# CS330 - Computer Organization and Assembly Language Programming

Lecture 14

-Machine Level Programming / 4-

Professor : Mahmut Unan – UAB CS

# Agenda

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

# Mechanisms in Procedures

- **Passing control**
  - To beginning of procedure code
  - Back to return point
- **Passing data**
  - Procedure arguments
  - Return value
- **Memory management**
  - Allocate during procedure execution
  - Deallocate upon return
- **Mechanisms all implemented with machine instructions**
- **x86-64 implementation of a procedure uses only those mechanisms required**

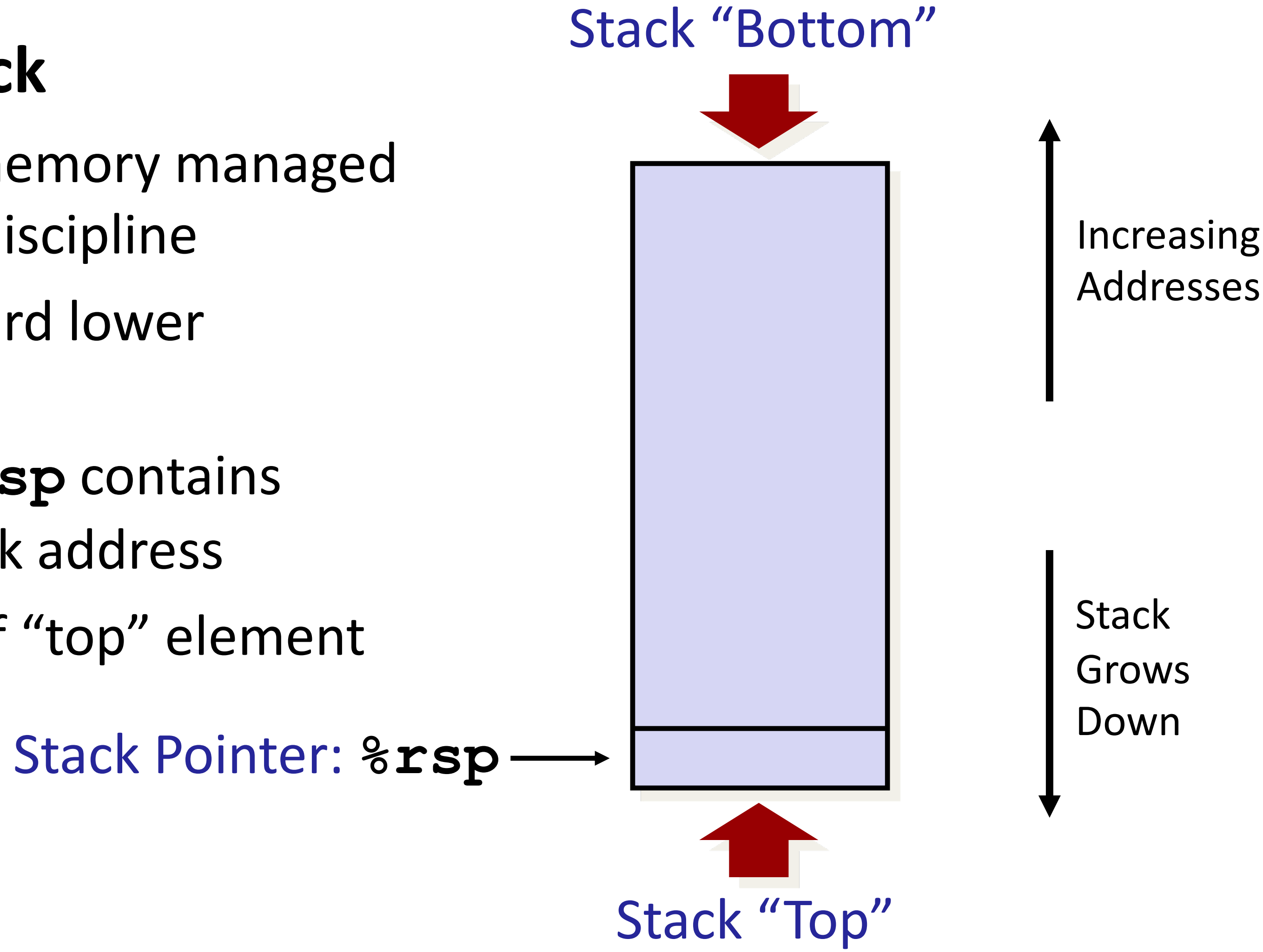
```
P(…) {
  •
  •
  y = Q(x);
  print(y)
  •
}
```

