CSED211 : Microprocessor & Assembly Programming

Lecture 6: Procedures

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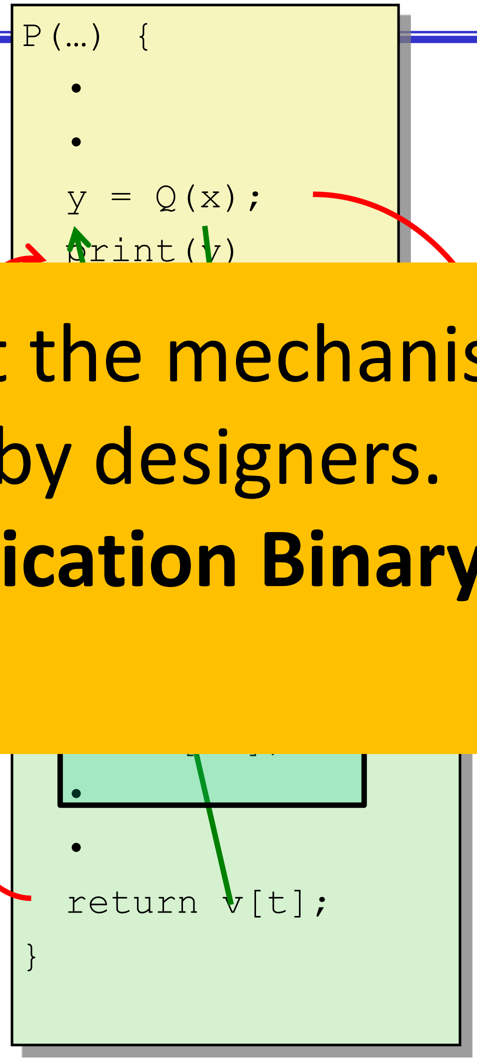
*Disclaimer:
Most slides are taken from author’s lecture slides.

Mechanisms in Procedures

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

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

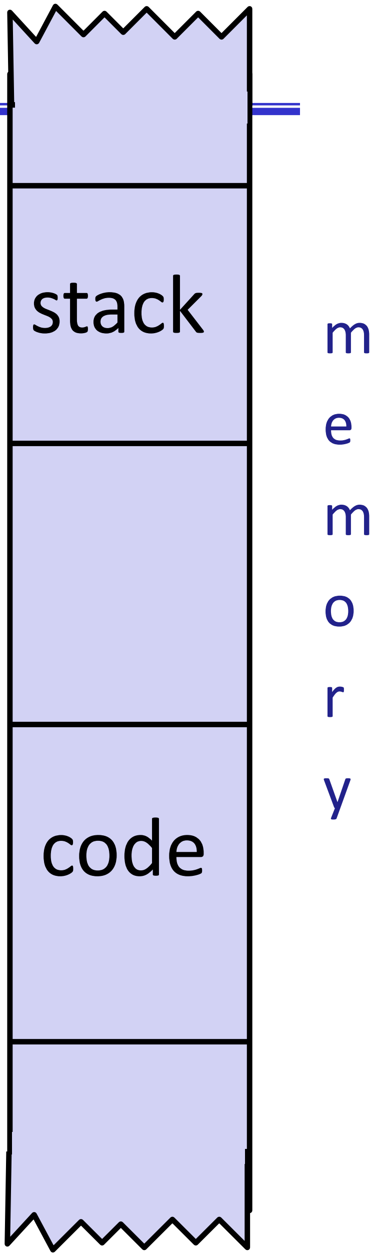
```
  •
  •
  return v[t];
}
```

Today

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

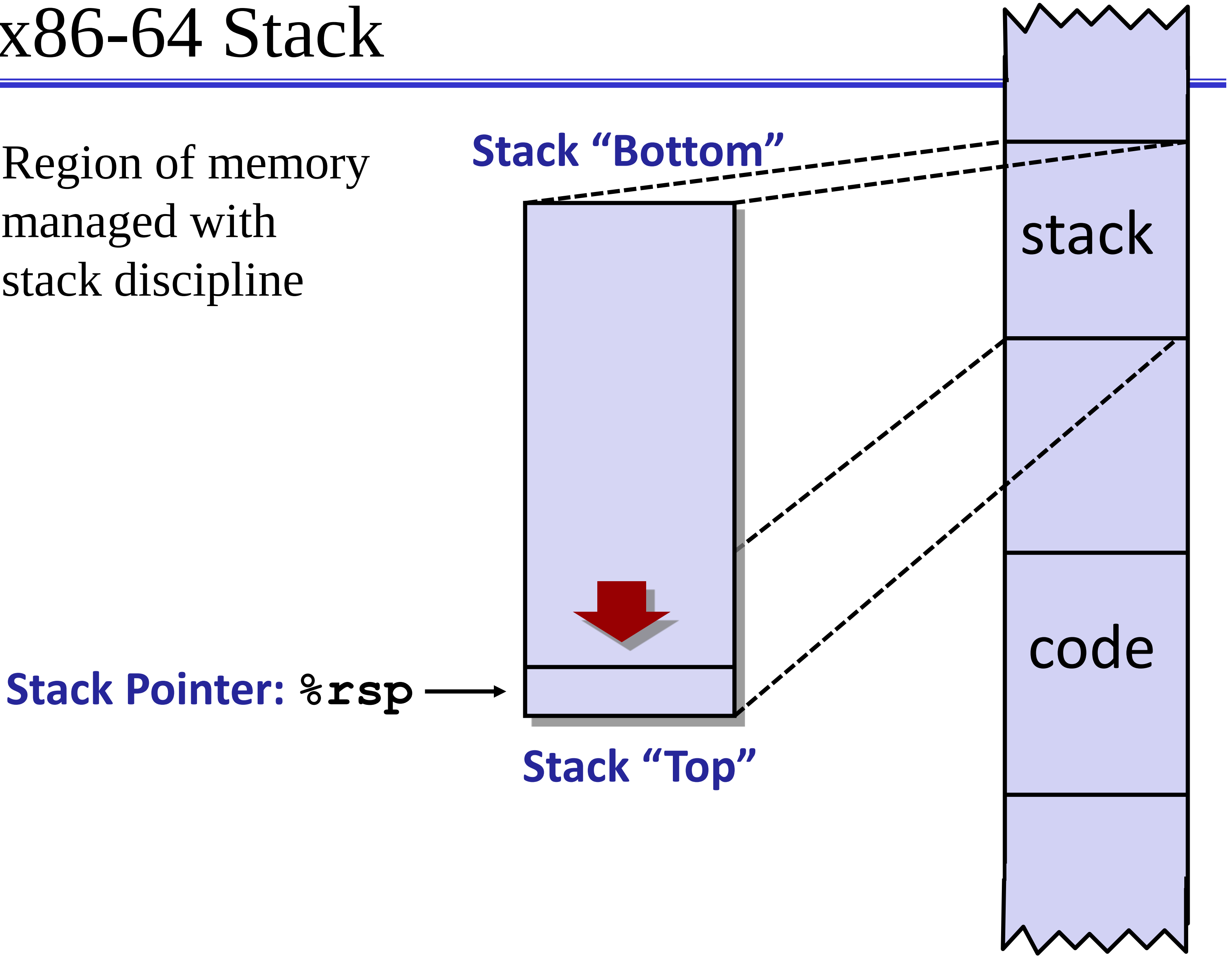
x86-64 Stack

- Region of memory managed with stack discipline
  - Memory viewed as array of bytes.
  - Different regions have different purposes.
  - (Like ABI, a policy decision)



