# Lecture 01
# Introduction

CS213 – Intro to Computer Systems

Branden Ghena – Winter 2023

Slides adapted from:
St-Amour, Hardavellas, Bustamente (Northwestern), Bryant, O'Hallaron (CMU), Garcia, Weaver (UC Berkeley)

# Welcome to CS213!

- In brief: how *does* a computer work anyway?

- We will explore that question across four major sections:
  - **Representations** of information on a computer
  - How the **machine** executes software
  - How **memory** is organized
  - How the **operating system** manages this all for efficiency and security

# Branden Ghena (he/him)

- Assistant Faculty of Instruction
- Education
  - Undergrad: Michigan Tech
  - Master's: University of Michigan
  - PhD: University of California, Berkeley
- Research
  - Resource-constrained sensing systems
  - Low-energy wireless networks
  - Embedded operating systems
- Teaching
  - Computer Systems
    - CS211: Fundamentals of Programming II
    - CS213: Intro to Computer Systems
    - CS343: Operating Systems
    - CE346: Microprocessor System Design
    - CS397: Wireless Protocols for the IoT


Things I love


# Today’s Goals

- Introduce the theme and goals of the course
- Describe how this class is going to function
- Discuss how a computer system works at a high level
- Begin exploring how computers represent information with bits and bytes

# Outline

- **Course Themes**
- Logistics
- Running a program
- Representing numbers with binary

# Convenient computing

- Computers operate on integers, reals, structs, arrays, etc.
- Computers operate on variables and functions
- Computers execute conditionals, loops, etc.
- Memory is an infinite bag of objects my program can allocate
- Memory doesn’t have to be shared with any other program
- Memory is always equivalently fast to access
- Etc.

# Convenient **illusions** in computing

- Computers operate on integers, reals, structs, arrays, etc.
- Computers operate on variables and functions
- Computers execute conditionals, loops, etc.
- Memory is an infinite bag of objects my program can allocate
- Memory doesn’t have to be shared with any other program
- Memory is always equivalently fast to access
- Etc.

- None of these are actually true!
  - But we usually program as if they were, and we get away with it!
  - What’s going on?

# The power of abstraction

- These illusions are called ***abstractions***
- They approximate reality, but leave out details
  - Instead, they provide an *interface* that we can work and think with
- We can forget about those details, and be more productive

- Abstractions we love
  - Abstract data types
  - Asymptotic analysis
  - High-level programming languages
  - Operating systems
  - Etc.

# The Limits of Abstraction

- Sometimes, abstractions break down
  - Their implementation is buggy
  - Mismatch between expected interface and implementation
  - Their performance is inadequate
  - We need control over the details they hide
  - Security concerns make these details important

- At that point, details come rushing back
  - Can’t pretend they don’t exist anymore
  - We must know how to deal with them

- This class prepares you to be ready when that happens

# Complicated designs fail in unexpected ways

- Some software engineers at Microsoft came up with a cute way of storing dates
  - Two-digit year, month, date, hour, minute concatenated into a 10-digit number
  - Example: 2005230710 -> May 23, 2020 at 7:10 AM

- Stored as a 32-bit signed number
  - Maximum value: 2147483647

- Result: Starting January 1st, 2022, Microsoft Exchange email servers could no longer send email
  - 2201010001 is greater than the largest 32-bit number
  - Microsoft had to issue an emergency patch

# Expectation mismatches lead to real-world problems

- Ariane 5 explosion (1996)                                                  `double`                 `short`
  - Inertial reference system converted a 64-bit float to a 16-bit integer
  - Expectation: converting from decimal to whole numbers is safe
  - Had worked in the past in Ariane 4, but Ariane 5 was faster
  - Speed too large to fit in a 16-bit integer -> software fault
  - Reality: rocket explodes

# Hardware realities impact software performance

- Abstracted lower-level details can affect performance a lot!
- Question: does the order of iterating through an array matter?
  - Each column in a row OR each row in a column?
- Answer: right code is 10-32 times slower on Intel systems
  - Due to caches

```c
void copyij(int src[4096][4096],
            int dst[4096][4096])
{
  for (int i=0; i<4096; i++){
    for (int j=0; j<4096; j++){
      dst[i][j] = src[i][j];
    }
  }
}
```

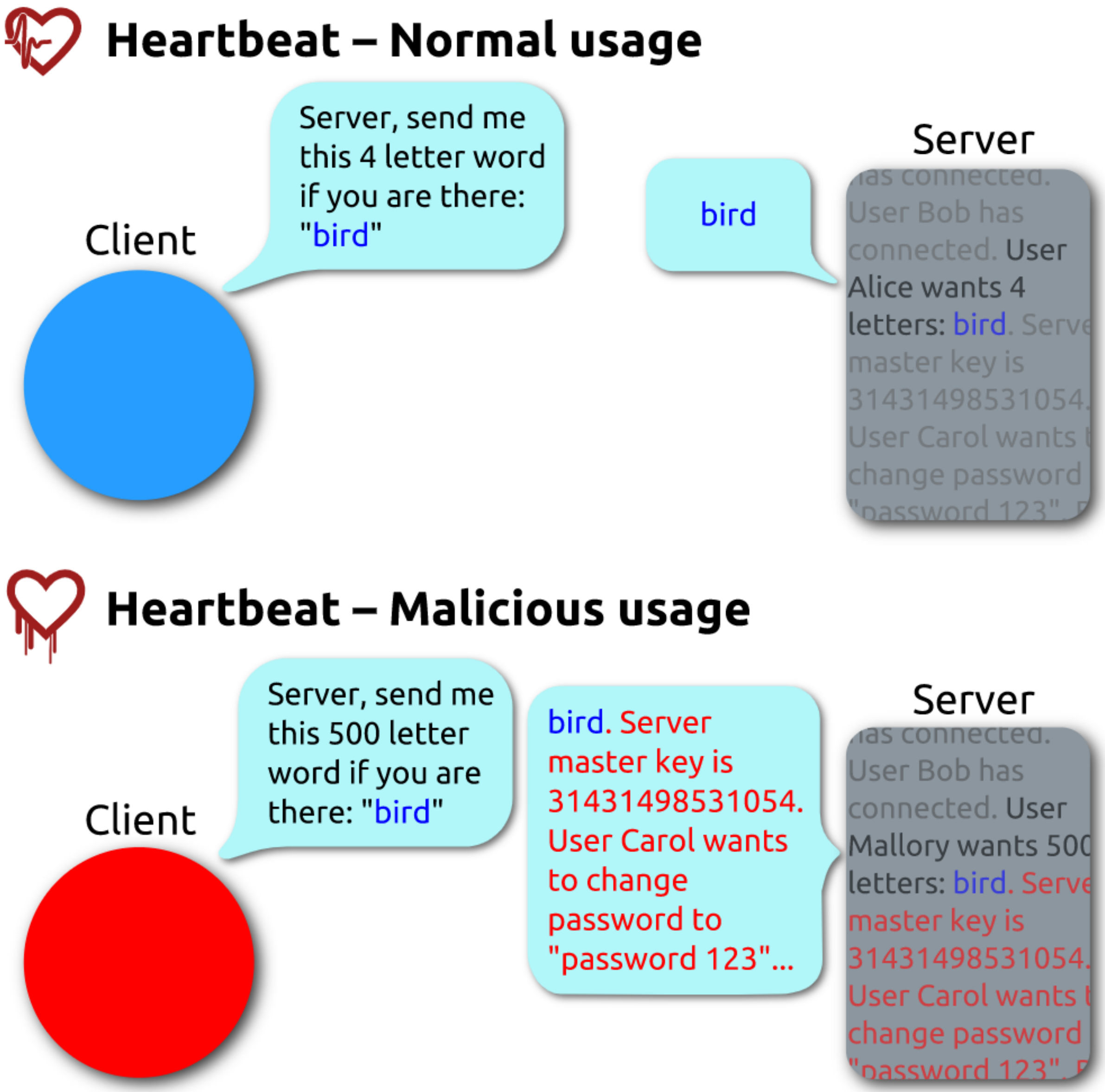
```c
void copyji(int src[4096][4096],
            int dst[4096][4096])
{
  for (int j=0; j<4096; j++){
    for (int i=0; i<4096; i++){
      dst[i][j] = src[i][j];
    }
  }
}
```

