Chapter 1
Basic Computer Organization
COURSE OUTCOME

▪ Course Outcome (CO) – CO1
  ▪ Explain the basic principles of modern computer systems organization

▪ Program Outcome (PO) – PO1
  ▪ Apply knowledge of mathematics, science and engineering fundamentals to the solution of complex electrical / electronic engineering problems
  ▪ L01-Knowledge in specific area-content
BASIC COMPUTER ORGANISATION

Explain the basic principles in the design of modern computer systems

Describe the functionality workings of a computer
LEARNING OUTCOMES

- Describe the basic principles in the design of modern computer systems
- Describe the functionality workings of a computer
"5 MINUTE QUESTIONS"

- What, in general terms, is the distinction between computer organization and computer architecture?
- What are the 4 main functions of a computer?
- Brief the main structural component of a computer
- Brief the main structural component of a processor
DEFINITION OF COMPUTER ARCHITECTURE & ORGANIZATION

A. Computer

- A device that transforms data. Data processing machine which is operated automatically under the control of a program stored in its main memory.

B. Computer System

- Consists of a computer and its peripherals (input devices, output devices, secondary memories)
Computer

Peripheral devices
COMPUTER ARCHITECTURE (CA)

- How do I design a computer?
- Attributes of a system that have a direct impact on the logical execution of a program
- Instruction set, memory addressing technique, number of bits used to present various data types, I/O mechanism,
How does a computer work?

- Refers to operational units & their interconnections that realize the architectural specifications
- Control signals (how the computer is controlled?), interfaces between computer & peripherals, memory technology
ISSUE ON CO + CA

- Example: Issue of adding new instruction

Architectural design issue:
- Whether a computer will have multiply instruction
ISSUE ON CO + CA

- Example: Issue of adding new instruction

Organizational issue:
- Decision based on anticipated frequency of use, cost & physical size of a special multiply unit
Computer manufacturers offer a family of computer models, all with the same architecture but with differences in organization.

A particular architecture may span many years and encompass a number of different computer models.

Its organization is changing with changing technology.
CONCLUSION

- Intel x86 family share same basic architecture
- IBM System/370 family share same basic architecture
- Organization differs between different versions
- Code compatibility
How do we clearly describe computers?
HOW DO WE DESCRIBE COMPUTERS?

- A set of interrelated subsystems
- Each subsystem is organized in a hierarchical structure until we reach some lowest level of elementary subsystem
- At each level, the system consists of a set of components and their interrelationships.
- The components are interrelated in a particular structure
- The components have particular functions
HOW DO WE DESCRIBE COMPUTERS?

- **Structure:** the way in which the component are interrelated.
- **Function:** the operation of each individual component as part of the structure.
COMPUTER STRUCTURE

- Central processing unit (CPU) – controls the operation of the computer and performs its data processing functions
- Main memory – stores memory
- Input/Output – moves data between the computer and its external environment
- System Interconnection – communication lines between CPU, memory and I/O
CPU STRUCTURE

Figure 1.4 A Top-Down View of a Computer
CENTRAL PROCESSING UNIT (CPU)

- **Control unit**: Controls the operation of the CPU and hence the computer. It also does the timing function.
- **Arithmetic and logic unit (ALU)**: Performs the computer's data processing functions.
- **Registers**: Provides storage internal to the CPU.
- **CPU interconnection**: Communication lines between the control unit, ALU, and registers.
**COMPUTER FUNCTION**

- The operation of each individual component as part of the structure
- Data processing
- Data storage
- Data movement
- Control
DATA MOVEMENT

- Process of transferring data
- **What?** Data movement between itself and outside the world
- **How?** Data received from and delivered to device that is directly connected to computer e.g. keyboard to screen (Input-Output)
- When data moved over longer distances to/from remote device – data communication
DATA STORAGE

- Process of saving data on the computer
- Involve a permanent storage
- Long term data storage: output of the process stored in hard disk
- Short term data storage: during data processing
DATA PROCESSING

- Manipulation of information
- Data processing uses the CPU and temporary storage (memory) to store data during process
- Processing from/to storage: updating bank statement
DATA PROCESSING

- Manipulation of information
- Data processing uses the CPU and temporary storage (memory) to store data during process
- Processing from/to storage: updating bank statement
- Processing from storage to I/O devices: printing bank statement
CONTROL

