The Hardware/Software Interface

Memory, Data, & Addressing I

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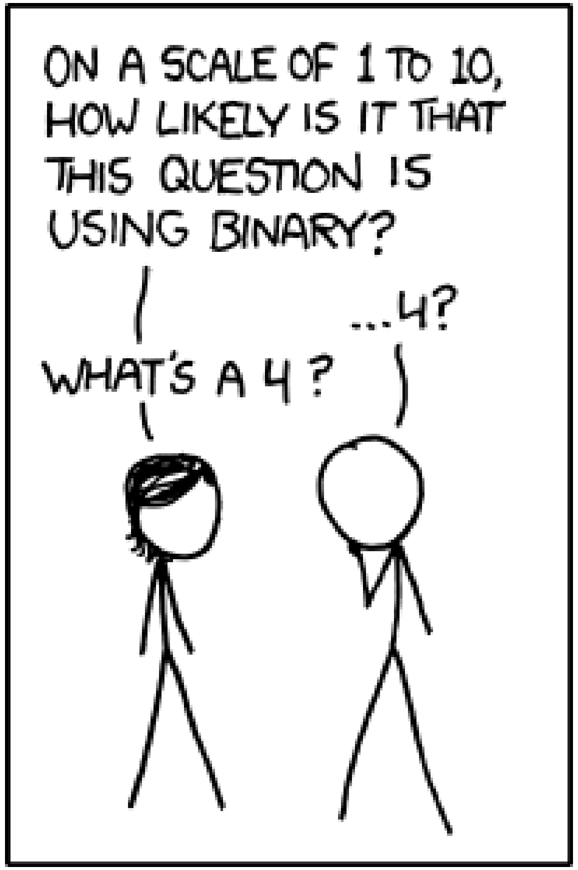


http://xkcd.com/953/

Relevant Course Information

- Upcoming deadlines
  - Pre-Course Survey and HW0 due tonight
  - HW1 due Monday (9/29) night
  - Lab 0 due Monday (9/29) night
    - This lab is *exploratory* and looks like a HW; the other labs will look a lot different
  - Reminder: Readings due before every lecture!

- Ed Discussion etiquette
  - For anything that doesn't involve sensitive information or a solution, post publicly (you can post anonymously!)
  - If you feel like you question has been sufficiently answered, make sure that a response has a checkmark

