Memory, Data, & Addressing I

CSE 351 Autumn 2020

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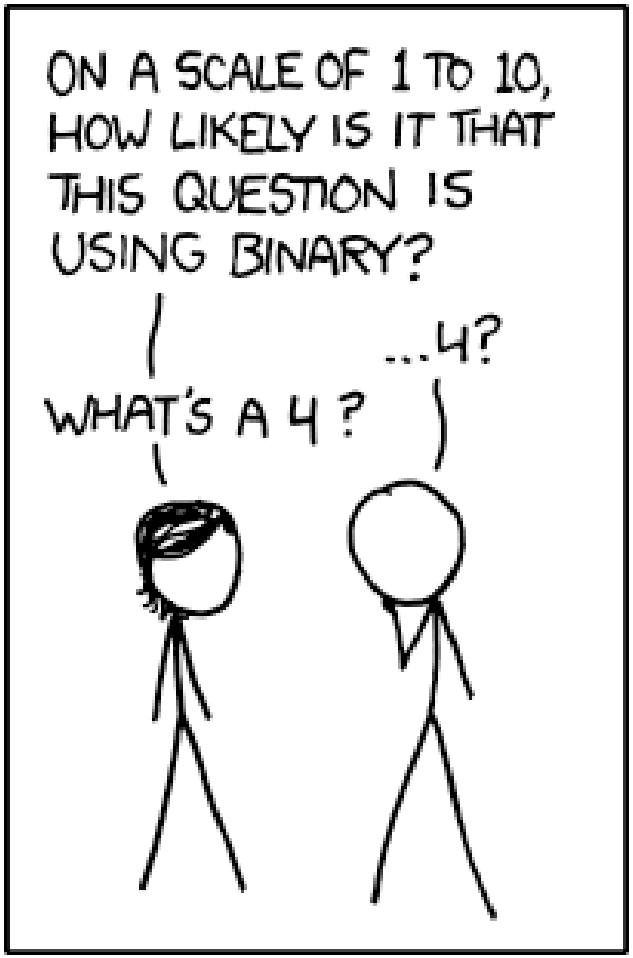


http://xkcd.com/953/

Administrivia

- Pre-Course Survey and hw0 due tonight @ 11:59 pm
  - All other hw due at 11:00 am (Seattle time)
- hw1 due Monday (10/5)
- Lab 0 due Monday (10/5) @ 11:59 pm
  - This lab is *exploratory* and looks like a hw; the other labs will look a lot different

- 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

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();
```

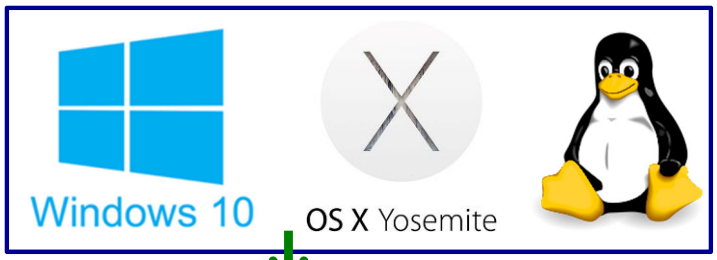
Assembly language:

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

