https://forms.gle/uGUBDvKyTuZHrrbK7

Code: mov

CS 107, Lecture 11
Assembly Continued

Reading: B&O 3.1-3.4

mov

The **mov** instruction copies bytes from one place to another;
it is similar to the assignment operator (=) in C.

```
mov        src,dst
```

The **src** and **dst** can each be one of:

- Immediate (constant value, like a number) (*only **src***) `$0x104`
- Register `%rbx`
- Memory Location (*at most one of **src, dst***) Direct address `0x6005c0`

Operand Forms: Immediate

```
mov        $0x104,_____
```

Copy the value 0x104 into some destination.

Operand Forms: Registers

Copy the value in register %rbx into some destination.

```
mov     %rbx,____

mov     ____,%rbx
```

Copy the value from some source into register %rbx.

Operand Forms: Absolute Addresses

Copy the value at address 0x104 into some destination.

```
mov     0x104,_____
```

```
mov     _____,0x104
```

Copy the value from some source into the memory at address 0x104.

Operand Forms: Indirect

Copy the value at the address stored in register %rbx into some destination.

```
mov        (%rbx),_____
```

```
mov        _____,(%rbx)
```

Copy the value from some source into the memory at the address stored in register %rbx.

Operand Forms: Base + Displacement

*Copy the value at the address (**<u>0x10 plus</u>** what is stored in register %rax) into some destination.*

```
mov     0x10(%rax),__________

mov     __________,0x10(%rax)
```

*Copy the value from some source into the memory at the address (**<u>0x10 plus</u>** what is stored in register %rax).*

Operand Forms: Indexed

Copy the value at the address which is (the sum of the values in registers %rax and %rdx) into some destination.

```
mov     (%rax,%rdx),__________

mov     __________,(%rax,%rdx)
```

Copy the value from some source into the memory at the address which is (the sum of the values in registers %rax and %rdx).

Operand Forms: Indexed

Copy the value at the address which is (the sum of ***0x10 plus*** *the values in registers %rax and %rdx) into some destination.*

```
mov      0x10(%rax,%rdx),______

mov      _______,0x10(%rax,%rdx)
```

Copy the value from some source into the memory at the address which is (the sum of ***0x10 plus*** *the values in registers %rax and %rdx).*

Practice #2: Operand Forms

What are the results of the following move instructions (executed separately)? For this problem, assume the value *0x11* is stored at address *0x10C*, *0xAB* is stored at address *0x104*, *0x100* is stored in register %rax and *0x3* is stored in %rdx.

1. `mov    $0x42,(%rax)`
2. `mov    4(%rax),%rcx`
3. `mov    9(%rax,%rdx),%rcx`

`Imm(`r_b`, `r_i`)` is equivalent to address `Imm + R[`r_b`] + R[`r_i`]`

Displacement: positive or negative constant (if missing, = 0)

Base: register (if missing, = 0)

Index: register (if missing, = 0)

Operand Forms: Scaled Indexed

*Copy the value at the address which is (**4 times** the value in register %rdx) into some destination.*

```
mov    (,%rdx,4),______
```

```
mov    ______,(,%rdx,4)
```

The *scaling factor* (e.g. 4 here) must be hardcoded to be either 1, 2, 4 or 8.

*Copy the value from some source into the memory at the address which is (**4 times** the value in register %rdx).*

Operand Forms: Scaled Indexed

*Copy the value at the address which is (4 times the value in register %rdx, **plus 0x4)**, into some destination.*

`mov 0x4(,%rdx,4),______`

`mov ______,0x4(,%rdx,4)`

*Copy the value from some source into the memory at the address which is (4 times the value in register %rdx, **plus 0x4).***

Operand Forms: Scaled Indexed

*Copy the value at the address which is (**the value in register %rax** plus 2 times the value in register %rdx) into some destination.*

```
mov      (%rax,%rdx,2),________
```

```
mov      ________,(%rax,%rdx,2)
```

*Copy the value from some source into the memory at the address which is (**the value in register %rax** plus 2 times the value in register %rdx).*

Operand Forms: Scaled Indexed

*Copy the value at the address which is (**0x4 plus** the value in register %rax plus 2 times the value in register %rdx) into some destination.*

```
mov     0x4(%rax,%rdx,2),_____
```

```
mov     ______,0x4(%rax,%rdx,2)
```

*Copy the value from some source into the memory at the address which is (**0x4 plus** the value in register %rax plus 2 times the value in register %rdx).*

Most General Operand Form

$Imm(r_b,r_i,s)$

is equivalent to…

$Imm + R[r_b] + R[r_i]*s$

Most General Operand Form

$\texttt{Imm(}r_b\texttt{, }r_i\texttt{, s)}$ is equivalent to address $\texttt{Imm + R[}r_b\texttt{] + R[}r_i\texttt{]*s}$

Displacement: pos/neg constant (if missing, = 0)

Base: register (if missing, = 0)

Index: register (if missing, = 0)

Scale must be 1,2,4, or 8 (if missing, = 1)

Operand Forms

Type	Form	Operand Value	Name
Immediate	$\$Imm$	Imm	Immediate
Register	$r_{!}$	$R[r_{!}]$	Register
Memory	Imm	$M[Imm]$	Absolute
Memory	$(r_{!})$	$M[R[r_{!}]]$	Indirect
Memory	$Imm(r_{"})$	$M[Imm + R[r_{"}]]$	Base + displacement
Memory	$(r_{"}, r_{\#})$	$M[R[r_{"}] + R[r_{\#}]]$	Indexed
Memory	$Imm(r_{"}, r_{\#})$	$M[Imm + R[r_{"}] + R[r_{\#}]]$	Indexed
Memory	$(, r_{\#}, s)$	$M[R[r_{\#}] \,.\, s]$	Scaled indexed
Memory	$Imm(, r_{\#}, s)$	$M[Imm + R[r_{\#}] \,.\, s]$	Scaled indexed
Memory	$(r_{"}, r_{\#}, s)$	$M[R[r_{"}] + R[r_{\#}] \,.\, s]$	Scaled indexed
Memory	$Imm(r_{"}, r_{\#}, s)$	$M[Imm + R[r_{"}] + R[r_{\#}] \,.\, s]$	Scaled indexed

Figure 3.3 from the book: "Operand forms. Operands can denote immediate (constant) values, register values, or values from memory. The scaling factor *s* must be either. 1, 2, 4, or 8."

