CS107, Lecture 10
Introduction to Assembly

Reading: B&O 3.1-3.4

This document is copyright (C) Stanford Computer Science, Lisa Yan, and Nick Troccoli, licensed under Creative Commons Attribution 2.5 License. All rights reserved.
Based on slides created by Marty Stepp, Cynthia Lee, Chris Gregg, and others.

Attendance

https://forms.gle/jvUDKCbY9FHbFd5n9

What is Assembly Code?

- Computers execute "machine code," which is a sequence of bytes that encode low-level operations for manipulating data, managing memory, read and write from storage, and communicate with networks.
- The "assembly code" for a computer is a textual representation of the machine code giving the individual instructions to the underlying machine.

What is Assembly Code?

- `gcc` generates assembly code from C code
- Assembly is raw — there is no type checking, and the instructions are simple. It is unique to the type of processor (e.g., the assembly for your computer cannot run on your phone)
- Humans can write assembly (and, in fact, in the early days of computing they had to write assembly), but it is more productive to be able to read and understand what the compiler produces, than to write it by hand.
- `gcc` is almost always going to produce better optimized code than a human could, and understanding what the compiler produces is important.

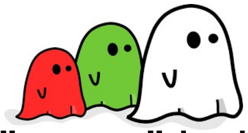
x86 Assembly

- The Intel-based computers we use are direct descendants of Intel's 16-bit, 1978 processor with the name 8086.
- Intel has taken a strict backwards-compatibility approach to new processors, and their 32- and 64-bit processors have built upon the original 8086 Assembly code.
- These days, when we learn x86 assembly code, we have to keep this history in mind. Naming of "registers," for example, has historical roots, so bear with it.

Machine-Level Code

- Before we look at some assembly code, let's talk about some things that have been hidden from us when writing C code.
- Machine code is based on the "instruction set architecture" (ISA), which defines the behavior and layout of the system. Behavior is defined as if instructions are run one after the other, and memory appears as a very large byte array.

Machine-Level Code

- New things that have been hidden: 
  - The *program counter* (PC), called "`%rip`" indicates the address of the next instruction ("r"egister "i"nstruction "p"ointer". We cannot modify this directly.
  - The "register file" contains 16 named locations that store 64-bit values.
    Registers are the fastest memory on your computer. They *are not* in main memory, and *do not* have addresses. You cannot pass a pointer to a register, but a pointer may *hold* a register as its value.
    - Registers can hold addresses, or integer data. Some registers are used to keep track of your program's state, and others hold temporary data.
    - Registers are used for arithmetic, local variables, and return values for functions.
  - The condition code registers hold status information about the most recently executed arithmetic or logical instruction. These are used to control program flow — e.g., if the result of an addition is negative, exit a loop.
  - There are vector registers, which hold integer or floating point values.

Machine-Level Code

- Unlike C, there is no model of different data types, and memory is simply a large, byte-addressable array.

- There is no distinction between signed and unsigned integers, between different types of pointers, or even between pointers and integers.

- A single machine instruction performs only a very elementary operation. For example:
  - there is an instruction to add two numbers in registers. That's all the instruction does.
  - there is an instruction that transfers data between a register and memory.
  - there is an instruction that conditionally branches to a new instruction address.

- Often, one C statement generates multiple assembly code instructions.

Learning Goals

- Learn what assembly language is and why it is important
- Become familiar with the format of human-readable assembly and x86
- Learn the **mov** instruction and how data moves around at the assembly level

Lecture Plan

- **Overview:** GCC and Assembly
- **Demo:** Looking at an executable
- Registers and The Assembly Level of Abstraction
- The **mov** Instruction
- Live Session

Lecture Plan

- **Overview: GCC and Assembly**
- **Demo:** Looking at an executable
- Registers and The Assembly Level of Abstraction
- The **mov** Instruction
- Live Session

Bits all the way down

Data representation so far

- Integer (`unsigned int`, 2’s complement signed `int`)
- `char` (ASCII)
- Address (unsigned long)
- Aggregates (arrays, `structs`)

The code itself is binary too!

- Instructions (machine encoding)

GCC

- **GCC** is the compiler that converts your human-readable code into machine-readable instructions.
- C, and other languages, are high-level abstractions we use to write code efficiently. But computers don’t really understand things like data structures, variable types, etc. Compilers are the translator!
- Pure machine code is 1s and 0s – everything is bits, even your programs! But we can read it in a human-readable form called **assembly**. (Engineers used to write code in assembly before C).
- There may be multiple assembly instructions needed to encode a single C instruction.
- We’re going to go behind the curtain to see what the assembly code for our programs looks like.

Lecture Plan

- **Overview:** GCC and Assembly
- **Demo: Looking at an executable**
- Registers and The Assembly Level of Abstraction
- The **mov** Instruction
- Live Session

Examining the Assembly

objdump -d

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;
}
```

What does this look like in assembly?

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;
}
```

```
make
objdump -d sum
```

```
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
```

Our First Assembly

```
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
```

Our First Assembly

```
0000000000401136 <sum_array>:
  401136:   b8 00 00 00 00          mov     $0x0,%eax
  40113b:   ba 00 00 00 00          mov     $0x0,%edx
                                      p     %esi,%eax
                                      e     40114f <sum_array+0x19>
                                    vslq    %eax,%rcx
                                      d     (%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
```

This is the name of the function (same as C) and the memory address where the code for this function starts.

Our First Assembly

```
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                                _array+0x19>
  401144: 48
  401147: 03                              4),%edx
  40114a: 83
  40114d: eb f1                 jmp    401140 <sum_array+0xa>
  40114f: 89 d0                 mov    %edx,%eax
  401151: c3                    retq
```

These are the memory addresses where each of the instructions live. Sequential instructions are sequential in memory.

Our First Assembly

```
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
                                 jge    40114f <sum_array+0x19>
                                 movslq %eax,%rcx
                                 add    (%rdi,%rcx,4),%edx
                                 add    $0x1,%eax
  40114d:   eb f1                jmp    401140 <sum_array+0xa>
  40114f:   89 d0                mov    %edx,%eax
  401151:   c3                   retq
```

This is the assembly code: "human-readable" versions of each machine code instruction.

Our First Assembly

```
0000000000401136 <sum_array>:
  401136:   b8 00 00 00 00          mov     $0x0,%eax
  40113b:   ba 00 00 00 00          m
  401140:   39 f0                   c
  401142:   7d 0b                   j
  401144:   48 63 c8                m
  401147:   03 14 8f                a
  40114a:   83 c0 01                a
  40114d:   eb f1                   j
  40114f:   89 d0                   mov     %edx,%eax
  401151:   c3                      retq
```

This is the machine code: raw hexadecimal instructions, representing binary as read by the computer. Different instructions may be different byte lengths.

Our First Assembly

```
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
```

Our First Assembly

```
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
```

Each instruction has an operation name ("opcode").

Our First Assembly

```
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
```

Each instruction can also have arguments ("operands").

Our First Assembly

```
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
```

$[number] means a constant value, or "immediate" (e.g. 1 here).

Our First Assembly

```
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
```

%[name] means a register, a storage location on the CPU (e.g. edx here).

