The Hardware/Software Interface

CSE 351 Spring 2020

Instructor:
Porter Jones

Teaching Assistants:
Amy Xu
Callum Walker
Sam Wolfson
Tim Mandzyuk

http://xkcd.com/676/

Introductions: Course Staff

- Instructor: Porter Jones
- TAs:

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

Introductions: You!

- ~60 students registered
- CSE majors, ECE 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 Summer 2020!

- Thanks in advance for working with us to make this the best online experience we can!

- Help us figure out the best ways to handle:
  - Lecture
  - Office Hours (Schedule on Website & Zoom links coming soon!)
  - Sections (Zoom links coming soon!)
  - Students in different time zones
  - Other challenges/opportunities!

- We'll be experimenting with different formats/approaches to see what works best!

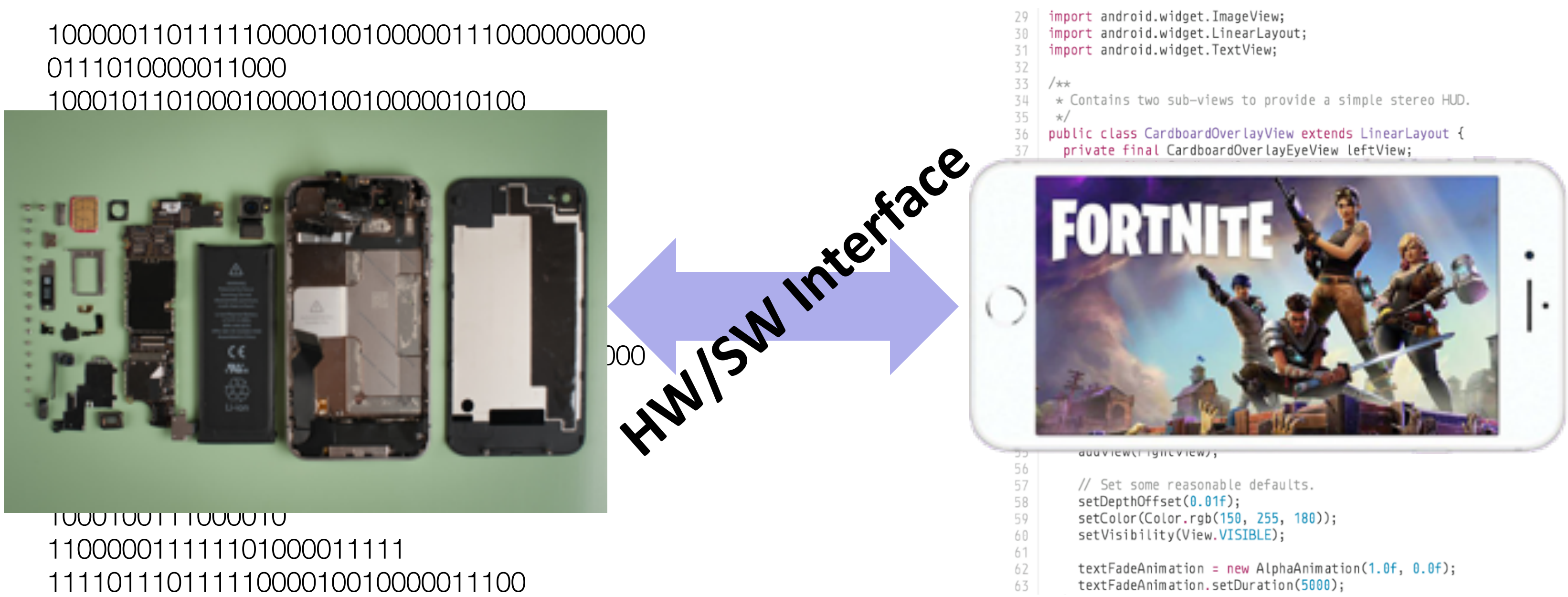
Aside: Lecture Questions

- Ask lots of questions, please!!!
- The Zoom chat box is convenient, but that means it can become cluttered fast
  - Good for clarifying questions, asking me to repeat stuff, telling me that my Zoom cutout, etc.

- Each lecture will have a google doc for asking questions that TAs will monitor/answer
  - Good for curiosity questions, tangential questions, etc.

