CSC 252: Computer Organization
Spring 2018: Lecture 8

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University of Rochester

Action Items:

- **Assignment 1 grades are out**
- **Assignment 2 is due soon!**

Announcement

- Programming Assignment 2 is out
  - Due on **This Friday, Feb 16, 11:59 PM**
  - You may still have 3 slip days…
- Programming Assignment 1 grades are out
  - Talk to a TA if you get a 0

Switch Statement Example

```
long switch_eg (long x, long y, long z)
{
    long w = 1;
    switch(x) {
    case 1:
        w = y*z;
        break;
    case 2:
        w = y/z;
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;
    }
    return w;
}
```

Fall-through case

Multiple case labels

For missing cases, fall back to default

Converting to a cascade of if-else statements is simple, but cumbersome with too many cases.

Implementing Switch Using Jump Table

Switch Form

```
switch(x) {
  case val_0:
    Block 0
  case val_1:
    Block 1

  ....
  case val_n-1:
    Block n–1
}
```

Implementing Switch Using Jump Table

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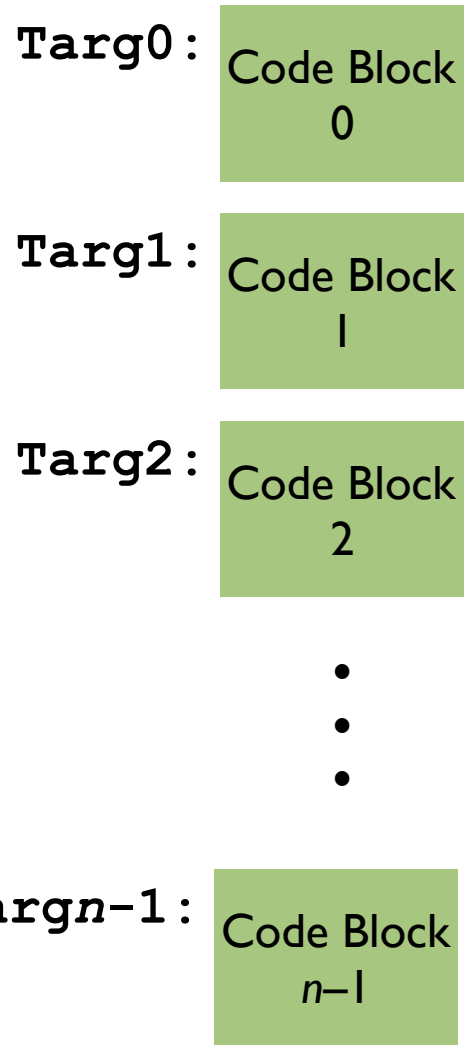
Jump Targets



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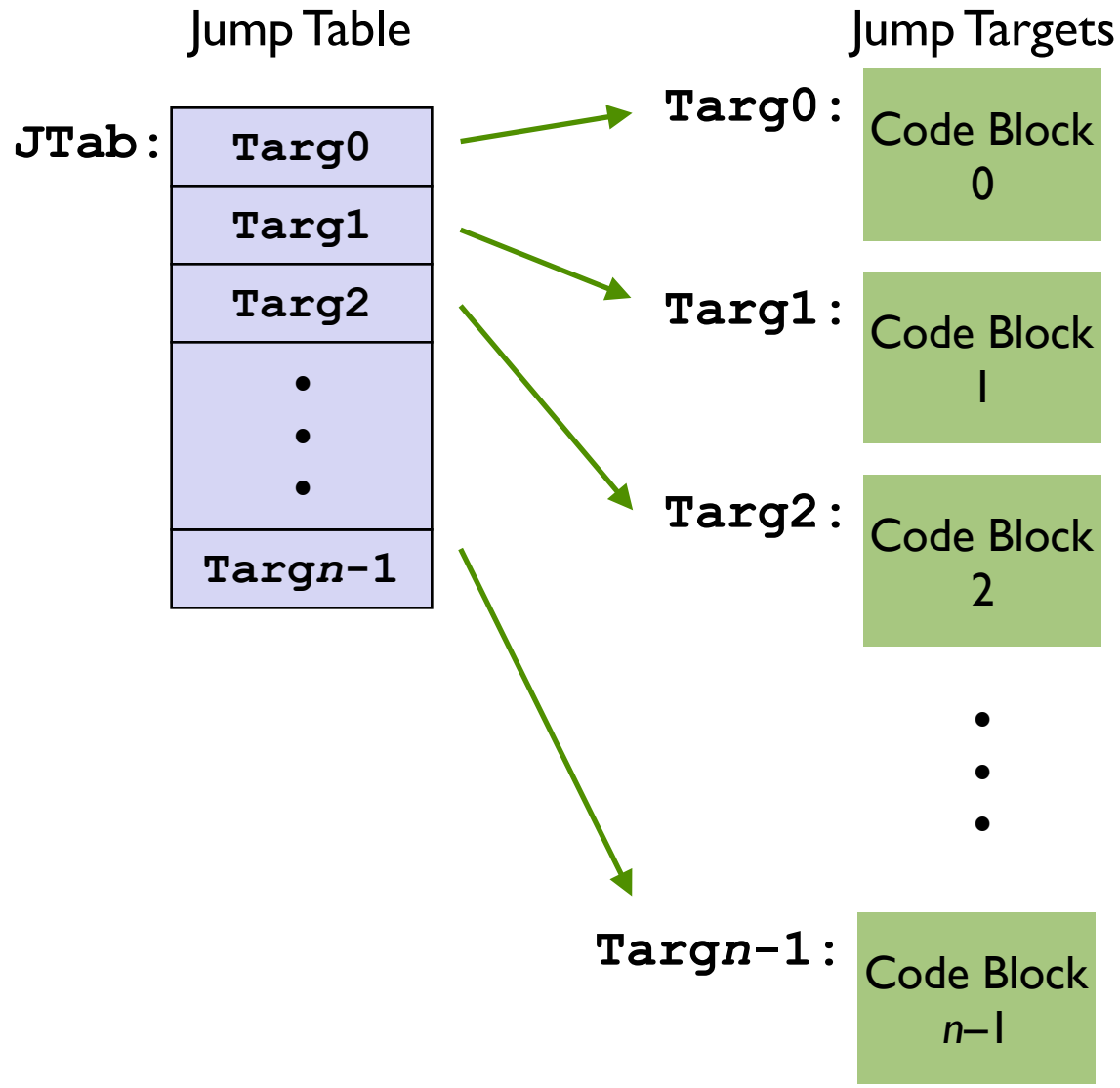

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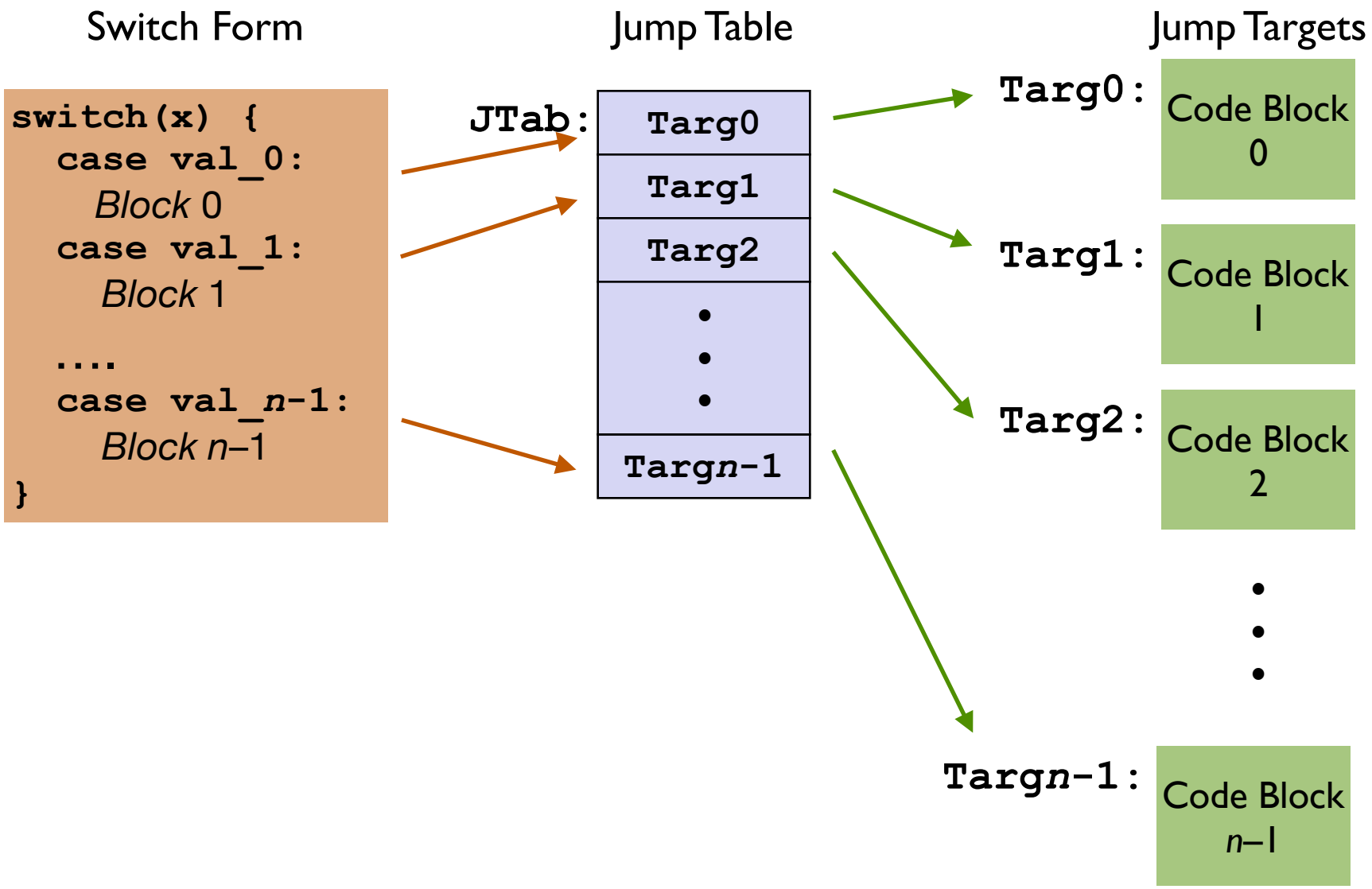

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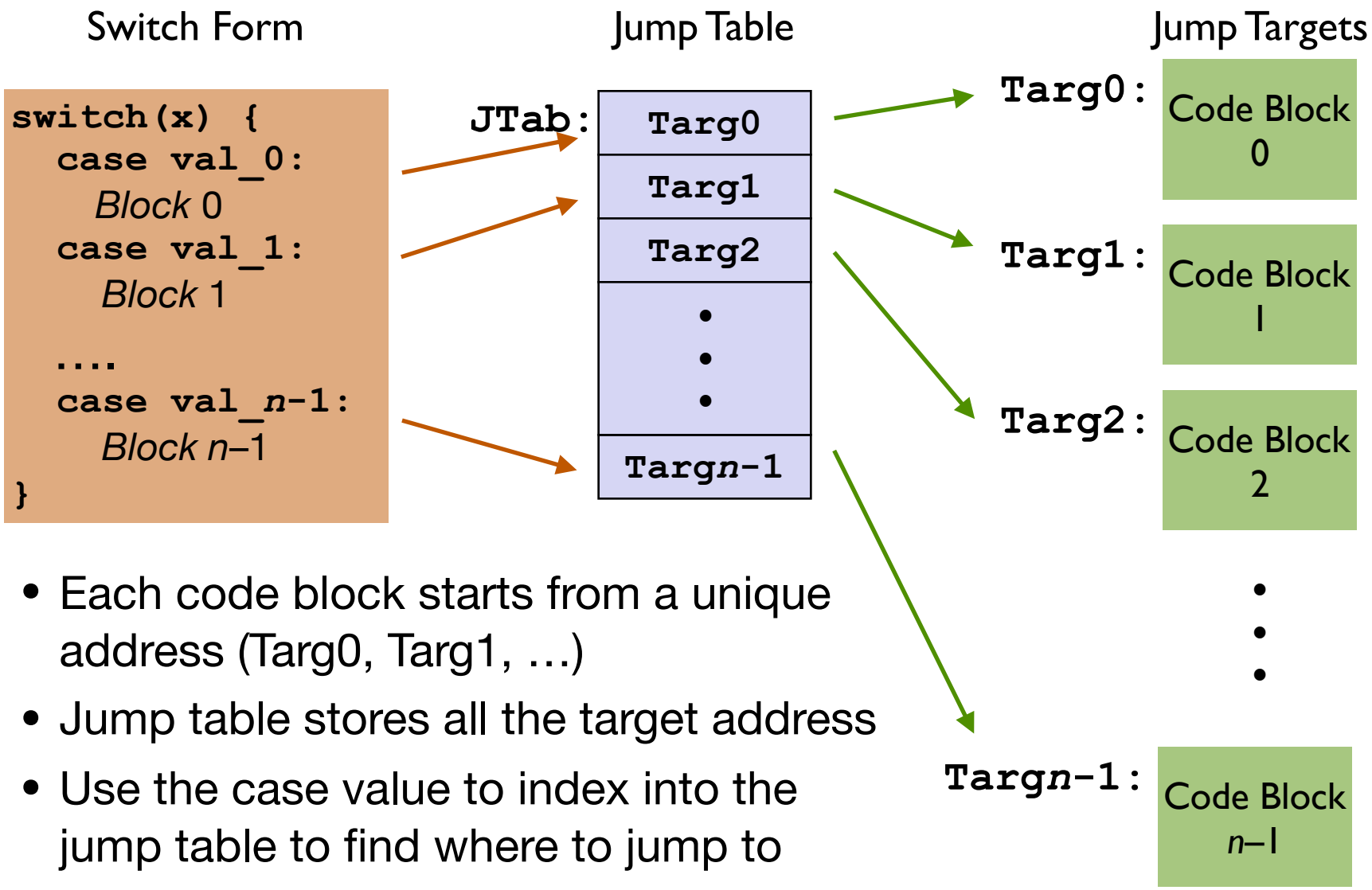


- Each code block starts from a unique address (Targ0, Targ1, …)
- Jump table stores all the target address
- Use the case value to index into the jump table to find where to jump to

Jump Table and Jump Targets

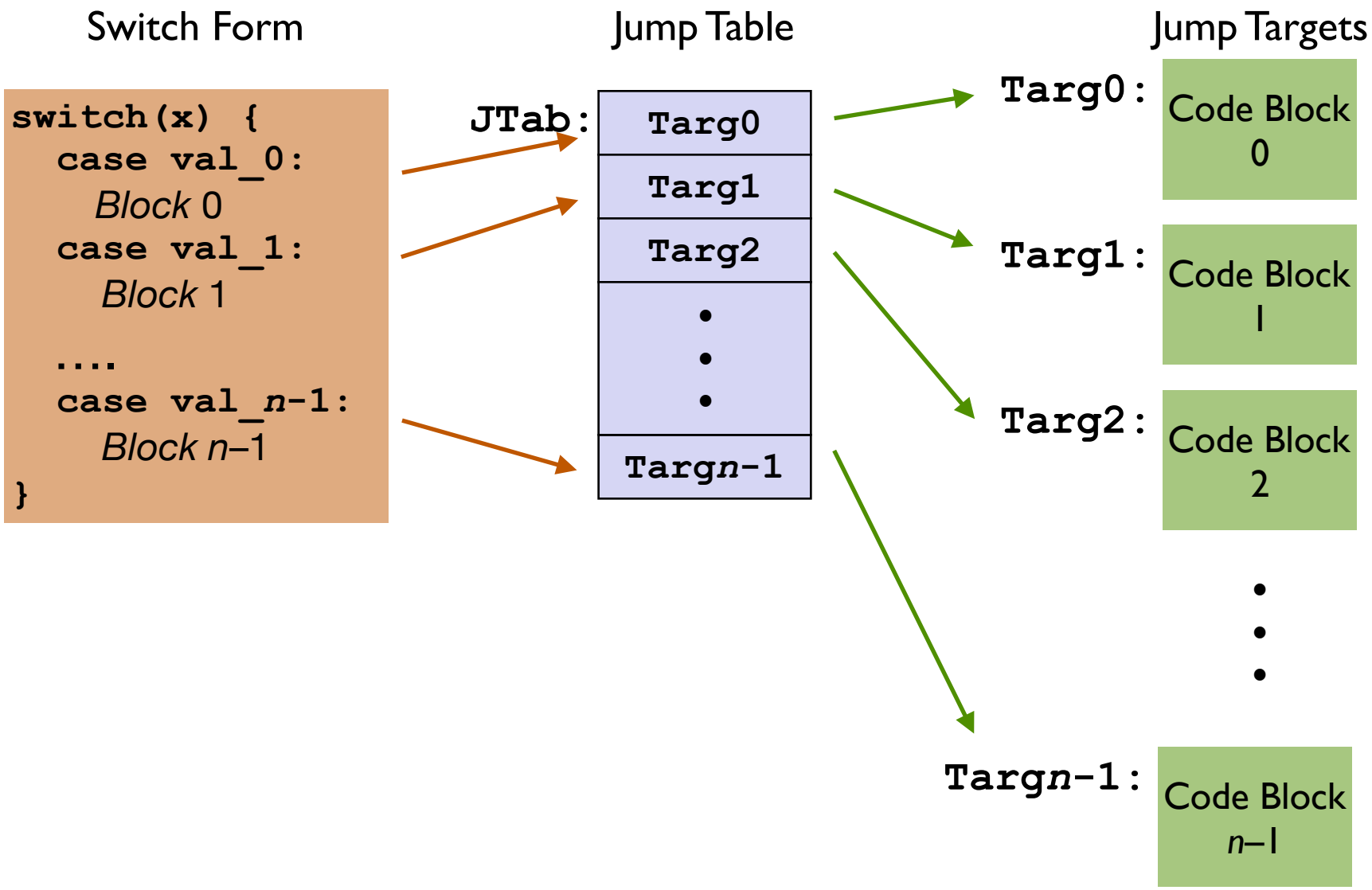
Jump Table

```
.section   .rodata
  .align 8
.L4:
  .quad .L8 # x = 0
  .quad .L3 # x = 1
  .quad .L5 # x = 2
  .quad .L9 # x = 3
  .quad .L8 # x = 4
  .quad .L7 # x = 5
  .quad .L7 # x = 6
```

Jump Targets

```
.L3:                    # Case 1
   movq    %rsi, %rax
   imulq   %rdx, %rax
   jmp     .done
.L5:                    # Case 2
   movq    %rsi, %rax
   cqto
   idivq   %rcx
.L9:                    # Case 3
   addq    %rcx, %rax
   jmp     .done
.L7:                    # Case 5,6
   subq    %rdx, %rax
   jmp     .done
.L8:                    # Default
  movl     $2, %eax
  jmp     .done
```

