CS 31007 Autumn 2020

COMPUTER ORGANIZATION AND ARCHITECTURE

Instructors

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Computer Science and Engineering

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Class Schedule

12:00-12:55 (Mon), 10:00-11:55 (Tue), and 8:00-8:55 (Thurs)

Additional Slots: 3:30 pm – 5:00 pm (Saturday)

Online Classes may be held in real-time mode
or in pre-recorded mode

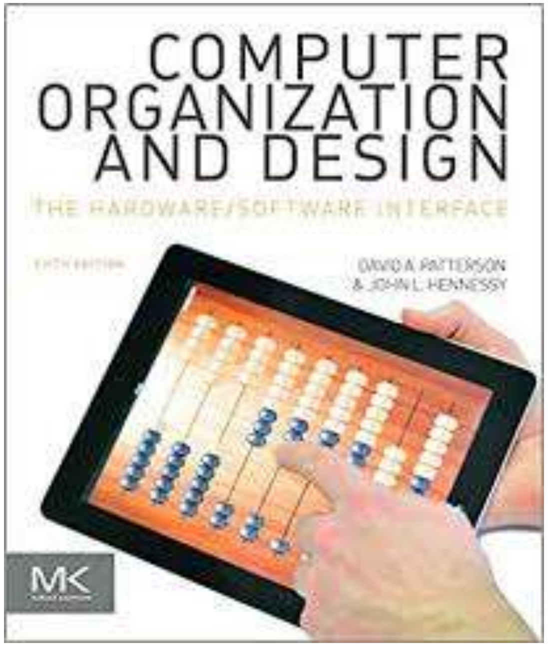
Tutorials and doubt-clearing sessions will be held
in real-time mode

Lab Course (39001): Computer Organization Laboratory

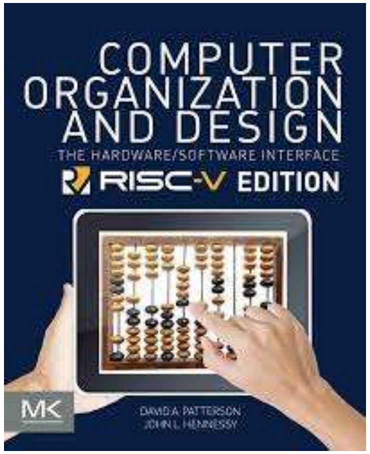
Prerequisites

Basic logic design, combinational and sequential circuits, knowledge of high-level programming language

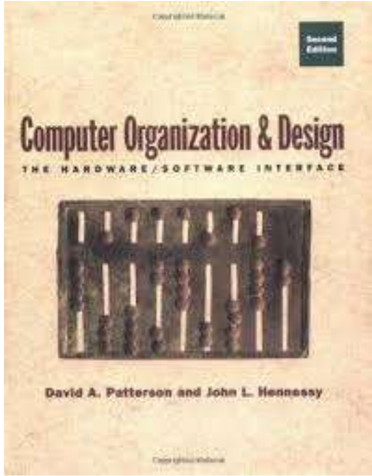
Textbook



D. A. Patterson and J. L. Hennessy
Computer Organization and Design
- The Hardware Software Interface
5th Edition, Morgan Kaufmann, 2014
(MIPS Version)



RISC-V Edition 2018



Second Edition 1998

2017 ACM Turing Award

Course Page:
https://moodlecse.iitkgp.ac.in/moodle/login/index.php
Moodle Student Registration Key for Course: Student03

Further Reading

1. Smruti R. Sarangi, *Computer Organisation and Architecture*, McGraw Hill India, 2014

2. William Stallings, *Computer Organization and Architecture: Designing for Performance*, Eight Edition, Prentice Hall, 2010.

3. John P. Hayes, *Computer Architecture and Organization*, 3rd Edition, Tata McGraw Hill, 2012.

Grading Policy

- No Mid-Sem or End-Sem Examination
- Evaluation at regular intervals
- Homework for practicing
- Online exams/quizzes
- 24-hour take-home tests
- Lecture scribing

The exams/quizzes would usually be scheduled in the regular class hours (including the Saturday slot)

Today's agenda

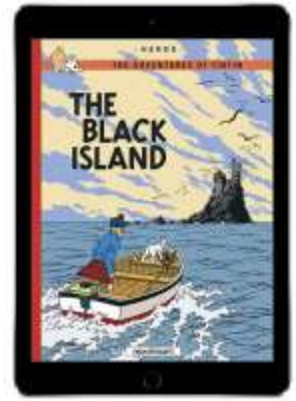
- Overview of the course
- Evolution and history of computer design
- Moore's law
- Basic components of a computer
- Instruction Set Architecture (ISA)
- Computer organization and computer architecture: Bottom-up and Top-down view

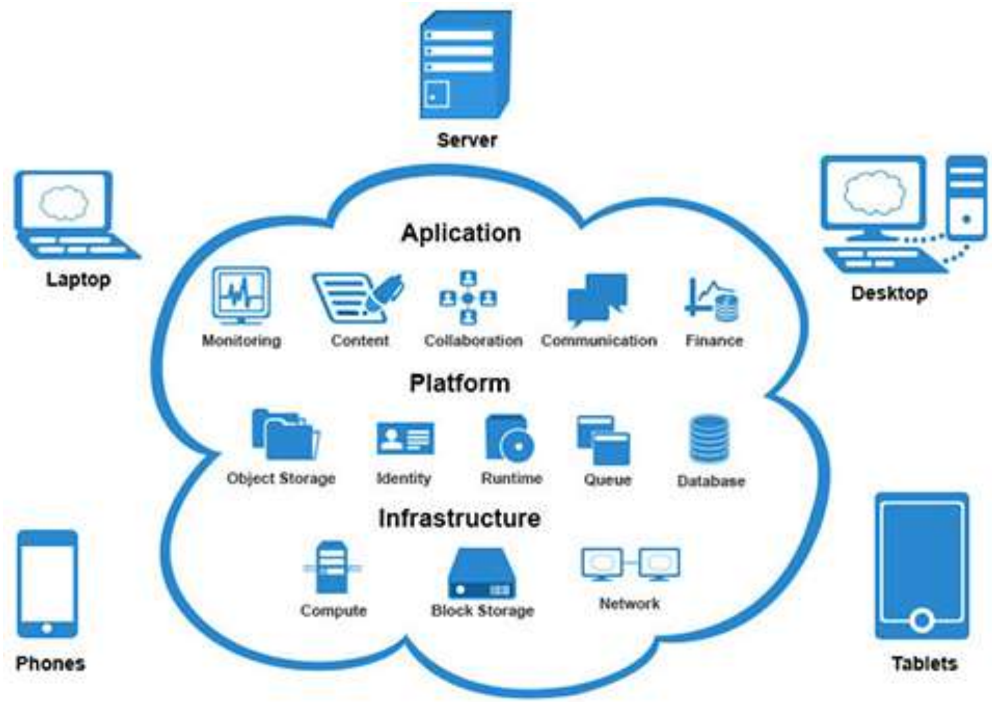
Acknowledgement: Patterson and Hennessy; V. D. Agrawal; S. R. Sarangi

Goal is to understand ….

- What are the principles of computer design?
- What is the hardware-software interface?
- Computer organization *versus* computer architecture?
- How to design the instruction set of a machine?
- How instructions are executed in a machine?
- What are the techniques for performing fast computation?
- How a complete processor is designed?

What is a Computer ?





Cloud Computing

Car or Computers?

BMW
345i

- 2,000,000 lines of code
- Fiftythree 8-bit microprocessors
- Eleven 32-bit microprocessors
- Seven 16-bit microprocessors

The Computer Revolution

- Makes novel applications feasible
  - Computers in automobiles
  - Cell phones
  - Human genome project
  - World Wide Web
  - Search Engines
- Computers are all pervasive

Classes of Computers

- Personal computers
  - General purpose, variety of software
  - Subject to cost/performance tradeoff

- Server computers
  - Network based
  - High capacity, performance, reliability
  - Range from small servers to building sized
  - Cloud

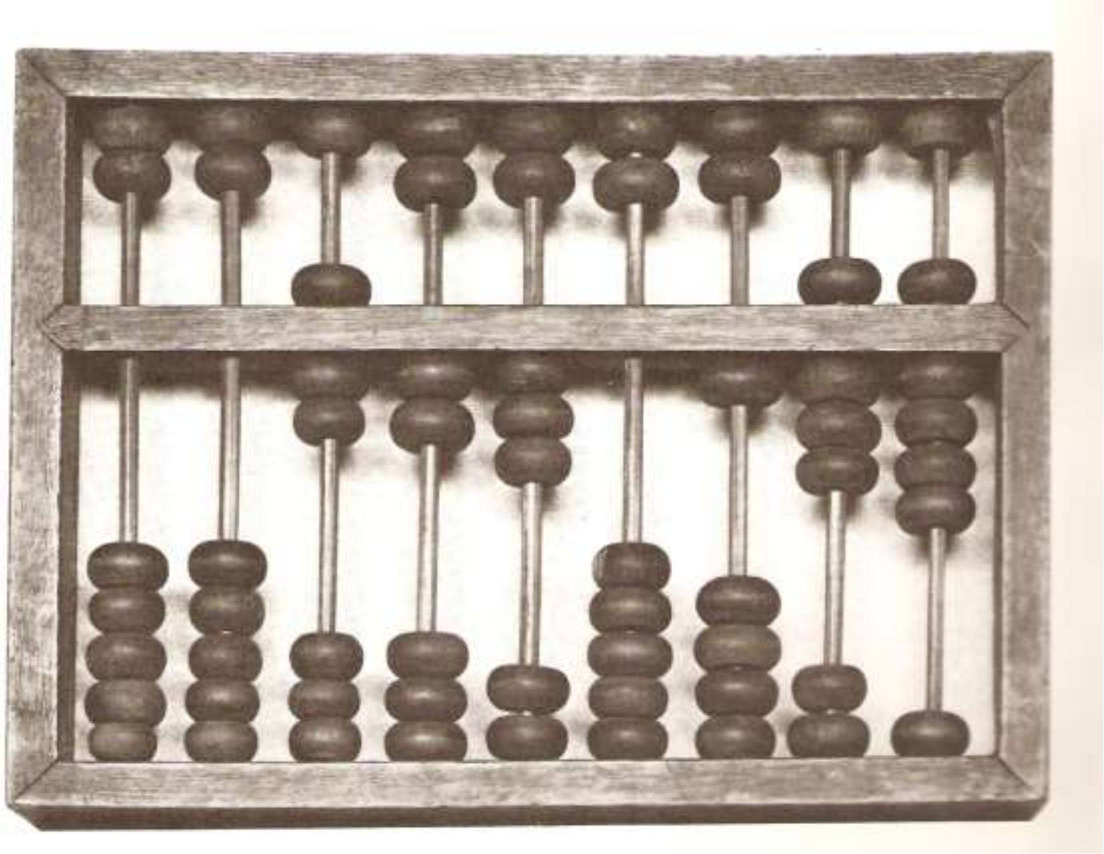
Classes of Computers

- Supercomputers
  - High-end scientific and engineering calculations
  - Highest capability but represent a small fraction of the overall computer market
- Embedded computers
  - Hidden as components of systems
  - Stringent power/performance/cost constraints
  - Autonomous vehicles, robotics

A computer is a general purpose machine which can process Information and yield results

However, centuries ago, by a computer was meant …

The First Mechanical Computing Device



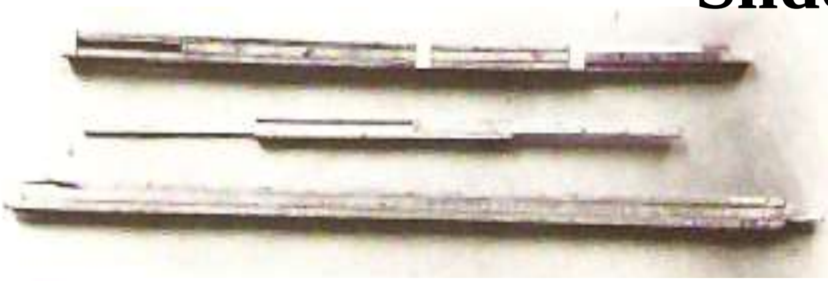
The nineteenth century Chinese abacus, numbers are entered by sliding the beads towards the crossbar.

