# Memory, Data, & Addressing I

CSE 351 Autumn 2024

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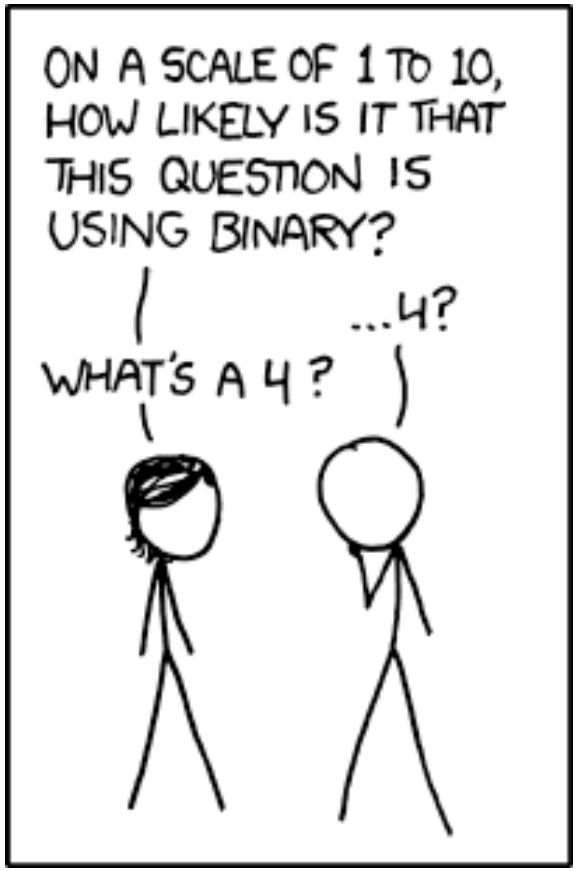


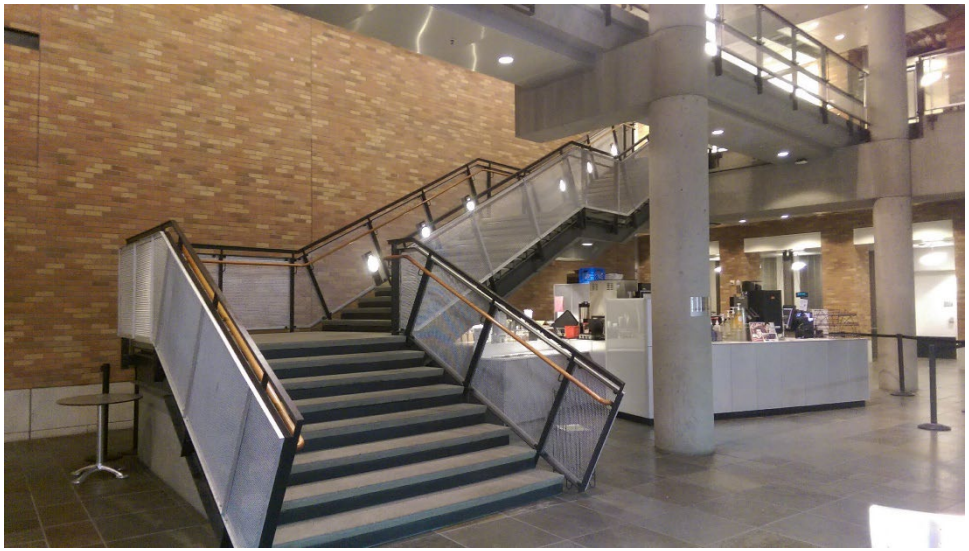

http://xkcd.com/953/

# Relevant Course Information

- Pre-Course Survey and HW0 due tonight @ 11:59 pm
- HW1 due Monday (9/30) @ 11:59 pm
- Lab 0 due Monday (9/30) @ 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