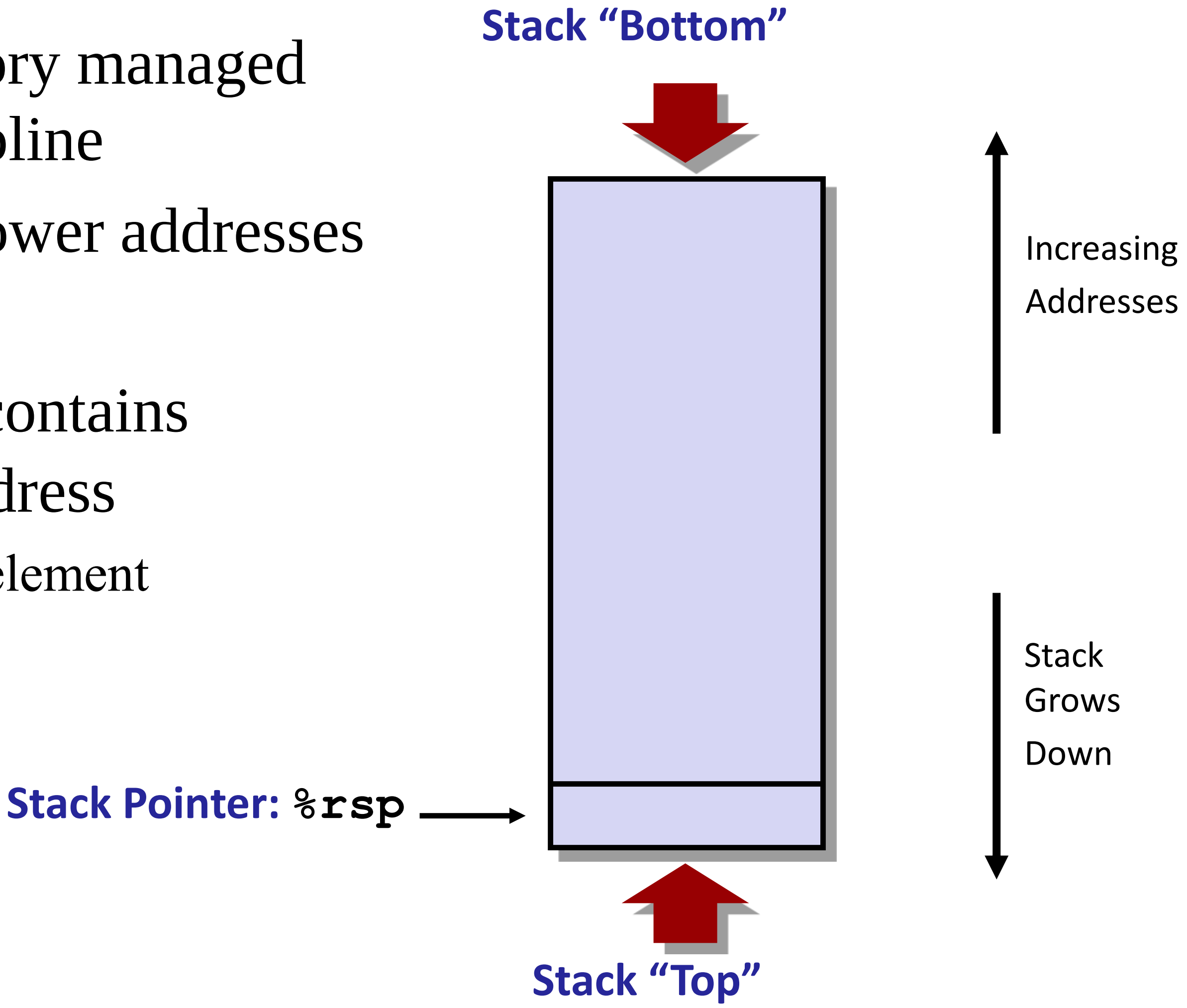
x86-64 Stack

- Region of memory managed with stack discipline



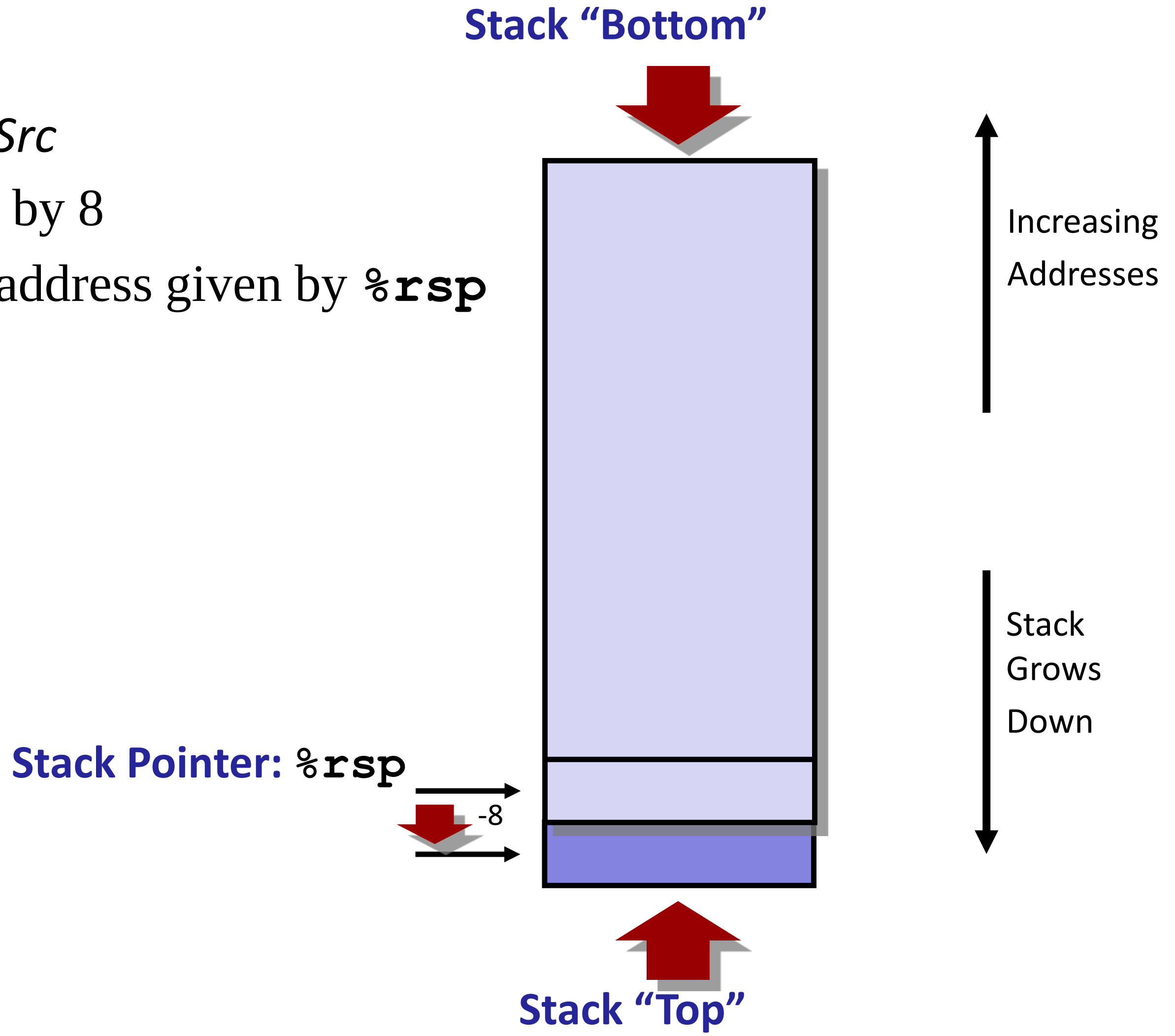
x86-64 Stack

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



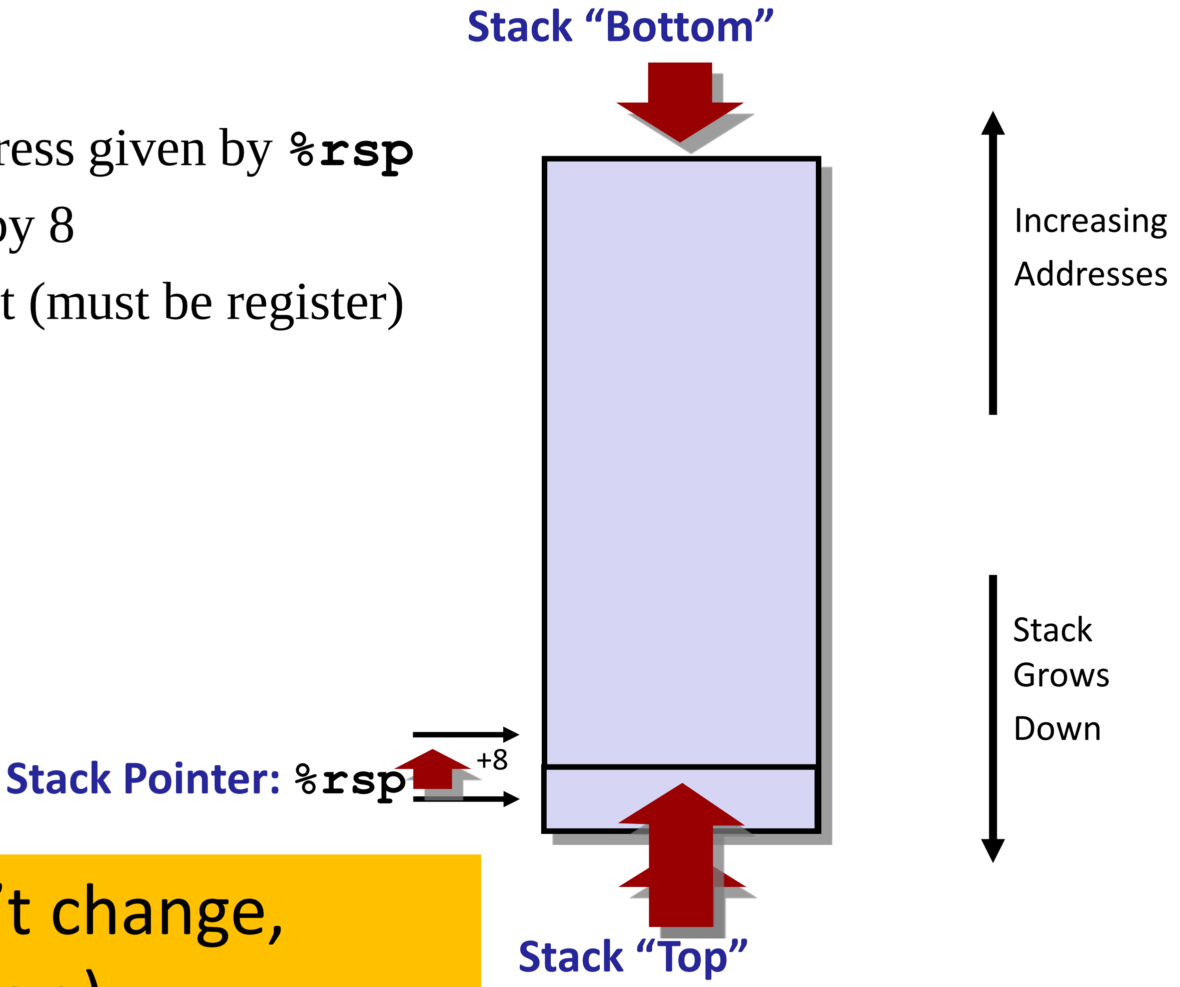
x86-64 Stack: Push

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



x86-64 Stack: Pop

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



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

Today

- Procedures
  - Stack Structure
  - Calling Conventions
    - Passing control
    - Passing data
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  - Illustrations of Recursion & Pointers

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
```

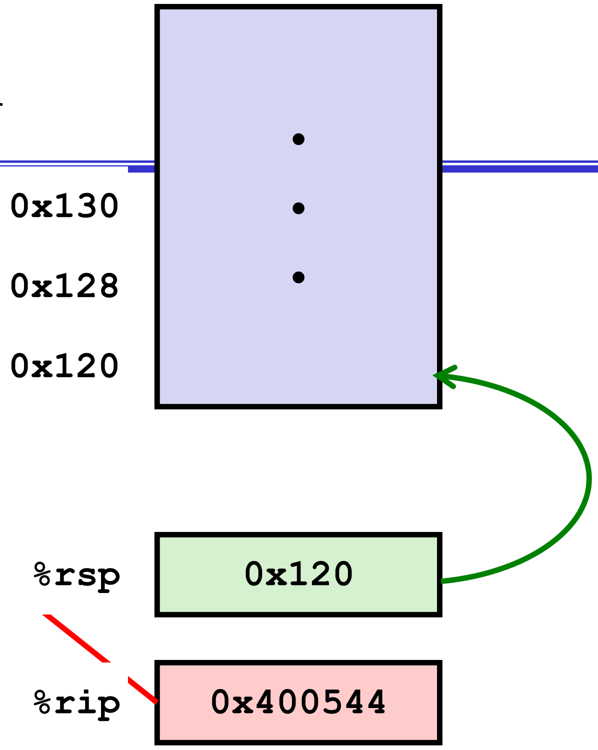
Procedure Control Flow

- 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)
  •
  •
```

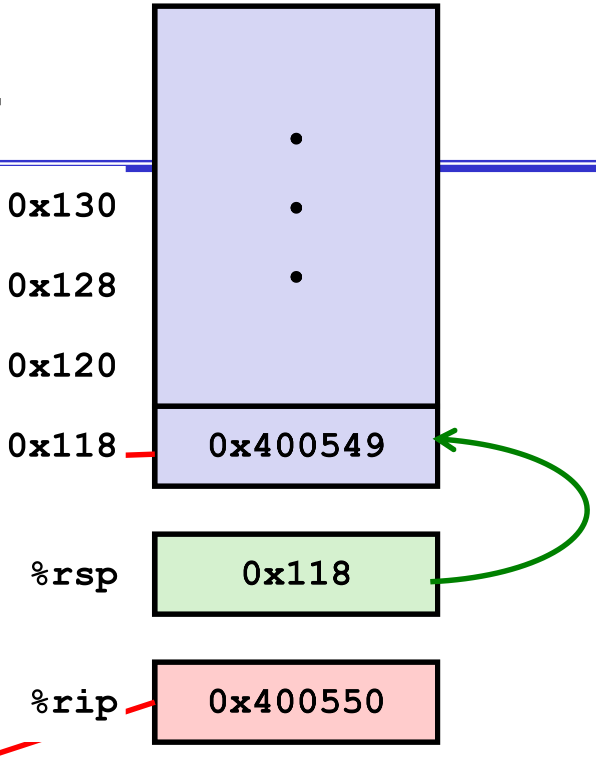
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