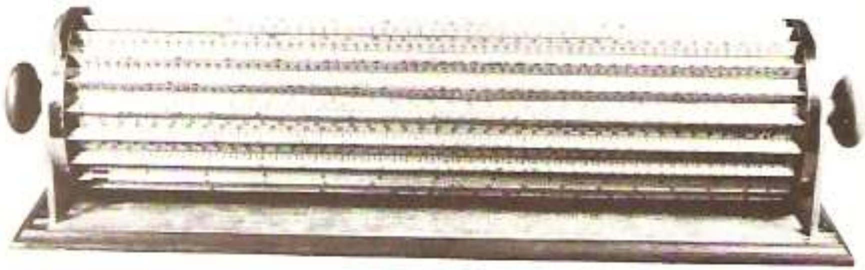
First Steps in Computing

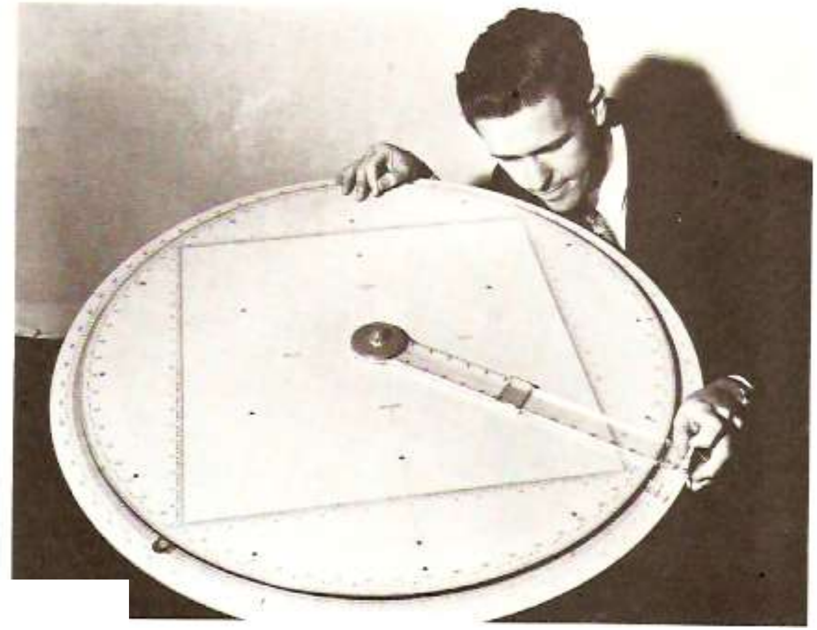
John Napier (1550-1617)

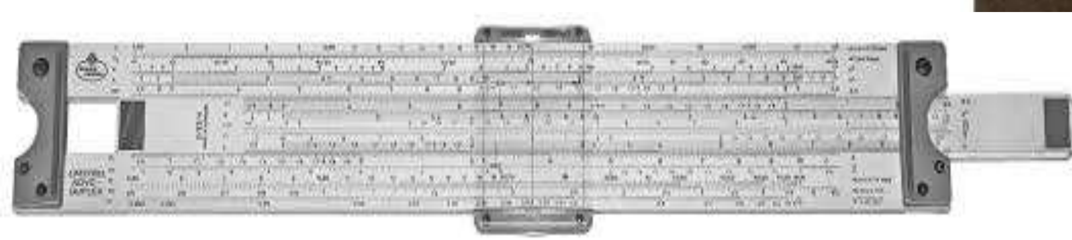
The front page of Napier's famous paper (1614) that introduced logarithm and contained ninety pages of tables.

Slide Rule



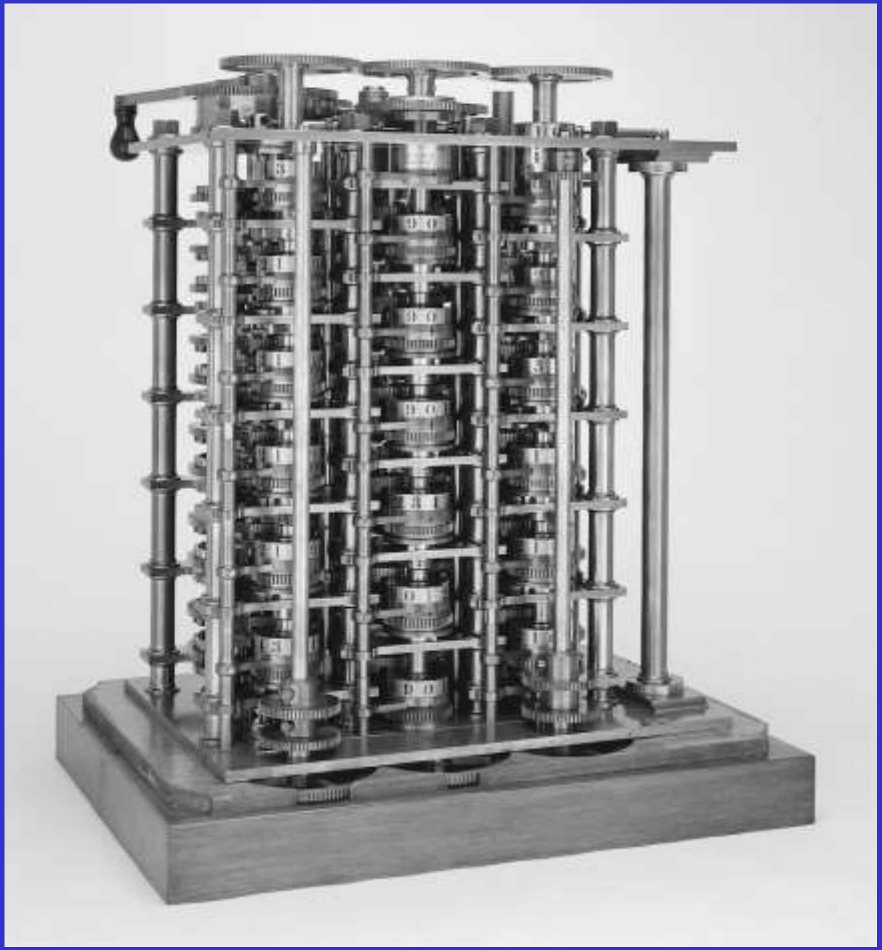






The first slide rule (top left) was made in 1654; the cylindrical slide rule (below left) and circular slide rules are useful modifications that were used for various computations; Slide rule (left-bottom) used by early generation of engineers.

The First Computer (1832)



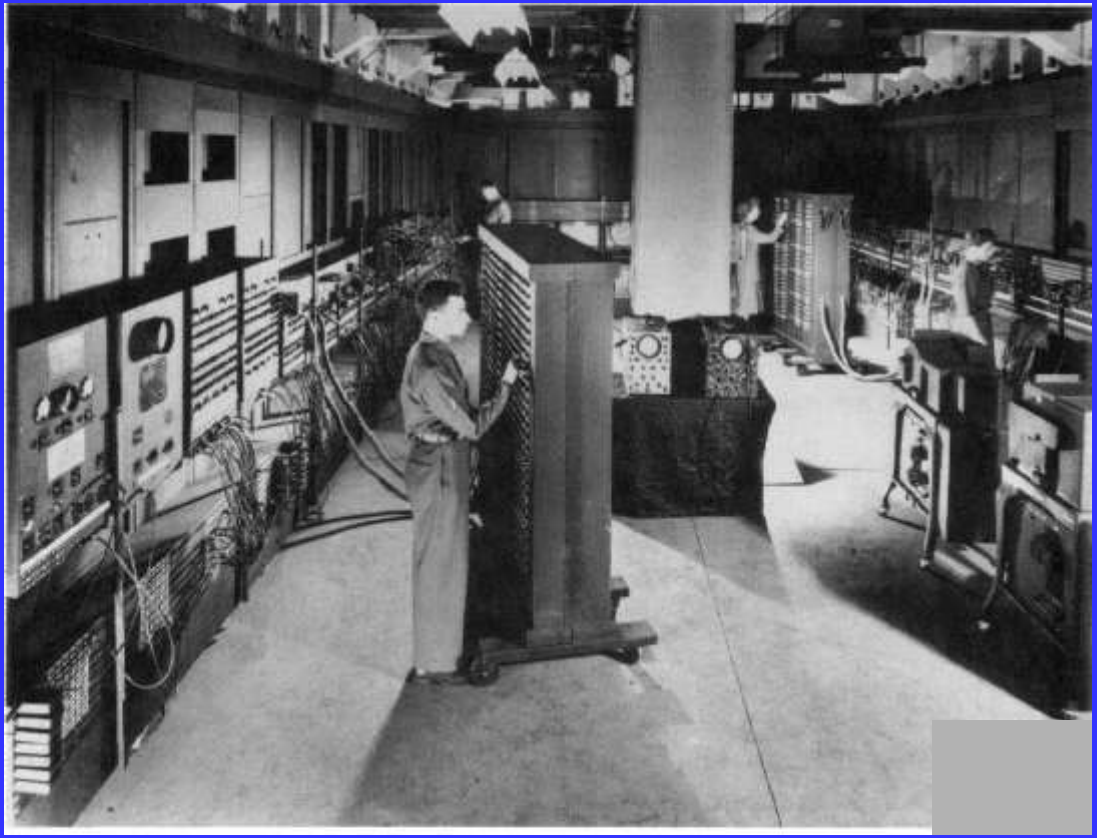
Babbage Difference Engine

25000 parts

In 1941, Conrad Zuse built Z3, the first programmable computer in Germany.

Conrad Zuse
(1910-1995)

ENIAC - The First Electronic Computer (1943-1946)



Length = 80 ft

Height =8.5 ft

Floor area = 1500 sq ft

Weight = 30 tons

18000 vacuum tubes

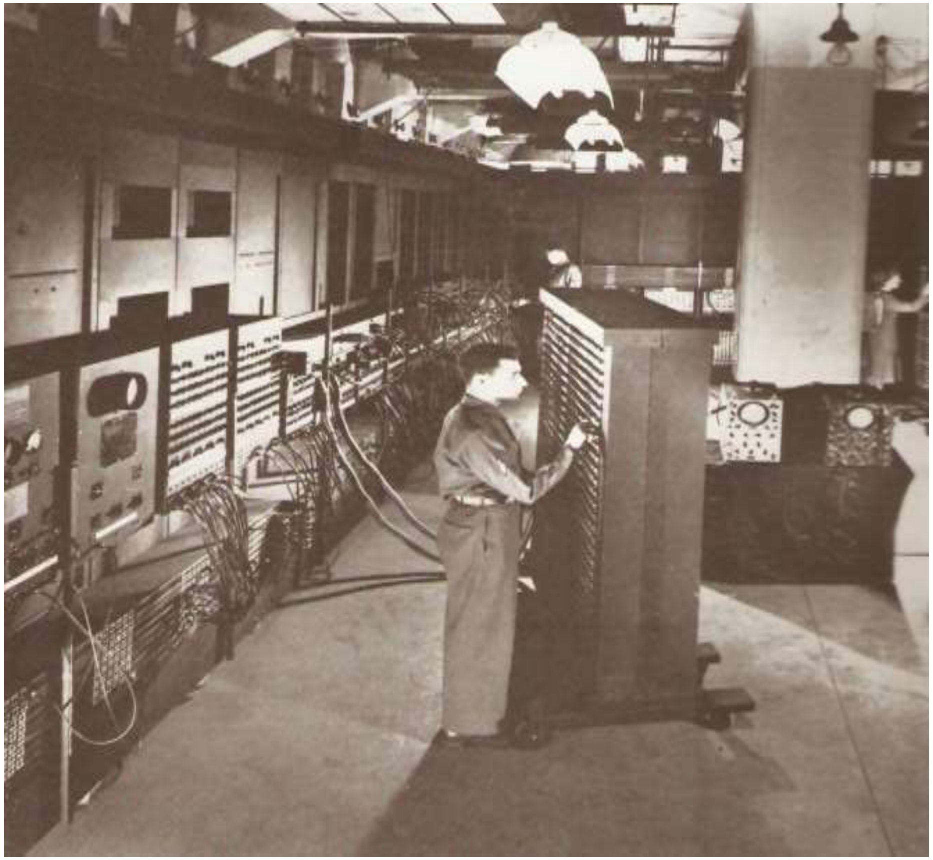
70,000 resistors

140 kw of power

John Mauchly (professor) and J. Presper Eckert (graduate student) built ENIAC at the University of Pennsylvania, Philadelphia

The Snapshots of ENIAC (1946)

This advertisement shows the amazing calculating powers of the ENIAC



A technician tracks down a misplaced cable in the ENIAC.

