Assembly: Functions

Function mechanics

- **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

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

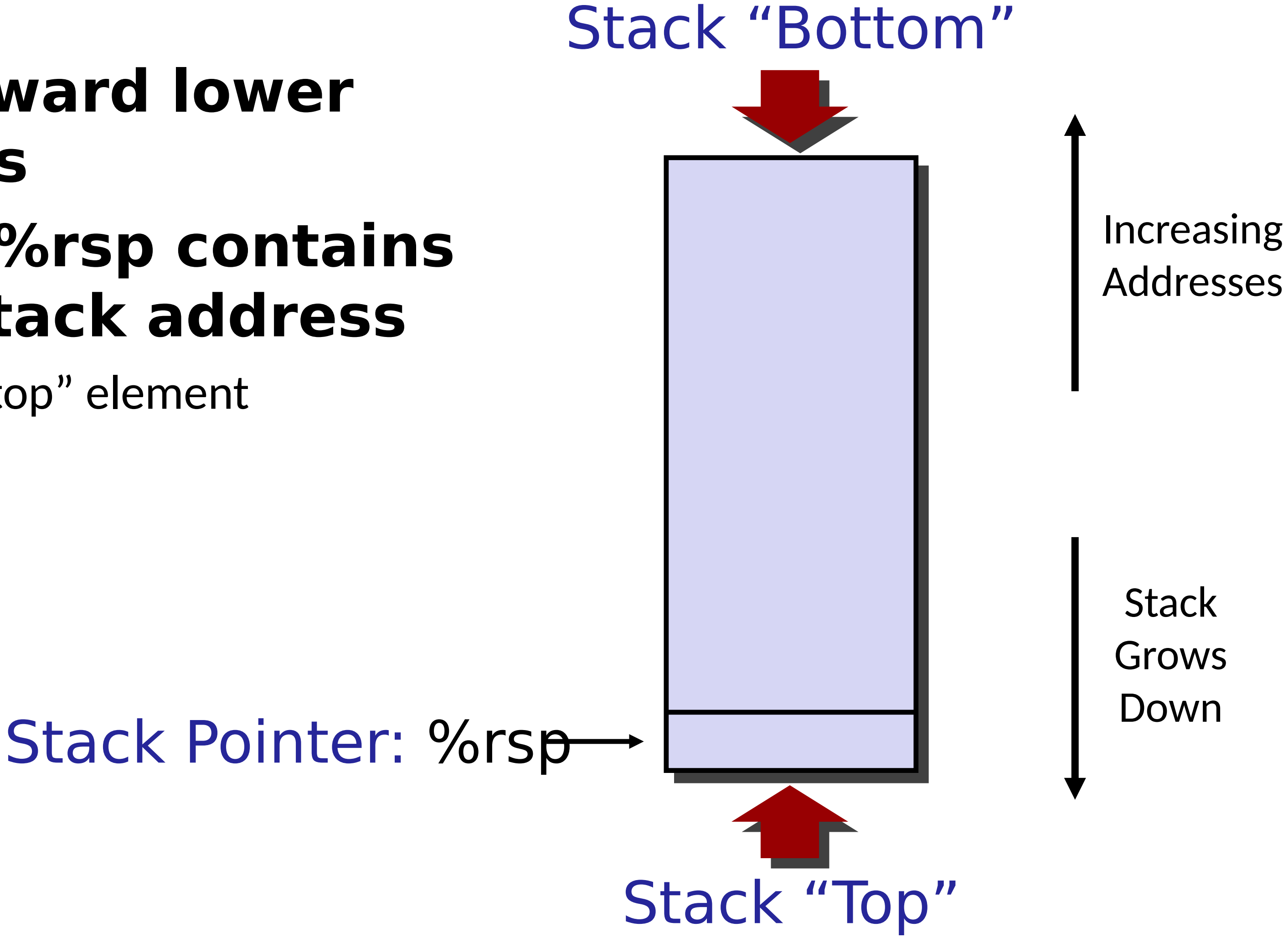
```
int Q(int i)
{
  int t = 3*i;
  int v[10];
  •
  •
  return v[t];
}
```

Today

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

x86-64 Stack

- **Grows toward lower addresses**
- **Register %rsp contains lowest stack address**
  - address of “top” element



Stack “Bottom”

Increasing Addresses

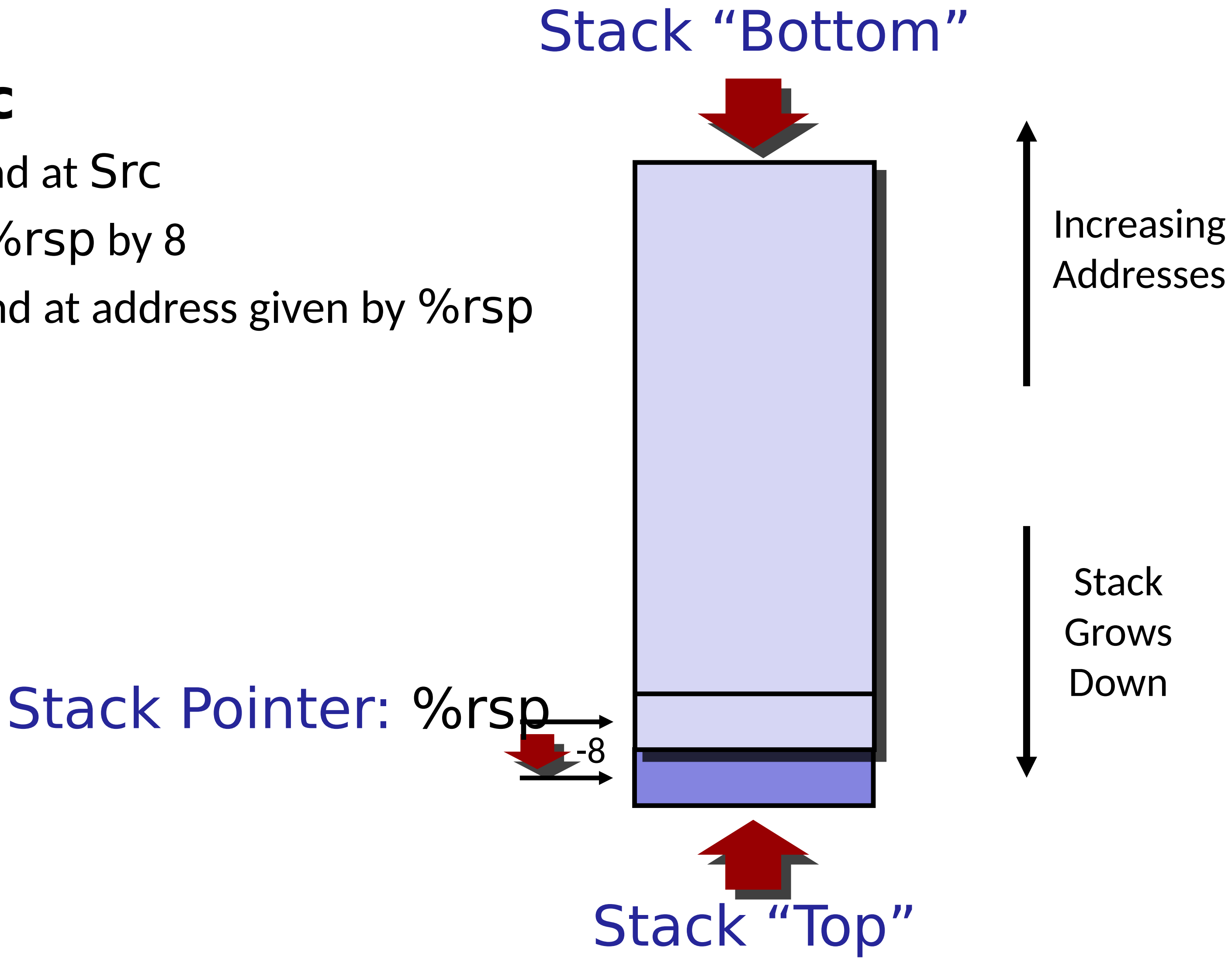
Stack Grows Down

Stack Pointer: %rsp

Stack “Top”

