# The Hardware/Software Interface

CSE 351 Spring 2019

**Instructor:**

Ruth Anderson

**Teaching Assistants:**

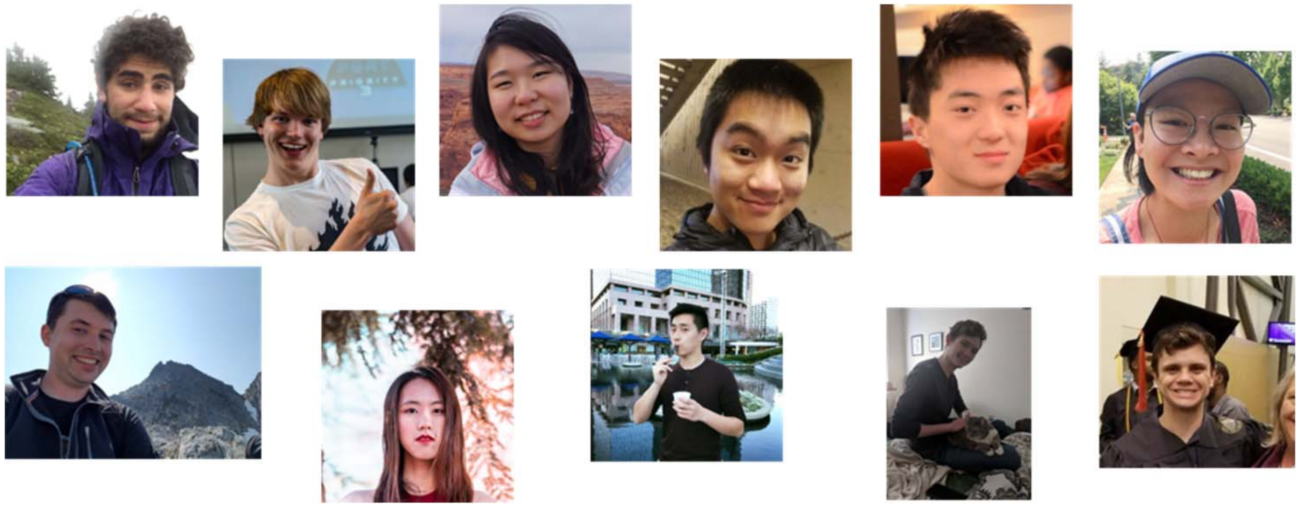
Gavin Cai
Jack Eggleston
John Feltrup
Britt Henderson
Richard Jiang
Jack Skalitzky
Sophie Tian
Connie Wang
Sam Wolfson
Casey Xing
Chin Yeoh

AN x64 PROCESSOR IS SCREAMING ALONG AT BILLIONS OF CYCLES PER SECOND TO RUN THE XNU KERNEL, WHICH IS FRANTICALLY WORKING THROUGH ALL THE POSIX-SPECIFIED ABSTRACTION TO CREATE THE DARWIN SYSTEM UNDERLYING OS X, WHICH IN TURN IS STRAINING ITSELF TO RUN FIREFOX AND ITS GECKO RENDERER, WHICH CREATES A FLASH OBJECT WHICH RENDERS DOZENS OF VIDEO FRAMES EVERY SECOND
BECAUSE I WANTED TO SEE A CAT JUMP INTO A BOX AND FALL OVER.
I AM A GOD.

http://xkcd.com/676/

## Introductions: Course Staff

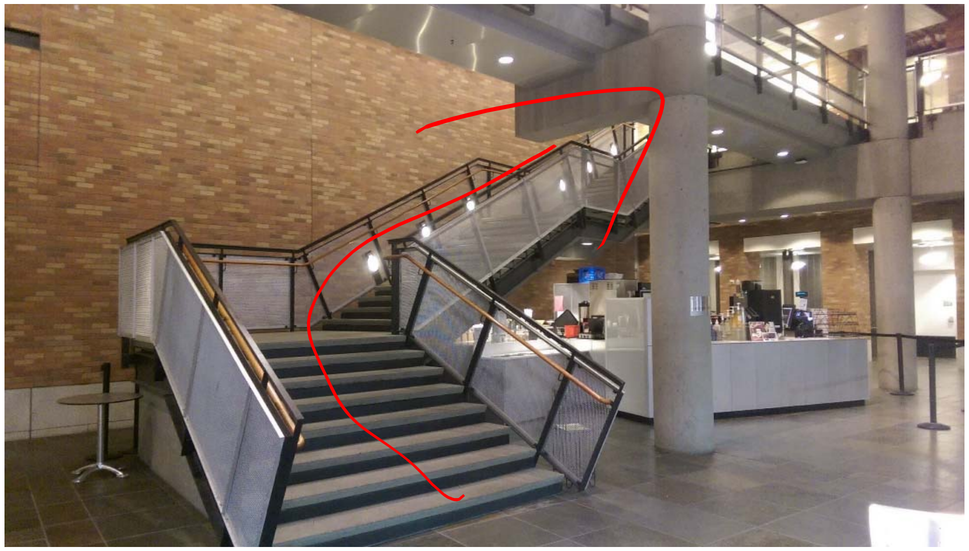
- Instructor: Ruth Anderson
  - Learn more about me and the staff on the course website!
- TAs:

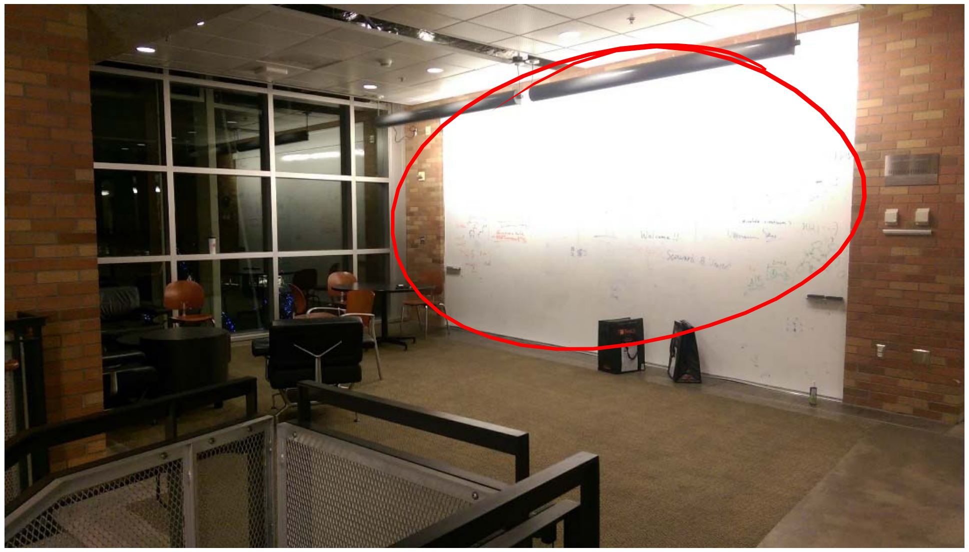


  - Available in section, office hours, and on Piazza
  - An invaluable source of information and help
- Get to know us
  - We are here to help you succeed!

## TA Office Hours – in Allen Center (CSE)

- CSE 2nd floor breakout
  - Up the stairs in the CSE Atrium (next to the café)
  - At the top of that first flight, the open area with the whiteboard wall is the 2nd floor breakout!