# In-Person Office Hours

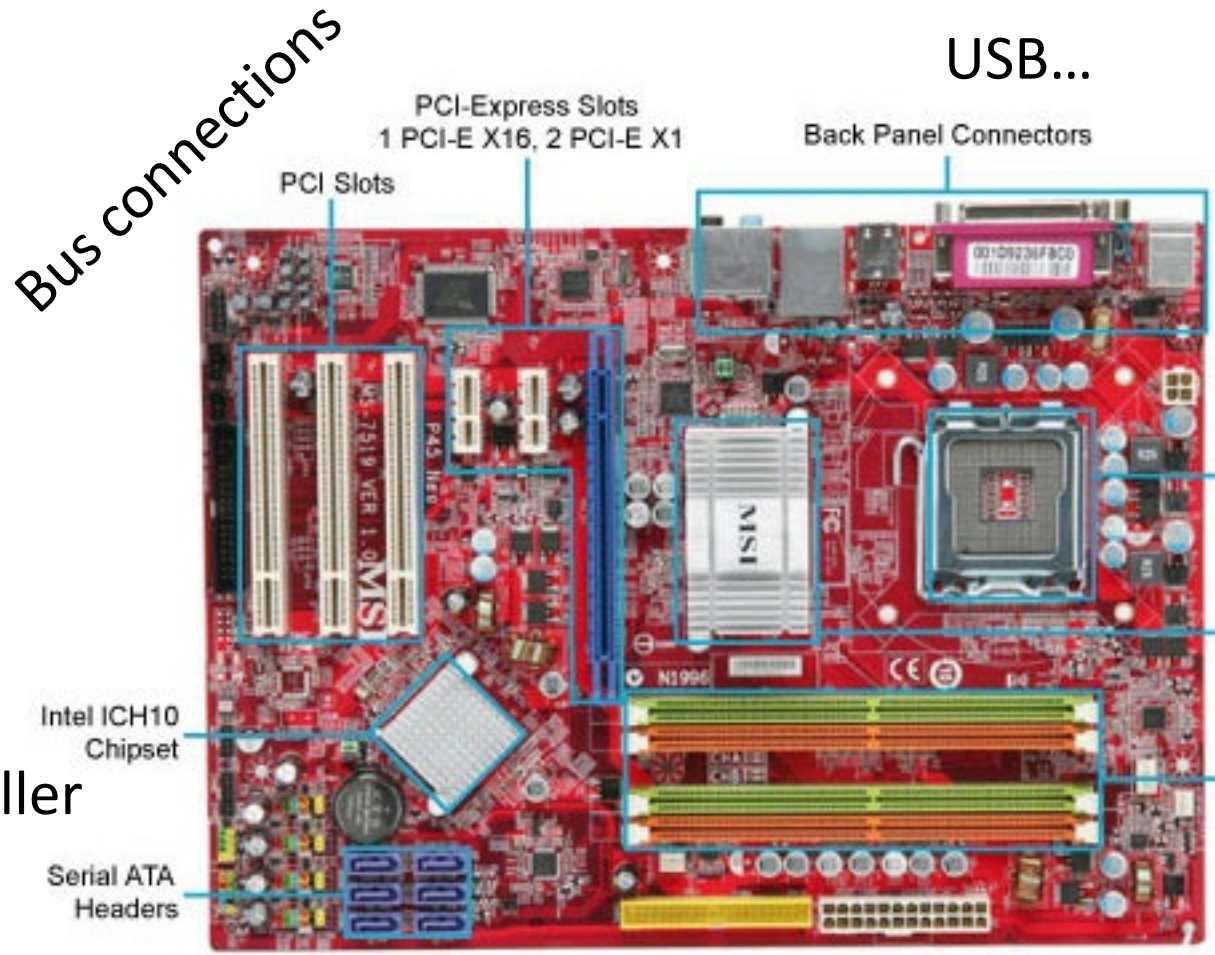
- Many are in the CSE/Allen Center breakouts
  - Up the stairs in the CSE Atrium (Allen Center, not Gates)
  - 2nd, 3rd , 4th, 5th floors
  - At the top of the stairs, the open area with the whiteboard wall is a breakout!



