Machine-Level Programming III: Procedures

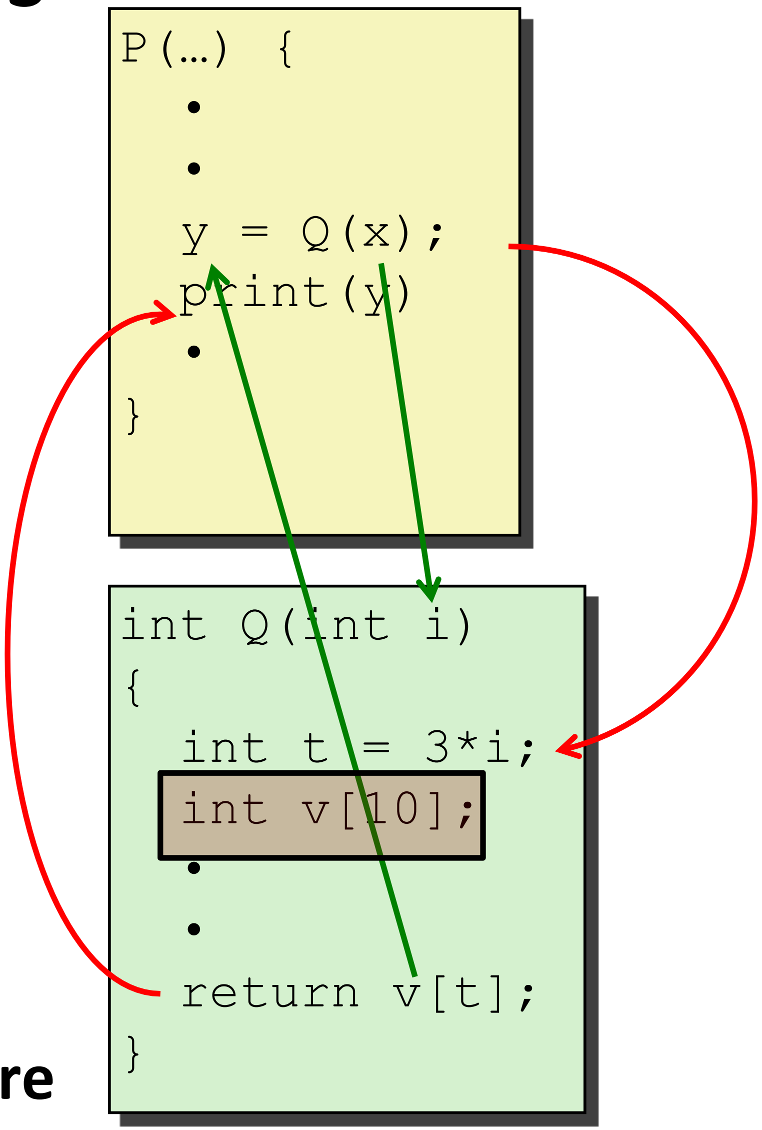
Introduction to Computer Systems
7th Lecture, March 29, 2019

Instructors:

Yili Gong

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)
   •
}
```

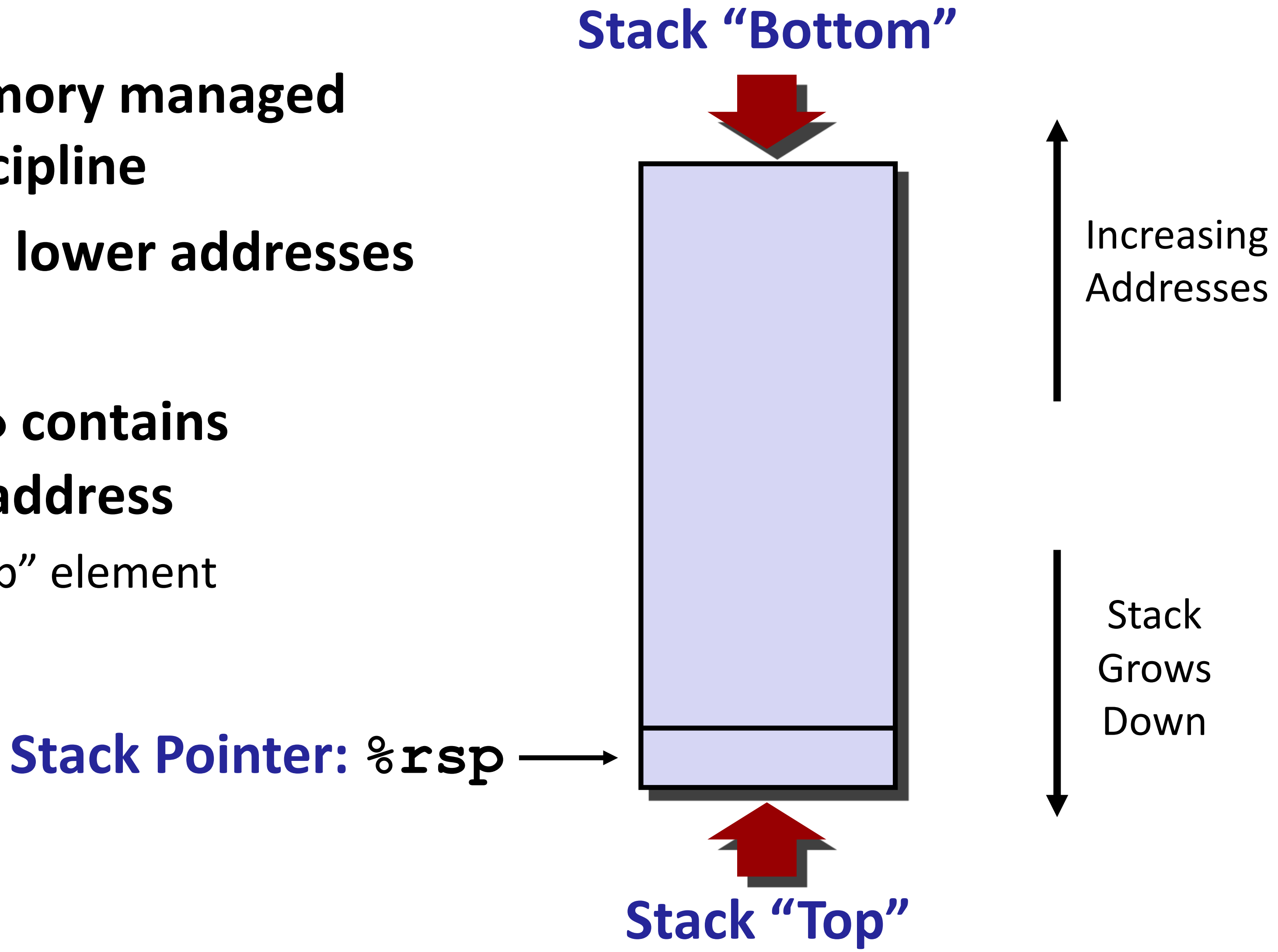
```
int Q(int i)
{
   int t = 3*i;
   int v[10];
   •
   •
   return v[t];
}
```

Today

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

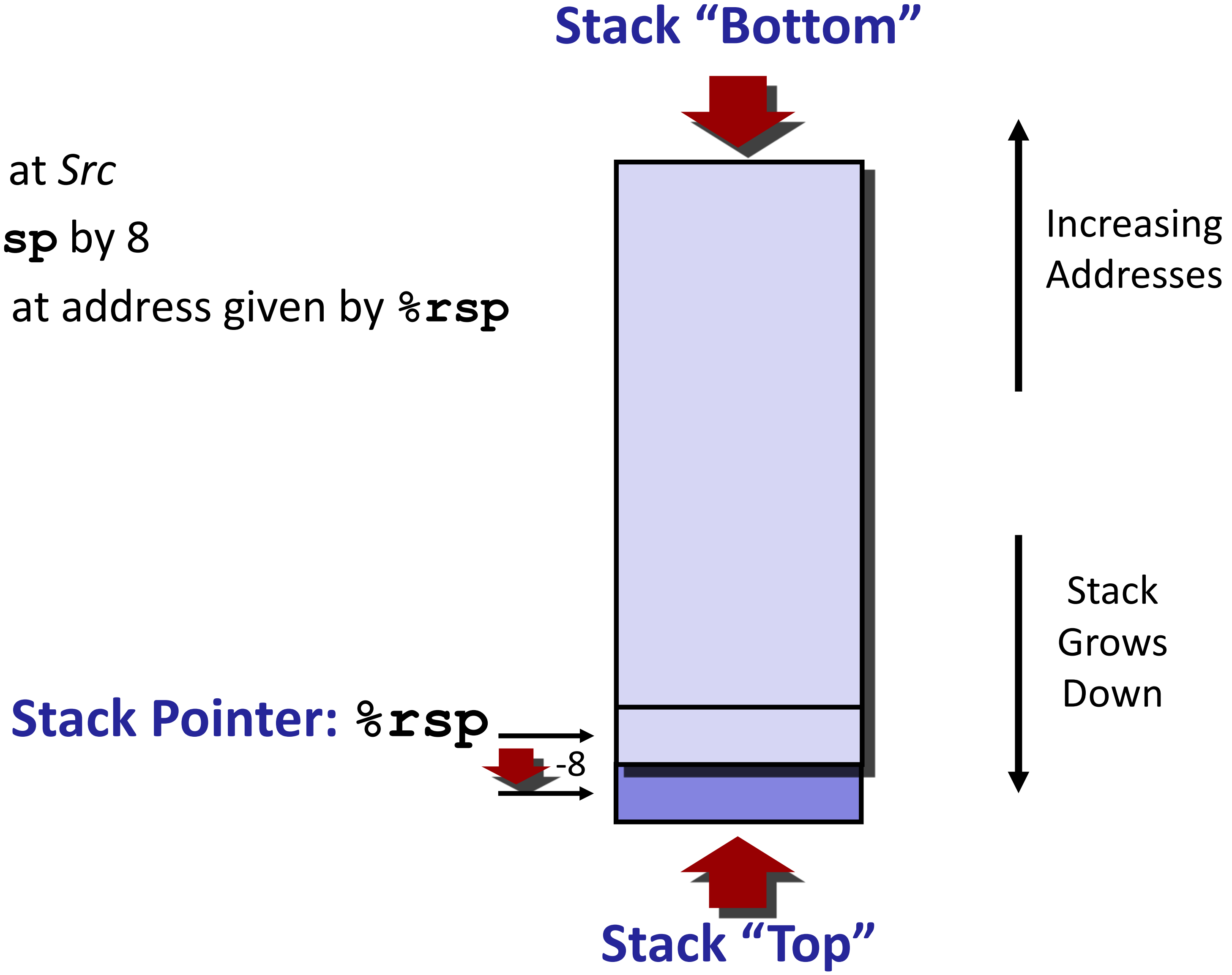
x86-64 Stack

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



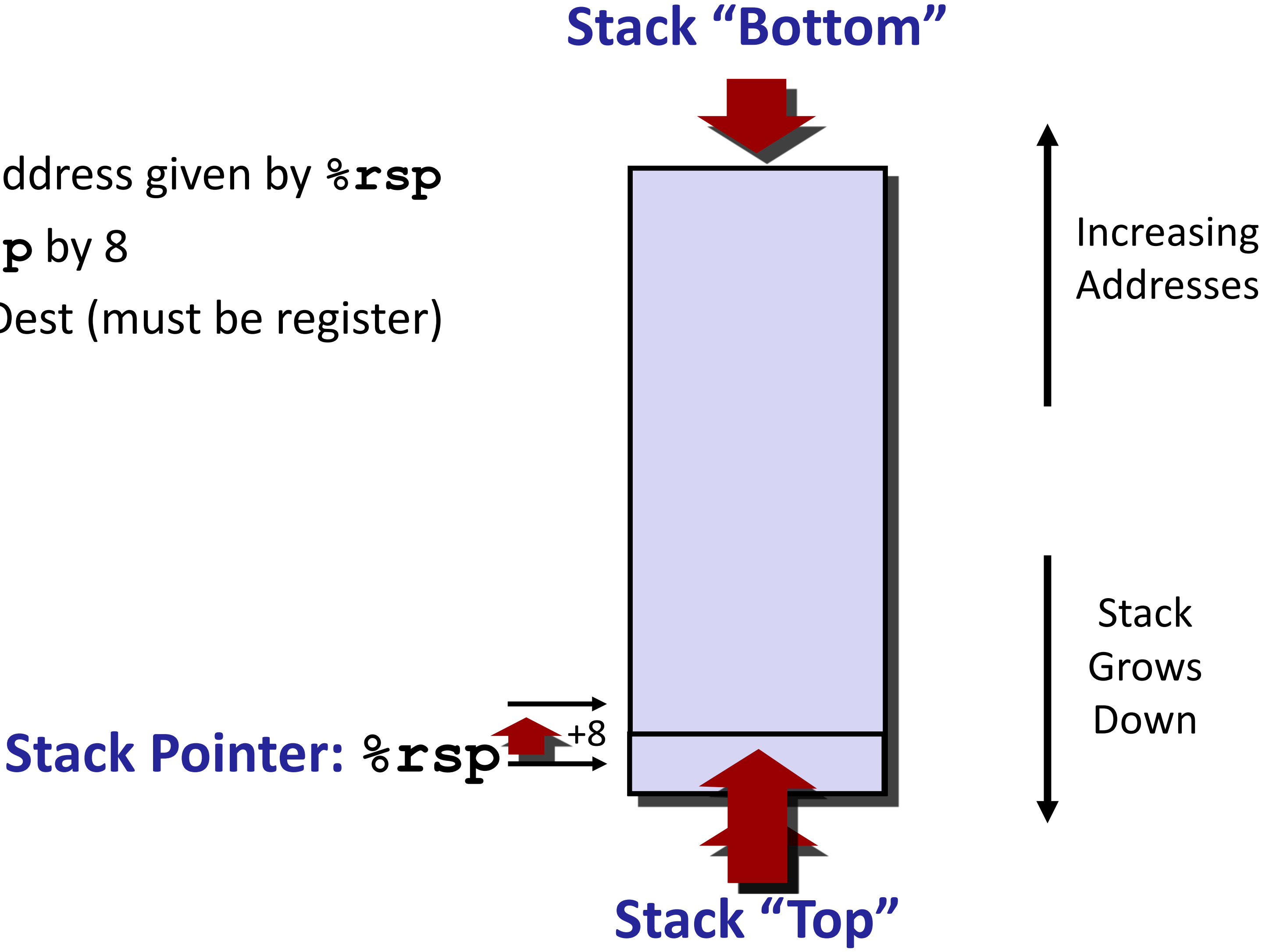
x86-64 Stack: Push

- `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)



Today

- **Procedures**
    - **Stack Structure**
    - **Calling Conventions**
        - **Passing control**
        - **Passing data**
        - **Managing local data**
    - **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: 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
```

