

# Memory, Data, & Addressing I

CSE 351 Spring 2021

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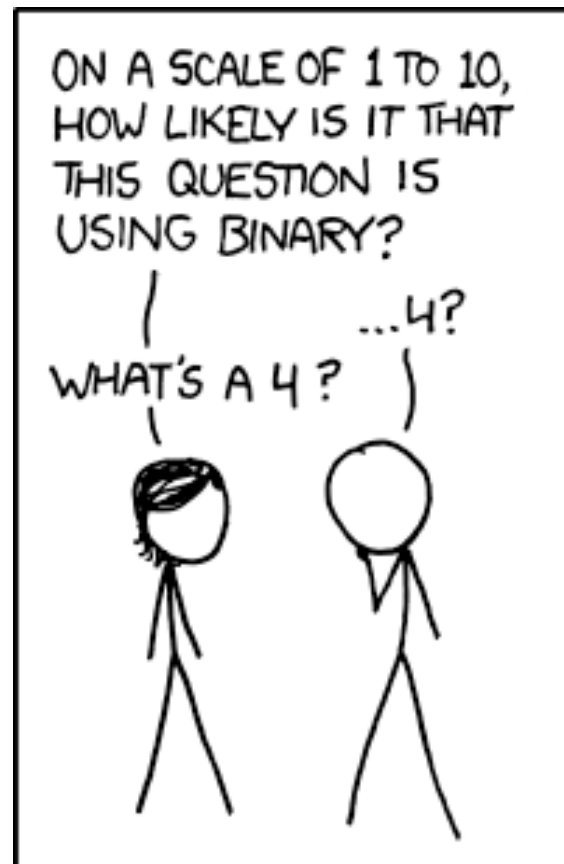
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<http://xkcd.com/953/>

# Administrivia

- ❖ Pre-Course Survey and hw0 due tonight @ 11:59 pm
- ❖ hw1 due Friday (4/02) @ 11:59 pm
- ❖ Lab 0 due Monday (4/05) @ 11:59 pm
  - This lab is *exploratory* and looks like a hw; the other labs will look a lot different (involve writing code etc.)
  - Don't worry if everything in Lab 0 doesn't make perfect sense right now! We will cover all of these topics in more detail later in the course.
  - Lab 0 is about getting you used to modifying C code and running it to see what the outcome is – a powerful tool for understanding the concepts in this course!
- ❖ Readings should be completed by 11am on day of lecture
- ❖ Lecture activities should be completed by 11am of NEXT lecture

# Questions During Lecture

- ❖ Asking too many questions in **chat window** during lecture is very distracting to some students
- ❖ ***While I am lecturing***
  - If you need to ask a question about content, please use the **Google doc**
  - Staff will answer your questions in the **Google doc** during lecture
  - We will reserve the **chat window** for short logistical questions (e.g. “which slide deck?”, “We can’t see your screen”)
- ❖ ***When I explicitly pause to take questions*** - Use **chat window** to type your question, or speak
- ❖ We will **not** be saving the **chat window**. We WILL be saving, and anonymizing the **Google doc** and sharing with the class.
- ❖ **You must log on with your @uw google account to access!!**
  - <https://tinyurl.com/CSE351-21sp-Questions>
  - Open the TODAY's Lecture Questions doc for 11:30/2:30

# Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Memory & data

- Integers & floats
- x86 assembly
- Procedures & stacks
- Executables
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

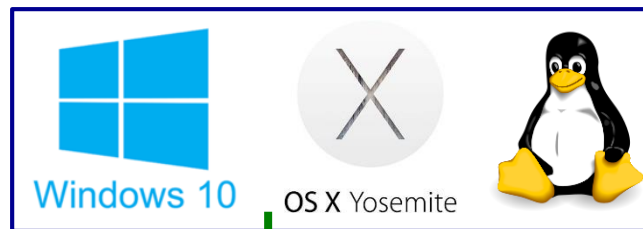
Assembly language:

```
get_mpg:
    pushq    %rbp
    movq    %rsp, %rbp
    ...
    popq   %rbp
    ret
```

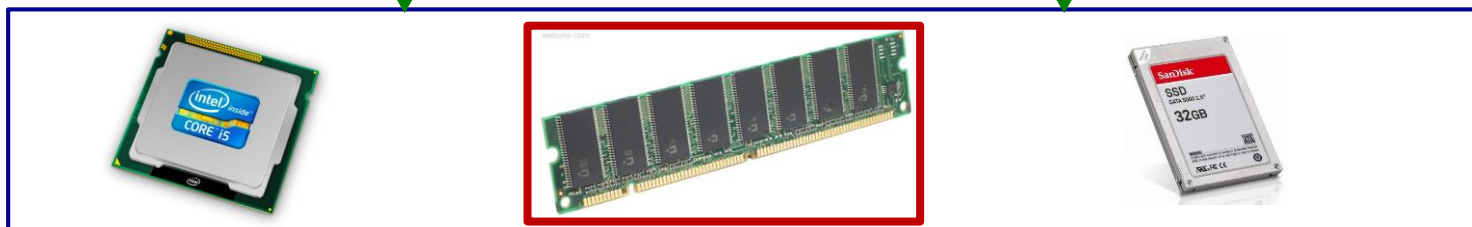
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:



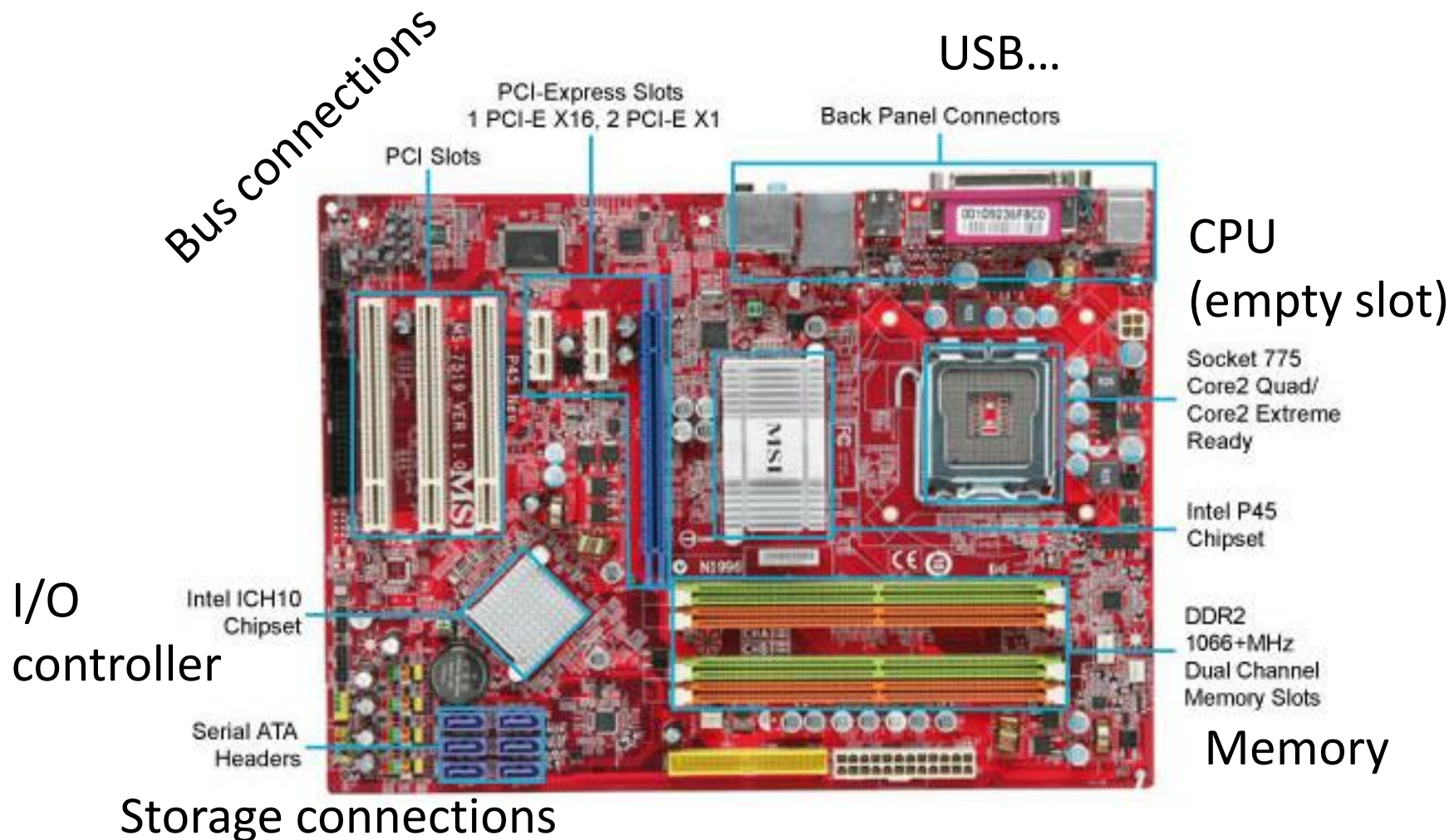
Computer system:



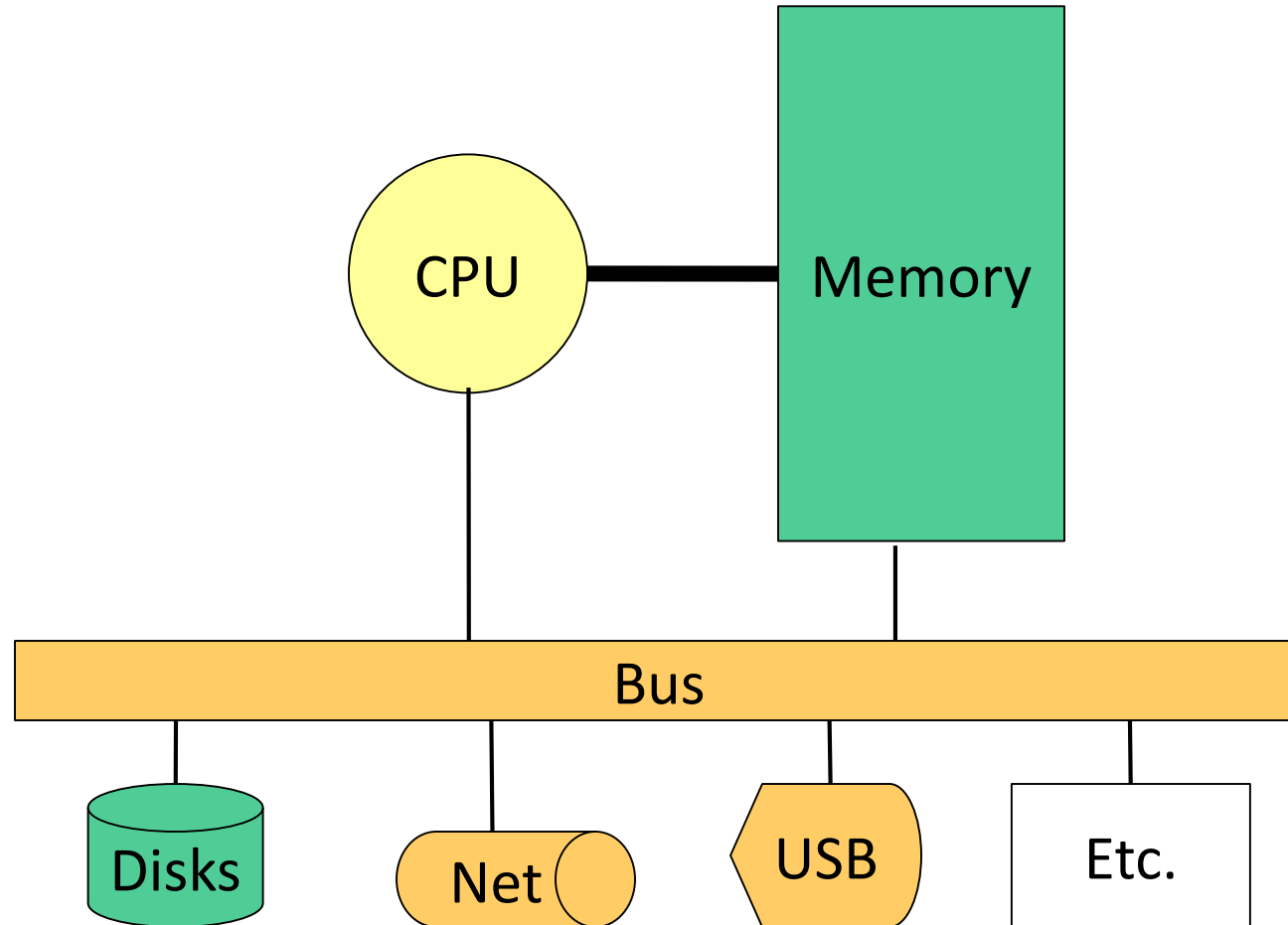
# Memory, Data, and Addressing

- ❖ Hardware - High Level Overview
- ❖ Representing information as bits and bytes
  - Memory is a byte-addressable array
  - Machine “word” size = address size = register size
- ❖ Organizing and addressing data in memory
  - Endianness – ordering bytes in memory
- ❖ Manipulating data in memory using C
- ❖ Boolean algebra and bit-level manipulations