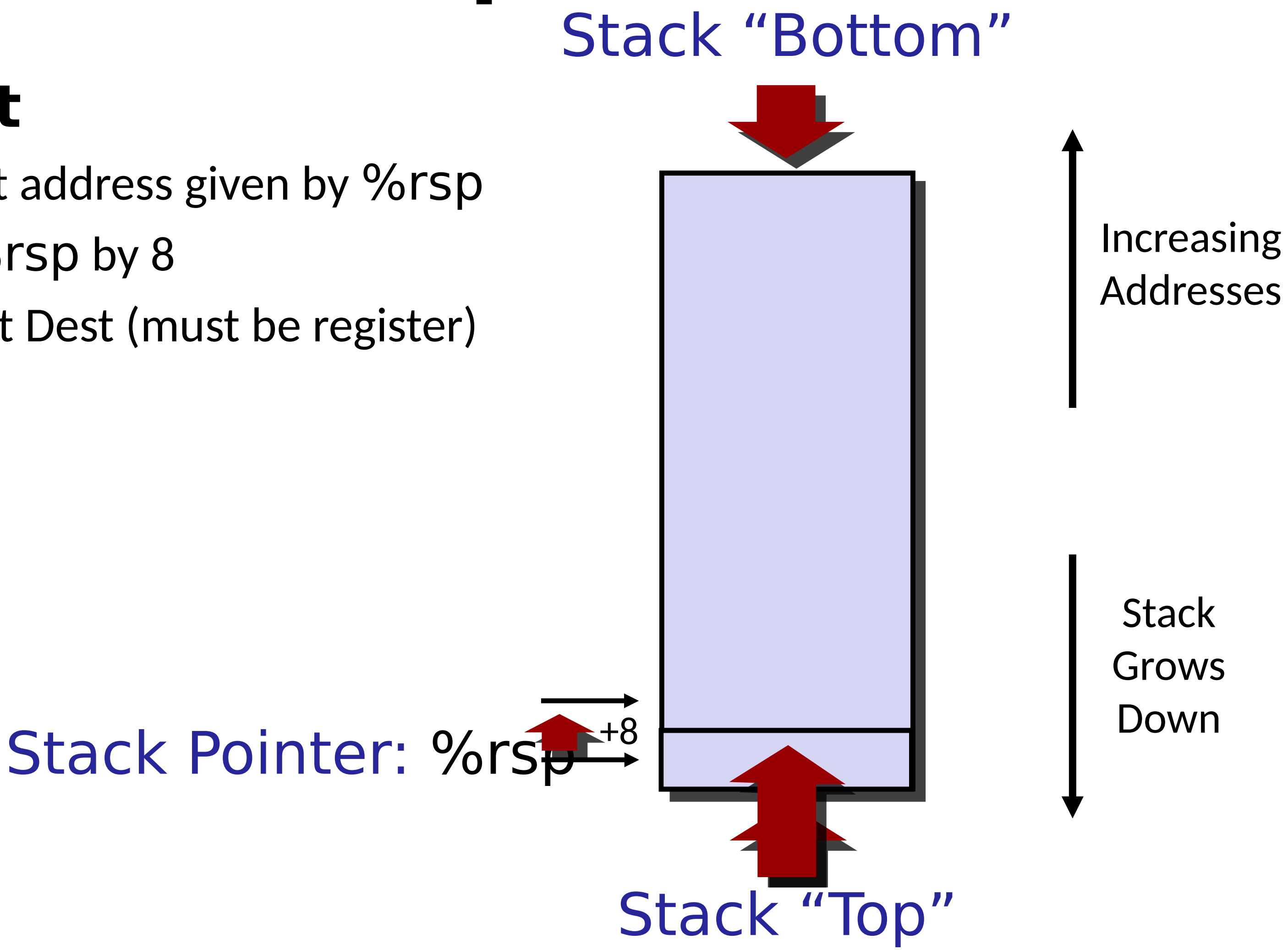
x86-64 Stack: Push

- **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
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Code Examples

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

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

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

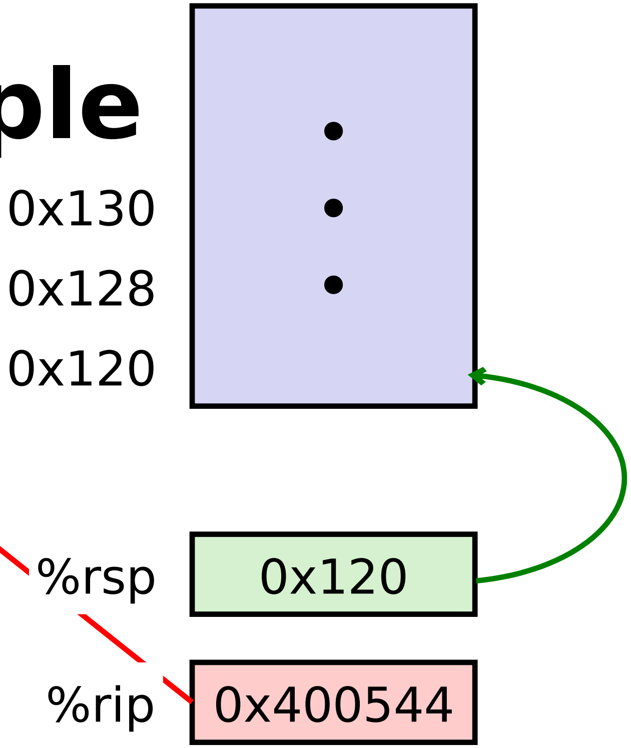
```
0000000000400550 <mult2>:
  mov    %rdi,%rax  # a
  imul   %rsi,%rax  # a * b
  retq              # Return
```

Procedure Control Flow

- **Use stack to support function 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

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

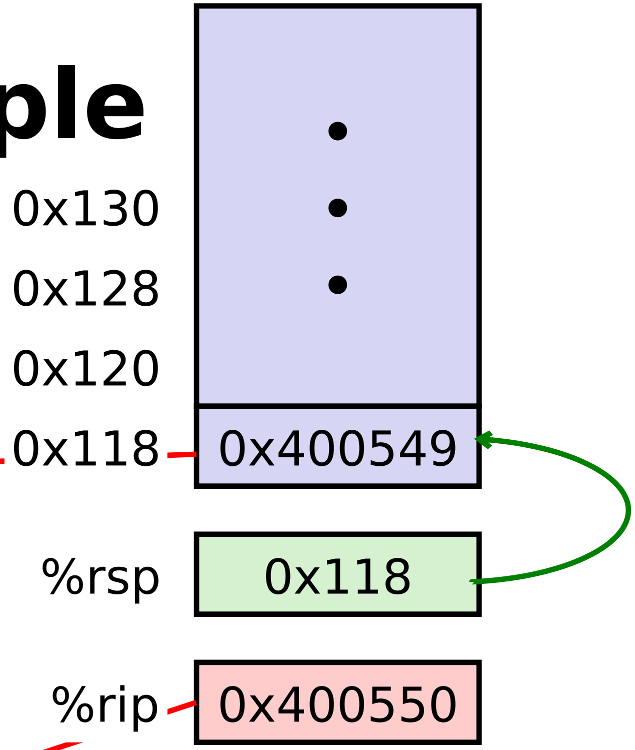


```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```

Control Flow Example

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

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



•
•
•

0x130

0x128

0x120

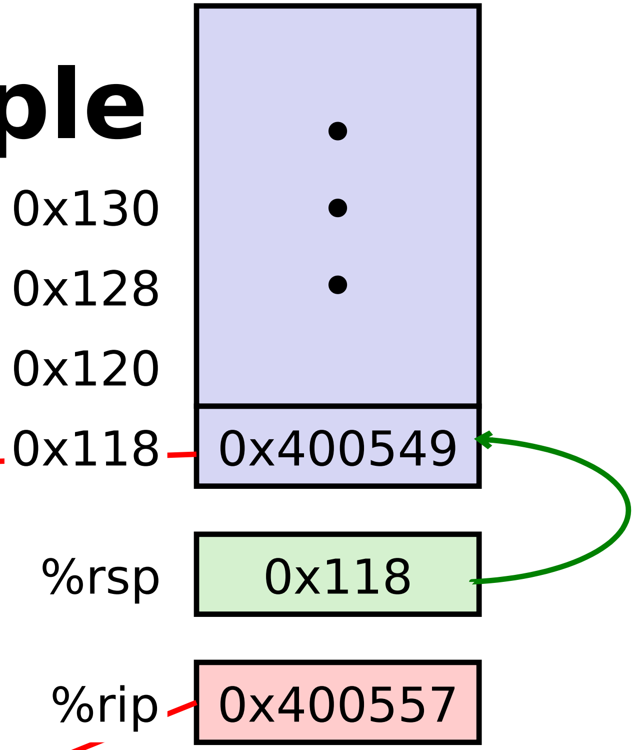
0x118 0x400549

%rsp 0x118

%rip 0x400550

Control Flow Example

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

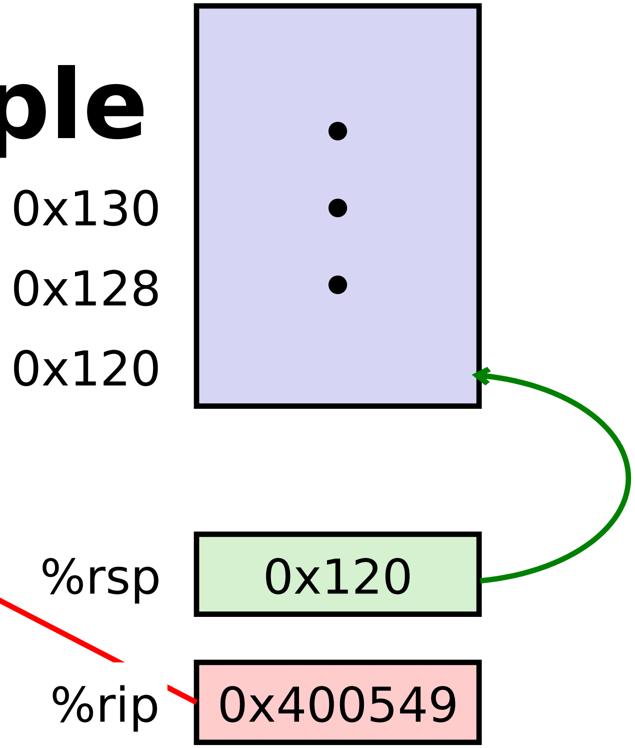


