The Hardware/Software Interface

CSE 351 Autumn 2022

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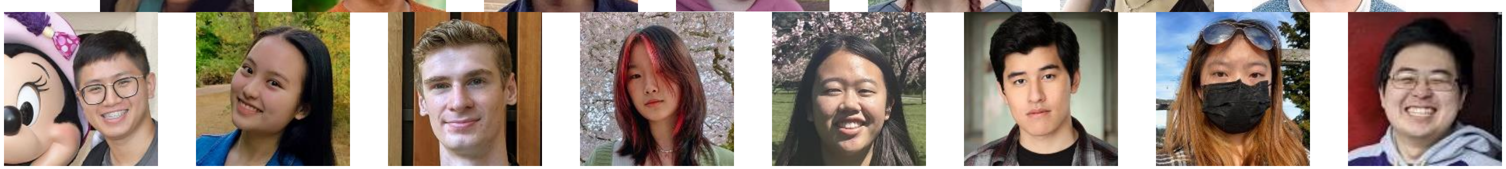
http://xkcd.com/676/

Lecture Outline

- **Course Introduction**
- Course Policies
  - https://courses.cs.washington.edu/courses/cse351/22au/syllabus.html
- Binary and Numerical Representation

Introductions: Course Staff

- Instructor: just call me Justin
  - CSE Associate Teaching Professor
  - Raising a toddler this quarter, will be tired
- TAs:

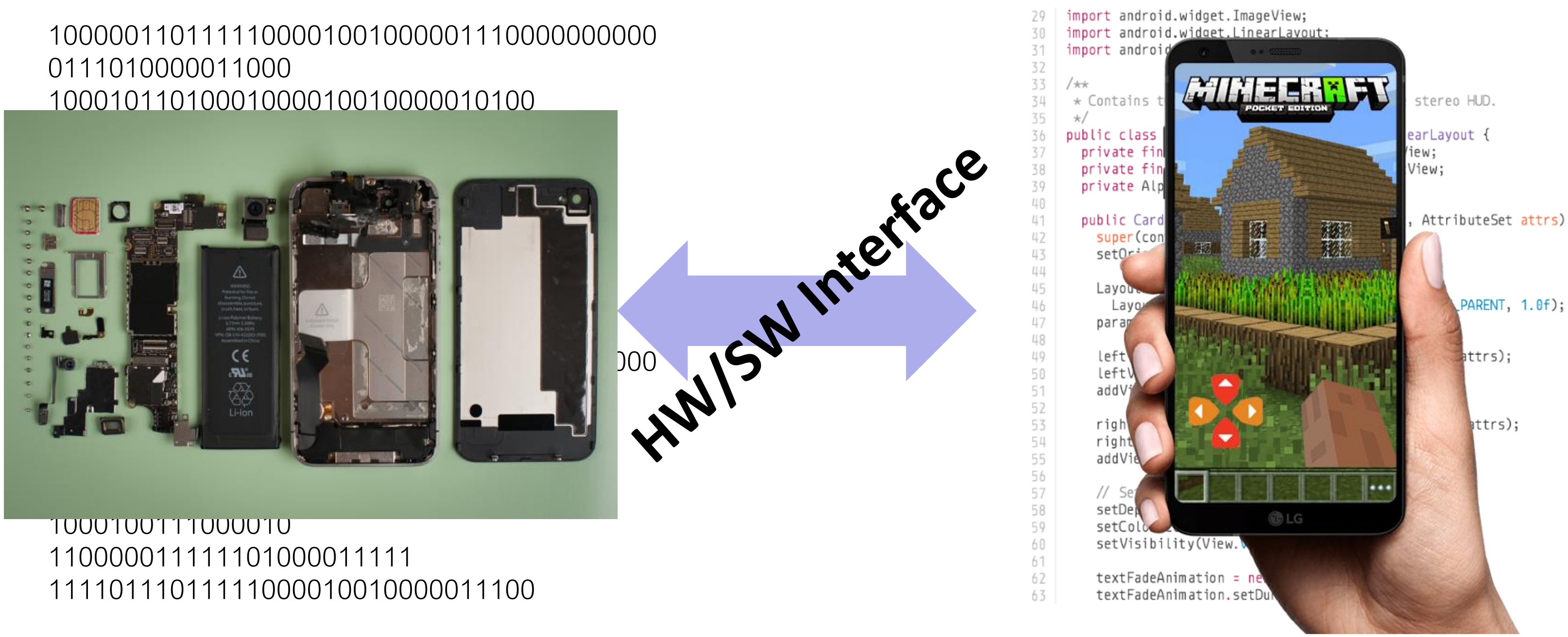


  - Available in section, office hours, and on Ed Discussion
- More than anything, we want you to feel…
  - ✓ Comfortable and welcome in this space
  - ✓ Able to learn and succeed in this course
  - ✓ Comfortable reaching out if you need help or want change

Introductions: You!

- ~320 students registered, split across two lectures
- CSE majors, ECE majors, and more
  - Most of you will find almost everything in the course new
  - Many of you are new to CSE and/or UW (and campus)!
- Get to know each other! Help each other out!
  - Science says that learning happens best in groups
  - Working well with others is a valuable life skill
  - Diversity of perspectives expands your horizons
  - Take advantage of group work, where permissible, to *learn*, not just get a grade

Welcome to CSE351!



- Our goal is to teach you the key abstractions "under the hood"
  - How does your source code become something that your computer understands?
  - What happens as your computer is executing one or more processes?

Layers of Computing Below Programming

Software Applications
(written in Java, Python, C, etc.)

Programming Languages & Libraries
(*e.g.*, Java Runtime Env, C Standard Lib)

OS/App interface

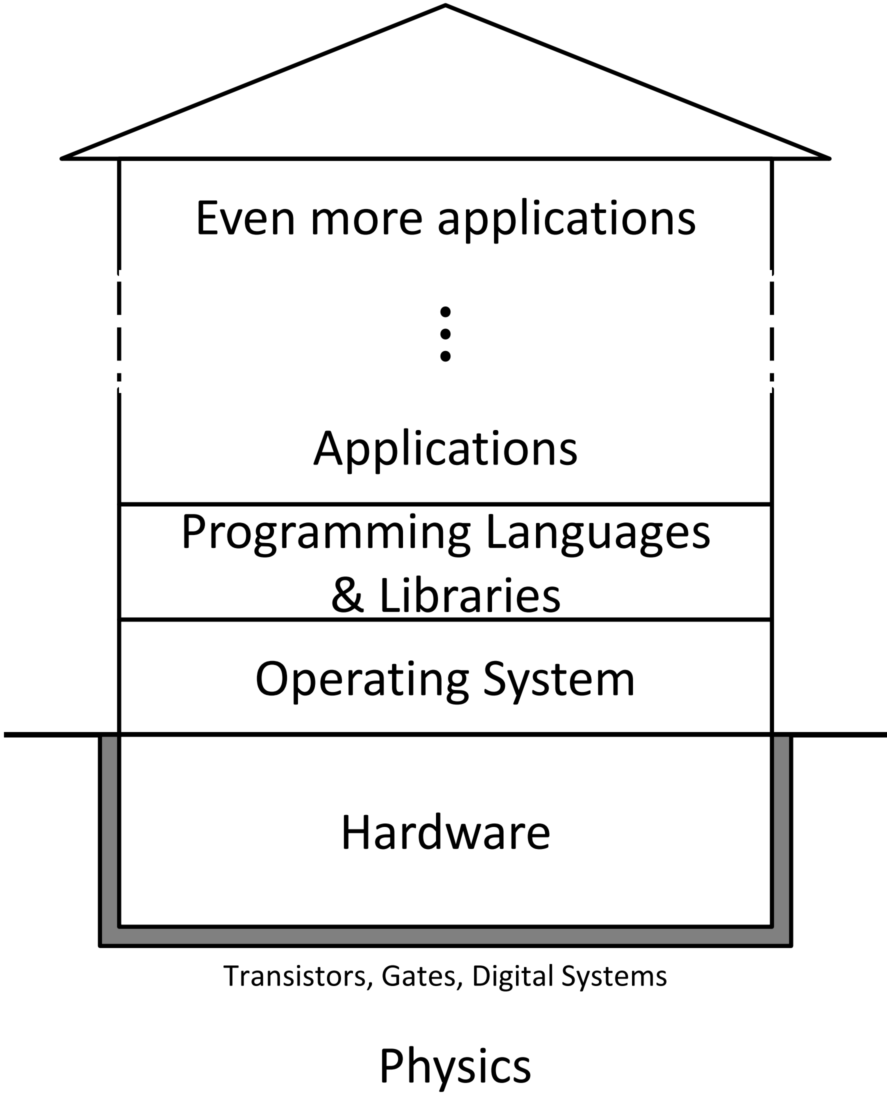
Operating System
(*e.g.*, Linux, MacOS, Windows)

