The Plan

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

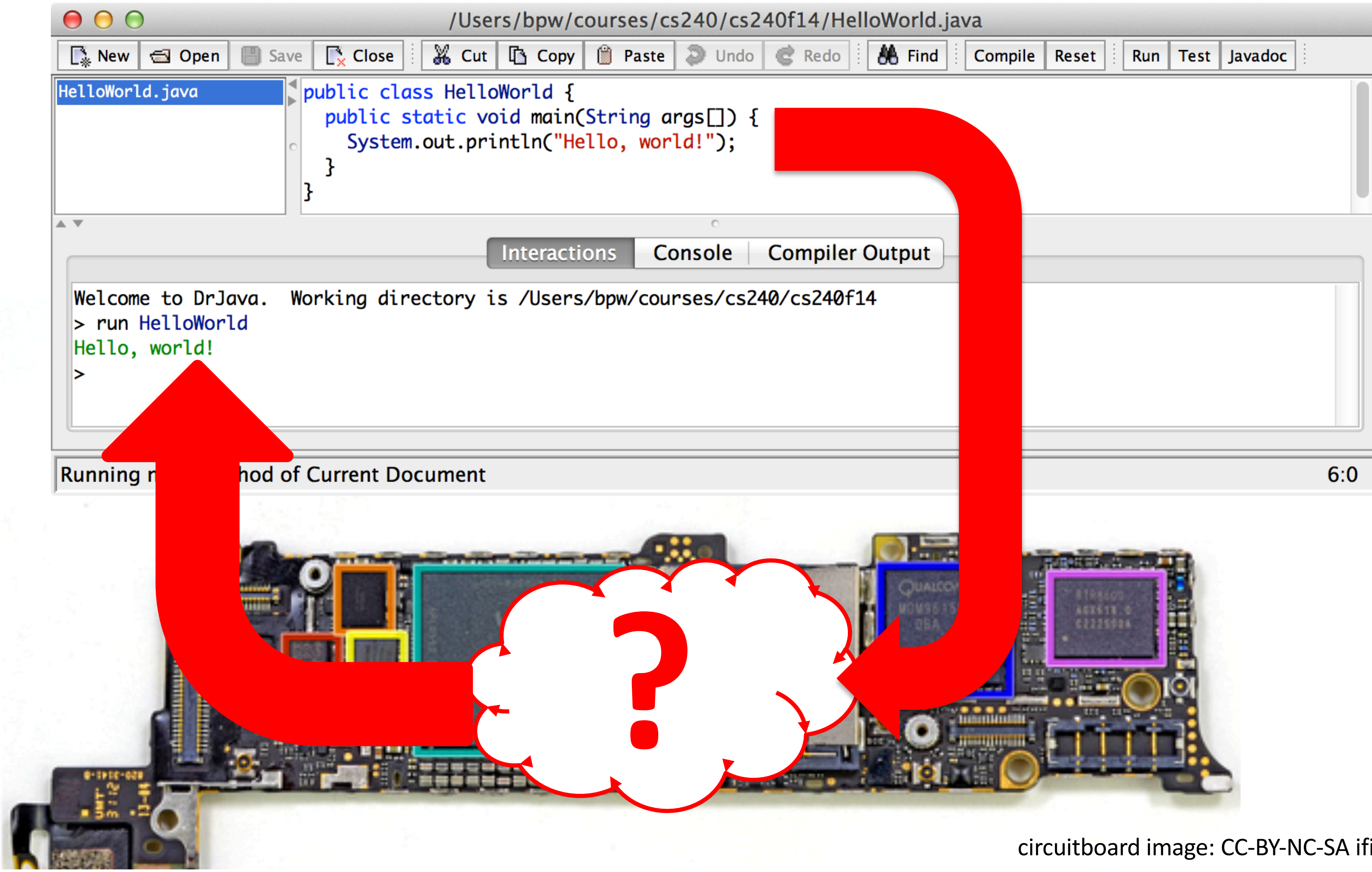
1. **What is CS 240?**
2. Why take CS 240?
3. How does CS 240 work?
4. Dive into foundations of computer hardware.

CS 111, 230, 231, 235, 251:

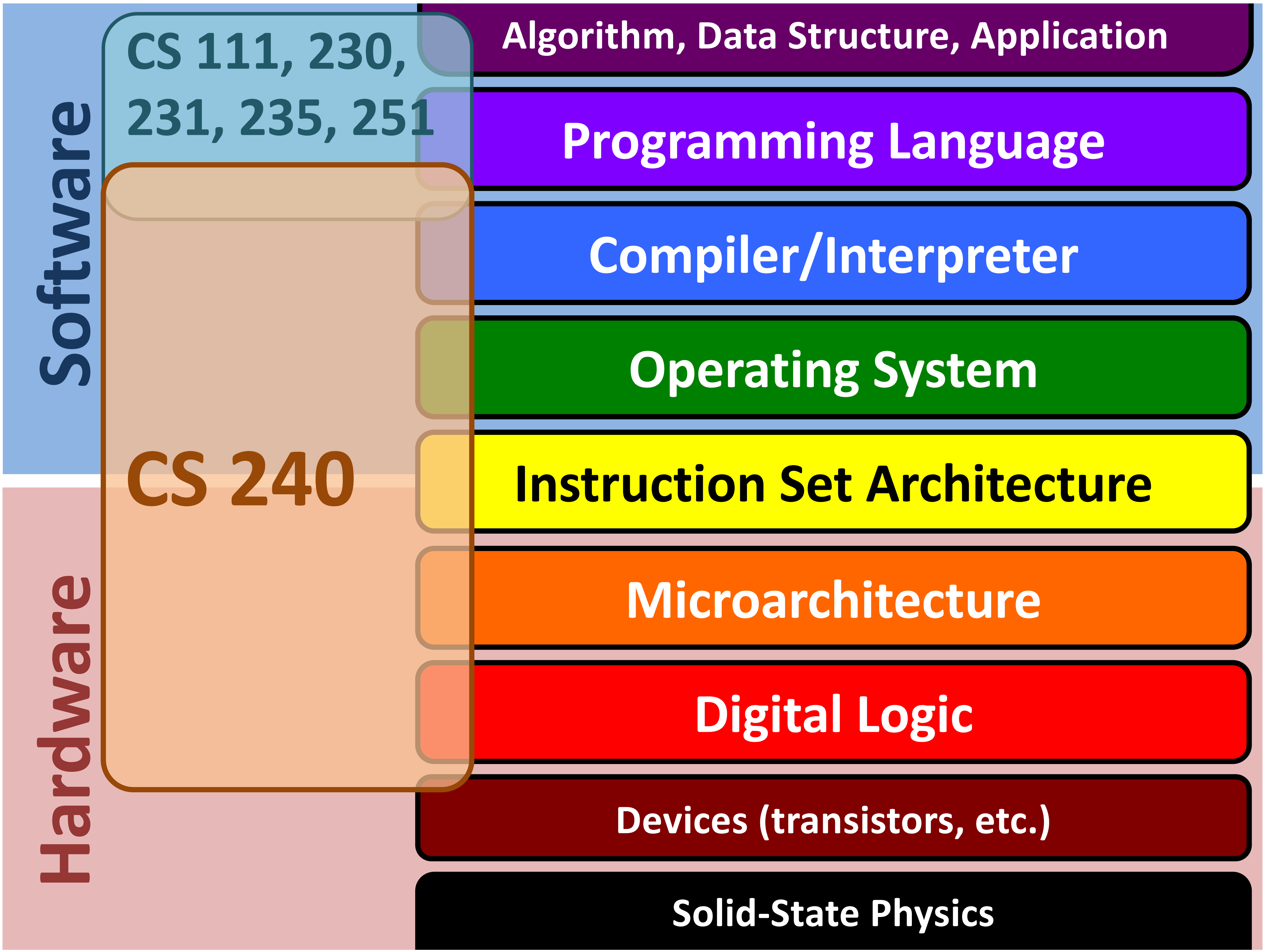
- What can a program do?
- How can a program solve a problem?
- How do you structure a program?
- How do you know it is correct or efficient?
- How hard is it to solve a problem?
- How is computation expressed?
- What does a program mean?
- …

