The Hardware/Software Interface

CSE 351 Spring 2022

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Armin Magness
Hamsa Shankar
Dara Stotland
Jeffery Tian
Assaf Vayner
Tom Wu
Angela Xu
Effie Zheng

http://xkcd.com/676/

Lecture Outline

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

Introductions: Course Staff

- Ruth Anderson (Instructor)
- Melissa Birchfield
- Jacob Christy
- Alena Dickmann
- Kyrie Dowling
- Ellis Haker
- Maggie Jiang
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- Tom Wu
- Angela Xu
- Effie Zheng

  - Learn more about me and the staff on the course website!
  - Available in section, office hours, and on Ed Discussion
  - An invaluable source of information and help
- Get to know us
  - We are here to help you succeed!

Introductions: You!

- ~200 students registered across 2 lecture sections

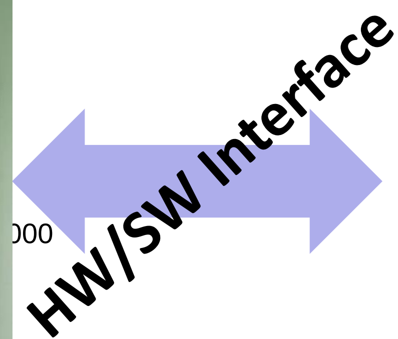
- CSE majors, EE majors, and more!
  - Most of you will find almost everything in the course new

- Get to know each other and help each other out!
  - Learning is much more fun with friends
  - Working well with others is a valuable life skill
  - Diversity of perspectives expands your horizons

Welcome to CSE351!

1000001101111100001001000001110000000000
0111010000011000
10001011010001000010010000010100

10001001111000010
1100000111111010000011111
1111011101111110000100100000011100



- 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?

Welcome to CSE351!

- This is an *introduction* that will:
  - Profoundly change/augment your view of computers and programs
  - Leave you impressed that computers ever work

Code in Many Forms

```
if (x != 0) y = (y+z)/x;
```

High Level Language (*e.g.* C, Java)

Compiler

```
    cmpl   $0, -4(%ebp)
    je     .L2
    movl   -12(%ebp), %eax
    movl   -8(%ebp), %edx
    leal   (%edx,%eax), %eax
    movl   %eax, %edx
    sarl   $31, %edx
    idivl  -4(%ebp)
    movl   %eax, -8(%ebp)
.L2:
```

Assembly Language

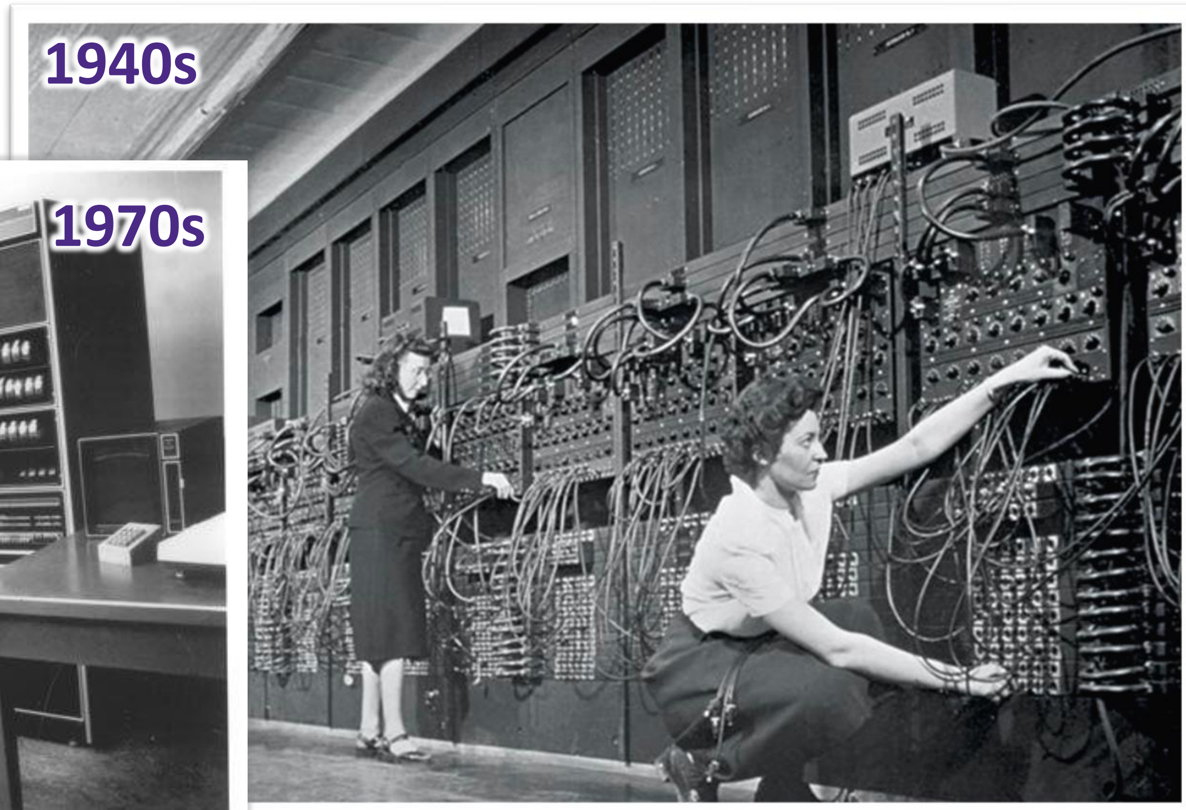
Assembler

```
1000001101111100001001000001110000000000
0111010000011000
10001011010001000010010000010100
10001011010001100010010100010100
100011010000010000000010
1000100111000010
110000011111101000011111
11110111011111000010010000011100
10001001010001000010010000011000
```