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

# Stack Structure

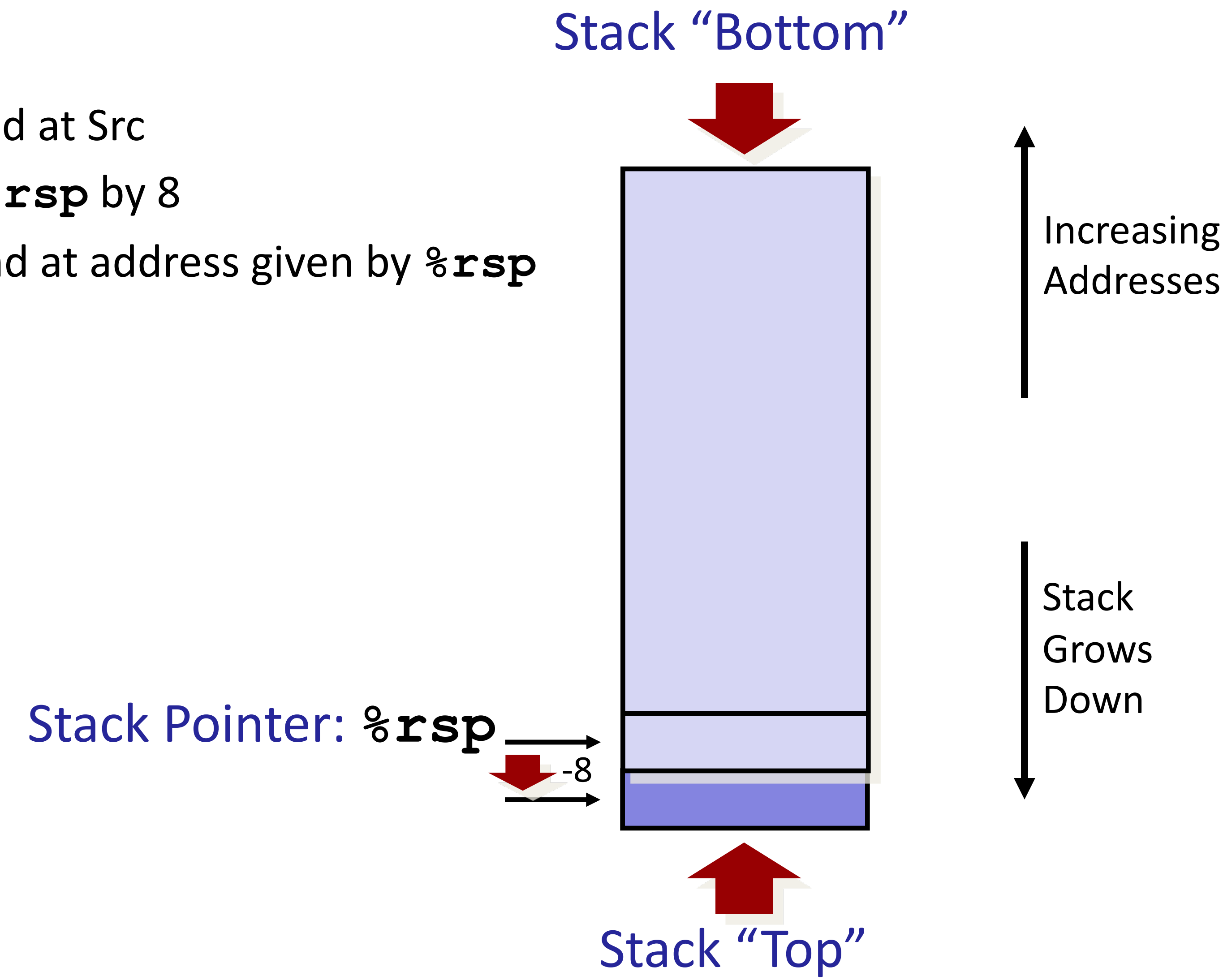
## x86-64 Stack

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



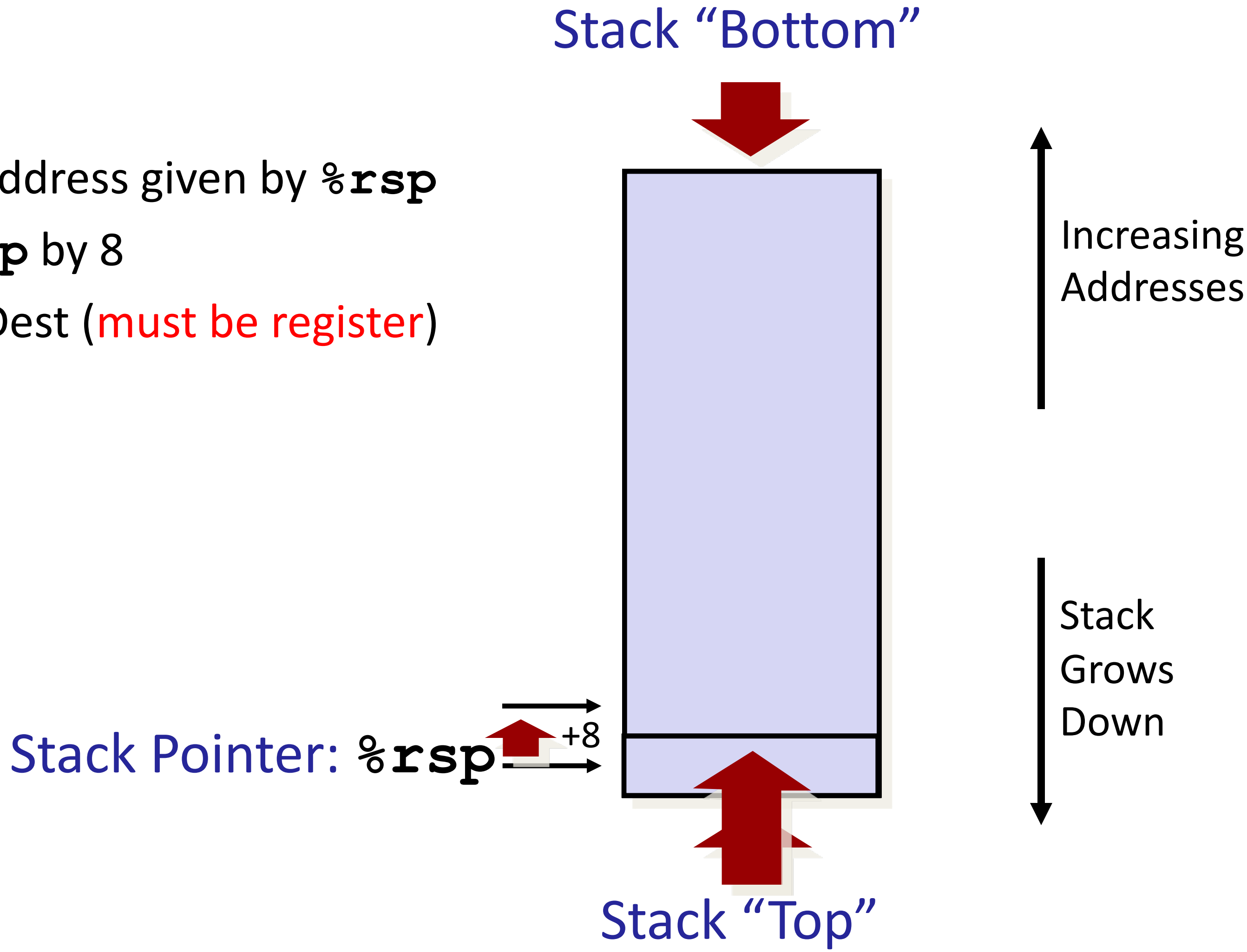
# x86-64 Stack: Push

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



# x86-64 Stack: Pop

- **`popq` Dest**
  - Read value at address given by `%rsp`
  - Increment `%rsp` by 8
  - Store value at Dest (must be register)



# Passing control
# Code Examples

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

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

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

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

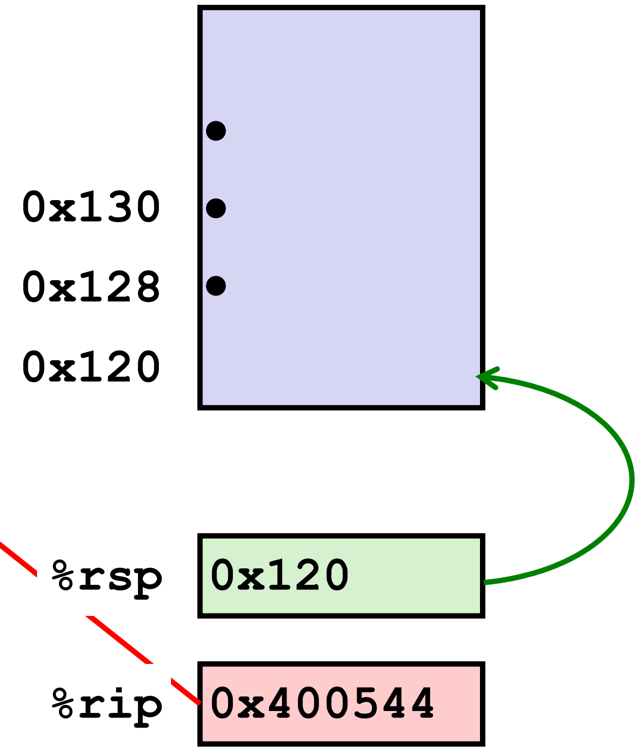
# Procedure Control Flow

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

# Control Flow Example #1

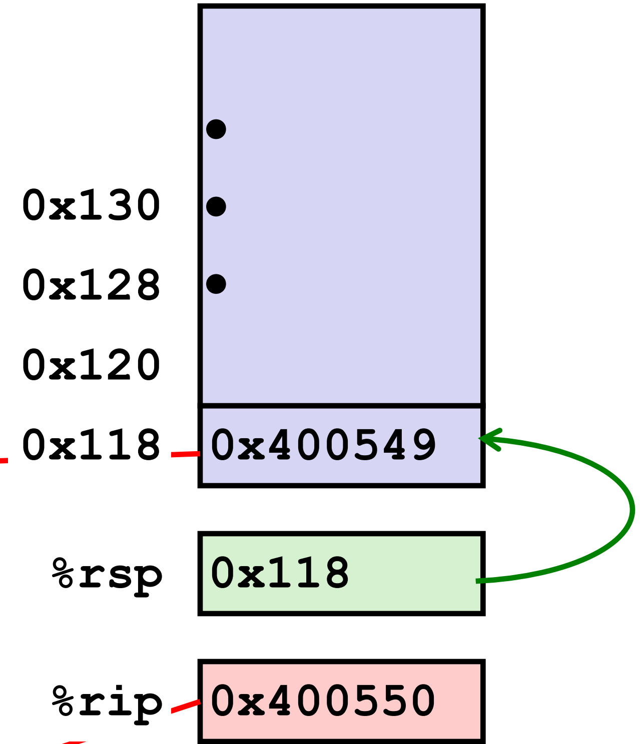
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

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



# Control Flow Example #2

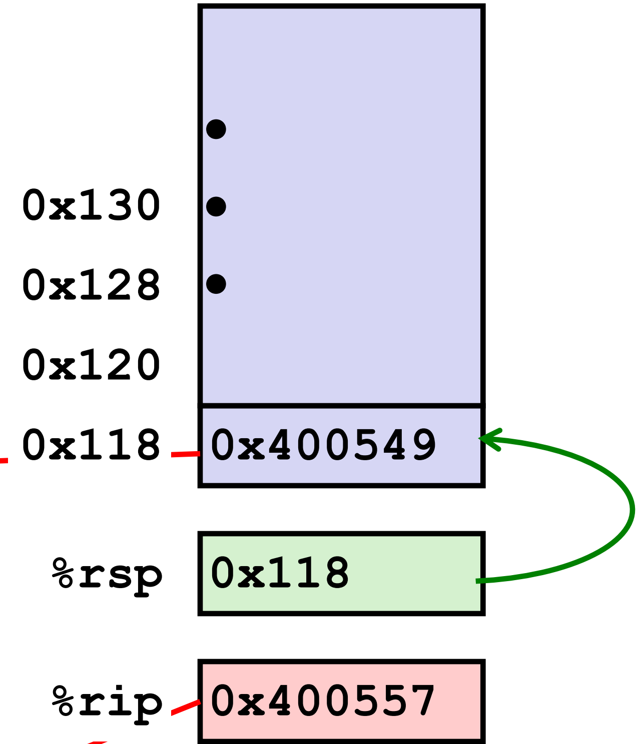
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```




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

# Control Flow Example #3

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

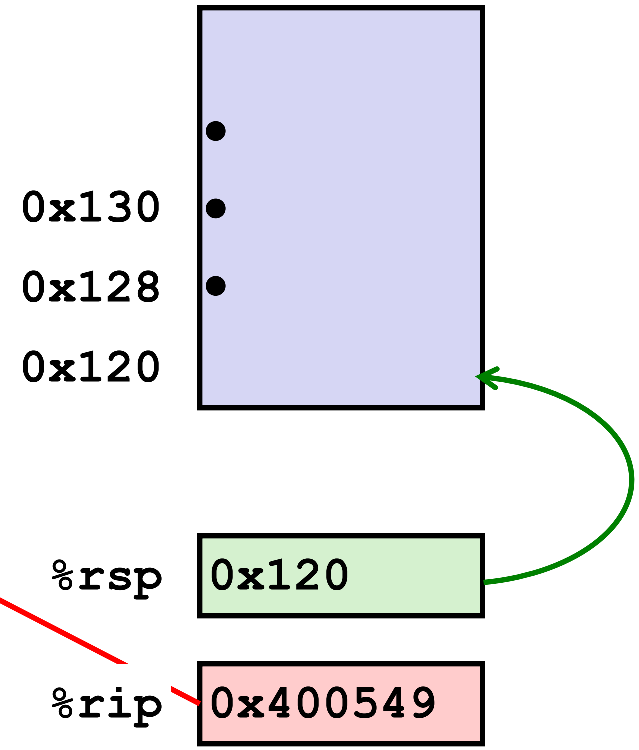



```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```

# Control Flow Example #4

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

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



# **Passing data :** Procedure Data Flow

## Registers

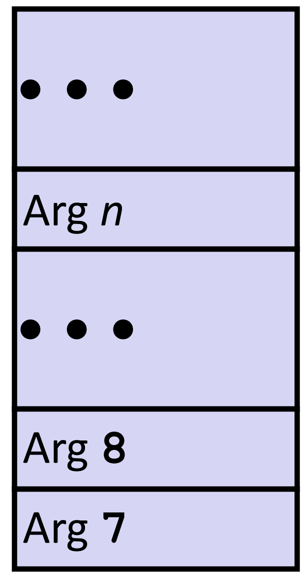
- First 6 arguments

| |
|---|
| `%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: callq  400550 <mult2>   # mult2(x,y)
  # t in %rax
  400549: mov    %rax,(%rbx)   # Save at dest
  • • •
```