Control Flow Example #2

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

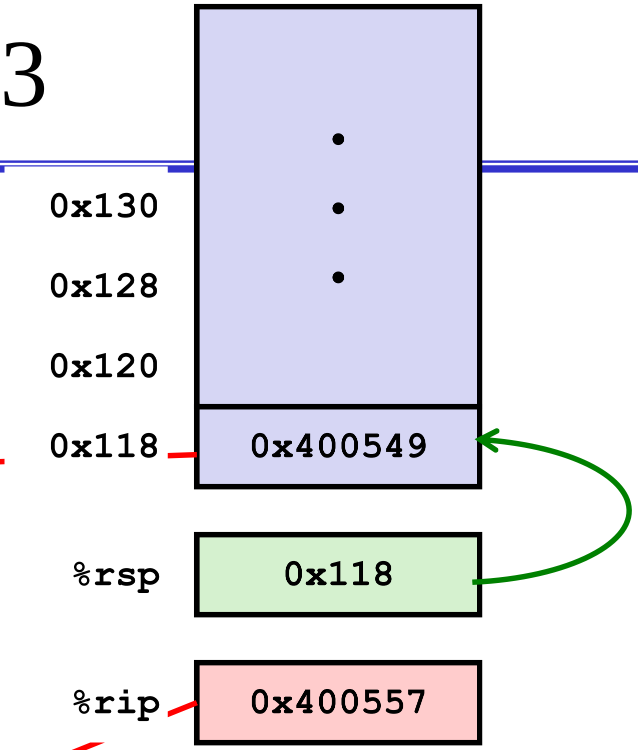
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



Control Flow Example #3

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

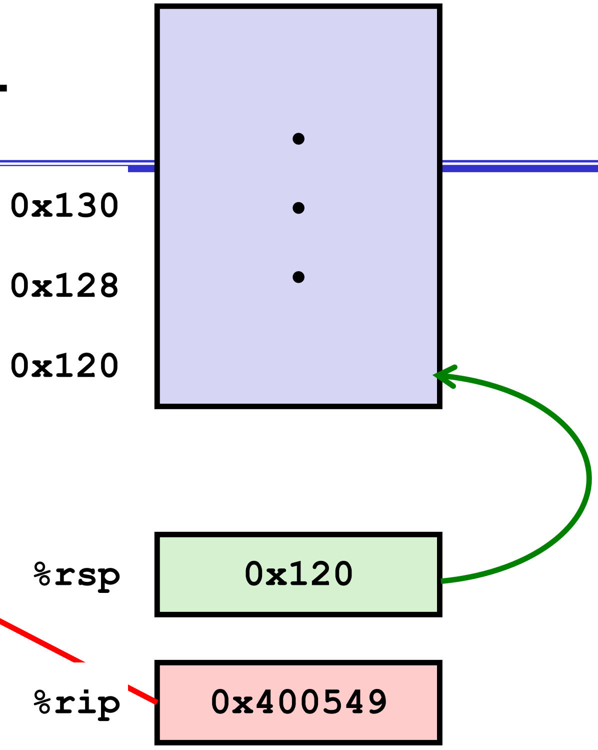
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



Control Flow Example #4

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

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



Today

- Procedures
  - Stack Structure
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    - Passing control
    - Passing data
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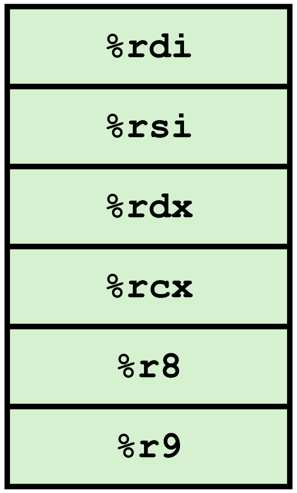
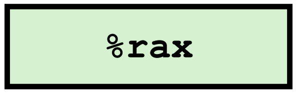
Procedure Data Flow

Registers

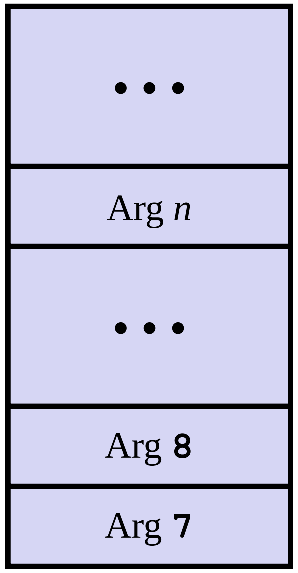
- First 6 arguments



- Return value



Stack



Only allocate stack space when needed

Data Flow Examples

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

```
0000000000400540 <multstore>:
  # x in %rdi, y in %rsi, dest in %rdx
  • • •
  400541: mov    %rdx,%rbx                 # Save dest
  400544: callq  400550 <mult2>    # mult2(x,y)
  # t in %rax
  400549: mov    %rax,(%rbx)       # Save at dest
  • • •
```

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

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

Today

- Procedures
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    - Passing control
    - Passing data
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  - Illustrations of Recursion & Pointers

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

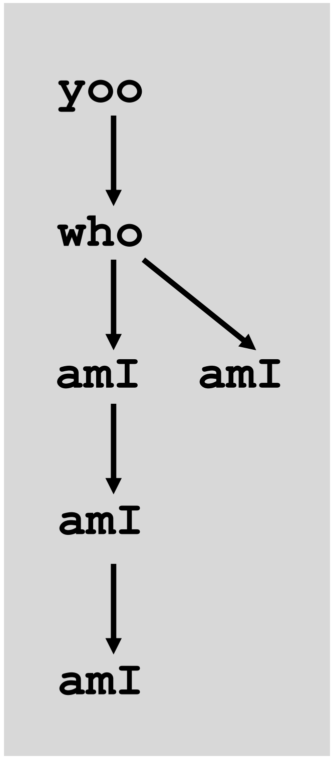
```
yoo(…)
{
  •
  •
  who();
  •
  •
}
```

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

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

Example

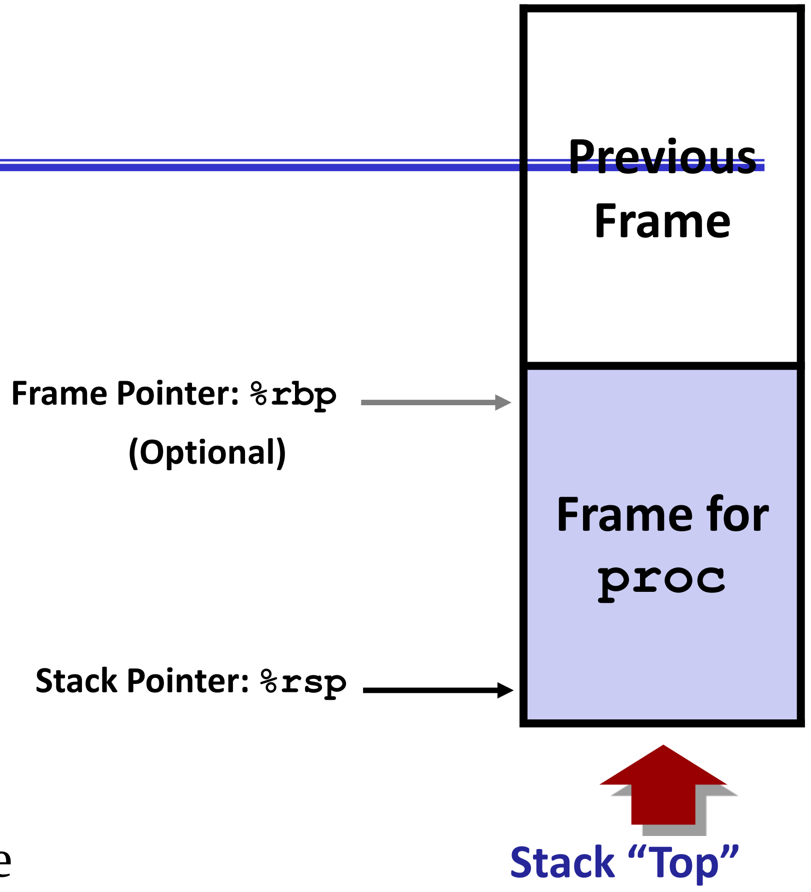
Call Chain


$$\begin{tikzcd}
\texttt{yoo} \arrow[d] & \\
\texttt{who} \arrow[d] \arrow[dr] & \\
\texttt{amI} \arrow[d] & \texttt{amI} \\
\texttt{amI} \arrow[d] & \\
\texttt{amI} &
\end{tikzcd}$$

Procedure `amI()` is recursive

Stack Frames

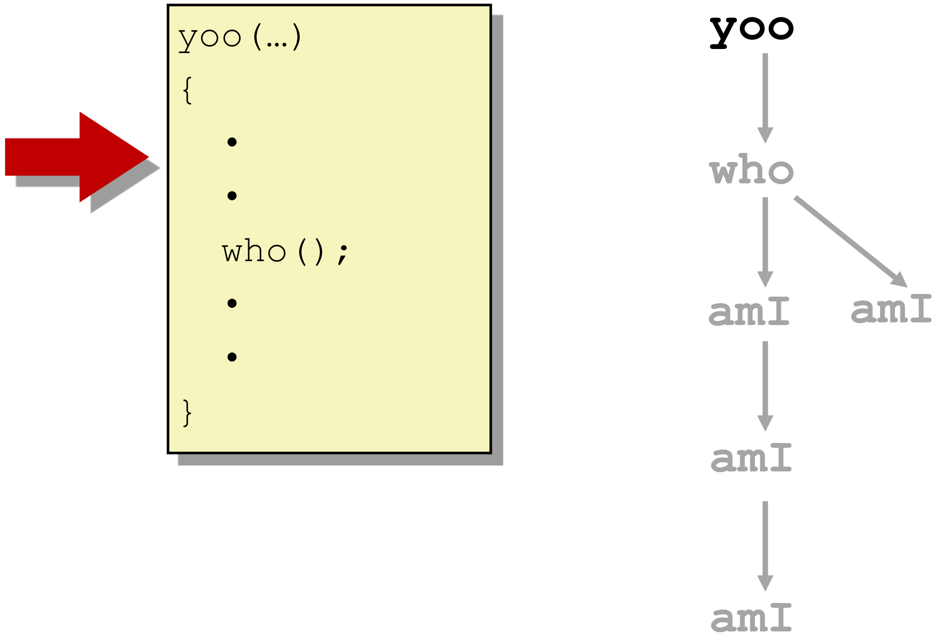
- Contents
  - Return information
  - Local storage (if needed)
  - Temporary space (if needed)

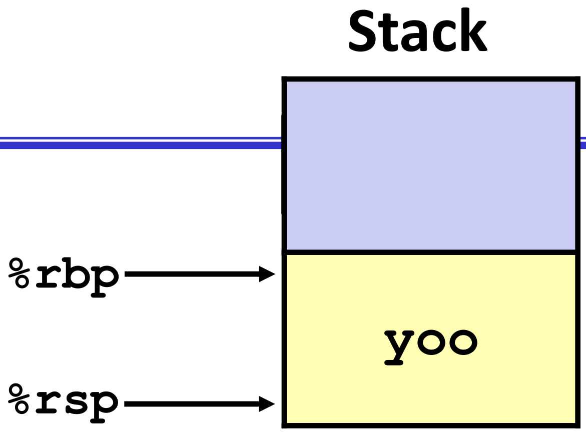


- Management
  - Space allocated when enter procedure
    - "Set-up" code
    - Includes push by **`call`** instruction
  - Deallocated when return
    - "Finish" code
    - Includes pop by **`ret`** instruction