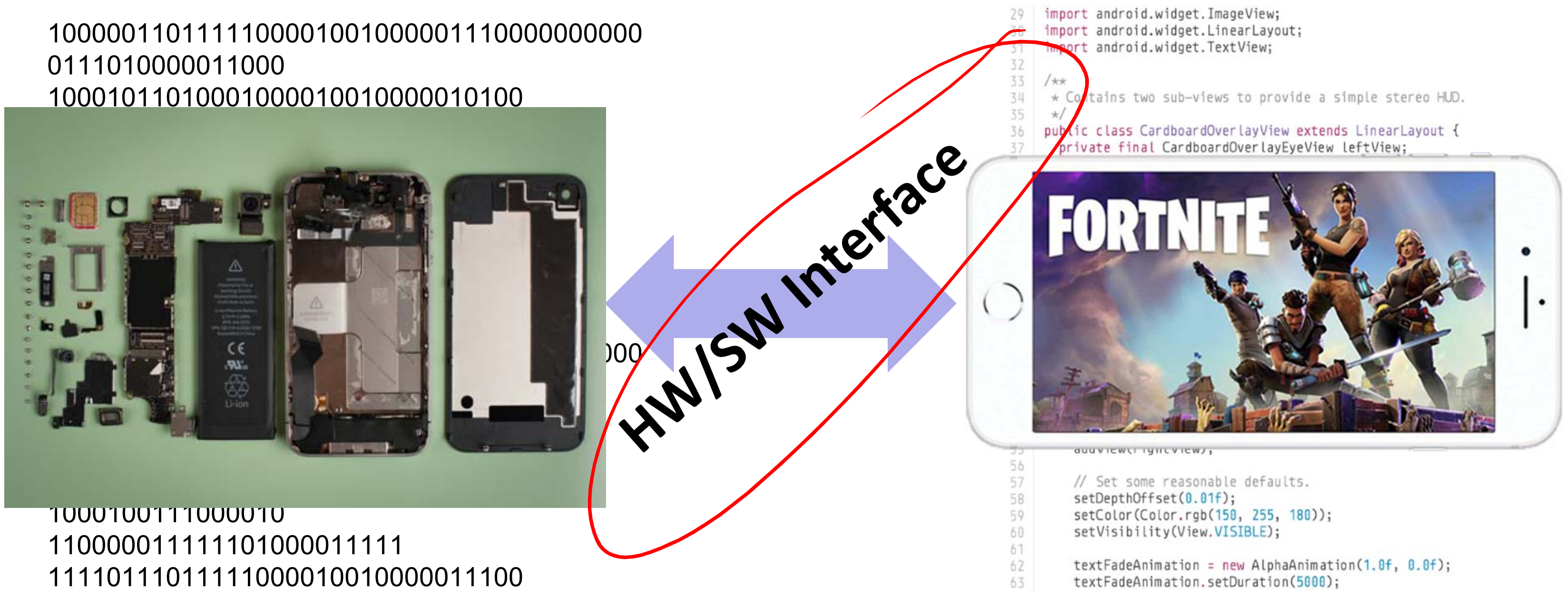




## Introductions: You!

- ~250 students registered, split across two lectures
- 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!



```
10000001101111110000100100000011100000000000
0111010000011000
100010110100010000100100000010100
000
10001001110000010
110000011111101000011111
111101110111110000100100000011100
```

```
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;
```

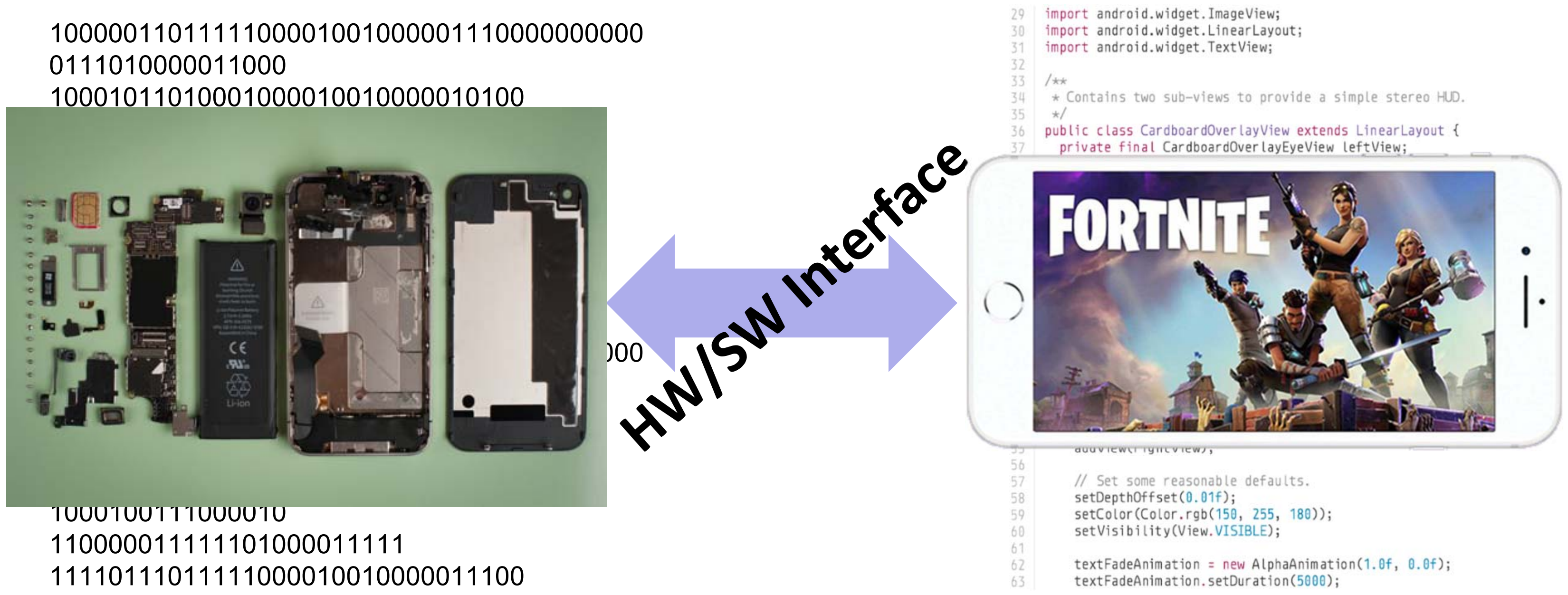
```
    addView(rightView);

    // 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?

## Welcome to CSE351!