- Today’s doc: https://tinyurl.com/CSE351-6-22

Welcome to CSE351!



```
10000001101111110000100100000011100000000000
0111010000011000
1000101101000100001001000000010100
1000100111000010
1100000011111101000011111
1111011101111110000100100000011100
```

```
import android.widget.ImageView;
import android.widget.LinearLayout;
import android.widget.TextView;

/**
 * Contains two sub-views to provide a simple stereo HUD.
 */
public class CardboardOverlayView extends LinearLayout {
  private final CardboardOverlayEyeView leftView;
```

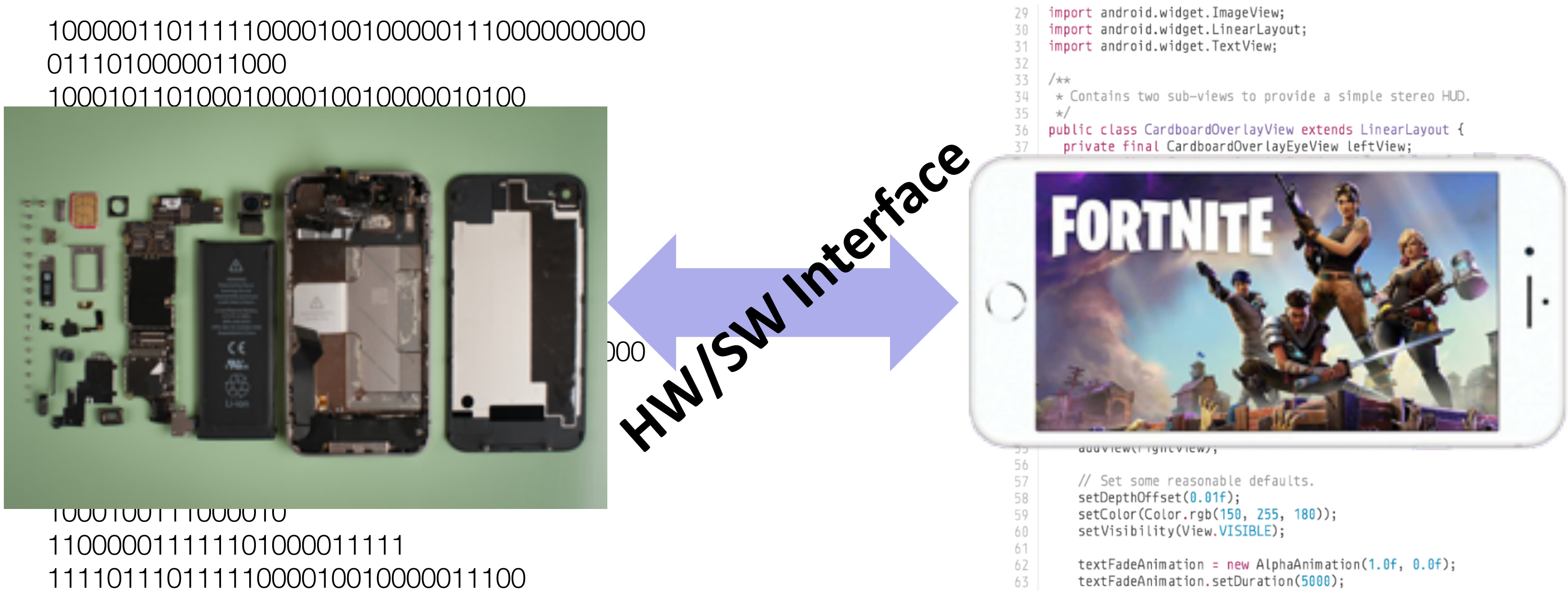
```

    // Set some reasonable defaults.
    setDepthOffset(0.01f);
    setColor(Color.rgb(150, 255, 180));
    setVisibility(View.VISIBLE);

    textFadeAnimation = new AlphaAnimation(1.0f, 0.0f);
    textFadeAnimation.setDuration(5000);
```

- 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 (applications)?

Welcome to CSE351!



```
1000001101111100001001000001110000000000
0111010000011000
10001011010001000010010000010100
000
1000100111000010
110000011111101000011111
11110111011111000010010000011100
```

```
import android.widget.ImageView;
import android.widget.LinearLayout;
import android.widget.TextView;

/**
 * Contains two sub-views to provide a simple stereo HUD.
 */
public class CardboardOverlayView extends LinearLayout {
  private final CardboardOverlayEyeView leftView;

    // Set some reasonable defaults.
    setDepthOffset(0.01f);
    setColor(Color.rgb(150, 255, 180));
    setVisibility(View.VISIBLE);

    textFadeAnimation = new AlphaAnimation(1.0f, 0.0f);
    textFadeAnimation.setDuration(5000);
```

- 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;
```

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:
```