Courtesy: S. Augarten, Bit by Bit

First-Generation Computers

- Late 1940s and 1950s
- Stored-program computers
- Programmed in assembly language
- Used magnetic devices and earlier forms of memories
- Examples: IAS, ENIAC, EDVAC, UNIVAC, Mark I, IBM 701

Second Generation Computers

- 1955 to 1964
- Transistor replaced vacuum tubes
- Magnetic core memories
- Floating-point arithmetic
- High-level languages used: ALGOL, COBOL and FORTRAN
- System software: compilers, subroutine libraries, batch processing
- Example: IBM 7094

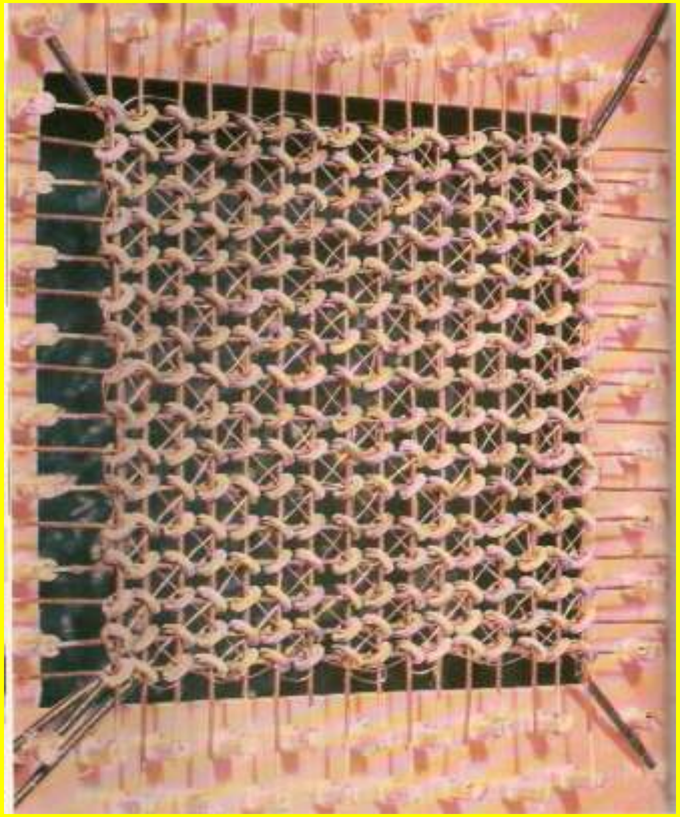
Third Generation Computers

- Beyond 1965
- Integrated circuit (IC) technology
- Semiconductor memories
- Memory hierarchy, virtual memories and caches
- Time-sharing
- Parallel processing and pipelining
- Microprogramming
- Examples: IBM 360 and 370, CYBER, ILLIAC IV, DEC PDP and VAX, Amdahl 470

The Miracle of Electronic Evolution

What is this??

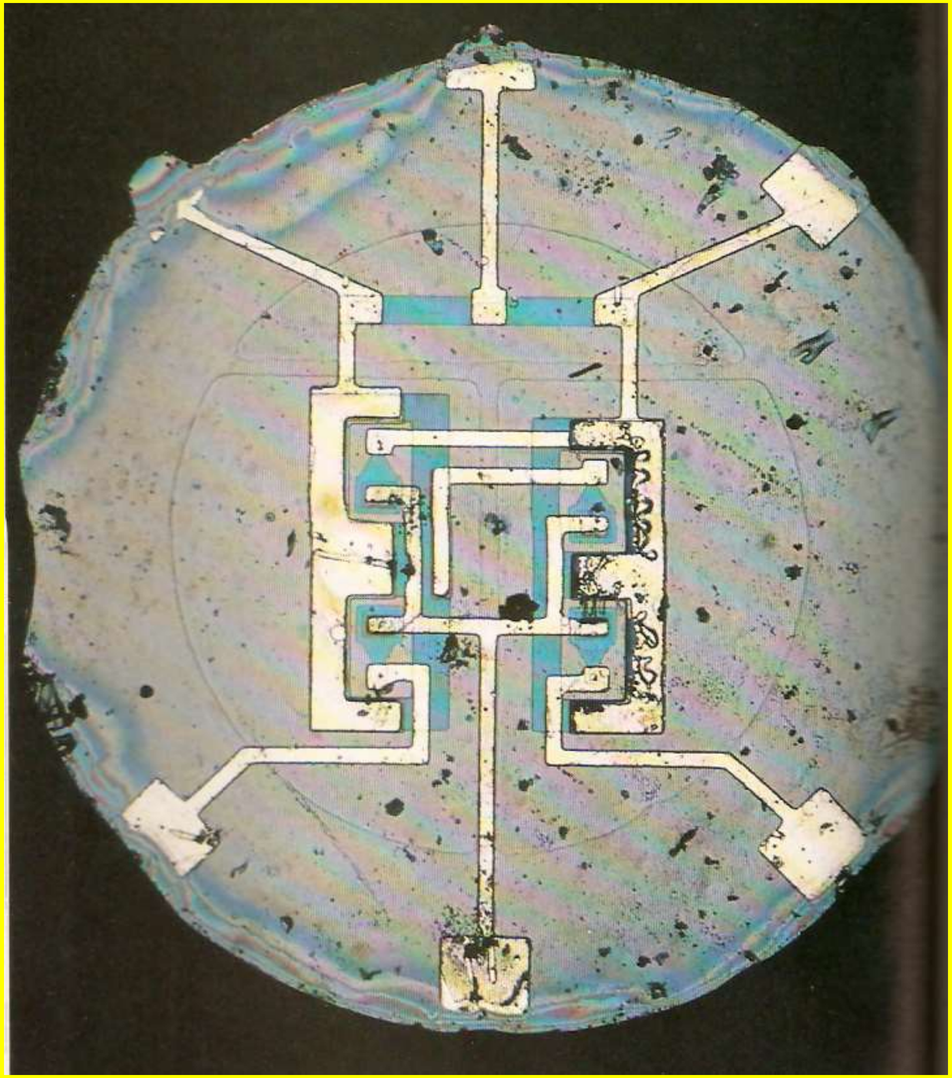
No, an early 1024-bit memory!



An early *one-bit* binary adder: built on a kitchen table!

An electrical relay network??

The First Integrated Circuit



An early integrated circuit made by Fairchild Corporation in 1961. This is a logic IC with two flip flops, the 4 blue structures in the center are transistors, and the white lines are aluminum connecters.

Hardware Design Creating History ……

Andy Grove, Robert Noyce, and Gordon Moore (1978)

Intel Founders

Entering the World of Microprocessors

Intel’s first advertisement for the 4004 microprocessor that appeared in November 1971.

Evolution of Microprocessors

1970: 4004 μP

#T = 2300
Auditorium

1982: 286 μP

#T = 1,34,000
Stadium

1999: Pent III

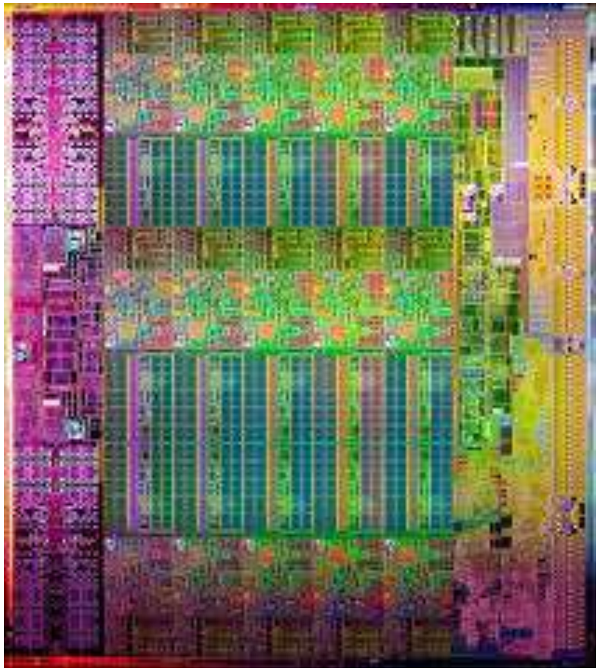
#T = 32 million
Population of
Tokyo

2008: Core i7

#T = 1.3 billion
Population of China

Number of transistors (#T)

Modern Processors



Intel 15-Core Xeon Ivy Bridge-Ex (2014)

22 *nm* technology

4.3 billion transistors

Die size ~600 mm^2

Intel Broadwell EP Xeon SoC (2016) – 7.2 billion T; 14 *nm*

IBM Deep Blue defeated Grand Master Garry Kasparov in May 1997

Gordon Moore: 1965

Progress in computer technology underpinned by Moore’s Law

- Predicted that the number of transistors integrated on a die would grow exponentially (doubling every 12 to 18 months)
- Million transistors/chip barrier crossed in the 1980s
- Today:

Around several billion transistors per chip

Transistor Count in a Chip

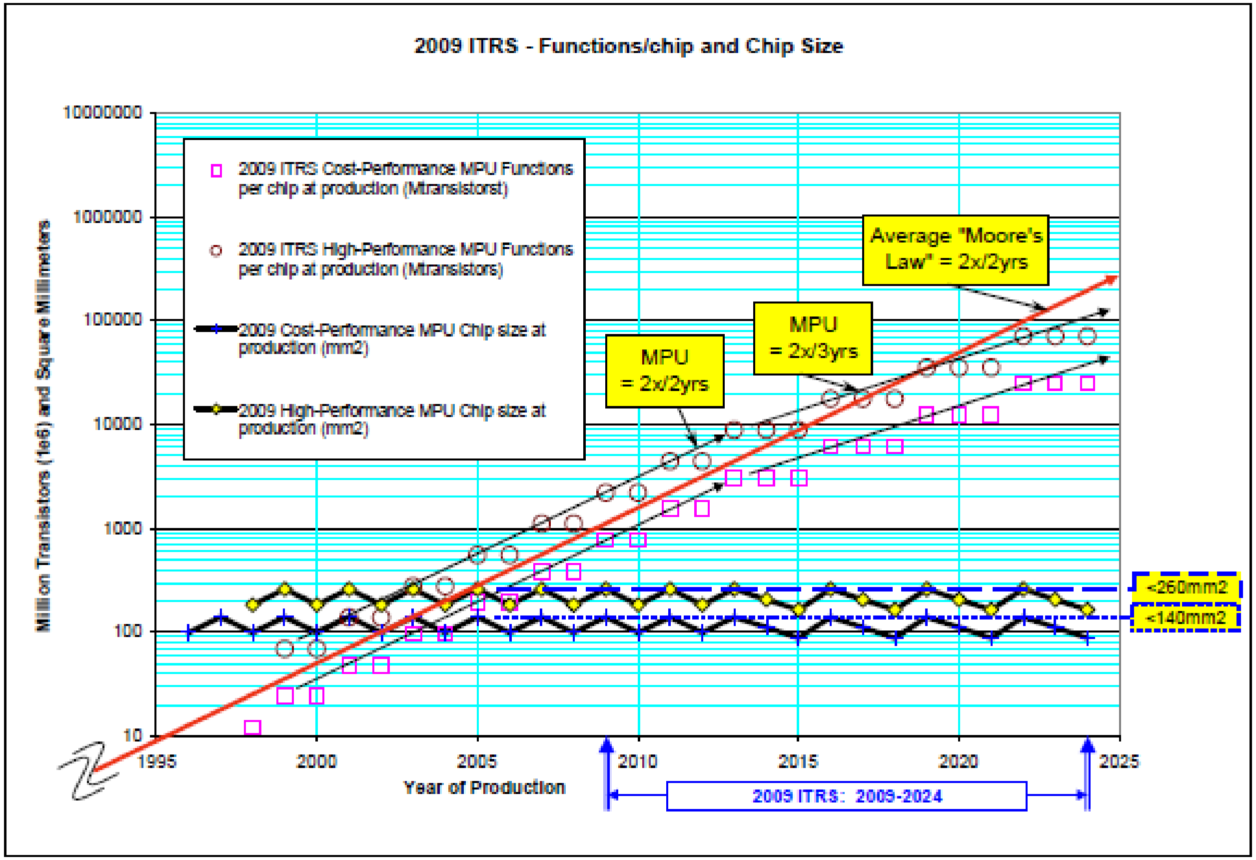


Figure 7b 2009 ITRS Product Technology Trends:
MPU Product Functions/Chip and Industry Average "Moore's Law" and Chip Size Trends