Implementing Switch Using Jump Table



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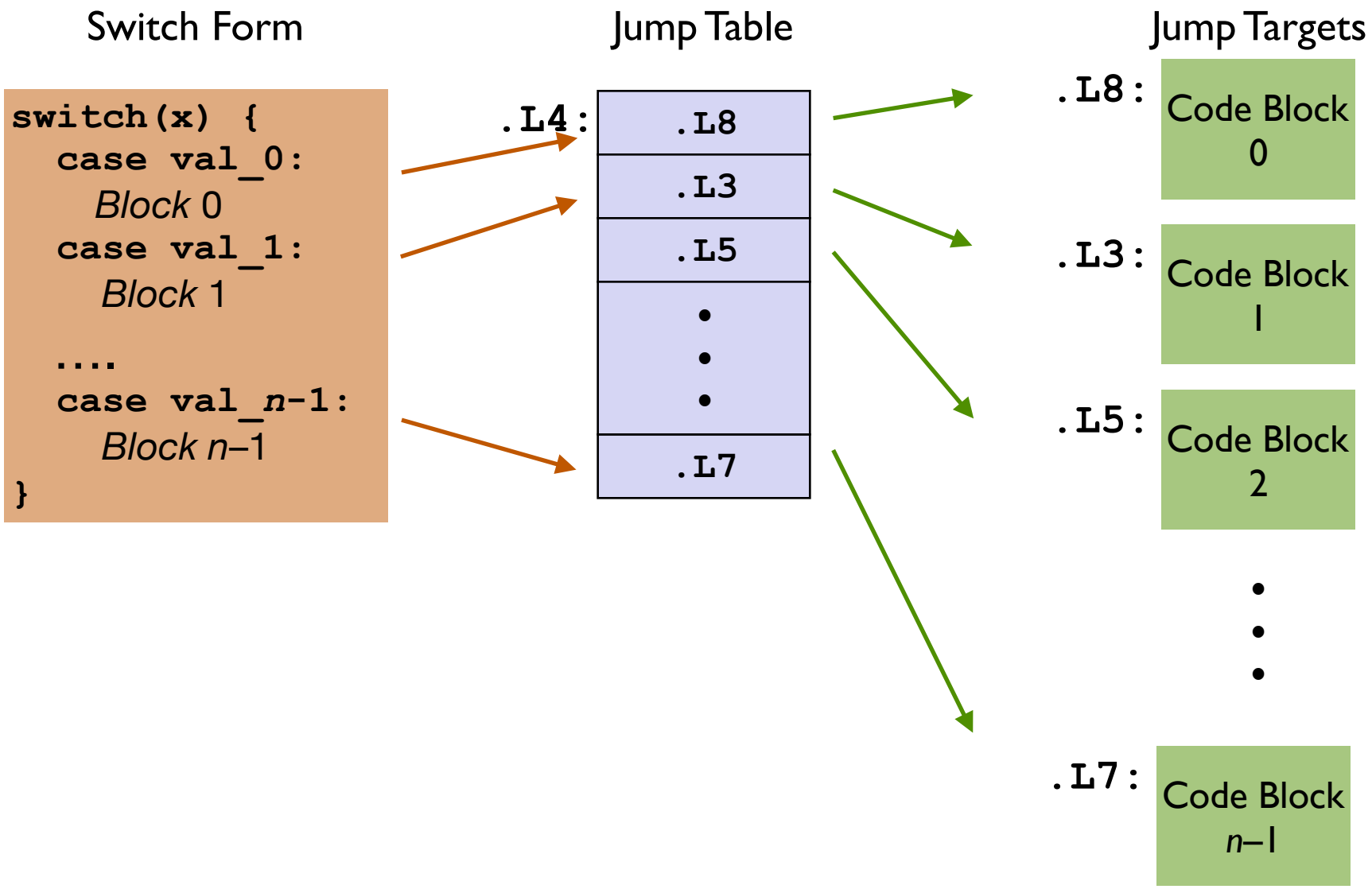
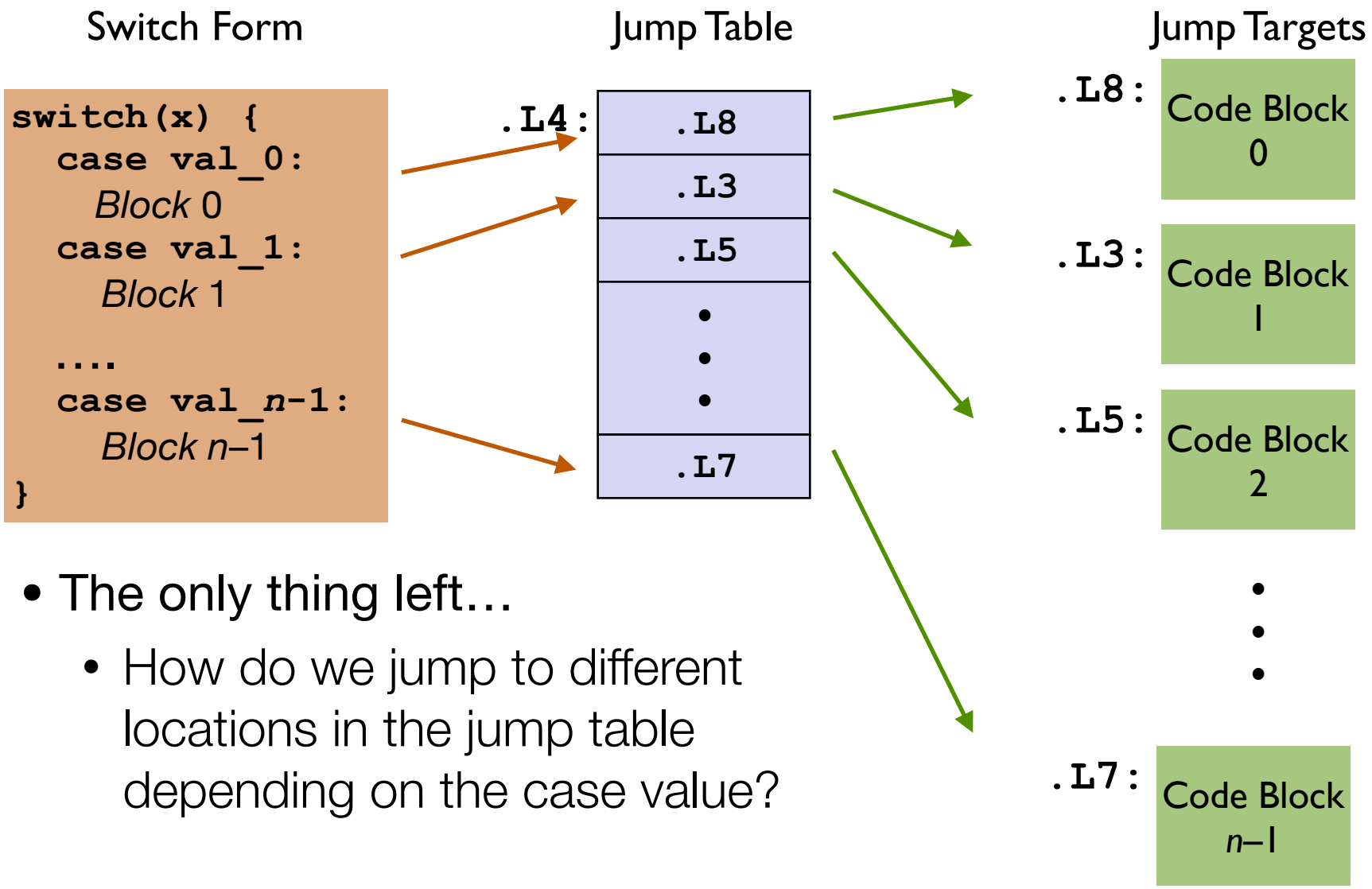


Implementing Switch Using Jump Table



- The only thing left…
  - How do we jump to different locations in the jump table depending on the case value?

Indirect Jump Instruction

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Indirect Jump Instruction

Address we want = .L4 + 8 * x

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```

Address we want = .L4 + 8 * `x`

```
# assume x in %rdi
movq  .L4(,%rdi,8), %rax
jmp   *%rax
```

- Indirect Jump: **`jmp *%rax`**
  - `%rax` specifies the address to jump to (PC = `%rax`)
- Direct Jump (**`jmp .L4`**), directly specifies the jump address
- Indirect Jump specifies where the jump address is located

Indirect Jump Instruction

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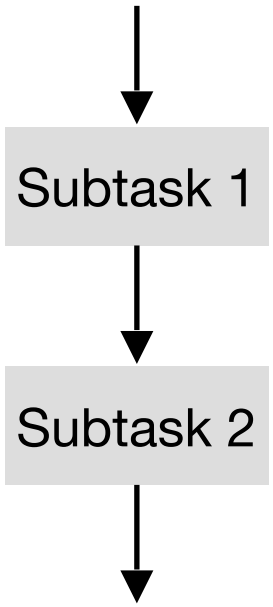
```
jmp      *.L4(,%rdi,8)
```

Summary

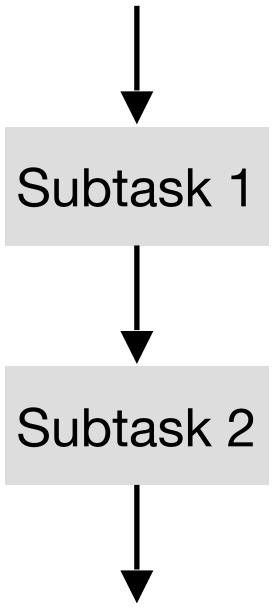
Sequential




```
a = x + y;
y = a - c;
...
```

Summary

Sequential




```
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…
```

Memory

```
.section .text

…

<subtask 1>

…

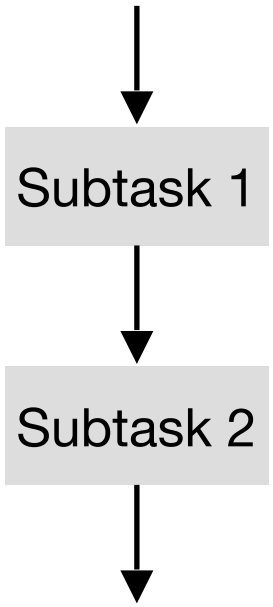
…

<subtask 2>

…
```

Summary

Sequential

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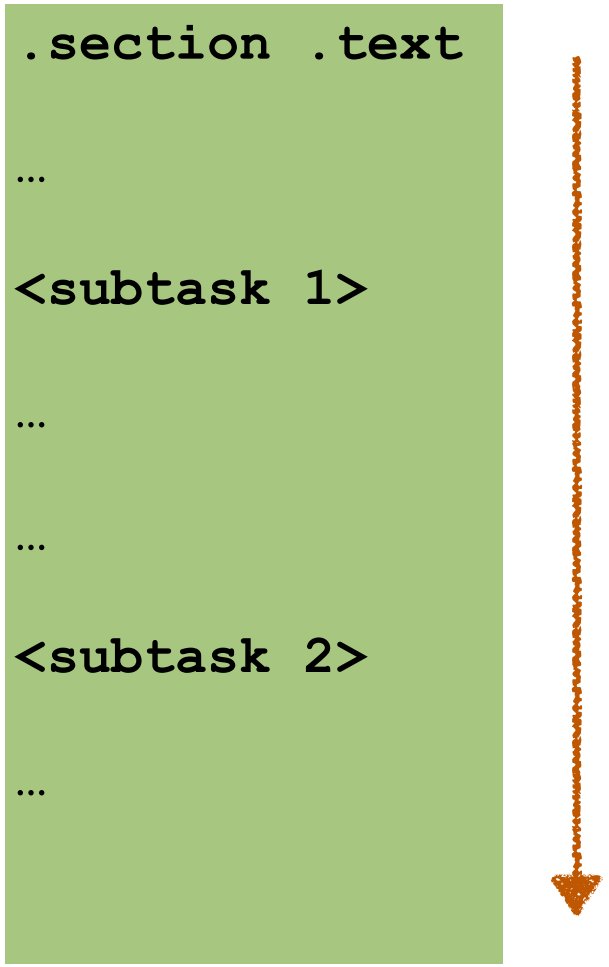

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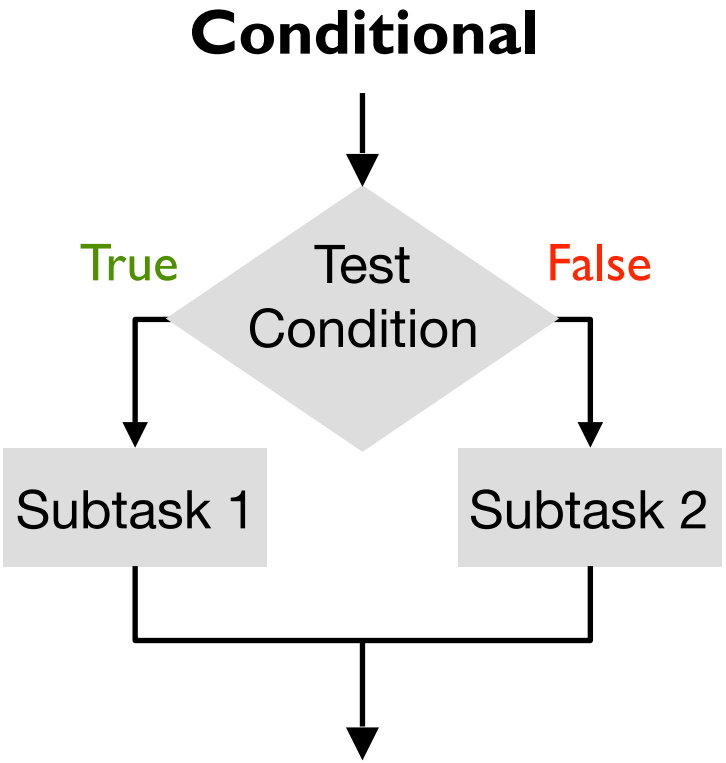


```
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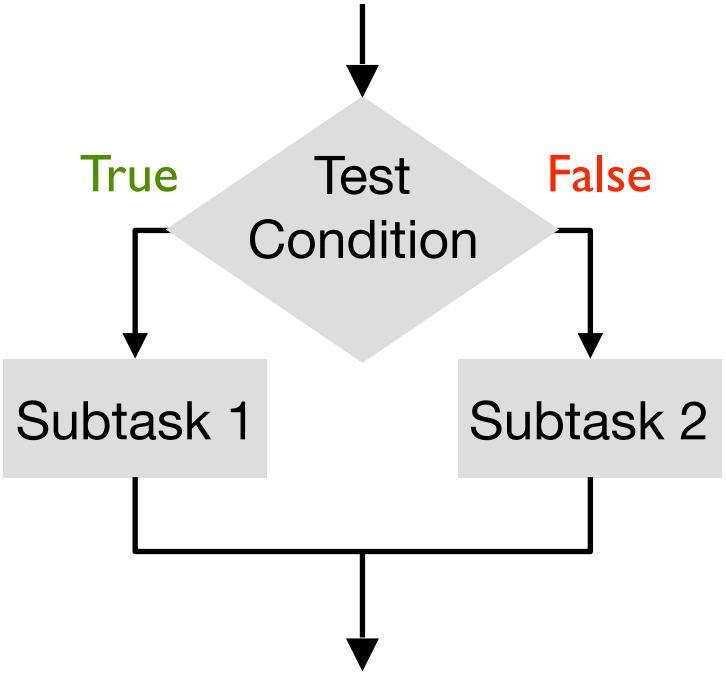
Summary

Conditional

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if (x > y) r = x - y;
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```

Memory

```
.section .text

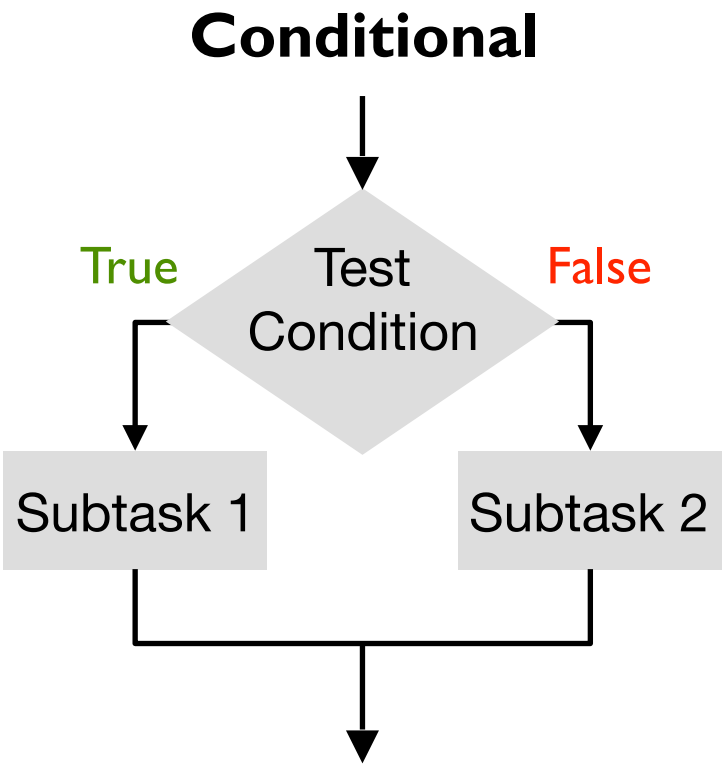
…
cmpq
jle .L2
.L1 <subtask 1>

…

jmp .done
.L2 <subtask 2>

…
.done
```

Summary

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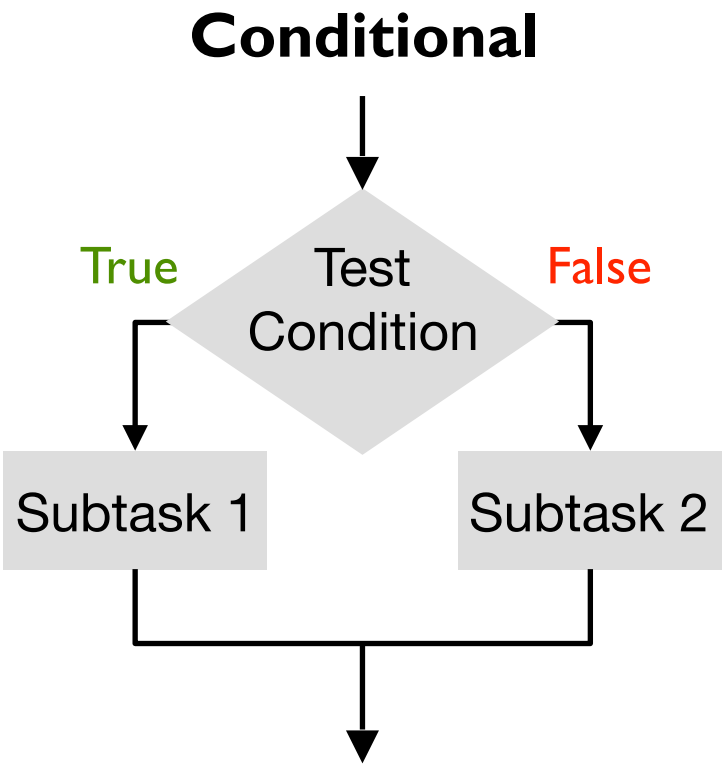


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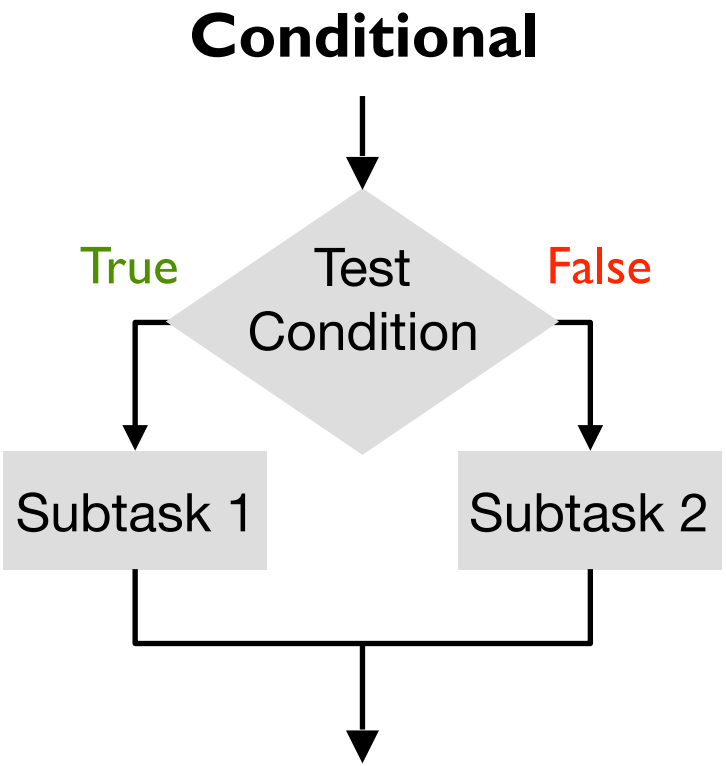


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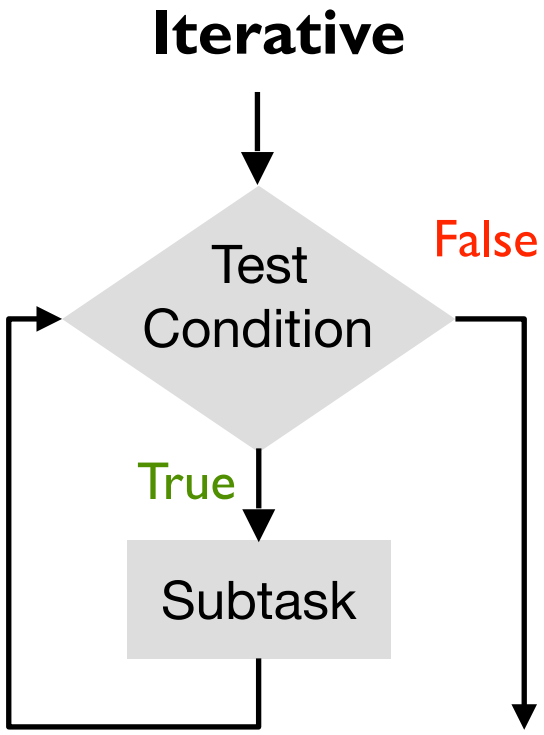
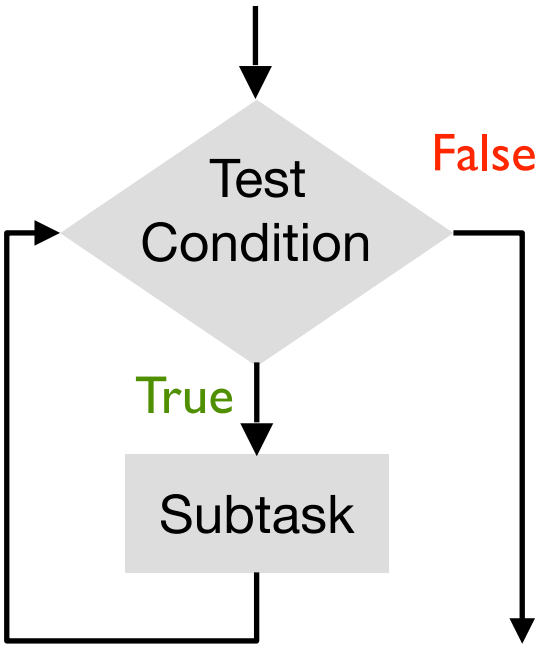



```
while (x > 0) {
  x--;
}
```

Summary

Iterative

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Memory

```
.section .text

…
addq
jmp .L2
.L1:

…
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…
.L2:
  cmpq A, B
  jg .L1
…
…
```

Summary

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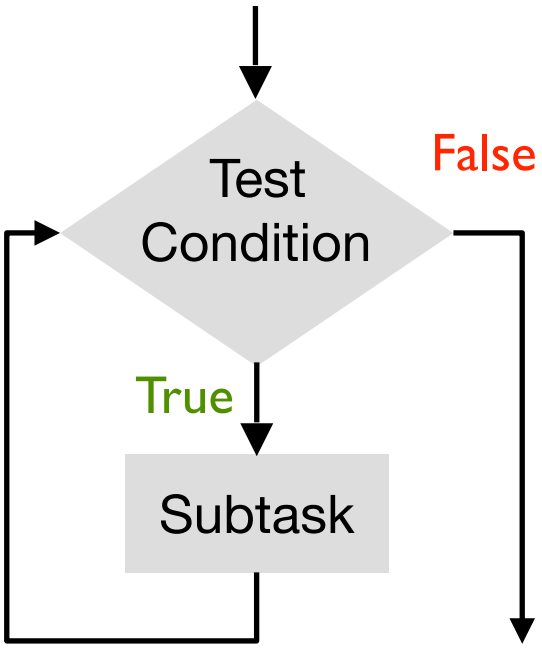


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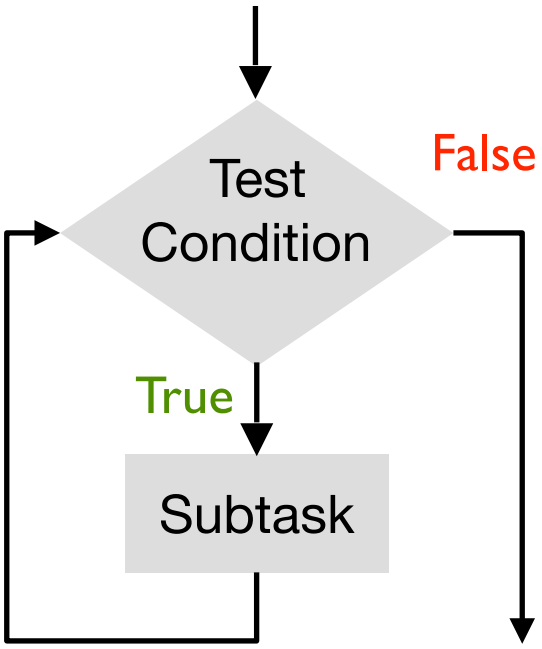


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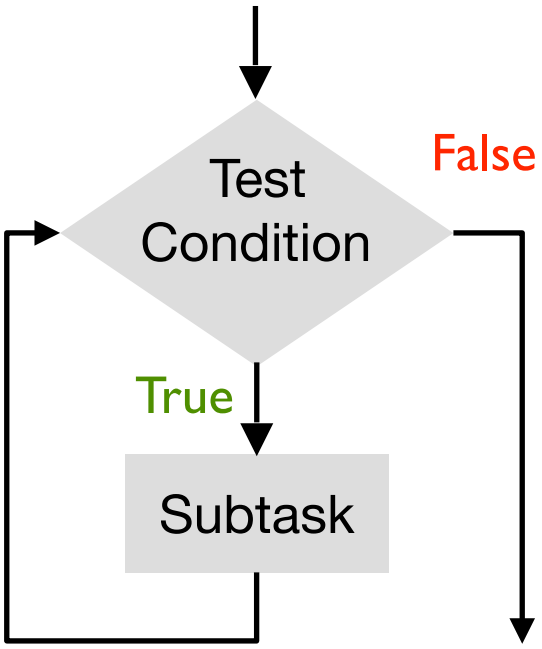


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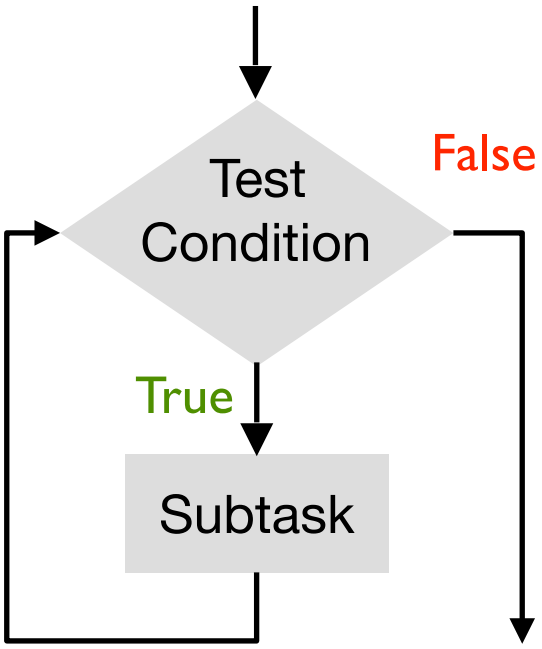


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Today: How to Implement Function Call

- What are functions and why do we use them?
- General idea of implementing functions: Stack
- Passing control
- Passing data
- Managing local data

Example of a Go Program Structure

```
main()
{
  /* place pieces on board */
  SetupBoard();

  /* choose black/white */
  DetermineSides();

  /* Play game */
  do {
    WhitesTurn();
    BlacksTurn();
  } while (NoOutcomeYet());
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Structure of program is evident, even without knowing implementation.

Function

- Smaller, simpler, subcomponent of program that:
  - hides low-level details
  - gives high-level structure to program, easier to understand overall program flow
  - enables separable, independent development

- C functions
  - zero or multiple arguments passed in
  - single result returned (optional)
  - return value is always a particular type

- In other languages, called procedures, subroutines, ...

Functions Declaration in C

Declaration (also called prototype)

- States return type, name, types of arguments

```
int Factorial(int);
```

type of return value

name of function

types of all arguments

Function Definition

- Must match function declaration
- Implement the functionality of the function

```
int Factorial(int n)
{
  int i;
  int result = 1;
  for (i = 1; i <= n; i++)
    result *= i;
  return result;
}
```

gives control back to calling function and returns value

Mechanisms in Procedures

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

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

Mechanisms in Procedures

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

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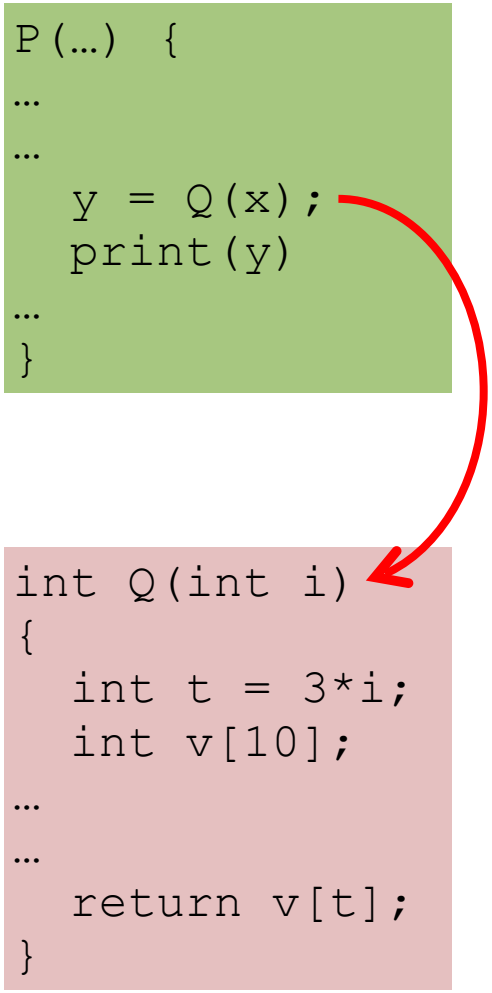

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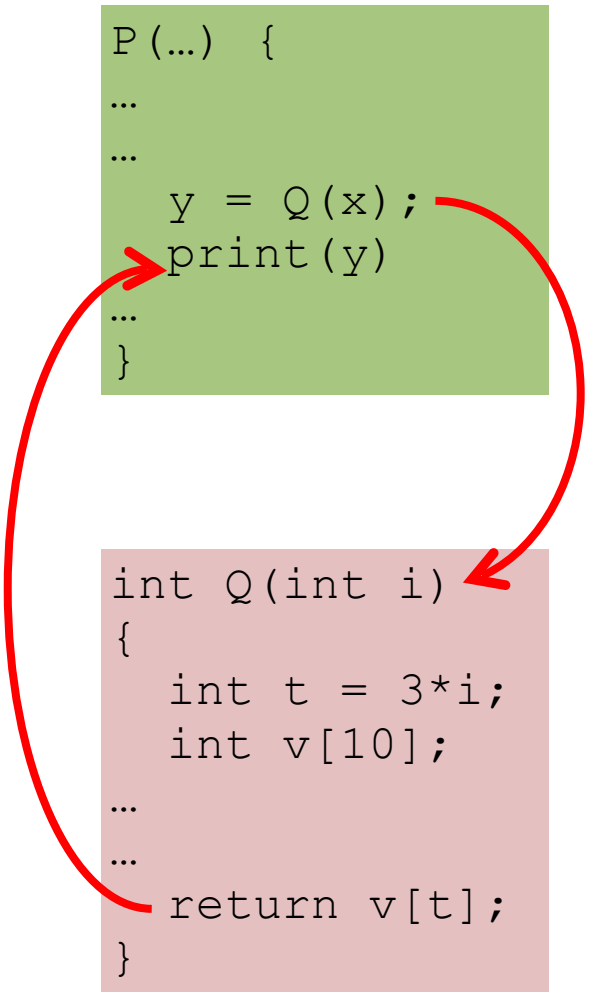

Mechanisms in Procedures

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  - Procedure arguments
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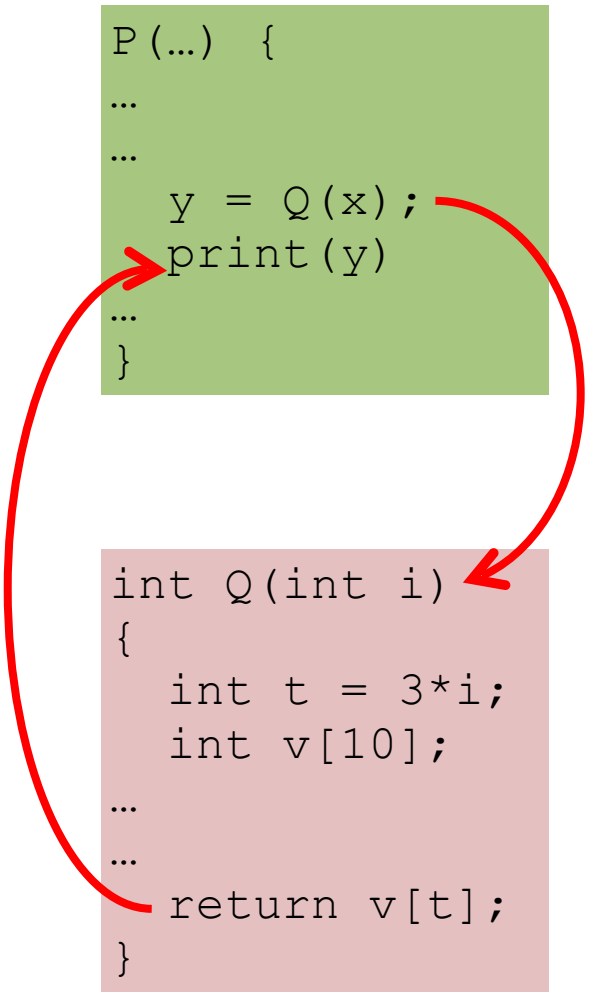

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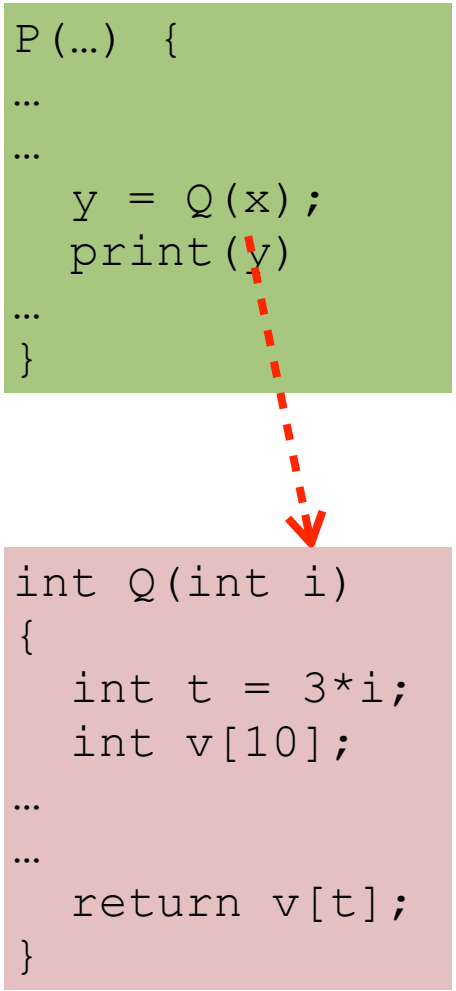

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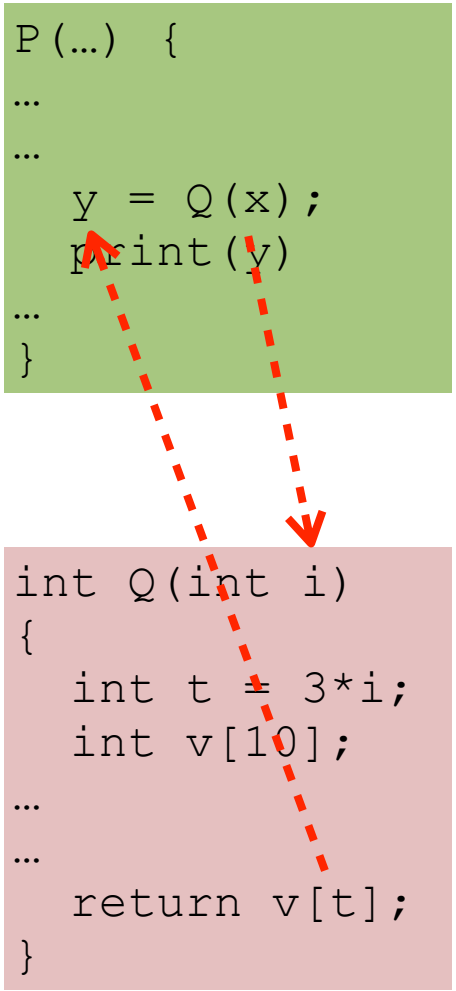

