# CSCI-UA.0201

## Computer Systems Organization

# Machine-Level Programming IV

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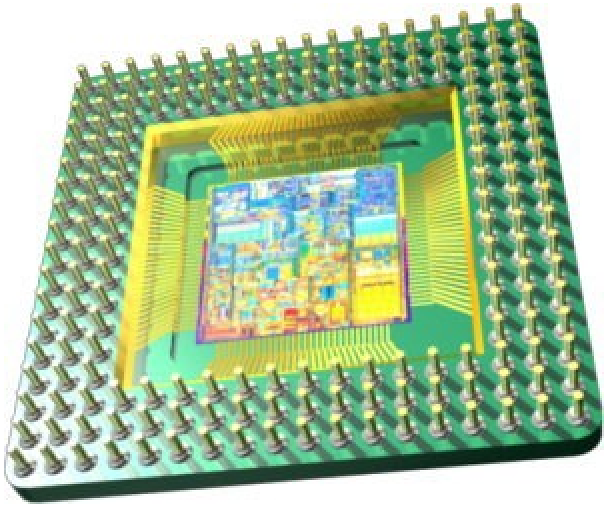
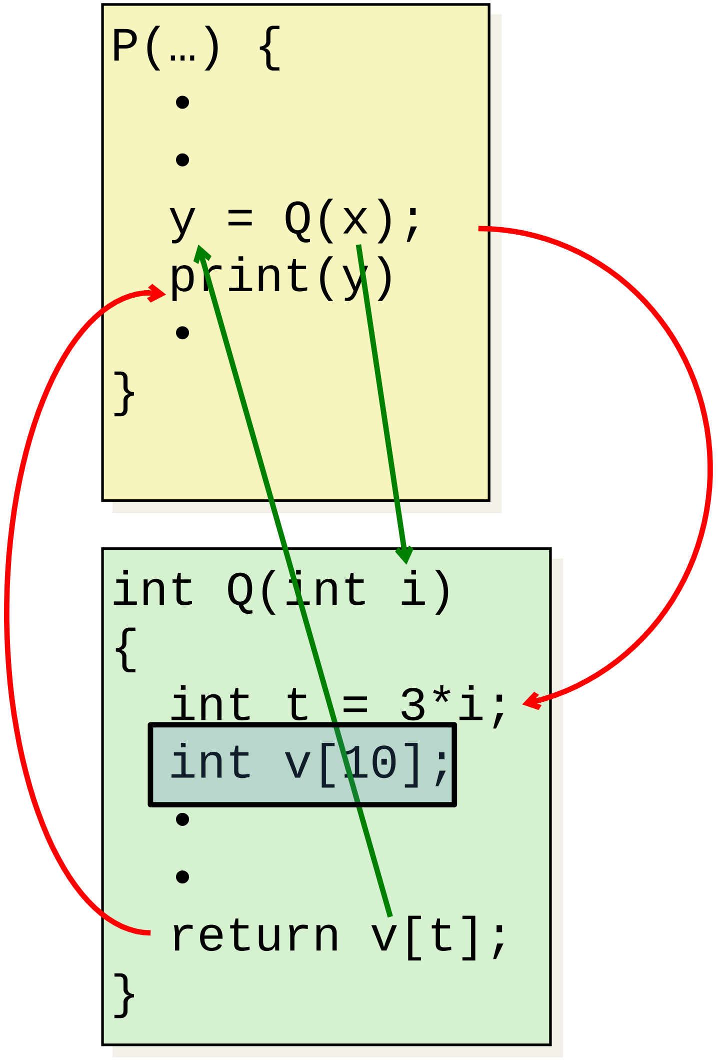
Some slides adapted (and slightly modified) from:

- Clark Barrett
- Jinyang Li
- Randy Bryant
- Dave O'Hallaron



# Suppose P calls Q

- **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)
   •
}
```

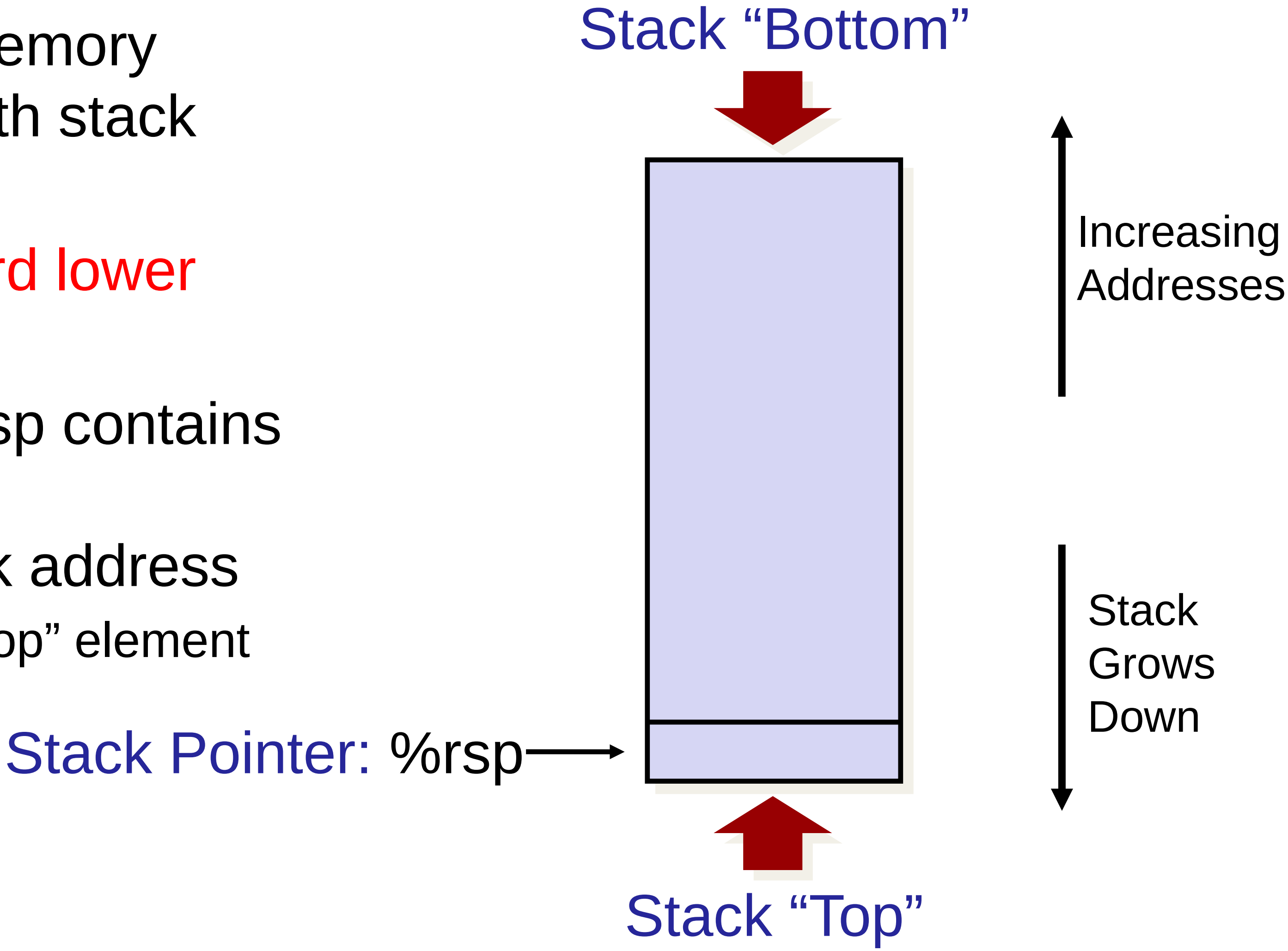
```
int Q(int i)
{
   int t = 3*i;
   int v[10];
   •
   •
   return v[t];
}
```

# A quick glimpse at how stack works…

# x86-64 Stack

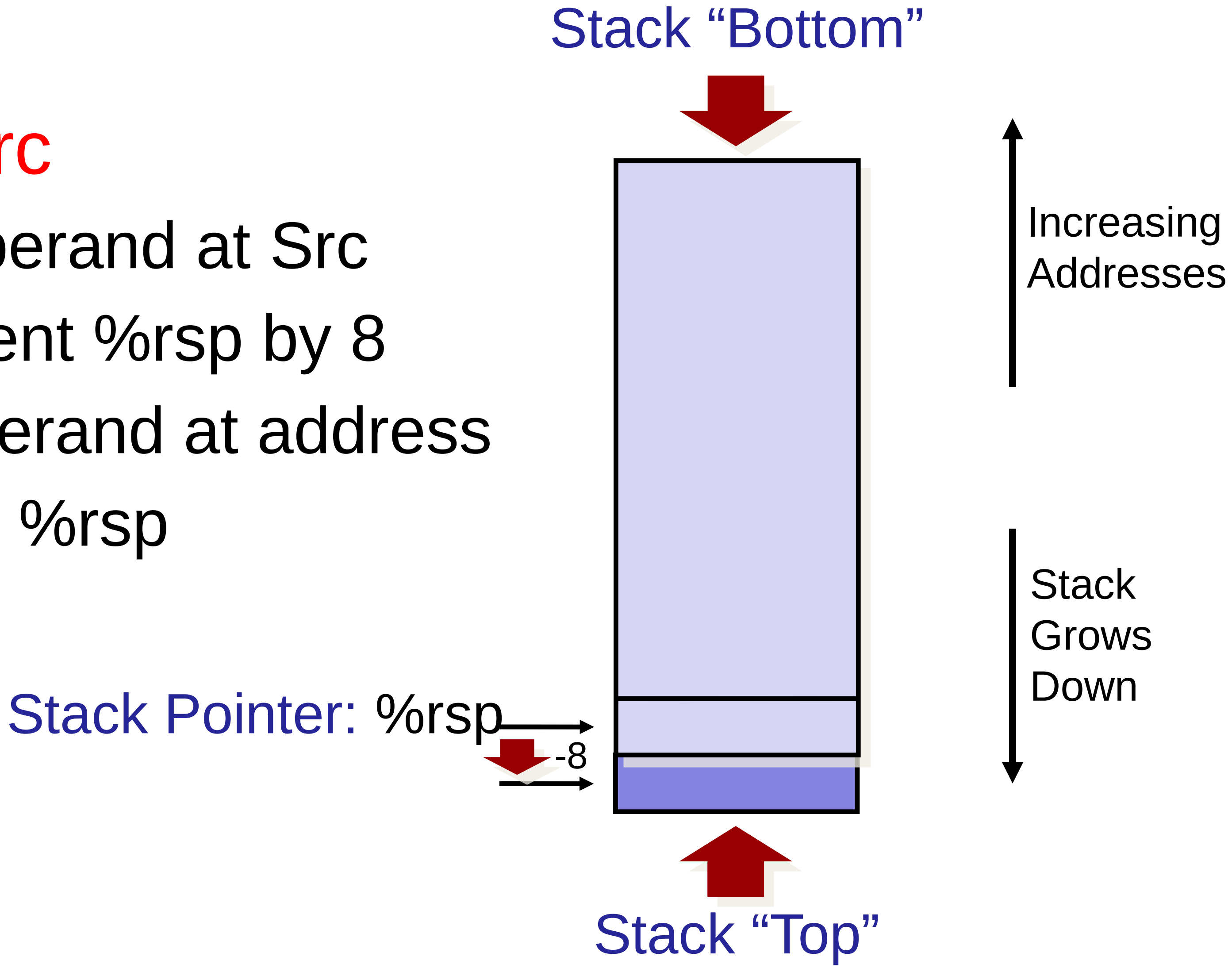
- Region of memory managed with stack discipline
- Grows toward lower addresses
- Register %rsp contains

  lowest  stack address
  - address of "top" element



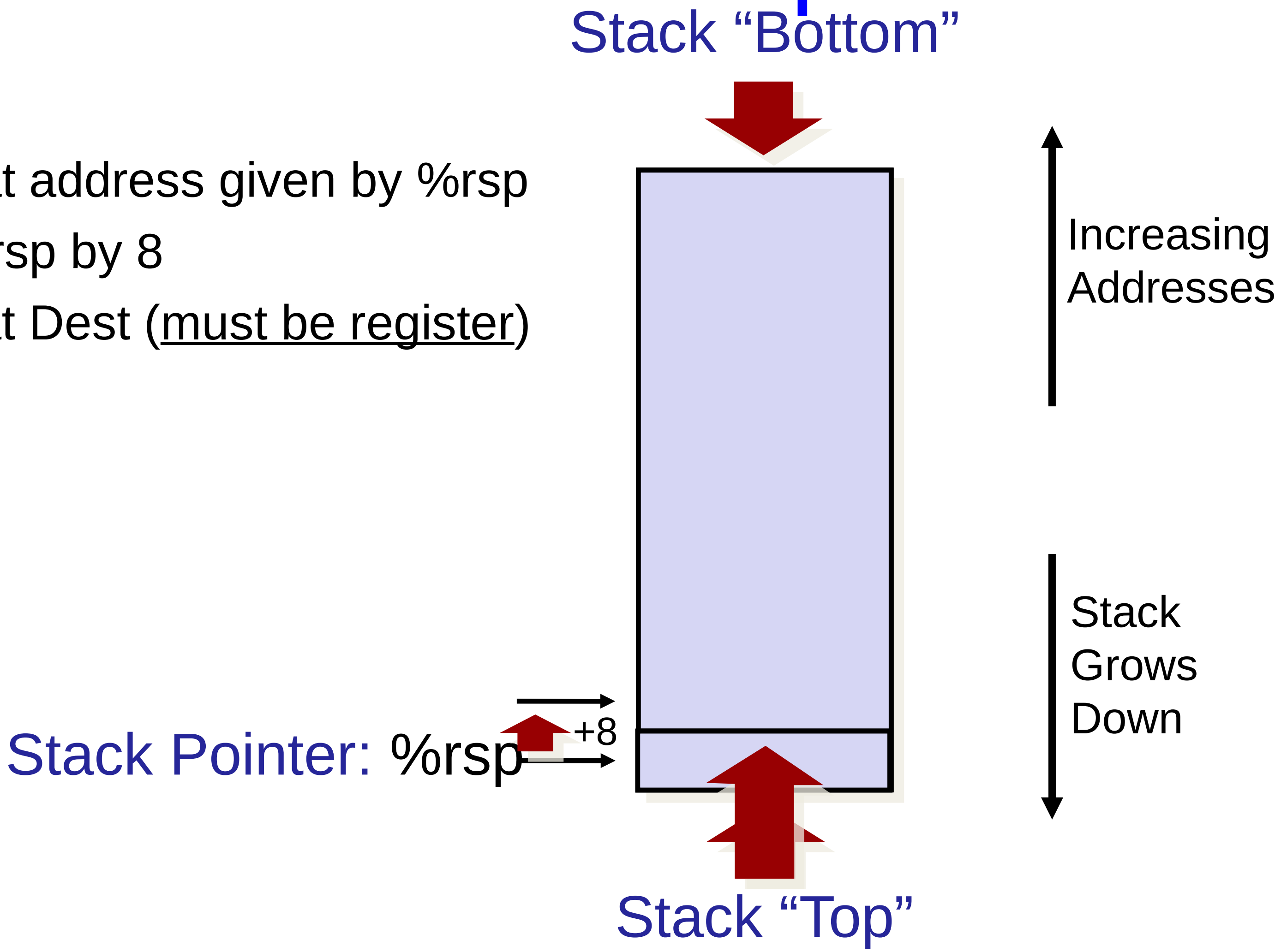
# x86-64 Stack: Push

- 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)



# Examples:

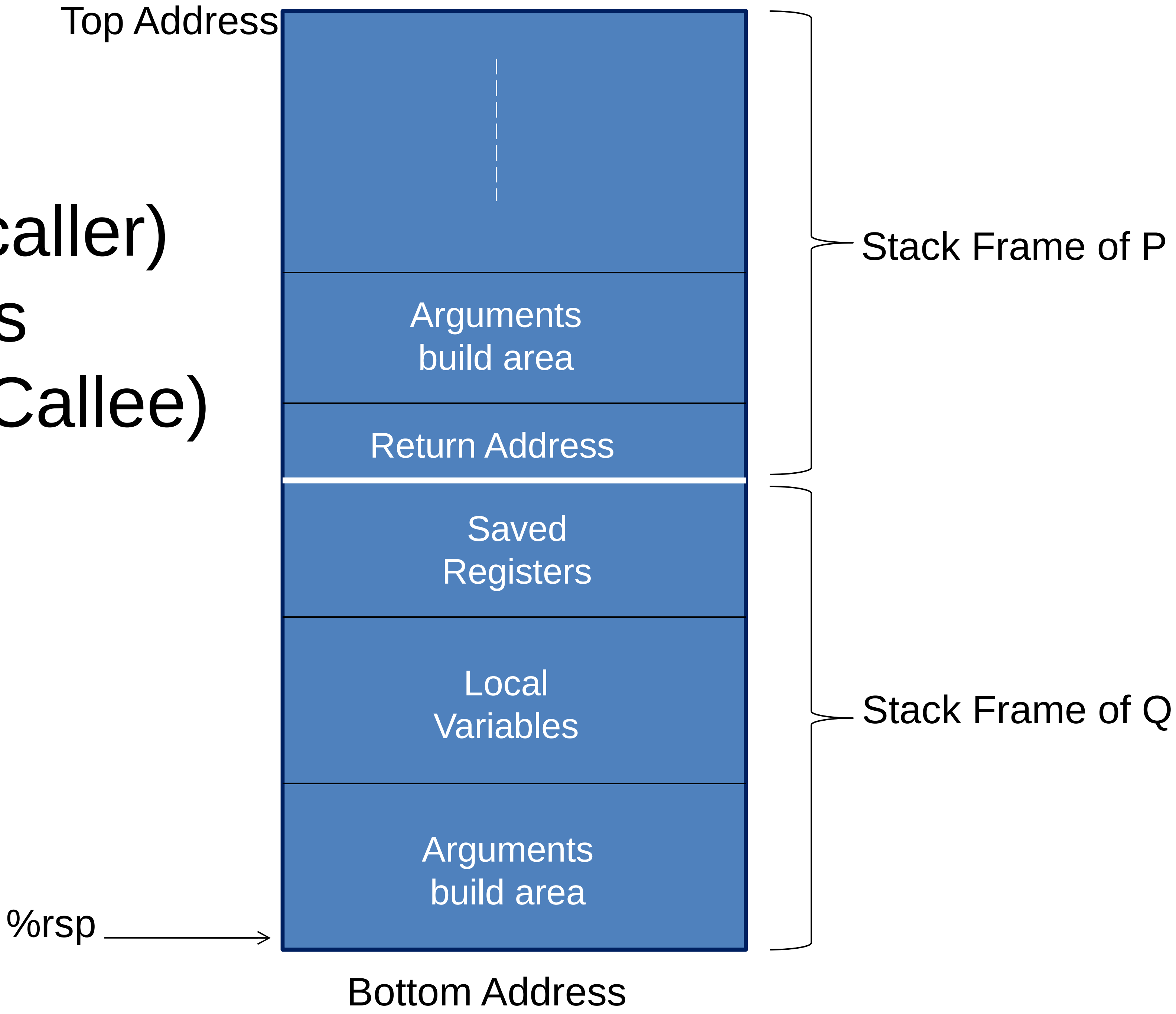
```
void multstore
 (long x, long y, long *dest)
{
    long t = mult2(x, y);
    *dest = t;
}
```

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