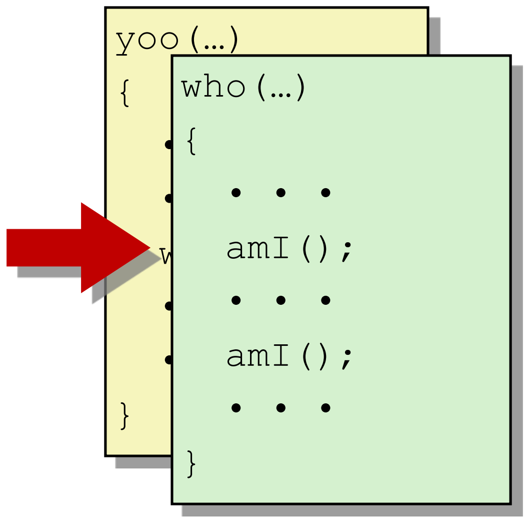
Example

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

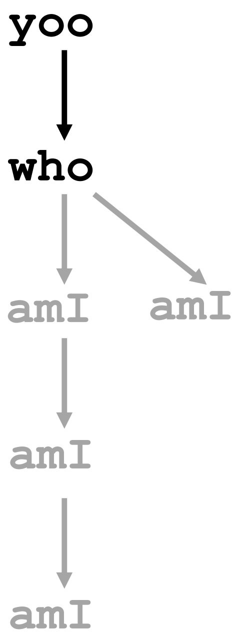


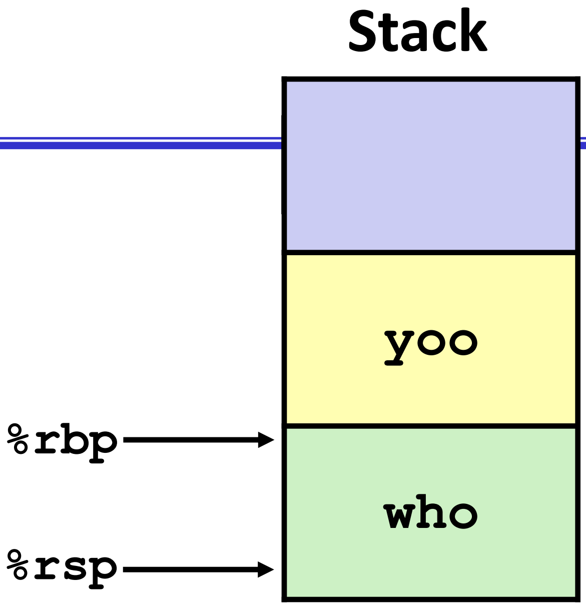


Example

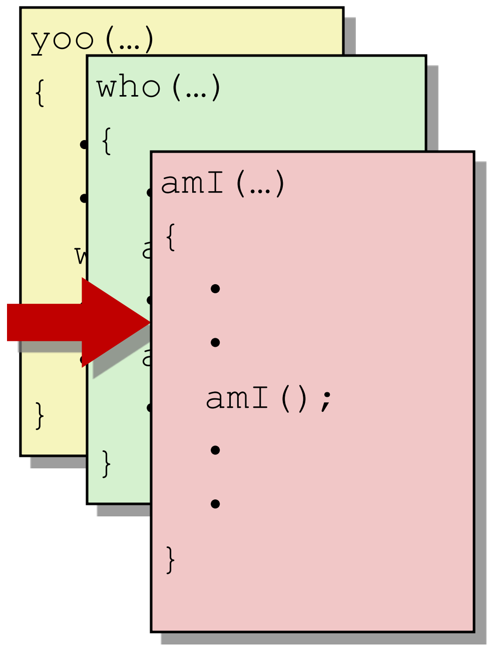


```
who(…)
{
   • • •
   amI();
   • • •
   amI();
   • • •
}
```

