Memory, Data, & Addressing I
CSE 351 Spring 2024

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Announcements, Reminders

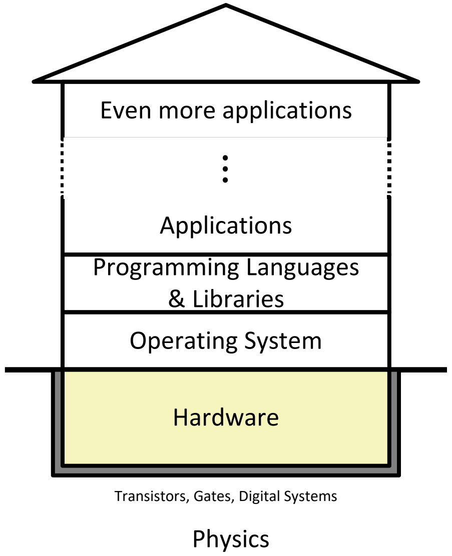
- Everything not a reading or lecture lesson due @ 11:59:00 PM
  - e.g. LC1 and RD2 were due today at 11:00 AM
  - Pre-Course Survey (Canvas) and HW0 due tonight
  - HW1 due Friday (3/29) by 11:59 PM
  - Lab 0 due Monday (4/01) by 11:59 PM
    - This lab is *exploratory* and looks more like a HW; the other labs will look a lot different!
- Labs: Partners allowed! One lab submission between both students.
- 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; make sure your post is in Question form!

EPA

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

The Hardware/Software Interface

- Topic Group 1: **Data**
  - **Memory, Data**, Integers, Floating Point, Arrays, Structs
- Topic Group 2: **Programs**
  - x86-64 Assembly, Procedures, Stacks, Executables
- Topic Group 3: **Scale & Coherence**
  - Caches, Processes, Virtual Memory, Memory Allocation



The Hardware/Software Interface

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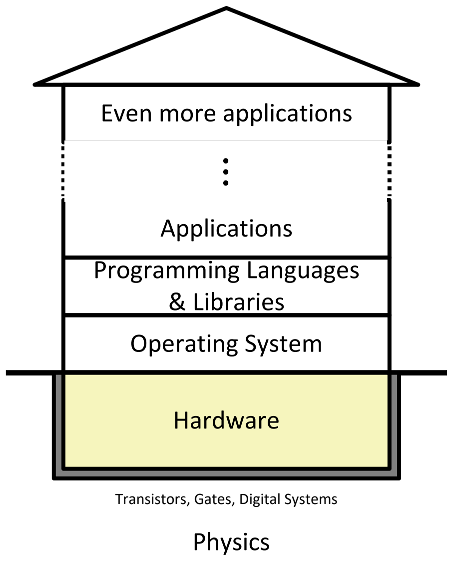
  - **Memory, Data**, Integers, Floating Point, Arrays, Structs



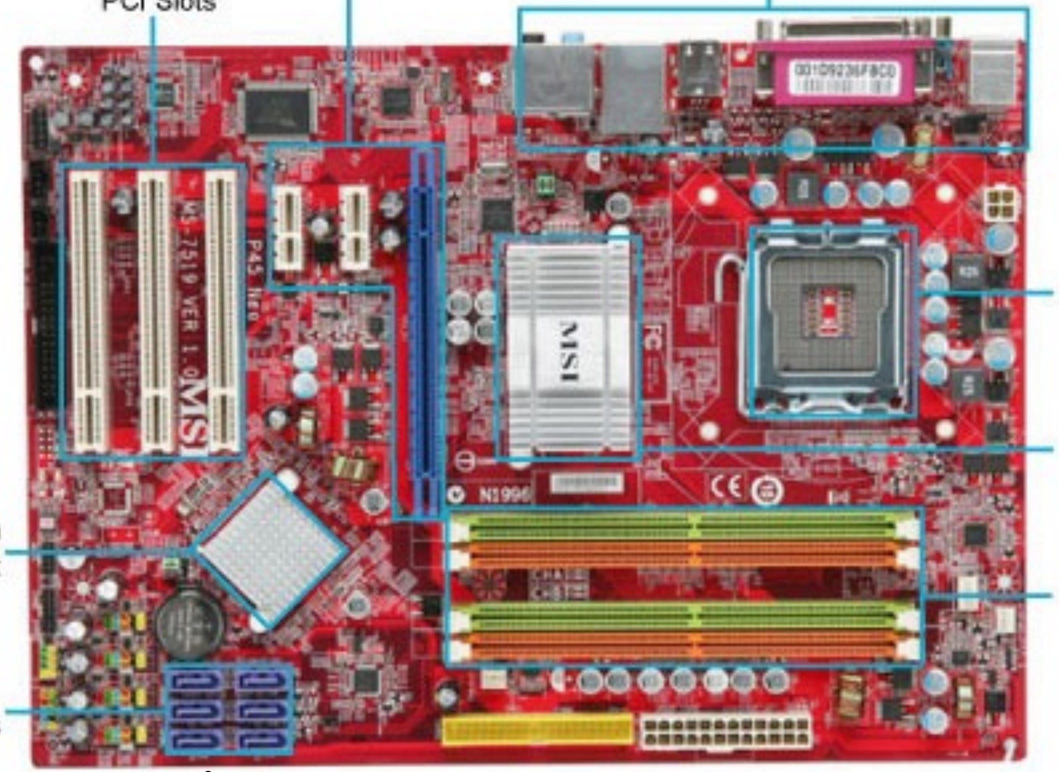
- Topic Question: How do we store information for other parts of the house of computing to access?
  - How do we represent data and what limitations exist?
  - What design decisions and priorities went into these encodings? → Helps understand thought process!

Hardware: Physical View

ew...