- **What?** Control all above function
- **Who?** Exercised by individual who provides computer with instructions
- **Control unit** manages computer's resources & performance of its functional parts in response to those instructions
SUMMARY

- Computer organization
- Computer architecture
- CPU structure
  - CPU
  - Main memory
  - I/O
  - System interconnection
- CPU function
  - Data processing
  - Data storage
  - Data movement
  - Control
1\textsuperscript{st} Generation Computers

- Vacuum Tubes
- First generation computers used Thermion valves.
- These computers were large in size and writing programs on them was difficult
- ENIAC:
  i. first electronic computer built in 1946 at University of Pennsylvania, USA by John Mauchy and John Presper Eckert.
  ii. It was named Electronic Numerical Integrator and Calculator (ENIAC).
  iii. Occupying 1500sq feet, weighed 30 tons, contained 18,000 vacuum tubes, consumed 140,000 watts of electricity.
  iv. Capable of 5000 additions per second
  v. Today a computer is many times as powerful as ENIAC, still size is very small.
Vacuum tubes

http://www.computerhope.com

Vacuum tube
ENIAC

- A decimal rather than a binary machine - arithmetic was performed in the decimal
- Memory consisted of 20 accumulators, each capable of holding a 10-digit decimal number.
- Manually programmed
- Setting switches and plugging and unplugging cables.
ENIAC

- 20 accumulators of 10 digits
- 18,000 vacuum tubes
- 15,000 square feet
- Use 140 kW power consumption
- 5,000 additions per second
ENIAC - Electronic Numerical Integrator and Computer
Writing and altering programs for ENIAC was extremely tedious.

The programming process could be facilitated if the program could be stored in memory alongside the data.

Then a computer could get its instructions by reading them from memory.

The program later can be set or altered by setting the values of a portion of memory.

“Stored-program concept” - Von Neumann machine
**1st Generation Computers**

- Electronic Discrete Variable Automatic Computer (EDVAC) later referred to as **IAS computer** is the first proposal by von Neumann and was developed in 1952.

  i. Concept of storing data and instructions inside the computer

  ii. Much faster operation since the computer had rapid access to both data and instructions.

  iii. Other advantages of storing instruction was that computer could do logical decision internally.
Figure 2.1 Structure of the IAS Computer
Universal Automatic Computer UNIVAC

Electronic Delay Storage Automatic Calculator (EDSA C)

Electronic Discrete Variable Automatic Computer (EDVAC)
c. Other Important Computers of First Generation as EDSAC: It stands for Electronic Delay Storage Automatic Computer and was developed by M.V. Wilkes at Cambridge University in 1949.

and;

UNIVAC-1: Ecker and Mauchly produced it in 1951 by Universal Accounting Computer setup.
1\textsuperscript{st} GENERATION COMPUTERS

Drawbacks/limitations

a. The operating speed was quite slow
b. Power consumption was very high
c. It required large space for installation
d. The programming capability was quite low
2\textsuperscript{ND} GENERATION COMPUTERS

- Transistors
- 1955 - Transistor replaced the bulky electric tubes in the first generation computer.
- Transistor smaller than electric tubes and have higher operating speed.
- No filament and require no heating.
- Manufacturing cost was also very low.
- Size of the computer got reduced considerably.
  - This began the mini-computer phenomenon
2nd Generation Computers

- Computer technology based on transistors – fully transistorized computers
- More complex arithmetic and logic units
- Use of high-level programming languages
  - COBOL, FORTRAN
## 2nd Generation Computers

