CS 240 Spring 2020
Foundations of Computer Systems
Ben Wood

WELLESLEY

The Plan

https://cs.wellesley.edu/~cs240/s20/

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

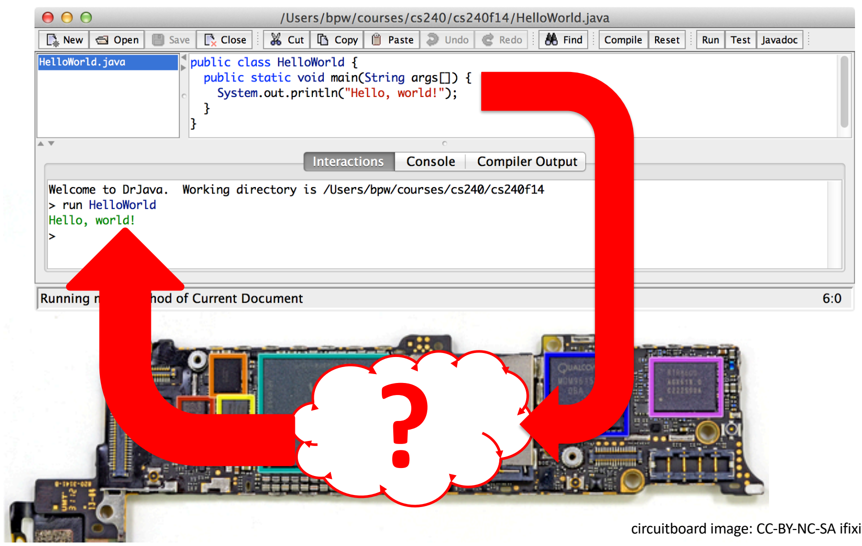
1. **What is CS 240?**
2. Why take CS 240?
3. How does CS 240 work?
4. Dive into foundations of computer hardware.

CS 111, 230, 231, 235, 251:

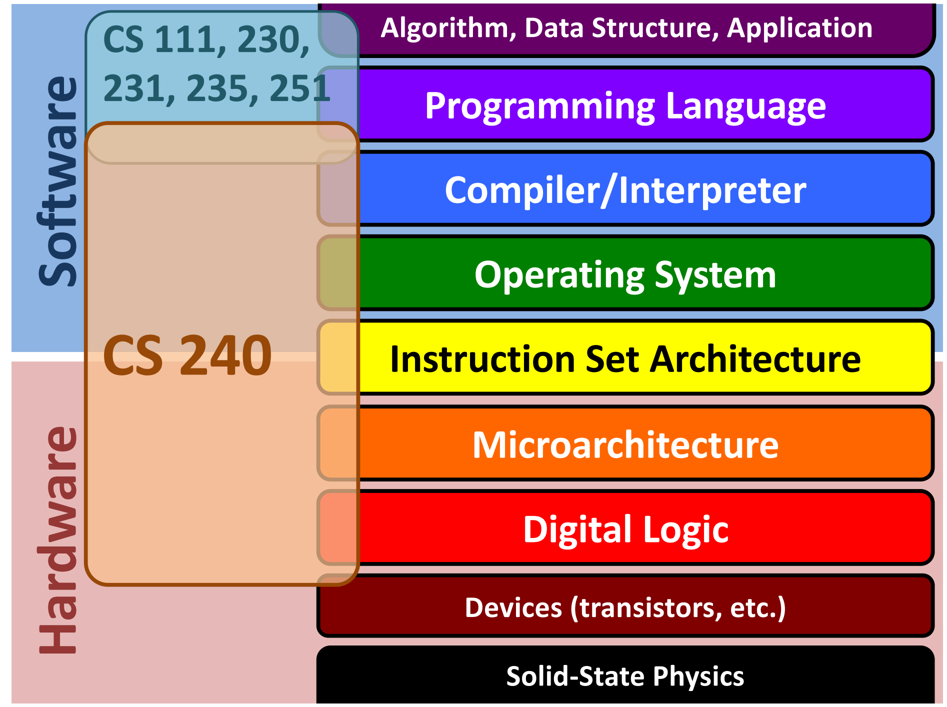
- What can a program do?
- How can a program solve a problem?
- How do you structure a program?
- How do you know it is correct or efficient?
- How hard is it to solve a problem?
- How is computation expressed?
- What does a program mean?
- ...