Bus connections

USB…



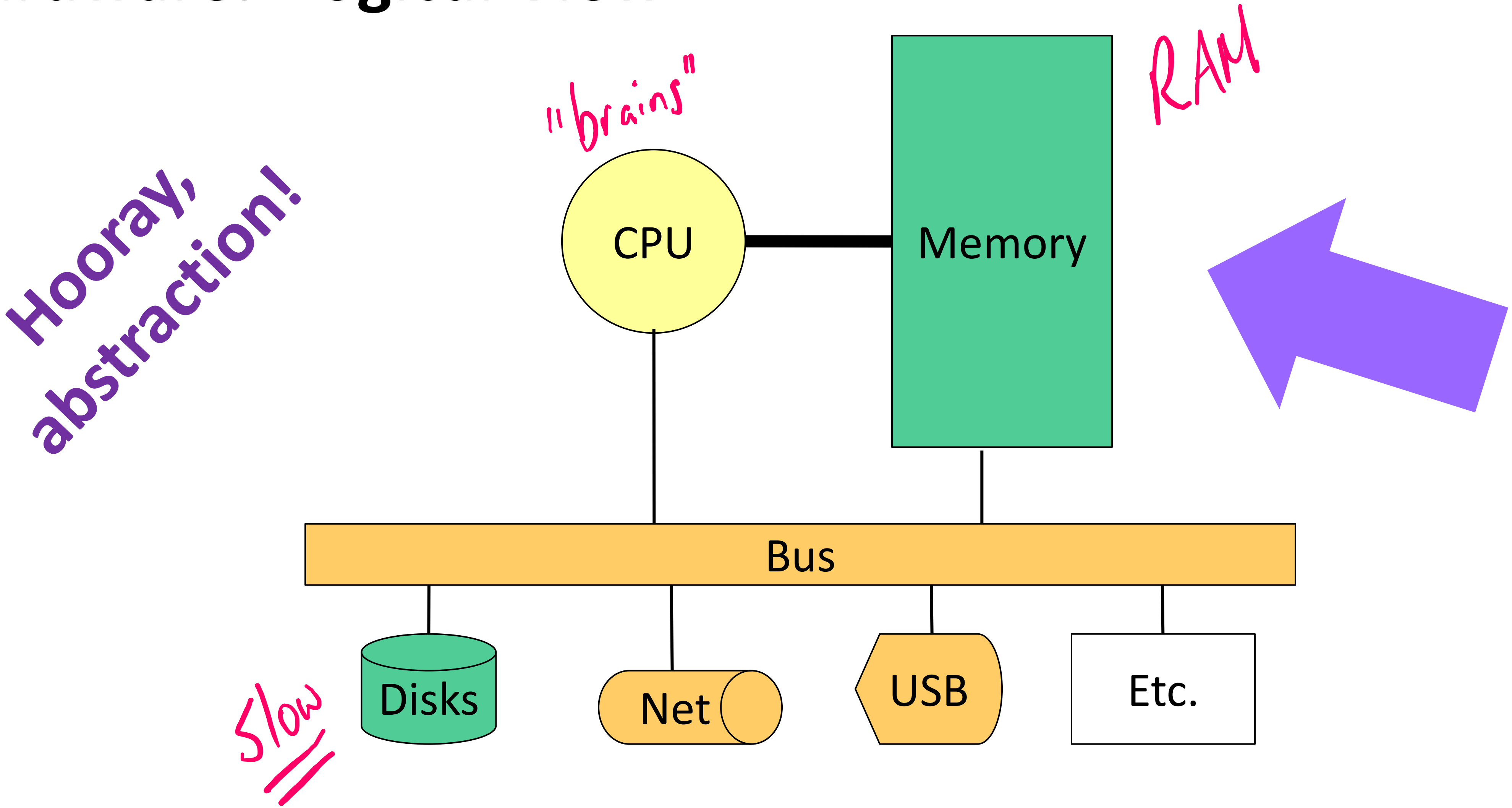
CPU
(empty slot)