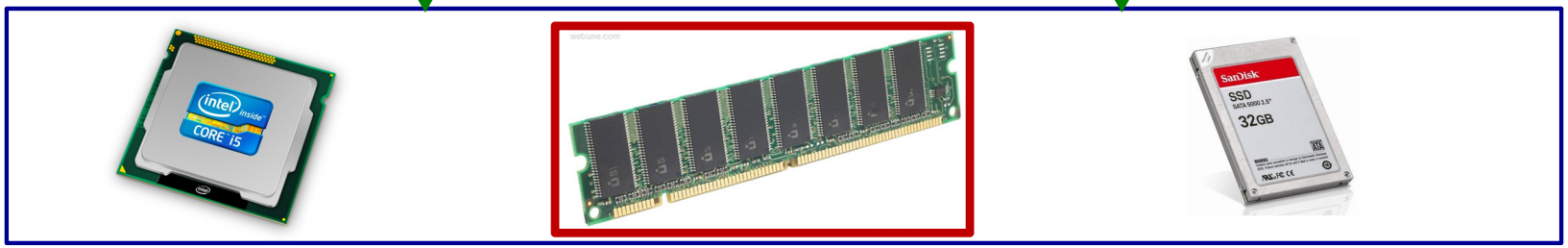
Machine code:

```
0111010000011000
100011010000010000000010
100010011000010
11000001111110100011111
```

OS:



Computer system:



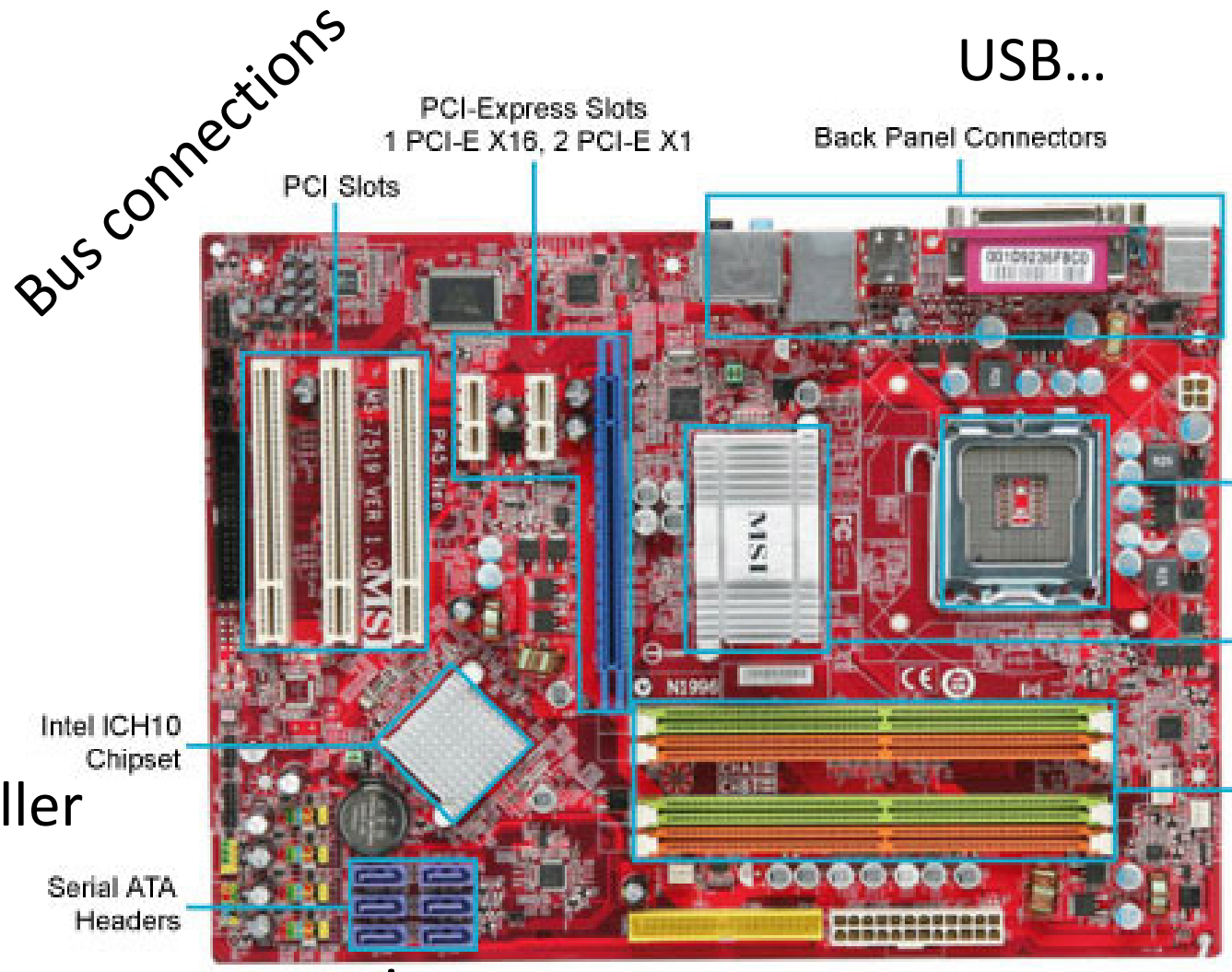
Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

Reading Review

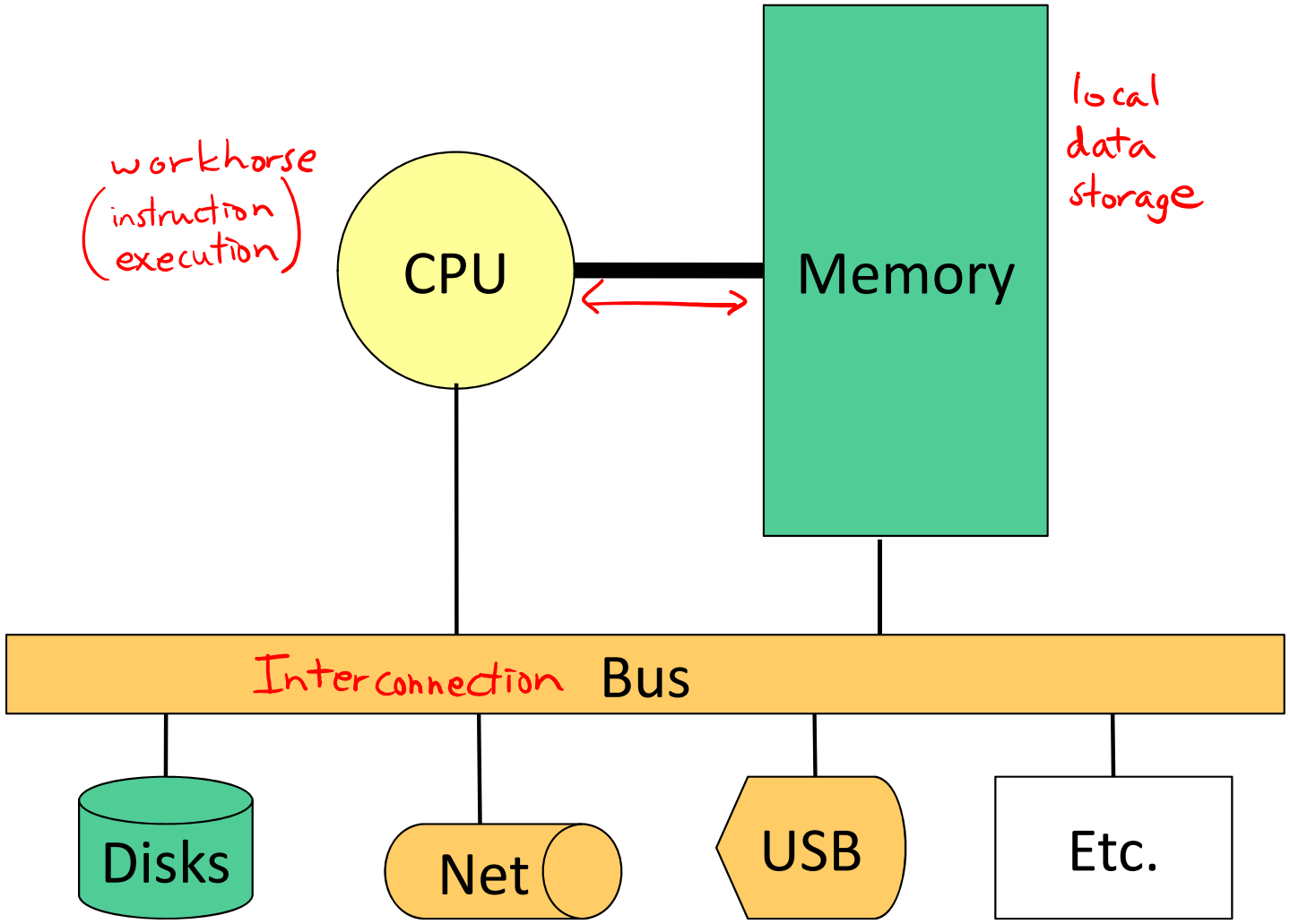
- Terminology:
  - word size, byte-oriented memory
  - address, address space
  - most-significant bit (MSB), least-significant bit (LSB)
  - big-endian, little-endian
  - pointer

- Questions from the Reading?

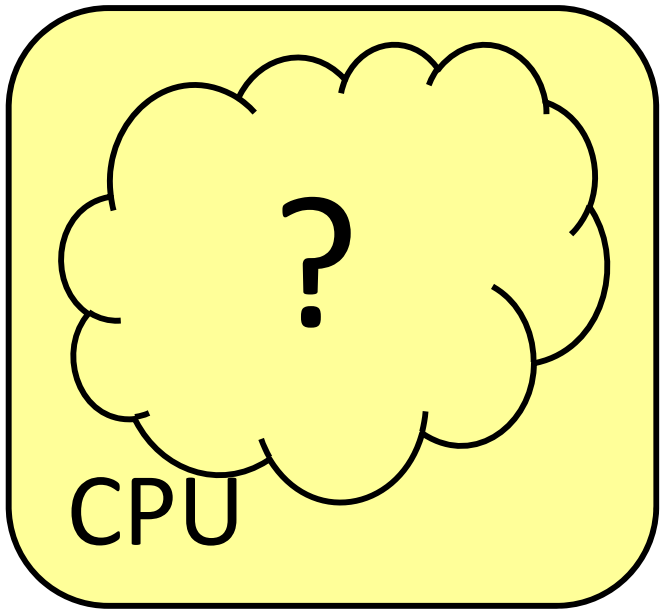
Hardware: Physical View

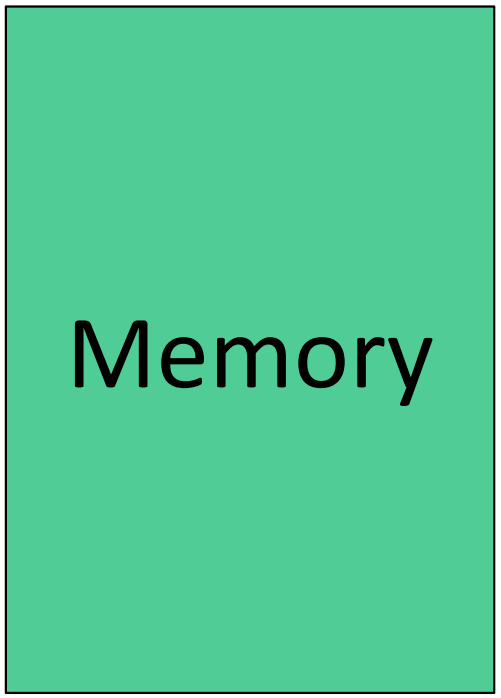


