Memory, Data, & Addressing I

CSE 351 Winter 2018

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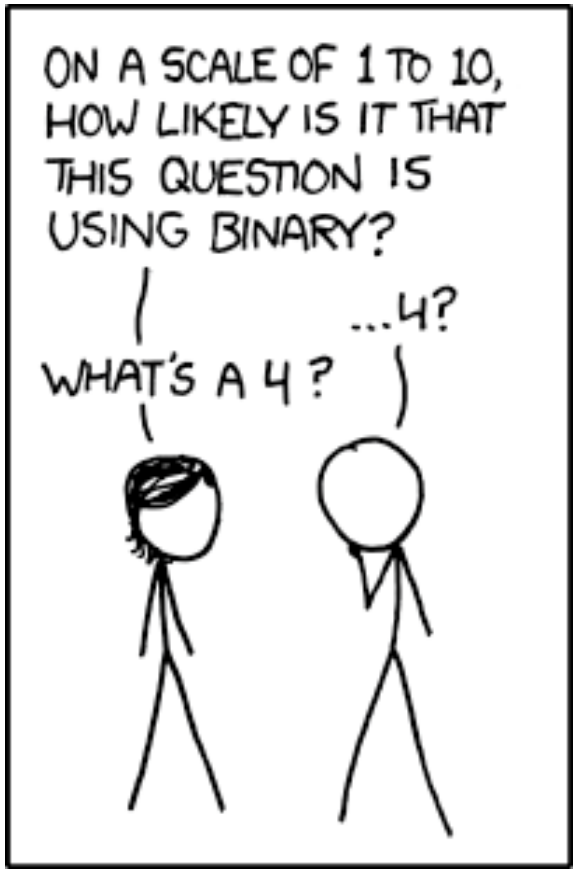


http://xkcd.com/953/

Administrivia

- Pre-Course Survey due tonight @ 11:59pm
- Lab 0 due Monday (1/8)
- Homework 1 due Wednesday (1/10)

- All course materials can be found on the website/schedule
- Course Overloads – fill out the Google Form linked in lecture 1!
- Make sure you're also enrolled in CSE391 (EEs and non-majors included!)

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();
```

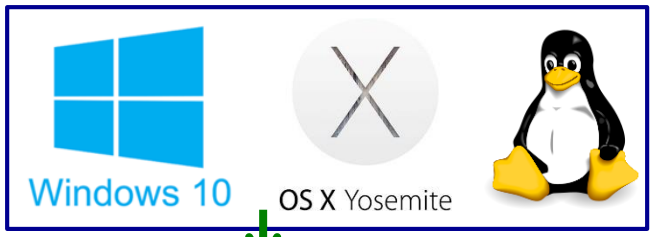
Assembly language:

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

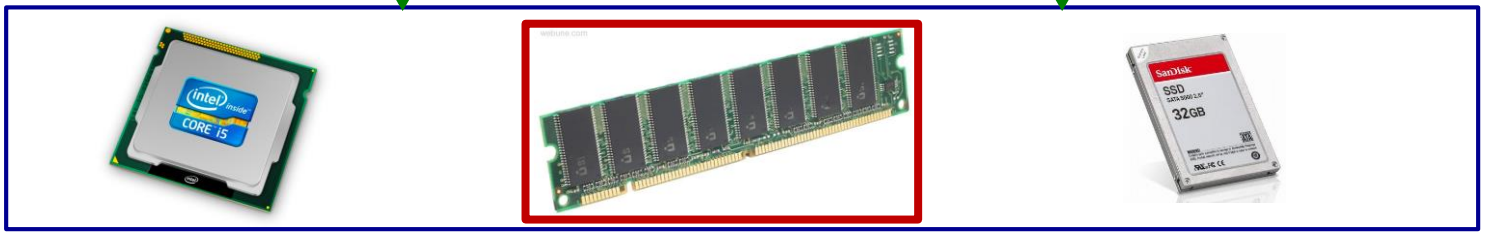
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
11000001111110100011111
```

OS:

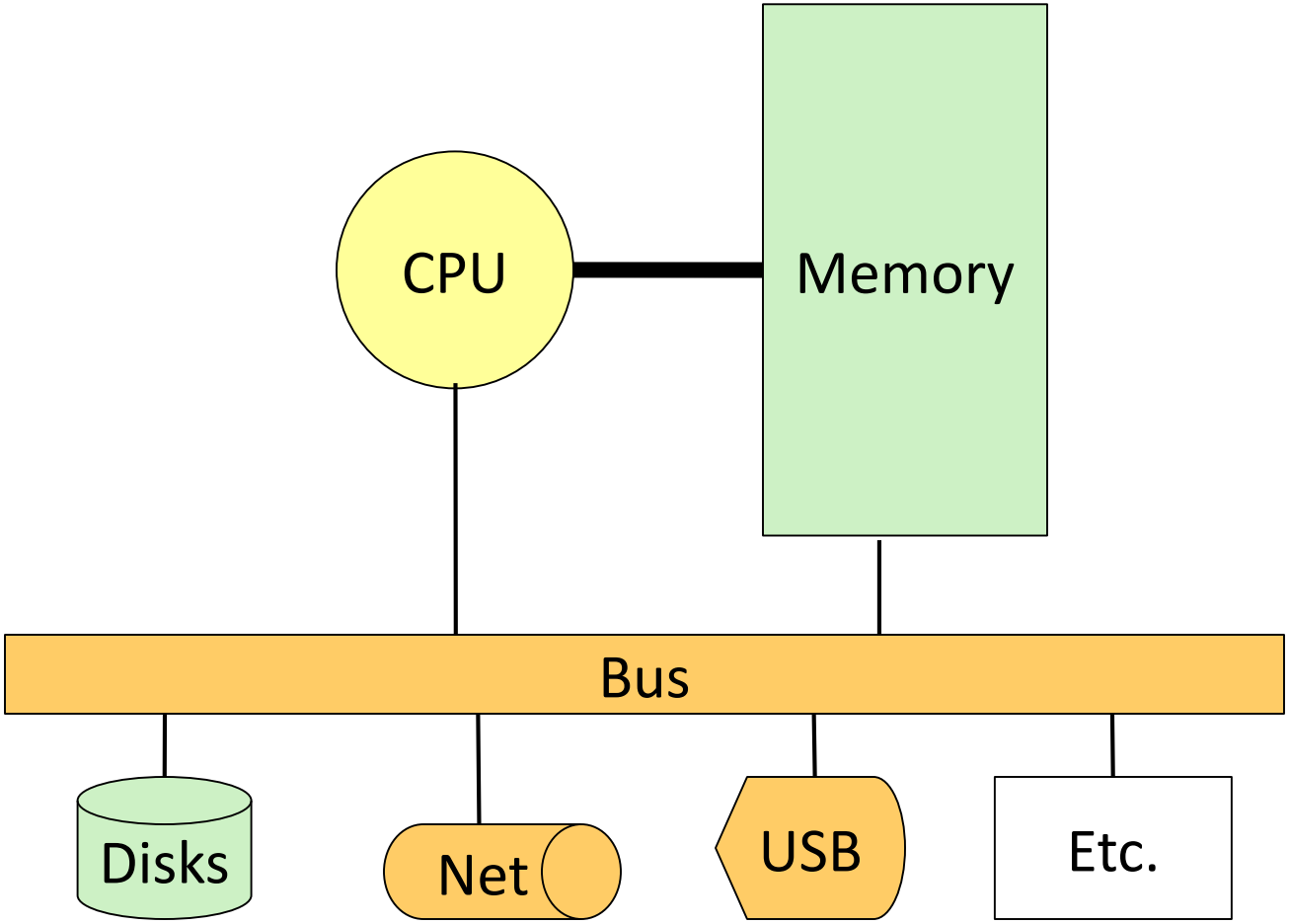


Computer system:

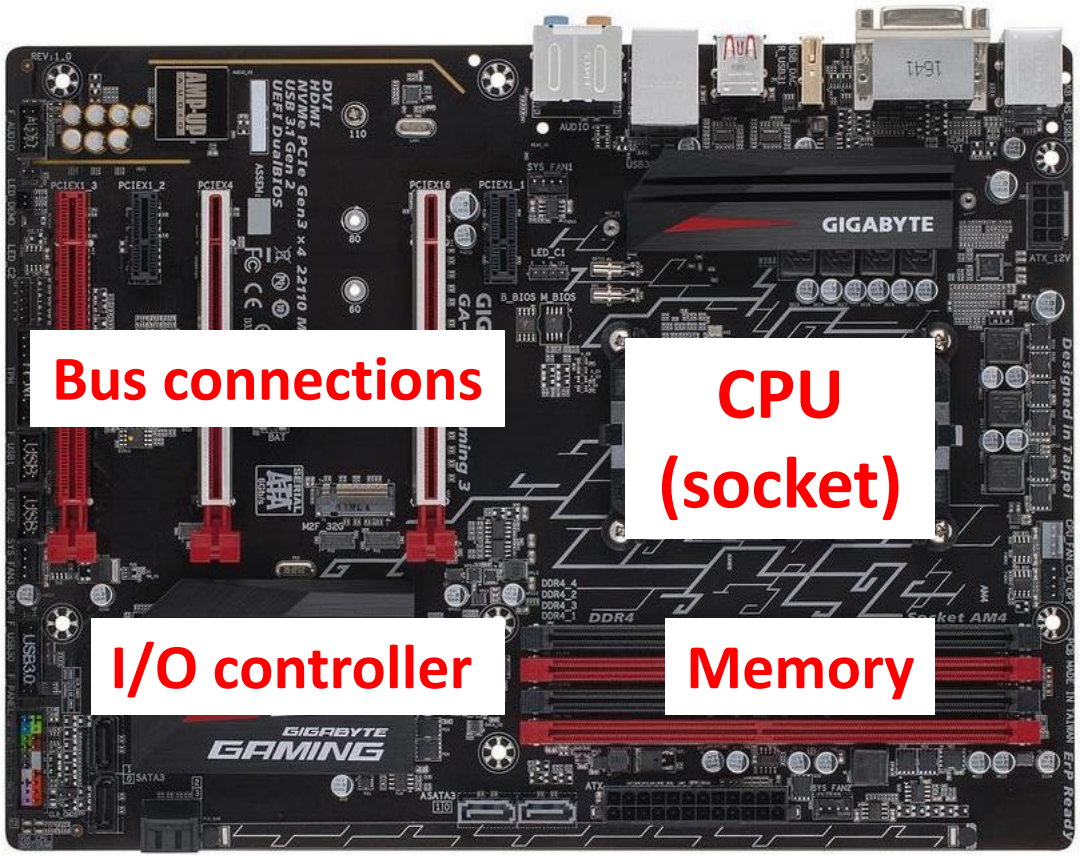


Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

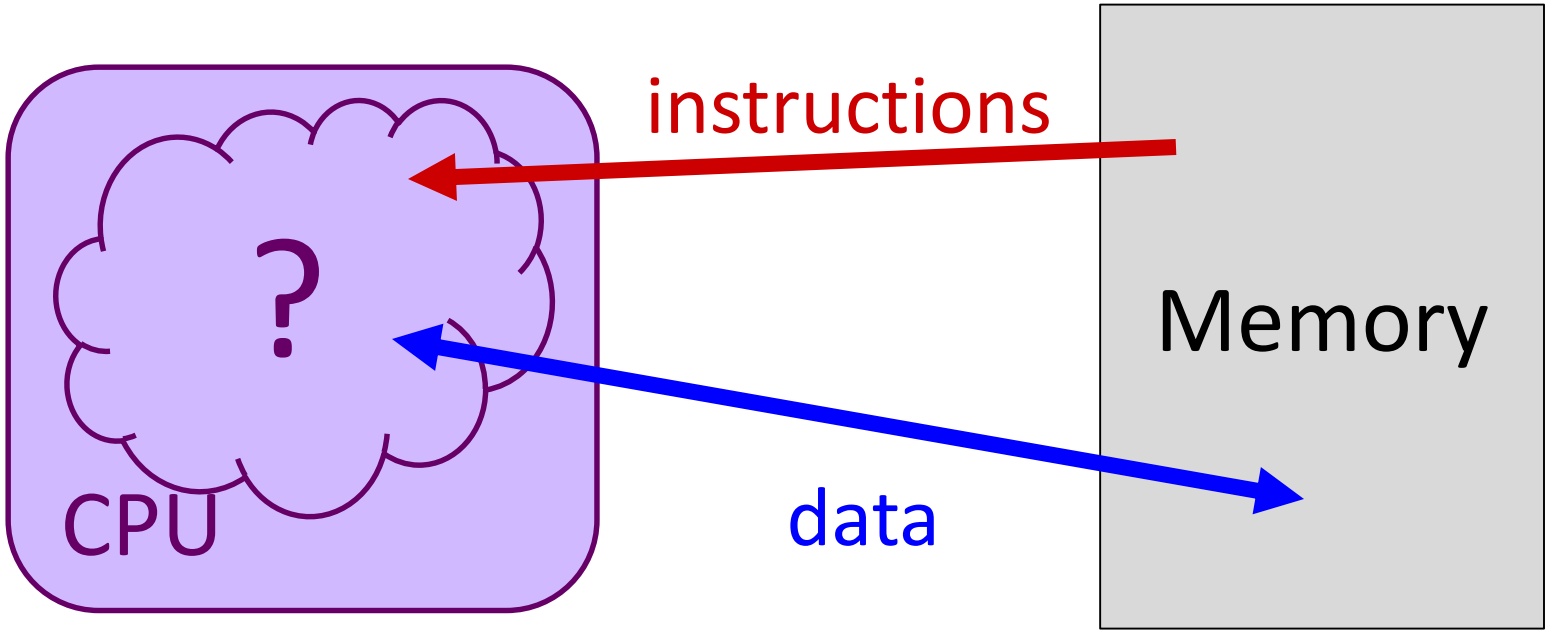
Hardware: Logical View



Hardware: Physical View

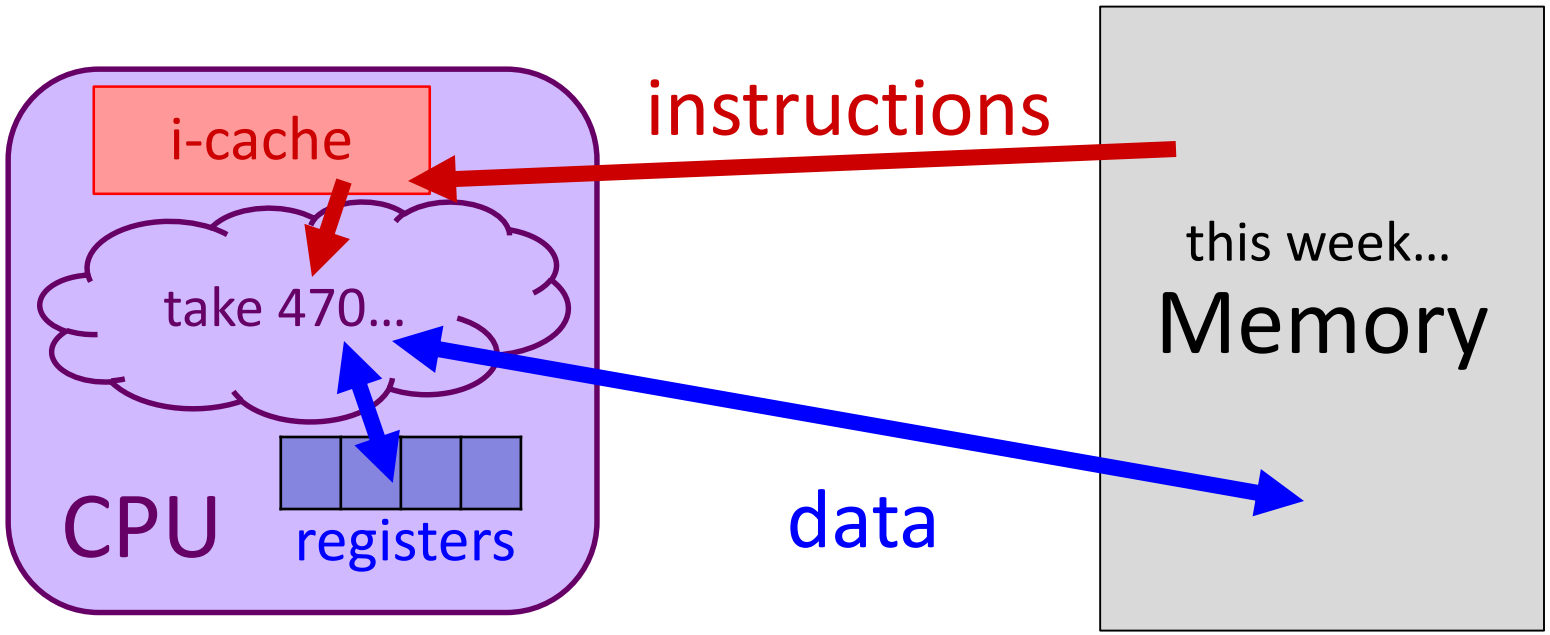


Hardware: 351 View (version 0)



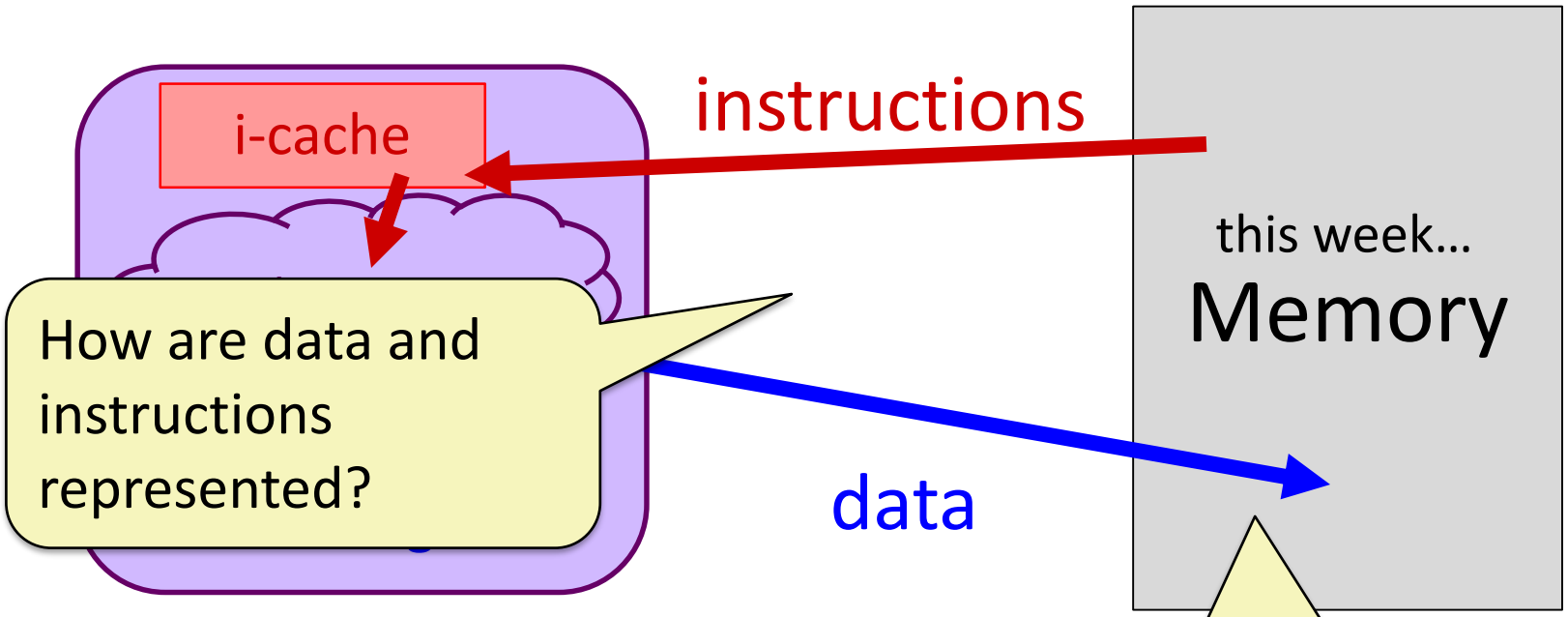
- CPU executes instructions; memory stores data
- To execute an instruction, the CPU must:
  - fetch an instruction;
  - fetch the data used by the instruction; and, finally,
  - execute the instruction on the data…
  - which may result in writing data back to memory

Hardware: 351 View (version 1)