A BIG question is missing…

1 CS 240: How do computers work?



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



Big Idea: **Abstraction**

interface

implementation

Layers manage complexity.

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

Big Idea: Abstraction

with a few recurring subplots

Simple, general interfaces:

Hide complexity of efficient implementation.

Make higher-level systems easy to build.

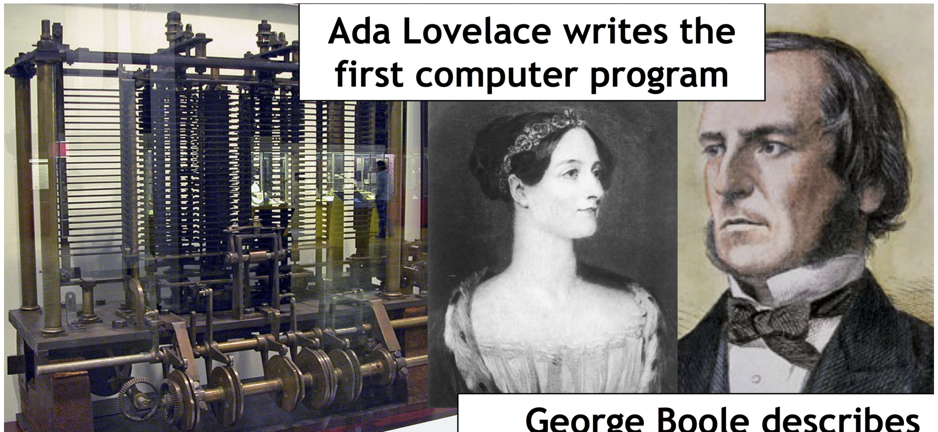
But they are not perfect.

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

1800s | 1810s | 1820s | **1830s** | **1840s** | **1850s** | **1860s** | 1870s | 1880s



Ada Lovelace writes the first computer program

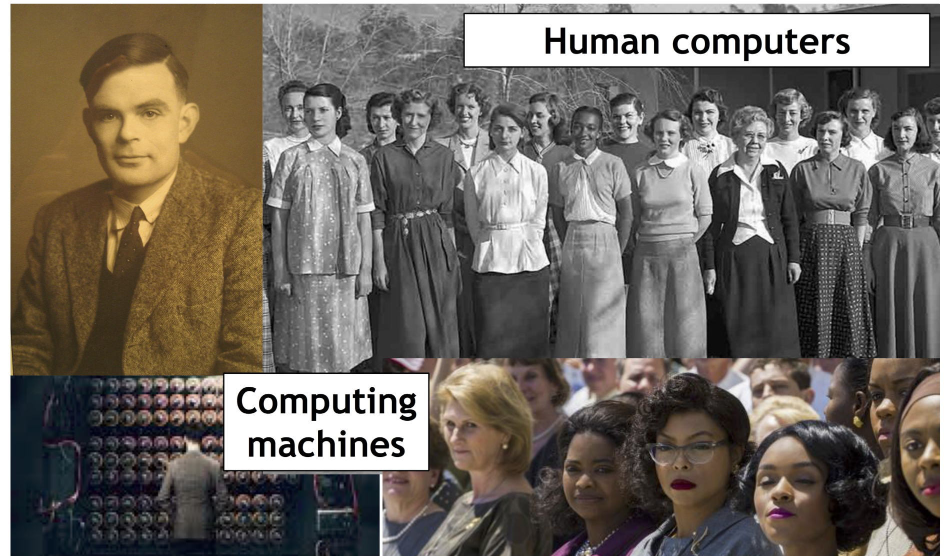
Charles Babbage designs Analytical Engine