I/O
controller

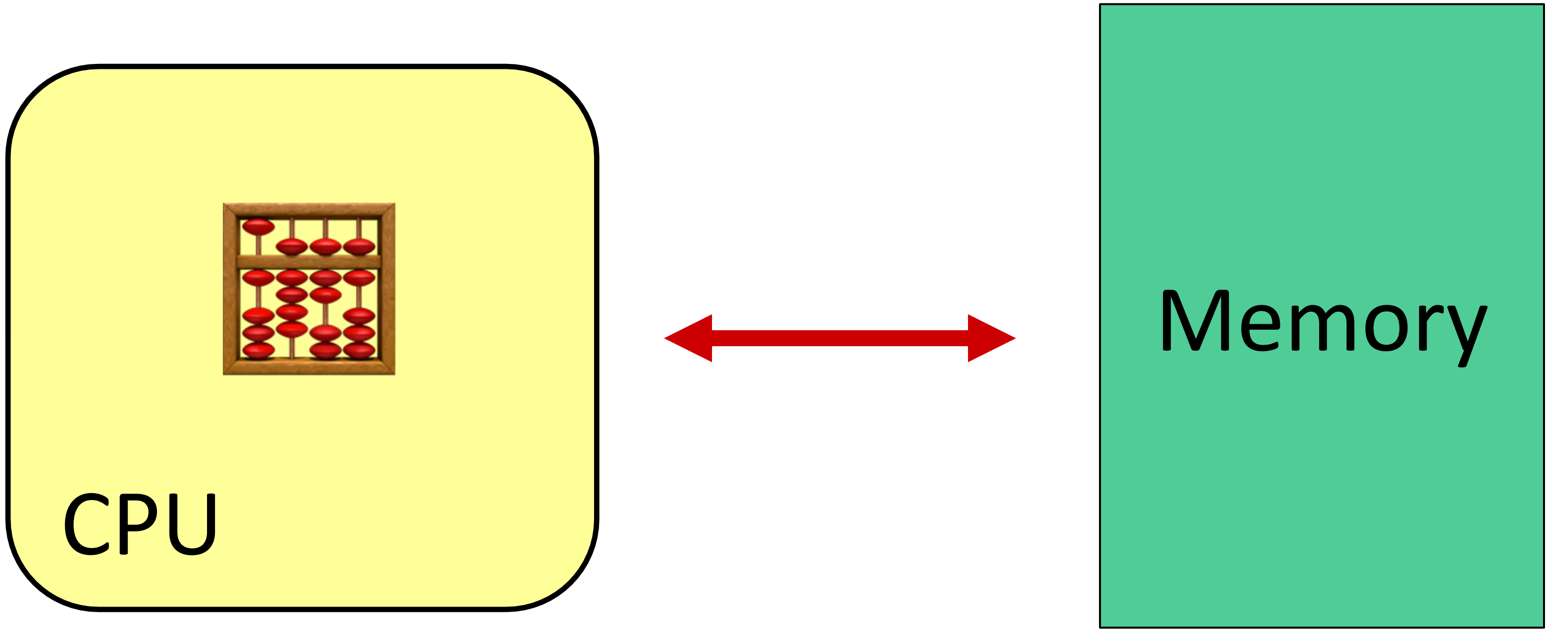
Memory

Storage connections

Hardware: Logical View



Hardware: 351 View (version 0)



- The CPU **executes** instructions
- Memory **stores** data

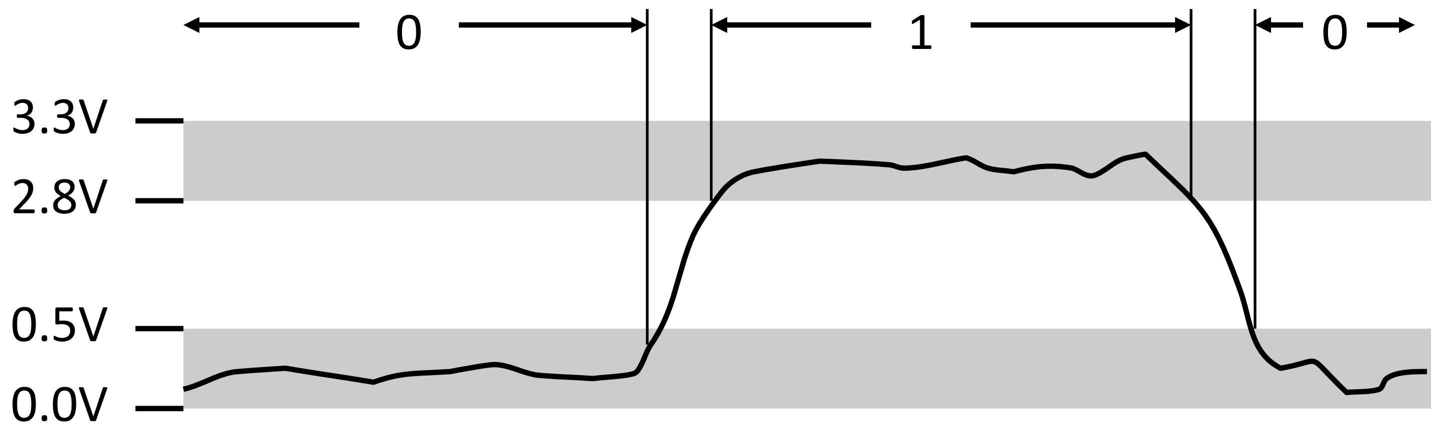
Q1: How are data and instructions represented?

Binary encoding!

Instructions *are* just data; also stored in memory!

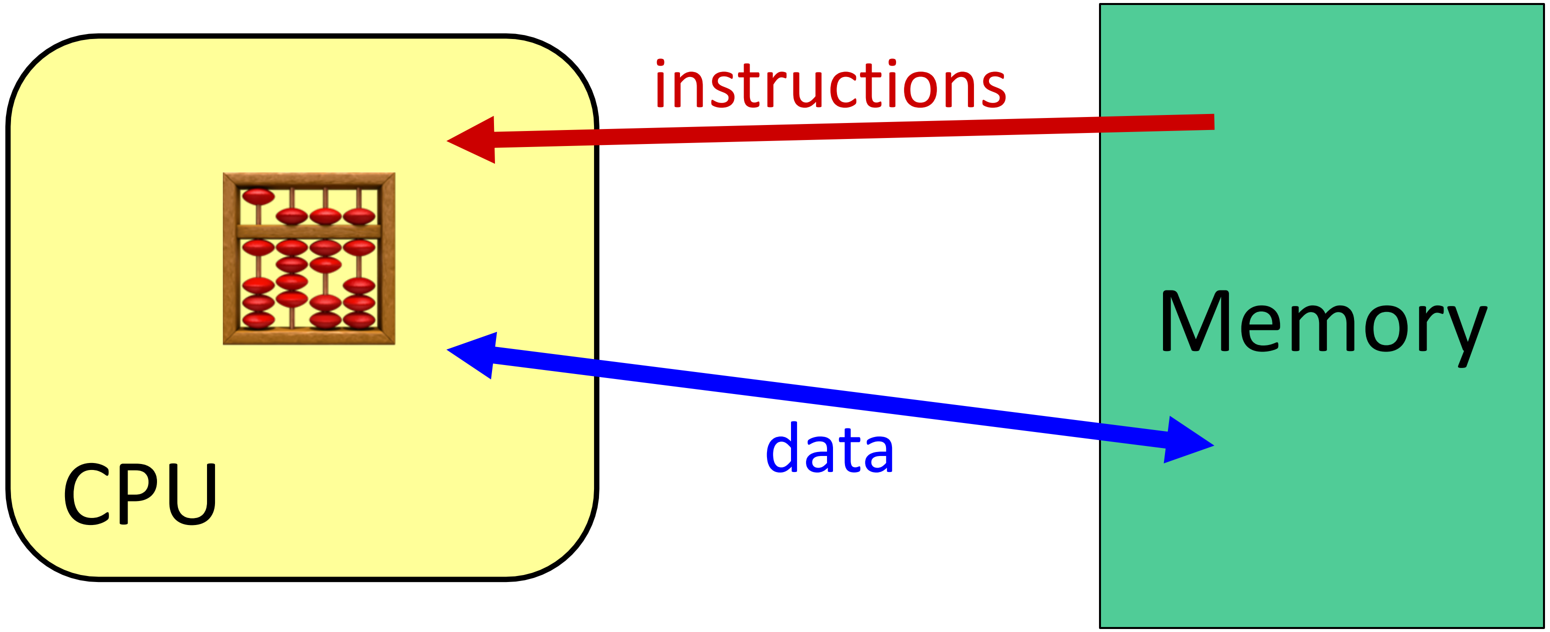
Aside: Why Base 2?