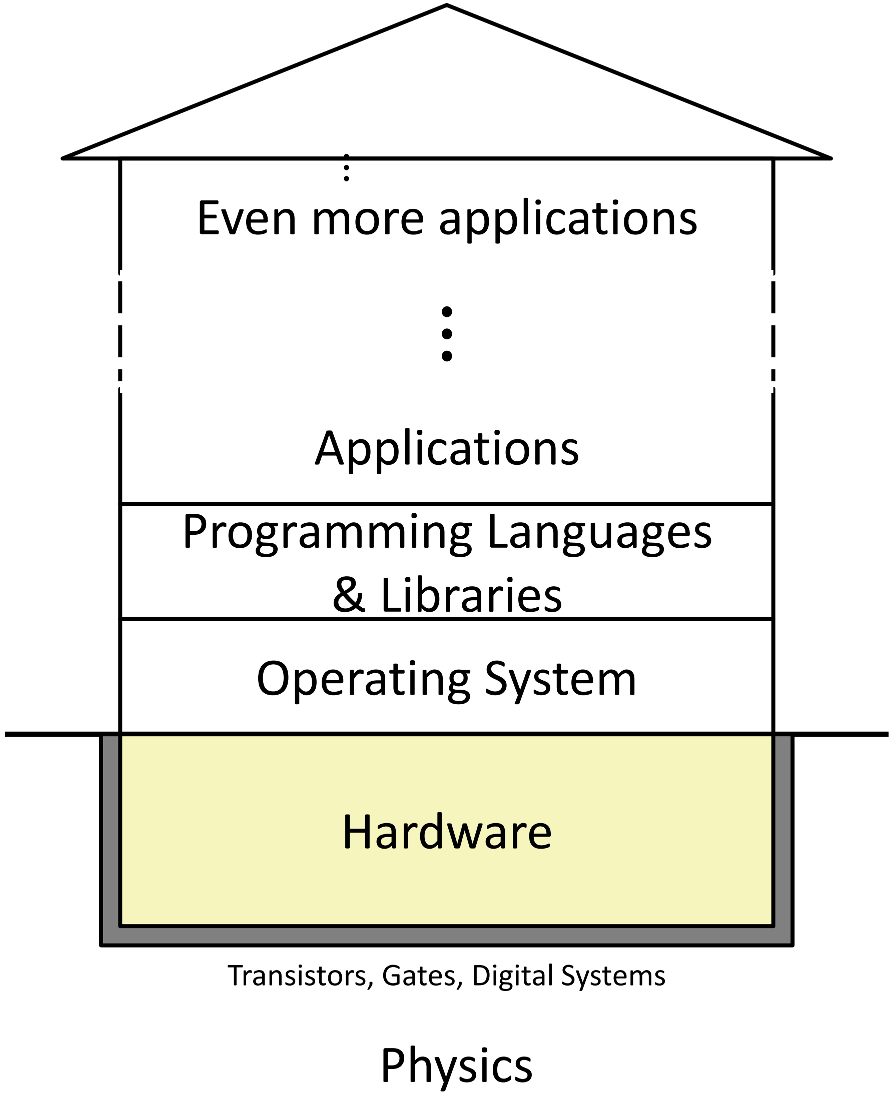
EPA

- Encourage class-wide learning!
- Effort
  - Attending support hours, completing all assignments
  - Keeping up with Ed Discussion activity
- Participation
  - Making the class more interactive by asking questions in lecture, section, support hours, and on Ed Discussion
- Altruism
  - Helping others in section, support hours, and on Ed Discussion

House of Computing Check-In

- Topic Group 1: **Data**
  - **Memory**, **Data**, Integers, Floating Point, Arrays, Structs

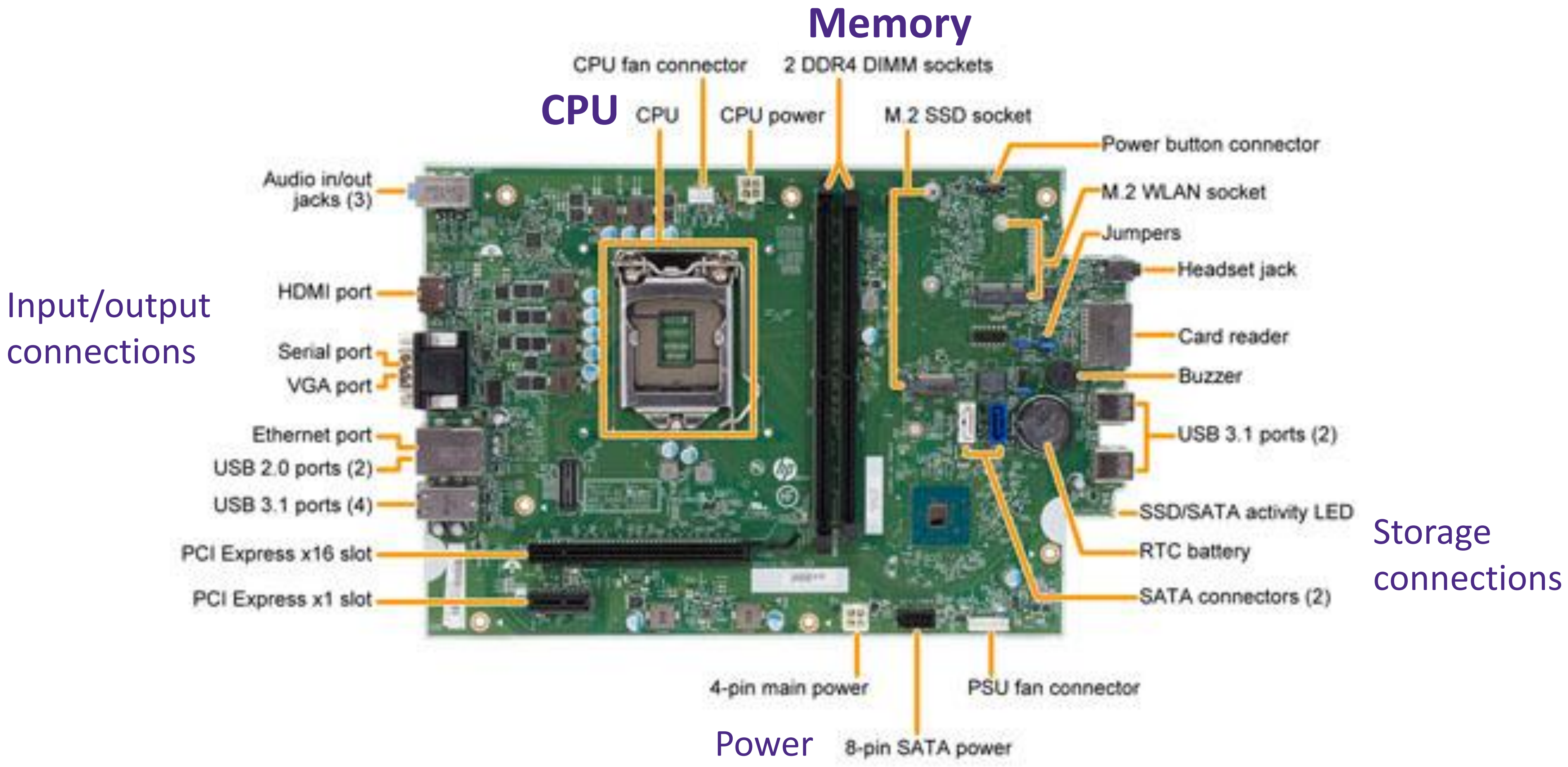
- How do we store information for other parts of the house of computing to access?
  - How do we represent data and what limitations exist?
  - What design decisions and priorities went into these encodings?