```
100000110111111000010010000011100000000000
0111010000011000
10001011010001000010010000010100
000
1000100111000010
1100000111111010000011111
11110111011111000010010000011100
```

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

/**
 * Contains two sub-views to provide a simple stereo HUD.
 */
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    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;
```

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

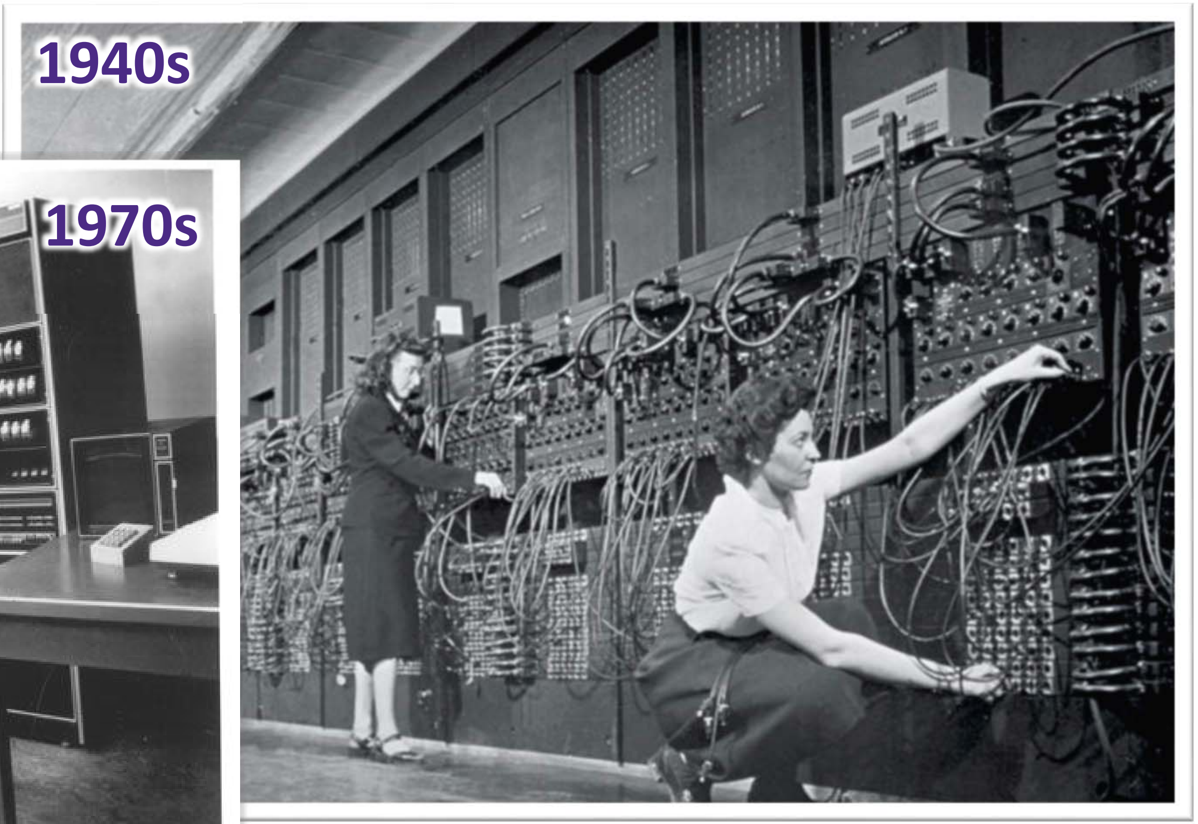
Assembler

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

Machine Code

## HW/SW Interface: Historical Perspective

- Hardware started out quite primitive

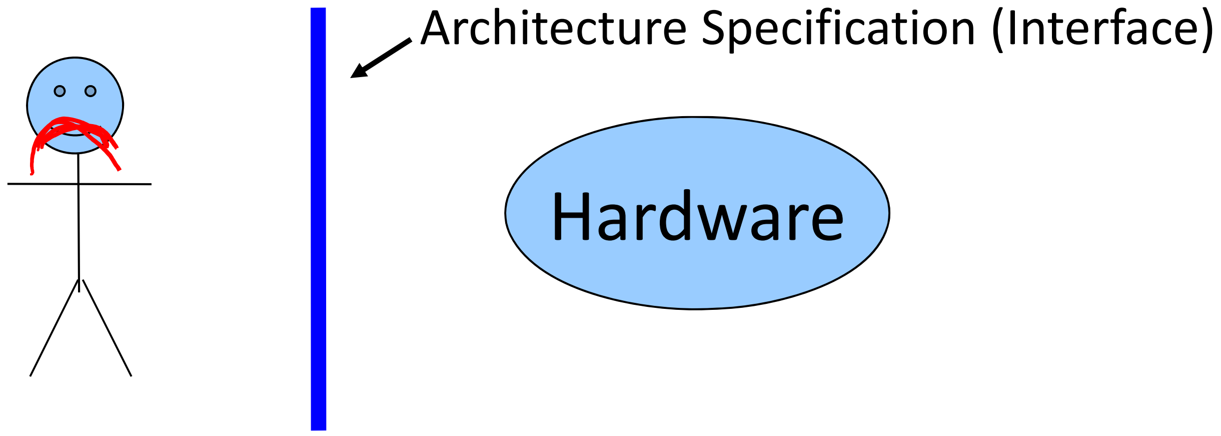


https://s-media-cache-ak0.pinimg.com/564x/91/37/23/91372375e2e6517f8af128aab655e3b4.jpg