<table>
<thead>
<tr>
<th>Model Number</th>
<th>First Delivery</th>
<th>CPU Technology</th>
<th>Memory Technology</th>
<th>Cycle Time (μs)</th>
<th>Memory Size (K)</th>
<th>Number of Opcodes</th>
<th>Hardwired Floating-Point</th>
<th>I/O Overlap (Channels)</th>
<th>Instruction Fetch Overlap</th>
<th>Speed (relative to 701)</th>
</tr>
</thead>
<tbody>
<tr>
<td>701</td>
<td>1952</td>
<td>Vacuum tubes</td>
<td>Electrostatic tubes</td>
<td>30</td>
<td>2-4</td>
<td>24</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>1</td>
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<tr>
<td>704</td>
<td>1955</td>
<td>Vacuum tubes</td>
<td>Core</td>
<td>12</td>
<td>4-32</td>
<td>80</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>2.3</td>
</tr>
<tr>
<td>709</td>
<td>1958</td>
<td>Vacuum tubes</td>
<td>Core</td>
<td>12</td>
<td>32</td>
<td>140</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>4</td>
</tr>
<tr>
<td>7090</td>
<td>1960</td>
<td>Transistor</td>
<td>Core</td>
<td>2.18</td>
<td>32</td>
<td>169</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>25</td>
</tr>
<tr>
<td>7094 I</td>
<td>1962</td>
<td>Transistor</td>
<td>Core</td>
<td>2</td>
<td>32</td>
<td>185</td>
<td>yes (double precision)</td>
<td>yes</td>
<td>yes</td>
<td>30</td>
</tr>
<tr>
<td>7094 II</td>
<td>1964</td>
<td>Transistor</td>
<td>Core</td>
<td>1.4</td>
<td>32</td>
<td>185</td>
<td>yes (double precision)</td>
<td>yes</td>
<td>yes</td>
<td>50</td>
</tr>
</tbody>
</table>
Transistor based Computer
3rd Generation Computers

- Integrated Circuits
- Used Integrated Circuits (ICs) and popularly known as Chips
- The size of the computer got further reduced
- IC-based computer introduced in 1964 by IBM
  - IBM System/360
- Computers are small in size, low cost, large memory and processing speed is very high.
First planned family of computers

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Model 30</th>
<th>Model 40</th>
<th>Model 50</th>
<th>Model 65</th>
<th>Model 75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum memory size (bytes)</td>
<td>64K</td>
<td>256K</td>
<td>256K</td>
<td>512K</td>
<td>512K</td>
</tr>
<tr>
<td>Data rate from memory (Mbytes/sec)</td>
<td>0.5</td>
<td>0.8</td>
<td>2.0</td>
<td>8.0</td>
<td>16.0</td>
</tr>
<tr>
<td>Processor cycle time (μs)</td>
<td>1.0</td>
<td>0.625</td>
<td>0.5</td>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td>Relative speed</td>
<td>1</td>
<td>3.5</td>
<td>10</td>
<td>21</td>
<td>50</td>
</tr>
<tr>
<td>Maximum number of data channels</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Maximum data rate on one channel (Kbytes/s)</td>
<td>250</td>
<td>400</td>
<td>800</td>
<td>1250</td>
<td>1250</td>
</tr>
</tbody>
</table>

A program written for one model can be executed by another model in the series
IBM SYSTEM/360

- Similar (identical) instruction set
  - Lower end of the family has an instruction set that is subset of that of the top end of the family
- Similar operating system
- Increasing speed
- Increasing number of I/O ports
- Increasing memory size
- Increasing cost
An IBM System/360-20 (with front panels removed), with IBM 2560 MFCM (Multi-Function Card Machine)

This image of the System/360 Model 91 was taken by NASA sometime in the late 1960s.
**4th Generation Computers**

- Present day computers are the fourth generation computers that started around 1975.
- Uses large scale Integrated Circuits (LSIC) built on a single silicon chip called microprocessors.
- Microprocessor – A chip that contains all CPU components on a single chip.
- Later very large scale Integrated Circuits (VLSIC) replaced LSICs.
- Very large room in earlier days can now be placed on a table.
INTEL MICROPROCESSOR