Courtesy: ITRS 2010

Example: Moore's Law

Intel 80486

1.18 million T

1989

Intel Xeon SoC

7.2 billion T

2016

1989

New York

$ 900

Flight

7 hours

Paris

2016

New York

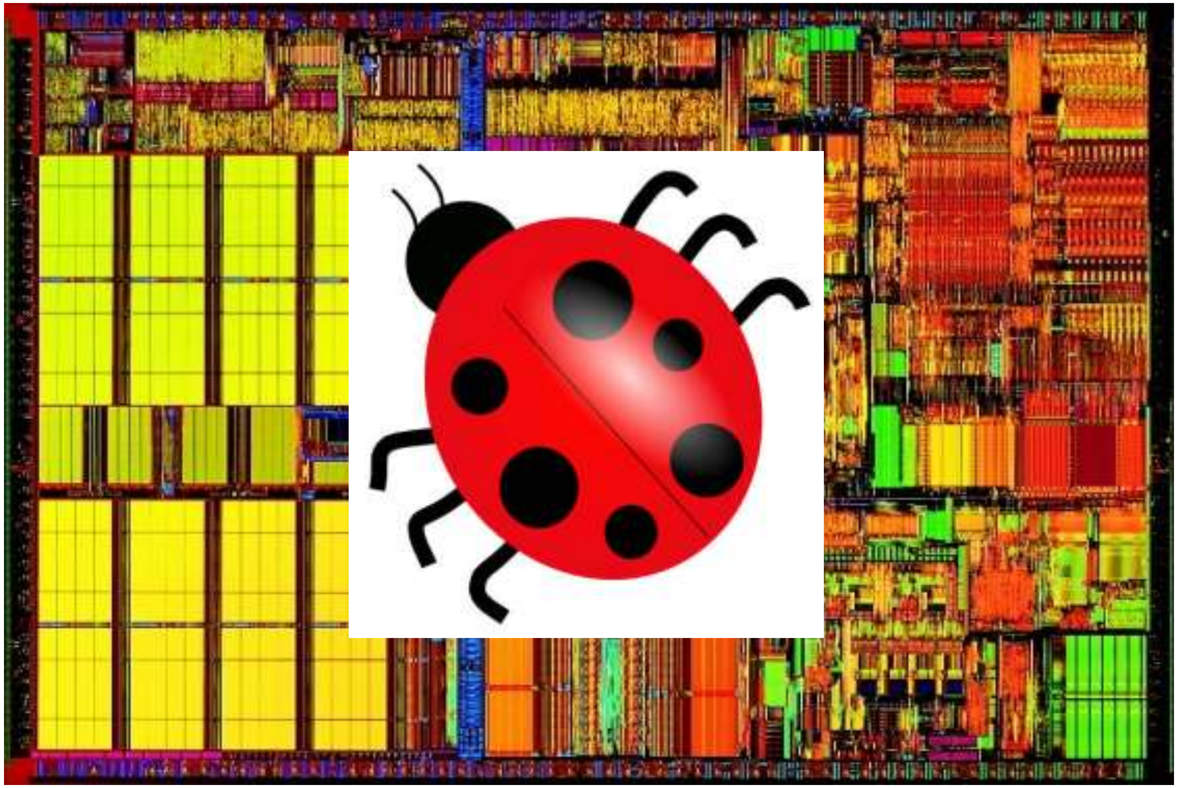
1 c

Flight

0.25 sec

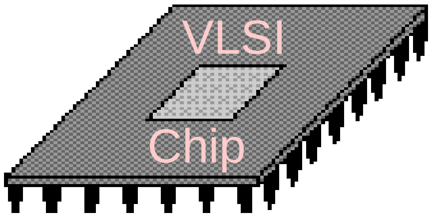
Paris

Today’s chips encapsulate billions of transistors



Design bugs/manufacturing defects/
field malfunctioning/aging

Reliability of Hardware Design (managing defects/hazards/errors)



US Airways jet crash landed in the Hudson river on January 16, 2009

Example: Intel Pentium Bug (1994)

66 MHz Intel Pentium

- The FDIV-bug (in floating-point division unit) was discovered in 1994 by Prof. Thomas R. Nicely at Lynchburg College, USA
- 4 to 5 million Pentium chips produced with bug
- Scientists suspected errors and posted on the Internet in September 1994
- On Nov. 22, 1994, Intel made Press release:

  "Can make errors in 9th digit ...."

Courtesy: D. A. Patterson and J. L. Hennessy, *Computer Organization and Design*, Morgan Kaufmann

Pentium Conclusion: Dec. 21, 1994
$ 500M write-off

"To owners of Pentium processor-based computers and the PC community:

We at Intel wish to sincerely apologize for our handling of the recently publicized Pentium processor flaw.

Intel will exchange the current version of the Pentium processor for an updated version, in which this floating-point divide flaw is corrected, for any owner who requests it, free of charge anytime during the life of their computer. Just call 1-800-628-8686."

Sincerely,

Andrew S. Grove   Craig R. Barrett   Gordon E. Moore

Computers of the Future …

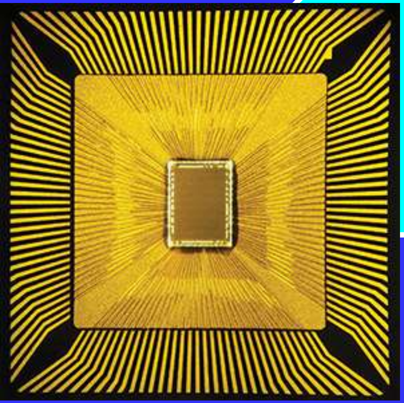
Computers – Present and Future

- Personal computers
- Laptops and Palmtops
- Networking and wireless
- SOC and MEMS technology
- Future generations
  - Biological computing
  - Neuromorphic computing
  - Molecular computing
  - Nanotechnology – Carbon Nano-tube (CNT) based CPU
  - Optical computing
  - Quantum computing

Neuromorphic Chips

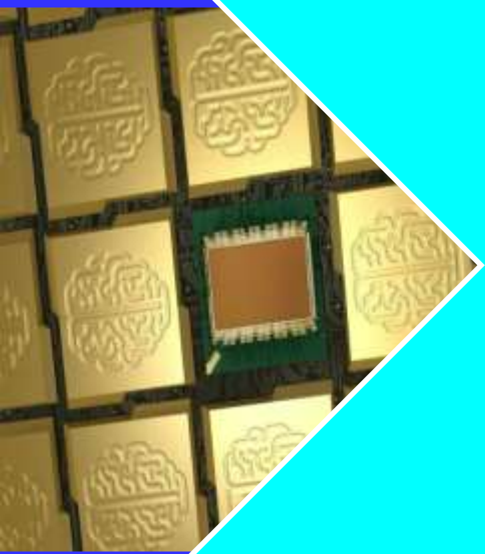
Bridging the gap between artificial and natural computation

Advances in neuroscience and chip technology now enable to process data in a similar way like brain. These "neuromorphic" chips will play chess, drive cars reliably in all conditions, and empower smartphones to act as personal assistants.



Neuromorphic Chips

Bridging the gap between artificial and natural computation



IBM TrueNorth
cores, which r
human neuron
synapses, two
biological build
up the h

This IBM chip
patterns of puls
to one of t
neuroscientis
stores i

SyNAPSE (Systems of Neur
Scalable Electronics) project

Recognizes people, cyclists, cars, buses, and trucks with about 80 percent accuracy.

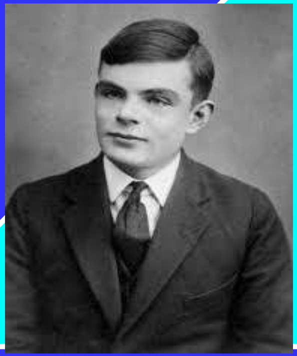
Do not separate processor & memory

Burns only 63 mW of power to process streaming video with 30 frames per sec.

Google and IBM Announce Quantum Computers (2015 - 2019)

These processors will work on sub-atomic levels based on the principles of quantum mechanics making them much faster

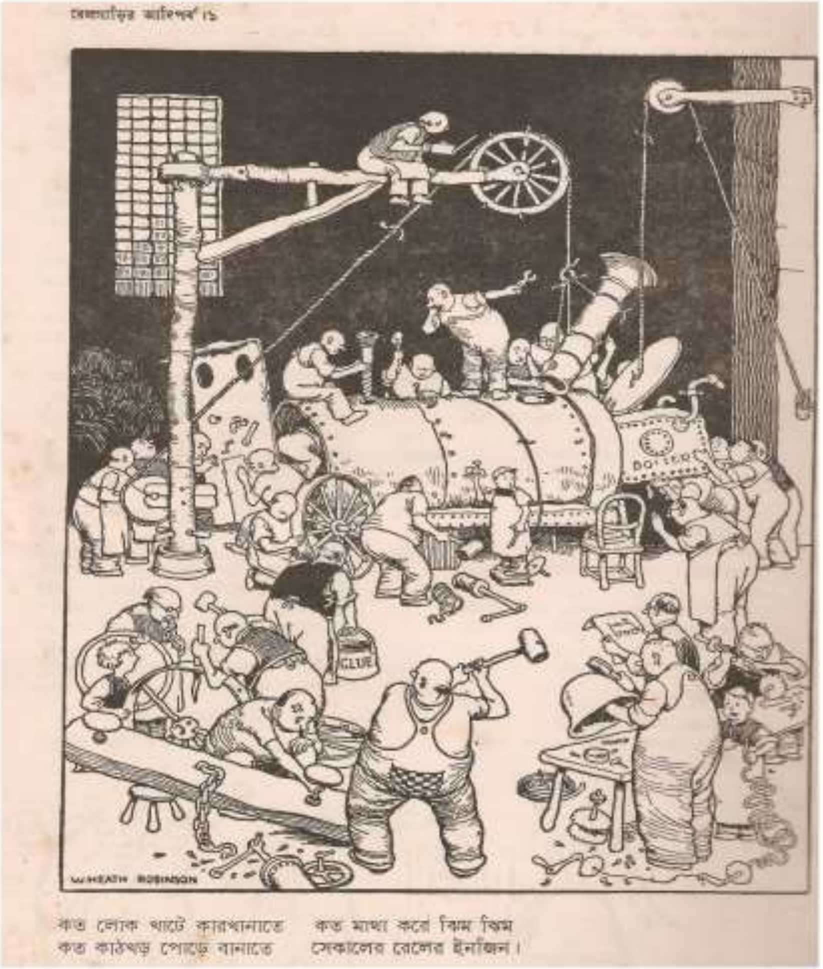
Technology could one day lead to intelligent machines that are capable of thinking



Alan Turing
(1912-1954)

Can machines think?