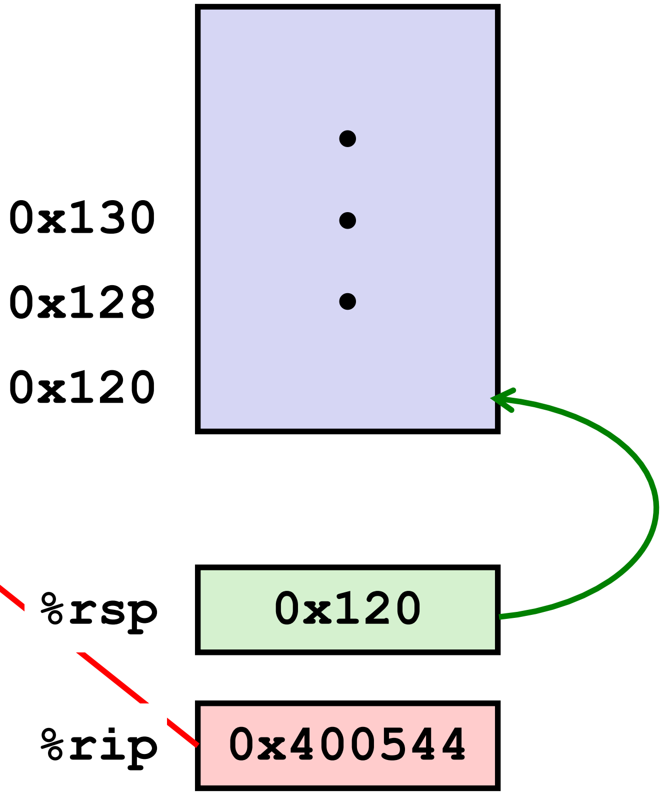
Procedure Control Flow

- **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

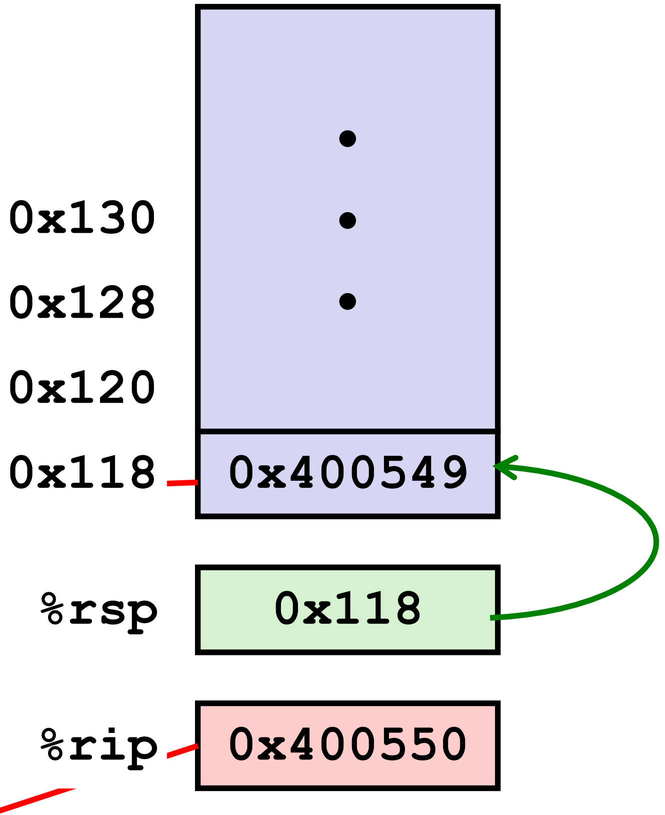
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

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



Control Flow Example #2

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

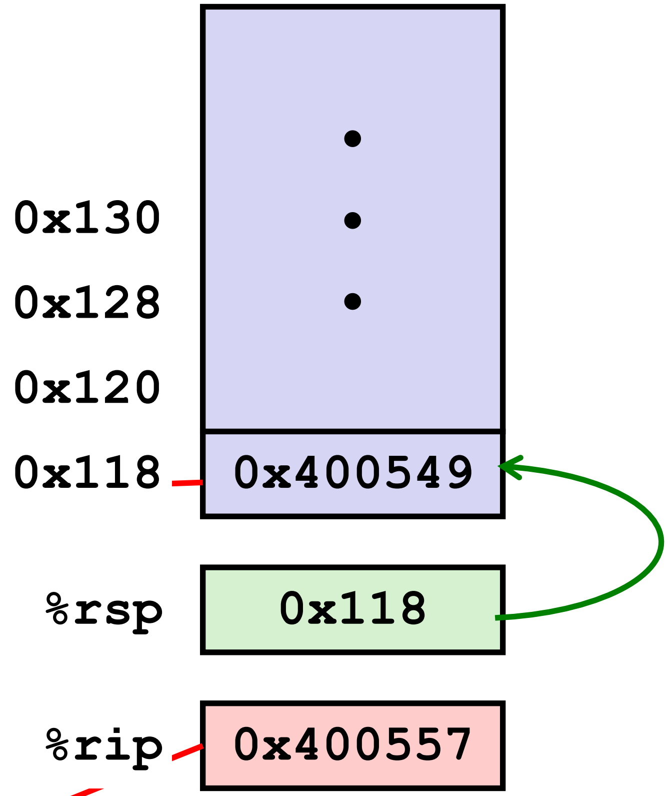


```
0000000000400550 <mult2>:
  400550:   mov    %rdi,%rax
  •
  •
  400557:   retq
```

Control Flow Example #3

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

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

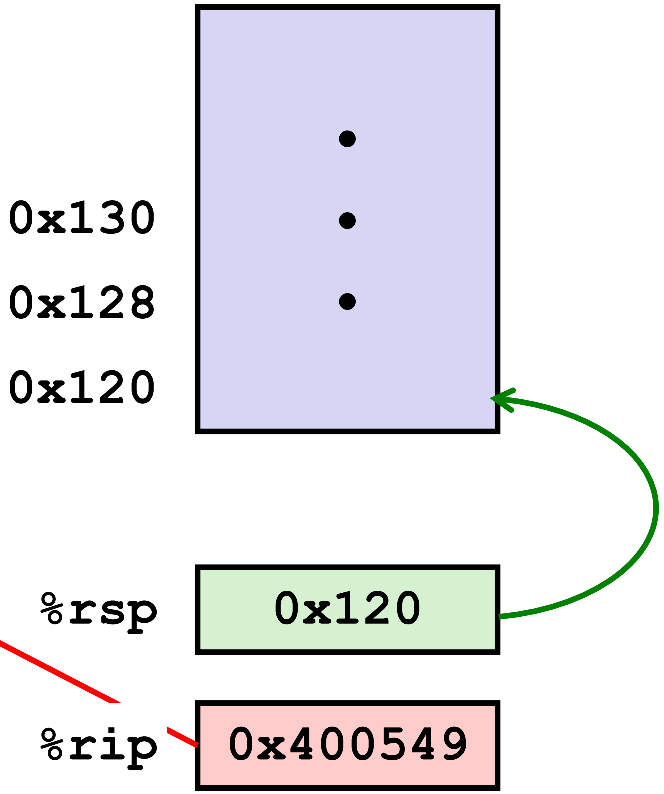


Bryant and O'Hallaron, Computer Systems: A Programmer's Perspective, Third Edition

