Computer Science 1000: Part #5

Computer Organization

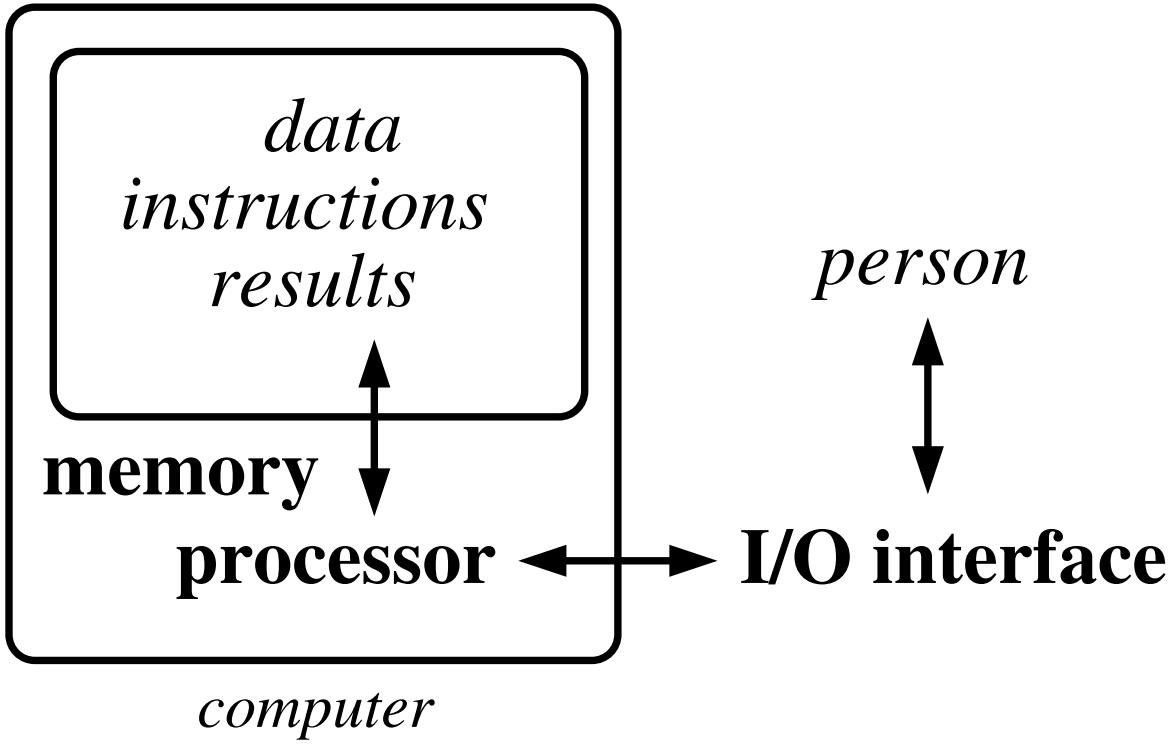
COMPUTER ORGANIZATION: AN OVERVIEW

COMPUTER MEMORY

COMPUTER PROCESSOR

IMPLEMENTING COMPUTERS

Computer Organization: An Overview
The Von Neumann Architecture (1945)



Also known as the stored-program architecture

Computer Organization: An Overview (Cont'd)
What is a Computer (Really)?

A computer is a machine that

(1) stores a very, very large number of numbers and
(2) performs very, very long specified sequences of very simple operations on these numbers
(3) very, very fast.

Computer Organization: An Overview (Cont'd)
Guiding Principles

There are two main principles of computer organization:

1. **Levels of Abstraction**: A complex system can be described as a hierarchy of levels, where collections of interacting entities at one level are encapsulated in a single entity at a higher level (see Textbook, Figure 5.1, p. 223).
2. **Internal vs. External Representation**: Within a complex system, the representations used internally by an entity to perform its functions need not be those with which it interacts externally with other entities.

The Von Neumann Architecture: An Abstract View

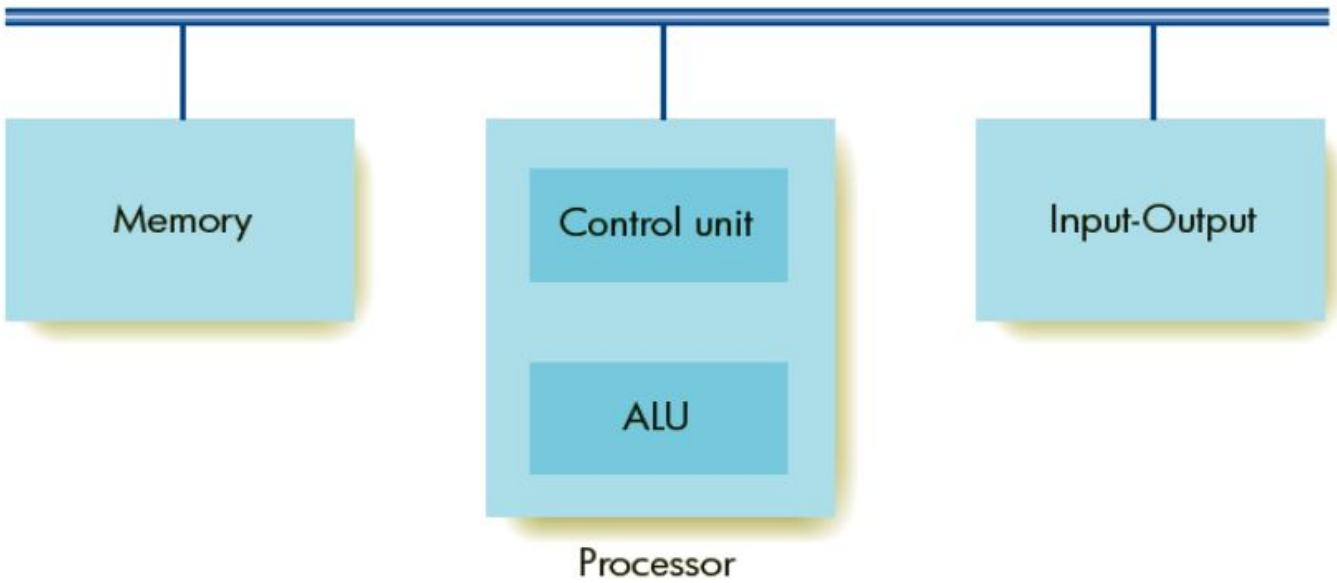


Figure 5.2 Components of the Von Neumann Architecture

The Von Neumann Architecture: A Detailed View

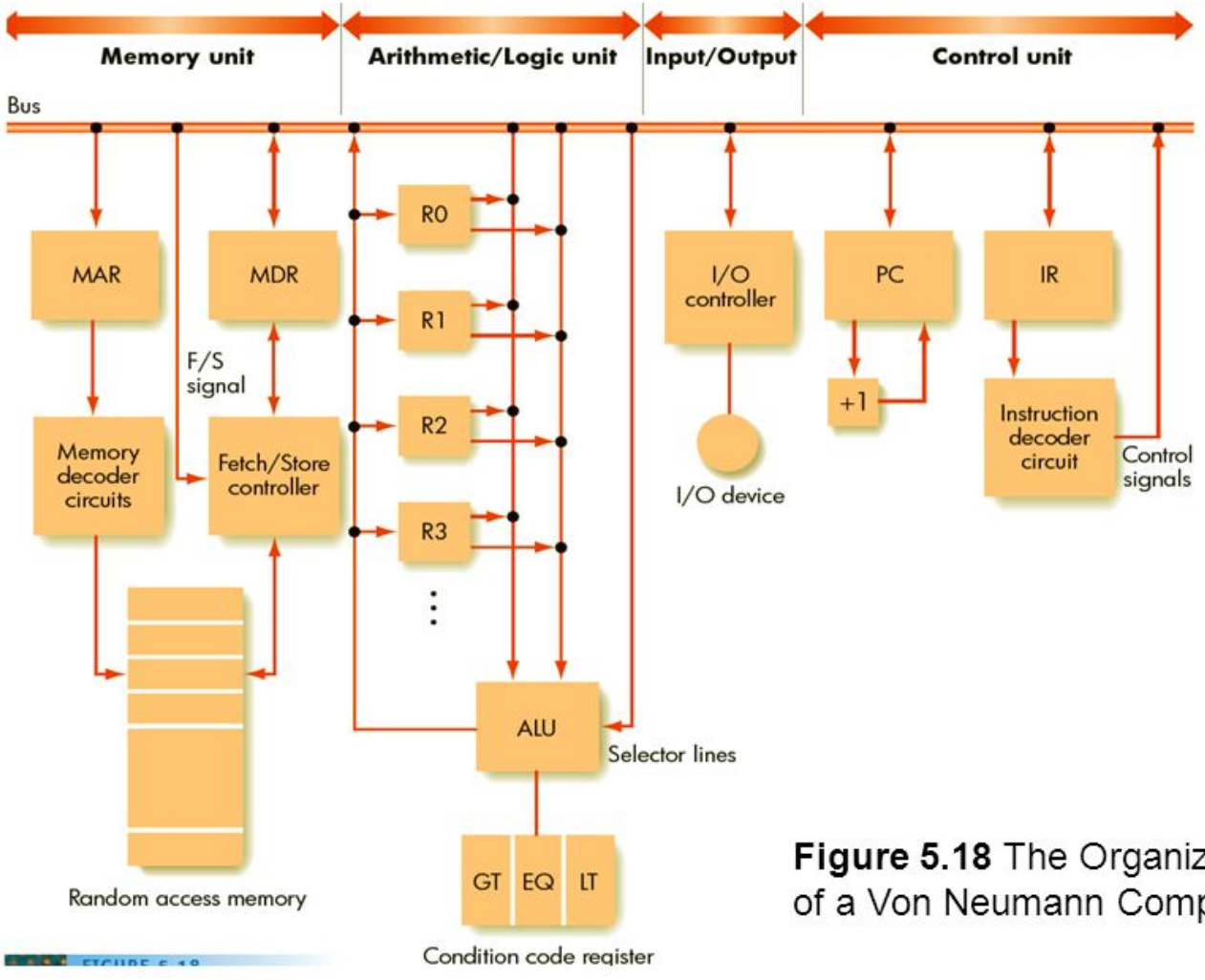


Figure 5.18 The Organization of a Von Neumann Computer

The Von Neumann Architecture: An Operational View

The Von Neumann Execution Cycle:

repeat
    Fetch next instruction
    Decode instruction
    Execute instruction

Computer Memory : Overview

- Focus here on (volatile) **Random-Access Memory (RAM)**, cf. (non-volatile) **Read-Only Memory (ROM)**.
- Three characteristics of RAM:
  1. Divided into fixed-width **cells**, each of which has a unique unsigned-integer **address** $0, 1, 2, \ldots, MAX$ (**address space**).
  2. The cell is the minimal unit of fetch / store access.
  3. All cells have the same access time.
- Crucial to distinguish a memory address and the contents of memory at a particular address, e.g.,

$$\text{address} \Longrightarrow \quad 5743_{10}\text{:} \ \boxed{-29_{10}} \ \Longleftarrow \text{contents}$$

Computer Memory : Overview (Cont'd)

- Standard cell-width $W = 8$ bits (**byte**); standard address $=$ 32 or 64 bits; standard access time $\approx$ 5-10 nanoseconds.
- Memory size stated in terms of number of bytes:

Kilobyte	(KB)	$= 10^3$ (thousand) bytes
Megabyte	(MB)	$= 10^6$ (million) bytes
Gigabyte	(GB)	$= 10^9$ (billion) bytes
Terabyte	(TB)	$= 10^{12}$ (trillion) bytes
Petabyte	(PB)	$= 10^{15}$ (quadrillion) bytes
Exabyte	(EB)	$= 10^{18}$ (quintillion) bytes

$\vdots$

Computer Memory : Overview (Cont'd)

- All communication done via the **Memory Address Register (MAR)** and the **Memory Data Register (MDR)**.
- Two basic operations:
  - Fetch(address):
    1. Load address into MAR
    2. Decode address in MAR
    3. Copy cell contents at address into MDR
  - Store(address, value):
    1. Load address into MAR
    2. Load value into MDR
    3. Decode address in MAR
    4. Copy MDR value into addressed cell

Computer Memory : Internal Structure (1D Abstract)

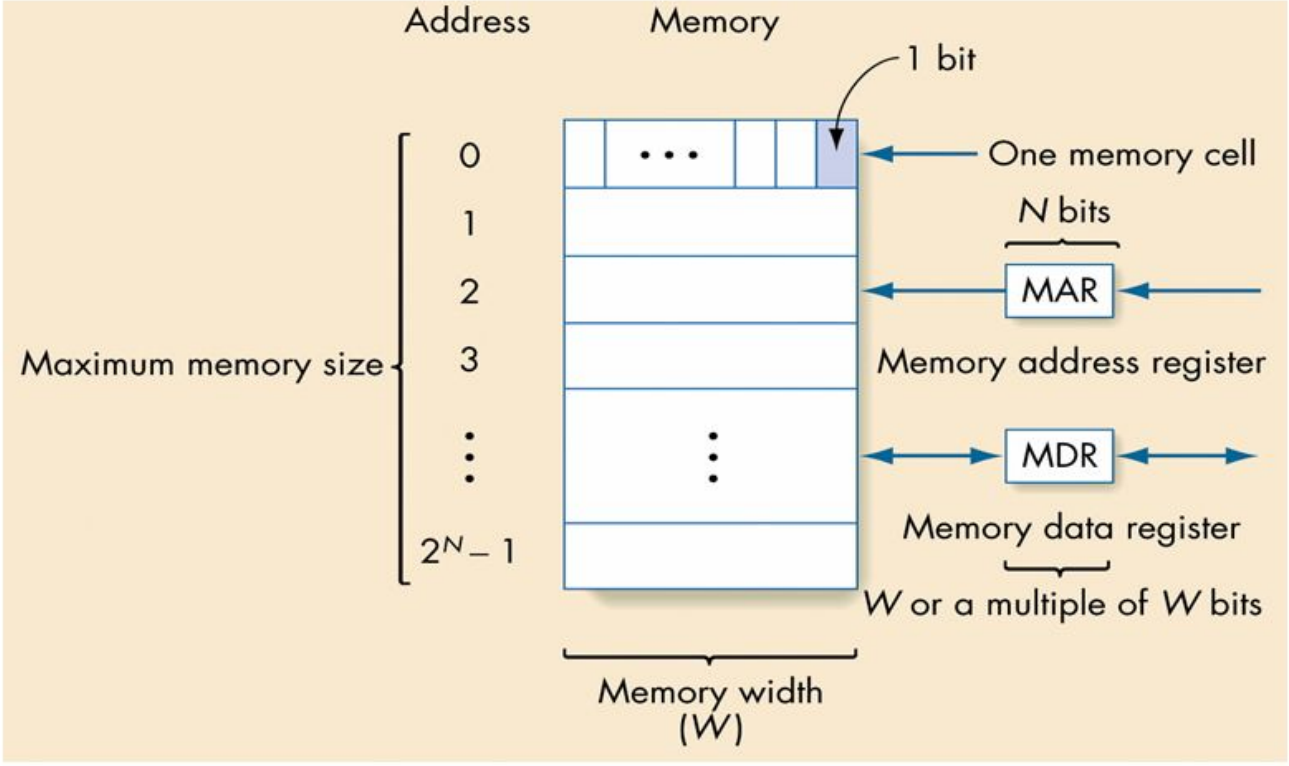


Figure 5.3
Structure of Random Access Memory

Computer Memory: Internal Structure (1D)