Hardware: Logical View



Hardware: 351 View (version 0)

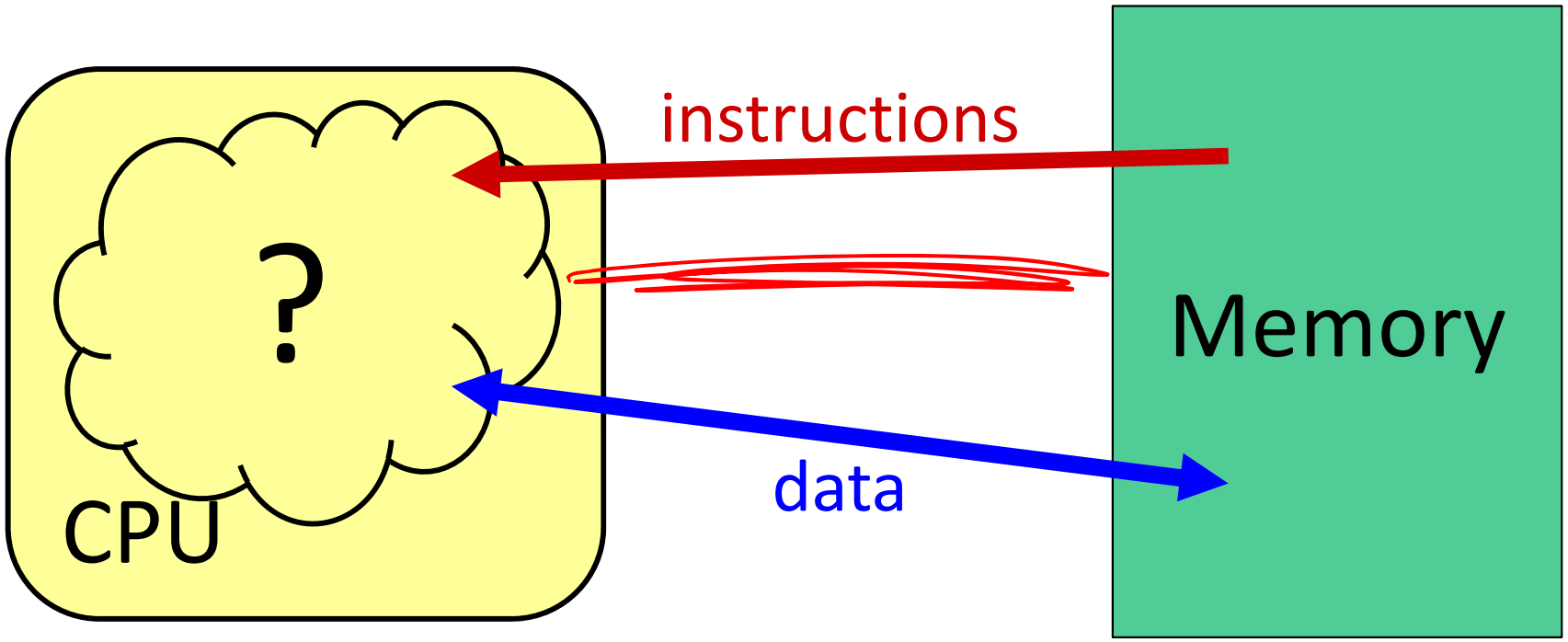




- The CPU executes instructions
- Memory stores data
- Binary encoding!
  - Instructions *are* just data (and stored in Memory)

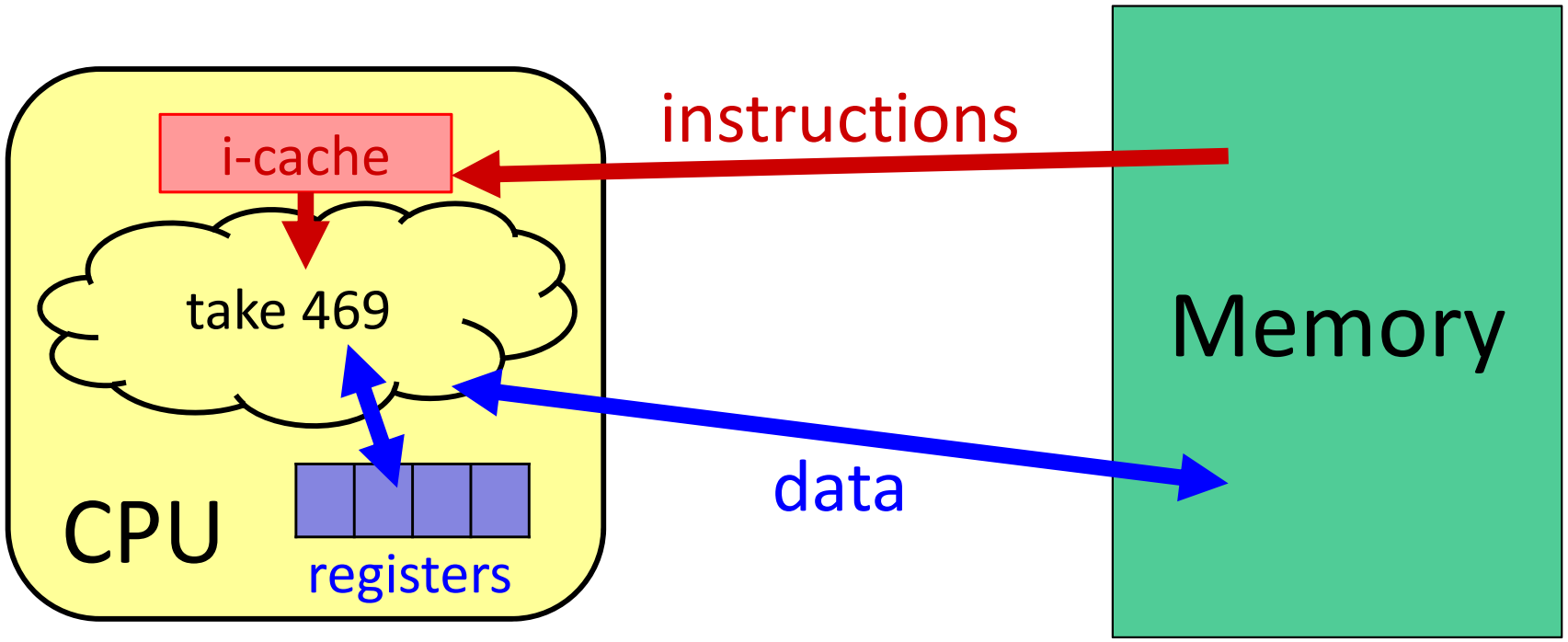
How are data and instructions represented?

Hardware: 351 View (version 0)



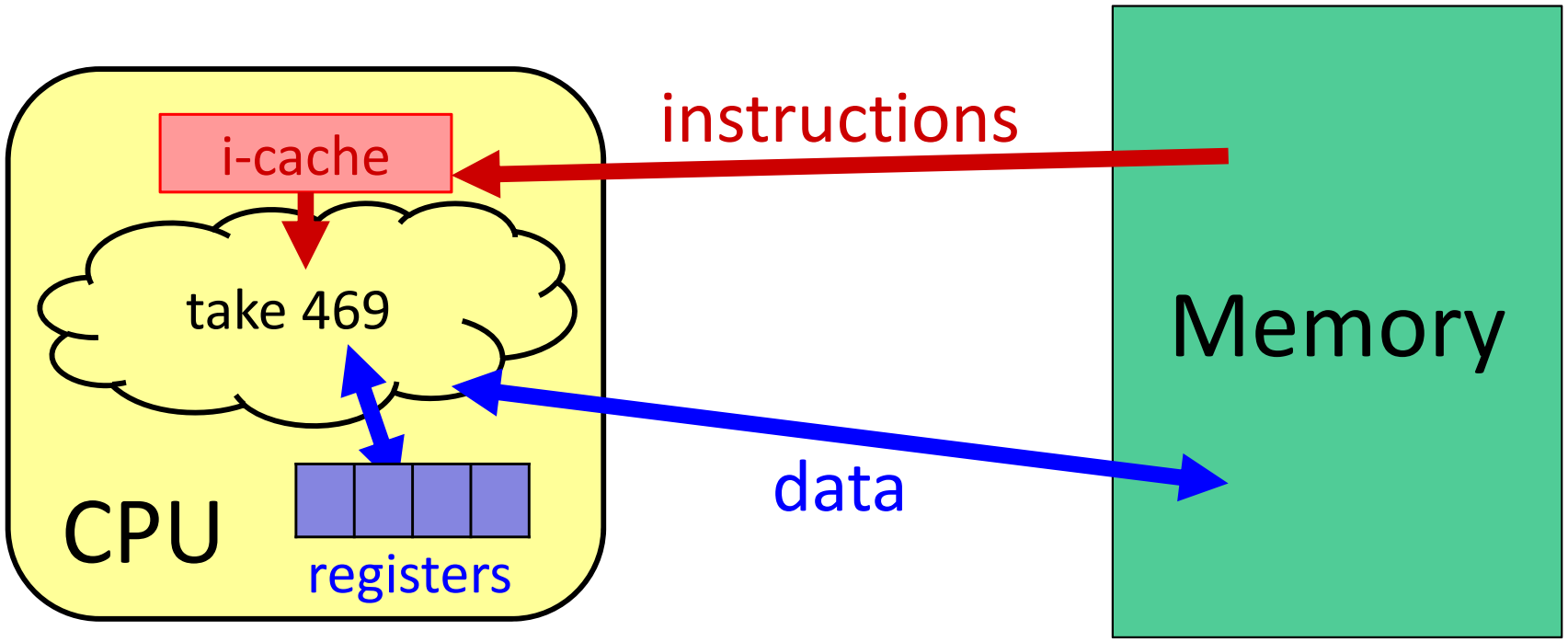
- To execute an instruction, the CPU must:
  1) Fetch the instruction
  2) (if applicable) Fetch data needed by the instruction
  3) Perform the specified computation
  4) (if applicable) Write the result back to memory

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?