# Simple bugs can result in massive vulnerabilities

- 2014 vulnerability in OpenSSL

- Clients can check if server is active by sending a message and listening for echoed response

- C library forgot to check bounds of array and could be abused to return important memory



# CS213 goals

1. Break through abstractions to understand how computer processors and memories affect software design and performance

2. Introduce concepts of “computer systems” areas:
   - Architecture, Compilers, Security, Embedded, Operating Systems, etc.

# Course design goal

- Most systems courses are builder-centric
  - **Computer Architecture**: design a pipelined processor in Verilog
  - **Operating Systems**: implement portions of an operating system
  - **Compilers**: write a compiler for a simple language
  - **Networking**: implement and simulate network protocols
  - Fun, for sure
    - But ultimately, many more of you will ***build on*** systems
    - Rather than ***build systems*** directly

- This course is programmer-centric
  - Purpose is to show that by knowing more about the underlying system, one can be more effective as a programmer
  - Not just a course for dedicated hackers
    - **We want to bring out the hacker in everyone!**

# Outline

- Course Themes
- **Logistics**
- Running a program
- Representing numbers with binary

# Course Staff

- TA (1)
  - Mohammad Kavousi
    - PhD student in Computer Science

- PMs (13):
  - Francis Brenner
  - Adam Chen
  - Elena Fabian
  - Dimitri Hatzisavas
  - Dilan Nair
  - Sean Rhee
  - Evan Waite
  - Kellen Bryant
  - Huaxuan Chen
  - Joseph Grantham
  - Alex Kang
  - Danny Pineda
  - Santi Roches

Their role: support student questions via office hours and piazza

# Course details - how to learn stuff

- Lectures: here in class, Mondays and Wednesdays
  - Please attend and ask questions!
  - Panopto tab on Canvas should have best-effort recordings (a few hours later)

- Textbook:
  - Computer Systems: A Programmer’s Perspective **3rd Edition**
  - A *very* useful reference

- Office hours: (starting next week)
  - Planning a mix of in-person and online (gather.town)
  - More info will be posted to Piazza when schedule is ready
    - Can reach out on Piazza to schedule a meeting too

# Asking questions

- Class and office hours are always an option!
  - We can do extra questions right after class too
- Piazza: (similar to Campuswire)
  - Post questions
  - Answer each other’s questions
  - Find lab partners
  - Find posts from the course staff
  - Post private info just to course staff
- Please do not email me! Post to Piazza instead!
  - I’ll be updating roster again a few times

# Programming Labs

- Four labs
  1. Pack Lab (new) – manipulate bits and bytes of a file
  2. Bomb Lab – deconstruct software to understand it
  3. Attack Lab – exploit security vulnerabilities in software
  4. SETI Lab – make software faster with concurrency

- Work on these preferably as a group of two
  - Work together and don’t split up assignments (otherwise you won’t learn)
  - Individual is acceptable but less good
  - We’ll do a pairing survey if you don’t already have a partner in mind

- Very different from CS211 style projects
  - Emphasis on the thinking rather than the programming

# Homeworks

- Worksheet-style practice problems to help you actually understand what's going on and practice for exams

- Four homeworks that cover class topics
  1. Bits and Bytes (releases on Wednesday)
  2. Floating Point
  3. Assembly
  4. Caches

# Midterm Exams

- First midterm exam will be during class time
  - Should be back in person well before then

- Second midterm exam will be during exam week
  - **Important:** Wednesday of exam week is our scheduled slot

- Not cumulative, second midterm is second half of class
  - But material in this class builds on itself…

# Grades

- Grade breakdown
  - 50% Programming Labs (4 labs at 12.5% each)
  - 20% Homeworks (4 homeworks at 5% each)
  - 15% Midterm Exam 1
  - 15% Midterm Exam 2

- Exact number to letter mapping is a little flexible
  - But this course is NOT curved

# Late Policy

- You can submit homeworks and labs late

- 20% penalty to maximum grade per day late
  - Example: three days late means maximum grade is 40%

- There are exceptions to this:

1. We will be flexible with deadlines for problems outside of your control
   - Sick, family emergency, broken computer
   - Contact me (via Piazza)