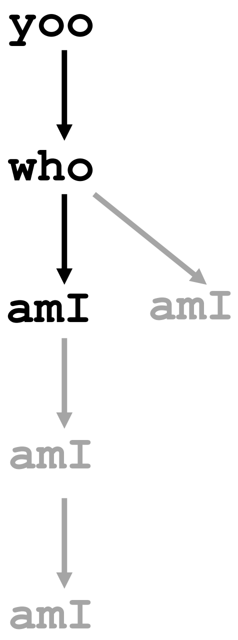




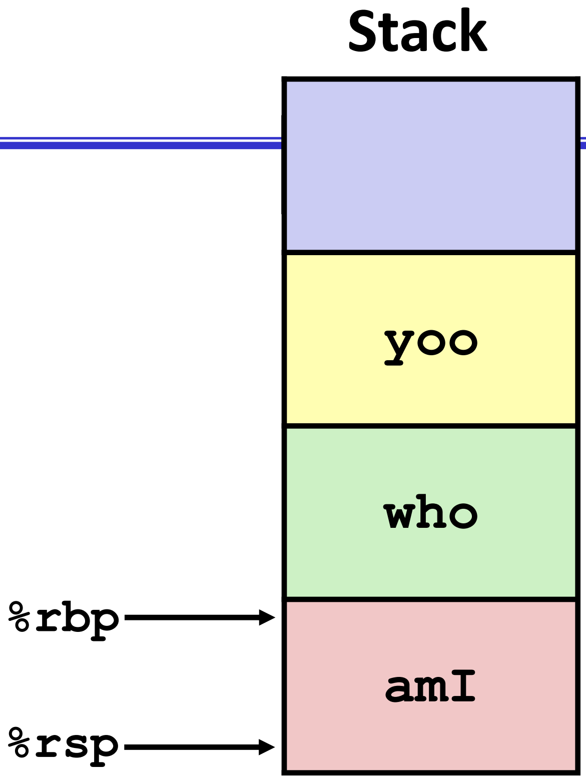
Example



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

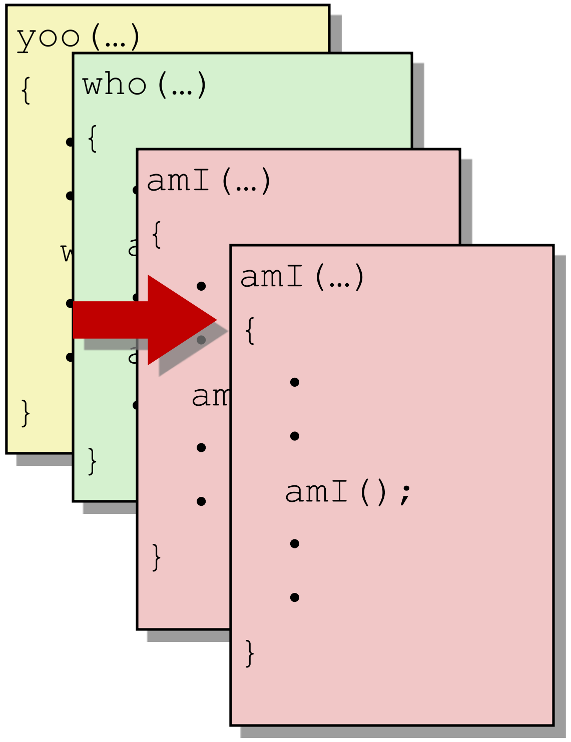


yoo
who
amI
amI
amI
amI

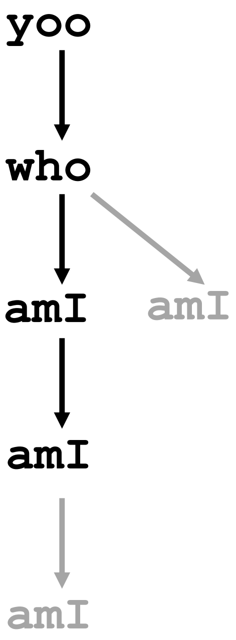


Stack
yoo
who
amI
%rbp
%rsp

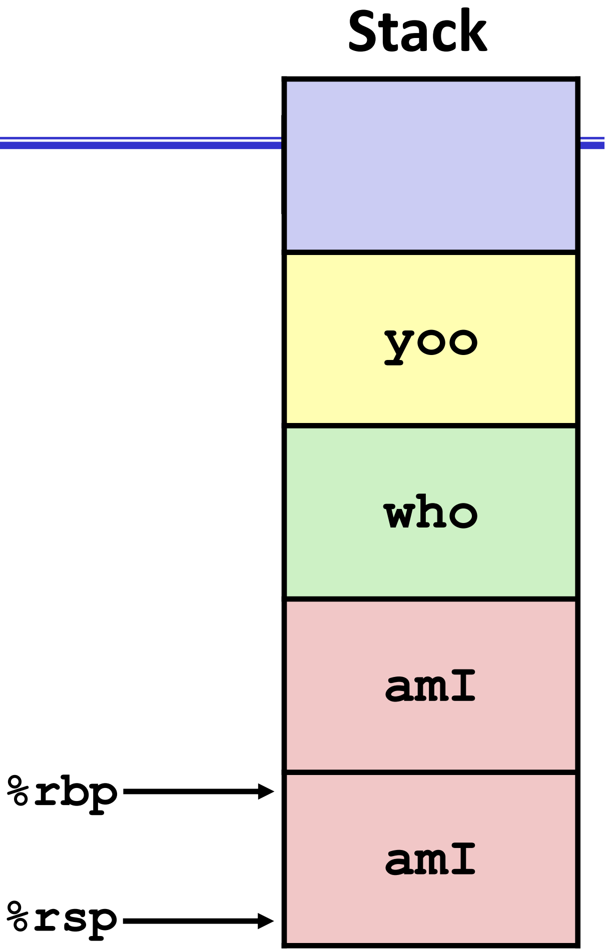
Example



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



yoo
who
amI
amI
amI
amI



Stack
yoo
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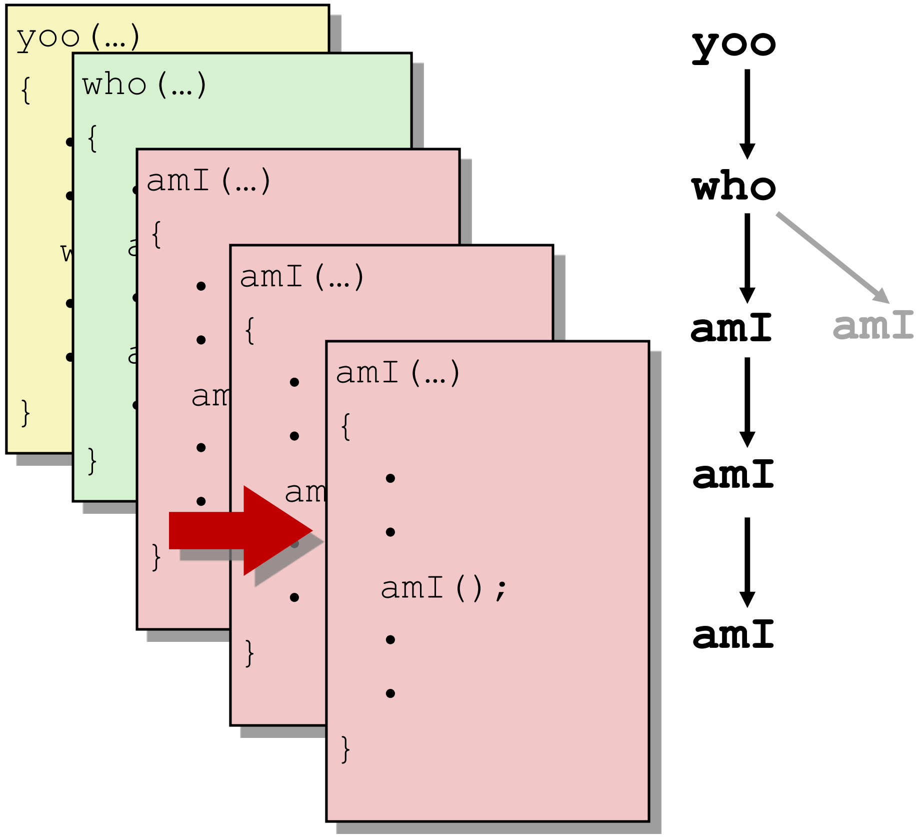
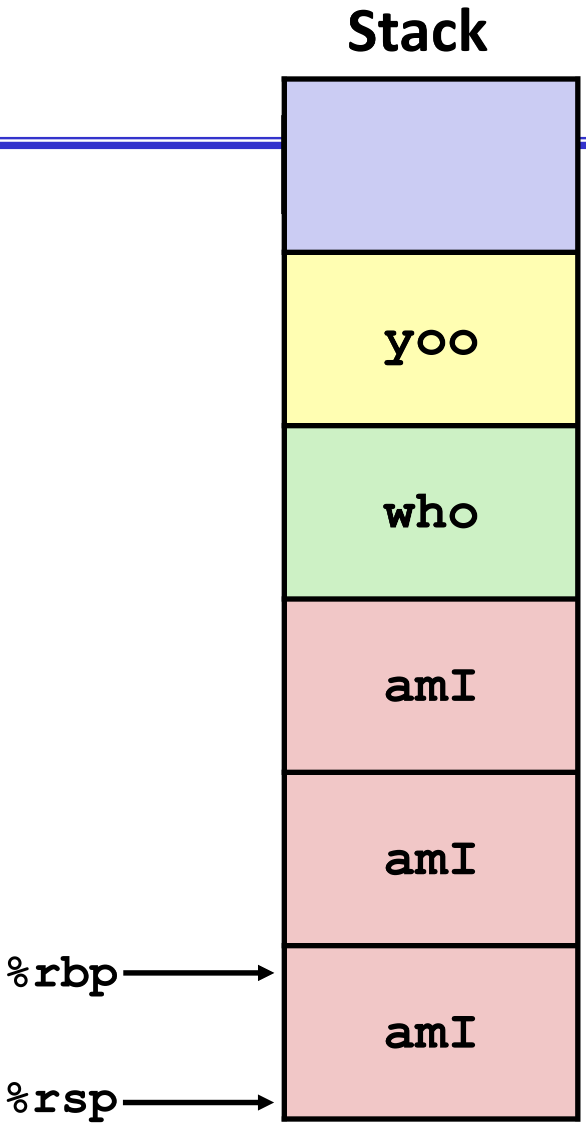
Example



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



Stack
yoo
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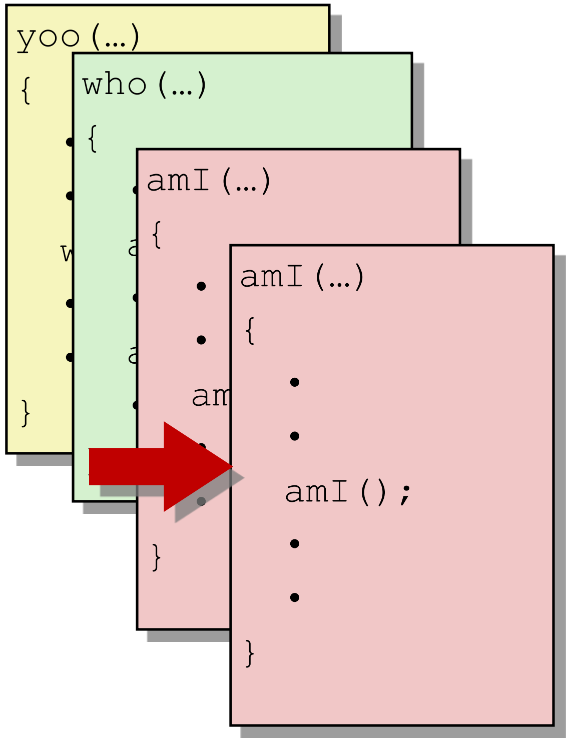
%rsp

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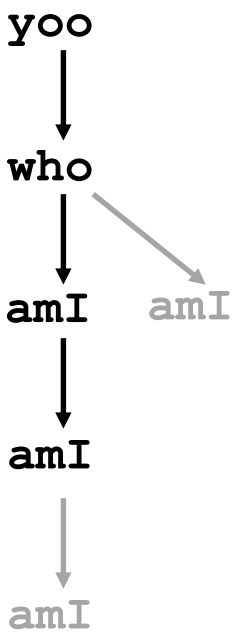
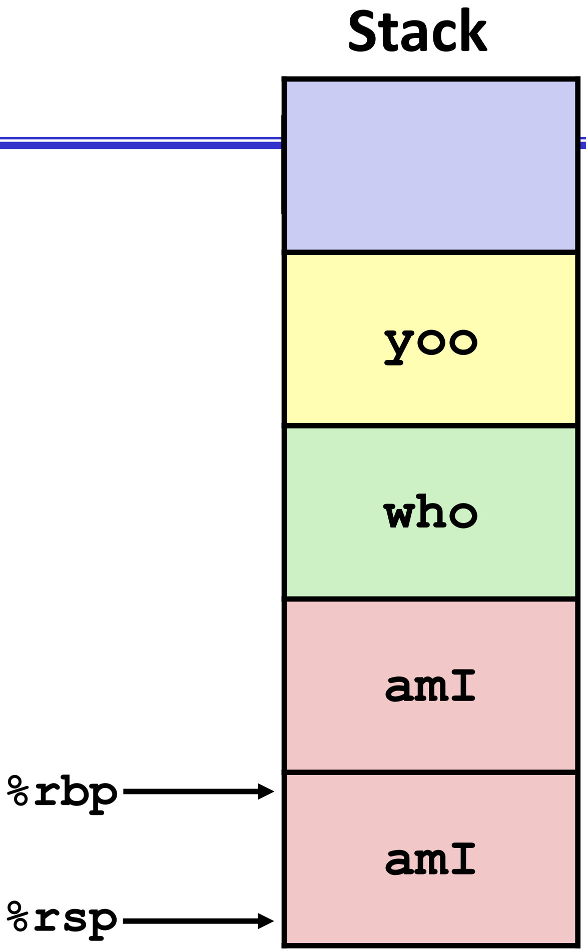
who(…)
{
amI(…)
{
}
amI(…)
{
amI();
}


yoo
who
amI
amI
amI
amI


Stack
yoo
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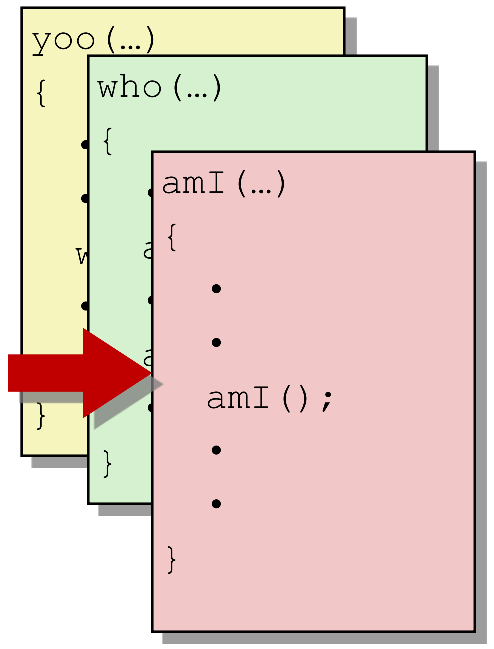
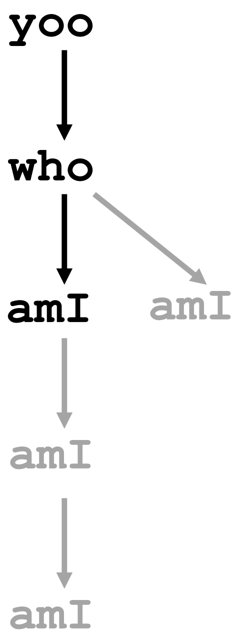
Example


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


yoo
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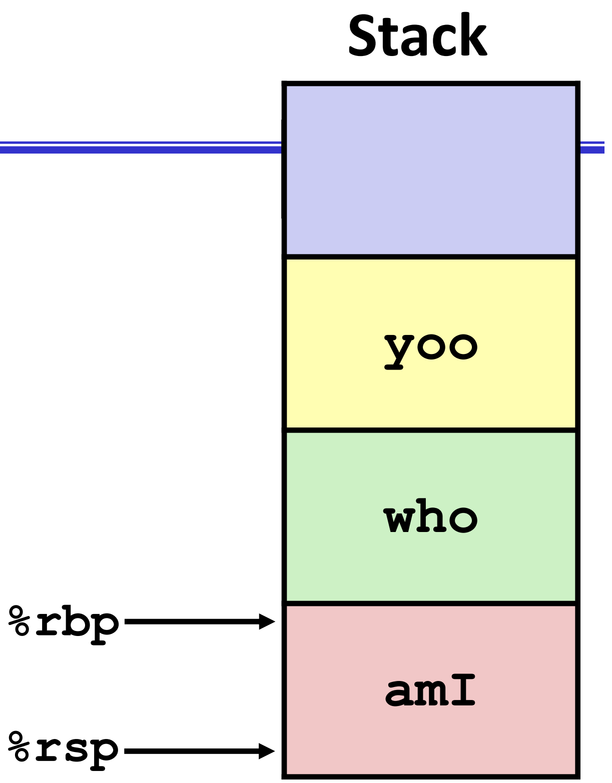
Stack
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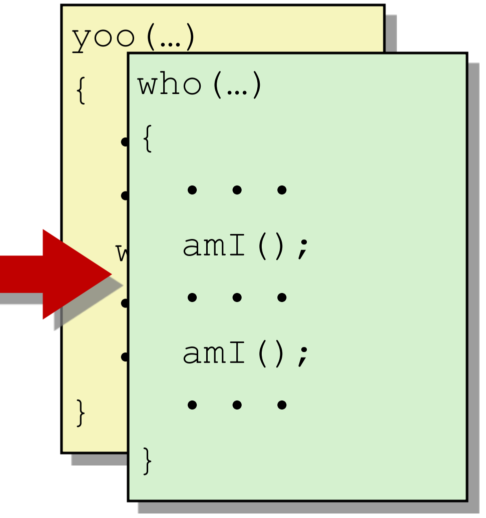
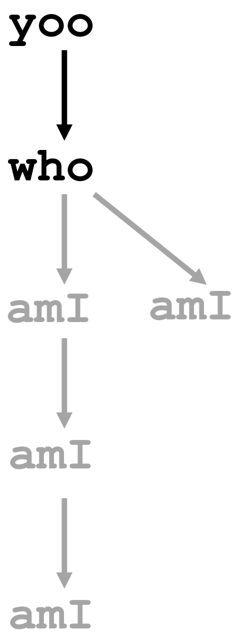
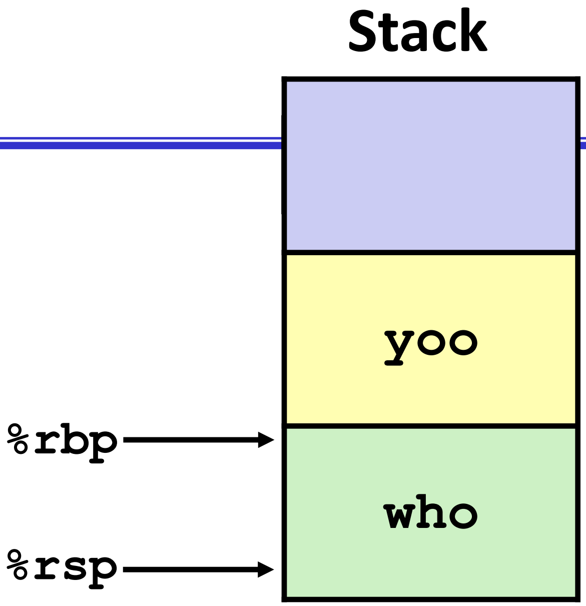
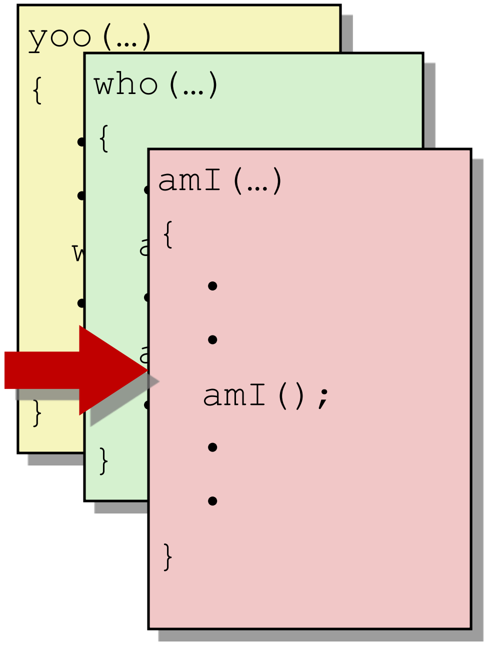
Example



