CS107 Lecture 11
Introduction to Assembly

reading:

B&O 3.1-3.4

Slides by Jerry Cain and Lisa Yan, who leveraged prior work by Nick Troccoli, Julie Zelenski, Marty Stepp, Cynthia Lee, Chris Gregg, and others.

Warm-up: Float review (bank)

Lisa was unable to deposit $1 into her bank account with $16,777,216. Why?

32-bit float for $V = 16{,}777{,}216 = 1.0 \times 2^{24}$

s	exponent (8 bits)	fraction (23 bits):
`0`	`1011 0111`	`0000 0000 0000 0000 0000 000`

$V = (-1)^s \times M \times 2^E$

$E = \text{exponent} - 127$

$M = 1.[\text{fraction bits}]$

A. Overflow in `float` when trying to store 16,777,217
B. `float` does not have enough **precision** to store 16,777,217
C. `float` does not have enough **range** to store 16,777,217
D. Bug in the code
E. Use `double` (64-bit floating point)
F. Other

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E. Use `double` (64-bit floating point)

F. Other

❌ overflow for floats means INF; underflow means 0

Precision ≈ # bits in fraction

Range ≈ # bits in exponent

Maybe ☺

Different account balances could still have limitations in precision

Mid-quarter feedback

Thank you for your honest opinions about CS107!

We're happy that CS107 is working well for some of you,
but we also realize that CS107 is a *huge* step up in **difficulty**, **time**, and **independent learning** compared to the CS106 series.

Learning goals for this course:

Improve programming skills	Learn C and computer system design/layout
Develop ability to glean important information from dense resources (C manual, website, lecture, lab/assignment specs, **textbook**)	

(We also realize that Hewlett 200 is a *gigantic* lecture hall!)

Course Topic Overview

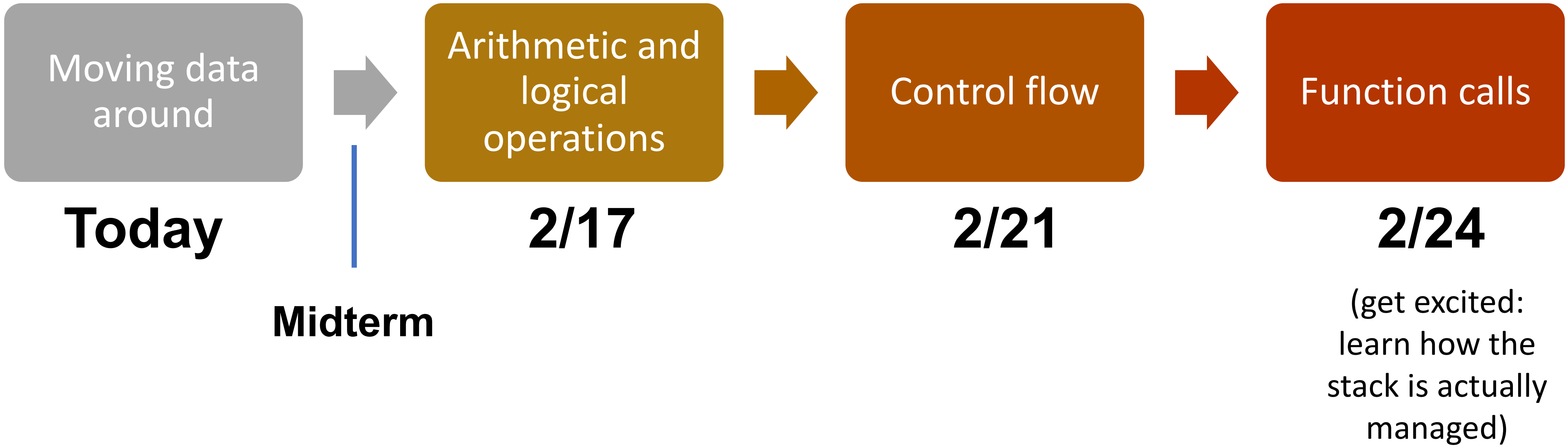
1. **Bits and Bytes** - *How can a computer represent integer numbers?*
2. **Chars and C-Strings** - *How can a computer represent and manipulate more complex data like text?*
3. **Pointers, Stack and Heap** – *How can we effectively manage all types of memory in our programs?*
4. **Generics** - *How can we use our knowledge of memory and data representation to write code that works with any data type?*

---

5. **Floats** - *How can a computer represent floating point numbers in addition to integer numbers?*
6. **Assembly** - *How does a computer interpret and execute C programs?*
7. **Heap Allocators** - *How do core memory-allocation operations like malloc and free work?*

CS107 Topic 6: How does a computer interpret and execute C programs?

Learning Assembly



Today’s 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

Plan For Today

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

```
cp -r /afs/ir/class/cs107/samples/lectures/lect11 .
```

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It’s bits all the way down...

Data representation so far

- Integer (`unsigned int`, 2’s complement signed `int`)
- `char` (ASCII)
- Address (unsigned long)
- `float`/`double` (IEEE floating point)
- Aggregates (arrays, `structs`)

The code itself is binary too!

- Instructions (machine encoding)

GCC

High-level programming code

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

gcc (compiler) compiles human-readable code into machine-readable instructions (bits and bytes).