Mechanisms in Procedures

- Passing control
  - To beginning of procedure code
  - Back to return point
- Passing data
  - Procedure arguments
  - Return value
- Local Memory management
  - Allocate during procedure execution
  - Deallocate upon return

```
P(…) {
…
…
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Mechanisms in Procedures

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- Passing data
  - Procedure arguments
  - Return value
- Local Memory management
  - Allocate during procedure execution
  - Deallocate upon return
- Mechanisms all implemented with machine instructions

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Today: How to Implement Function Call

- What are functions and why do we use them?
- General idea of implementing functions: Stack
- Passing control
- Passing data
- Managing local data

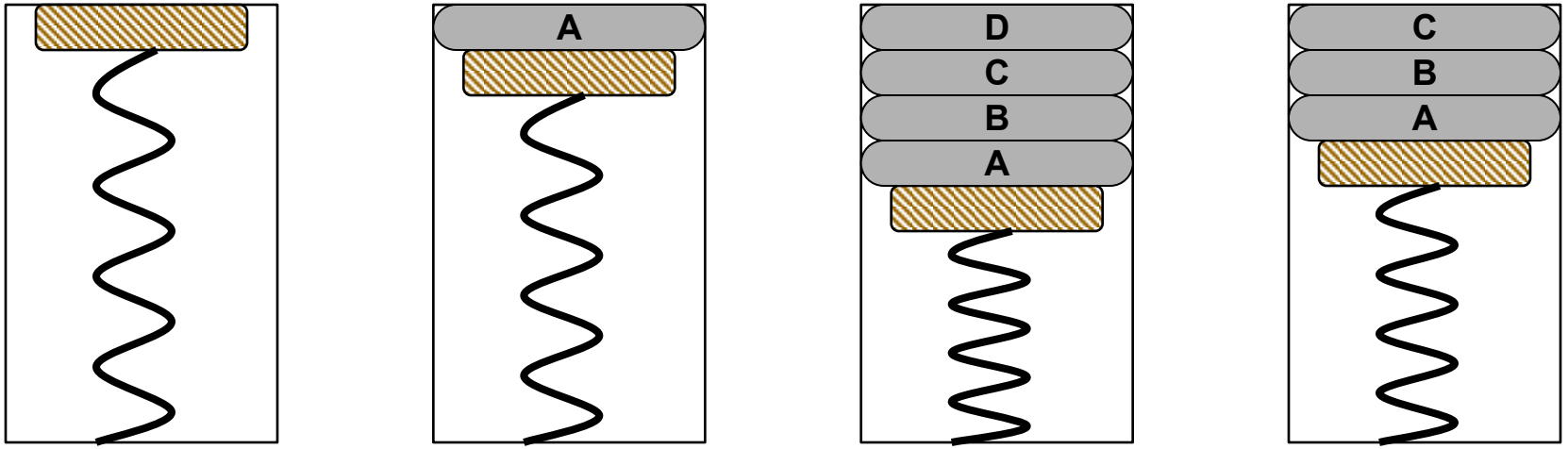
General Idea

- Frame (Active Record)
  - information about each function, including arguments and local variables
  - Every function has a frame, which keeps tracks of (almost) all the information needed to execute that function

- Frames are stored in memory in a *stack* fashion
  - When a new function is called, its frame is pushed on the stack (by the caller function)
  - When it returns, its frame is popped off of the stack.

A Physical Stack: A Coin Holder

First quarter out is the last quarter in.



Initial State

After
One Push

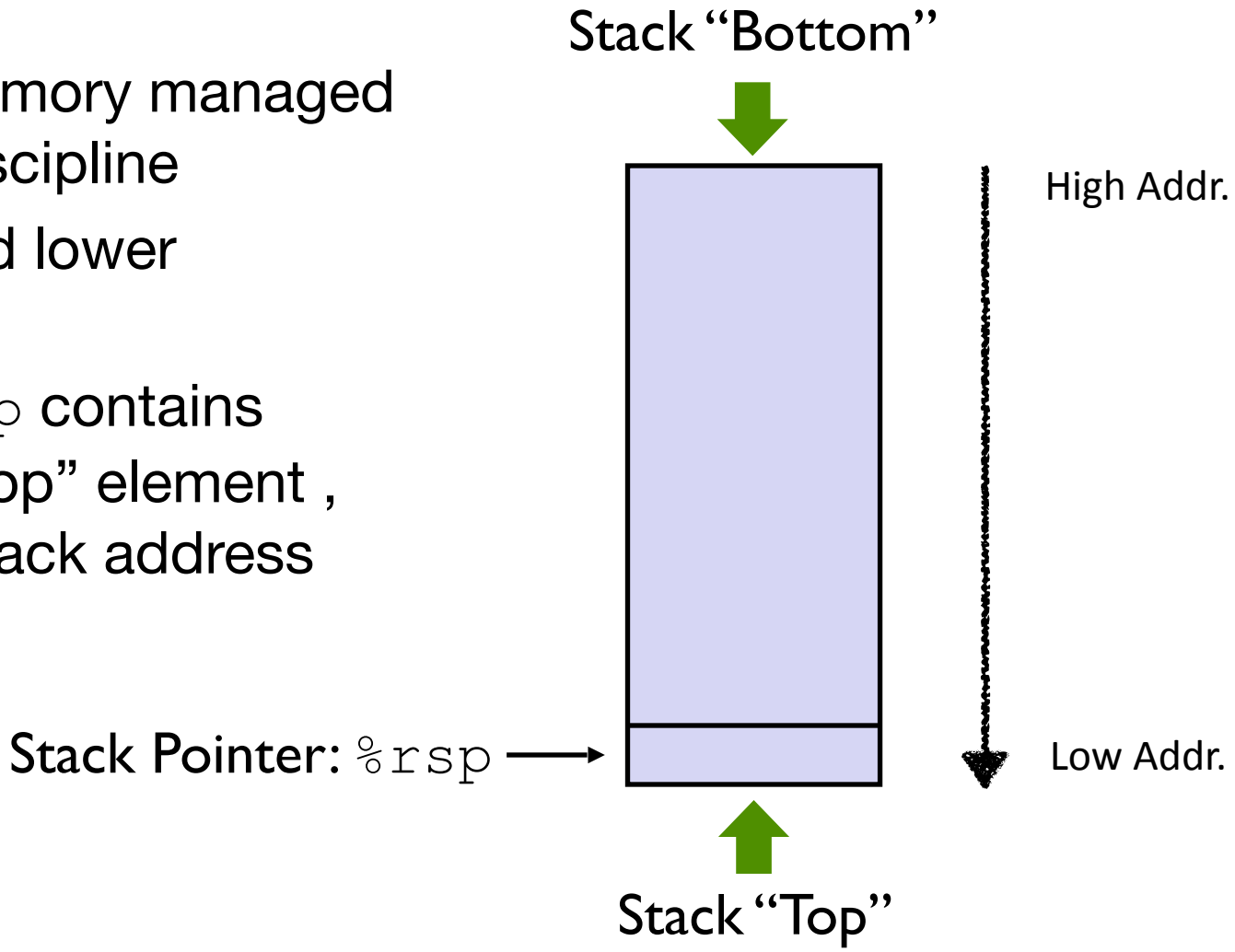
After Three
More Pushes

After
One Pop

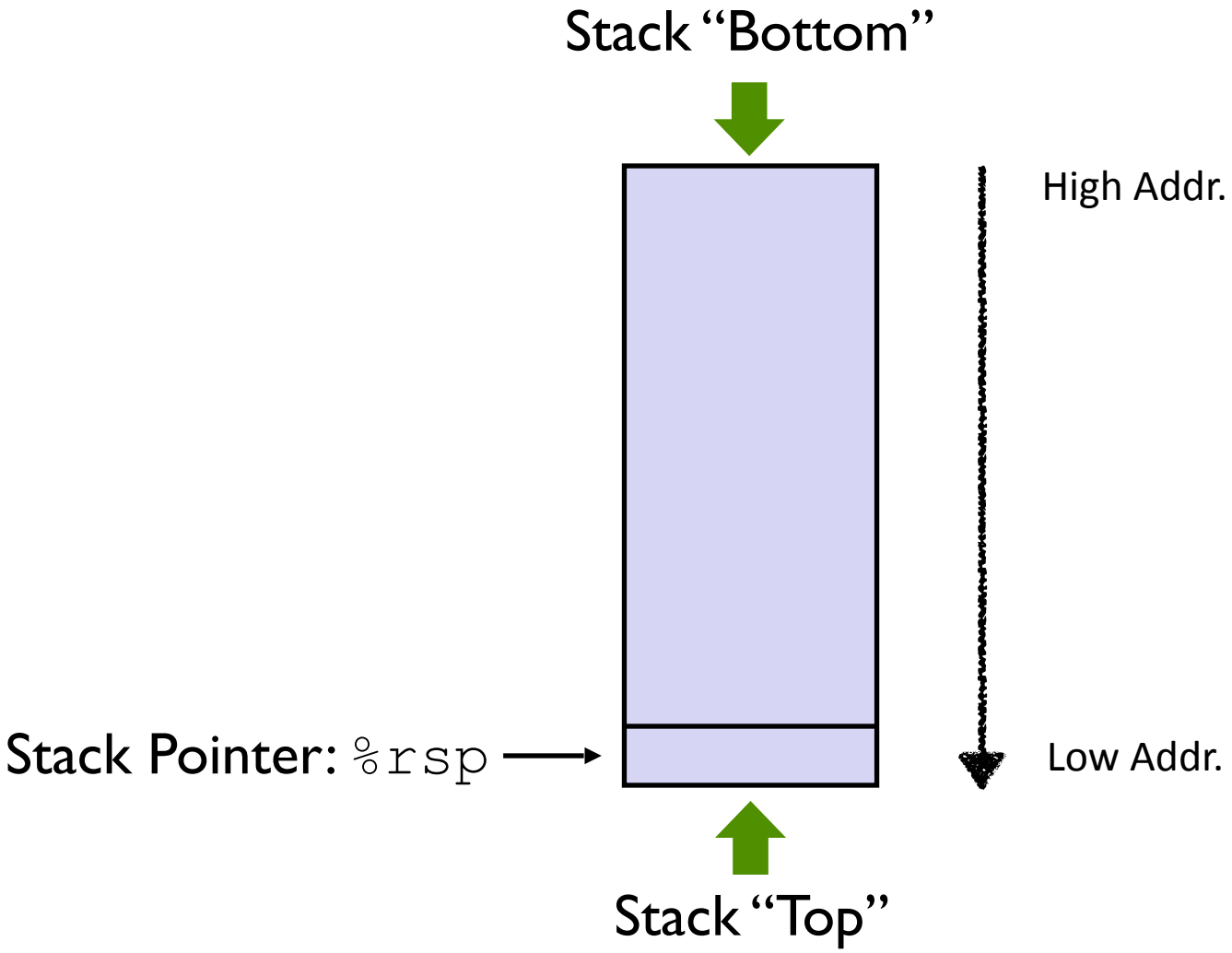
- Stack is the right data structure for function call / return
  - If A calls B, then B returns before A

Stack in X86-64

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

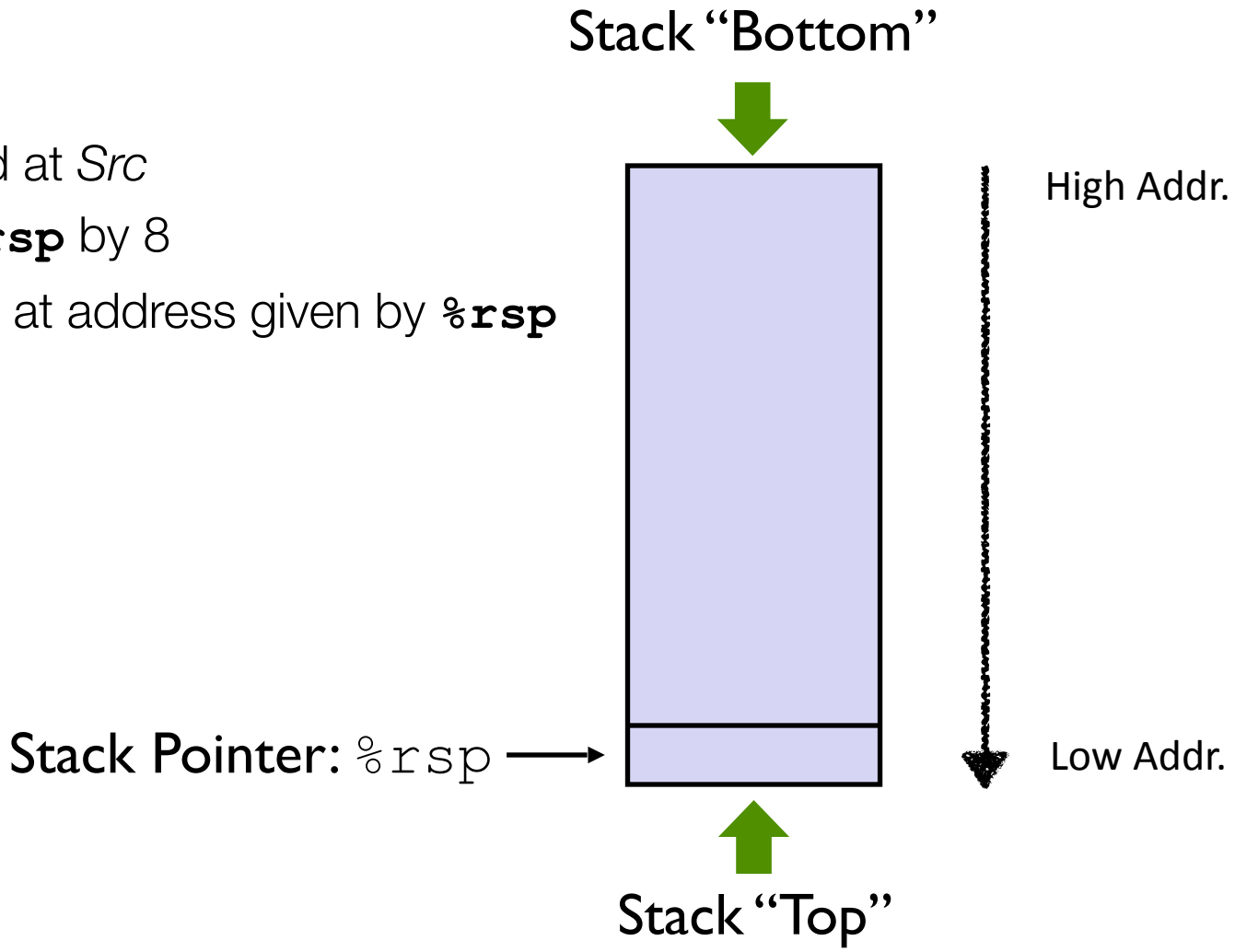


x86-64 Stack: Push



x86-64 Stack: Push

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



x86-64 Stack: Push

- **`pushq` *`Src`***
  - Fetch operand at *Src*
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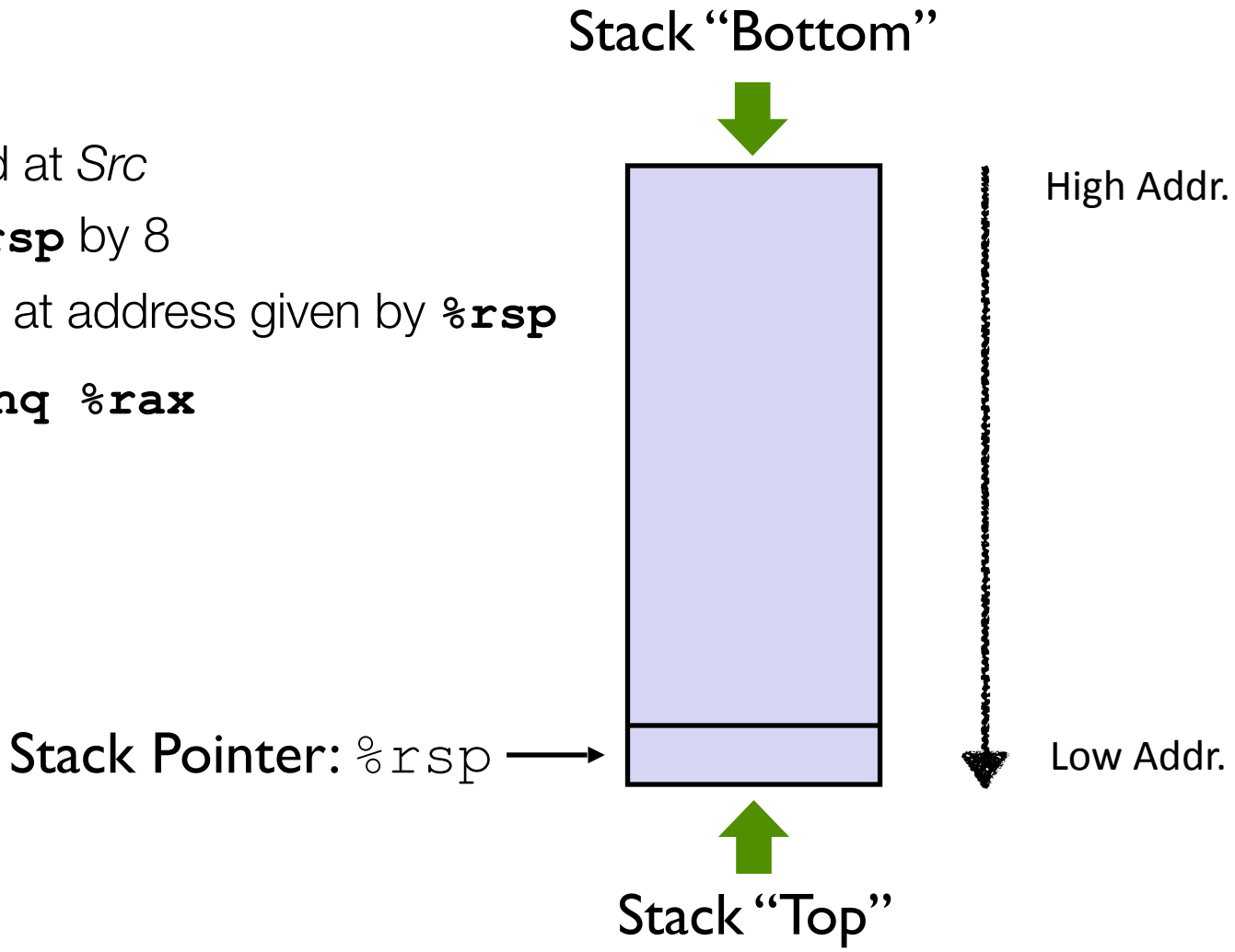