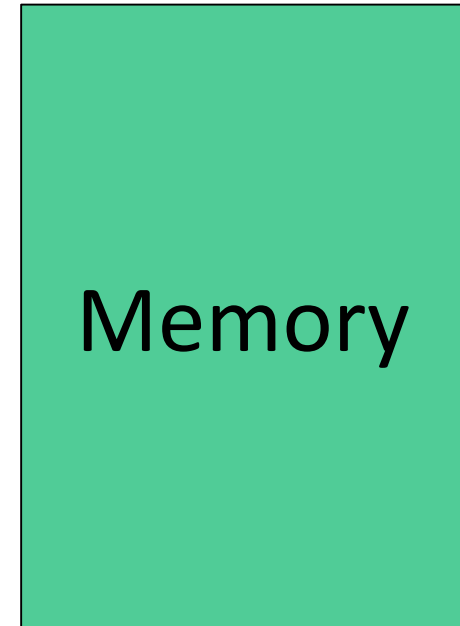
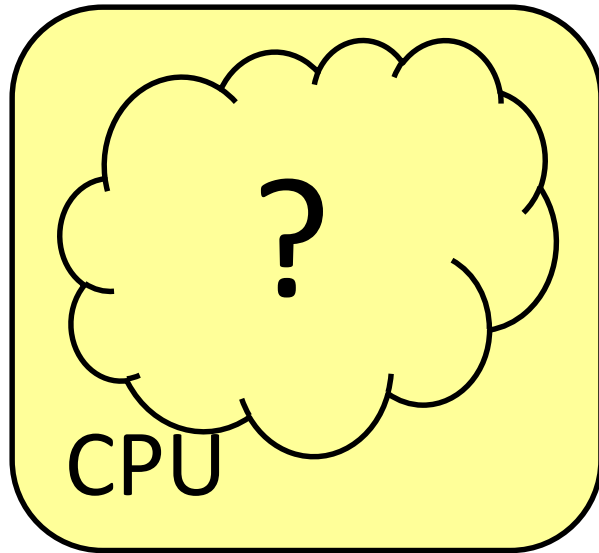
# Hardware: Physical View



# Hardware: Logical View



# Hardware: 351 View (version 0)

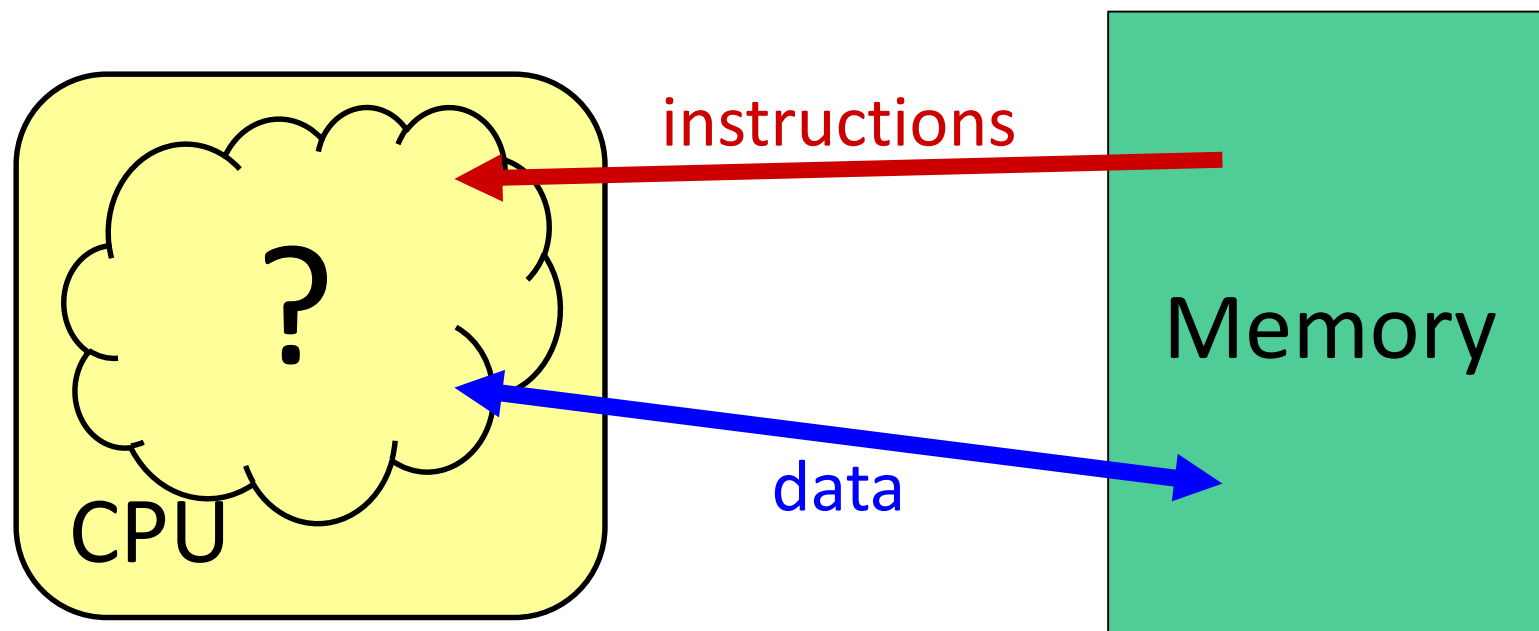


- ❖ The CPU **executes** instructions
- ❖ Memory **stores** data
- ❖ Binary encoding!
  - Instructions *are* just data

How are data  
and instructions  
represented?