Assembly code

```
mov    $0x0,%edx
mov    $0x0,%eax
jmp    4005cb <sum_array+0x15>
movslq %edx,%rcx
```

Assembly/machine code is **processor**-dependent (C code isn't).

Machine code

```
ba 00 00 00 00
b8 00 00 00 00
eb 09
48 63 ca
```

Assembly code is a shorthand/ legible version of machine code.

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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
```

```
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
  4005cb:    39 f2                   cmp    %esi,%edx
  4005cd:    7c f3                   jl     4005c2 <sum_array+0xc>
  4005cf:    f3 c3                   repz retq
```

What’s in an object file?

function pointer: name of function, mem. address of code

```
00000000004005b6 <sum_array>:
  4005b6:    ba 00 00 00 00        mov    $0x0,%edx
  4005bb:    b8 00 00 00 00        mov    $0x0,%eax
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  4005cf:    f3 c3                 repz retq
```

sequential instructions are at sequential addresses

machine code
each instruction encoded in binary

assembly code
each machine instruction decoded into human-readable assembly

What is an assembly instruction?

```
00000000004005b6 <sum_array>:
  4005b6:    ba 00 00 00 00       mov     $0x0,%edx
  4005bb:    b8 00 00 00 00       mov     $0x0,%e
  4005c0:    eb 09                jmp     4005cb