```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```

Control Flow Example

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

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



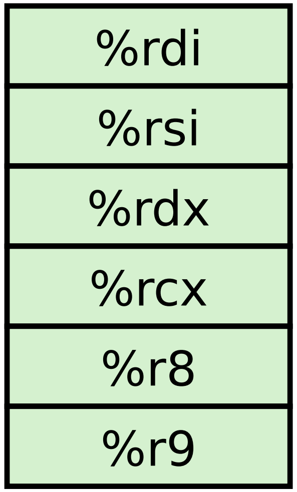
Today

- **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

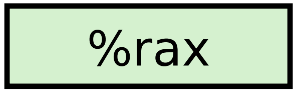
%rdx

%rcx

%r8

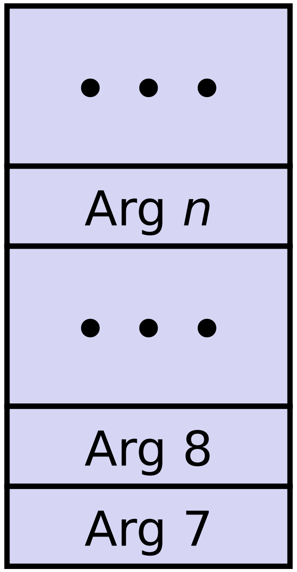
%r9

- **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
```

Today

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

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

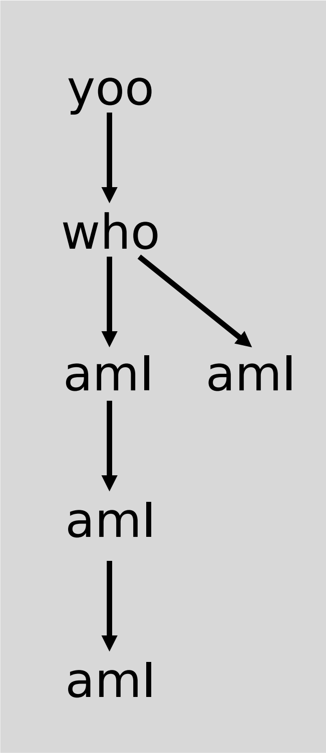
```
yoo(…)
{
  •
  •
  who();
  •
  •
}
```

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

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

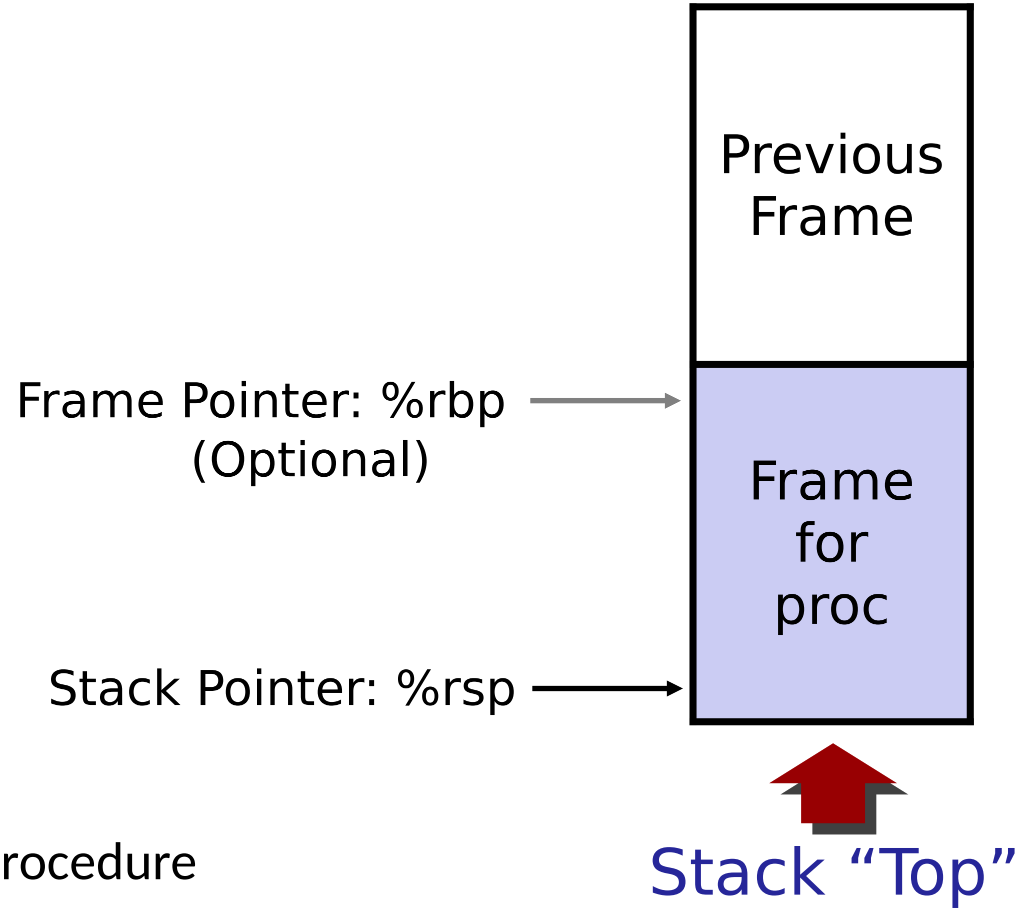
Procedure amI() is recursive

Example
Call Chain



Stack Frames

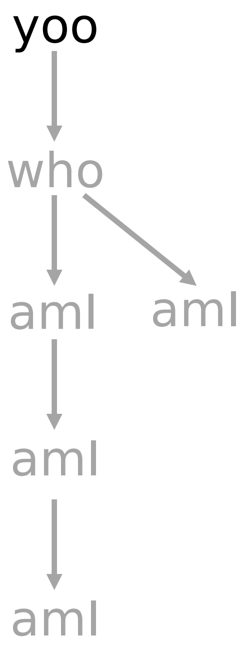
- **Contents**
  - Return information
  - Local storage (if needed)
  - Temporary space (if needed)

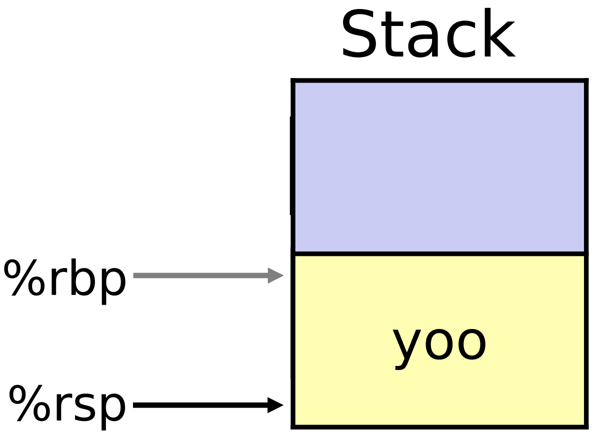


- **Management**
  - Space allocated when enter procedure
    - “Set-up” code
    - Includes push by `call` instruction
  - Deallocated when return
    - “Finish” code
    - Includes pop by `ret` instruction

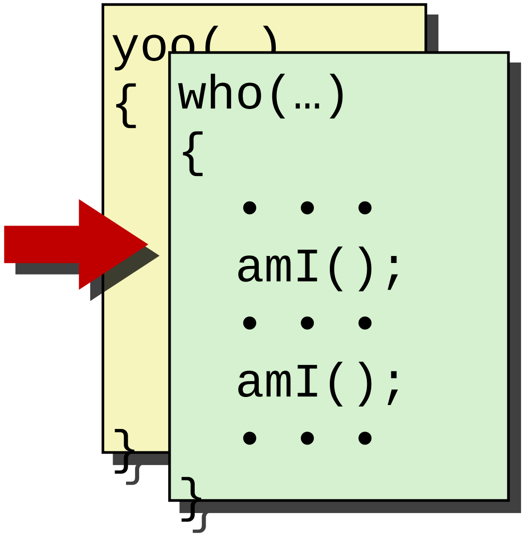
Example

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



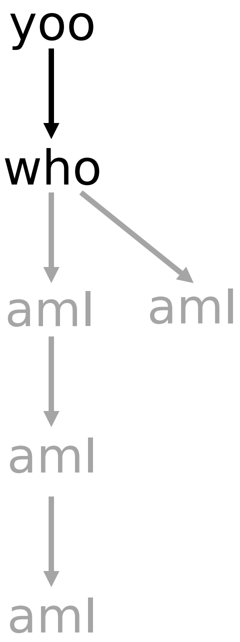


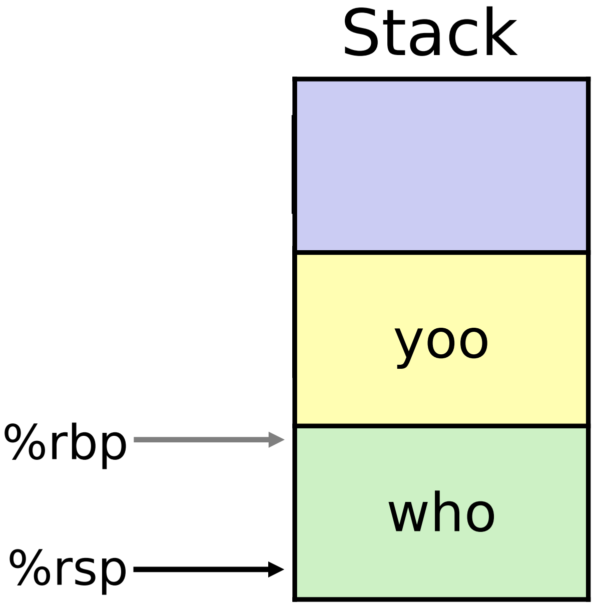
Example



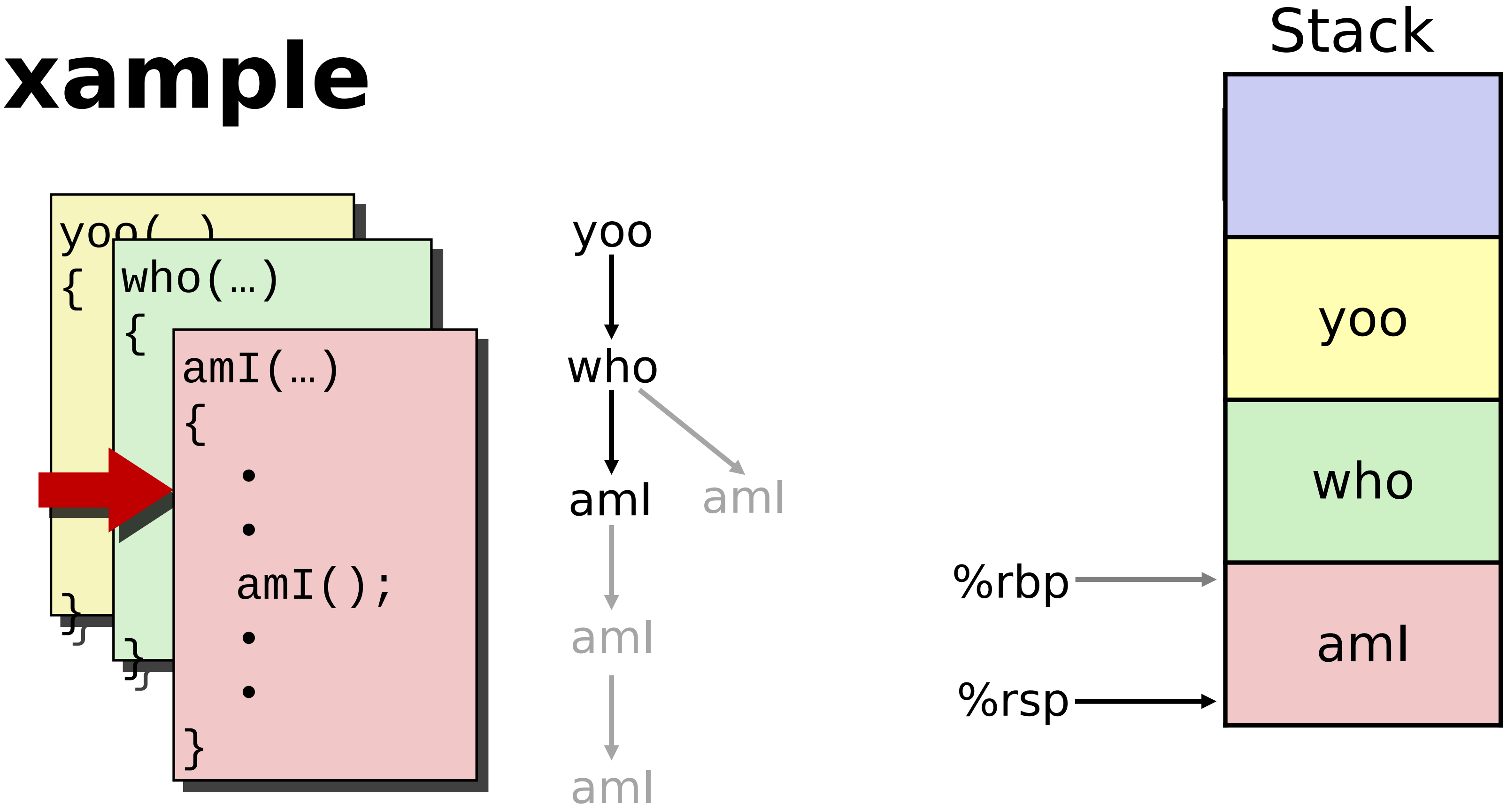
```
yoo(…)
{
}
```

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





Example

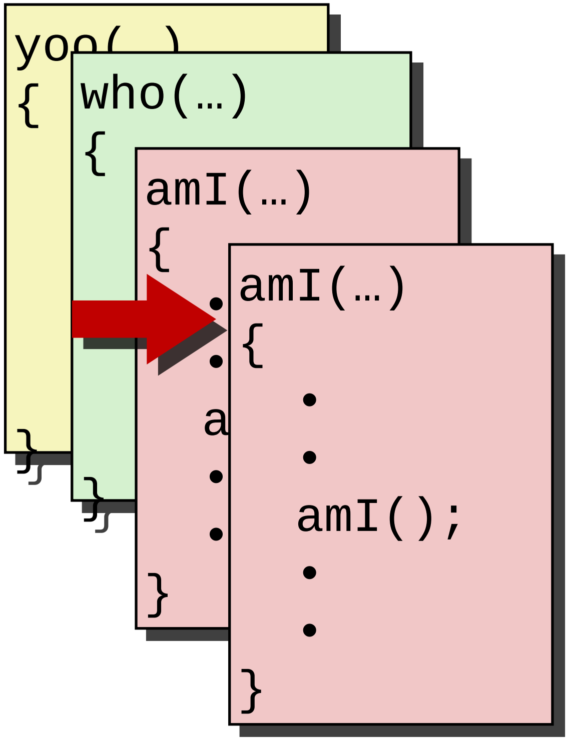