Assembler

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

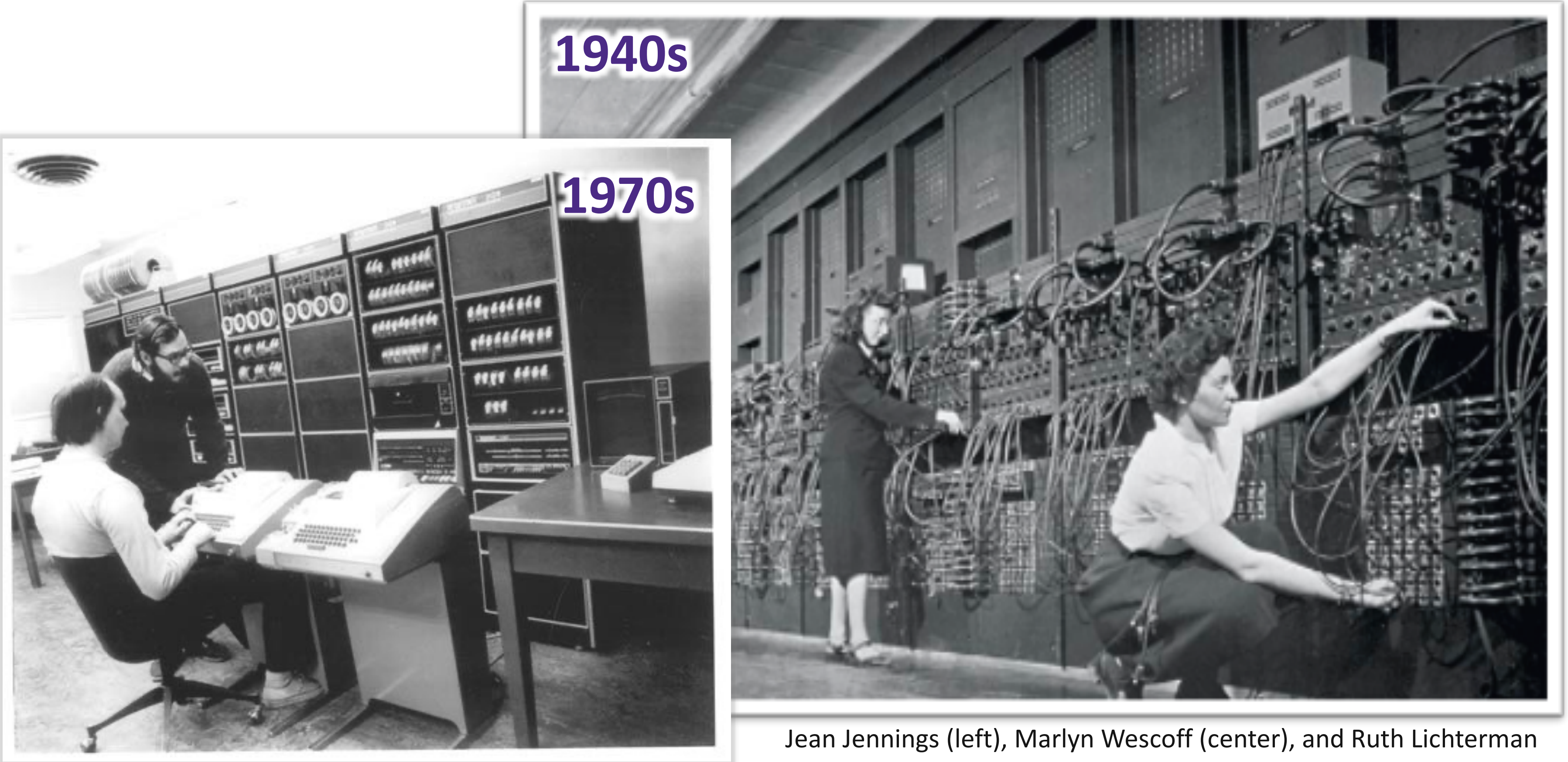
High Level Language (*e.g.* C, Java)

Assembly Language

Machine Code

HW/SW Interface: Historical Perspective

- Hardware started out quite primitive

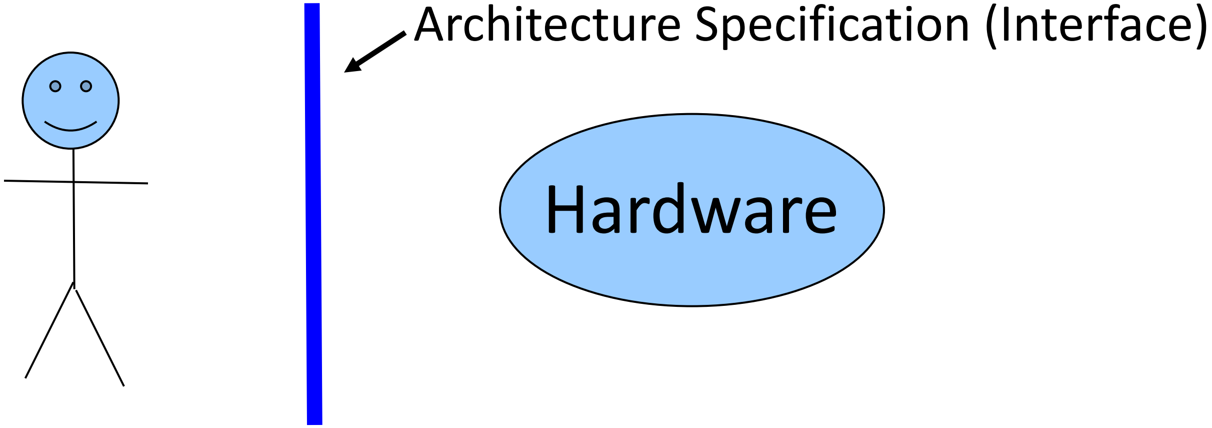


https://s-media-cache-ak0.pinimg.com/564x/91/37/23/91372375e2e6517f8af128aab655e3b4.jpg