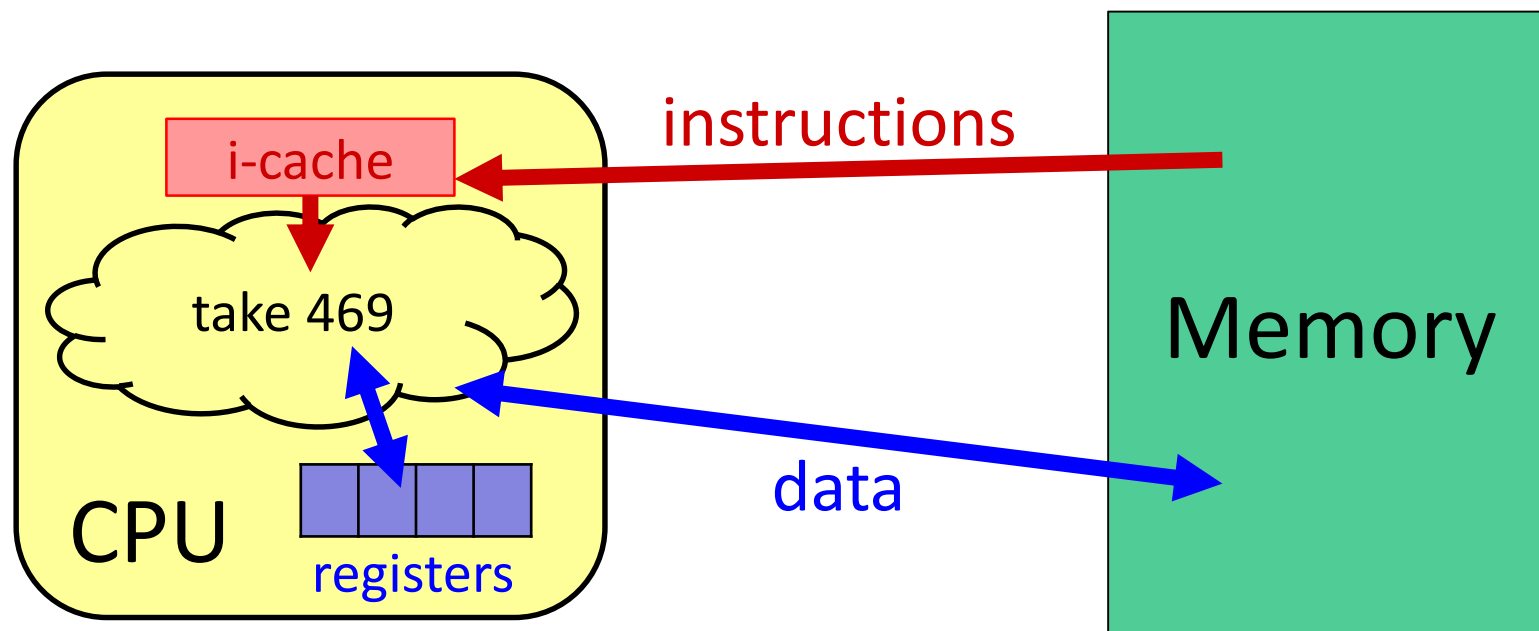


# Hardware: 351 View (version 0)



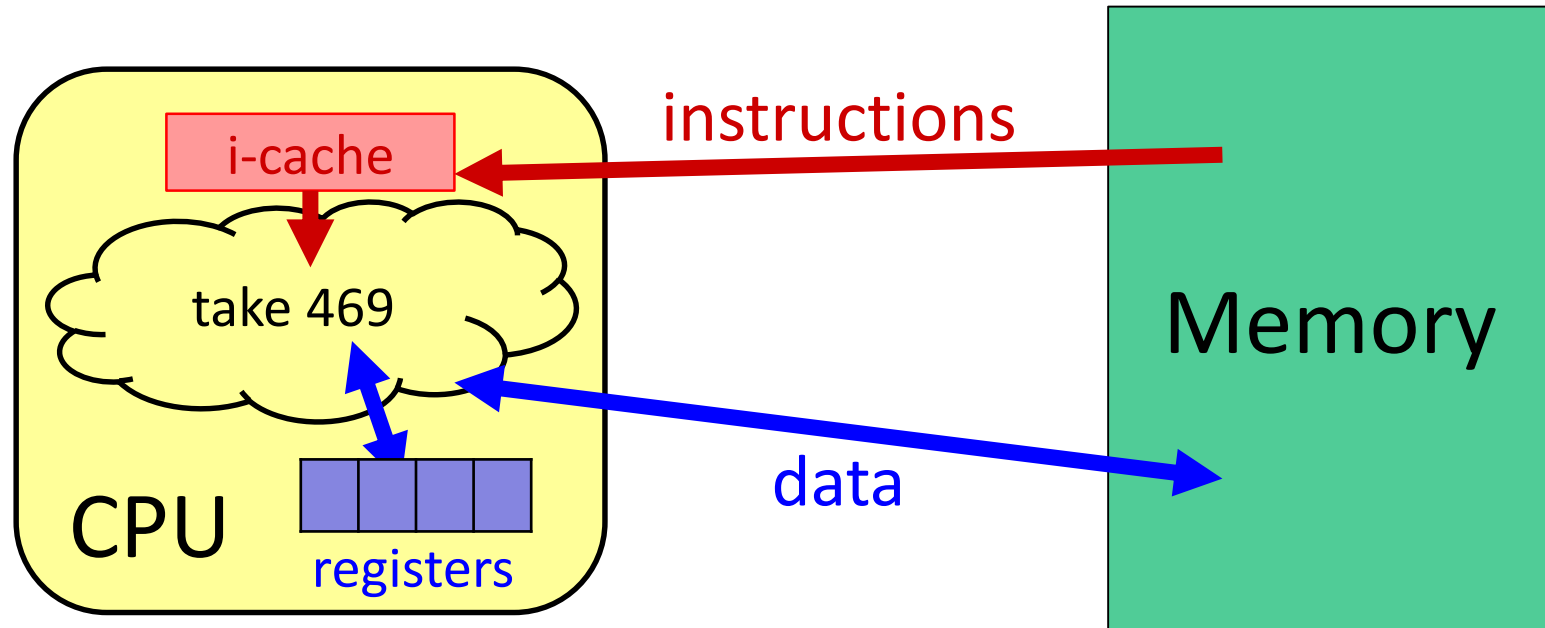
- ❖ To execute an instruction, the CPU must:
  - 1) Fetch the instruction
  - 2) (if applicable) Fetch data needed by the instruction
  - 3) Perform the specified computation
  - 4) (if applicable) Write the result back to memory

# Hardware: 351 View (version 1)



- ❖ More CPU details:
  - Instructions are held temporarily in the **instruction cache**
  - Other data are held temporarily in **registers**
- ❖ **Instruction fetching** is hardware-controlled
- ❖ **Data movement** is programmer-controlled (assembly)

# Hardware: 351 View (version 1)



- ❖ We will start by learning about Memory

How does a program find its data in memory?