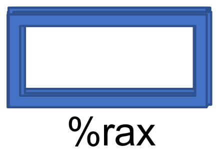
Lecture Plan

- **Overview:** GCC and Assembly
- **Demo:** Looking at an executable
- **Registers and The Assembly Level of Abstraction**
- The **mov** instruction

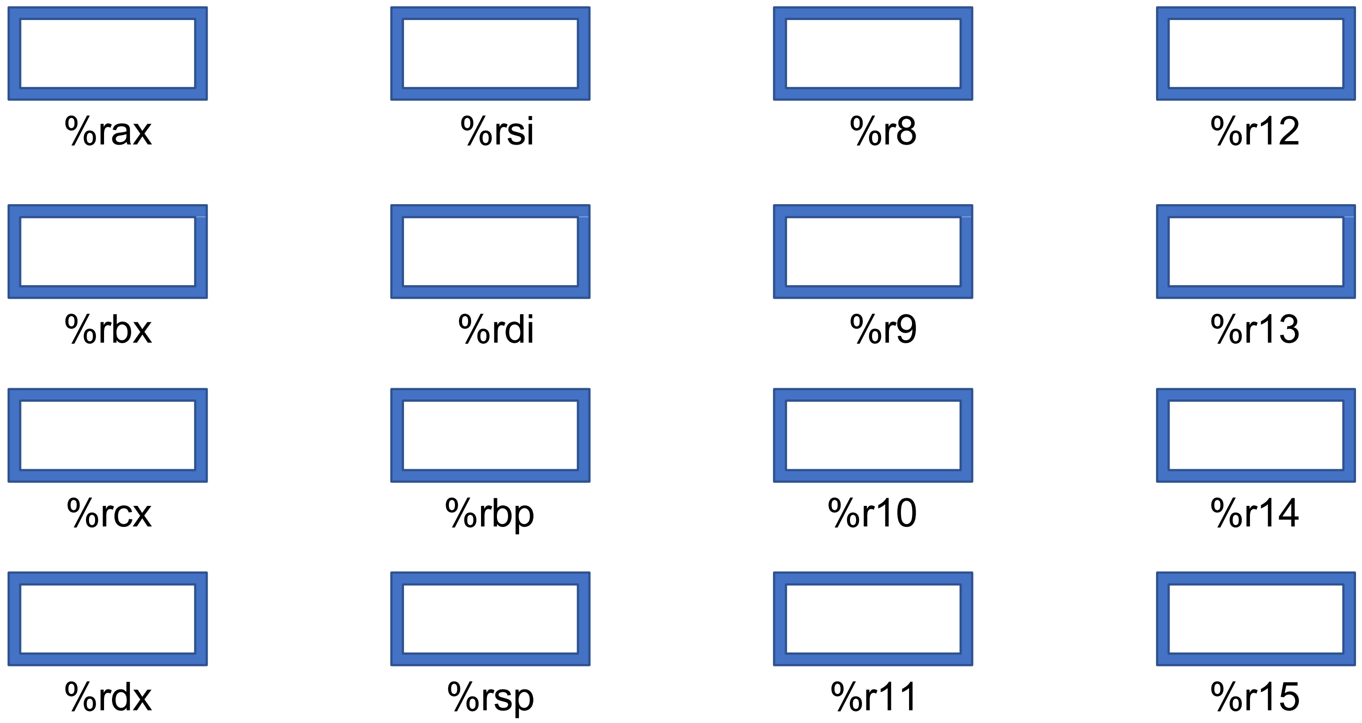
Assembly Abstraction

- C abstracts away the low-level details of machine code. It lets us work using variables, variable types, and other higher-level abstractions.
- C and other languages let us write code that works on most machines.
- Assembly code is just bytes! No variable types, no type checking, etc.
- Assembly/machine code is processor-specific.
- What is the level of abstraction for assembly code?

Registers



Registers



Registers

What is a register?

A register is a fast read/write memory slot right on the CPU that can hold variable values.

Registers are **not** located in memory.

Registers

- A **register** is a 64-bit space inside the processor.
- There are 16 registers available, each with a unique name.
- Registers are like “scratch paper” for the processor. Data being calculated or manipulated is moved to registers first. Operations are performed on registers.
- Registers also hold parameters and return values for functions.
- Registers are extremely *fast* memory!
- Processor instructions consist mostly of moving data into/out of registers and performing arithmetic on them. This is the level of logic your program must be in to execute!

Machine-Level Code

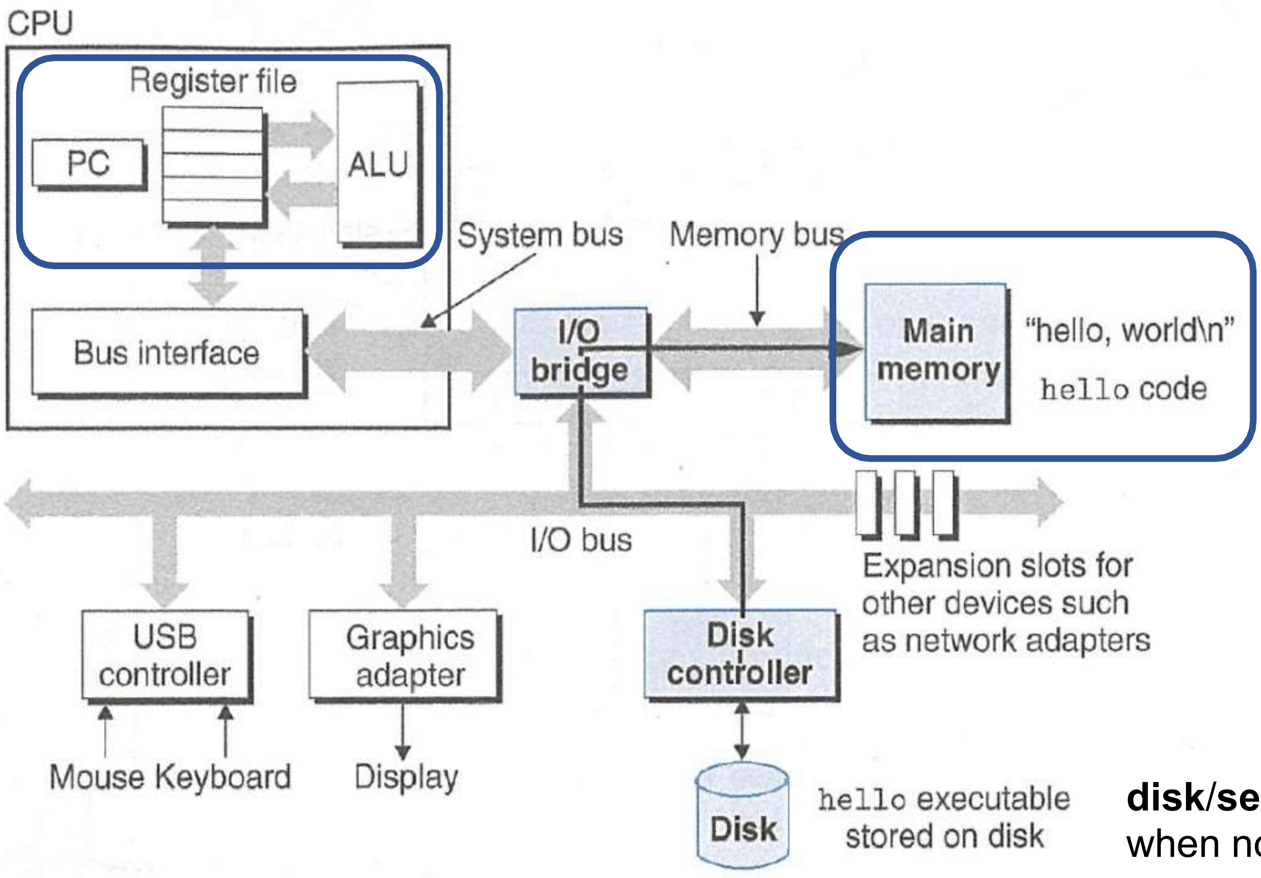
Assembly instructions manipulate these registers. For example:

- One instruction adds two numbers in registers
- One instruction transfers data from a register to memory
- One instruction transfers data from memory to a register

Computer architecture

registers accessed by name

ALU is main workhorse of CPU



memory needed for program execution (stack, heap, etc.) accessed by address

disk/**server** stores program when not executing

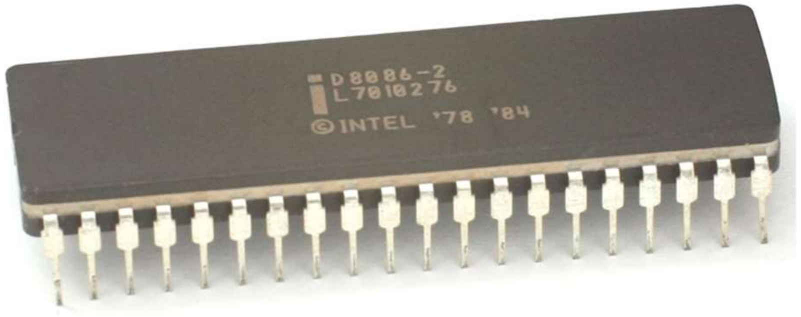
GCC And Assembly

- GCC compiles your program – it lays out memory on the stack and heap and generates assembly instructions to access and do calculations on those memory locations.
- Here's what the "assembly-level abstraction" of C code might look like:

C	Assembly Abstraction
`int sum = x + y;`	1) Copy x into register 1 2) Copy y into register 2 3) Add register 2 to register 1 4) Write register 1 to memory for sum

Assembly

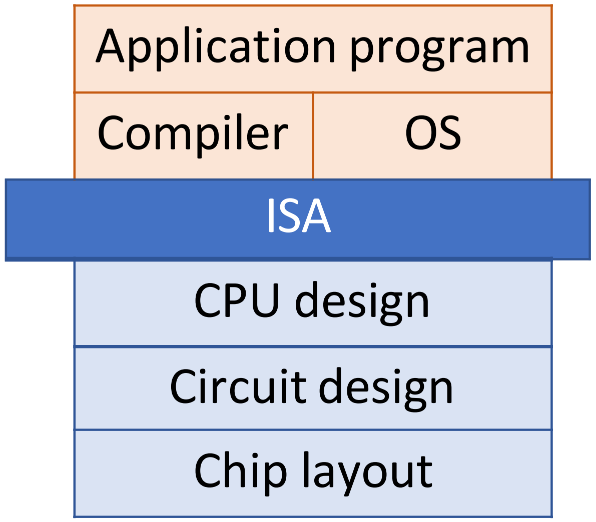
- We are going to learn the **x86-64** instruction set architecture. This instruction set is used by Intel and AMD processors.
- There are many other instruction sets: ARM, MIPS, etc.



Instruction set architecture (ISA)

A contract between program/compiler and hardware:

- Defines operations that the processor (CPU) can execute
- Data read/write/transfer operations
- Control mechanisms



Intel originally designed their instruction set back in 1978.

- Legacy support is a huge issue for x86-64
- Originally 16-bit processor, then 32 bit, now 64 bit.
  These design choices dictated the register sizes
  (and even register/instruction names).

Lecture Plan

- **Overview:** GCC and Assembly
- **Demo:** Looking at an executable
- Registers and The Assembly Level of Abstraction
- **The mov Instruction**
- Live Session

mov

The **`mov`** instruction <u>copies</u> 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.

Practice #1: Operand Forms

What are the results of the following move instructions (executed separately)? For this problem, assume the value *5* is stored at address 0x42, and the value *8* is stored in %rbx.

```
1. mov   $0x42,%rax

2. mov    0x42,%rax

3. mov    %rbx,0x55
```

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 (****0x10 plus**** 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 (****0x10 plus**** 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)
```

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

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

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

$\texttt{Imm}(r_b, r_i, s)$

is equivalent to…

$\texttt{Imm} + R[r_b] + R[r_i]*s$

Most General Operand Form

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

```
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!

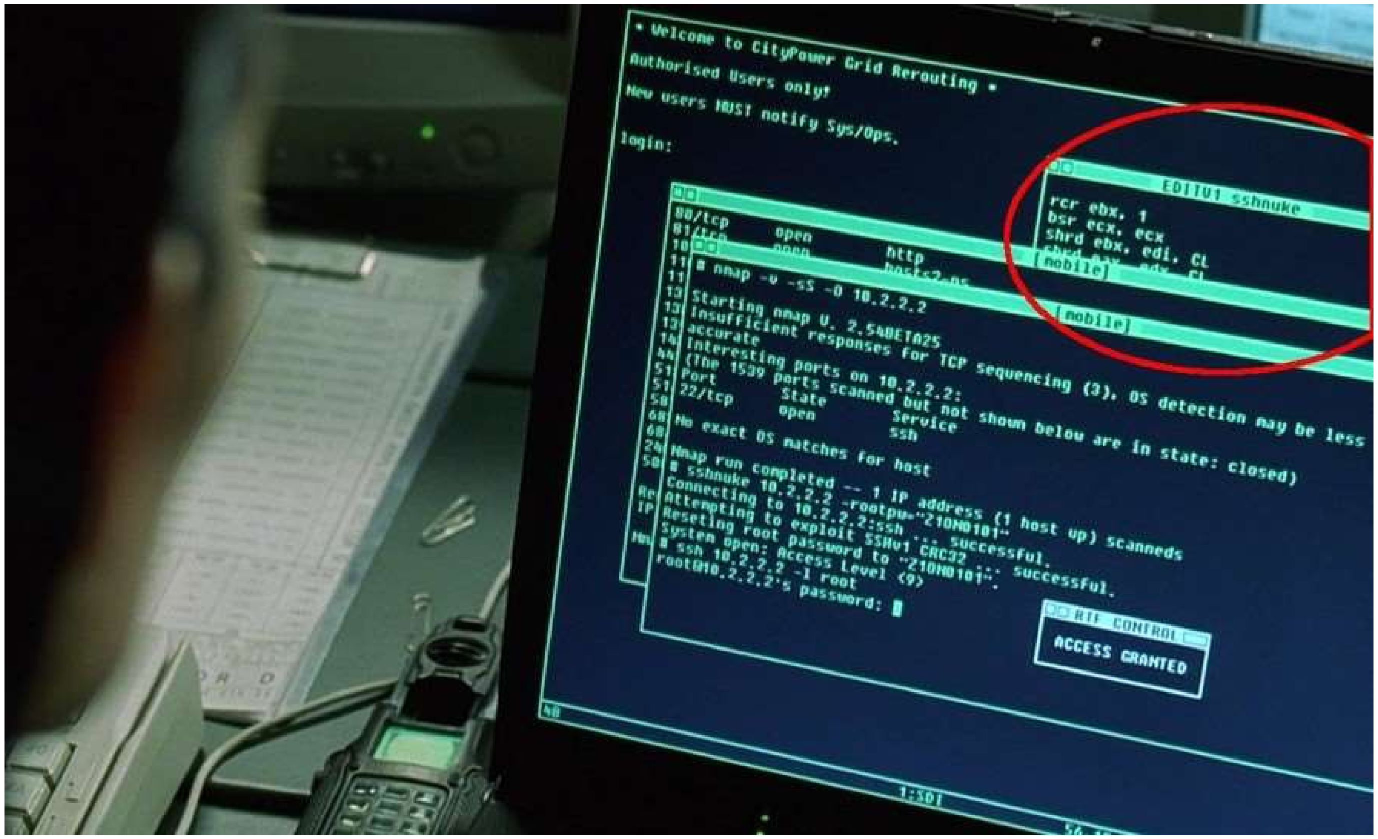
Central Processing Units (CPUs)

