Welcome to

CS 240:

Foundations of

Computer Systems

- Program, Application
- Programming Language
- Compiler/Interpreter
- Operating System
- Instruction Set Architecture
- Microarchitecture
- Digital Logic
- Devices (transistors, etc.)
- Solid-State Physics

Today

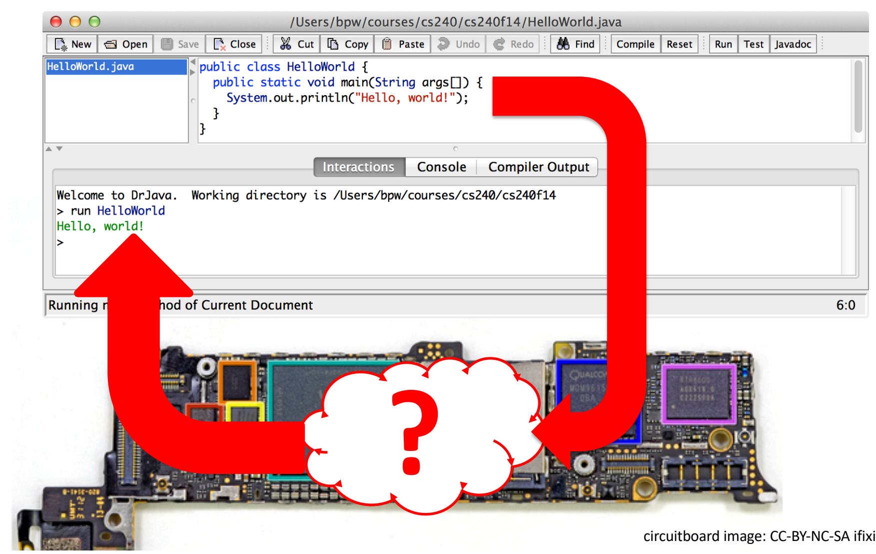
1. **What is CS 240?**
2. Why take CS 240?
3. How does CS 240 work?
4. Dive into foundations of computer hardware.

CS 111, 230, 231, 235, 251:

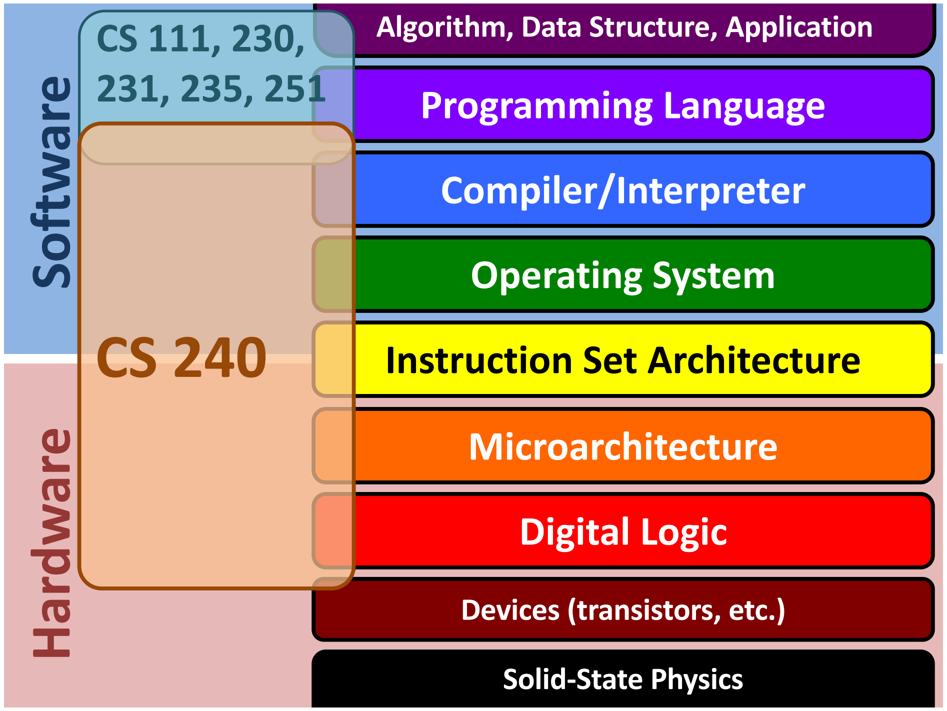
- What can a program do?
- How can a program solve a problem?
- How do you structure a program?
- How do you know it is correct or efficient?
- How hard is it to solve a problem?
- How is computation expressed?
- What does a program mean?
- ...

