The Hardware/Software Interface

CSE 351 Winter 2018

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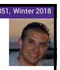
http://xkcd.com/676/

Welcome to CSE351!

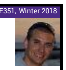
- See the key abstractions "under the hood" to describe "what really happens" when a program runs
  - How is it that "everything is 1s and 0s"?
  - Where does all the data get stored and how do you find it?
  - How can more than one program run at once?
  - What happens to a Java or C program before the hardware executes it?
  - And much, much, much more…
- An *introduction* that will:
  - Profoundly change/augment your view of computers and programs
  - Connect your source code down to the hardware
  - Leave you impressed that computers ever work

Who: Course Staff



- Your Instructor: call me Mark
- TAs:
  - Available in section, office hours, via email, on Piazza
  - An invaluable source of information and help
- Get to know us
  - We are here to help you succeed!

About Me



- CSE PhD student, Computer Architecture
- Washington native
- Food lover – I'll try to cook almost anything
- Post-Grad Scholar at AMD Research during 2017
  - Also, 18 of past 24 months
  - Future GPU microarchitecture for compute applications
- Teaching 351 for the first time!
  - TA'd in Wi13, Wi14, and Su14 (Coursera offering)

Who are You?

- ~ 115 students registered, single lecture
  - See me if you are interested in taking the class but are not yet 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

Registration

- If you need to register for the course:
  - https://goo.gl/forms/L7dG4a9RYfJzucZ72
- There is an option for EE – 351 only
- Non-majors: select 'Other' for major
- Continue to attend lectures!
- Go to a section with open space tomorrow
- See me after class to write down UW-ID

The Hardware/Software Interface

- Why do we need a hardware/software interface?
- Why do we need to understand both sides of this interface?

C/Java, assembly, and machine code

```
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

```
10000011011111000010010000011100000000000
0111010000011000
10001011010001000010010000010100
10001011010001100010010100010100
100011010000010000000010
1000100111000010
1100000111111010000011111
11110111011111000010010000011100
10001001010001000010010000011000
```

Machine Code

C/Java, assembly, and machine code

```
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:
```

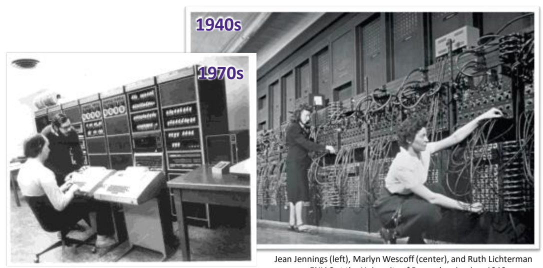
Assembler