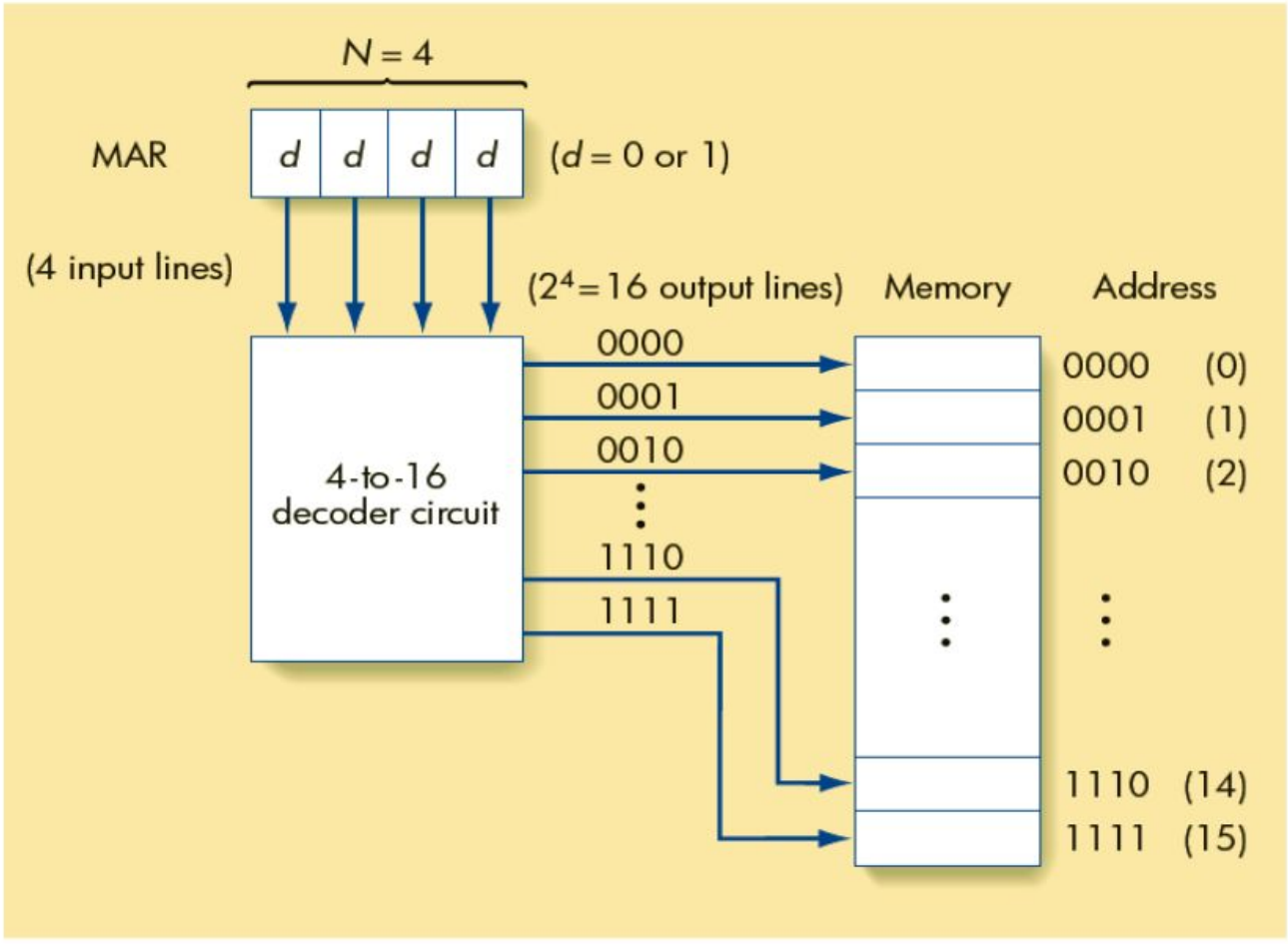


Figure 5.5 Organization of Memory and the Decoding Logic

Computer Memory: Internal Structure (2D Abstract)

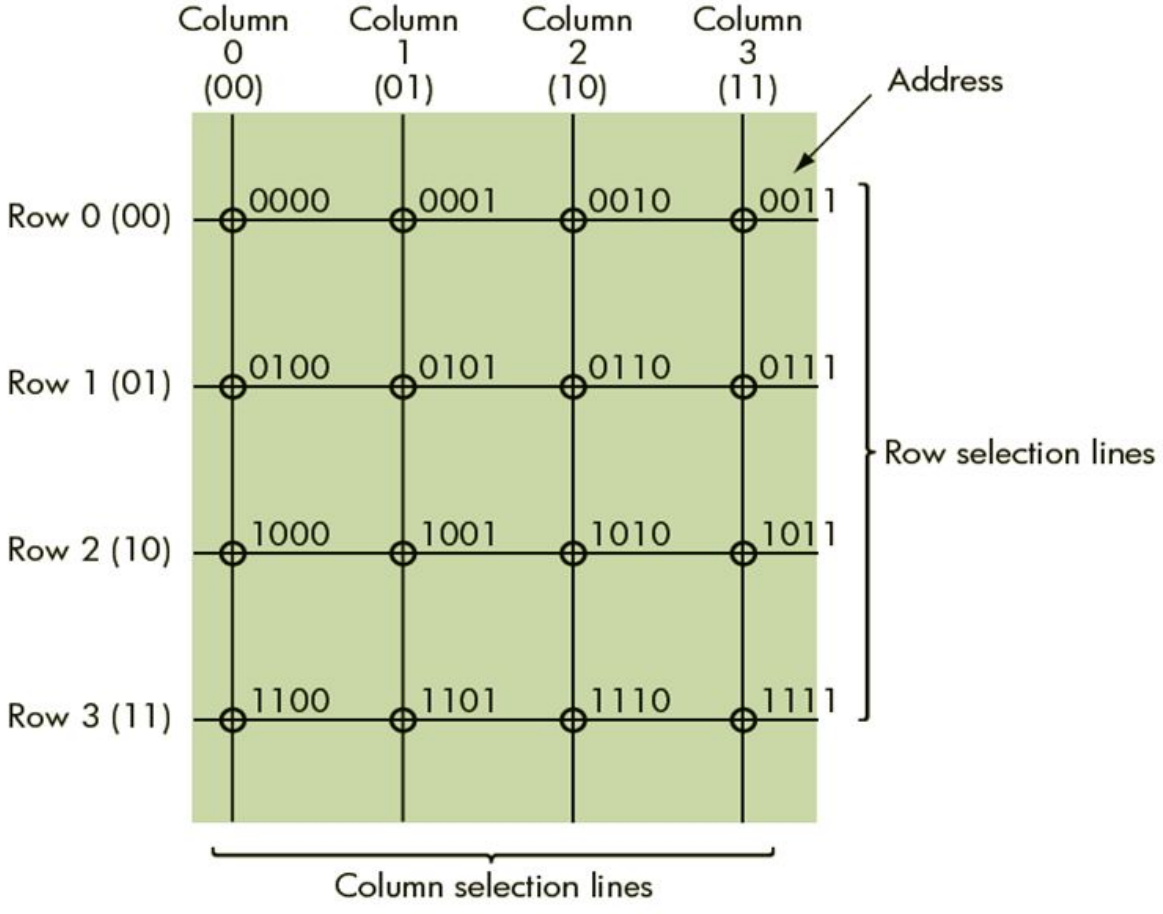


Figure 5.6 Two-Dimensional Memory Address Organization

Computer Memory: Internal Structure (2D)

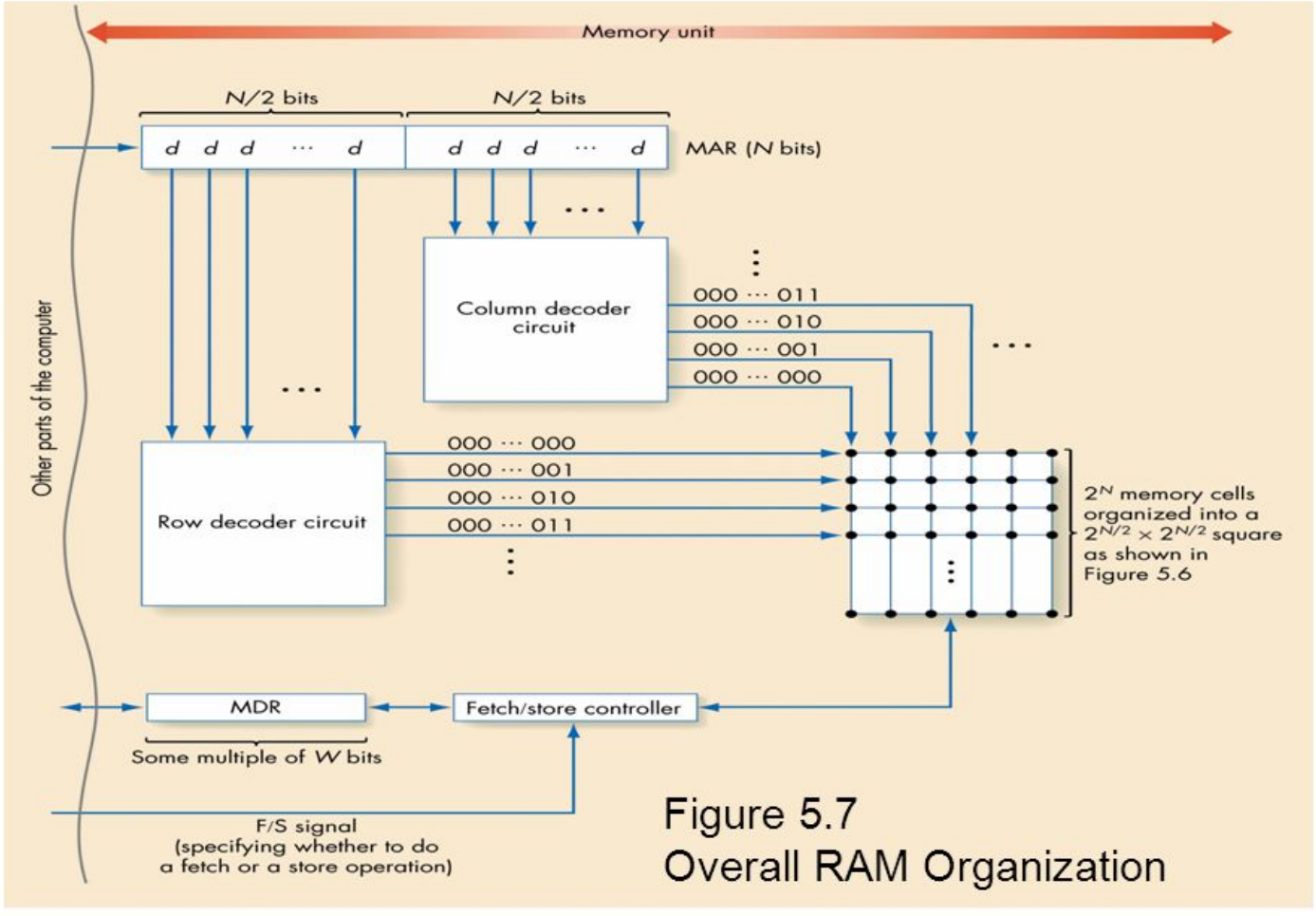
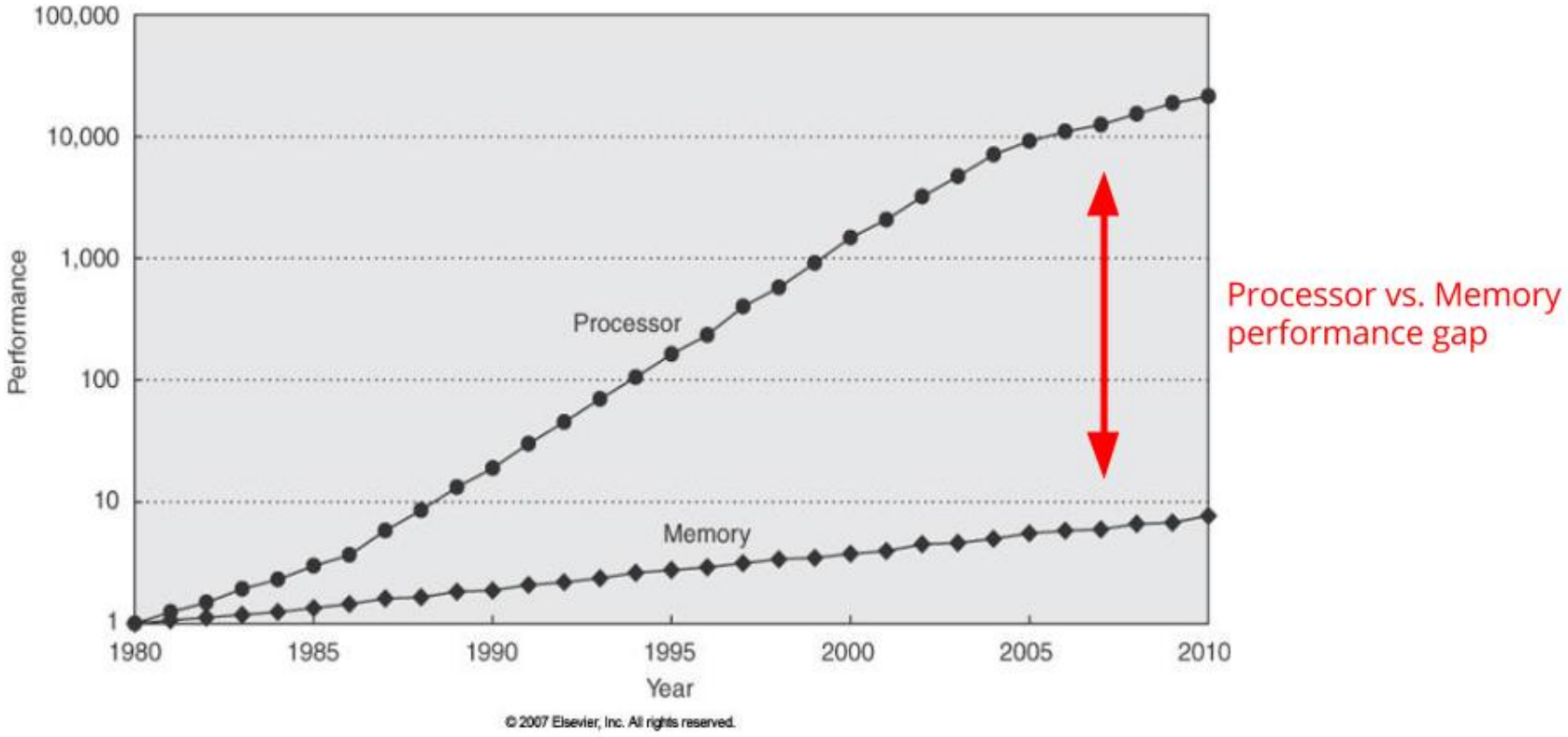