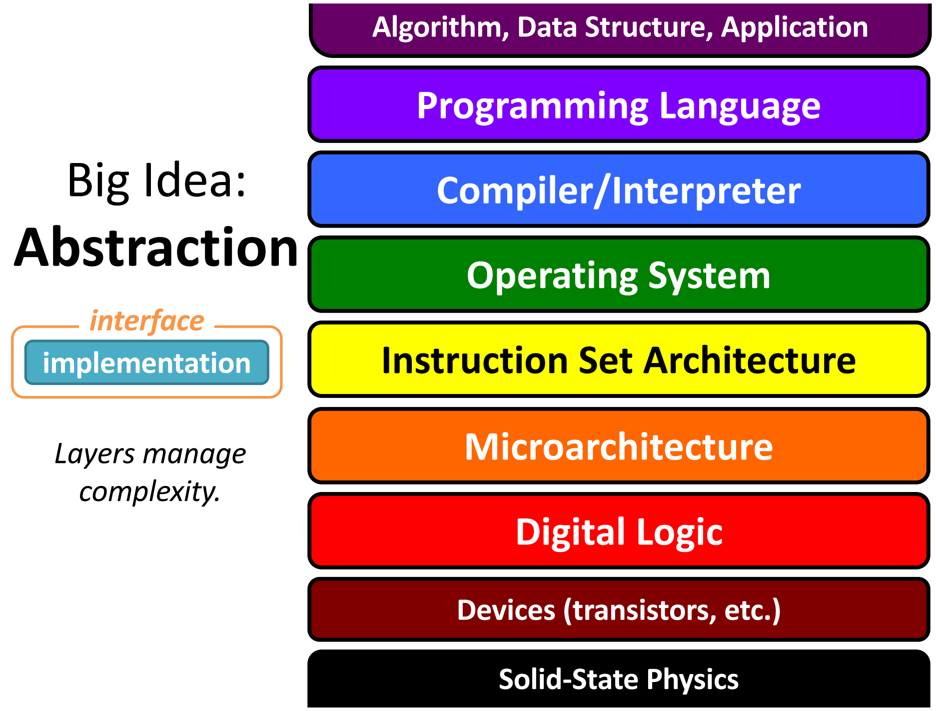
A BIG question is missing…

1 CS 240: How do computers work?



circuitboard image: CC-BY-NC-SA ifixit.com





Big Idea: Abstraction

with a few recurring subplots

Simple, general interfaces:

- Hide complexity of efficient implementation.
- Make higher-level systems easy to build.
- **But they are not perfect.**

Representation of data and programs — 0s and 1s, electricity

Translation of data and programs — compilers, assemblers, decoders

Control flow within/across programs — branches, procedures, OS

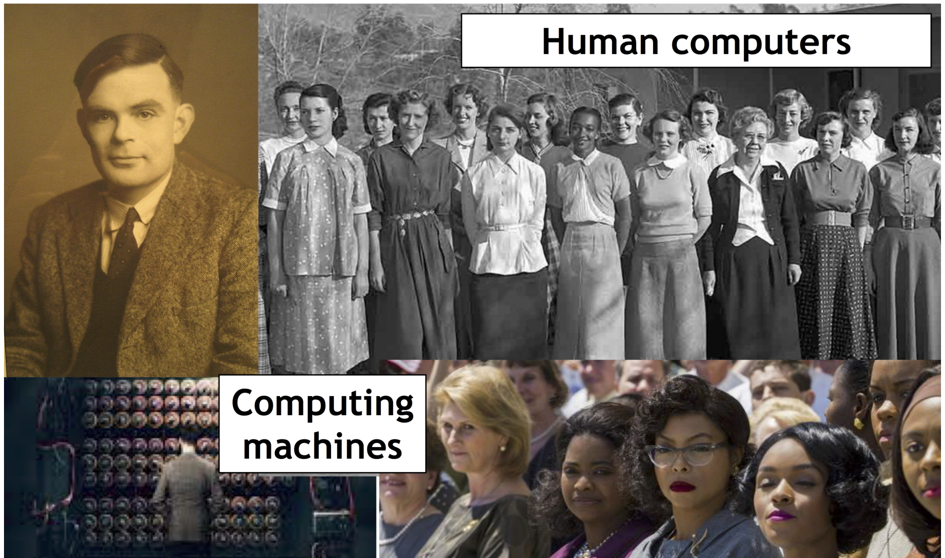
Charles Babbage designs Analytical Engine