- Addresses!
  - Can be stored in *pointers*

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

  many possible encoding schemes

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

  A. True B. False

  need: ① address ✓
  ② data size ✗

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

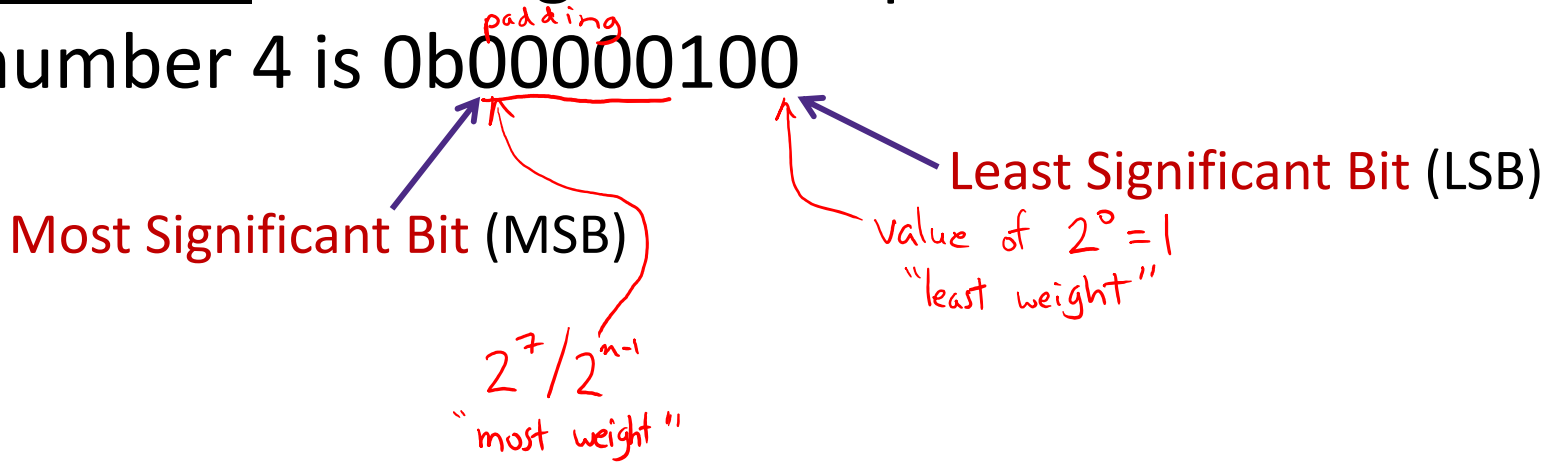
  → 8 bits = 2 hex digits

  A. 0x63 (0b 0110 0011) B. 0x90 (0b 1001 0000) C. 0xCA (0b 1100 1010) D. ~~0xF~~ 0x0F (0b 0000 1111)

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

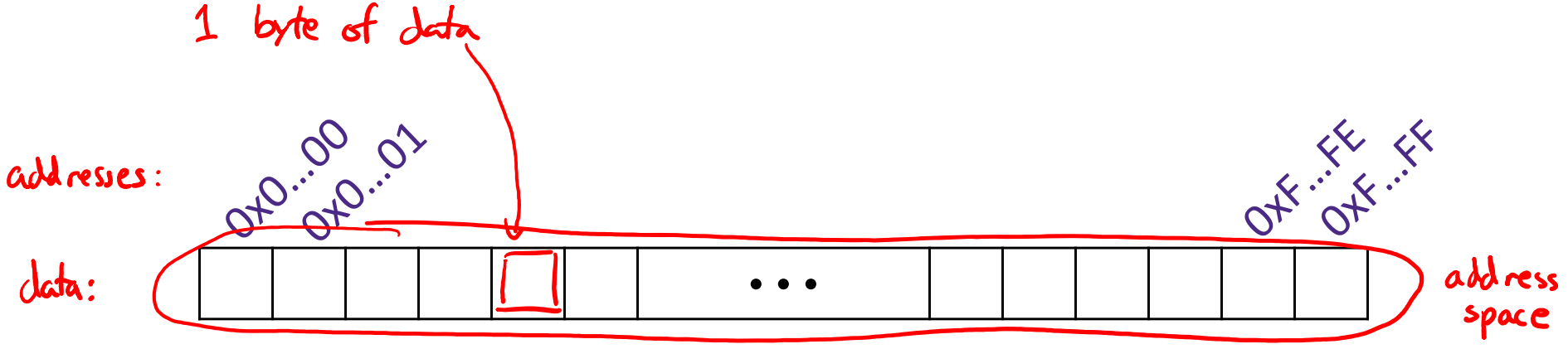


Bits and Bytes and Things

- 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? 2^a addresses : 0b _ _ … _ _ (a bits, each a 0/1)

- What does each address refer to?