- Electronic implementation
  - Easy to store with bi-stable elements
  - Reliably transmitted on noisy and inaccurate wires



- Other bases possible, but not yet viable:
  - Ternary has existed (Setun, 1958)
  - DNA data storage (base 4: A, C, G, T) here at UW
  - Quantum computing

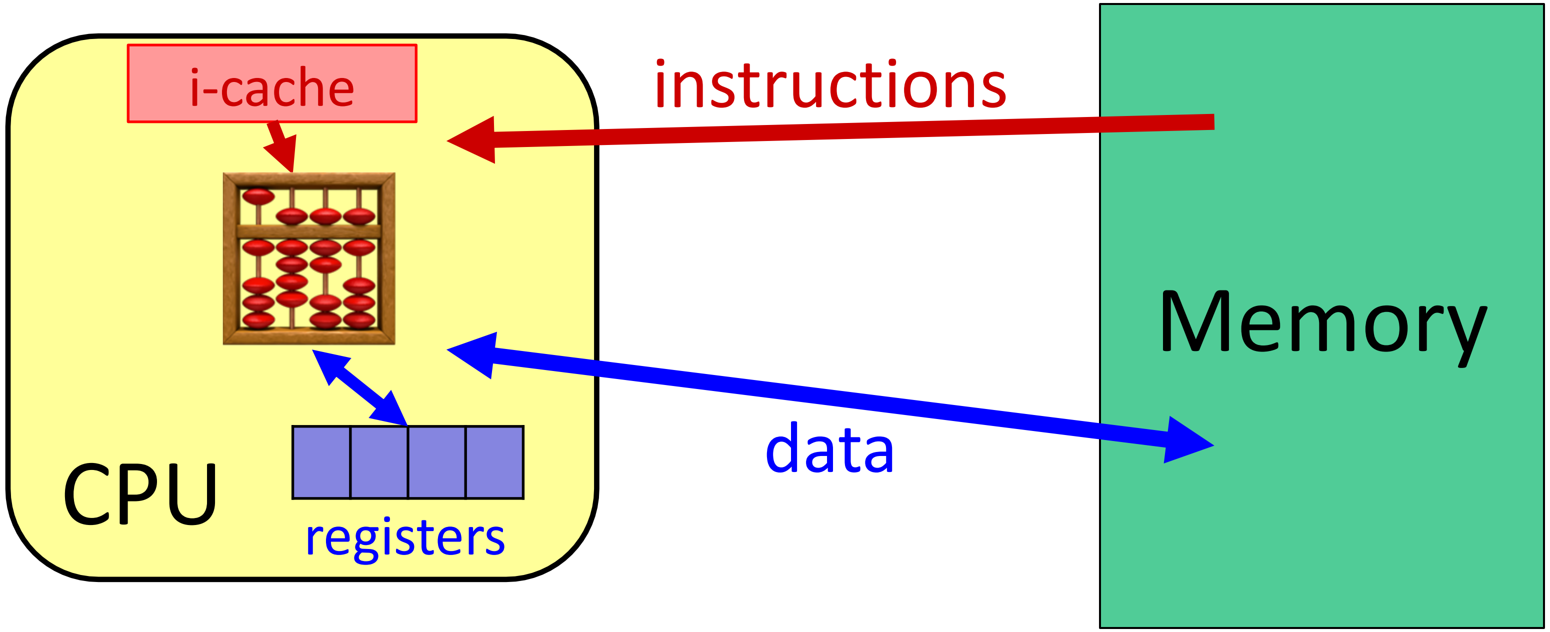
Hardware: 351 View (version 0)



- 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

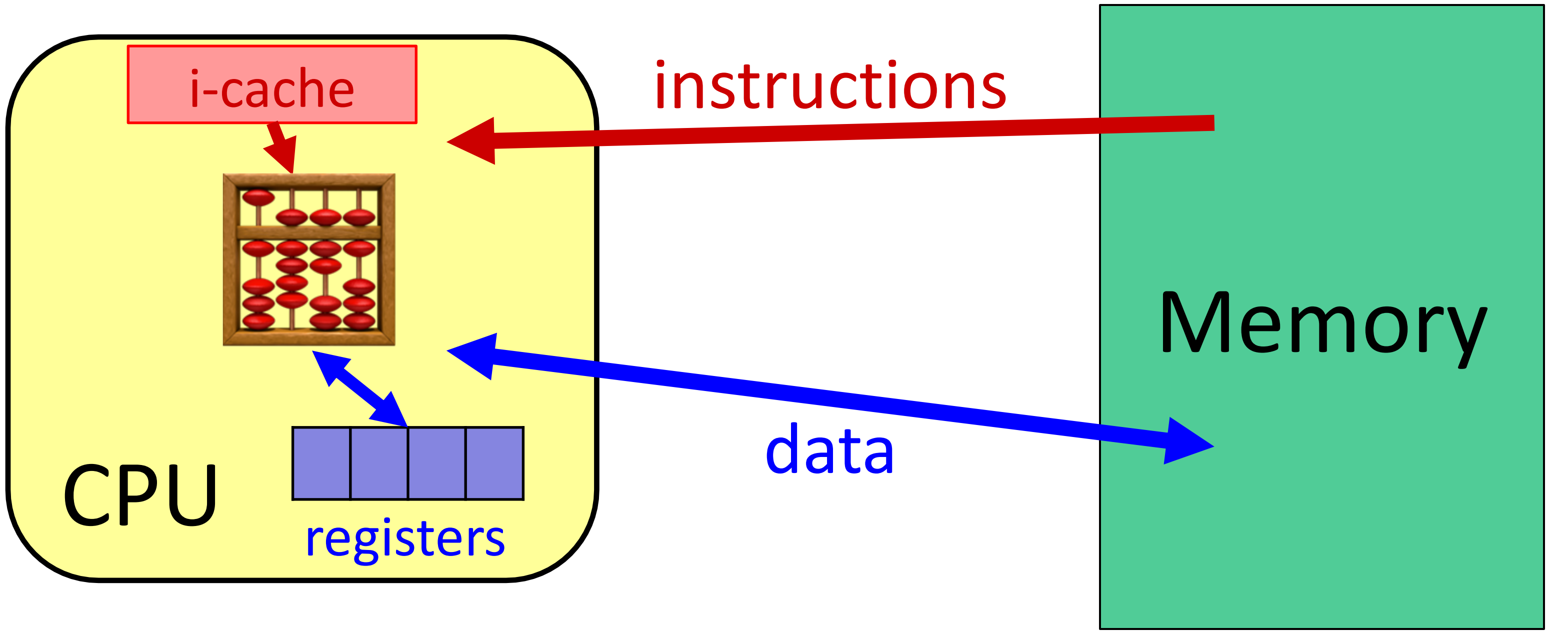
Hardware: 351 View (version 1)