George Boole describes formal logic for computers *Boolean Algebra*

Prototype of Analytical Engine, (was never actually built), Science Museum, London
Image: public domain

Countess Ava Lovelace, 1840s
George Boole, 1860s
University College Cork, Ireland
Image: public domain

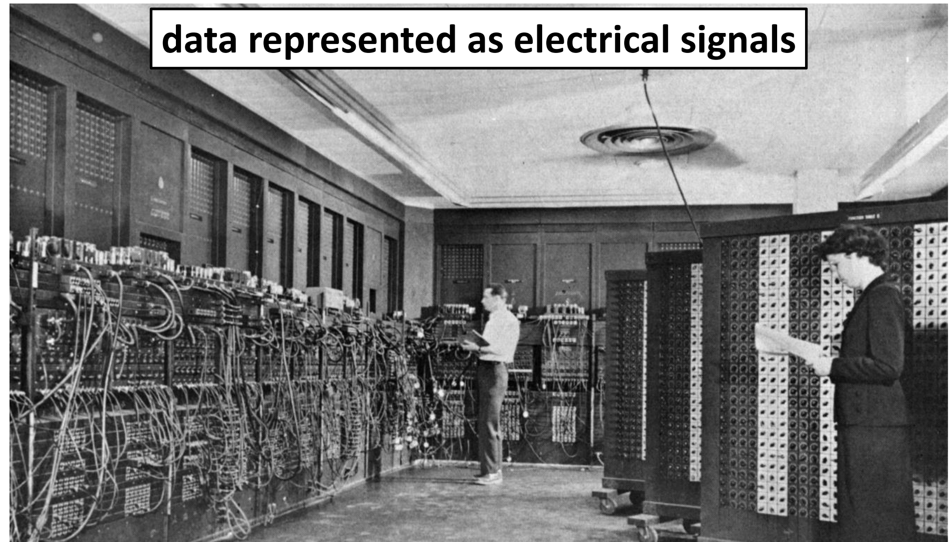
1890s | 1900s | 1910s | 1920s | **1930s** | **1940s** | **1950s** | 1960s | 1970s



Alan Turing, 1940s
Imitation Game, 2014
nage: Flikr mark_am_kramer, Imitation Game poster

NASA computers, 1953
Hidden Figures, 2016
Image: NASA/JPL/Caltech, Hidden Figures

1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s



ENIAC (Electronic Numerical Integrator and Computer),
First Turing-complete all-electronic programmable digital computer.
University of Pennsylvania, 1940s