Figure 5.7
Overall RAM Organization

Computer Memory: The Memory Hierarchy



Memory speed lags behind CPU speed

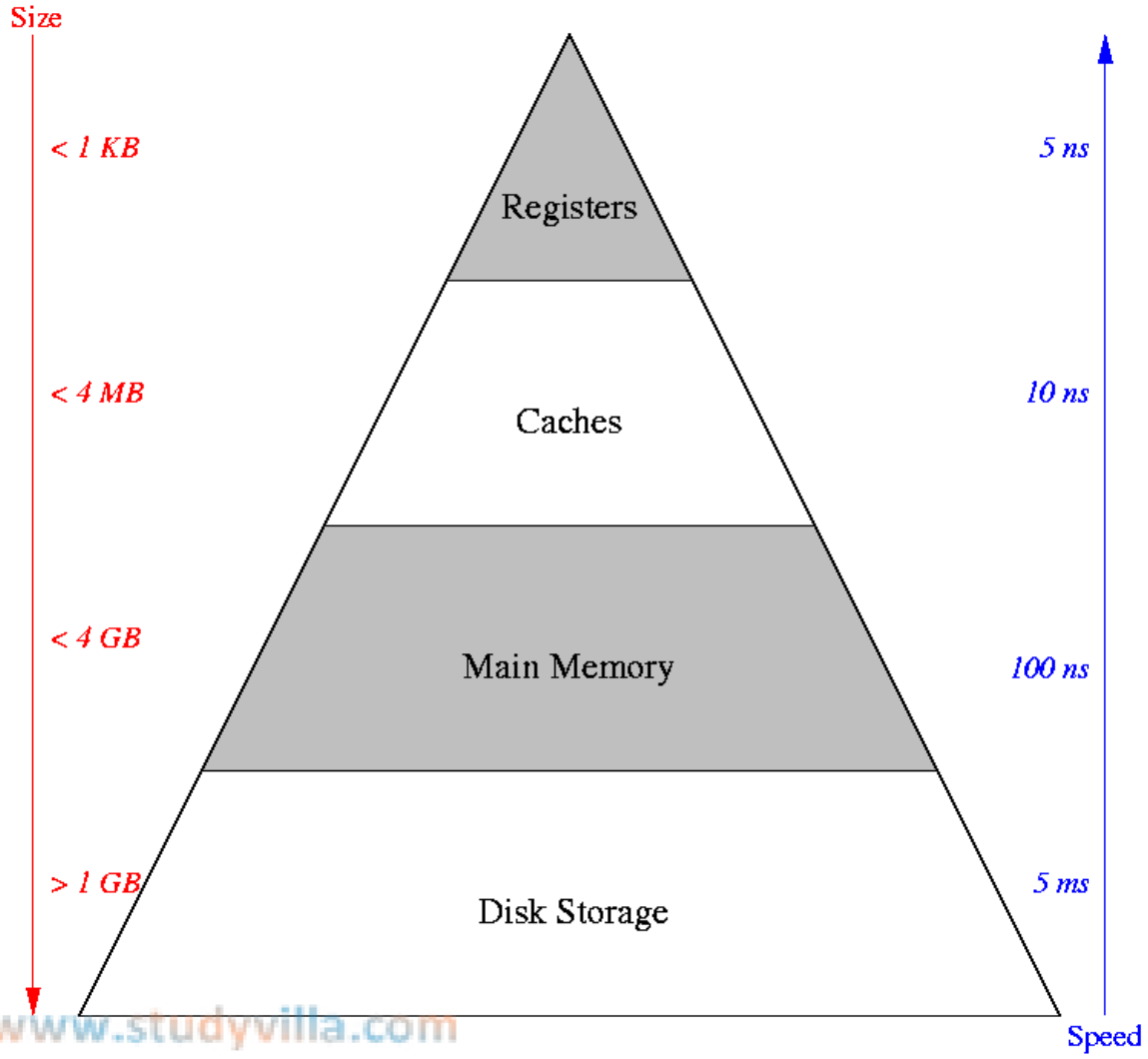
Computer Memory: The Memory Hierarchy (Cont'd)

Deal with processor / memory speed differences as follows:

1. **Registers**: Communicate with(in) processor; contain currently-executed instruction and data and associated information.
2. **Cache**: Communicates with registers and primary; uses **principle of locality** to pre-load anticipated instructions and data from primary.
3. **Primary**: Communicates with cache and secondary; contains programs being executed and their data.
4. **Secondary**: Communicates with primary; contains all programs and data of interest.

I/O interface devices, e.g., keyboards, screens, are treated as secondary memory devices.

Computer Memory: The Memory Hierarchy (Cont'd)



Computer Memory: The Memory Hierarchy (Cont'd)

- Deal with very large access-time difference between primary and secondary memory using an **I/O controller**, a special-purpose computer consisting of one or more **I/O buffers** and associated control logic.
- When fetching from secondary, the I/O controller loads data from the appropriate device into the buffer and, when full, sends the buffer's contents to the processor.
- When storing to secondary, the I/O controller loads data from the processor into the buffer and sends the buffer's contents to the appropriate device.
- Special **interrupt signals** used to let the processor know when I/O operations are done.