A BIG question is missing…

1 CS 240: How do computers work?

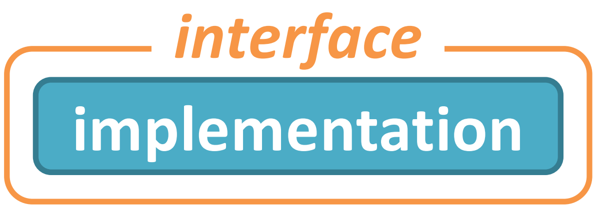


circuitboard image: CC-BY-NC-SA ifixit.com

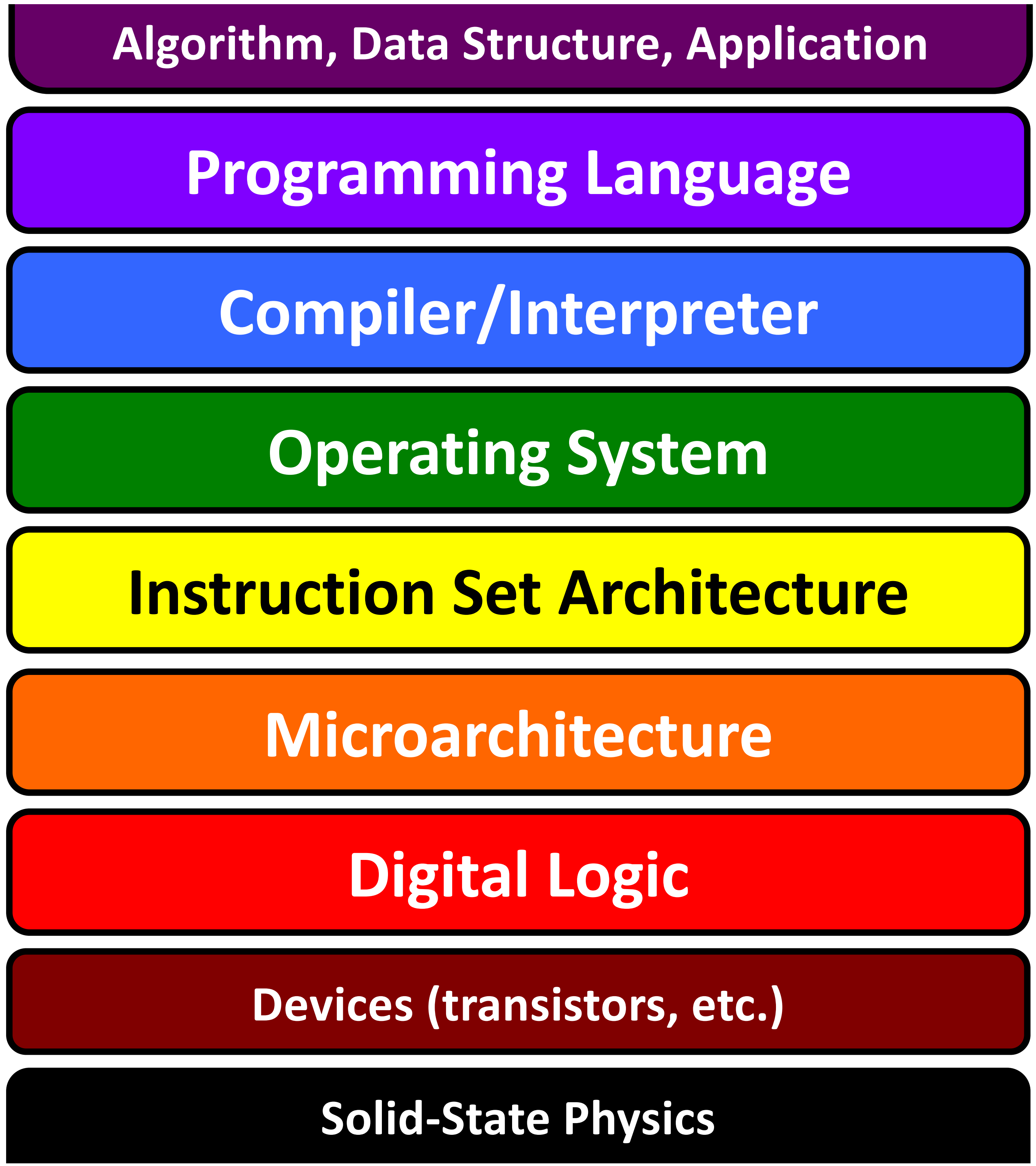

Software
Hardware
CS 111, 230, 231, 235, 251
CS 240
Algorithm, Data Structure, Application
Programming Language
Compiler/Interpreter
Operating System
Instruction Set Architecture
Microarchitecture
Digital Logic
Devices (transistors, etc.)
Solid-State Physics

Big Idea:

Abstraction



Layers manage complexity.