Control Flow Example #4

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

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



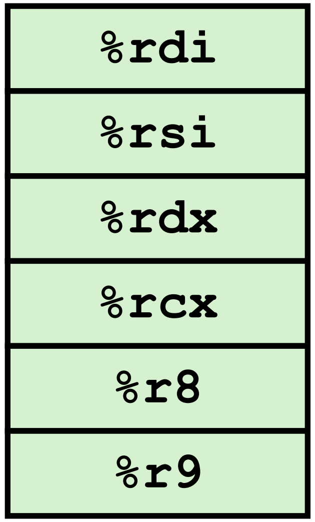
Today

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

Procedure Data Flow

Registers

- First 6 arguments



%rdi

%rsi

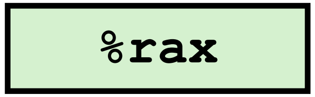
%rdx

%rcx

%r8

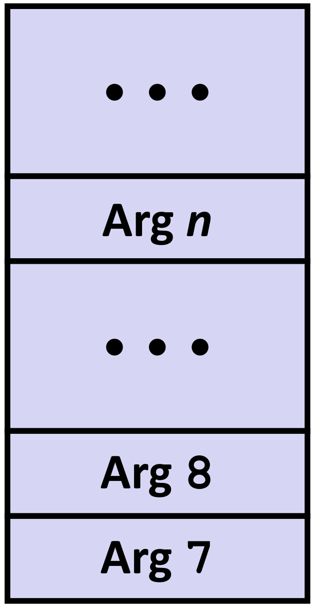
%r9

- Return value



%rax

Stack



• • •

Arg *n*

• • •

Arg 8

Arg 7

- 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
```

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- **Procedures**
  - Stack Structure
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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

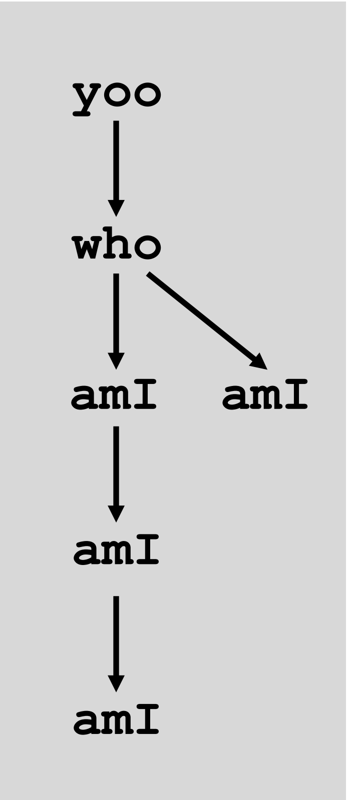
```
yoo(…)
{
   •
   •
   who();
   •
   •
}
```

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

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

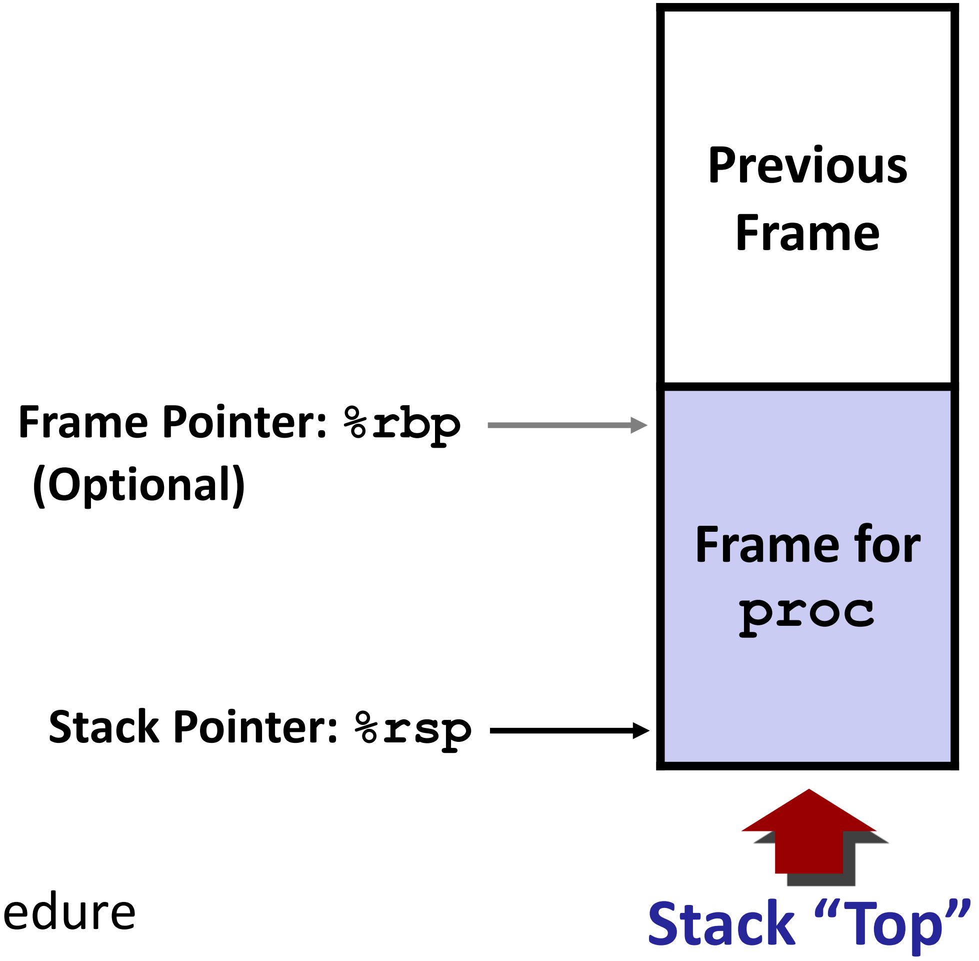
Procedure `amI()` is recursive

Example Call Chain



Stack Frames

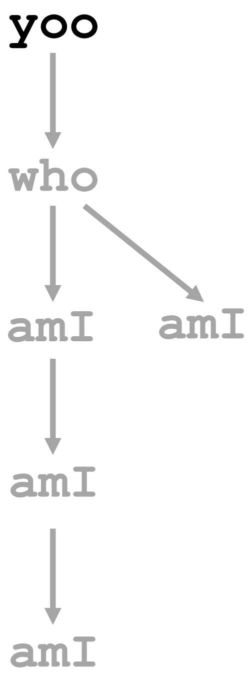
- **Contents**
  - Return information
  - Local storage (if needed)
  - Temporary space (if needed)

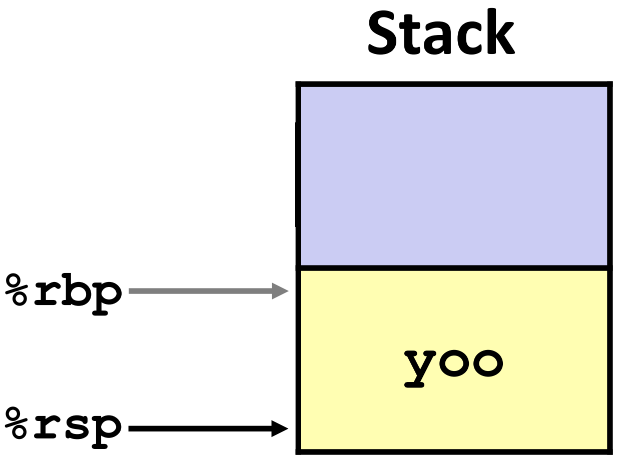


- **Management**
  - Space allocated when enter procedure
    - "Set-up" code
    - Includes push by **`call`** instruction
  - Deallocated when return
    - "Finish" code
    - Includes pop by **`ret`** instruction

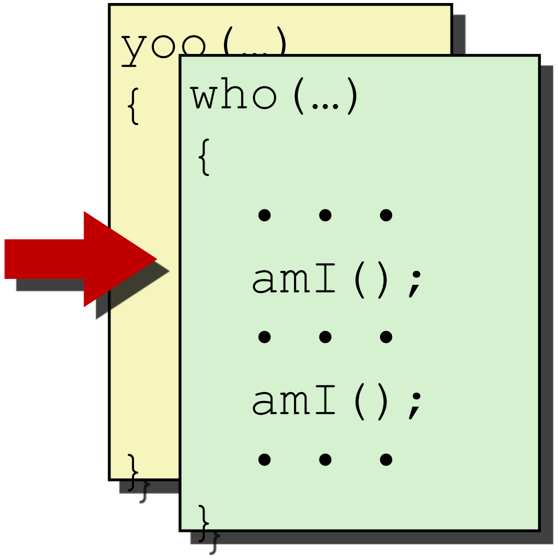
Example

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



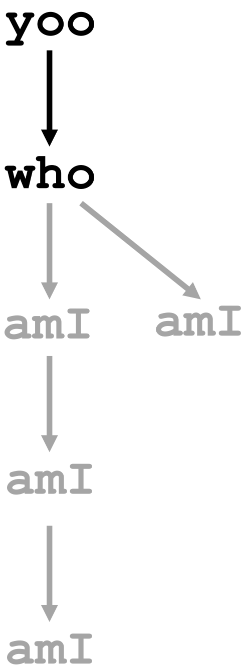


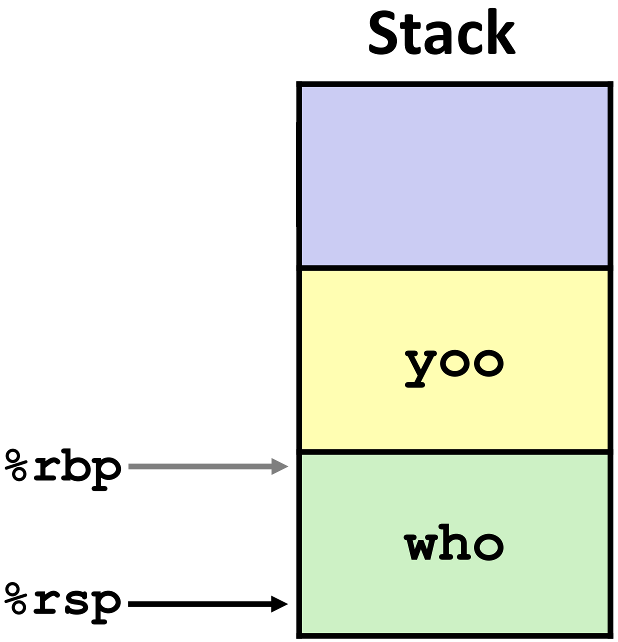
Example



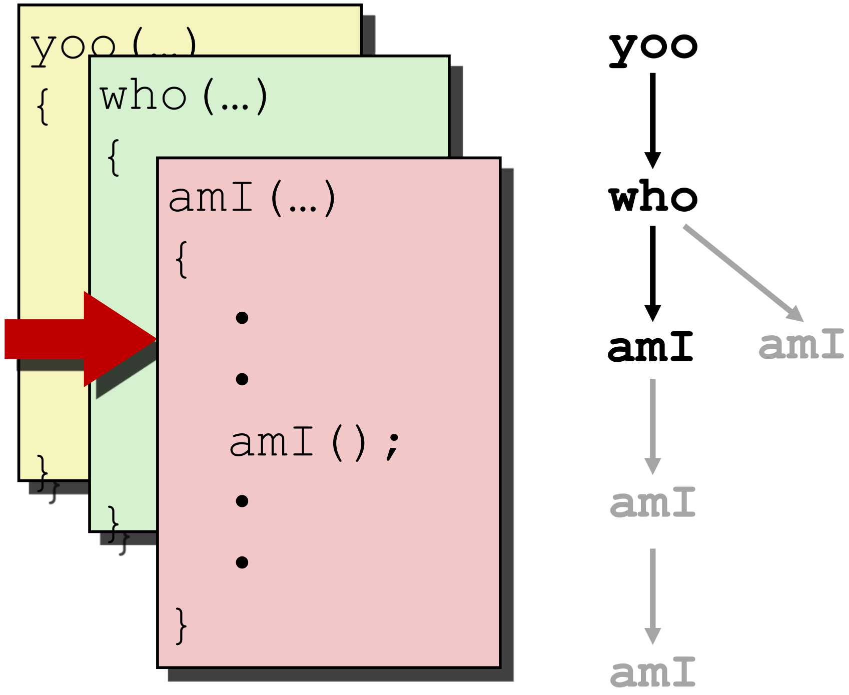
```
yoo(…)
{