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

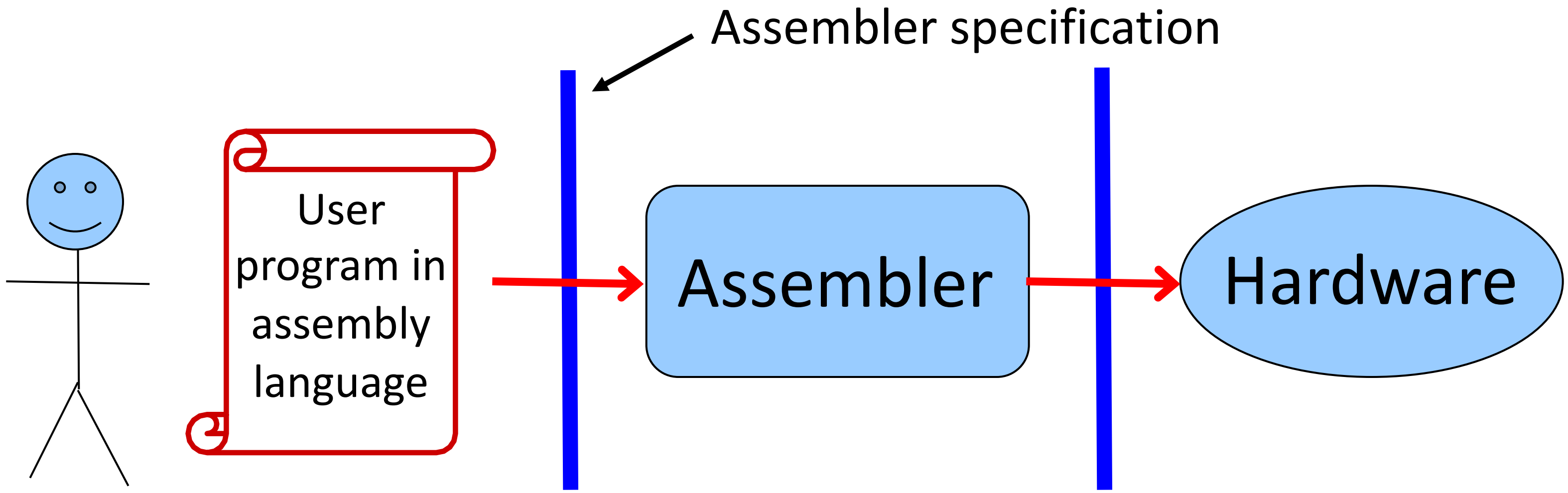
- Hardware started out quite primitive
  - Programmed with very basic instructions (*primitives*)
  - e.g., a single instruction for adding two integers
- Software was also very basic
  - Closely reflected the actual hardware it was running on
  - Specify each step manually



Architecture Specification (Interface)