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

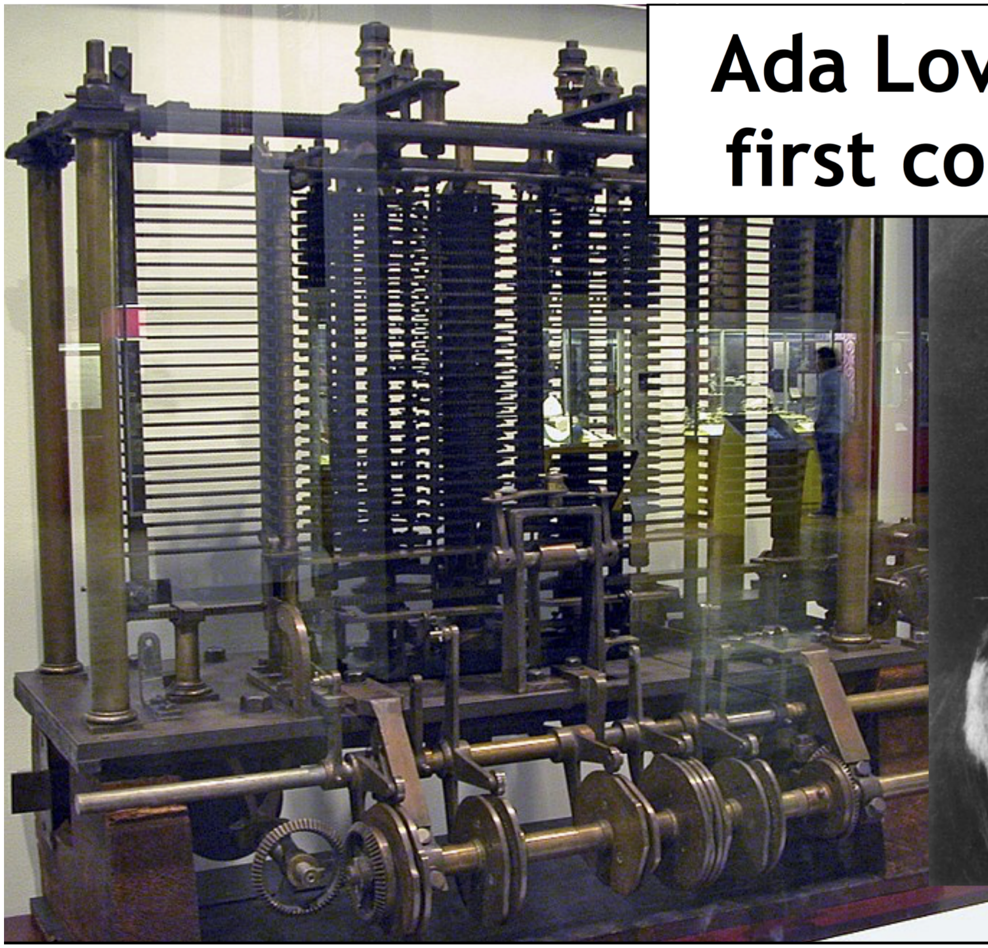
compilers, assemblers, decoders

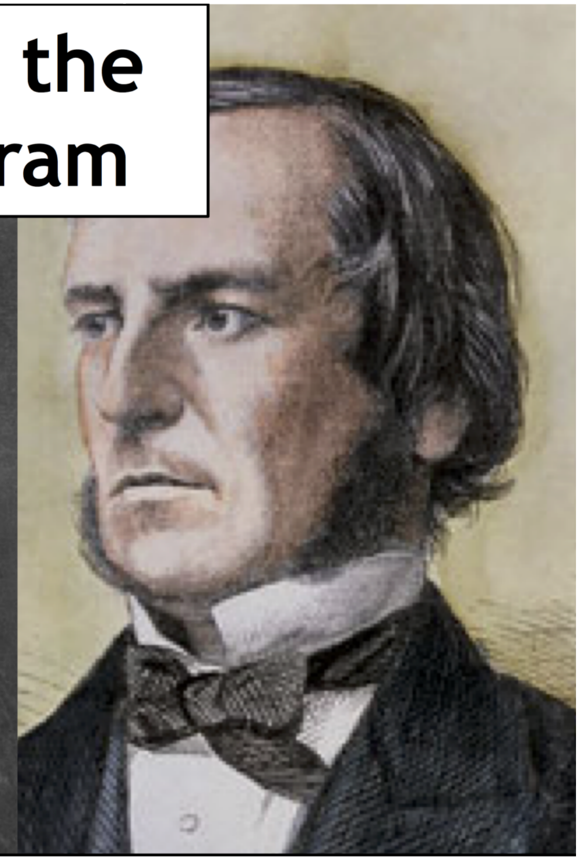
Control flow within/across programs

branches, procedures, OS

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

Ada Lovelace writes the first computer program





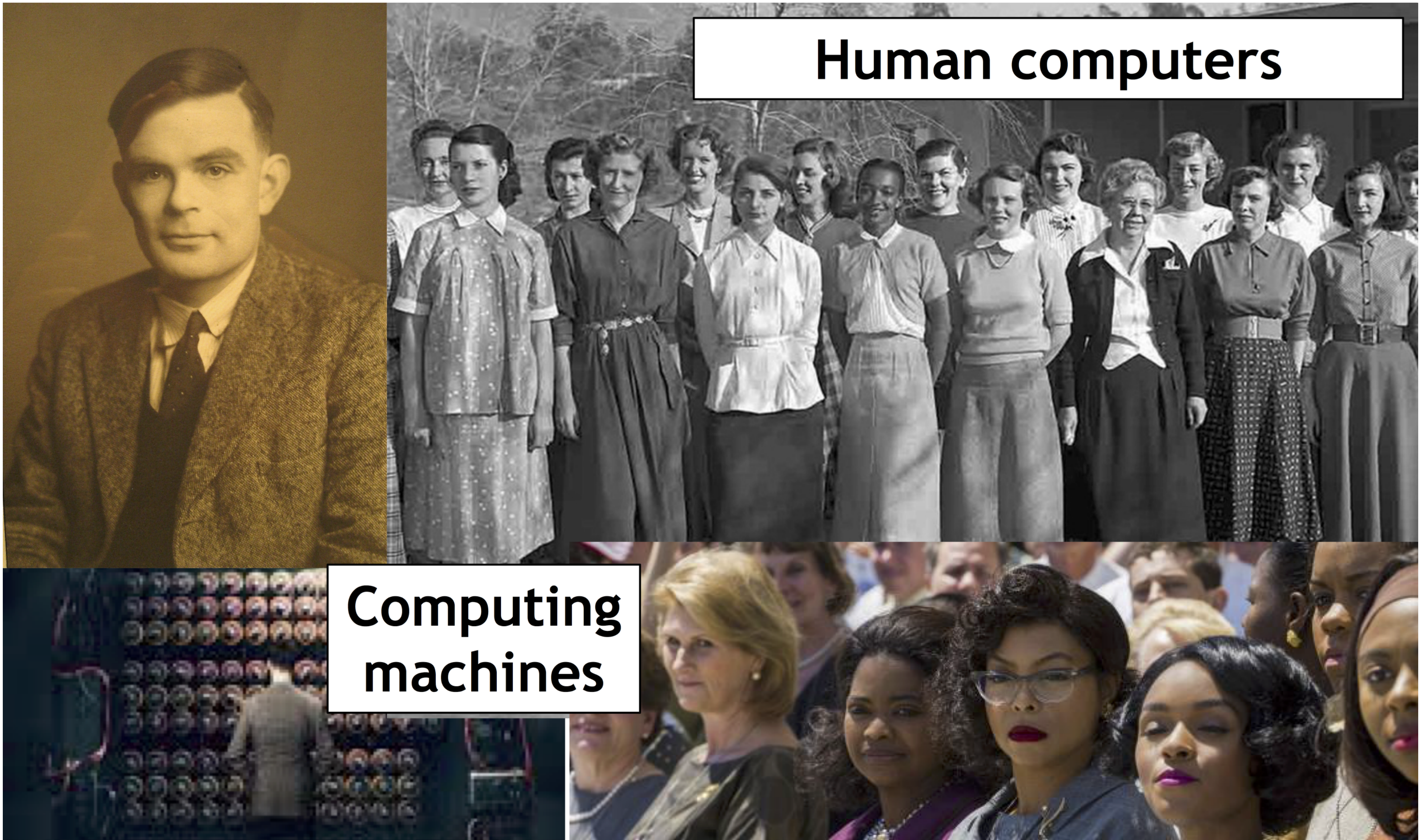
Charles Babbage designs Analytical Engine

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

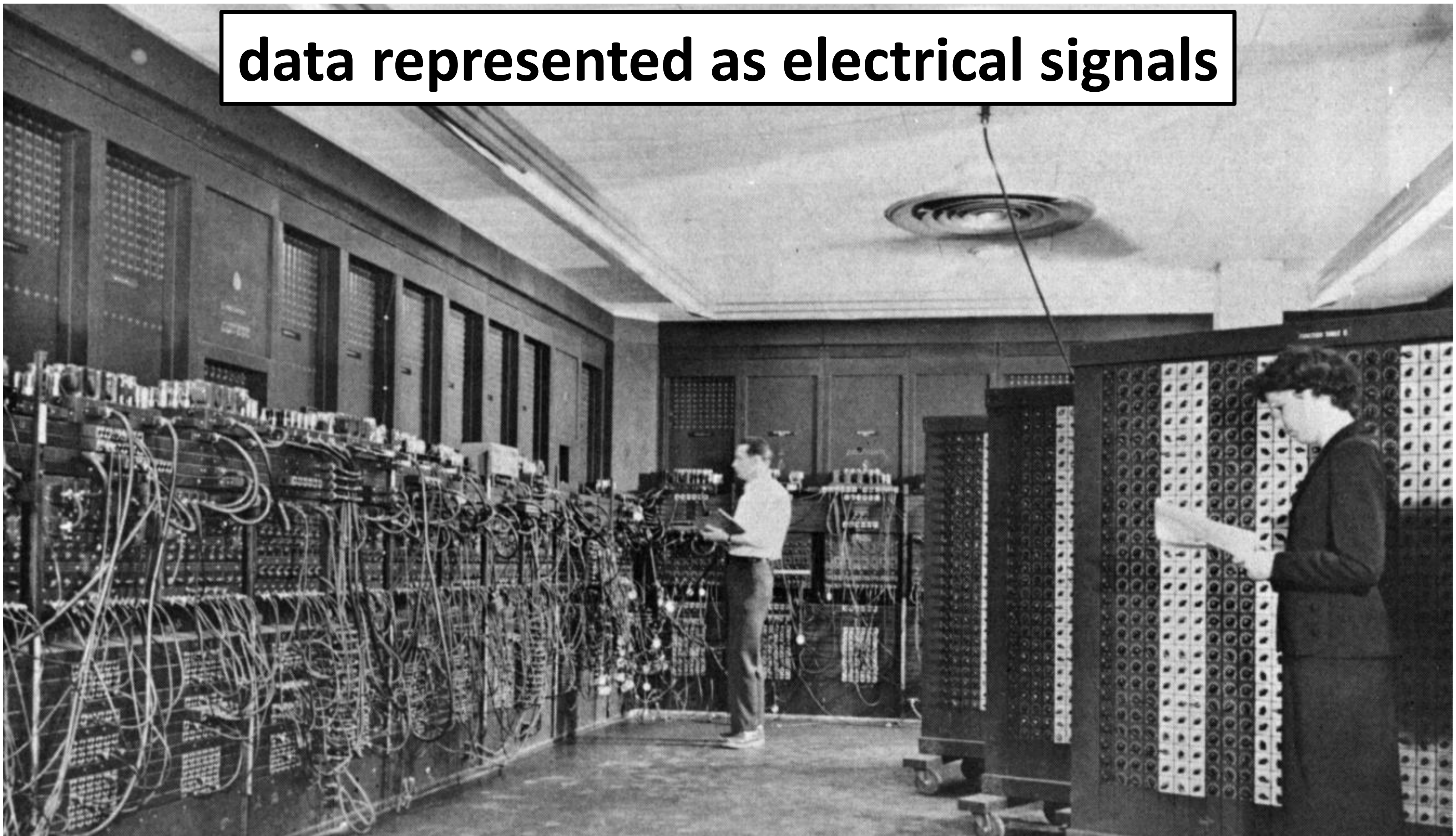


Alan Turing, 1940s
Imitation Game, 2014
nage: Flikr mark_am_kramer, Imitation Game poster