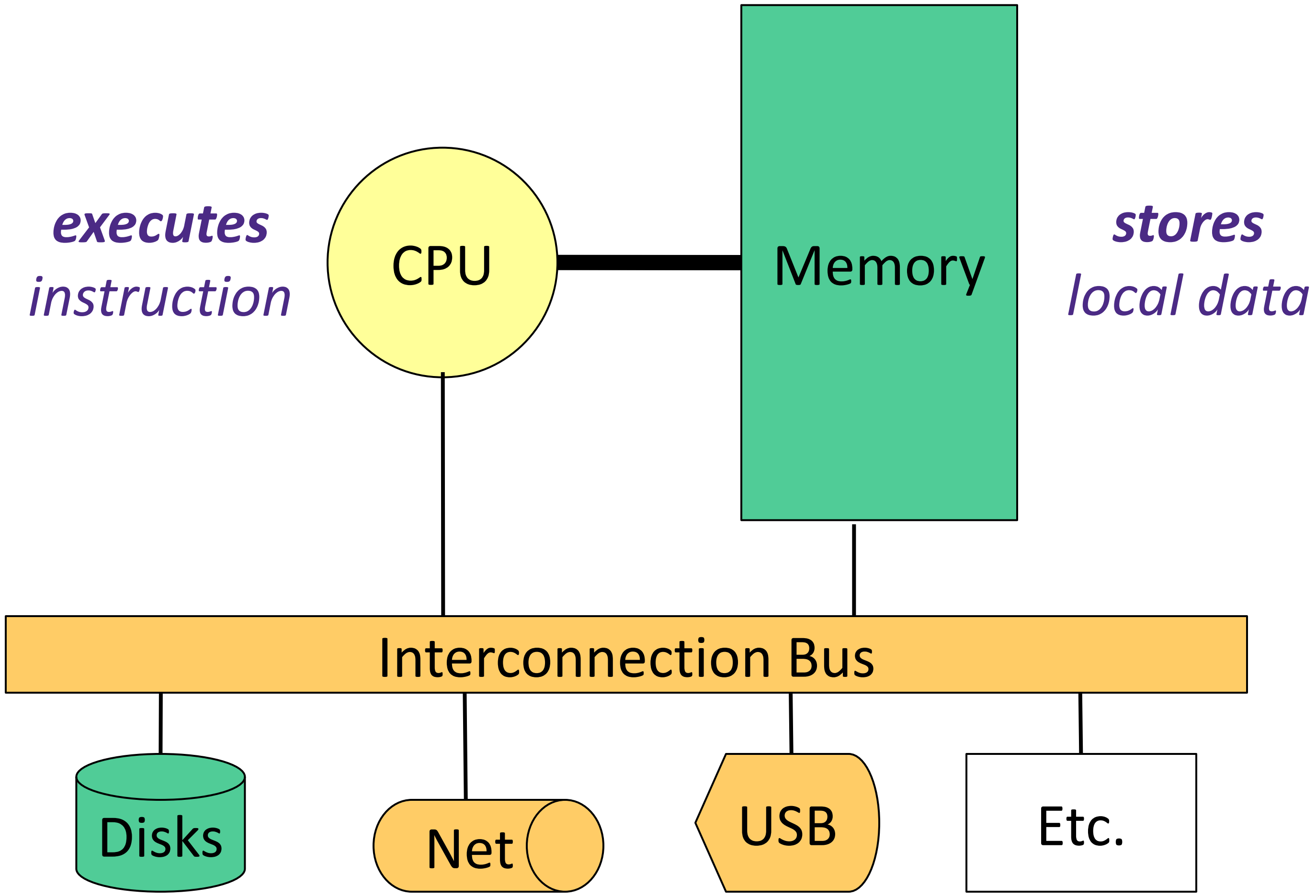
Lecture Outline (1/3)