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

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

# **Managing local data :** 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

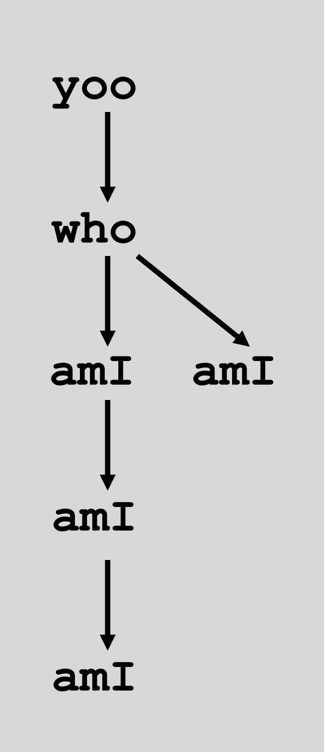
```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```

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

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

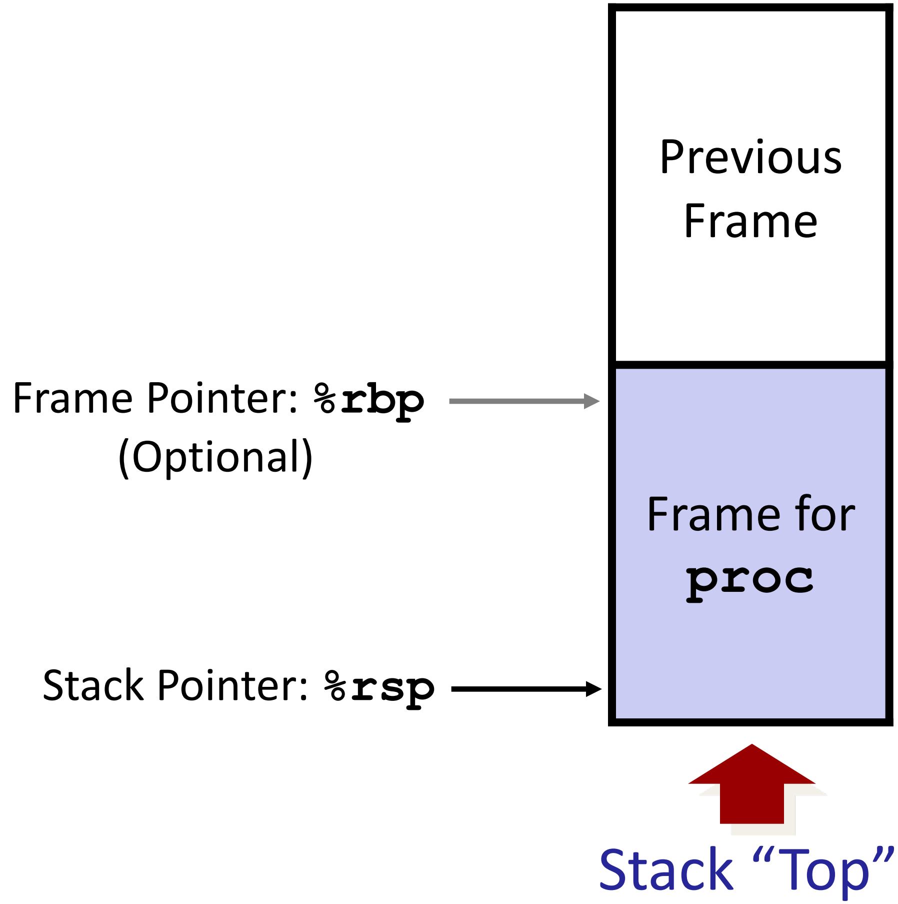
Procedure **`amI()`** is recursive

Example
Call Chain



# Stack Frames

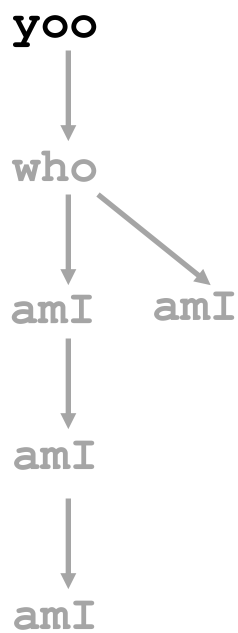
- **Contents**
  - Return information
  - Local storage (if needed)
  - Temporary space (if needed)

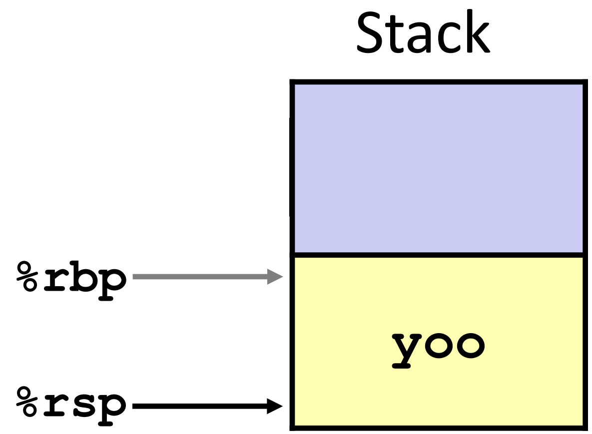



- **Management**
  - Space allocated when enter procedure
    - “Set-up” code
    - Includes push by `call` instruction
  - Deallocated when return
    - “Finish” code
    - Includes pop by `ret` instruction

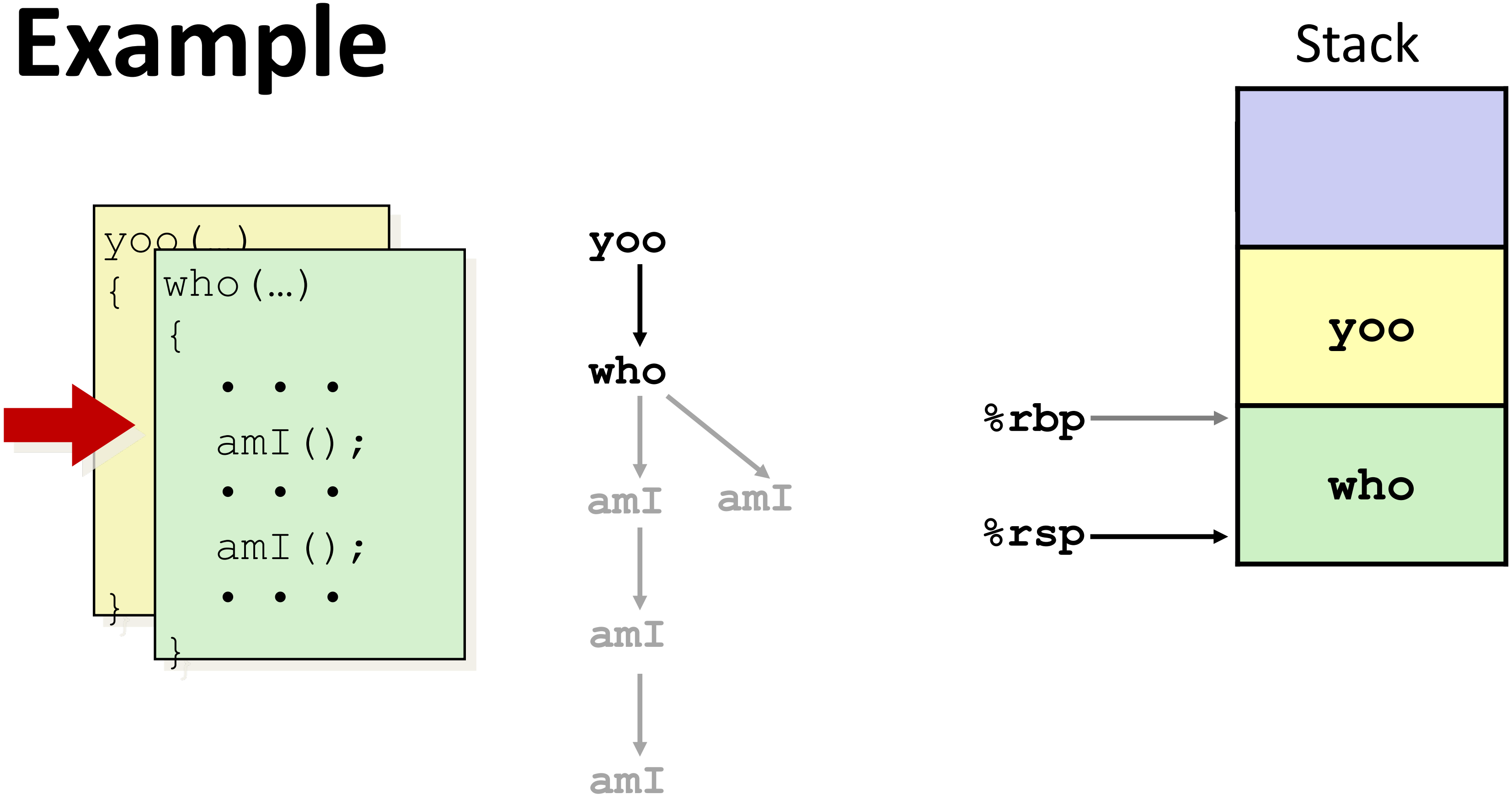
# Example

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

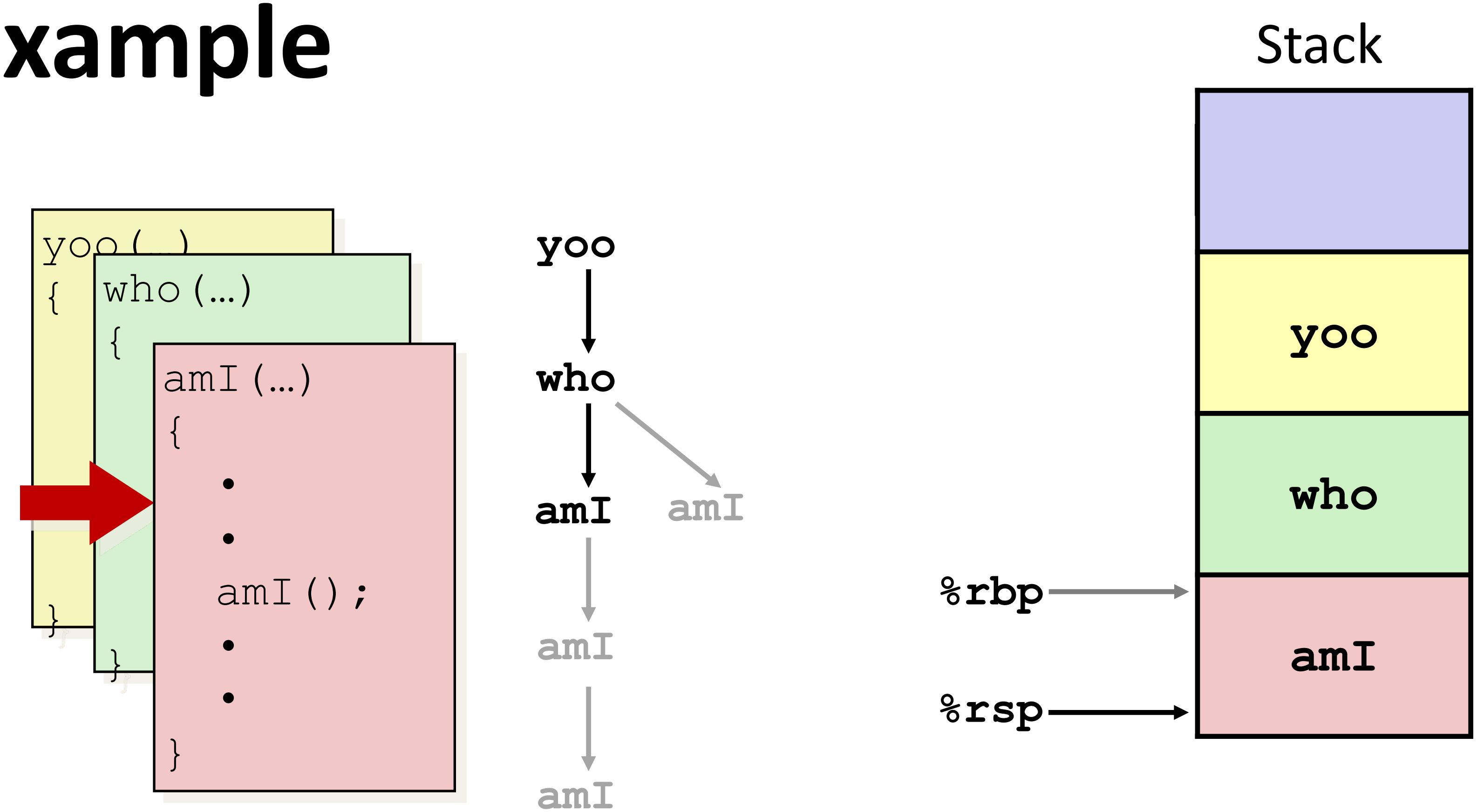


# Example

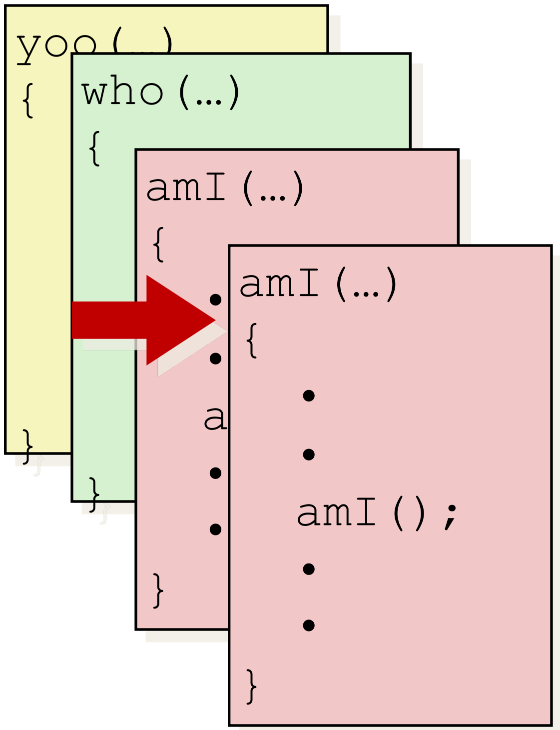


# Example

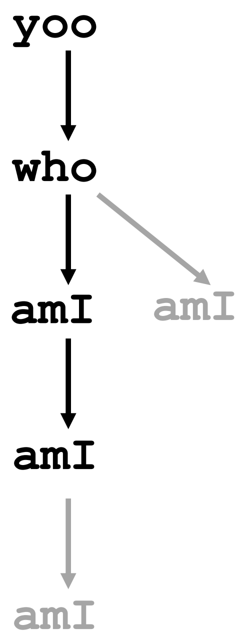


yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
amI();
•
•