HW/SW interface

Hardware
(*e.g.*, CPU, memory, disk, network, peripherals)

"House" of Computing Metaphor

- We continue to build upward but everything relies on the base & foundation
  - We'll explore parts of Hardware, OS, and PL
- Built a long time ago
  - Some parts have been updated over the years, some have not
  - More remodeling necessary, but should understand *how* and *why* things are this way before demolishing anything



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

- Learning in this class
  - You might miss Java, but we just ask you to keep your heart open; something unexpected might pique your interest!
  - Notice and nurture any wants to linger in some space
    - Many future classes to explore this space more

Some fun topics that we will touch on

- Which of the following seems the most interesting to you? (vote in Ed Lessons)

a) What is a GFLOP and why is it used in computer benchmarks?
b) How and why does running many programs for a long time eat into your memory (RAM)?
c) What is stack overflow and how does it happen?
d) Why does your computer slow down when you run out of *disk* space?
e) What was the flaw behind the original Internet worm, the Heartbleed bug, and the Cloudbleed bug?
f) What is the meaning behind the different CPU specifications? (*e.g.*, # of cores, size of cache)

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- Binary and Numerical Representation

Bookmarks

- Website: https://courses.cs.washington.edu/courses/cse351/22au/
  - Schedule, policies, materials, videos, assignment specs, etc.
- Ed Course: https://edstem.org/us/courses/23927
  - Discussion: announcements, ask and answer questions
  - Lessons: readings, lecture questions, homework
  - Resources: links to other tools and information
- Linked from website and Ed
  - Canvas: surveys, grade book, Zoom links
  - Gradescope: lab submissions, take-home exams
  - Panopto: lecture recordings

Grading

groupwork allowed

- **Pre-lecture Readings:** 5%
  - Can reveal solution after one attempt (completion)
- **Homework:** 20% total
  - Unlimited submission attempts (autograded correctness)
- **Labs:** 40% total

  partners allowed
  - Last submission graded (correctness)
- **Exams:** Midterm (16%) and Final (16%)

  individual work
  - Take-home; individual, but some discussion permitted
- **EPA:** Effort, Participation, and Altruism (3%)

Group Work in 351

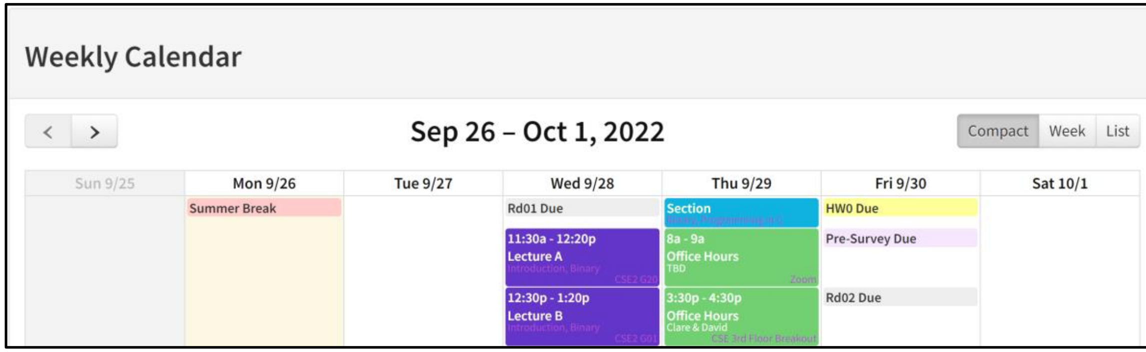
- Group work will be *emphasized* in this class
  - Lecture and section will have built-in group work time – you will get the most out of it if you actively participate!
    - TAs will circle around the room and interact with groups
    - Raise your hand to get the attention of a staff member
  - Most assignments allow collaboration – talking to classmates will help you synthesize concepts and terminology
    - *The major takeaways for this course will be the ability to explain the major concepts verbally and/or in writing to others*
  - However, the responsibility for learning falls on *you*