- The CPU holds instructions temporarily in the instruction cache
- The CPU holds data temporarily in a fixed number of registers
- Instruction and operand fetching is hardware-controlled
- Data movement is programmer-controlled (in assembly)
- We'll learn about the instructions the CPU executes –
  take CSE/EE 469 and 470 to find out how it actually executes them

Hardware: 351 View (version 1)



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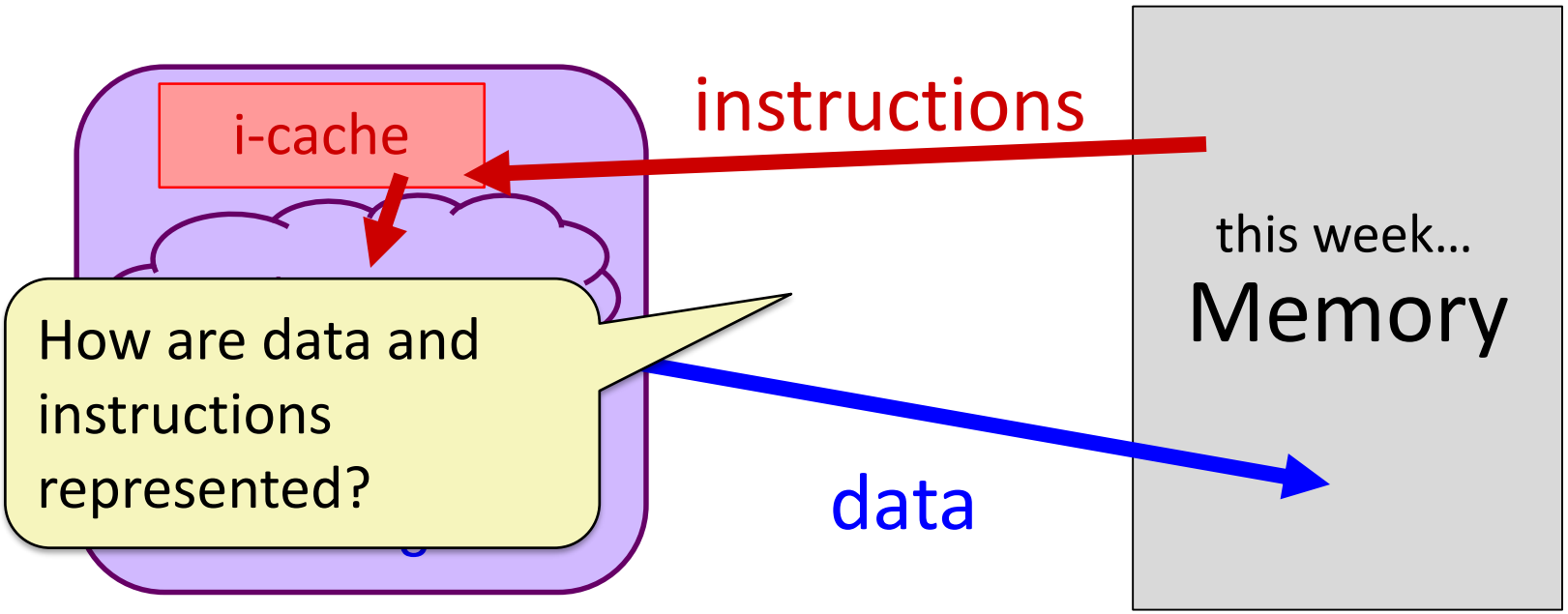
Question 1:



- Binary Encoding!

Question 1: Some Additional Details

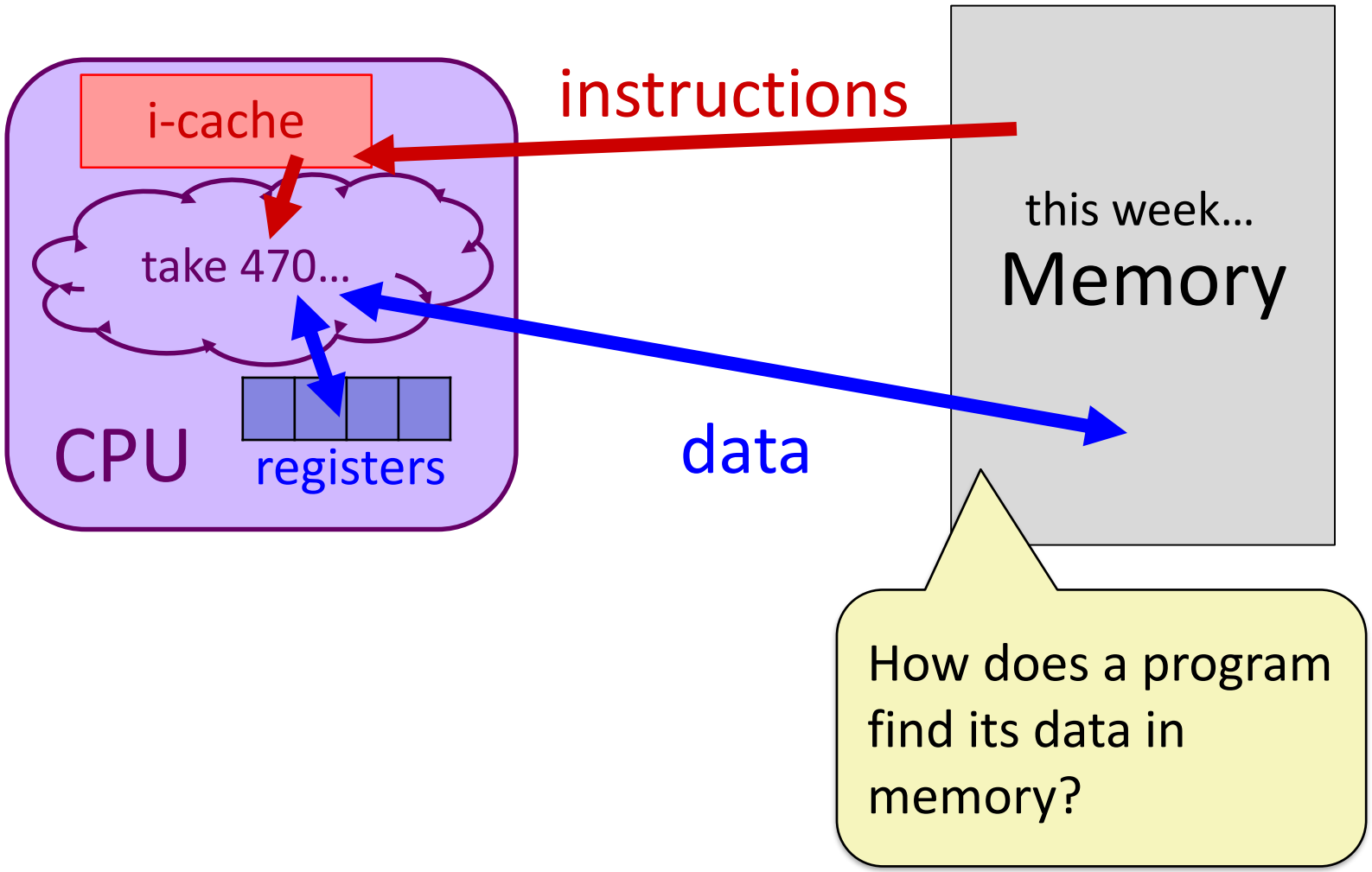
- Because storage is finite in reality, everything is stored as "fixed" length
  - Data is moved and manipulated in fixed-length chunks
  - Multiple fixed lengths (e.g. 1 byte, 4 bytes, 8 bytes)
  - Leading zeros now *must* be included up to "fill out" the fixed length

