CSC 252/452: Computer Organization
Fall 2024: Lecture 8

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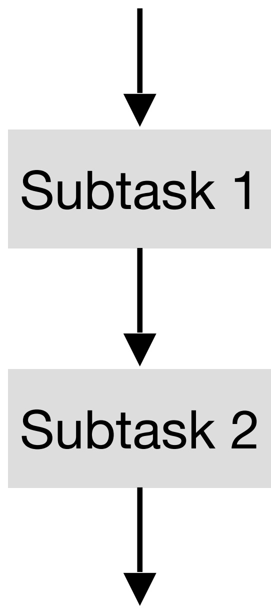
Announcement

- Programming Assignment 2 is out
  - Details: https://www.cs.rochester.edu/courses/252/fall2024/labs/assignment2.html
  - Due on **Sep. 30th**, 11:59 PM
  - You (may still) have 3 slip days

Summary

Sequential




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

Summary

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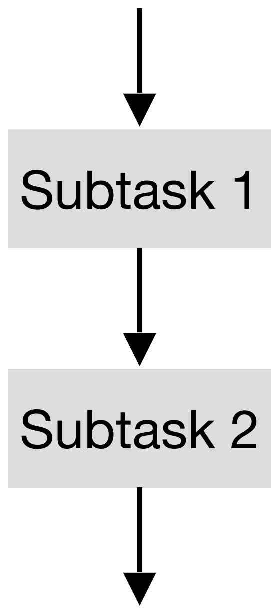


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Memory

```
.section .text

...

<subtask 1>

...

...

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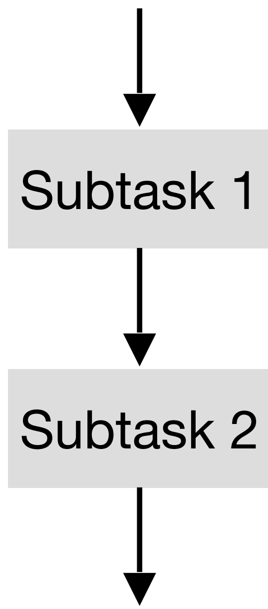
Sequential

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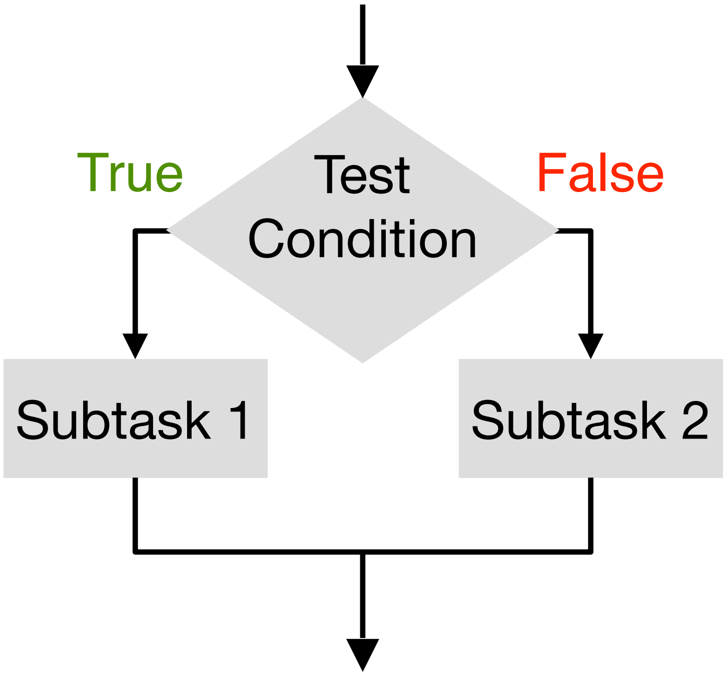
Summary

Conditional



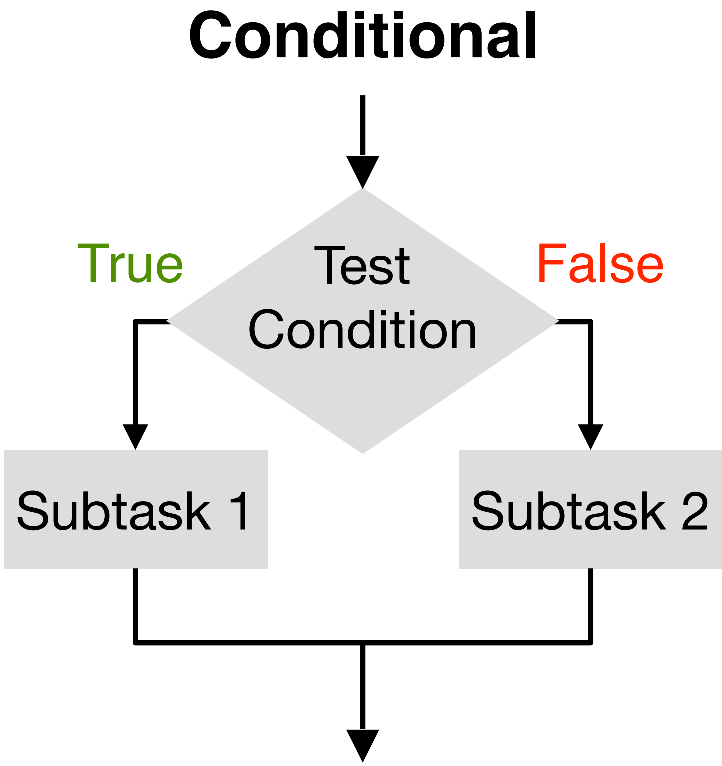

```
if (x > y) r = x - y;
else r = y - x;
```

Direct Jump Instructions

- Jump to different part of code (designated by a label) depending on condition codes

Instruction	Jump Condition	Description
`jmp`	`1`	Unconditional
`je`	`ZF`	Equal / Zero
`jne`	`~ZF`	Not Equal / Not Zero
`js`	`SF`	Negative
`jns`	`~SF`	Nonnegative
`jg`	`~(SF^OF)&~ZF`	Greater (Signed)
`jge`	`~(SF^OF)`	Greater or Equal (Signed)
`jl`	`(SF^OF)`	Less (Signed)
`jle`	`(SF^OF)|ZF`	Less or Equal (Signed)
`ja`	`~CF&~ZF`	Above (unsigned)
`jae`	`~CF`	Above or Equal (unsigned)
`jb`	`CF`	Below (unsigned)
`jbe`	`CF|ZF`	Below or Equal (unsigned)

Summary

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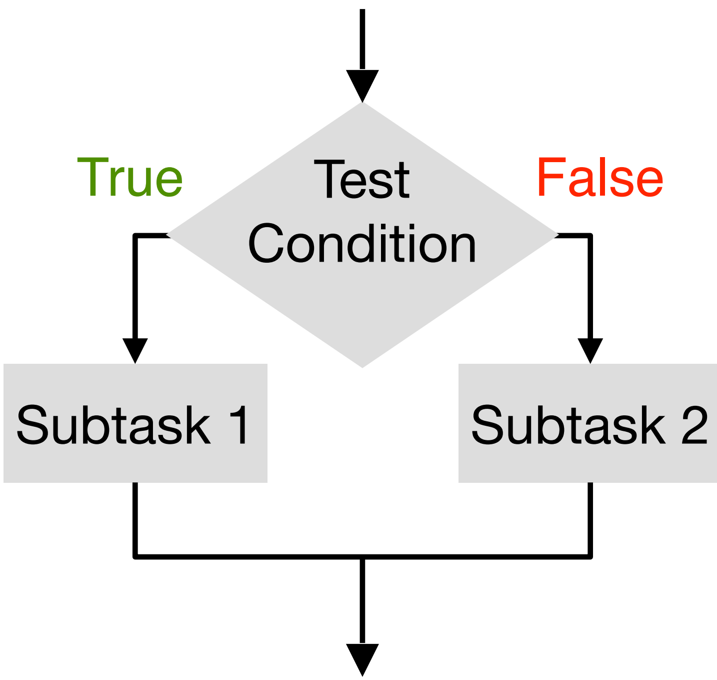


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.section .text

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cmpq
jle .L2
.L1 <subtask 1>

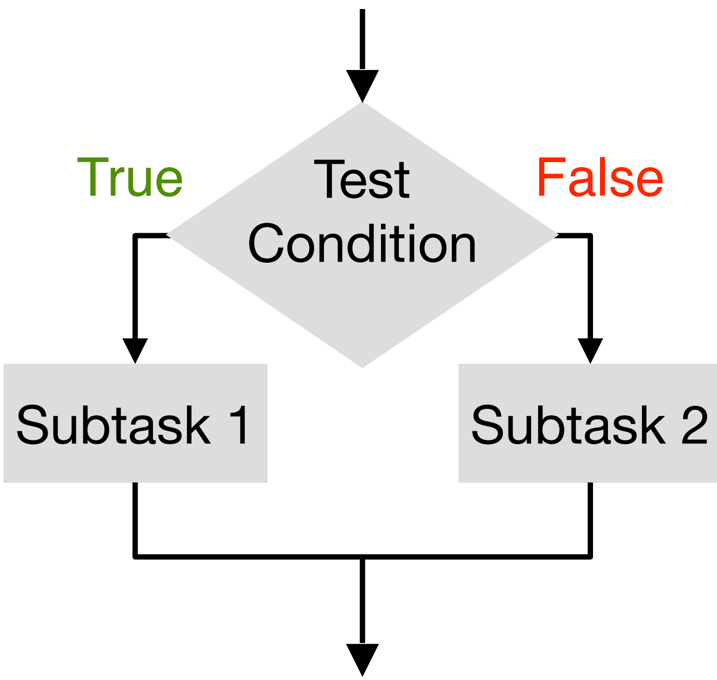
…

jmp .done
.L2 <subtask 2>

…
.done
```

Summary

Conditional

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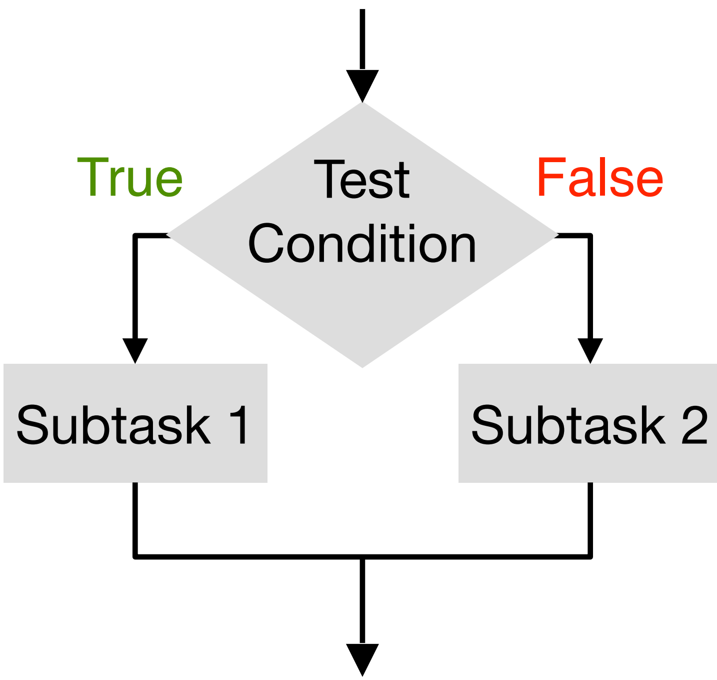


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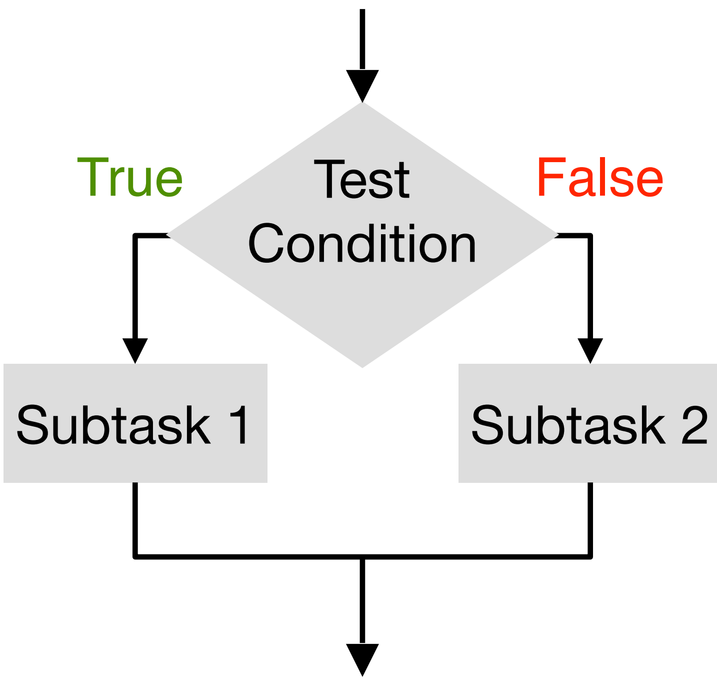


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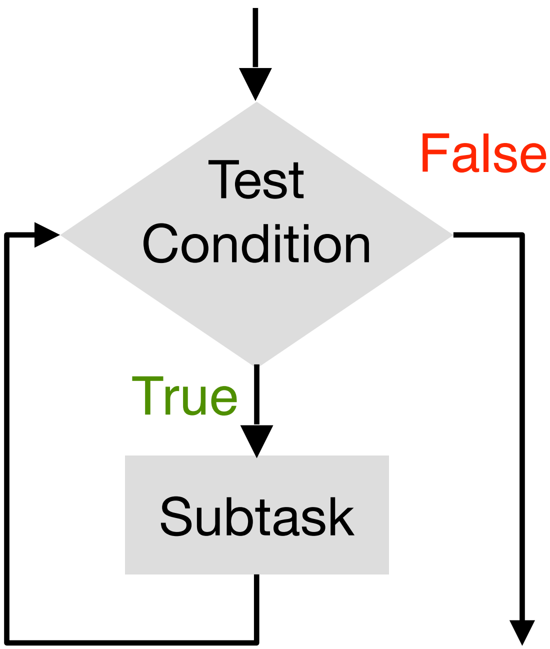
Iterative

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while (x > 0) {
   x--;
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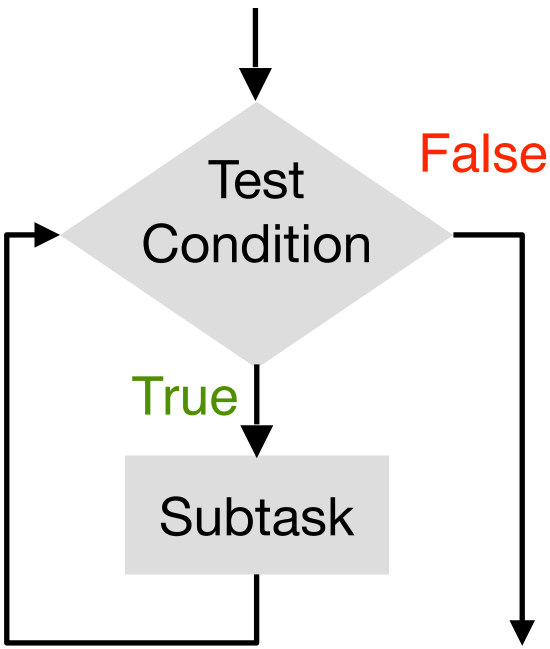


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   x--;
}
```

Memory

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.section .text

…
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.L1:

…
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…
.L2:
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   jg .L1
…
…
```

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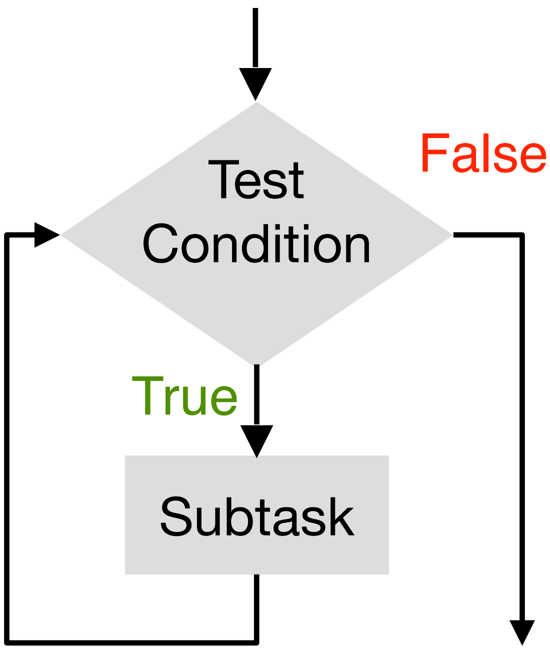


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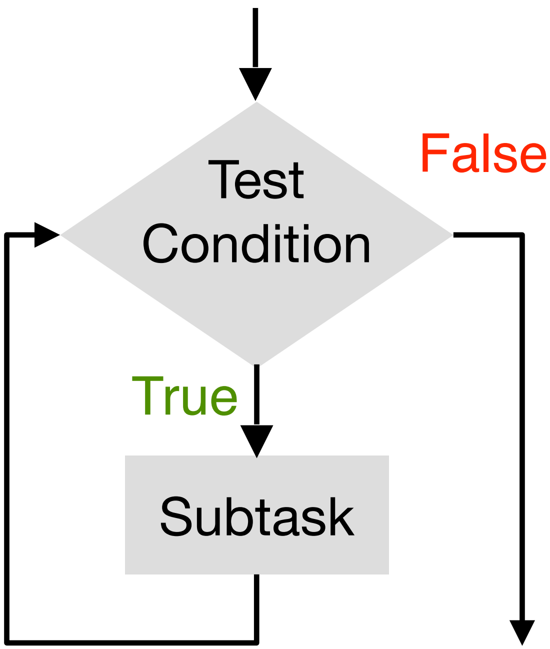