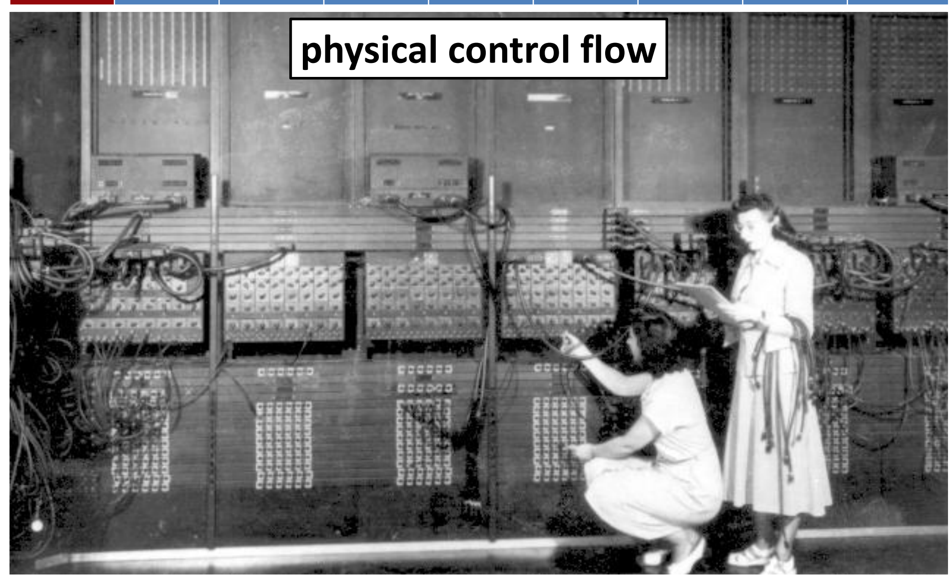
Image: public domain

1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s

Jean Jennings Bartik and Frances Bilas Spence with part of ENIAC.
The programmers of ENIAC were six women.
http://eniacprogrammers.org/, http://sites.temple.edu/topsecretrosies/

Image: public domain

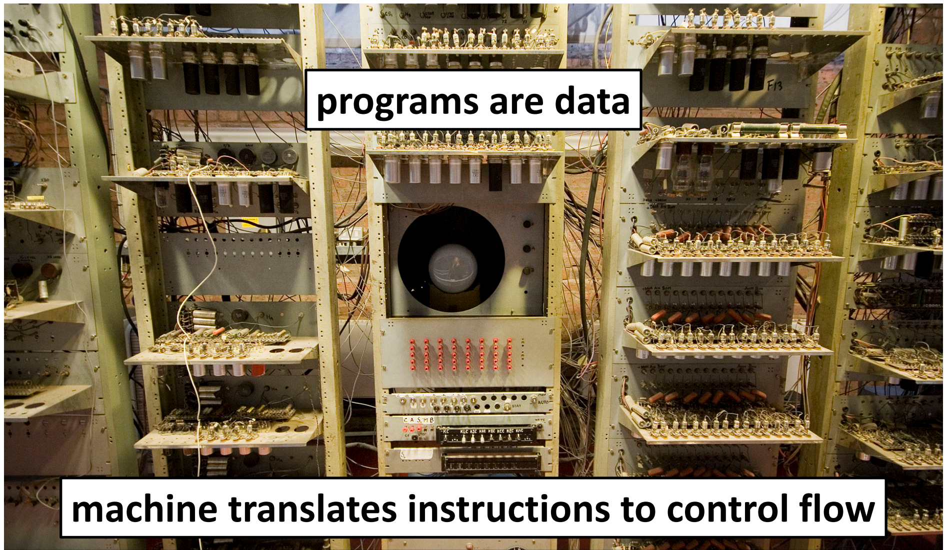
1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s



Programming 1940s-style *with switches and cables.*

Image: public domain

1940s	**1950s**	1960s	1970s	1980s	1990s	2000s	2010s	2020s



programs are data

machine translates instructions to control flow

Manchester "Baby" SSEM (Small-Scale Experimental Machine), replica
first **stored-program computer** -- University of Manchester (UK), 1948

Image: "SSEM Manchester museum close up" by Parrot of Doom - Own work. Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:SSEM_Manchester_museum_close_up.jpg

1940s	1950s	**1960s**	**1970s**	1980s	1990s	2000s	2010s	2020s

PDP-11 "**minicomputers**"

http://simh.trailing-edge.com/

http://www.pcworld.com/article/249951/if_it_aint_broke_dont_fix_it_ancient_computers_in_use_today.html?page=2

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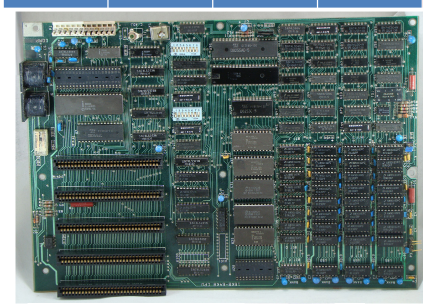