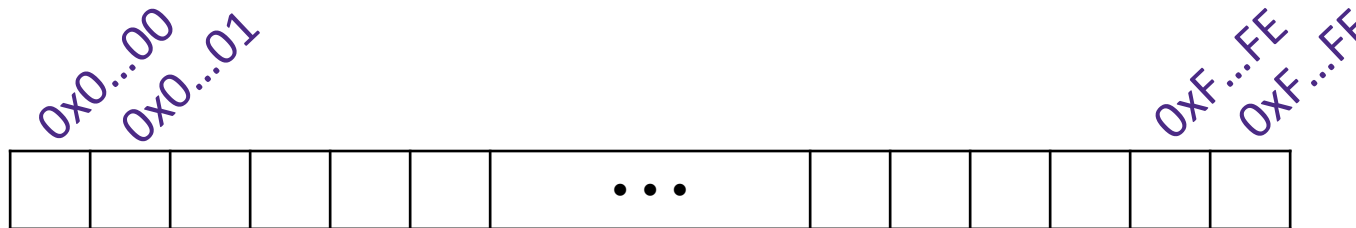
# Review Questions

- ❖ 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**

# Binary Encoding Additional Details

- ❖ 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 “eight-bit” representation of the number 4 is 0b00000100
  - Most Significant Bit (MSB)
  - Least Significant Bit (LSB)

# An Address Refers to a Byte of Memory



- ❖ Conceptually, memory is a single, large array of bytes, each with a unique *address* (index)
  - Each address is just a number represented in *fixed-length* binary
- ❖ Programs refer to bytes in memory by their *addresses*
  - Domain of possible addresses = *address space*
  - We can store addresses as data to “remember” where other data is in memory
- ❖ But not all values fit in a single byte... (e.g. 351)
  - Many operations actually use multi-byte values

# Machine “Words”

- ❖ Instructions encoded into machine code (0’s and 1’s)
  - Historically (still true in some assembly languages), all instructions were exactly the size of a **word**
- ❖ We have *chosen* to tie word size to address size/width
  - word size = address size = register size
  - word size =  $w$  bits  $\rightarrow 2^w$  addresses
- ❖ Current x86 systems use **64-bit (8-byte) words**
  - Potential address space:  $2^{64}$  addresses  
 $2^{64}$  bytes  $\approx$   **$1.8 \times 10^{19}$  bytes**  
= 18 billion billion bytes = 18 EB (exabytes)
  - Actual physical address space: **48 bits**

# Data Representations

## ❖ Sizes of data types (in bytes)

Java Data Type	C Data Type	32-bit (old)	x86-64
boolean	bool	1	1
byte	char	1	1
char		2	2
short	short int	2	2
int	int	4	4
float	float	4	4
	long int	4	8
double	double	8	8
long	long long	8	8
	long double	8	16
<b>(reference)</b>	<b>pointer *</b>	<b>4</b>	<b>8</b>