# Slip Days

2. Slip days let you turn in a homework late and receive no penalty

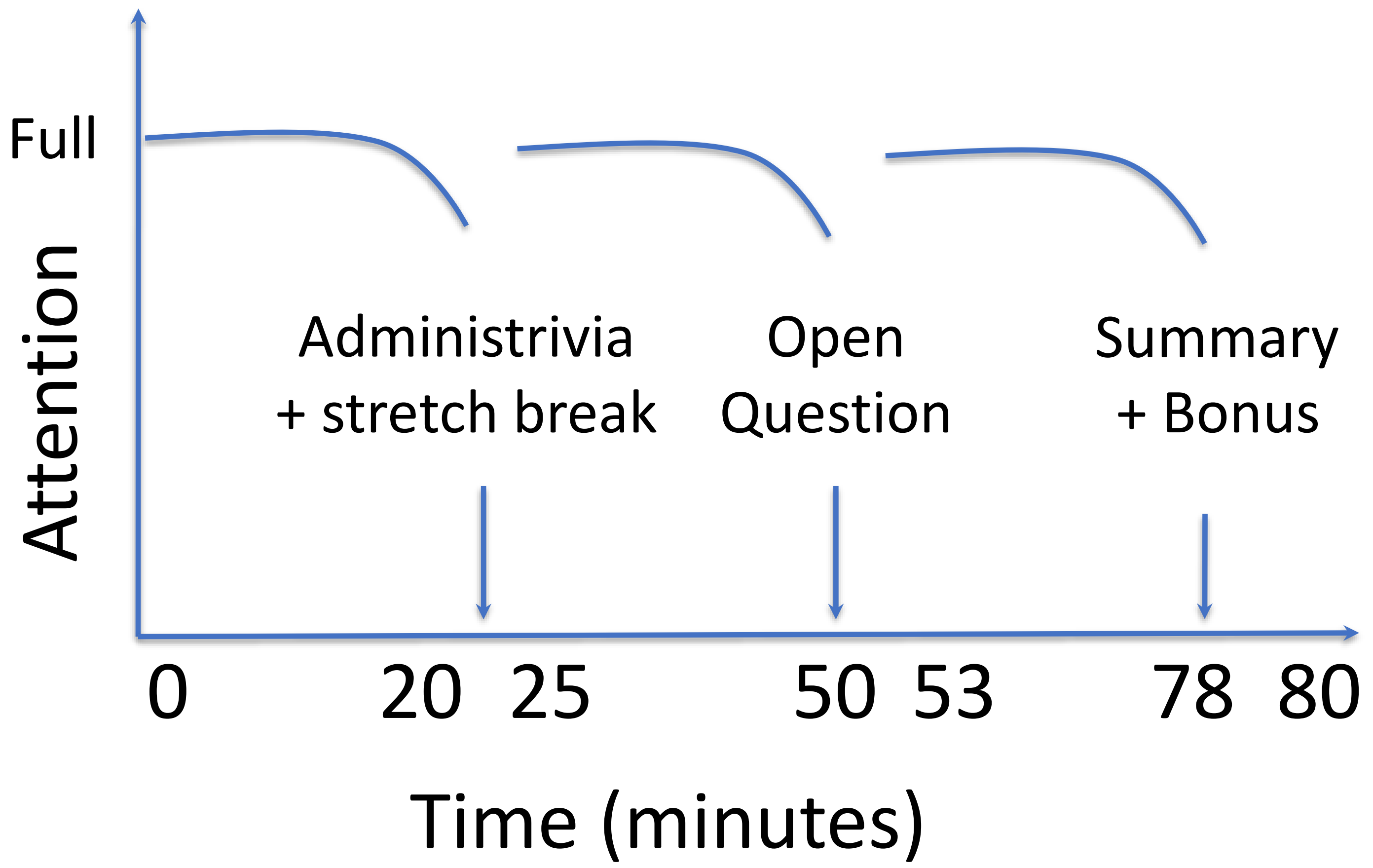
- Each student gets **3 slip days**
  - Apply to **homeworks and labs**
  - You don’t need to tell us you’re using them, we’ll just automatically apply them at the end of the year
  - Be sure to coordinate about them on partner assignments

- Examples:
  - Turn in homework 1 three days late
  - Turn in homework 4 two days late and SETI lab one day late
  - Turn in homework 2 four days late with only a one-day penalty

# Academic Integrity

- This is something I take very seriously
- Collaboration good; plagiarism bad
  - You should know where that line is, and be nowhere near it
  - When in doubt, ask the instructor *before* you do something you're not sure about
- At no point should you see someone else's solutions
  - Not your colleagues', not your friends', not your cousin's, not something you found online
- I report everything suspicious to the dean

# Break + Architecture of a lecture



# Expectations

- This class is **hard**
  - And it’s hard in a different way. Lots of new material that builds on itself
  - You have an opportunity to learn a lot from it
- I’m confident that you can all succeed
  - Labs, Homeworks, Lecture, Office Hours are all designed to support you
- You’ll gain a much deeper understanding of how computers operate
  - Maybe it’s not for you, maybe you’ll love it

# How to succeed in this class

- Come to lecture
- Ask questions
- Consult the textbook for clarity and practice
- Start assignments early
- Stay on top of the material

# Outline

- Course Themes
- Logistics
- **Running a program**
- Representing numbers with binary

# Hello World

- What happens when you run “hello” on your system?
  - And *why* does it happen?

```
/*
 * hello world
 */
#include <stdio.h>

int main()
{
   printf(“hello, world\n”);
}
```

- **Goal**: introduce key concepts, terminology, and components

# Compiling **`hello`**

- Compiling **`hello`**

```
unix> gcc -o hello hello.c
```

- GCC is our compiler

1. It takes our source code (**`hello.c`**)
   - A text file containing characters
   - Text file = readable by humans
2. And translates (compiles) it into **assembly code**
   - A text representation of x86 instructions
   - Here, not explicitly stored in a file
   - We'll be working with assembly a lot this quarter
3. Then translates (assembles) that into an executable (**`hello`**)
   - A binary file containing x86 machine code
   - Binary file = not meant to be read by humans (but sometimes we have to)