Practice #3: Operand Forms

What are the results of the following move instructions (executed separately)? For this problem, assume the value *0x1* is stored in register %rcx, the value *0x100* is stored in register %rax, the value *0x3* is stored in register %rdx, and value *0x11* is stored at address *0x10C*.

1. `mov    $0x42,0xfc(,%rcx,4)`

2. `mov    (%rax,%rdx,4),%rbx`

Imm(r_b, r_i, s) is equivalent to address **Imm + R[r_b] + R[r_i]*s**

Displacement — Imm; Base — r_b; Index — r_i; Scale — s (1,2,4,8)

Goals of indirect addressing: C

Why are there so many forms of indirect addressing?

We see these indirect addressing paradigms in C as well!

Our First Assembly

```c
int sum_array(int arr[], int nelems) {
    int sum = 0;
    for (int i = 0; i < nelems; i++) {
        sum += arr[i];
    }
    return sum;
}
```

We're 1/4th of the way to understanding assembly!

What looks understandable right now?

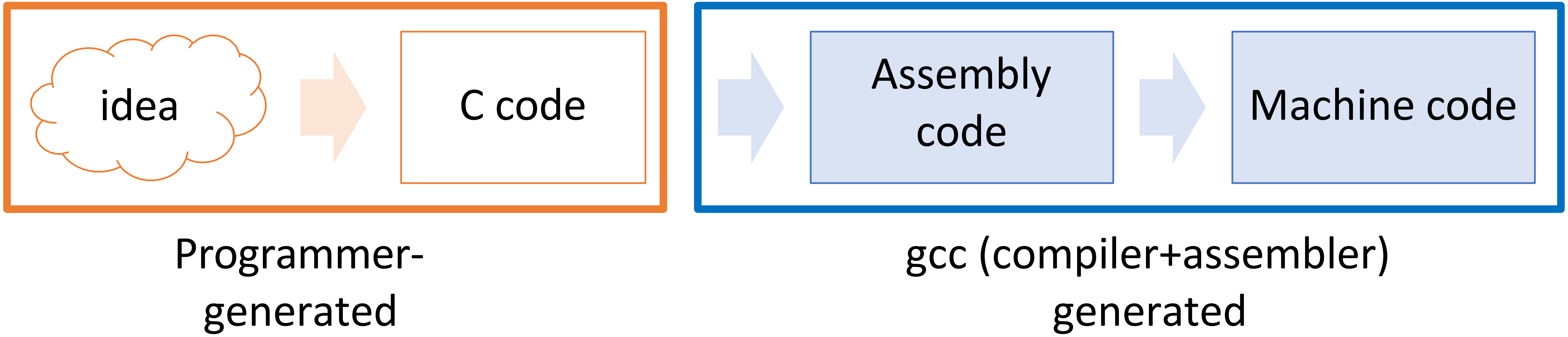
Some notes:

- Registers store addresses and values
- `mov src, dst` ***copies*** value into dst
- `sizeof(int)` is 4
- Instructions executed sequentially

```
00000000004005b6 <sum_array>:
  4005b6:     ba 00 00 00 00          mov    $0x0,%edx
  4005bb:     b8 00 00 00 00          mov    $0x0,%eax
  4005c0:     eb 09                   jmp    4005cb <sum_array+0x15>
  4005c2:     48 63 ca                movslq %edx,%rcx
  4005c5:     03 04 8f                add    (%rdi,%rcx,4),%eax
  4005c8:     83 c2 01                add    $0x1,%edx
                                      cmp    %esi,%edx
                                      jl     4005c2 <sum_array+0xc>
                                      repz retq
```

We'll come back to this example in future lectures!

Why are we reading assembly?



Main goal: Information retrieval

- We will not be writing assembly! (that’s the compiler’s job)
- Rather, we want to translate the assembly ***back*** into our C code.
- Knowing how our C code is converted into machine instructions gives us insight into how to write more efficient, cleaner code.

Extended warmup: Information Synthesis

Spend a few minutes thinking about the main paradigms of the `mov` instruction.

- What might be the equivalent C-like operation?
- Examples (note %r__ registers are 64-bit):

1. `mov      $0x0,%rdx`
2. `mov      %rdx,%rcx`
3. `mov      $0x42,(%rdi)`
4. `mov      (%rax,%rcx,8),%rax`

Extended warmup: Information Synthesis

Spend a few minutes thinking about the main paradigms of the mov instruction.

- What might be the equivalent C-like operation?
- Examples (note %r__ registers are 64-bit):

1. `mov $0x0,%rdx -> maybe long x = 0`
2. `mov %rdx,%rcx -> maybe long x = y;`
3. `mov $0x42,(%rdi) -> maybe *ptr = 0x42;`
4. `mov (%rax,%rcx,8),%rax -> maybe long x = arr[i];`

Indirect addressing is like pointer arithmetic/deref!

Lecture Plan

Reference Sheet: `cs107.stanford.edu/resources/x86-64-reference.pdf`
See more guides on Resources page of course website!