}
```

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

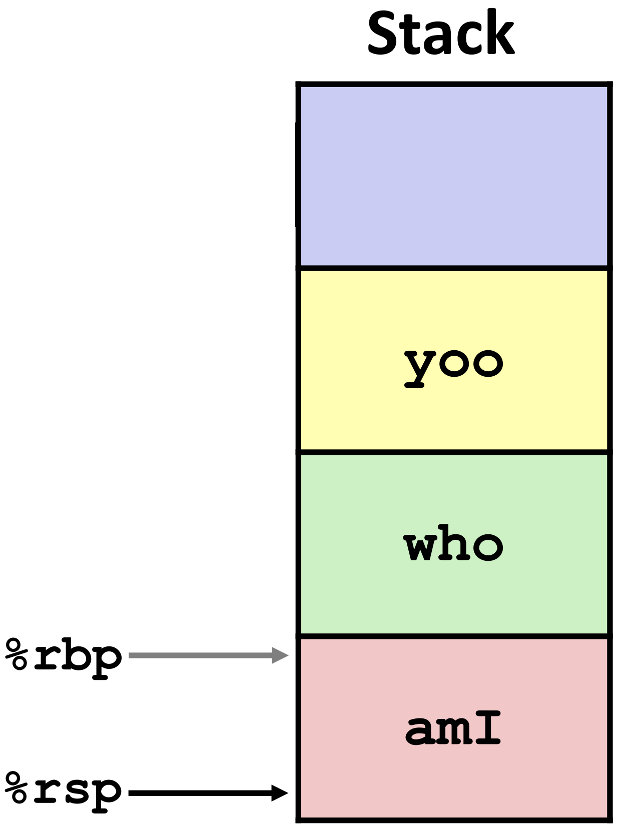




Example

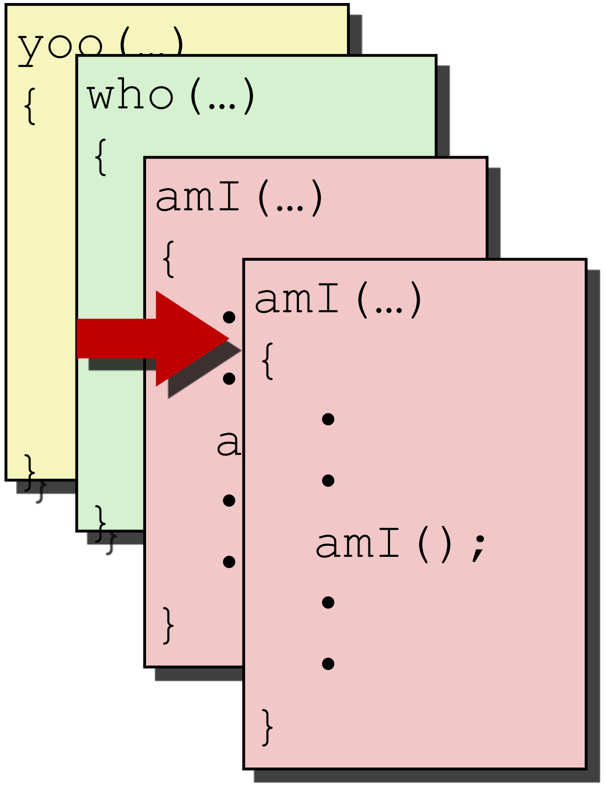


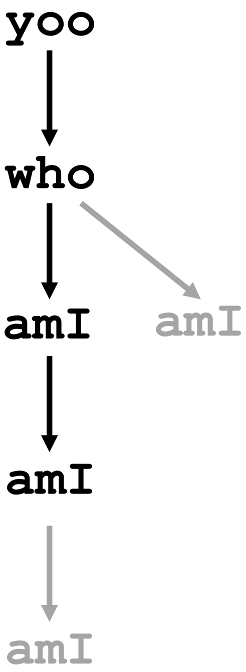
yoo(…)
{
}
who(…)
{
}
amI(…)
{
•
•
amI();
•
•
}
yoo
who
amI
amI
amI
amI

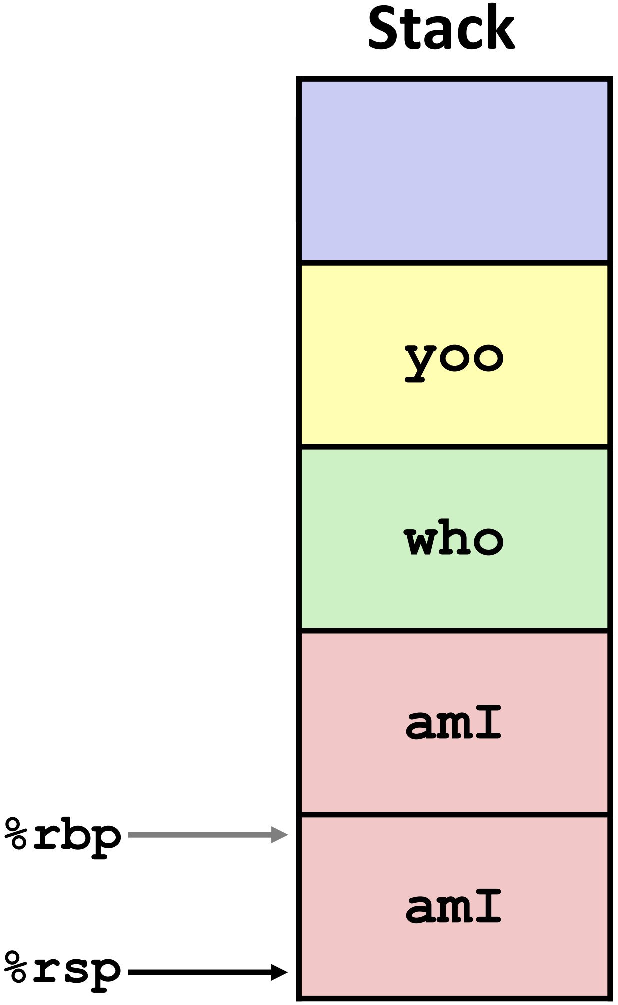


Stack
yoo
who
amI
%rbp
%rsp

Example


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


yoo
who
amI
amI
amI
amI


Stack
yoo
who
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amI
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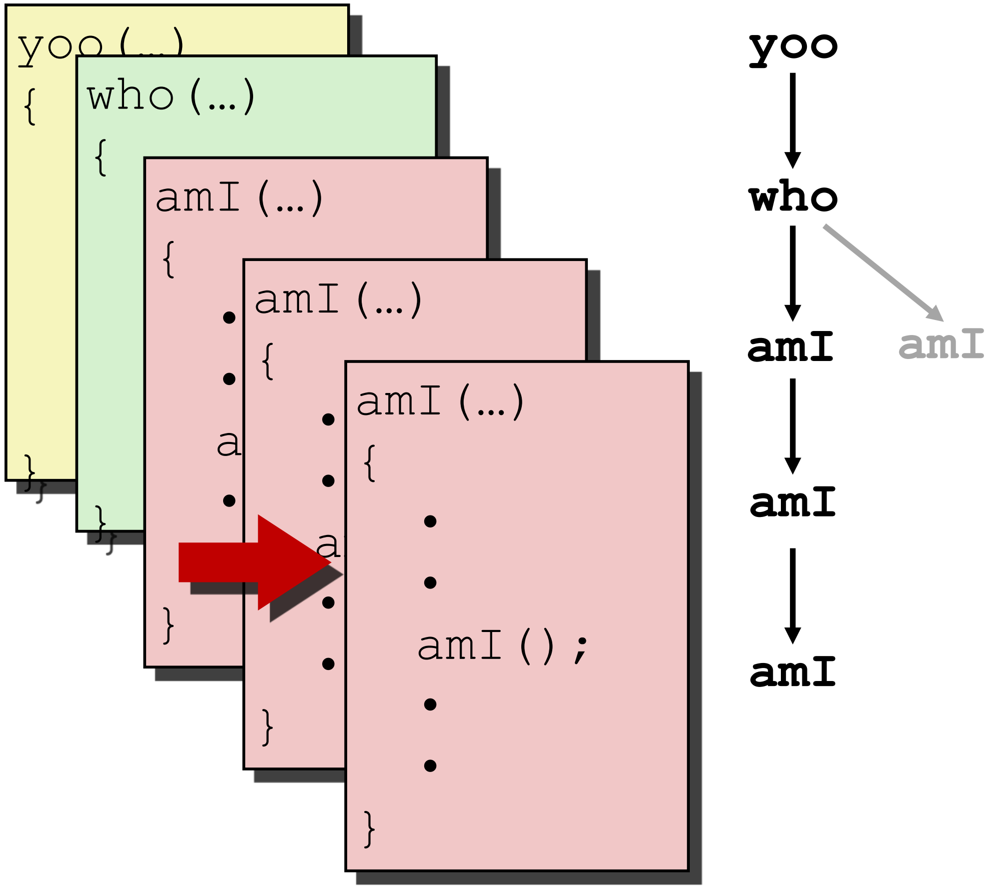
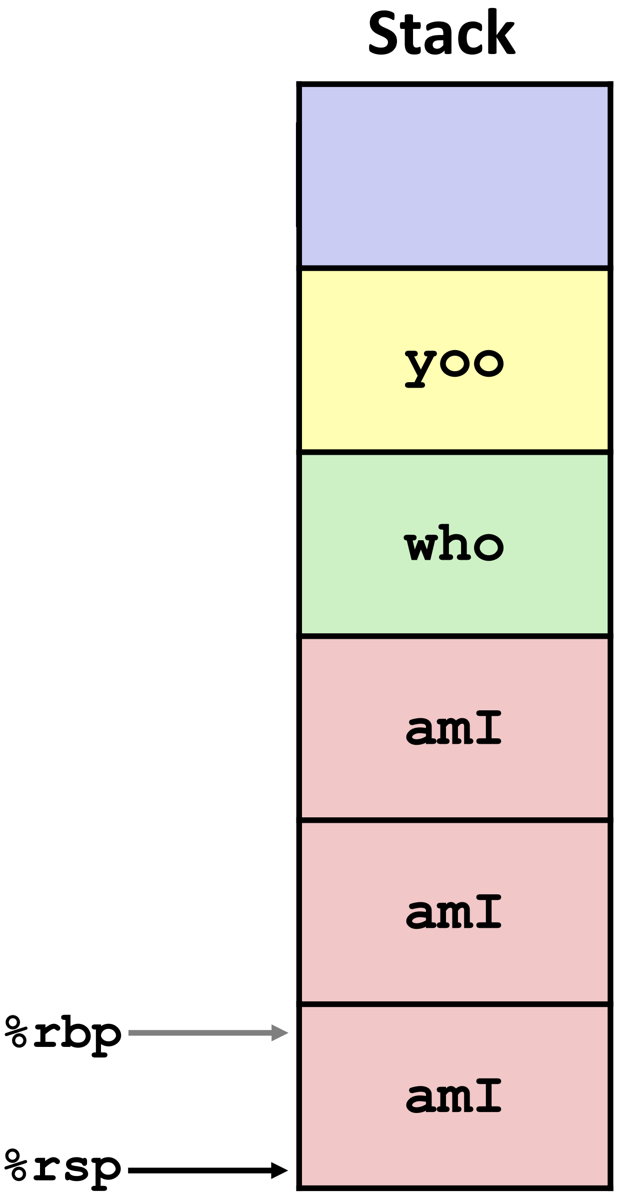
%rsp

Example


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


Stack
yoo
who
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amI
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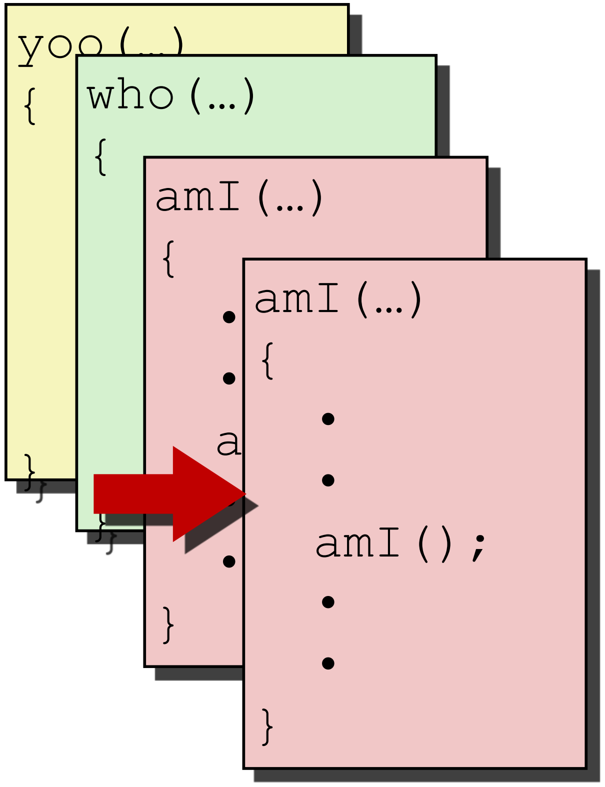
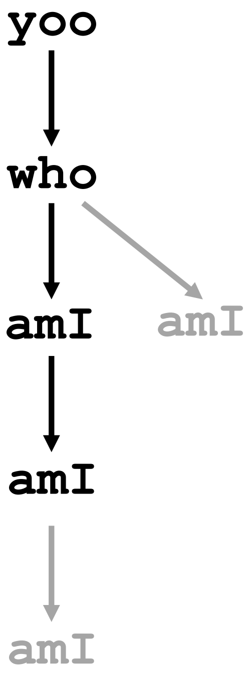
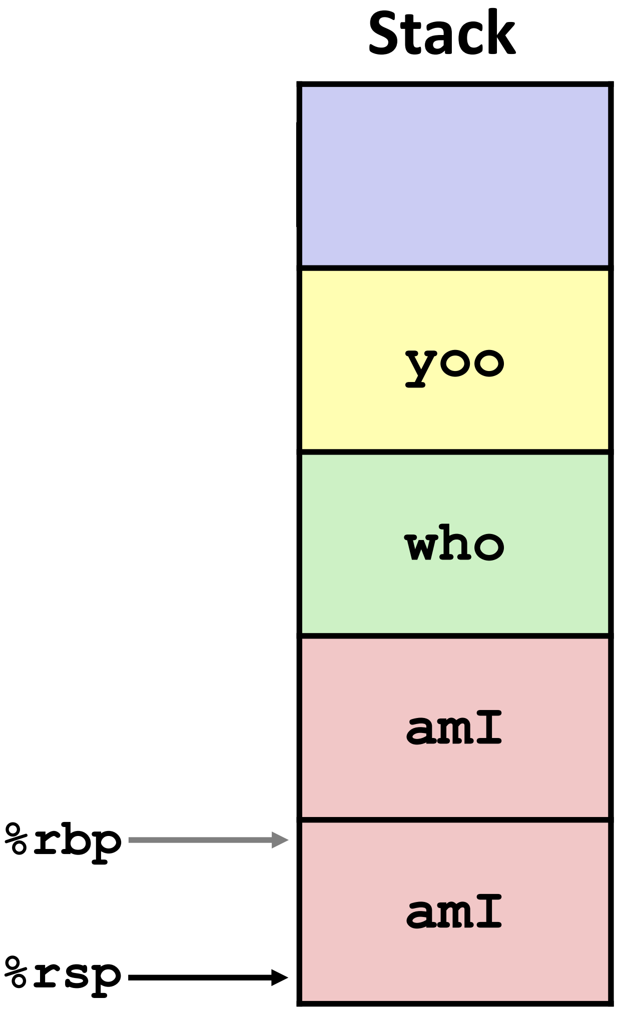
%rsp

Example


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


yoo
who
amI
amI
amI
amI


Stack
yoo
who
amI
amI
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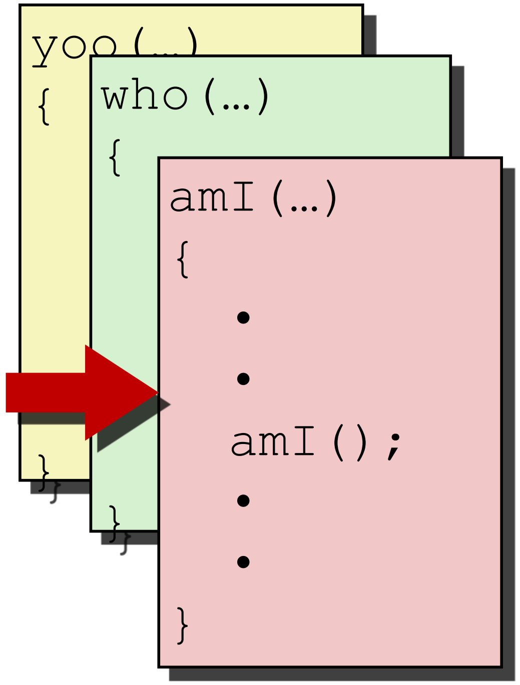
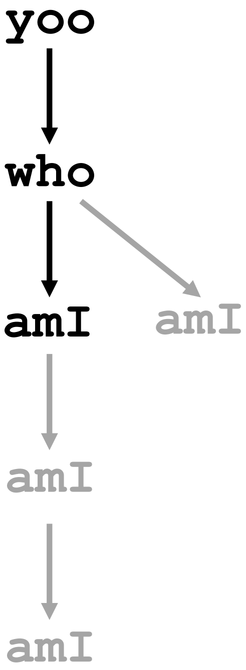
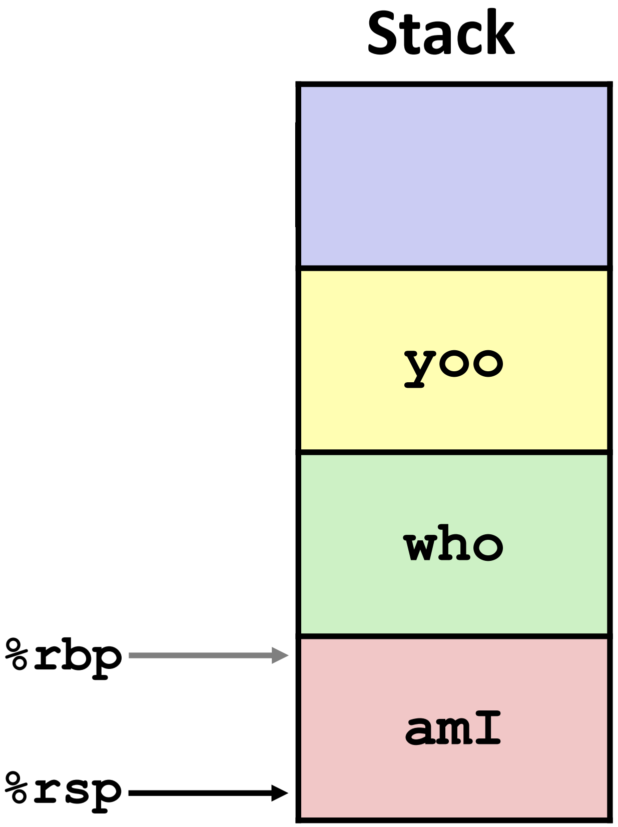
%rsp

Example

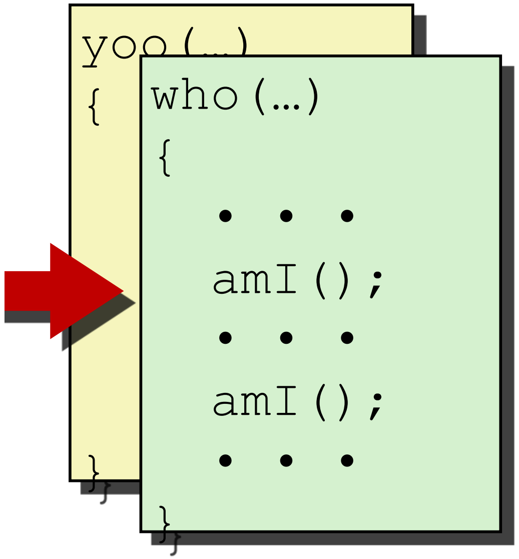