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

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

P (caller)
calls
Q (Callee)



Top Address

Arguments build area

Return Address

Saved Registers

Local Variables

Arguments build area

%rsp

Bottom Address

Stack Frame of P

Stack Frame of Q

# When P calls Q

- P is suspended and control moves to Q.
- A stack frame is setup on top of the stack for Q
- That stack frame contains:
  - saved registers
  - local variables
  - arguments if Q is calling another function
- Some procedures may not need a stack frame (why?).

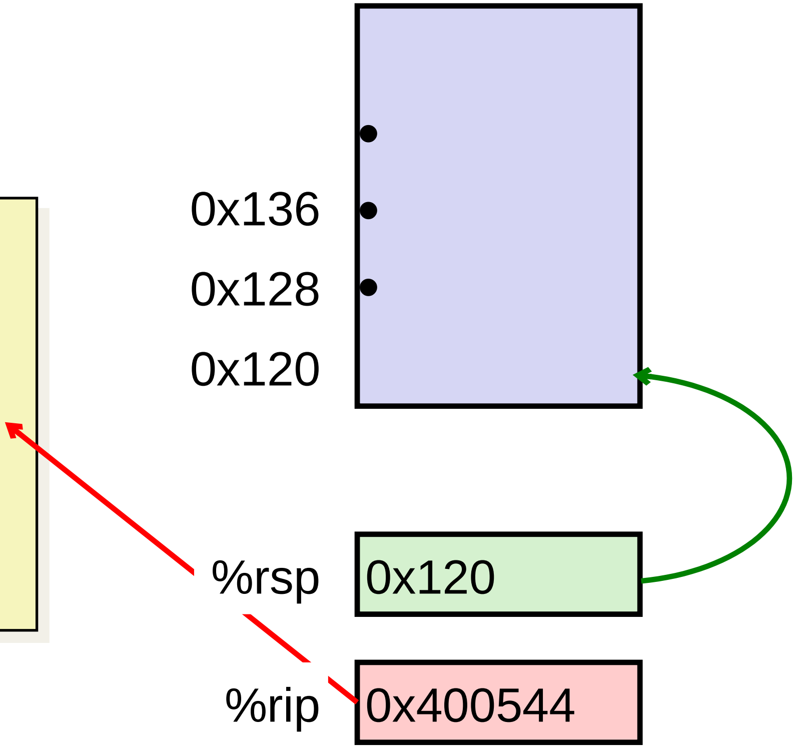
# Procedure Control Flow

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

# Example

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

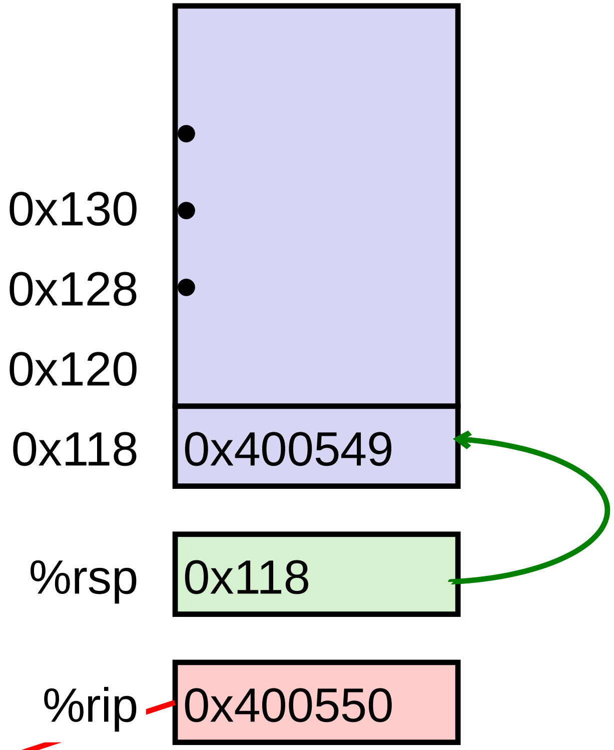
```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```