Computer Memory: The Memory Hierarchy (Cont'd)

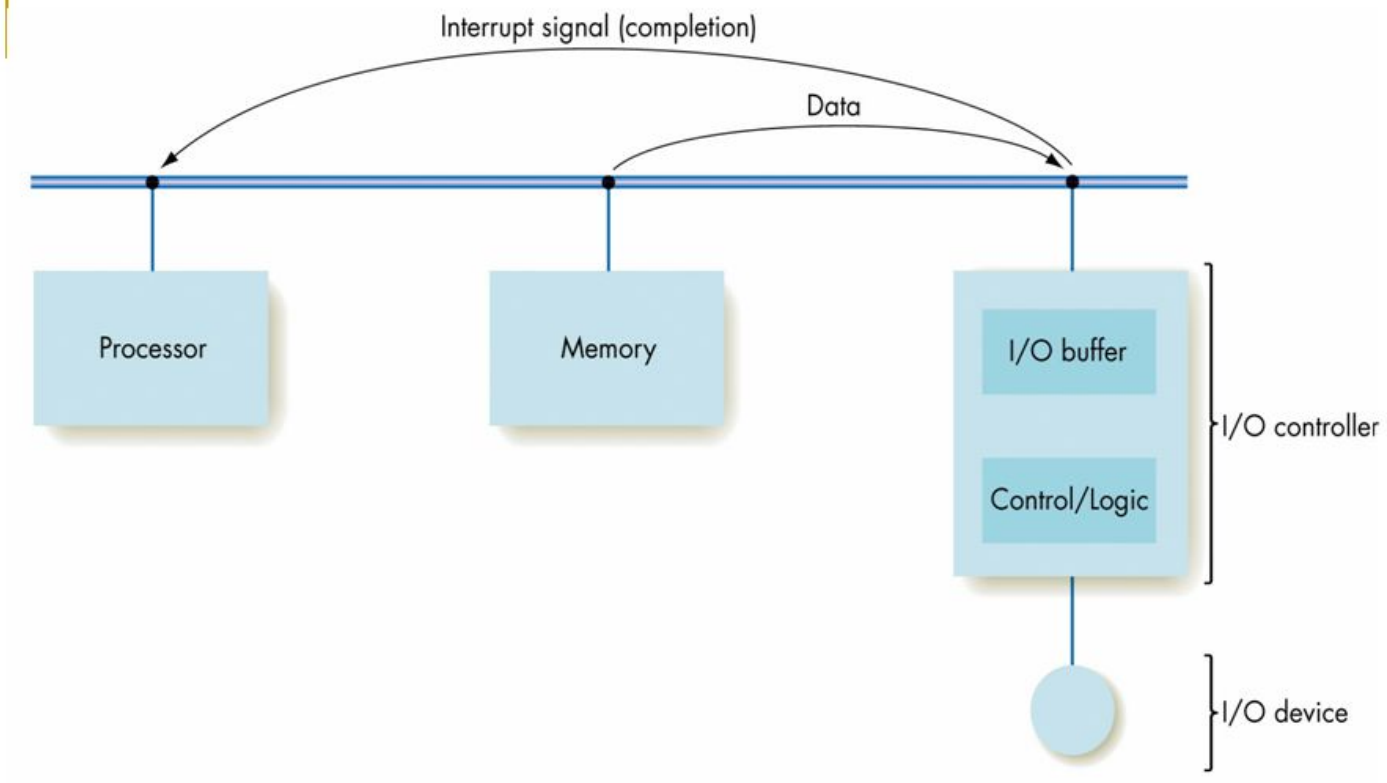


Figure 5.9
Organization of an I/O Controller

Computer Processor: Overview

- Two main parts:
  1. **Arithmetic Logic Unit (ALU)**: Performs arithmetic and logical operations.
  2. **Control Unit**: Handles interpretation and execution of program instructions. This involves directing the operations of the ALU and memory as well as interacting with the I/O controller.
- Both the ALU and the Control Unit have their own associated groups of special-purpose registers associated with their internal operations.

Computer Processor: The Arithmetic Logic Unit (ALU)

- Two types of ALU registers:
  1. **Value Registers (R0, R1, R2, . . .)**: A set of 16–128 registers which contain data for current and upcoming operations as well as intermediate results.
  2. **Condition Code Register (CCR)**: A collection of bits specifying the results (1 if true, 0 if false) of the most recently executed value comparison, e.g., LT (less-than), EQ (equal-to), GT (greater-than).
- Value registers communicate with memory and the ALU and can specified as either the left or right operand.
- The CCR communicates with the ALU, which passes the value of any condition-bit as requested to the control unit.

Computer Processor: The Arithmetic Logic Unit (ALU) (Cont'd)

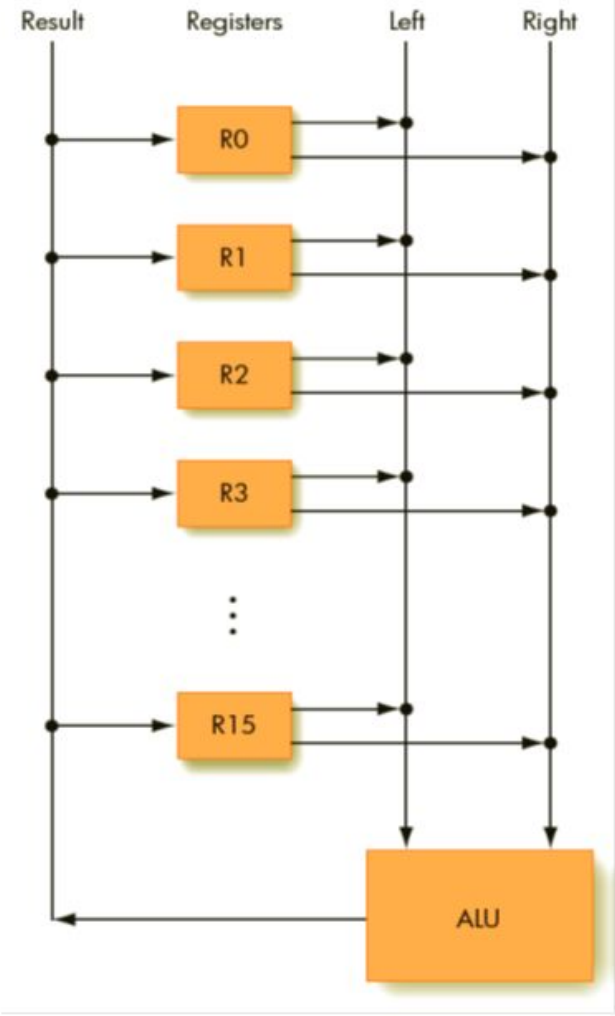


Figure 5.11 Multiregister ALU Organization

Computer Processor: The Arithmetic Logic Unit (ALU) (Cont'd)

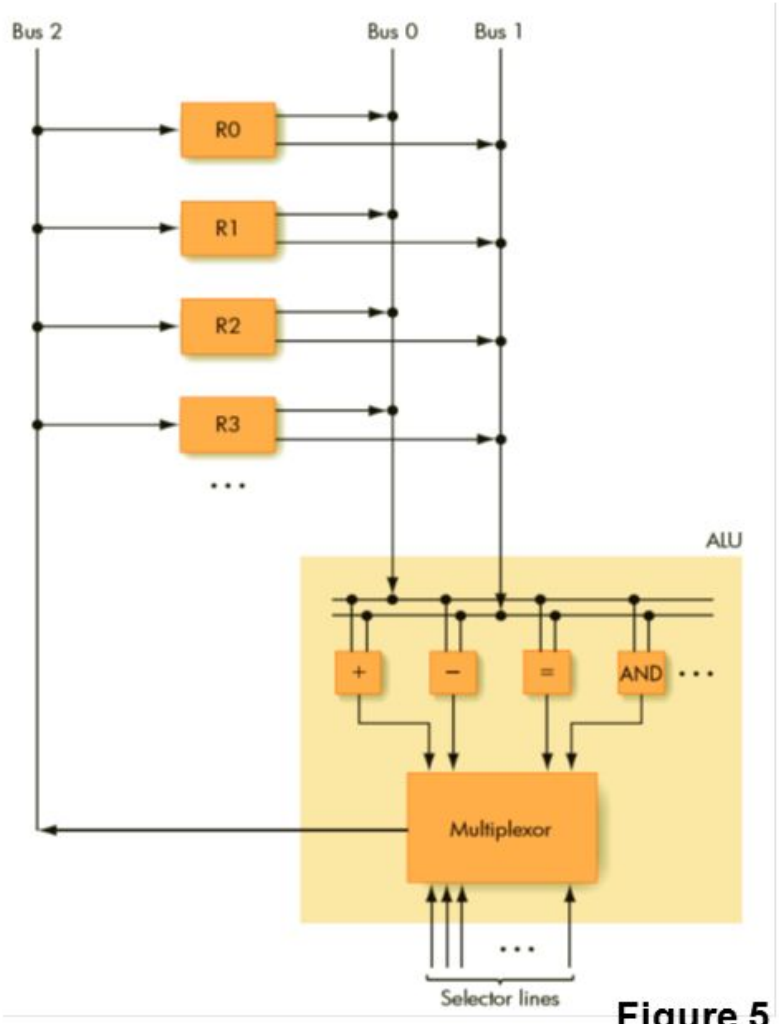


Figure 5.13 Overall ALU Organization

Computer Processor: The Control Unit

- Two Control Unit registers:
  1. **Program Counter (PC)**: Holds address in memory of next instruction to be executed.
  2. **Instruction Register (IR)**: Holds the current instruction being executed. This includes not only the op-code (IR_{op}) but the addresses of the instruction operands (IR_{add}, e.g., memory / ALU value registers).
- Instruction decoder circuitry uses the the k-bit opcode in the instruction in the IR to specify the appropriate one of the 2^k signals to that instruction's execution circuitry and/or other computer components.