Intel 8086, 16-bit microprocessor ($86.65, 1978)

Raspberry Pi BCM2836
32-bit **ARM** microprocessor
($35 for everything, 2015)

Intel Core i9-9900K 64-bit
8-core multi-core processor
($449, 2018)

Assembly code in movies



```
* Welcome to CityPower Grid Rerouting *
Authorised Users only!
New users MUST notify Sys/Ops.

login:
```

```
EDITV1 sshnuke
rcr ebx, 1
bsr ecx, ecx
shrd ebx, edi, CL
[mobile]
```

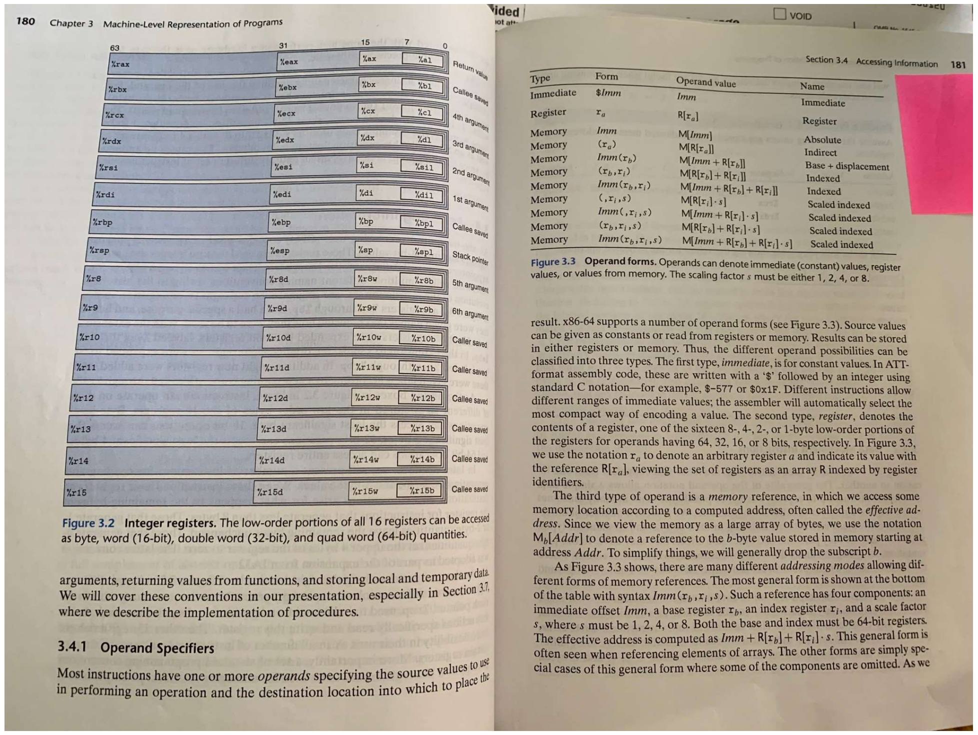
```
80/tcp     open          http
# nmap -v -sS -O 10.2.2.2
Starting nmap V. 2.54BETA25
Insufficient responses for TCP sequencing (3), OS detection may be less
accurate
Interesting ports on 10.2.2.2:
(The 1539 ports scanned but not shown below are in state: closed)
Port       State         Service
22/tcp     open          ssh
No exact OS matches for host
Nmap run completed -- 1 IP address (1 host up) scanneds
# sshnuke 10.2.2.2 -rootpw="Z1ON0101"
Connecting to 10.2.2.2:ssh ... successful.
Attempting to exploit SSHv1 CRC32 ... successful.
Reseting root password to "Z1ON0101".
System open: Access Level <9>
# ssh 10.2.2.2 -l root
root@10.2.2.2's password:
```

Trinity saving the world by hacking into the power grid using Nmap Network Scanning
The Matrix Reloaded, 2003

🌟 Keep a resource guide handy 🌟

- https://web.stanford.edu/class/cs107/resources/x86-64-reference.pdf
- B&O book:
  - Canvas -> Files -> Bryant_OHallaron_ch3.1-3.8.pdf
- It's like study abroad:
  - You took LANG 1A
  - Your tools give too much/too little information (a book reference, a rudimentary translator)
  - No one expects you to **speak** the language fluently…
  - …But the more you internalize, the better you can use tools to **read** the language

BING OVERSEAS STUDIES PROGRAM
STANFORD UNIVERSITY



180 Chapter 3 Machine-Level Representation of Programs

63	31	15	7	
%rax	%eax	%ax	%al	Return value
%rbx	%ebx	%bx	%bl	Callee saved
%rcx	%ecx	%cx	%cl	4th argument
%rdx	%edx	%dx	%dl	3rd argument
%rsi	%esi	%si	%sil	2nd argument
%rdi	%edi	%di	%dil	1st argument
%rbp	%ebp	%bp	%bpl	Callee saved
%rsp	%esp	%sp	%spl	Stack pointer
%r8	%r8d	%r8w	%r8b	5th argument
%r9	%r9d	%r9w	%r9b	6th argument
%r10	%r10d	%r10w	%r10b	Caller saved
%r11	%r11d	%r11w	%r11b	Caller saved
%r12	%r12d	%r12w	%r12b	Callee saved
%r13	%r13d	%r13w	%r13b	Callee saved
%r14	%r14d	%r14w	%r14b	Callee saved
%r15	%r15d	%r15w	%r15b	Callee saved

Figure 3.2 Integer registers. The low-order portions of all 16 registers can be accessed as byte, word (16-bit), double word (32-bit), and quad word (64-bit) quantities.

arguments, returning values from functions, and storing local and temporary data. We will cover these conventions in our presentation, especially in Section 3.7, where we describe the implementation of procedures.

3.4.1 Operand Specifiers

Most instructions have one or more *operands* specifying the source values to use in performing an operation and the destination location into which to place the

Section 3.4 Accessing Information 181

Type	Form	Operand value	Name
Immediate	$\$Imm$	Imm	Immediate
Register	r_a	$R[r_a]$	Register
Memory	Imm	$M[Imm]$	Absolute
Memory	(r_a)	$M[R[r_a]]$	Indirect
Memory	$Imm(r_b)$	$M[Imm + R[r_b]]$	Base + displacement
Memory	(r_b,r_i)	$M[R[r_b] + R[r_i]]$	Indexed
Memory	$Imm(r_b,r_i)$	$M[Imm + R[r_b] + R[r_i]]$	Indexed
Memory	$(,r_i,s)$	$M[R[r_i] \cdot s]$	Scaled indexed
Memory	$Imm(,r_i,s)$	$M[Imm + R[r_i] \cdot s]$	Scaled indexed
Memory	(r_b,r_i,s)	$M[R[r_b] + R[r_i] \cdot s]$	Scaled indexed
Memory	$Imm(r_b,r_i,s)$	$M[Imm + R[r_b] + R[r_i] \cdot s]$	Scaled indexed

Figure 3.3 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.