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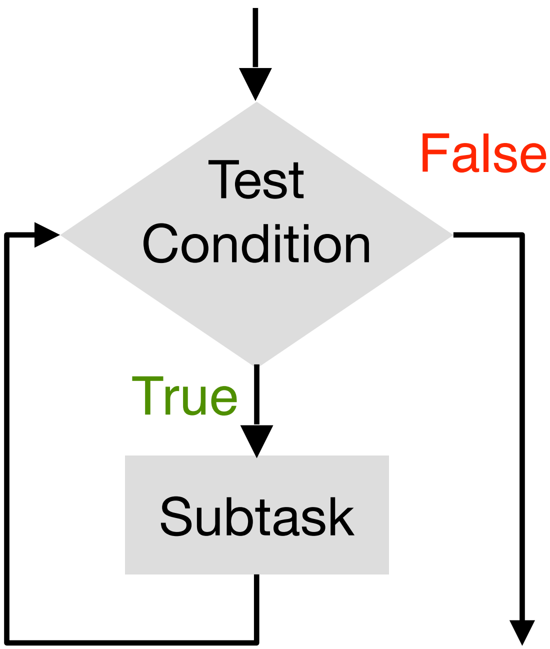


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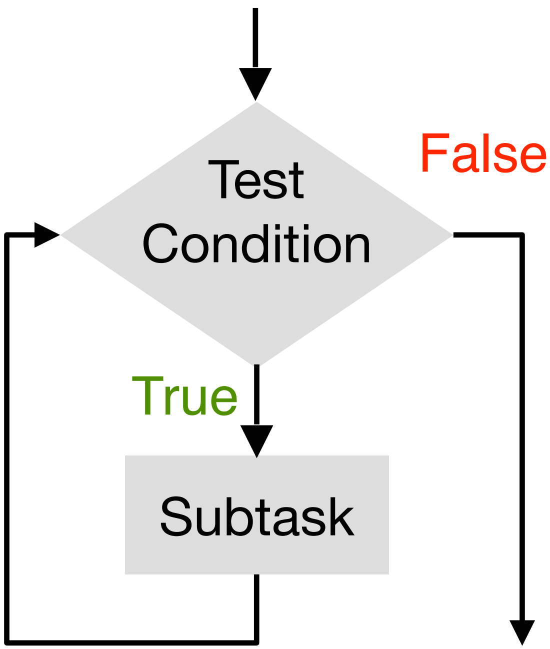


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…
```

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

Switch Form

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switch(x) {
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```

Jump Targets

Targ0: Code Block 0

Targ1: Code Block 1

Targ2: Code Block 2

•
•
•

Targ*n*-1: Code Block *n*–1

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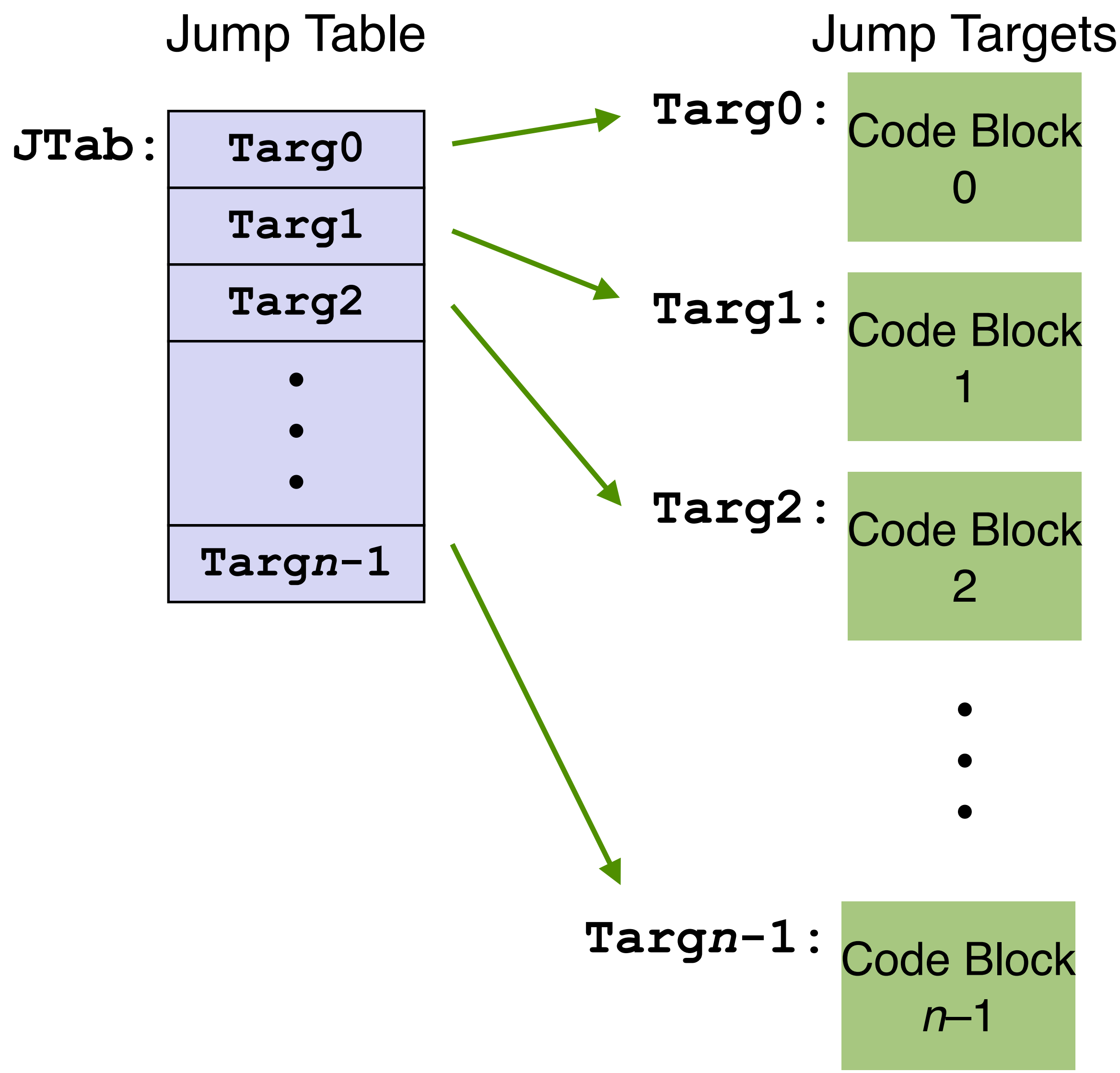

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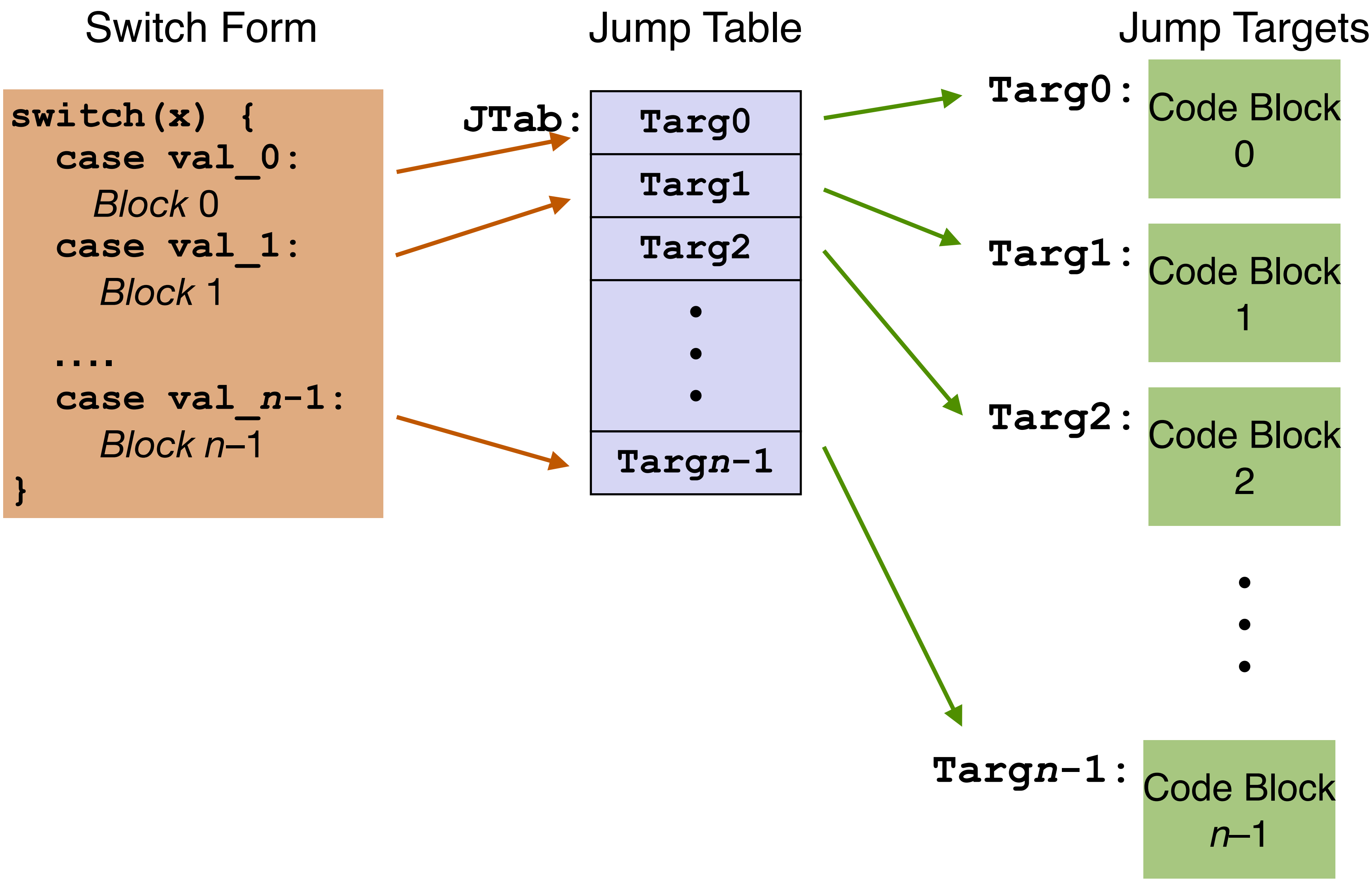

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Jump Table

JTab:
Targ0
Targ1
Targ2
• • •
Targ*n*-1

Jump Targets

Targ0: Code Block 0

Targ1: Code Block 1

Targ2: Code Block 2

• • •

Targ*n*-1: Code Block *n*–1

- 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

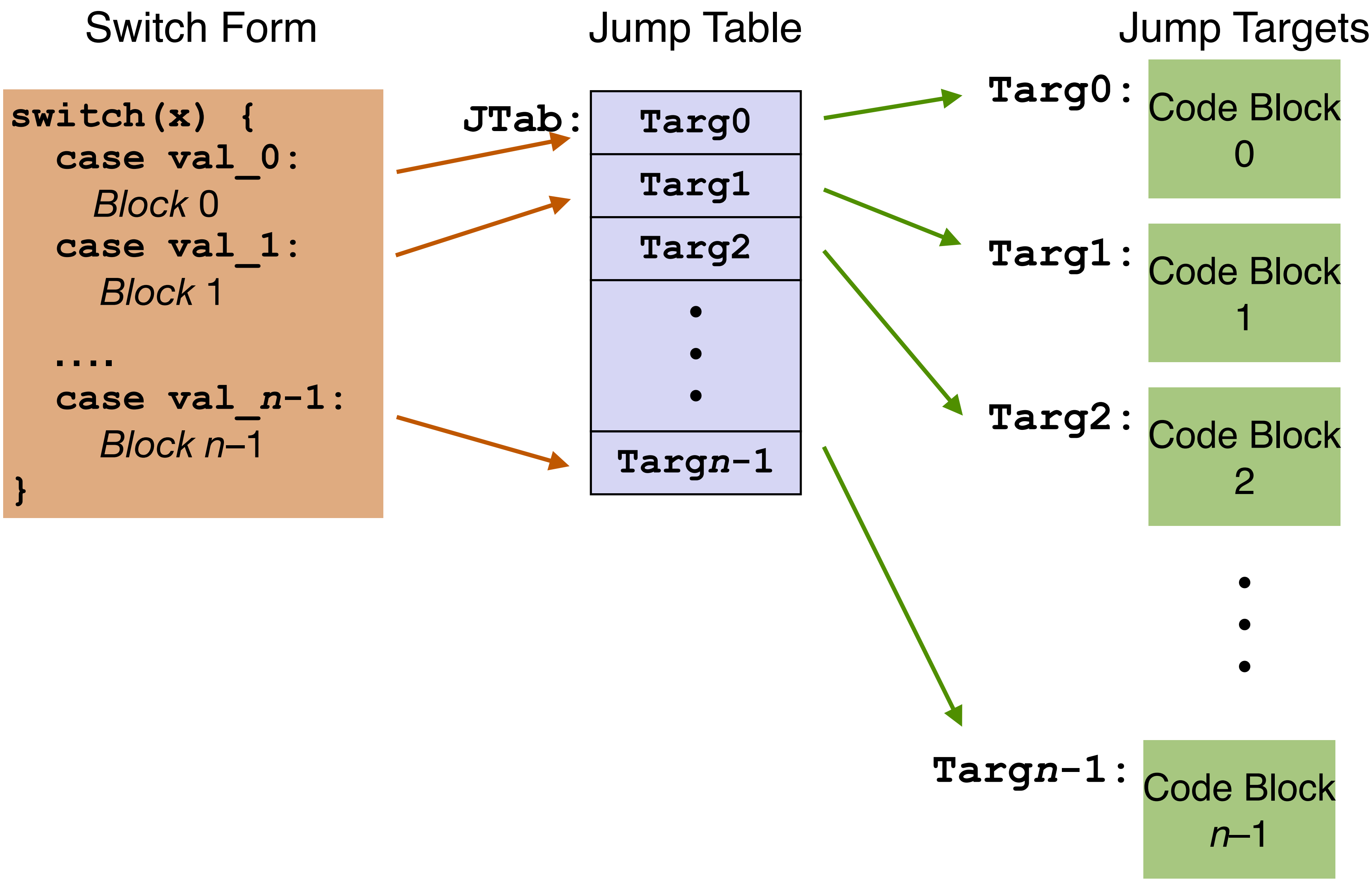
```
.section   .rodata
  .align 8
.L4:
  .quad .LD # x = 0
  .quad .L1 # x = 1
  .quad .L2 # x = 2
  .quad .L3 # x = 3
  .quad .LD # x = 4
  .quad .L5 # x = 5
  .quad .L5 # x = 6
```

`jmp .L3` will go to `.L3` and start executing from there

Jump Targets

```
.L1:                    # Case 1
    movq    %rsi, %rax
    imulq   %rdx, %rax
    jmp     .done
.L2:                    # Case 2
    movq    %rsi, %rax
    cqto
    idivq   %rcx
.L3:                    # Case 3
    addq    %rcx, %rax
    jmp     .done
.L5:                    # Case 5,6
    subq    %rdx, %rax
    jmp     .done
.LD:                    # Default
   movl     $2, %eax
   jmp     .done
```

Implementing Switch Using Jump Table



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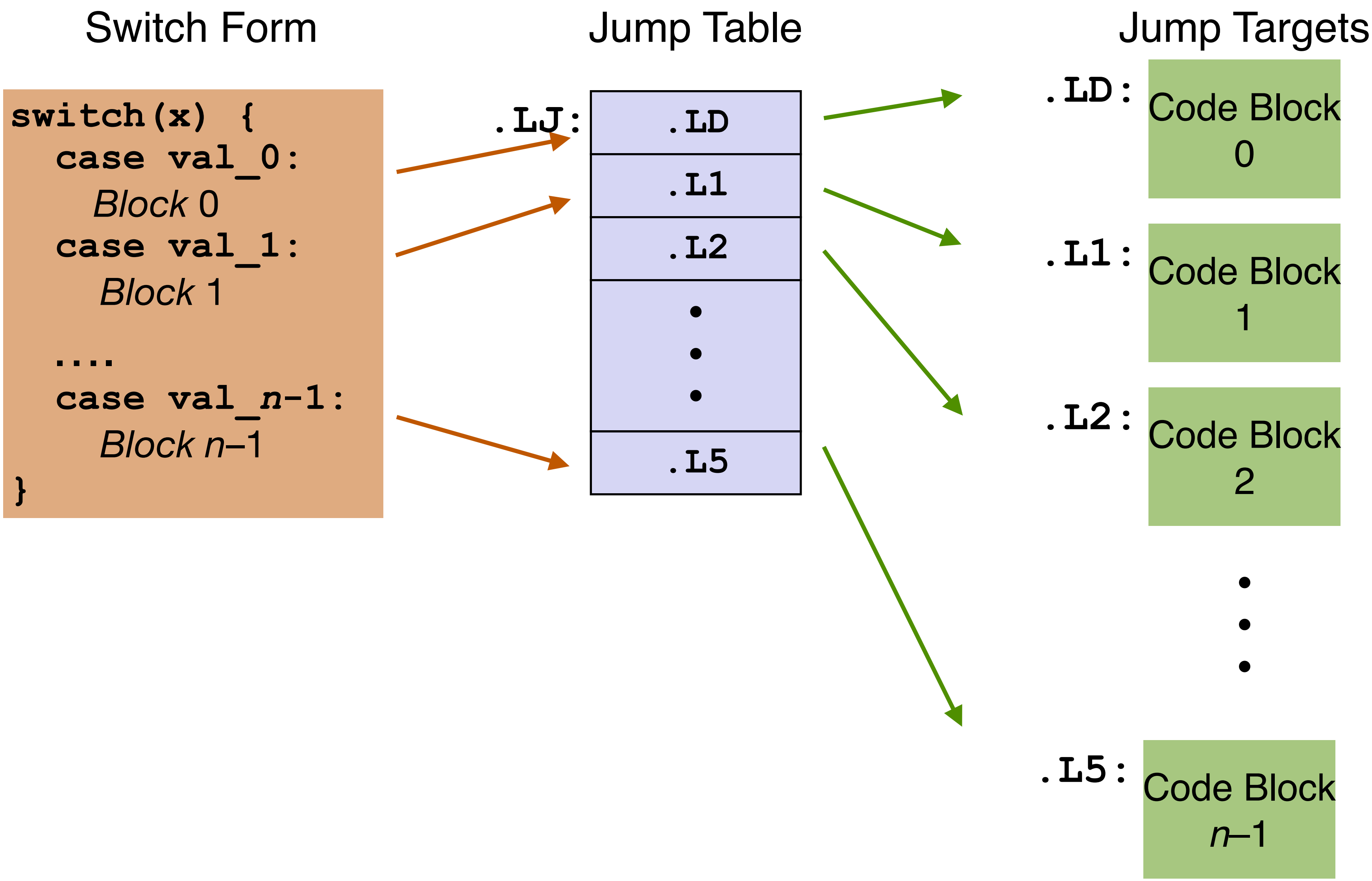

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Jump Table

.LJ:	
	.LD
	.L1
	.L2
	• • •
	.L5

Jump Targets

.LD: Code Block 0

.L1: Code Block 1

.L2: Code Block 2

• • •

.L5: Code Block *n*–1

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

Indirect Jump Instruction

```
.section  .rodata
  .align 8
.LJ:
  .quad .LD # x = 0
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Indirect Jump Instruction

The address we want to jump to is stored at `.LJ + 8 * x`

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```

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

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An equivalent syntax in x86:

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

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.