# Example

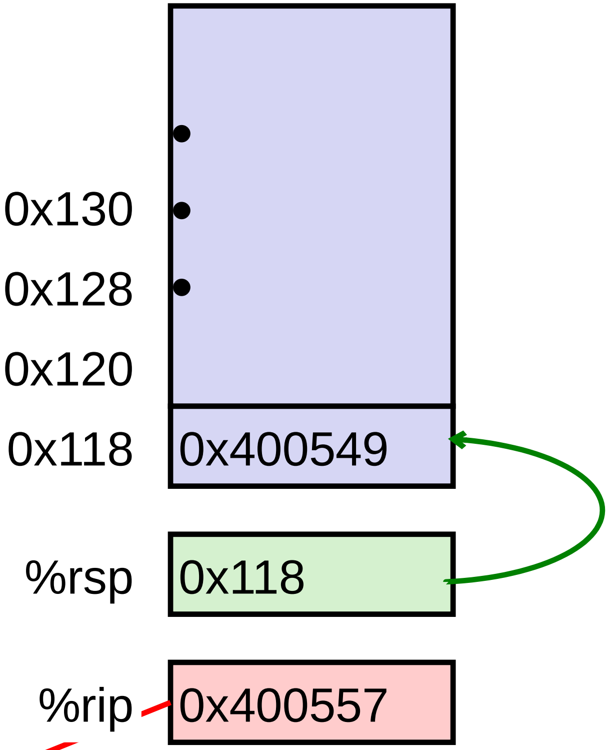
```
0000000000400540 <multstore>:
  •
  •
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  •
  •
```