This is extra (non-testable) material



- More CPU details:
  - Instructions are held temporarily in the instruction cache (i.e. Harvard Architecture)
  - Other data are held temporarily in registers ← Very fast, but few.
- Instruction fetching is hardware-controlled (My research! 👩🏻‍💻)
- Data movement is programmer-controlled (assembly)

Hardware: 351 View (version 1)



- We will start by learning about Memory

Q2: How does a program find its data in memory?

Addresses!

Can be stored in *pointers*

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?

Review Questions

- By looking at the bits stored in memory, I can tell what a particular 16 bytes is being used to represent.

  A. True B. False

  Encodings differ!

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

  A. True B. False

  Need both

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

  A. 0x3F B. 0xA0 C. 0xCA D. 0xD

  0b 1010 0000 0b 1100 1010 0b 0000 1101

Base Comparison

Slide from last time for reference!

- Why does all of this matter?
  - *Humans* think about numbers in **base 10**, but *computers* “think” about numbers in **base 2**
  - Binary encoding is what allows computers to do all of the amazing things that they do!
- You should have this table memorized by the end of the class
  - Might as well start now!

Base 10	Base 2	Base 16
0	0000	0
1	0001	1
2	0010	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F

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 “eight-bit” representation of the number 4 is 0b00000100

Most Significant Bit (MSB)   Least Significant Bit (LSB)

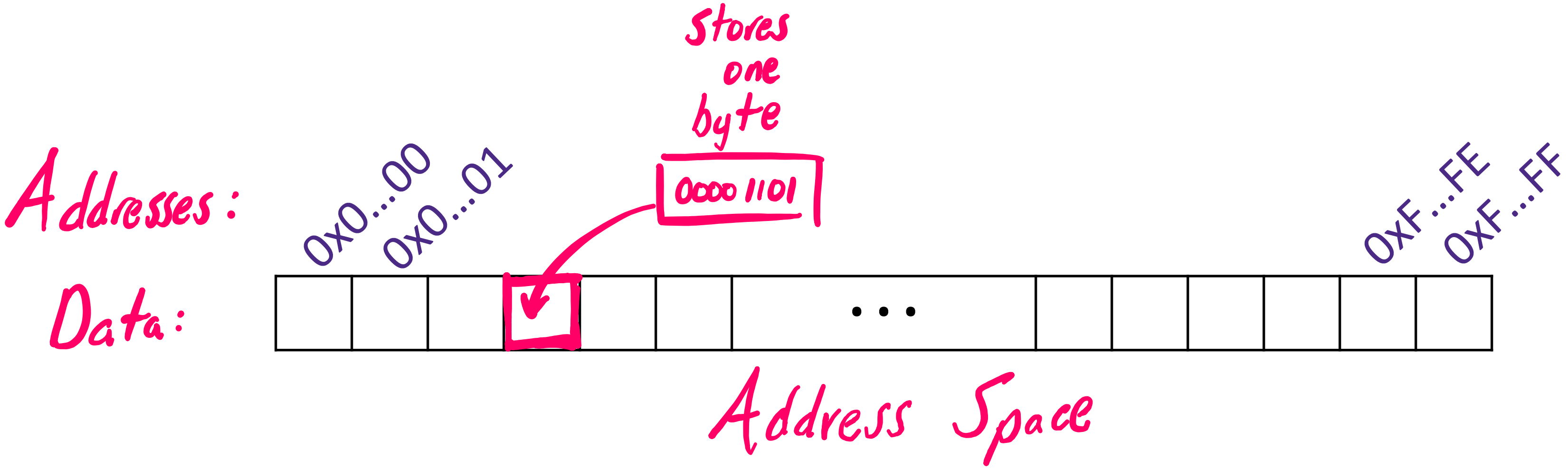
Bits and Bytes and Things (Review)

if $n=2$: 00, 01, 10, 11 — $2^n = 4$

- 1 byte = 8 bits
- n bits can represent up to 2^n things
  - Sometimes (oftentimes?) those "things" are bytes!
- If addresses are a-bits wide, how many distinct addresses are there?

∴ 2^a addresses

- What does each address refer to?



2^a bytes total

2^{a+3} bits total

Machine "Words" (Review)

- 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, no deviation. (Now, there exists much deviation...)
- We have *chosen* to tie word size to address size/width
  - word size = address size = register size
  - word size = w bits → 2^w addresses
- Current x86 systems use **64-bit (8-byte) words**
  - Potential address space: $\mathbf{2^{64}}$ addresses
    2^{64} bytes ≈ $\mathbf{1.8 \times 10^{19}}$ **bytes**
    = 18 billion billion bytes = 18 EB (exabytes)
  - Actual physical address space: **48 bits**

remember this when we do virtual memory...