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

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- Local Memory management
  - Allocate during procedure execution
  - Deallocate upon return
- Mechanisms all implemented with machine instructions

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- General idea of implementing functions: Stack
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General Idea

- Frame (Active Record)
  - A frame refers to a piece of memory that contains (almost) all the information needed to execute a function, e.g., arguments and local variables

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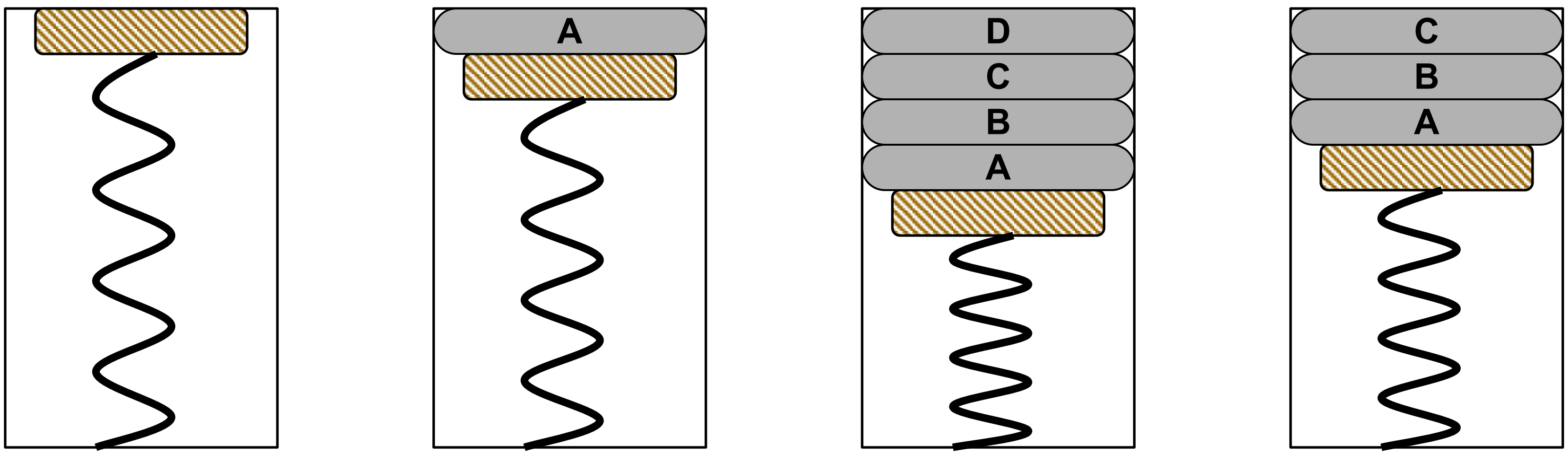
  - A frame refers to a piece of memory that contains (almost) all the information needed to execute a function, e.g., arguments and local variables
- When a function is called, create a frame, and push it to the memory
- When a function is returned, pop the frame out of the memory
- Frames are stored in memory in a *stack* fashion

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

Run-Time Stack During Function Call

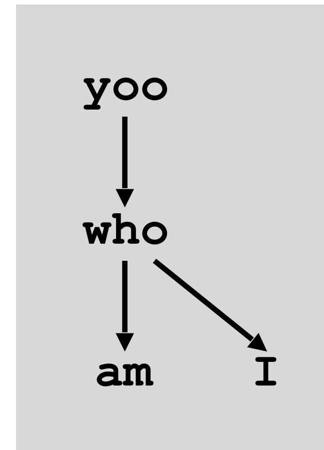
```
yoo(…)
{
   •
   •
   who();
   •
   return
}
```