Machine Code

HW/SW Interface: Historical Perspective

- Hardware started out quite primitive



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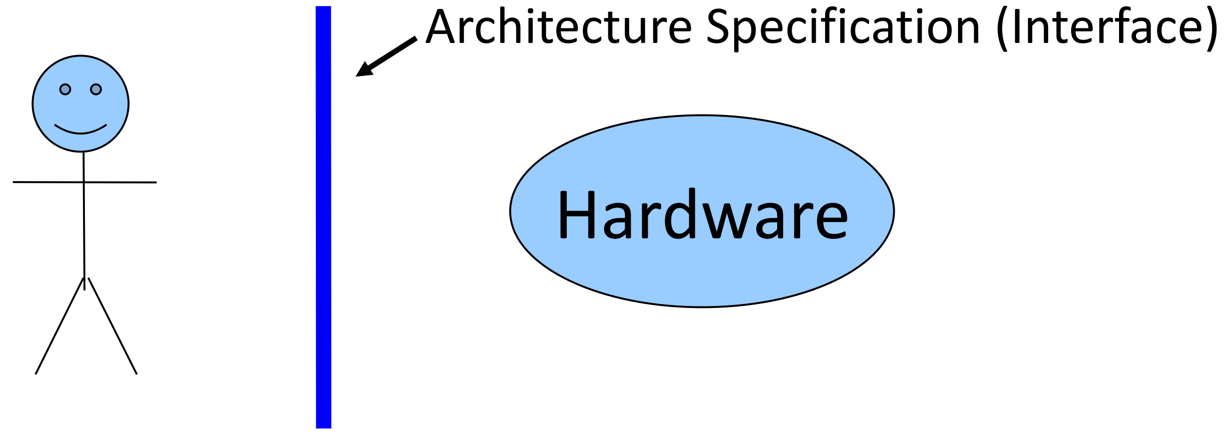
Jean Jennings (left), Marlyn Wescoff (center), and Ruth Lichterman program ENIAC at the University of Pennsylvania, circa 1946.
Photo: Corbis
http://fortune.com/2014/09/18/walter-isaacson-the-women-of-eniac/

