CS107, Lecture 15
Introduction to Assembly

Reading: B&O 3.1-3.4

CS107 Topic 5: How does a computer interpret and execute C programs?

CS107 Topic 5

How does a computer interpret and execute C programs?

Why is answering this question important?

- Learning how our code is really translated and executed helps us write better code
- We can learn how to reverse engineer and exploit programs at the assembly level

assign5: find and exploit vulnerabilities in an ATM program, reverse engineer a program without seeing its code, and de-anonymize users given a data leak.

Learning Assembly

Moving data around → Arithmetic and logical operations → Control flow → Function calls

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

```
cp -r /afs/ir/class/cs107/lecture-code/lect15 .
```

Lecture Plan

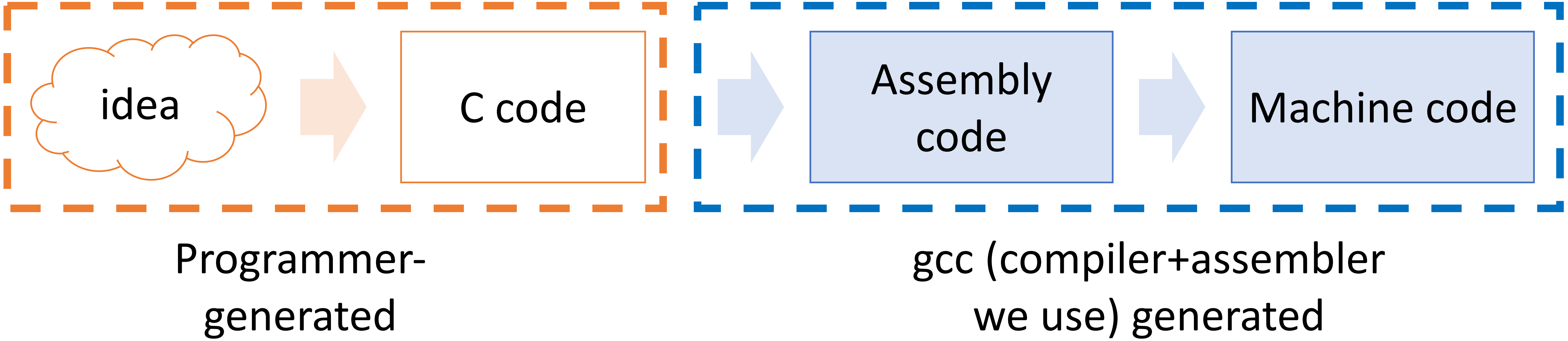
- **Overview: Assembly**
- **Demo:** Looking at an executable
- Registers and The Assembly Level of Abstraction
- The **mov** Instruction

```
cp -r /afs/ir/class/cs107/lecture-code/lect15 .
```

Assembly Overview

Assembly is the human-readable version of how the computer actually sees our programs.

- Compiler tools translate code we write into lower-level machine code that the computer runs. Assembly is a "human-readable" version of machine code.



Bits all the way down

Data representation so far

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

The code itself is binary too!

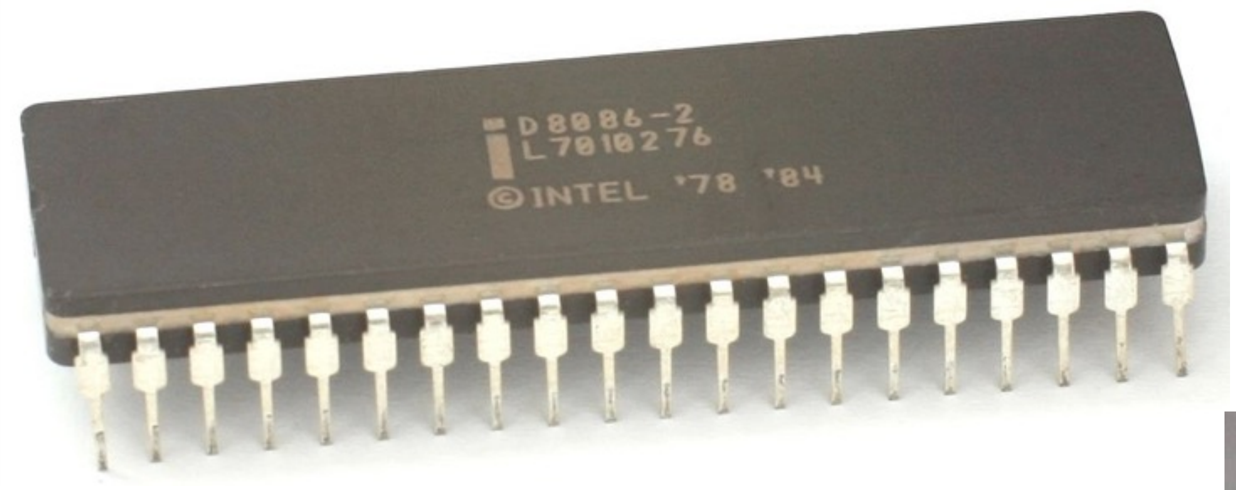
- Instructions (machine encoding)