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/

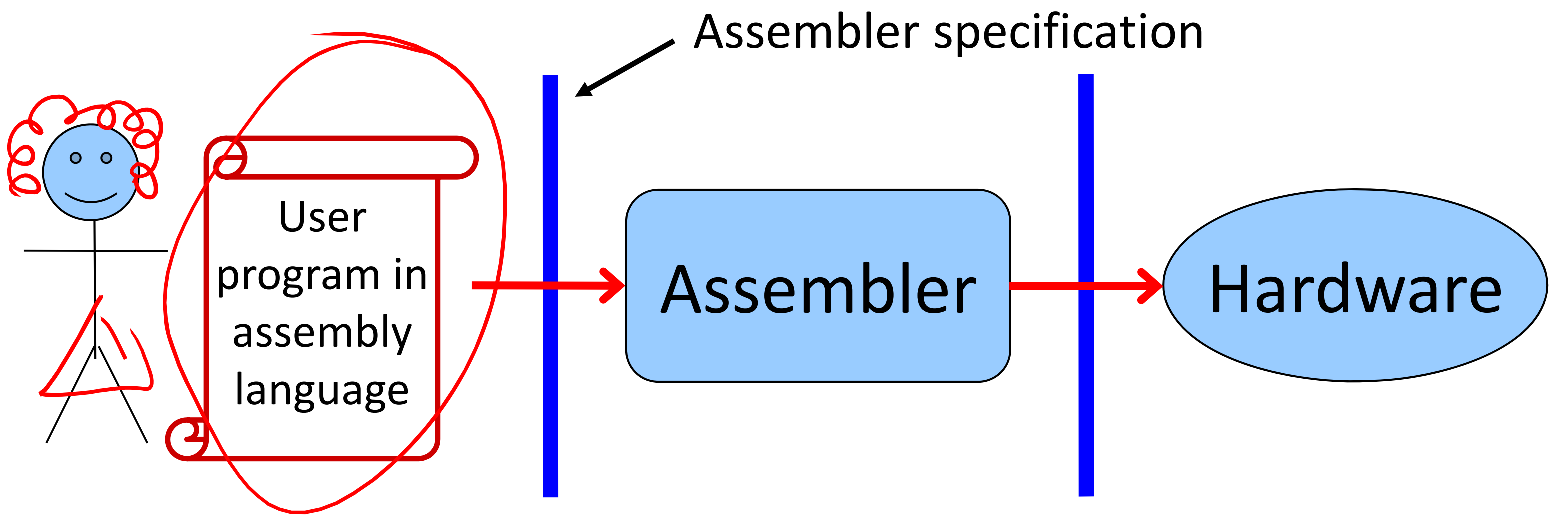
## HW/SW Interface: Historical Perspective

- 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



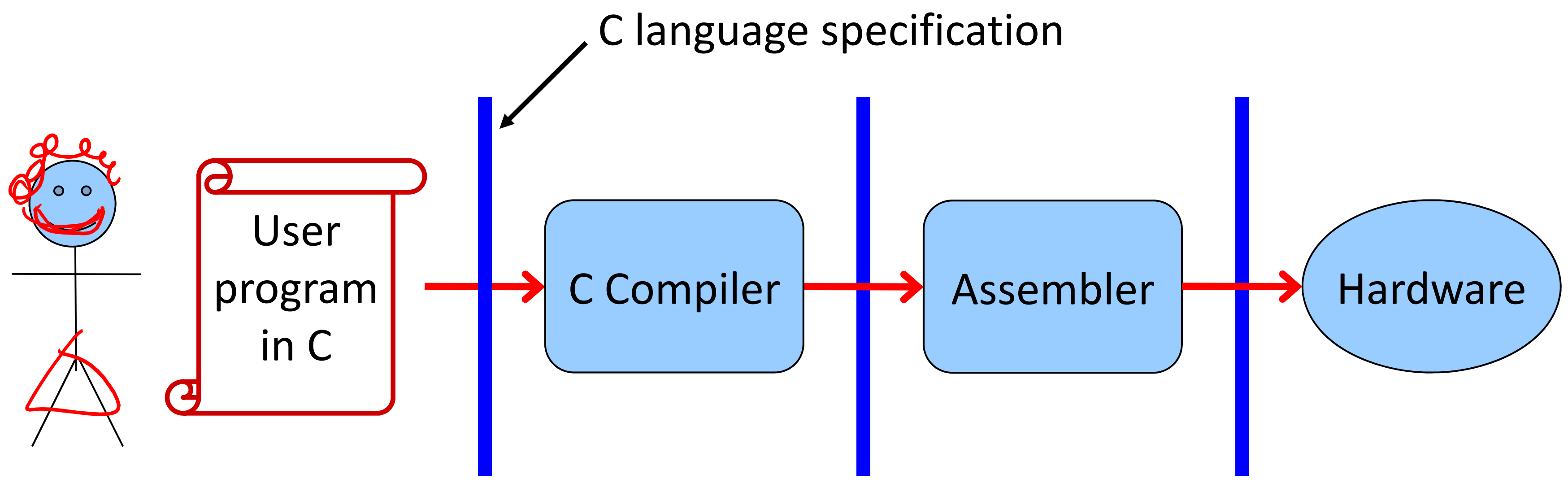
## HW/SW Interface: Assemblers

- 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

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:

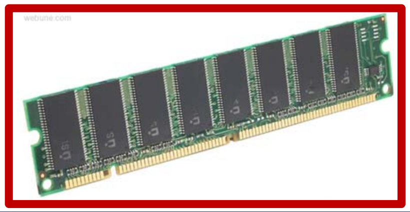
```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

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

## 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

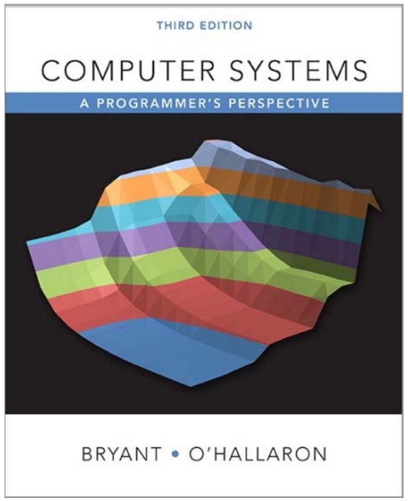
- Course Introduction
- **Course Policies**
  - https://courses.cs.washington.edu/courses/cse351/19sp/syllabus/
- Binary

## Bookmarks

- Course Website: http://cs.uw.edu/351
  - Schedule, policies, materials, videos, assignments, etc.
- Discussion: http://piazza.com/washington/spring2019/cse351
  - Announcements made here
  - Ask and answer questions – staff will monitor and contribute
- Canvas: https://canvas.uw.edu/courses/1271313
  - Assignment submissions and gradebook
- Poll Everywhere: http://PollEv.com/rea
  - In-lecture voting

## Textbooks

- *Computer Systems: A Programmer's Perspective*
  - Randal E. Bryant and David R. O'Hallaron
  - Website: http://csapp.cs.cmu.edu
  - Must be (North American) 3rd edition
    - http://csapp.cs.cmu.edu/3e/changes3e.html
    - http://csapp.cs.cmu.edu/3e/errata.html
  - This book really matters for the course!
    - Lecture readings
    - Practice problems and homework



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

## Grading

- **Homework:** 20% total
  - Autograded; 20 submission attempts
  - *Group work okay*
- **Labs:** 30% total
  - Graded by TAs; last submission graded
  - *Individual work only*
- **Exams:** Midterm (15%) and Final (30%)
  - Midterm date is still tentative!!
  - Many old exams on course website
- **EPA:** Effort, Participation, and Altruism (5%)

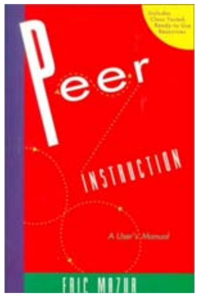
## Collaboration and Academic Integrity

- 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)
- Our goal is that *YOU* learn the material so you will be prepared for exams, interviews, and the future

## EPA

- Encourage class-wide learning!
- Effort
  - Attending office hours, completing all assignments
  - Keeping up with Piazza activity
- Participation
  - Making the class more interactive by asking questions in lecture, section, office hours, and on Piazza
  - Peer instruction voting
- Altruism
  - Helping others in section, office hours, and on Piazza

## Peer Instruction



- Increase real-time learning in lecture, test your understanding, increase student interactions