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



# Example

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

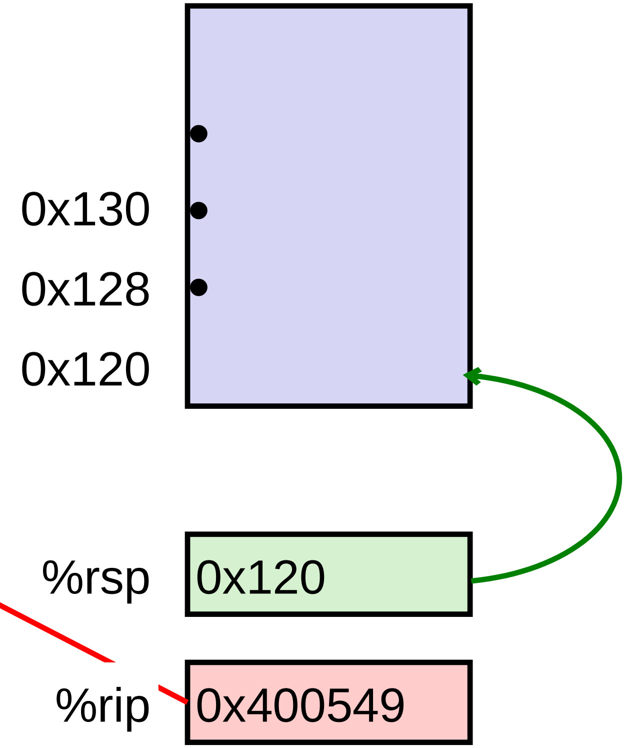


```
0000000000400550 <mult2>:
  400550:  mov    %rdi,%rax
  •
  •
  400557:  retq
```

# Example

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

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



# Procedure Data Flow

**Registers**

- First 6 arguments

%rdi

%rsi

%rdx

%rcx

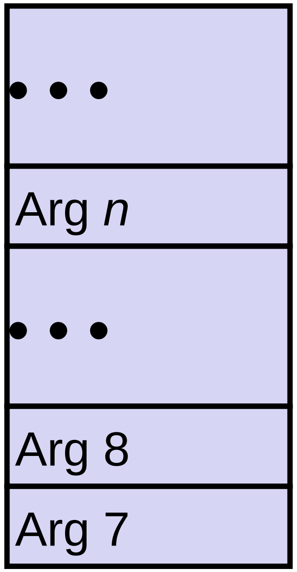
%r8

%r9

- Return value

%rax

**Stack**



• • •

Arg *n*

• • •

Arg 8

Arg 7

- Only allocate stack space when needed
- When passing parameters on the stack, all data sizes are rounded up to be multiple of eight.

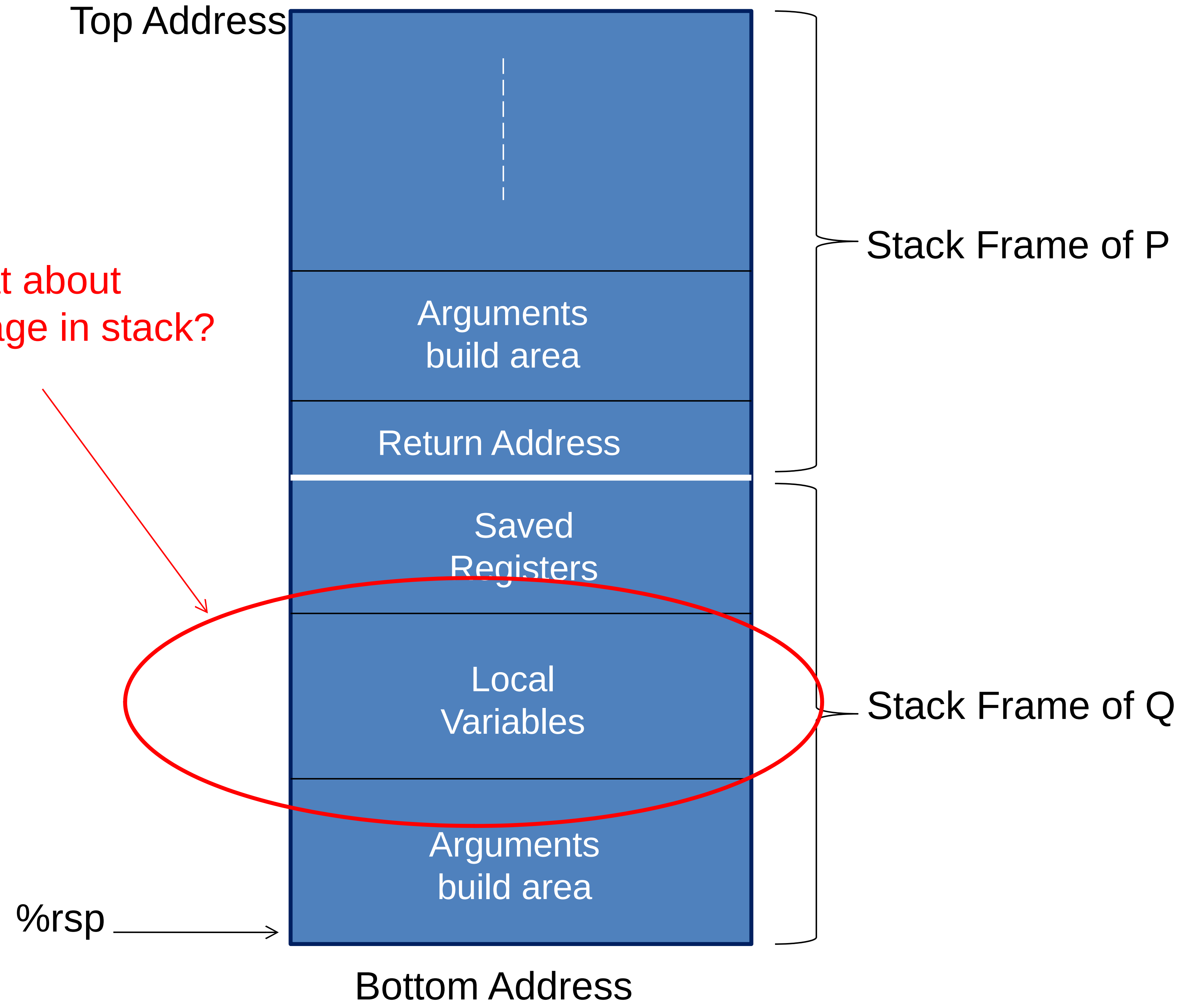
# Example: multstore calls mult2

```
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
```



What about
local storage in stack?