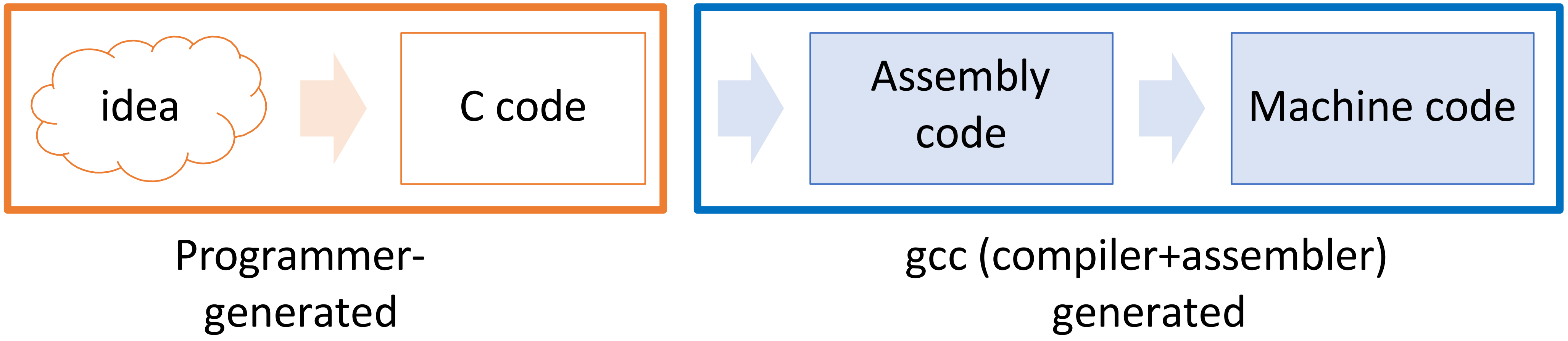
result. x86-64 supports a number of operand forms (see Figure 3.3). Source values can be given as constants or read from registers or memory. Results can be stored in either registers or memory. Thus, the different operand possibilities can be classified into three types. The first type, *immediate*, is for constant values. In ATT-format assembly code, these are written with a '$' followed by an integer using standard C notation—for example, $-577 or $0x1F. Different instructions allow different ranges of immediate values; the assembler will automatically select the most compact way of encoding a value. The second type, *register*, denotes the contents of a register, one of the sixteen 8-, 4-, 2-, or 1-byte low-order portions of the registers for operands having 64, 32, 16, or 8 bits, respectively. In Figure 3.3, we use the notation r_a to denote an arbitrary register a and indicate its value with the reference $R[r_a]$, viewing the set of registers as an array R indexed by register identifiers.

The third type of operand is a *memory* reference, in which we access some memory location according to a computed address, often called the *effective address*. Since we view the memory as a large array of bytes, we use the notation $M_b[Addr]$ to denote a reference to the b-byte value stored in memory starting at address $Addr$. To simplify things, we will generally drop the subscript b.

As Figure 3.3 shows, there are many different *addressing modes* allowing different forms of memory references. The most general form is shown at the bottom of the table with syntax $Imm(r_b,r_i,s)$. Such a reference has four components: an immediate offset Imm, a base register r_b, an index register r_i, and a scale factor s, where s must be 1, 2, 4, or 8. Both the base and index must be 64-bit registers. The effective address is computed as $Imm + R[r_b] + R[r_i] \cdot s$. This general form is often seen when referencing elements of arrays. The other forms are simply special cases of this general form where some of the components are omitted. As we

Chapter 3, Figures 3.2-3.3 (p. 180-181)

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!

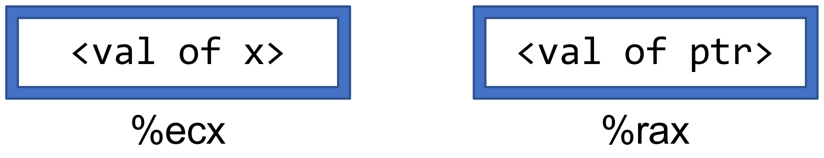
1. Extra Practice

Fill in the blank to complete the C code that

1. generates this assembly
2. has this register layout

```
int x = ...
int *ptr = malloc(…);
...
___???___ = _???_;
```

```
mov %ecx,(%rax)
```



(Pedantic: You should sub in <x> and <ptr> with actual values, like 4 and 0x7fff80)

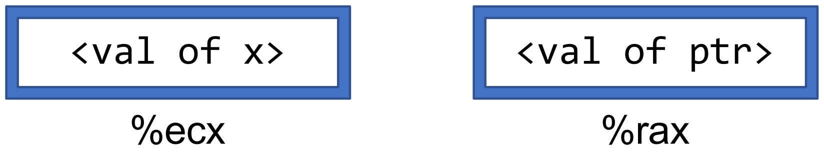
1. Extra Practice

Fill in the blank to complete the C code that

1. generates this assembly
2. has this register layout

```
int x = ...
int *ptr = malloc(…);
...
___???___ = _???_;    *ptr = x;
```

```
mov %ecx,(%rax)
```



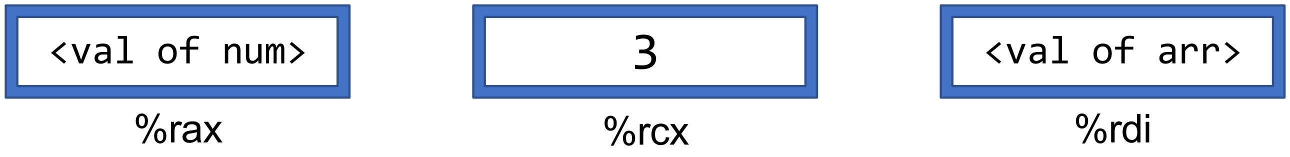
2. Extra Practice

Fill in the blank to complete the C code that

1. generates this assembly
2. **results in** this register layout

```
long arr[5];
...
long num = ____???___;
```

```
mov (%rdi, %rcx, 8),%rax
```



2. Extra Practice

Fill in the blank to complete the C code that

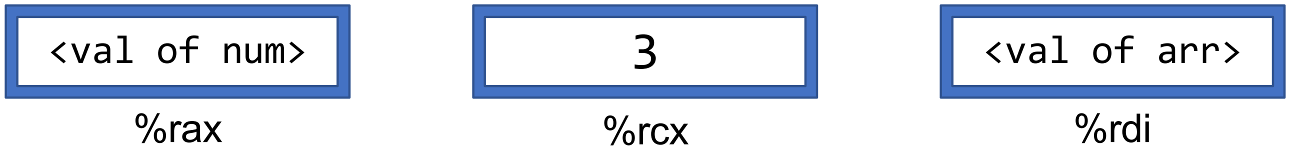
1. generates this assembly
2. **results in** this register layout

```
long arr[5];
...
long num = ____???___;
```

```
long num = arr[3];
long num = *(arr + 3);
long num = *(arr + y);
```

(assume `long y = 3;` declared earlier)

```
mov (%rdi, %rcx, 8),%rax
```



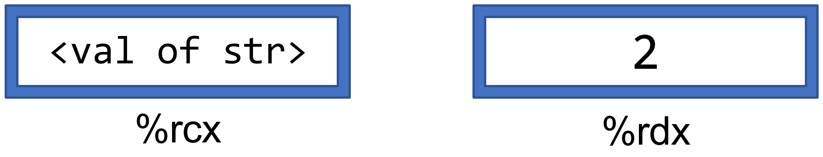
3. Extra Practice

Fill in the blank to complete the C code that

1. generates this assembly
2. has this register layout

```
char str[5];
...
___???___ = 'c';
```

```
mov $0x63,(%rcx,%rdx,1)
```



3. Extra Practice

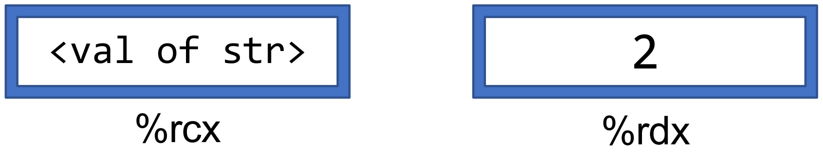
Fill in the blank to complete the C code that

1. generates this assembly
2. has this register layout

```
char str[5];
...
___???___ = 'c';
```

```
str[2] = 'c';
*(str + 2) = 'c';
```