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
%rbp
%rsp

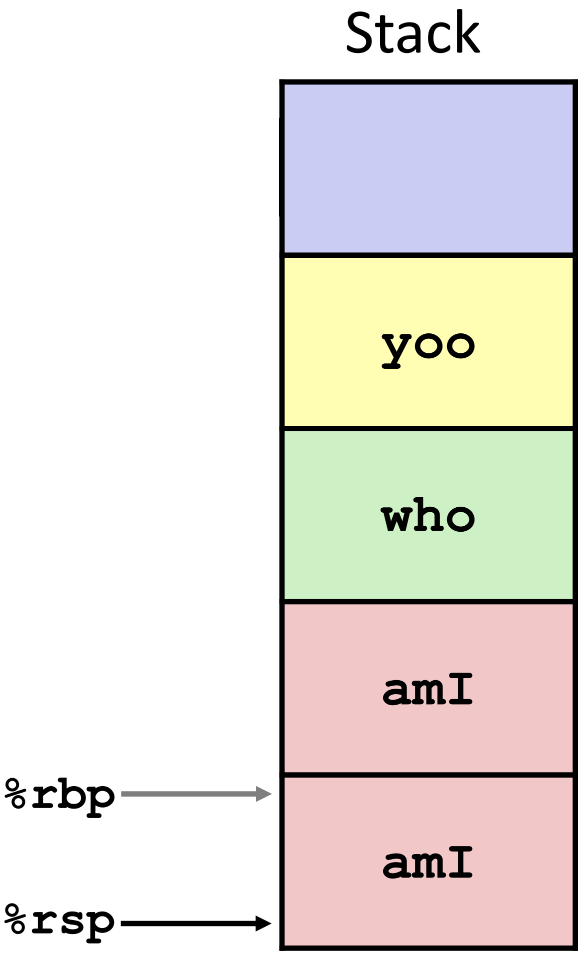
# Example



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

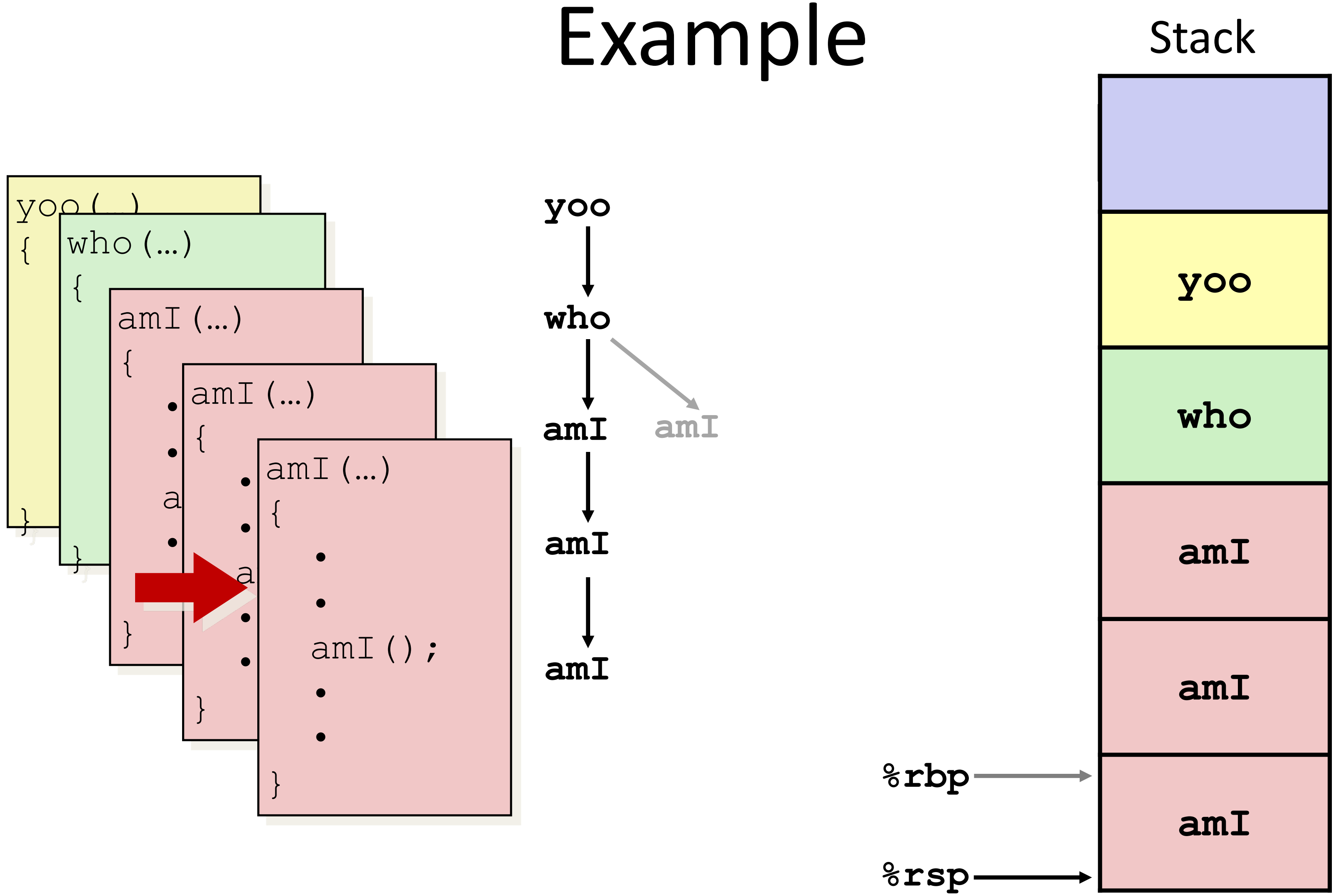



yoo
who
amI
amI
amI
amI

Stack
yoo
who
amI
amI
%rbp
%rsp

# Example


yoo(…)
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who(…)
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amI(…)
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amI(…)
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Stack
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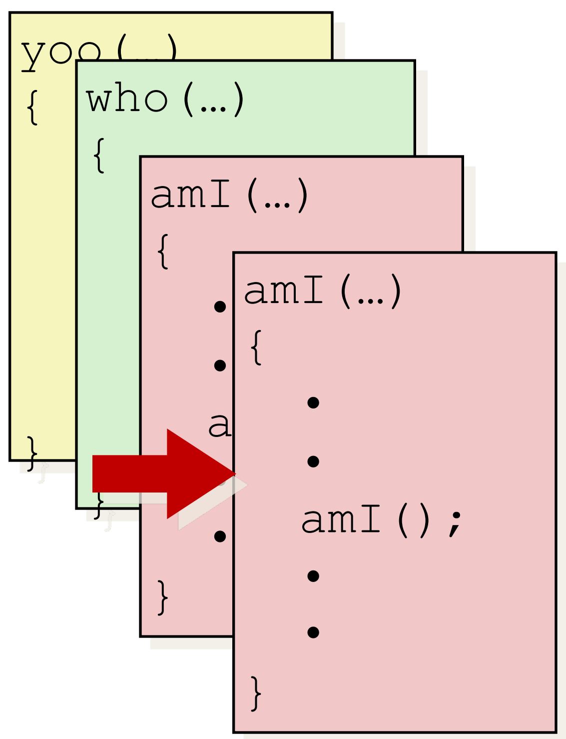
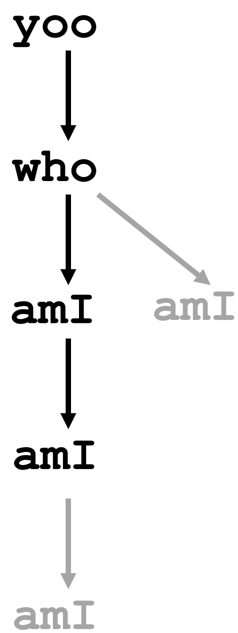
%rbp
%rsp

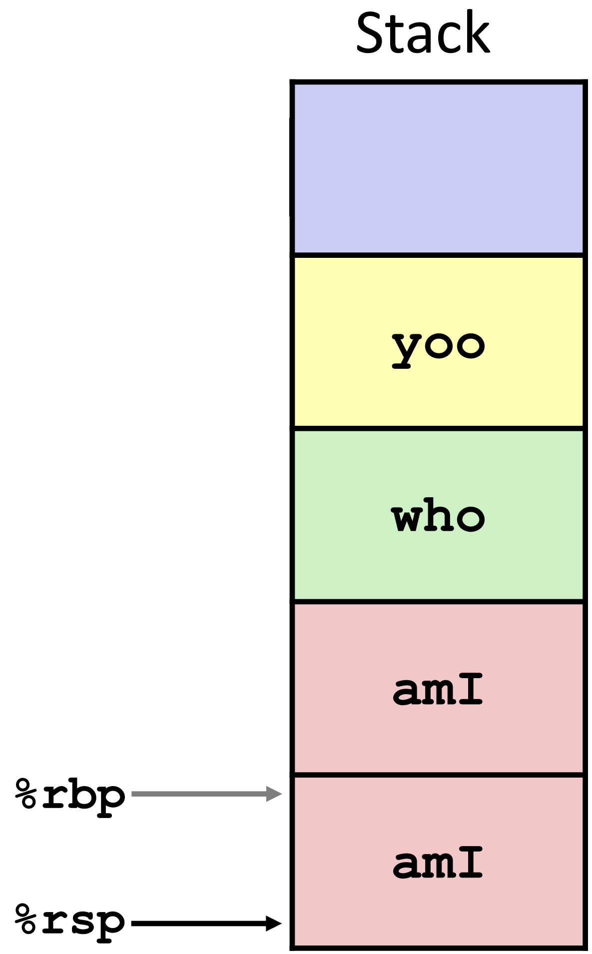
# Example



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

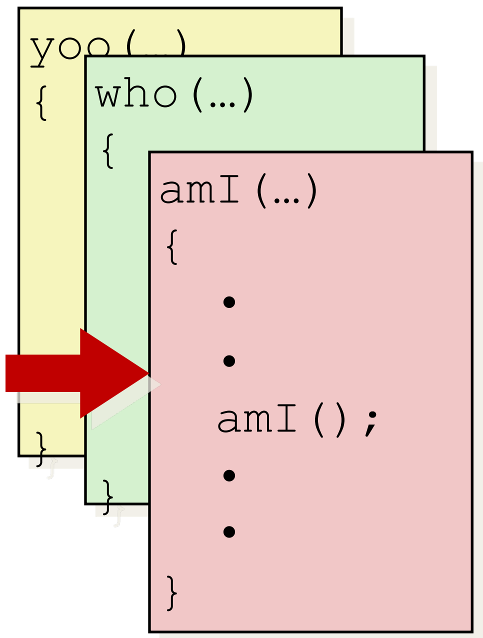



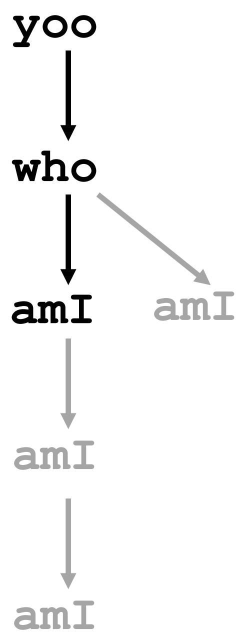
yoo
who
amI
amI
amI
amI

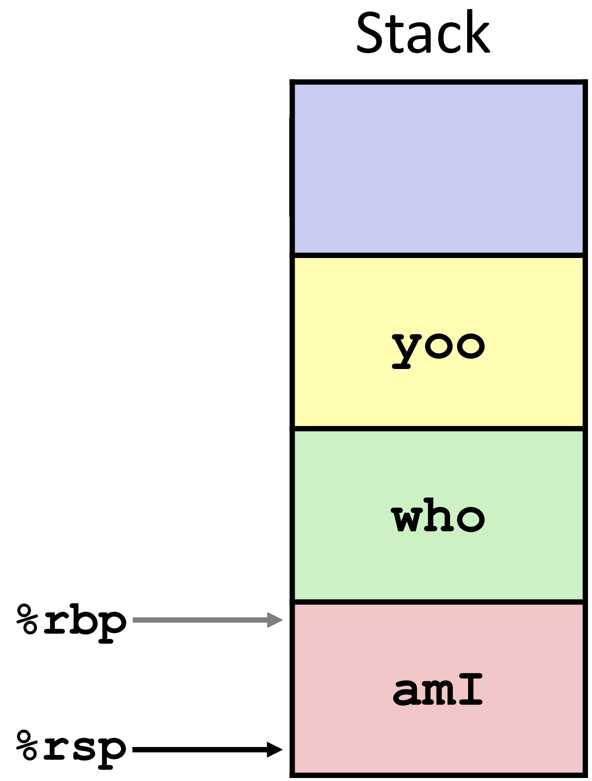



Stack
yoo
who
amI
amI
%rbp
%rsp

# Example


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

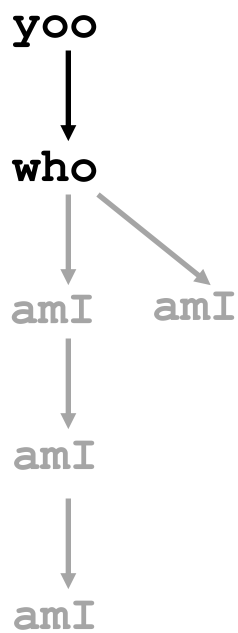

yoo
who
amI
amI
amI
amI

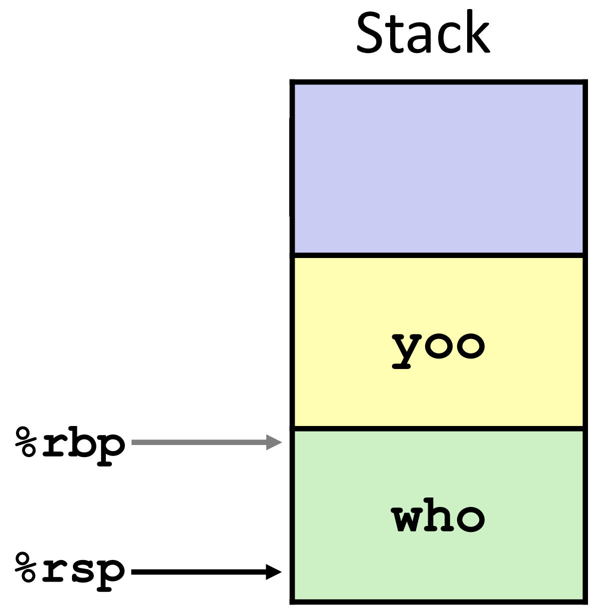

Stack
yoo
who
amI
%rbp
%rsp

# Example

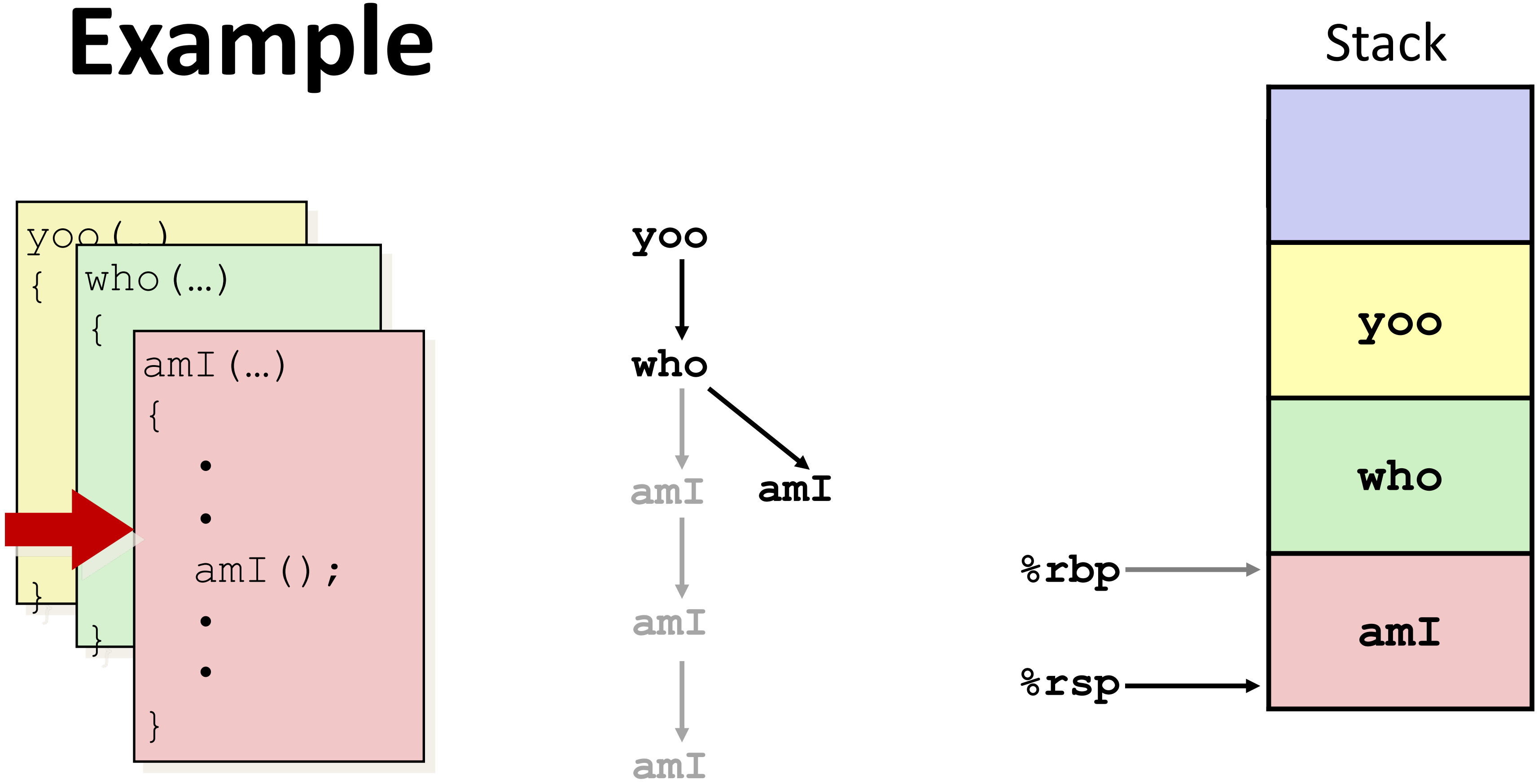
```
yoo(…)
{