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 → 2^w addresses → 2^w-byte address space
- Current x86 systems use **64-bit (8-byte) words**
  - 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**

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
(reference)	**pointer ***	**4**	**8**

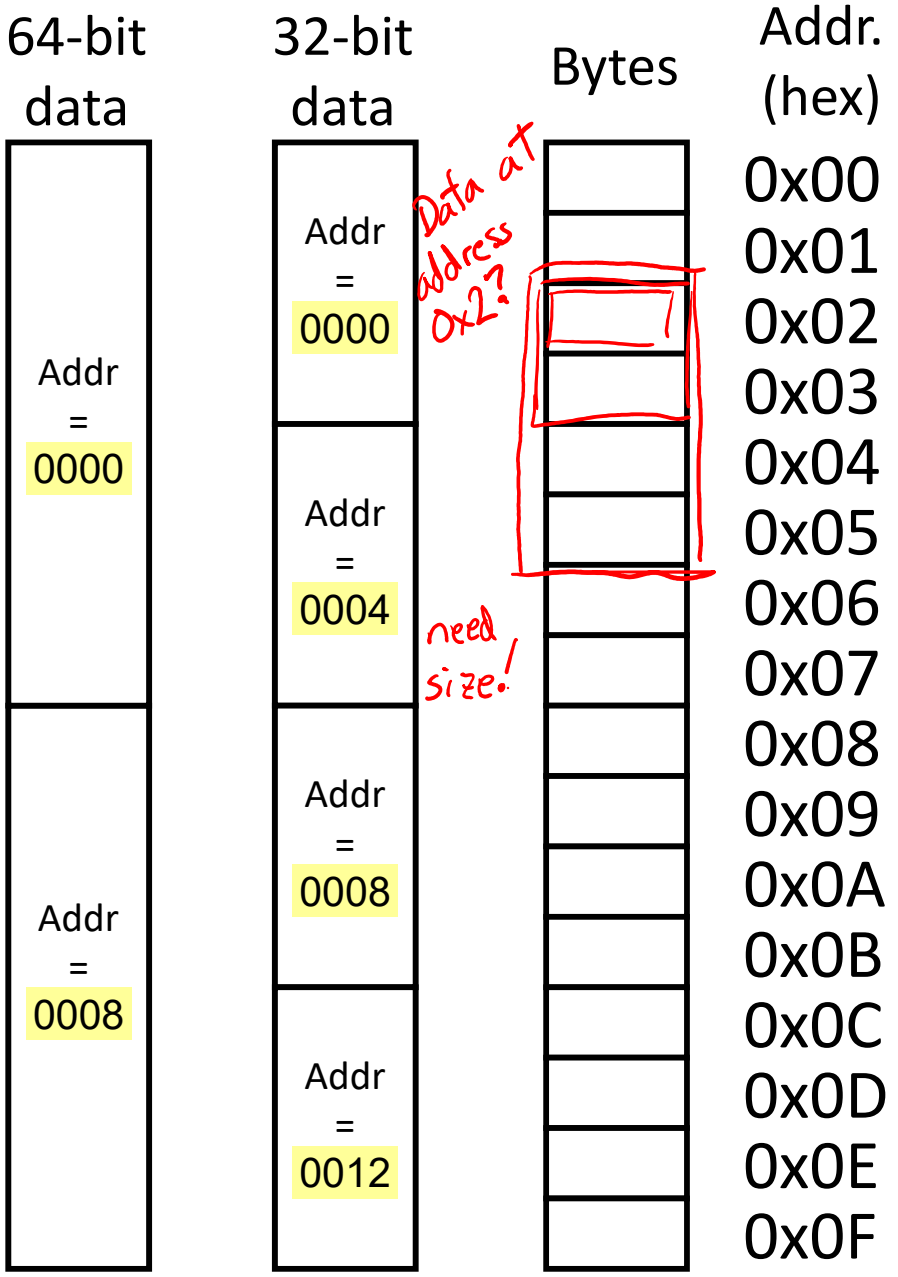
64-bit

address size = word size

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

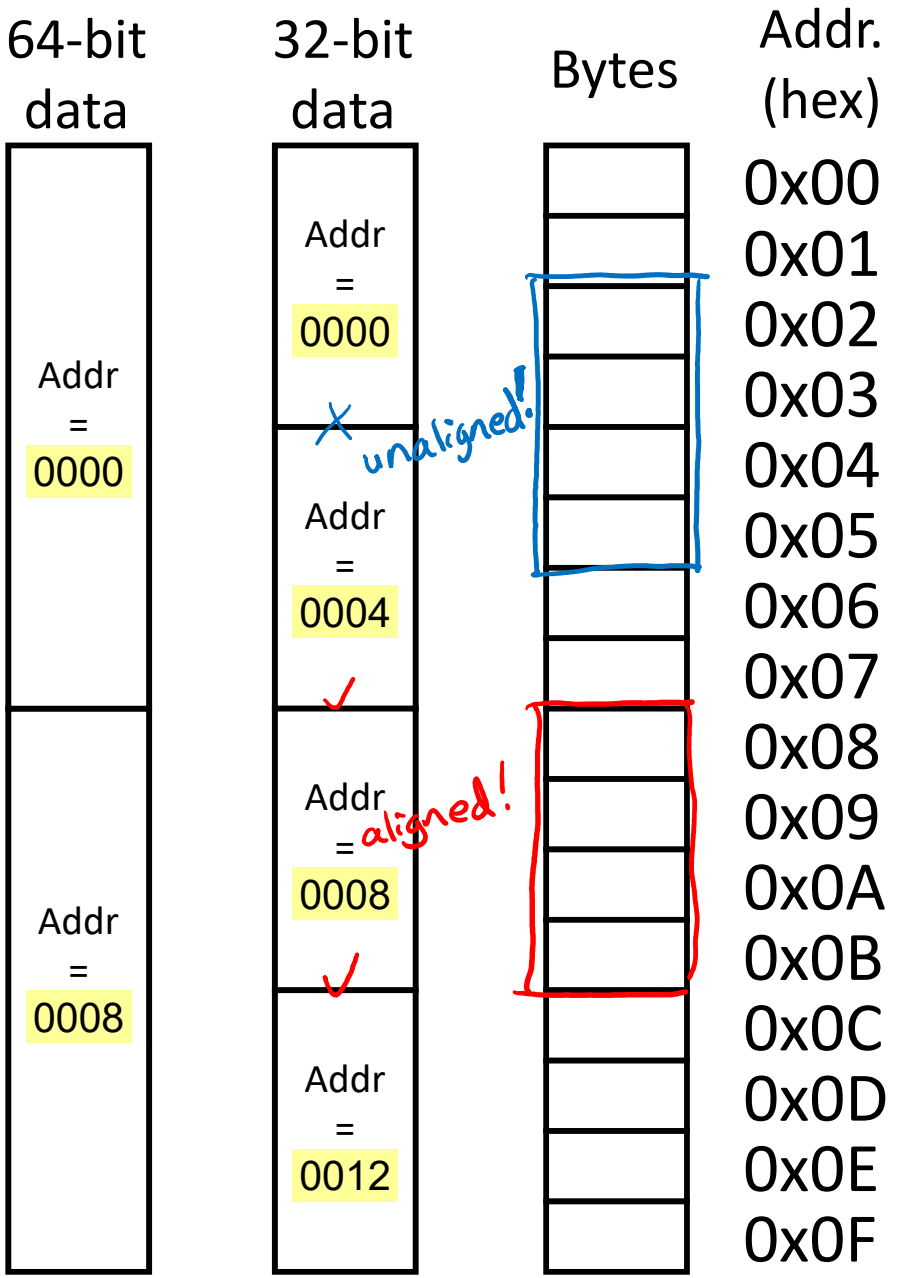