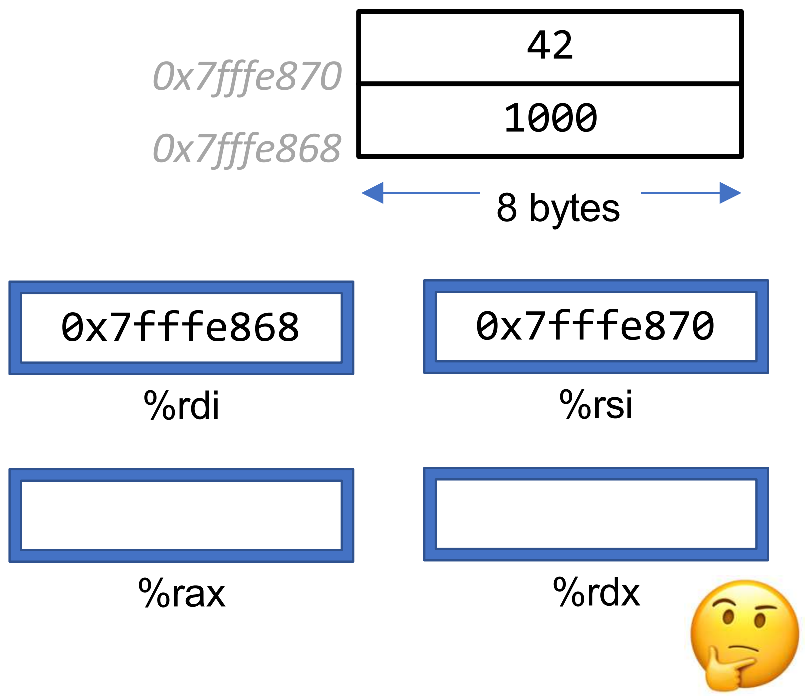
```
mov $0x63,(%rcx,%rdx,1)
```



Coming Up Soon To A Slide Near You

- The below code is the objdump of a C function, `foo`.
  - `foo` keeps its 1st and 2nd parameters are in registers %rdi and %rsi, respectively.

```
0x4005b6 <foo>     mov    (%rdi),%rax
0x4005b9 <foo+3>   mov    (%rsi),%rdx
0x4005bc <foo+6>   mov    %rdx,(%rdi)
0x4005bf <foo+9>   mov    %rax,(%rsi)
```



1. **What does this function do?**
2. **What C code could have generated this assembly?**

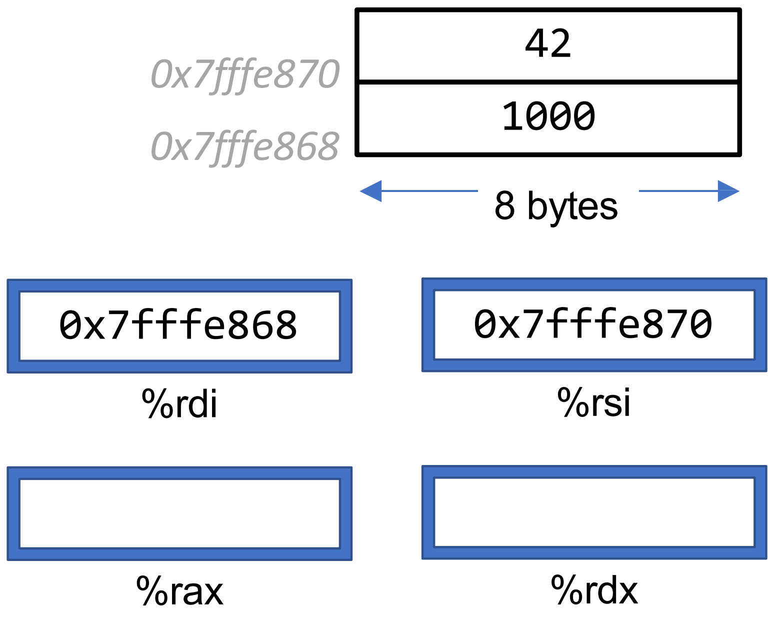
(Hints: make up C variable names as needed, assume all regs 64-bit)

Coming Up Soon To A Slide Near You

- The below code is the objdump of a C function, `foo`.
  - `foo` keeps its 1st and 2nd parameters are in registers %rdi and %rsi, respectively.

```
0x4005b6 <foo>     mov    (%rdi),%rax
0x4005b9 <foo+3>   mov    (%rsi),%rdx
0x4005bc <foo+6>   mov    %rdx,(%rdi)
0x4005bf <foo+9>   mov    %rax,(%rsi)
```

```
void foo(int *a, int *b) {
   int temp = *a;
   *a = *b;
   *b = temp;
}
```



Lecture Plan

- **Recap: mov so far**
- Data and Register Sizes
- The **lea** Instruction
- Logical and Arithmetic Operations
- Practice: Reverse Engineering

Reference Sheet:
`https://web.stanford.edu/class/archive/cs/cs107/cs107.1248/guide/x86-64.html`
See more guides on Resources page of course website!

mov

The **`mov`** instruction <u>copies</u> 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	$r_{!}$	$\mathrm{R}[r_{!}]$	Register
Memory	Imm	$\mathrm{M}[Imm]$	Absolute
Memory	$(r_{!})$	$\mathrm{M}[\mathrm{R}[r_{!}]]$	Indirect
Memory	$Imm(r_{"})$	$\mathrm{M}[Imm + \mathrm{R}[r_{"}]]$	Base + displacement
Memory	$(r_{"}, r_{\#})$	$\mathrm{M}[\mathrm{R}[r_{"}] + \mathrm{R}[r_{\#}]]$	Indexed
Memory	$Imm(r_{"}, r_{\#})$	$\mathrm{M}[Imm + \mathrm{R}[r_{"}] + \mathrm{R}[r_{\#}]]$	Indexed
Memory	$(, r_{\#}, s)$	$\mathrm{M}[\mathrm{R}[r_{\#}] \,.\, s]$	Scaled indexed
Memory	$Imm(, r_{\#}, s)$	$\mathrm{M}[Imm + \mathrm{R}[r_{\#}] \,.\, s]$	Scaled indexed
Memory	$(r_{"}, r_{\#}, s)$	$\mathrm{M}[\mathrm{R}[r_{"}] + \mathrm{R}[r_{\#}] \,.\, s]$	Scaled indexed
Memory	$Imm(r_{"}, r_{\#}, s)$	$\mathrm{M}[Imm + \mathrm{R}[r_{"}] + \mathrm{R}[r_{\#}] \,.\, s]$	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

- **Recap: mov** so far
- **Data and Register Sizes**
- The **lea** Instruction
- Logical and Arithmetic Operations
- Practice: Reverse Engineering

Reference Sheet:
`https://web.stanford.edu/class/archive/cs/cs107/cs107.1248/guide/x86-64.html`
See more guides on Resources page of course website!