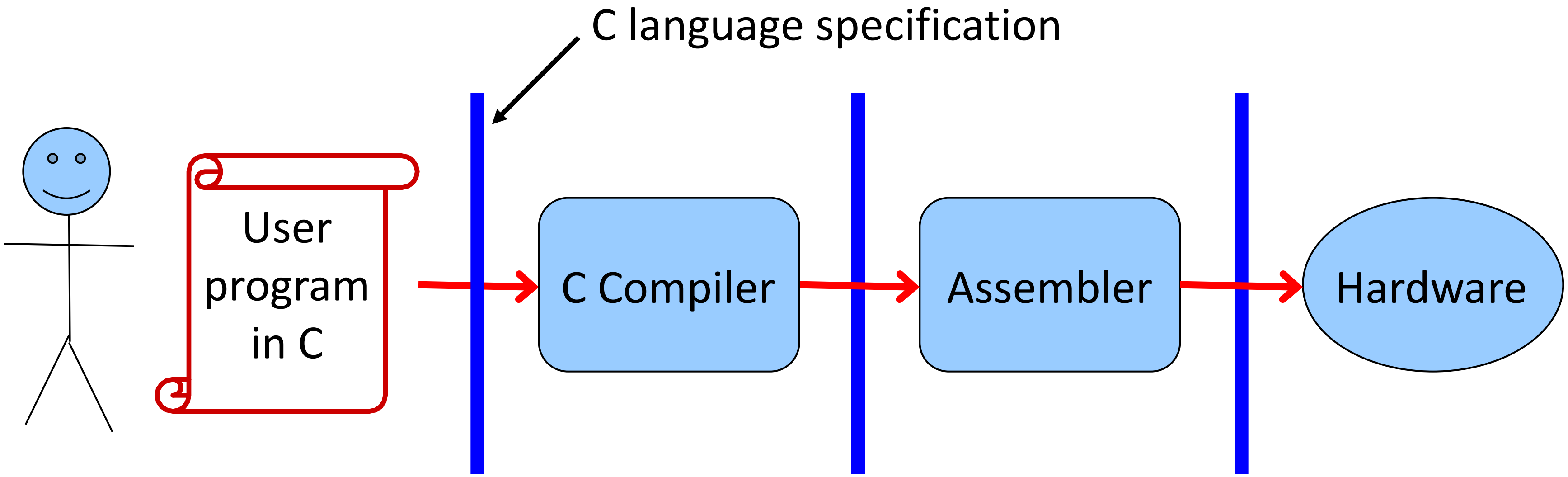
HW/SW Interface: Assemblers

- 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
```

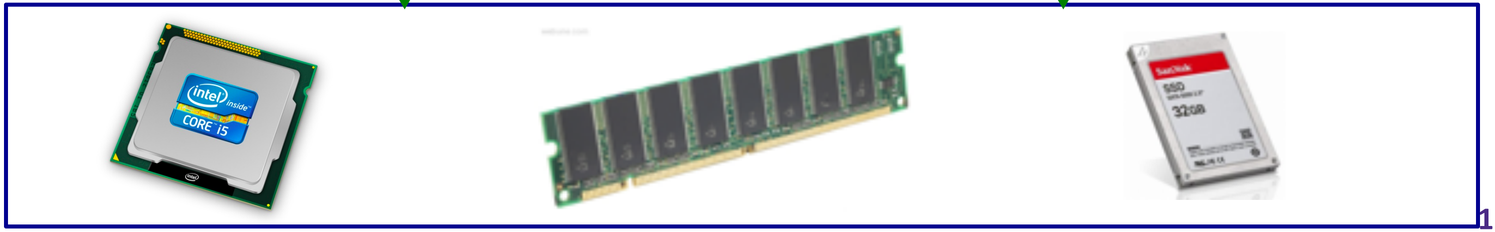
Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

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

OS:

Computer system:



Roadmap

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

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();
```

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

Assembly language:

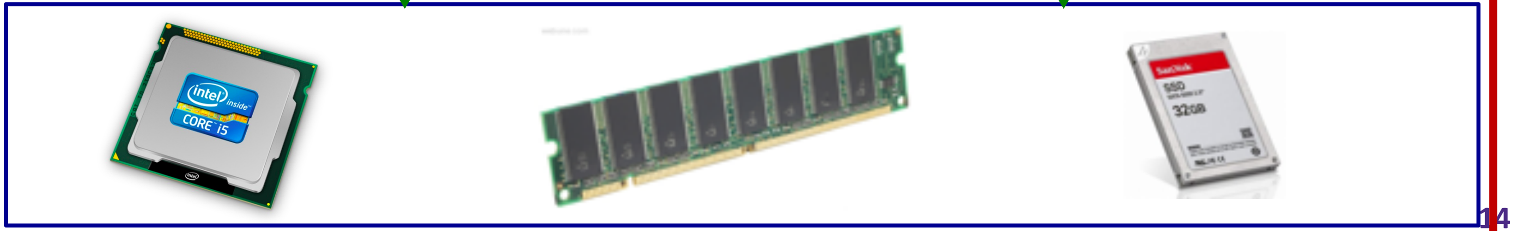
```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

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

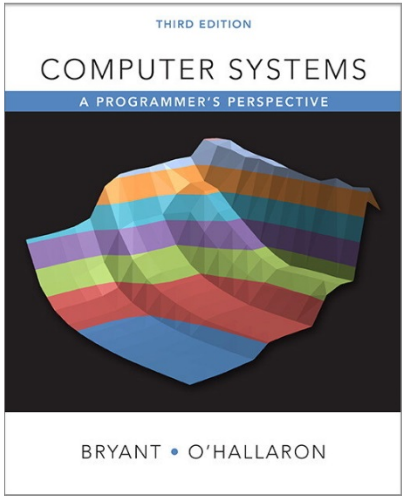
- Course Introduction
- **Course Policies**
    - https://courses.cs.washington.edu/courses/cse351/20su/syllabus/
- Binary

Bookmarks

- Course Website: https://cs.uw.edu/351
  - Schedule, policies, materials, videos, assignments, etc.
- Discussion: https://piazza.com/washington/summer2020/cse351
  - Announcements made here
  - Ask and answer questions – staff will monitor and contribute
- Gradescope: https://www.gradescope.com/courses/140414
  - Assignment submissions
- Canvas: https://canvas.uw.edu/courses/1381167
  - Few Quizzes, Zoom Links, and Gradebook
- Poll Everywhere: http://pollev.com/pbjones
  - In-lecture voting

Recommended Textbooks

- *Computer Systems: A Programmer's Perspective*
  - Randal E. Bryant and David R. O'Hallaron
  - Website: http://csapp.cs.cmu.edu
  - Latest edition: (North American) 3rd edition
    - http://csapp.cs.cmu.edu/3e/changes3e.html
    - http://csapp.cs.cmu.edu/3e/errata.html
  - Well done textbook
    - Students have found useful in 351 and beyond
    - Recommended lecture readings on website



- A good C book – any will do
  - *The C Programming Language* (Kernighan and Ritchie)
  - *C: A Reference Manual* (Harbison and Steele)

Course Components:

- Lectures (26)
  - Via Zoom, meant to introduce the concepts
  - Slides posted before, recordings/ink posted after
- Sections (9)
  - Via Zoom, short review then mainly group work
  - Not recorded, but materials/helpful videos posted after
- Office Hours
  - Via Zoom, schedule on the course calendar. Not recorded.
  - Come ask questions! (course material or others)
  - If things are busy we will use a queue for organization. https://tinyurl.com/351-queue

Course Components:

- Pre-quarter and Mid-quarter surveys (on Canvas)
  - Meant to check in and get to know you better
- Online Homework (23)
  - Solidify concept understanding, submitted via Gradescope
- Labs (6)
  - In depth applications/investigations of course material
  - Specs on website, submitted via Gradescope
- Unit Summaries (3)
  - Summaries/reflections on course material
  - Spec on website, submitted via Gradescope
- Can use up to 7 late days on labs and unit summaries (see syllabus for more details)

Grading:

- **Homework:** 25% total
  - Autograded; unlimited submission attempts
  - *Group work encouraged*
- **Labs:** 50% total
  - Graded by TAs; last submission graded
  - *Individual work only (high-level discussions OK)*
- **Unit Summaries:** 15% total
  - Meant to replace the review, summarizing, and reflecting that studying for exams provides. More info on these later.
  - *Individual work only (high-level discussions OK)*
- **Participation:** 10%

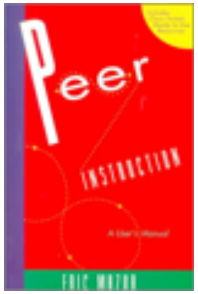
Lab Collaboration and Academic Integrity

- All submissions are expected to be yours and yours alone
- You are encouraged to discuss your assignments with other students (*high level 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)
- Our goal is that *YOU* learn the material so you will be prepared for exams, interviews, and the future

