The Hardware/Software Interface
CSE 351 Winter 2020

Instructor:
Ruth Anderson

Teaching Assistants:
Jonathan Chen
Justin Johnson
Porter Jones
Josie Lee
Jeffery Tian
Callum Walker
Eddy (Tianyi) Zhou

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 2\textsuperscript{nd} 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 2\textsuperscript{nd} floor breakout!
Introductions: You!

- ~150 students registered

- 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!

- 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;
```

### 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

```
01000001101111111000010010000000111000000000000
01111010000011000
10001011010001000100010001000101000010100
1000110100000000000000000010
1000100111000010
11000000111111010000011111
1111011101111100000100100000011100
100010010100001000010000011000
```

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

### Assembly Language

### Machine Code
HW/SW Interface: Historical Perspective

- Hardware started out quite primitive

Jean Jennings (left), Marlyn Wescoff (center), and Ruth Lichterman program ENIAC at the University of Pennsylvania, circa 1946. Photo: Corbis

**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

![Diagram](image_url)
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:

```c
 car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```java
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg = c.getMPG();
```

Assembly language:

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

Machine code:

```
0111010000110000 1000110100000100 00000010
1000100111000010 1100000111110101 0100001111
```

Computer system:

```
Intel Core i5
```

OS:

```
Windows 10
OS X Yosemite
```

Memory & data
Integers & floats
x86 assembly
Procedures & stacks
Executables
Arrays & structs
Virtual memory
Memory & caches
Memory allocation
Java vs. C
What happens as your computer is executing one or more processes?

C:
```c
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:
```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
11000001111111010100001111
```

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/cse351/20wi/syllabus/
- Binary
Bookmarks

❖ Course Website:  http://cs.uw.edu/351
  ▪ Schedule, policies, materials, videos, assignments, etc.

❖ Discussion:
  http://piazza.com/washington/winter2020/cse351
  ▪ Announcements made here
  ▪ Ask and answer questions – staff will monitor and contribute

❖ Gradescope:  https://www.gradescope.com/courses/75879
  ▪ Assignment submissions

❖ Canvas:  https://canvas.uw.edu/courses/1352194
  ▪ 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](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/changes3e.html)
    - [http://csapp.cs.cmu.edu/3e/errata.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; unlimited submission attempts
  - *Group work encouraged*

- **Labs**: 30% total
  - Graded by TAs; last submission graded
  - *Individual work only*

- **Exams**: Midterm (15%) and Final (30%)
  - Many old exams on course website

- **EPA**: Effort, Participation, and Altruism (5%)
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)
- 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
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
Some fun topics that we will touch on

- Which of the following seems the most interesting to you? (vote at 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](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 2:30-3:20 in SIG 134

❖ **Assignments**
  - Pre-Course Survey and hw0 due Wednesday (1/08) – 11:59pm  
  - hw1 due Friday (1/10) – 11am & Lab 0 due Friday (1/10) – 11:59pm
  - hw2 due Monday (1/13) – 11am
  - hw3 due Wednesday (1/15) – 11am, etc.

*Special case!*
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 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 34₈ in base 10?

- No voting for this question

A. 32₁₀
B. 34₁₀
C. 7₁₀
D. 28₁₀
E. 35₁₀
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?
  - $0xA5 = A5_{16} = (10 \times 16^1) + (5 \times 16^0) = 165_{10}$
Polling Question

Which of the following orderings is correct?

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/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\textsubscript{10} into binary_

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

- **Discuss with your neighbor(s)**
  - No voting for this question
Converting from Decimal to Binary

- Given a decimal number N:
  - List increasing powers of 2 from *right to left* until $\geq N$
  - 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

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$2^4 = 16$</td>
<td>$2^3 = 8$</td>
<td>$2^2 = 4$</td>
<td>$2^1 = 2$</td>
<td>$2^0 = 1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Converting from Decimal to Base B

- Given a decimal number N:
  - List increasing powers of B from right to left until \( \geq N \)
  - Then from left to right, ask is that (power of B) \( \leq N \)?
    - If \textbf{YES}, put \textit{how many} of that power go into N and subtract from N
    - If \textbf{NO}, put a 0 below and keep going