# Running **hello**

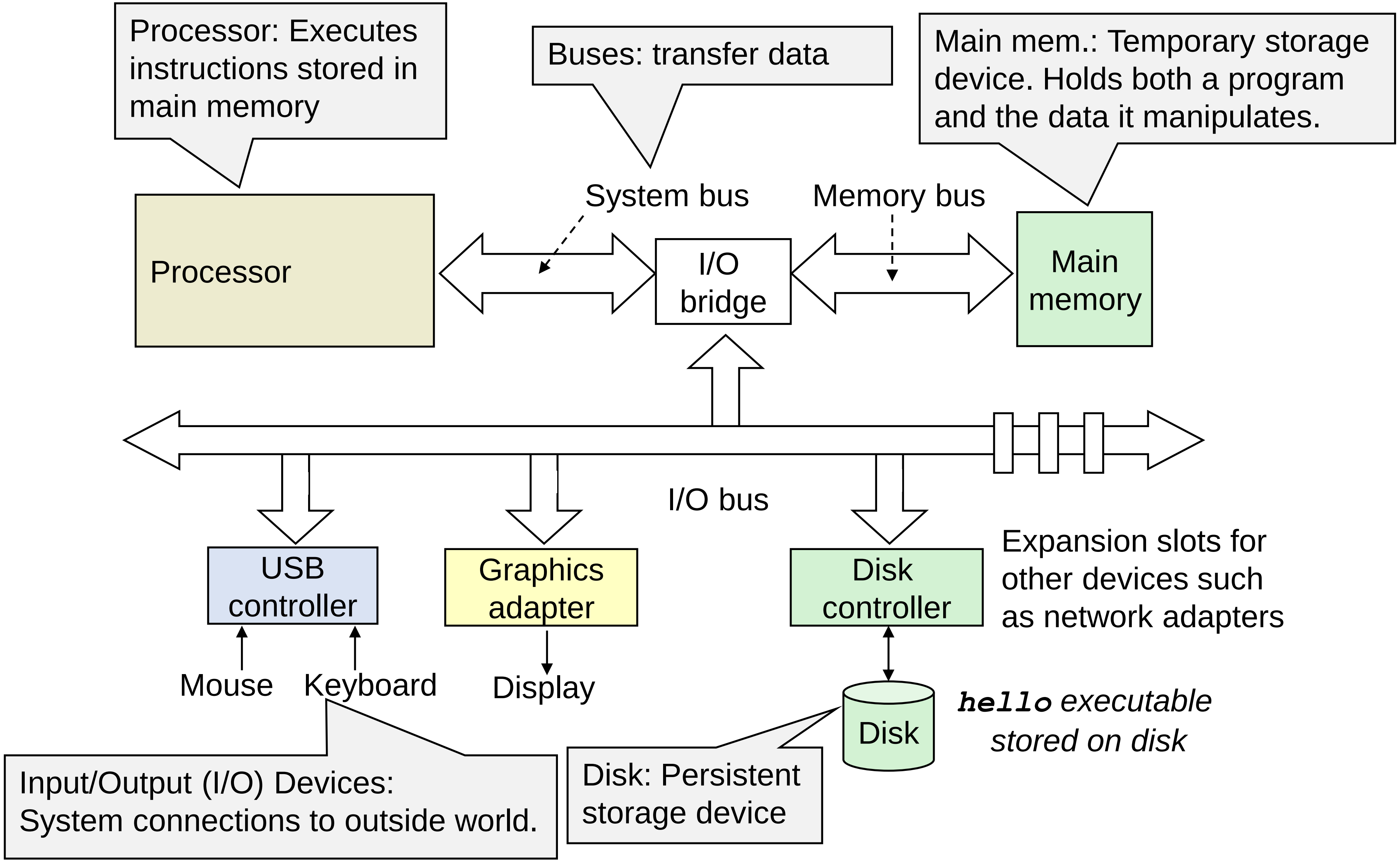
- Running **hello**

```
unix> ./hello
hello, world
unix>
```

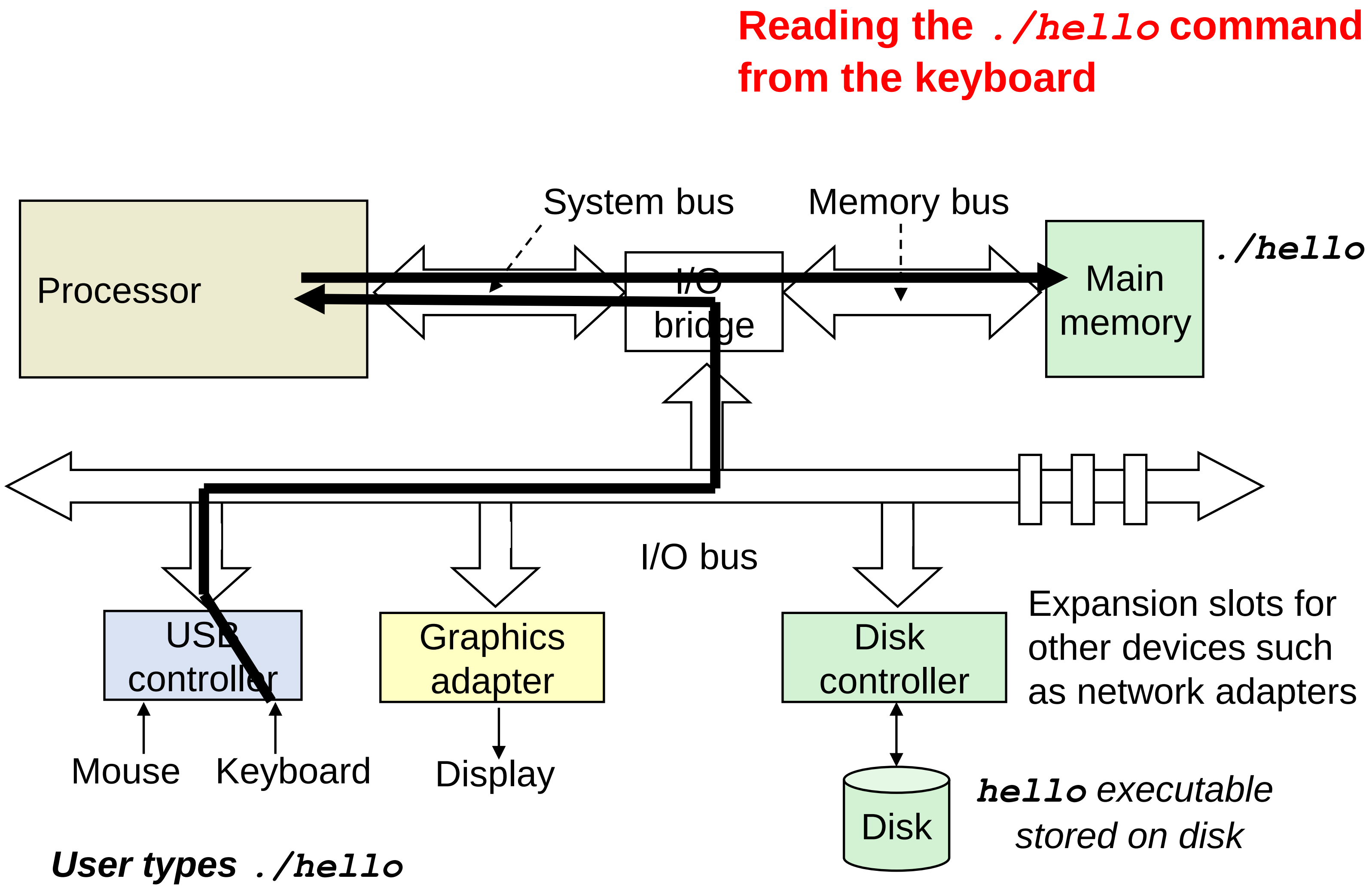
- What does the shell do?
  - Prints a prompt
  - Waits for you to type a command
  - Interpret the command
  - Then loads and runs the **hello** program