```
yoo(…)
{
}
```

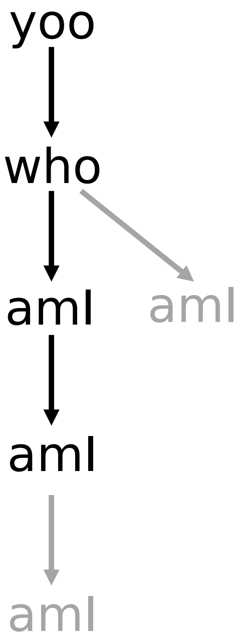
```
who(…)
{
}
```

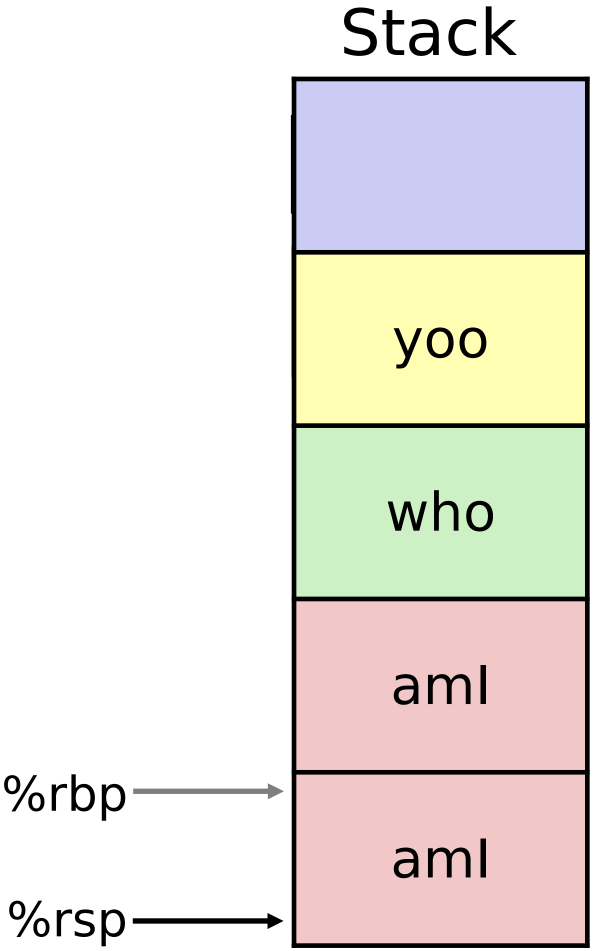
```
amI(…)
{
   •
   •
   amI();
   •
   •
}
```

Example

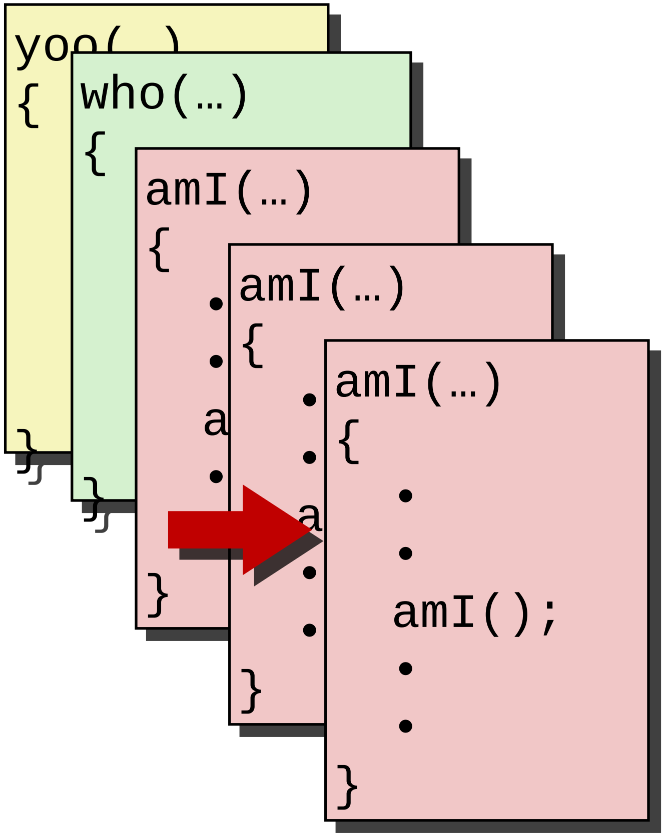


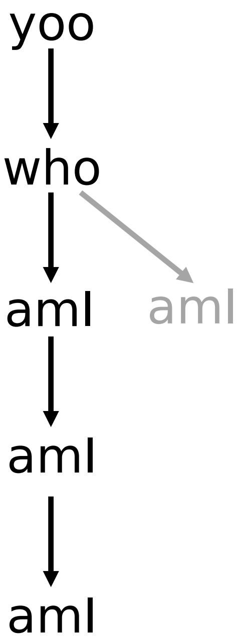
```
amI(…)
{
   •
   •
   amI();
   •
   •
}
```

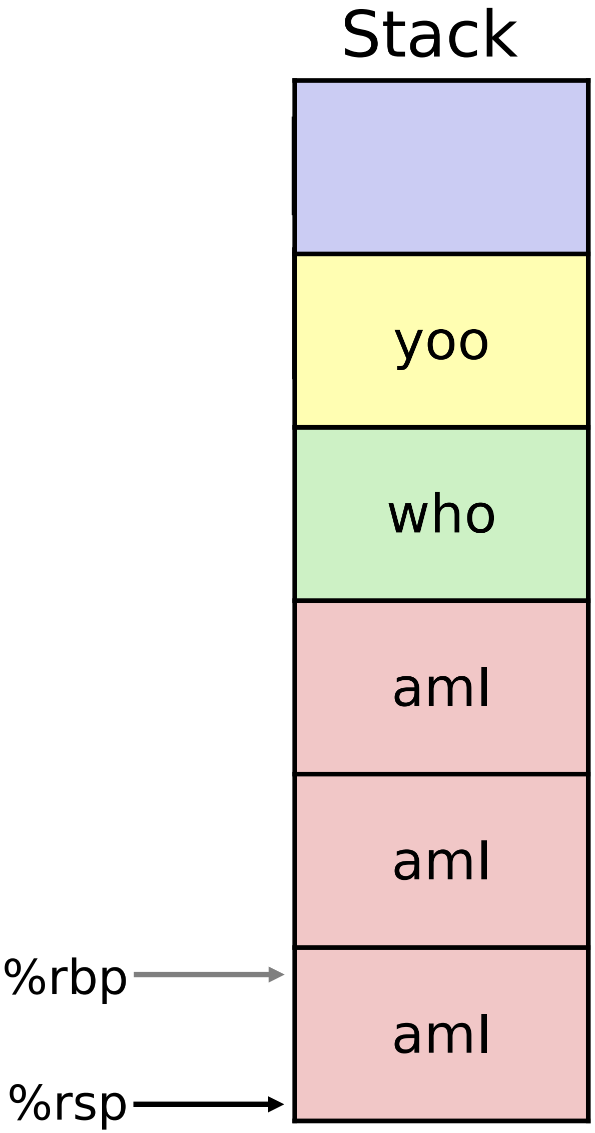




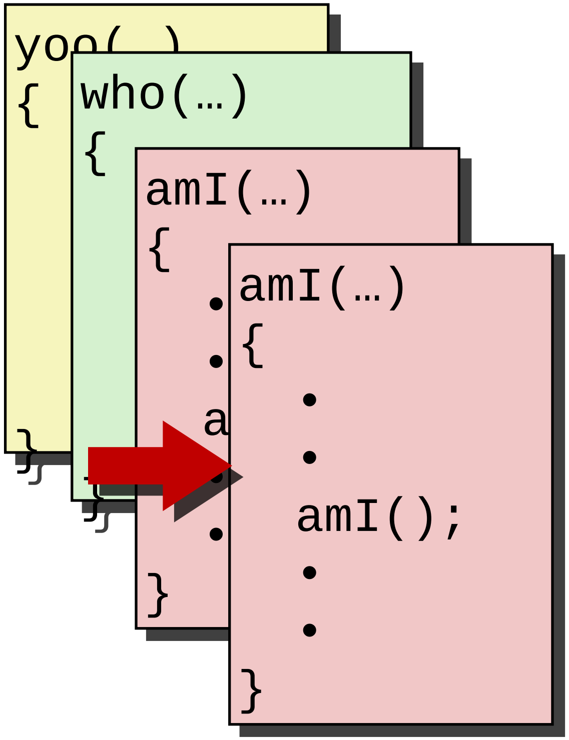
Example


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

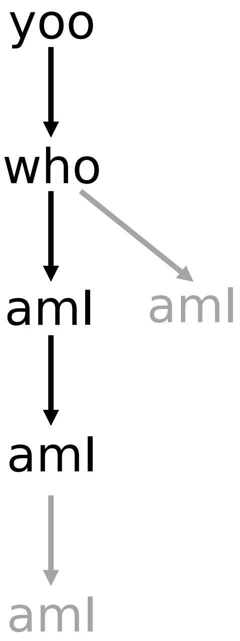

yoo
who
amI
amI
amI
amI

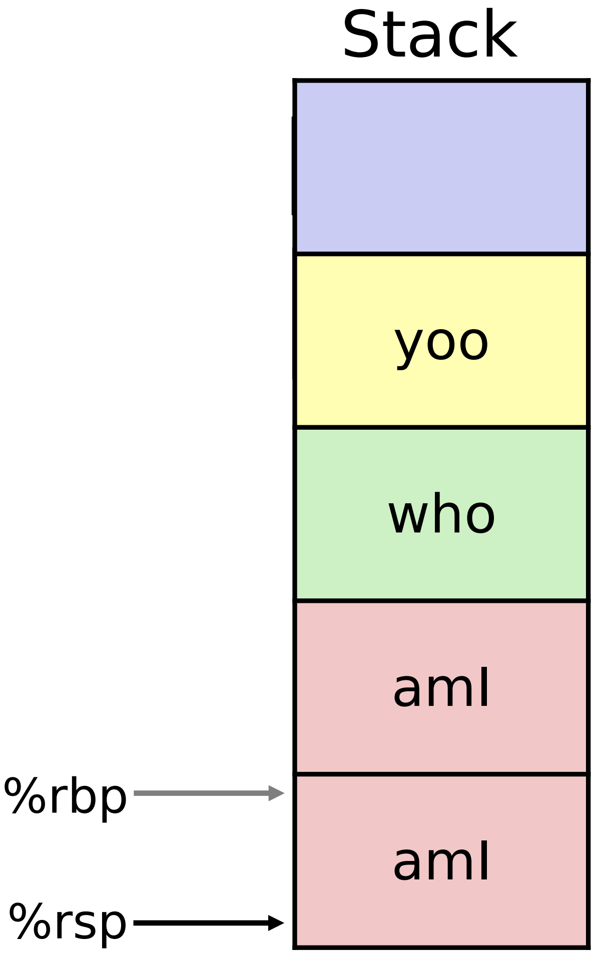

Stack
yoo
who
amI
amI
amI
%rbp
%rsp

Example

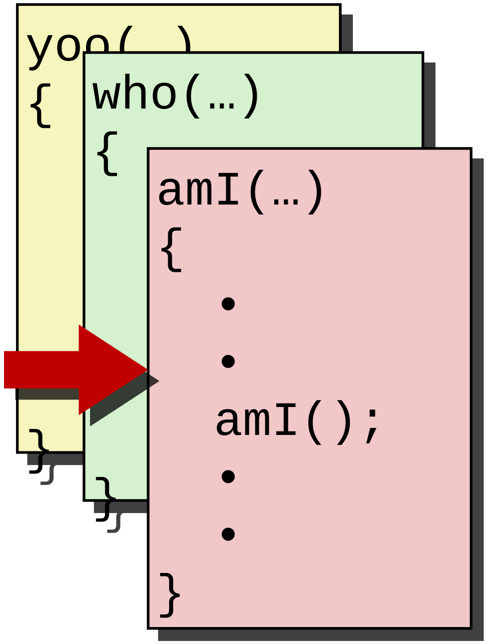