}
```

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



# Example

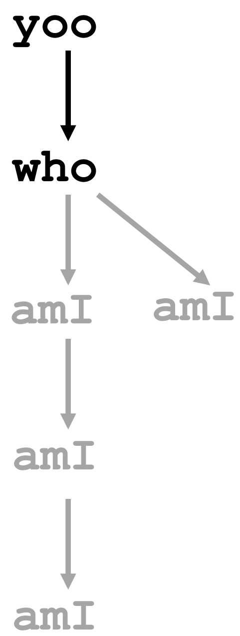


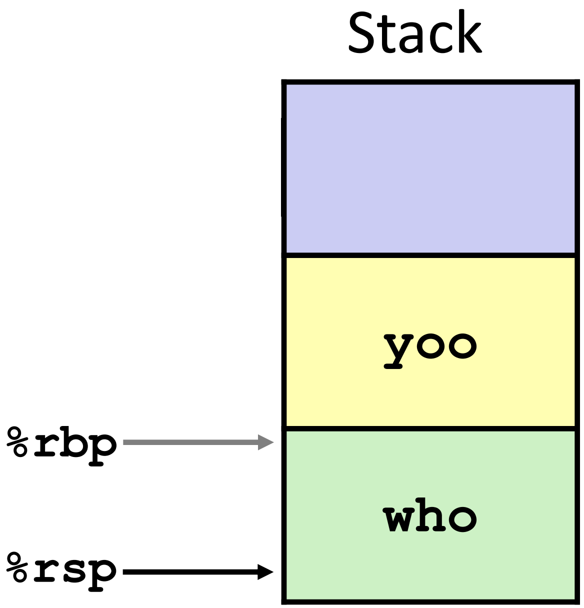
yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
amI();
•
•
}
yoo
who
amI
amI
amI
amI
Stack
yoo
who
amI
%rbp
%rsp

# Example