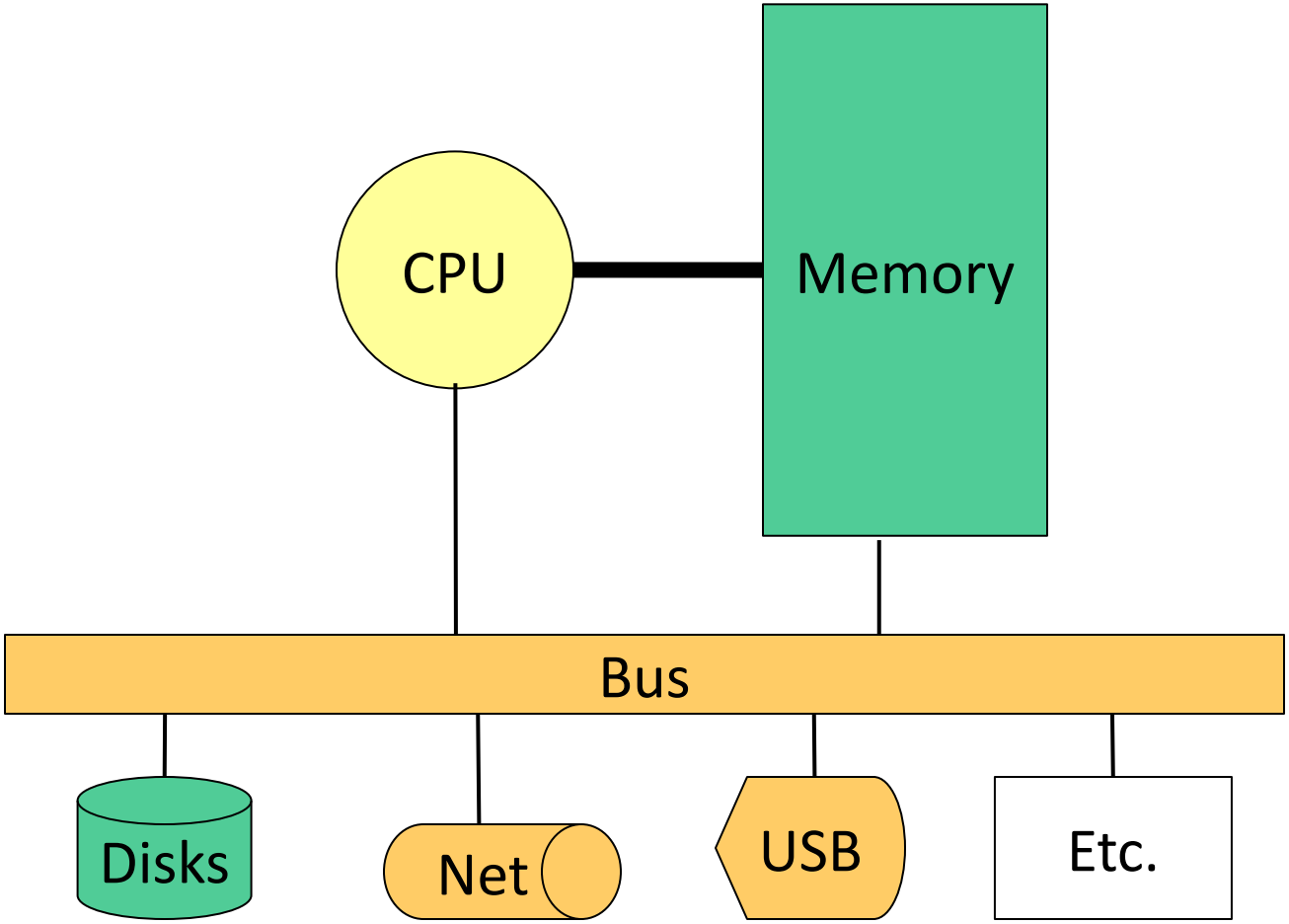
# Memory, Data, and Addressing

- 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

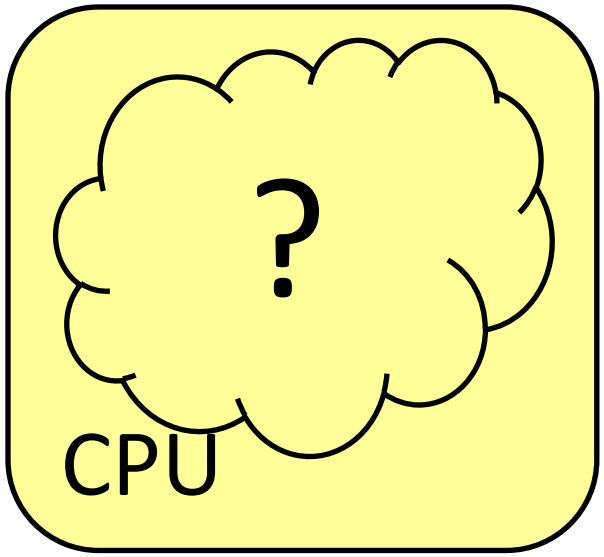
# Hardware: Physical View

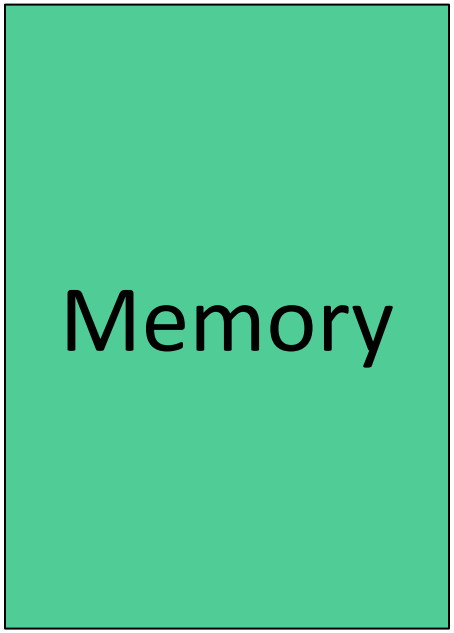