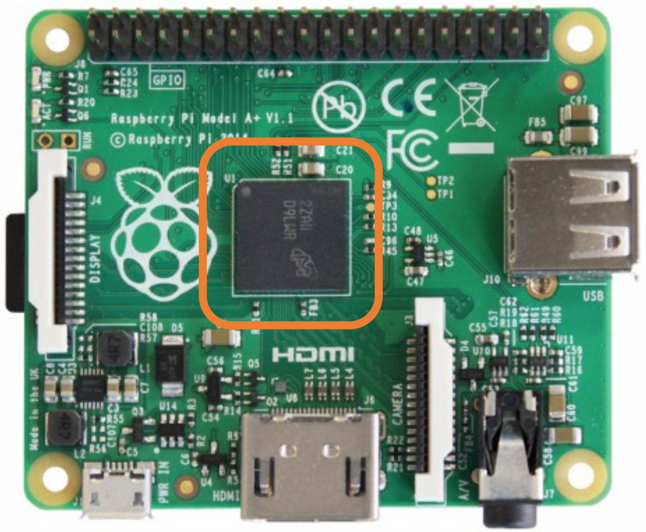
Translating from C to Assembly

- Programming languages like C 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!
- Assembly is lower level than our programming languages; e.g. there may be multiple assembly instructions needed to encode a single C instruction.
- The *CPU* is the brain of the computer that actually runs the instructions for our programs.

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)

Why Learn Assembly?

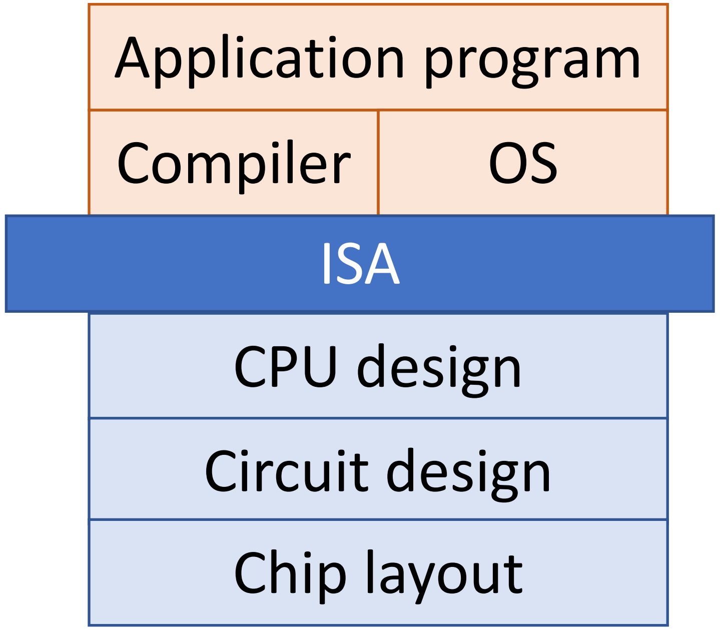
We will not be writing assembly! (that's the compiler's job). But learning about assembly allows us to:

- Read assembly and translate it back to C code that may have generated it
- Better understand how our program is converted into machine instructions -> use this understanding when writing code
- Understand the behavior of programs even without having access to their code ("reverse engineering")
- Better understand current technology developments