Address of Multibyte Data

- 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**



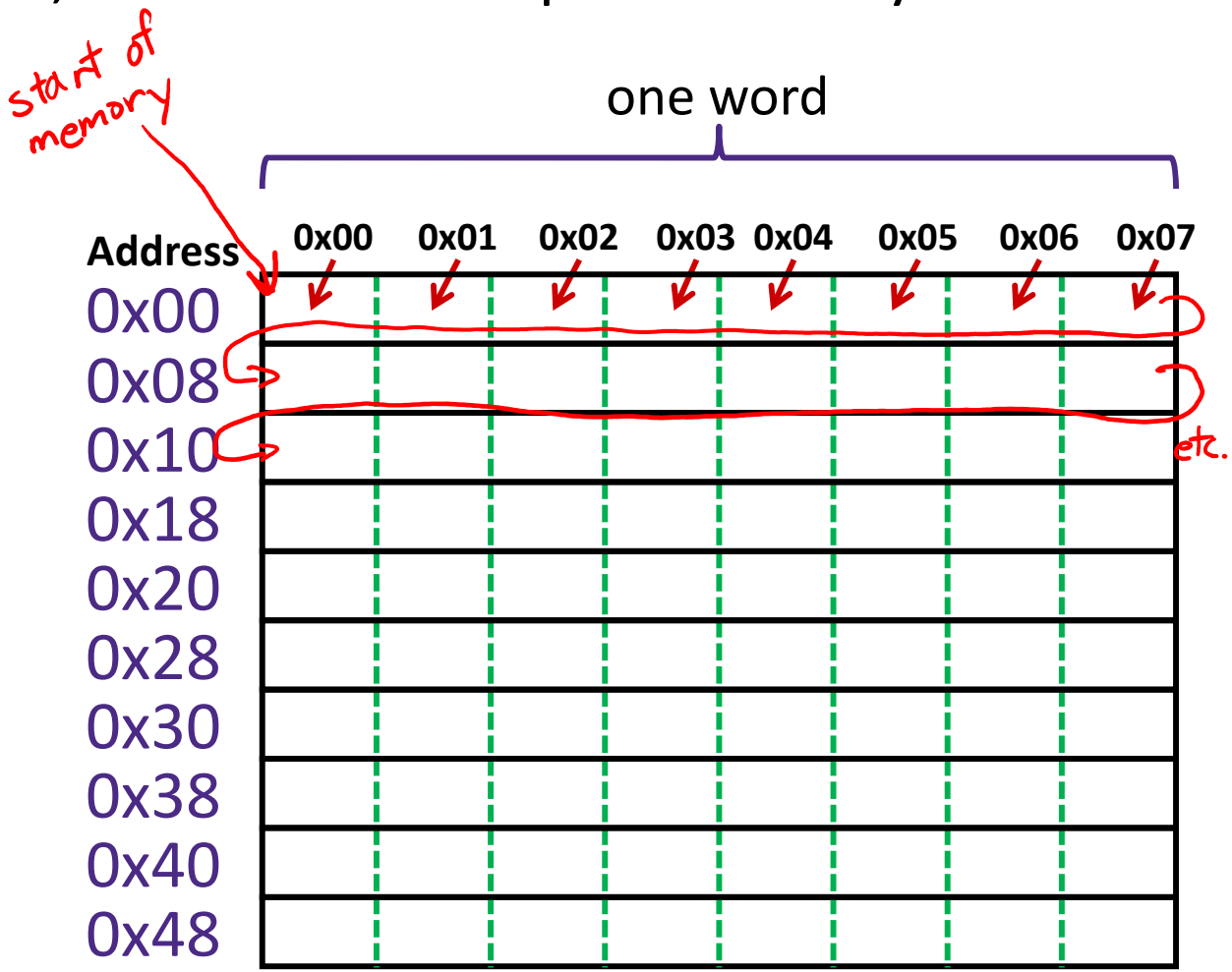
Alignment

- 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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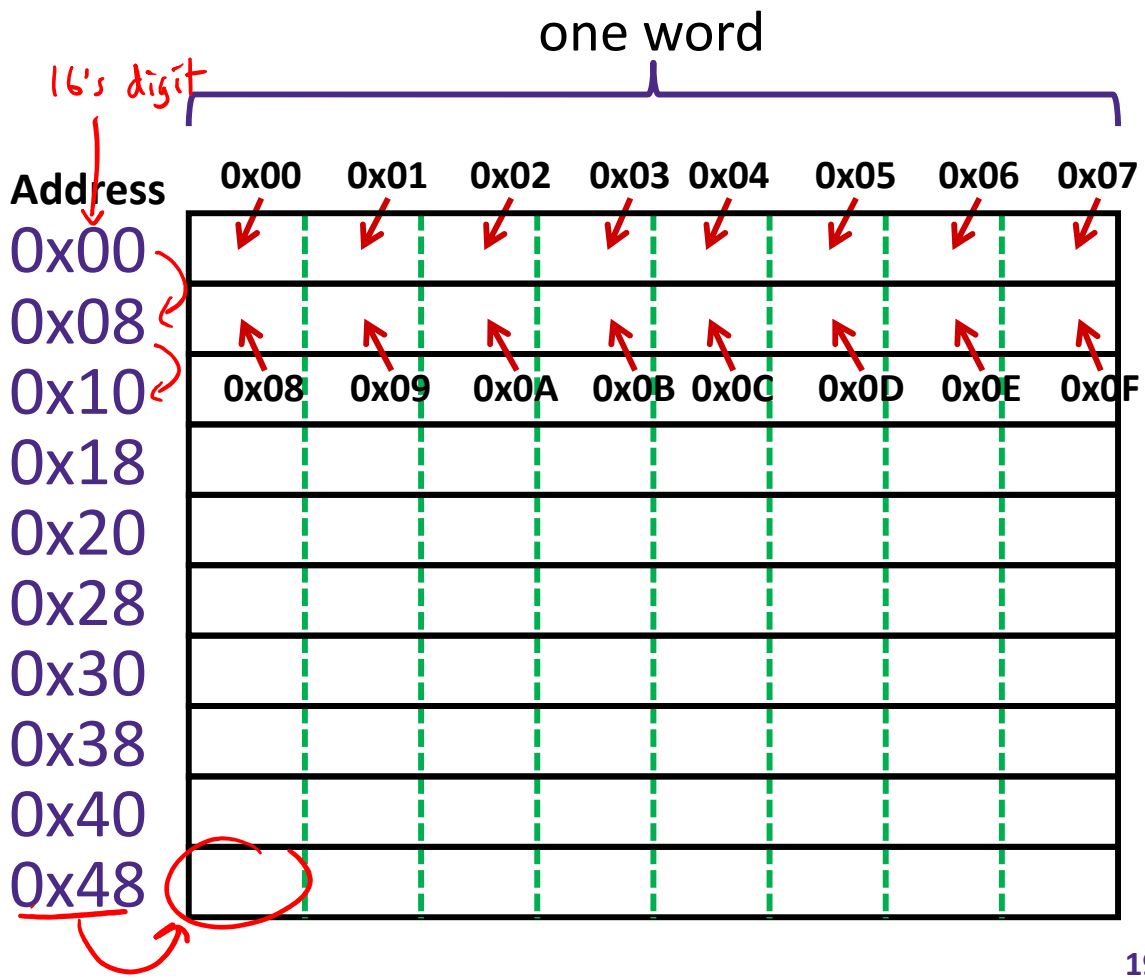
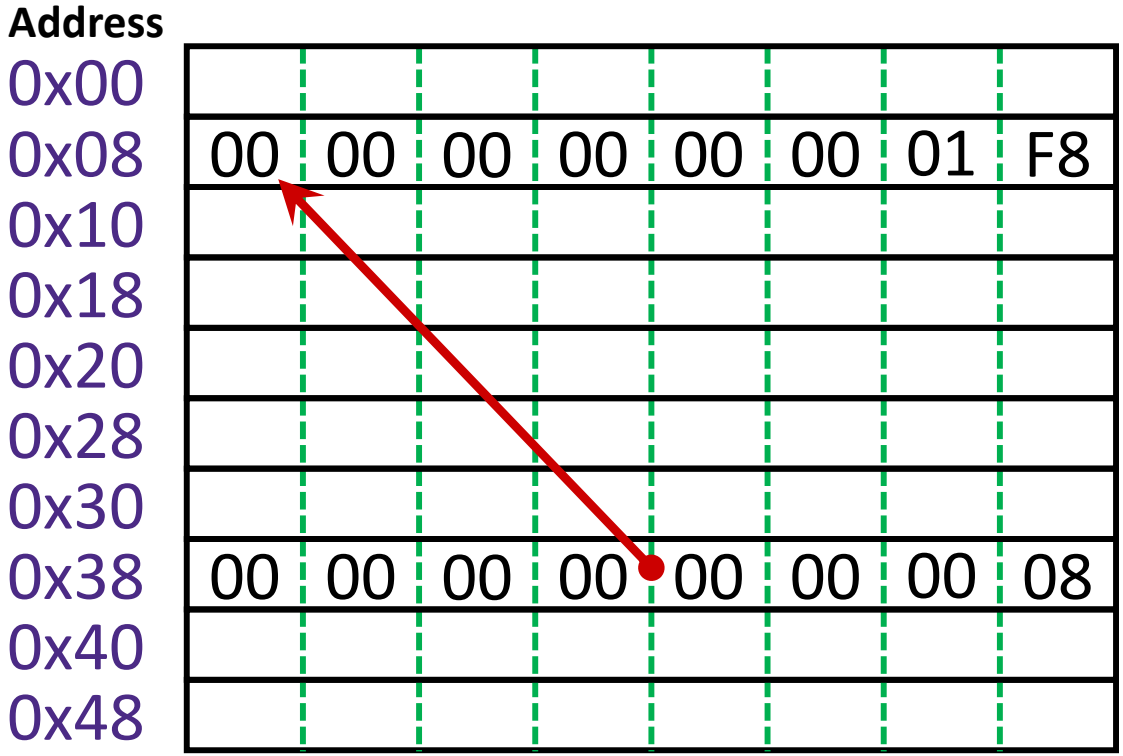


Addresses and Pointers

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

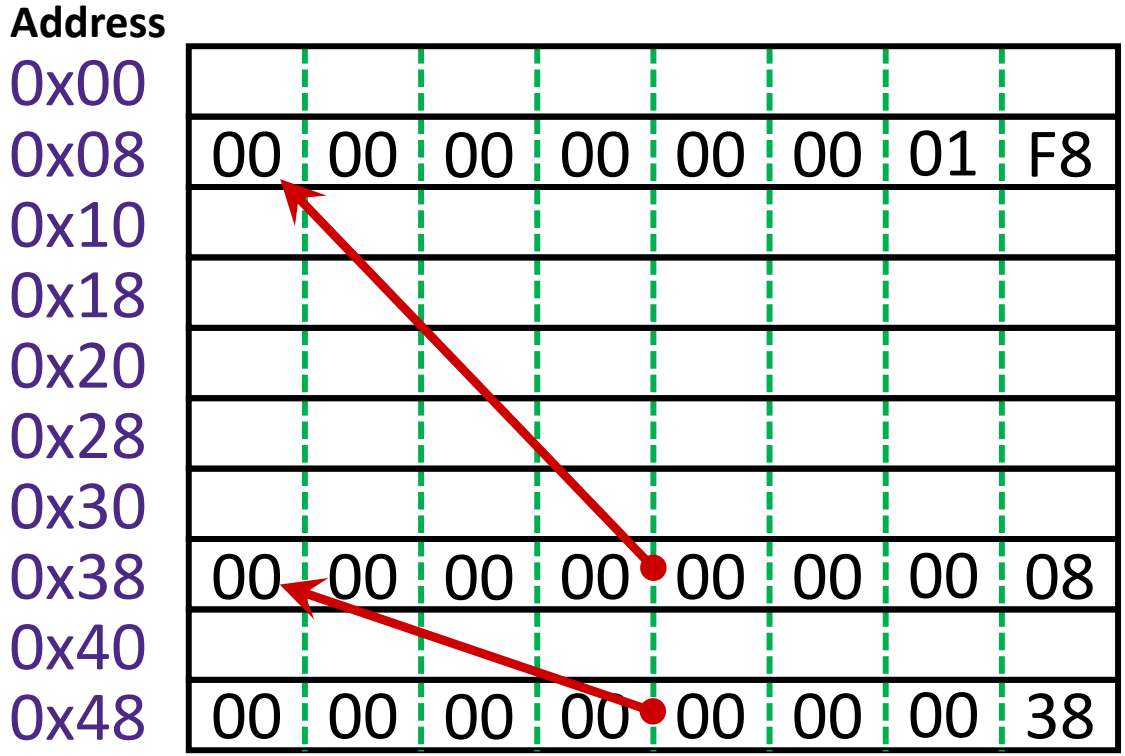


Addresses and Pointers

