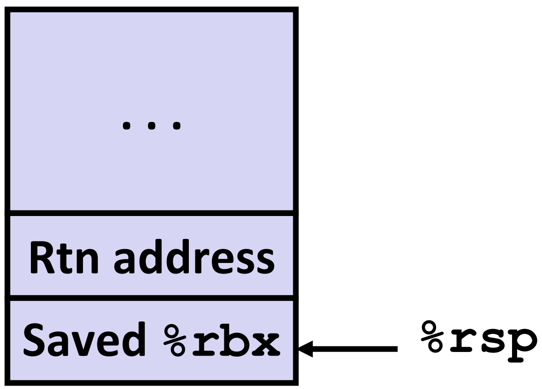
Register	Use(s)	Type
%rdi	x	Argument
%rax	Return value	Return value

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
```

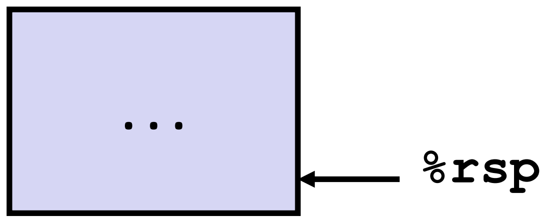
Register	Use(s)	Type
%rbx	x & 1	Callee-saved
%rax	Return value	

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**