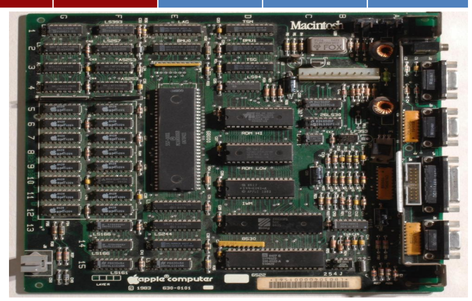

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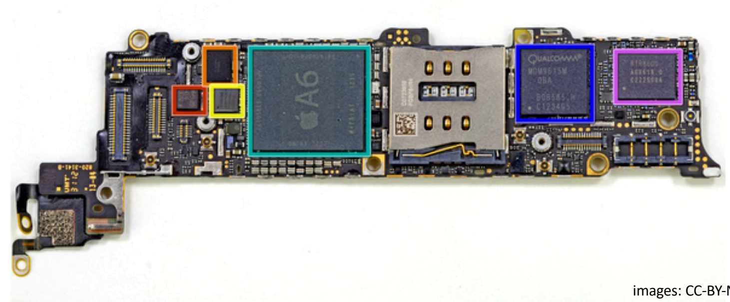
1940s	1950s	1960s	1970s	1980s	1990s	**2000s**	**2010s**	2020s



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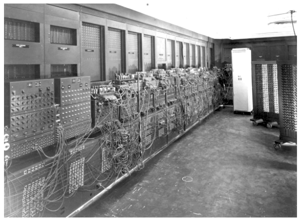
1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s

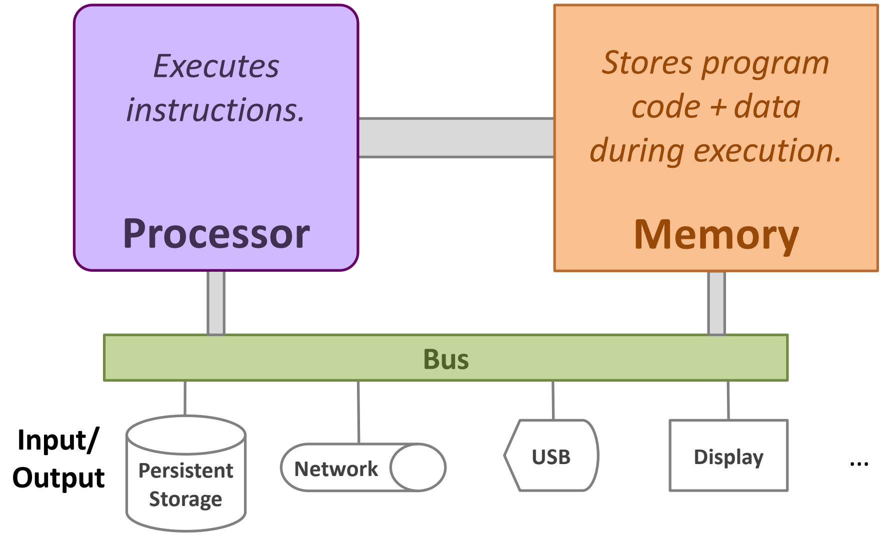


ENIAC image: public domain; iPhone image: CC-BY-NC-SA ifixit.com

	ENIAC	iPhone 5
Year	1946	2012
Weight	30 tons	4 oz
Volume	2,400 ft^3	3.4 in^3
Cost (USD, 2014)	$6,000,000	$600
Speed	few 1000 ops/sec	2,500,000,000 ops/sec
Memory	~100 bytes	1,073,741,824 bytes (1 GB)
Power	150,000 W	<5W
Input/Output	Switches, lights, later punchcards	Touchscreen, audio, camera, wifi, cell, …
Production	1	5,000,000 sold in first 3 days