  4005c2:    48 63 ca             movslq  %edx,%rcx
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  4005cf:    f3 c3                repz retq
```

opcode (instruction name/type)

operands (arguments to instruction)

%eax is **register** name (storage location on CPU)

$0x1 is constant value ("**immediate**")

4005c2 is direct address in memory

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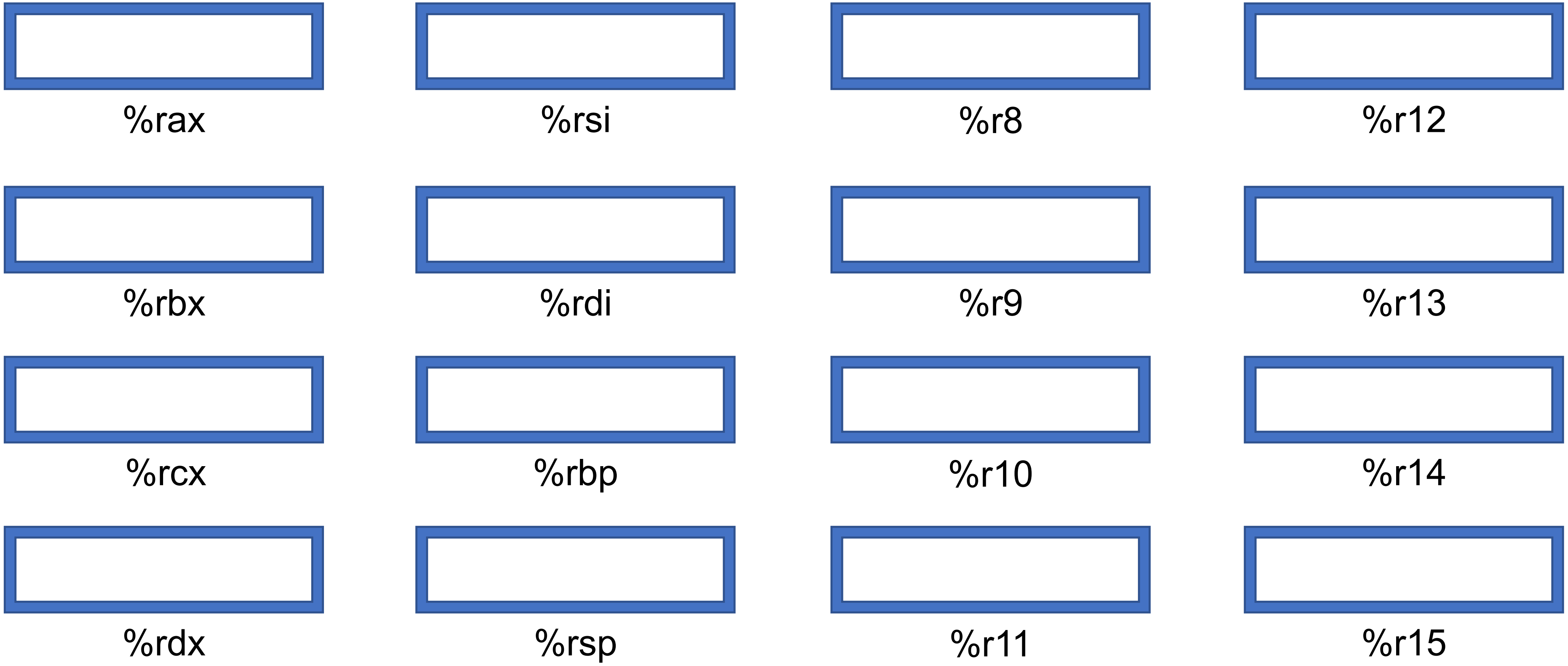
Registers

What is a register?

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

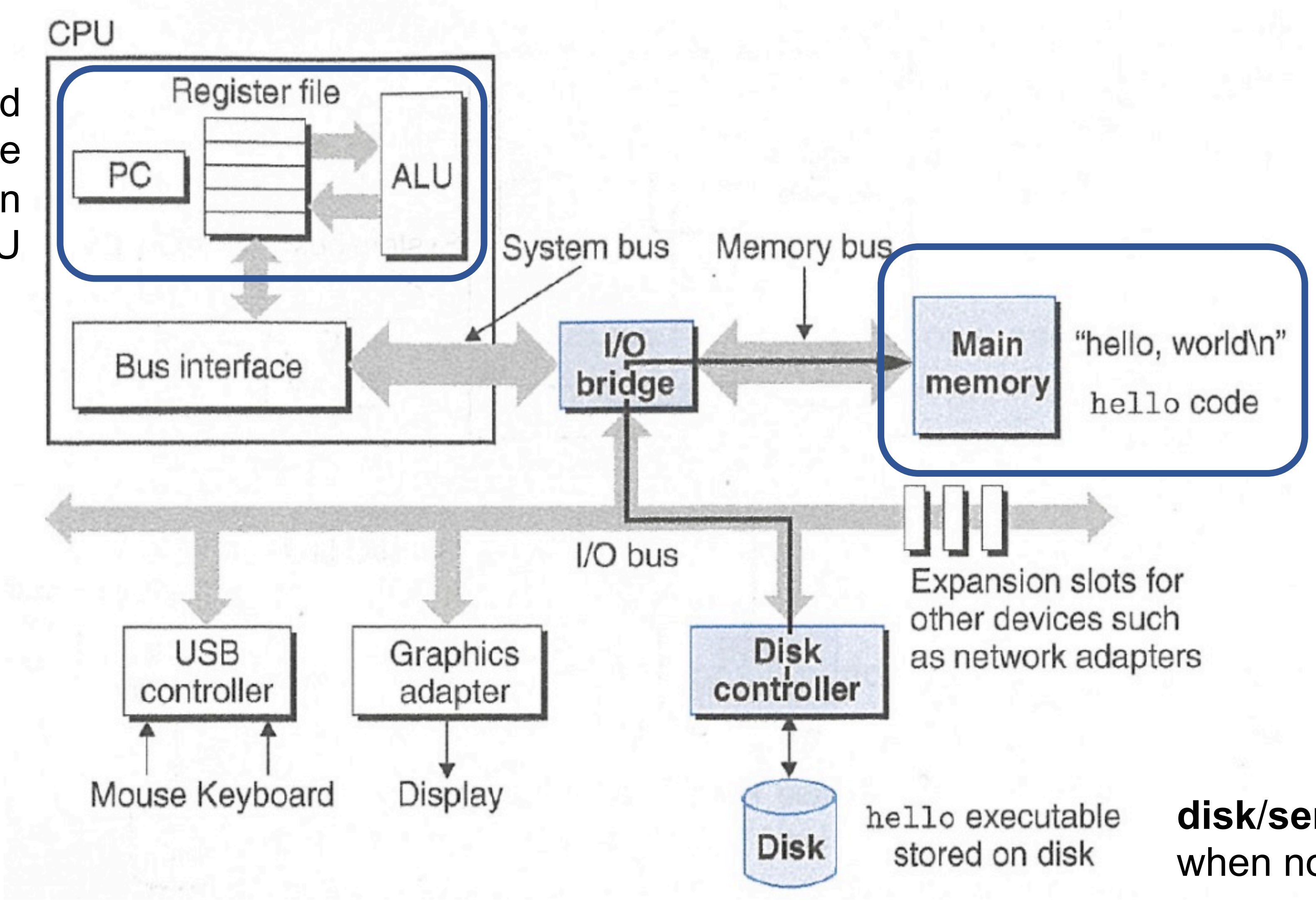
Registers are **not** located in memory.

Registers



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

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!

Storage abstraction: C vs assembly

High-level programming language (C)

Variable

- Variable type (`int`, `char`, `void*`, etc.) determines # of bytes stored + valid ops
- Local to stack frame (current function call)

Assembly language (x86-**64**)

Register

- **64**-bit space inside processor, simply holds bits
- Registers are shared across all function calls

Storage abstraction: C vs assembly

High-level programming language (C)

Variable

- Variable type (`int`, `char`, `void*`, etc.) determines # of bytes stored + valid ops
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Assembly language (x86-**64**)

Register