Computer Processor: The Control Unit (Cont'd)

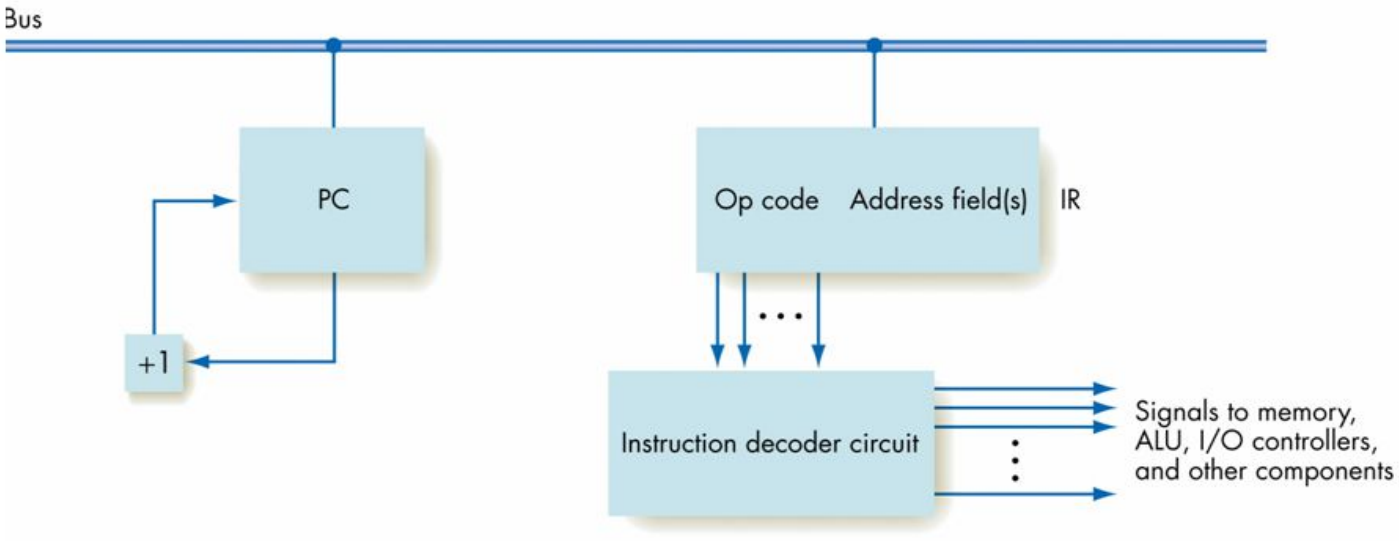


Figure 5.16
Organization of the Control Unit Registers and Circuits

Computer Processor: Machine Language

- An instruction = op-code + 0–3 address fields, e.g.,

op-code	address-1	address-2
000101	000000110011	000010001100
`COMPARE`	`Addr1`	`Addr2`

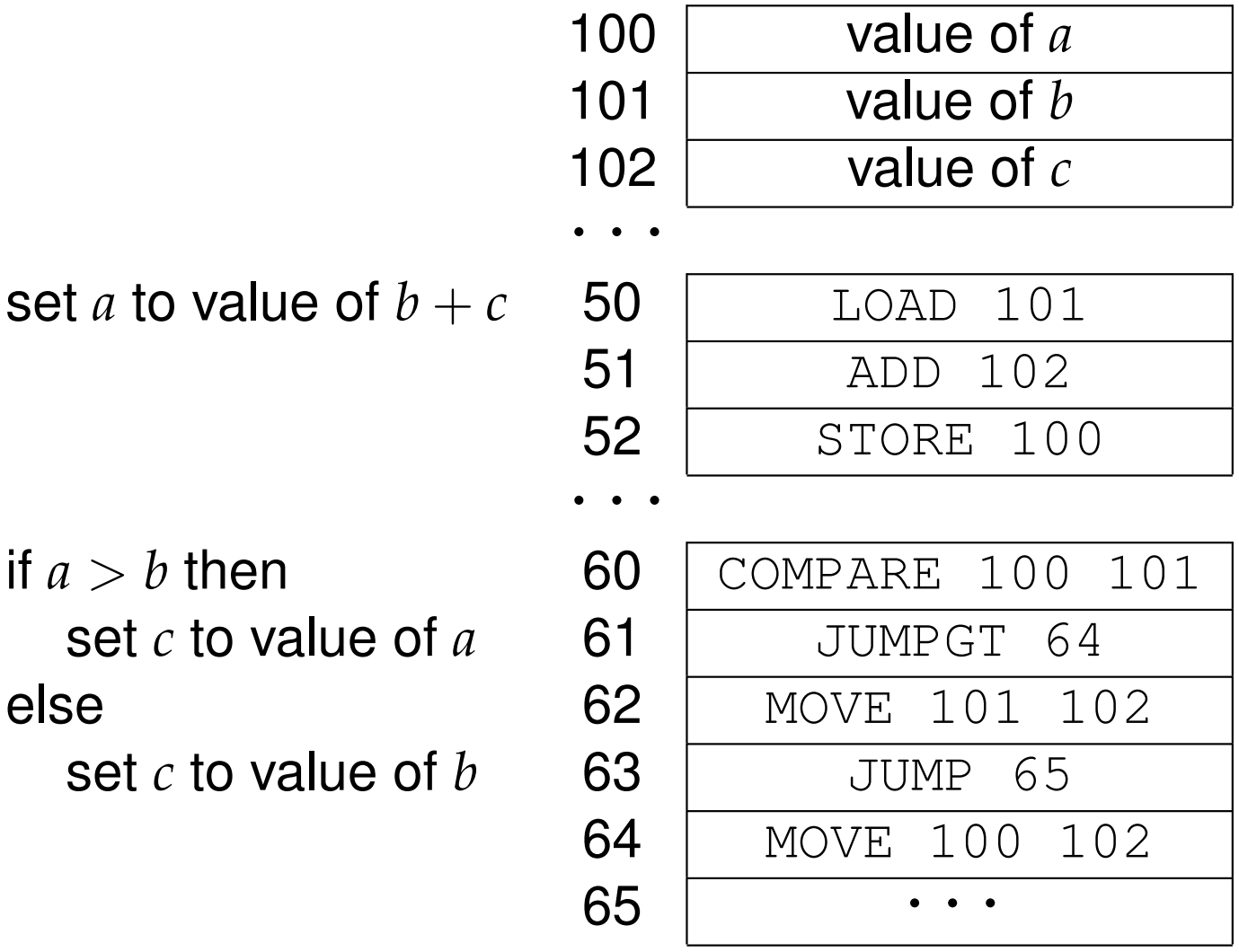
- Is part of either **Reduced or Complex Instruction Set Computer (RISC / CISC)** machine language; differ in tradeoff of required hardware vs. resulting program size.

Computer Processor: Machine Language (Cont'd)

Four types of machine language instructions:

1. **Data Transfer**: Move values between memory cells and/or ALU registers, e.g., `LOAD Addr1, LOAD Addr2, MOVE Addr1 Addr2.`
2. **Arithmetic**: Perform arithmetic / logical operations on values in memory cells and/or ALU registers, e.g., `ADD Addr1 Addr2 Addr3, ADD Addr1 Addr2.`
3. **Comparison**: Compare two values and set CCR bits, e.g., `COMPARE Addr1 Addr2.`
4. **Branch**: Alter next instruction to be executed (often on basis of preceding comparison), e.g., `JUMP Addr1, JUMPGT Addr1, HALT.`

Computer Processor: Machine Language (Cont'd)