  - Lots of research supports its effectiveness
- Multiple choice question at end of lecture "segment"
  - 1 minute to decide on your own
  - 2-4 minutes in pairs to reach consensus
  - Learn through discussion

- Vote using Poll Everywhere
  - Use website (https://www.polleverywhere.com) or app
  - Linked to your UWNetID

## Some fun topics that we will touch on

- Which of the following seems the most interesting to you? (vote at [http://pollEv.com/rea](http://pollEv.com/rea))

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, # and size of cache, supported memory types)

## Tips for Success in 351

- Attend all lectures and sections
  - Avoid devices during lecture except for Poll Everywhere
- Do the textbook readings ahead of time
- 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
- Find a study and homework group
- Start assignments early
- Don't be afraid to ask questions

## 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! (EEs included)
    - TOMORROW, Tuesday 1:30-2:20 in CSE2 G20
- Assignments
  - Pre-Course Survey due Wednesday (4/03)
  - Lab 0 due Monday (4/08)
  - HW 1 due Wednesday (4/10)

## 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
- Example: 7061$_{10}$ in decimal (base 10)
  - $7061_{10} = (7 \times 10^3) + (0 \times 10^2) + (6 \times 10^1) + (1 \times 10^0)$

$10^3$ $10^2$ $10^1$ $10^0$

## 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…`

"eight's digit"

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

subscript indicates base

now powers of 8

## Warmup Question

- What is $34_8$ in base 10?

  A. $32_{10}$
  B. $34_{10}$
  C. $7_{10}$
  [✓ D. $28_{10}$]
  E. $35_{10}$

$$3 \cdot 8^1 + 4 \cdot 8^0$$

$$24 + 4 = 28_{10}$$

- Think on your own for a minute, then discuss with your neighbor(s)
  - No voting for this question

## Binary and Hexadecimal

- Binary is base 2
  - Symbols: 0, 1
  - Convention: $2_{10} = 10_2 = \underline{0b}10$ ← "zero bee"
- 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, $\underset{10}{\text{A}}$, $\underset{11}{\text{B}}$, $\underset{12}{\text{C}}$, $\underset{13}{\text{D}}$, $\underset{14}{\text{E}}$, $\underset{15}{\text{F}}$ ← values
  - Convention: $16_{10} = 10_{16} = \underline{0x}10$ ← "zero ex"
- Example: What is 0xA5 in base 10?
