

The Hardware/Software Interface

CSE 351 Spring 2021

Instructor:

Ruth Anderson

Teaching Assistants:

Allen Aby

Joy Dang

Alena Dickmann

Catherine Guevara

Corinne Herzog

Ian Hsiao

Diya Joy

Jim Limprasert

Armin Magness

Aman Mohammed

Monty Nitschke

Allie Pflieger

Neil Ryan

Alex Saveau

Sanjana Sridhar

Amy Xu



<http://xkcd.com/676/>

Lecture Outline

- ❖ **Course Introduction**
- ❖ Course Policies
 - <https://courses.cs.washington.edu/courses/cse351/21sp/syllabus>
- ❖ Binary and Numerical Representation

Introductions: Course Staff

- ❖ Ruth Anderson (Instructor)
 - ❖ Allen Aby
 - ❖ Joy Dang
 - ❖ Alena Dickmann
 - ❖ Catherine Guevara
 - ❖ Corinne Herzog
 - ❖ Ian Hsiao
 - ❖ Diya Joy
 - ❖ Jim Limprasert
 - ❖ Armin Magness
 - ❖ Aman Mohammed
 - ❖ Monty Nitschke
 - ❖ Allie Pflieger
 - ❖ Neil Ryan
 - ❖ Alex Saveau
 - ❖ Sanjana Sridhar
 - ❖ Amy Xu
- Learn more about me and the staff on the course website!
 - Available in section, office hours, and on Ed Discussion
 - An invaluable source of information and help
 - ❖ **Get to know us**
 - We are here to help you succeed!

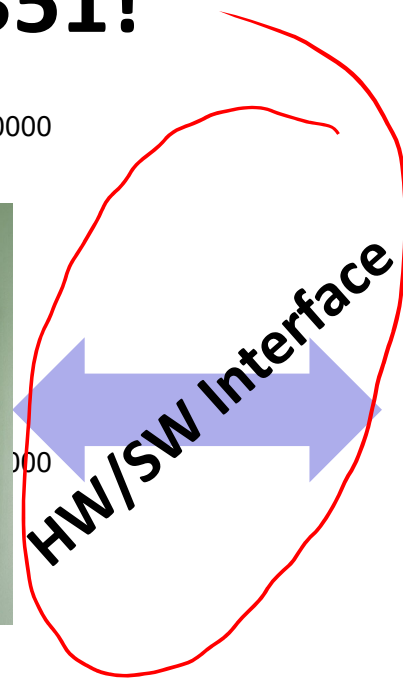
Introductions: You!

- ❖ ~200 students registered across 2 lecture sections
- ❖ CSE majors, EE majors, and more!
 - Most of you will find almost everything in the course new
- ❖ Get to know each other and help each other out!
 - Learning is much more fun with friends
 - Working well with others is a valuable life skill
 - Diversity of perspectives expands your horizons

Welcome to CSE351!



1000100111000010
 110000011111101000011111
 11110111011111000010010000011100



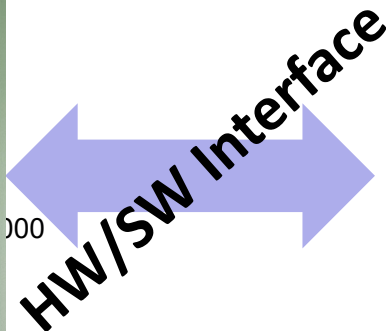
- ❖ Our goal is to teach you the key abstractions “under the hood”
 - How does your source code become something that your computer understands?
 - What happens as your computer is executing one or more processes?

Welcome to CSE351!