- **Memory and Addresses**
- Data in Memory
- Data Basics in Programming

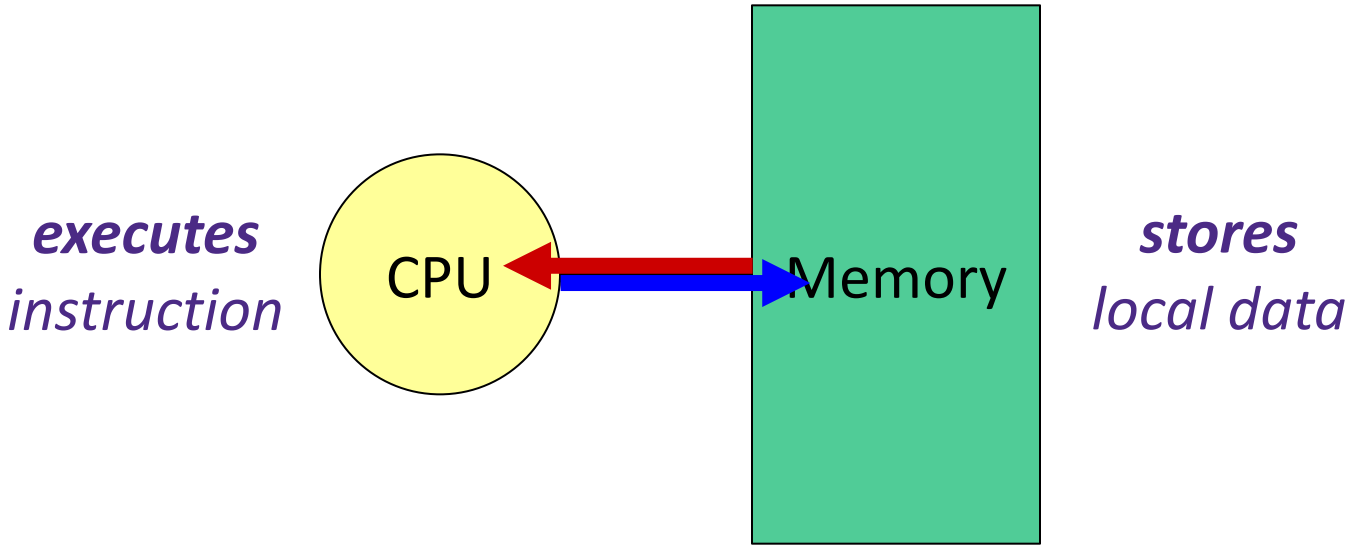
Hardware: Physical View



Hardware: Logical View

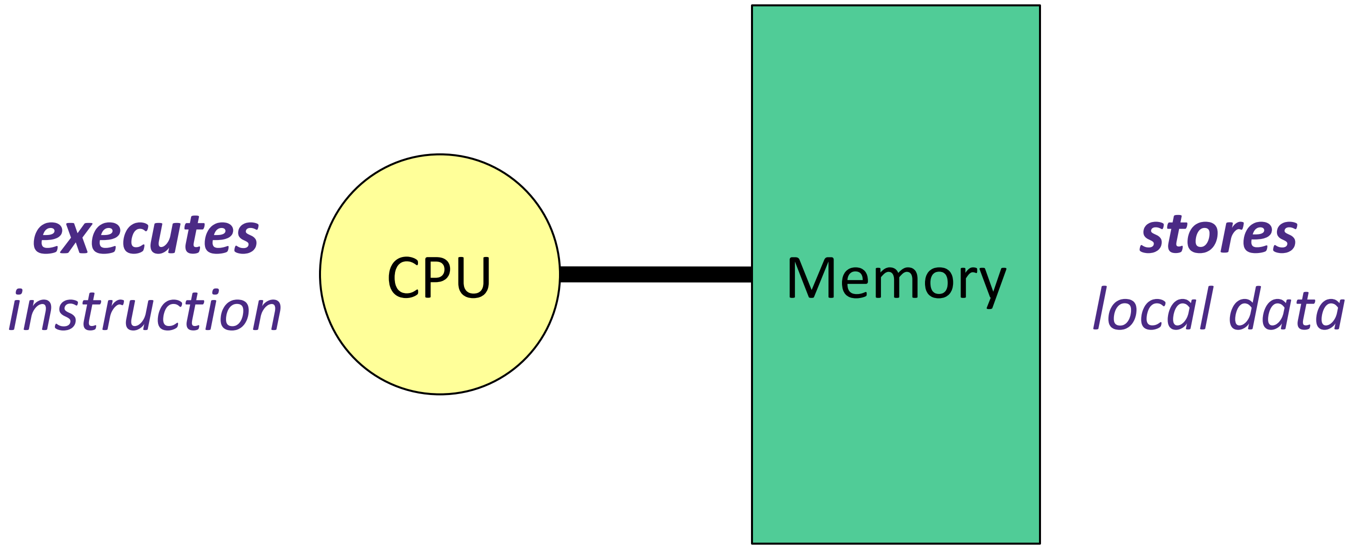


CPU and Memory



- The CPU communicates with memory frequently
  - **Fetches** (loads) data upon request from memory
  - **Writes** (stores) data to memory