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
- 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

the hardware doesn't know!



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`:

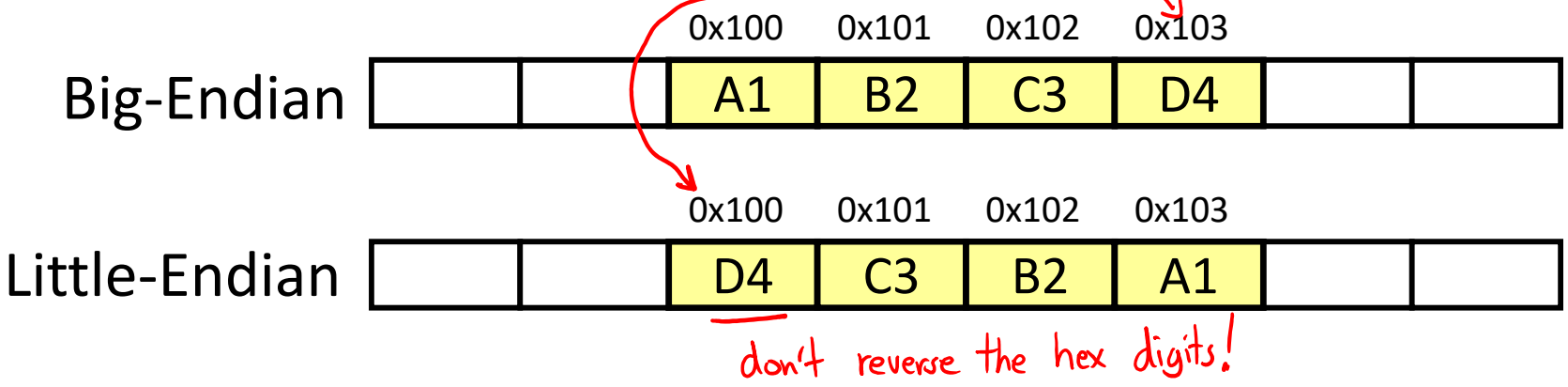
    `0x A1 B2 C3 D4`

    "least significant byte"

    each byte will have a different address
- 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



this class

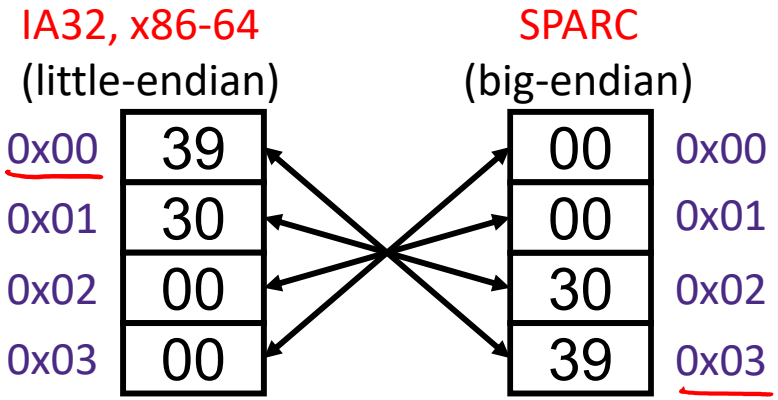
don't reverse the hex digits!