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

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

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

Example Call Chain



Run-Time Stack During Function Call

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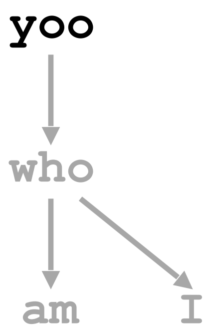
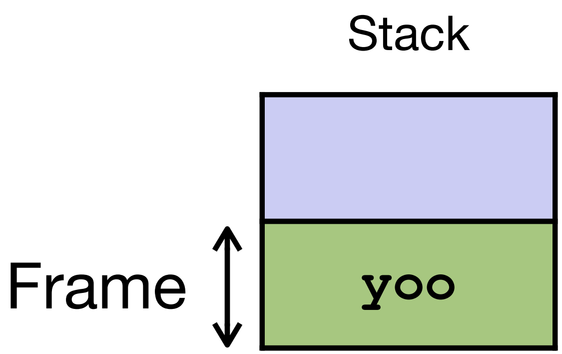
}
```





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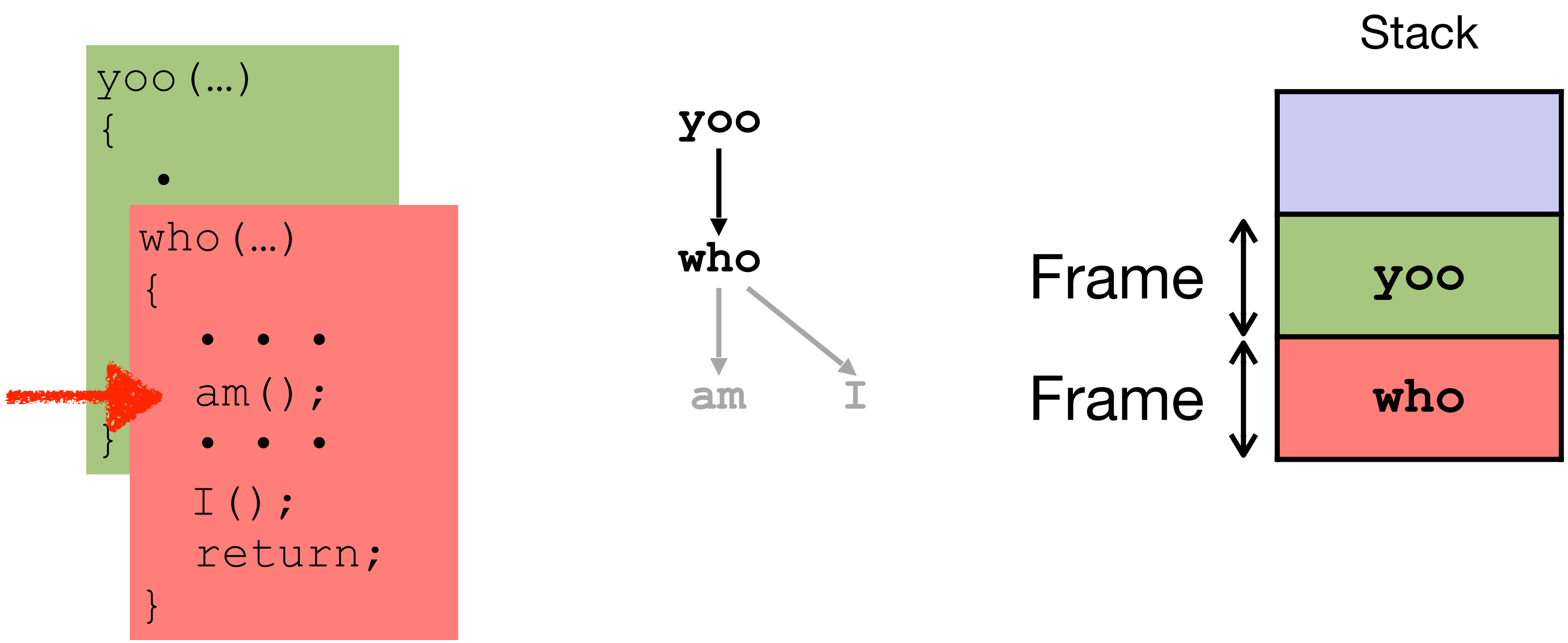

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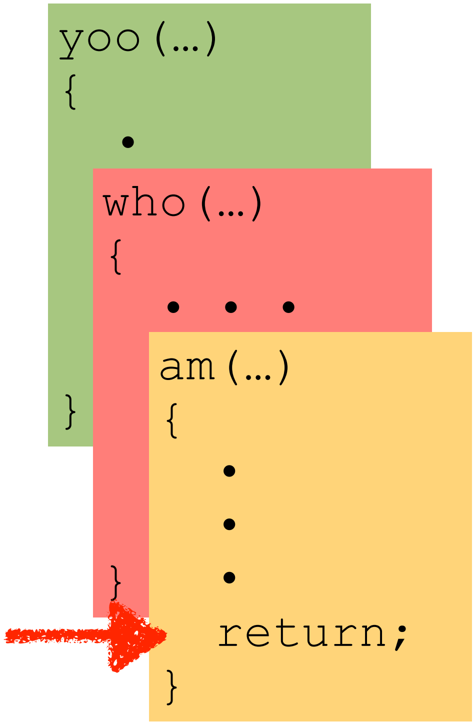

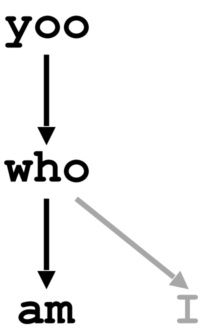

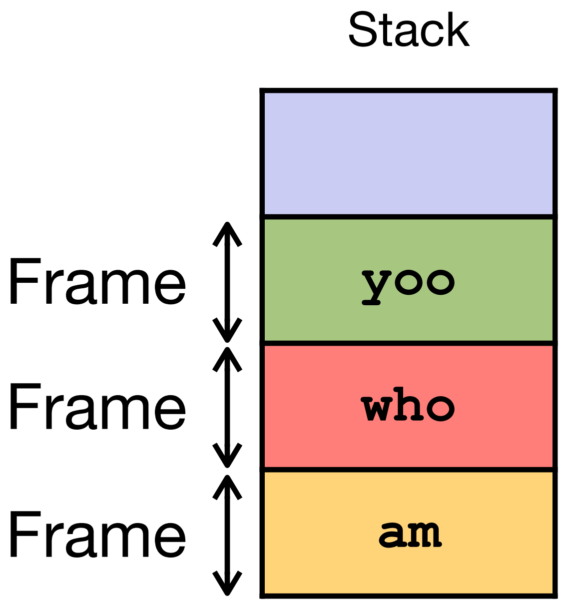

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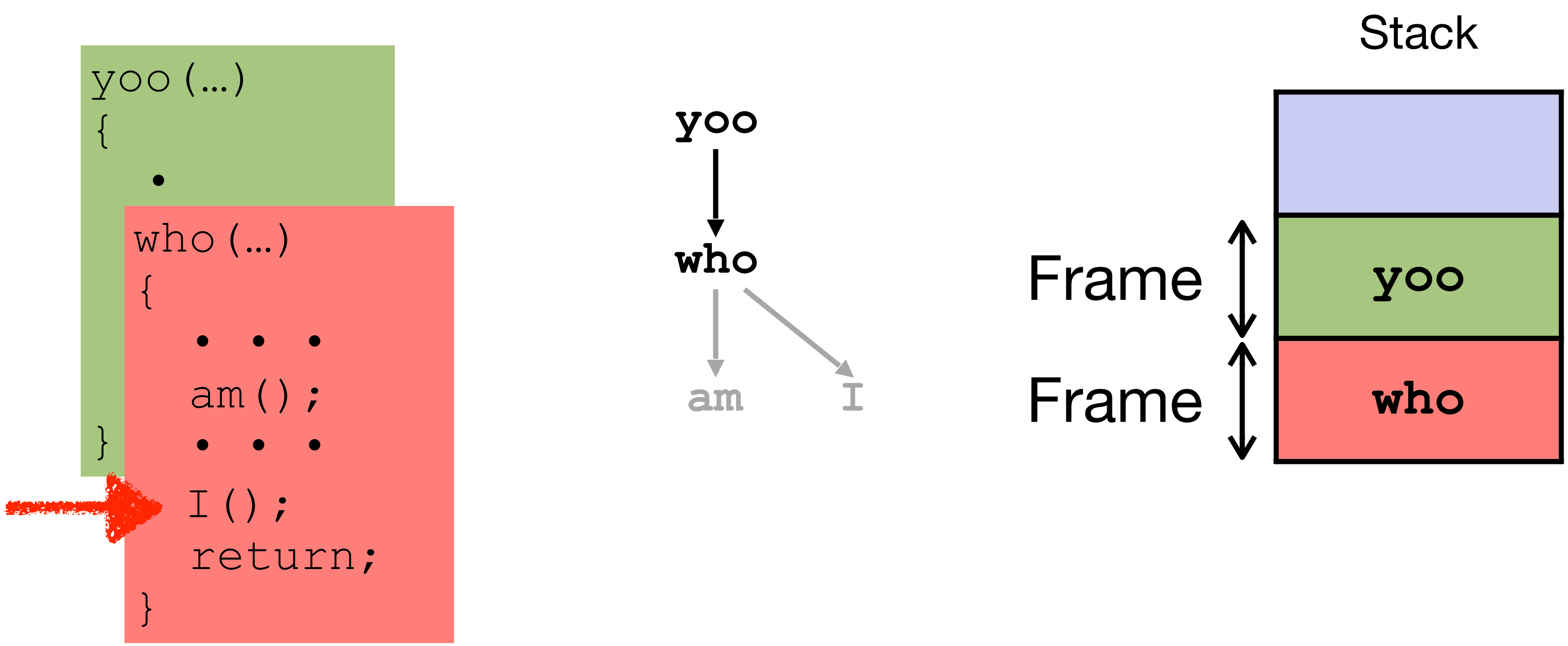

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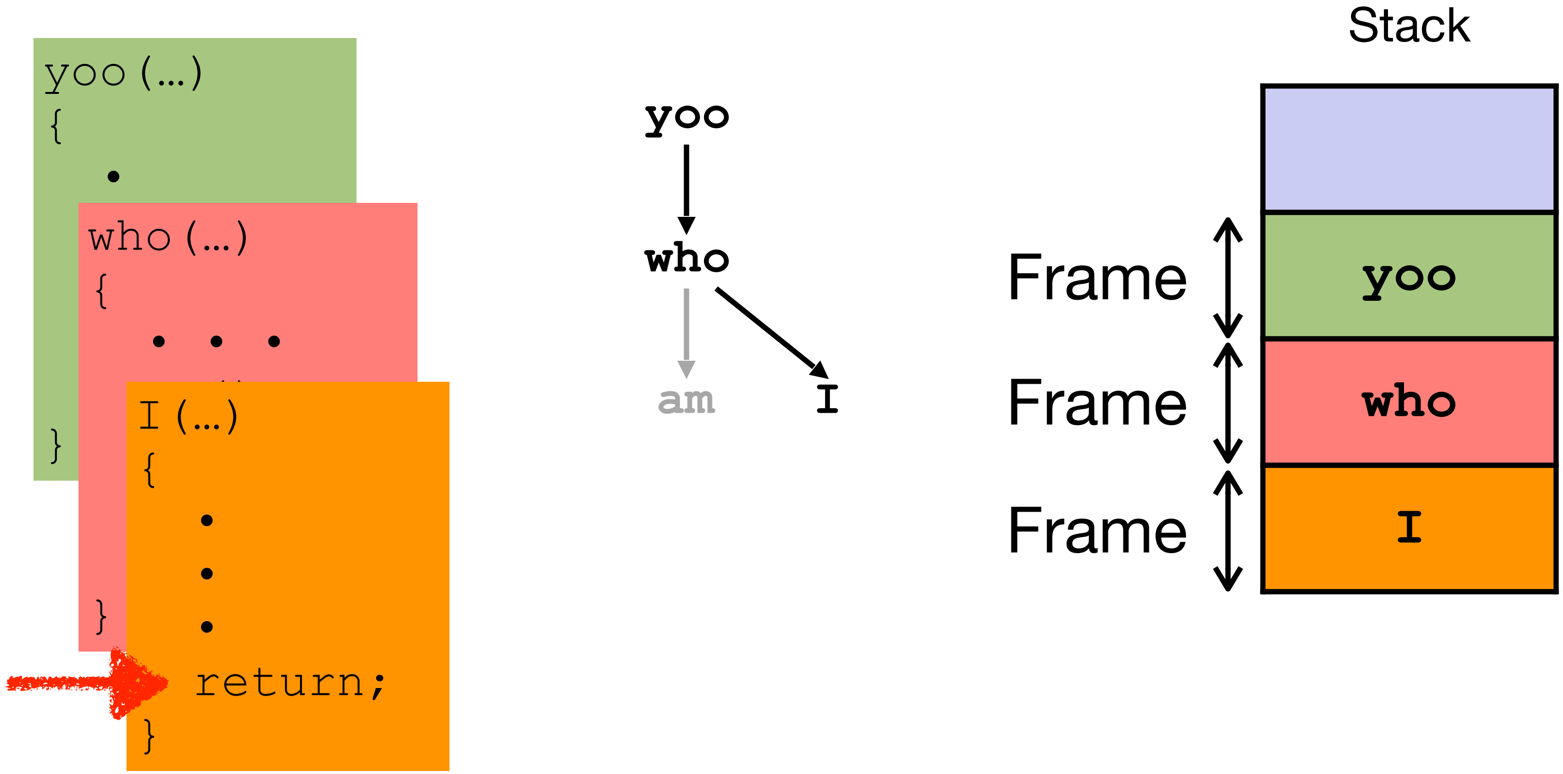

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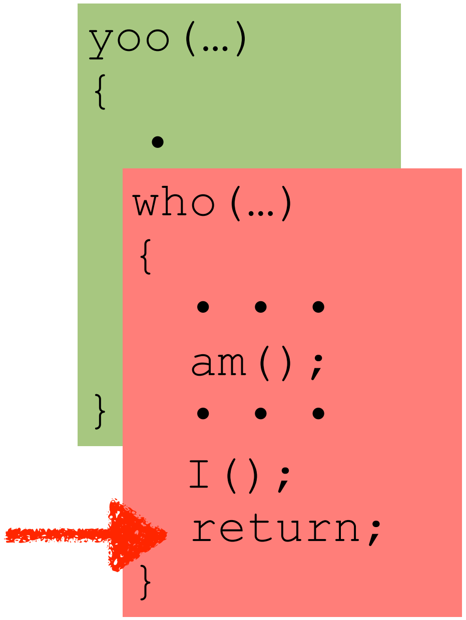

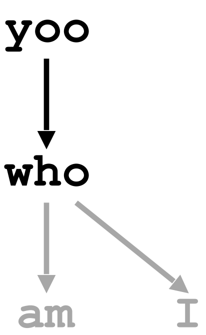

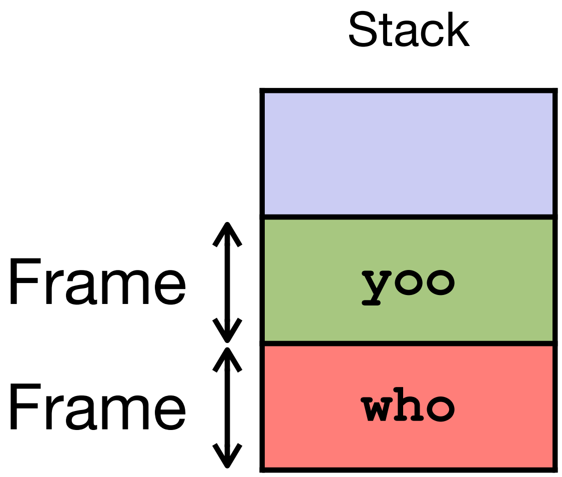

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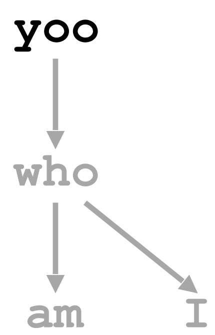
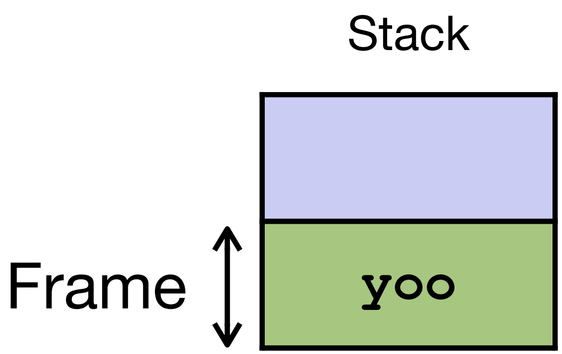
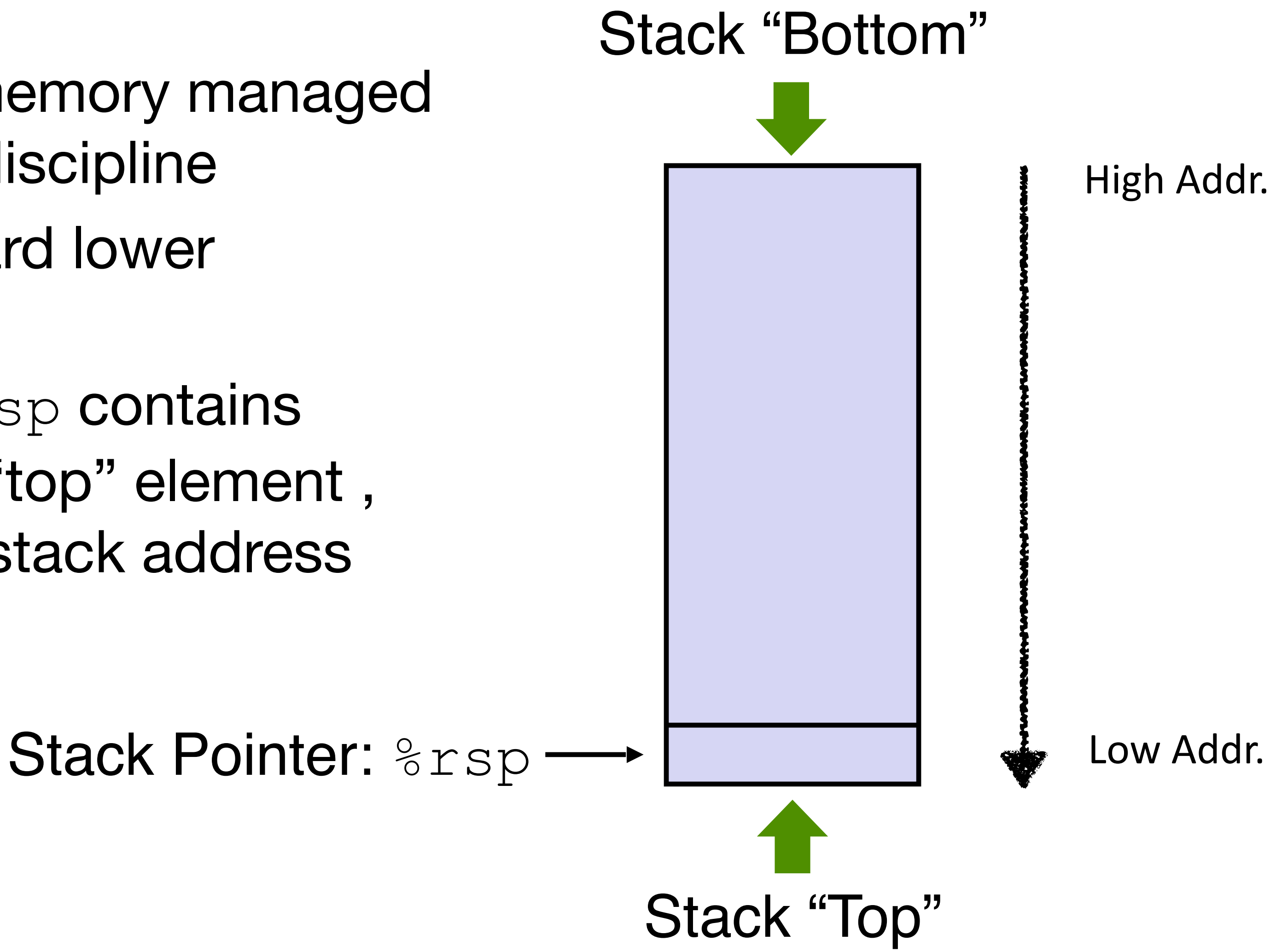




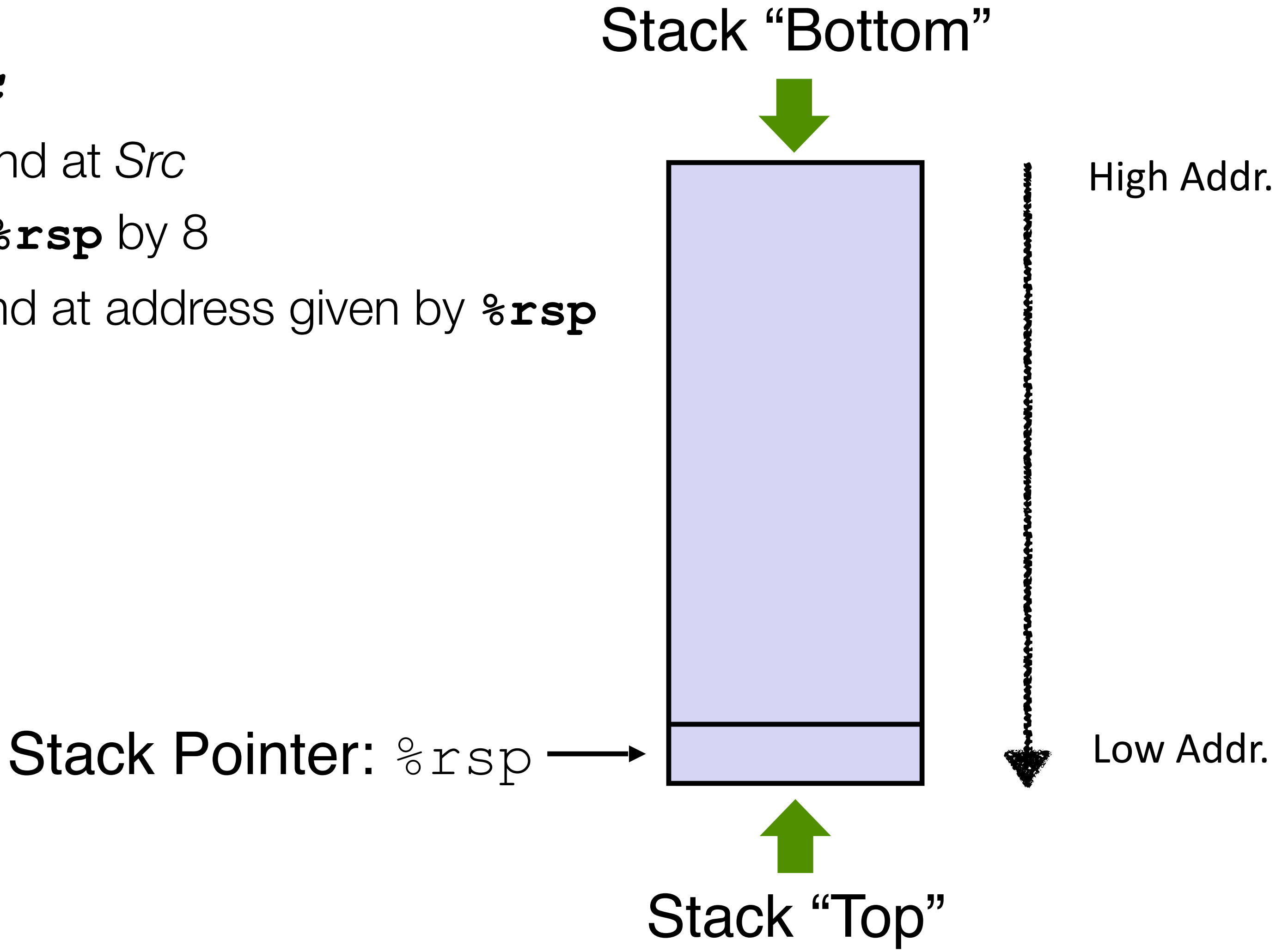
Stack in X86-64

- 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

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



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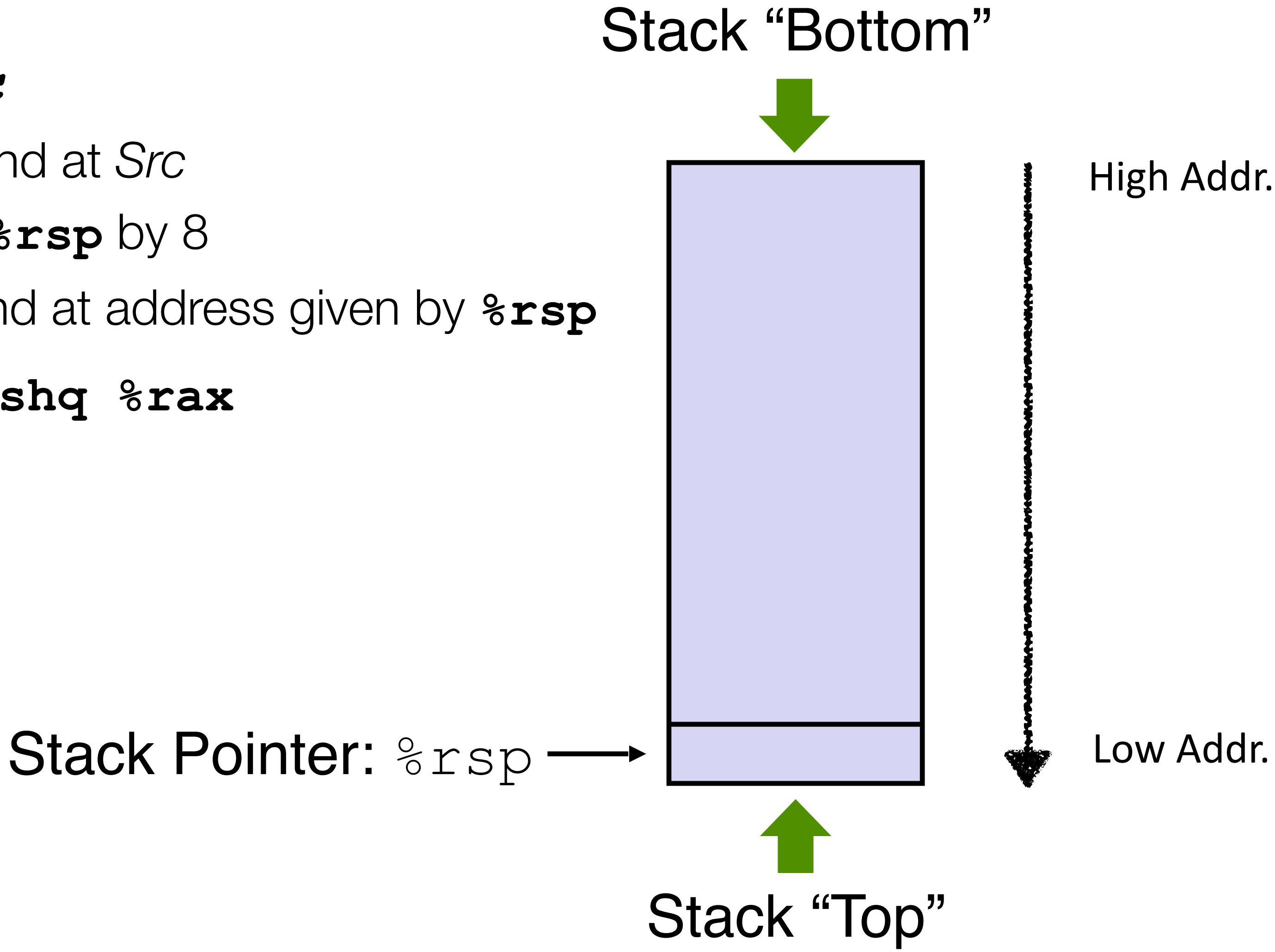

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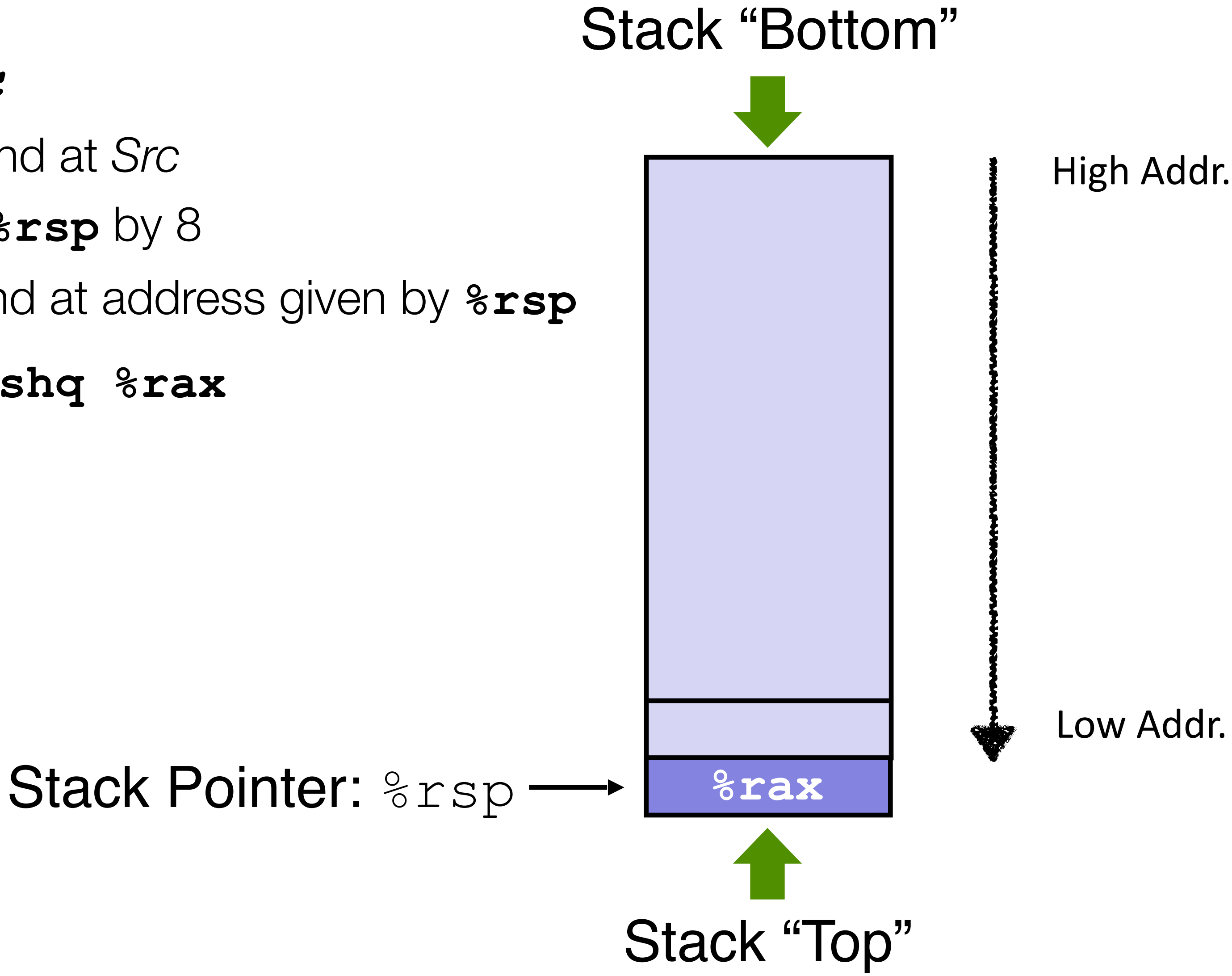