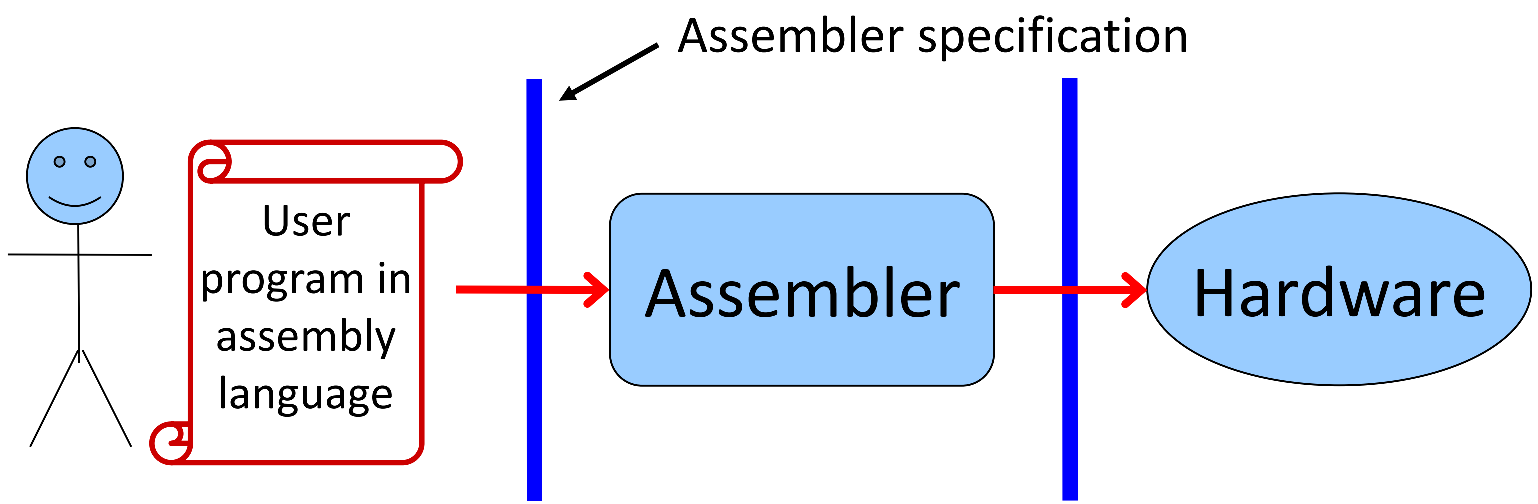
HW/SW Interface: Historical Perspective

- Hardware started out quite primitive
  - Programmed with very basic instructions (*primitives*)
  - e.g., a single instruction for adding two integers
- Software was also very basic
  - Closely reflected the actual hardware it was running on
  - Specify each step manually