- What happens at the hardware level?

# Hardware organization

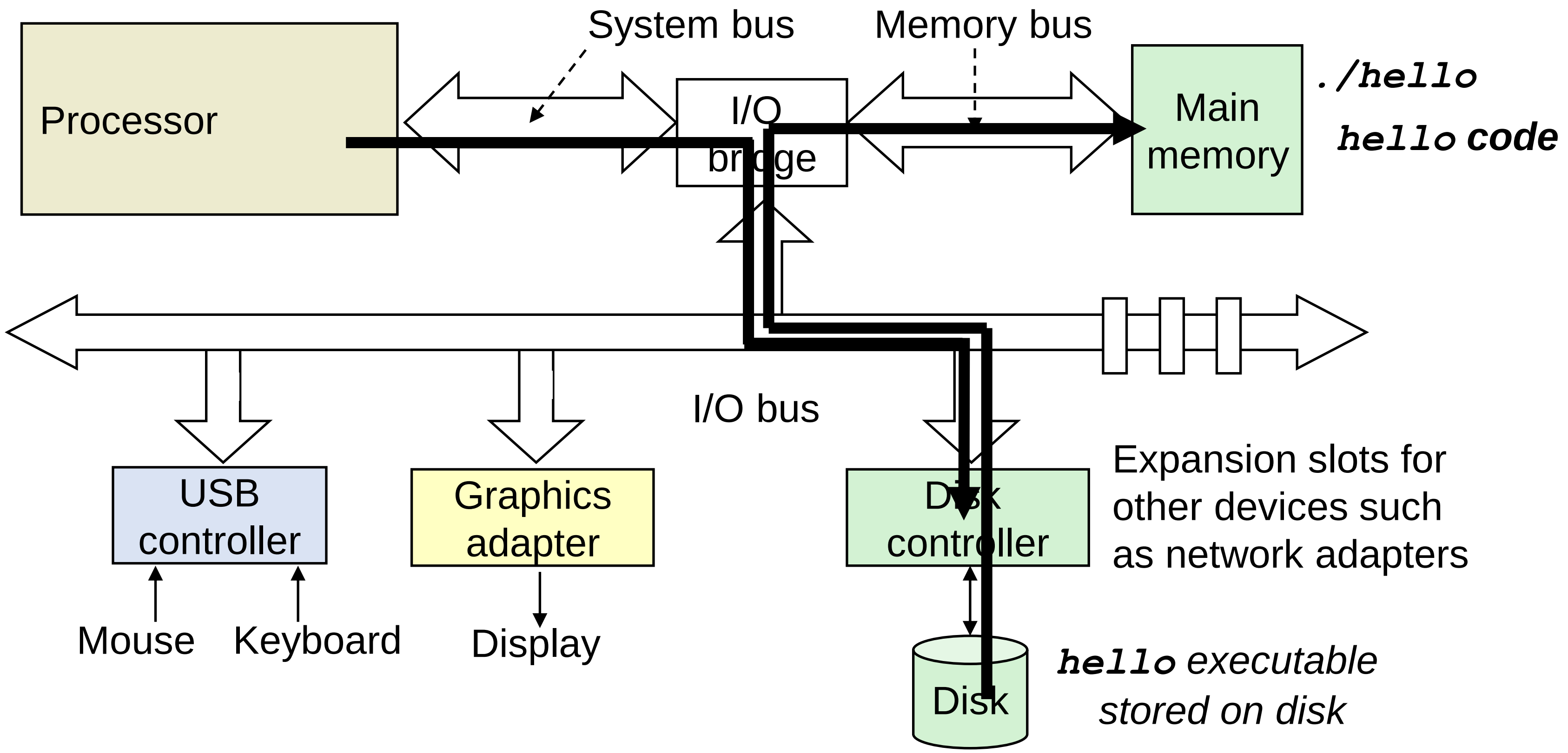


# Running `hello`



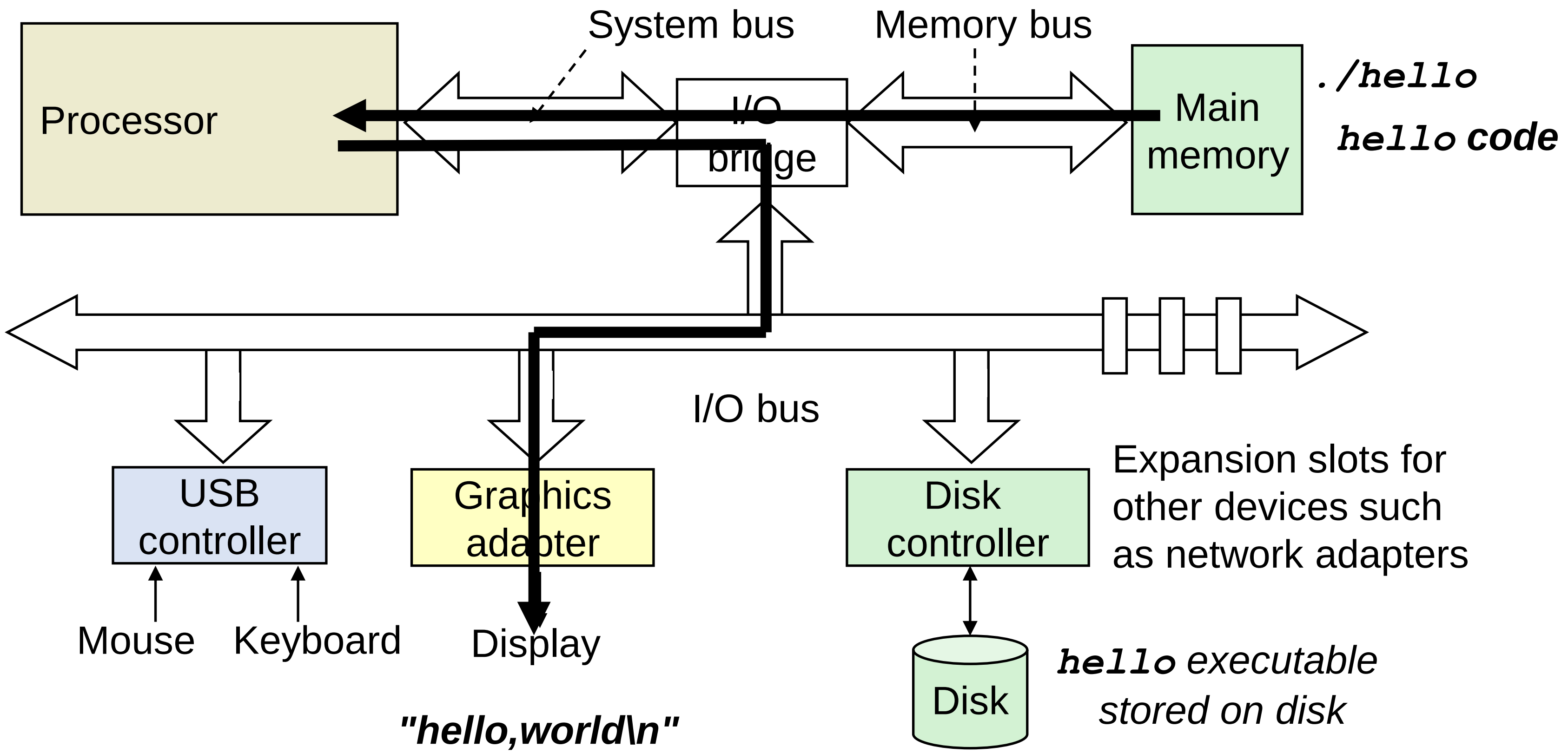
# Running **`hello`**

**Shell program loads the `hello` executable into main memory**



# Running `hello`

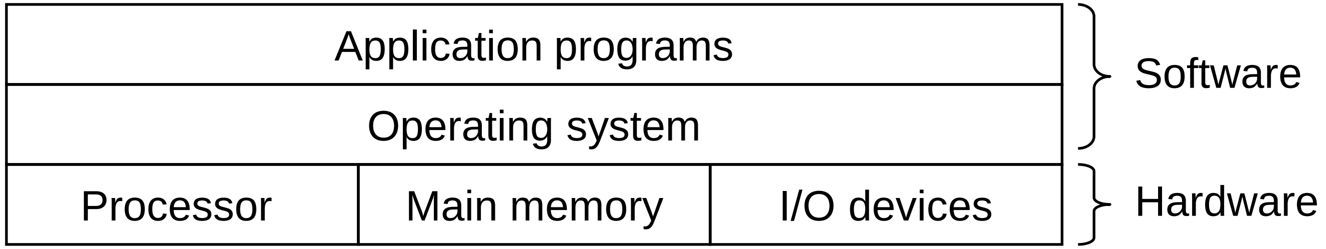
**The processor reads the `hello` code, executes instructions, and displays "hello…"**



# The Operating System (OS)

- Neither **`hello`** nor our shell interfaced with the hardware directly
  - All interactions were mediated by the ***operating system***

- ***Operating system:*** a layer of software interposed between the application program and the hardware




- Primary goals
  - Protect resources from misuse by applications
  - Provide simple and uniform mechanisms for manipulating hardware devices
  - Manage sharing of resources between applications

# A computer system is more than just HW

- A collection of intertwined hardware and software that must cooperate to achieve the end goal – running applications
  - **Hardware**: expensive, fast, immutable
  - **Software**: cheap (comparatively), slow, flexible
  - Different tradeoffs
    - So we'll use them for different roles!

- The rest of the course will expand on this

# Open Question + Break

- **What part of the `hello` example takes the longest to run on a computer?**

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- **What part of the `hello` example takes the longest to run on a computer?**

  - The user typing (seconds)
    - Maybe that’s cheating and we should start after they hit enter

# Open Question + Break

- **What part of the `hello` example takes the longest to run on a computer?**