1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s

Modern Computer Organization



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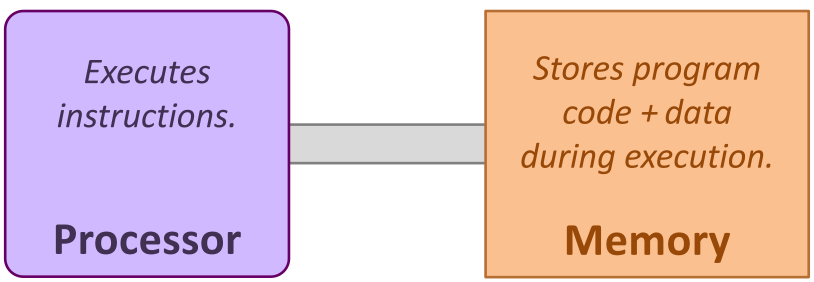
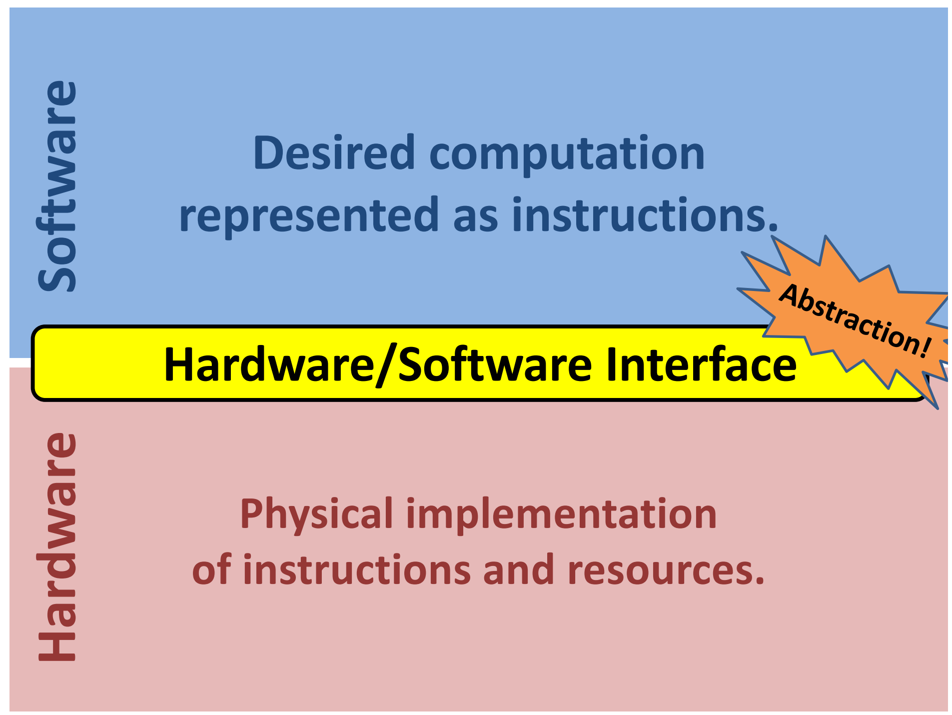
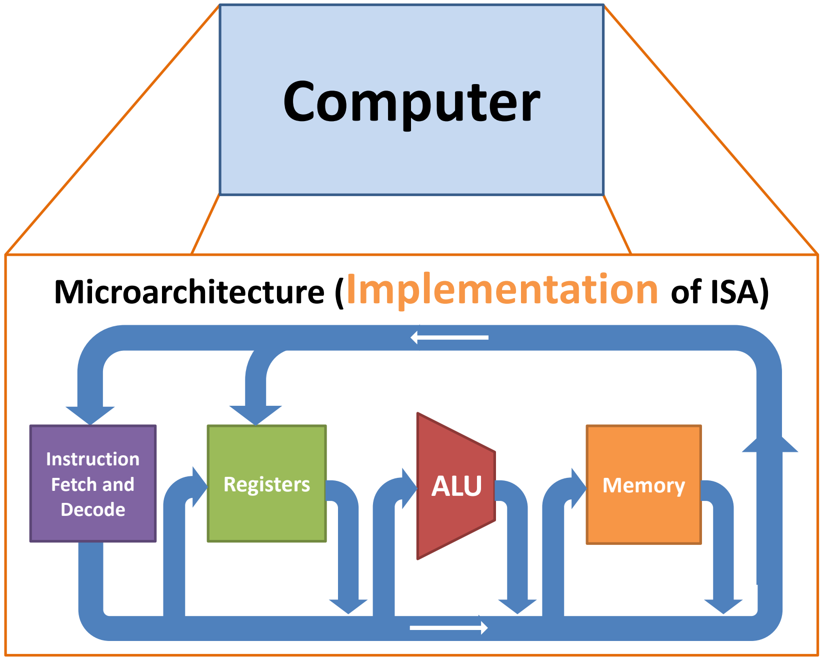
Modern Computer Organization