- Example: **`pushq %rax`**



x86-64 Stack: Push

- **`pushq` *`Src`***
  - Fetch operand at *Src*
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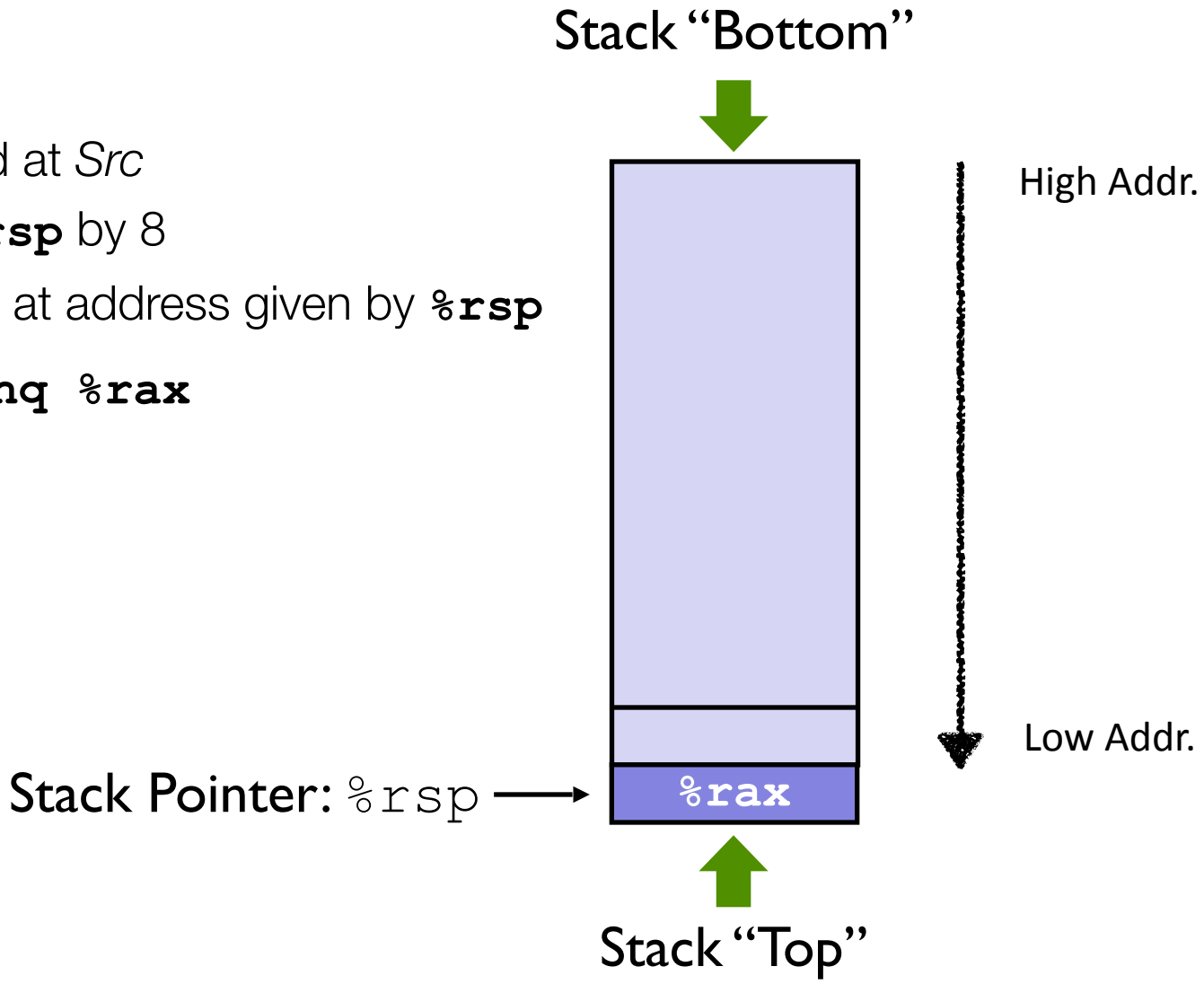
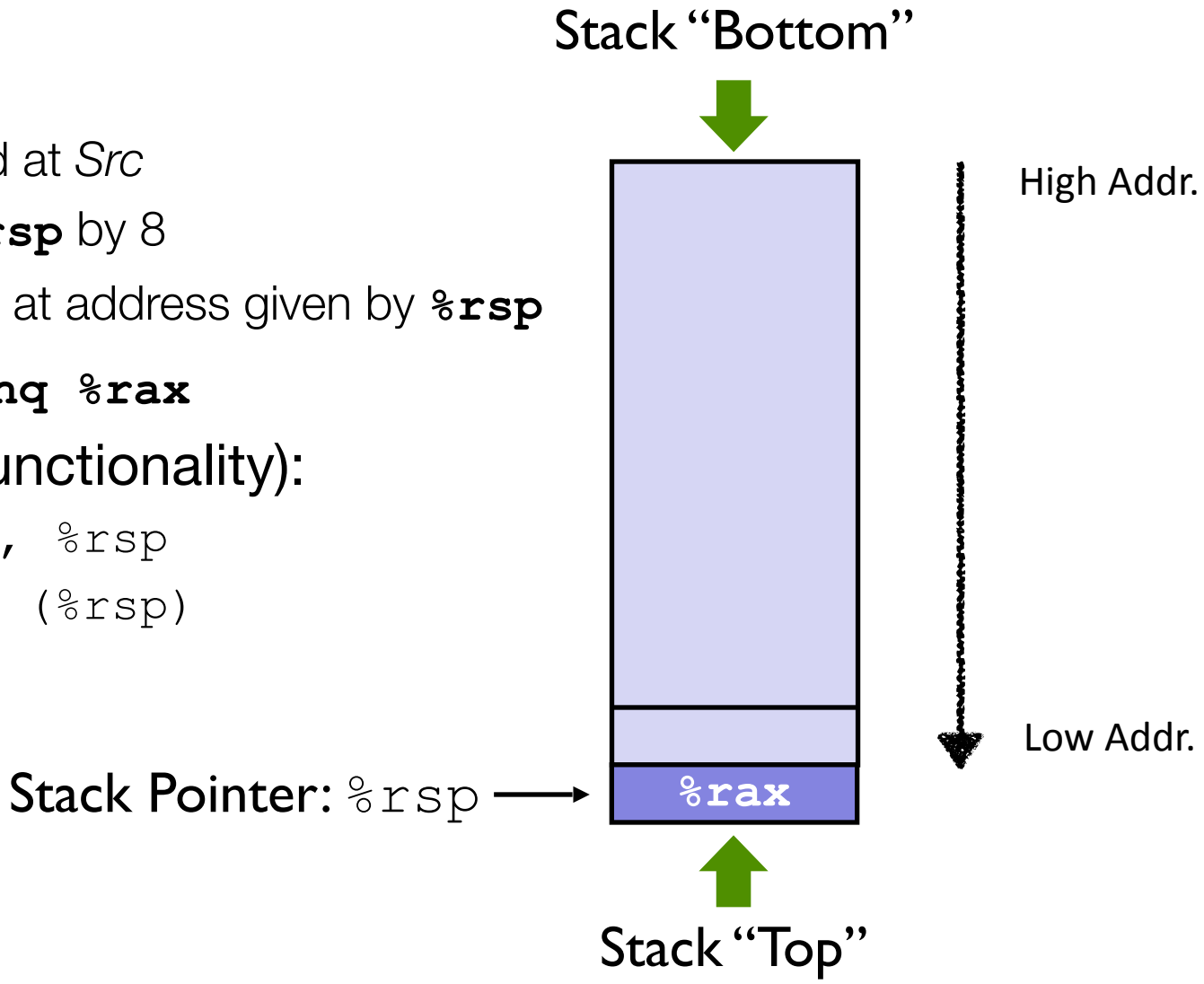
- Example: **`pushq %rax`**



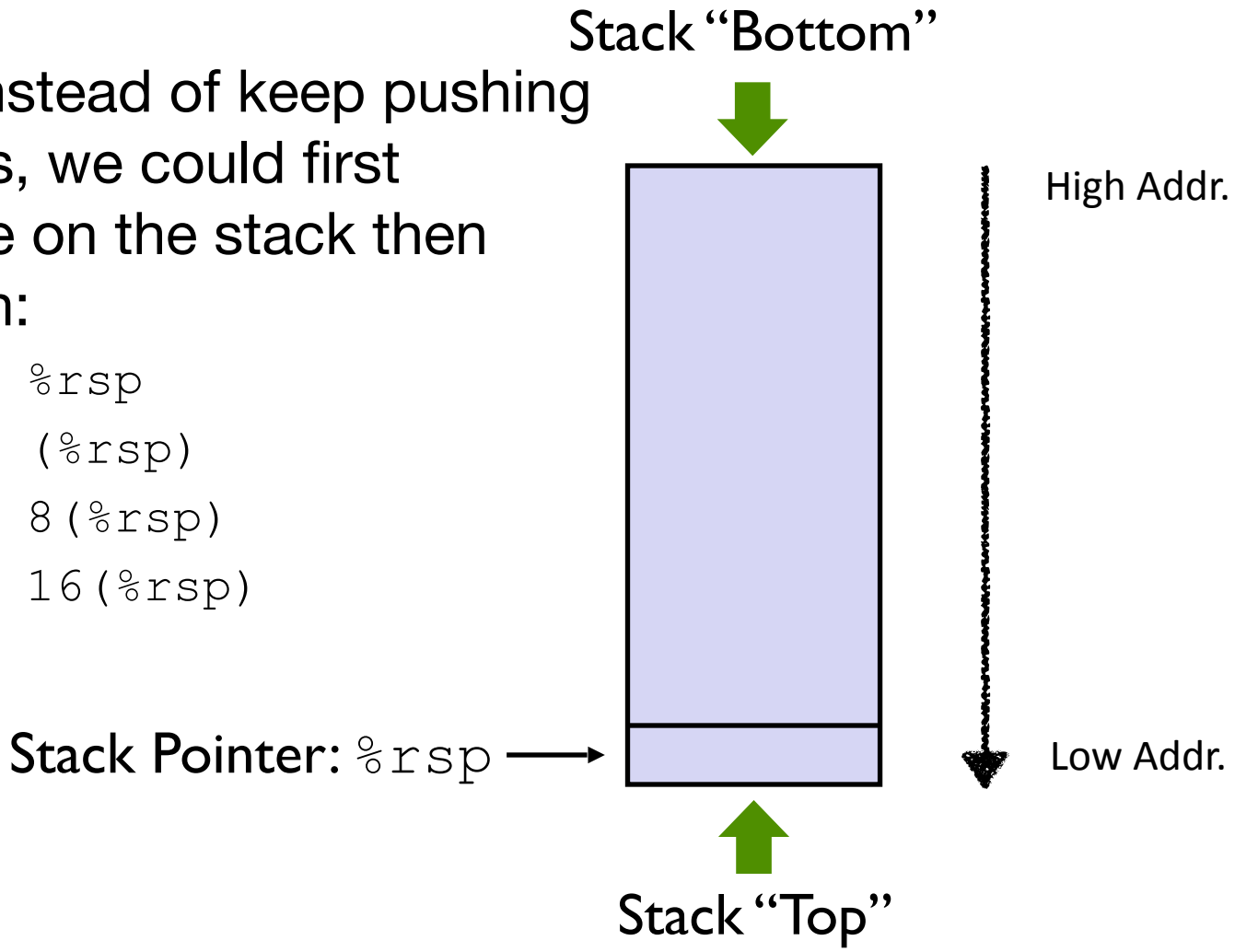
x86-64 Stack: Push

- **`pushq` *`Src`***
  - Fetch operand at *Src*
  - Decrement **`%rsp`** by 8
  - Write operand at address given by **`%rsp`**
- Example: **`pushq %rax`**
- Same as (in functionality):
  - `subq $0x08, %rsp`
  - `movq %rax, (%rsp)`



x86-64 Stack: Push

- Sometimes instead of keep pushing multiple items, we could first reserve space on the stack then move items in:
  - `subq 0x18, %rsp`
  - `movq %rax, (%rsp)`
  - `movq %rbx, 8(%rsp)`
  - `movq %rcx, 16(%rsp)`



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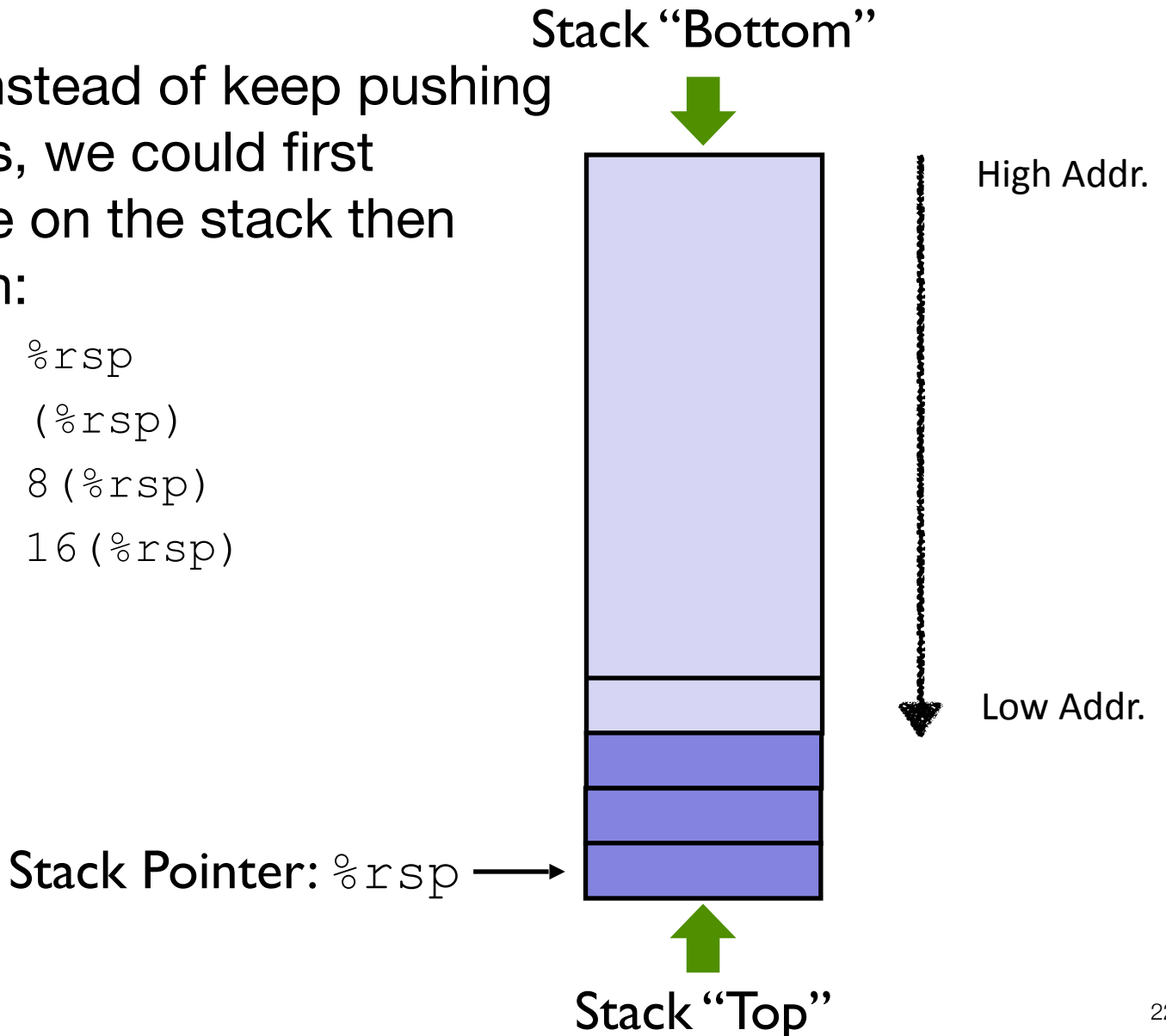

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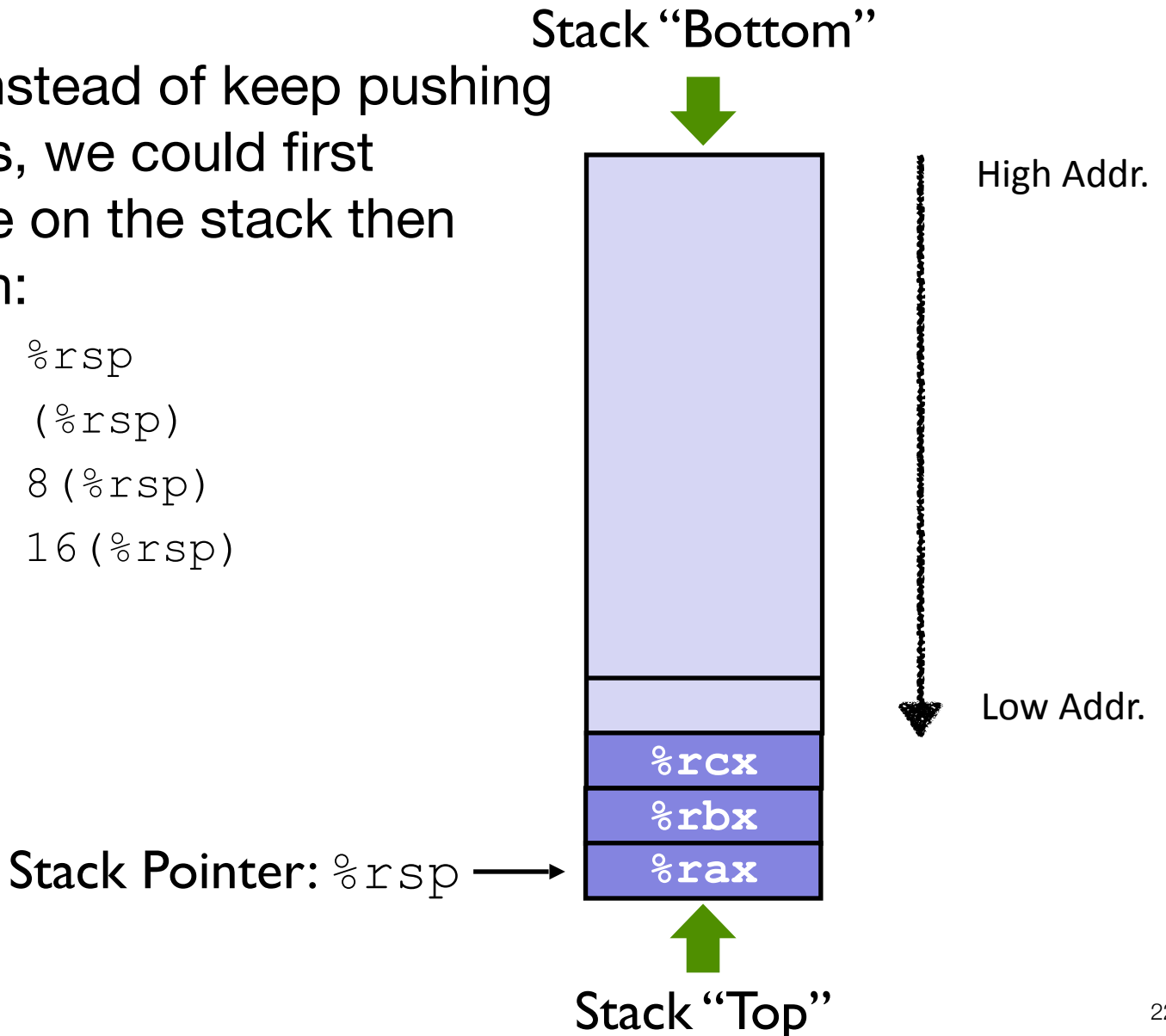
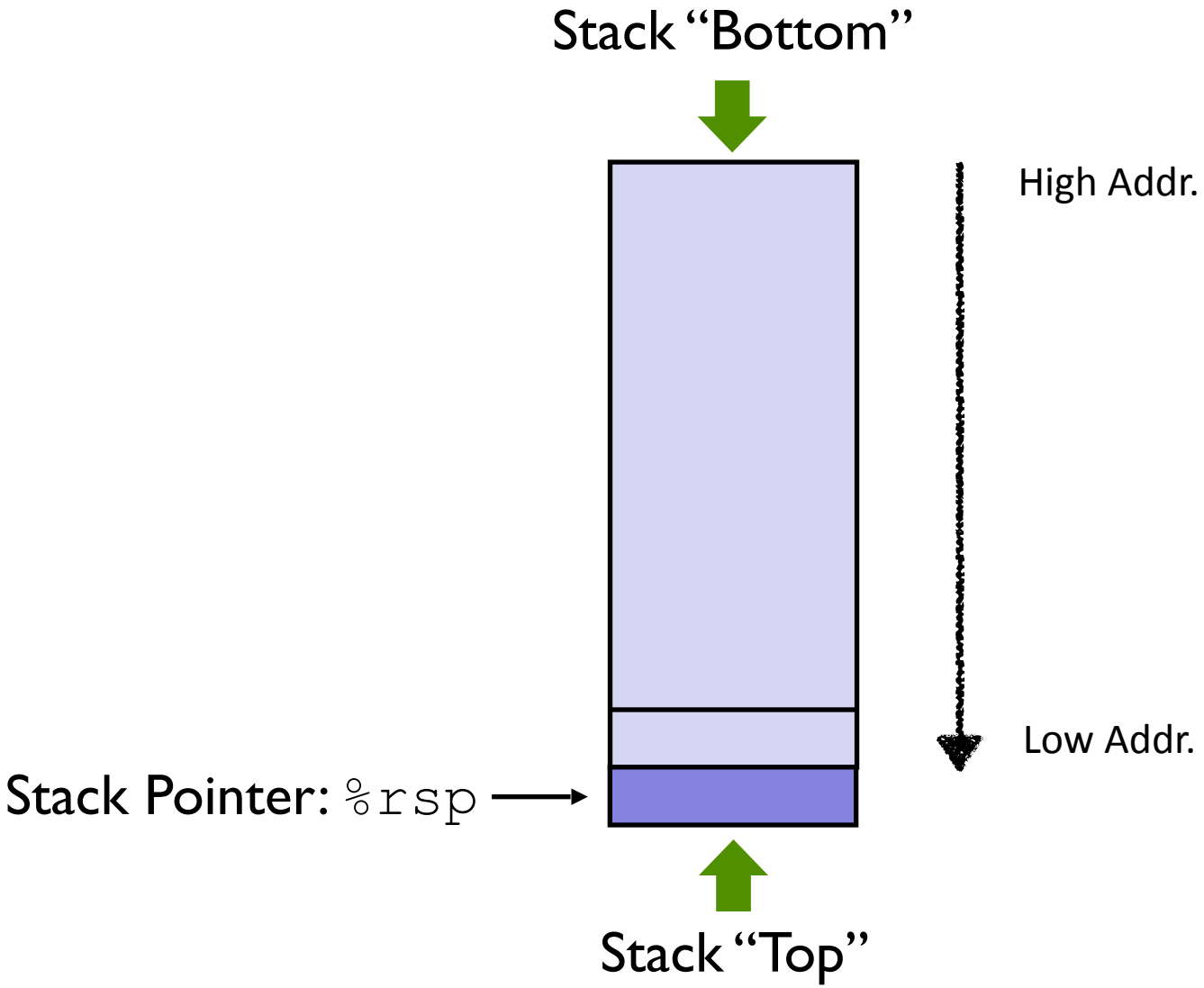
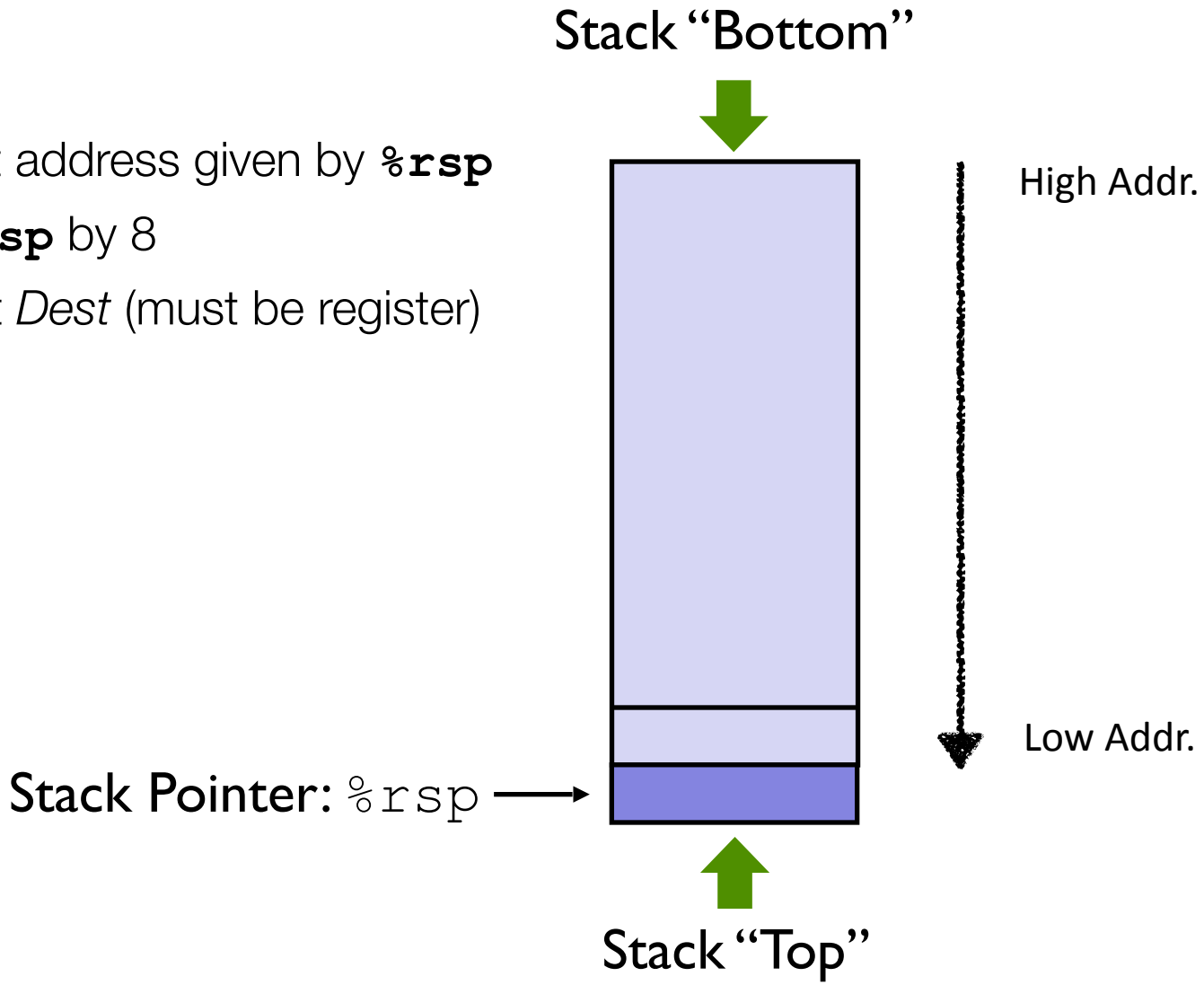


x86-64 Stack: Pop



x86-64 Stack: Pop

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



x86-64 Stack: Pop

- **`popq` *`Dest`***
  - Read value at address given by **`%rsp`**
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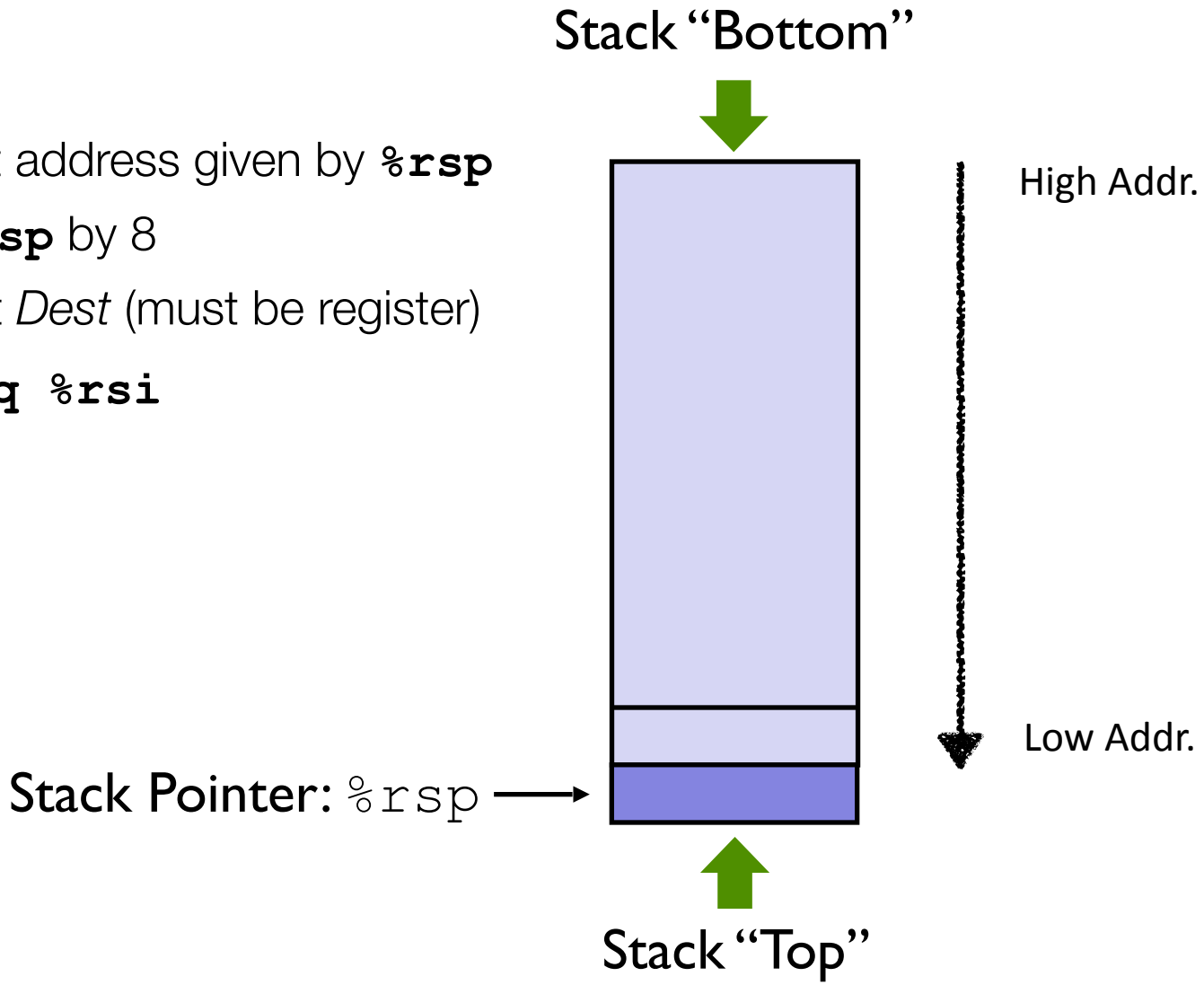
- Example: **`popq %rsi`**



x86-64 Stack: Pop

- **`popq` *`Dest`***
  - Read value at address given by **`%rsp`**
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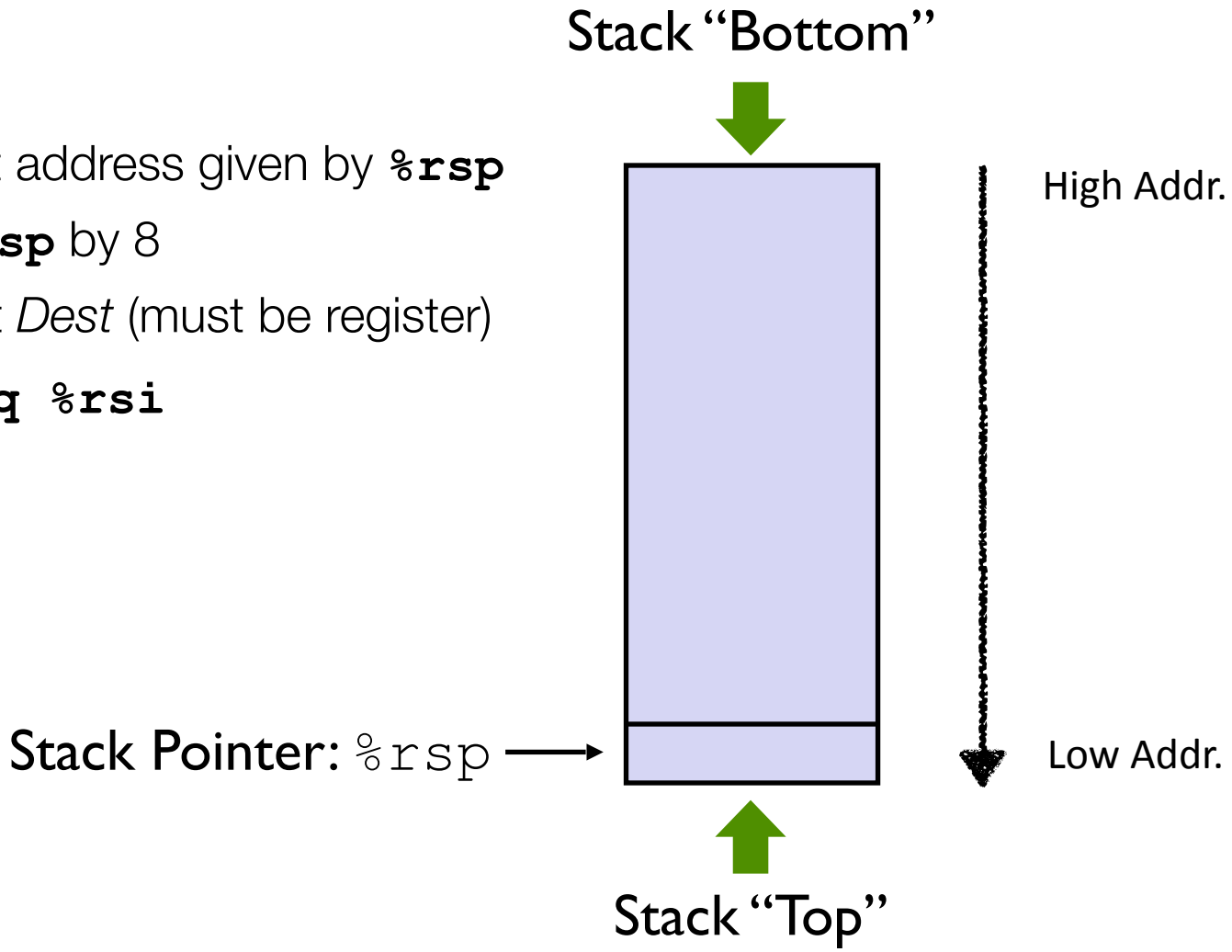
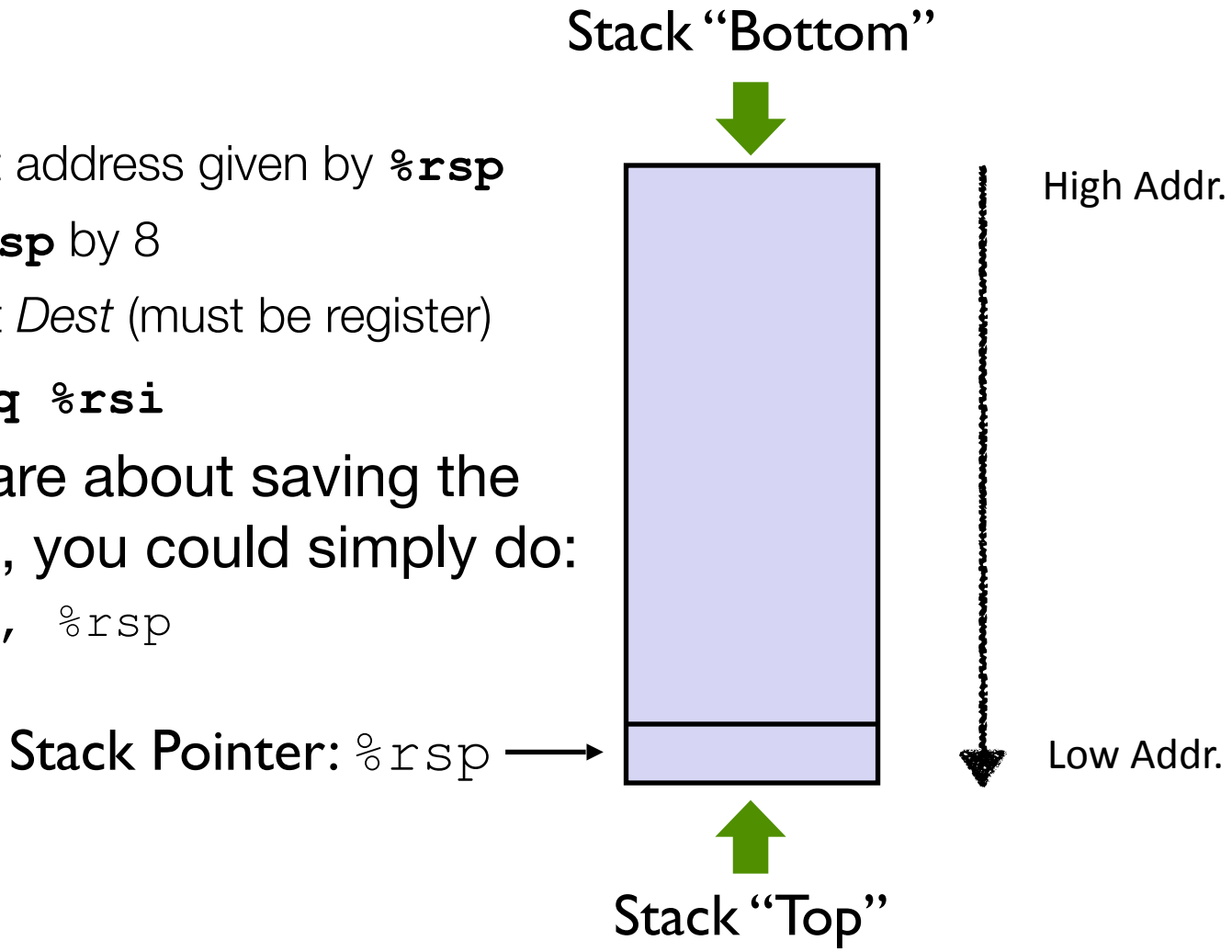
- Example: **`popq %rsi`**



x86-64 Stack: Pop

- **`popq` *`Dest`***
  - Read value at address given by **`%rsp`**
  - Increment **`%rsp`** by 8
  - Store value at *Dest* (must be register)
- Example: **`popq %rsi`**
- If you don't care about saving the popped value, you could simply do:
  - `addq $0x08, %rsp`



Run-Time Stack During Function Call

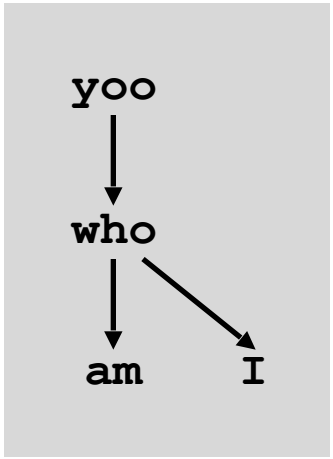
```
yoo(…)
{
   •
   •
   who();
   •
   return
}
```