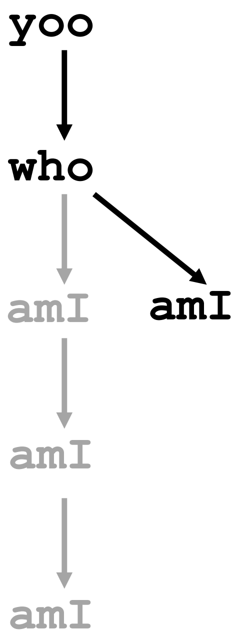




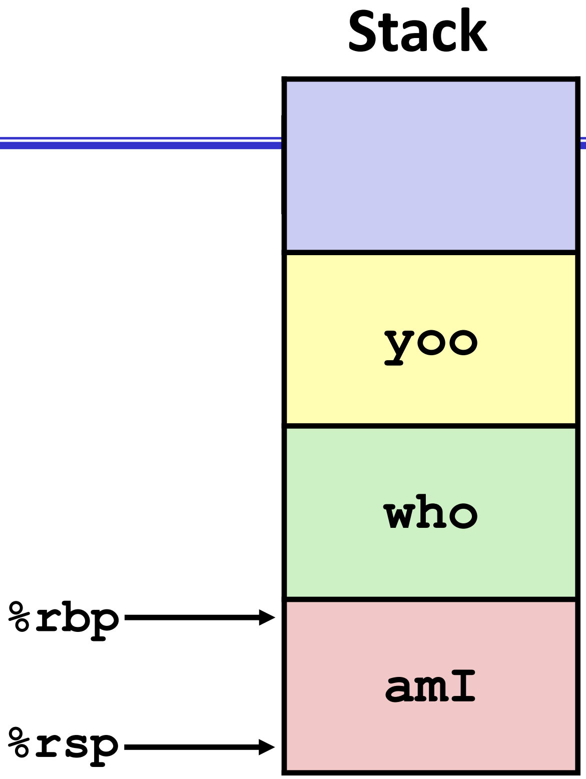
Example



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



yoo
who
amI
amI
amI
amI



Stack
yoo
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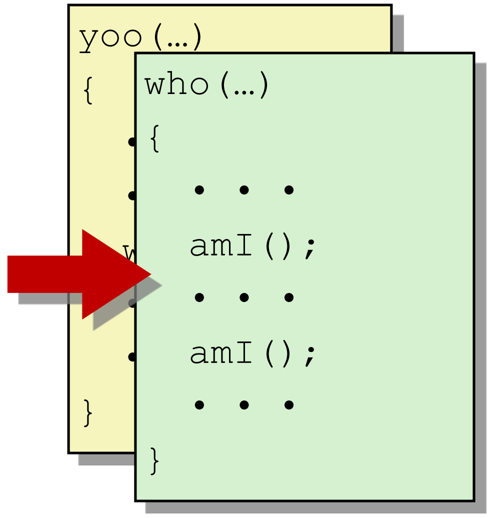
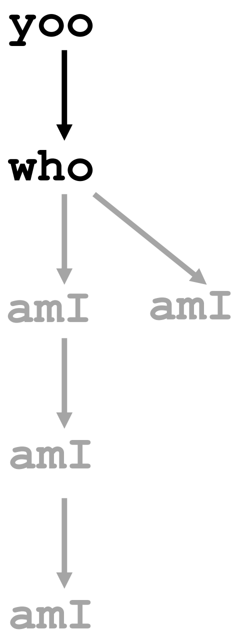
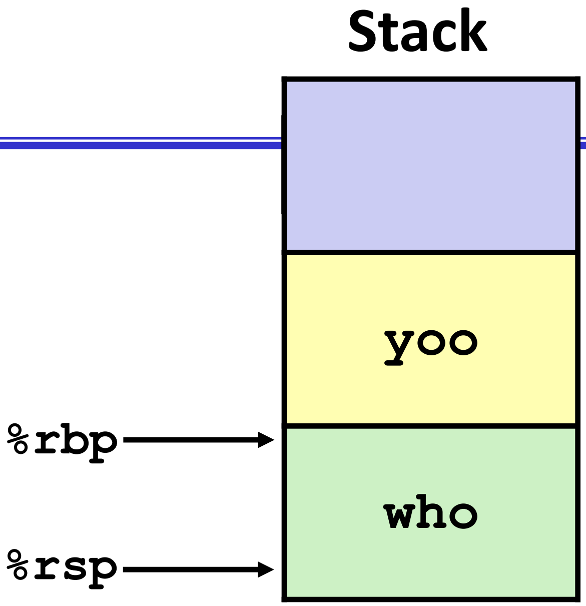
Example

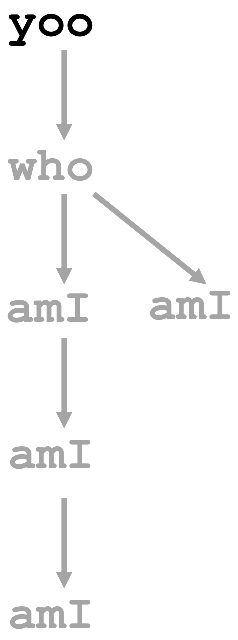


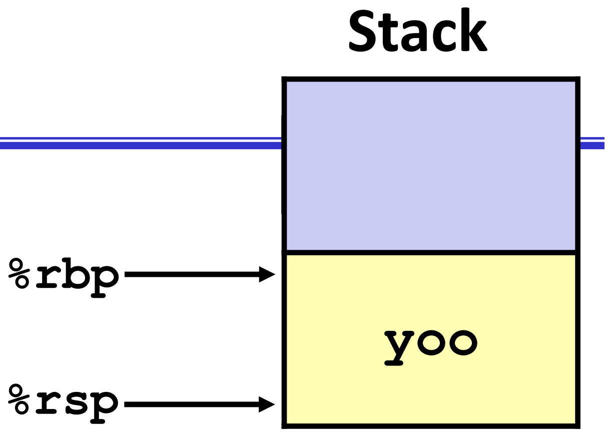




Example

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

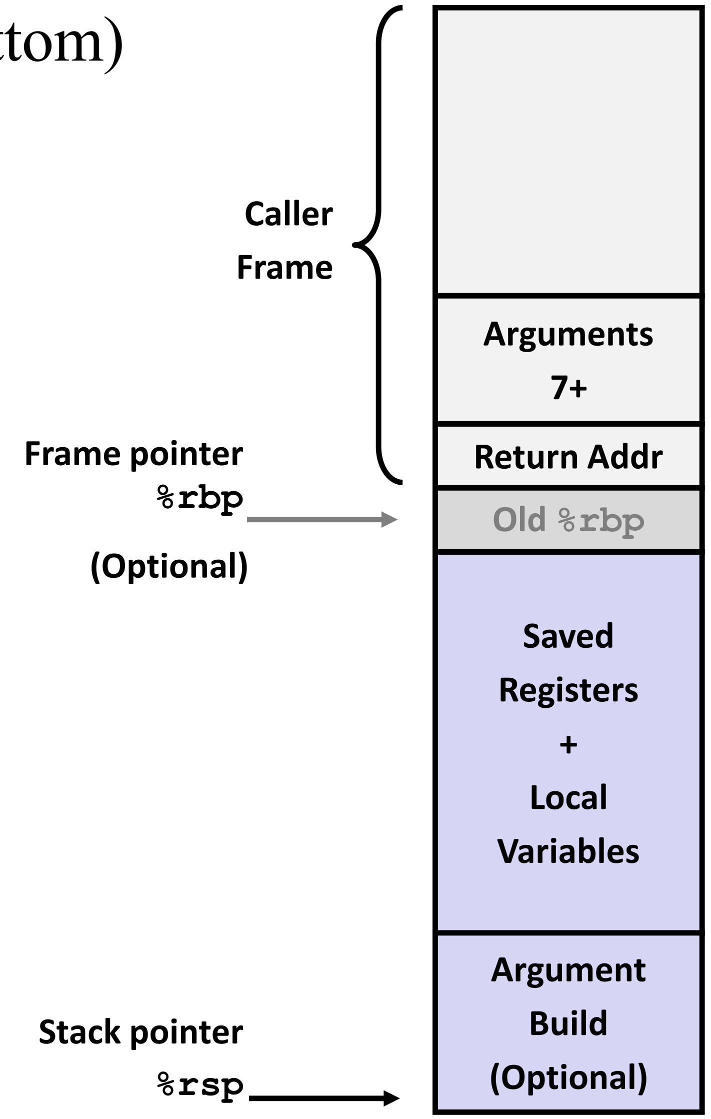




x86-64/Linux Stack Frame

- 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
```

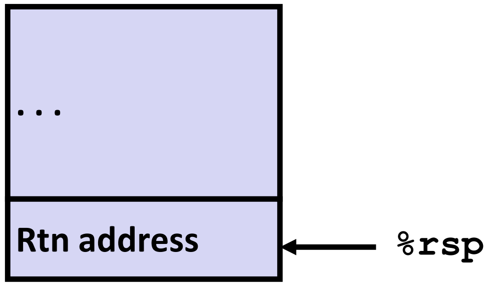
Register	Use(s)
`%rdi`	Argument **`p`**
`%rsi`	Argument **`val`**, **`y`**
`%rax`	**`x`**, Return value

Example: Calling `incr` #1

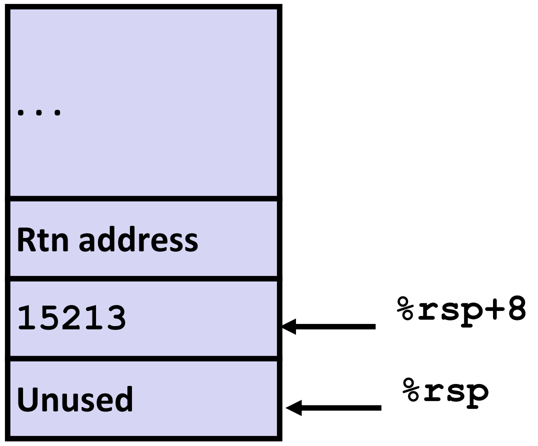
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
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
```