- **Example**: 165 to hex

  \[
  \begin{array}{ccc}
  16^2=256 & 16^1=16 & 16^0=1 \\
  \end{array}
  \]
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
Binary → Hex Practice

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

<table>
<thead>
<tr>
<th>Base 10</th>
<th>Base 2</th>
<th>Base 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0000</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0001</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0010</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0011</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>0100</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>0101</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>0110</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>0111</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>1001</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>1010</td>
<td>A</td>
</tr>
<tr>
<td>11</td>
<td>1011</td>
<td>B</td>
</tr>
<tr>
<td>12</td>
<td>1100</td>
<td>C</td>
</tr>
<tr>
<td>13</td>
<td>1101</td>
<td>D</td>
</tr>
<tr>
<td>14</td>
<td>1110</td>
<td>E</td>
</tr>
<tr>
<td>15</td>
<td>1111</td>
<td>F</td>
</tr>
</tbody>
</table>
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!

<table>
<thead>
<tr>
<th>Base 10</th>
<th>Base 2</th>
<th>Base 16</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0000</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0001</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0010</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0011</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>0100</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>0101</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>0110</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>0111</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>1000</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>1001</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>1010</td>
<td>A</td>
</tr>
<tr>
<td>11</td>
<td>1011</td>
<td>B</td>
</tr>
<tr>
<td>12</td>
<td>1100</td>
<td>C</td>
</tr>
<tr>
<td>13</td>
<td>1101</td>
<td>D</td>
</tr>
<tr>
<td>14</td>
<td>1110</td>
<td>E</td>
</tr>
<tr>
<td>15</td>
<td>1111</td>
<td>F</td>
</tr>
</tbody>
</table>
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
# Binary Encoding – Characters/Text

- **ASCII Encoding** ([www.asciitable.com](http://www.asciitable.com))
  - **American Standard Code for Information Interchange**

<table>
<thead>
<tr>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Char</th>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Html</th>
<th>Chr</th>
<th>Dec</th>
<th>Hx</th>
<th>Oct</th>
<th>Html</th>
<th>Chr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>000</td>
<td>NUL (null)</td>
<td>32</td>
<td>20</td>
<td>040</td>
<td> </td>
<td>Space</td>
<td>64</td>
<td>40</td>
<td>100</td>
<td> </td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>001</td>
<td>SOH (start of heading)</td>
<td>33</td>
<td>21</td>
<td>041</td>
<td> </td>
<td>!</td>
<td>65</td>
<td>41</td>
<td>101</td>
<td> </td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>002</td>
<td>STX (start of text)</td>
<td>34</td>
<td>22</td>
<td>042</td>
<td> </td>
<td>&quot;</td>
<td>66</td>
<td>42</td>
<td>102</td>
<td> </td>
<td>B</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>003</td>
<td>ETX (end of text)</td>
<td>35</td>
<td>23</td>
<td>043</td>
<td> </td>
<td>#</td>
<td>67</td>
<td>43</td>
<td>103</td>
<td> </td>
<td>C</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>004</td>
<td>EOT (end of transmission)</td>
<td>36</td>
<td>24</td>
<td>044</td>
<td> </td>
<td>$</td>
<td>68</td>
<td>44</td>
<td>104</td>
<td> </td>
<td>D</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>005</td>
<td>ENQ (enquiry)</td>
<td>37</td>
<td>25</td>
<td>045</td>
<td> </td>
<td>%</td>
<td>69</td>
<td>45</td>
<td>105</td>
<td> </td>
<td>E</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>006</td>
<td>ACK (acknowledge)</td>
<td>38</td>
<td>26</td>
<td>046</td>
<td> </td>
<td>&amp;</td>
<td>70</td>
<td>46</td>
<td>106</td>
<td> </td>
<td>F</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>007</td>
<td>BEL (bell)</td>
<td>39</td>
<td>27</td>
<td>047</td>
<td> </td>
<td>'</td>
<td>71</td>
<td>47</td>
<td>107</td>
<td> </td>
<td>G</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>010</td>
<td>BS (backspace)</td>
<td>40</td>
<td>28</td>
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Source: [www.LookupTables.com](http://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