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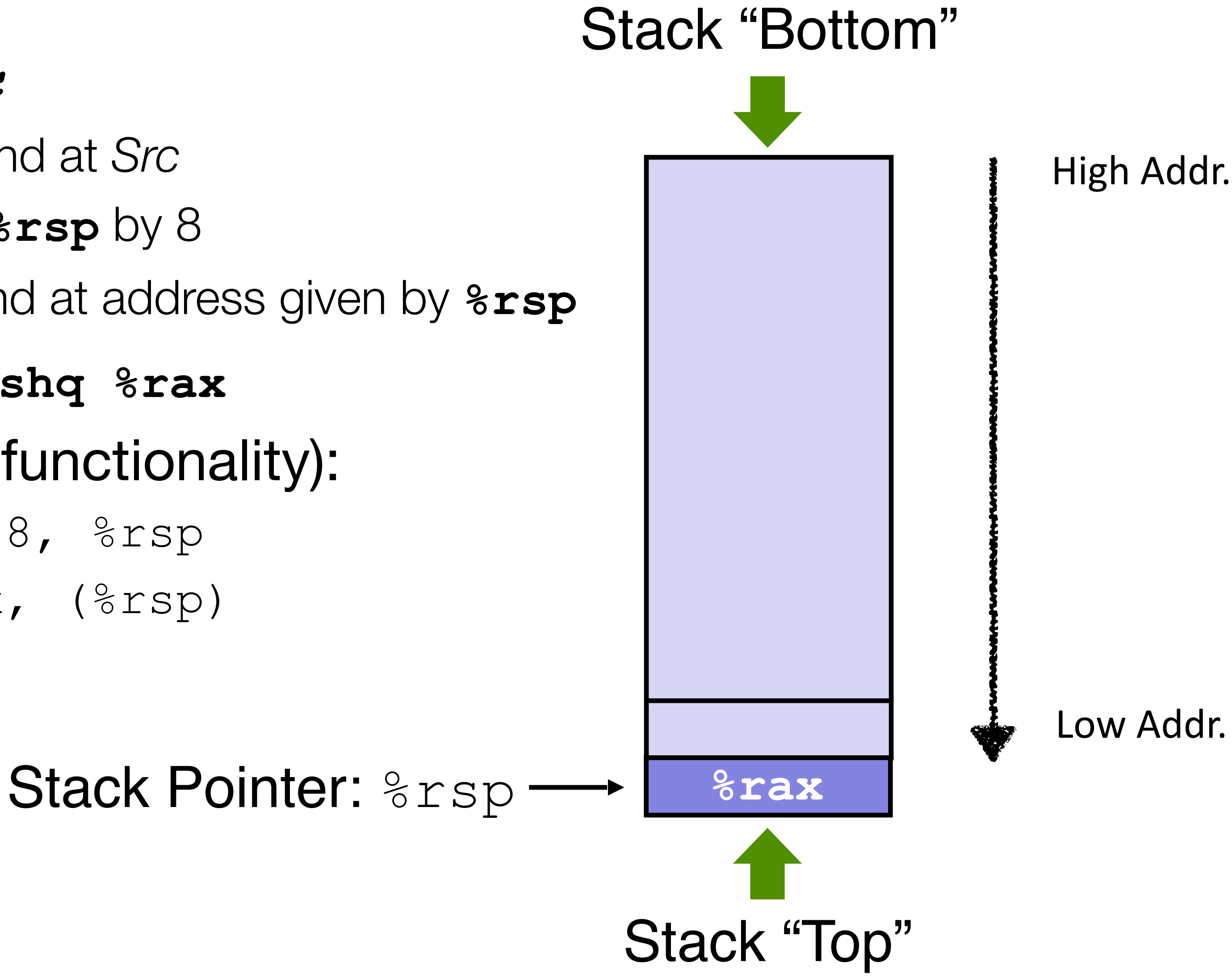
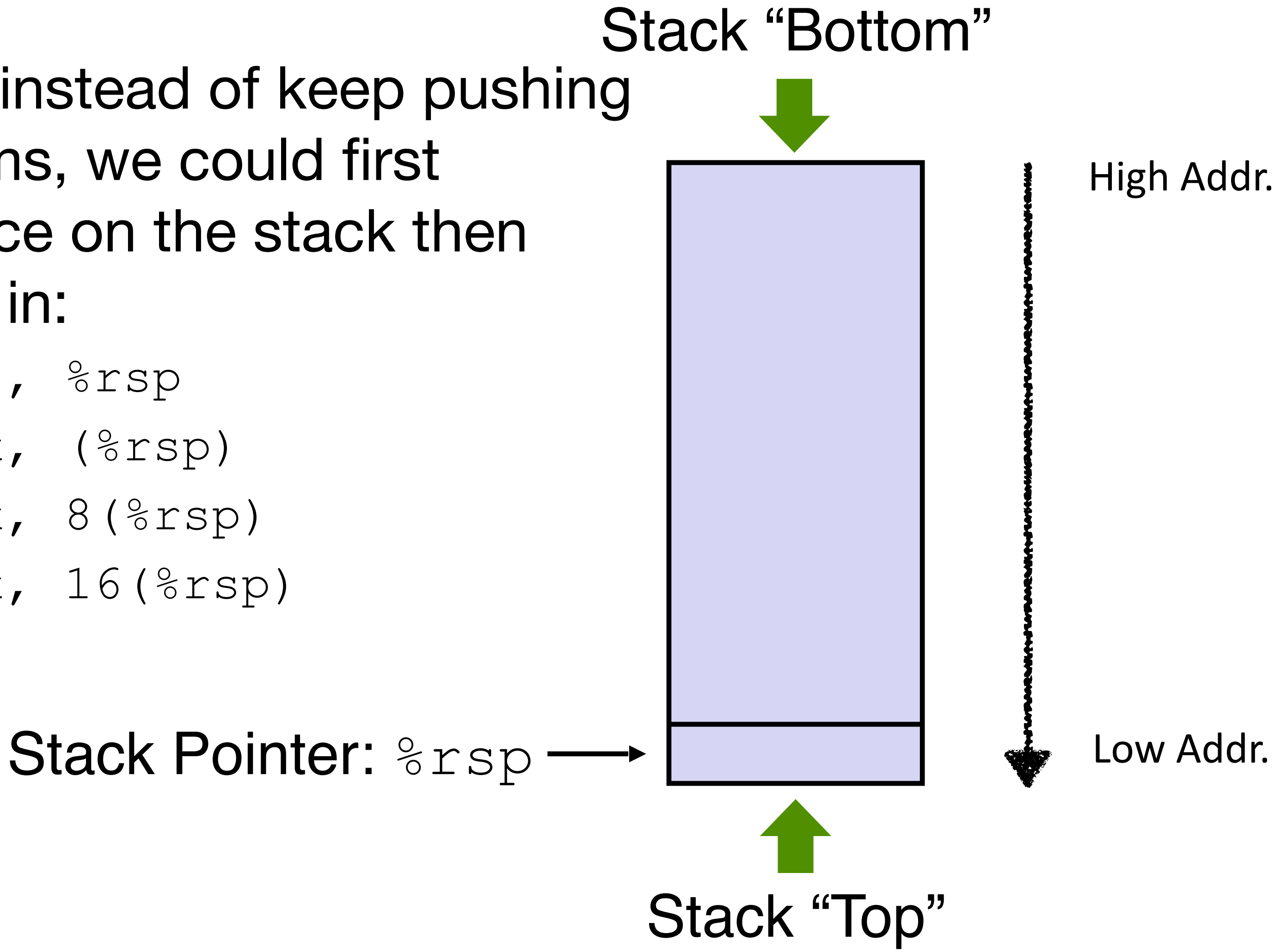
  - Fetch operand at *Src*
  - Decrement **`%rsp`** by 8
  - Write operand at address given by **`%rsp`**
- Example: **`pushq %rax`**
- Same as (in functionality):
  - `subq $0x08, %rsp`
  - `movq %rax, (%rsp)`



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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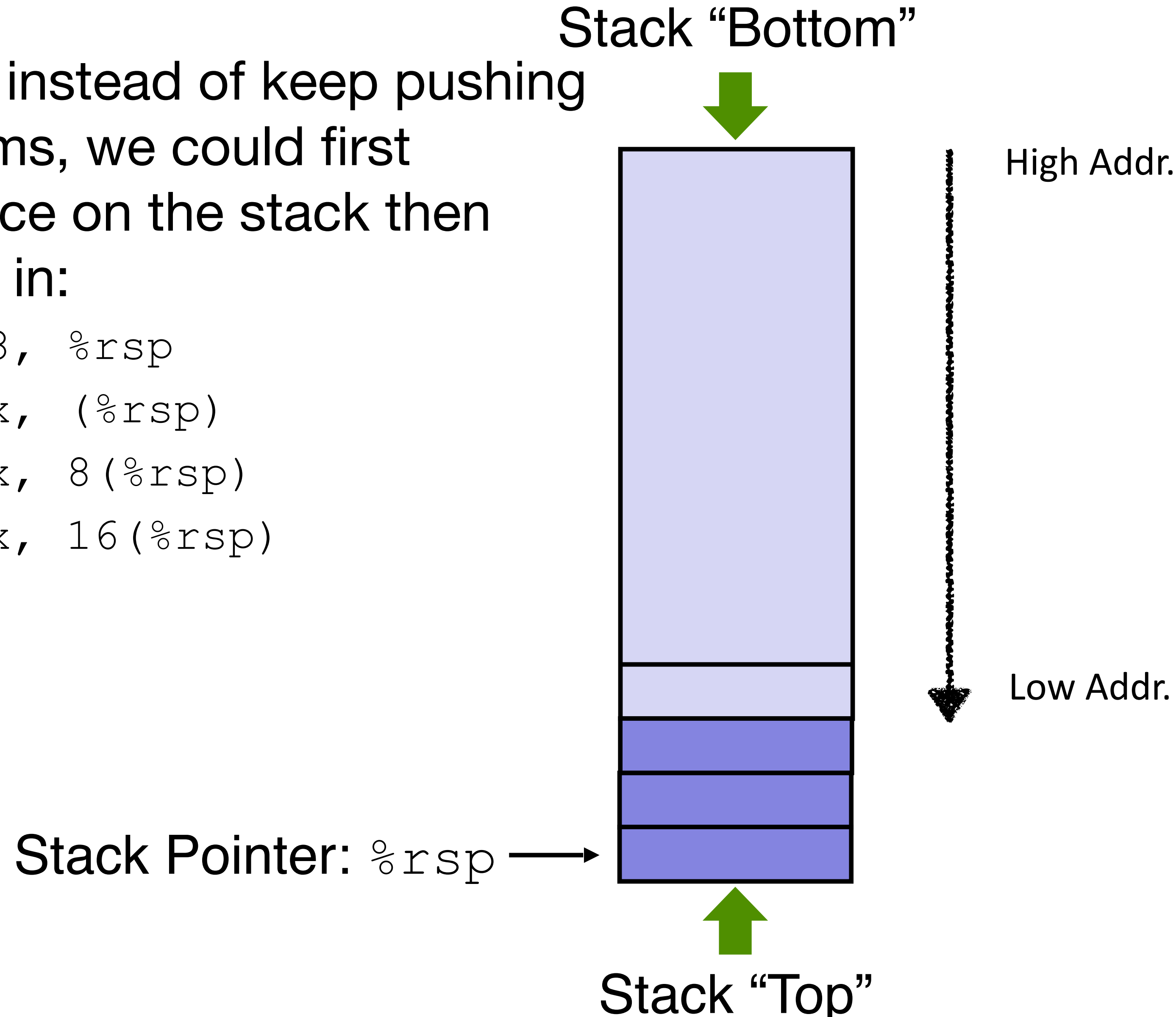

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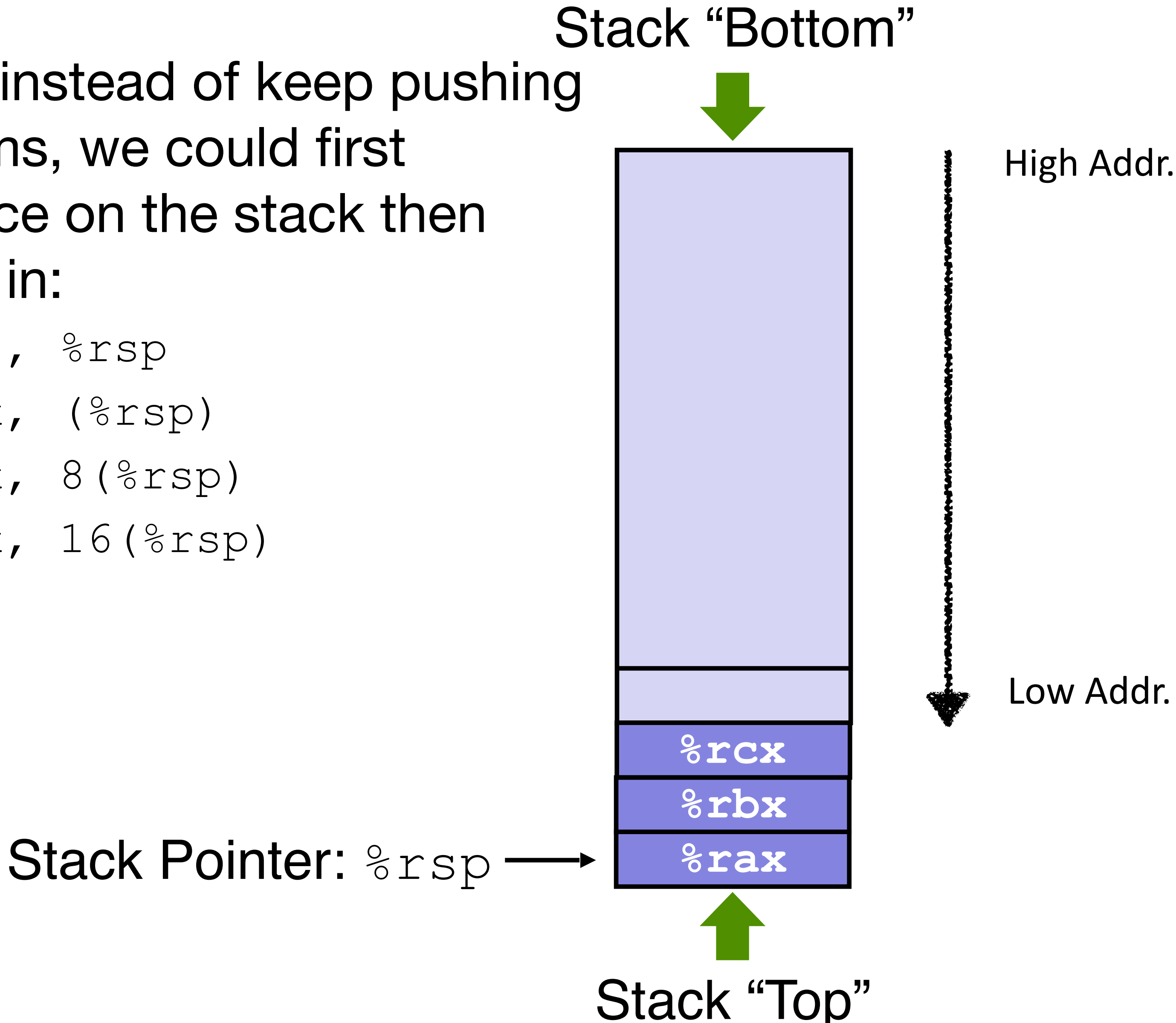
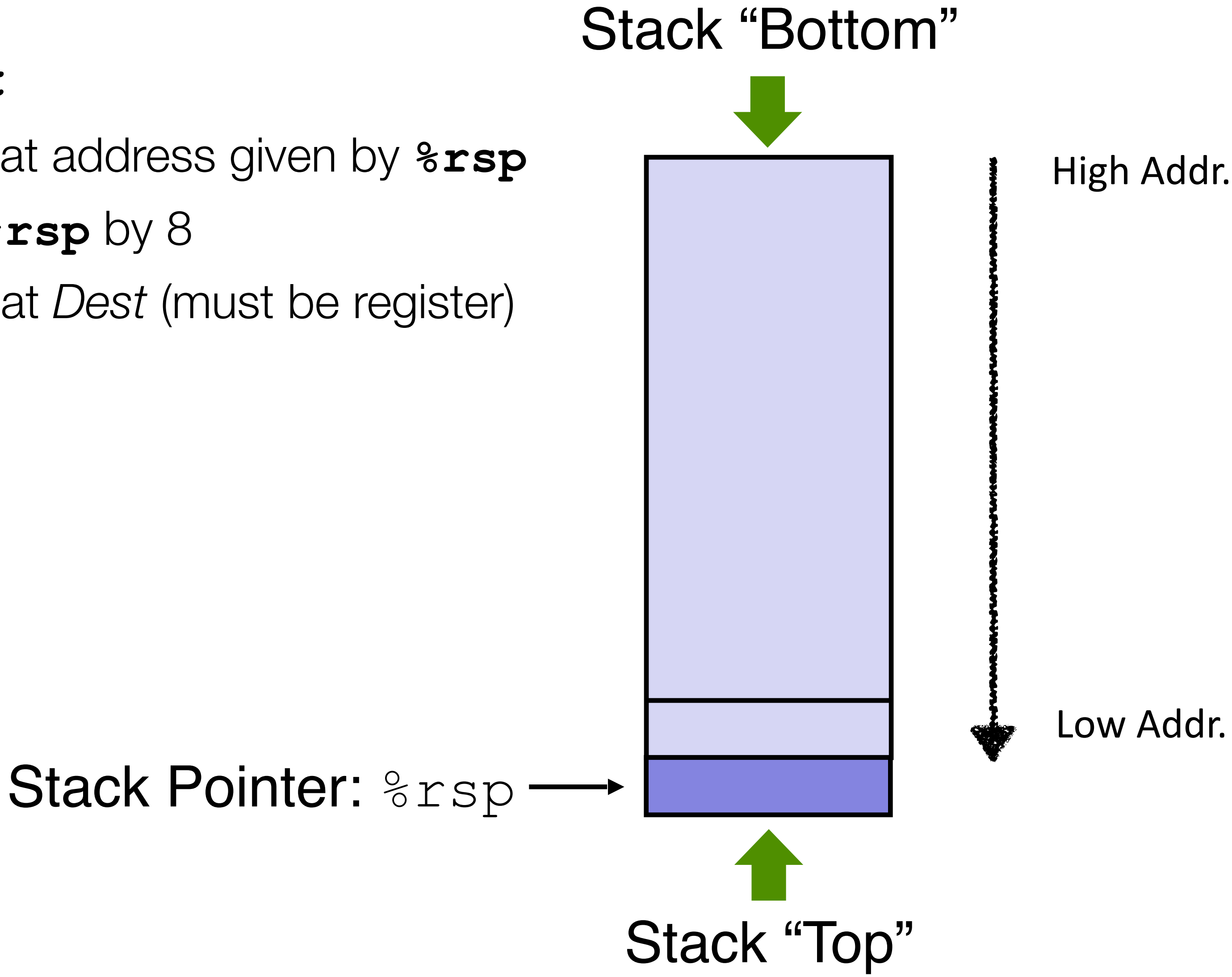


x86-64 Stack: Pop

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



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- **`popq`** ***`Dest`***
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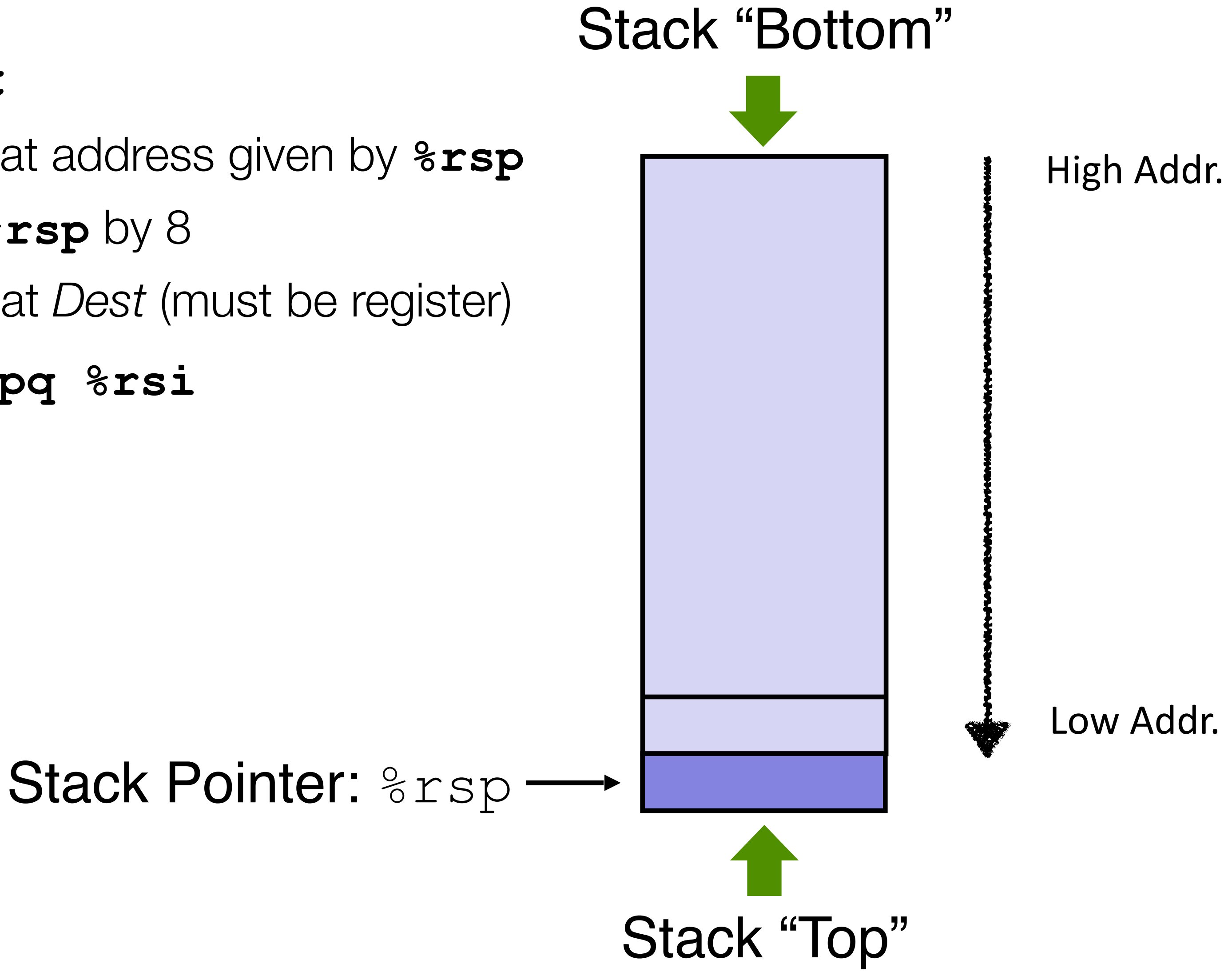
- Example: **`popq %rsi`**



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- **`popq`** ***`Dest`***
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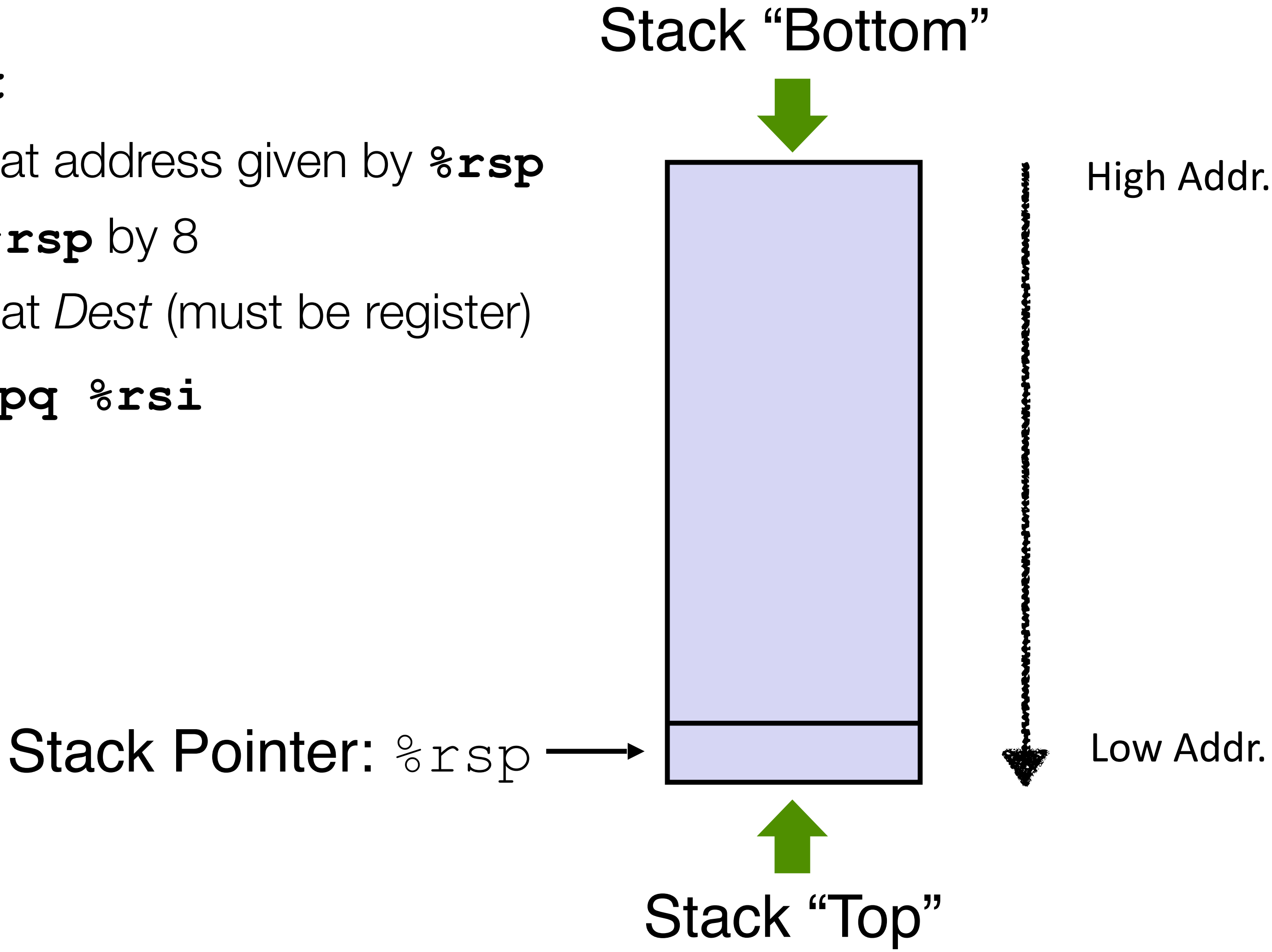
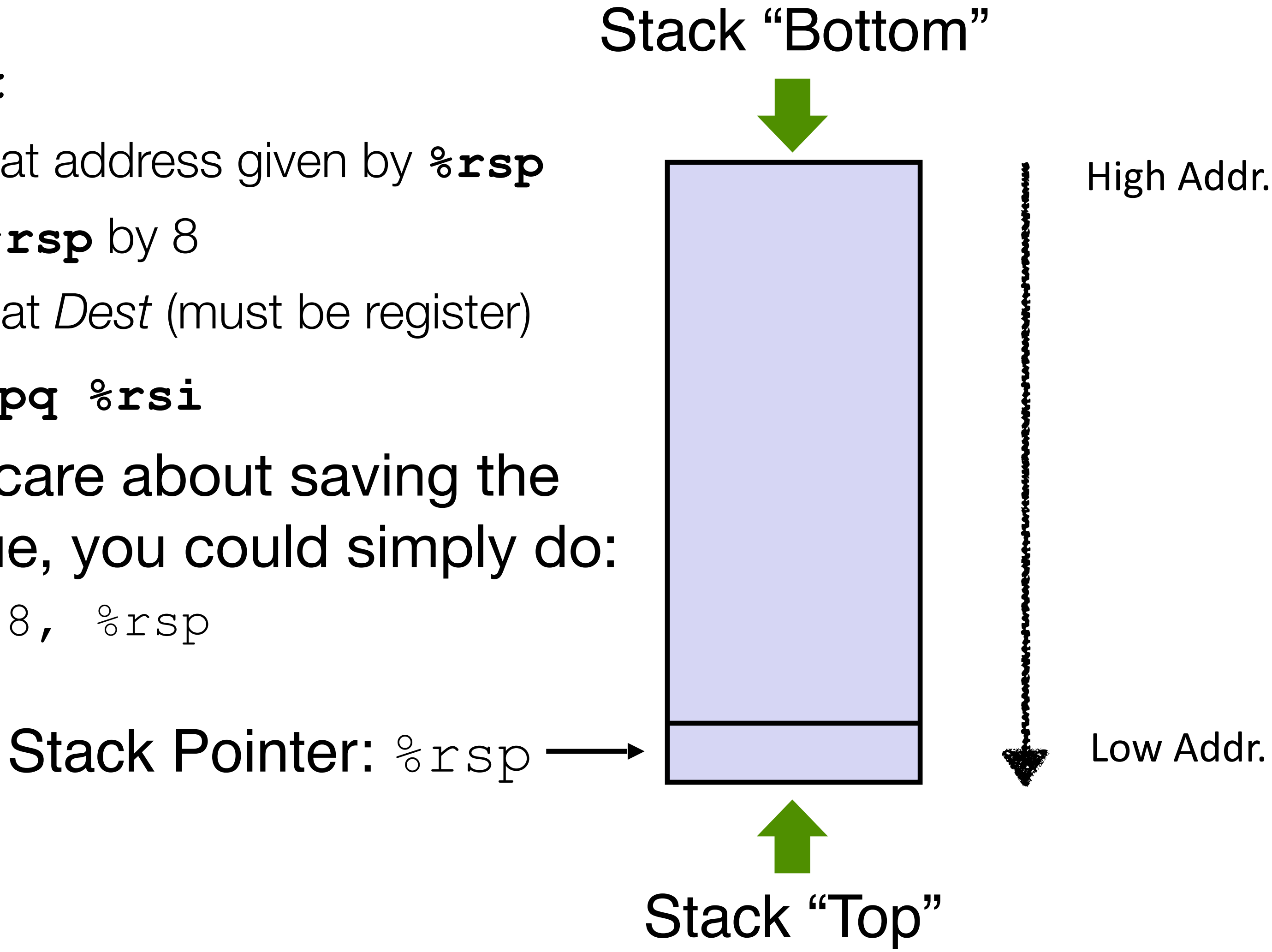


x86-64 Stack: Pop

- **`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`



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
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```

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

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```

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

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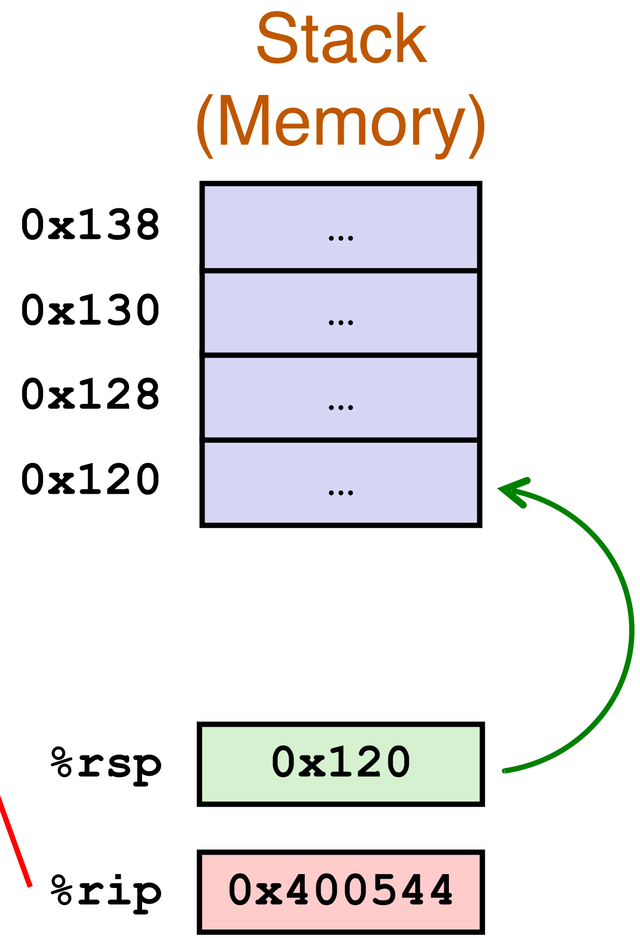