Still quite big!

Data Representations

- Sizes of data types (in bytes)

Java Data Type	C Data Type	IA-32 (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**

address size = word size

Why? Because pointers store addresses!

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

Discussion Question

- Over time, computers have grown in word size:

Word size	Instruction Set Architecture	First? Intel CPU	Year Introduced
8-bit	??? (Poor & Pyle)	Intel 8008	1972
16-bit	x86	Intel 8086	1978
32-bit	IA-32	Intel 386	1985
64-bit	IA-64	Itanium (Merced)	2001
64-bit	x86-64	Xeon (Nocona)	2004

  - What do you think were some of the *causes*, *advantages*, and *disadvantages* of this trend?

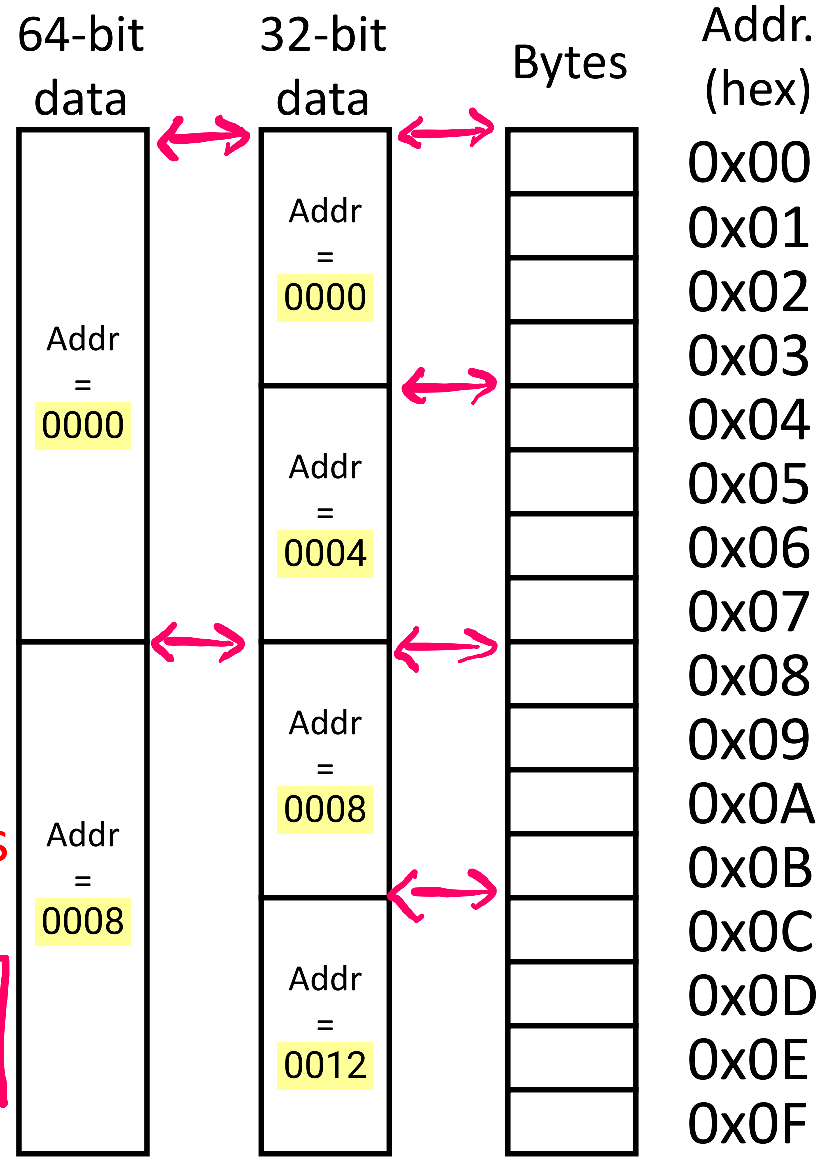
Causes: Dennard Scaling, Moore's Law, innovation

Advantages: Cheaper memory, more compute capabilities

Disadvantages: Environment :(, Sparse data, data overload

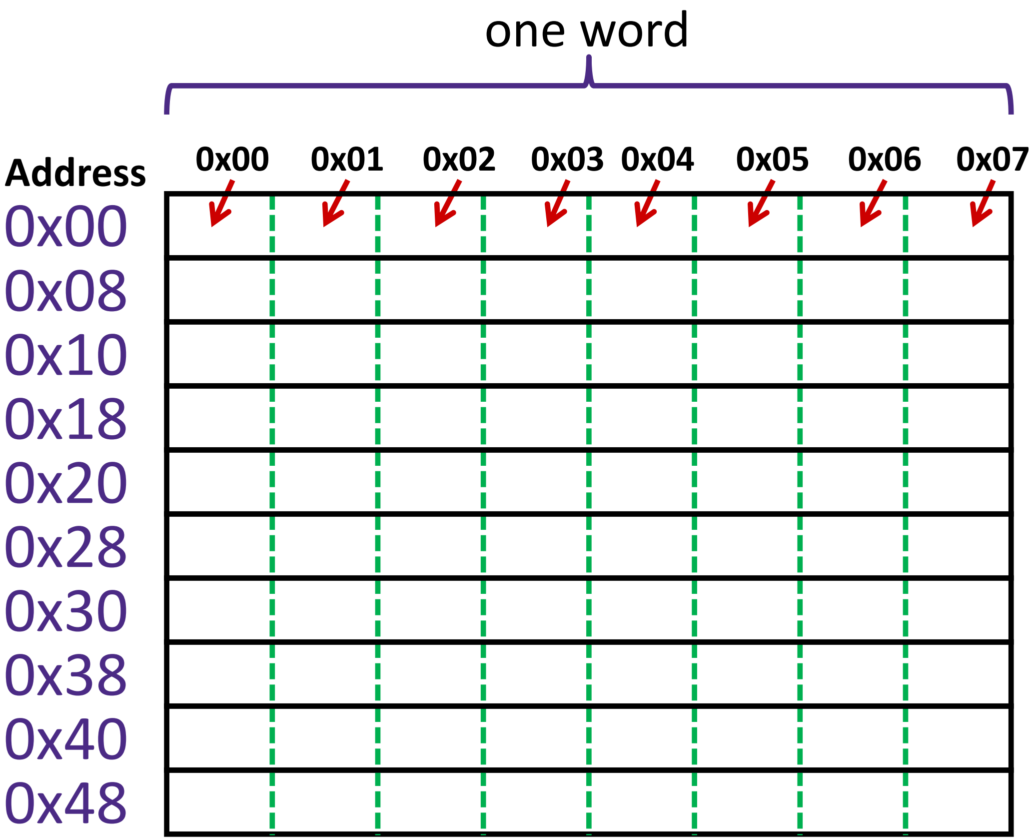
Address of Multibyte Data (Review)