# Hardware: Logical View



# Hardware: 351 View (version 0)

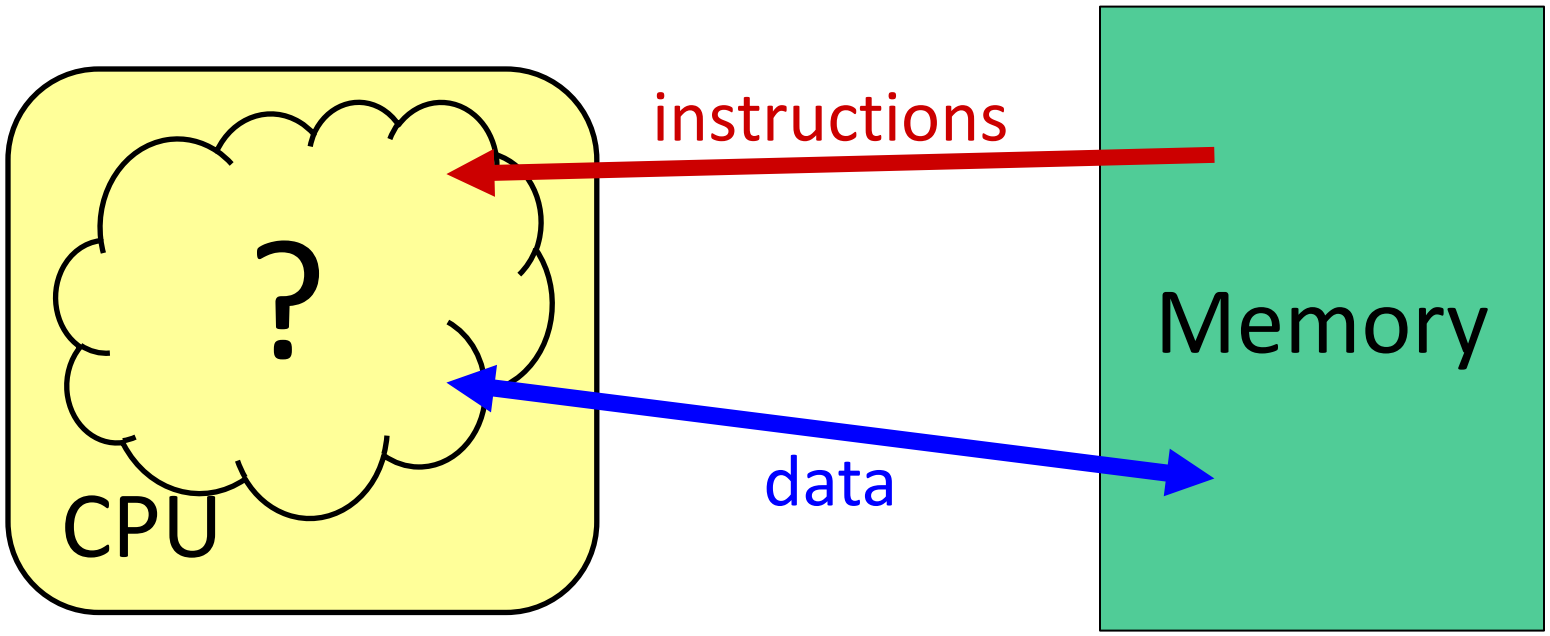



- The CPU executes instructions
- Memory stores data
- Binary encoding!
  - Instructions *are* just data

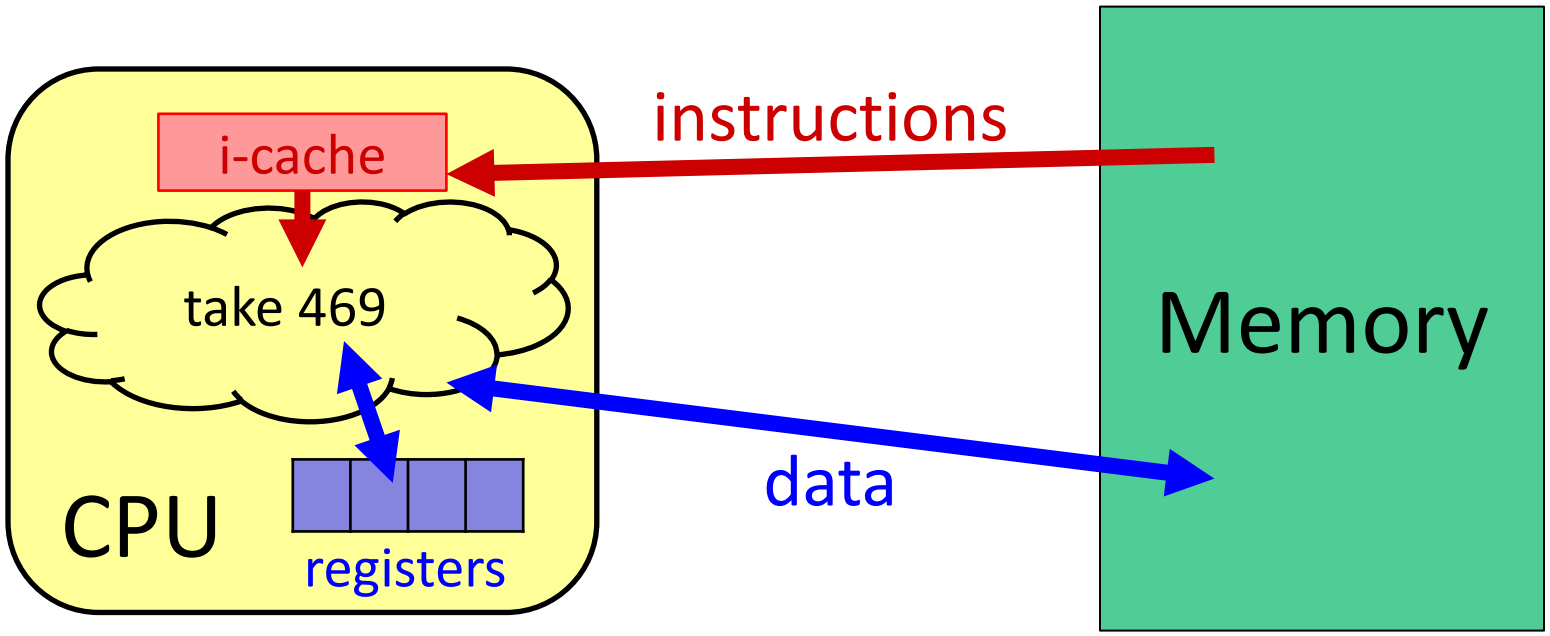
How are data and instructions represented?