```
yoo(…)
{
      •
      •
}
```

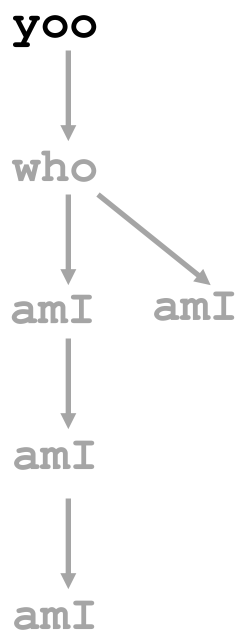
```
who(…)
{
   • • •
   amI();
   • • •
   amI();
   • • •
}
```

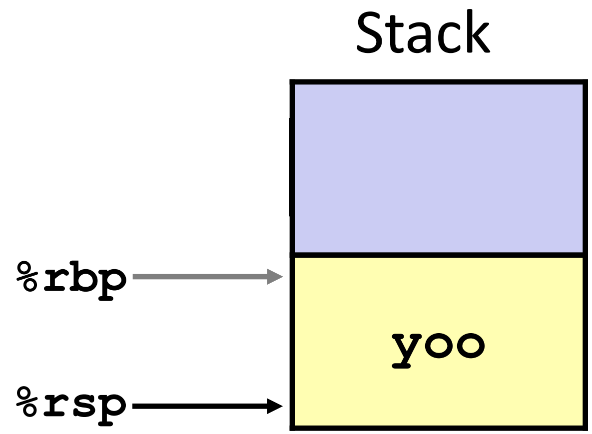


# Example

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

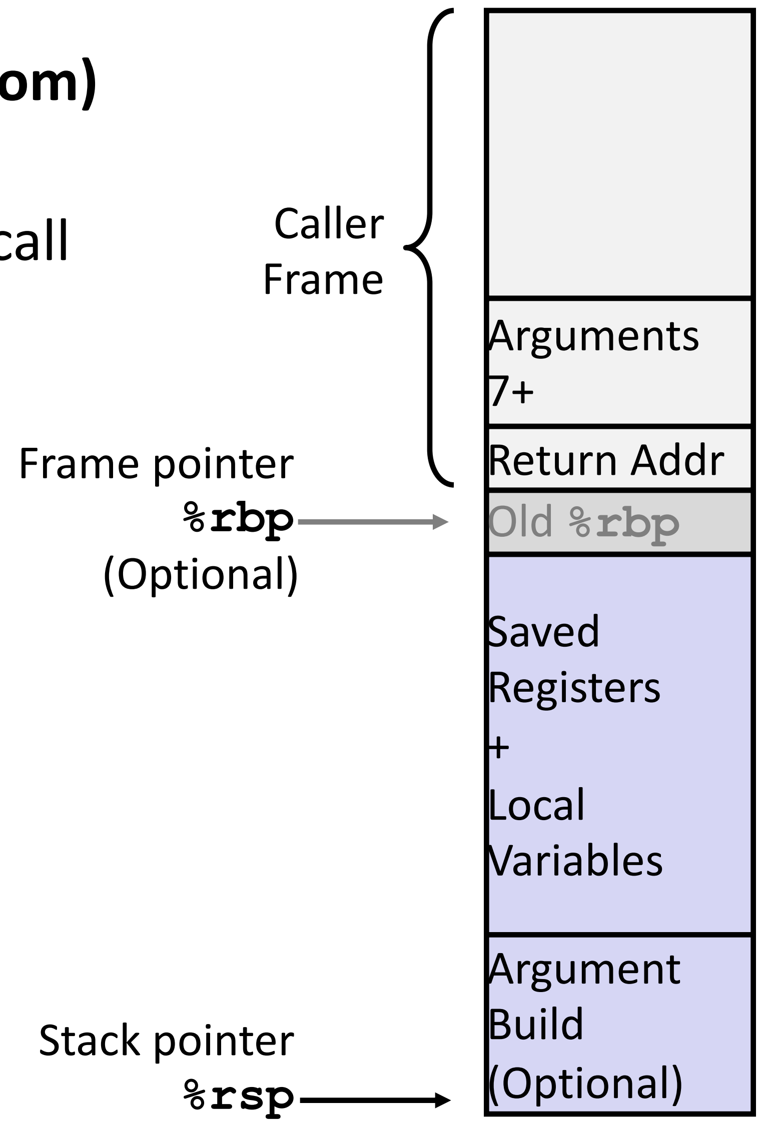


# x86-64/Linux Stack Frame

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

- **Caller Stack Frame**
  - Return address
    - Pushed by `call` instruction
  - Arguments for this call



# Example: `incr`

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

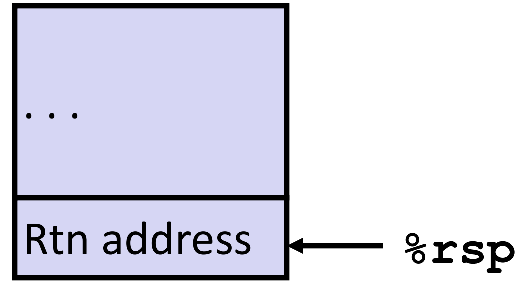
```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```