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

George Boole describes formal logic for computers
Boolean Algebra

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

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



Human computers

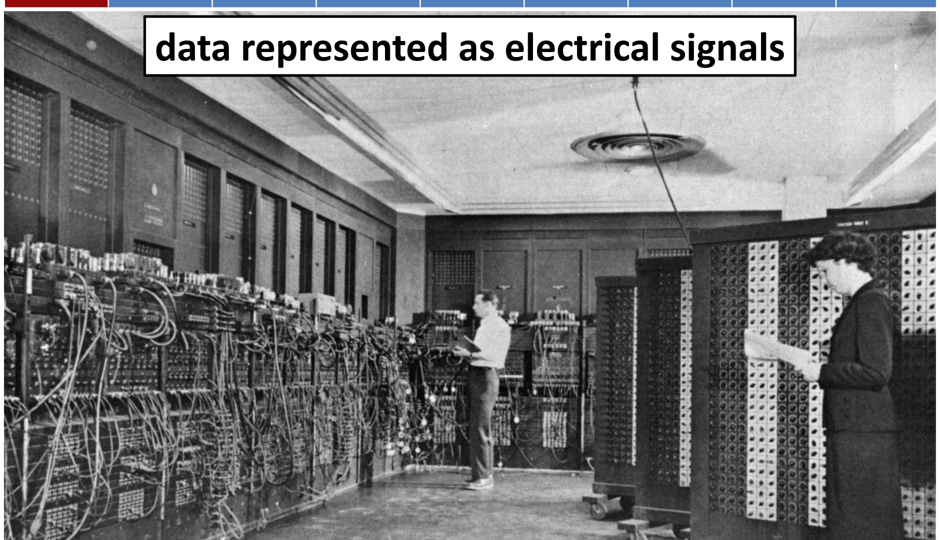
Computing machines

Alan Turing, 1940s
Imitation Game, 2014
age: 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

data represented as electrical signals



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

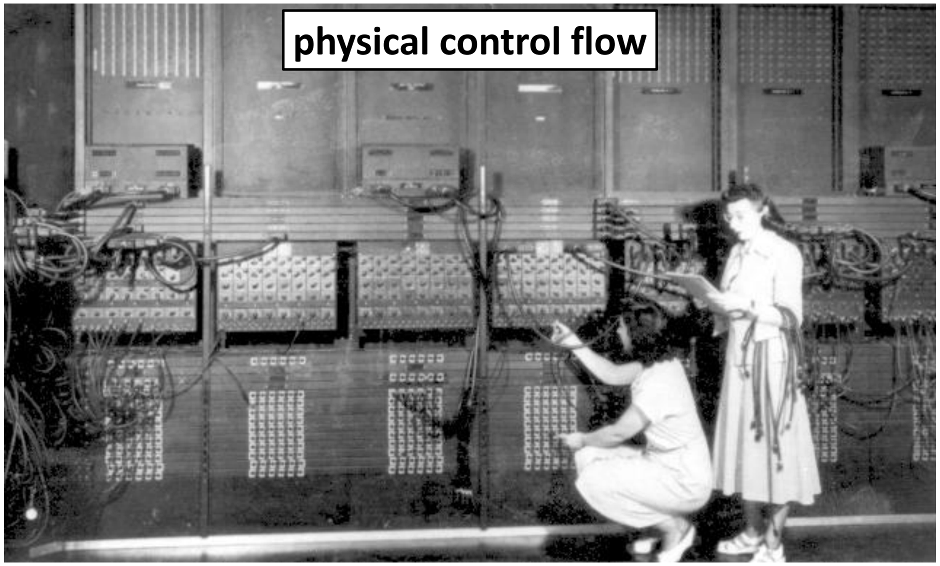
1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s