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

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

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

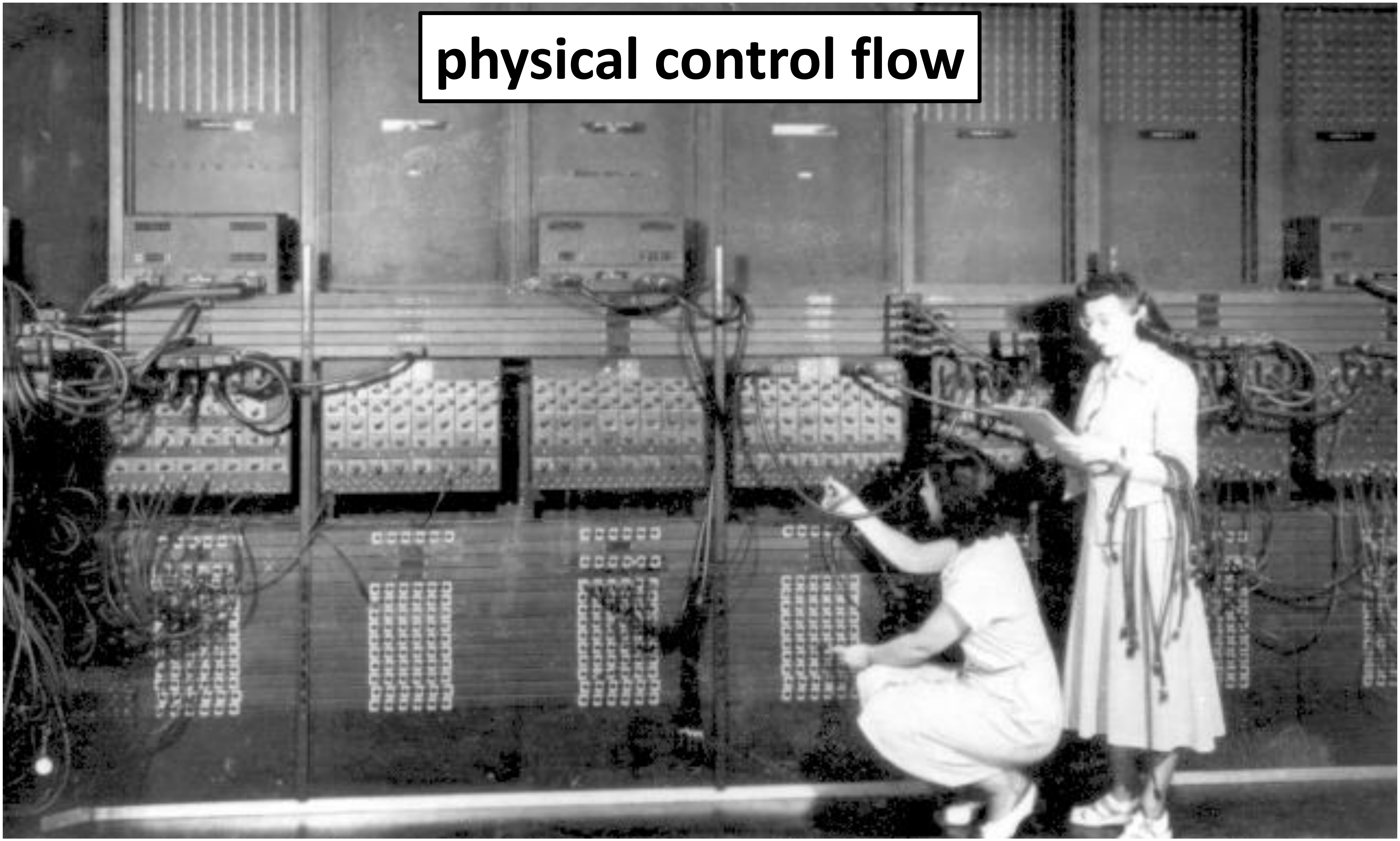
Jean Jennings Bartik and Frances Bilas Spence with part of ENIAC.

The programmers of ENIAC were six women.

http://eniacprogrammers.org/, http://sites.temple.edu/topsecretrosies/

Image: public domain

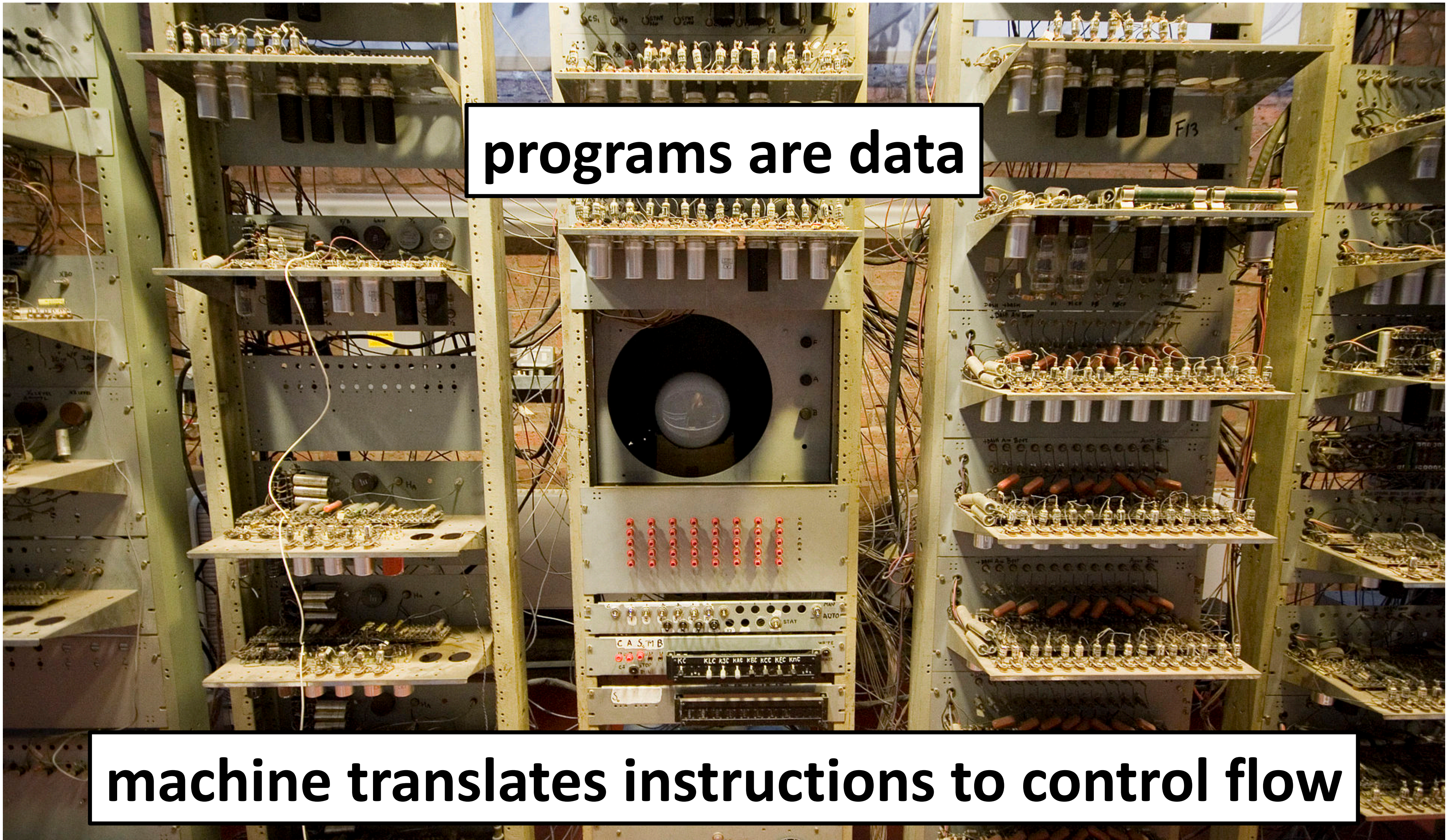
1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s	2020s



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

Image: public domain

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



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

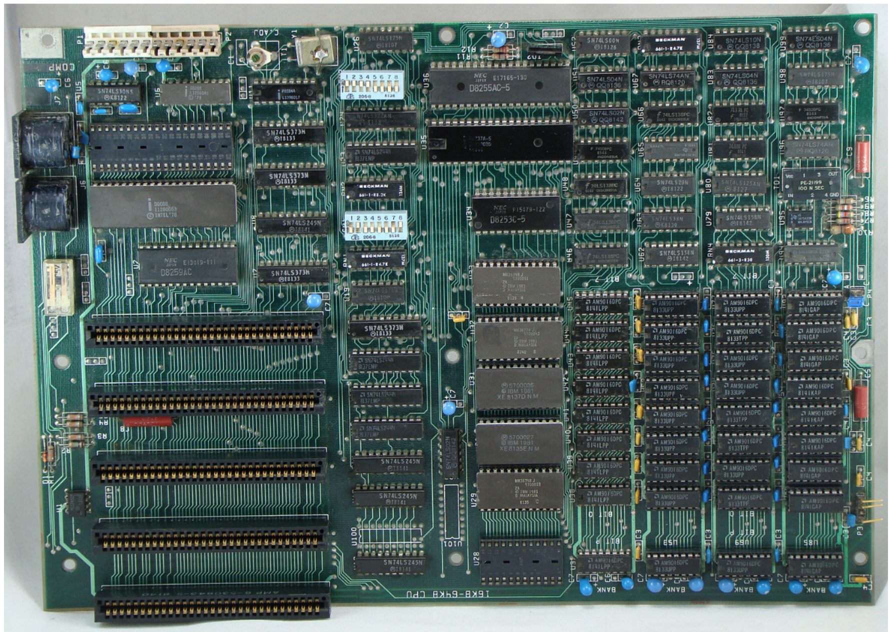
1940s	1950s	**1960s**	**1970s**	1980s	1990s	2000s	2010s	2020s