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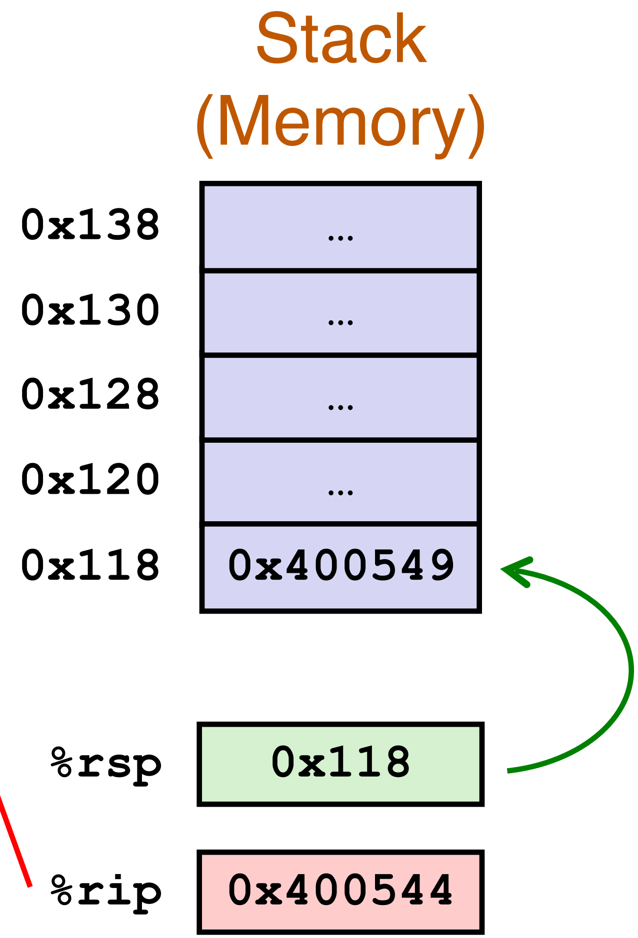

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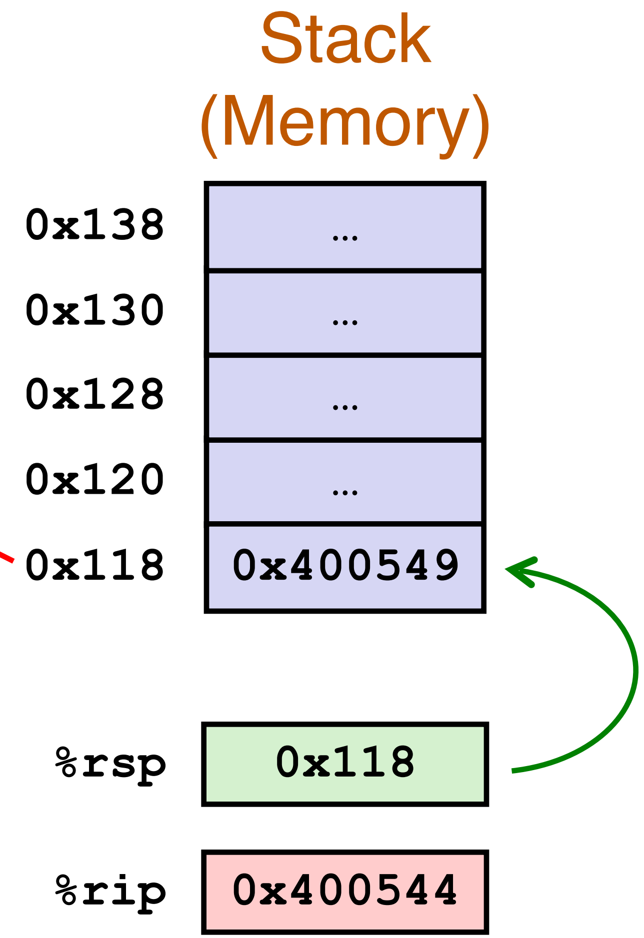

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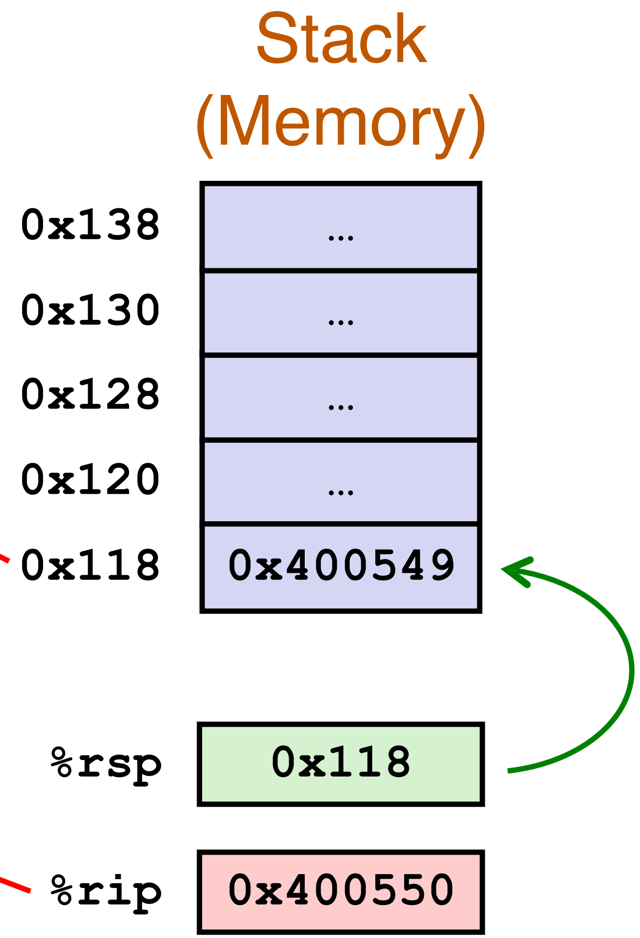

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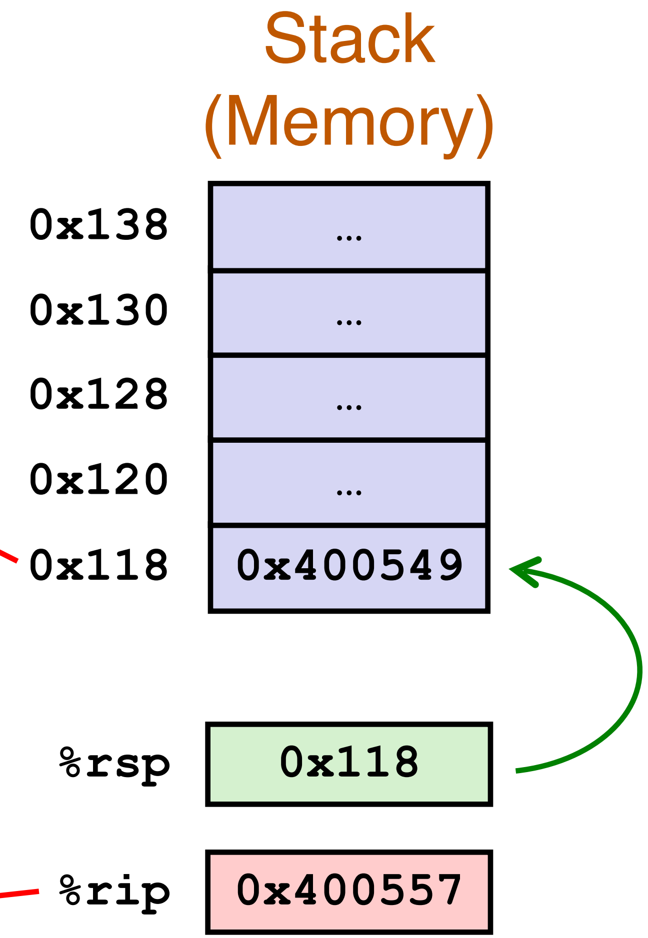

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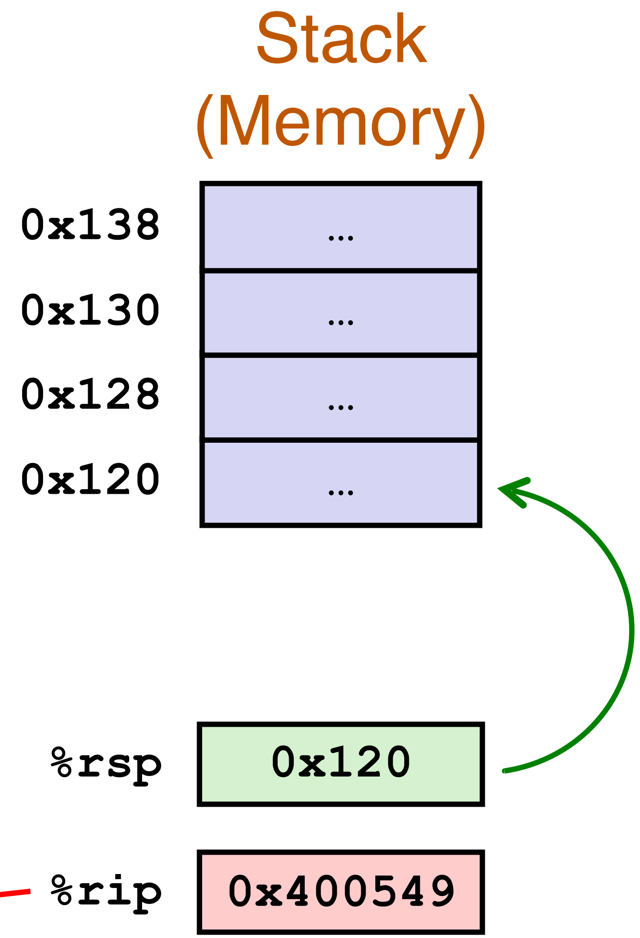

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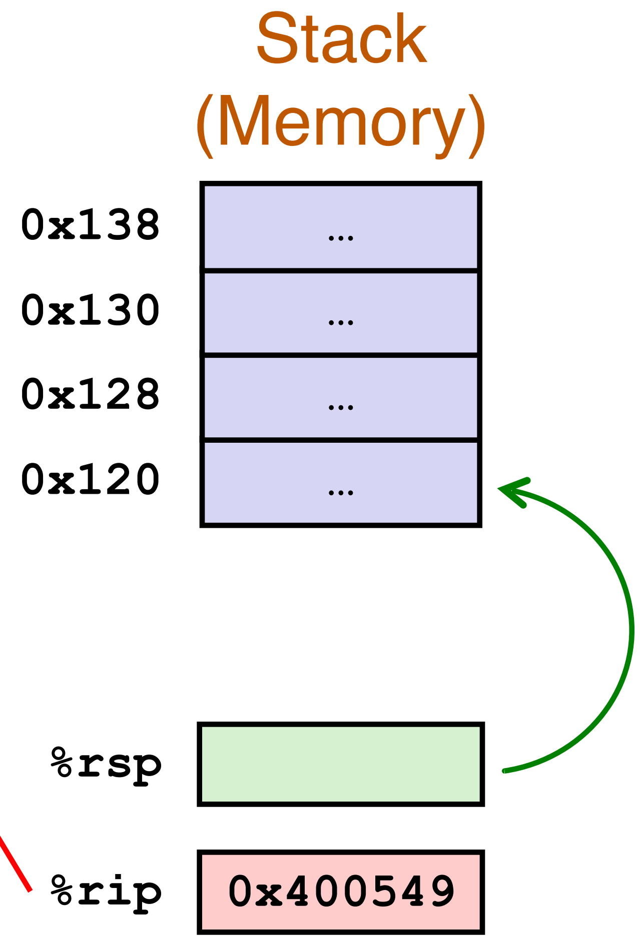
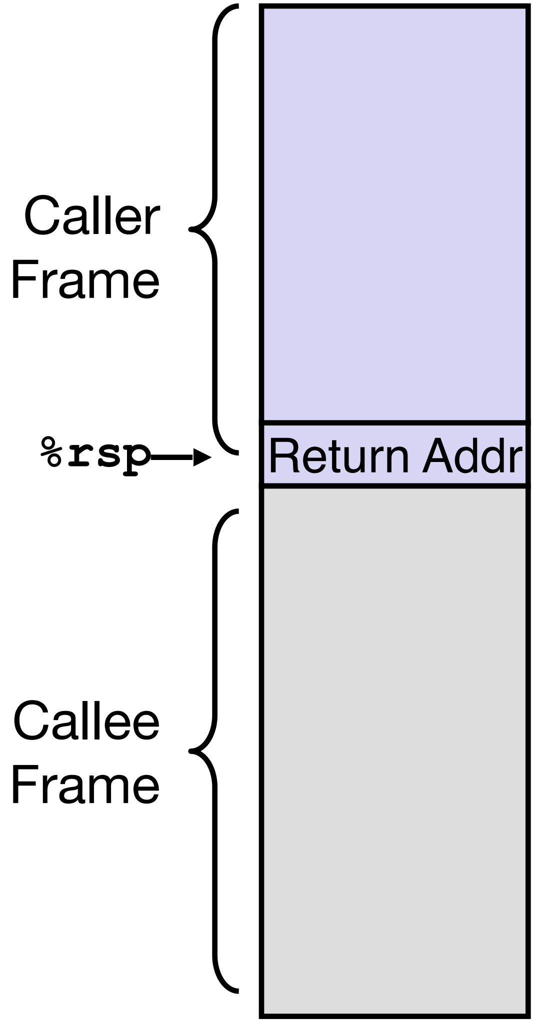


Stack Frame (So Far…)



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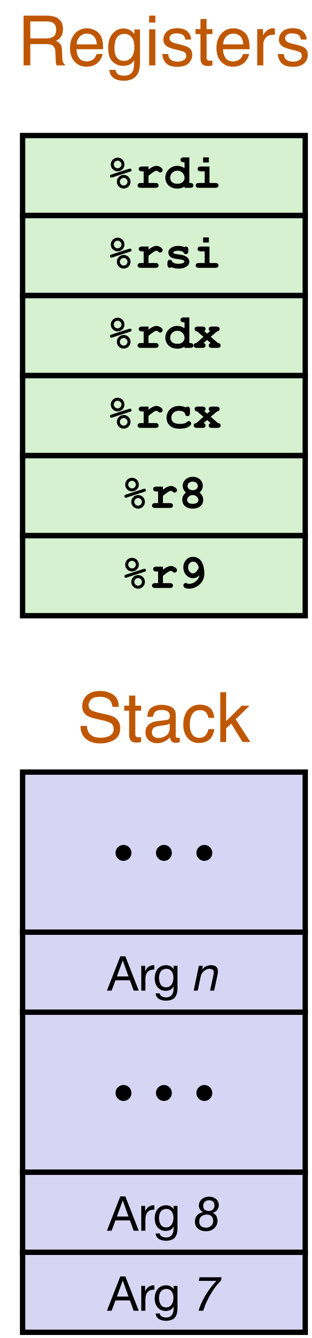

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  - First 6 arguments in registers, in specific order
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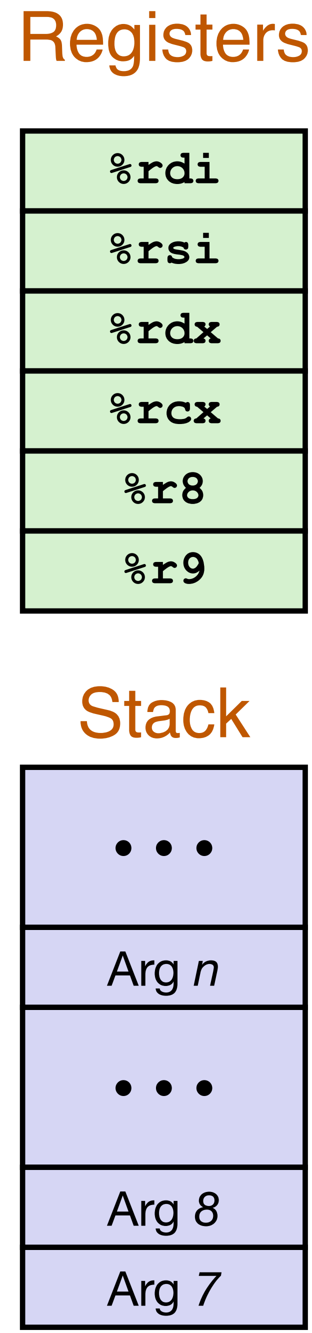
  - *Return value is always in* `%rax`
- Just conventions, not laws
  - Not necessary if you write both caller and callee as long as the caller and callee agree
  - But is necessary to interface with others' code



Function Call Data Flow Example

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%rdx
%rcx
%r8
%r9

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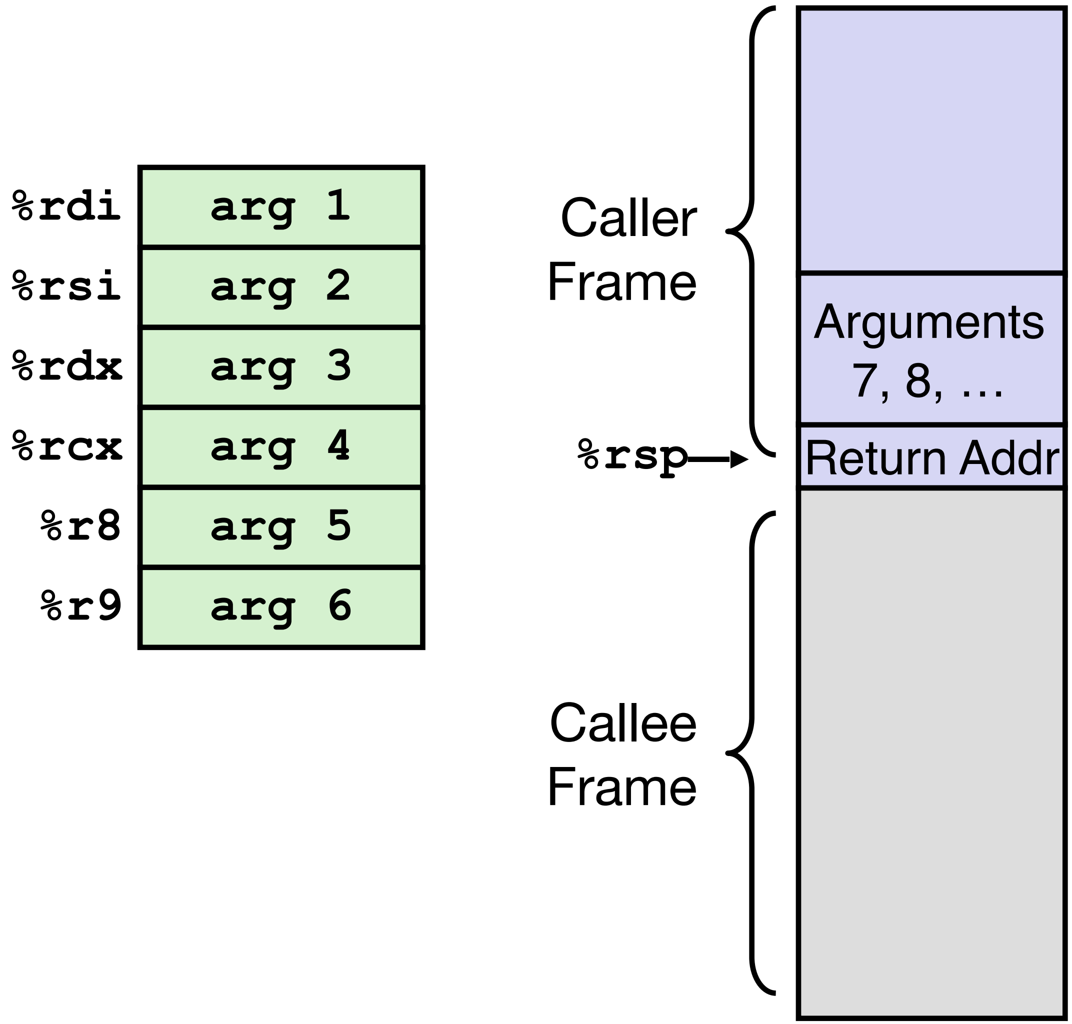
  # x in %rdi, y in %rsi, res in %rdx
…
  400541: movq    %rdx,%rbx
  400544: callq  400550 <mult2>
  # t in %rax
  400549: movq    %rax,(%rbx)
…
0000000000400550 <mult2>:
  # a in %rdi, b in %rsi
  400550:  movq   %rdi,%rax
  400553:  imul   %rsi,%rax
  # s in %rax
  400557:  retq
```