Course Environment and Culture

- It should go without saying we value your physical and mental health above the course material
- Simple course rules:
  - Respect one another
  - Ask questions
  - Have fun!
- If at any point you feel uncomfortable, disrespected, excluded, etc. by any staff member or students, please report the incident so we can address the issue and maintain a supportive and inclusive environment
  - Contact: staff (direct or anonymous), CSE undergraduate advising, UW Office of the Ombud

Lecture Polling



- Increase real-time learning in lecture, test your understanding, increase student interactions
  - Lots of research supports its effectiveness
- Multiple choice question during lecture
  - 1 minute to decide on your own
  - 2-4 minutes in pairs to reach consensus
  - Learn through discussion & teaching
- Vote using Poll Everywhere
  - Use website (https://www.polleverywhere.com) or app
  - Linked to your UWNetID

Lecture Polling Credit

- You receive participation credit for answering poll everywhere questions
  - 1 point for any answer, .05 extra points for correct answer
  - 80% of available points is full credit for participation
- Can makeup lecture credit with Canvas quiz
  - Don’t submit these if you answered in lecture
  - Released after lecture, due 10:30am before next lecture
  - Must include explanation to simulate in-lecture discussion
- First week does ***not*** count for credit

Some fun topics that we will touch on

- Which of the following seems the most interesting to you? (vote at http://pollev.com/pbjones)

a) What are some ways in which hackers exploit your machine?
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) How is your computer able to seemingly run hundreds of applications all at once?

Tips for Success in 351

- Attend all lectures and sections
  - Avoid devices during lecture except for Poll Everywhere
- Review the slides and/or readings before and after lecture
- Learn by doing
  - Can answer many questions by writing small programs
- Visit Piazza often
  - Ask questions and try to answer fellow students’ questions
- Go to office hours
  - Even if you don’t have specific questions in mind
- Start assignments early
- Don’t be afraid to ask questions
- Give us feedback on how things are going this quarter

To-Do List

- Admin
  - Explore/read website *thoroughly*: http://cs.uw.edu/351
  - Check that you are enrolled in Piazza; read posts
  - Log in to Poll Everywhere
  - **Get your machine set up for this class (VM or attu) *as soon as possible***
  - Make sure you're also enrolled in CSE391!
    - TOMORROW, Tuesday 10:50-11:50am
    - https://courses.cs.washington.edu/courses/cse391/20su/
- Assignments – Some this week!
  - Pre-Course Survey (Canvas), hw0 due Wednesday (6/24) – 11:59pm
  - hw1 due Friday (6/26) – 10:30am
  - Lab 0 due Friday (6/26) – 11:59pm

Lecture Outline

- Course Introduction
- Course Policies
- **Binary**
    - **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

thousands hundreds tens ones

- Example: 7061 in decimal (base 10)

power of 10: 3 2 1 0

  - $\underbrace{7061}_{\text{symbol}}{}_{10} = (\underbrace{7}_{\text{symbol}} \times \underbrace{10}_{\text{base}}{}^{3}) + (0 \times 10^{2}) + (6 \times 10^{1}) + (1 \times 10^{0})$