  - The user typing (seconds)
    - Maybe that's cheating and we should start after they hit enter

  - Almost certainly loading the program from disk (milliseconds)
    - Possibly sending text to graphics (microseconds – milliseconds)
    - Definitely not executing the code (nanoseconds – microseconds)

# Outline

- Course Themes
- Logistics
- Running a program
- **Representing numbers with binary**

# Learning binary

- To understand how a computer really works we need to understand that data it operates on

- Computers hold data in memory as individual ones and zeros
  - These ones and zeros make up binary values

- So, we’re going to need to understand binary
  - Binary will ***definitely*** come up again in this and other classes

# Positional Numbering Systems

- The position of a *numeral* (e.g., digit) determines its contribution to the overall number
  - Makes arithmetic simple (compared to, say, roman numerals)
  - Any number has one canonical representation

- Example: base 10
  - $10456_{10} = 1*10^4 \quad + \quad 0*10^3 \quad + \quad 4*10^2 \quad + \quad 5*10^1 \quad + \quad 6*10^0$
  - Usually, we leave out the zeros:
    - $1*10^4 \quad + \quad 4*10^2 \quad + \quad 5*10^1 \quad + \quad 6*10^0$

# Other bases are also possible

- Base 60, used by the Babylonians
  - The source of 60 seconds in a minute, 60 minutes in an hour
  - And 360 degrees in a circle

- Base 20, used by the Maya and Gauls
  - Parts of this remain in French today

- Base 2, used by computers
  - Example: $10010010_2$
  - Same idea as before: $1*2^7 + 1*2^4 + 1*2^1 = 128_{10} + 16_{10} + 2_{10} = 146_{10}$