  - $0xA5 = \underset{\text{symbol}}{\textcircled{A}}5_{16} = (\underset{\text{value}}{\textcircled{10}} \times 16^1) + (5 \times 16^0) = 165_{10}$

## Peer Instruction Question

- Which of the following orderings is correct?

  A. 0xC < 0b1010 < 11
  B. 0xC < 11 < 0b1010
  C. 11 < 0b1010 < 0xC
  $\boxed{\text{D. 0b1010 < 11 < 0xC}}$
  E. 0b1010 < 0xC < 11

$0xC = 12_{10}$

$0b\overset{3}{1}\overset{2}{0}\overset{1}{1}\overset{0}{0} = 1\times2^3 + 1\times2^1 = 8+2 = 10_{10}$

$11 = 11_{10}$

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

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

0b1101

$8+4 \quad +1 = 13$ ☑

- Discuss with your neighbor(s)
  - 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 $\geq$ N
  2. Then from *left to right*, ask is that (power of 2) $\leq$ 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

$$\begin{array}{r} -8 \\ \hline 5 \\ -4 \\ \hline 1 \end{array}$$

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

$$\begin{array}{r} -160 \\ \hline 5 \end{array}$$

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

0xA5

# Converting Binary ↔ Hexadecimal

- Hex → Binary
  - Substitute hex digits, then drop any leading zeros
  - Example: 0x2D to binary
    - 0x2 is 0b0010, 0xD is 0b1101 00101101 "can drop"
    - 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 6 digits
    - Pad to 0b0010 1101
    - Substitute to get 0x2D

| Base 10 | Base 2 (binary) | Base 16 (hex) |
|---|---|---|
| 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: 0100 1101 1010 1101
  - Substitute: $\boxed{0x4DAD}$

| 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

- 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?

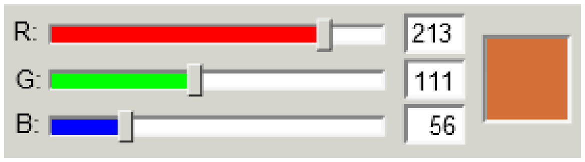
- *A sequence of bits can have many meanings!*

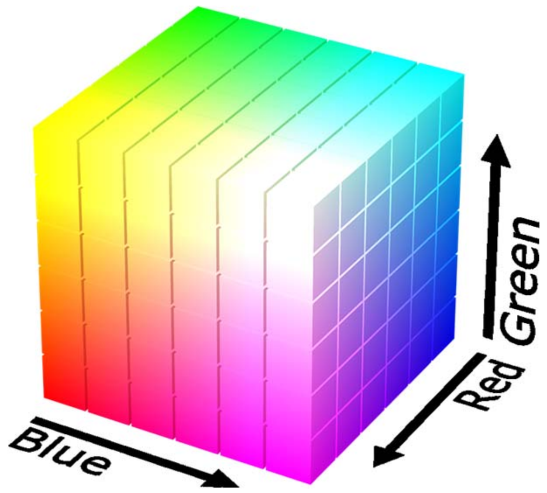
- Consider the hex sequence 0x4E6F21
  - Common interpretations include:
    - The decimal number 5140257
    - The characters "No!"
    - The background color of this slide
    - The real number $7.203034 \times 10^{-39}$

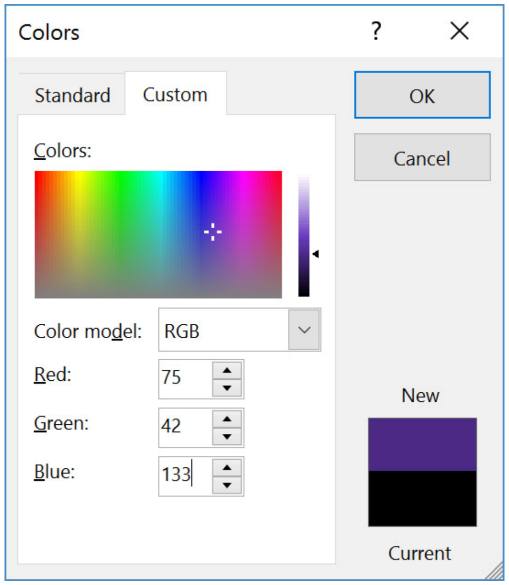
- It is up to the program/programmer to decide how to interpret the sequence of bits

# 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

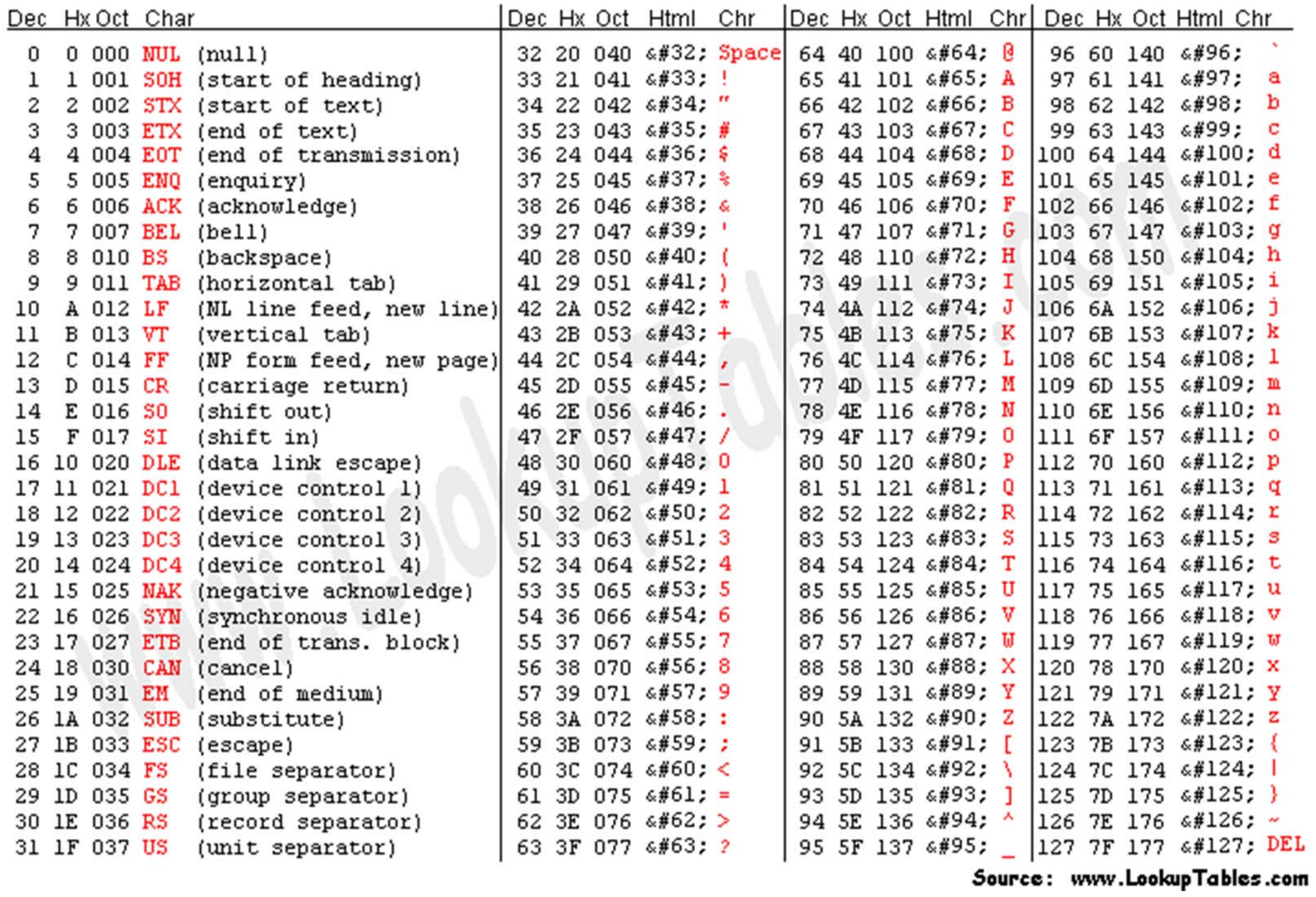




Color model: RGB
Red: 75
Green: 42
Blue: 133

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