```
yoo(…)
{
  who(…)
  {
    amI(…)
    {
      •
      •
      amI();
      •
      •
    }
  }
}
```



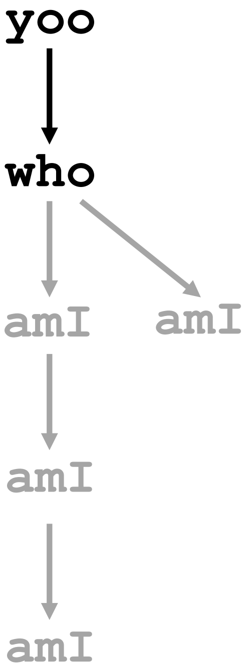


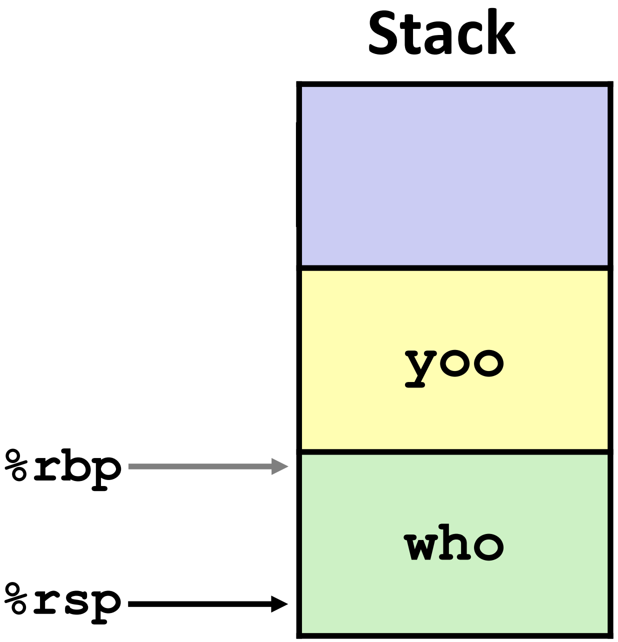
Example



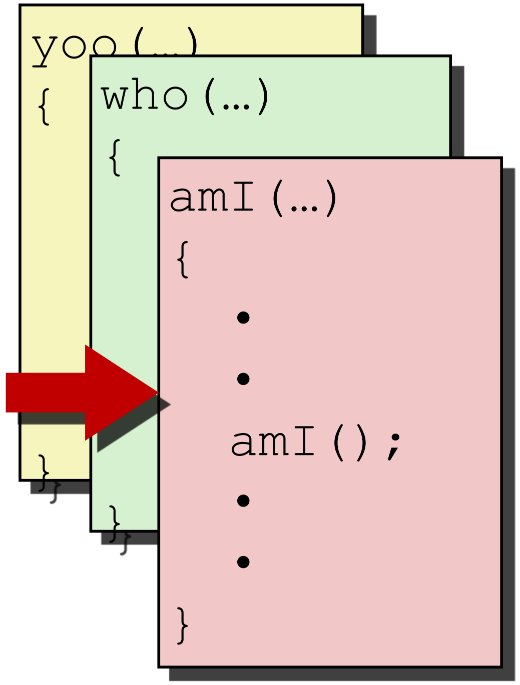
```
yoo(…)
{