program controls general-purpose hardware

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

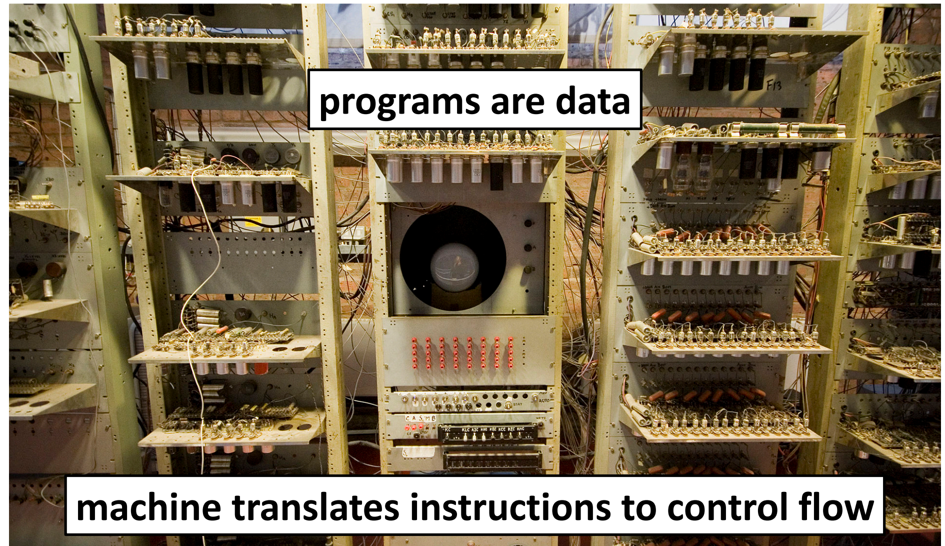
1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s



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

Image: public domain

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



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

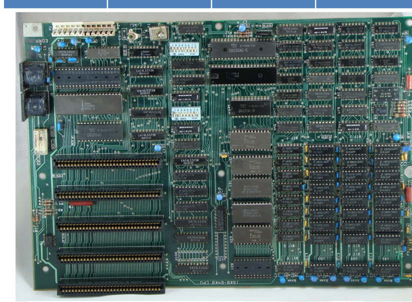
1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s

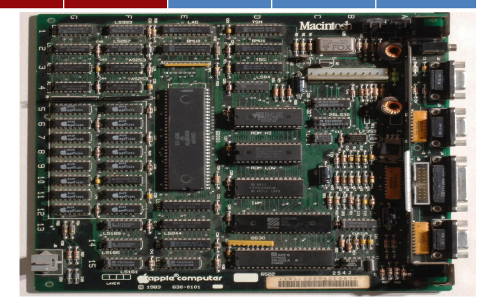
PDP-11 "**minicomputers**"

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

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





Images:
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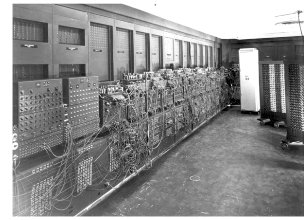
1940s | 1950s | 1960s | 1970s | 1980s | 1990s | **2000s** | **2010s** | 2020s

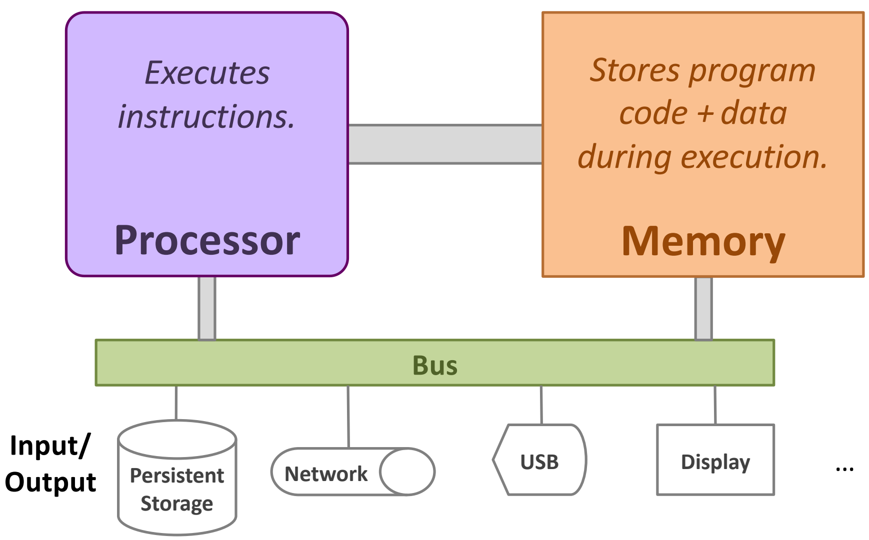
1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | **2010s** | 2020s