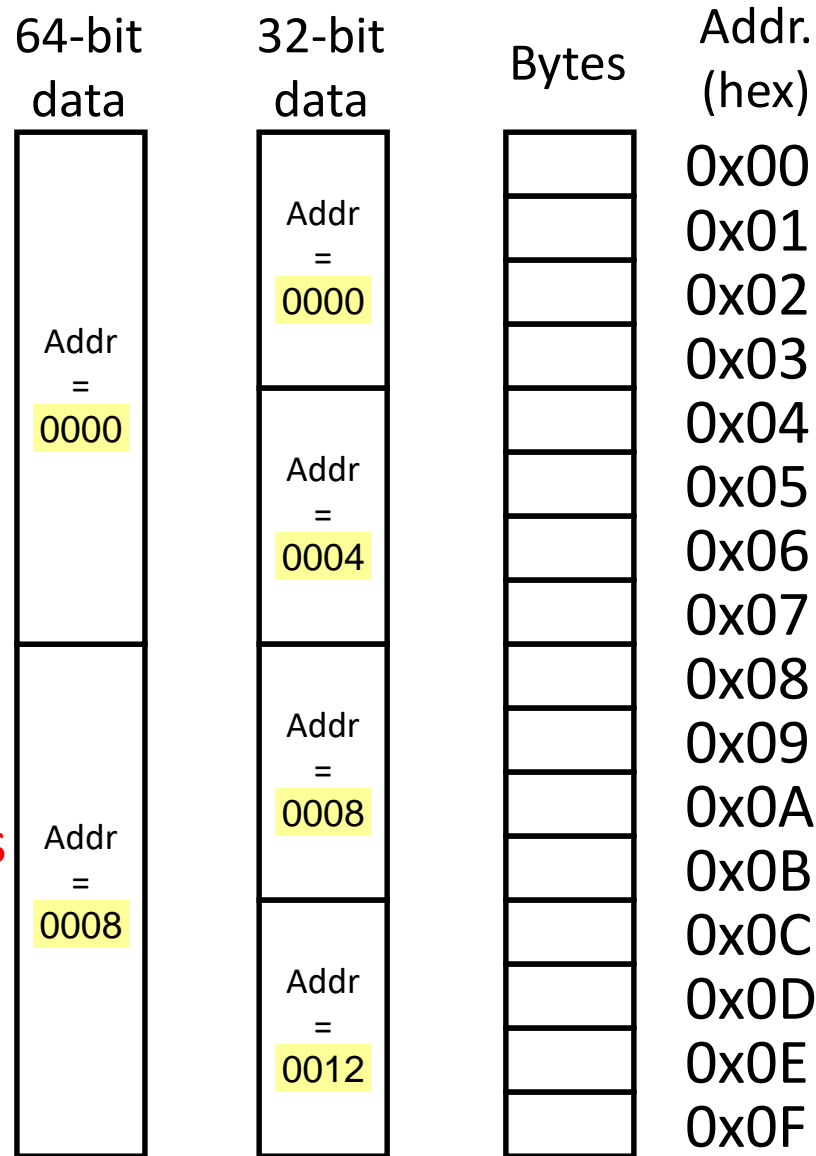
address size = word size

To use "bool" in C, you must `#include <stdbool.h>`



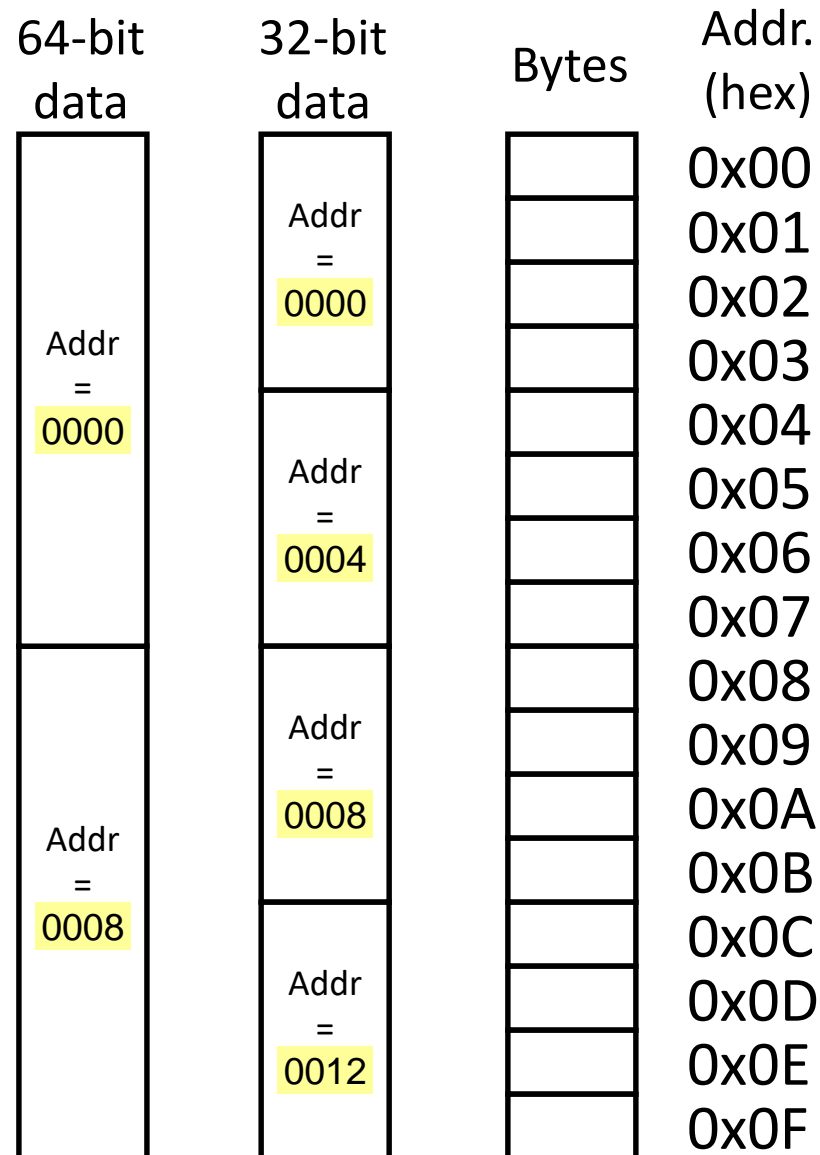
# Address of Multibyte Data

- ❖ Addresses still specify locations of bytes in memory, but we can choose to *view* memory as a series of chunks of fixed-sized data instead
  - Addresses of successive chunks differ by data size
  - Which byte's address should we use for each word?
- ❖ **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**



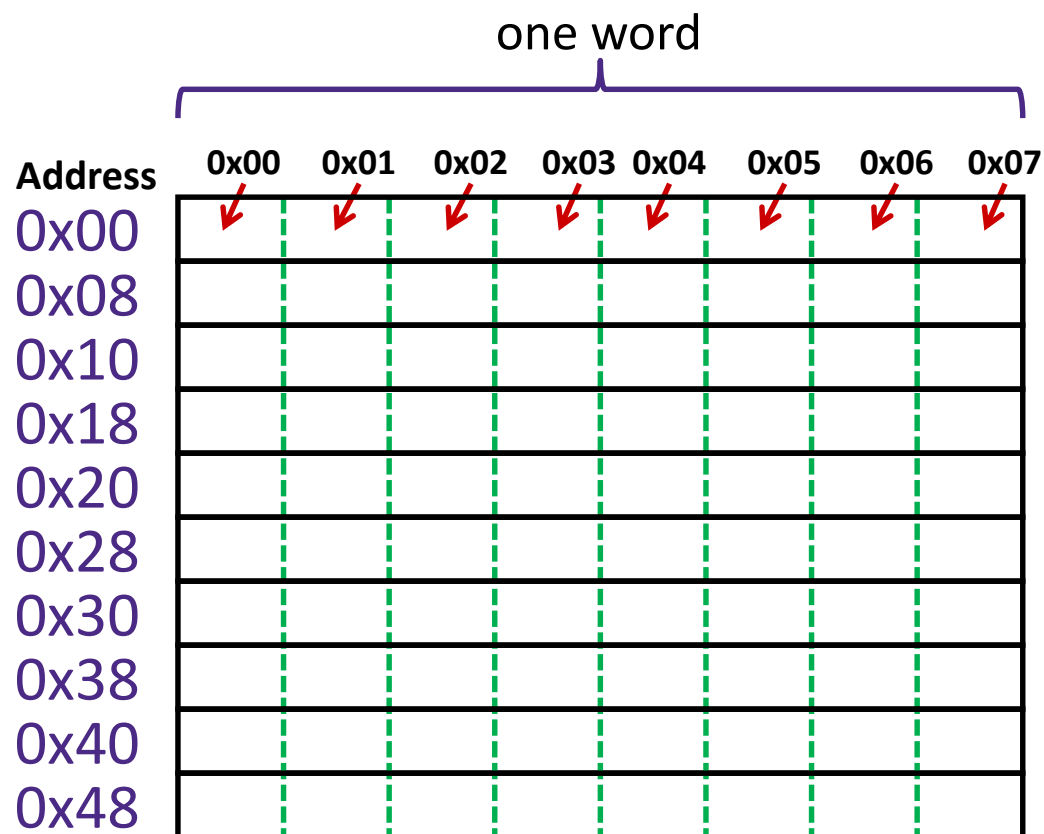
# Alignment

- ❖ The address of a chunk of memory is considered **aligned** if its address is a multiple of its size
  - View memory as a series of consecutive chunks of this particular size and see if your chunk doesn't cross a boundary