100001101111100001001000001110000000000
 0111010000011000
 10001011010001000010010000010100



1000100111000010
 110000011111101000011111
 11110111011111000010010000011100



- ❖ 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
```

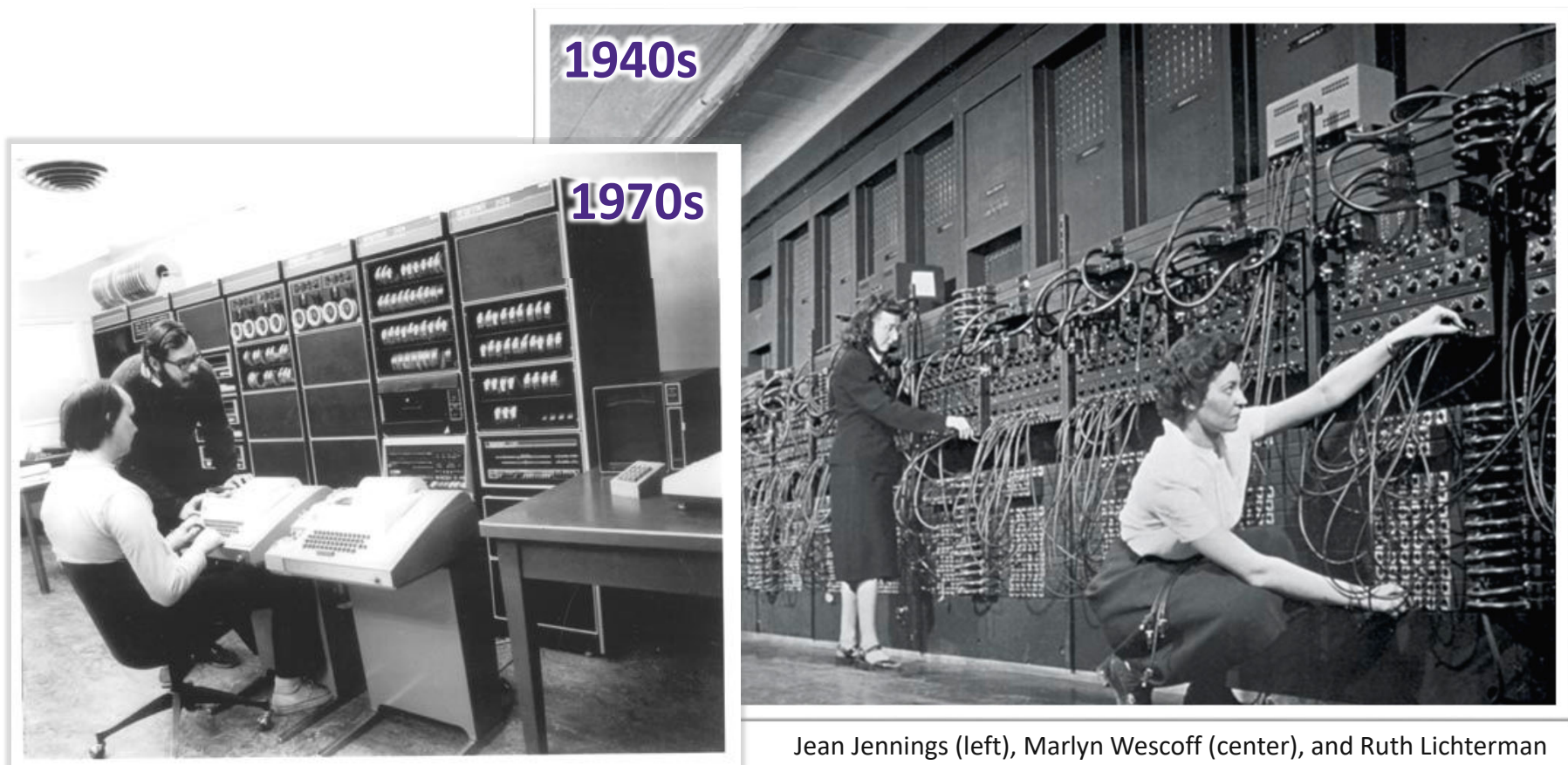
High Level Language
(e.g. C, Java)

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>

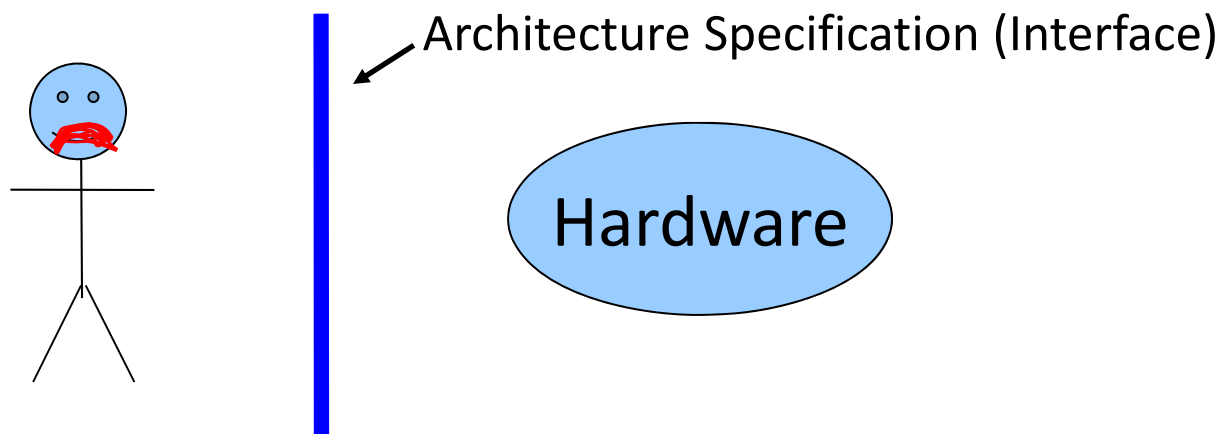