Instruction Set Architecture (ISA)

Different processors have different "formats" of machine code instructions – *Instruction Set Architecture (ISA).*

- E.g. Intel + AMD processors use **x86-64**. Apple and Qualcomm processors use **ARM**. Other architectures including MIPS, RISC, etc.
- Like the "processor's programming language". ISA defines operations that the processor can understand.
- ISAs can be old; e.g. Intel originally designed their instruction set in 1978! (and one of their design priorities is backwards compatibility).
- Programming languages are processor-agnostic, but machine code for one instruction set not compatible with a chip with another instruction set. Requires recompiling or emulation/translation.



Lecture Plan

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

```
cp -r /afs/ir/class/cs107/lecture-code/lect15 .
```

🌟 Keep a resource guide handy 🌟

- https://web.stanford.edu/class/cs107/resources/x86-64-reference.pdf
- CS107 x86 Guide: https://cs107.stanford.edu/guide/x86-64.html
- B&O book:
  - Canvas -> Files
    -> Bryant_OHallaron_ch3.1-3.8.pdf
- It’s like learning how to read (not speak) a new language! (again!)

Demo: Looking at an Executable (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
  40113b:   ba 00 00 00 00
  401140:   39 f0
  40114d:   eb f1
  40114f:   89 d0
  401151:   c3
```

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

```
mov     $0x0,%eax
mov     $0x0,%edx
cmp     %esi,%eax
jge     40114f <sum_array+0x19>
movslq  %eax,%rcx
add     (%rdi,%rcx,4),%edx
add     $0x1,%eax
jmp     401140 <sum_array+0xa>
mov     %edx,%eax
retq
```

Our First Assembly

```
0000000000401136 <sum_array>:
  401136:   b8 00 00 00 00     mov    $0x0,%eax
  40113b:   ba 00 00 00 00
  401140:   39 f0
  401142:   7d 0b
  401144:   48 63 c8
  401147:   03 14 8f
  40114a:   83 c0 01
  40114d:   eb f1
  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:** Assembly
- **Demo:** Looking at an executable
- **Registers and The Assembly Level of Abstraction**
- The **mov** instruction

```
cp -r /afs/ir/class/cs107/lecture-code/lect15 .
```