	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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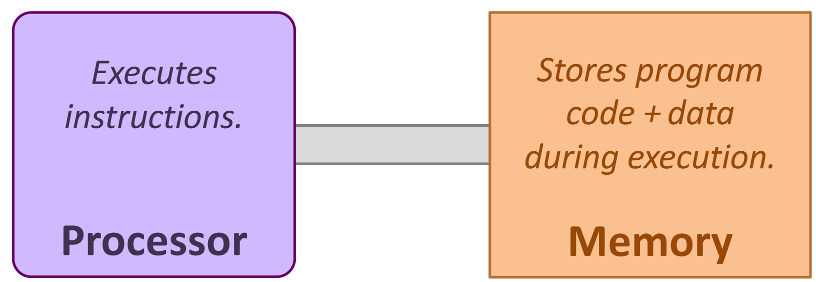
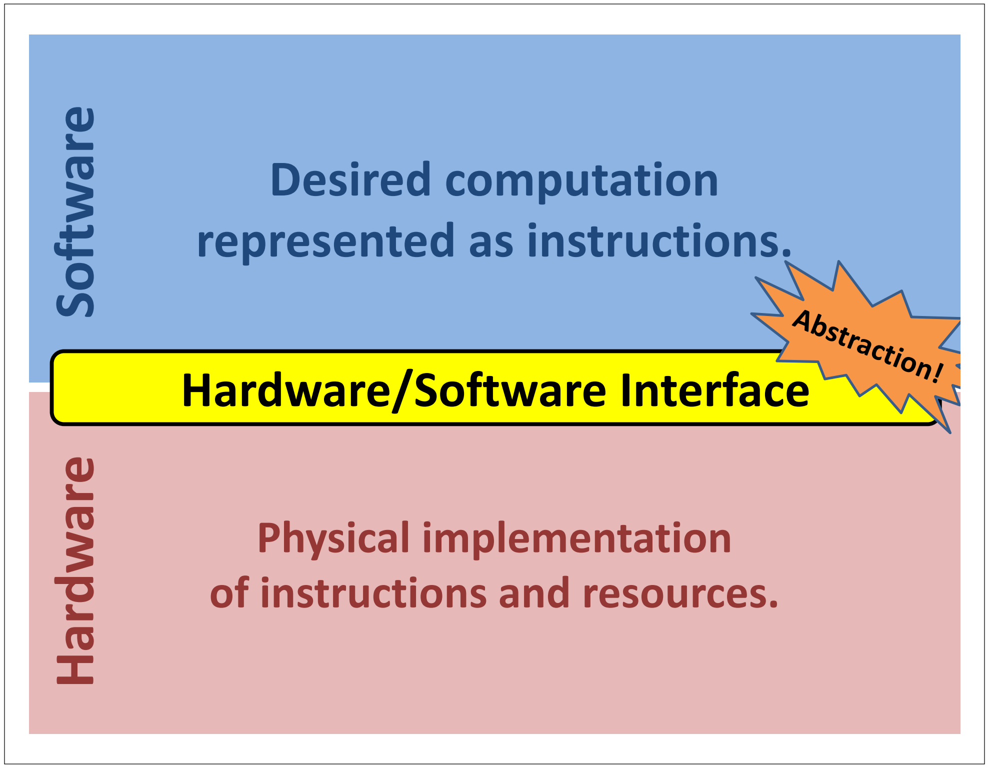
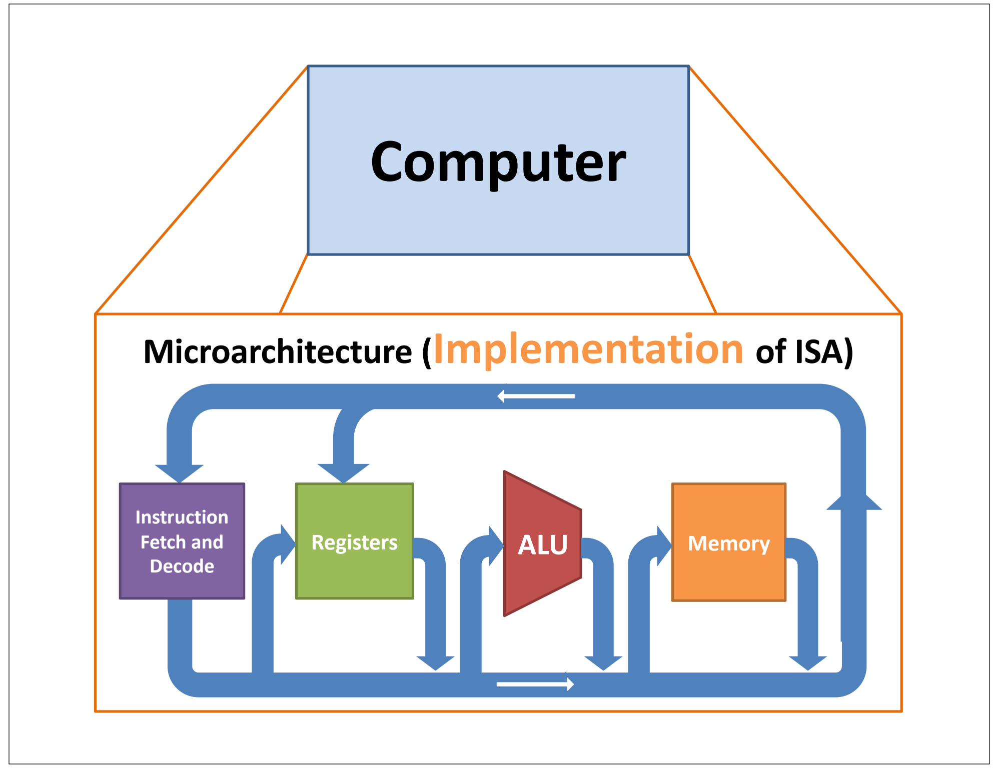
Modern Computer Organization