- **64**-bit space inside processor, simply holds bits
- Registers are shared across all function calls

Shared abstraction (C and x86-64)

Memory

- Byte-addressable:
  Each memory address refers to the start of one byte
- Stack managed automatically in C, manually in assembly

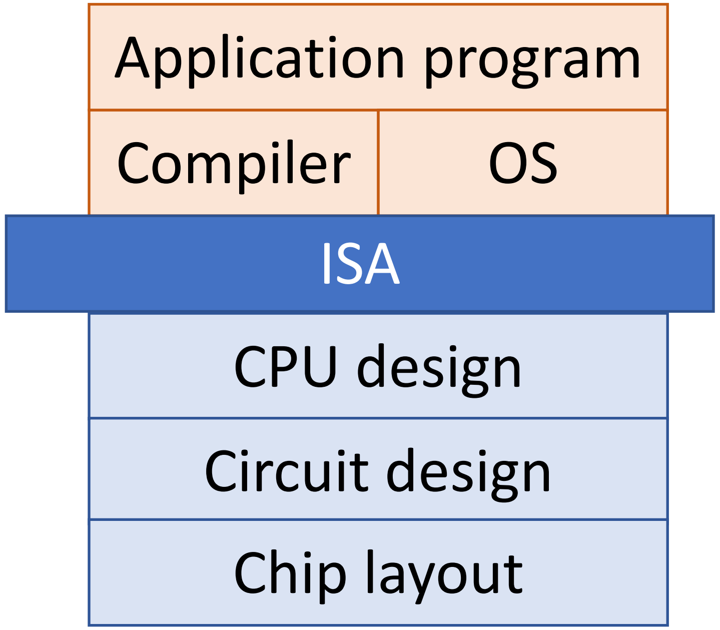
Shared abstraction (C and x86-64)

- Read/write to memory
- Assignment to variable/register
- Arithmetic on variables/registers

Instruction set architecture (ISA)

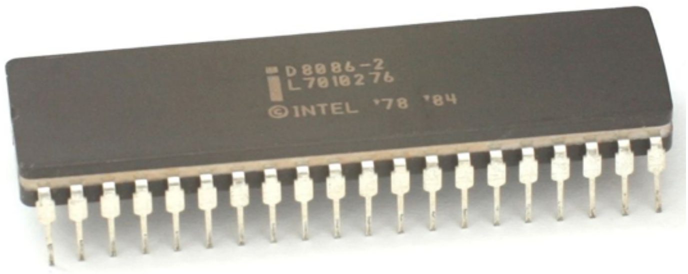
A contract between program/compiler and hardware:

- 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).



Two major categories of ISAs

CISC (e.g., x86)

- C for "Complex"
- **Large** set of expressive, specialized instructions
- Used in most computers
- Developed by AMD, cross-licensed by Intel

RISC (e.g., ARM, MIPS)

- R for "Reduced"
- **Small** set of simple instructions, but more instructions in code
- Used in low-power, low-cost embedded systems
- Former Stanford President John Hennessy designed the MIPS processor

JOHN L HENNESSY

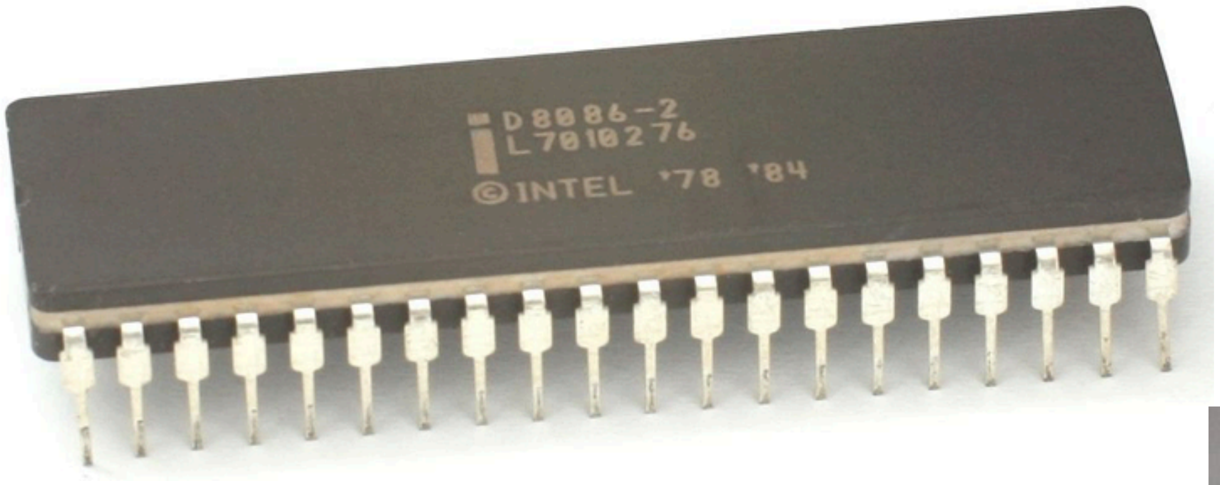
United States – 2017

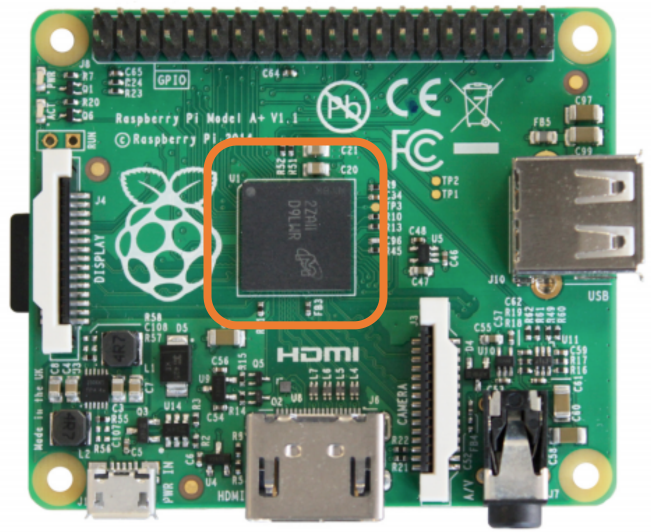
CITATION

For pioneering a systematic, quantitative approach to the design and evaluation of computer architectures with enduring impact on the microprocessor industry.

Central Processing Units (CPUs)