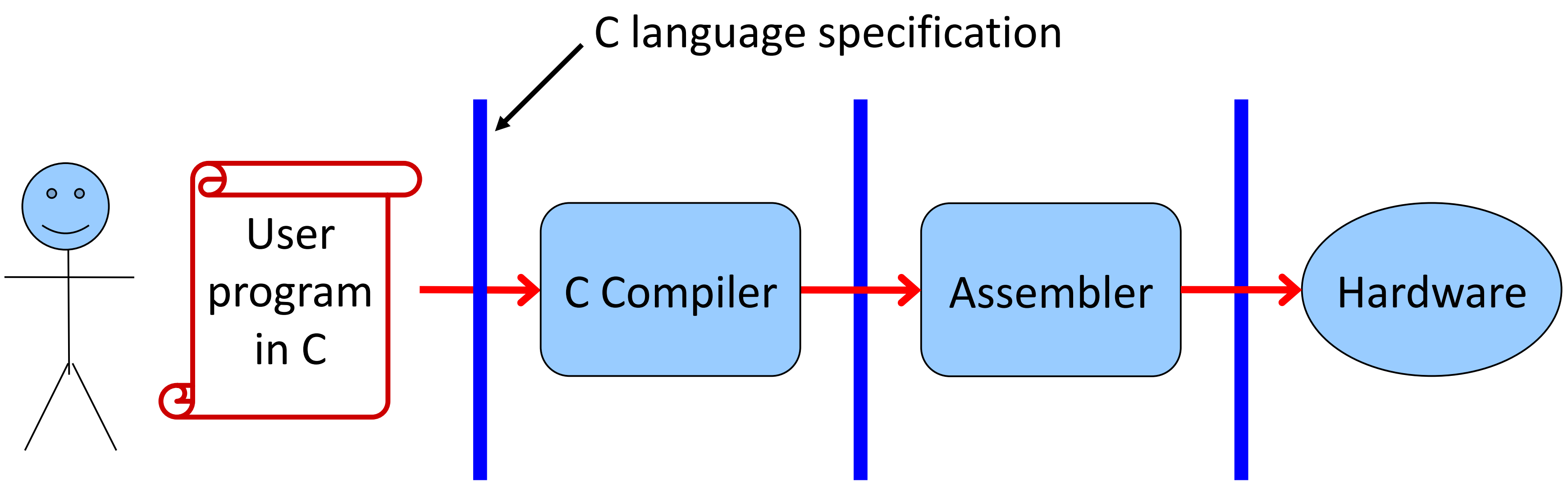
HW/SW Interface: Assemblers

- Life was made a lot better by assemblers
  - 1 assembly instruction = 1 machine instruction
  - More human-readable syntax
    - Assembly instructions are character strings, not bit strings
  - Can use symbolic names



HW/SW Interface: Higher-Level Languages

- Higher level of abstraction
  - 1 line of a high-level language is *compiled* into many (sometimes very many) lines of assembly language



Roadmap

How does your source code become something that your computer understands?