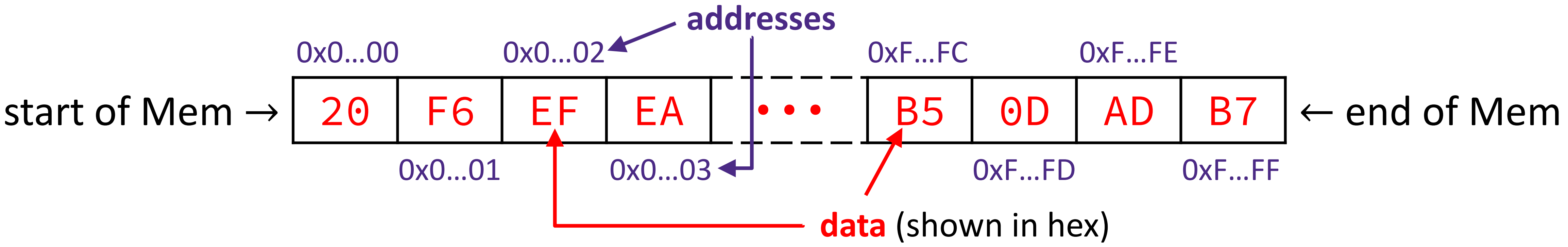
Memory Operation Basics



- What does data look like?
  - It turns out that instructions *are* data, too, and encoded in "machine code"
- How do we find or specify data in memory?
  - Programs have built-in ways to track addresses

Addresses (Review)

- Conceptually, memory is a single, large array of bytes (*i.e.*, ***byte-oriented***)
- Programs refer to bytes in memory by their unique *addresses* (indices)
  - We number addresses in increasing order starting from 0
  - By convention, address size = word size (*fixed-length*)
  - Domain of possible addresses = *address space*

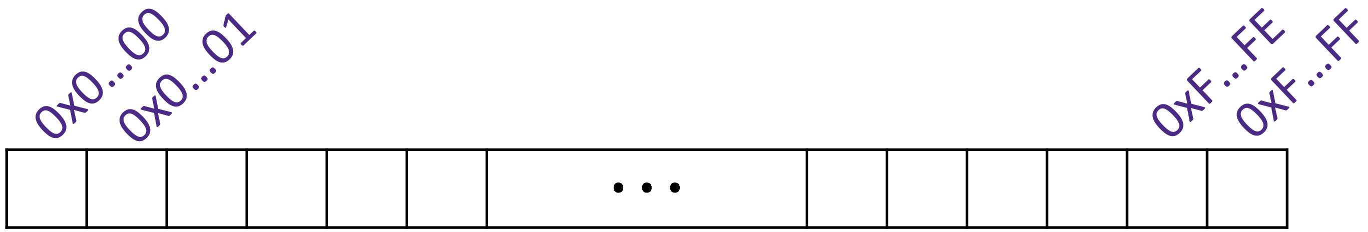


Bits and Bytes and Things

- 1 byte = 8 bits
- n bits can represent up to 2^n things
  - Sometimes (oftentimes?) those "things" are bytes!

- If an addresses are a-bits wide, how many distinct addresses are there?

- What does each address refer to?



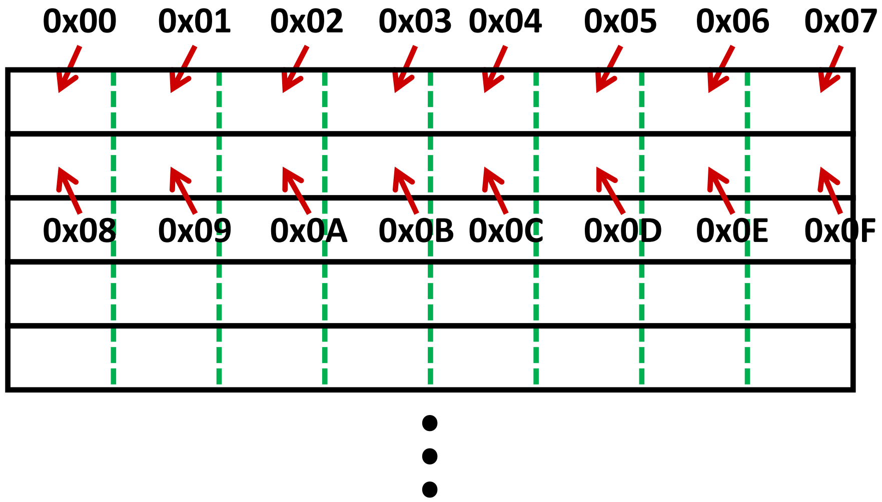
Modern System Details

- Current x86-64 systems use **64-bit (8-byte) words** (“64-bit machines”)
  - Potential address space: $\mathbf{2^{64}}$ addresses
    2^{64} bytes ≈ **1.8 x 10^{19} bytes**
    = 18 billion billion bytes = 18 EB (exabytes)
  - Actual physical address space: **48 bits**
    - This is sufficient space for now and allows for some operating system tricks
    - Example address: `0x 7f fc 3d d5 06 94`

- There’s a lot more to this story… stay tuned for virtual memory!