```
amI(…)
{
   •
   •
   amI();
   •
   •
}
```





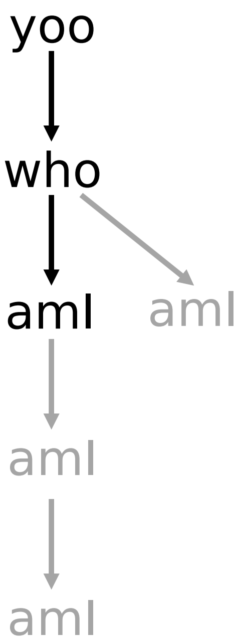
Example

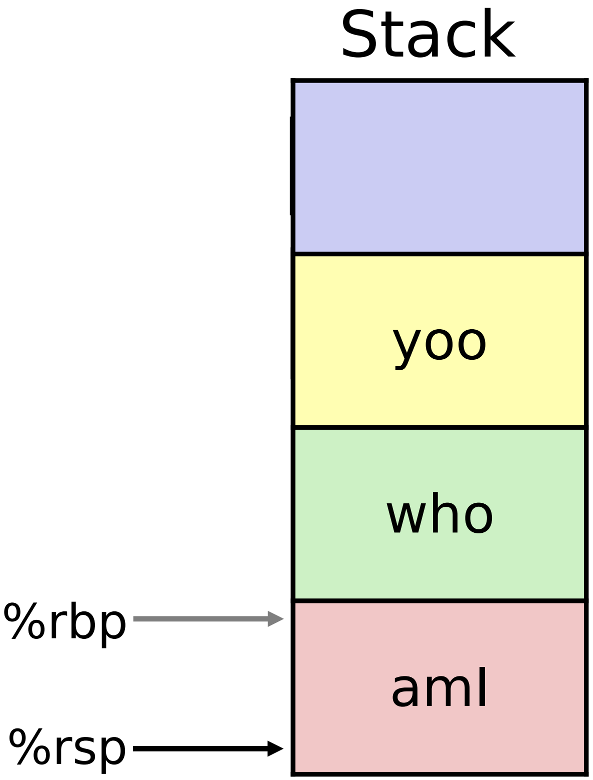