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

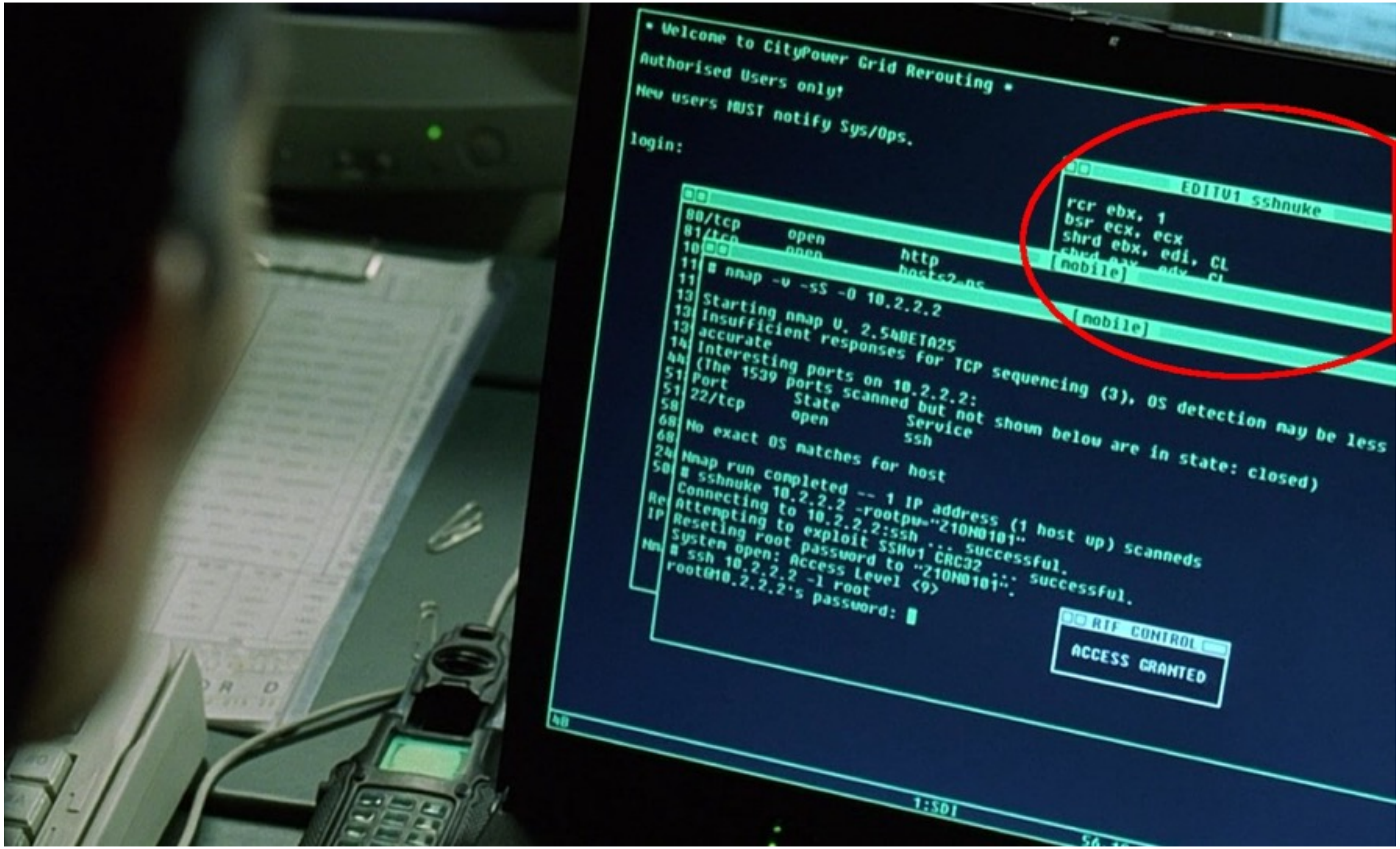




Raspberry Pi BCM2836
32-bit **ARM** microprocessor
($35 for everything, 2015)

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

Assembly code in movies



Trinity saving the world by hacking into the power grid using Nmap Network Scanning

The Matrix Reloaded, 2003

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- **Break:** Announcements
- The **mov** instruction

Midterm Exam

The midterm exam is **Fri. 2/14 12:30PM-2:20PM in Hewlett 200.**

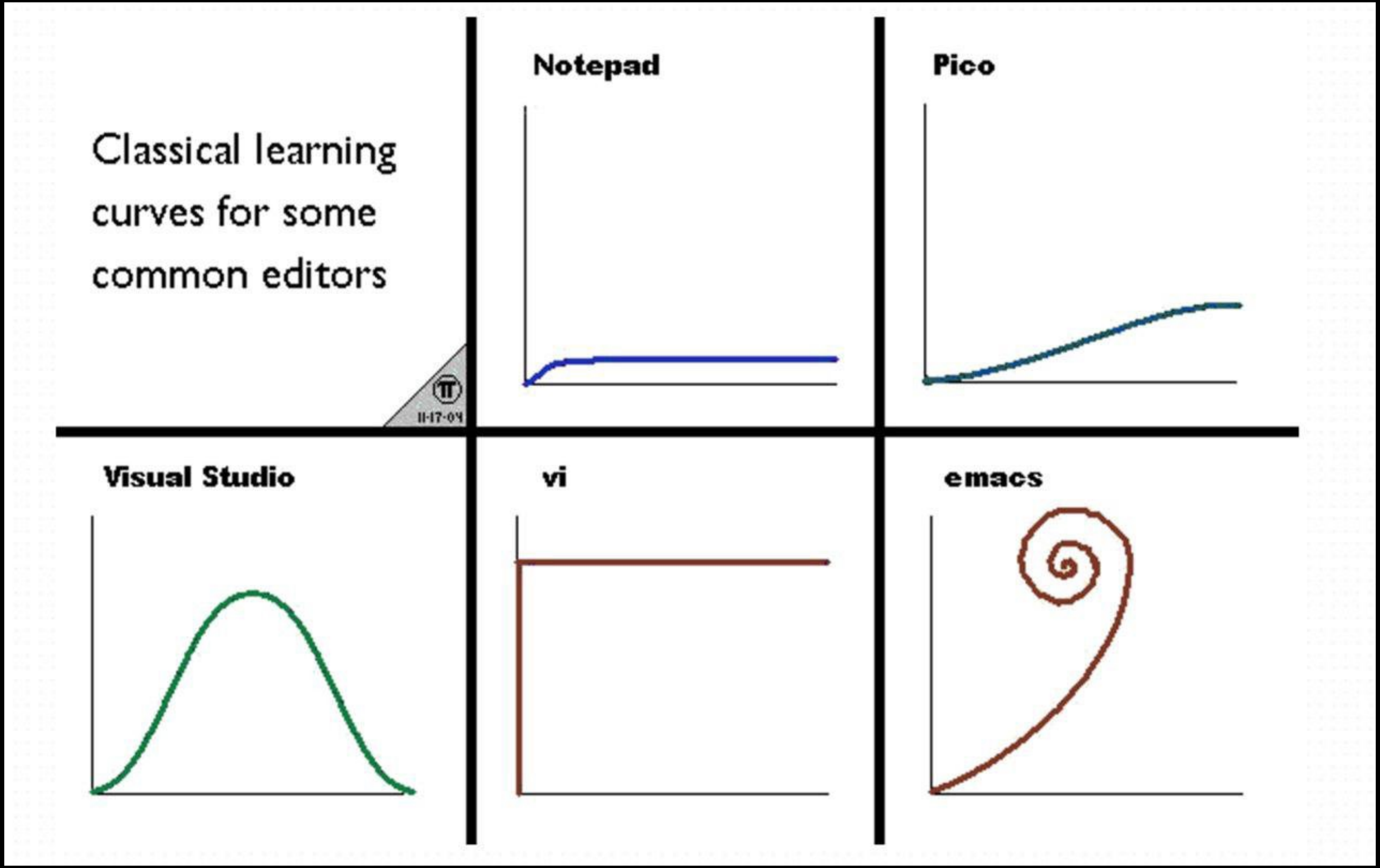
- Covers material through **lab4/assign4** (no floats or assembly language)
- Closed-book, 1 2-sided page of notes permitted, C reference sheet provided

Administered via BlueBook software (on your laptop)

- Practice materials and BlueBook download available on course website

Assignment 4 on time deadline is tonight, assignment 5 goes out today and is due **Fri. 2/21**. We recommend starting to work on it *after* the midterm exam.

Joke break


Classical learning curves for some common editors
11-17-04
Notepad
Pico
Visual Studio
vi
emacs

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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***) `$0x104`
- Register `%rbx`
- Memory Location (*at most one of **src, dst***) Direct address `0x6005c0`

Operand forms: load/store