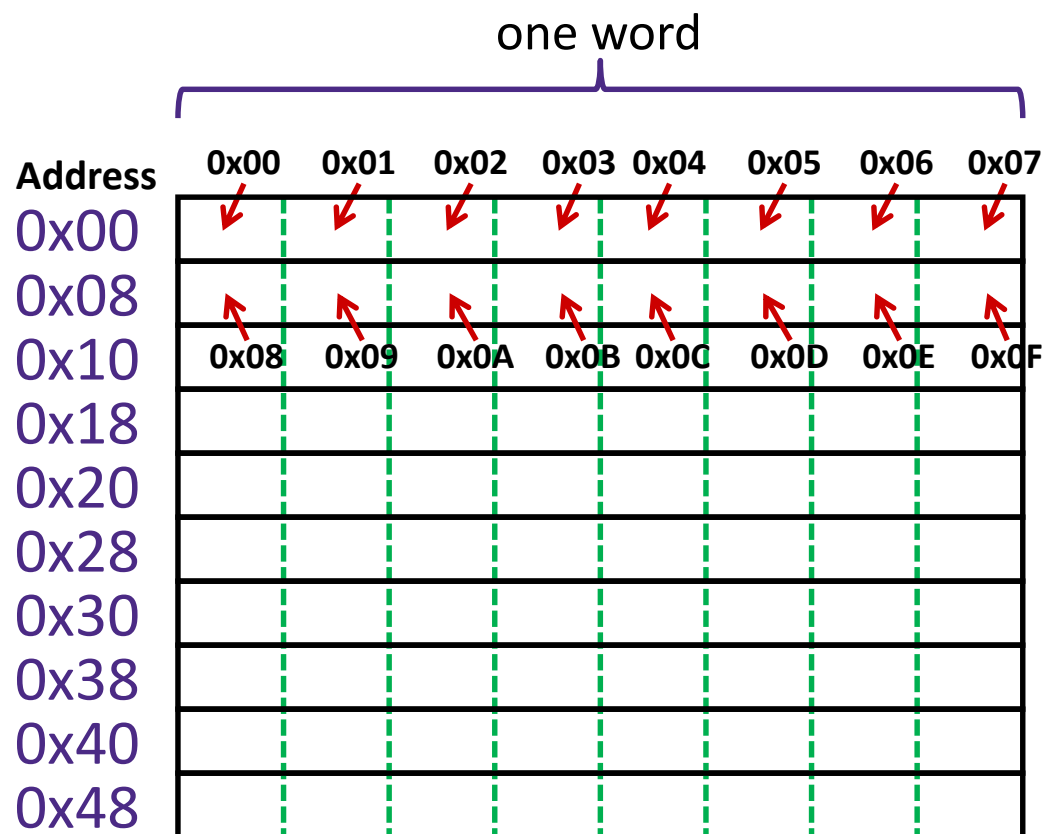
# A Picture of Memory (64-bit view)

- ❖ A “64-bit (8-byte) word-aligned” view of memory:
  - In this type of picture, each row is composed of 8 bytes
  - Each cell is a byte
  - An aligned, 64-bit chunk of data will fit on one row



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# Addresses and Pointers

64-bit example  
(pointers are 64-bits wide)

big-endian

- ❖ An *address* refers to a location in memory
- ❖ A *pointer* is a data object that holds an address
  - Address can point to *any* data

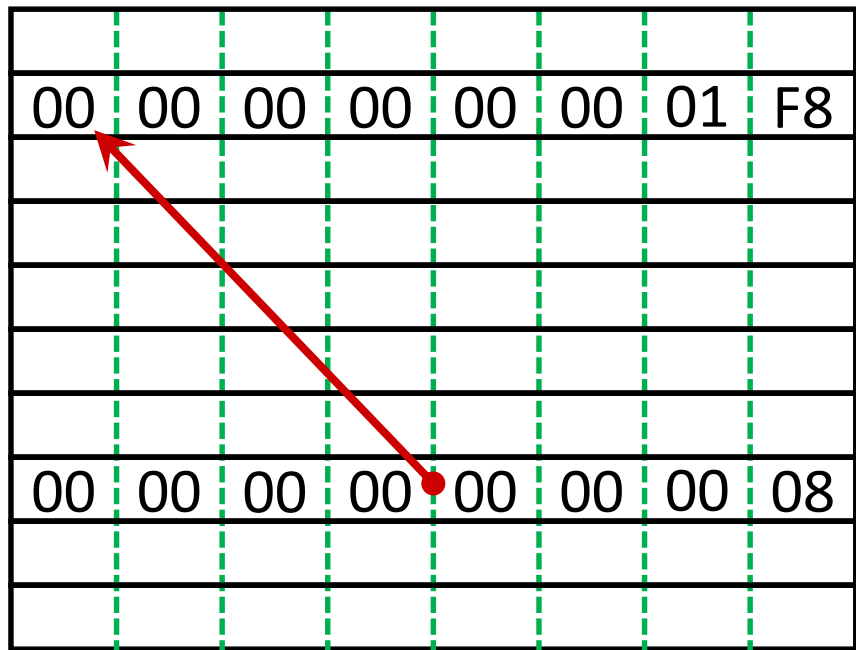
- ❖ Value 504 stored at address **0x08**

- $504_{10} = 1F8_{16}$   
= 0x 00 ... 00 01 F8

- ❖ Pointer stored at **0x38** points to address **0x08**

Address

0x00								
0x08	00	00	00	00	00	00	01	F8
0x10								
0x18								
0x20								
0x28								
0x30								
0x38	00	00	00	00	00	00	00	08
0x40								
0x48								



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- ❖ An *address* refers to a location in memory
- ❖ A *pointer* is a data object that holds an address
  - Address can point to *any* data
- ❖ Pointer stored at **0x48** points to address **0x38**
  - Pointer to a pointer!
- ❖ Is the data stored at **0x08** a pointer?
  - Could be, depending on how you use it

Address

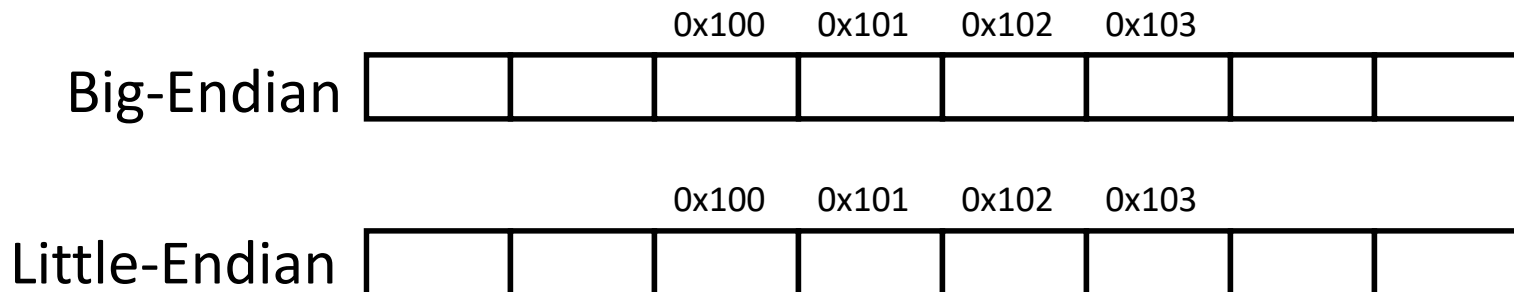
0x00								
0x08	00	00	00	00	00	00	01	F8
0x10								
0x18								
0x20								
0x28								
0x30								
0x38	00	00	00	00	00	00	00	08
0x40								
0x48	00	00	00	00	00	00	00	38