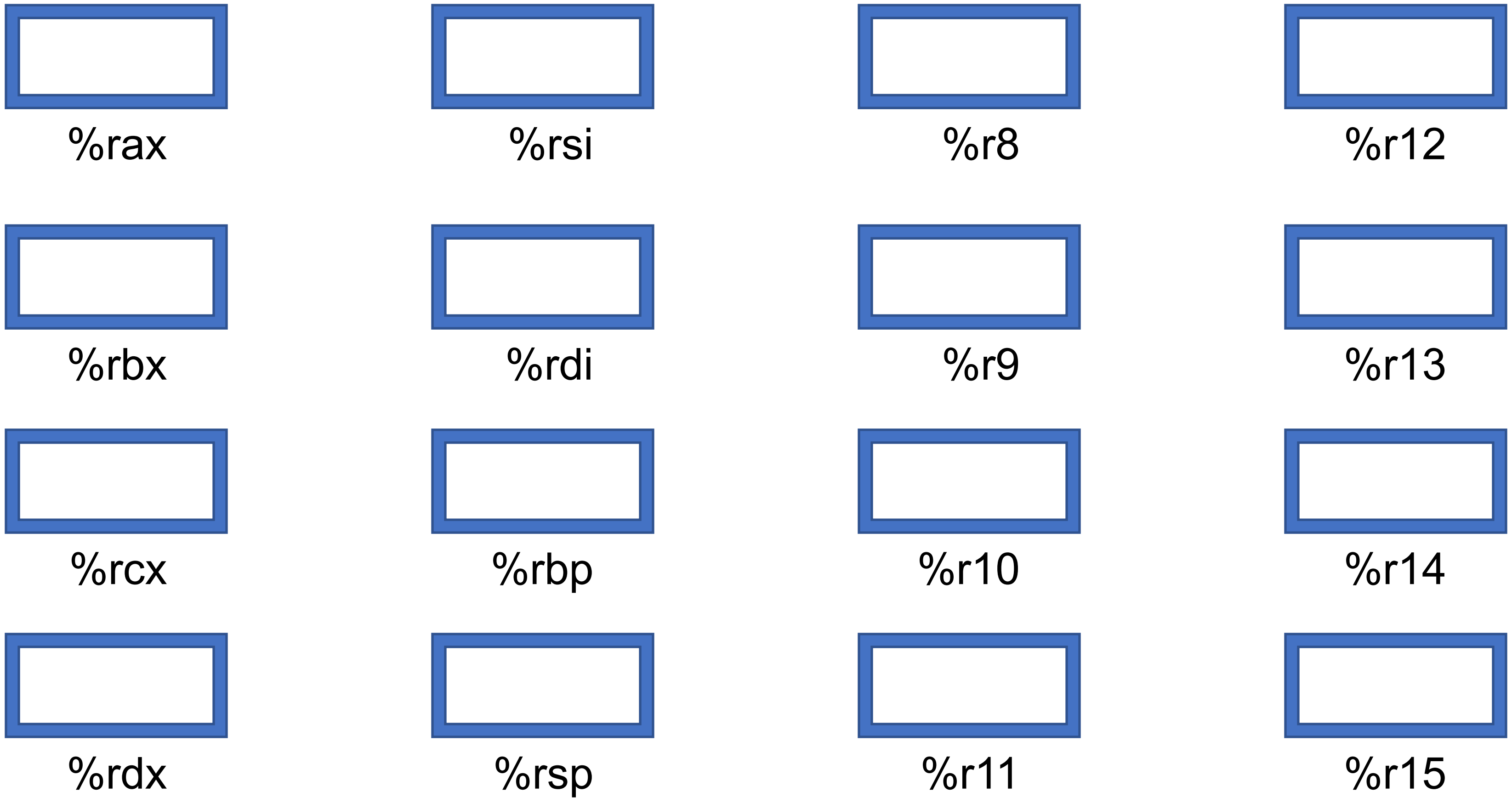
Assembly Abstraction

- C abstracts away the low-level details of machine code. It lets us work using variables, variable types, and other higher-level abstractions.
- Assembly code is just bytes! No variable types, no type checking, etc.
- What is the level of abstraction for assembly code?

Registers

%rax

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 located in the CPU; they are separate from main memory.