# Base 2 Example

- Computer Scientists use base 2 a ***LOT*** (especially in computer systems)
- Let's convert $138_{10}$ to base 2
- We need to decompose $138_{10}$ into a sum of powers of 2
  - Start with the largest power of 2 that is smaller or equal to $138_{10}$
  - Subtract it, then repeat the process

$$138_{10} - \boxed{128_{10}} = 10_{10}$$
$$10_{10} - \boxed{8_{10}} = 2_{10}$$
$$2_{10} - \boxed{2_{10}} = 0_{10}$$

$$138_{10} = \underline{\mathbf{1}}\times128 + 0\times64 + 0\times32 + 0\times16 + \underline{\mathbf{1}}\times8 + 0\times4 + \underline{\mathbf{1}}\times2 + 0\times1$$

$$138_{10} = \underline{\mathbf{1}}\times2^7 + 0\times2^6 + 0\times2^5 + 0\times2^4 + \underline{\mathbf{1}}\times2^3 + 0\times2^2 + \underline{\mathbf{1}}\times2^1 + 0\times2^0$$

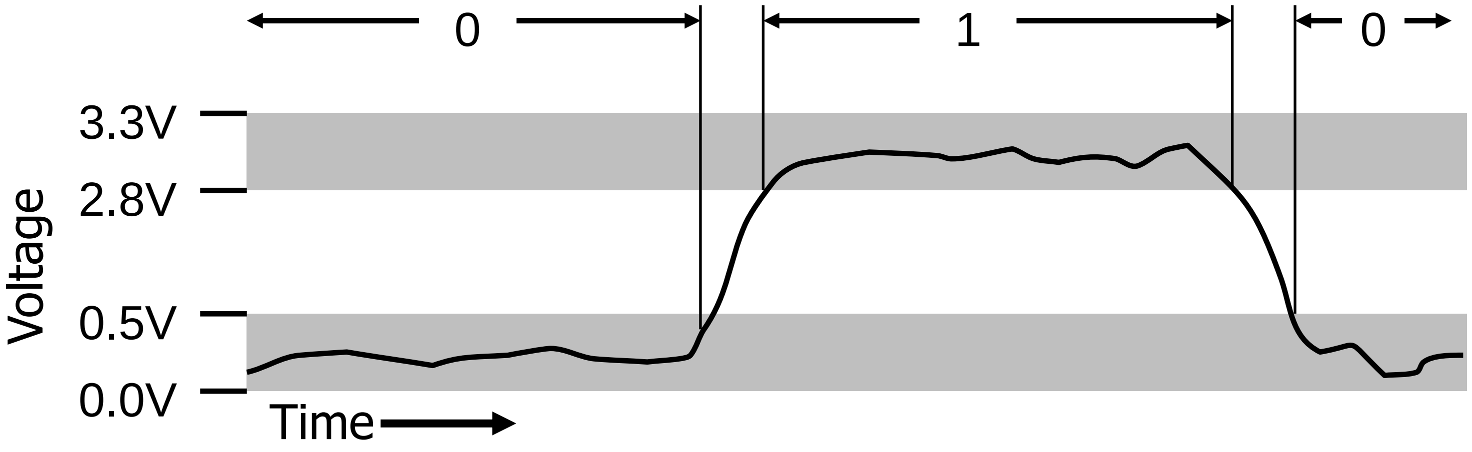
$$138_{10} = 10001010_2$$

# Binary practice

- Convert $101_2$ to decimal
  - $= 1\times2^2 + 0\times2^1 + 1\times2^0$
  - $= \quad 4 \; + \quad 0 \quad + \quad 1$
  - $= \quad 5_{10}$
- Convert $4_{10}$ to binary: $100_2$ (one less than 5)
- Convert $6_{10}$ to binary: $110_2$ (one more than 5)

# Why computers use Base 2

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

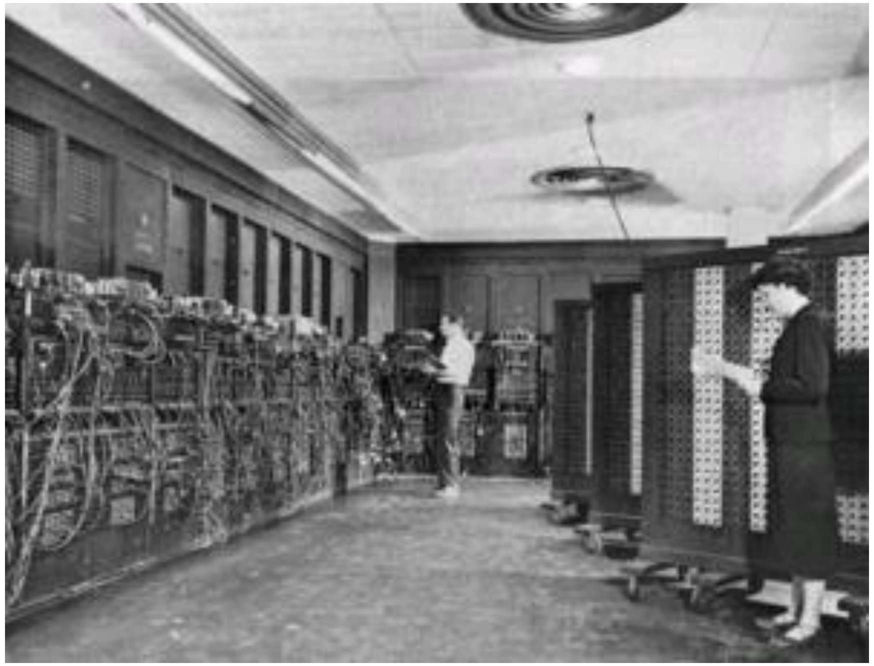



- Straightforward implementation of arithmetic functions

- (Pretty much) all computers use base 2

# Why don't computers use Base 10?

- Because implementing it electronically is a pain
  - Hard to store
    - ENIAC (first general-purpose electronic computer) used 10 vacuum tubes / digit
  - Hard to transmit
    - Need high precision to encode 10 signal levels on single wire
  - Messy to implement digital logic functions
    - Addition, multiplication, etc.
    - (See CE203 for details)