- Example: the "eight-bit" representation of the number 4 is 0b00000100

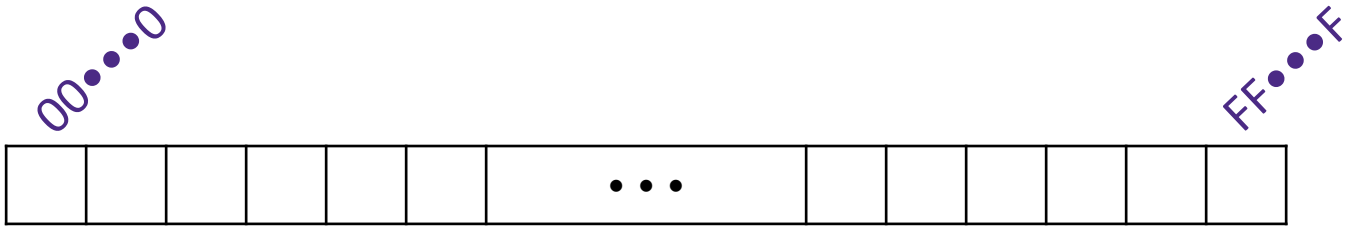
Most Significant Bit (MSB)

Least Significant Bit (LSB)

Question 2:


i-cache
instructions
take 470…
this week…
Memory
CPU
registers
data
How does a program find its data in memory?

Byte-Oriented Memory Organization



- Conceptually, memory is a single, large array of bytes, each with a unique *address* (index)
  - The value of each byte in memory can be read and written
- Programs refer to bytes in memory by their *addresses*
  - Domain of possible addresses = *address space*
- But not all values fit in a single byte… (*e.g.* 351)
  - Many operations actually use multi-byte values
- We can store addresses as data to "remember" where other data is in memory

Peer Instruction Question

- If we choose to use 8-bit addresses, how big is our address space?
  - *i.e.* How much space can we "refer to" using our addresses?

A. 256 bits
B. 256 bytes
C. 8 bits
D. 8 bytes
E. We're lost…

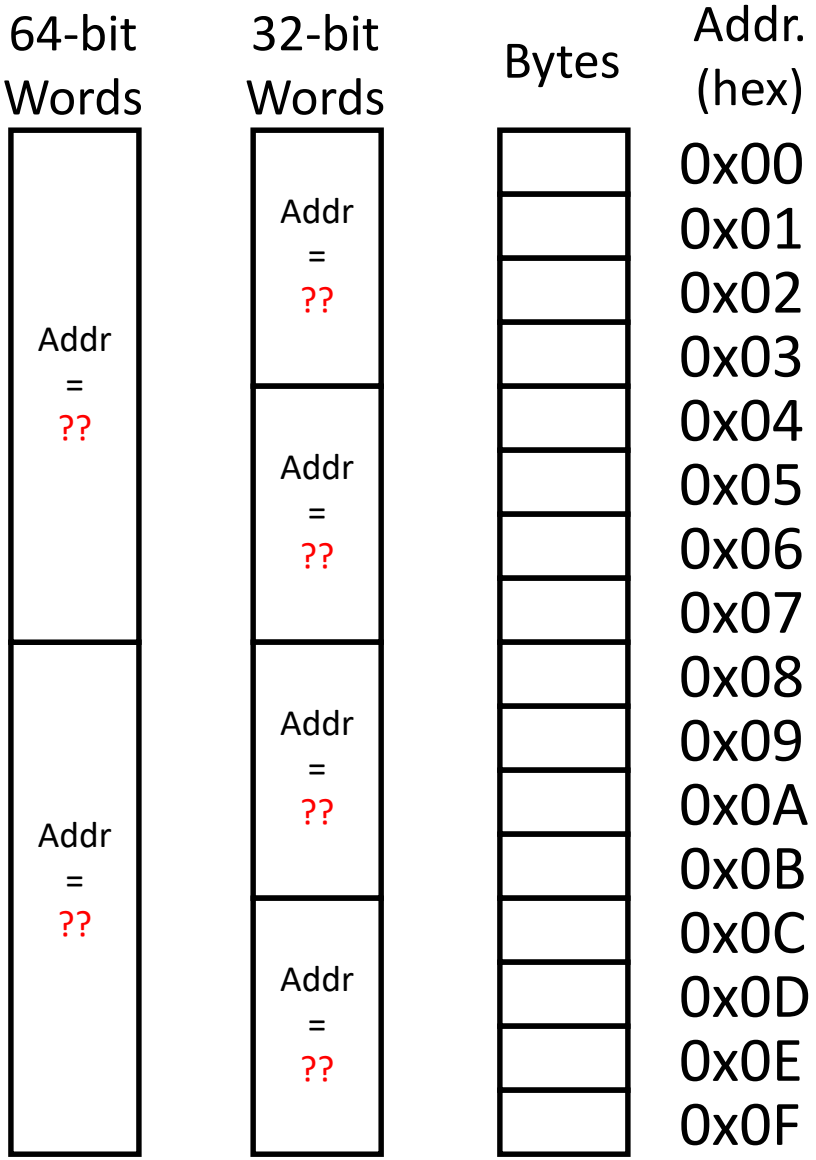
Machine "Words"

- 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
- Word size bounds the size of the *address space*
  - 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: $\mathbf{2^{64}}$ addresses
    2^{64} bytes $\approx$ **1.8 x 10^{19} bytes**
    = 18 billion billion bytes = 18 EB (exabytes)
  - Actual physical address space: **48 bits**

Word-Oriented Memory Organization

- Addresses still specify locations of *bytes* in memory
  - Addresses of successive words differ by word size (in bytes): *e.g.* 4 (32-bit) or 8 (64-bit)
  - Address of word 0, 1, … 10?