Lab Collaboration and Academic Integrity

- All submissions are expected to be yours and yours alone
- You are encouraged to discuss your assignments with other students (*ideas*), but we expect that what you turn in is yours
- It is NOT acceptable to copy solutions from other students or to copy (or start your) solutions from the Web (including Github, Chegg, and similar sites)
- Our goal is that *YOU* learn the material so you will be prepared for exams, interviews, and the future

Office Hours

- Check Weekly Calendar on website for scheduled office hours:
  - In-person or virtual, but NOT hybrid



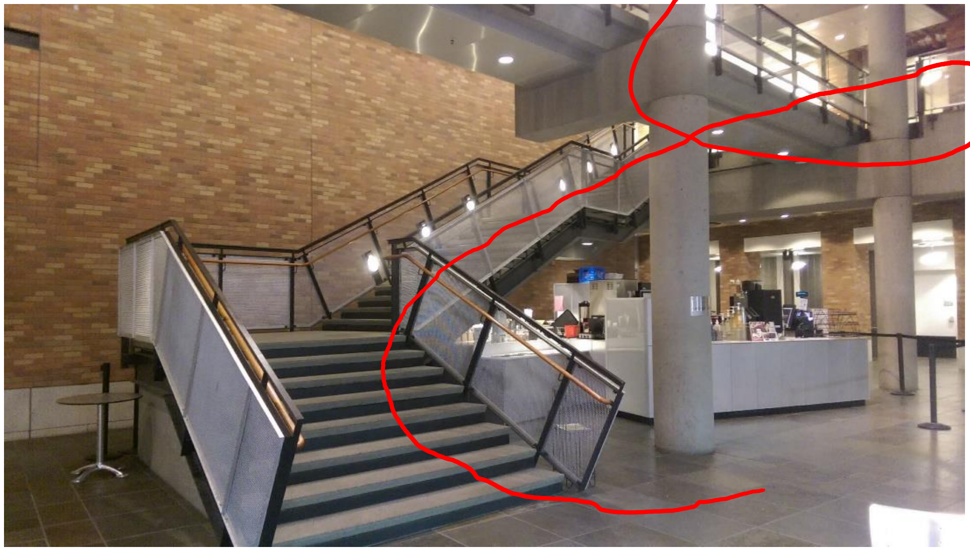
  - Zoom meeting links found in Zoom tab within Canvas
- *All* office hours will use a Google Sheets queue:
  - Fill out first 3 columns to enter queue:

Name(s)	Category	Description	Time Queued	Staff	Status
Example 1	Concept	Question about floating point encoding range.		Justin	Done
Example 2	Debugging	Lab 5: running into a segfault in mm_malloc after reaching end of the heap.		Justin	Done
Example 3	Spec	Lab 1a: confusion over within same block examples		Justin	Done
Example 4	Tools	GDB: how do I examine memory on the stack?		Justin	Done

- We encourage you to chat with other students if the TAs are busy!

In-Person Office Hours

- Allen 3rd floor breakout
  - Up the stairs in the CSE Atrium (Allen Center, not Gates)



  - At the top of two flights, the open area with the whiteboard wall is the 3rd floor breakout!