```
yoo(…)
{
}
```

```
who(…)
{
}
```

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

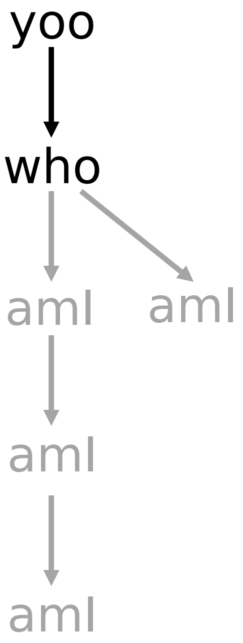


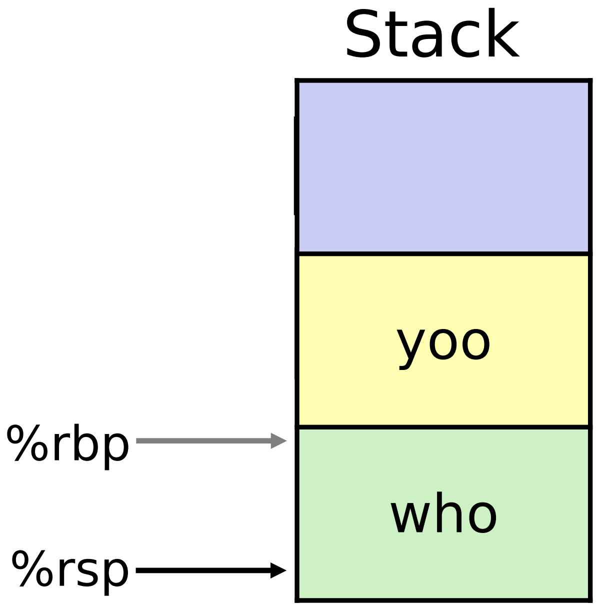


Example

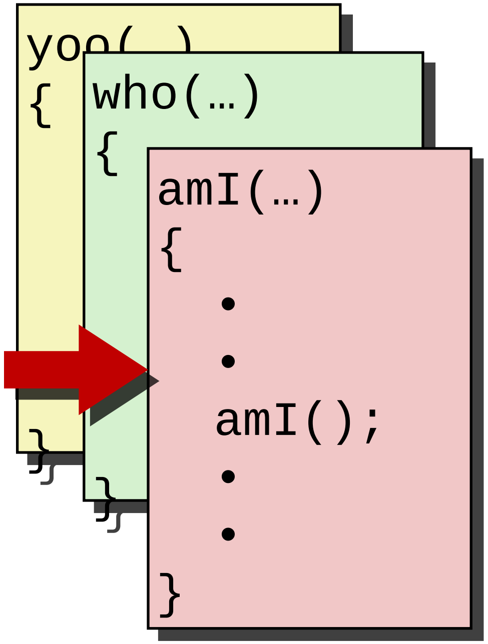
```
yoo(…)
{

}
```

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





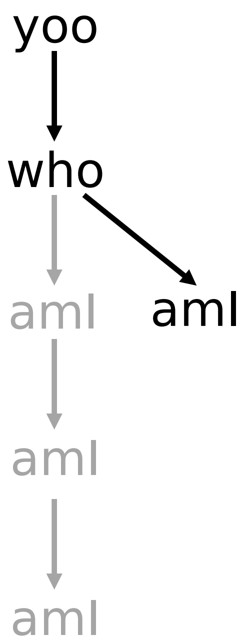
Example

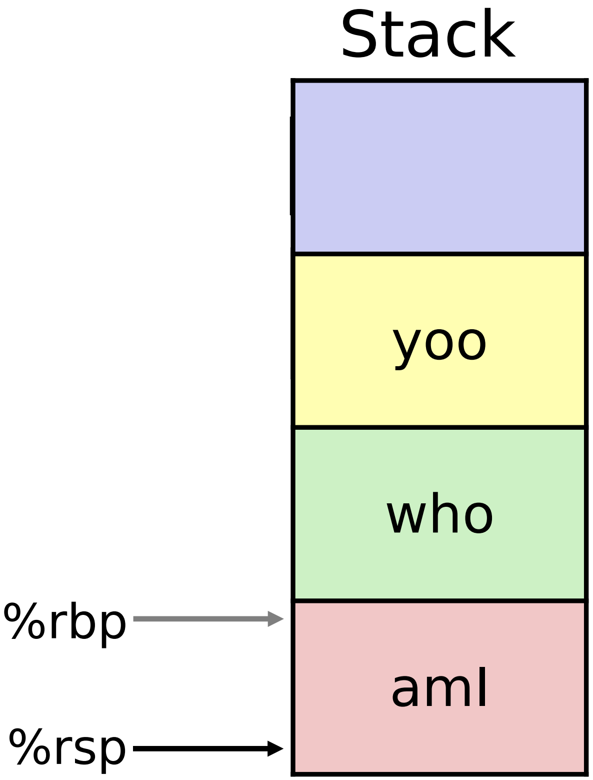


```
yoo(…)
{

}
```

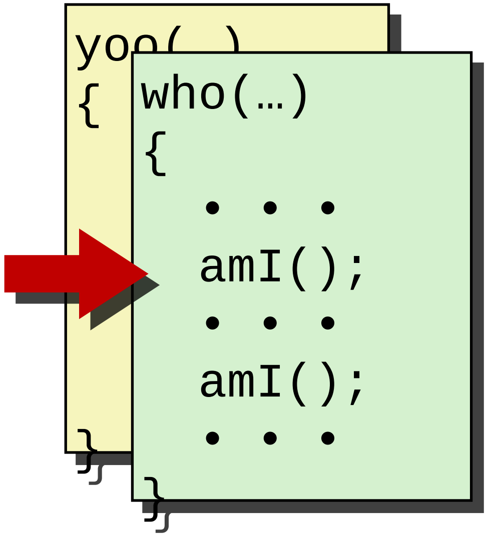
```
who(…)
{

}
```

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



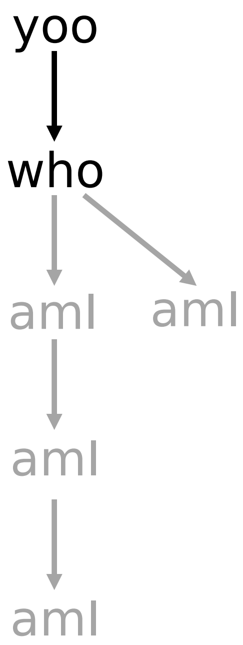


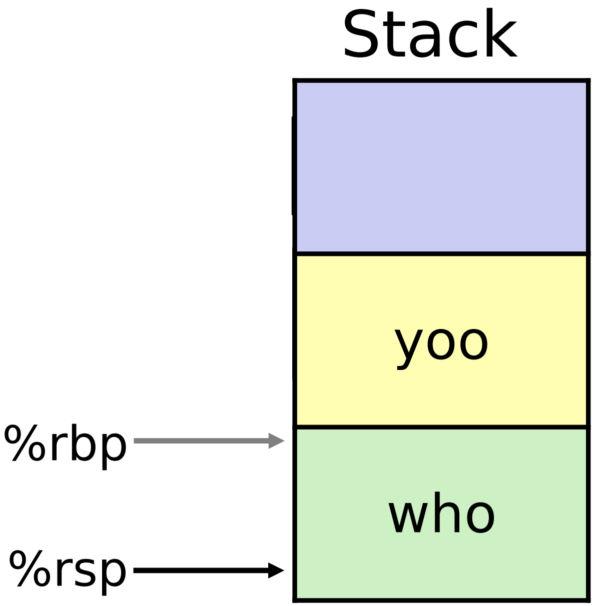
Example