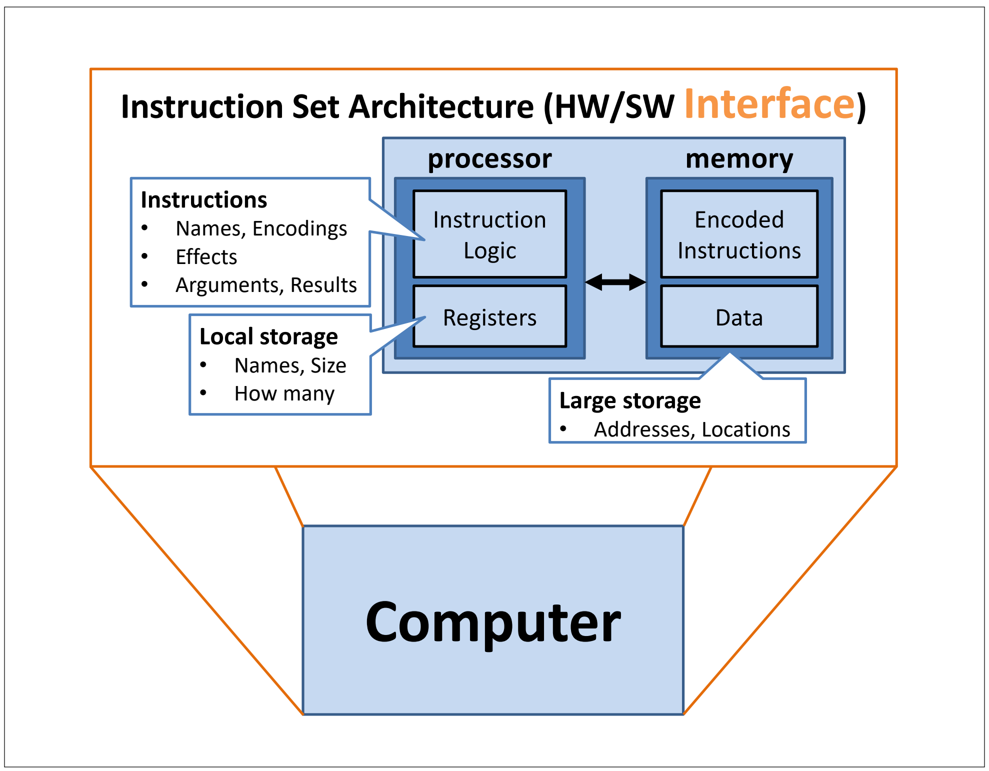


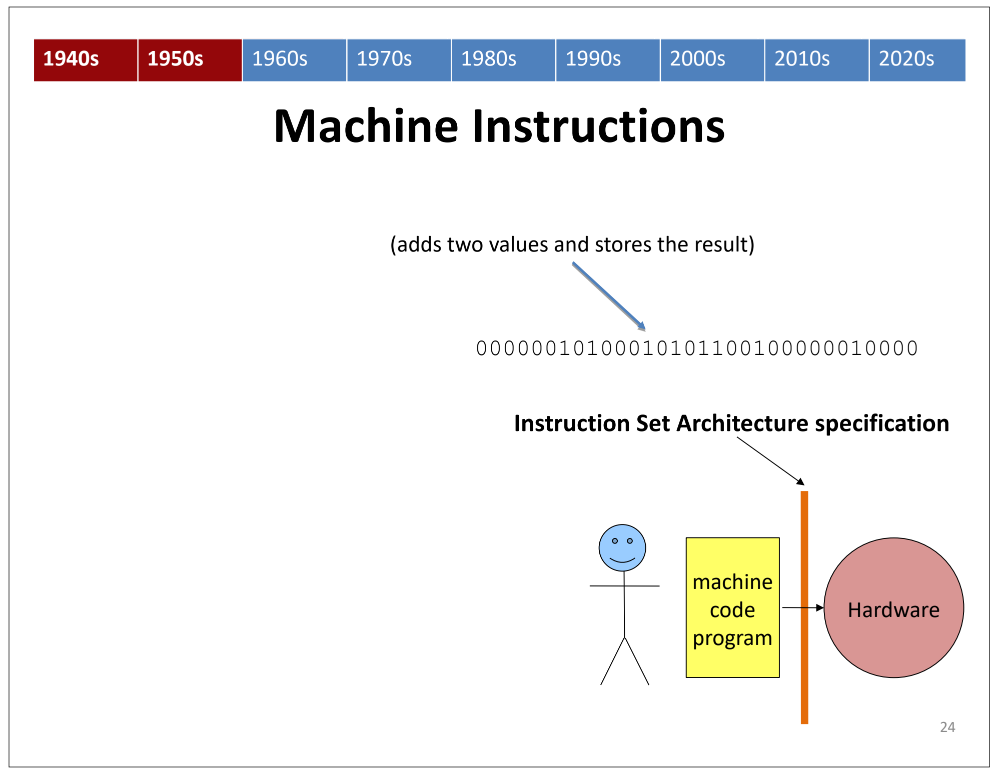
Processor repeats:

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


Software
Desired computation
represented as instructions.
Abstraction!