```
10000011011111000010010000011100000000000
0111010000011000
10001011010001000010010000010100
10001011010001100010010100010100
100011010000010000000010
1000100111000010
1100000111111010000011111
11110111011111000010010000011100
10001001010001000010010000011000
```

- All program fragments are equivalent
- You'd rather write C! (more human-friendly)
- Hardware executes strings of bits
  - The machine instructions are actually much shorter than the number of bits we would need to represent the characters in the assembly language
  - In reality everything is voltages and electrical signals

HW/SW Interface: Historical Perspective

- Hardware started out quite primitive

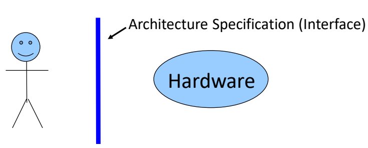


https://s-media-cache-ak0.pinimg.com/564x/91/37/23/91372375e2e6517f8af128aab655e3b4.jpg

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/

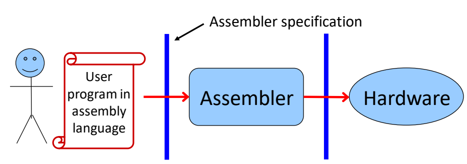
HW/SW Interface: Historical Perspective

- 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



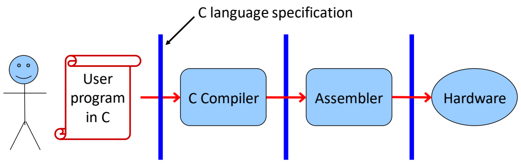
HW/SW Interface: Assemblers

- 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

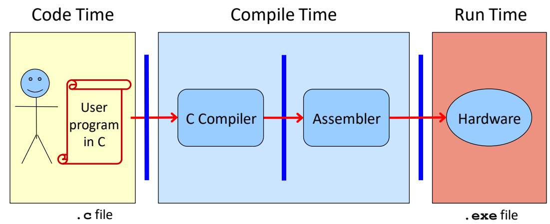


HW/SW Interface: Higher-Level Languages

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

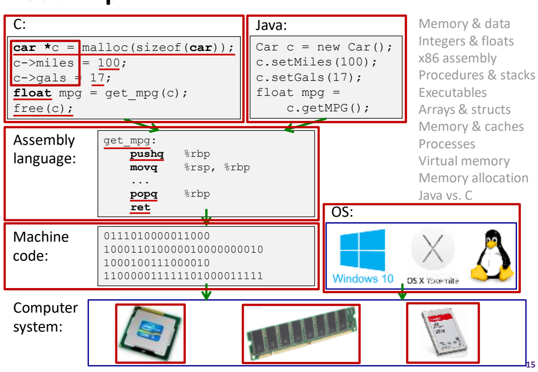


HW/SW Interface: Compiled Programs



Note: The compiler and assembler are just programs, developed using this same process.

Roadmap



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

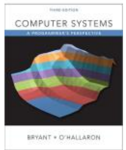
- Course Introduction
- **Course Policies**
  - https://courses.cs.washington.edu/courses/cse351/18wi/syllabus/
- Binary

Communication

- Website: http://cs.uw.edu/351
  - Schedule, policies, materials, videos, assignments, etc.
- Discussion: http://piazza.com/washington/winter2018/cse351
  - Announcements made here
  - Ask and answer questions – staff will monitor and contribute
- Office Hours: spread throughout the week
  - Can also e-mail to make individual appointments
- Anonymous feedback:
  - Comments about anything related to the course where you would feel better not attaching your name
  - Can send to individual staff member of whole staff

Textbooks

- *Computer Systems: A Programmer's Perspective*
  - Randal E. Bryant and David R. O'Hallaron
  - Website: http://csapp.cs.cmu.edu
  - Must be 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!
    - How to solve labs
    - 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)



Course Components

- Lectures (26)
  - Introduce the concepts; supplemented by textbook
- Sections (10)
  - Applied concepts, important tools and skills for labs, clarification of lectures, exam review and preparation
- Online homework assignments (5)
  - Problems to solidify understanding; submitted as Canvas quizzes
- Programming lab assignments (5.5)
  - Provide in-depth understanding (via practice) of an aspect of system
- Exams (2)
  - **Midterm:** Monday, February 5, in class
  - **Final:** Wednesday, March 14, 2:30-4:20pm (UW assigned time/location)

Grading

- **Homework:** 20% total
  - Autograded; 20 submission attempts
  - *Group work okay*
- **Labs:** 35% total
  - Graded by TAs; last submission graded
  - *Individual work only*
- **Exams:** Midterm (15%) and Final (30%)
  - Many old exams on course website (soon)
- More details on course website

Due Dates and Late Work Policy

- **Homework**
  - No late days/submissions.
- **Labs**
  - Turn in by the deadline, or 20% per day penalty
  - **No penalty-free late days**
  - 20% off per day, through 4th day after due date
  - Score = min(graded score, 100% - 20% * num_late_days)
    - num_late_days = ceil(hours late / 24)
    - E.g., if you receive 89%, but you turned it in within 24 hours after due date, your score will be 80%
- **Complete assignments by their due date!**

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

Course Environment and Culture

- Simple rules for our course:
  - Respect one another
  - Ask questions
  - Have fun!
- If at any point you feel uncomfortable, disrespected, excluded, etc. by any staff member or another student, please report the incident so we may address the issue and maintain a supportive and inclusive learning environment.
  - Contact: staff (direct or anonymous), CSE undergraduate advising, UW Office of the Ombud

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

- In-person voting during lecture
  - May switch to PollEverywhere if the in-person thing doesn't work well

Some fun topics that we will touch on

- Which of the following seems the most interesting to you? (show of hands)

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 (i.e., listen, engage, and ask questions)
- 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
  - **Get your machine set up for this class (VM or attu) *as soon as possible***
- Assignments
  - Pre-Course Survey due Friday (1/5)
  - Lab 0 due Monday (1/8)
  - HW 1 due Wednesday (1/10)

Other Details

- Consider taking CSE 391 Unix Tools, 1 credit
  - Useful skills to know and relevant to this course
  - Available to all CSE majors and anyone **registered** in this CSE351
  - If you are interested in taking this, attend the first lecture!!

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

Peer Instruction Question

- What is 34_8 in base 10?

  A. 32_{10}
  B. 34_{10}
  C. 7_{10}
  D. 28_{10}
  E. 35_{10}

- Think on your own for a minute, then discuss with your neighbor(s)

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 $= A5_{16} = (10 \times 16^1) + (5 \times 16^0) = 165_{10}$

Peer Instruction 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)

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

13_{10} = ?
13 = 8 + 4 + 1
Binary: 0b 1 1 0 1
Dec: 8 4 1

- Think on your own for a minute, then discuss with your neighbor(s)

Converting from Decimal to Binary

- Given a decimal number N:
  - List increasing powers of 2 from *right to left* until ≥ N
  - 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
0	**1**	**1**	**0**	**1**

Converting from Decimal to Base B

- Given a decimal number N:
  - List increasing powers of B from *right to left* until ≥ N
  - 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
0	**A**	**5**

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? **15**
  - Pad: **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

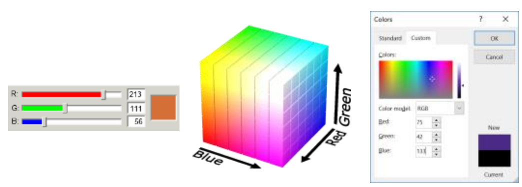
- With N binary digits, how many "things" can you represent?
  - Need N binary digits to represent n things, where $2^N \geq n$
  - Example: 5 binary digits for alphabet because $2^5 = 32 > 26$
- A binary digit is known as a bit
- A group of 4 bits (1 hex digit) is called a nibble
- A group of 8 bits (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

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