Building a Computer System ……



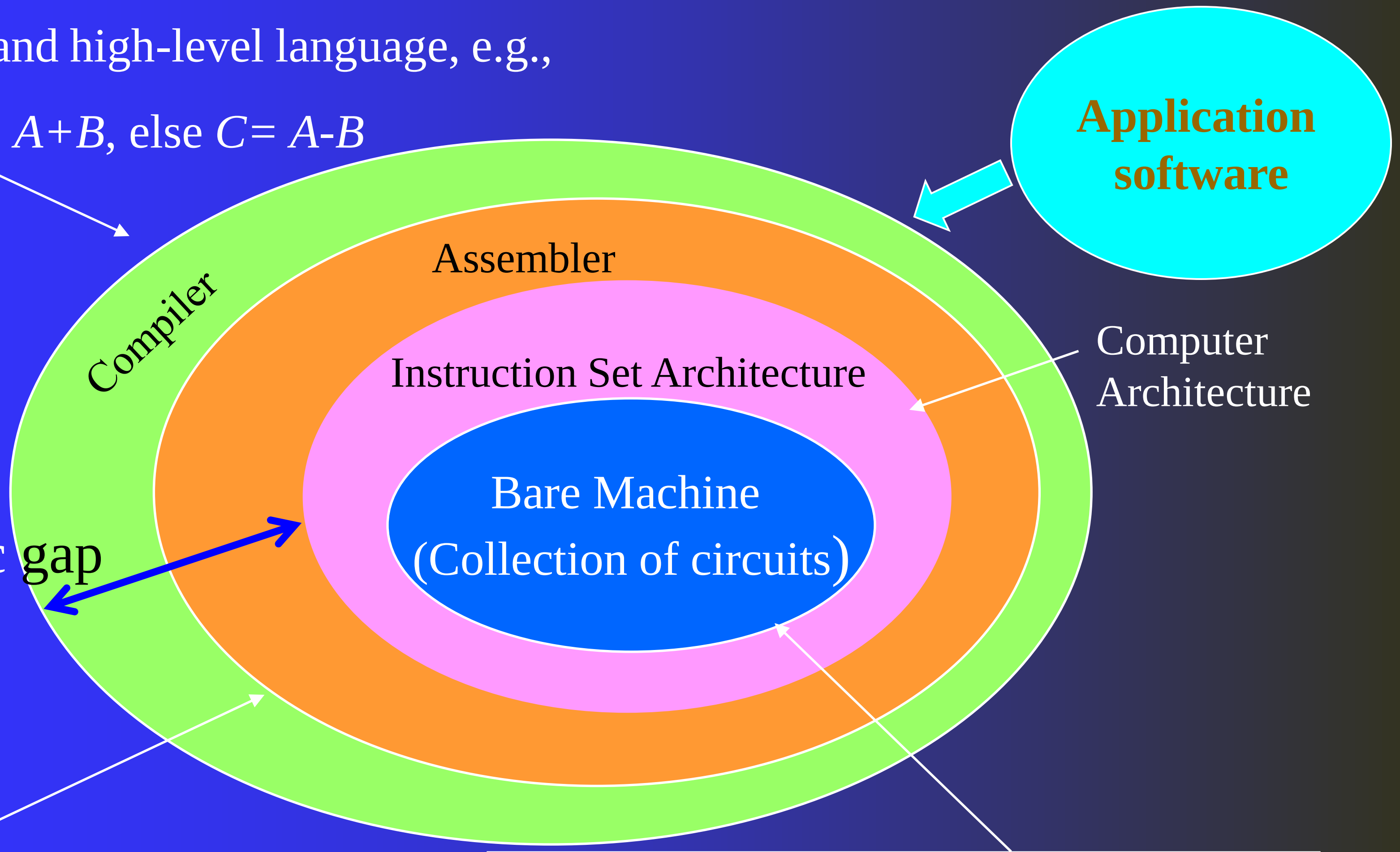
Courtesy: Satyajit Ray

What are the design issues?

Computing System Hierarchy

Can understand high-level language, e.g.,

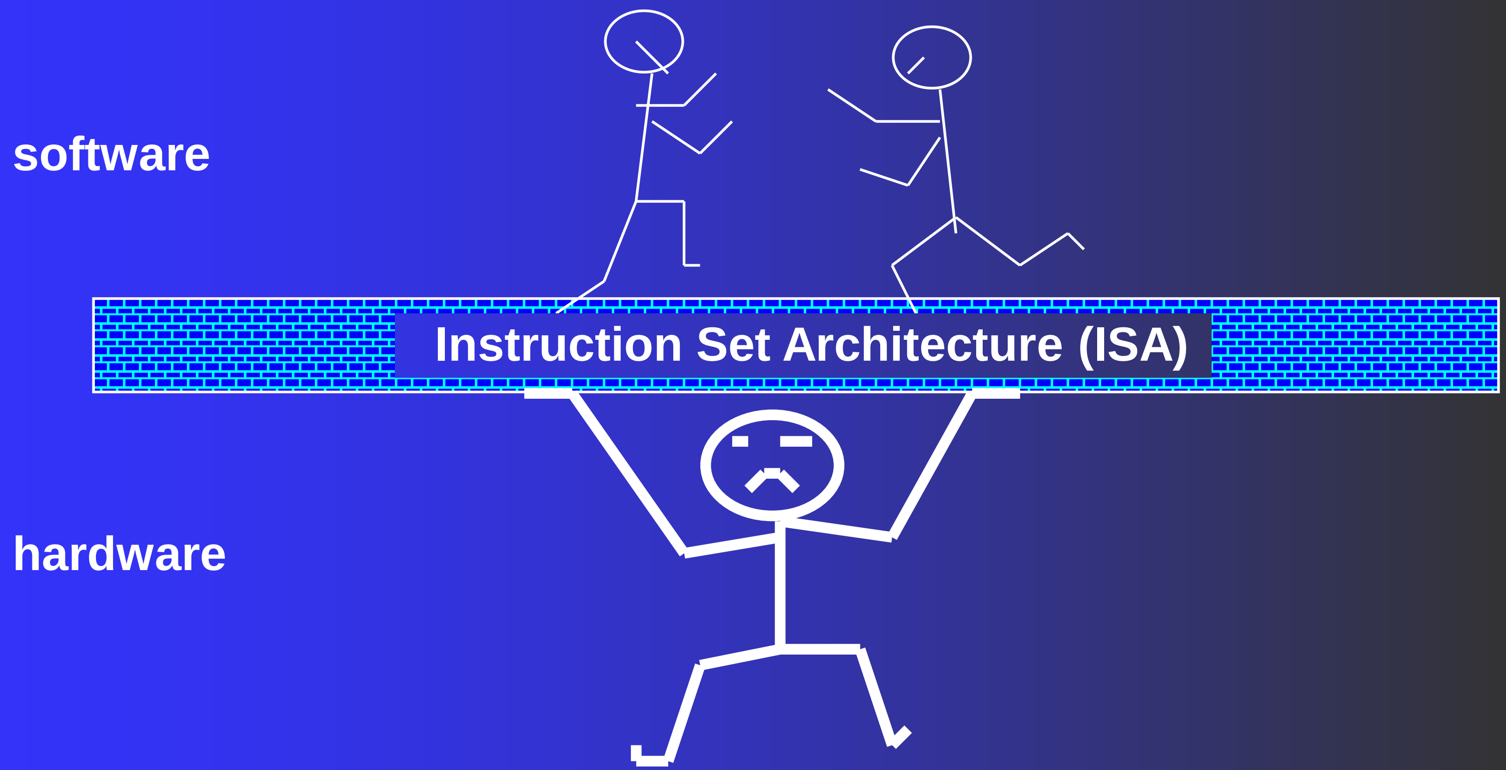
If *X* then *C*= *A*+*B*, else *C*= *A*-*B*



Can understand symbolic assembly language, e.g., add *C*, *A*, *B*

can understand only machine language – binary strings of 0's and 1's, (0101001100..) i.e., electrical *off* and *on* signals (Computer Organization)

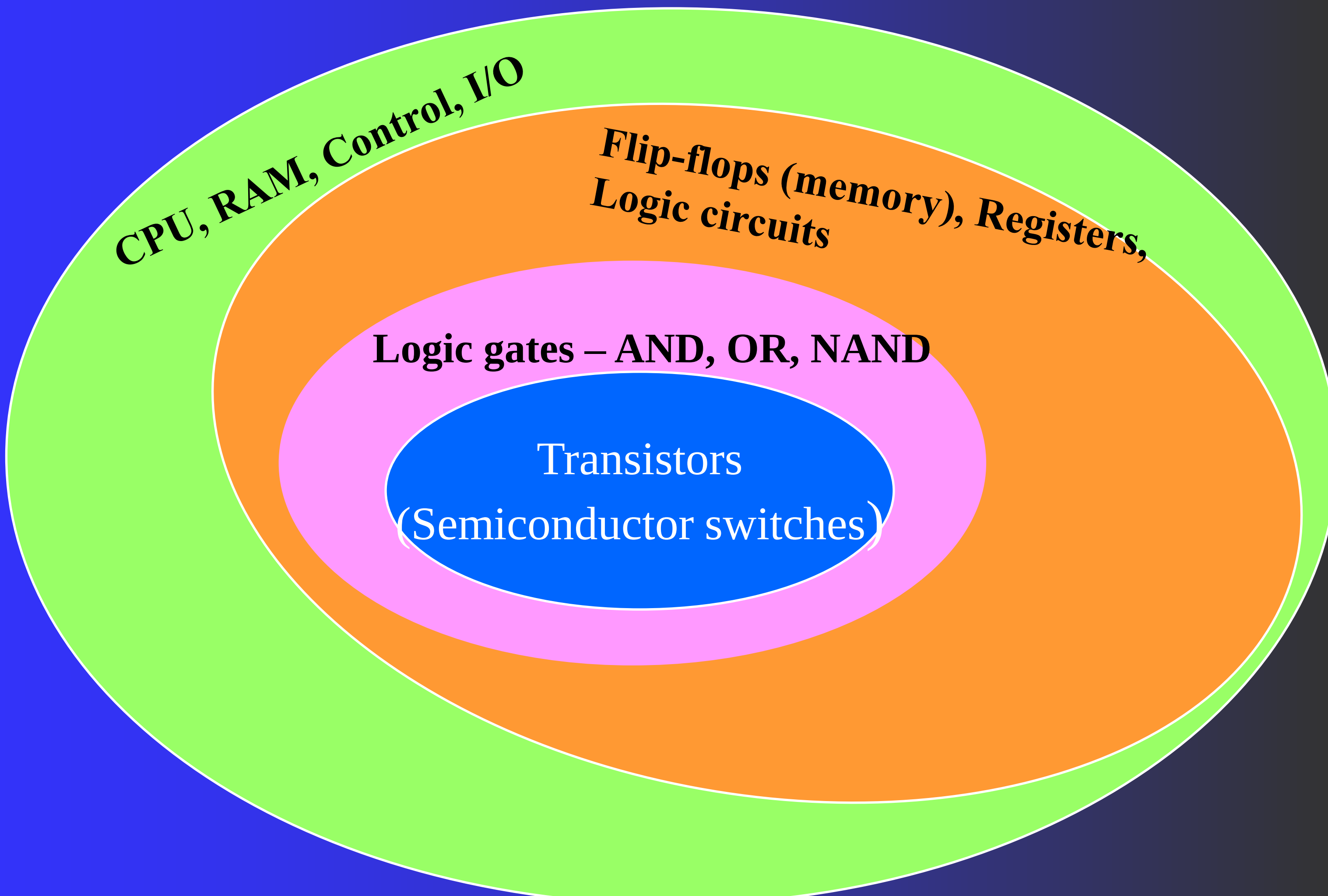
Hardware-Software Interface



ISA: Collective attributes of the machine-language instruction set

Courtesy: Patterson and Hennessy

Hardware Hierarchy



How a program is executed by a computer

Compiler → **Assembler**

Application software, a program in C:

```
swap (int  v[ ], int  k)
{int  temp;
          temp = v[k];
          v[k] = v[k+1];
          v[k+1] = temp;
}
```

Compiler translates it to assembly language program of the target machine

```
swap;
          muli     $2,     $5, 4
          add      $2,     $4, $2
          lw       $15,     0 ($2)
          lw       $16,     4 ($2)
          sw       $16,     0 ($2)
          sw       $15,     4 ($2)
          jr       $31
```