# Hardware: 351 View (version 0)



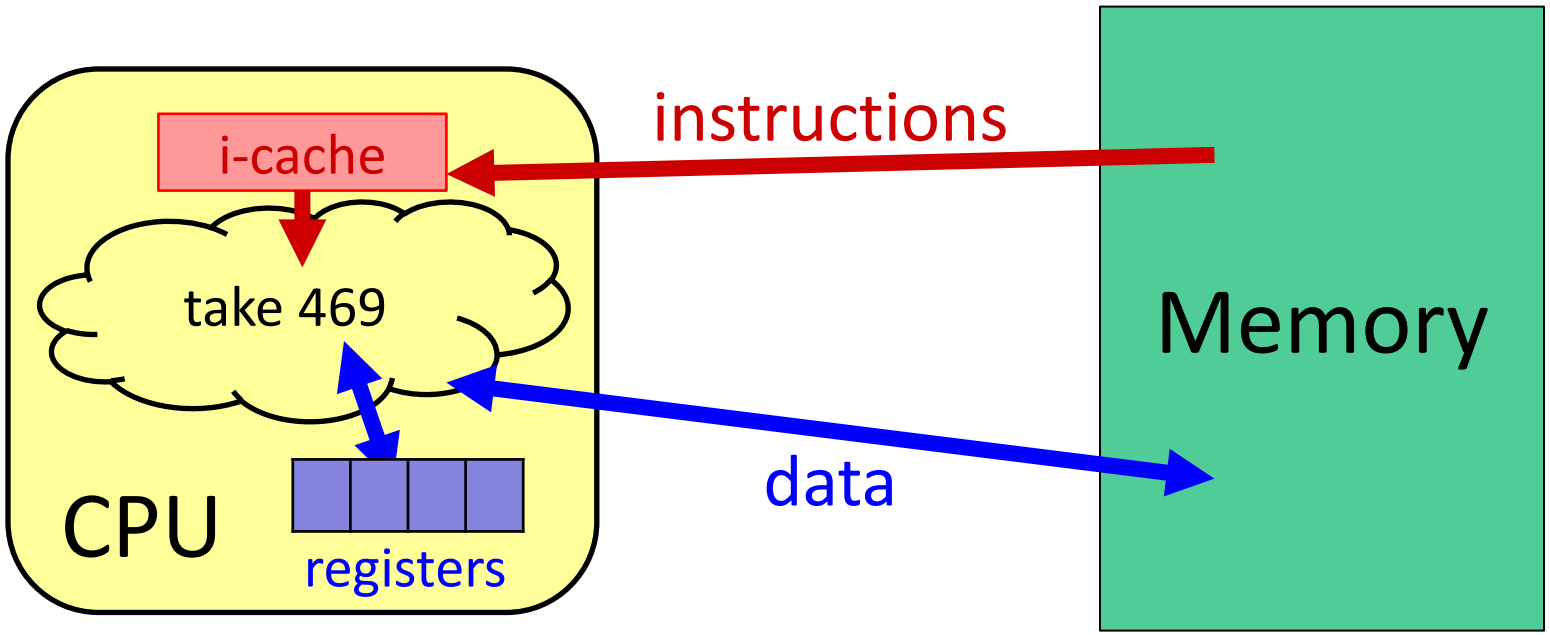

- To execute an instruction, the CPU must:
  1) Fetch the instruction
  2) (if applicable) Fetch data needed by the instruction
  3) Perform the specified computation
  4) (if applicable) Write the result back to memory

# 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 16 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 or its known size.

  **A. True** **B. False**

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

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

# 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)

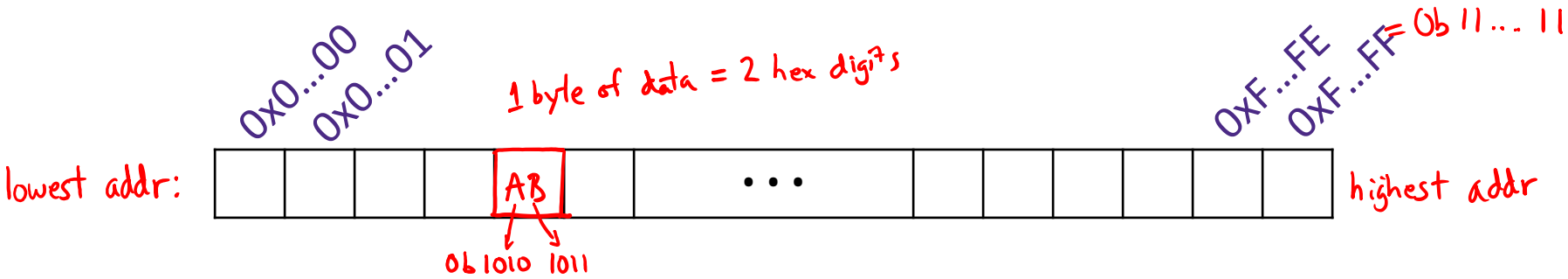
Least Significant Bit (LSB)

# Binary Encoding

- With N binary digits, how many "things" can you represent?
  - Need N binary digits to represent $n$ things, where $2^N \geq n$
  - Example: 5 binary digits for alphabet because $2^5 = 32 > 26$

- A binary digit is known as a bit
- A group of 4 bits (1 hex digit) is called a nibble
- A group of 8 bits (2 hex digits) is called a byte
  - 1 bit → 2 things, 1 nibble → 16 things, 1 byte → 256 things