# When is local storage needed?

- Not enough registers
- A variable in high-level language is referred by its (“&” in C) so needs to have address!
- Arrays, structures, …

# Example: incr

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

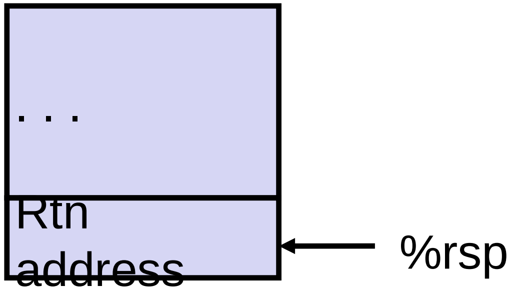
```
incr:
  movq    (%rdi), %rax
  addq    %rax, %rsi
  movq    %rsi, (%rdi)
  ret
```

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

# Example: Calling incr

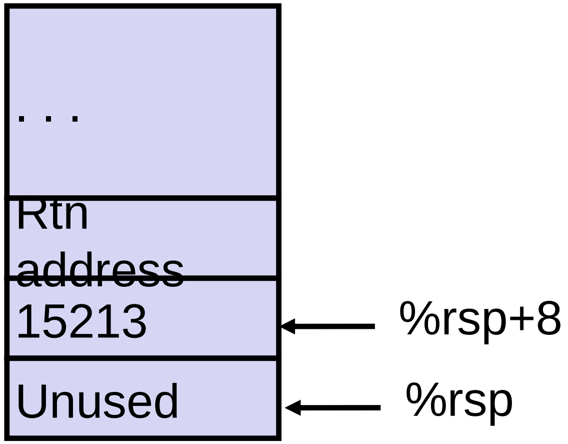
```
long call_incr() {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return v1+v2;
}
```

Initial Stack Structure



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

Resulting Stack Structure

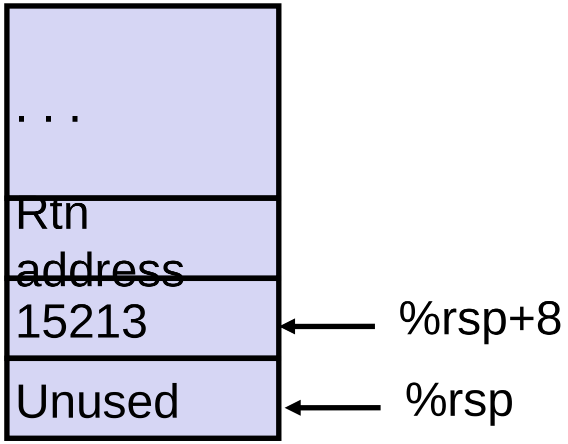


# Example: Calling incr

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

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

Stack Structure



. . .

Rtn address

15213

Unused

%rsp+8

%rsp

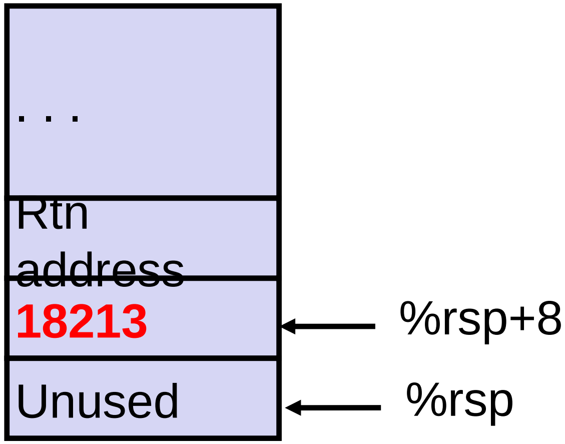
| Register | Use(s) |
|---|---|
| %rdi | &v1 |
| %rsi | 3000 |

# 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



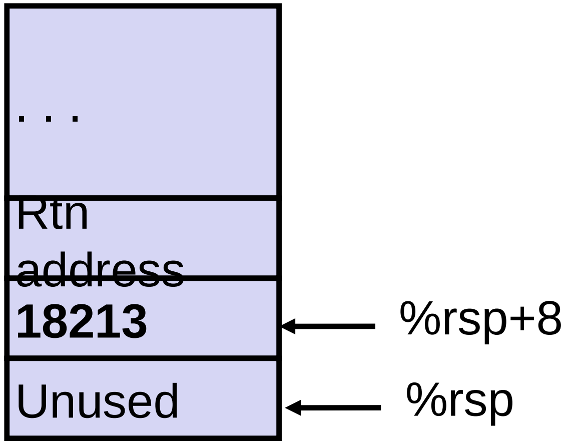
| Register | Use(s) |
|---|---|
| %rdi | &v1 |
| %rsi | 3000 |

# Example: Calling incr

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

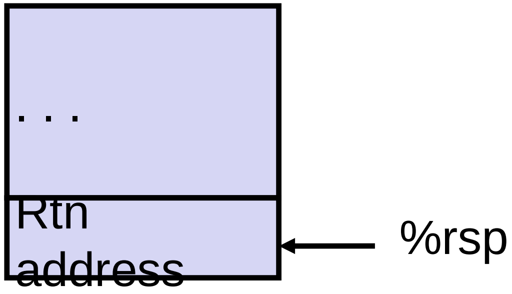
```
call_incr:
  subq    $16, %rsp
  movq    $15213, 8(%rsp)
  movl    $3000, %esi
  leaq    8(%rsp), %rdi
  call    incr
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

Stack Structure



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

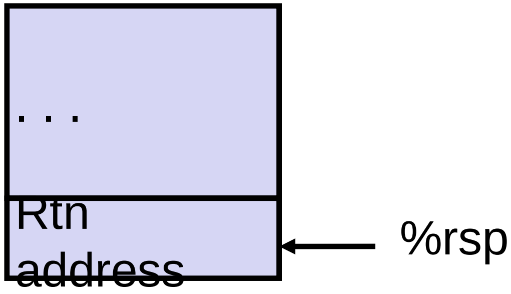
Updated Stack Structure



# Example: Calling incr

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

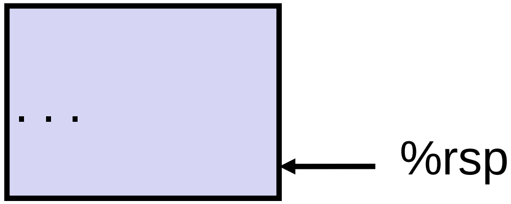
Updated Stack Structure