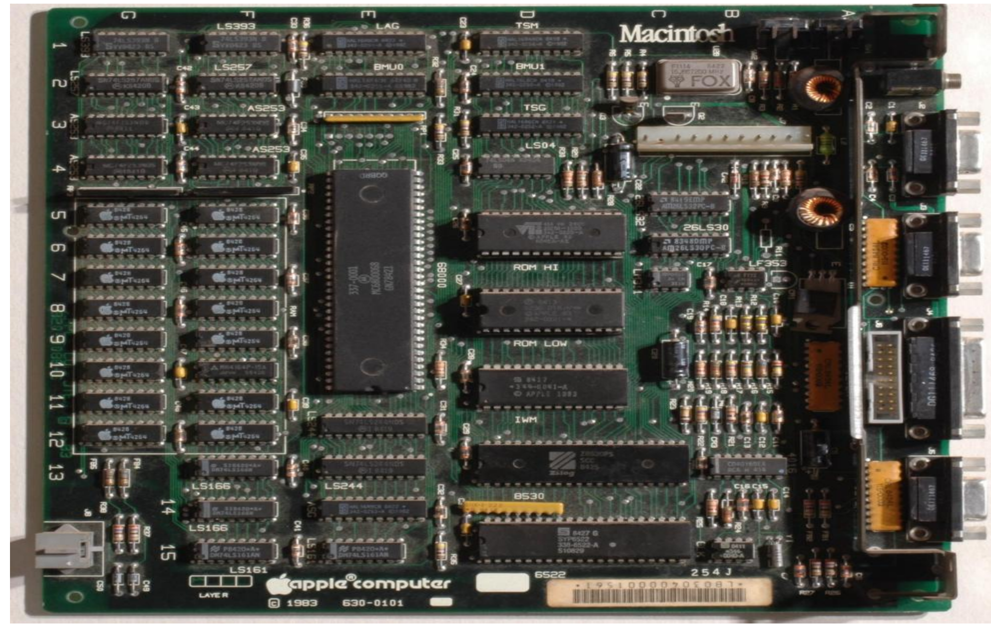
PDP-11 "**minicomputers**"

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

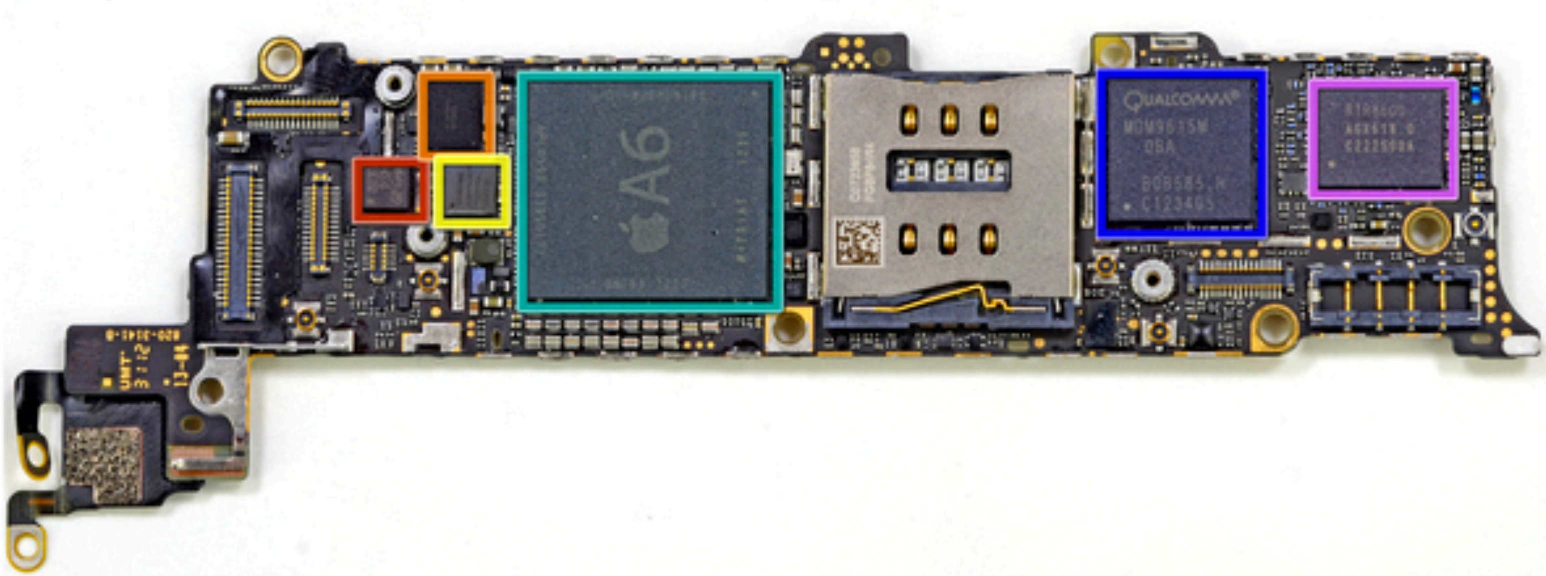
http://www.pcworld.com/article/249951/if_it_aint_broke_dont_fix_it_ancient_computers_in_use_today.html?page=2