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

# Example: Calling `incr` #1

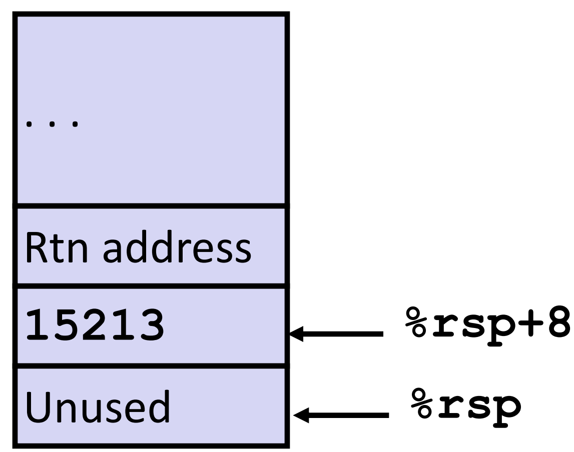
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

Initial Stack Structure




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

Resulting Stack Structure

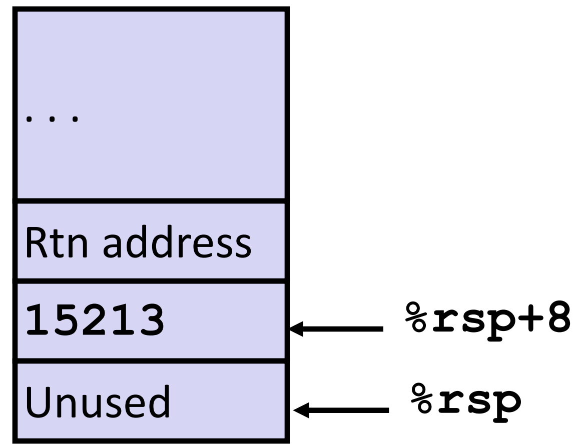


# Example: Calling **`incr`** #2

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

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

Stack Structure



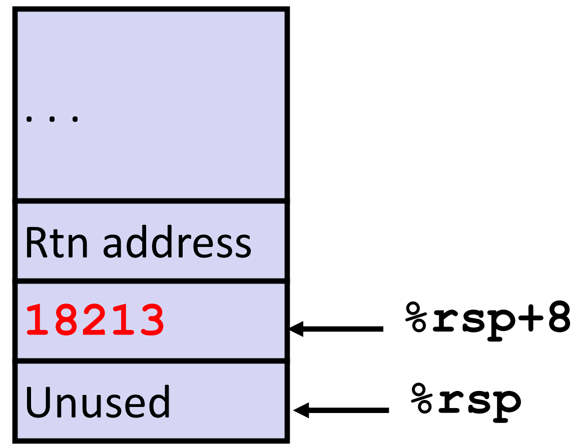

| Register | Use(s) |
|---|---|
| %rdi | &v1 |
| %rsi | 3000 |

# 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



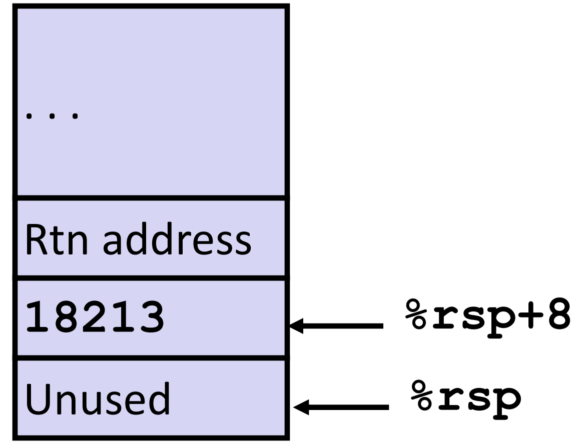

| Register | Use(s) |
|---|---|
| `%rdi` | `&v1` |
| `%rsi` | `3000` |

# Example: Calling **incr** #4

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

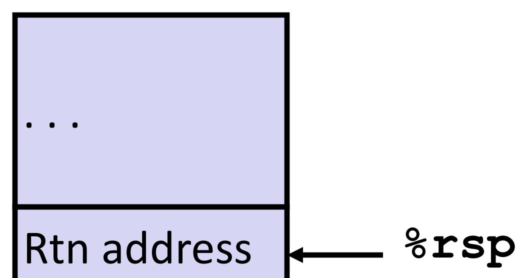
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure




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

Updated Stack Structure

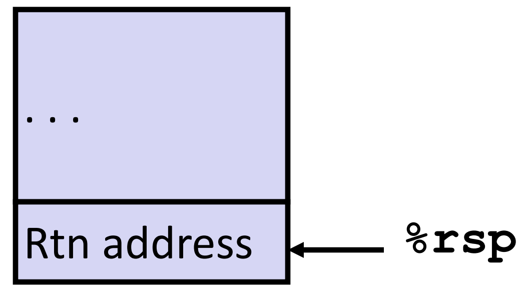


# Example: Calling **`incr`** #5

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

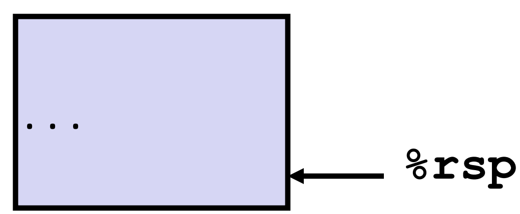
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Updated Stack Structure




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

Final Stack Structure



# Register Saving Conventions

- **When procedure `yoo` calls `who`:**
  - `yoo` is the caller
  - `who` is the callee
- **Can register be used for temporary storage?**

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

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

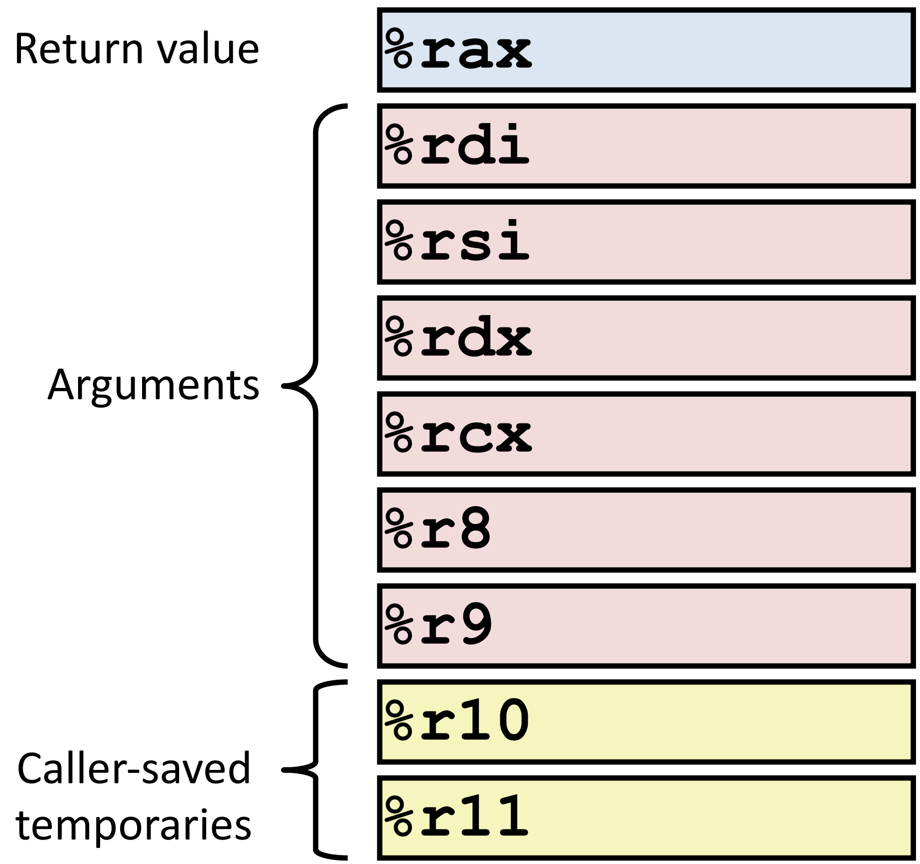
  - Contents of register `%rdx` overwritten by `who`
  - This could be trouble → something should be done!
    - Need some coordination