position/power

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…

“eights” digit

ones digit

- Example: What is 7061_8 in base 10?
  - $7061_{\textcircled{8}} = (7 \times 8^3) + (0 \times 8^2) + (6 \times \underline{8^1}) + (1 \times \underline{8^0}) = 3633_{10}$

base 8

now powers of 8

Warmup Question

- What is 34_8 in base 10?
  - No voting for this question

A. 32_{10}

B. 34_{10}

C. 7_{10}

[✓ D. 28_{10}]

E. 35_{10}

$$\overset{8^1}{3}\,\overset{8^0}{4}_{8}$$

$$(3 * 8^1) + (3 * 8^0) = 28_{10}$$

Binary and Hexadecimal

- Binary is base 2
  - Symbols: 0, 1
  - Convention: $2_{10} = 10_2 =$ 0b10

prefix indicating binary

does not affect value

- 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**

10 11 12 13 14 15

🤯

  - Convention: $16_{10} = 10_{16} =$ 0x10

prefix indicating hex

- Example: What is 0xA5 in base 10?
  - 0xA5 = $A5_{16} = (10 \times 16^1) + (5 \times 16^0) = 165_{10}$

symbol

value

Polling Question

- Which of the following orderings is correct?

$0x\,C = 12_{10}$

$11 = 11_{10}$

$0b1010 = 2^3 + 2^1 = 10_{10}$

A. 0xC < 0b1010 < 11
B. 0xC < 11 < 0b1010
C. 11 < 0b1010 < 0xC
[✓ D. 0b1010 < 11 < 0xC]
E. 0b1010 < 0xC < 11

- Think on your own for a minute, then discuss with your neighbor(s)
  - Vote at http://pollev.com/pbjones

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)

Challenge Question

- Convert 13_{10} into binary

$$13_{10} = 8 + 4 + 1$$

$$= 2^3 + 2^2 + 2^0$$

$$= (1 * 2^3) + (1 * 2^2) + (0 * 2^1) + (1 * 2^0)$$

$$= 0b1101$$

- 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

N= ~~13~~ ~~5~~ ~~1~~ 0

0b

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

N = ~~165~~ ~~5~~ 0

0x

$16^2=256$	$16^1=16$	$16^0=1$
0	A	5

↑

10

Converting Binary ↔ Hexadecimal

- Hex → Binary
  - Substitute hex digits, then drop any leading zeros
  - Example: 0x2D to binary
    - 0x2 is 0b0010, 0xD is 0b1101 =0b ~~00~~10 1101
    - Drop two leading zeros, answer is 0b101101

drop leading 0s

- Binary → Hex
  - Pad with leading zeros until multiple of 4, then substitute each group of 4
  - Example: 0b101101 only 6 digits....
    - 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? 15
  - Pad: 0b 0100 1101 1010 1101
  - Substitute: 0x4DAD

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

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

4 bits $\underline{2}\cdot\underline{2}\cdot\underline{2}\cdot\underline{2}$ = 16 patterns

n bits = 2^n patterns

- 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!*

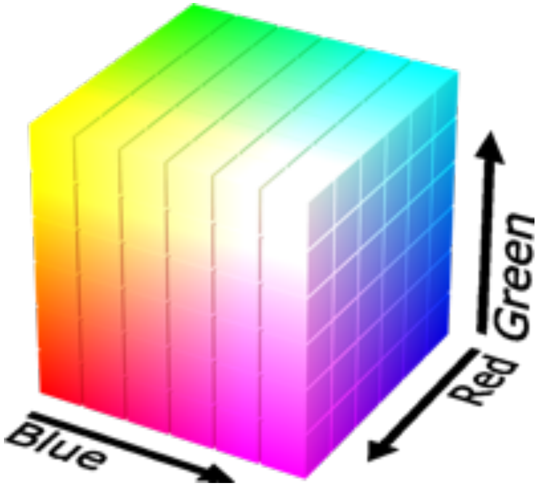
- Consider the hex sequence 0x4E6F21
  - Common interpretations include:
    - The decimal number 5140257
    - The characters "No!"
    - The background color of this slide
    - The real number 7.203034 × 10^{-39}

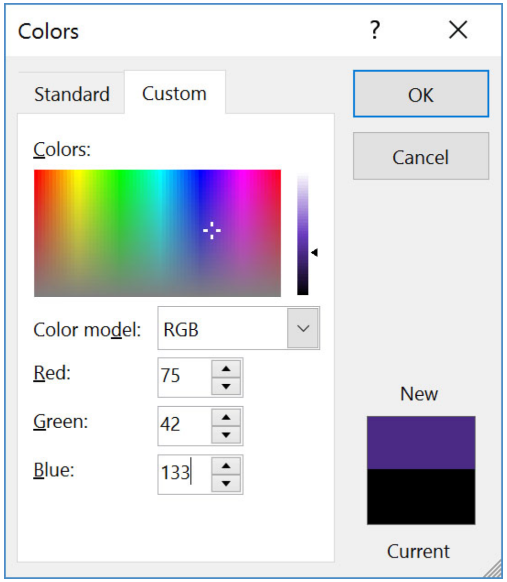
- It is up to the program/programmer to decide how to interpret the sequence of bits

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**

R: 213
G: 111
B: 56

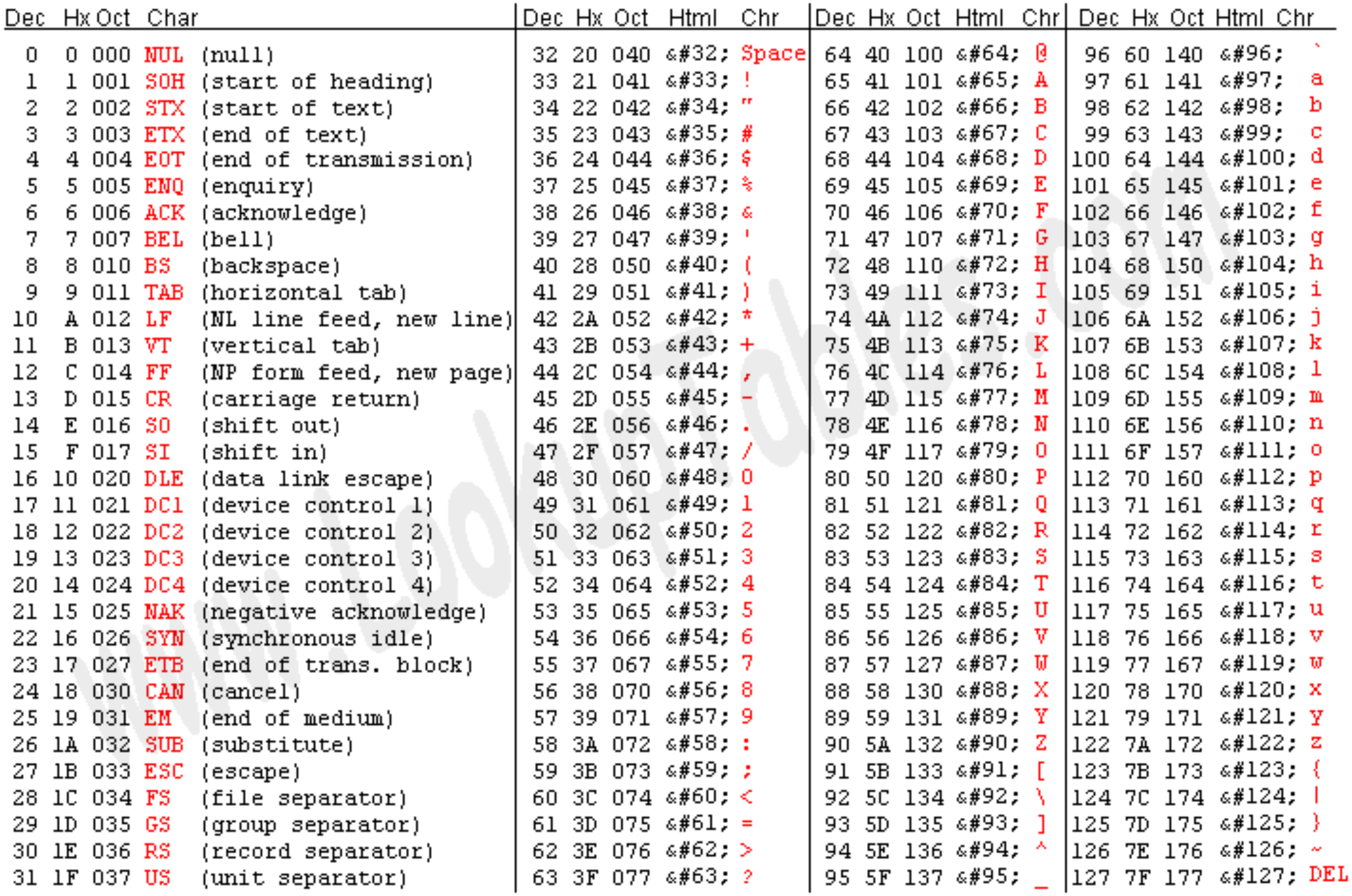




Color model: RGB
Red: 75
Green: 42
Blue: 133

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

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