- First microprocessor – Intel 4004 (1971)
- Add two 4-bit numbers
- Multiplication – repeated addition
- First 8-bit microprocessor – Intel 8008 (1072)
- Faster and richer instruction set
- First 16-bit microprocessor – Intel 8086 (1078)
<table>
<thead>
<tr>
<th></th>
<th>4004</th>
<th>8008</th>
<th>8080</th>
<th>8086</th>
<th>8088</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock speeds</td>
<td>108 kHz</td>
<td>108 kHz</td>
<td>2 MHz</td>
<td>5 MHz, 8 MHz, 10 MHz</td>
<td>5 MHz, 8 MHz</td>
</tr>
<tr>
<td>Bus width</td>
<td>4 bits</td>
<td>8 bits</td>
<td>8 bits</td>
<td>16 bits</td>
<td>8 bits</td>
</tr>
<tr>
<td>Number of transistors</td>
<td>2,300</td>
<td>3,500</td>
<td>6,000</td>
<td>29,000</td>
<td>29,000</td>
</tr>
<tr>
<td>Feature size (µm)</td>
<td>10</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Addressable memory</td>
<td>640 Bytes</td>
<td>16 KB</td>
<td>64 KB</td>
<td>1 MB</td>
<td>1 MB</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>80286</th>
<th>386TM DX</th>
<th>386TM SX</th>
<th>486TM DX CPU</th>
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</thead>
<tbody>
<tr>
<td>Clock speeds</td>
<td>6 MHz - 12.5 MHz</td>
<td>16 MHz - 33 MHz</td>
<td>16 MHz - 33 MHz</td>
<td>25 MHz - 50 MHz</td>
</tr>
<tr>
<td>Bus width</td>
<td>16 bits</td>
<td>32 bits</td>
<td>16 bits</td>
<td>32 bits</td>
</tr>
<tr>
<td>Number of transistors</td>
<td>134,000</td>
<td>275,000</td>
<td>275,000</td>
<td>1.2 million</td>
</tr>
<tr>
<td>Feature size (µm)</td>
<td>1.5</td>
<td>1</td>
<td>1</td>
<td>0.8 - 1</td>
</tr>
<tr>
<td>Addressable memory</td>
<td>16 MB</td>
<td>4 GB</td>
<td>16 MB</td>
<td>4 GB</td>
</tr>
<tr>
<td>Virtual memory</td>
<td>1 GB</td>
<td>64 TB</td>
<td>64 TB</td>
<td>64 TB</td>
</tr>
<tr>
<td>Cache</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>8 kB</td>
</tr>
<tr>
<td></td>
<td>486TM SX</td>
<td>Pentium</td>
<td>Pentium Pro</td>
<td>Pentium II</td>
</tr>
<tr>
<td>----------------------</td>
<td>----------</td>
<td>---------</td>
<td>-------------</td>
<td>------------</td>
</tr>
<tr>
<td>Introduced</td>
<td>1991</td>
<td>1993</td>
<td>1995</td>
<td>1997</td>
</tr>
<tr>
<td>Clock speeds</td>
<td>16 MHz - 33 MHz</td>
<td>60 MHz - 166 MHz,</td>
<td>150 MHz - 200 MHz</td>
<td>200 MHz - 300 MHz</td>
</tr>
<tr>
<td>Bus width</td>
<td>32 bits</td>
<td>32 bits</td>
<td>64 bits</td>
<td>64 bits</td>
</tr>
<tr>
<td>Number of transistors</td>
<td>1.185 million</td>
<td>3.1 million</td>
<td>5.5 million</td>
<td>7.5 million</td>
</tr>
<tr>
<td>Feature size (μm)</td>
<td>1</td>
<td>0.8</td>
<td>0.6</td>
<td>0.35</td>
</tr>
<tr>
<td>Addressable memory</td>
<td>4 GB</td>
<td>4 GB</td>
<td>64 GB</td>
<td>64 GB</td>
</tr>
<tr>
<td>Virtual memory</td>
<td>64 TB</td>
<td>64 TB</td>
<td>64 TB</td>
<td>64 TB</td>
</tr>
<tr>
<td>Cache</td>
<td>8 kB</td>
<td>8 kB</td>
<td>512 kB L1 and 1 MB L2</td>
<td>512 kB L2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Pentium III</th>
<th>Pentium 4</th>
<th>Core 2 Duo</th>
<th>Core i7 EE 990</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduced</td>
<td>1999</td>
<td>2000</td>
<td>2006</td>
<td>2011</td>
</tr>
<tr>
<td>Clock speeds</td>
<td>450 - 660 MHz</td>
<td>1.3 - 1.8 GHz</td>
<td>1.06 - 1.2 GHz</td>
<td>3.5 GHz</td>
</tr>
<tr>
<td>Bus width</td>
<td>64 bits</td>
<td>64 bits</td>
<td>64 bits</td>
<td>64 bits</td>
</tr>
<tr>
<td>Number of transistors</td>
<td>9.5 million</td>
<td>42 million</td>
<td>167 million</td>
<td>1170 million</td>
</tr>
<tr>
<td>Feature size (nm)</td>
<td>250</td>
<td>180</td>
<td>65</td>
<td>32</td>
</tr>
<tr>
<td>Addressable memory</td>
<td>64 GB</td>
<td>64 GB</td>
<td>64 GB</td>
<td>64 GB</td>
</tr>
<tr>
<td>Virtual memory</td>
<td>64 TB</td>
<td>64 TB</td>
<td>64 TB</td>
<td>64 TB</td>
</tr>
<tr>
<td>Cache</td>
<td>512 kB L2</td>
<td>256 kB L2</td>
<td>2 MB L2</td>
<td>1.5 MB L2/12 MB L3</td>
</tr>
</tbody>
</table>
The computers of 1990s are said to be Fifth Generation computers.