Visualizing Memory

- We will regularly depict memory as a two-dimensional array
  - Each cell is a byte
  - Addresses increase from left-to-right and then top-to-bottom
  - Row width will most commonly be chosen to the word size (8 bytes here)



Lecture Outline (2/3)

- Memory and Addresses
- **Data in Memory**
- Data Basics in Programming

Fixed-Length Binary (Review)

- Because storage is finite in reality, everything is stored as "fixed" length
  - Data is moved and manipulated in fixed-length chunks
  - Multiple fixed lengths (*e.g.*, 1 byte, 4 bytes, 8 bytes)
  - Leading zeros now *must* be included up to "fill out" the fixed length

- Example: The 1-byte representation of 4 is 0b00000100

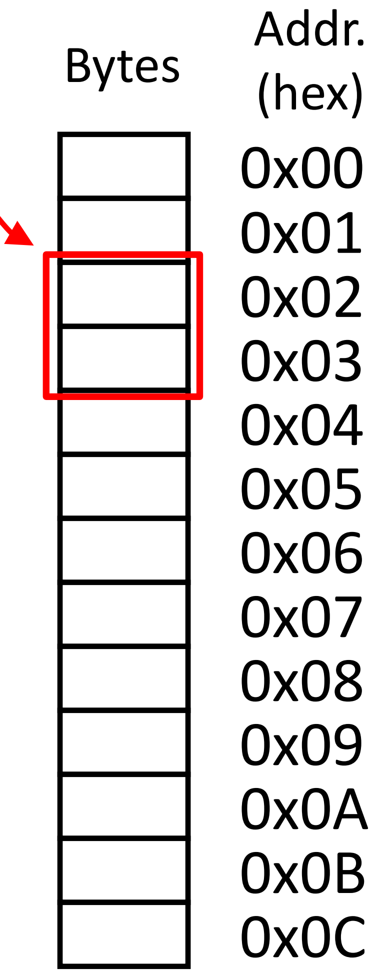
Most Significant Bit (MSB)

Least Significant Bit (LSB)

Address of Multibyte Data (Review)

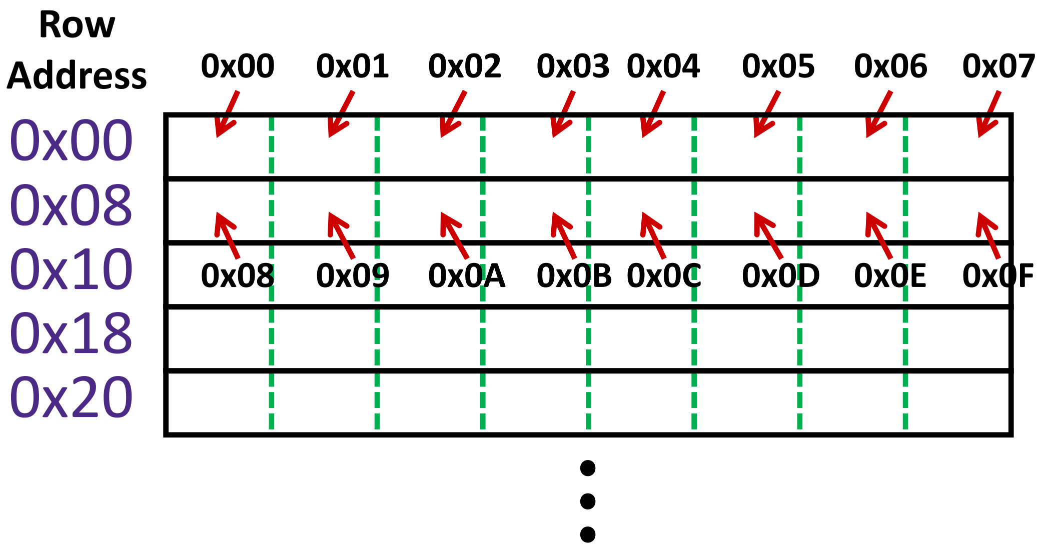
- Data that span multiple bytes can be thought of as "chunks" of memory
  - Example: 351 = 0b1 0101 1111, stored as 0x015F
  - Each individual byte has a unique address – how should we refer to the chunk's address/location?

- The address of *any* chunk of memory is given by the address of the first byte
  - To specify a chunk of memory, need *both* its **address** and its **size**



Visualizing Memory (Revisited)

- We will regularly depict memory as a two-dimensional array
  - Addresses increase from left-to-right and then top-to-bottom
  - Row width will most commonly be chosen to the word size (8 bytes here)
  - Row address is given by the lowest address in the row



Polling Questions (1/2)

- By looking at the bits stored in memory, I can tell what a particular 4 bytes is being used to represent.

  A. True B. False

- We can fetch a piece of data from memory as long as we have its address.

  A. True B. False

- Which of the following bytes have a most-significant bit (MSB) of 1?