}
```

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

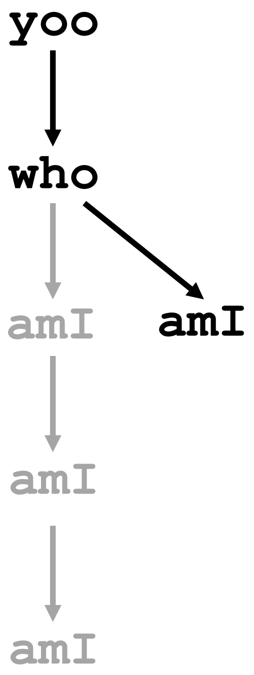




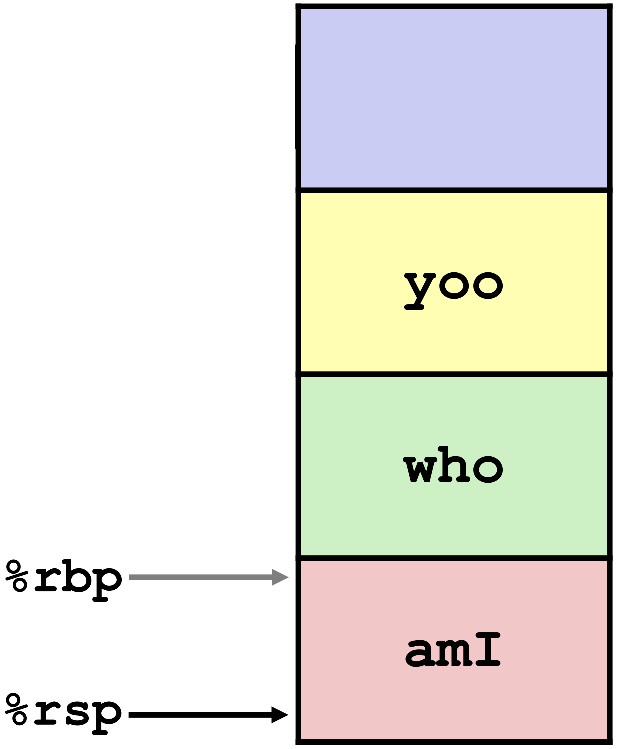
Example



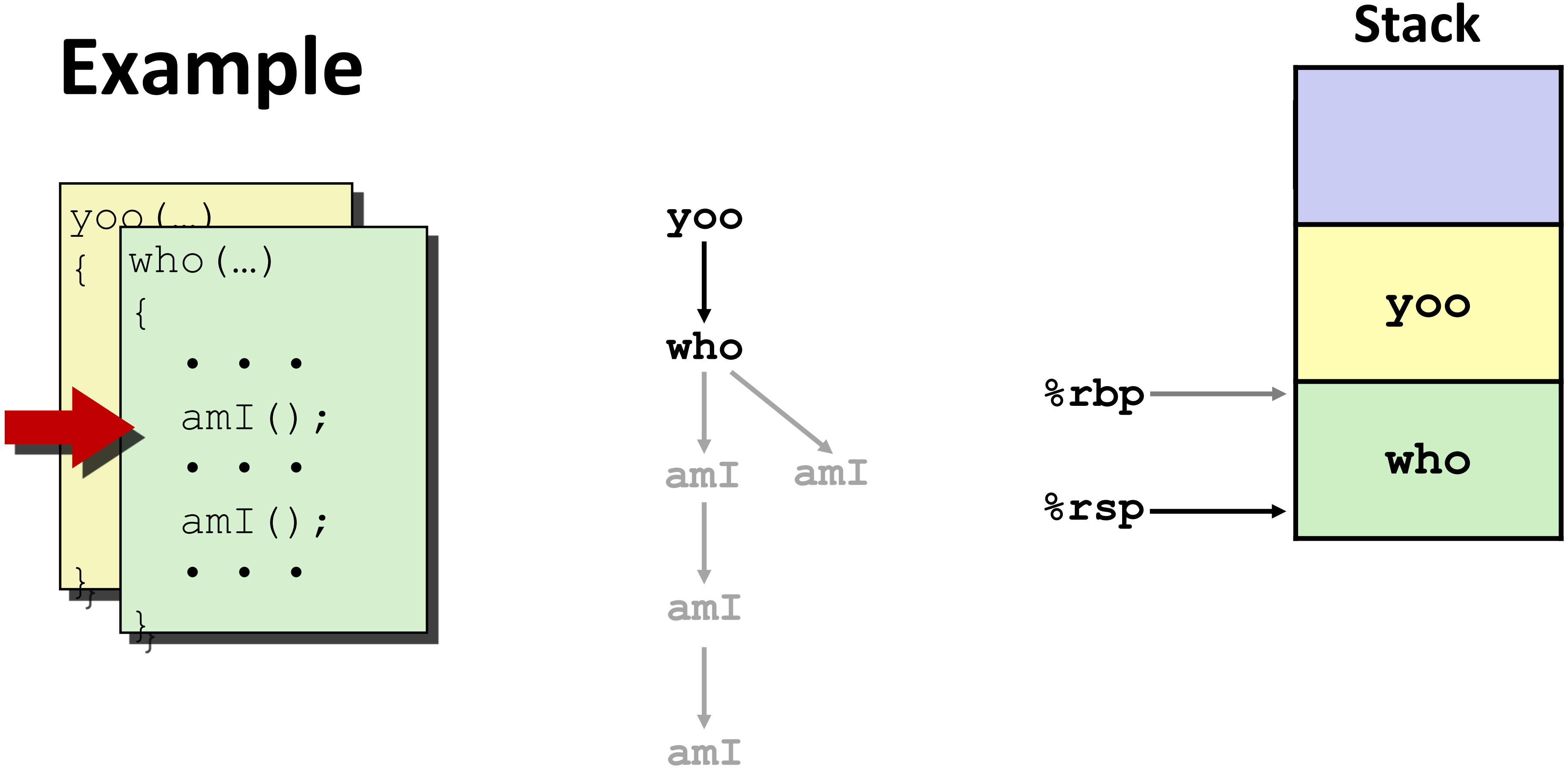
```
yoo(…)
{
  who(…)
  {
    amI(…)
    {
      •
      •
      amI();
      •
      •
    }
  }
}
```



Stack



Example

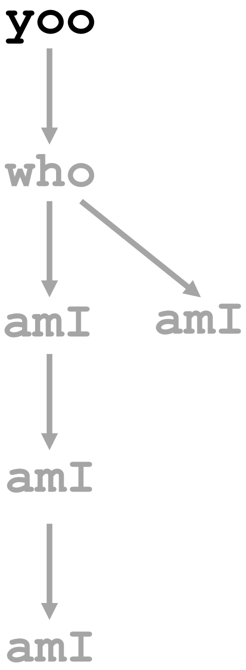


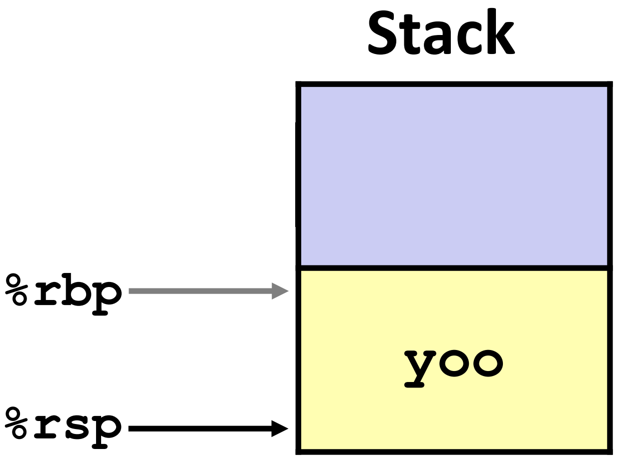
```
yoo(…)
{
  …
}
```

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

Example

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

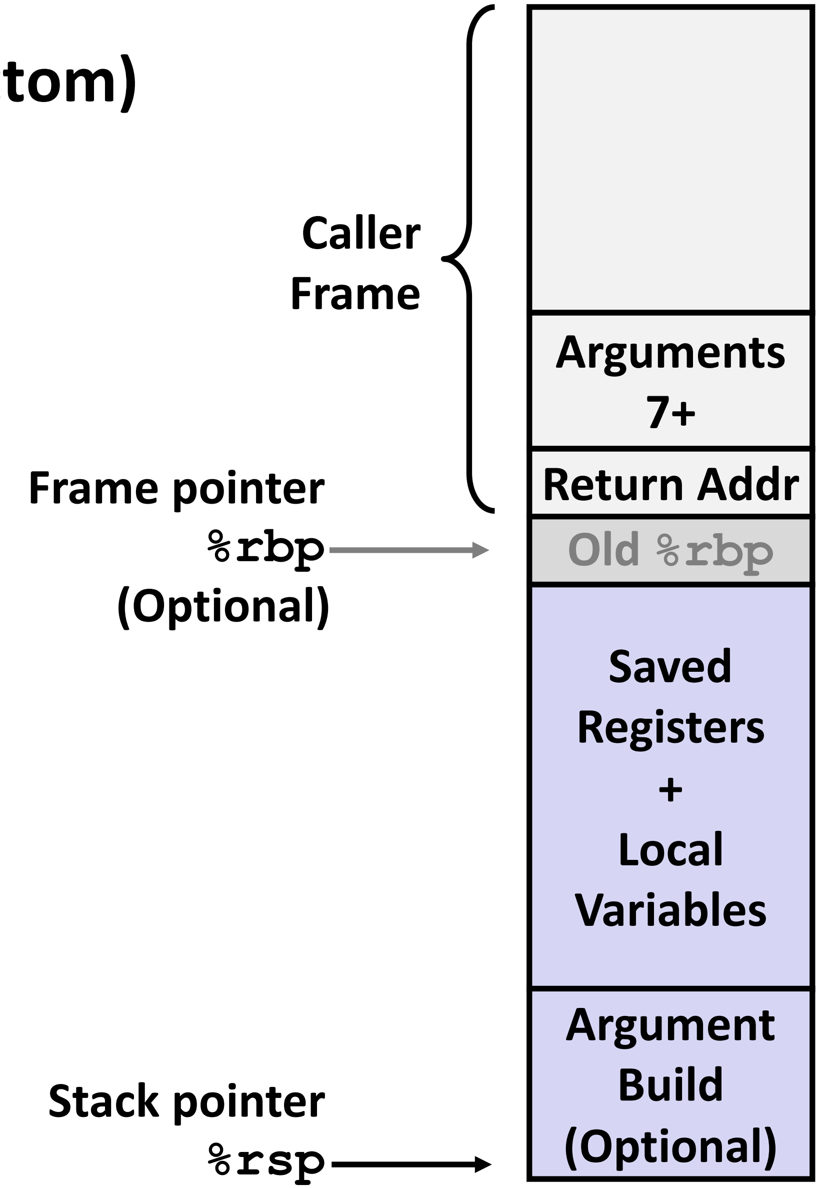




x86-64/Linux Stack Frame

- **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;
}
```

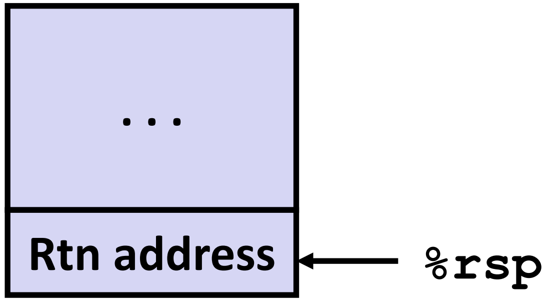
```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```

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



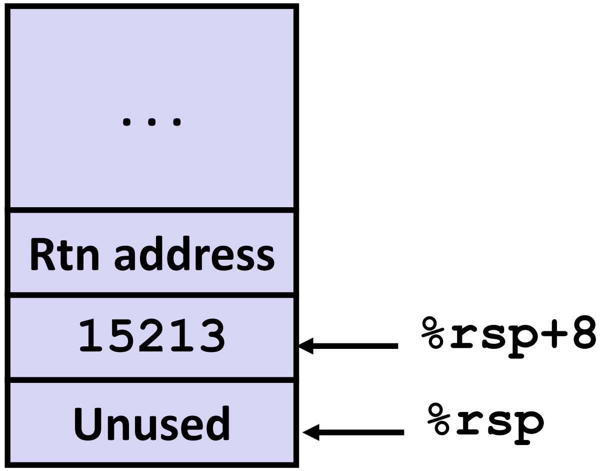
. . .

Rtn address

%rsp

```
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



. . .