Helpful Assembly Resources

- **Course textbook** (reminder: see relevant readings for each lecture on the Schedule page, http://cs107.stanford.edu/schedule.html)
- **CS107 Assembly Reference Sheet:** http://cs107.stanford.edu/resources/x86-64-reference.pdf
- **CS107 Guide to x86-64**: http://cs107.stanford.edu/guide/x86-64.html

References and Advanced Reading

- References:
  - Stanford guide to x86-64: https://web.stanford.edu/class/cs107/guide/x86-64.html
  - CS107 one-page of x86-64: https://web.stanford.edu/class/cs107/resources/onepage_x86-64.pdf
  - gdbtui: https://beej.us/guide/bggdb/
  - More gdbtui: https://sourceware.org/gdb/onlinedocs/gdb/TUI.html
  - Compiler explorer: https://gcc.godbolt.org
- Advanced Reading:
  - x86-64 Intel Software Developer manual: https://software.intel.com/sites/default/files/managed/39/c5/325462-sdm-vol-1-2abcd-3abcd.pdf
  - history of x86 instructions: https://en.wikipedia.org/wiki/X86_instruction_listings
  - x86-64 Wikipedia: https://en.wikipedia.org/wiki/X86-64

Lecture Plan

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mov

The **mov** instruction copies bytes from one place to another;
it is similar to the assignment operator (=) in C.

```
mov        src,dst
```

The **src** and **dst** can each be one of:

- Immediate (constant value, like a number) (*only* ***src***)
- Register
- Memory Location
  (*at most one of* ***src, dst***)

Memory Location Syntax

Syntax	Meaning
0x104	Address 0x104 (no $)
(%rax)	What's in %rax
4(%rax)	What's in %rax, plus 4
(%rax, %rdx)	Sum of what's in %rax and %rdx
4(%rax, %rdx)	Sum of values in %rax and %rdx, plus 4
(, %rcx, 4)	What's in %rcx, times 4 (multiplier can be 1, 2, 4, 8)
(%rax, %rcx, 2)	What's in %rax, plus 2 times what's in %rcx
8(%rax, %rcx, 2)	What's in %rax, plus 2 times what's in %rcx, plus 8

Operand Forms

Type	Form	Operand Value	Name
Immediate	$\$Imm$	Imm	Immediate
Register	$r_{!}$	$R[r_{!}]$	Register
Memory	Imm	$M[Imm]$	Absolute
Memory	$(r_{!})$	$M[R[r_{!}]]$	Indirect
Memory	$Imm(r_{"})$	$M[Imm + R[r_{"}]]$	Base + displacement
Memory	$(r_{"}, r_{\#})$	$M[R[r_{"}] + R[r_{\#}]]$	Indexed
Memory	$Imm(r_{"}, r_{\#})$	$M[Imm + R[r_{"}] + R[r_{\#}]]$	Indexed
Memory	$(, r_{\#}, s)$	$M[R[r_{\#}] . s]$	Scaled indexed
Memory	$Imm(, r_{\#}, s)$	$M[Imm + R[r_{\#}] . s]$	Scaled indexed
Memory	$(r_{"}, r_{\#}, s)$	$M[R[r_{"}] + R[r_{\#}] . s]$	Scaled indexed
Memory	$Imm(r_{"}, r_{\#}, s)$	$M[Imm + R[r_{"}] + R[r_{\#}] . s]$	Scaled indexed

Figure 3.3 from the book: "Operand forms. Operands can denote immediate (constant) values, register values, or values from memory. The scaling factor *s* must be either. 1, 2, 4, or 8."

Lecture Plan

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See more guides on Resources page of course website!

Data Sizes

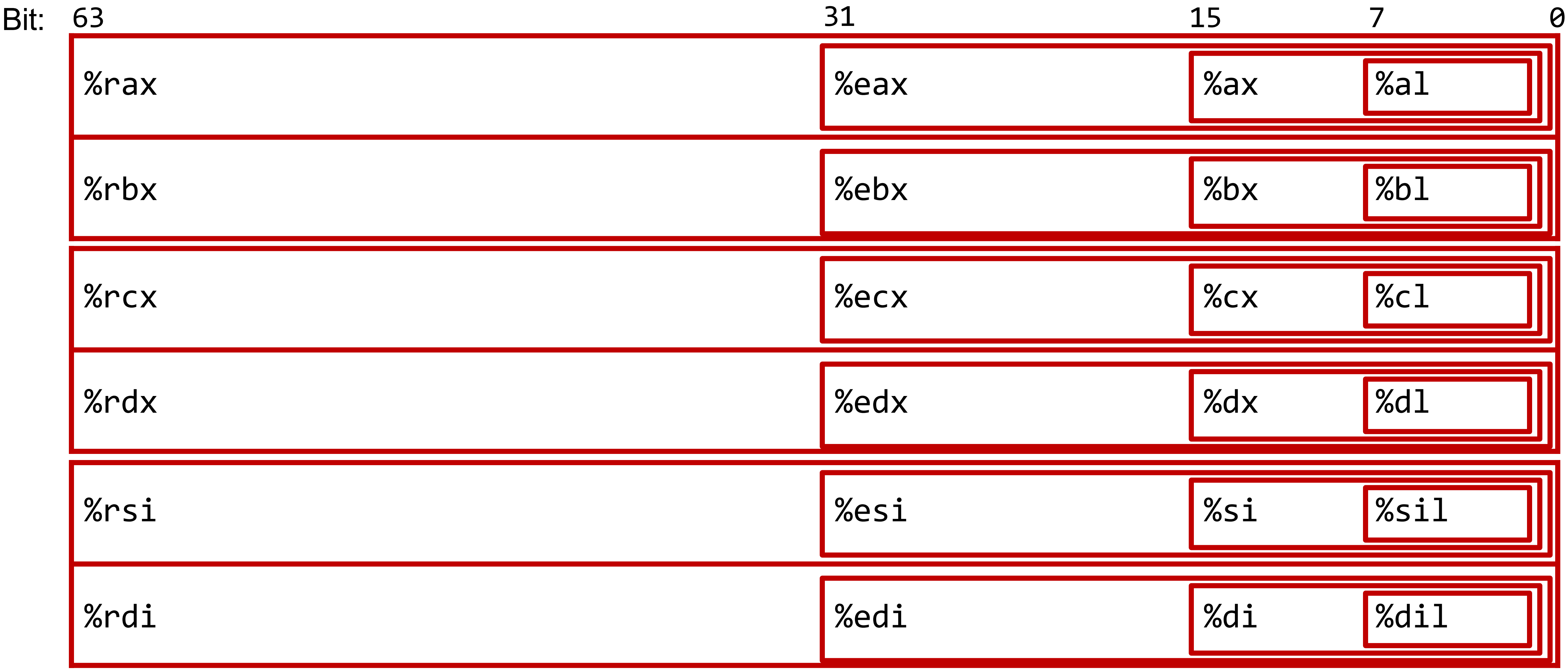
Data sizes in assembly have slightly different terminology to get used to:

- A **byte** is 1 byte.
- A **word** is 2 bytes.
- A **double word** is 4 bytes.
- A **quad word** is 8 bytes.

Assembly instructions can have suffixes to refer to these sizes:

- `b` means **byte**
- `w` means **word**
- `l` means **double word**
- `q` means **quad word**

Register Sizes



Register Sizes

Bit: 63	31	15	7 – 0
%rbp	%ebp	%bp	%bpl
%rsp	%esp	%sp	%spl
%r8	%r8d	%r8w	%r8b
%r9	%r9d	%r9w	%r9b
%r10	%r10d	%r10w	%r10b
%r11	%r11d	%r11w	%r11b

Register Sizes

Bit: 63	31	15	7 – 0
%r12	%r12d	%r12w	%r12b
%r13	%r13d	%r13w	%r13b
%r14	%r14d	%r14w	%r14b
%r15	%r15d	%r15w	%r15b

Register Responsibilities

Some registers take on special responsibilities during program execution.

- **%rax** stores the return value
- **%rdi** stores the first parameter to a function
- **%rsi** stores the second parameter to a function
- **%rdx** stores the third parameter to a function
- **%rip** stores the address of the next instruction to execute
- **%rsp** stores the address of the current top of the stack

Reference Sheet: `cs107.stanford.edu/resources/x86-64-reference.pdf`
See more guides on Resources page of course website!

mov Variants

- **mov** can take an optional suffix (b,w,l,q) that specifies the size of data to move: `movb, movw, movl, movq`
- **mov** only updates the specific register bytes or memory locations indicated.
  - **Exception: movl** writing to a register will also set high order 4 bytes to 0.

Practice: mov And Data Sizes

For each of the following mov instructions, determine the appropriate suffix based on the operands (e.g. **movb**, **movw**, **movl** or **movq**).

```
1. mov__ %eax, (%rsp)
2. mov__ (%rax), %dx
3. mov__ $0xff, %bl
4. mov__ (%rsp,%rdx,4),%dl
5. mov__ (%rdx), %rax
6. mov__ %dx, (%rax)
```

Practice: mov And Data Sizes

For each of the following mov instructions, determine the appropriate suffix based on the operands (e.g. **movb**, **movw**, **movl** or **movq**).

```
1. movl %eax, (%rsp)
2. movw (%rax), %dx
3. movb $0xff, %bl
4. movb (%rsp,%rdx,4),%dl
5. movq (%rdx), %rax
6. movw %dx, (%rax)
```

mov

- The **movabsq** instruction is used to write a 64-bit Immediate (constant) value.
- The regular **movq** instruction can only take 32-bit immediates.
- 64-bit immediate as source, only register as destination.

movabsq $0x0011223344556677, %rax

movz and movs

- There are two mov instructions that can be used to copy a smaller source to a larger destination: **movz** and **movs**.
- **movz** fills the remaining bytes with zeros
- **movs** fills the remaining bytes by sign-extending the most significant bit in the source.
- The source must be from memory or a register, and the destination is a register.

movz and movs

$$\texttt{MOVZ S,R} \qquad \texttt{R} \leftarrow \texttt{ZeroExtend(S)}$$

Instruction	Description
`movzbw`	Move zero-extended byte to word
`movzbl`	Move zero-extended byte to double word
`movzwl`	Move zero-extended word to double word
`movzbq`	Move zero-extended byte to quad word
`movzwq`	Move zero-extended word to quad word

movz and movs

`MOVS S,R` $\qquad$ `R ← SignExtend(S)`

Instruction	Description
`movsbw`	Move sign-extended byte to word
`movsbl`	Move sign-extended byte to double word
`movswl`	Move sign-extended word to double word
`movsbq`	Move sign-extended byte to quad word
`movswq`	Move sign-extended word to quad word
`movslq`	Move sign-extended double word to quad word
`cltq`	Sign-extend %eax to %rax `%rax <- SignExtend(%eax)`

Lecture Plan

Reference Sheet: `cs107.stanford.edu/resources/x86-64-reference.pdf`
See more guides on Resources page of course website!

lea

The **lea** instruction copies an "effective address" from one place to another.

```
lea        src,dst
```

Unlike **mov**, which copies data at the address src to the destination, **lea** copies the value of src *itself* to the destination.