```
yoo(…)
{

}
```

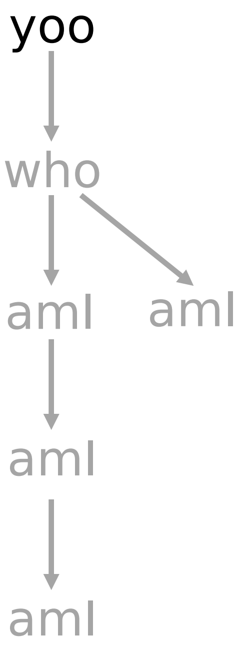
```
who(…)
{
  • • •
  amI();
  • • •
  amI();
  • • •
}
```

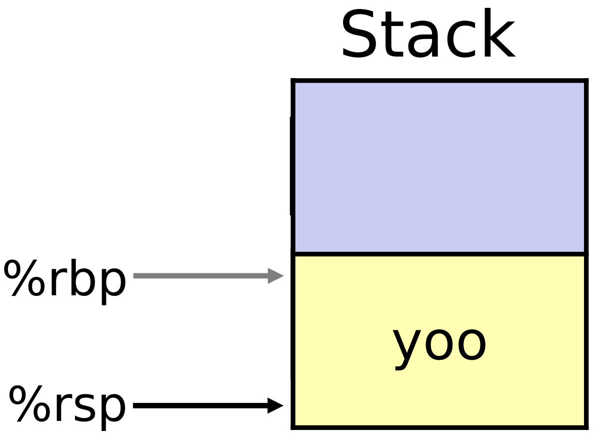




Example

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

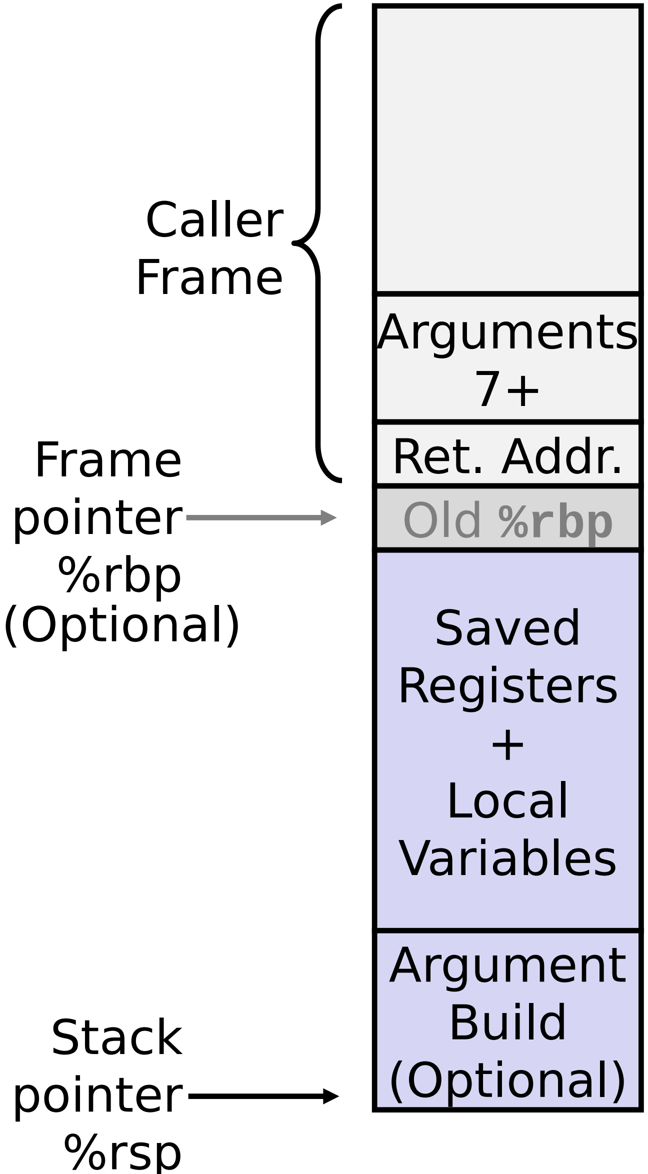




x86-64/Linux Stack Frame

- **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



Caller Frame
Arguments 7+
Ret. Addr.
Frame pointer %rbp (Optional)
Old %rbp
Saved Registers + Local Variables
Argument Build (Optional)
Stack pointer %rsp

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
```

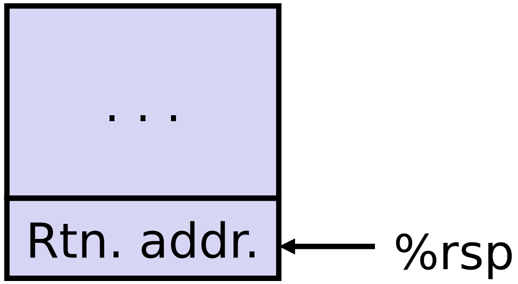
Register	Use(s)
`%rdi`	Argument **`p`**
`%rsi`	Argument **`val`**, **`y`**
`%rax`	**`x`**, Return value

Example: Calling incr

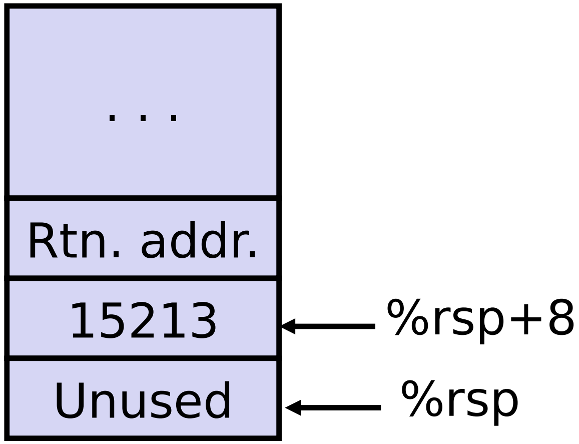
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

```
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

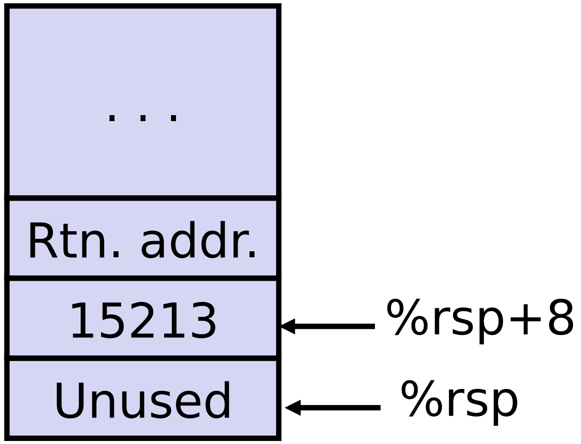


Example: Calling incr

```
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



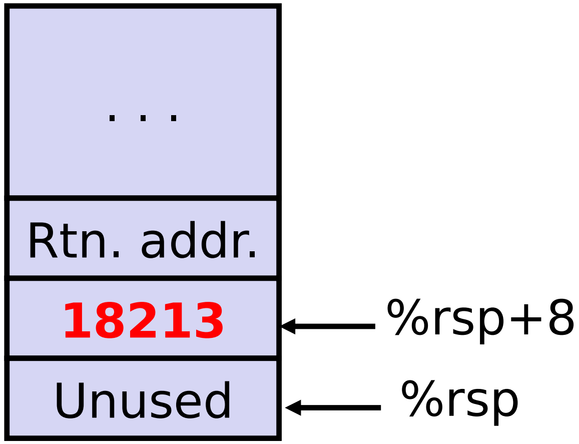
Register	Use(s)
%rdi	&v1
%rsi	3000

Example: Calling incr

```
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



. . .

Rtn. addr.

18213 ← %rsp+8

Unused ← %rsp

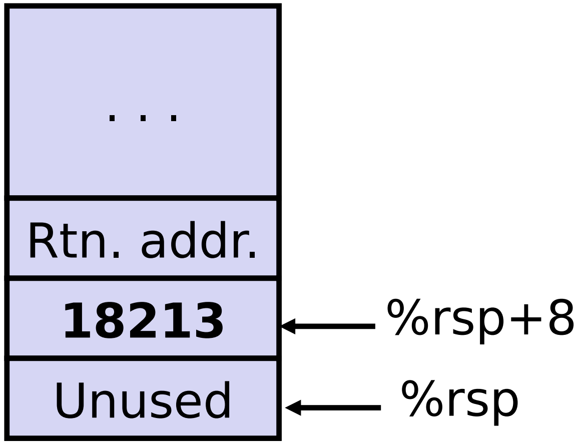
Register	Use(s)
%rdi	&v1
%rsi	3000

Example: Calling incr

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

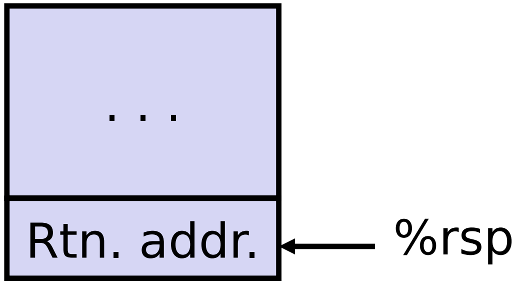
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure



Register	Use(s)
%rax	Return value

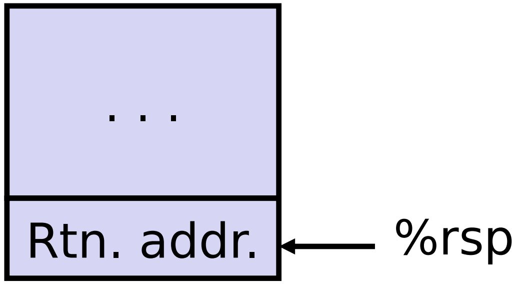
Updated Stack Structure



Example: Calling incr

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

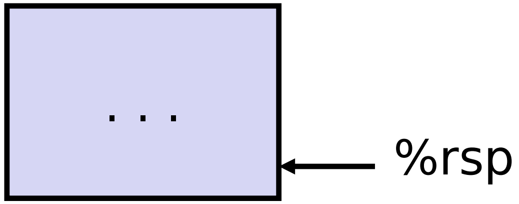
Updated Stack Structure