  A. 0x63 B. 0x90 C. 0xCA D. 0xF

Byte Ordering (Review)

- How should bytes within a word be ordered *in memory?*
  - Want to keep consecutive bytes in consecutive addresses
  - By convention, ordering of bytes called *endianness* – in which address does the least significant *byte* go?
    - Big-endian means least significant byte has highest address
    - Little-endian means least significant byte has lowest address

- **Example:** 4-byte data 0xA1B2C3D4 at address 0x100

			0x100	0x101	0x102	0x103		
Big-Endian			A1	B2	C3	D4		
Little-Endian			D4	C3	B2	A1		

Polling Questions (2/2)

- We store the value `0x 01 02 03 04` as a ***word*** at address 0x100 in a **big-endian**, 64-bit machine
- What is the ***byte of data*** stored at address 0x104?

A. 0x04

B. 0x40

C. 0x01

D. 0x10

E. We're lost…

Endianness Notes

- Endianness is a property of the architecture
  - We are using x86-64, which is little-endian
- *Endianness only applies to memory storage*
- Often programmer can ignore endianness because it is handled for you
  - Bytes wired into correct place when reading or storing from memory (hardware)
  - Compiler and assembler generate correct behavior (software)
- Endianness still shows up:
  - Logical issues: accessing different amount of data than how you stored it (C/C++)
  - Need to know exact values to debug memory errors (common)

Lecture Outline (3/3)

- Memory and Addresses
- Data in Memory
- **Data Basics in Programming**

Data Types and Sizes (Review)

- Variables stored in memory treated as "chunks"
  - C data type sizes vary somewhat by architecture (*e.g.*, IA-32 vs. x86-64)

C Data Type	Java "Equivalent"	Size in bytes (x86-64)
`char`	`byte`	1
`short`	`short`	2
`int`	`int`	4
`long`		8
`long long`	`long`	8
`float`	`float`	4
`double`	`double`	8
`long double`		16

Variables (Review)

- Variables stored in memory treated as “chunks”
  - A variable name is an alias for a *location* that contains its data/value
  - *Declaring* a variable allocates space for it (*e.g.*, `int x;`)
  - *Initializing* a variable also assigns an initial value to that space (*e.g.*, `int x = 3;`)

- Programming language differences
  - In Java, variable declaration implicitly performs initialization
  - In C, declaration does not perform initialization (initially “**mystery data**”)

C Data Type	x86-64 Size
`char`	1B
`short`	2B
`int`	4B
`long`	8B
`long long`	8B
`float`	4B
`double`	8B
`long double`	16B

Alignment (Review)

- Variables stored in memory treated as "chunks"
  - A variable name is an alias for a *location* that contains its data/value
  - *Declaring* a variable allocates space for it (*e.g.*, `int x;`)
  - *Initializing* a variable also assigns an initial value to that space (*e.g.*, `int x = 3;`)

- Alignment
  - A variable is considered **aligned** if its address is a multiple of its size
  - Not always required, but common

C Data Type	x86-64 Size
`char`	1B
`short`	2B
`int`	4B
`long`	8B
`long long`	8B
`float`	4B
`double`	8B
`long double`	16B

Assignment Example (1/4)

- Syntax: left-hand side (LHS) = right-hand side (RHS);
- Effect: store *value* of RHS into the *location* given by LHS

- Example: Little-endian, current state of memory
  - `int x, y;`
    - Assume x is at address 0x04, y is at 0x18

	0x00	0x01	0x02	0x03	
0x00	A7	00	32	00	
0x04	00	01	29	F3	x
0x08	DE	AD	BE	EF	
0x0C	FA	CE	CA	FE	
0x10	26	00	00	00	
0x14	00	00	10	00	
0x18	01	00	00	00	y
0x1C	FF	00	F4	96	
0x20	EE	EE	EE	EE	
0x24	00	00	00	00	

Assignment Example (2/4)

- Syntax: left-hand side (LHS) = right-hand side (RHS);
- Effect: store *value* of RHS into the *location* given by LHS