# Base 16: Hexadecimal

- Writing long sequences of 0s and 1s is tedious and error-prone
  - And takes up a lot of space on a page!
- So we'll often use base 16 (also called *hexadecimal*)
- 
- Base 2 = 2 symbols (0, 1)
  Base 10 = 10 symbols (0-9)
  Base 16, need 16 symbols
  - Use letters A-F once we run out of decimal digits

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

# Base 16: Hexadecimal

- $16 = 2^4$, so every group of 4 bits becomes a hexadecimal digit (or *hexit*)
  - If we have a number of bits not divisible by 4, add 0s on the left (always ok, just like base 10)

0 0 1 0 ¦ 1 0 0 1 ¦ 0 1 1 1 ¦ 1 0 1 1 ⟶ 0x297B

"0x" prefix = it's in hex

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

# Bytes

- A single bit doesn't hold much information
  - Only two possible values: 0 and 1
  - So we'll typically work with larger groups of bits

- For convenience, we'll refer to groups of 8 bits as ***bytes***
  - And usually work with multiples of 8 bits at a time
  - Conveniently, 8 bits = 2 hexits

- Some examples
  - 1 byte: 0b01100111 = 0x67
  - 2 bytes: $11000100\ 00101111_2$ = 0xC42F

"0b" prefix = it's in binary

# Practice problem

- **Convert 0x42 to decimal**

- Steps
  - Convert 0x42 to binary:
  - Convert binary to decimal:

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

# Practice problem

- **Convert 0x42 to decimal**

- Steps
  - Convert 0x42 to binary:
    - 0x4 -> 0b0100     0x2 -> 0b0010     0x42 -> 0b 0100 0010
  - Convert binary to decimal:

# Practice problem

- **Convert 0x42 to decimal**

- Steps
  - Convert 0x42 to binary:
    - 0x4 -> 0b0100     0x2 -> 0b0010     0x42 -> 0b 0100 0010
  - Convert binary to decimal:
    - $1*2^6 + 1*2^1 = 64 + 2 = 66$

# Practice problem

- **Convert 0x42 to decimal**

- Alternate method:
  - 0x42
  - $= 4 \times 16^1 + 2 \times 16^0$
  - = 64 + 2
  - = 66

- But you’re honestly better off converting hex to binary for now
  - It’s good practice!

# **Big idea:** bits can be used to represent anything

- Depending on the context, the bits **`11000011`** could mean
  - The number 195
  - The number -61
  - The number -1.1875
  - The value `True`
  - The character '├'
  - The **`ret`** x86 instruction

- You have to know the **context** to make sense of any bits you have!
  - People and software they write determine what the bits actually mean

# Outline

- Course Themes
- Logistics
- Running a program
- Representing numbers with binary

# Outline

- Backup: Boolean Algebra

# Boolean Algebra

- You've programmed with `and` and `or` in earlier classes
  - Written `&&` and `||` in C and C++

- **Boolean algebra is a generalization of that**
  - A mathematical system to represent (propositional) logic
  - 2 truth values: true = **1**, false = **0**
  - 3 operations: and = **&**, or = **|**, not (or complement) = **~**

- **Follow the rules for each operation to compute results**
  - Rules are the like those you know from programming

(1 | 0) & 0 → 1 & 0 → 0

(1 & 1) & ~(0 | 0) → 1 & ~(0) → 1 & 1 → 1

# Truth Tables for Boolean Algebra

- For each possible value of each input, what is the output
  - Axes are the inputs
  - Inside of the table are the outputs

not: ~A

| ~ | |
|---|---|
| 0 | 1 |
| 1 | 0 |

and: A & B

| & | 0 | 1 |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 1 |

or: A | B

| \| | 0 | 1 |
|---|---|---|
| 0 | 0 | 1 |
| 1 | 1 | 1 |

# De Morgan’s Laws, Exclusive Or

- Can express boolean operators in terms of the others

- De Morgan’s laws: & using | and ~, | using & and ~
  - A & B = ~(~A | ~B)
    - A and B are true if and only if neither A nor B is false
  - A | B = ~(~A & ~B)
    - A or B are true if and only if A and B are not both false

- Can define new operators in terms of existing ones:
  - Exclusive or (xor, ^) in terms of inclusive or (|)
    - A ^ B = (~A & B) | (A & ~B)
      - Exactly one of A and B is true
    - A ^ B = (A | B) & ~(A & B)
      - Either A is true, or B is true, but not both
    - The two definitions are equivalent

xor: A ^ B

| ^ | 0 | 1 |
|---|---|---|
| 0 | 0 | 1 |
| 1 | 1 | 0 |

# Generalized Boolean Algebra

- Binary bits can represent truth values: 0 = false, 1 = true

- Boolean operations can be extended to work on vectors of bits
  - Operations applied one bit at a time: ***bitwise***

```
    01101001      01101001      01101001
  & 01010101    | 01010101    ^ 01010101    ~ 01010101
  ----------    ----------    ----------    ----------
    01000001      01111101      00111100      10101010
```

- All of the properties of Boolean algebra apply
  - Relationships between operations, etc.

# Bit-level operations in C

- Operations &, |, ~, ^ available in C
  - Apply to any "integral" data type
    - **`long`**, **`int`**, **`short`**, **`char`**, **`unsigned`**
  - View arguments as bit vectors
  - Arguments applied bit-wise
- Examples (char data type, single byte)
  - **`~0x00 → 0xFF`**

    $\sim 00000000_2 \rightarrow 11111111_2$
  - **`~0x41 → 0xBE`**

    $\sim 01000001_2 \rightarrow 10111110_2$
  - **`0x69 | 0x55 → 0x7D`**

    $01101001_2 \mid 01010101_2 \rightarrow 01111101_2$

# Logic operations in C – not the same!

- Logical operations ||, && and ! (Logic OR, AND & Not)
  - Contrast to bit-wise operators
    - View 0 as "False"
    - *View anything nonzero as "True"*
    - Always return 0 or 1 (i.e., false or true) rather than a sequence of bits
    - Early termination *(if you can answer by just looking at the first argument, you are done)*
- Examples (char data type)
  - !0x41 → 0x00
  - !0x00 → 0x01
  - !!0x41 → 0x01
  - 0x59 && 0x35 → 0x01
  - 0x59 || 0x35 → 0x01
  - p && *p (avoids null pointer access)

Watch out for && vs. & (and || vs. |) … one of the more common slip-ups in C programming