# Register Saving Conventions

- When procedure **`yoo`** calls **`who`**:
  - **`yoo`** is the caller
  - **`who`** is the callee
- Can register be used for temporary storage?
- Conventions
  - "Caller Saved"
    - Caller saves temporary values in its frame before the call
  - "Callee Saved"
    - Callee saves temporary values in its frame before using
    - Callee restores them before returning to caller

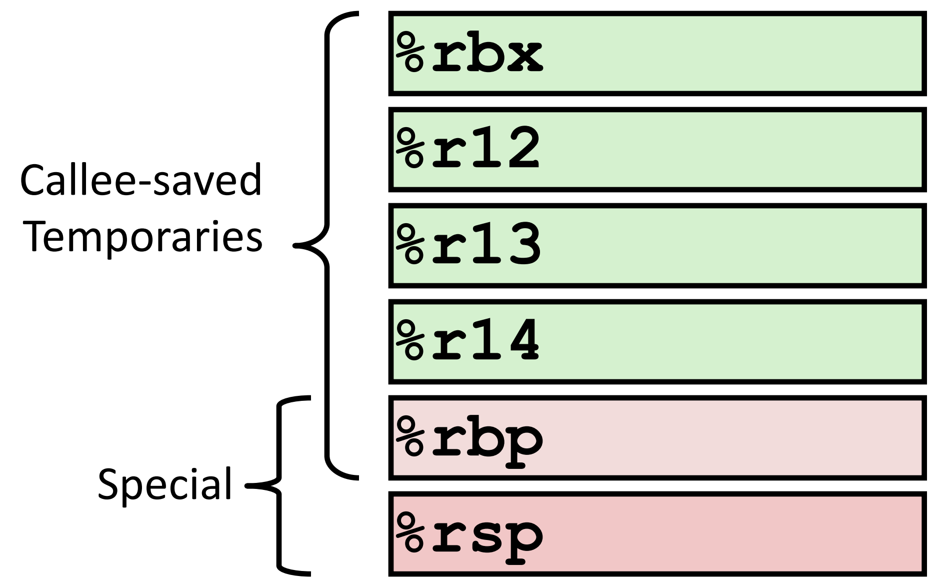
# x86-64 Linux Register Usage #1

- **`%rax`**
  - Return value
  - Also caller-saved
  - Can be modified by procedure
- **`%rdi`**, …, **`%r9`**
  - Arguments
  - Also caller-saved
  - Can be modified by procedure
- **`%r10`**, **`%r11`**
  - Caller-saved
  - Can be modified by procedure



# 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

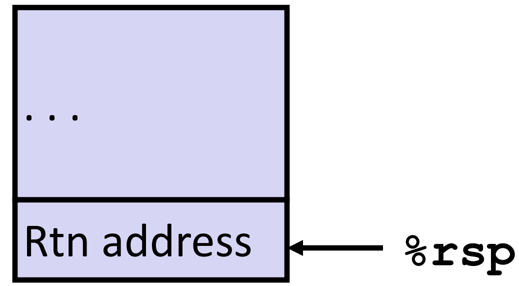


# Callee-Saved Example #1

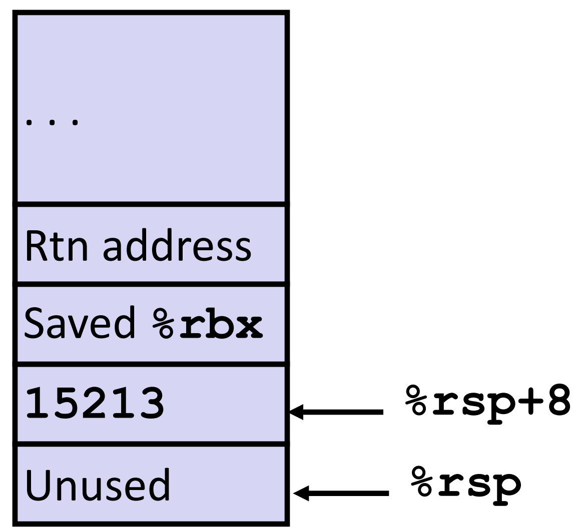
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

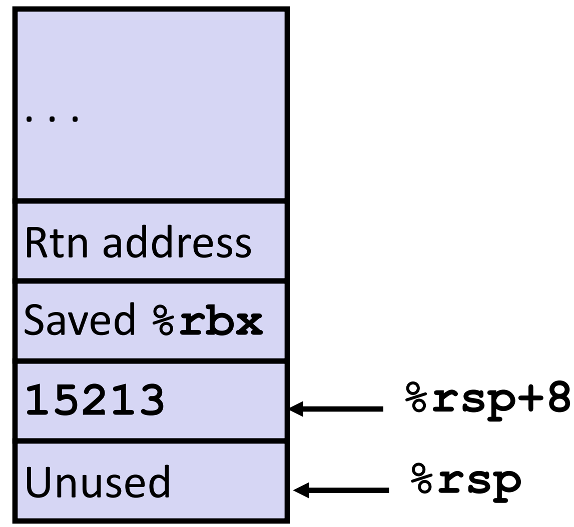


# Callee-Saved Example #2

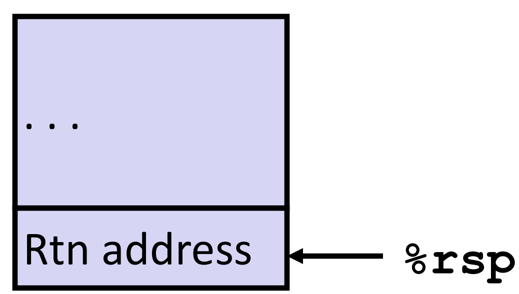
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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



# Illustration of Recursion

## Recursive Function

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

# Recursive Function Terminal Case

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

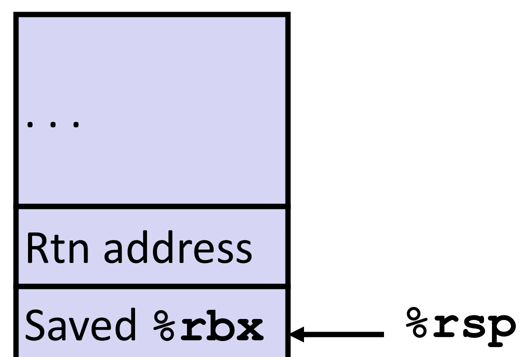
| Register | Use(s) | Type |
|---|---|---|
| `%rdi` | `x` | Argument |
| `%rax` | Return value | Return value |

# Recursive Function Register Save

```c
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

| Register | Use(s) | Type |
|---|---|---|
| `%rdi` | `x` | Argument |



# Recursive Function Call Setup

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

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

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

# Recursive Function Result

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

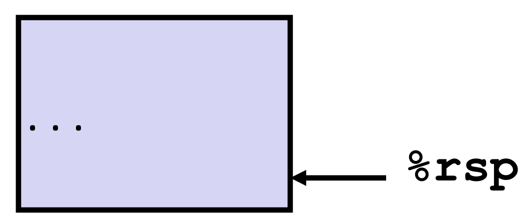
| Register | Use(s) | Type |
|---|---|---|
| `%rbx` | `x & 1` | Callee-saved |
| `%rax` | Return value | |

# Recursive Function Completion

```
/* Recursive popcount */
long pcount_r(unsigned long x) {
  if (x == 0)
    return 0;
  else
    return (x & 1)
           + pcount_r(x >> 1);
}
```

```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

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



# Observations About Recursion

- **Handled Without Special Consideration**
  - Stack frames mean that each function call has private storage
    - Saved registers & local variables
    - Saved return pointer
  - Register saving conventions prevent one function call from corrupting another's data
    - Unless the C code explicitly does so (e.g., buffer overflow in Lecture 9)
  - Stack discipline follows call / return pattern
    - If P calls Q, then Q returns before P
    - Last-In, First-Out
- **Also works for mutual recursion**
  - P calls Q; Q calls P

# x86-64 Procedure Summary

- Important Points
  - Stack is the right data structure for procedure call / return
    - If P calls Q, then Q returns before P
- Recursion (& mutual recursion) handled by normal calling conventions
  - Can safely store values in local stack frame and in callee-saved registers
  - Put function arguments at top of stack
  - Result return in **`%rax`**
- Pointers are addresses of values
  - On stack or global