The syntax for the destinations is the same as **mov**. The difference is how it handles the src.

lea vs. mov

Operands	mov Interpretation	lea Interpretation
`6(%rax), %rdx`	Go to the address (6 + what's in %rax), and copy data there into %rdx	Copy 6 + what's in %rax into %rdx.

lea vs. mov

Operands	mov Interpretation	lea Interpretation
`6(%rax), %rdx`	Go to the address (6 + what's in %rax), and copy data there into %rdx	Copy 6 + what's in %rax into %rdx.
`(%rax, %rcx), %rdx`	Go to the address (what's in %rax + what's in %rcx) and copy data there into %rdx	Copy (what's in %rax + what's in %rcx) into %rdx.

lea vs. mov

Operands	mov Interpretation	lea Interpretation
`6(%rax), %rdx`	Go to the address (6 + what's in %rax), and copy data there into %rdx	Copy 6 + what's in %rax into %rdx.
`(%rax, %rcx), %rdx`	Go to the address (what's in %rax + what's in %rcx) and copy data there into %rdx	Copy (what's in %rax + what's in %rcx) into %rdx.
`(%rax, %rcx, 4), %rdx`	Go to the address (%rax + 4 * %rcx) and copy data there into %rdx.	Copy (%rax + 4 * %rcx) into %rdx.

lea vs. mov

Operands	mov Interpretation	lea Interpretation
`6(%rax), %rdx`	Go to the address (6 + what's in %rax), and copy data there into %rdx	Copy 6 + what's in %rax into %rdx.
`(%rax, %rcx), %rdx`	Go to the address (what's in %rax + what's in %rcx) and copy data there into %rdx	Copy (what's in %rax + what's in %rcx) into %rdx.
`(%rax, %rcx, 4), %rdx`	Go to the address (%rax + 4 * %rcx) and copy data there into %rdx.	Copy (%rax + 4 * %rcx) into %rdx.
`7(%rax, %rax, 8), %rdx`	Go to the address (7 + %rax + 8 * %rax) and copy data there into %rdx.	Copy (7 + %rax + 8 * %rax) into %rdx.

Unlike **mov**, which copies data at the address src to the destination, **lea** copies the value of src *itself* to the destination.

Lecture Plan

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Unary Instructions

The following instructions operate on a single operand (register or memory):

Instruction	Effect	Description
`inc D`	D ← D + 1	Increment
`dec D`	D ← D - 1	Decrement
`neg D`	D ← -D	Negate
`not D`	D ← ~D	Complement

Examples:

```
incq 16(%rax)
dec %rdx
not %rcx
```

Binary Instructions

The following instructions operate on two operands (both can be register or memory, source can also be immediate). Both cannot be memory locations. Read it as, e.g. “Subtract S from D”:

Instruction	Effect	Description
`add S, D`	D ← D + S	Add
`sub S, D`	D ← D - S	Subtract
`imul S, D`	D ← D * S	Multiply
`xor S, D`	D ← D ^ S	Exclusive-or
`or S, D`	D ← D | S	Or
`and S, D`	D ← D & S	And

Examples:

```
addq %rcx,(%rax)
xorq $16,(%rax, %rdx, 8)
subq %rdx,8(%rax)
```

Large Multiplication

- Multiplying 64-bit numbers can produce a 128-bit result. How does x86-64 support this with only 64-bit registers?
- If you specify two operands to **imul**, it multiplies them together and truncates until it fits in a 64-bit register.

```
imul S, D        D ← D * S
```

- If you specify one operand, it multiplies that by **%rax**, and splits the product across **2** registers. It puts the high-order 64 bits in **%rdx** and the low-order 64 bits in **%rax**.

Instruction	Effect	Description
`imulq S`	`R[%rdx]:R[%rax] ← S x R[%rax]`	Signed full multiply
`mulq S`	`R[%rdx]:R[%rax] ← S x R[%rax]`	Unsigned full multiply

Division and Remainder

Instruction	Effect	Description
`idivq S`	`R[%rdx] ← R[%rdx]:R[%rax] mod S;` `R[%rax] ← R[%rdx]:R[%rax] ÷ S`	Signed divide
`divq S`	`R[%rdx] ← R[%rdx]:R[%rax] mod S;` `R[%rax] ← R[%rdx]:R[%rax] ÷ S`	Unsigned divide

- Terminology: **dividend / divisor = quotient + remainder**
- **x86-64** supports dividing up to a 128-bit value by a 64-bit value.
- The high-order 64 bits of the dividend are in **%rdx**, and the low-order 64 bits are in **%rax**. The divisor is the operand to the instruction.
- The quotient is stored in **%rax**, and the remainder in **%rdx**.

Division and Remainder

Instruction	Effect	Description
`idivq S`	`R[%rdx] ← R[%rdx]:R[%rax] mod S;` `R[%rax] ← R[%rdx]:R[%rax] ÷ S`	Signed divide
`divq S`	`R[%rdx] ← R[%rdx]:R[%rax] mod S;` `R[%rax] ← R[%rdx]:R[%rax] ÷ S`	Unsigned divide
`cqto`	`R[%rdx]:R[%rax] ← SignExtend(R[%rax])`	Convert to oct word

- Terminology: **dividend / divisor = quotient + remainder**
- The high-order 64 bits of the dividend are in **%rdx**, and the low-order 64 bits are in **%rax**. The divisor is the operand to the instruction.
- Most division uses only 64-bit dividends. The **cqto** instruction sign-extends the 64-bit value in **%rax** into **%rdx** to fill both registers with the dividend, as the division instruction expects.

Shift Instructions

The following instructions have two operands: the shift amount **k** and the destination to shift, **D**. **k** can be either an immediate value, or the byte register **%cl** (and only that register!)