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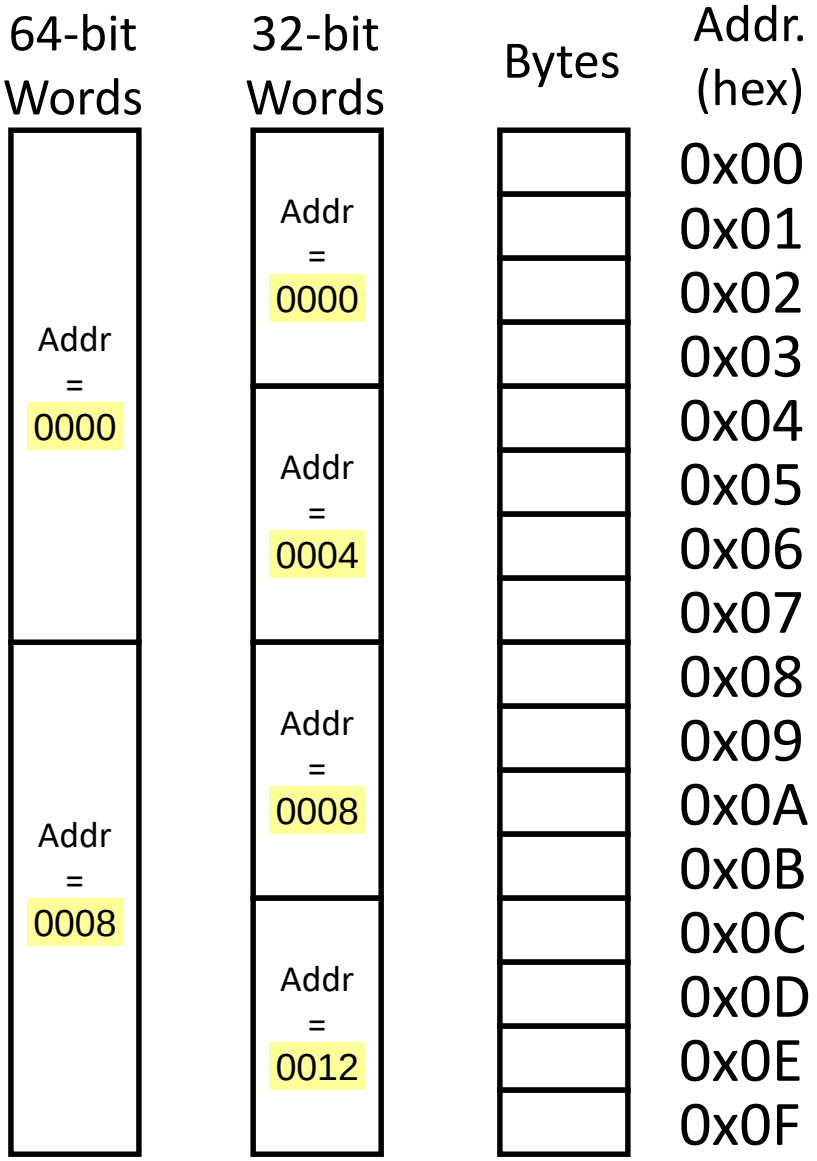
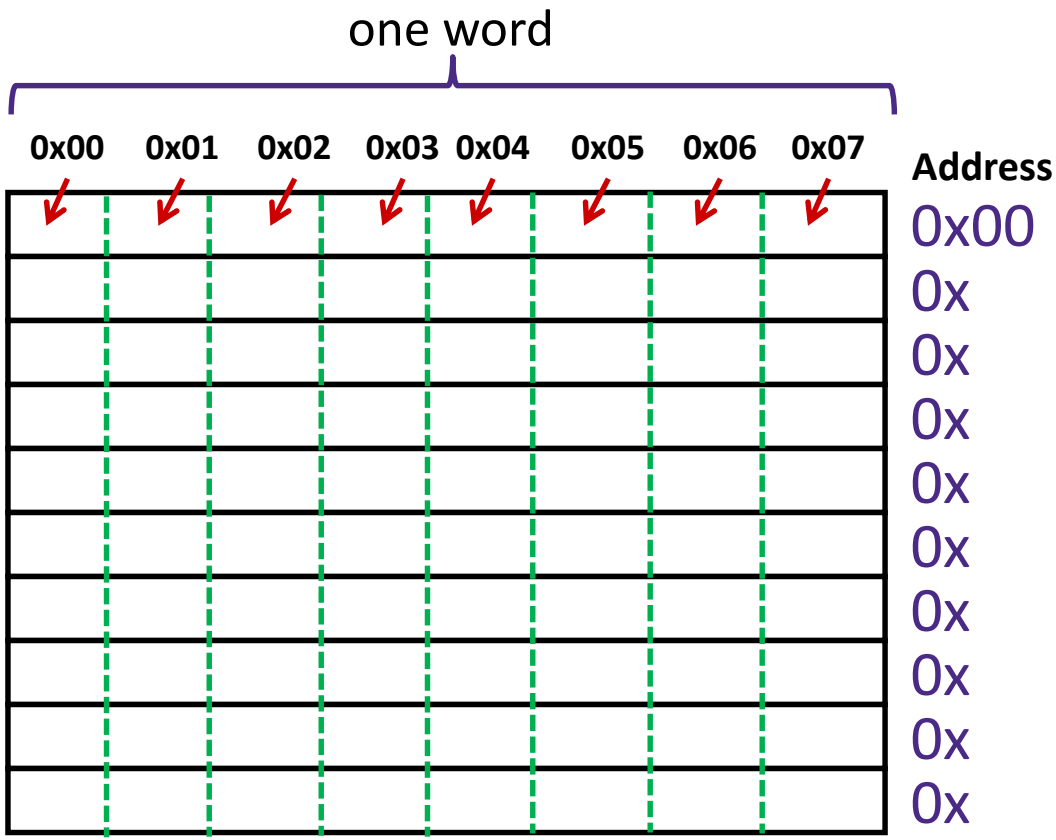
  - Address of word 0, 1, … 10?
- Address of word
  = address of *first* byte in word
  - The address of *any* chunk of memory is given by the address of the first byte
  - ***Alignment***



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
  - A 64-bit pointer will fit on one row