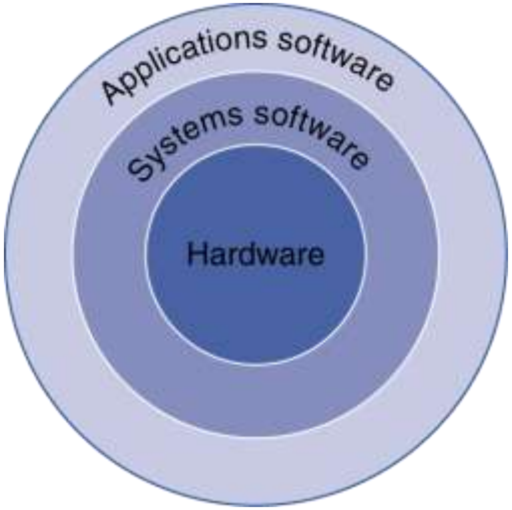
binary machine code

```
00000000101000010000000000011000
00000000000110000001100000100001
10001100011000100000000000000000
10001100111100100000000000000100
10101100111100100000000000000000
10101100011000100000000000000100
00000011111000000000000000001000
```

Hardware

output

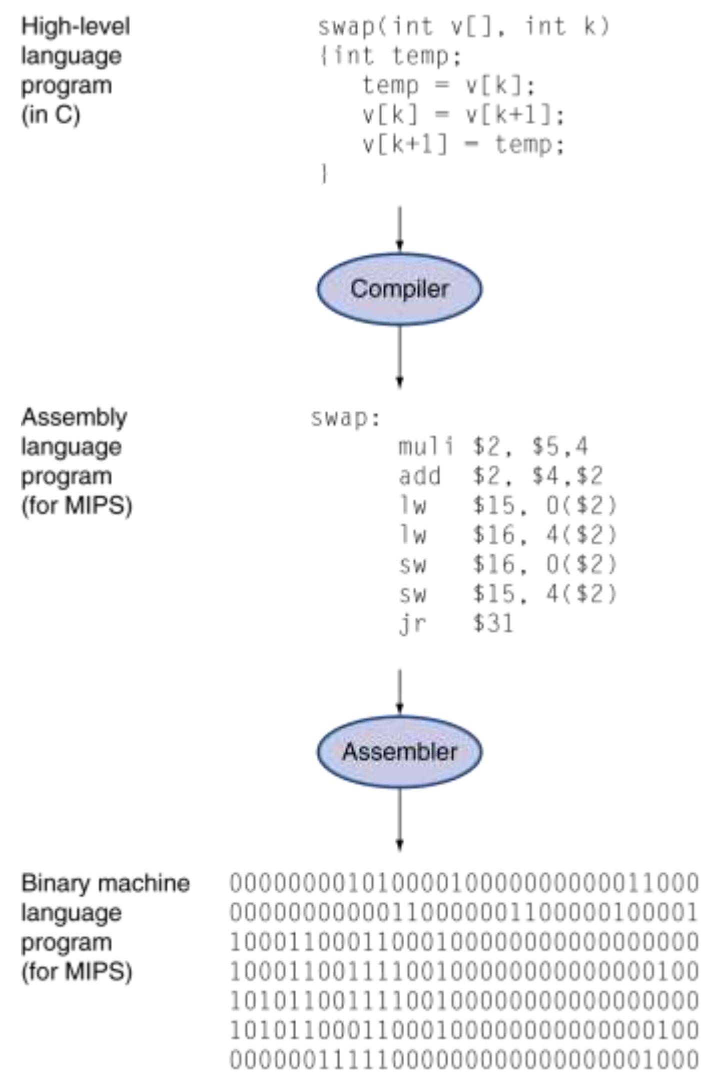
Below Your Program



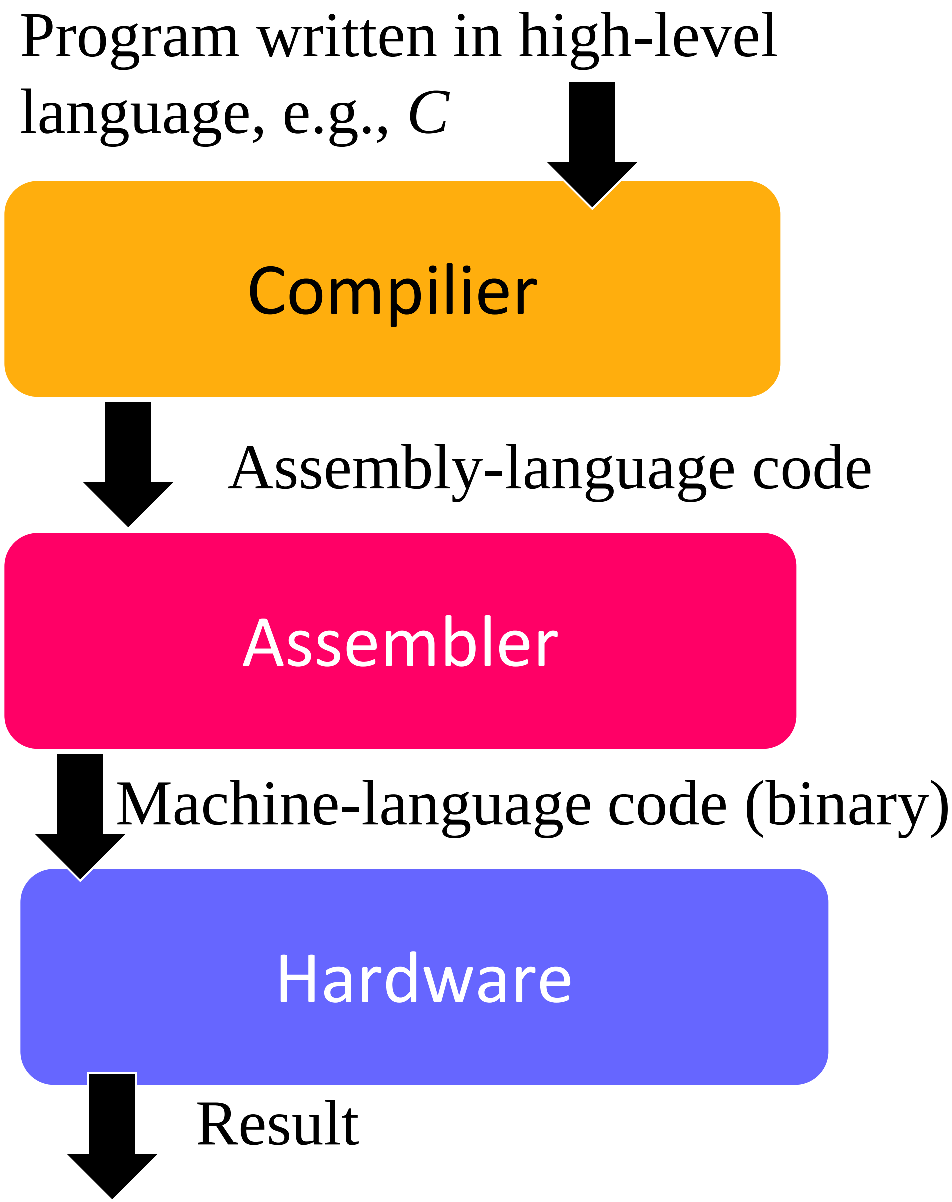
- Application software
  - Written in high-level language
- System software
  - Compiler: translates HLL code to machine code
  - Operating System: service code
    - Handling input/output
    - Managing memory and storage
    - Scheduling tasks & sharing resources
- Hardware
  - Processor, memory, I/O controllers

Levels of Program Code

- High-level language
  - Level of abstraction closer to problem domain
  - Provides for productivity and portability
- Assembly language
  - Textual representation of machine instructions
- Hardware representation
  - Binary digits (bits)
  - Encoded instructions and data



Program Execution



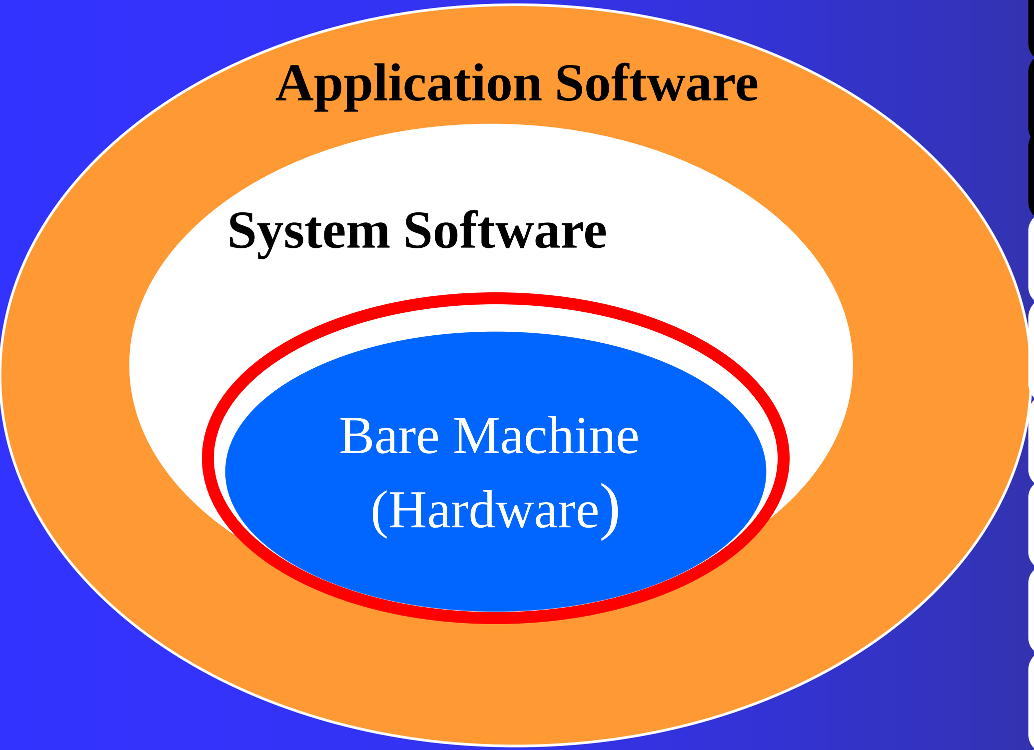
Questions:

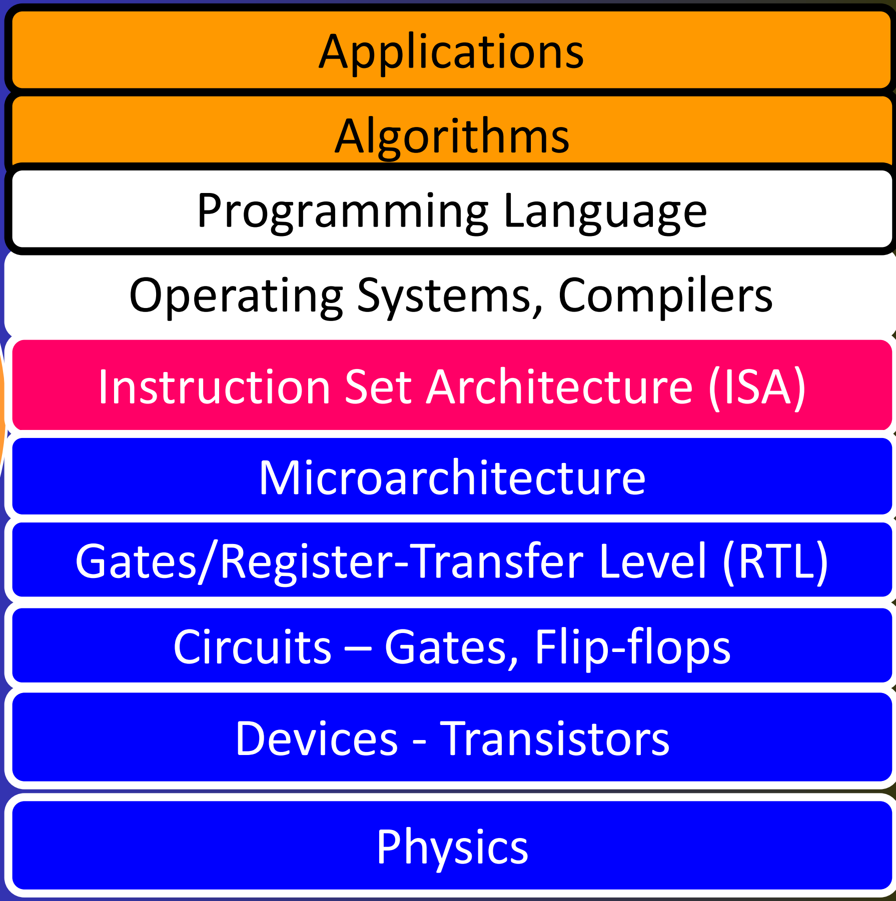
Where is the compiler running?