Instruction	Effect	Description
`sal k, D`	$D \leftarrow D << k$	Left shift
`shl k, D`	$D \leftarrow D << k$	Left shift (same as `sal`)
`sar k, D`	$D \leftarrow D >>_A k$	Arithmetic right shift
`shr k, D`	$D \leftarrow D >>_L k$	Logical right shift

Examples:

```
shll $3,(%rax)
shrl %cl,(%rax,%rdx,8)
sarl $4,8(%rax)
```

Shift Amount

Instruction	Effect	Description
`sal k, D`	D ← D << k	Left shift
`shl k, D`	D ← D << k	Left shift (same as `sal`)
`sar k, D`	$D \leftarrow D >>_A k$	Arithmetic right shift
`shr k, D`	$D \leftarrow D >>_L k$	Logical right shift

- When using **%cl**, the width of what you are shifting determines what portion of **%cl** is used.
- For **w** bits of data, it looks at the low-order **log2(w)** bits of **%cl** to know how much to shift.
  - If **%cl** = 0xff, then: **shlb** shifts by 7 because it considers only the low-order log2(8) = 3 bits, which represent 7. **shlw** shifts by 15 because it considers only the low-order log2(16) = 4 bits, which represent 15.

Lecture Plan

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Assembly Exploration

- Let’s pull these commands together and see how some C code might be translated to assembly.
- Compiler Explorer is a handy website that lets you quickly write C code and see its assembly translation. Let’s check it out!
- https://godbolt.org/z/WPzz6G4a9

Code Reference: add_to_first

```
// Returns the sum of x and the first element in
arr
int add_to_first(int x, int arr[]) {
    int sum = x;
    sum += arr[0];
    return sum;
}

----------

add_to_first:
  movl %edi, %eax
  addl (%rsi), %eax
  ret
```

Code Reference: full_divide

```
// Returns x/y, stores remainder in location stored in
remainder_ptr
long full_divide(long x, long y, long *remainder_ptr) {
    long quotient = x / y;
    long remainder = x % y;
    *remainder_ptr = remainder;
    return quotient;
}
-------

full_divide:
  movq %rdi, %rax
  movq %rdx, %rcx
  cqto
  idivq %rsi
  movq %rdx, (%rcx)
  ret
```

Assembly Exercise 1

```
000000000040116e <sum_example1>:
  40116e: 8d 04 37              lea   (%rdi,%rsi,1),%eax
  401171: c3                    retq
```

Which of the following is most likely to have generated the above assembly?

```
// A)
void sum_example1() {
    int x;
    int y;
    int sum = x + y;
}
```

```
// B)
int sum_example1(int x, int y) {
    return x + y;
}
```

```
// C)
void sum_example1(int x, int y) {
    int sum = x + y;
}
```

Assembly Exercise 1

```
000000000040116e <sum_example1>:
  40116e: 8d 04 37        lea   (%rdi,%rsi,1),%eax
  401171: c3              retq
```

Which of the following is most likely to have generated the above assembly?

```
// A)
void sum_example1() {
    int x;
    int y;
    int sum = x + y;
}
```

```
// B)
int sum_example1(int x, int y) {
    return x + y;
}
```

```
// C)
void sum_example1(int x, int y) {
    int sum = x + y;
}
```

Assembly Exercise 2

```
0000000000401172 <sum_example2>:
      401172: 8b 47 0c        mov   0xc(%rdi),%eax
      401175: 03 07           add   (%rdi),%eax
      401177: 2b 47 18        sub   0x18(%rdi),%eax
      40117a: c3              retq
```

```c
int sum_example2(int arr[]) {
    int sum = 0;
    sum += arr[0];
    sum += arr[3];
    sum -= arr[6];
    return sum;
}
```

What location or value in the assembly above represents the C code's **sum** variable?

Assembly Exercise 2

```
0000000000401172 <sum_example2>:
    401172: 8b 47 0c       mov  0xc(%rdi),%eax
    401175: 03 07          add  (%rdi),%eax
    401177: 2b 47 18       sub  0x18(%rdi),%eax
    40117a: c3             retq
```

```
int sum_example2(int arr[]) {
    int sum = 0;
    sum += arr[0];
    sum += arr[3];
    sum -= arr[6];
    return sum;
}
```

What location or value in the assembly above represents the C code's **sum** variable?

%eax

Assembly Exercise 3

```
0000000000401172 <sum_example2>:
      401172: 8b 47 0c       mov   0xc(%rdi),%eax
      401175: 03 07          add   (%rdi),%eax
      401177: 2b 47 18       sub   0x18(%rdi),%eax
      40117a: c3             retq
```

```c
int sum_example2(int arr[]) {
    int sum = 0;
    sum += arr[0];
    sum += arr[3];
    sum -= arr[6];
    return sum;
}
```

What location or value in the assembly code above represents the C code's **6** (as in **arr[6]**)?

Assembly Exercise 3

```
0000000000401172 <sum_example2>:
      401172: 8b 47 0c        mov   0xc(%rdi),%eax
      401175: 03 07           add   (%rdi),%eax
      401177: 2b 47 18        sub   0x18(%rdi),%eax
      40117a: c3              retq
```

```c
int sum_example2(int arr[]) {
    int sum = 0;
    sum += arr[0];
    sum += arr[3];
    sum -= arr[6];
    return sum;
}
```

What location or value in the assembly code above represents the C code's **6** (as in **arr[6]**)?

0x18

Our First Assembly

```
int sum_array(int arr[], int nelems) {
    int sum = 0;
    for (int i = 0; i < nelems; i++) {
        sum += arr[i];
    }
    return sum;
}
```

We're 1/2 of the way to understanding assembly!