```
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



# Registers Usage Convention

# 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
```

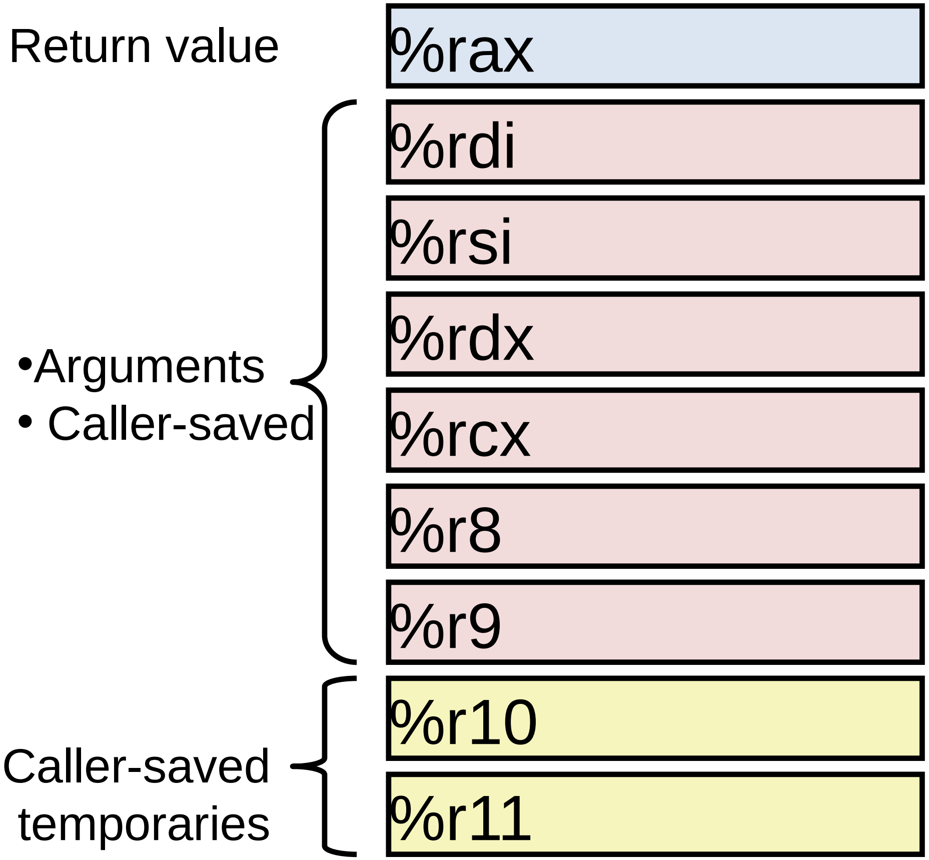
  - Contents of register %rdx overwritten by who
  - This could be trouble ➝ something should be done!
    - Need some coordination

# 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 of register in its frame before using the registers.
    - 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

• Caller-saved

%rdi

%rsi

%rdx

%rcx

%r8

%r9

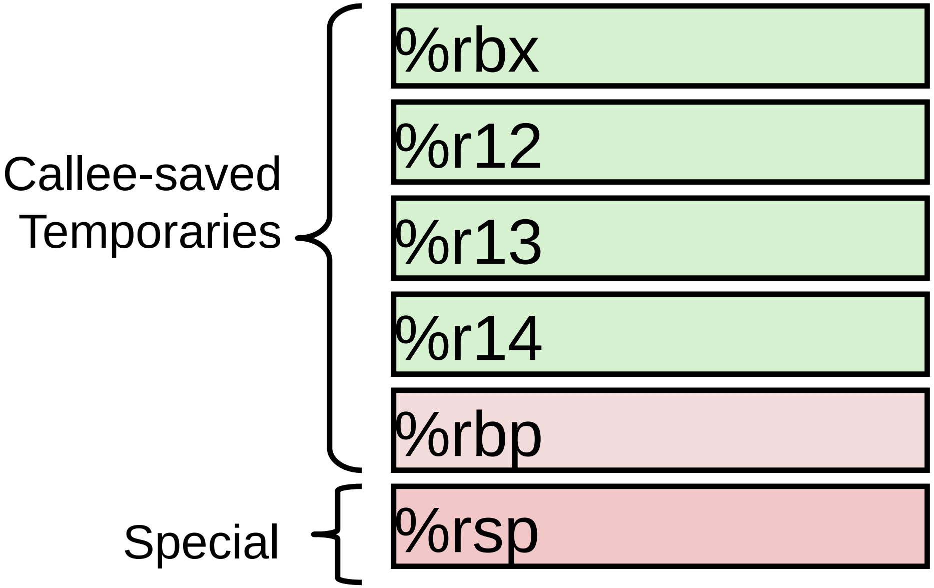
Caller-saved temporaries

%r10

%r11

# x86-64 Linux Register Usage #2

- %rbx, %r12, %r13, %r14
  - Callee-saved
  - Callee must save & restore
- %rbp
  - Callee-saved
  - Callee must save & restore
- %rsp
  - Special form of callee save
  - Restored to original value upon exit from procedure

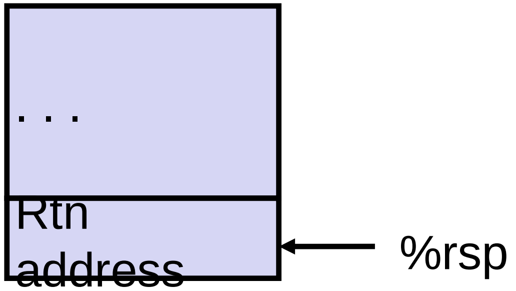


# Callee-Saved Example #1