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

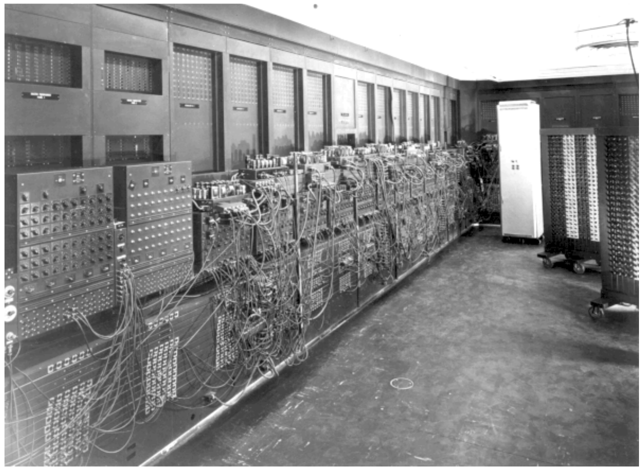




1940s	1950s	1960s	1970s	1980s	1990s	**2000s**	**2010s**	2020s



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

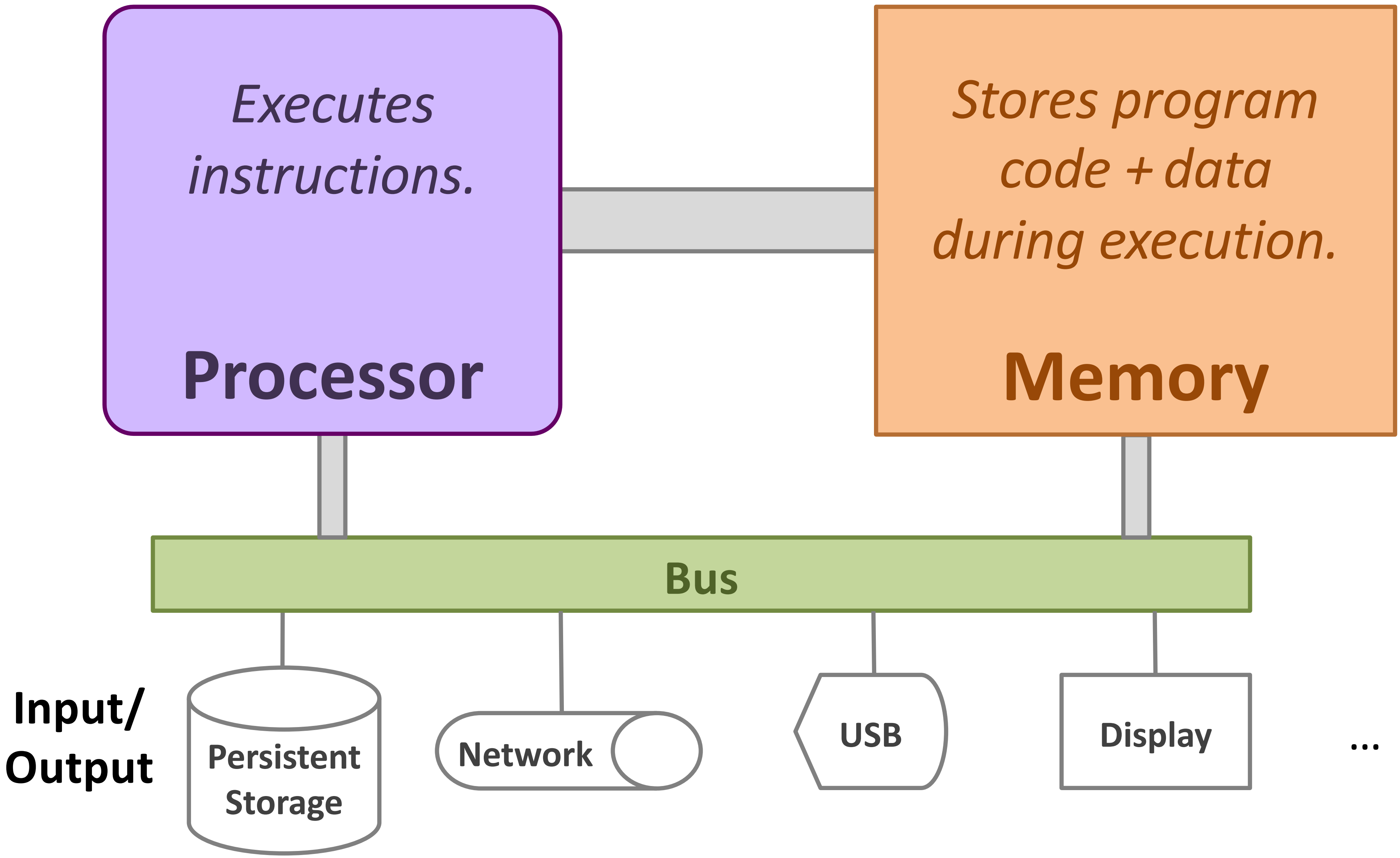


ENIAC image: public domain; iPhone image: CC-BY-NC-SA ifixit.com

	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

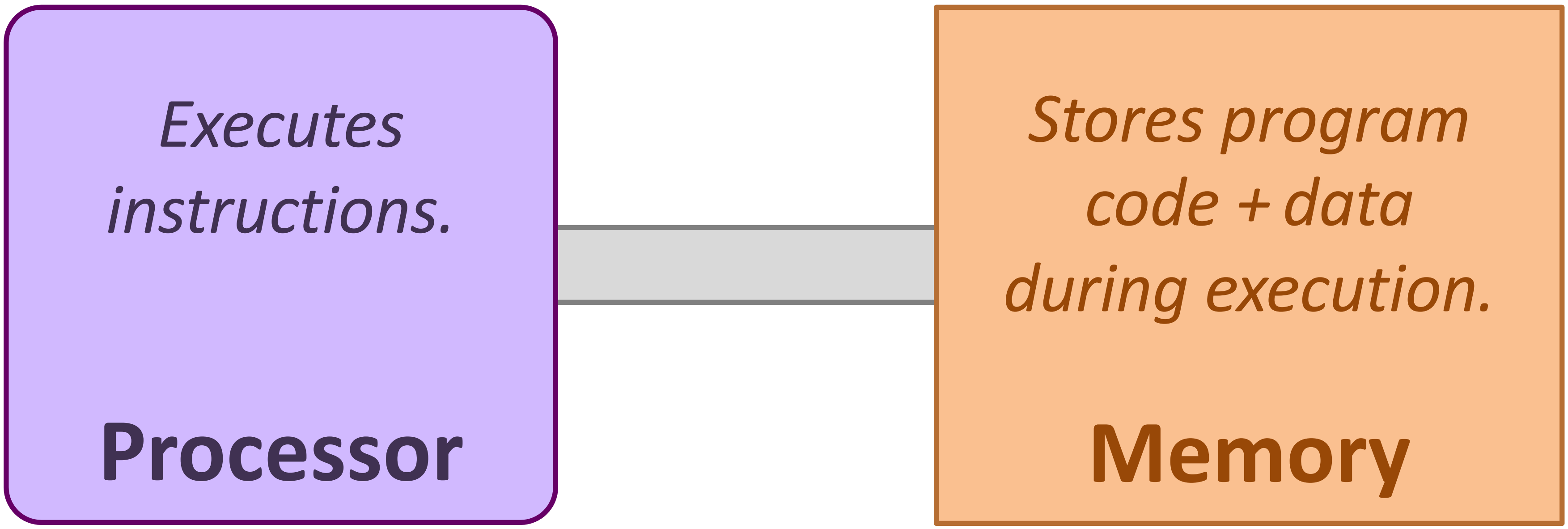
1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s	2020s

Modern Computer Organization



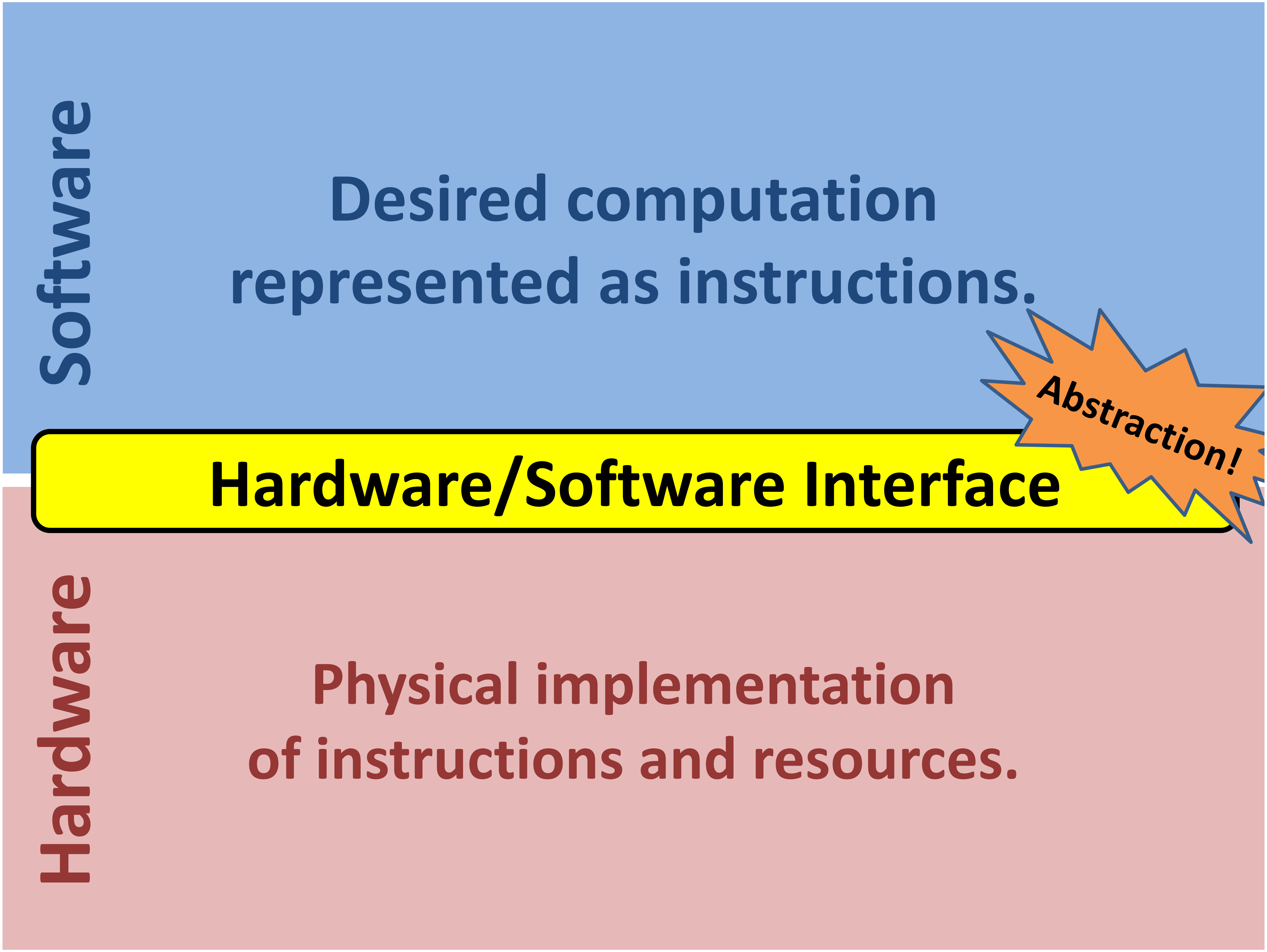
1940s | 1950s | 1960s | 1970s | 1980s | 1990s | 2000s | 2010s | 2020s