What looks understandable right now?

```
0000000000401136 <sum_array>:
  401136:      b8 00 00 00 00          mov    $0x0,%eax
  40113b:      ba 00 00 00 00          mov    $0x0,%edx
  401140:      39 f0                   cmp    %esi,%eax
  401142:      7d 0b                   jge    40114f <sum_array+0x19>
  401144:      48 63 c8                movslq %eax,%rcx
  401147:      03 14 8f                add    (%rdi,%rcx,4),%edx
  40114a:      83 c0 01                add    $0x1,%eax
  40114d:      eb f1                   jmp    401140 <sum_array+0xa>
  40114f:      89 d0                   mov    %edx,%eax
  401151:      c3                      retq
```

A Note About Operand Forms

- Many instructions share the same address operand forms that **mov** uses.
  - Eg. 7(%rax, %rcx, 2).
- These forms work the same way for other instructions, e.g. sub:
  - sub 8(%rax,%rdx),%rcx -> Go to 8 + %rax + %rdx, subtract what's there from %rcx
- The exception is **lea:**
  - It interprets this form as just the calculation, *not the dereferencing*
  - lea 8(%rax,%rdx),%rcx -> Calculate 8 + %rax + %rdx, put it in %rcx

Extra Practice

https://godbolt.org/z/hGKPWszq4

Learning Goals

- Learn about how assembly stores comparison and operation results in condition codes
- Understand how assembly implements loops and control flow

Executing Instructions

What does it mean for a program to execute?

Executing Instructions

So far:

- Program values can be stored in memory or registers.
- Assembly instructions read/write values back and forth between registers (on the CPU) and memory.
- Assembly instructions are also stored in memory.

Today:

- **Who controls the instructions**?
  How do we know what to do now or next?

Answer:

- The **program counter** (PC), %rip.

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

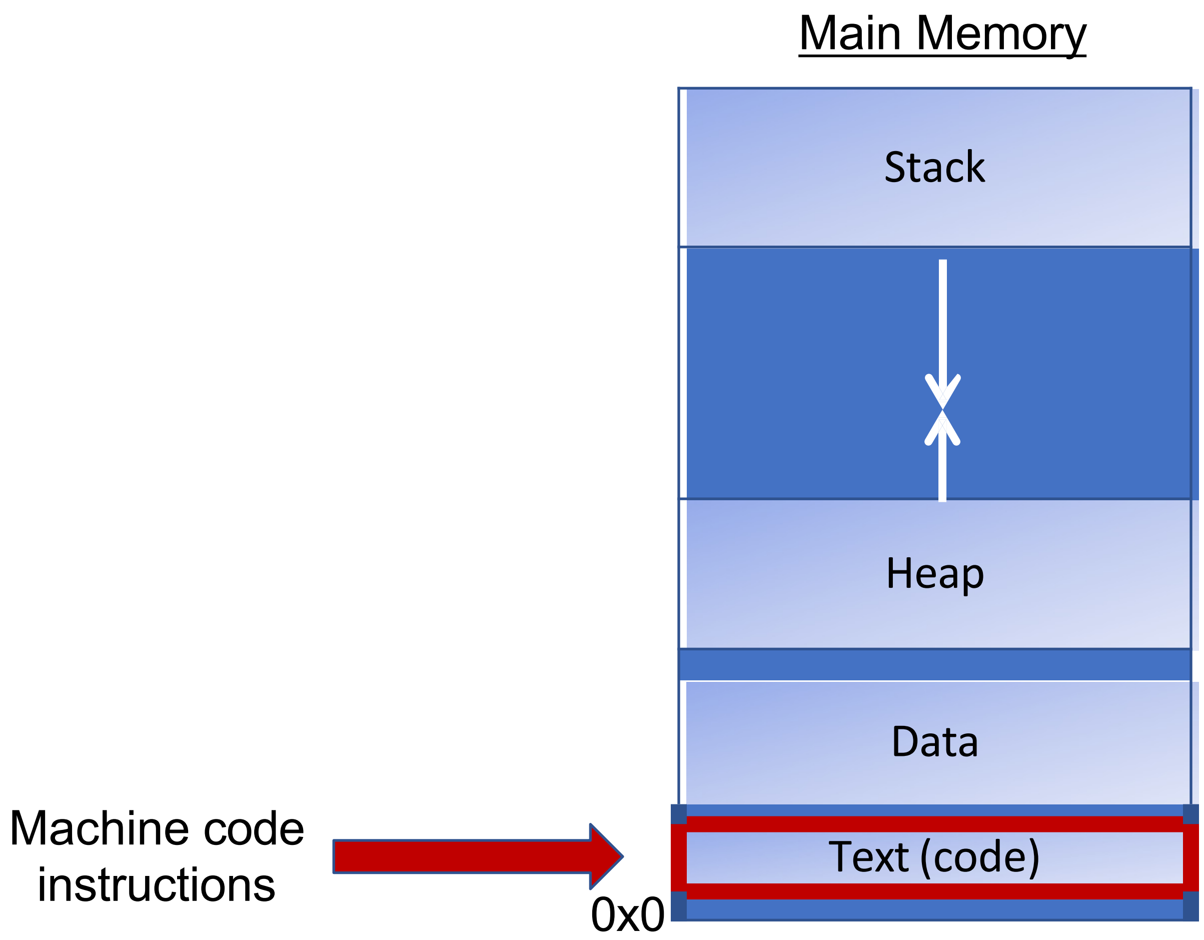
Register Responsibilities

Some registers take on special responsibilities during program execution.

- **%rax** stores the return value
- **%rdi** stores the first parameter to a function
- **%rsi** stores the second parameter to a function
- **%rdx** stores the third parameter to a function
- **%rip** stores the address of the next instruction to execute
- **%rsp** stores the address of the current top of the stack

See the x86-64 Guide and Reference Sheet on the Resources webpage for more!