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

# 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** |

address size = word size

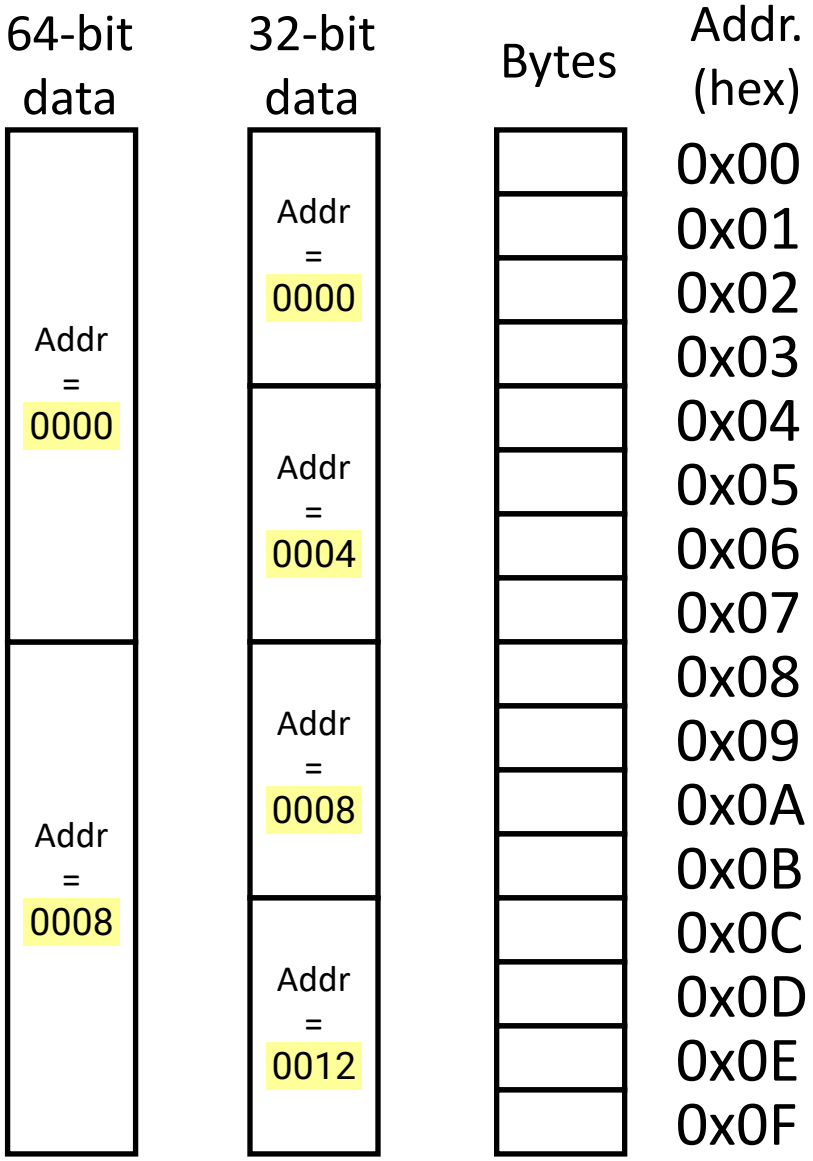
To use "`bool`" in C, you must `#include <stdbool.h>`

# Questions about Multibyte Data

- 1) What do we use as the address of this data object?
- 2) Are there any rules about where you can place multibyte data in memory?