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
```

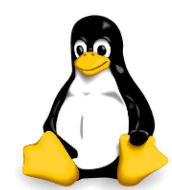
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Windows 10

OS X Yosemite



Computer system:

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

Roadmap

What happens as your computer is executing one or more processes?

C:

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car *c = malloc(sizeof(car));
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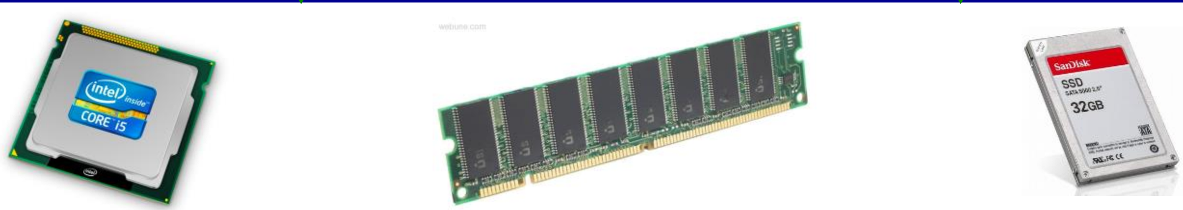
Computer system:



Course Perspective

- CSE351 will make you a better programmer
  - Purpose is to show how software really works
    - Understanding of some of the abstractions that exist between programs and the hardware they run on, why they exist, and how they build upon each other
  - Understanding the underlying system makes you more effective
    - Better debugging
    - Better basis for evaluating performance
    - How multiple activities work in concert (e.g. OS and user programs)
  - "Stuff everybody learns and uses and forgets not knowing"

- CSE351 presents a world-view that will empower you
  - The intellectual and software tools to understand the trillions+ of 1s and 0s that are "flying around" when your program runs

Lecture Outline

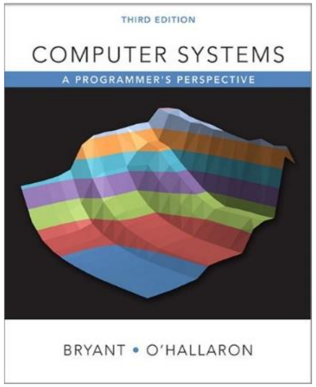
- Course Introduction
- **Course Policies**
  - https://courses.cs.washington.edu/courses/cse351/22sp/syllabus
- Binary and Numerical Representation

Bookmarks

- Website: https://courses.cs.washington.edu/courses/cse351/22sp/
  - Schedule, policies, materials, videos, assignments, etc.
- Discussion: https://us.edstem.org/courses/21044/discussion/
  - Announcements made here
  - Ask and answer questions – staff will monitor and contribute
- Lessons: https://us.edstem.org/courses/21044/lessons/
  - Pre-lecture Readings, lecture polling questions, homework
- Gradescope: https://www.gradescope.com/courses/381494
  - Lab submissions, Exams
- Canvas: https://canvas.uw.edu/courses/1546970
  - Calendar, grade book

Reference Material

- The readings on Ed Lessons - constitute a "mini-textbook" for this course, but may not have enough detail for everyone
- *Computer Systems: A Programmer's Perspective*
  - Randal E. Bryant and David R. O'Hallaron
  - Website: http://csapp.cs.cmu.edu
  - North American 3rd edition
  - Optional, additional readings



- C reference (physical or online)
  - *The C Programming Language* (Kernighan and Ritchie)
  - *C: A Reference Manual* (Harbison and Steele)
  - http://www.cplusplus.com

Grading

- **Readings:** ~5%
  - Can reveal solution after one attempt (completion)
- **Homework:** ~20%
  - Unlimited submission attempts (autograded correctness)
- **Labs:** ~40% (optional partner)
  - Last submission graded (correctness)
- **Exams:** Midterm (~16%) and Final (~16%)
  - Take-home; individual, but some discussion permitted. More info on these later.
- **Participation :** ~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

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)

To-Do List

- Admin
  - Explore/read 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
    - TOMORROW, Tuesday 1:30-2:20pm, in CSE2 G20
- Assignments
  - Pre-Course Survey and hw0 due Wednesday (3/30) – 11:59pm
  - Hw1 due Friday (4/01) – 11:59pm
  - Lab 0 due Monday (4/04) – 11:59pm
  - Readings due before each lecture – 11am
  - Lecture activities from that day are due before NEXT lecture – 11am

Lecture Outline

- Course Introduction
- Course Policies