Rtn address

15213

Unused

%rsp+8

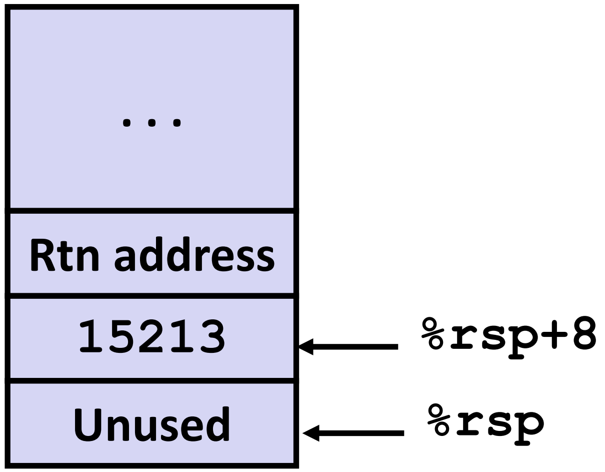
%rsp

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



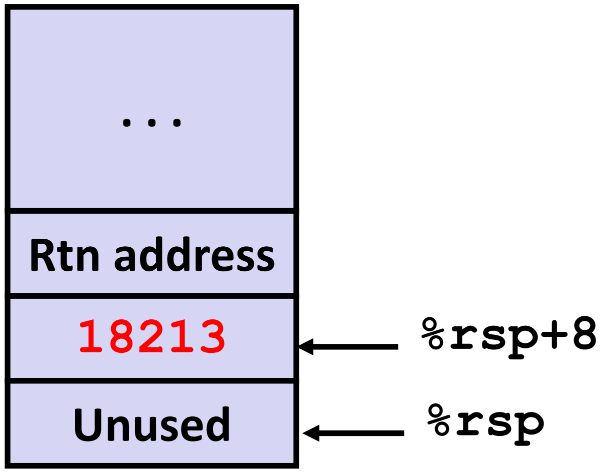
Register	Use(s)
%rdi	&v1
%rsi	3000

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



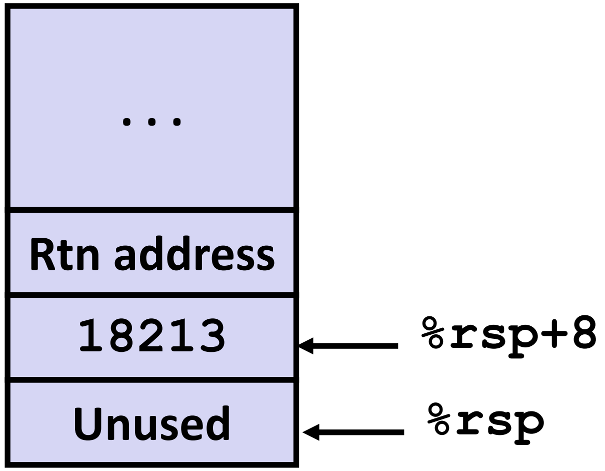
Register	Use(s)
%rdi	&v1
%rsi	3000

Example: Calling `incr` #4

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

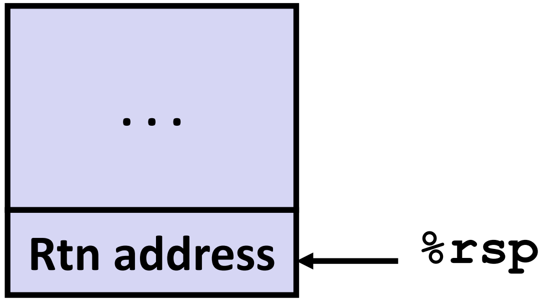
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure



Register	Use(s)
%rax	Return value

Updated Stack Structure

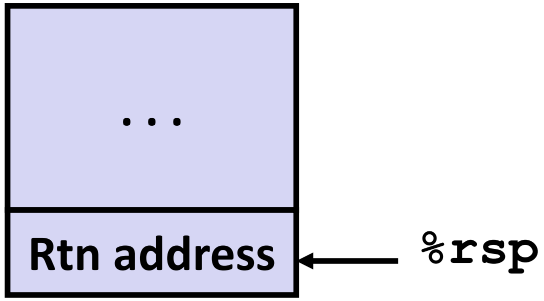


Example: Calling `incr` #5

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

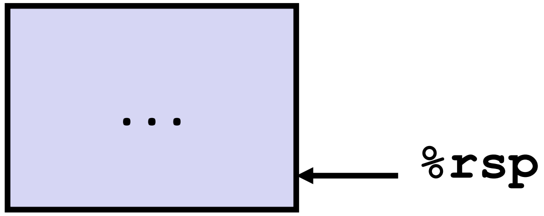
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

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
```

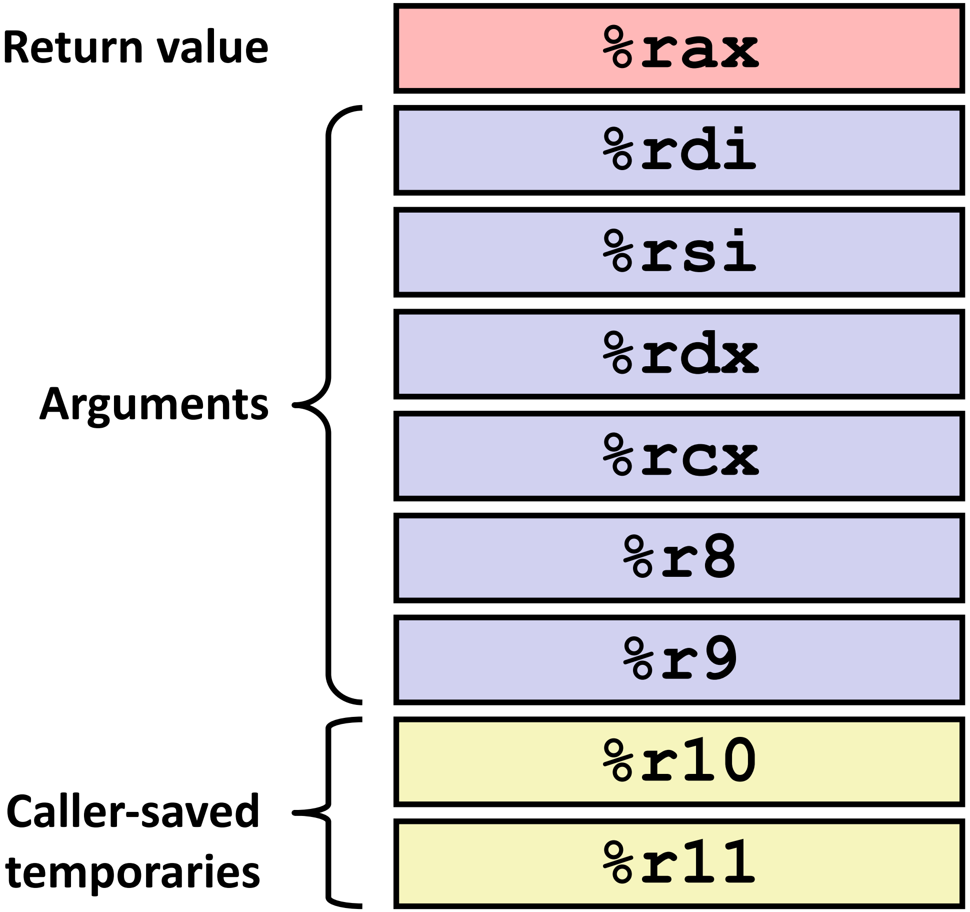
  - Contents of register **`%rdx`** overwritten by **`who`**
  - This could be trouble ➙ something should be done!
    - Need some coordination

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



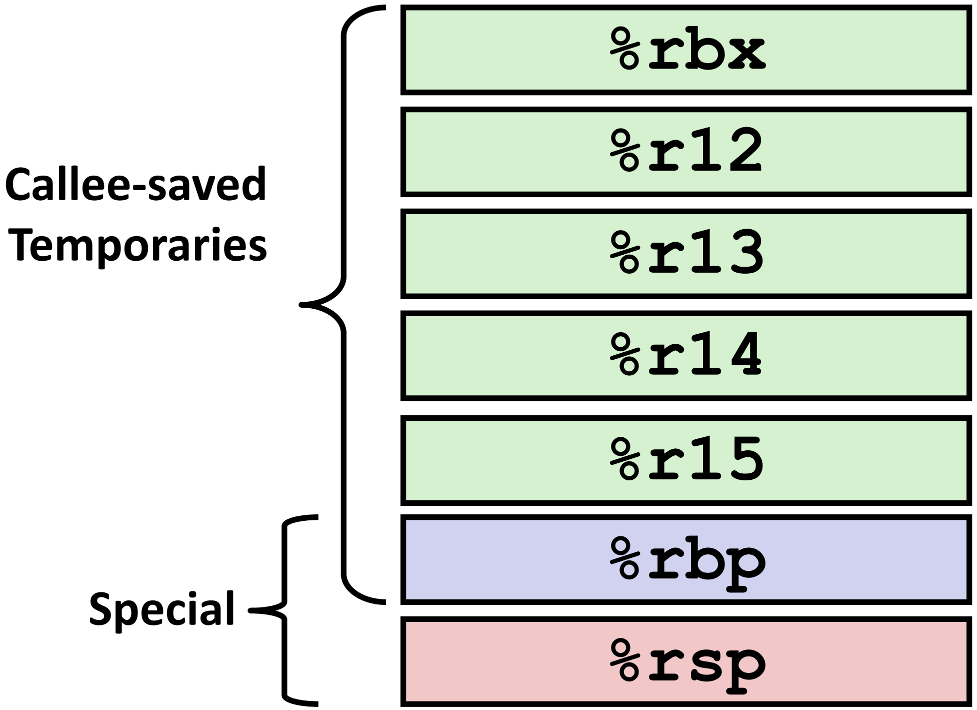
Return value: `%rax`

Arguments: `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9`

Caller-saved temporaries: `%r10`, `%r11`

x86-64 Linux Register Usage #2

- **`%rbx, %r12, %r13, %r14, %r15`**
  - 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

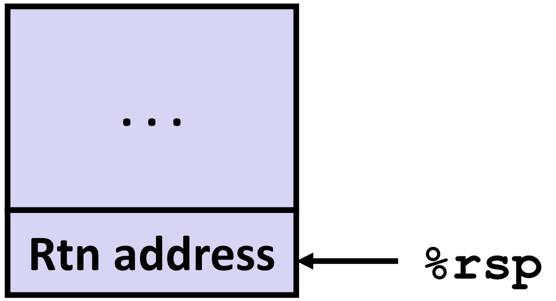


Callee-Saved Example #1

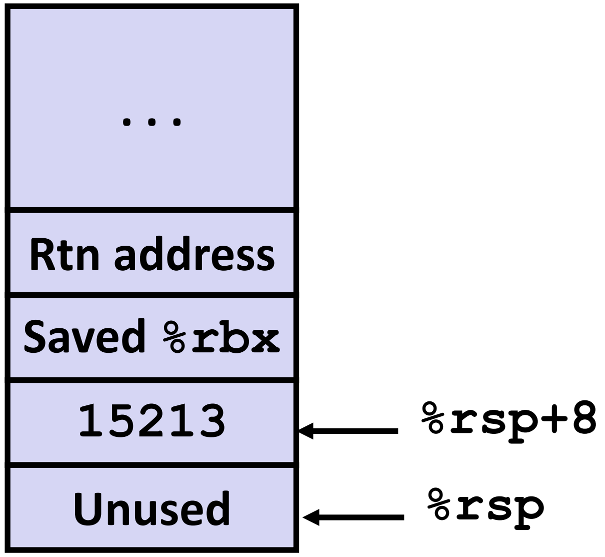
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

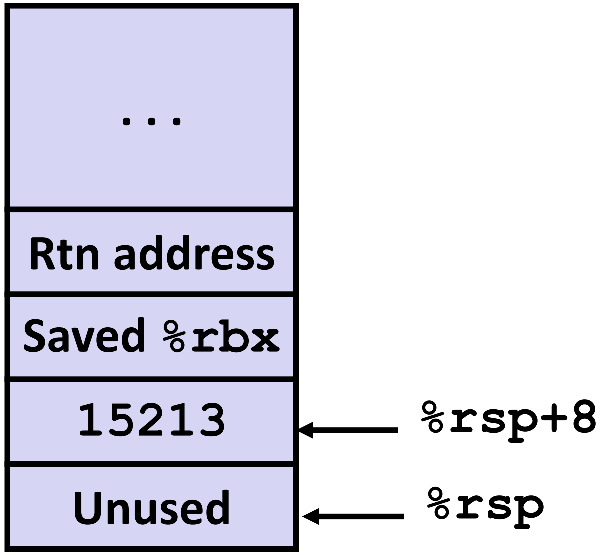


Callee-Saved Example #2