The Von Neumann Architecture: A Detailed View Redux

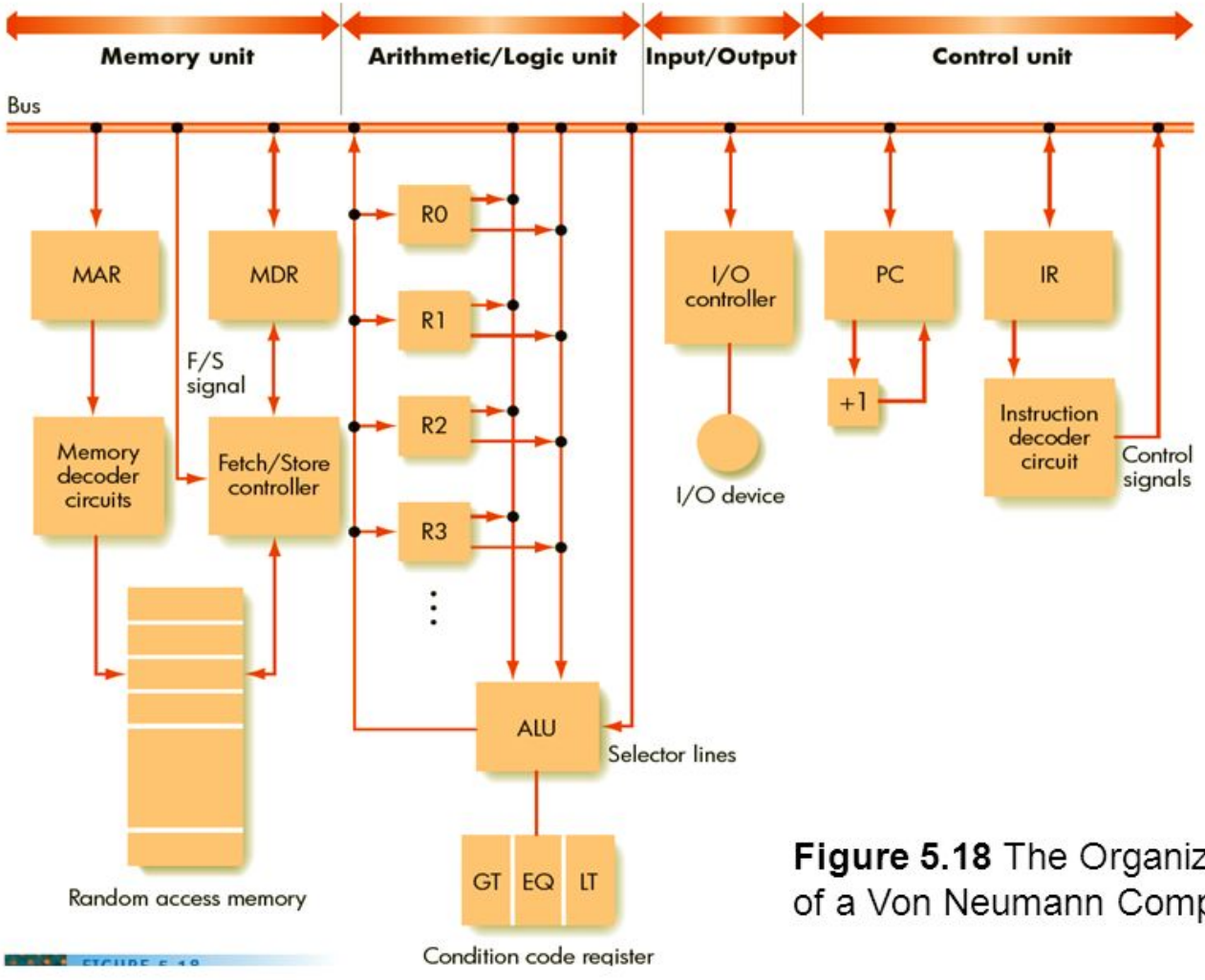


Figure 5.18 The Organization of a Von Neumann Computer

The Von Neumann Architecture: An Operational View Redux

The Von Neumann Execution Cycle:

while no `HALT` or fatal error do
Fetch next instruction
Decode instruction
Execute instruction

- Let us consider the details of this cycle in the context of a 16-instruction RISC machine language for a computer with a single-register ALU.

The Von Neumann Architecture: An Operational View Redux (Cont'd)

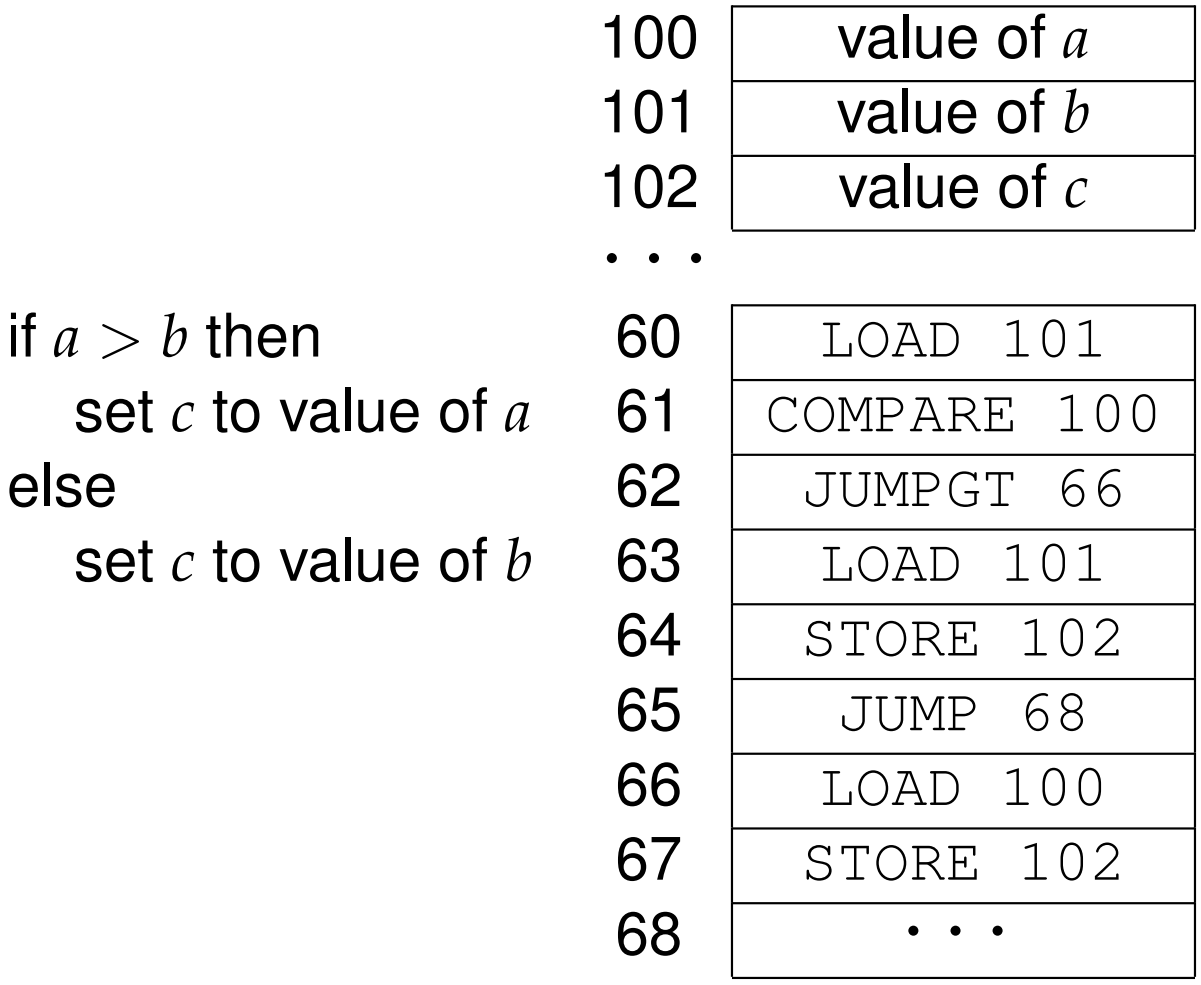
OC	Instruction	Meaning
0	`LOAD Addr`	$CON(Addr) \longrightarrow R$
1	`STORE Addr`	$R \longrightarrow CON(Addr)$
2	`CLEAR Addr`	$0 \longrightarrow CON(Addr)$
3	`ADD Addr`	$R + CON(Addr) \longrightarrow R$
4	`INCREMENT Addr`	$CON(Addr) + 1 \longrightarrow CON(Addr)$
5	`SUBTRACT Addr`	$R - CON(Addr) \longrightarrow R$
6	`DECREMENT Addr`	$CON(Addr) - 1 \longrightarrow CON(Addr)$
7	`COMPARE Addr`	if $CON(Addr) > R$ then $GT = 1$ else 0
		if $CON(Addr) = R$ then $EQ = 1$ else 0
		if $CON(Addr) < R$ then $LT = 1$ else 0

The Von Neumann Architecture: An Operational View Redux (Cont'd)

OC	Instruction	Meaning
8	`JUMP Addr`	$Addr \longrightarrow PC$
9	`JUMPGT Addr`	if $GT = 1$ then $Addr \longrightarrow PC$
10	`JUMPEQ Addr`	if $EQ = 1$ then $Addr \longrightarrow PC$
11	`JUMPLT Addr`	if $LT = 1$ then $Addr \longrightarrow PC$
12	`JUMPNEQ Addr`	if $EQ = 0$ then $Addr \longrightarrow PC$
13	`IN Addr`	Store input value at $Addr$
14	`OUT Addr`	Output $CON(Addr)$
15	`HALT`	Stop program execution

See page 261 of textbook for notations in "Meaning" column.