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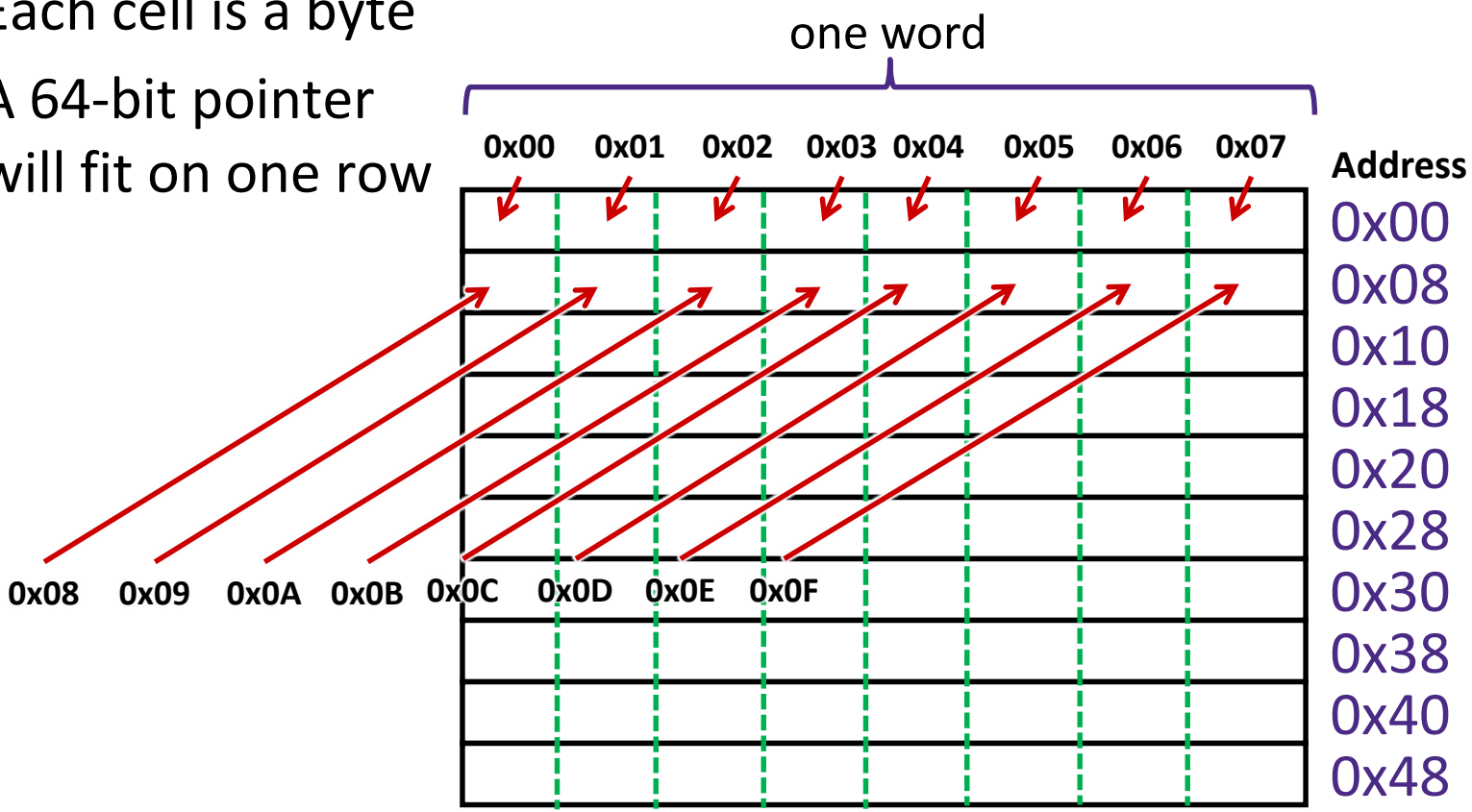
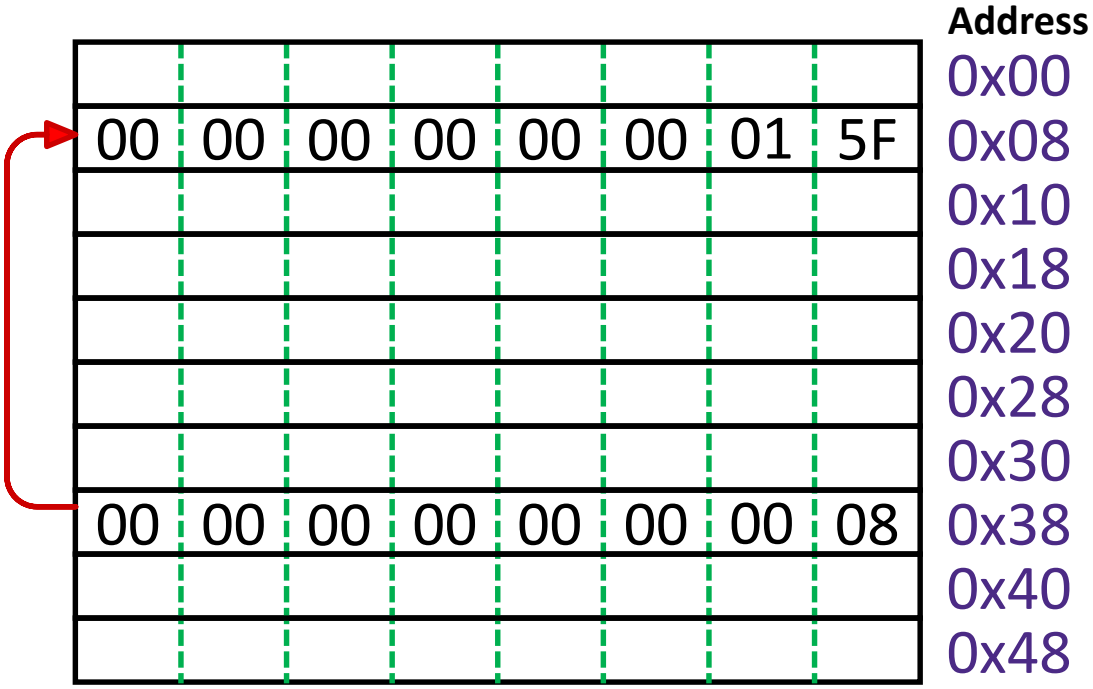


Addresses and Pointers

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

big-endian

- An *address* is a location in memory
- A *pointer* is a data object that holds an address
  - Address can point to *any* data
- Value 351 stored at address 0x08
  - $351_{10} = 15F_{16}$
    = 0x 00 … 00 01 5F
- Pointer stored at 0x38 points to address 0x08

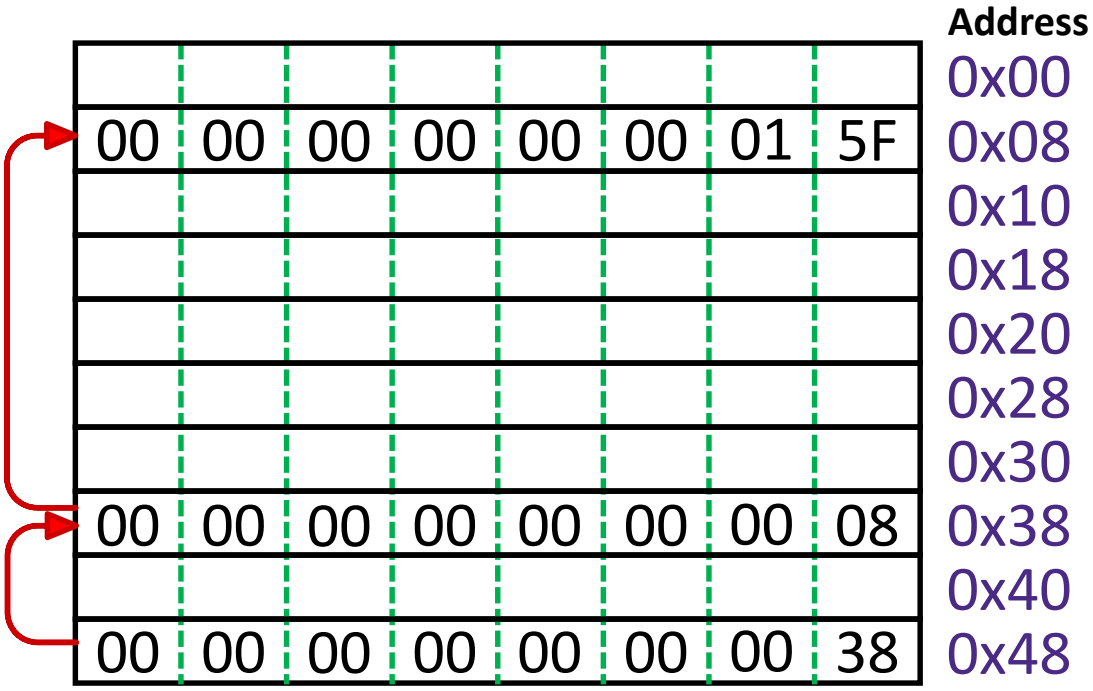


Addresses and Pointers

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

big-endian

- An *address* is 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



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	8	8
	long double	8	16
(reference)	**pointer ***	**4**	**8**