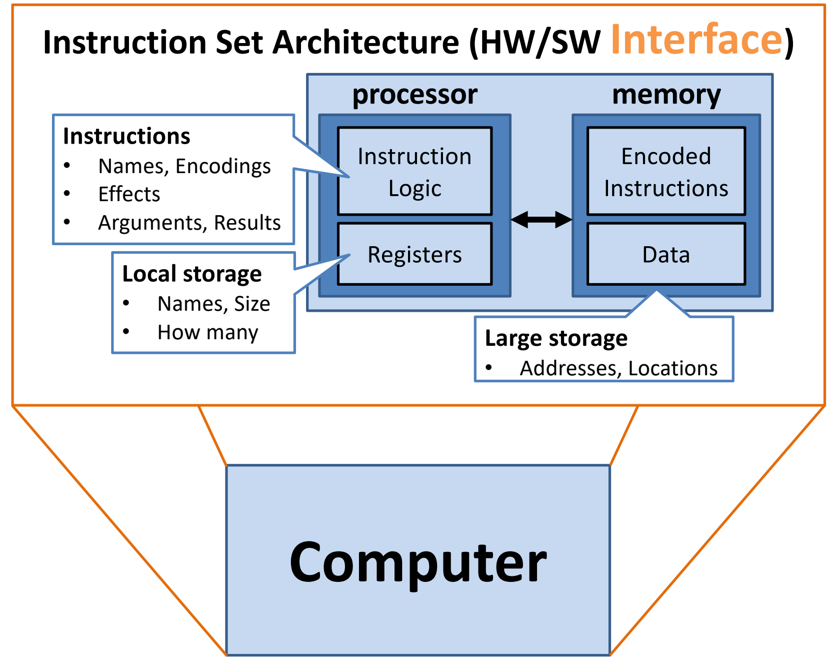


Processor repeats:

1. fetch instruction
2. fetch data used by instruction
3. execute instruction on data
4. store result or choose next instruction







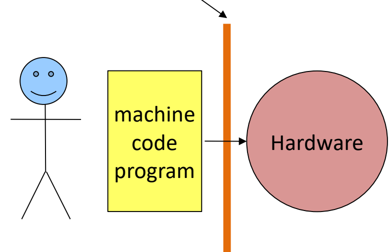
1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s

Machine Instructions

(adds two values and stores the result)

```
00000010100010101100100000010000
```

Instruction Set Architecture specification

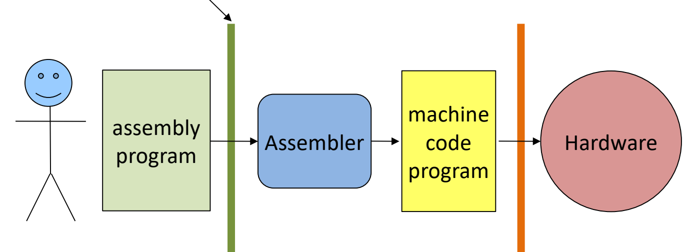


1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s

Assemblers and Assembly Languages

```
addl %eax, %ecx   →   00000010100010101100100000010000
```

Assembly Language specification



1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s

Higher-Level Programming Languages

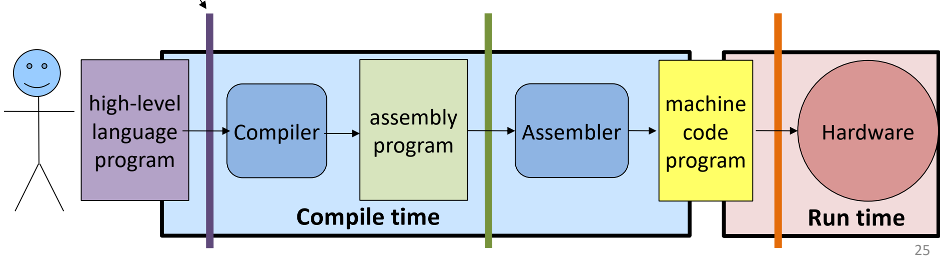
```
x = x + y;
```

↓

```
addl %eax, %ecx
```

→ 00000010100010101100100000010000

Programming Language specification



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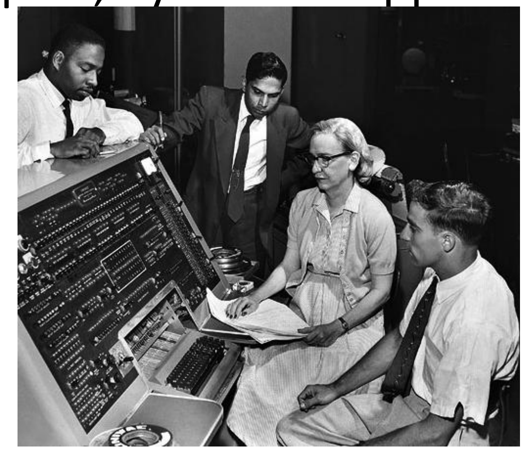
A-0: first compiler, by Grace Hopper