```
mov   $0x0,0x6040
```

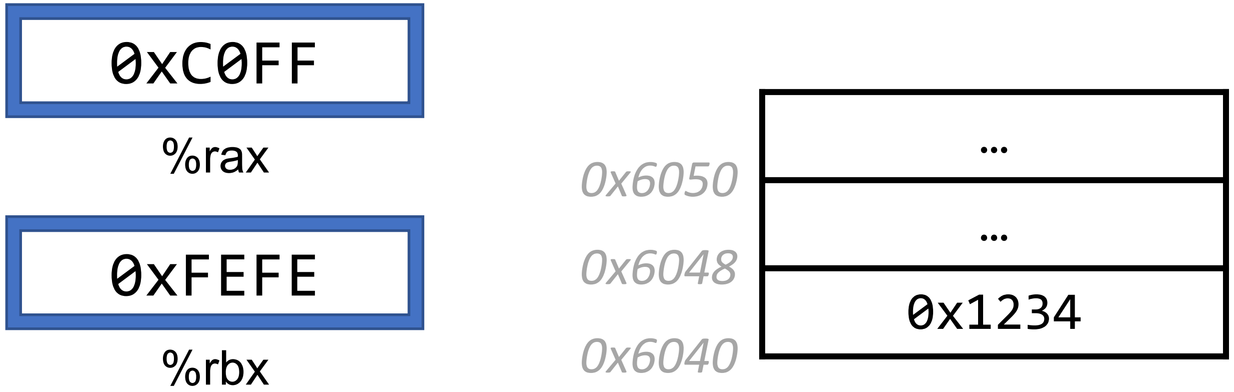
Store the value 0 into memory at address 0x6040.