# Byte Ordering

- ❖ How should bytes within a word be ordered *in memory*?
  - Want to keep consecutive bytes in consecutive addresses
  - **Example:** store the 4-byte (32-bit) `int`:  
0x a1 b2 c3 d4
- ❖ By convention, ordering of bytes called *endianness*
  - The two options are **big-endian** and **little-endian**
    - In which address does the least significant *byte* go?
    - Based on *Gulliver's Travels*: tribes cut eggs on different sides (big, little)

# Byte Ordering

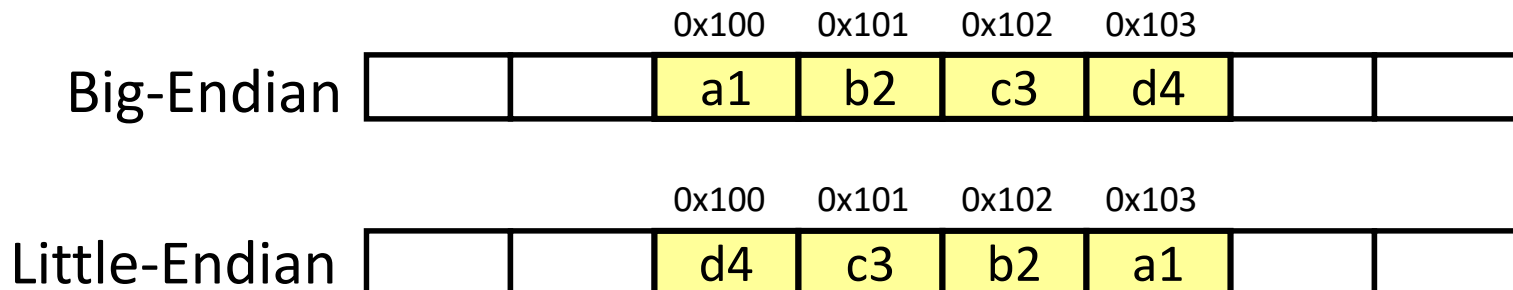
- ❖ Big-endian (SPARC, z/Architecture)
  - Least significant byte has highest address
- ❖ Little-endian (x86, x86-64)
  - Least significant byte has lowest address
- ❖ Bi-endian (ARM, PowerPC)
  - Endianness can be specified as big or little
- ❖ **Example:** 4-byte data 0xa1b2c3d4 at address 0x100





# Byte Ordering

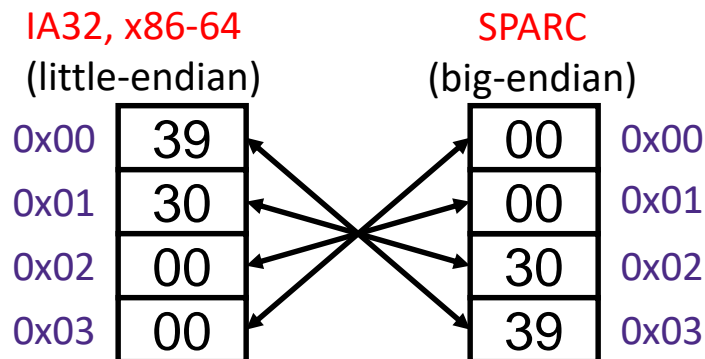
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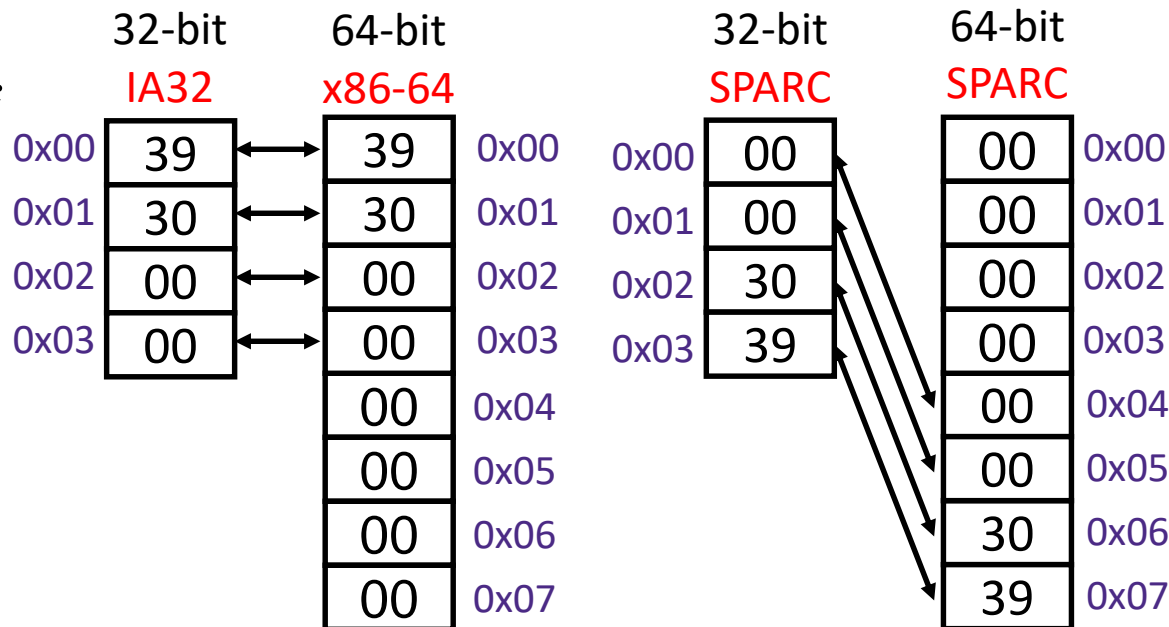
# Byte Ordering Examples

Decimal:	12345
Binary:	0011 0000 0011 1001
Hex:	3 0 3 9

```
int x = 12345;
// or x = 0x3039;
```



```
long int y = 12345;
// or y = 0x3039;
```



(A long int is the size of a word)

# Polling Question

- ❖ 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  $0x104$ ?
  - Vote in Ed Lessons

A. **0x04**

B. **0x40**

C. **0x01**

D. **0x10**

E. **We're lost...**

# Endianness

- ❖ *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 (*e.g.* store `int`, access byte as a `char`)
  - Need to know exact values to debug memory errors
  - Manual translation to and from machine code (in 351)



# Summary

- ❖ Memory is a long, *byte-addressed* array
  - Word size bounds the size of the *address space* and memory
  - Different data types use different number of bytes
  - Address of chunk of memory given by address of lowest byte in chunk
  - Object of  $K$  bytes is *aligned* if it has an address that is a multiple of  $K$
- ❖ Pointers are data objects that hold addresses
- ❖ Endianness determines memory storage order for multi-byte data