Early 1950s
Maybe closer to assembler/linker/loader

Later: B-0 → FLOW-MATIC
→ COBOL, late 50s



Jean Sammet also involved

- headed first sci comp group at Sperry in the '50s
- Later first female president of ACM
- Mount Holyoke alum, class of 1948

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More and more layers…

- Operating systems
- Virtual machines
- Hypervisors
- Web browsers
- …

CS 240 in 3 acts

(4-5 weeks each)

Hardware *implementation*

From transistors to a simple computer

Hardware-software *interface*

From instruction set architecture to C

Abstraction for practical systems

Memory hierarchy
Operating systems
Higher-level languages

2 *I just like to program.* ***Why*** *study the implementation?*

It's fascinating, great for critical thinking.

System design principles apply to software too.

Sometimes system abstractions "leak."
Implementation details affect your programs.

`int` ≠ integer
`float` ≠ real

```
int x=…;
x*x >= 0 ?
  40000 * 40000  ==  1600000000
  50000 * 50000  == -1794967296

float a=…, b=…, c=…;
(a + b) + c  ==  a + (b + c) ?
  (-2.7e23 +  2.7e23) + 1.0  == 1.0
   -2.7e23 + (2.7e23  + 1.0) == 0.0
```


Reliability?

Ariane 5 Rocket, 1996

Exploded due to **cast** of 64-bit floating-point number to 16-bit signed number. **Overflow.**

Boeing 787, 2015

"... a **Model 787 airplane** ... can lose all alternating current (AC) electrical power ... caused by a **software counter** internal to the GCUs that will **overflow** after **248 days** of continuous power. We are issuing this AD to prevent loss of all AC electrical power, which could result in **loss of control of the airplane**." --FAA, April 2015

Arithmetic Performance

x / 973 **x / 1024**

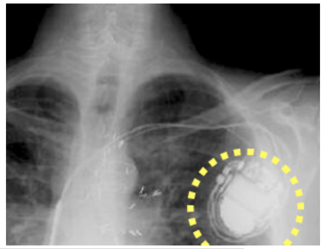
Memory Performance

```
void copyji(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (j = 0; j < 2048; j++)
    for (i = 0; i < 2048; i++)
      dst[i][j] = src[i][j];
}
```

```
void copyij(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (i = 0; i < 2048; i++)
    for (j = 0; j < 2048; j++)
      dst[i][j] = src[i][j];
}
```

several times faster due to hardware caches

Security



The *GHOST vulnerability* is a buffer overflow condition that can be easily exploited lo remotely, which makes it extremely dangerous. This vulnerability is named after the *GetHOS* function involved in the exploit.

Cyber-Safe

All computers are flawed -- and the fix will take years

by Selena Larson @selenalarson

January 26, 2018: 12:07 PM ET

Meltdown and Spectre

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A Heart Device Is Found Vulnerable to Hacker Attacks

By BARNABY J. FEDER
Published: March 12, 2008

To the long list of objects vulnerable to attack by computer hackers, add the human heart.

The threat seems largely theoretical. But a team of computer security researchers plans to report Wednesday that it had been able to gain wireless access to a combination heart defibrillator and pacemaker.

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https://cs.wellesley.edu/~cs240/

3

Everything is here.
Please read it.

Why take CS 240?

- **Learn how computers execute programs.**
- **Build software tools** and appreciate the value of those you use.
- Deepen your appreciation of **abstraction.**
- Learn enduring **system design principles**.
- Improve your **critical thinking** skills.
- Become a **better programmer**:
  - Think rigorously about execution models.
  - Program carefully, defensively.
  - Debug and reason about programs effectively.
  - Identify limits and impacts of abstractions and representations.
  - Learn to use software development tools.
- **Foundations** for:
  - Compilers, security, computer architecture, operating systems, …
- Have fun and feel accomplished!