Jean Jennings (left), Marlyn Wescoff (center), and Ruth Lichterman program ENIAC at the University of Pennsylvania, circa 1946.

Photo: Corbis

<http://fortune.com/2014/09/18/walter-isacson-the-women-of-eniac/>

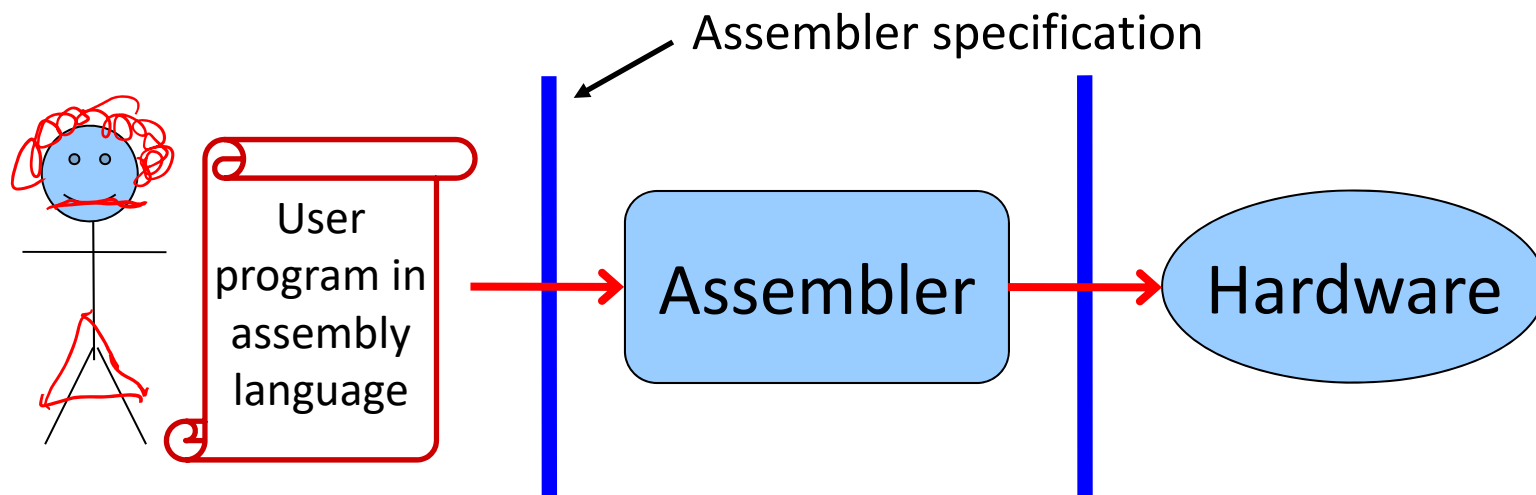
HW/SW Interface: Historical Perspective

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



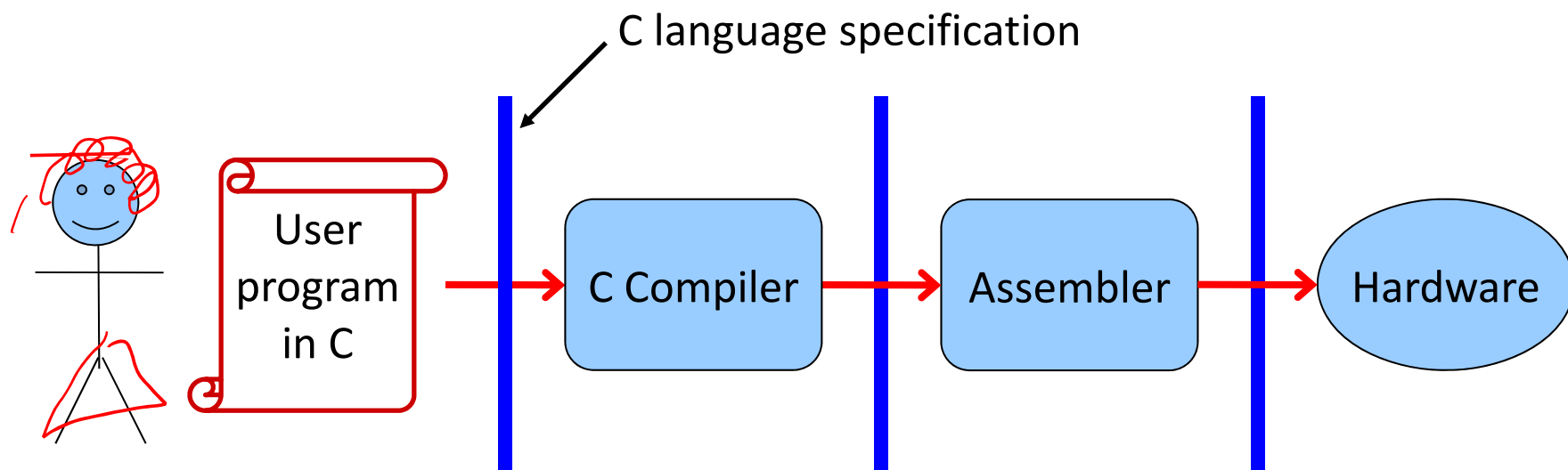