```
mov   %rbx,%rax
```

Load the value in register %rbx, store into register %rax

```
mov   0x6040,%rbx
```

Load value from address 0x6040 into register %rbx



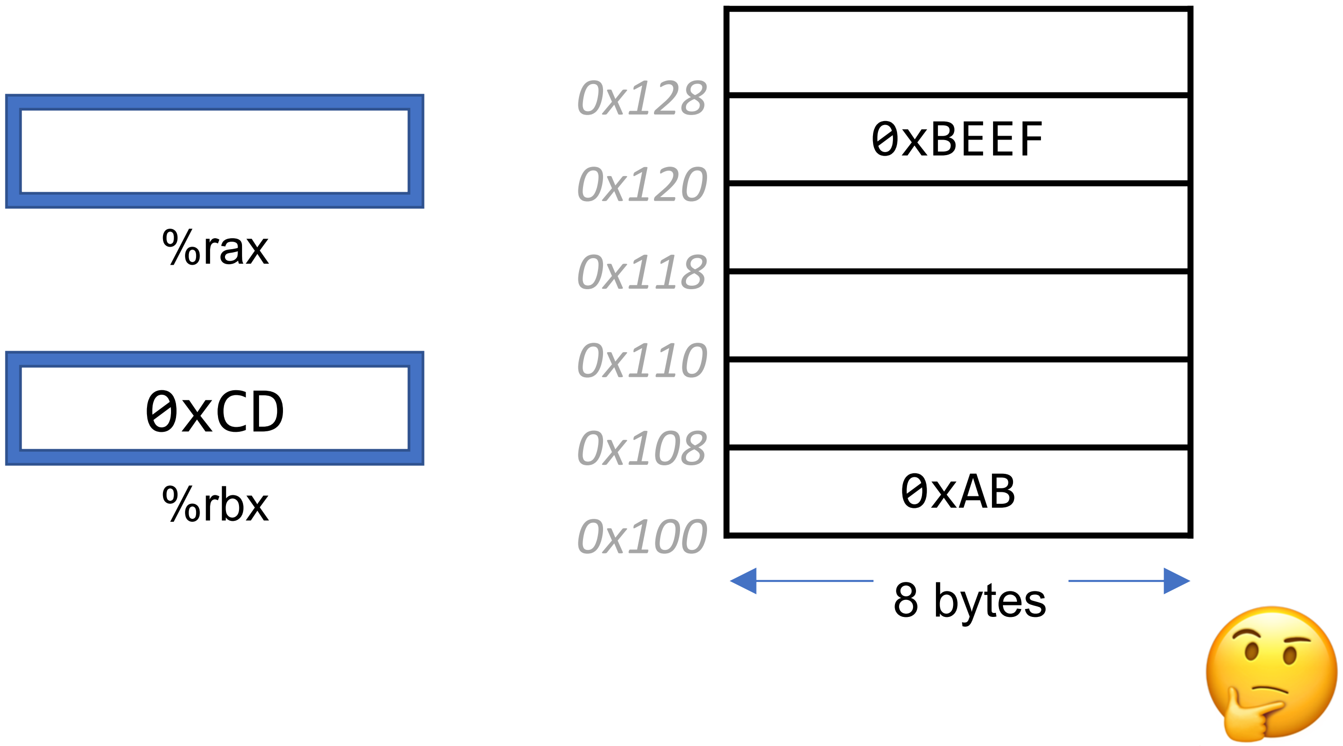
Practice #1: Imm/reg/direct

What are the results of the following move instructions (executed separately)?