Data Sizes

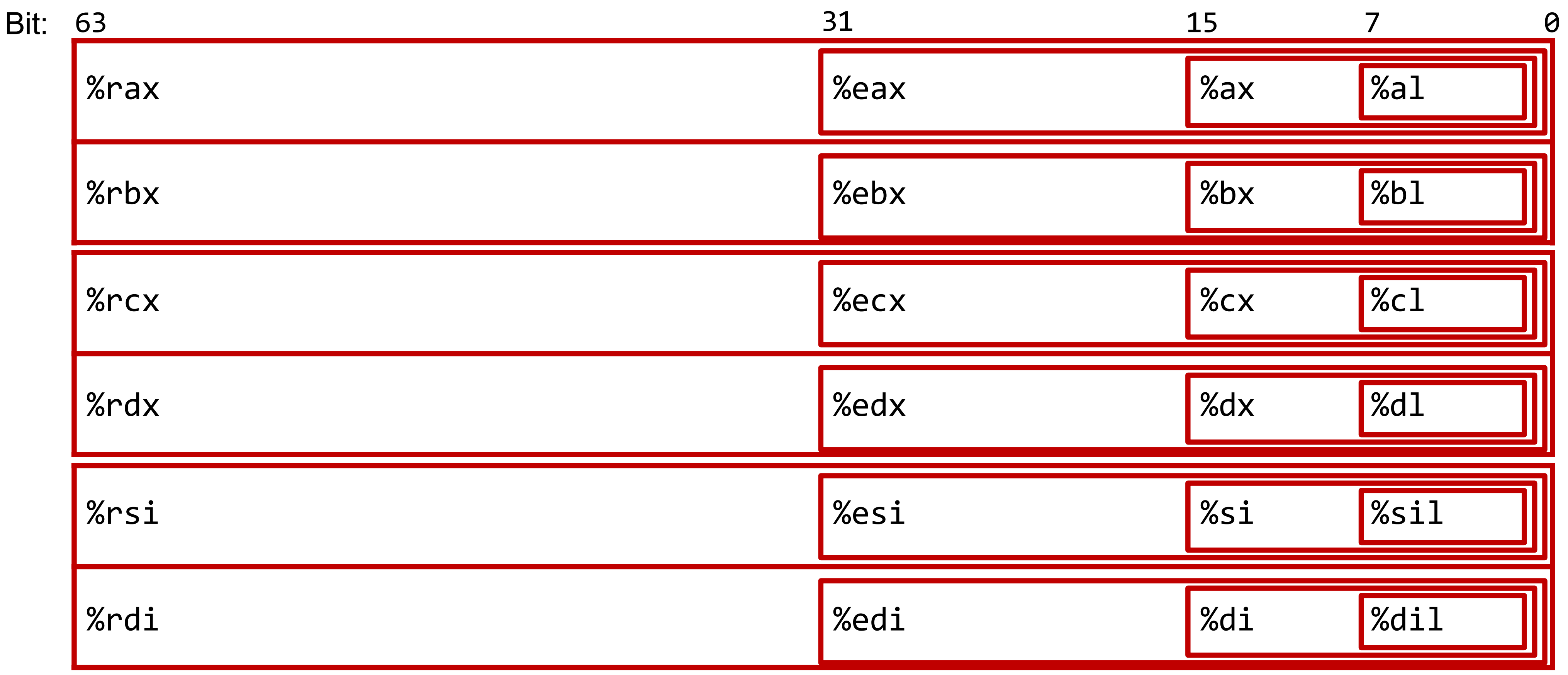
Data sizes in assembly have slightly different terminology to get used to:

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

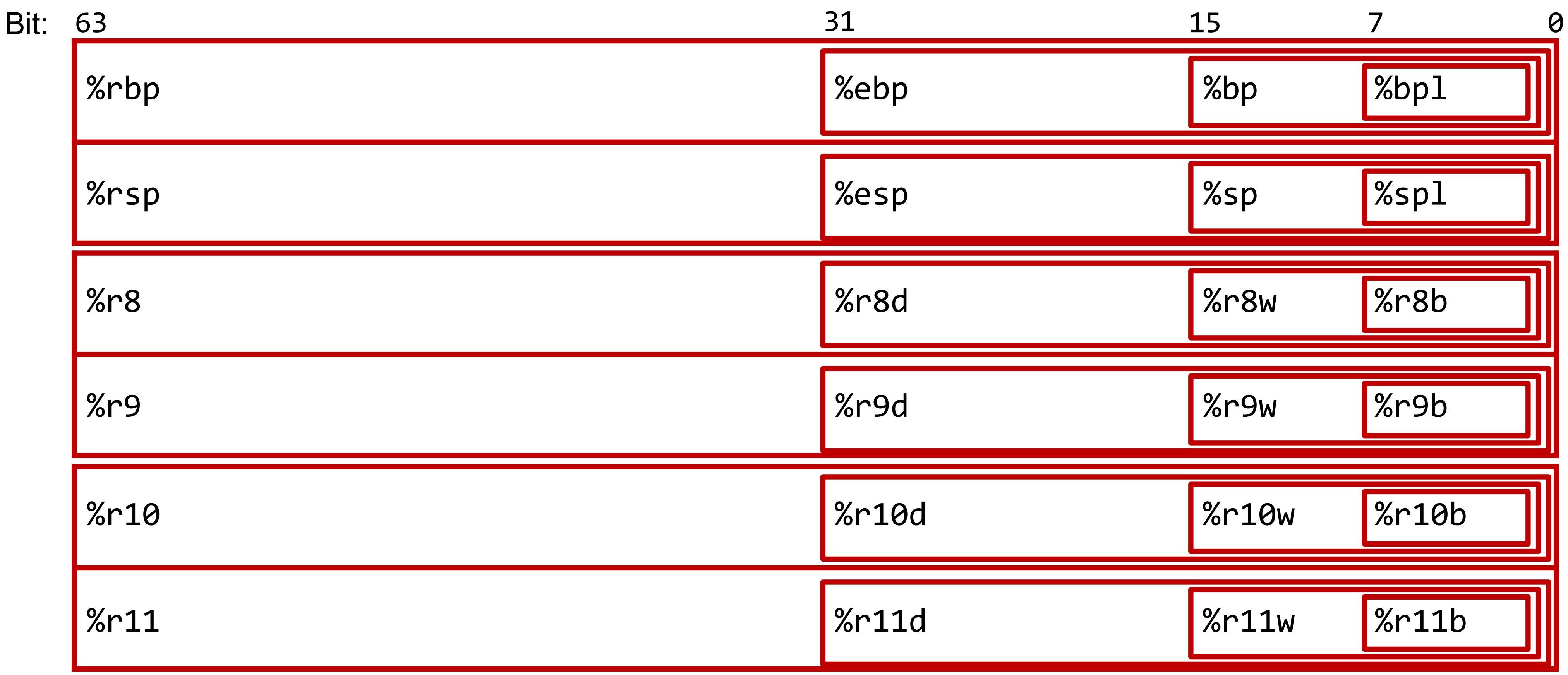
Assembly instructions can have suffixes to refer to these sizes:

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

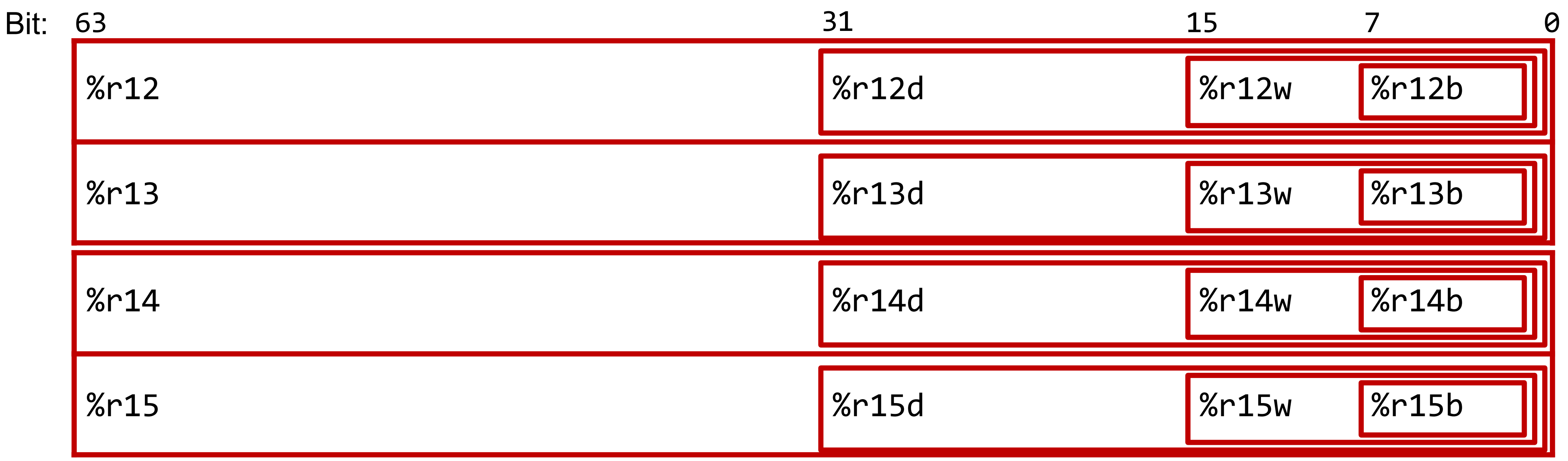
Register Sizes



Register Sizes



Register Sizes



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:
`https://web.stanford.edu/class/archive/cs/cs107/cs107.1248/guide/x86-64.html`
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

```
MOVZ S,R          R ← 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          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

- **Recap: mov** so far
- Data and Register Sizes
- **The lea Instruction**
- Logical and Arithmetic Operations
- Practice: Reverse Engineering

Reference Sheet:
`https://web.stanford.edu/class/archive/cs/cs107/cs107.1248/guide/x86-64.html`
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

- **Recap: mov** so far
- Data and Register Sizes
- The **lea** Instruction
- **Logical and Arithmetic Operations**
- Practice: Reverse Engineering

Reference Sheet:
`https://web.stanford.edu/class/archive/cs/cs107/cs107.1248/guide/x86-64.html`
See more guides on Resources page of course website!

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`	$D \leftarrow D \ll k$	Left shift
`shl k, D`	$D \leftarrow D \ll k$	Left shift (same as `sal`)
`sar k, D`	$D \leftarrow D \gg_A k$	Arithmetic right shift
`shr k, D`	$D \leftarrow D \gg_L k$	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 ← D $>>_A$ k	Arithmetic right shift
`shr k, D`	D ← 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

- **Recap: mov** so far
- Data and Register Sizes
- The **lea** Instruction
- Logical and Arithmetic Operations
- **Practice: Reverse Engineering**

Reference Sheet:
`https://web.stanford.edu/class/archive/cs/cs107/cs107.1248/guide/x86-64.html`
See more guides on Resources page of course website!

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 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?

%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
```

```
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

Shift Amount

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

- 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.

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**.

Extra Practice

https://godbolt.org/z/hGKPWszq4

Reverse Engineering 1

```
int add_to(int x, int arr[], int i)
    { int sum = _?___;
    sum += arr[___?___];
    return ___?___;
}

----------

add_to:
  movslq %edx, %rdx
  movl %edi, %eax
  addl (%rsi,%rdx,4), %eax
  ret
```

Reverse Engineering 1

```
int add_to(int x, int arr[], int i)
    { int sum = _?___;
    sum += arr[___?___];
    return ___?___;
}

----------
// x in %edi, arr in %rsi, i in
%edx add_to:
  movslq %edx, %rdx             // sign-extend i into full register
  movl %edi, %eax               // copy x into %eax
  addl (%rsi,%rdx,4), %eax      // add arr[i] to %eax
  ret
```

Reverse Engineering 1

```
int add_to(int x, int arr[], int i)
    { int sum = x;
    sum += arr[i];
    return sum;
}

----------
// x in %edi, arr in %rsi, i in
%edx add_to:
  movslq %edx, %rdx           // sign-extend i into full register
  movl %edi, %eax             // copy x into %eax
  addl (%rsi,%rdx,4), %eax    // add arr[i] to %eax
  ret
```

Reverse Engineering 2

```
int elem_arithmetic(int nums[], int y)
    { int z = nums[_?___] * ___?___;
    z -= ___?___;
    z >>= ___?___;
    return ___?___;
}
----------

elem_arithmetic:
  movl %esi, %eax
  imull (%rdi), %eax
  subl 4(%rdi), %eax
  sarl $2, %eax
  addl $2, %eax
  ret
```

Reverse Engineering 2

```
int elem_arithmetic(int nums[], int y)
    { int z = nums[_?___] * ___?___;
    z -= ___?___;
    z >>= ___?___;
    return ___?___;
}
----------
// nums in %rdi, y in %esi
elem_arithmetic:
  movl %esi, %eax          // copy y into %eax
  imull (%rdi), %eax       // multiply %eax by nums[0]
  subl 4(%rdi), %eax       // subtract nums[1] from %eax
  sarl $2, %eax            // shift %eax right by 2
  addl $2, %eax            // add 2 to %eax
  ret
```

Reverse Engineering 2

```
int elem_arithmetic(int nums[], int y)
    { int z = nums[0] * y;
    z -= nums[1];
    z >>= 2;
    return z + 2;
}
----------
// nums in %rdi, y in %esi
elem_arithmetic:
  movl %esi, %eax           // copy y into %eax
  imull (%rdi), %eax        // multiply %eax by nums[0]
  subl 4(%rdi), %eax        // subtract nums[1] from %eax
  sarl $2, %eax             // shift %eax right by 2
  addl $2, %eax             // add 2 to %eax
  ret
```

Reverse Engineering 3

```
long func(long x, long *ptr) {
    *ptr = ___?___ + 1;
    long result = x % ___?___;
    return ___?___;
}
----------

func:
  movq %rdi, %rax
  leaq 1(%rdi), %rcx
  movq %rcx, (%rsi)
  cqto
  idivq %rcx
  movq %rdx, %rax
  ret
```

Reverse Engineering 3

```
long func(long x, long *ptr) {
    *ptr = ___?___ + 1;
    long result = x % ___?___;
    return ___?___;
}
----------
// x in %rdi, ptr in %rsi
func:
  movq %rdi, %rax            // copy x into %rax
  leaq 1(%rdi), %rcx         // put x + 1 into %rcx
  movq %rcx, (%rsi)          // copy %rcx into *ptr
  cqto                       // sign-extend x into %rdx
  idivq %rcx                 // calculate x / (x + 1)
  movq %rdx, %rax            // copy the remainder into %rax
  ret
```

Reverse Engineering 3

```
long func(long x, long *ptr) {
    *ptr = x + 1;
    long result = x % *ptr; // or x +
    1
    return result;
}---------
// x in %rdi, ptr in %rsi
func:
  movq %rdi, %rax          // copy x into %rax
  leaq 1(%rdi), %rcx       // put x + 1 into %rcx
  movq %rcx, (%rsi)        // copy %rcx into *ptr
  cqto                     // sign-extend x into %rdx
  idivq %rcx               // calculate x / (x + 1)
  movq %rdx, %rax          // copy the remainder into %rax
  ret
```

Side Note: Old GCC Output

```
long func(long x, long *ptr) {
    *ptr = x + 1;
    long result = x % *ptr; // or x +
    1
    return result;
}---------
// x in %rdi, ptr in %rsi
func:
  leaq 1(%rdi), %rcx        // put x + 1 into %rcx
  movq %rcx, (%rsi)         // copy %rcx into *ptr
  movq %rdi, %rax           // copy x into %rax
  cqto                      // sign-extend x into %rdx
  idivq %rcx                // calculate x / (x + 1)
  movq %rdx, %rax           // copy the remainder into %rax
  ret
```

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