HW/SW Interface: Assemblers

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



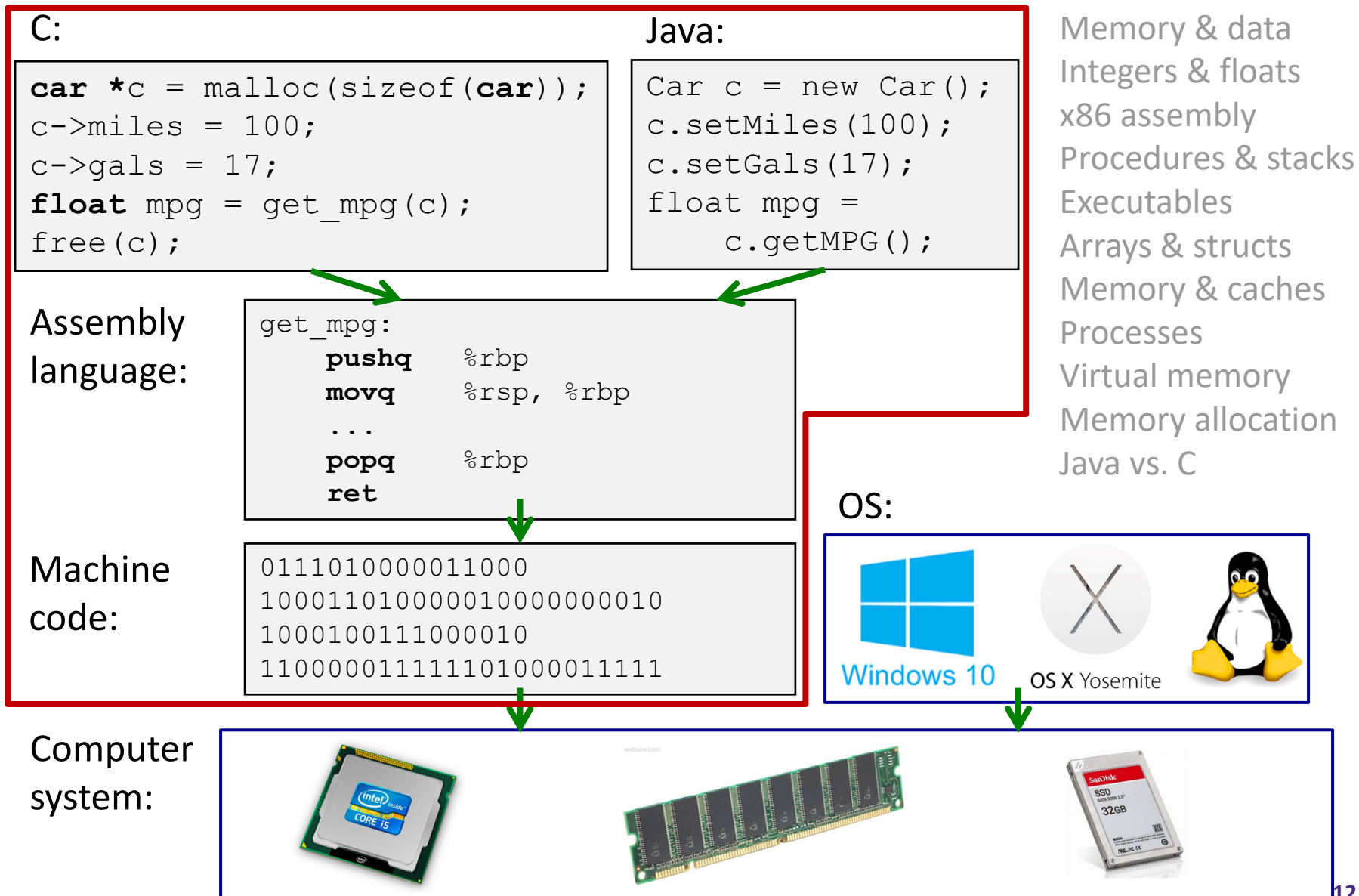
HW/SW Interface: Higher-Level Languages

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



Roadmap

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



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

Roadmap

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

C:

```
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

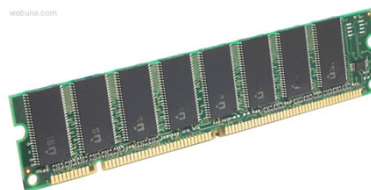
Assembly language:

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

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

Computer system:



OS:



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

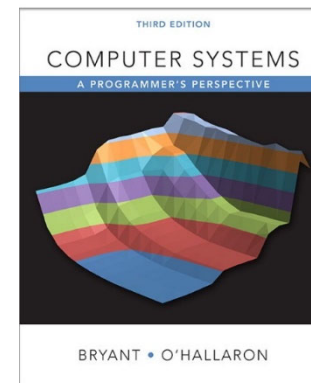
- ❖ Course Introduction
- ❖ **Course Policies**
 - <https://courses.cs.washington.edu/courses/cse351/21sp/syllabus>
- ❖ Binary and Numerical Representation

Bookmarks





- ❖ Website: <https://courses.cs.washington.edu/courses/cse351/21sp/>
 - Schedule, policies, materials, videos, assignments, etc.
- ❖ Discussion: <https://us.edstem.org/courses/4805/discussion/>
 - Announcements made here
 - Ask and answer questions – staff will monitor and contribute
- ❖ Lessons: <https://us.edstem.org/courses/4805/lessons/>
 - Pre-lecture Readings, lecture polling questions, homework
- ❖ Gradescope: <https://www.gradescope.com/courses/258051>
 - Lab submissions
- ❖ Canvas: <https://canvas.uw.edu/courses/1448796>
 - Calendar, groups, grade book

Reference Material

- ❖ The readings on Ed Lessons - constitute a “mini-textbook” for this course, but may not have enough detail for everyone
- ❖ *Computer Systems: A Programmer’s Perspective*
 - Randal E. Bryant and David R. O’Hallaron
 - Website: <http://csapp.cs.cmu.edu>
 - North American 3rd edition
 - Optional, additional readings
- ❖ C reference (physical or online)
 - *The C Programming Language* (Kernighan and Ritchie)
 - *C: A Reference Manual* (Harbison and Steele)
 - <http://www.cplusplus.com>