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. Take 255/455.

```
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

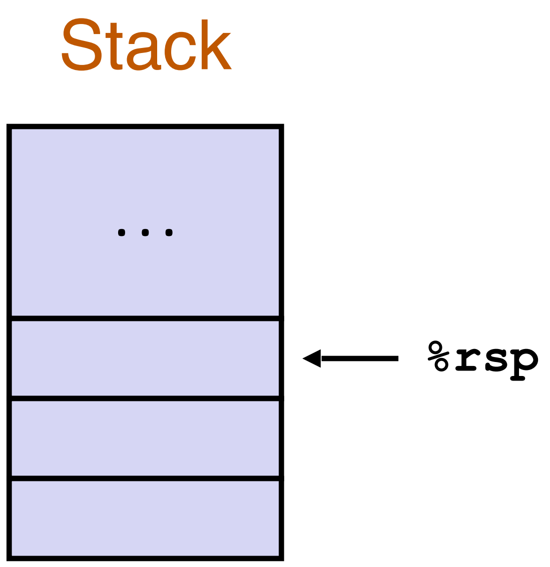
```
long incr(long *p, long val) {
    long x = *p;
    long y = x + val;
    *p = y;
    return x;
}
```

```
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 v2+v3;
}
```

```
call_add:
  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 v2 = 3000;
    long v3 = add(&v1, &v2);
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}
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call_add:
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  leaq    (%rsp), %rdi
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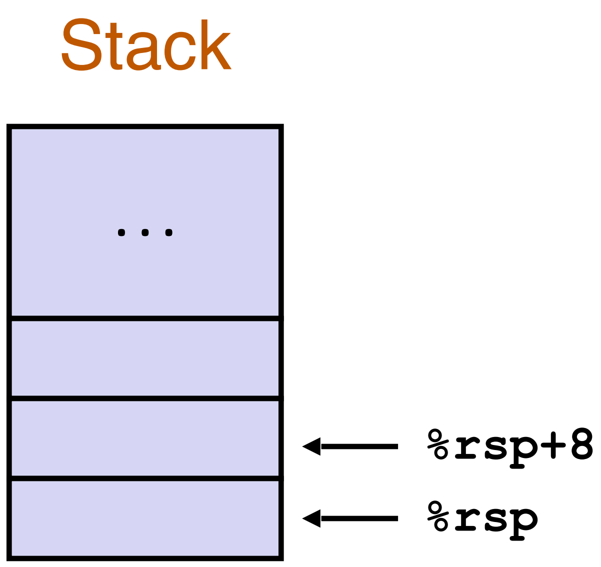
  call    add
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```