Who compiles the compiler?

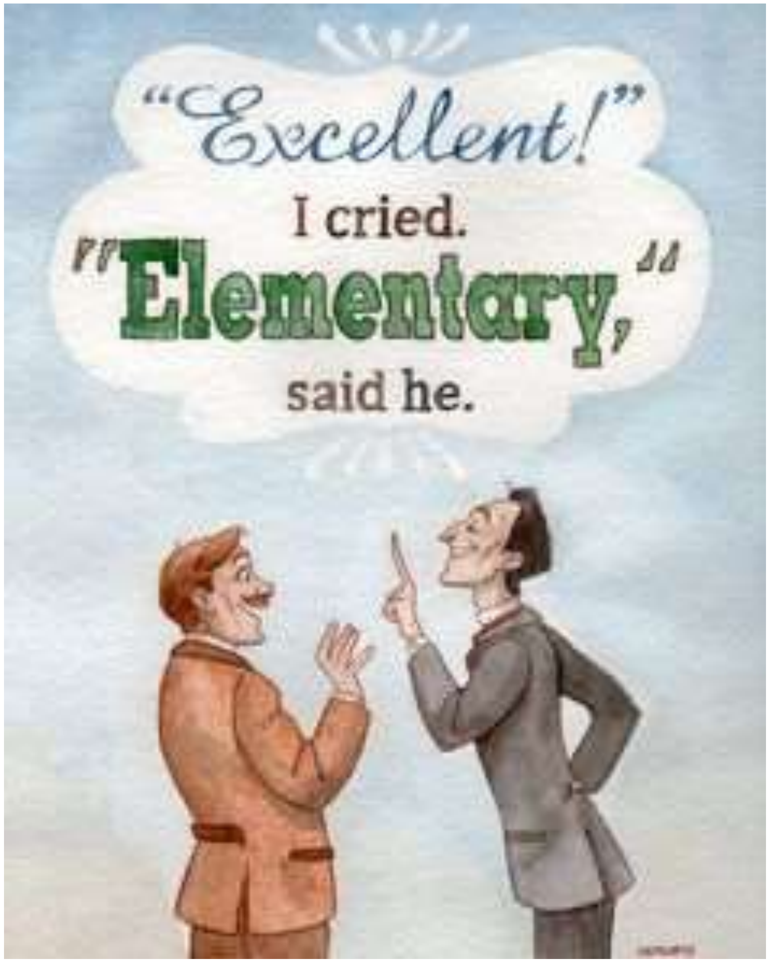
How is the Assembler running?

System Hierarchy





Deductive and Inductive Approach



Sherlock Holmes' deductive reasoning

Top-down approach (deductive):
from general to particular

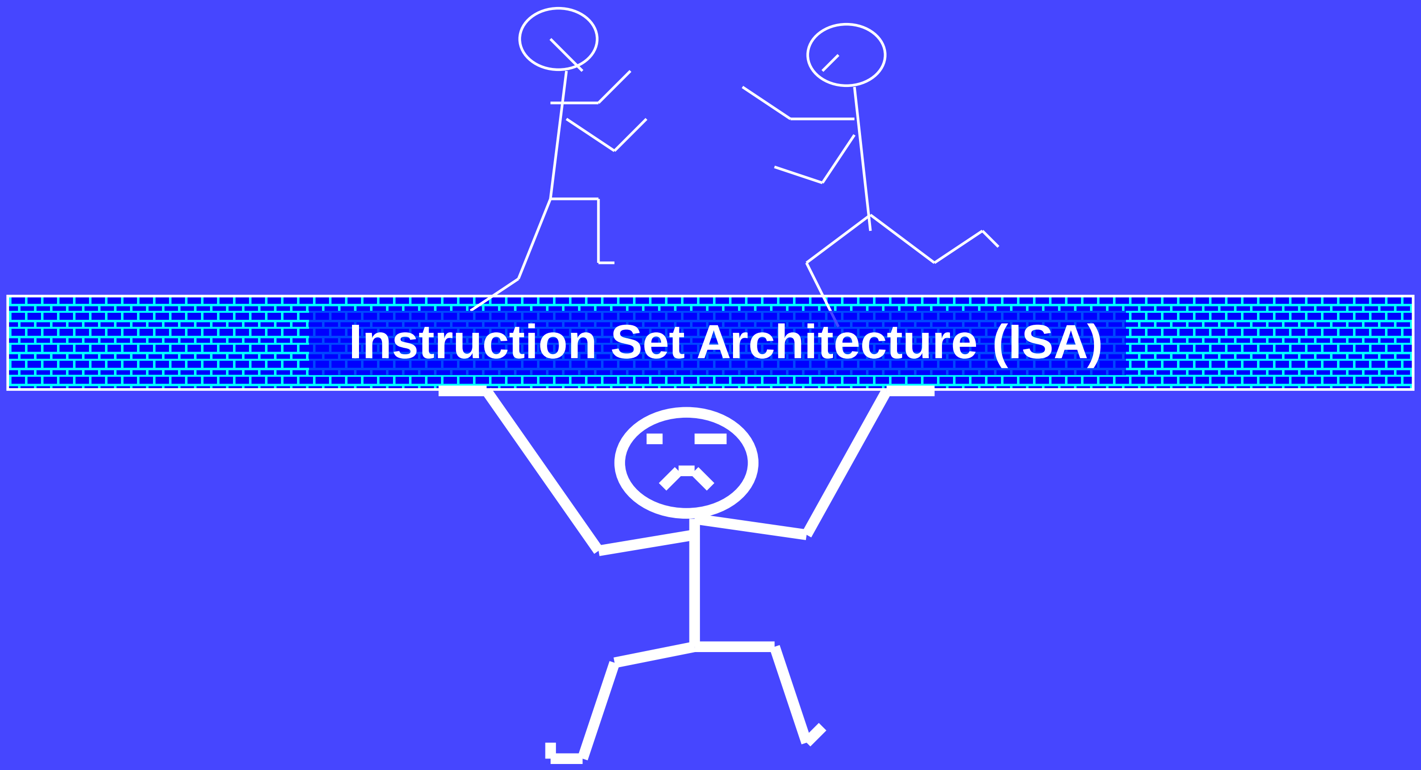
Bottom-up approach (inductive):
from particular instances to generality

Arthur Conan Doyle, The Memoirs of Sherlock Holmes (1893)

Computer Organization *versus* Computer Architecture

Computer Architecture (top-down view)

The view of a computer as perceived by software designers

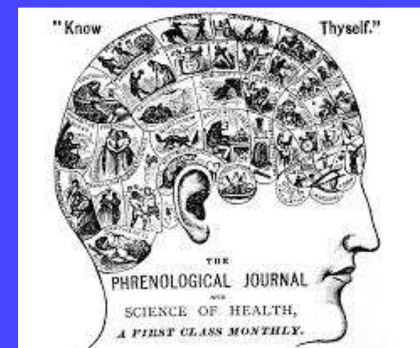


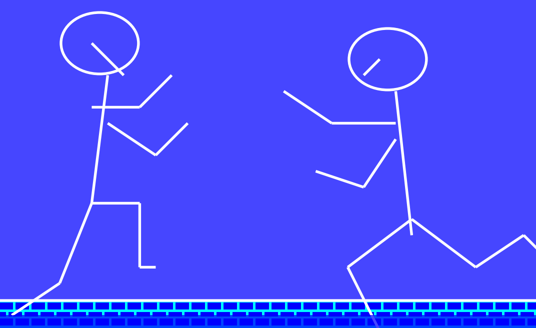
Computer Organization (bottom-up view)

The actual implementation of components in hardware

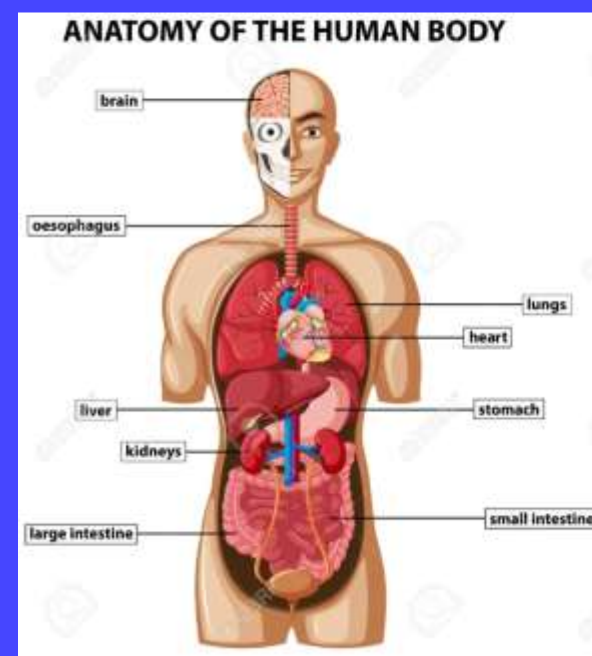
Computer Organization *versus* Computer Architecture

Computer Architecture: The personality of a machine
(behavioral view)





Instruction Set Architecture (ISA)



Computer Organization:
The anatomy of a machine
(structural view)

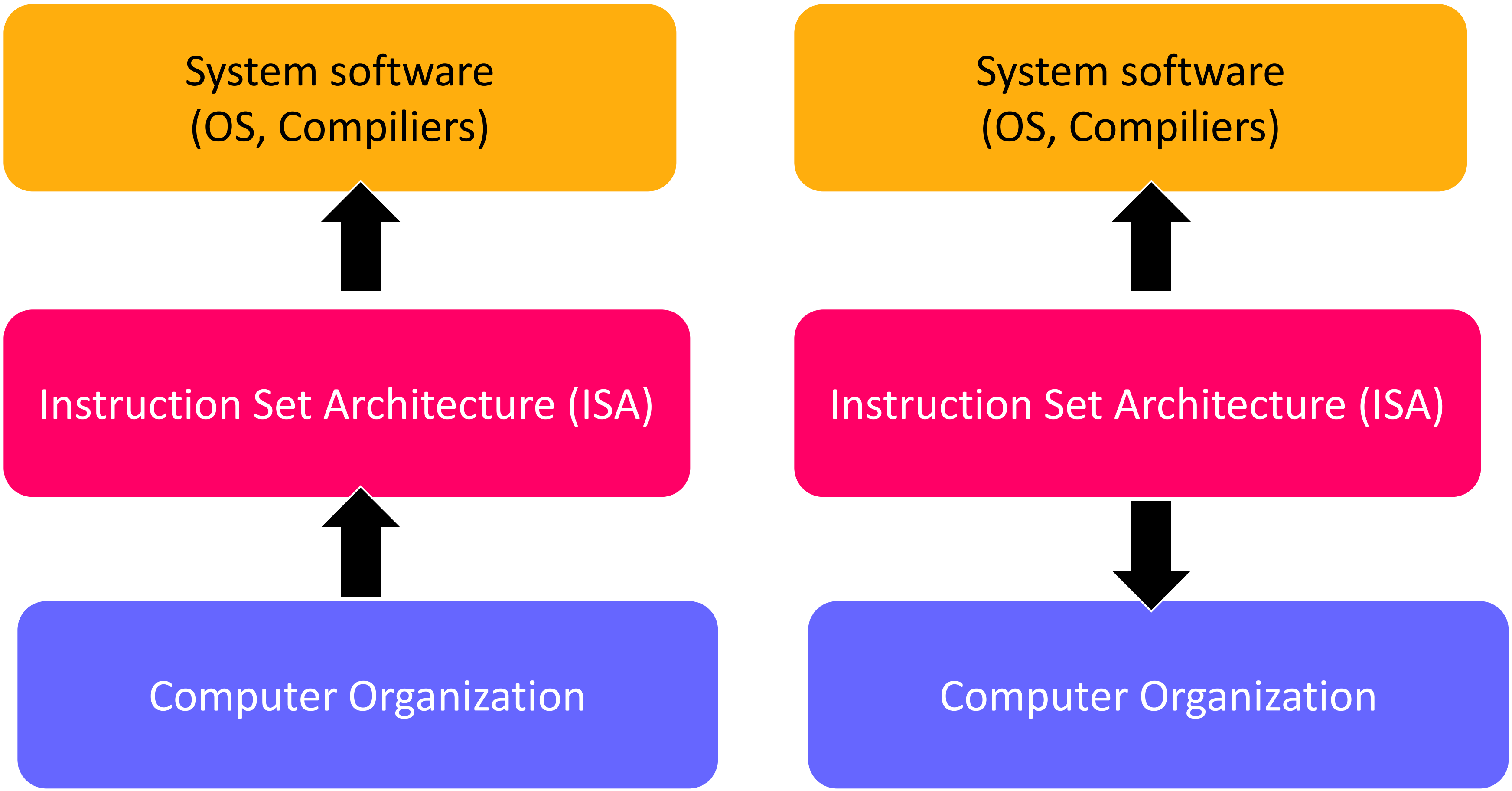
Computer Architecture

- Architecture is visible to a programmer
  - Instruction set
  - Registers
  - Data representation, addressing modes
  - I/O mechanisms
  - Virtual view of memory