Extensions, Accommodations, Help

- Extenuating circumstances
  - Students (and staff) face an extremely varied set of environments and circumstances
  - For formal accommodations, go through Disability Resources for Students (DRS)
  - We will try to be accommodating otherwise, but *the earlier you reach out*, the better

- Don't suffer in silence – talk to a staff member!
  - We have a 1-on-1 meeting request form

To-Do List

- Admin
  - Explore/read the course website *thoroughly*
  - Check that you can access Ed Discussion & Lessons
  - **Get your machine set up to access the CSE Linux environment (CSE VM or attu) *as soon as possible***
  - Optionally, sign up for CSE 391: System and Software Tools

- Assignments
  - Pre-Course Survey and hw0 due Friday (9/30)
  - hw1 and Lab 0 due Monday (10/3)
  - Pre-lecture readings due before each lecture – 11 am

Lecture Outline

- Course Introduction
- Course Policies
  - Return to in-person instruction
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- **Binary and Numerical Representation**

Reading Review

- Terminology:
  - numeral, digit, base, symbol, digit position, leading zeros
  - binary, bit, nibble, byte, hexadecimal
  - numerical representation, encoding scheme

- Questions from the Reading?

Review Questions

- What is the *decimal value* of the numeral 107_8?

position: 2 1 0

$1\times8^2+0\times8^1+7\times8^0$

$64 + 0 + 7$

$= 71$

  A. $\boxed{71}$

  B. 87

  C. 107

  D. 568

- What is the decimal number 108 in hex?

(base 16)

$16^0=1$

$16^1=16$

$16^2=256$

$108 = 96+12$

$= 6\times16^1+12\times16^0$

$=$ 0x6C

  A. $\boxed{\text{0x6C}}$

  B. 0xA8

  C. 0x108

  D. 0x612

- Represent 0b100110110101101 in hex.

$16 = 2^4$

1 hex digit ⟷ 4 bits

0x4DAD

- Represent 0x3C9 in binary.

0b 0011 1100 1001

could drop leading zeros

Base Comparison

MEMORIZE ME!!!

- 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

Numerical Encoding

- **AMAZING FACT: You can represent *anything* countable using numbers!**
  - Need to agree on an encoding
  - Kind of like learning a new language

chat $\xrightarrow{\text{English}}$ to talk

chat $\xrightarrow{\text{French}}$ cat

same word, different meanings!

- Examples:
  - Decimal Integers: 0→0b0, 1→0b1, 2→0b10, etc.
  - English Letters: CSE→0x435345, yay→0x796179
  - Emoticons: 😃 0x0, 😔 0x1, 😎 0x2, 😇 0x3, 😈 0x4, 🙋‍♀️ 0x5

Binary Encoding

1 bit:

0b0 → thing 1

0b1 → thing 2

2 bits:

0b00 → thing 1

0b01 → thing 2

0b10 → thing 3

0b11 → thing 4

- With n binary digits, how many "things" can you represent? 2^n things
  - 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

So What's It Mean?

- *A sequence of bits can have many meanings!*

- Consider the hex sequence 0x4E6F21
  - Common interpretations include:
    - The decimal number 5140257
    - The real number 7.203034×10^{-39}
    - The characters "No!"
    - The background color of this slide

- It is up to the program/programmer to decide how to interpret the sequence of bits

Binary Encoding – Characters/Text

- ASCII Encoding (www.asciitable.com)
  - American Standard Code for Information Interchange