Stack Example: `call_add`

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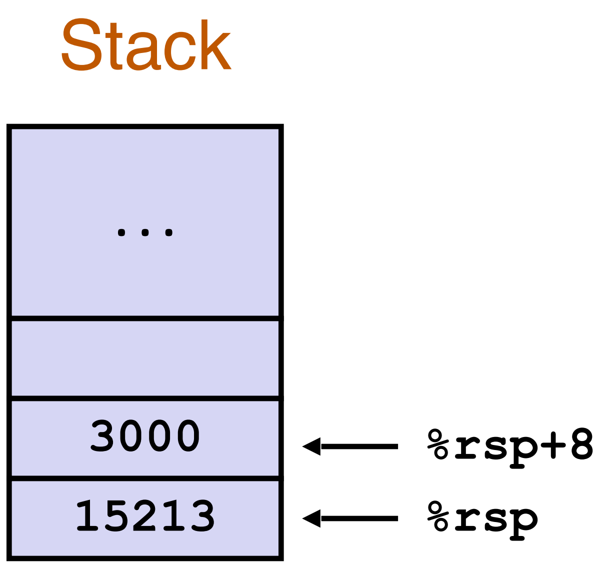
  call    add
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```



Stack Example: `call_add`

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

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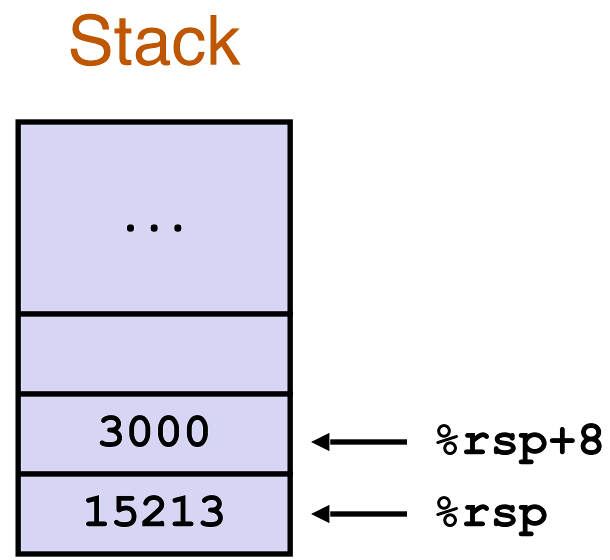
  leaq     (%rsp), %rdi
  leaq     8(%rsp), %rsi
  call     add
  addq     8(%rsp), %rax
  addq     $16, %rsp
  ret
```



Register	Value(s)
%rdi	&v1
%rsi	&v2

Stack Example: `call_add`

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

```
call_add:
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  leaq     (%rsp), %rdi
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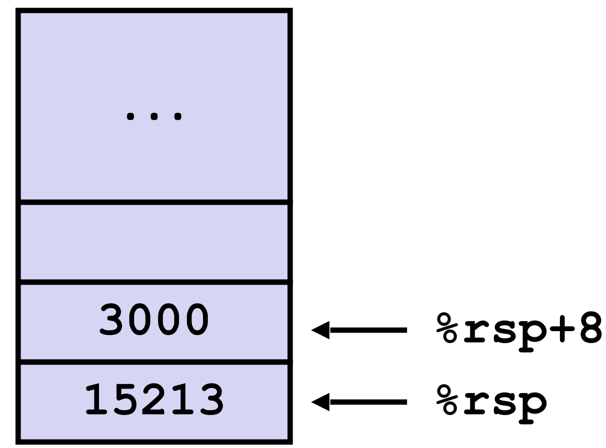
  addq     8(%rsp), %rax
  addq     $16, %rsp
  ret
```

Stack

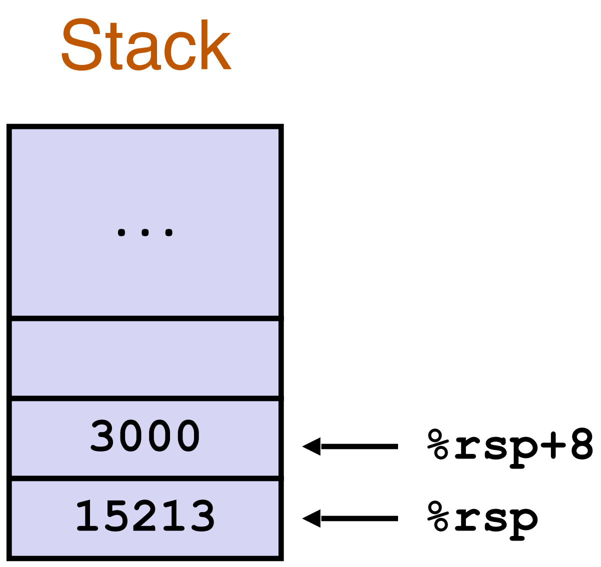


Register	Value(s)
%rdi	&v1
%rsi	&v2
%rax	18213

Stack Example: `call_add`

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

```
call_add:
  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
```

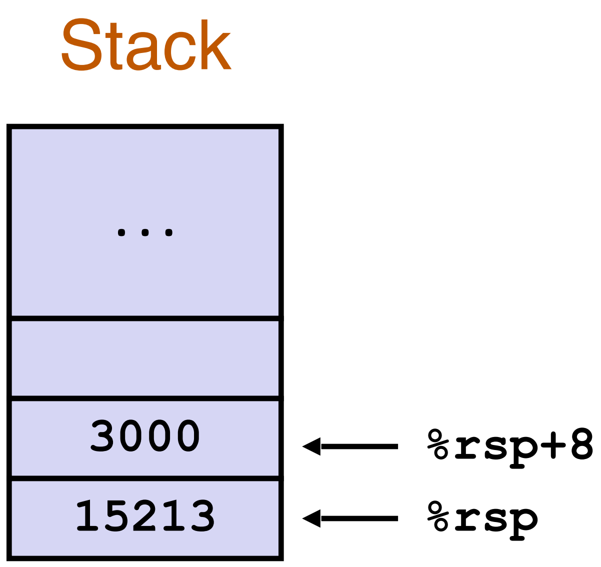


Register	Value(s)
%rdi	&v1
%rsi	&v2
%rax	21213

Stack Example: `call_add`

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

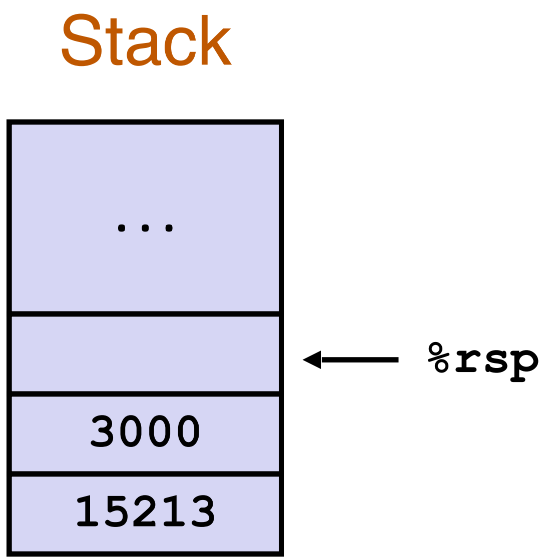
```
call_add:
  subq    $16, %rsp
  movq    $15213, (%rsp)
  movq    $3000, 8(%rsp)
  leaq    (%rsp), %rdi
  leaq    8(%rsp), %rsi
  call    add
  addq    8(%rsp), %rax
  addq    $16, %rsp
  ret
```



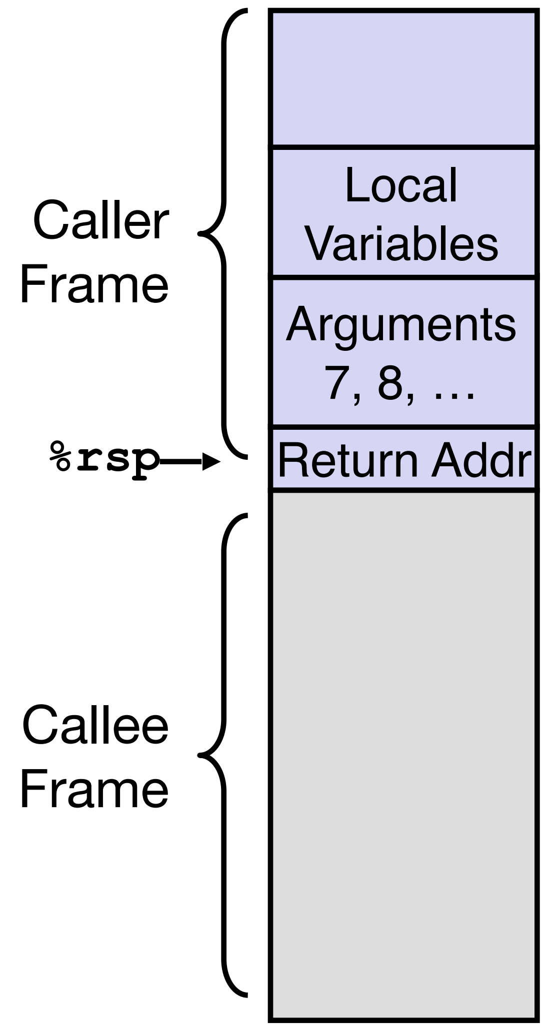
Stack Example: `call_add`

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

```
call_add:
  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

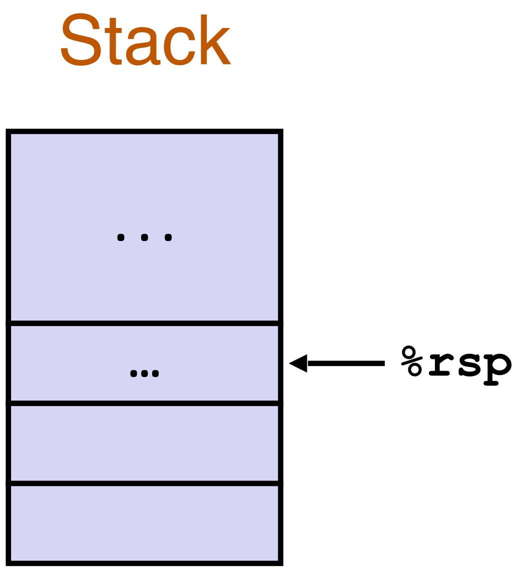
- Common conventions
  - "*Caller Saved*"
    - Caller saves temporary values in its frame (on the stack) before the call
    - Callee is then free to modify their values
  - "*Callee Saved*"
    - Callee saves temporary values in its frame before using
    - Callee restores them before returning to 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;
}
```

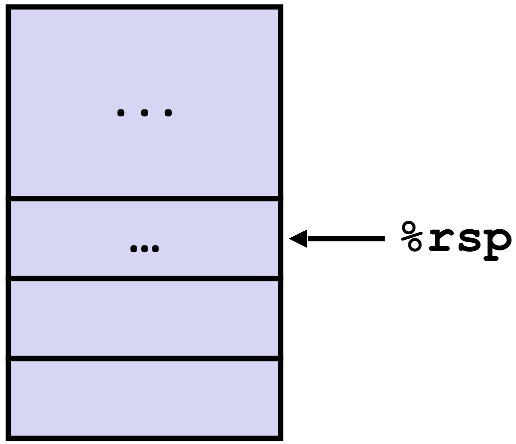


Example

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

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

Stack



Example

```
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    long v1 = 15213;
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  call    incr
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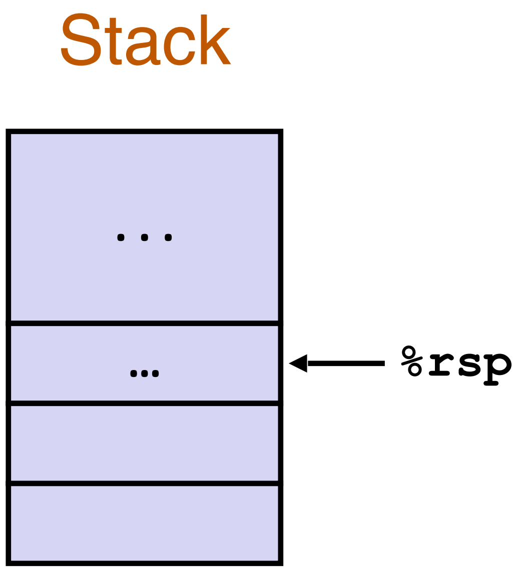
  ret
```



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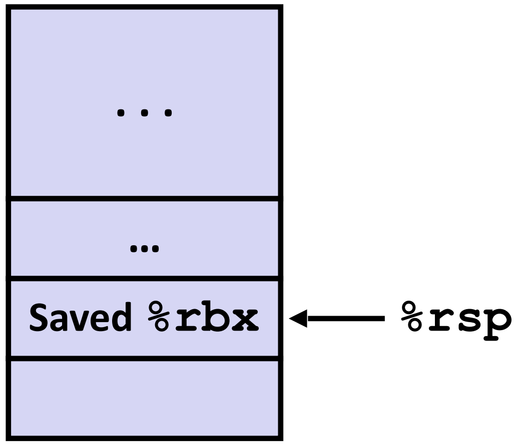
Stack



Example

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    long v1 = 15213;
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  call    incr
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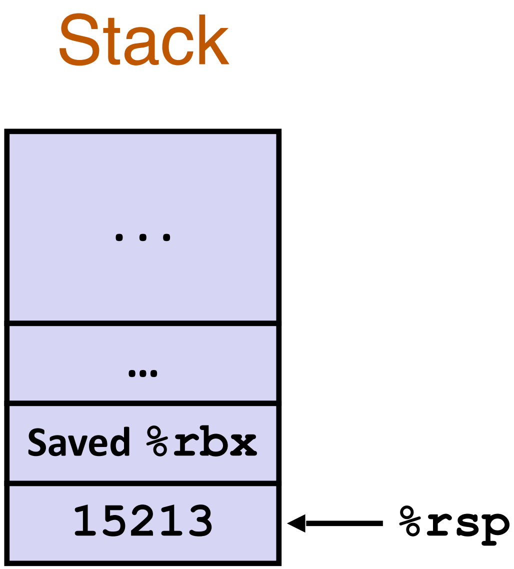
  ret
```



Example

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  addq    $8, %rsp
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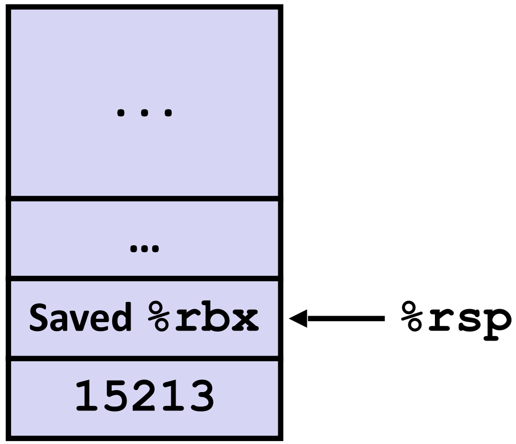
```

Stack



Example

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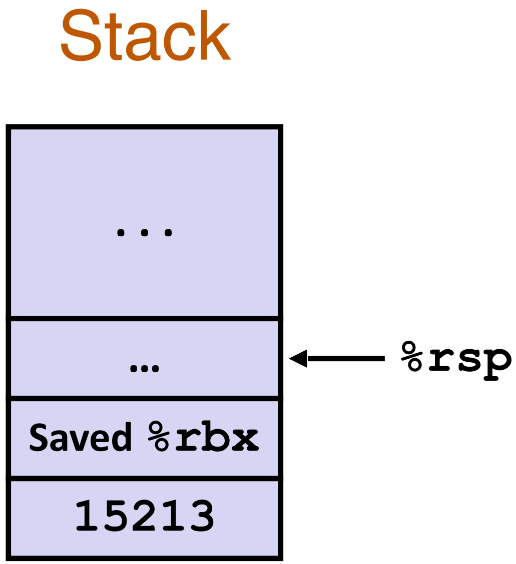

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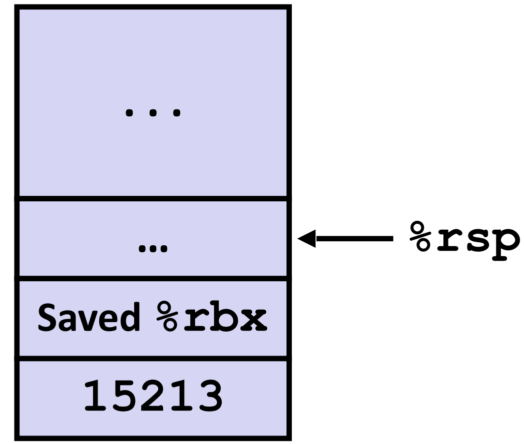
Stack



- `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