Byte Ordering Examples

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

4 bytes

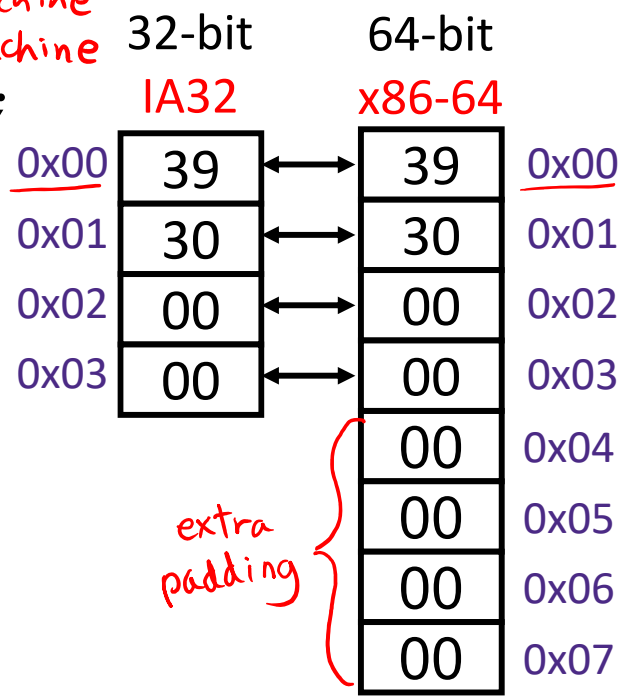
```
int x = 12345;
// or x = 0x3039;
```

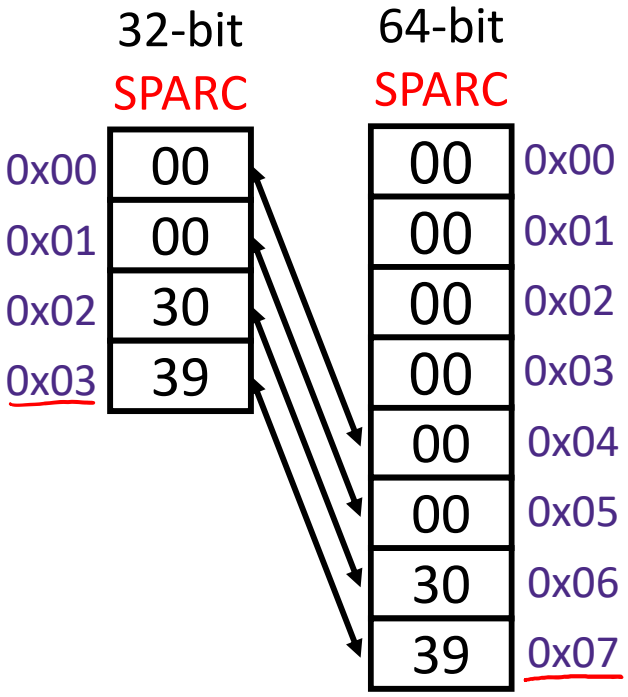


4 bytes on 32-bit machine
8 bytes on 64-bit machine

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

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

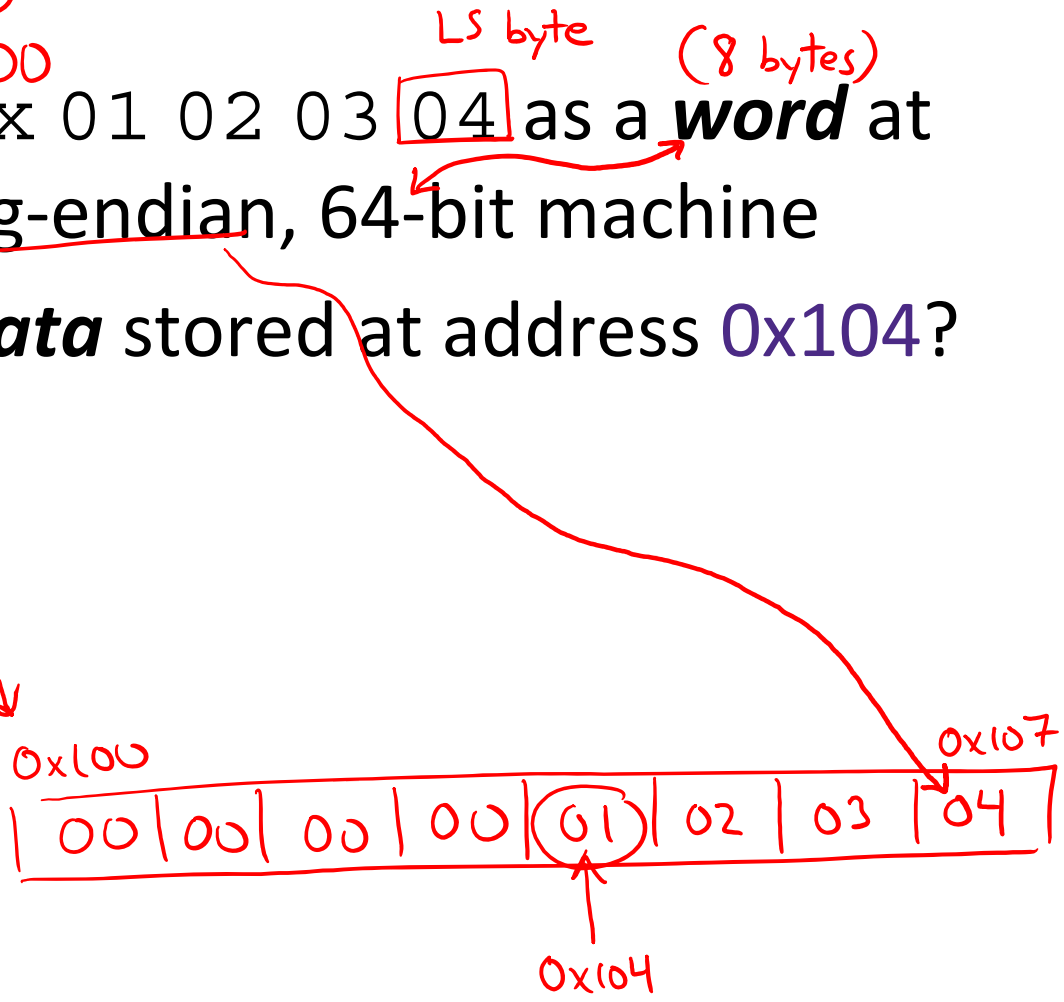




Polling Question

- 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…

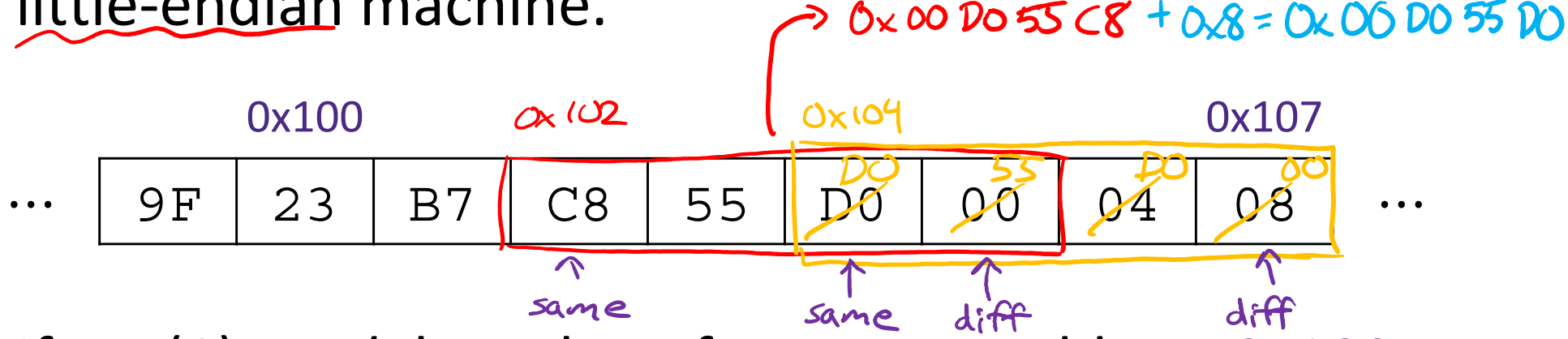


Endianness

- *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)

Challenge Question

- Assume the state of memory is as shown below for a little-endian machine.



- If we (1) *read* the value of an `int` at address 0x102, (2) add 8 to it, and then (3) store the new value as an `int` at address 0x104, which of the following addresses retain their original value?

A. 0x102 **B. 0x104** **C. 0x105** **D. 0x107**

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