```
1. mov    $0x100,%rax

2. mov     0x100,%rax

3. mov     %rbx,0x120
```



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- Register `%rbx`
- Memory Location
  (*at most one of **src, dst***)
  - Direct address `0x6005c0`
  - Indirect address `(%rbx)`

Example for next slide

Register	Value
%rax	0x6068
%rbx	0x6050
%rcx	-8

Address	Value (8 bytes)
0x6068	0xFACE
0x6060	0xB00B00
0x6058	0xC0FFEE
0x6050	0xBEEF
0x6048	0x5678
0x6040	0x1234

8 bytes

Operand forms: Indirect (1/2)

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

Load value at address %rax and store into register %rax.

```
mov    $0x0,16(%rbx)
```

*Store the constant 0 at address (**16 plus** %rbx)*

```
mov    $0x0,(%rbx,%rcx)
```

Store the constant 0 at address (%rbx + %rcx)

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

Displacement: positive or negative constant

Base: register

Index

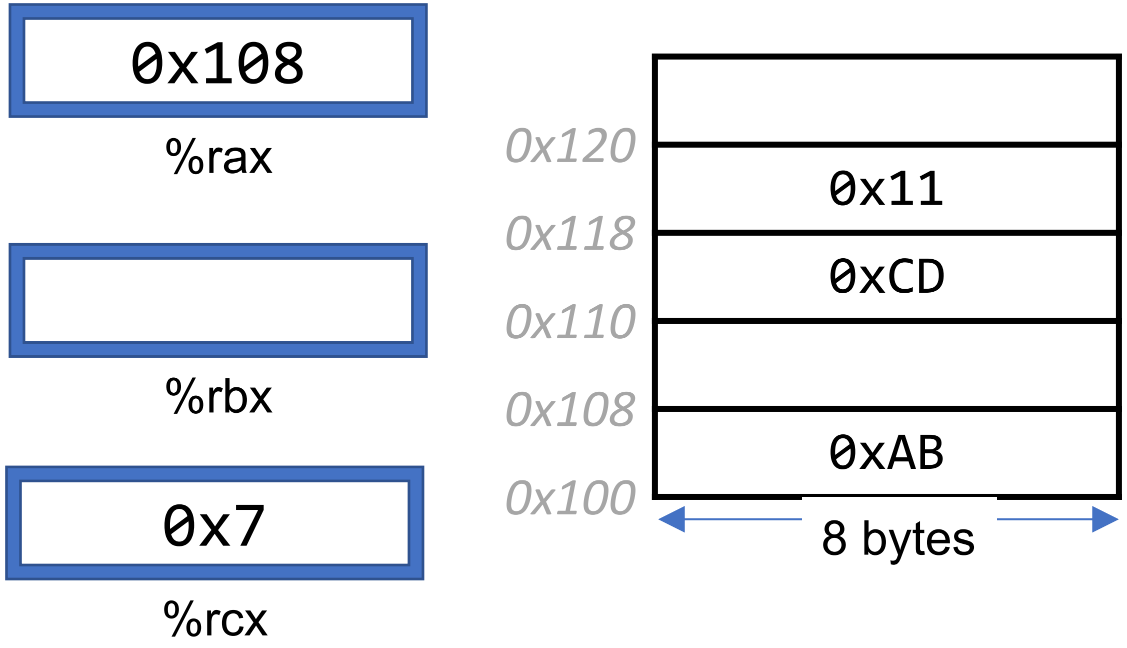
Practice #2: Operand Forms

What are the results of the following move instructions (executed separately)?

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

2. mov    -8(%rax),%rbx

3. mov    9(%rax,%rcx),%rbx
```



Imm(r_b, r_i) is equivalent to address

Imm + R[r_b] + R[r_i]

Displacement   Base   Index

Operand forms: Indirect (2/2)

```
mov   (,%rax,4),%rbx
```

*Load value at address (**4 times** %rax) and store in register %rbx.*

```
mov   $0x0,0x10(%rbx,%rax,2)
```

*Store the constant 0 at address (**0x10 plus** %rbx + (2 times %rax))*

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

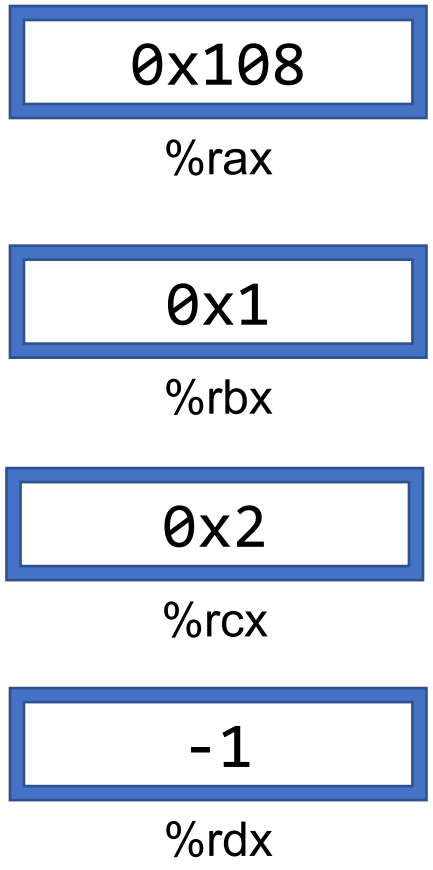
Scale must be 1,2,4, or 8 (if missing, = 1)

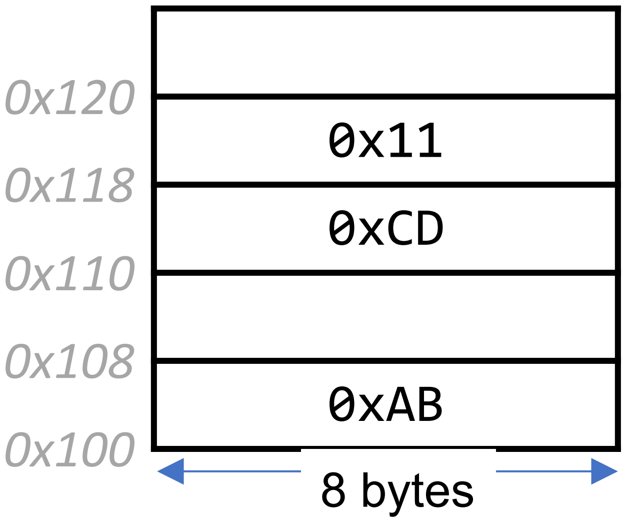
Practice #3: Operand Forms

What are the results of the following move instructions (executed separately)?

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

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





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

Displacement Base Index Scale (1,2,4,8)

Most General Operand Form

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

is equivalent to…

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

Operand Forms

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

Goals of indirect addressing: C

Why are there so many forms of indirect addressing?

We see these indirect addressing paradigms in C as well!

Goals of indirect addressing: C

```c
long exchange(long *xp, long y) {
    long x = *xp;
    *xp = y;
    return y;
}
void last_element(long *arr, int nelems) {
    long z = arr[nelems - 1];
}
```

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)

Try your intuition: How do you think each of the C assignments ***might*** map to mov instructions?

(many right answers!)

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 a week!