- **Binary and Numerical Representation**
  - **Decimal, Binary, and Hexadecimal**
  - **Base Conversion**
  - **Binary Encoding**

Decimal Numbering System

- Ten symbols: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9
- Represent larger numbers as a sequence of digits
  - Each digit is one of the available symbols
- Example: 7061 in decimal (base 10)
  - $7061_{10} = (7 \times 10^3) + (0 \times 10^2) + (6 \times 10^1) + (1 \times 10^0)$

Octal Numbering System

- Eight symbols: 0, 1, 2, 3, 4, 5, 6, 7
  - Notice that we no longer use 8 or 9
- Base comparison:
  - Base 10: `0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12…`
  - Base 8: `0, 1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 13, 14…`
- Example: What is 7061_8 in base 10?
  - $7061_8 = (7 \times 8^3) + (0 \times 8^2) + (6 \times 8^1) + (1 \times 8^0) = 3633_{10}$

Warmup Question

- What is 34_8 in base 10?
  - Not a polling question

A. 32_{10}

B. 34_{10}

C. 7_{10}

D. 28_{10}

E. 35_{10}

Binary and Hexadecimal

- Binary is base 2
  - Symbols: 0, 1
  - Convention: $2_{10} = 10_2 =$ 0b10
- Example: What is 0b110 in base 10?
  - $0b110 = 110_2 = (1 \times 2^2) + (1 \times 2^1) + (0 \times 2^0) = 6_{10}$
- Hexadecimal (hex, for short) is base 16
  - Symbols? 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, **A, B, C, D, E, F**
  - Convention: $16_{10} = 10_{16} =$ 0x10
- Example: What is 0xA5 in base 10?
  - $0xA5 = A5_{16} = (10 \times 16^1) + (5 \times 16^0) = 165_{10}$

Converting to Base 10

- Can convert from any base *to* base 10
  - 0b110 = 110_2 = $(1 \times 2^2) + (1 \times 2^1) + (0 \times 2^0) = 6_{10}$
  - 0xA5 = $A5_{16}$ = $(10 \times 16^1) + (5 \times 16^0) = 165_{10}$
- We learned to think in base 10, so this is fairly natural for us
- **Challenge:** Convert into other bases (*e.g.* 2, 16)

Decimal to Binary

- Convert 13_{10} into binary

- Hints:
  - $2^3 = 8$
  - $2^2 = 4$
  - $2^1 = 2$
  - $2^0 = 1$

- Think!
  - No voting for this question

Converting from Decimal to Binary

- Given a decimal number N:
  1. List increasing powers of 2 from *right to left* until ≥ N
  2. Then from *left to right*, ask is that (power of 2) ≤ N?
     - If **YES**, put a 1 below and subtract that power from N
     - If **NO**, put a 0 below and keep going

- Example: 13 to binary

2^4=16	2^3=8	2^2=4	2^1=2	2^0=1

Converting from Decimal to Base B

- Given a decimal number N:
  1. List increasing powers of B from *right to left* until ≥ N
  2. Then from *left to right*, ask is that (power of B) ≤ N?
     - If **YES**, put *how many* of that power go into N and subtract from N
     - If **NO**, put a 0 below and keep going

- Example: 165 to hex

16^2=256	16^1=16	16^0=1

Converting Binary ↔ Hexadecimal

- Hex → Binary
  - Substitute hex digits, then drop any leading zeros
  - Example: 0x2D to binary
    - 0x2 is 0b0010, 0xD is 0b1101
    - Drop two leading zeros, answer is 0b101101
- Binary → Hex
  - Pad with leading zeros until multiple of 4, then substitute each group of 4
  - Example: 0b101101
    - Pad to 0b 0010 1101
    - Substitute to get 0x2D

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

Binary → Hex Practice

- Convert 0b100110110101101
  - How many digits?
  - Pad:
  - Substitute:

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

Polling Questions – Answer in Ed Lessons

- What is the *decimal value* of the numeral 107_8?
  A. 71
  B. 87
  C. 107
  D. 568

- What is the decimal number 108 in hex?
  A. 0x6C
  B. 0xA8
  C. 0x108