Grading

- ❖ **Readings:** ~5%  *groupwork allowed*
 - One attempt per question (completion)
- ❖ **Homework:** ~25% 
 - Unlimited submission attempts (autograded correctness)
- ❖ **Labs:** ~40%  *individual work*
 - Last submission graded (correctness)
- ❖ **Unit Summaries:** ~25% 
 - Meant to replace the review, summarizing, and reflecting that studying for exams provides. More info on these later.
- ❖ **Participation :** ~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

Some fun topics that we will touch on

- ❖ Which of the following seems the most interesting to you? (~~vote in Ed Lessons~~)
 - a) What is a GFLOP and why is it used in computer benchmarks?
 - b) How and why does running many programs for a long time eat into your memory (RAM)?
 - c) What is stack overflow and how does it happen?
 - d) Why does your computer slow down when you run out of *disk* space?
 - e) What was the flaw behind the original Internet worm, the Heartbleed bug, and the Cloudbleed bug?
 - f) What is the meaning behind the different CPU specifications? (*e.g.*, # of cores, size of cache)

To-Do List

❖ Admin

- Explore/read website *thoroughly*:
- Check that you can access Ed Discussion & Lessons
- **Get your machine set up to access the CSE Linux environment (CSE VM or attu) as soon as possible**
- Optionally, sign up for CSE 391: System and Software Tools
 - TOMORROW, Tuesday 1:30-2:20pm

❖ Assignments

- Pre-Course Survey and hw0 due Wednesday (3/31) – 11:59pm
- Hw1 due Friday (4/02) – 11:59pm
- Lab 0 due Monday (4/05) – 11:59pm
- Readings due before each lecture – **11am**
- Lecture activities from that day are due before NEXT lecture – **11am**

Lecture Outline

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

Decimal Numbering System

- ❖ Ten **symbols**: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9
- ❖ Represent larger numbers as a sequence of **digits**
 - Each digit is one of the available symbols

❖ Example: 7061 in decimal (base 10)

position: ^{3 2 1 0}

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

Handwritten annotations:
 "thousands digit" (points to 7), "hundreds digit" (points to 0), "tens digit" (points to 6), "ones digit" (points to 1).
 "digit position" (points to the superscript 1 in 10¹).
 "base" (points to the 10 in 10¹).

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"

- ❖ 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?
 - Not a polling this question

A. 32_{10}

B. 34_{10}

C. 7_{10}

D. 28_{10}

E. 35_{10}

$$(3 \times 8^1) + (4 \times 8^0)$$
$$24 + 4 = 28_{10}$$

Binary and Hexadecimal

❖ Binary is base 2

- Symbols: 0, 1

- Convention: $2_{10} = 10_2 = 0b10$

10

↑ "zero-bee"

❖ Example: What is 0b110 in base 10?

- $0b110 = 110_2 = (1 \times 2^2) + (1 \times 2^1) + (0 \times 2^0) = 6_{10}$

4

2

❖ Hexadecimal (**hex**, for short) is base 16

- Symbols? 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, **A, B, C, D, E, F**

values: 8, 9, 10, 11, 12, 13, 14, 15

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

↑ "zero-ex"

❖ Example: What is 0xA5 in base 10?

- $0xA5 = A5_{16} = (10 \times 16^1) + (5 \times 16^0) = 165_{10}$

symbol ↔ value

Question

- ❖ Which of the following orderings is correct?
 - Not a polling this question

A. $0xC < 0b1010 < 11$

B. $0xC < 11 < 0b1010$

C. $11 < 0b1010 < 0xC$

D. $0b1010 < 11 < 0xC$

E. $0b1010 < 0xC < 11$

$$\begin{aligned}0xC &= 12_{10} \\ 0b1010 &= 1 \times 2^3 + 1 \times 2^1 = 8 + 2 = 10_{10} \\ 11 &= 11_{10}\end{aligned}$$

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:

■ $2^3 = 8$ — |

■ $2^2 = 4$ — |

■ $2^1 = 2$

■ $2^0 = 1$ — |

$$\begin{aligned} 13_{10} &= 8 + 4 + 1 \\ &= 2^3 + 2^2 + 2^0 \\ &= 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 \\ &= \boxed{0b1101} \end{aligned}$$