Initial Stack Structure



Resulting Stack Structure

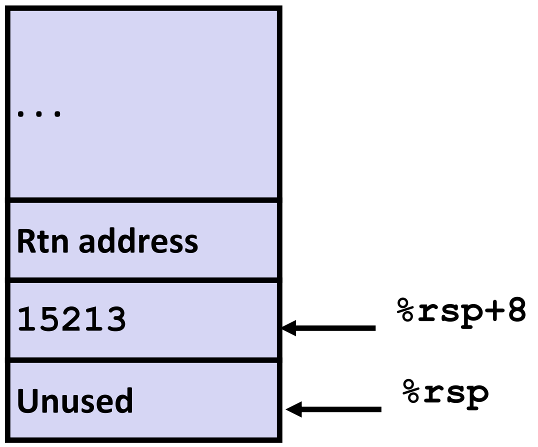


Example: Calling **`incr`** #2

```
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

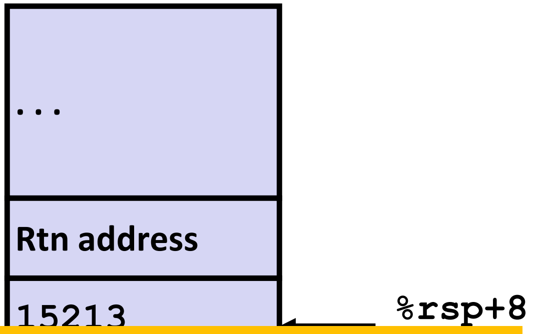


Register	Use(s)
`%rdi`	`&v1`
`%rsi`	`3000`

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

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

Stack Structure



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

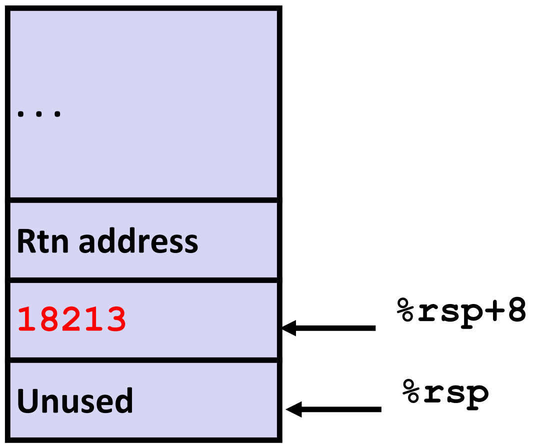
`%rdi`	`&v1`
`%rsi`	`3000`

Aside 1: **`movl   $3000, %esi`**
- Note: movl -> %exx zeros out high order 32 bits.
- Why use movl instead of movq? 2 bytes shorter.

Example: Calling **`incr`** #3

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

Stack Structure



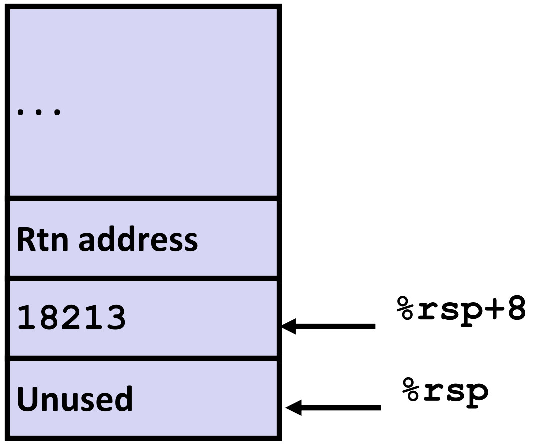
```
call_incr:
  subq     $16, %rsp
  movq     $15213, 8(%rsp)
  movl     $3000, %esi
  leaq     8(%rsp), %rdi
  call     incr
  addq     8(%rsp), %rax
  addq     $16, %rsp
  ret
```

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

Example: Calling `incr` #4

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

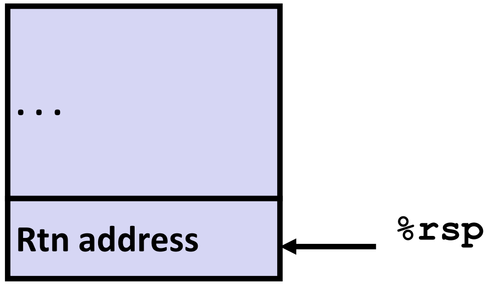
Stack Structure



```
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

Updated Stack Structure

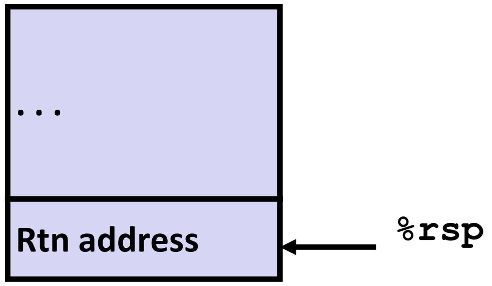


Example: Calling `incr` #5

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

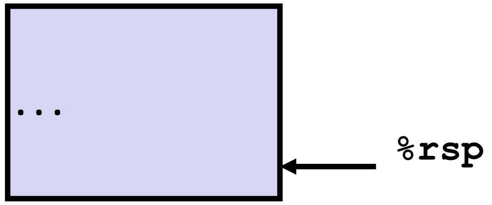
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

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
```

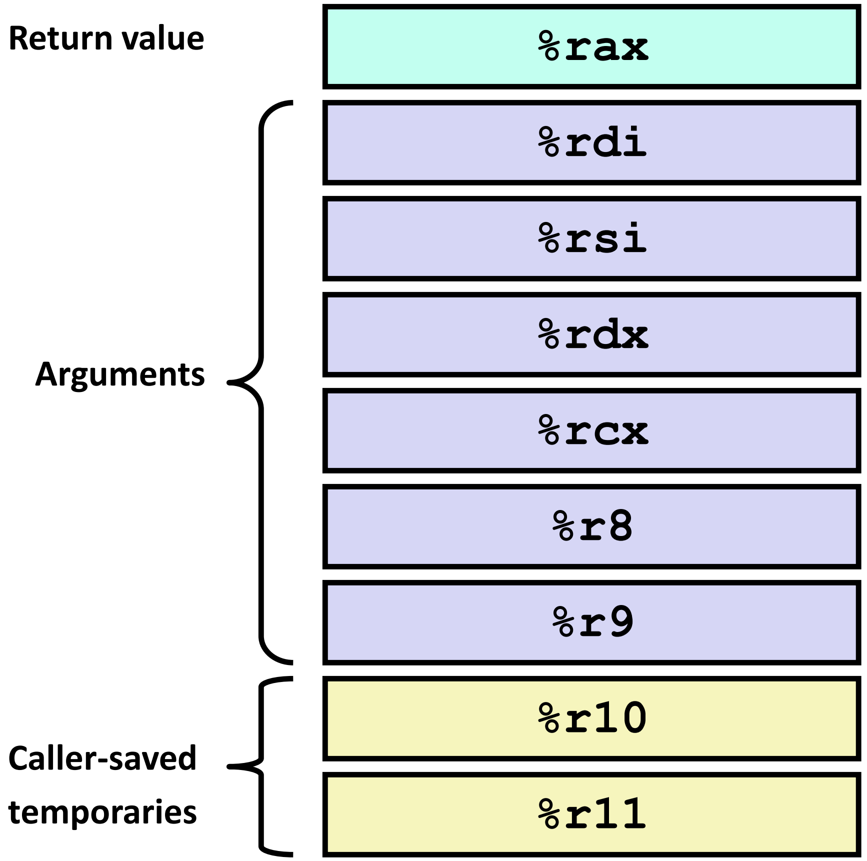
- Contents of register **`%rdx`** overwritten by **`who`**
- This could be trouble ➞ something should be done!
  - Need some coordination

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

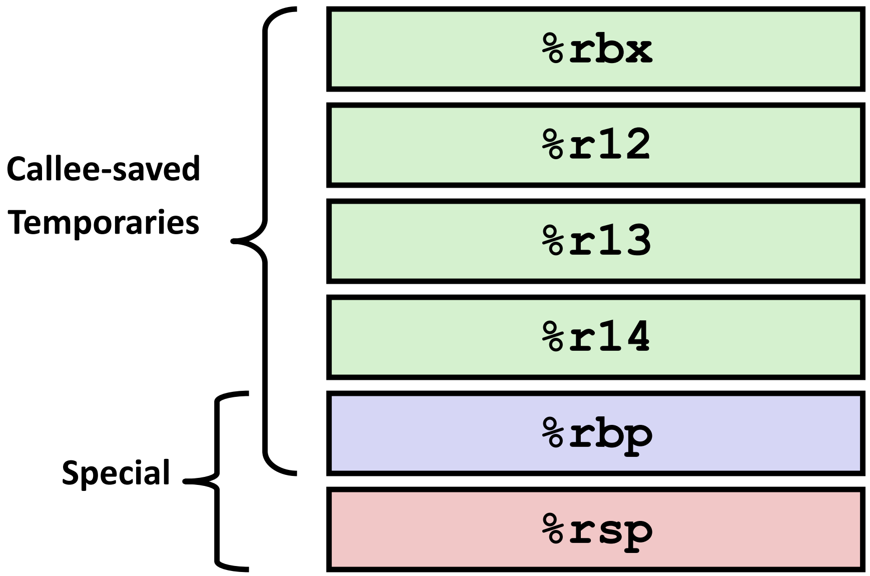
x86-64 Linux Register Usage #1

- **`%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

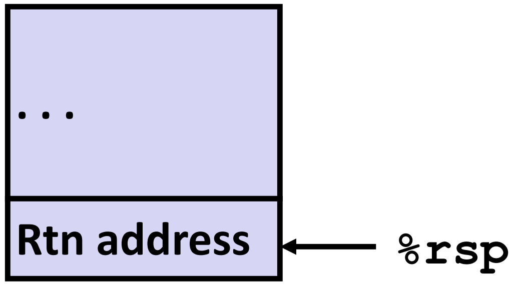
- **`%rbx`**, **`%r12`**, **`%r13`**, **`%r14`**
  - Callee-saved
  - Callee must save & restore
- **`%rbp`**
  - Callee-saved
  - Callee must save & restore
  - May be used as frame pointer
  - Can mix & match
- **`%rsp`**
  - Special form of callee save
  - Restored to original value upon exit from procedure



Callee-Saved Example #1

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

Initial Stack Structure



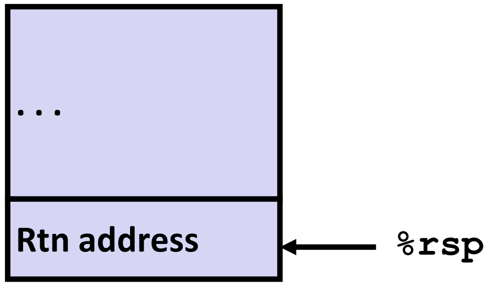
- X comes in register **`%rdi`**.
- We need **`%rdi`** for the call to incr.
- Where should be put x, so we can use it after the call to incr?

Callee-Saved Example #1

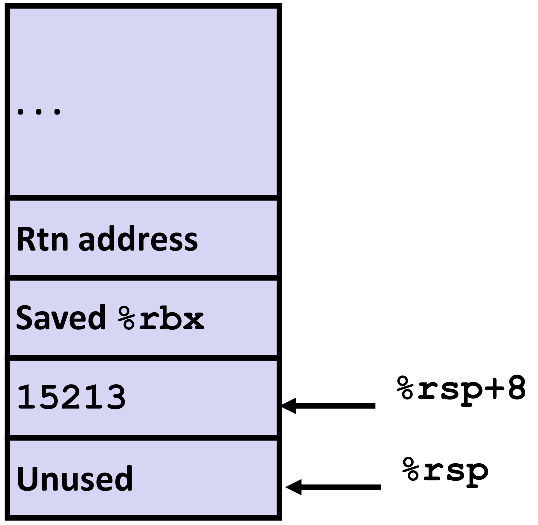
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

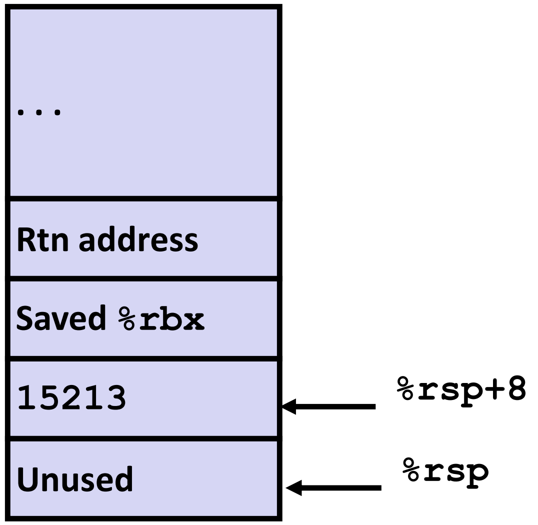


Callee-Saved Example #2

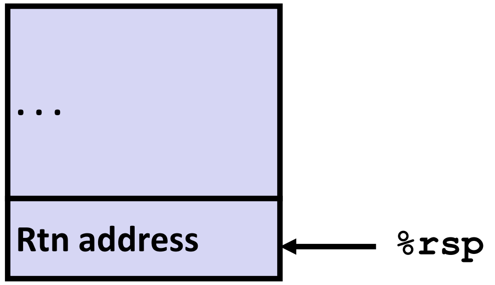
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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



Today

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

Recursive Function