Dec	Hx	Oct	Char	
0	0	000	NUL	(null)
1	1	001	SOH	(start of heading)
2	2	002	STX	(start of text)
3	3	003	ETX	(end of text)
4	4	004	EOT	(end of transmission)
5	5	005	ENQ	(enquiry)
6	6	006	ACK	(acknowledge)
7	7	007	BEL	(bell)
8	8	010	BS	(backspace)
9	9	011	TAB	(horizontal tab)
10	A	012	LF	(NL line feed, new line)
11	B	013	VT	(vertical tab)
12	C	014	FF	(NP form feed, new page)
13	D	015	CR	(carriage return)
14	E	016	SO	(shift out)
15	F	017	SI	(shift in)
16	10	020	DLE	(data link escap[illegible]
17	11	021	DC1	[illegible]
18	12	022	DC2	[illegible]
19	13	023	[illegible]	[illegible]
20	14	[illegible]	[illegible]	[illegible]
21	15	[illegible]	[illegible]	[illegible] acknowledge)
22	16	[illegible]	[illegible]	[illegible]nchronous idle)
23	17	[illegible]	[illegible]	(end of trans. block)
24	18	030	CAN	(cancel)
25	19	031	EM	(end of medium)
26	1A	032	SUB	(substitute)
27	1B	033	ESC	(escape)
28	1C	034	FS	(file separator)
29	1D	035	GS	(group separator)
30	1E	036	RS	(record separator)
31	1F	037	US	(unit separator)

Dec	Hx	Oct	Html	Chr
32	20	040		Space
33	21	041	!	!
34	22	042	"	"
35	23	043	#	#
36	24	044	$	$
37	25	045	%	%
38	26	046	&	&
39	27	047	'	'
40	28	050	(	(
41	29	051	)	)
42	2A	052	*	*
43	2B	053	[illegible]	[illegible]
44	2C	[illegible]	[illegible]	[illegible]
45	2D	[illegible]	[illegible]	[illegible]
[illegible]	2E	[illegible]	[illegible]	.
[illegible]	2F	[illegible]	[illegible]	/
[illegible]	[illegible]	060	[illegible]	0
[illegible]	[illegible]	061	1	1
50	32	062	2	2
51	33	063	3	3
52	34	064	4	4
53	35	065	5	5
54	36	066	6	6
55	37	067	7	7
56	38	070	8	8
57	39	071	9	9
58	3A	072	:	:
59	3B	073	;	;
60	3C	074	<	<
61	3D	075	=	=
62	3E	076	>	>
63	3F	077	?	?

Dec	Hx	Oct	Html	Chr
64	40	100	@	@
65	41	101	A	A
66	42	102	B	B
67	43	103	C	C
68	44	104	D	D
69	45	105	E	E
70	46	106	F	F
71	47	107	G	G
72	48	110	[illegible]	[illegible]
73	49	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	4B	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	L	L
[illegible]	[illegible]	115	M	M
78	4E	116	N	N
79	4F	117	O	O
80	50	120	P	P
81	51	121	Q	Q
82	52	122	R	R
83	53	123	S	S
84	54	124	T	T
85	55	125	U	U
86	56	126	V	V
87	57	127	W	W
88	58	130	X	X
89	59	131	Y	Y
90	5A	132	Z	Z
91	5B	133	[	[
92	5C	134	\	\
93	5D	135	]	]
94	5E	136	^	^
95	5F	137	_	_

Dec	Hx	Oct	Html	Chr
96	60	140	`	`
97	61	141	a	a
98	62	142	b	b
99	63	143	c	c
100	64	[illegible]	[illegible]	d
101	65	[illegible]	[illegible]	e
102	[illegible]	[illegible]	[illegible]	f
[illegible]	[illegible]	[illegible]	[illegible]	g
[illegible]	[illegible]	150	[illegible]	h
[illegible]	[illegible]	[illegible]	i	i
[illegible]	[illegible]	[illegible]	j	j
107	6B	153	k	k
108	6C	154	l	l
109	6D	155	m	m
110	6E	156	n	n
111	6F	157	o	o
112	70	160	p	p
113	71	161	q	q
114	72	162	r	r
115	73	163	s	s
116	74	164	t	t
117	75	165	u	u
118	76	166	v	v
119	77	167	w	w
120	78	170	x	x
121	79	171	y	y
122	7A	172	z	z
123	7B	173	{	{
124	7C	174			|
125	7D	175	}	}
126	7E	176	~	~
127	7F	177	&#127;	DEL

What's Missing?