```
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



...

Rtn address

Saved %rbx

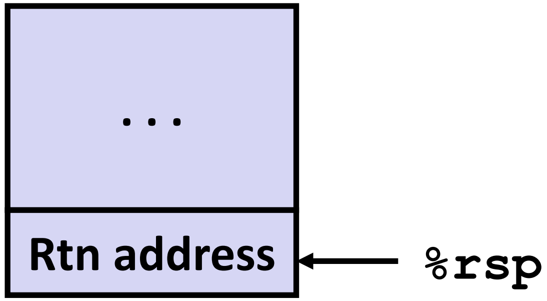
15213

Unused

%rsp+8

%rsp

Pre-return Stack Structure



...

Rtn address

%rsp

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
```

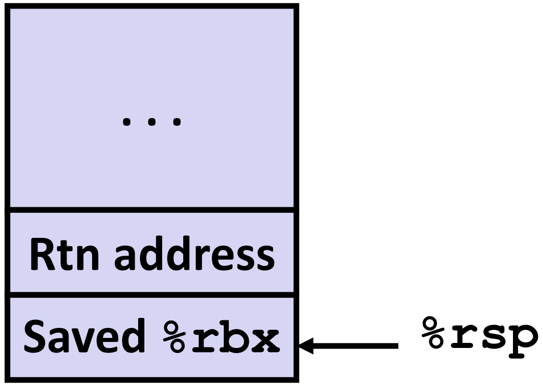
Register	Use(s)	Type
%rdi	x	Argument
%rax	Return value	Return value

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
```

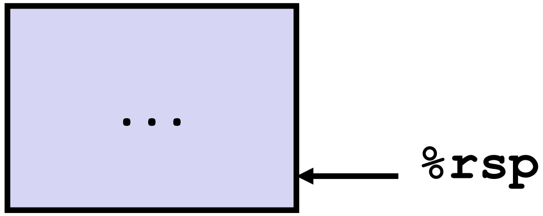
Register	Use(s)	Type
%rbx	x & 1	Callee-saved
%rax	Return value	

Recursive Function Completion

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

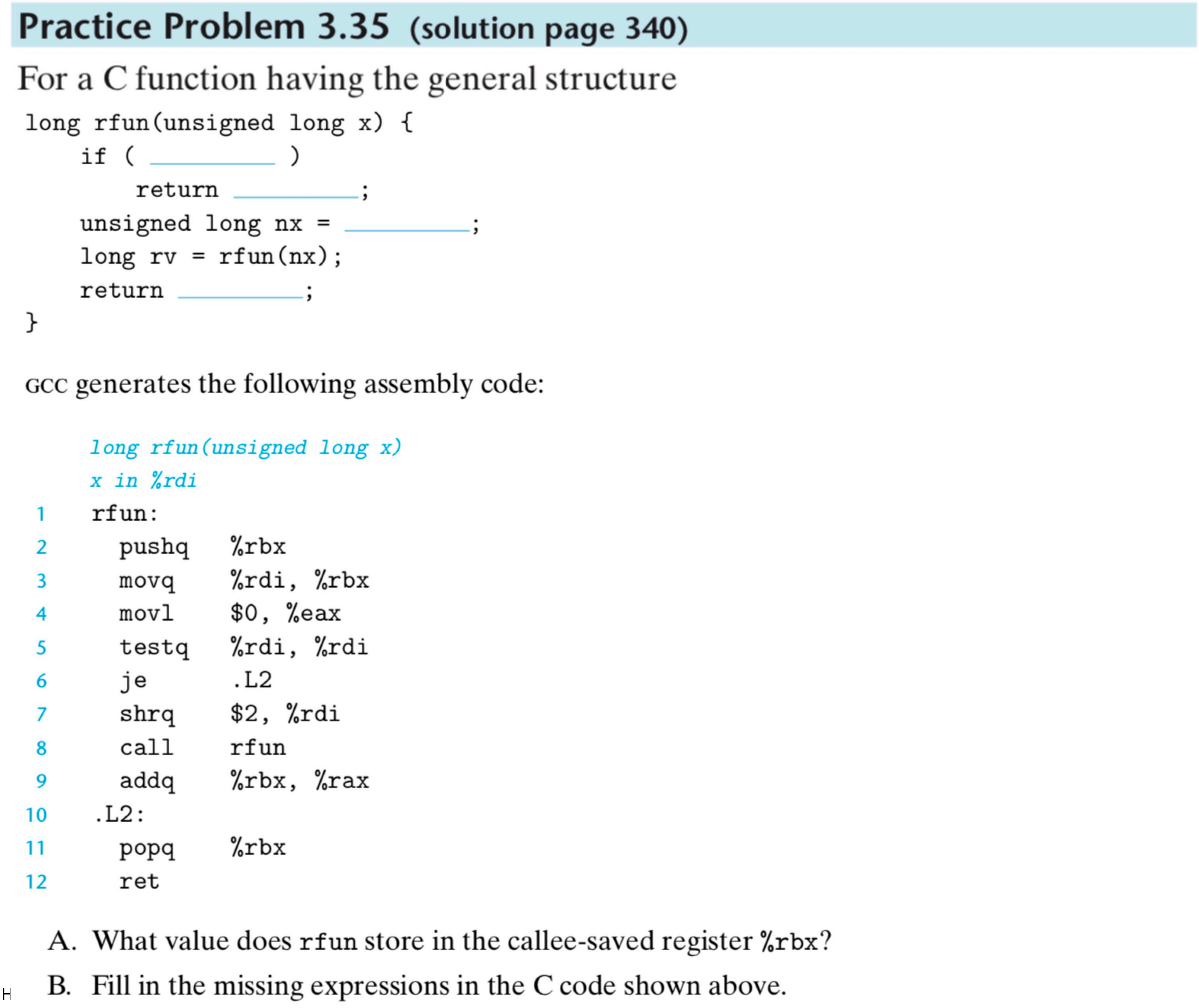
```
pcount_r:
  movl    $0, %eax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andl    $1, %ebx
  shrq    %rdi
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  rep; ret
```

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



Practice Problem 3.35 (solution page 340)

For a C function having the general structure

```
long rfun(unsigned long x) {
    if ( __________ )
        return __________;
    unsigned long nx = __________;
    long rv = rfun(nx);
    return __________;
}
```

GCC generates the following assembly code:

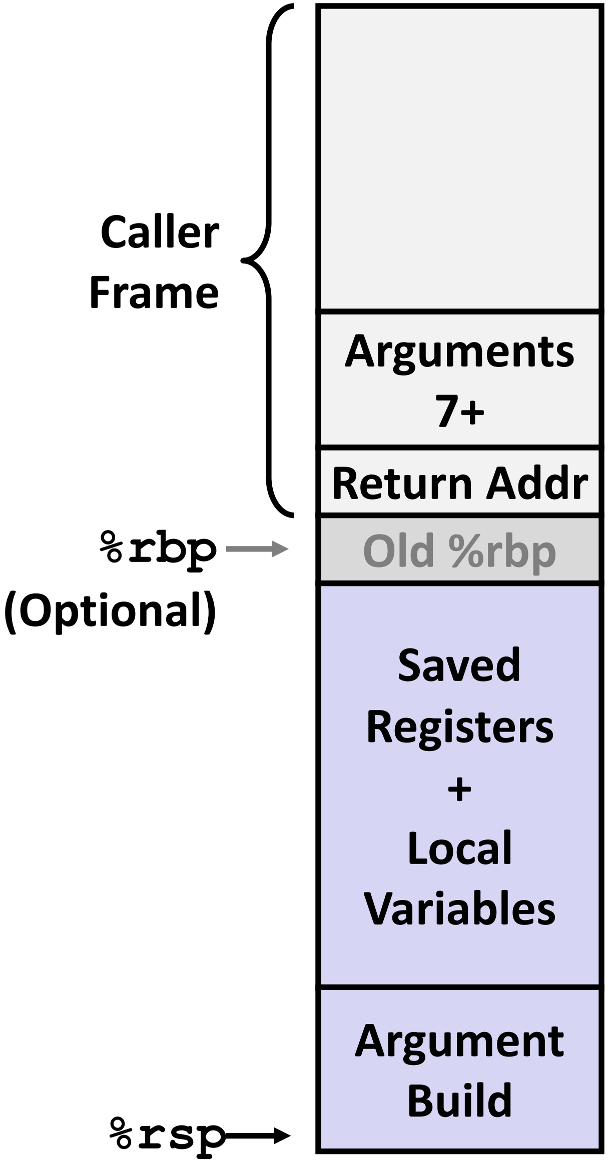
```
    long rfun(unsigned long x)
    x in %rdi
    rfun:
      pushq   %rbx
      movq    %rdi, %rbx
      movl    $0, %eax
      testq   %rdi, %rdi
      je      .L2
      shrq    $2, %rdi
      call    rfun
      addq    %rbx, %rax
    .L2:
      popq    %rbx
      ret
```

A. What value does `rfun` store in the callee-saved register `%rbx`?

B. Fill in the missing expressions in the C code shown above.

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**


Caller Frame
Arguments 7+
Return Addr
%rbp
(Optional)
Old %rbp
Saved Registers + Local Variables
Argument Build
%rsp