```
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)
  movq    $3000, %rsi
  leaq    8(%rsp), %rdi
  call    incr
  addq    %rbx, %rax
  addq    $16, %rsp
  popq    %rbx
  ret
```

Initial Stack Structure

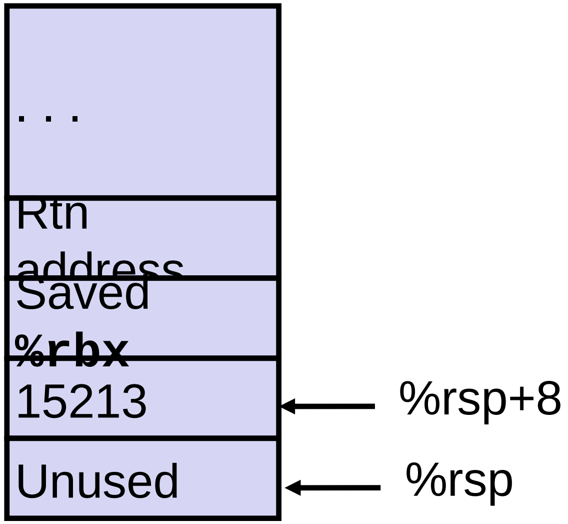


. . .

Rtn address

%rsp

Resulting Stack Structure



. . .

Rtn address

Saved %rbx

15213

Unused

%rsp+8

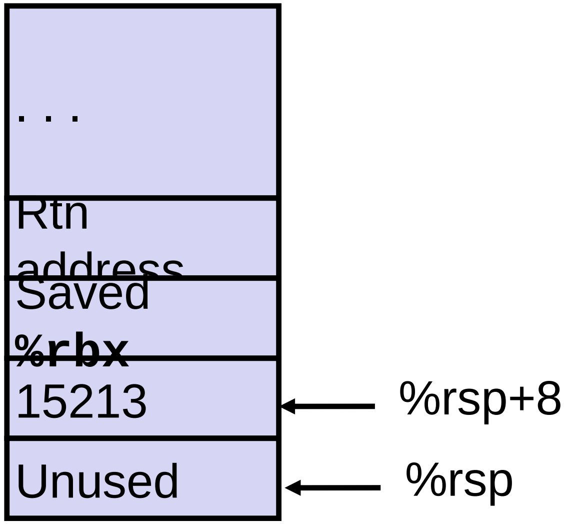
%rsp

# Callee-Saved Example #2

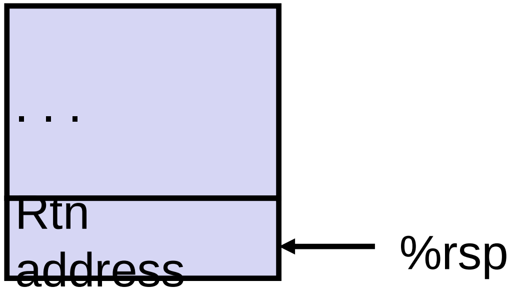
```
long call_incr2(long x) {
    long v1 = 15213;
    long v2 = incr(&v1, 3000);
    return x+v2;
}
```

```
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



# What About 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:
  movq     $0, %rax
  testq    %rdi, %rdi
  je       .L6
  pushq    %rbx
  movq     %rdi, %rbx
  andq     $1, %rbx
  shrq     %rdi
  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:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

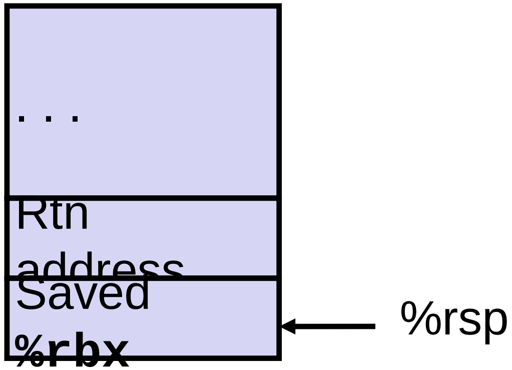
| Register | Use(s) | Type |
|---|---|---|
| `%rdi` | `x` | Argument |
| `%rax` | Return value | Return value |

# 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:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  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:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  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:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  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:
  movq     $0, %rax
  testq    %rdi, %rdi
  je       .L6
  pushq    %rbx
  movq     %rdi, %rbx
  andq     $1, %rbx
  shrq     %rdi
  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:
  movq    $0, %rax
  testq   %rdi, %rdi
  je      .L6
  pushq   %rbx
  movq    %rdi, %rbx
  andq    $1, %rbx
  shrq    %rdi
  call    pcount_r
  addq    %rbx, %rax
  popq    %rbx
.L6:
  ret
```

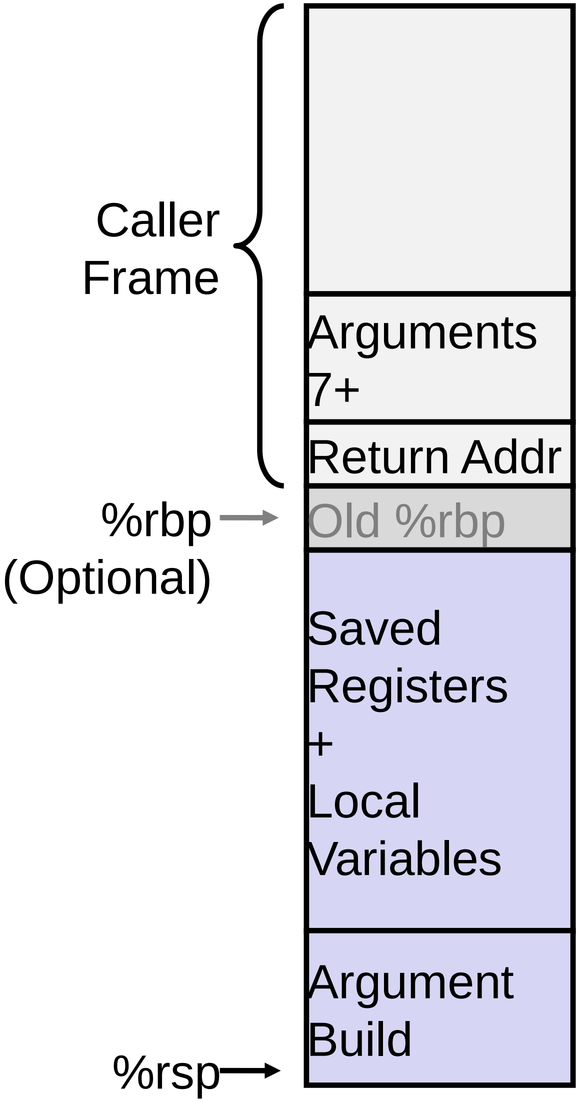
| Register | Use(s) | Type |
|---|---|---|
| %rax | Return value | Return value |

# Observations About Recursion

- Handled Without Special Consideration
  - Register saving conventions prevent one function call from corrupting another’s data
  - 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

# Conclusions

- 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


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