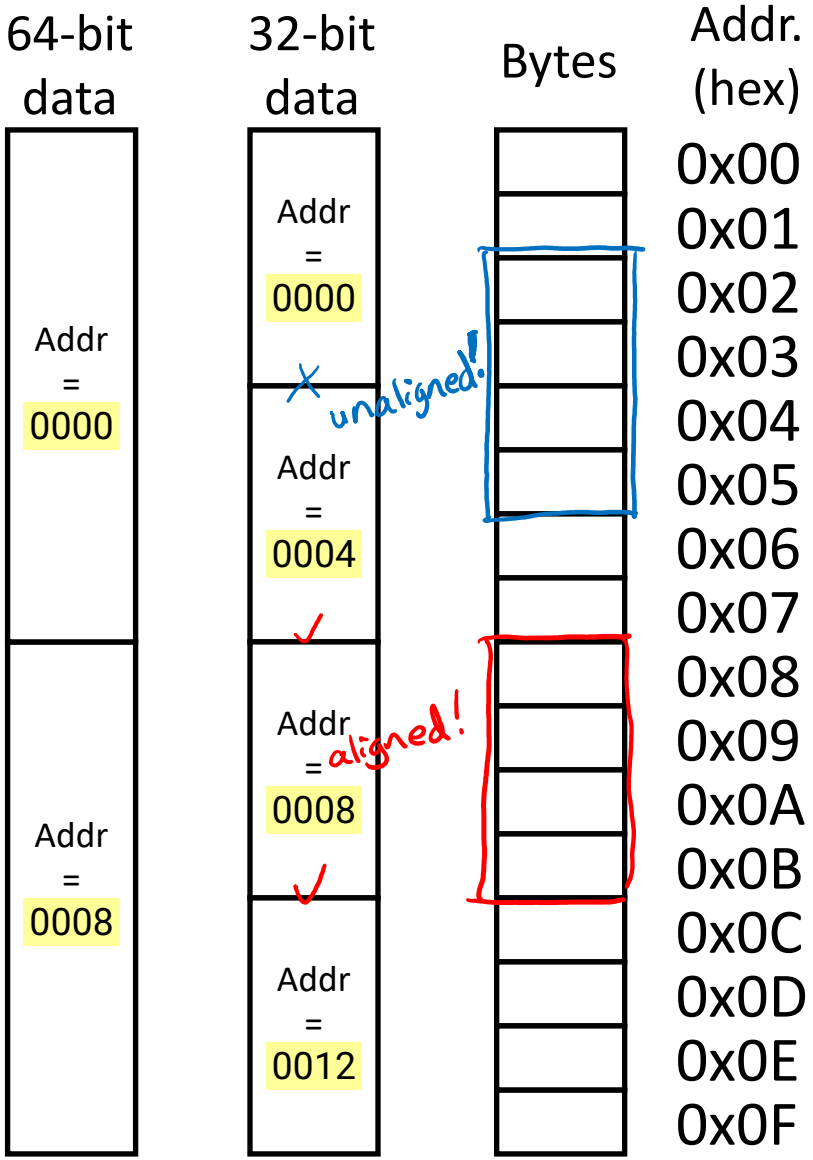
# Address of Multibyte Data

- 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**



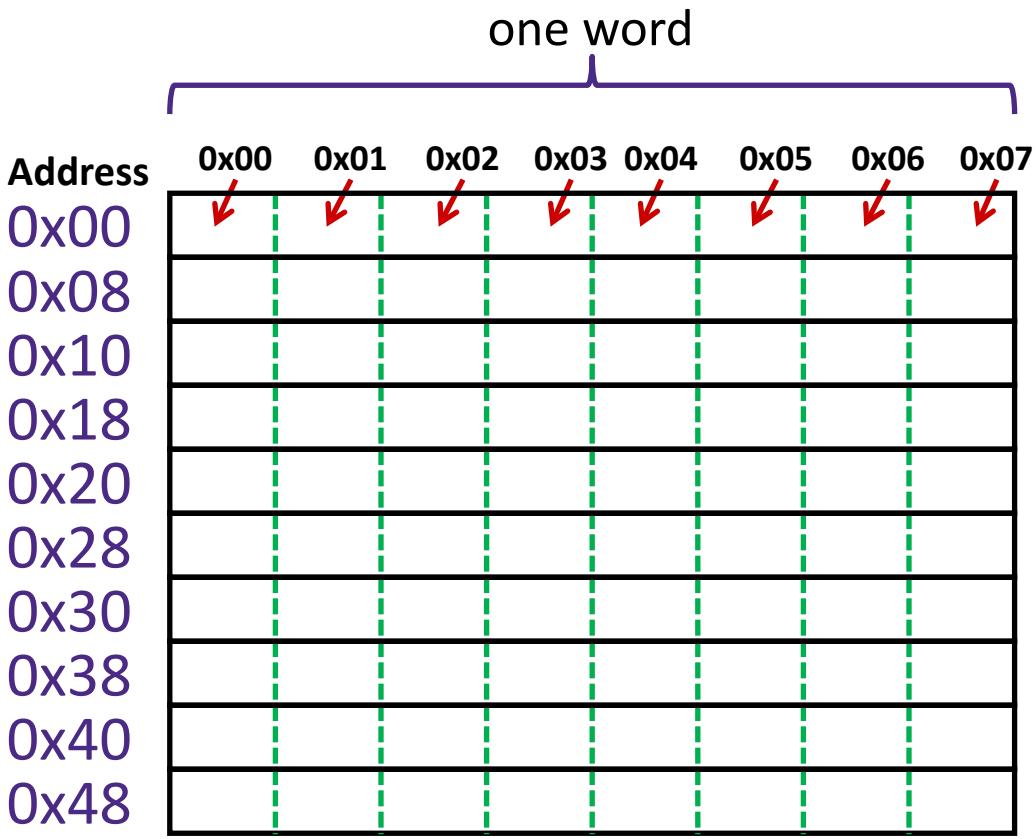
# Alignment of Multibyte Data

- 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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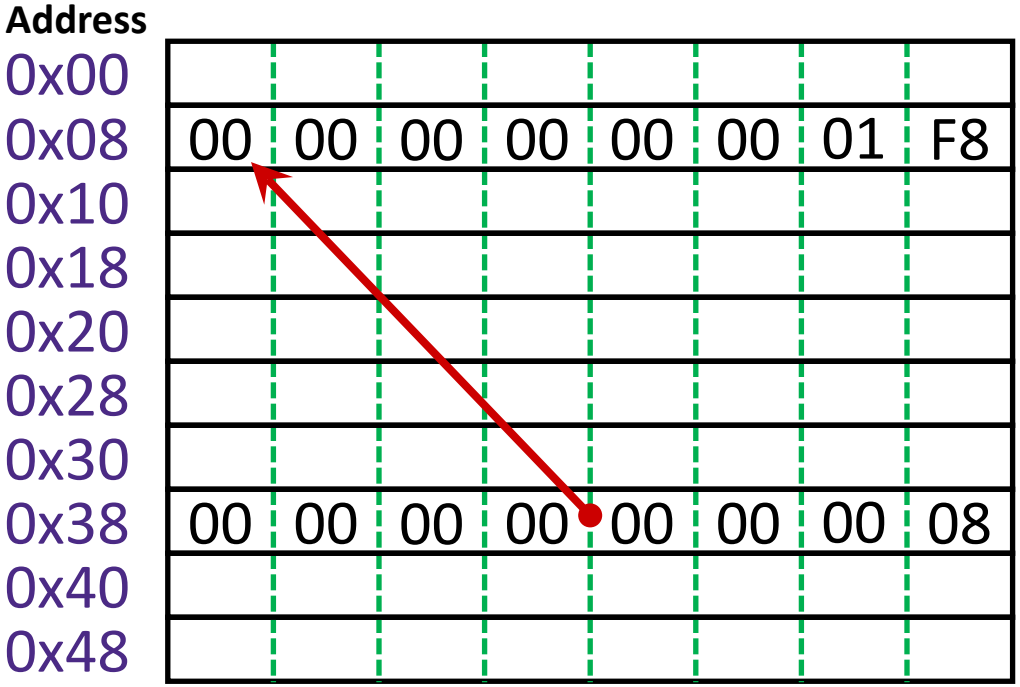
# Addresses and Pointers (step 1)

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* type of data
- Value 504 stored at address 0x08
  - $504_{10} = 1F8_{16}$
    = 0x 00 … 00 01 F8
- Pointer stored at 0x38 points to address 0x08