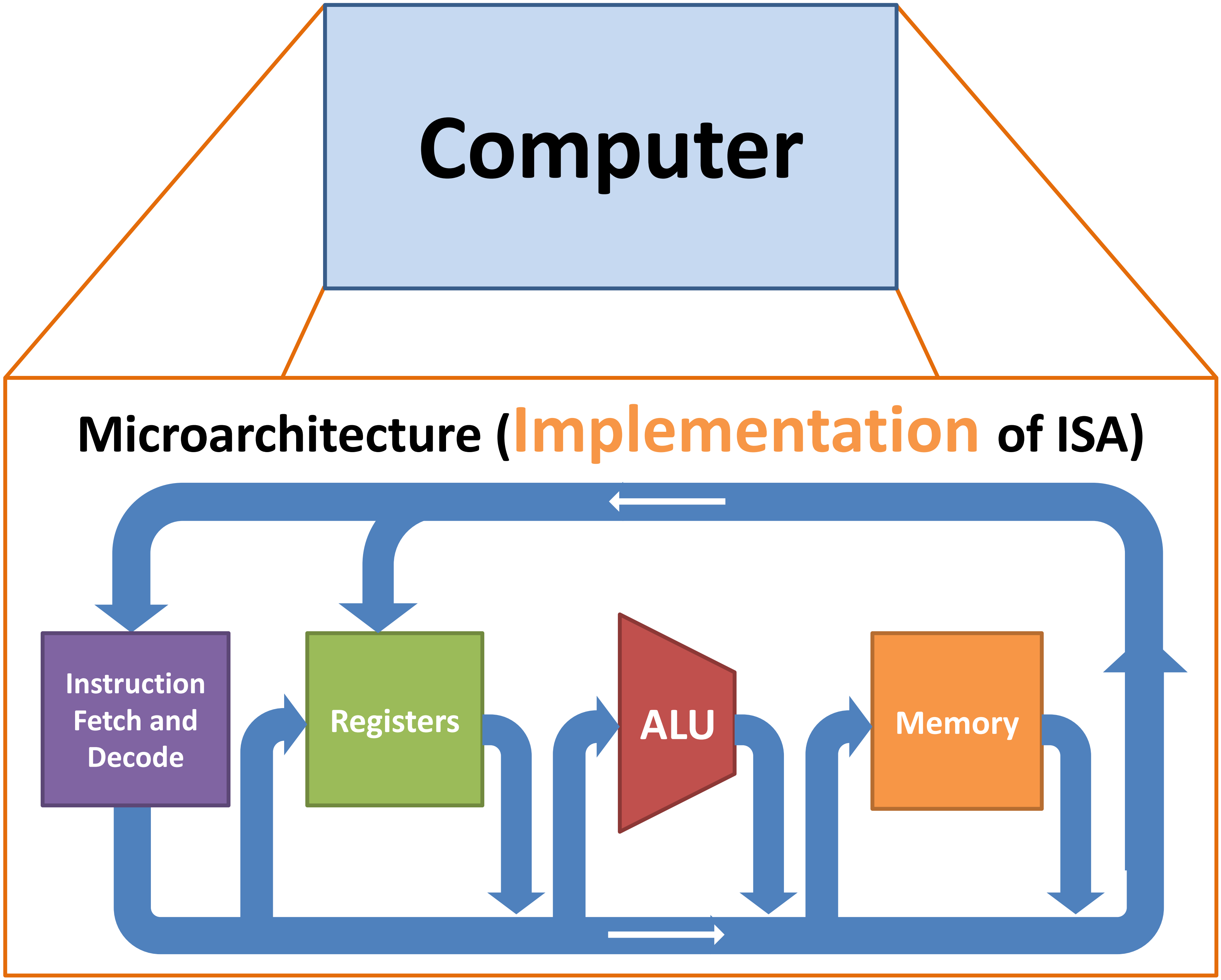
Modern Computer Organization

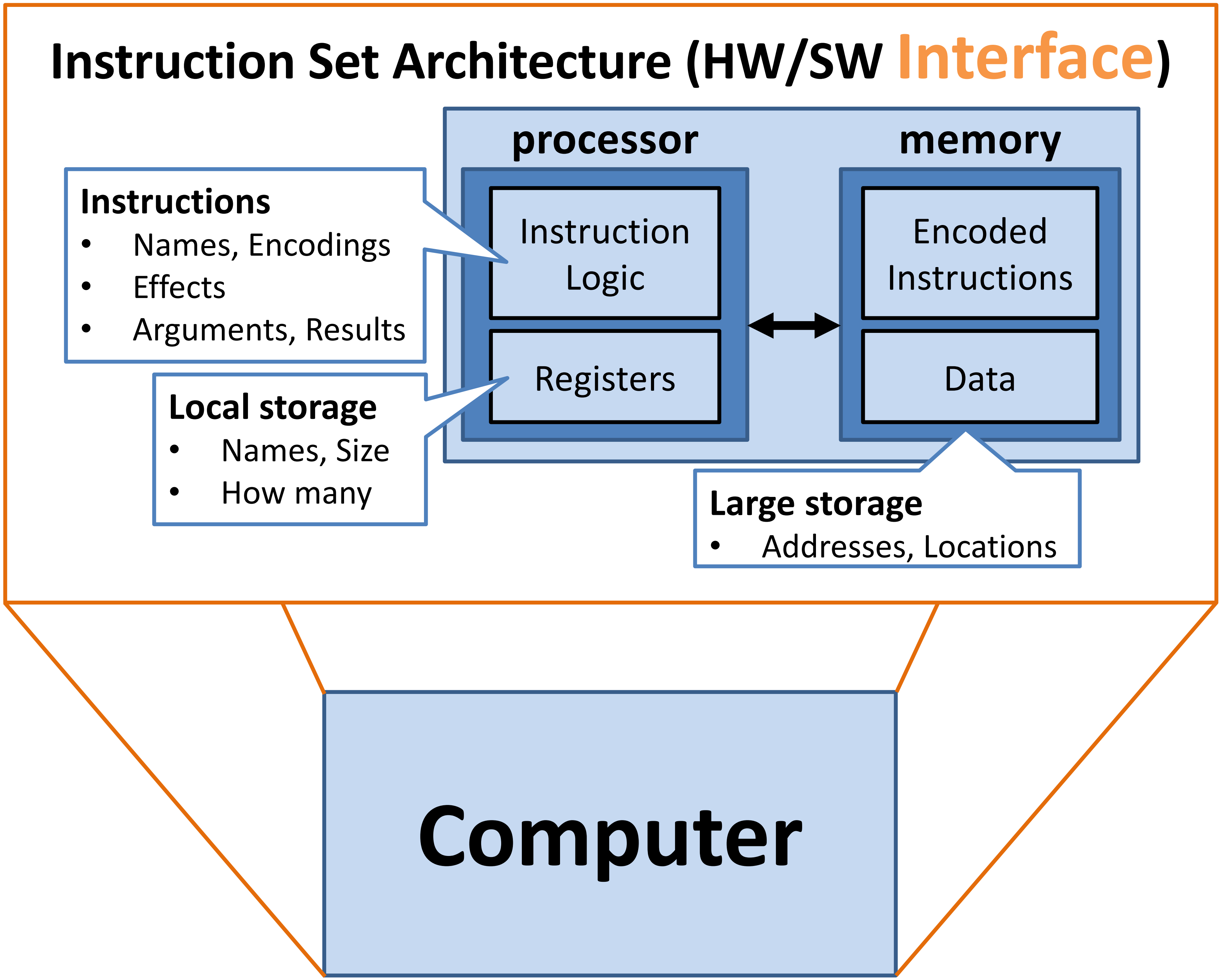


Processor repeats:

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
Registers
Encoded Instructions
Data
Local storage
• Names, Size
• How many
Large storage
• Addresses, Locations
Computer

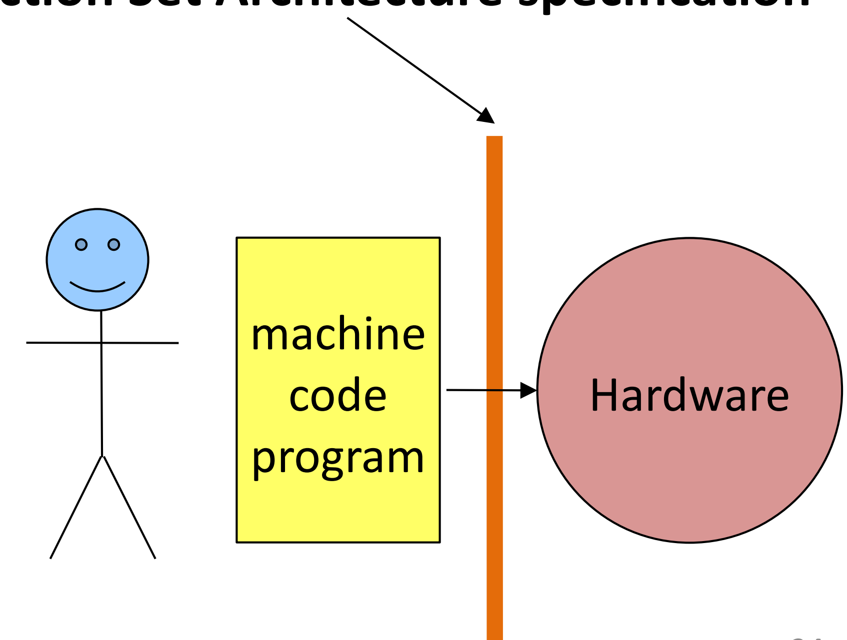
1940s	1950s	1960s	1970s	1980s	1990s	2000s	2010s	2020s