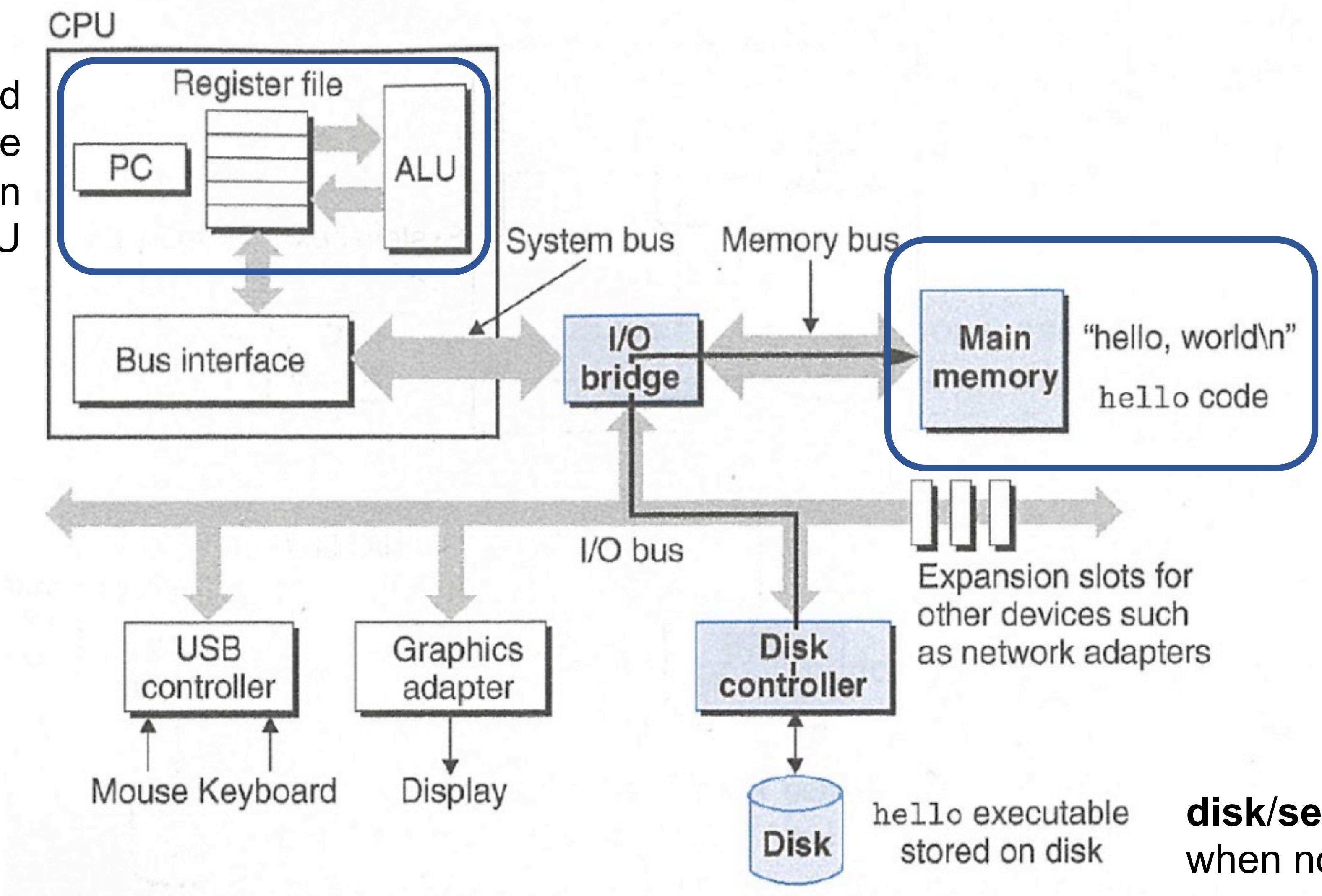
Registers

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!

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

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

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

Aside: 32-to-64-bit Transition

- **Early 2000s:** most computers were **32-bit.** This means that pointers (and registers) were **4 bytes (32 bits).**
- 32-bit pointers store a memory address from 0 to 2^{32}-1, equaling **2^{32} bytes of addressable memory**. This equals **4 Gigabytes**, meaning that 32-bit computers could have at most **4GB** of memory (RAM)!
- Because of this, computers transitioned to **64-bit.** This means that datatypes were enlarged; pointers (and registers) were now **64 bits.**
- 64-bit pointers store a memory address from 0 to 2^{64}-1, equaling **2^{64} bytes of addressable memory.** This equals **16 Exabytes**, meaning that 64-bit computers could have at most **1024*1024*1024*16 GB** of memory (RAM)!

Lecture Plan

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

```
cp -r /afs/ir/class/cs107/lecture-code/lect15 .
```

mov

The **mov** instruction copies bytes from one place to another;
it is like 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 **<u>0x10 plus</u>** 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 **<u>0x10 plus</u>** 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.

For #3, respond with your thoughts on PollEv: pollev.com/cs107 or text CS107 to 22333 once to join.

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

$\texttt{Imm}(\texttt{r}_\texttt{b},\ \texttt{r}_\texttt{i})$ is equivalent to address $\texttt{Imm} + \texttt{R}[\texttt{r}_\texttt{b}] + \texttt{R}[\texttt{r}_\texttt{i}]$

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

Base: register (if missing, = 0)

Index: register (if missing, = 0)

For #3, what is in %rcx after this instruction?

0x10C

0%

0x11

0%

0x103

0%

0xAB

0%

Recap

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

Next time: diving deeper into assembly

Lecture 15 takeaway: Assembly is the human-readable version of the form our programs are ultimately executed in by the processor. The compiler translates source code to machine code. The most common assembly instruction is *mov* to move data around.

Extra Practice

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)
```

<val of x>	<val of ptr>
%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)
```

<val of x>	<val of ptr>
%ecx	%rax