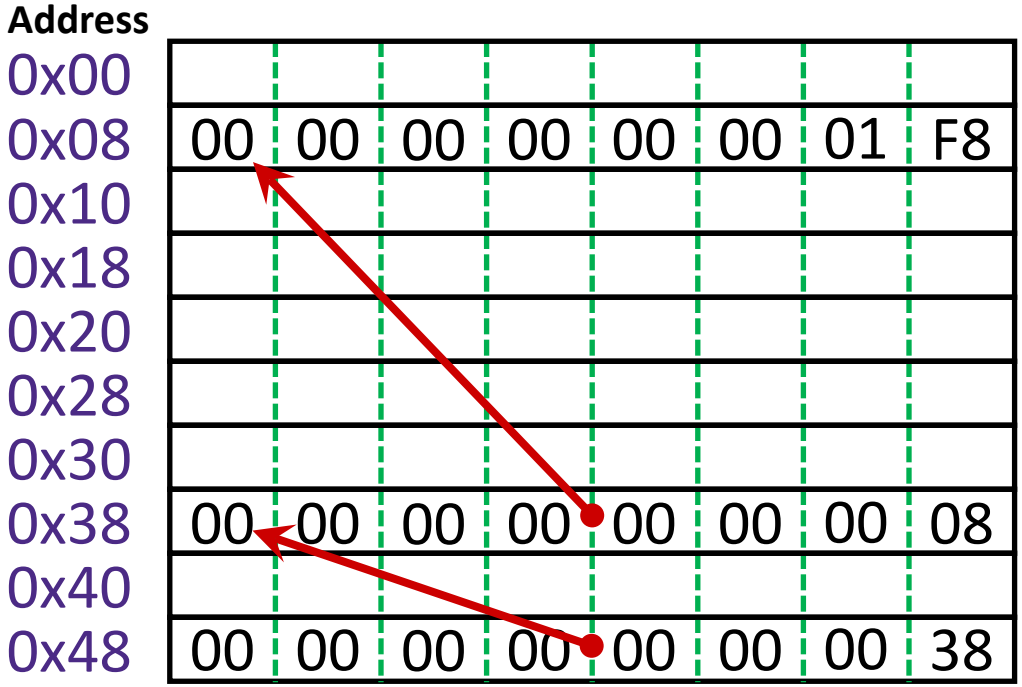


# Addresses and Pointers (step 2)

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* type of 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



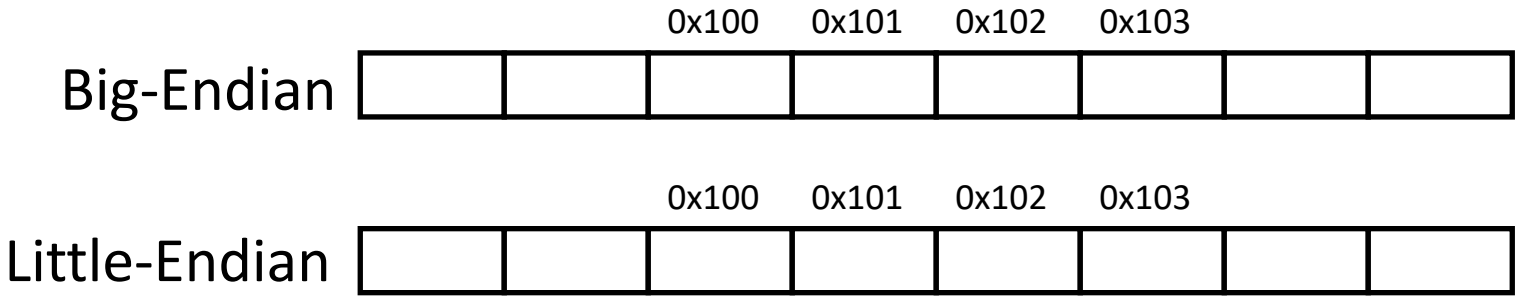
# Byte Ordering (Review)

- 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?
    - 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 (solution)

- Big-endian (SPARC, z/Architecture)
  - Least significant byte has highest address
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- Bi-endian (ARM, PowerPC)
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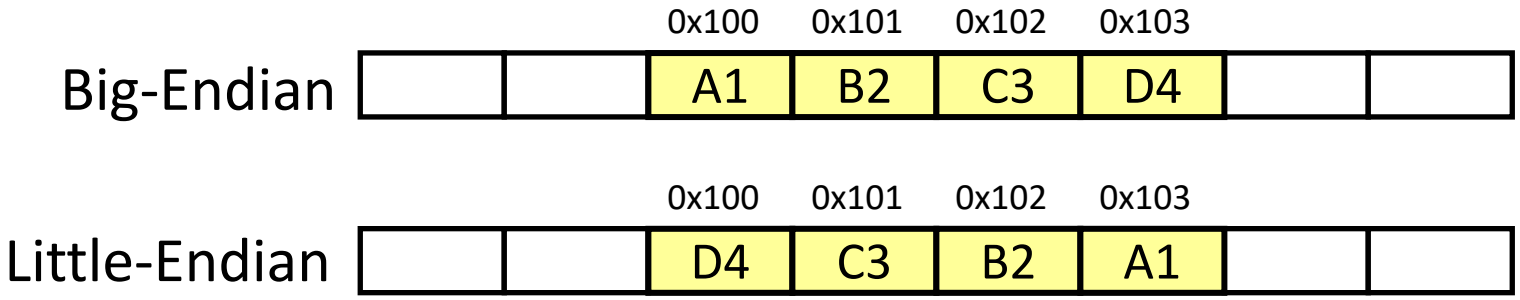

# Polling Question

- 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