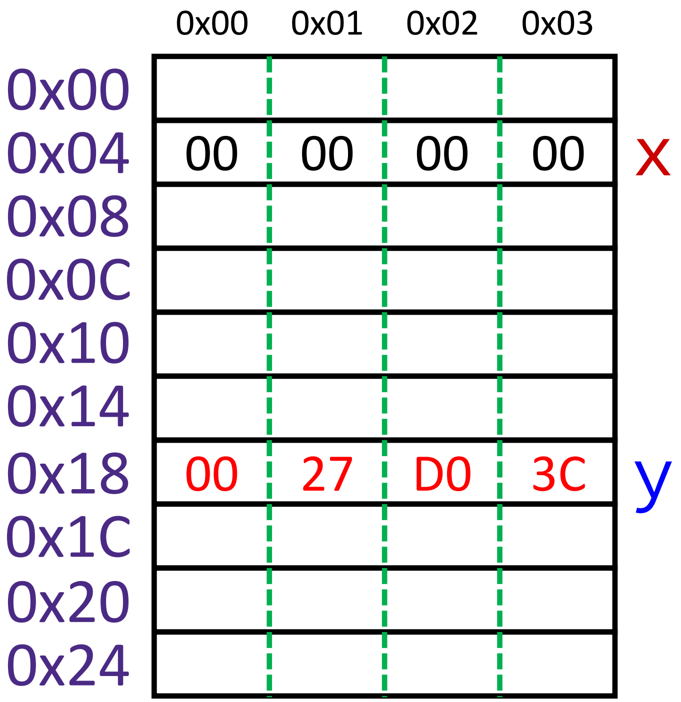
- Example: Little-endian, *partial* state of memory
  - `int x, y;`
    - Assume x is at address 0x04, y is at 0x18
  - `x = 0;`

	0x00	0x01	0x02	0x03	
0x00					
0x04	00	00	00	00	x
0x08					
0x0C					
0x10					
0x14					
0x18	01	00	00	00	y
0x1C					
0x20					
0x24					

Assignment Example (3/4)

- Syntax: left-hand side (LHS) = right-hand side (RHS);
- Effect: store *value* of RHS into the *location* given by LHS

- <u>Example</u>: Little-endian, *partial* state of memory
  - `int x, y;`
    - Assume x is at address 0x04, y is at 0x18
  - `x = 0;`
  - `y = 0x3CD02700;`



Assignment Example (4/4)

- Syntax: left-hand side (LHS) = right-hand side (RHS);
- Effect: store *value* of RHS into the *location* given by LHS

- <u>Example</u>: Little-endian, *partial* state of memory
  - `int x, y;`
    - Assume x is at address 0x04, y is at 0x18
  - `x = 0;`
  - `y = 0x3CD02700;`
  - `x = y + 3;`
    - Get value at y, add 3, store in x

	0x00	0x01	0x02	0x03	
0x00					
0x04	03	27	D0	3C	x
0x08					
0x0C					
0x10					
0x14					
0x18	00	27	D0	3C	y
0x1C					
0x20					
0x24					

Homework Setup (If Time)

- Assume that a snippet of memory is shown below (in hex), starting with the byte at address 0x08 on a *little-endian* machine:

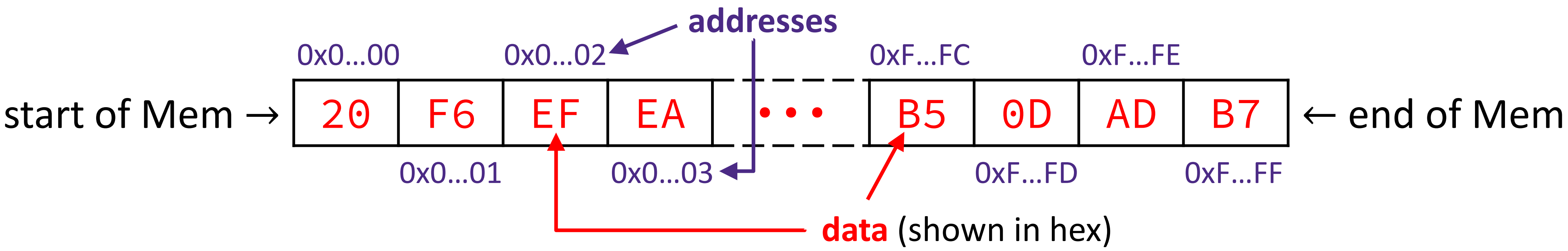
```
addr:  0x08 0x09 0x0A 0x0B 0x0C 0x0D 0x0E 0x0F
data: | A2 | D0 | 4F | C4 | A0 | 0C | F7 | 27 |
```

- What is the value of the `int` stored at address `0x0C`?

Summary (1/2)

- Memory is a long, *byte-addressed* array
  - Word size bounds the size of the *address space* and memory
  - Address of a chunk of memory given by the address of the lowest byte in chunk

- Endianness determines memory storage order for multi-byte data
  - Least significant byte in lowest (little-endian) or highest (big-endian) address of memory chunk



Summary (2/2)

- Programming Data
  - Variable declaration allocates space for data type size
  - Assignment results in value being put in memory location

C Data Type	x86-64 Size
char	1B
short	2B
int	4B
long	8B
long long	8B
float	4B
double	8B
long double	16B

	0x00	0x01	0x02	0x03	
0x00	A7	00	32	00	
0x04	00	01	29	F3	x
0x08	DE	AD	BE	EF	
0x0C	FA	CE	CA	FE	
0x10	26	00	00	00	
0x14	00	00	10	00	
0x18	01	00	00	00	y
0x1C	FF	00	F4	96	
0x20	EE	EE	EE	EE	
0x24	00	00	00	00	