```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
  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
```

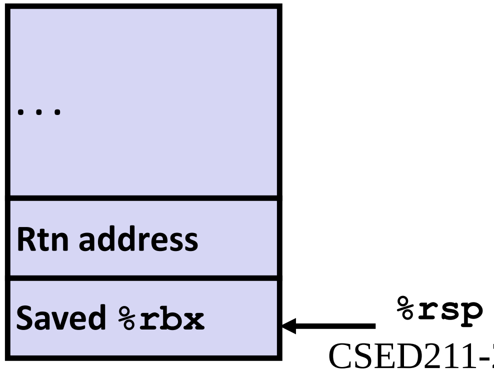
Register	Use(s)	Type
`%rdi`	`x`	Argument
`%rax`	Return value	Return value

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
```

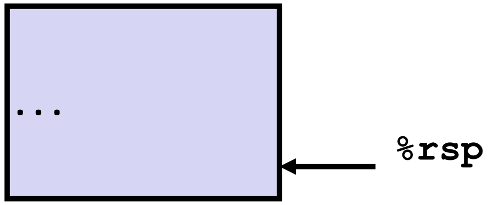
Register	Use(s)	Type
`%rbx`	`x & 1`	Callee-saved
`%rax`	Return value	

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

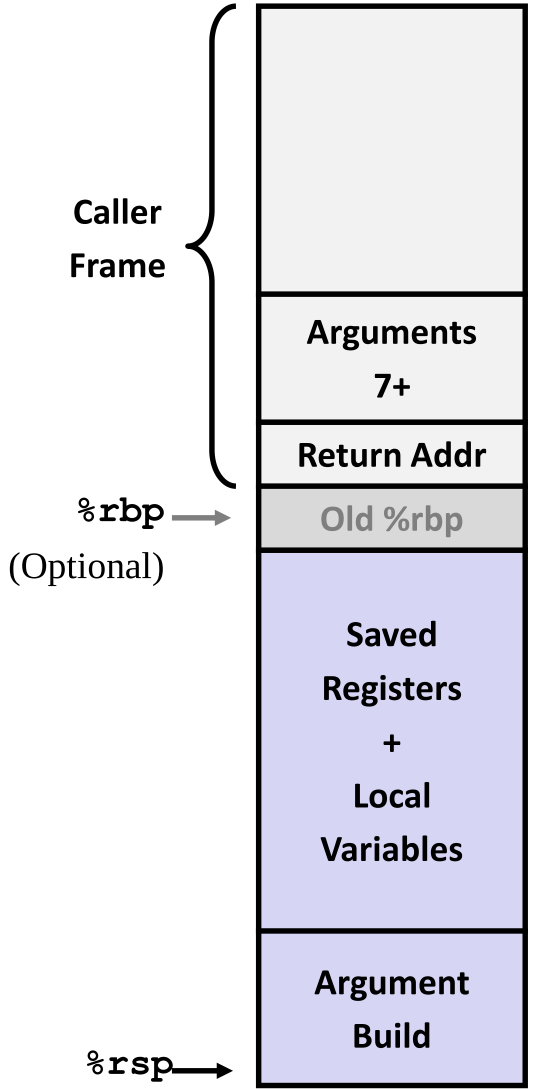


Observations About Recursion

- 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

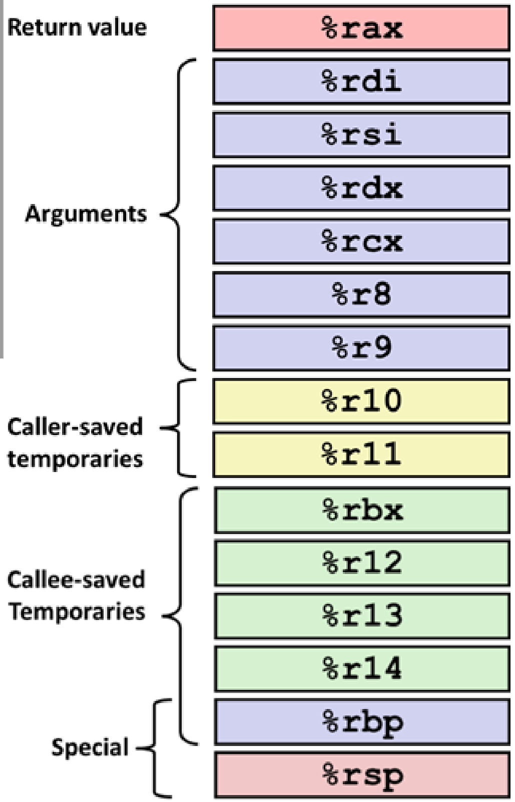
- Important Points
  - Stack is the right data structure for procedure call / return
    - If P calls Q, then Q returns before P
- Recursion (& mutual recursion) handled by normal calling conventions
  - Can safely store values in local stack frame and in callee-saved registers
  - Put function arguments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



Small Exercise

```
long add5(long b0, long b1, long b2, long b3, long b4) {
    return b0+b1+b2+b3+b4;
}

long add10(long a0, long a1, long a2, long a3, long a4, long a5,
    long a6, long a7, long a8, long a9) {
    return add5(a0, a1, a2, a3, a4)+
        add5(a5, a6, a7, a8, a9);
}
```



- **Where are `a0`,…, `a9` passed?**

  `rdi`, `rsi`, `rdx`, `rcx`, `r8`, `r9`, stack

- **Where are `b0`,…, `b4` passed?**

  `rdi`, `rsi`, `rdx`, `rcx`, `r8`

- **Which registers do we need to save?**

  Ill-posed question. Need assembly.

  `rbx`, `rbp`, `r9` (during first call to `add5`)

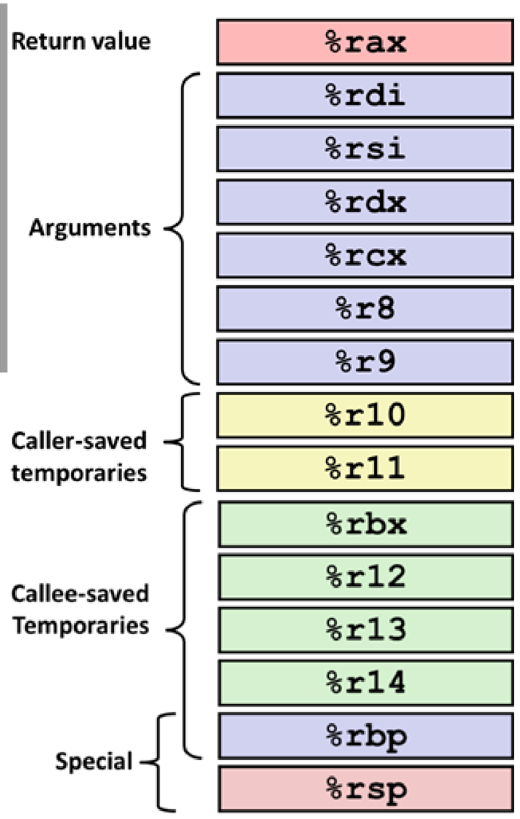
Small Exercise

```
long add5(long b0, long b1, long b2, long b3, long b4) {
    return b0+b1+b2+b3+b4;
}

long add10(long a0, long a1, long a2, long a3, long a4, long a5,
    long a6, long a7, long a8, long a9) {
    return add5(a0, a1, a2, a3, a4)+
        add5(a5, a6, a7, a8, a9);
}
```

```
add10:
        pushq   %rbp
        pushq   %rbx
        movq    %r9, %rbp
        call    add5
        movq    %rax, %rbx
        movq    48(%rsp), %r8
        movq    40(%rsp), %rcx
        movq    32(%rsp), %rdx
        movq    24(%rsp), %rsi
        movq    %rbp, %rdi
        call    add5
        addq    %rbx, %rax
        popq    %rbx
        popq    %rbp
        ret
```

```
add5:
        addq    %rsi, %rdi
        addq    %rdi, %rdx
        addq    %rdx, %rcx
        leaq    (%rcx,%r8), %rax
        ret
```


Return value
%rax
Arguments
%rdi
%rsi
%rdx
%rcx
%r8
%r9
Caller-saved temporaries
%r10
%r11
Callee-saved Temporaries
%rbx
%r12
%r13
%r14
%rbp
Special
%rsp