Machine Instructions

(adds two values and stores the result)

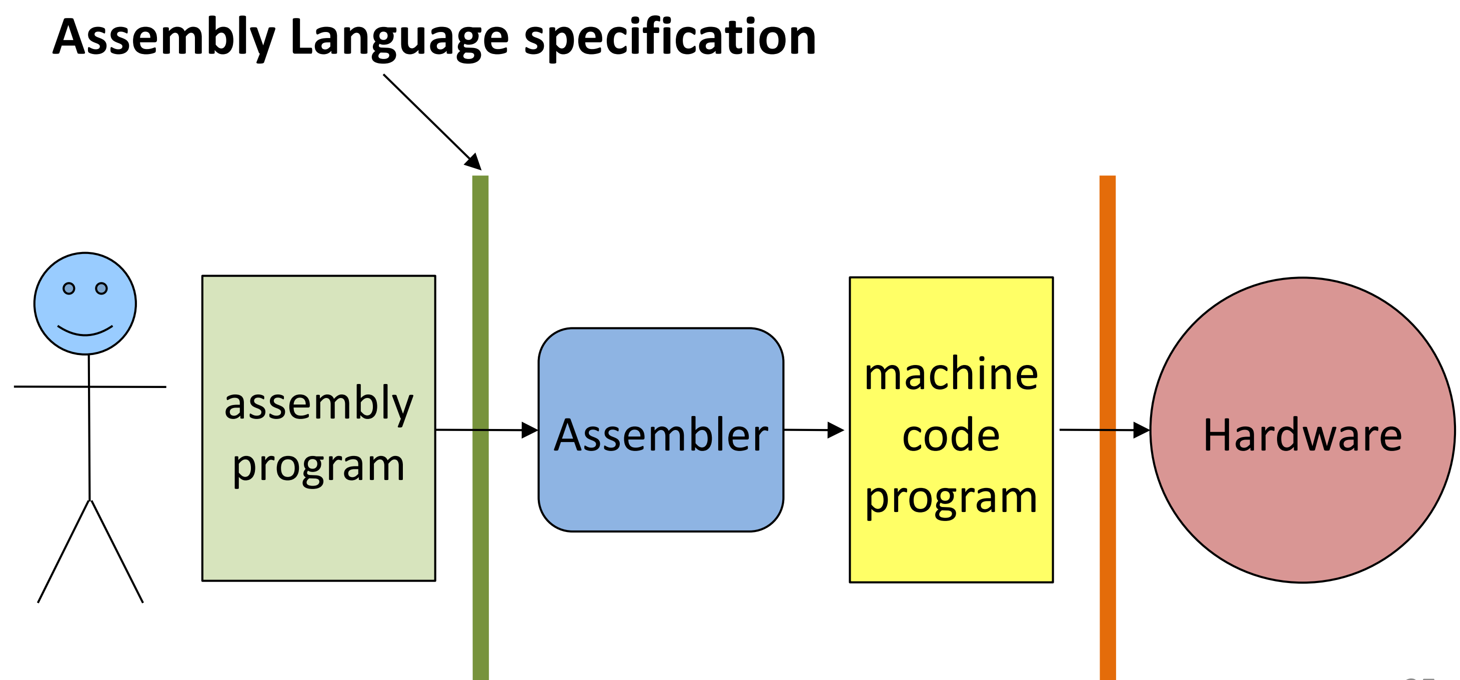
00000010100010101100100000010000

Instruction Set Architecture specification



Assemblers and Assembly Languages

`addl %eax, %ecx` ➡ `00000010100010101100100000010000`

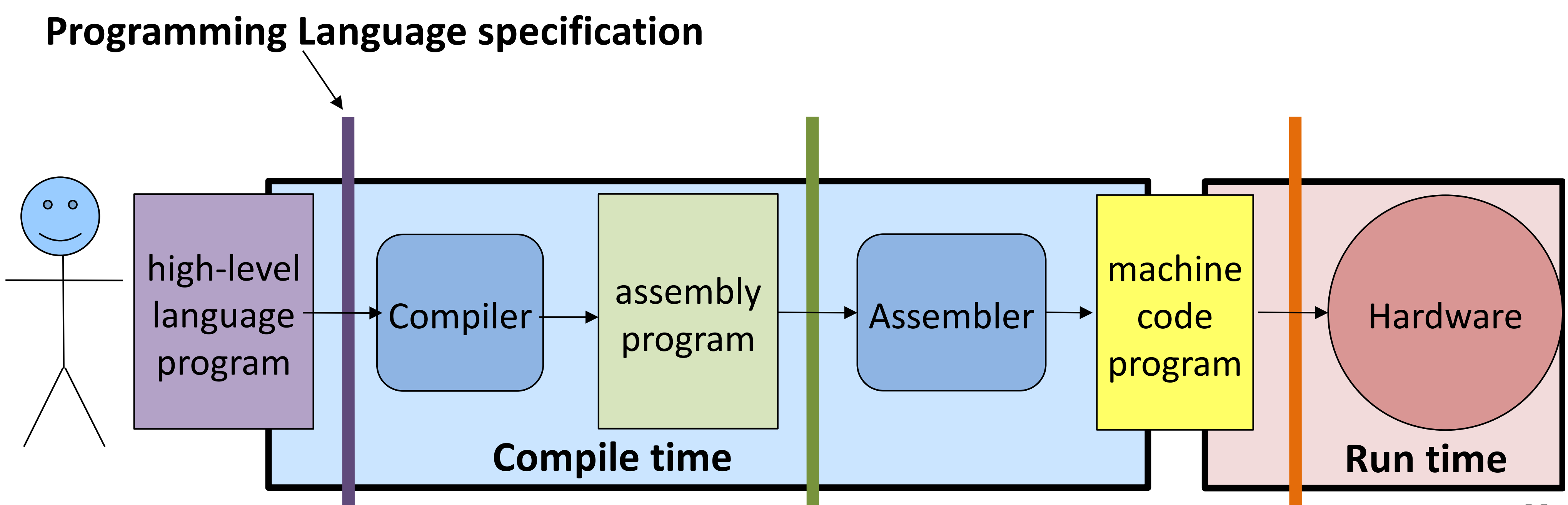


Higher-Level Programming Languages

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

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

```
00000010100010101100100000010000
```



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

More and more layers…

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

CS 240 in 3 acts

Hardware *implementation* (4-5 weeks each)

- 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

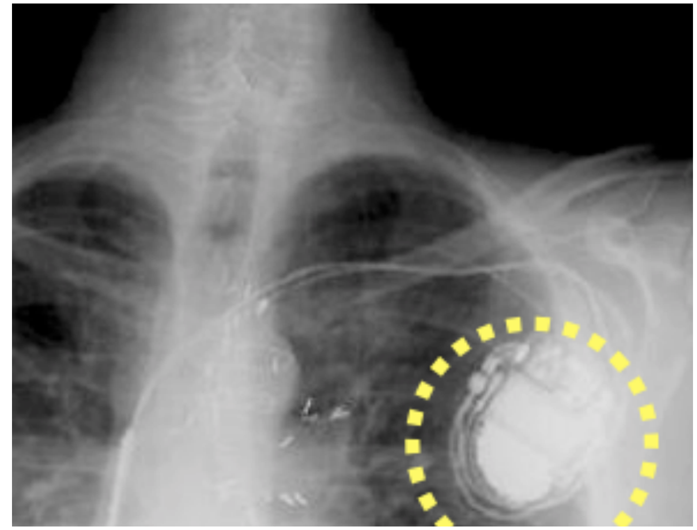
```
void copyji(int src[2048][2048],
            int dst[2048][2048])
{
  int i,j;
  for (j = 0; j < 2048; j++)
    for (i = 0; i < 2048; i++)
      dst[i][j] = src[i][j];
}
```

```
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 loc 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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The New York Times **Business**

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A Heart Device Is Found Vulnerable to Hacker Attacks

By BARNABY J. FEDER
Published: March 12, 2008

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REPRINTS

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!

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

3 Everything is here.
Please read it.