Hardware/Software Interface
Hardware
Physical implementation
of instructions and resources.

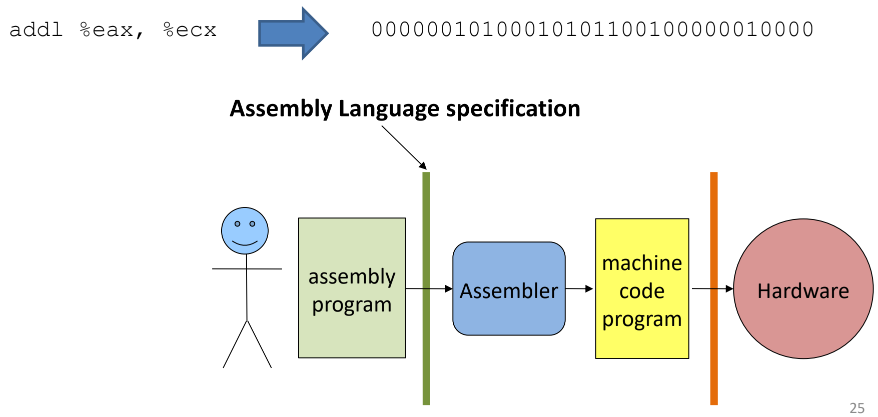

Computer
Microarchitecture (Implementation of ISA)
Instruction Fetch and Decode
Registers
ALU
Memory