  D. 0x612

- Represent 0b100110110101101 in hex.

- Represent 0x3C9 in binary.

Base Comparison

- 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

- 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

- 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

So What's It Mean?

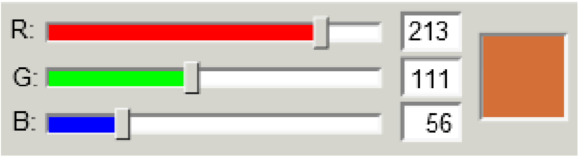
- *A sequence of bits can have many meanings!*

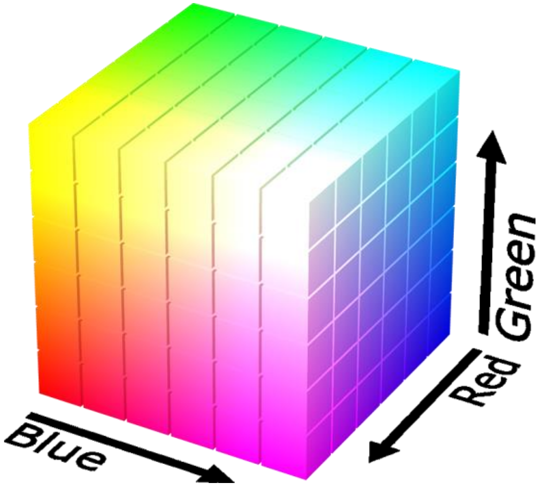
- Consider the hex sequence 0x4E6F21
  - Common interpretations include:
    - The decimal number 5140257
    - The characters "No!"
    - The background color of this slide
    - The real number 7.203034×10^{-39}

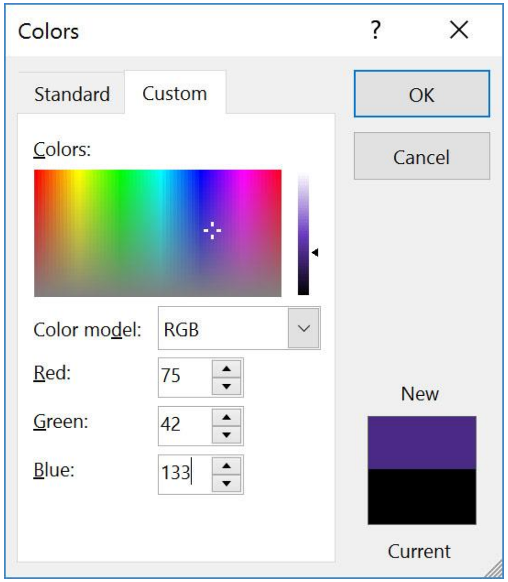
- It is up to the program/programmer to decide how to interpret the sequence of bits

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 – Characters/Text

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

Dec	Hx	Oct	Char		Dec	Hx	Oct	Html	Chr	Dec	Hx	Oct	Html	Chr	Dec	Hx	Oct	Html	Chr
0	0	000	NUL	(null)	32	20	040		Space	64	40	100	@	@	96	60	140	`	`
1	1	001	SOH	(start of heading)	33	21	041	!	!	65	41	101	A	A	97	61	141	a	a
2	2	002	STX	(start of text)	34	22	042	"	"	66	42	102	B	B	98	62	142	b	b
3	3	003	ETX	(end of text)	35	23	043	#	#	67	43	103	C	C	99	63	143	c	c
4	4	004	EOT	(end of transmission)	36	24	044	$	$	68	44	104	D	D	100	64	144	d	d
5	5	005	ENQ	(enquiry)	37	25	045	%	%	69	45	105	E	E	101	65	145	e	e
6	6	006	ACK	(acknowledge)	38	26	046	&	&	70	46	106	F	F	102	66	146	f	f
7	7	007	BEL	(bell)	39	27	047	'	'	71	47	107	G	G	103	67	147	g	g
8	8	010	BS	(backspace)	40	28	050	(	(	72	48	110	H	H	104	68	150	h	h
9	9	011	TAB	(horizontal tab)	41	29	051	)	)	73	49	111	I	I	105	69	151	i	i
10	A	012	LF	(NL line feed, new line)	42	2A	052	*	*	74	4A	112	J	J	106	6A	152	j	j
11	B	013	VT	(vertical tab)	43	2B	053	+	+	75	4B	113	K	K	107	6B	153	k	k
12	C	014	FF	(NP form feed, new page)	44	2C	054	,	,	76	4C	114	L	L	108	6C	154	l	l
13	D	015	CR	(carriage return)	45	2D	055	-	-	77	4D	115	M	M	109	6D	155	m	m
14	E	016	SO	(shift out)	46	2E	056	.	.	78	4E	116	N	N	110	6E	156	n	n
15	F	017	SI	(shift in)	47	2F	057	/	/	79	4F	117	O	O	111	6F	157	o	o
16	10	020	DLE	(data link escape)	48	30	060	0	0	80	50	120	P	P	112	70	160	p	p
17	11	021	DC1	(device control 1)	49	31	061	1	1	81	51	121	Q	Q	113	71	161	q	q
18	12	022	DC2	(device control 2)	50	32	062	2	2	82	52	122	R	R	114	72	162	r	r
19	13	023	DC3	(device control 3)	51	33	063	3	3	83	53	123	S	S	115	73	163	s	s
20	14	024	DC4	(device control 4)	52	34	064	4	4	84	54	124	T	T	116	74	164	t	t
21	15	025	NAK	(negative acknowledge)	53	35	065	5	5	85	55	125	U	U	117	75	165	u	u
22	16	026	SYN	(synchronous idle)	54	36	066	6	6	86	56	126	V	V	118	76	166	v	v
23	17	027	ETB	(end of trans. block)	55	37	067	7	7	87	57	127	W	W	119	77	167	w	w
24	18	030	CAN	(cancel)	56	38	070	8	8	88	58	130	X	X	120	78	170	x	x
25	19	031	EM	(end of medium)	57	39	071	9	9	89	59	131	Y	Y	121	79	171	y	y
26	1A	032	SUB	(substitute)	58	3A	072	:	:	90	5A	132	Z	Z	122	7A	172	z	z
27	1B	033	ESC	(escape)	59	3B	073	;	;	91	5B	133	[	[	123	7B	173	{	{
28	1C	034	FS	(file separator)	60	3C	074	<	<	92	5C	134	\	\	124	7C	174			|
29	1D	035	GS	(group separator)	61	3D	075	=	=	93	5D	135	]	]	125	7D	175	}	}
30	1E	036	RS	(record separator)	62	3E	076	>	>	94	5E	136	^	^	126	7E	176	~	~
31	1F	037	US	(unit separator)	63	3F	077	?	?	95	5F	137	_	_	127	7F	177	&#127;	DEL

www.LookupTables.com

Source: www.LookupTables.com

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 (try it!)
  - From vim: `%!xxd`
  - From emacs: `M-x hexl-mode`

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