- 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**



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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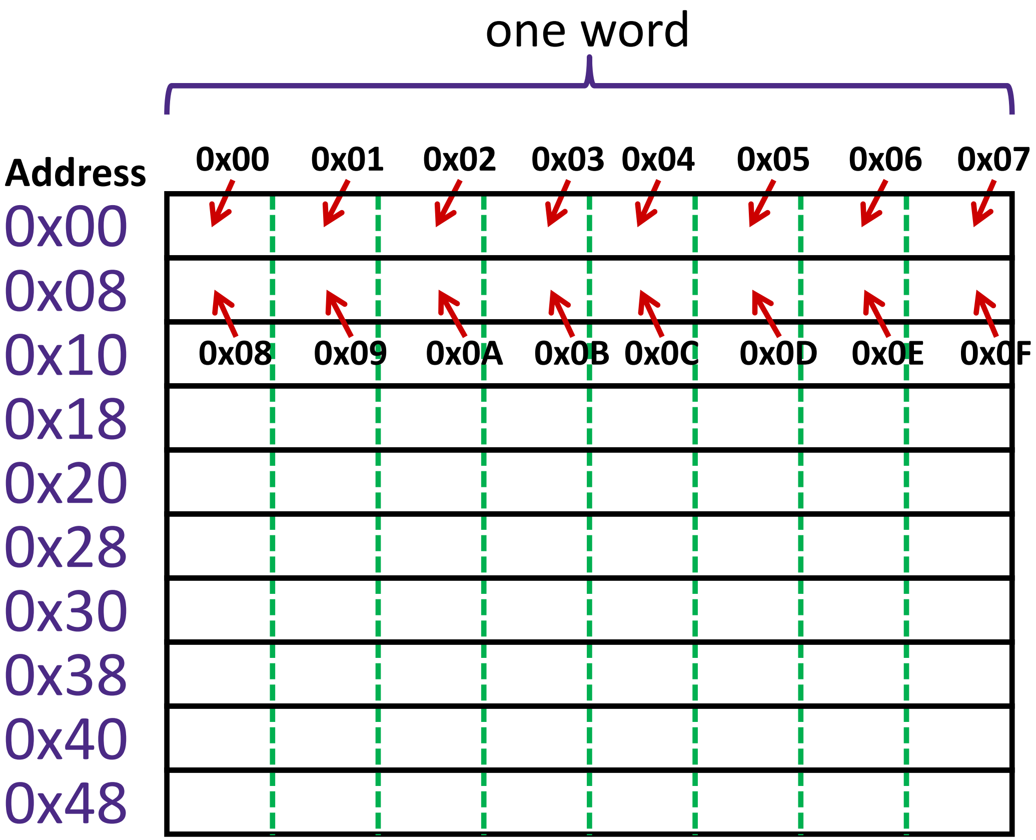


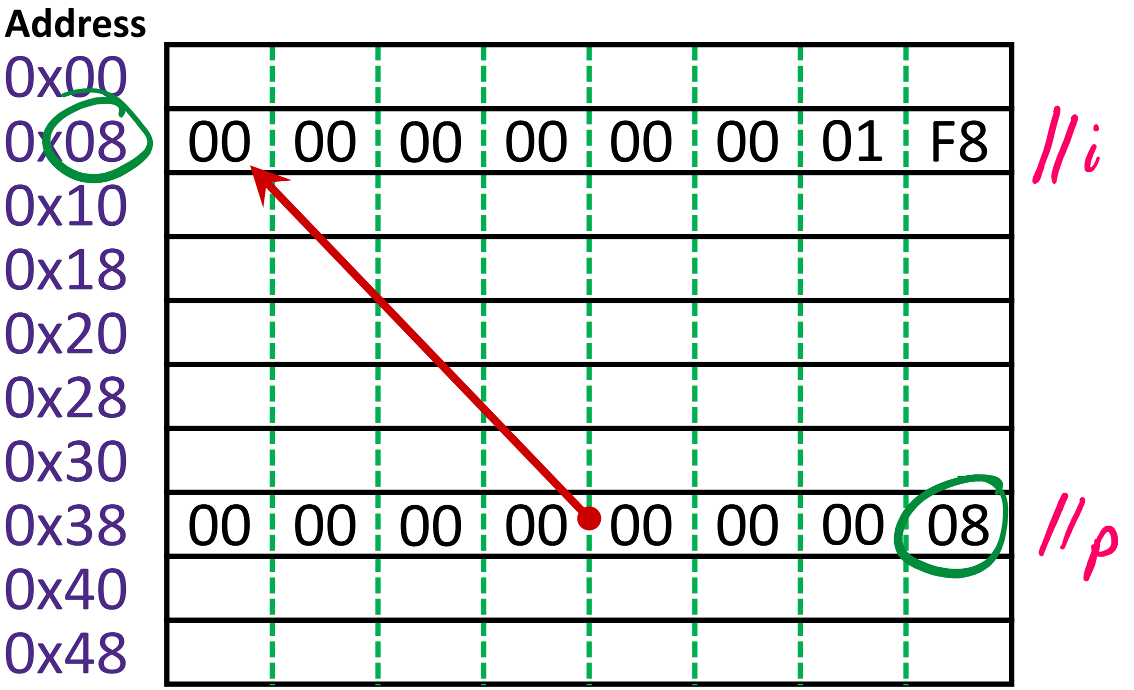
Addresses and Pointers

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 as a word at addr 0x08
  - $504_{10} = 1F8_{16}$
    = 0x 00 … 00 01 F8
- Pointer stored at 0x38 points to address 0x08

int i = 504;
int *p = &i;