address size = word size

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

More on Memory Alignment in x86-64

- For good memory system performance, Intel recommends data be aligned
  - However the x86-64 hardware will work correctly regardless of alignment of data
  - Design choice: x86-64 instructions are *variable* bytes long
- **Aligned:** Primitive object of K bytes must have an address that is a multiple of K
  - More about alignment later in the course

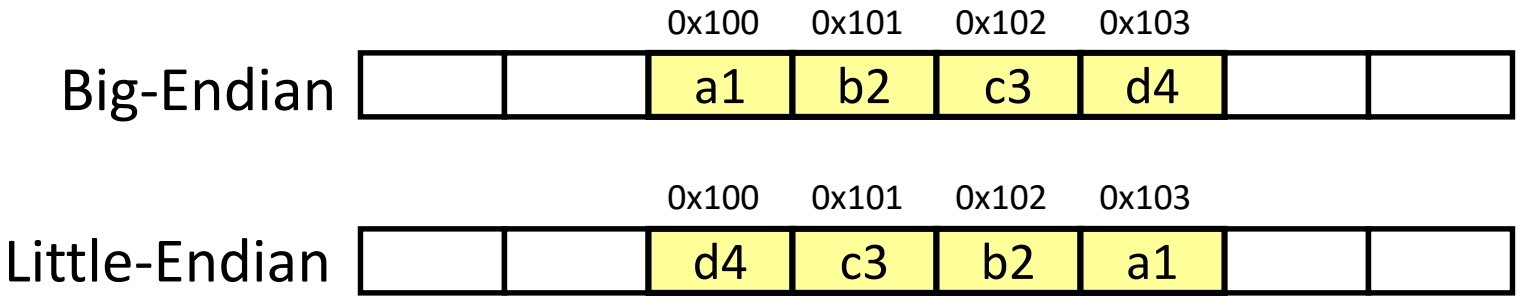
K	Type
1	`char`
2	`short`
4	`int, float`
8	`long, double,` pointers

Byte Ordering

- How should bytes within a word be ordered *in memory?*
  - **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)

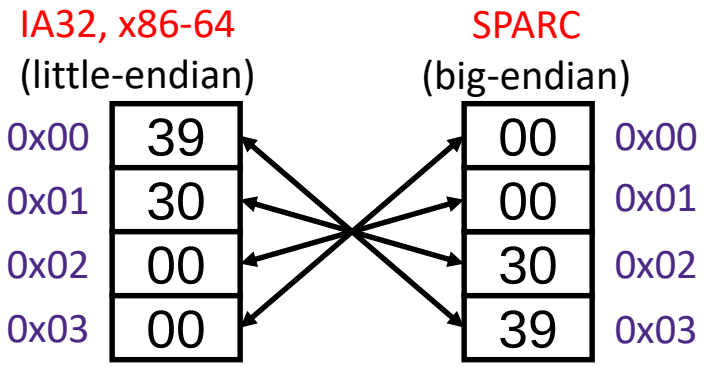
Byte Ordering

- 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 (default)
- **Example:** 4-byte data 0xa1b2c3d4 at address 0x100



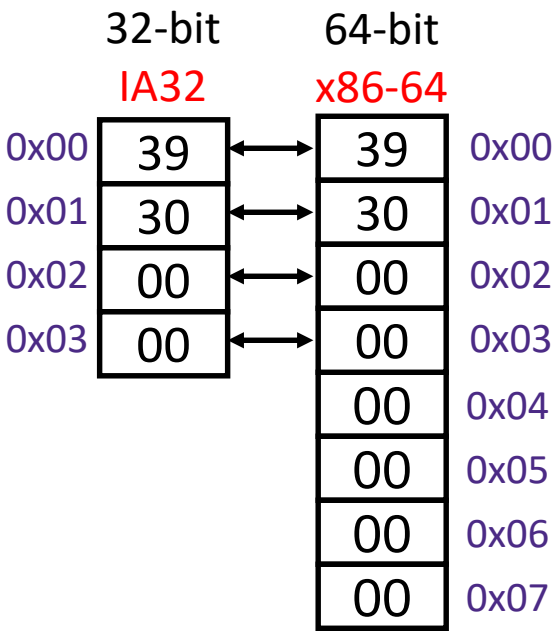
Byte Ordering Examples

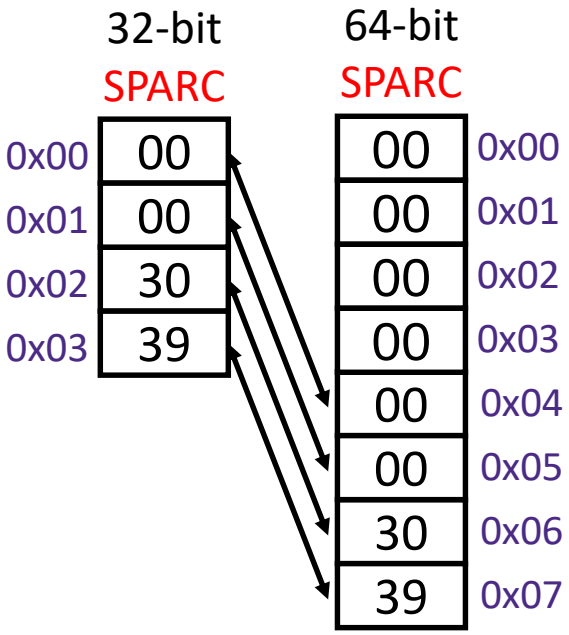
```
int x = 12345;
// or x = 0x3039;
```




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

(A `long int` is the size of a word)

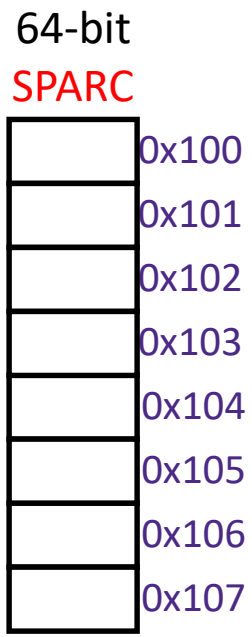




Peer Instruction Question:

- 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?

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