```
who(…)
{
   • • •
   am();
   • • •
   I();
   return;
}
```

```
am(…)
{
   •
   •
   •
   return;
}
```

```
I(…)
{
   •
   •
   •
   return;
}
```

Example Call Chain



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   who();
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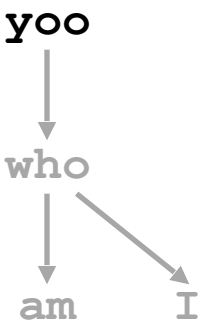
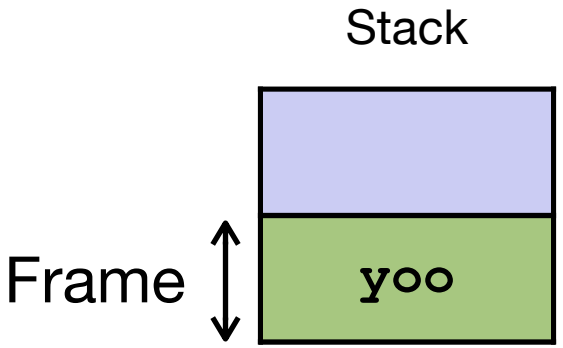
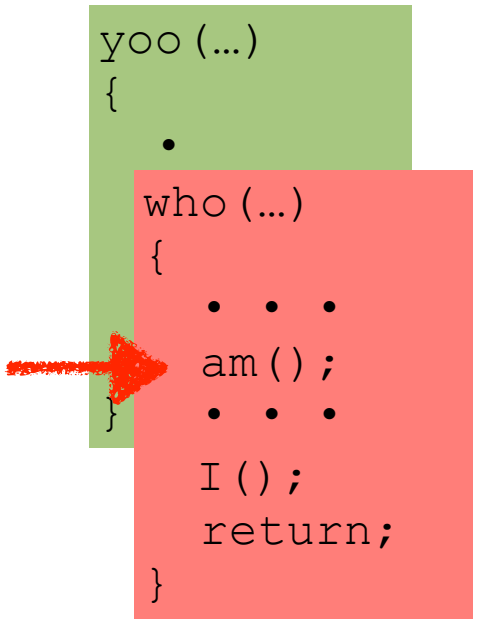
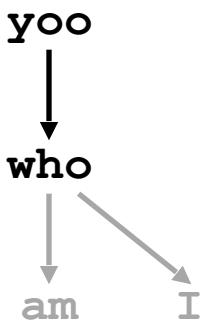
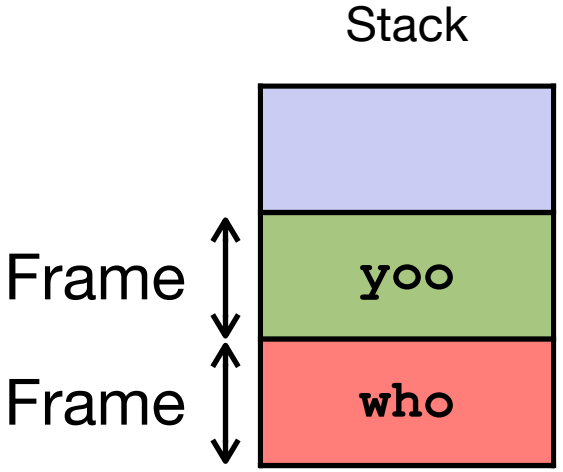




Run-Time Stack During Function Call







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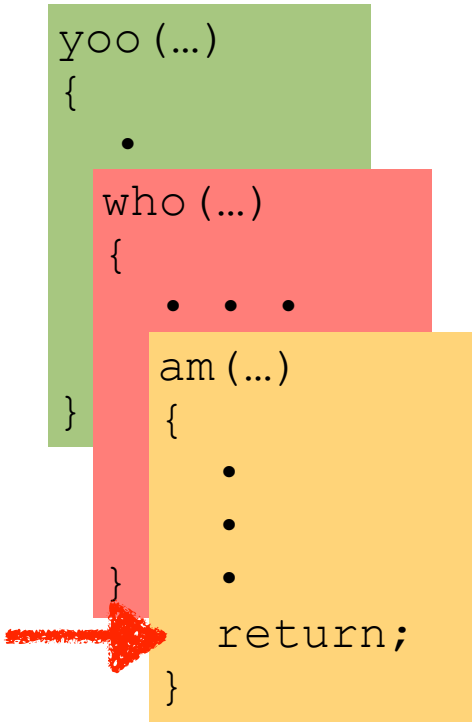

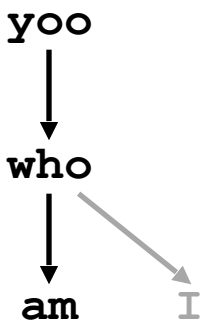

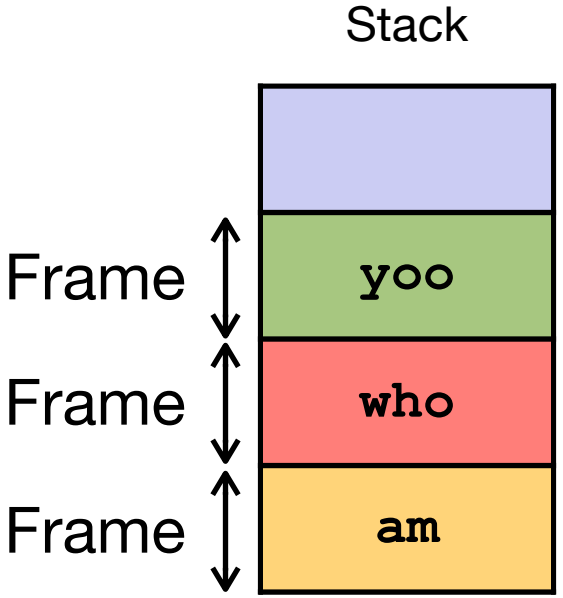

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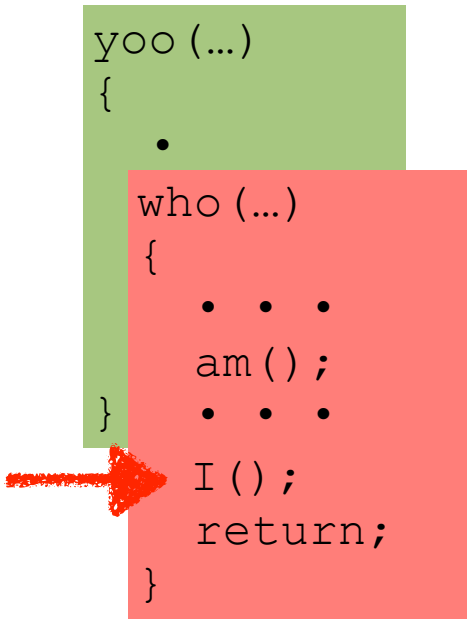

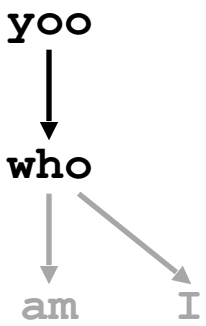

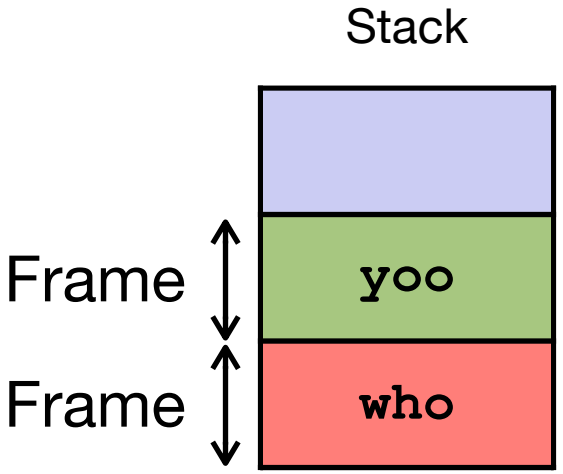

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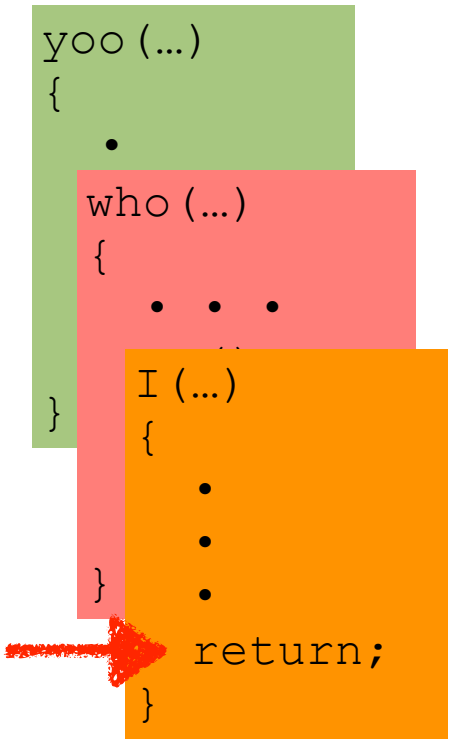

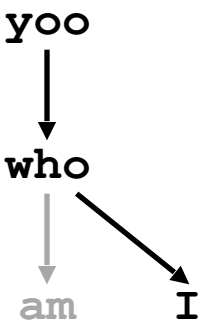

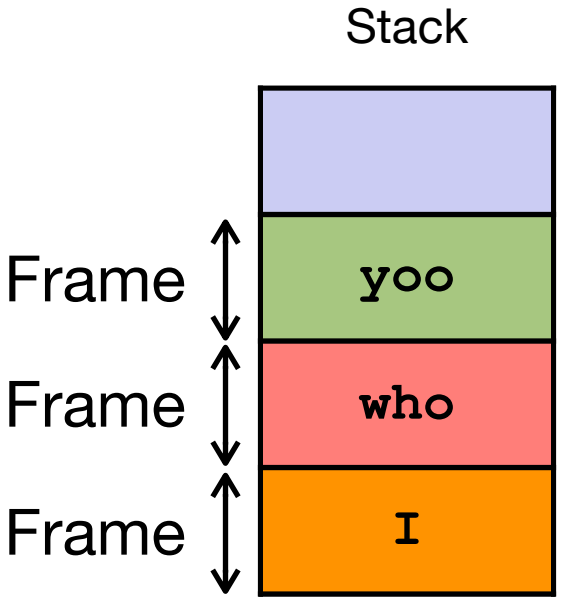

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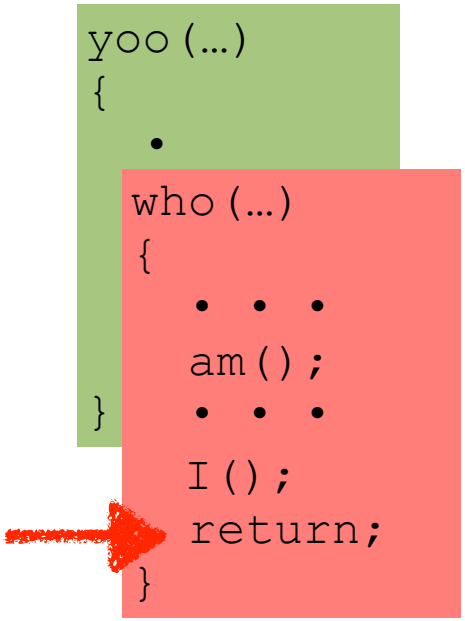

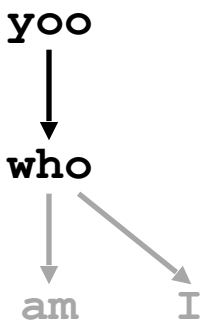

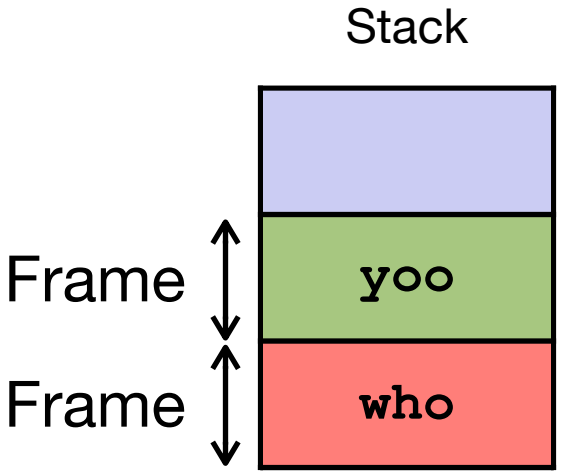

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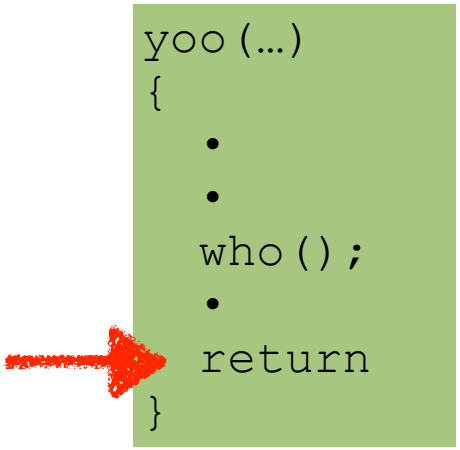

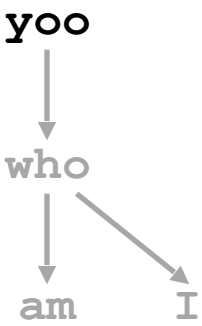

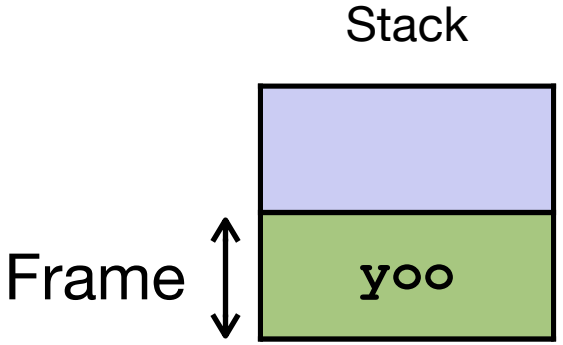

Today: How to Implement Function Call

- What are functions and why do we use them?
- General idea of implementing functions: Stack
- Passing control
- Passing data
- Managing local data

Code Examples

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

…

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

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```
400540 <multstore>:
  400540: push   %rbx
  400541: mov    %rdx,%rbx
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
  40054c: pop    %rbx
  40054d: retq

…

400550 <mult2>:
  400550:  mov    %rdi,%rax
  400553:  imul   %rsi,%rax
  400557:  retq
```

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…

400550 <mult2>:
  400550:  mov    %rdi,%rax
  400553:  imul   %rsi,%rax
  400557:  retq
```

`retq` returns to (by changing the PC) 400549.
But how would `retq` know where to return?

Non-Solution

- Replace `callq` with `jmp`
- assign a label to the instruction next to `callq` (e.g., `.L1`)
- replace `retq` with `jmq .L1`

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Non-Solution

- Replace `callq` with `jmp`
- assign a label to the instruction next to `callq` (e.g., `.L1`)
- replace `retq` with `jmq .L1`

- Will this work?!
- How about when other functions call `mult2`?