The speed is extremely high in fifth generation computer.

Apart from this it can perform parallel processing.

Artificial intelligence has been introduced to allow the computer to take its own decision. It is still in a developmental stage.
SUMMARY OF COMPUTER GENERATIONS

- Vacuum tube - 1946-1957
- Transistor - 1958-1964
- Small scale integration - 1965 onwards: Up to 100 devices on a chip
- Medium scale integration - to 1971: 100-3,000 devices on a chip
- Large scale integration - 1971-1977: 3,000 - 100,000 devices on a chip
- Very large scale integration - 1978 to date: 100,000 - 100,000,000 devices on a chip
- Ultra large scale integration: Over 100,000,000 devices on a chip
TYPES OF COMPUTERS

Microcomputer

- Microcomputer is at the lowest end of the computer range in terms of speed and storage capacity
- Its CPU is a 8-bit microprocessor
- The most common application of personal computers (PC)
- The PC supports a number of input and output devices – Keyboard, Monitor, Joystick, Data storage
- An improvement of 8-bit chip is 16-bit and 32-bit chips.
Processor Technology Sol-20 Terminal Computer

Helios II Disk Memory System,
the giant dual 8-inch floppy drive system
The **Commodore 64** was one of the most popular microcomputers of its era, and is the best-selling model of **home computer** of all time.

A collection of early microcomputers, including a **Processor Technology** SOL-20 (top shelf, right), an **MITS Altair 8800** (second shelf, left), a **TV Typewriter** (third shelf, center), and an **Apple I** in the case at far right.
MINICOMPUTER

- A computer designed for control, instrumentation, human interaction and communication switching
- Large storage capacity and operates at a higher speed
- Multi-user system in which various users can work at the same time
A PDP-11, model 40, an early member of DEC's 16-bit minicomputer family.

First generation Digital Equipment Corporation (DEC) PDP-8

Data General Nova, serial number 1, the first 16-bit minicomputer.
**Mainframe**

- Computers used primarily by large organizations for critical applications, bulk data processing
- Large storage capacity, I/O capacity
- Run multiple instances of operating systems at the same time
- Used in centralised databases
- Controlling nodes in Wide Area Networks (WAN)
An IBM System z9 mainframe

Inside an IBM System z9 mainframe

An IBM 704 mainframe (1964)
SUPERCOMPUTER

- High performance computer
- High processing speed compared to other computers
- Multiprocessing technique
- Built is by interconnecting hundreds of microprocessors
- Used for massive scientific and engineering calculations
- Whether forecasting, biomedical research, remote sensing, aircraft design and other areas of science and technology
The **Blue Gene/P** supercomputer at **Argonne National Lab** runs over 250,000 processors using normal data center air conditioning, grouped in 72 racks/cabinets connected by a high-speed optical network.
PERFORMANCE MEASURES

- CPU clock cycles for executing a job / Cycle count (CC)
- Cycle time (CT)
- Clock frequency ($f$) = $1/CT$
- The time taken by the CPU to execute a job can be expressed as: $CPU\ time = CC \times CT = CC/f$
PERFORMANCE MEASURES

- It’s easier to count the number of instructions executed in a given program as compared to counting the number of CPU clock cycles needed for executing that program.
- Therefore, the average number of clock cycles per instruction (CPI) has been used as an alternate performance measure.

\[
CPI = \frac{CPU \text{ clock cycles for the program}}{Instruction \text{ count}}
\]

\[
CPU \text{ time} = \text{Instruction count} \times CPI \times \text{Clock cycle time}
\]

\[
= \frac{\text{Instruction count} \times CPI}{\text{Clock rate}}
\]
Performance Measures

- Instruction set of a given machine consists of a number of instruction categories: ALU (arithmetic and logic instructions), load, store, branch, and so on.