Computer Organization

- Organization is visible to hardware designer
  - Hardware implementation of an instruction
  - Registers, program counter
  - Arithmetic and logical units
  - Control logic, internal states
  - Pipelining hardware
  - Cache and main memory

Computer Design Approach



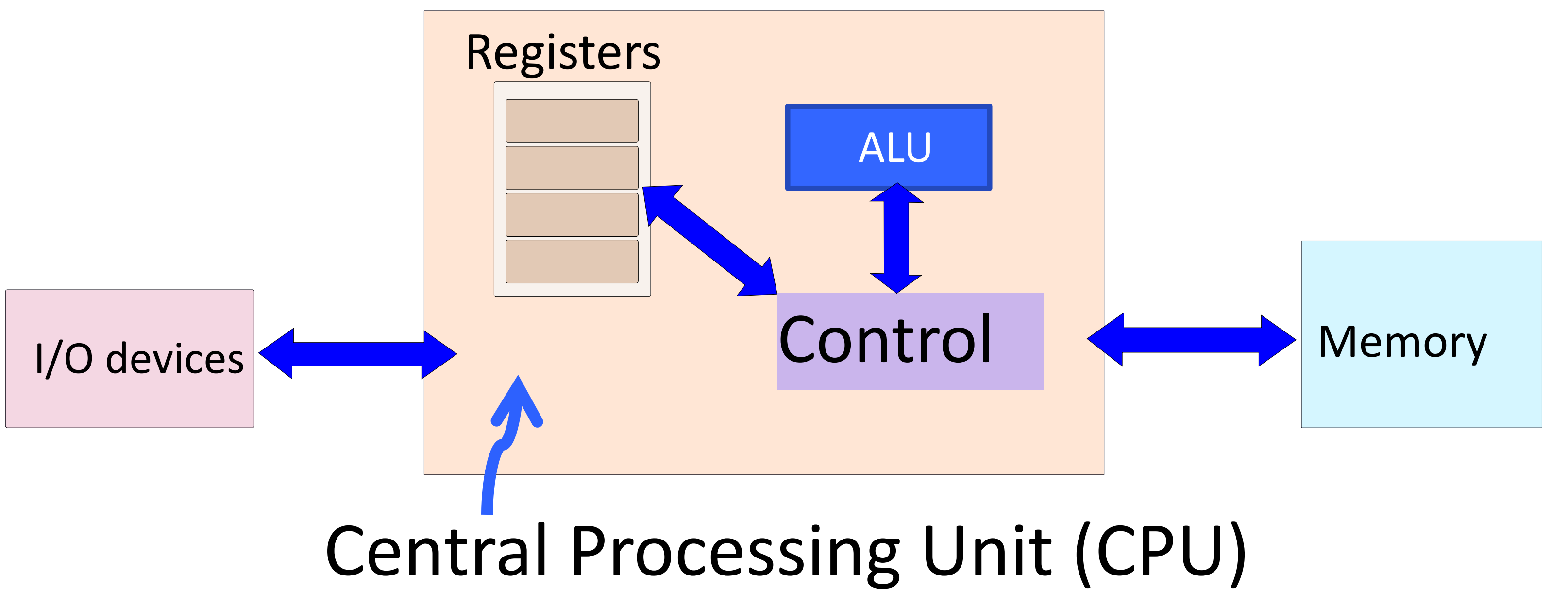
Bottom-up approach:
Hardware first, ISA later

Top-down approach:
ISA first, hardware later

Instruction Set Architecture (ISA)

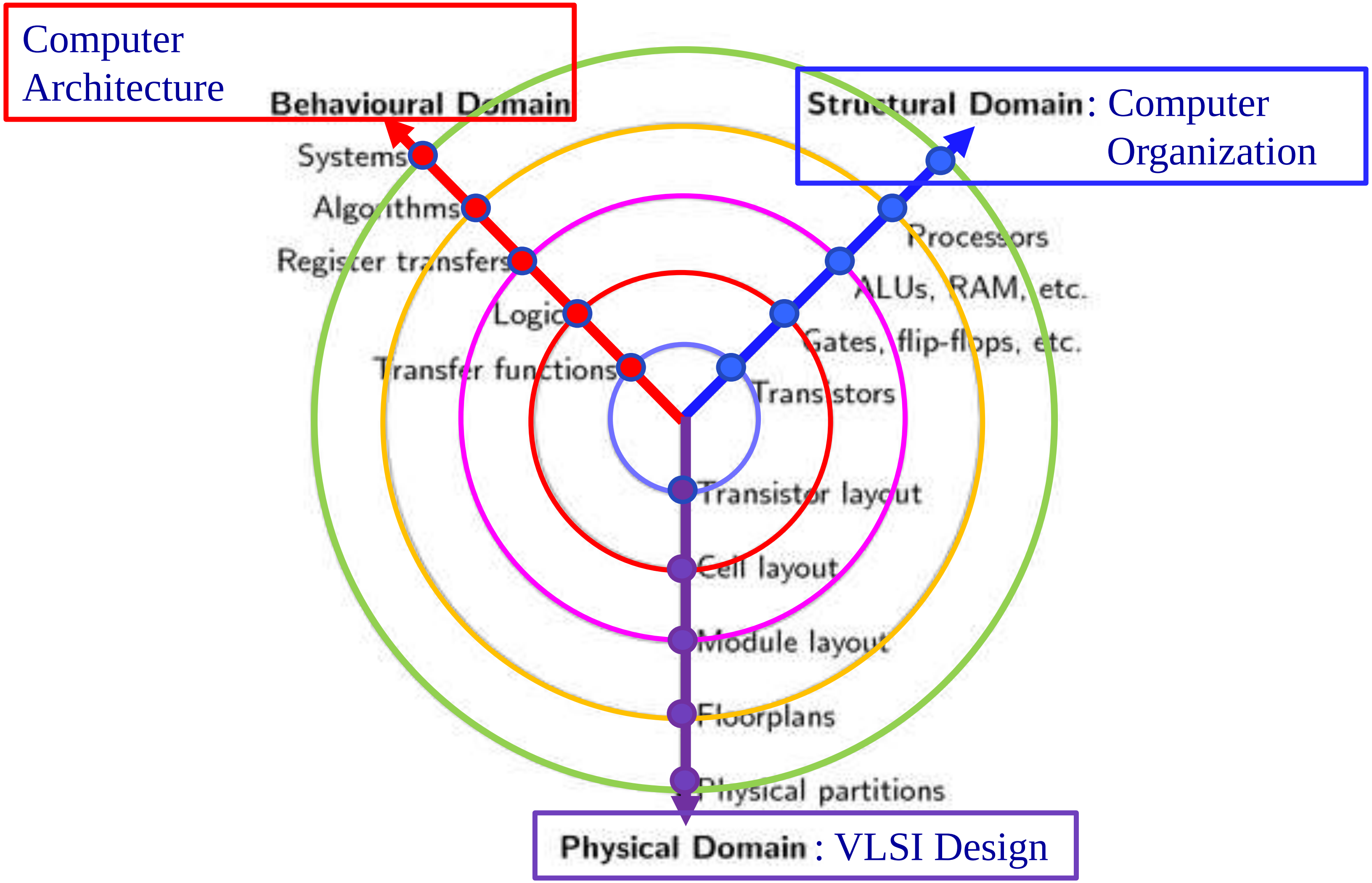
- A set of assembly language instructions that separates the interface between software and hardware
- In top-down design, given an ISA, an appropriate hardware platform is built to support it
- Based on ISA, OS and compilers are to be developed accordingly further going up
- Once ISA is fixed, software and hardware engineers can work independently
- ISA is designed to optimize the performance supported by the available hardware technology

The Hardware of a Computer



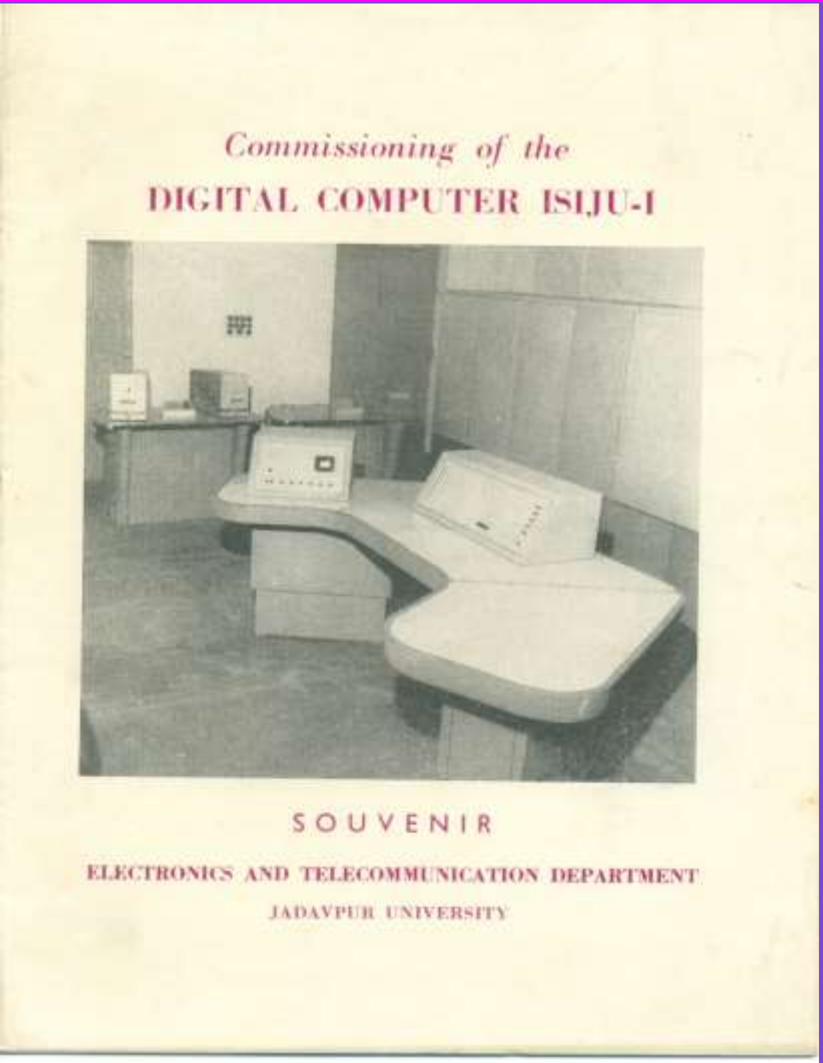
Five easy pieces:
Control, Arithmetic Logic Unit (ALU), Memory,
Input/Output, Datapath (Bus)

Digital System Design from Three Perspectives



Gajski-Kuhn Y-Chart (1983)

First Digital Computer Built in India



In 1966, a digital computer named ISIJU is designed and commissioned, with joint collaboration between Indian Statistical Institute (ISI) and Jadavpur University (JU), Kolkata

Next Class

- Model for Computation and Turing Machine
- von Neumann Architecture
- Basic Features of Instruction Set Architecture (ISA)
- CPU Performance Equation
- Amdahl’s Law
- RISC *versus* CISC