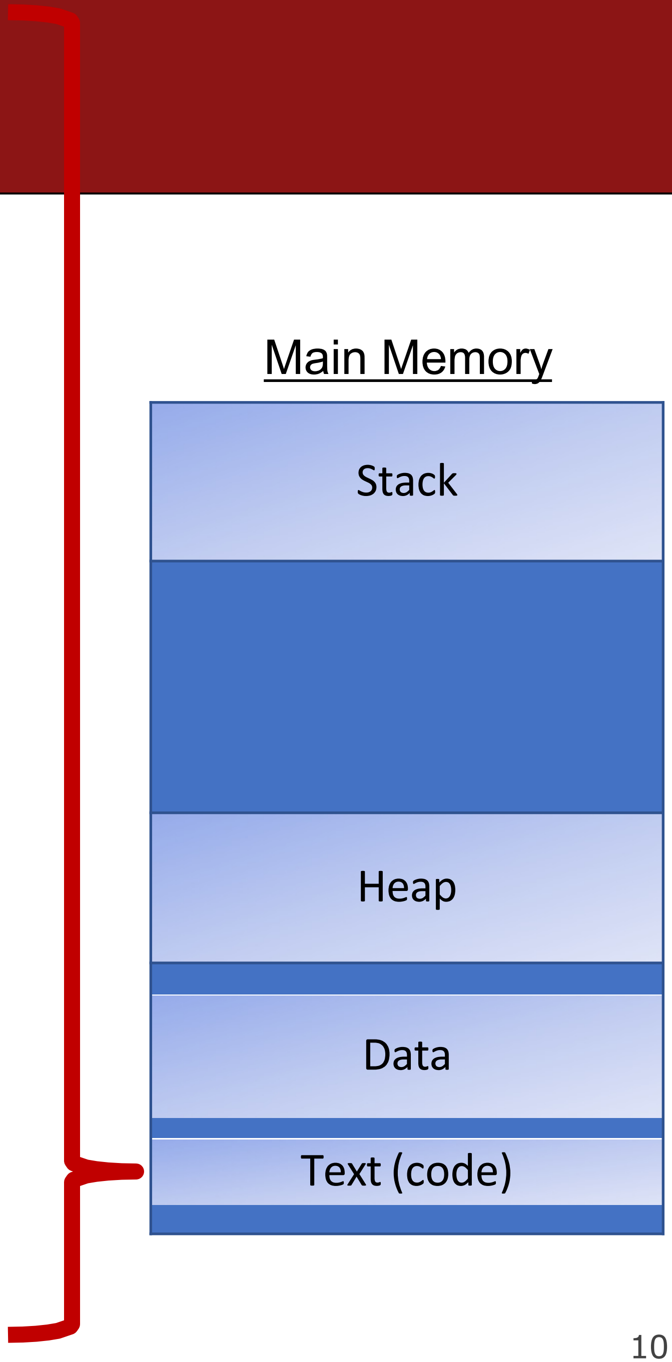
Instructions Are Just Bytes!



%ri

```
00000000004004ed <loop>:
4004ed: 55                    push   %rbp
4004ee: 48 89 e5              mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00  movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01           addl   $0x1,-0x4(%rbp)
4004fc: eb fa                 jmp    4004f8 <loop+0xb>
```

	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55



%rip

```
00000000004004ed <loop>:
4004ed: 55                    push   %rbp
4004ee: 48 89 e5              mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00  movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01           addl   $0x1,-0x4(%rbp)
4004fc: eb fa                 jmp    4004f8 <loop+0xb>
```

The **program counter** (PC), known as %rip in x86-64, stores the address in memory of the ***next instruction*** to be executed.

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

`0x4004ed`

%rip

%rip

```
0000000004004ed <loop>:
4004ed: 55                    push   %rbp
4004ee: 48 89 e5              mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00  movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01           addl   $0x1,-0x4(%rbp)
4004fc: eb fa                 jmp    4004f8 <loop+0xb>
```

The **program counter** (PC), known as %rip in x86-64, stores the address in memory of the ***next instruction*** to be executed.

`0x4004ee`

%rip

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

%rip

```
0000000004004ed <loop>:
4004ed: 55                      push   %rbp
4004ee: 48 89 e5                mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
4004fc: eb fa                   jmp    4004f8 <loop+0xb>
```

4004fd	fa
4004fc	eb
4004fb	01
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4004f9	45
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4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

The **program counter** (PC), known as %rip in x86-64, stores the address in memory of the ***next instruction*** to be executed.

0x4004f1

%rip

%rip

```
00000000004004ed <loop>:
4004ed: 55                    push   %rbp
4004ee: 48 89 e5              mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00  movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01           addl   $0x1,-0x4(%rbp)
4004fc: eb fa                 jmp    4004f8 <loop+0xb>
```

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

The **program counter** (PC), known as %rip in x86-64, stores the address in memory of the ***next instruction*** to be executed.

0x4004f8

%rip

%rip

```
00000000004004ed <loop>:
4004ed: 55                      push   %rbp
4004ee: 48 89 e5                mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
4004fc: eb fa                   jmp    4004f8 <loop+0xb>
```

The **program counter** (PC), known as %rip in x86-64, stores the address in memory of the ***next instruction*** to be executed.

`0x4004fc`

%rip

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

%rip

```
0000000004004ed <loop>:
4004ed: 55                    push   %rbp
4004ee: 48 89 e5              mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00  movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01           addl   $0x1,-0x4(%rbp)
4004fc: eb fa                 jmp    4004f8 <loop+0xb>
```

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

Special hardware sets the program counter to the next instruction:

%rip += size of bytes of current instruction

0x4004fc

%rip