Binary Encoding – Characters/Text

- ASCII Encoding (www.asciitable.com)
  - *American* Standard Code for Information Interchange
- Created in 1963
  - Memory was expensive, 32KB in brand new machines
  - *Economic incentive* to use fewer bits for encoding
- **Design Goals:**
  - Represent everything on an *American* typewriter as *efficiently* as possible
  - Organize similar characters together
    - Numbers, uppercase, lowercase, then other stuff

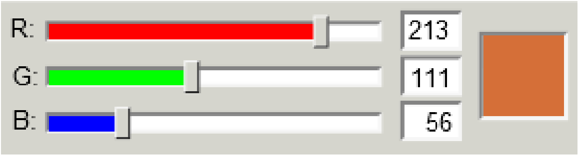
Binary Encoding – Unicode & Emoji

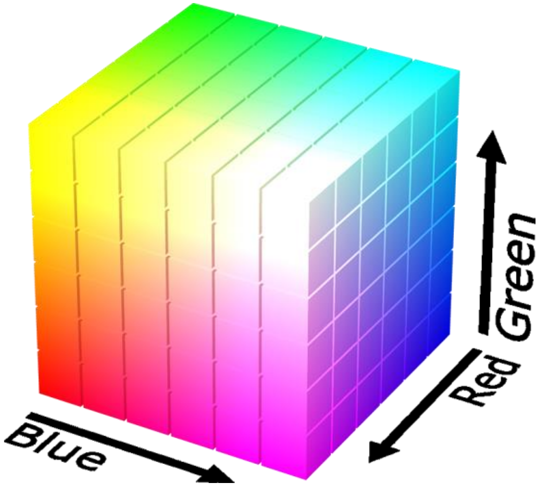
- Unicode Standard is managed by the Unicode Consortium
  - "Universal language" that uses 1-4 bytes to represent a much larger range of characters/languages, including emoji
  - Adds new emojis every year, though adoption often lags: ⍰
    - https://emojipedia.org/new/

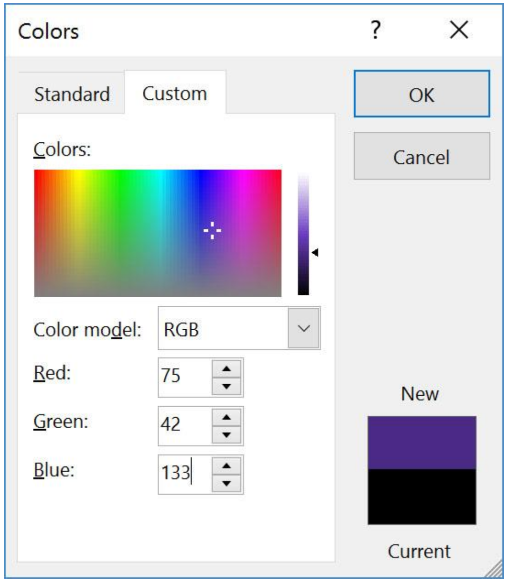
- Emojipedia demo: http://www.emojipedia.org
  - Desktop Computer: 🖥️
  - Code points: U+1F5A5, U+FE0F
  - Display:

Binary Encoding – Colors

- RGB – Red, Green, Blue
  - Additive color model (light): byte (8 bits) for each color
  - Commonly seen in hex (in HTML, photo editing, etc.)
  - Examples: **Blue**→0x0000FF, **Gold**→0xFFD700, **White**→0xFFFFFF, **Deep Pink**→0xFF1493







Binary Encoding – Files and Programs

- At the lowest level, all digital data is stored as bits!
- Layers of abstraction keep everything comprehensible
  - Data/files are groups of bits interpreted by program
  - Program is actually groups of bits being interpreted by your CPU
- Computer Memory Demo (if time)
  - Linux tool: `xxd`

Summary

- Humans think about numbers in decimal; computers think about numbers in binary
  - Base conversion to go between them
  - Hexadecimal is more human-readable than binary
- All information on a computer is binary
- Binary encoding can represent *anything*!
  - Computer/program needs to know how to interpret the bits
  - Encodings aren't "neutral"; priorities are baked in