- In the case that the CPI for each instruction category is known, the overall CPI can be computed as

\[
CPI = \frac{\sum IC_i \times CC_i}{IC}
\]

- \(IC_i\): number of times an instruction of type \(i\) is executed in the program

- \(CC_i\): clock cycles needed to execute instruction of type \(i\)

- \(IC\): total instruction count
Consider computing the overall CPI of a machine A for which the following performance measures were recorded when executing a set of benchmark programs. Assume that the clock rate of the CPU is 200MHz.

\[
CPI = \frac{\sum IC_i \times CC_i}{IC} = \frac{1 \times 38 + 3 \times 15 + 4 \times 42 + 5 \times 5}{100} = 2.76
\]
A different performance measure that has been given a lot of attention in recent years is MIPS (million instructions-per-second), the rate of instruction execution per unit time.

MIPS is defined as

\[ MIPS = \frac{\text{Instruction count}}{\text{Execution time} \times 10^6} = \frac{\text{Clock rate}}{\text{CPI} \times 10^6} \]
Consider computing the overall CPI of a machine A for which the following performance measures were recorded when executing a set of benchmark programs. Assume that the clock rate of the CPU is 200MHz and the instruction count is 100.

<table>
<thead>
<tr>
<th>Instruction category</th>
<th>Percentage of occurrence</th>
<th>No. of cycles per instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALU</td>
<td>38</td>
<td>1</td>
</tr>
<tr>
<td>Load &amp; store</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>Branch</td>
<td>42</td>
<td>4</td>
</tr>
<tr>
<td>Others</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

\[
MIPS = \frac{IC}{Execution\ time \times 10^6} = \frac{Clock\ rate}{CPI \times 10^6}
\]

\[
MIPS = \frac{Clock\ rate}{CPI \times 10^6} = \frac{200 \times 10^6}{ave(1,3,4,5) \times 10^6} = 70.24
\]
Suppose the same benchmark programs were executed on another machine B for which the following measures were recorded.

<table>
<thead>
<tr>
<th>Instruction category</th>
<th>Percentage of occurrence</th>
<th>No. of cycles per instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALU</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>Load &amp; store</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>Branch</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>Others</td>
<td>20</td>
<td>5</td>
</tr>
</tbody>
</table>

\[
CPI = \frac{\sum IC_i \times CC_i}{IC} = \frac{1 \times 35 + 2 \times 30 + 3 \times 15 + 5 \times 20}{100} = 2.4
\]

\[
MIPS = \frac{Clock rate}{CPI \times 10^6} = \frac{200 \times 10^6}{\text{ave}(1,2,3,5) \times 10^6} = 83.67
\]
PERFORMANCE MEASURES

\[
CPI = \frac{\sum IC_i \times CC_i}{IC} = \frac{1 \times 38 + 3 \times 15 + 4 \times 42 + 5 \times 5}{100} = 2.76
\]

\[
MIPS = \frac{\text{Clock rate}}{CPI \times 10^6} = \frac{200 \times 10^6}{\text{ave}(1,3,4,5) \times 10^6} = 70.24
\]

\[
CPI_B = \frac{\sum IC_i \times CC_i}{IC} = \frac{1 \times 35 + 2 \times 30 + 3 \times 15 + 5 \times 20}{100} = 2.4
\]

\[
MIPS_B = \frac{\text{Clock rate}}{CPI \times 10^6} = \frac{200 \times 10^6}{\text{ave}(1,2,3,5) \times 10^6} = 83.67
\]
### EXAMPLE

<table>
<thead>
<tr>
<th></th>
<th>No. of instructions (million)</th>
<th>Machine A (200MHz)</th>
<th>Machine B (200MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALU</td>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Load &amp; Store</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Branch</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Others</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

- Calculate $\text{CPI}_A$, $\text{MIPS}_A$, $\text{CPU}_A$ and $\text{CPI}_B$, $\text{MIPS}_B$, $\text{CPU}_B$