```
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

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
```

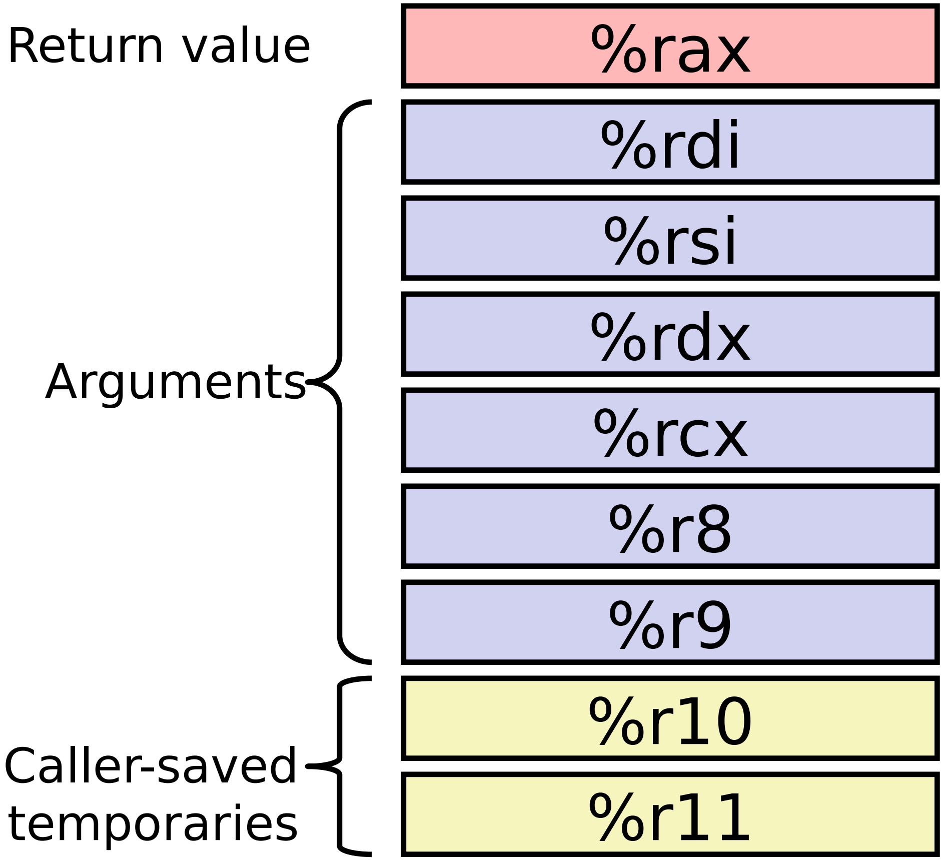
  - Contents of register %rdx overwritten by who
  - This could be trouble → something should be done!
    - Need some coordination

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

- **%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

Arguments

Caller-saved temporaries

%rax

%rdi

%rsi

%rdx

%rcx

%r8

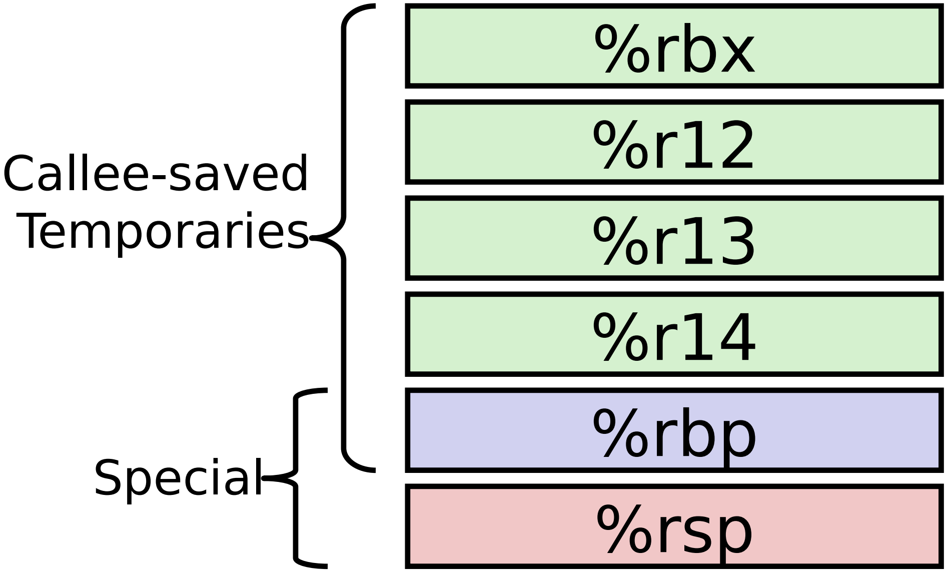
%r9

%r10

%r11

x86-64 Linux Register Usage

- **%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

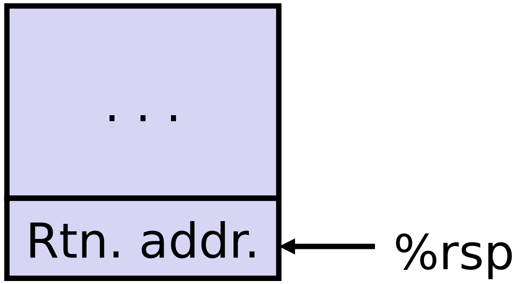


Callee-Saved Example

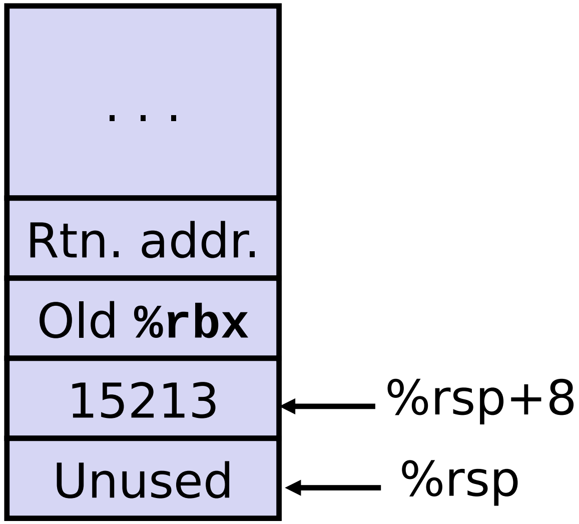
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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

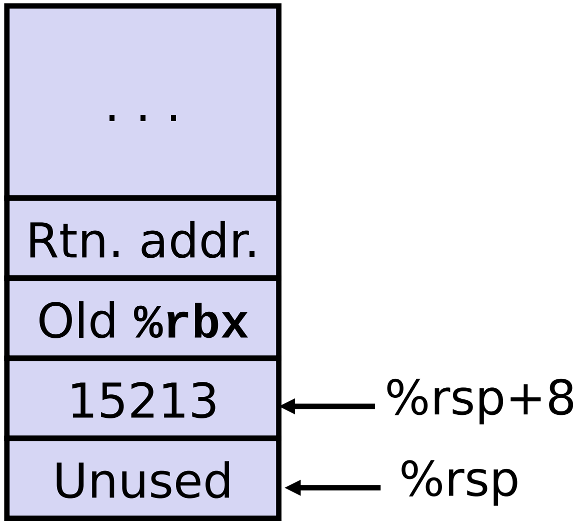


Callee-Saved Example

```
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



. . .

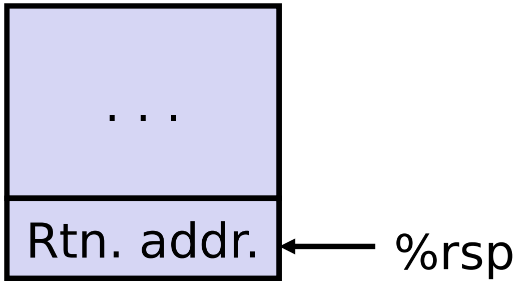
Rtn. addr.

Old %rbx

15213 ← %rsp+8

Unused ← %rsp

Pre-return Stack Structure



. . .

Rtn. addr. ← %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 # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  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:
  ret
```

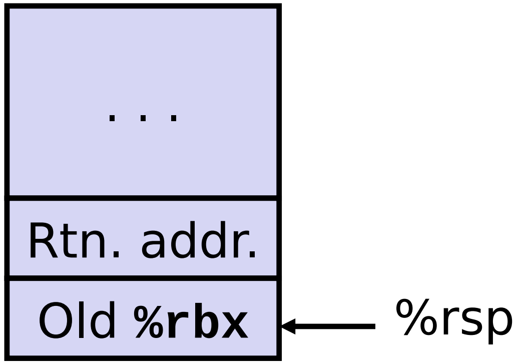
Register	Use(s)	Type
%rdi	x	Argument
%rax	Return value	Return value

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 # (by 1)
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  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:
  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:
  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:
  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:
  ret
```

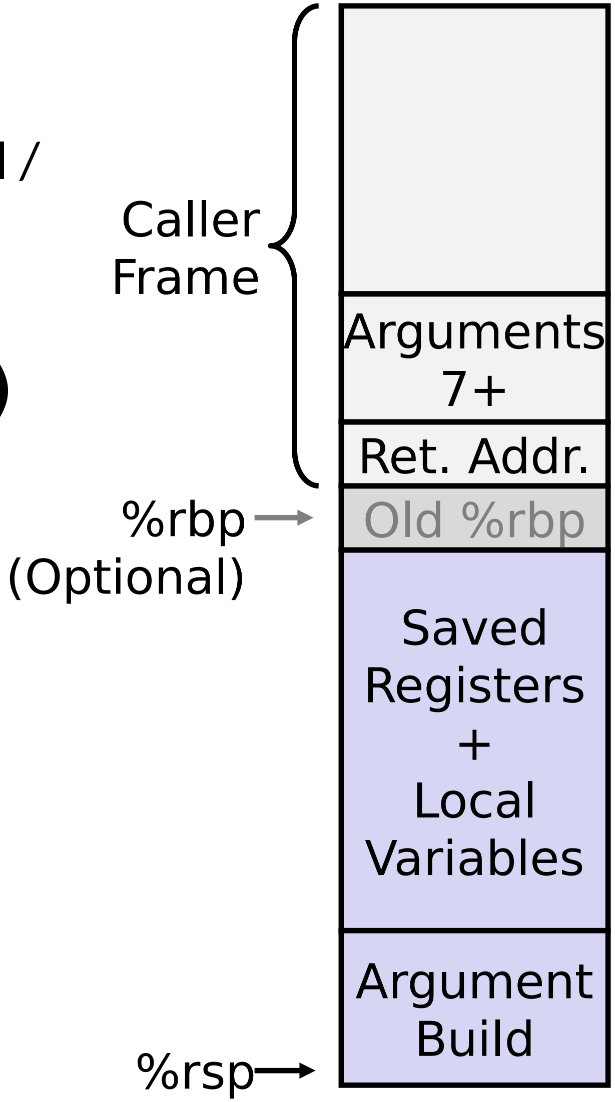
Register	Use(s)	Type
`%rax`	Return value	Return value

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


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