```
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  400540: push   %rbx
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  400544: jmp    400550 <mult2>
.L1
  400549: mov    %rax,(%rbx)
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…

400550 <mult2>:
  400550:  mov    %rdi,%rax
  400553:  imul   %rsi,%rax
  400557:  jmp    .L1
```

Using Stack for 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 (`400549` here)
- Procedure return: `ret`
  - Pop address from stack
  - Jump to address

```
400540 <multstore>:
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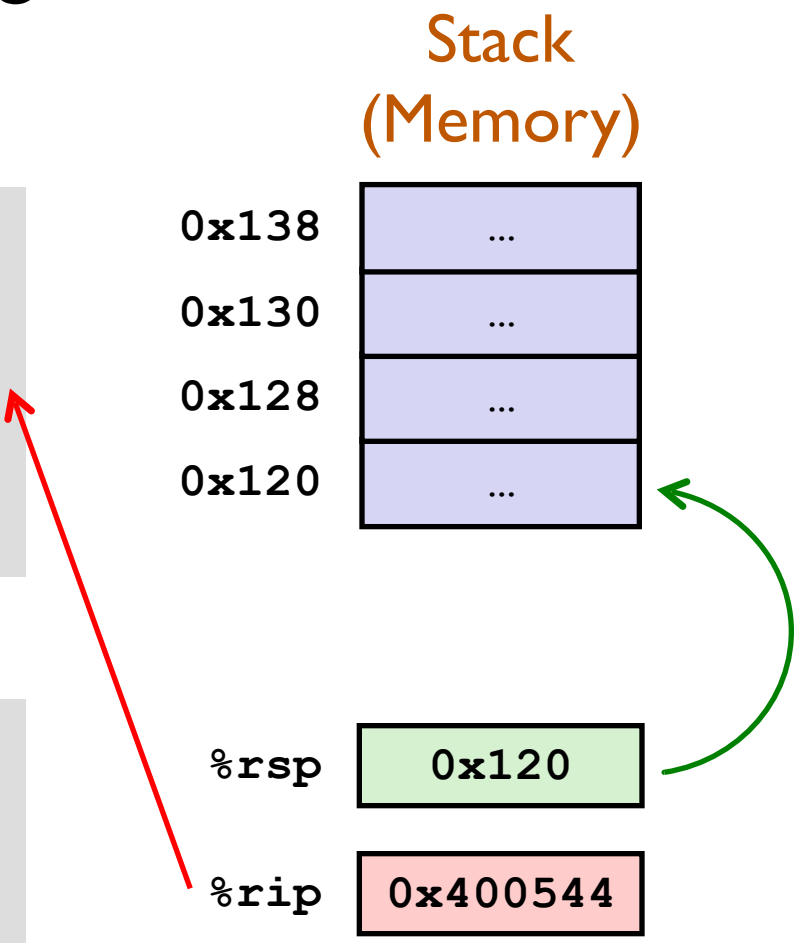

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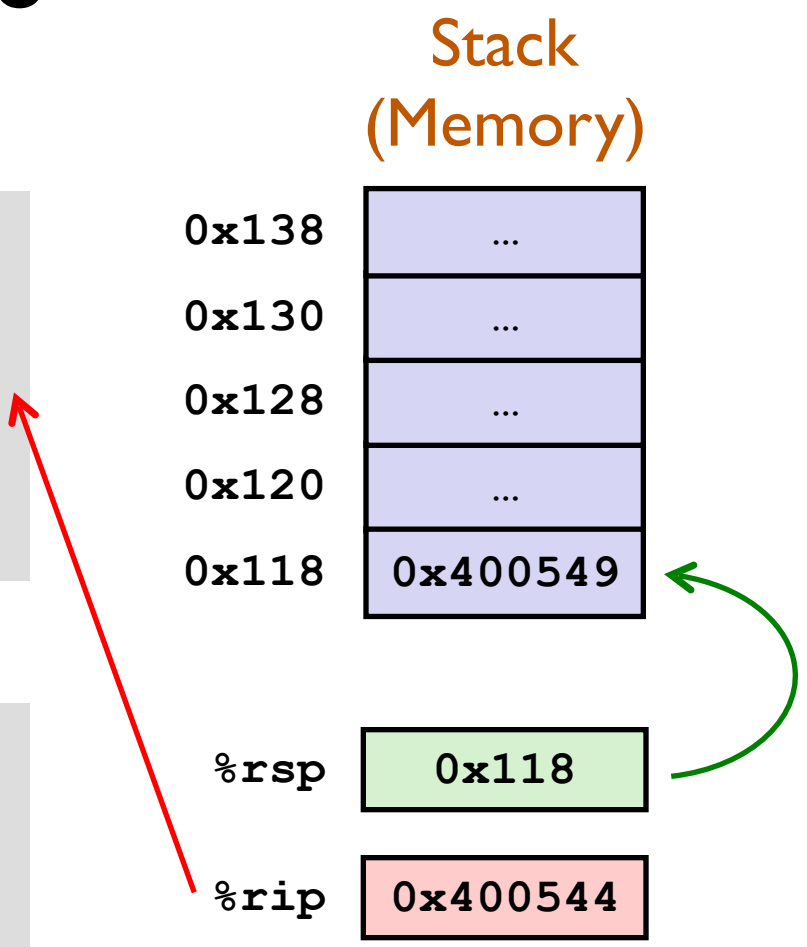

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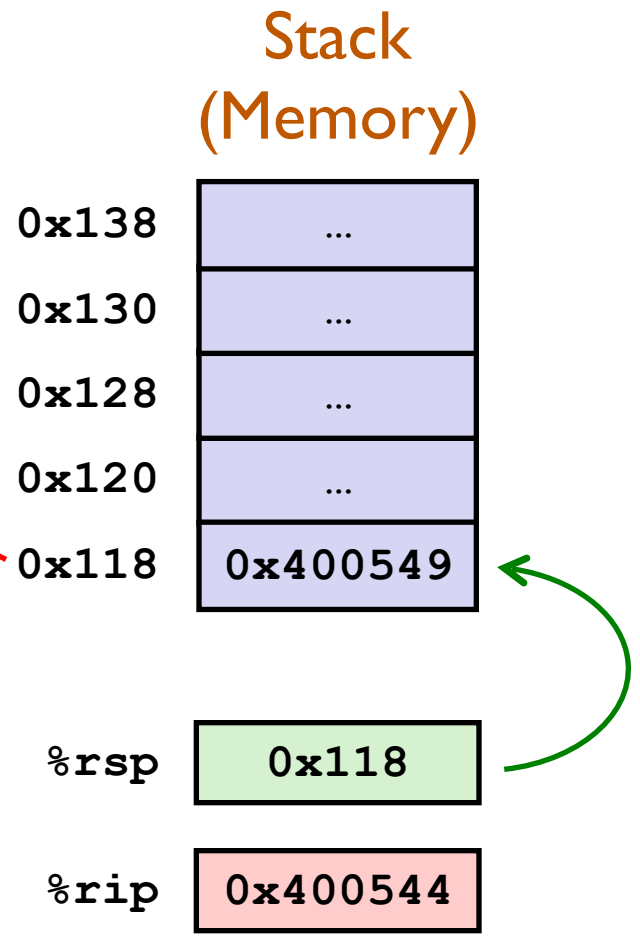

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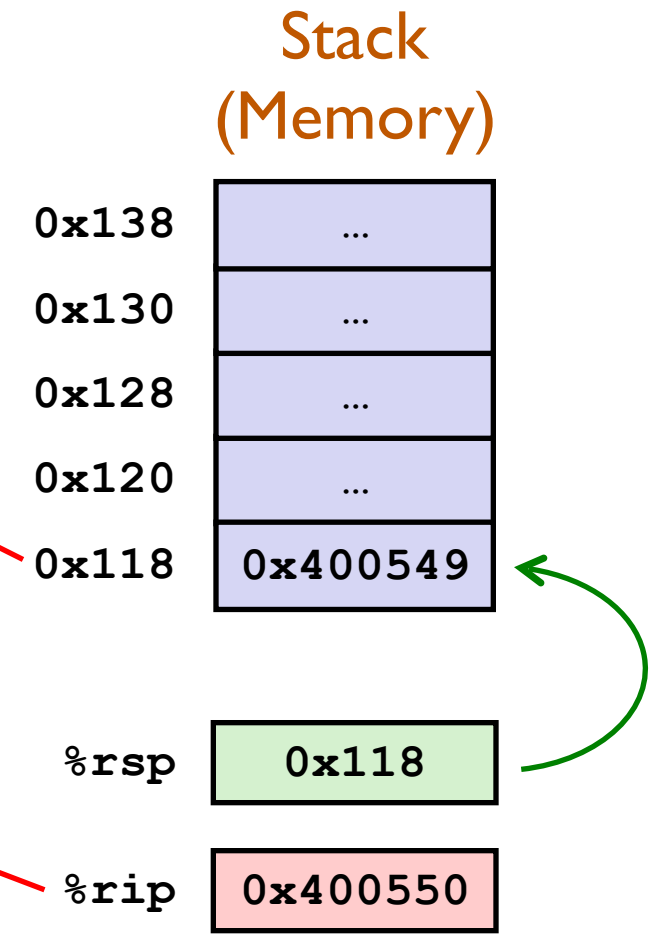
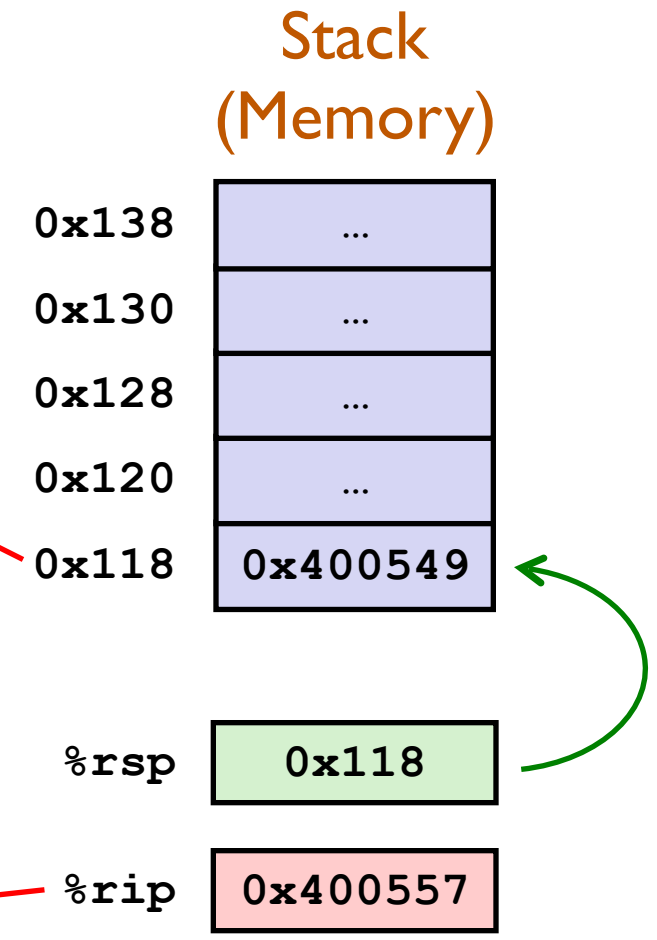
  400557:  retq
```



Function Call Example

```
400540 <multstore>:
…
…
  400544: callq  400550 <mult2>
  400549: mov    %rax,(%rbx)
…
…
```

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



Function Call Example

```
400540 <multstore>:
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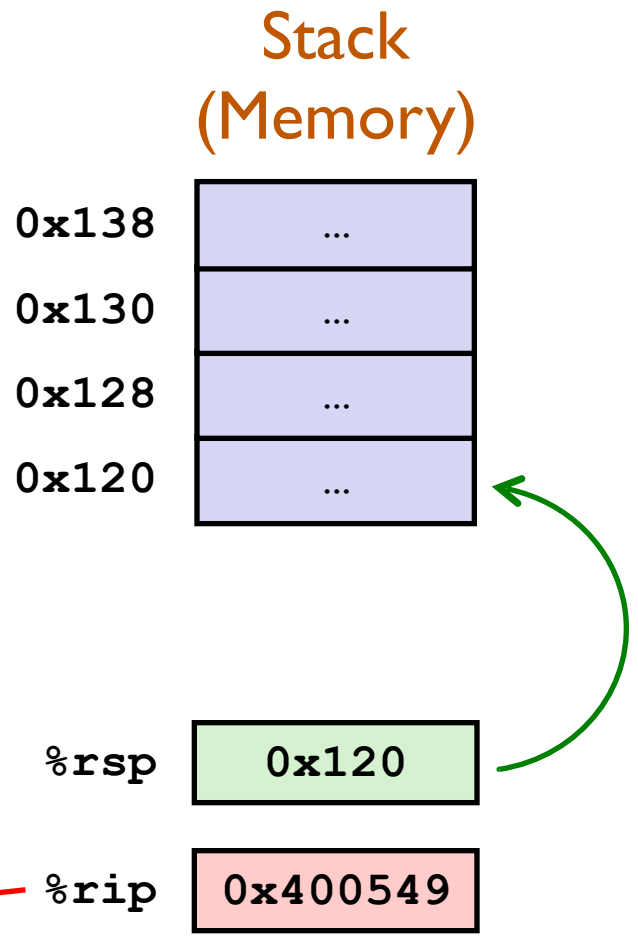

Function Call Example

```
400540 <multstore>:
…
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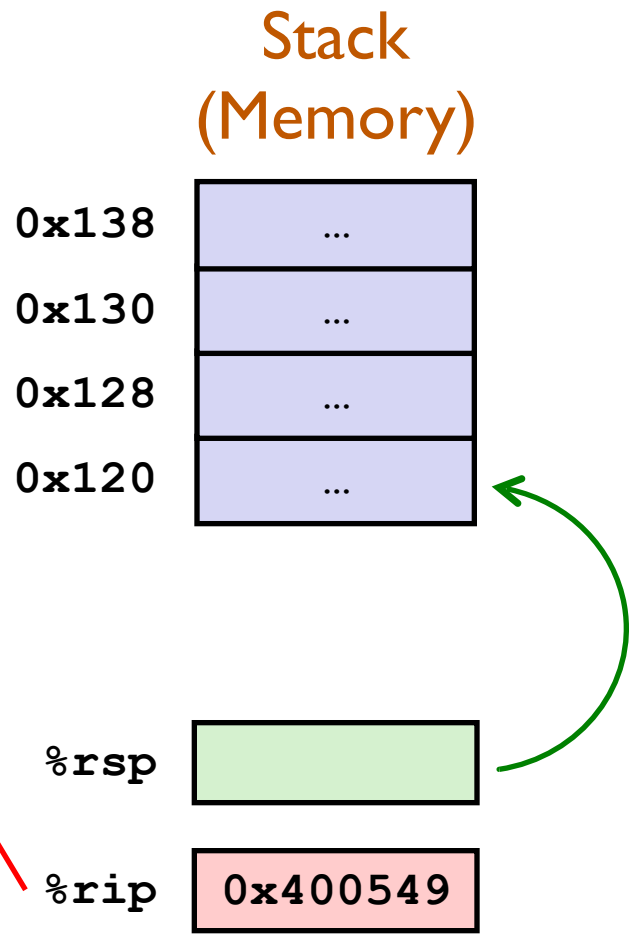
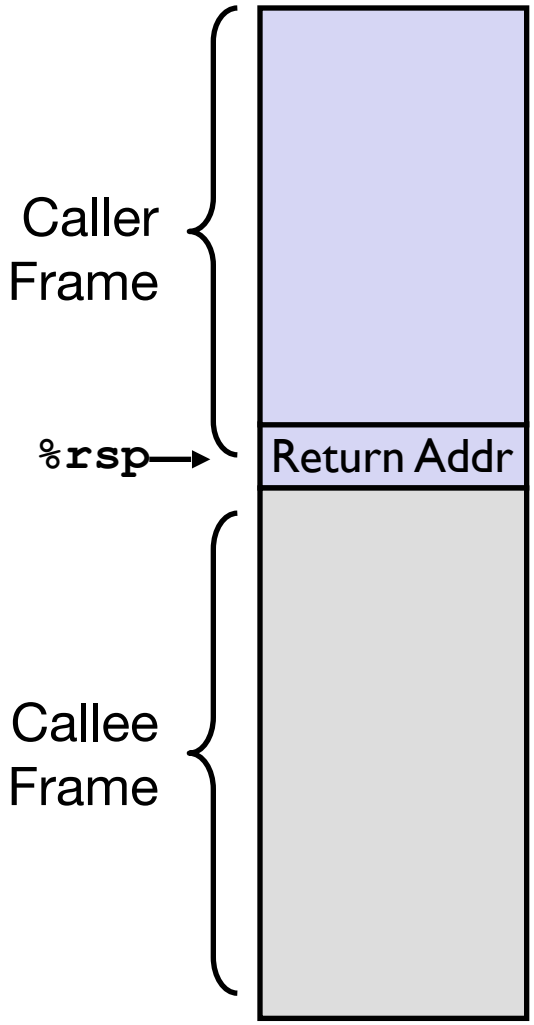


Stack Frame (So Far…)

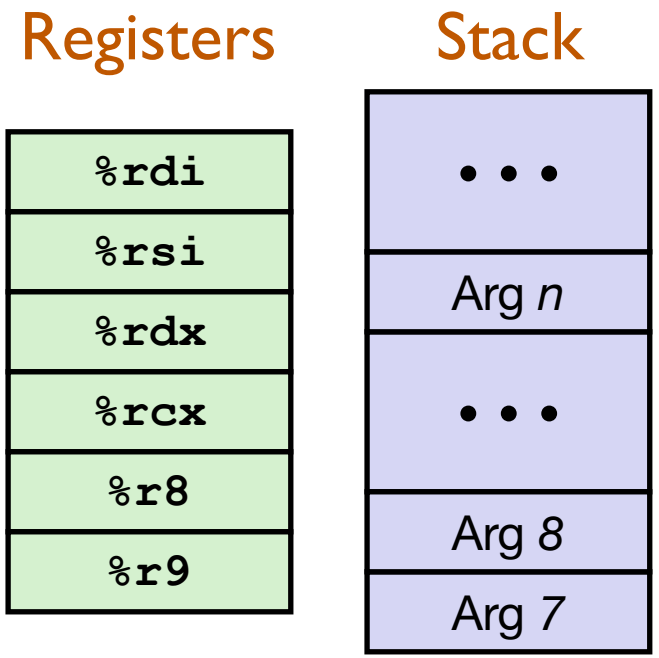


Today: How to Implement Function Call

- What are functions and why do we use them?
- General idea of implementing functions: Stack
- Passing control
- Passing data
- Managing local data

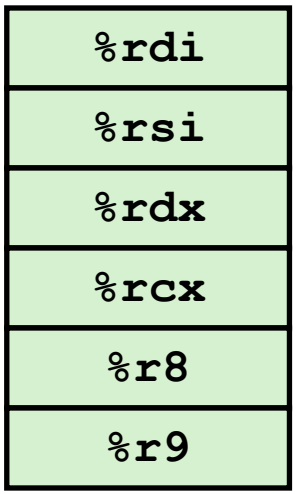
Passing Function Arguments

- Two choices: memory or registers
  - Registers are faster, but have limited amount
- x86-64 convention (Part of the *Calling Conventions*):
  - First 6 arguments in registers, in specific order
  - The rest are pushed to stack
  - Return value is always in `%rax`
- Just conventions, not laws
  - Necessary to interface with other code

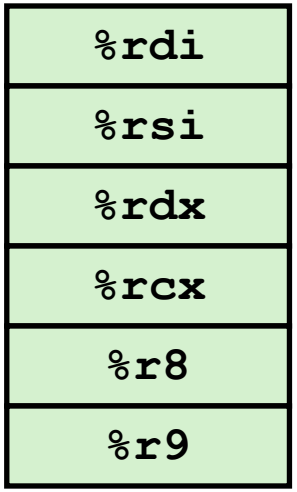


Function Call Data Flow Example

```
void multstore
 (long x, long y, long *res) {
    long t = mult2(x, y);
    *res = t;
}
…
long mult2
  (long a, long b)
{
  long s = a * b;
  return s;
}
```



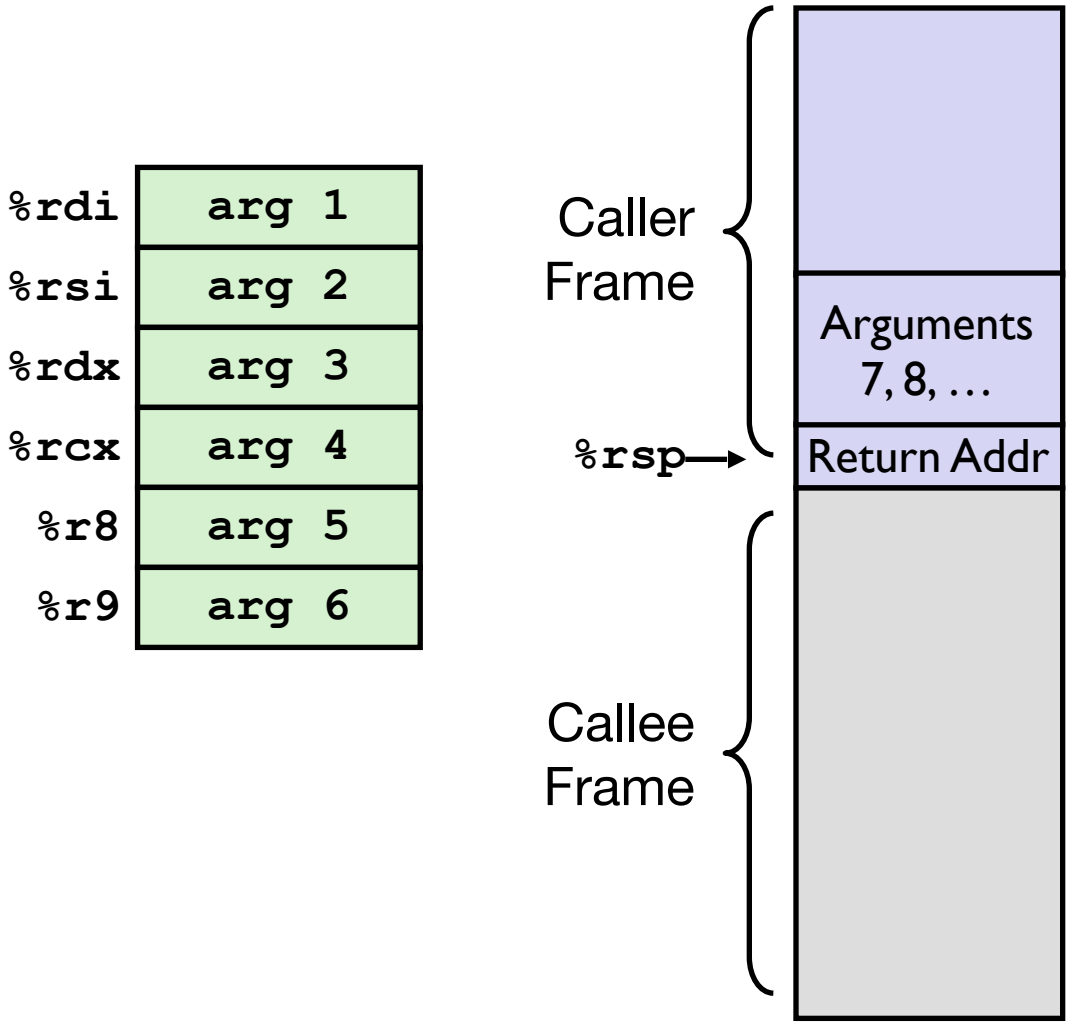
Function Call Data Flow Example




```
void multstore
 (long x, long y, long *res) {
    long t = mult2(x, y);
    *res = t;
}
…
long mult2
  (long a, long b)
{
  long s = a * b;
  return s;
}
```