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

```
int i = 504;
int *p = &i;
int **q = &p;
```

Address									
0x00									
0x08	00	00	00	00	00	00	01	F8	// i
0x10									
0x18									
0x20									
0x28									
0x30									
0x38	00	00	00	00	00	00	00	08	// p
0x40									
0x48	00	00	00	00	00	00	00	38	// q

64-bit example

Ad

```
[elba@attu1 ~]$ tail pointer_example.c
int main(int argc, char* argv[]) {

    int i = 504;    // i
    int *p = &i;    // p
    int **q = &p;   // q

    printf("i = %i\np = %p\nq = %p\n", i, p, q);

    return 0;
}
[elba@attu1 ~]$ ./pointer_example
i = 504
p = 0x7ffd048b97e4
q = 0x7ffd048b97d8
[elba@attu1 ~]$
```

Code equivalent of the previous Slide !!

Execution of Code above!

Byte Ordering (Review)

- 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?
    - Historical: Based on *Gulliver's Travels*—tribes cut their eggs on different sides (big, little)
    - Language aside: how we write languages differs too!

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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

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

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

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

padding!

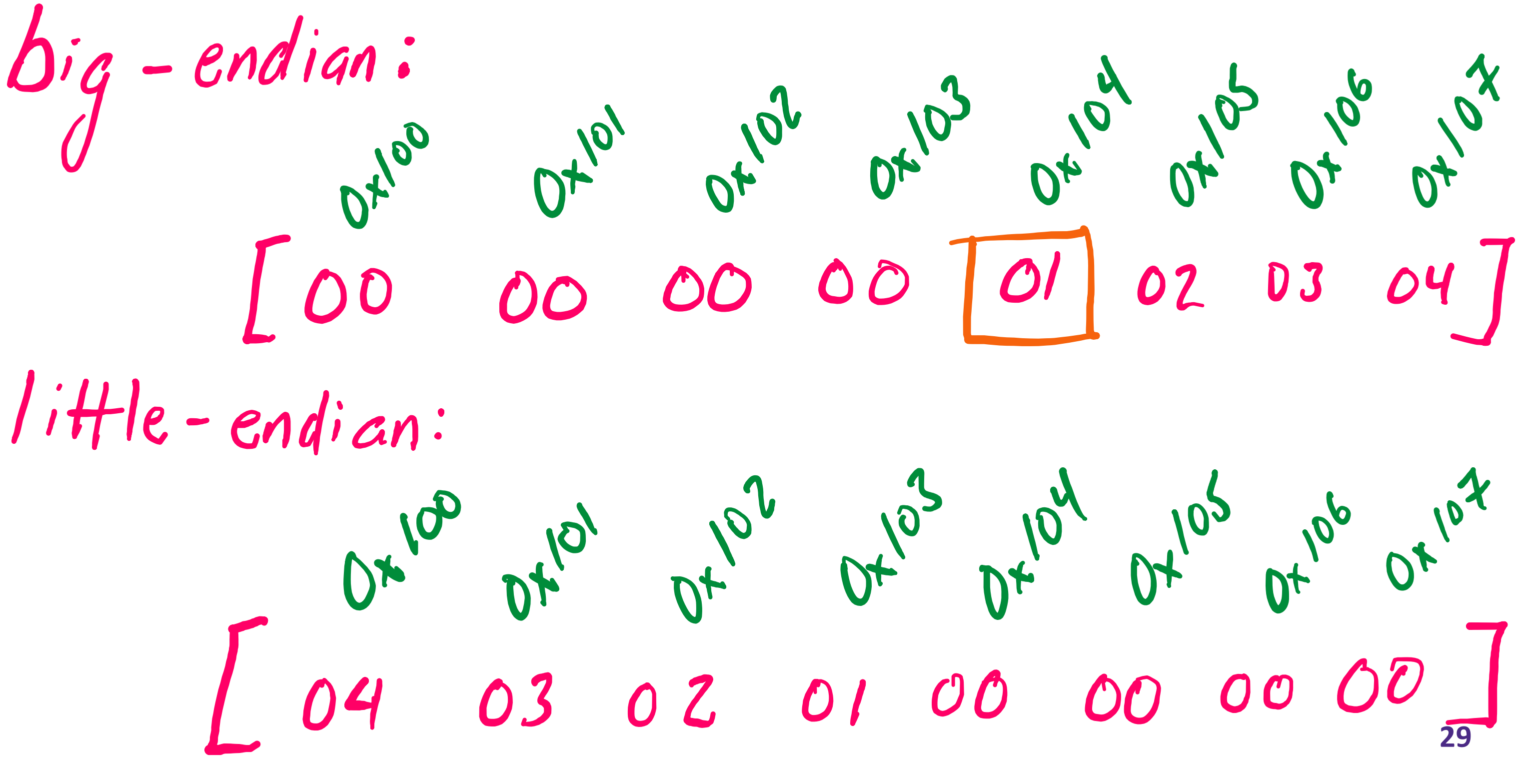
A. **0x04**

B. **0x40**

C. **0x01**

D. **0x10**

E. **We're lost…**



Endianness

btw…

- *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
- Pointers are data objects that hold addresses
  - Type of pointer determines size of thing being pointed at, which could be another pointer
- Endianness determines memory storage order for multi-byte data
  - Least significant byte in lowest (little-endian) or highest (big-endian) address of memory chunk