Instruction Set Architecture (HW/SW Interface)
processor
memory
Instructions
• Names, Encodings
• Effects
• Arguments, Results
Instruction Logic
Encoded Instructions
Local storage
• Names, Size
• How many
Registers
Data
Large storage
• Addresses, Locations
Computer


1940s
1950s
1960s
1970s
1980s
1990s
2000s
2010s
2020s
Machine Instructions
(adds two values and stores the result)
00000010100010101100100000010000
Instruction Set Architecture specification
machine code program
Hardware
24

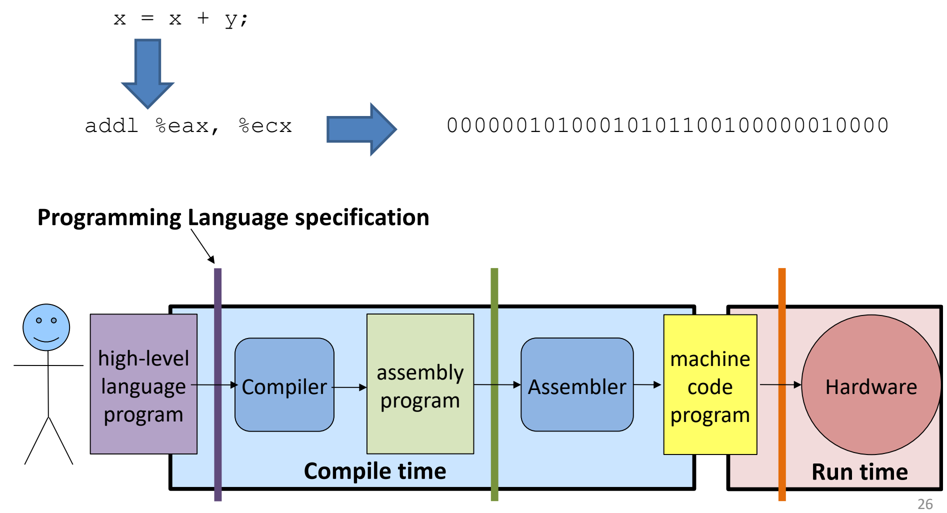
1940s | **1950s** | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s

Assemblers and Assembly Languages



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

Higher-Level Programming Languages



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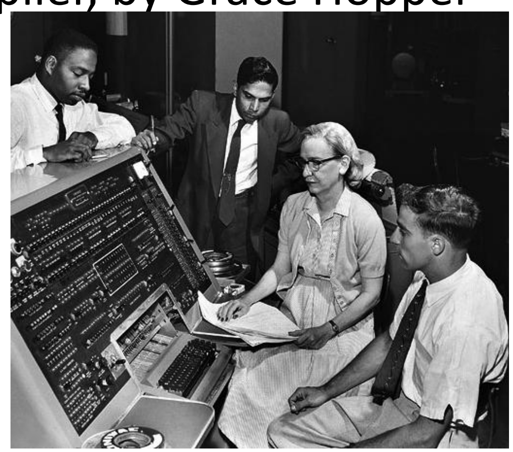
A-0: first compiler, by Grace Hopper

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

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

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**

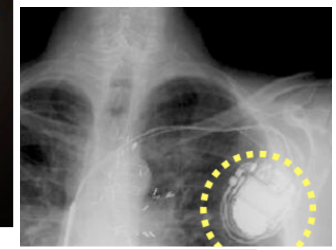
Memory Performance

```
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.

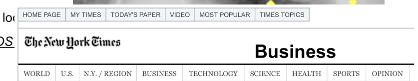
Cyber-Safe

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

by Selena Larson @selenalarson

January 26, 2018: 12:07 PM ET

Meltdown and Spectre



A Heart Device Is Found Vulnerable to Hacker Attacks

By BARNABY J. FEDER

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.

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!

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3 Everything is here.
Please read it.

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