```
0000000000400540 <multstore>:
  # x in %rdi, y in %rsi, res in %rdx
…
  400541: movq    %rdx,%rbx
  400544: callq  400550 <mult2>
  # t in %rax
  400549: movq    %rax,(%rbx)
…
0000000000400550 <mult2>:
  # a in %rdi, b in %rsi
  400550:  movq    %rdi,%rax
  400553:  imul    %rsi,%rax
  # s in %rax
  400557:  retq
```

Stack Frame (So Far…)



Today: How to Implement Function Call

- What are functions and why do we use them?
- General idea of implementing functions: Stack
- Passing control
- Passing data
- Managing local data

Managing Function Local Variables

- Two ways: registers and memory (stack)
- Registers are faster, but limited. Memory is slower, but large. Smart compilers will optimize the usage.
- We will show different uses. Compiler optimizations later in the course.

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

Register Example: `incr`

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

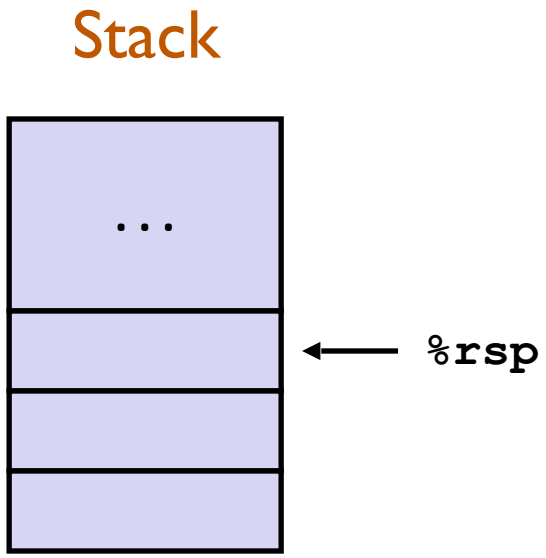
```
long incr(long *p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

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

Stack Example: `call_add`

```
long call_add() {
    long v1 = 15213;
    long v2 = 3000;
    long v3 = add(&v1, &v2);
    return v1+v3;
}
```

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



Stack Example: `call_add`

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    long v1 = 15213;
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    long v3 = add(&v1, &v2);
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call_incr:
  subq    $16, %rsp
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  leaq    (%rsp), %rdi
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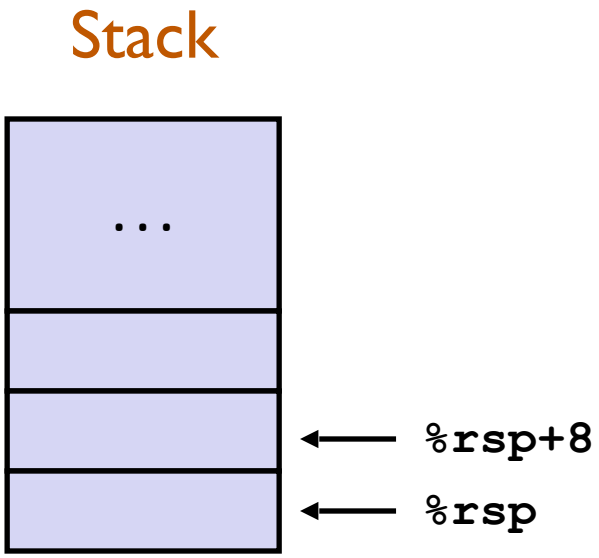
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```



Stack Example: `call_add`

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}
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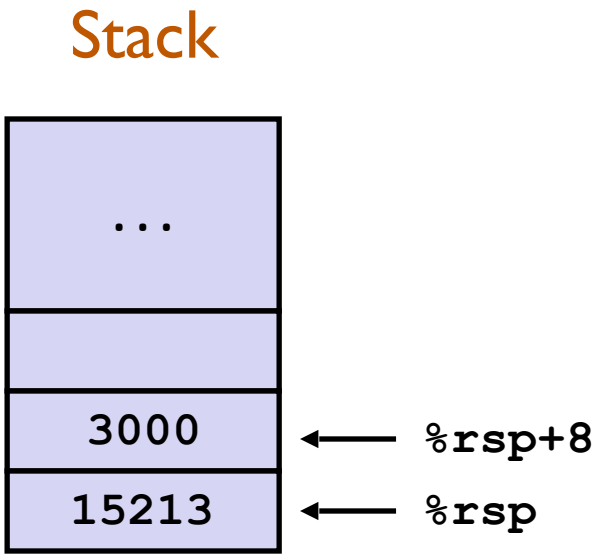
  call    add
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```



Stack Example: `call_add`

```
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    long v1 = 15213;
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    long v3 = add(&v1, &v2);
    return v1+v3;
}
```

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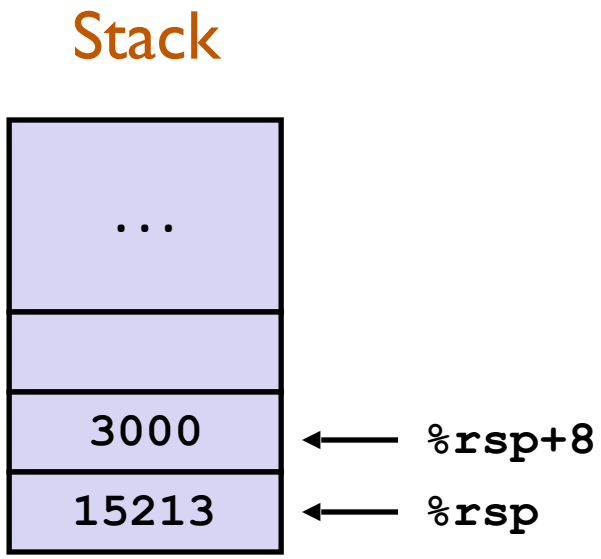
  leaq    (%rsp), %rdi
  leaq    8(%rsp), %rsi
  call    add
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```

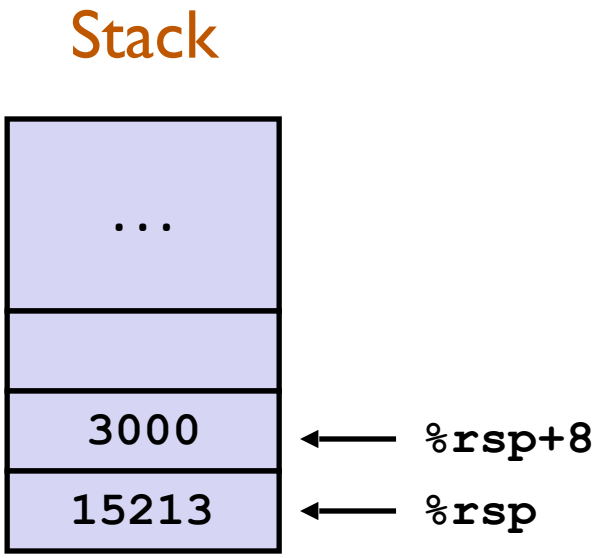


Register	Use(s)
%rdi	&v1 (15213)
%rsi	&v2 (3000)

Stack Example: `call_add`

```
long call_add() {
    long v1 = 15213;
    long v2 = 3000;
    long v3 = add(&v1, &v2);
    return v2+v3;
}
```

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

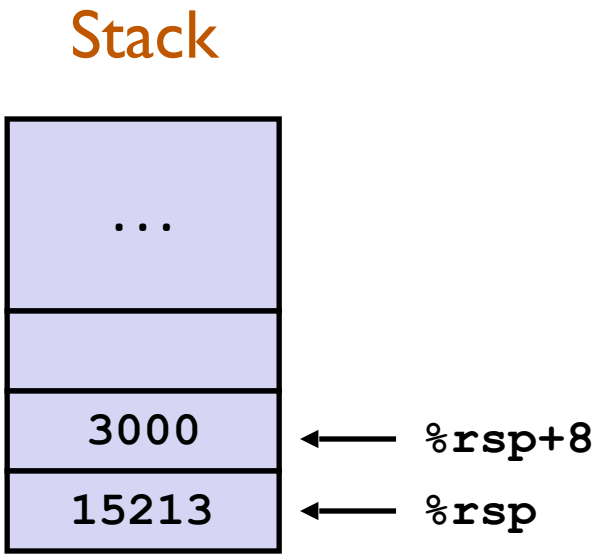


Register	Use(s)
%rdi	&v1 (15213)
%rsi	&v2 (3000)
%rax	18213

Stack Example: `call_add`

```
long call_add() {
    long v1 = 15213;
    long v2 = 3000;
    long v3 = add(&v1, &v2);
    return v2+v3;
}
```

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

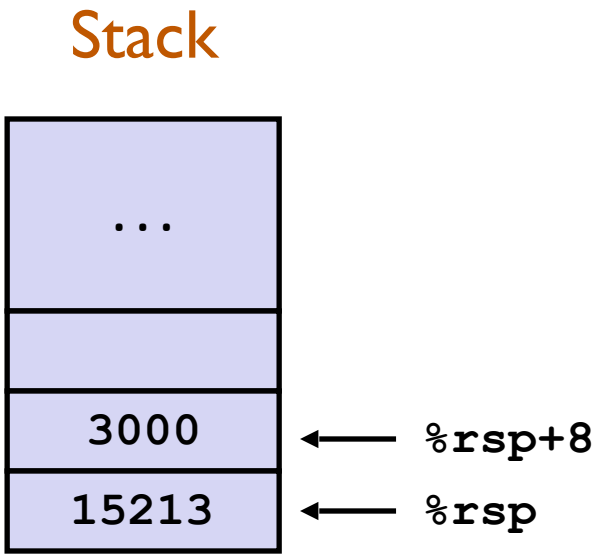


Register	Use(s)
%rdi	&v1 (15213)
%rsi	&v2 (3000)
%rax	21213

Stack Example: `call_add`

```
long call_add() {
    long v1 = 15213;
    long v2 = 3000;
    long v3 = add(&v1, &v2);
    return v2+v3;
}
```

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



Stack Example: `call_add`

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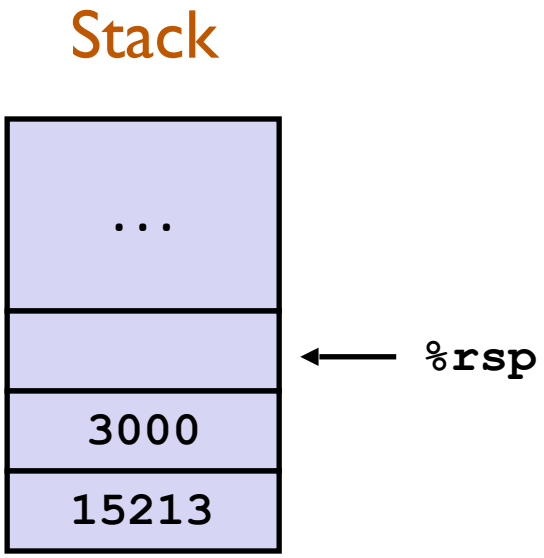
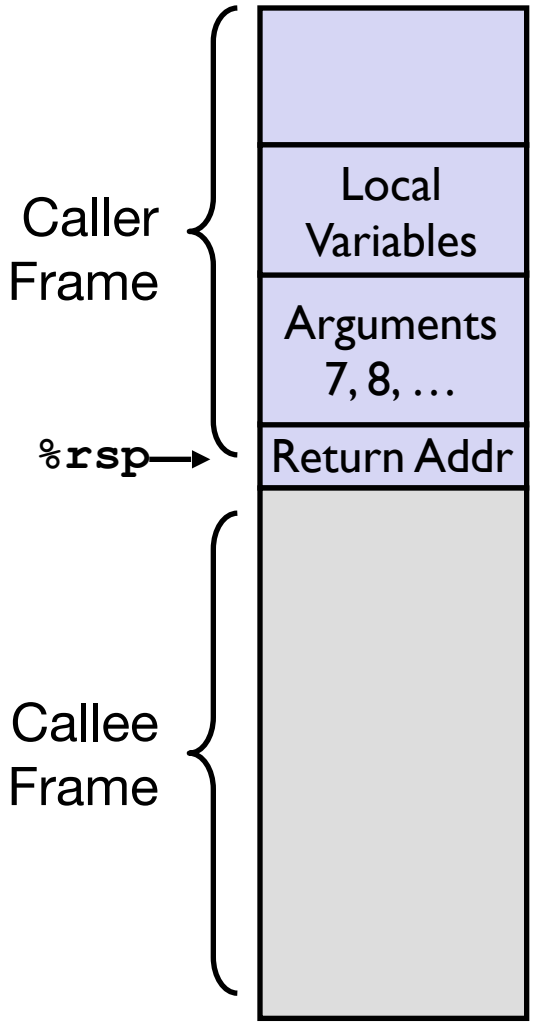
long call_add() {
    long v1 = 15213;
    long v2 = 3000;
    long v3 = add(&v1, &v2);
    return v2+v3;
}
```

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



Stack Frame (So Far…)



Register Saving Conventions

Register Saving Conventions

- Any issue with using registers for temporary storage?

Caller

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

Callee

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

Register Saving Conventions

- Any issue with using registers for temporary storage?
  - Contents of register **`%rdx`** overwritten by **`who()`**

Caller

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

Callee

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

Register Saving Conventions

- Any issue with using registers for temporary storage?
  - Contents of register **`%rdx`** overwritten by **`who()`**
  - This could be trouble ➙ Need some coordination

Caller

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

Callee

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

Register Saving Conventions

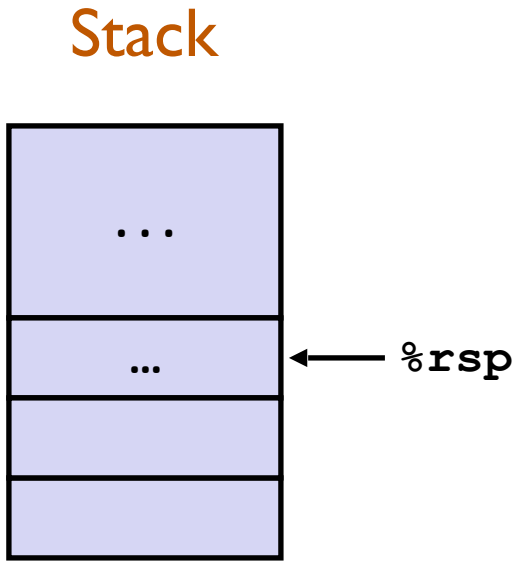
- Common conventions
  - "*Caller Saved*"
    - Caller saves temporary values in its frame before the call
    - Callee is then free to modify their values
  - "*Callee Saved*"
    - Callee saves temporary values in its frame before using
    - Callee restores them before returning to caller
    - Caller can safely assume that register values won't change after the function call

Register Saving Conventions

- Conventions used in x86-64 (*Part of the Calling Conventions*)
  - Some registers are saved by caller, some are by callee.
  - Caller saved: `%rdi,%rsi,%rdx,%rcx,%r8,%r9,%r10, %r11`
  - Callee saved: `%rbx,%rbp,%r12,%r13,%14,%r15`
  - `%rax` holds return value, so implicitly caller saved
  - `%rsp` is the stack pointer, so implicitly callee saved

Example

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

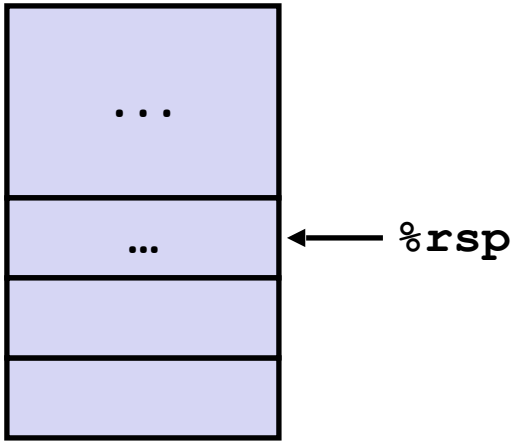


Example

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

```
call_incr2:
  pushq   %rbx
  subq    $8, %rsp
  movq    %rdi, %rbx
  movq    $15213, (%rsp)
  movl    $3000, %esi
  leaq    (%rsp), %rdi
  call    incr
  addq    %rbx, %rax
  addq    $8, %rsp
  popq    %rbx
  ret
```

Stack



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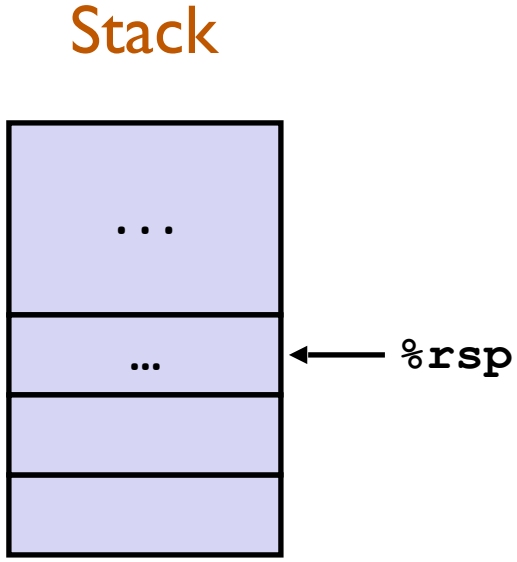

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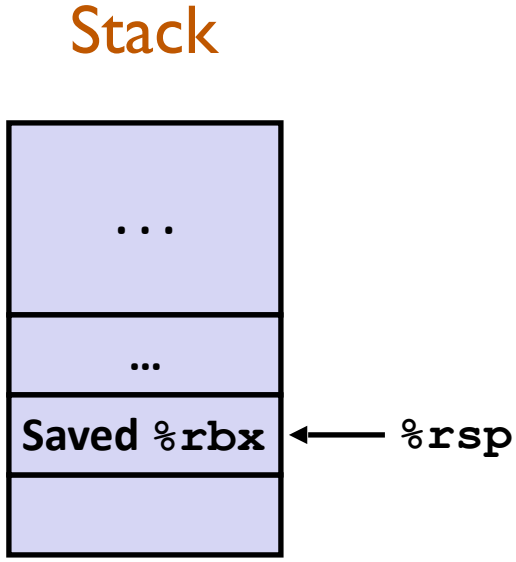

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  addq    $8, %rsp
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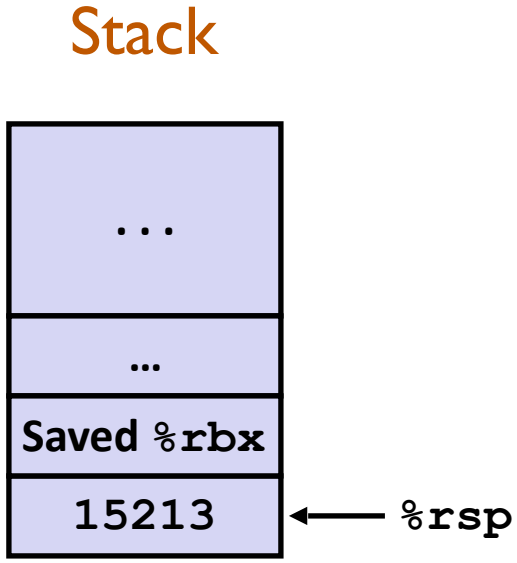
  ret
```



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  addq    $8, %rsp
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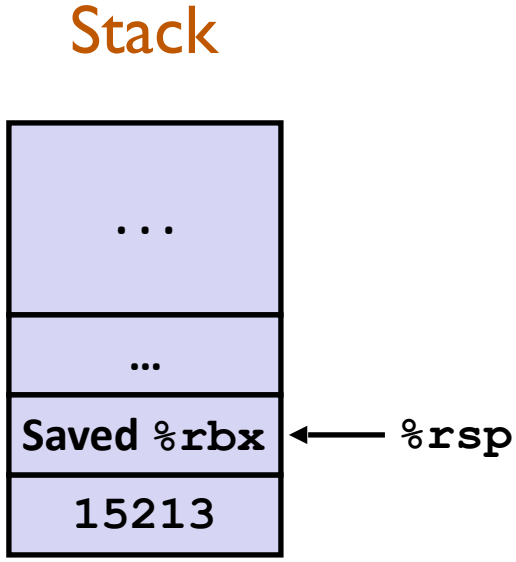
  ret
```



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  call    incr
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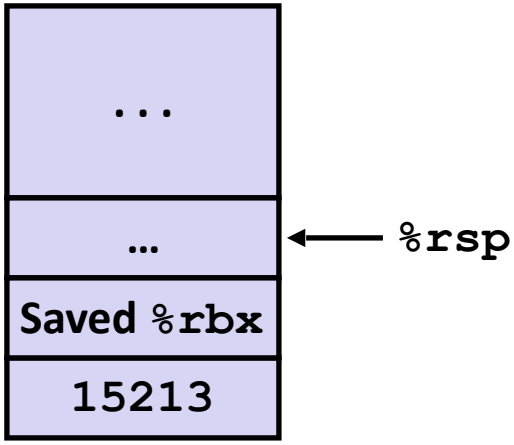
  ret
```

Stack



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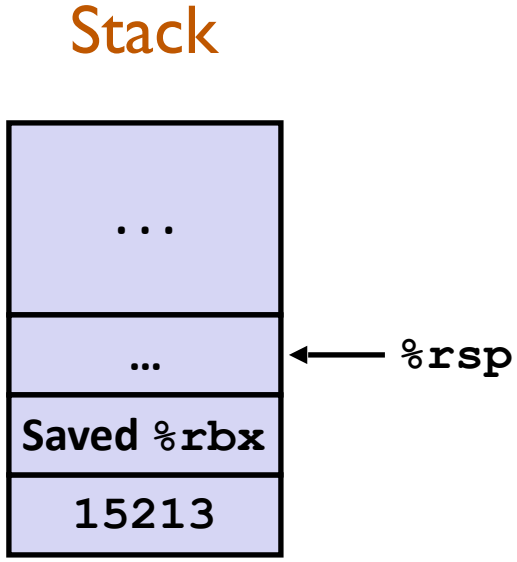
  movl    $3000, %esi
  leaq    (%rsp), %rdi
  call    incr
  addq    %rbx, %rax
  addq    $8, %rsp
  popq    %rbx
  ret
```



- `call_incr2` needs to save `%rbx` (callee-saved) because it will modify its value
- It can safely use `%rbx` after `call incr` because `incr` will have to save `%rbx` if it needs to use it (again, `%rbx` is callee saved)

Stack Frame: Putting It Together