The Von Neumann Architecture: An Operational View Redux (Cont'd)



The Von Neumann Architecture: An Operational View Redux

Details of the three phases of the Von Neumann cycle:

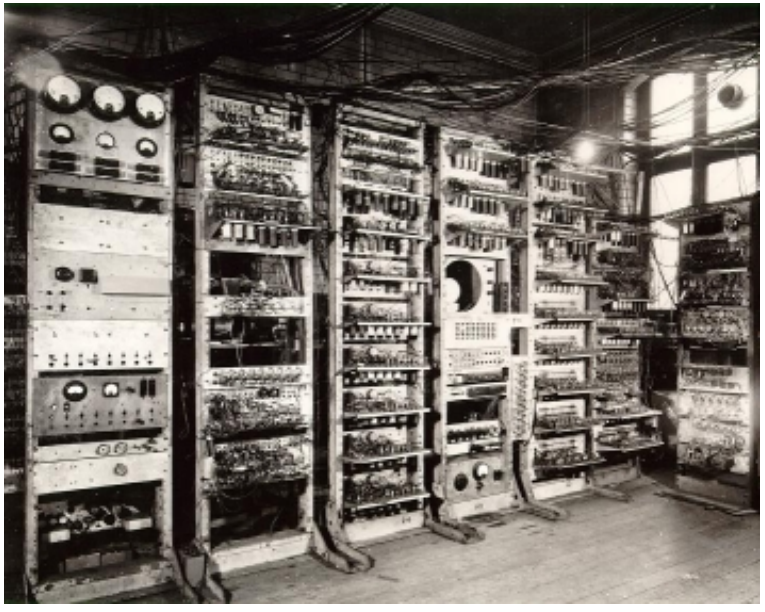
1. **Fetch next instruction**: Load next instruction into IR and update PC, i.e.,
    1. $PC \longrightarrow MAR$
    2. $FETCH$
    3. $MDR \longrightarrow IR$
    4. $PC + 1 \longrightarrow PC$
2. **Decode instruction**: Determine which circuitry must be activated to execute the instruction, i.e.,
    1. $IR_{op} \longrightarrow instruction\ decoder$

The Von Neumann Architecture: An Operational View Redux

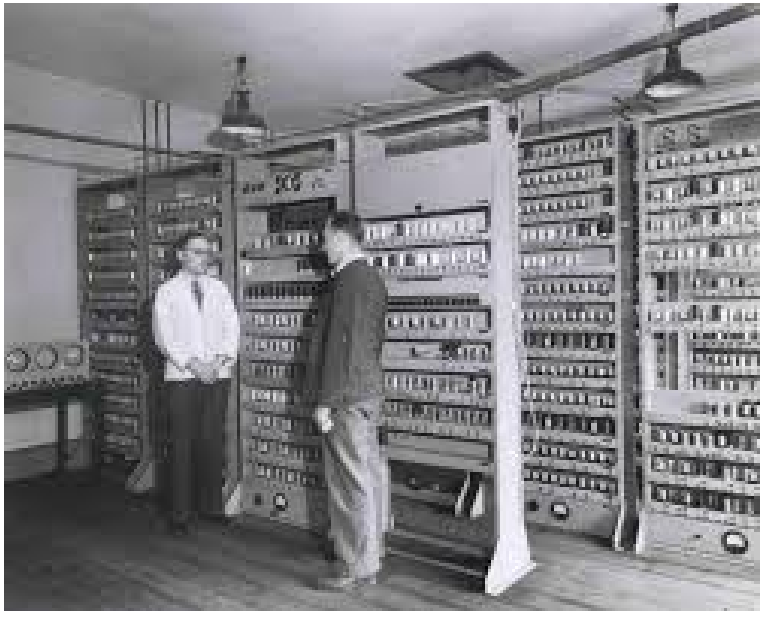
3. **Execute instruction**: Trigger the unique circuitry required to execute the instruction, e.g.,

`LOAD Addr`	1.	$IR_{addr} \longrightarrow MAR$
	2.	$FETCH$
	3.	$MDR \longrightarrow R$
`STORE Addr`	1.	$IR_{addr} \longrightarrow MAR$
	2.	$R \longrightarrow MDR$
	3.	$STORE$
`ADD Addr`	1.	$IR_{addr} \longrightarrow MAR$
	2.	$FETCH$
	3.	$MDR \longrightarrow ALU$
	4.	$R \longrightarrow ALU$
	5.	ADD
	6.	$ALU \longrightarrow R$

Implementing Computers: Beginnings



SSEM ("Baby")
(1948, U. Manchester)



EDSAC
(1949, U. Cambridge)

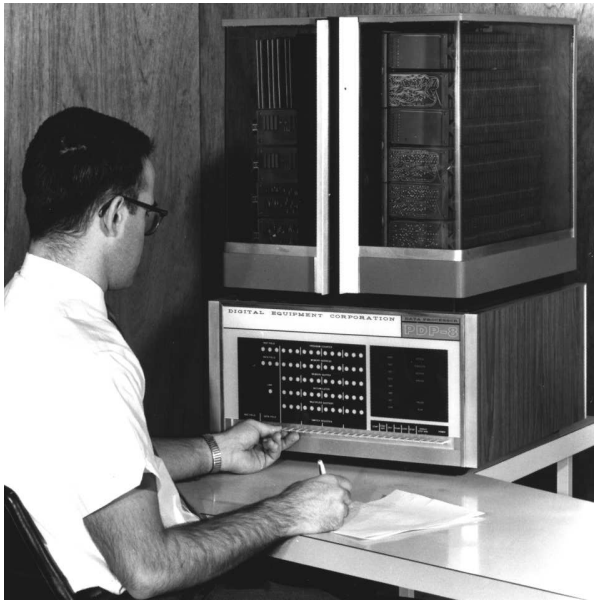
SSEM and EDSAC were world's first operational electronic stored-program computers.

Implementing Computers: Mainframes

IBM System/360 (1967)

Implementing Computers: Minicomputers

PDP I (1960)

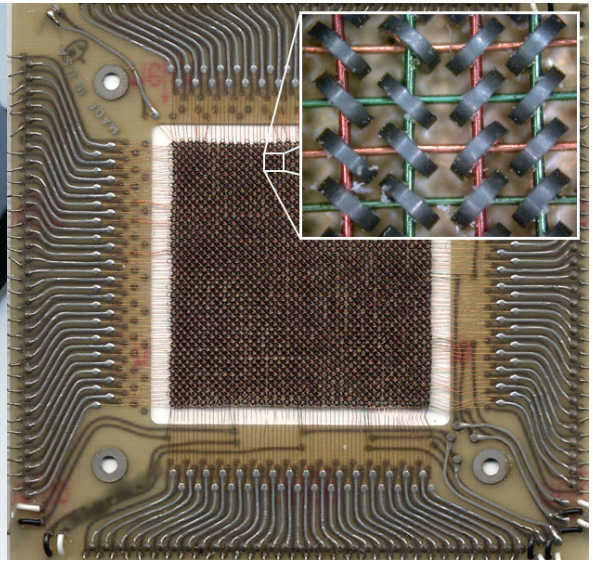


PDP 8 (1965)

Implementing Computers: Memory

Magnetic tape (1951)

Magnetic disk (1956)



Magnetic core (1953)

Massive cheap transistor-based storage possible in 1990s.

Implementing Computers: I/O Interfaces

Punch card / tape
(1940s)

Teletype
(1940s)

CRT Display
(1940s)

Implementing Computers: Microprocessors

Instead of being a little mainframe, the PC is, in fact, more like an incredibly big chip. – Robert X. Cringely

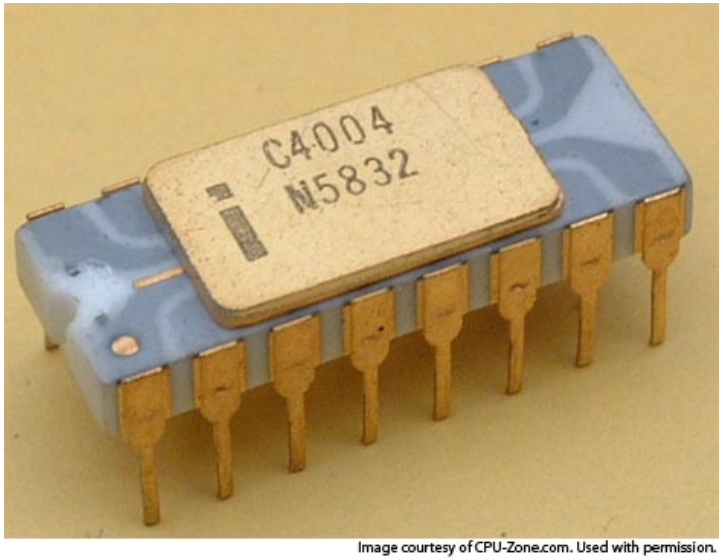


Image courtesy of CPU-Zone.com. Used with permission.

The microprocessor was invented by Ted Hoff in 1971.

Implementing Computers: Microcomputers

IBM PC (1981)

Apple Macintosh (1984)

Implementing Computers: Non-Von Neumann Architectures

CM-2 (1987)

DWAVE 2000Q (2017)

Based on massively parallel instruction execution by multiple processors (CM-2) or quantum entanglement (DWAVE 2000Q).

. . . And If You Liked This . . .

- MUN Computer Science courses on this area:
  - COMP 2003: Computer Architecture
  - COMP 4723: Introduction to Microprocessors
- MUN Computer Science professors teaching courses / doing research in in this area:
  - Rod Byrne
  - Ashoke Deb
  - Paul Gillard (Retired)