❖ 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 $\geq N$
 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

$$\begin{array}{r}
 13 \\
 \underline{-8} \\
 5 \\
 \underline{-4} \\
 1 \\
 \underline{-1} \\
 0
 \end{array}$$

$2^4=16$	$2^3=8$	$2^2=4$	$2^1=2$	$2^0=1$
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 $\geq N$
 2. Then from *left to right*, ask is that (power of B) $\leq N$?
 - 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	¹⁰ 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
- Drop two leading zeros, answer is 0b101101

can "drop"
0b00101101

❖ Binary → Hex

- Pad with **leading zeros** until multiple of 4, then substitute each group of 4

- Example: 0b101101 *6 digits*

- Pad to 0b/0010/1101/
- Substitute to get 0x2D

	binary	hex
Base 10	Base 2	Base 16
0	0000	0
1	0001	1
2	0010 ← →	2
3	0011	3
4	0100	4
5	0101	5
6	0110	6
7	0111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101 ← →	D
14	1110	E
15	1111	F

Binary → Hex Practice

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

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

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!

MEMORIZE ME!!!

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: $0 \rightarrow 0b0$, $1 \rightarrow 0b1$, $2 \rightarrow 0b10$, etc.
 - English Letters: $CSE \rightarrow 0x435345$, $yay \rightarrow 0x796179$
 - Emoticons: 😊 0x0, 😞 0x1, 😎 0x2, 😇 0x3, 😈 0x4, 🙋 0x5

Binary Encoding

1 bit 0 1
2 bits 0 1
0 1
1 0
1 1

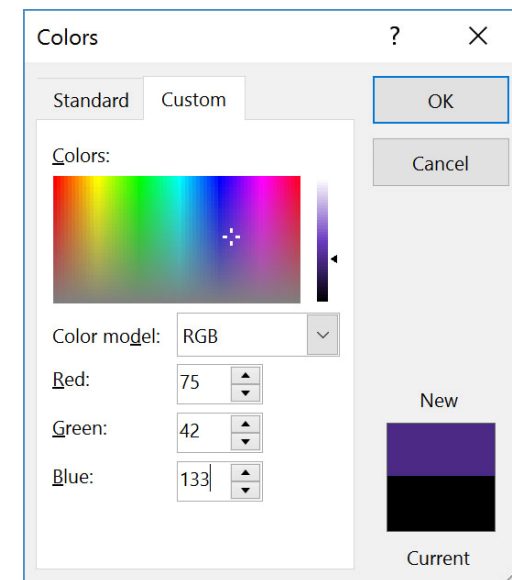
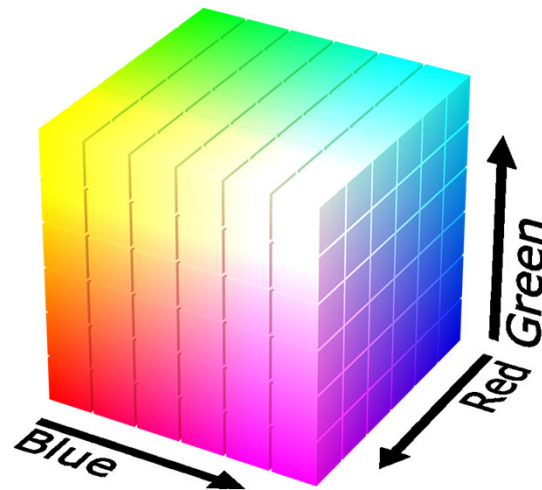
- ❖ With N binary digits, how many “things” can you represent? 2^N
 - Need N binary digits to represent n things, where $2^N \geq n$
 - Example: 5 binary digits for alphabet because $2^5 = 32 > 26$
- ❖ A binary digit is known as a **bit**
- ❖ A group of 4 bits (1 hex digit) is called a **nibble**
- ❖ A group of 8 bits (2 hex digits) is called a **byte**
 - 1 bit \rightarrow 2 things, 1 nibble \rightarrow 16 things, 1 byte \rightarrow 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

man ascii

❖ 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		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