Unit 3 Basic Structure of a Digital Computer

Structure:

3.1 Introduction

A computer is a digital device that is capable of computing and processing data. Computers run instructions that are given to it. Instructions are low-level commands like add, subtract, or compare two numbers, and run some instruction if the comparison is true, and run some other instruction if it's false.

The list of instructions is called ***program*** and internal storage is called ***memory***. Information fed to a computer can be categorized as either *instruction* or *data*. ***Instructions*** **are the explicit commands that govern the transfer of information within the computer as well as between the computer and its I/O devices and specify the operations to be performed.**

A computer is defined as a machine for manipulating data according to a list of instructions. Earlier the term "computer" referred to a person who performed numerical calculations often with the aid of a mechanical calculating device.

Objectives:

By the end of Unit 3, you should be able to:

1. Define mini computers, micro computers, main frames and super computers.
2. Explain the basic structure of the computer.
3. Discuss the Central Processing Unit of the computer
4. Explain the bus or interconnection system.

3.2 Mechanical and Electromechanical ancestors

The first machine to attract widespread attention was built in 1642, by a French philosopher and scientist **B. Pascal**. This machine was a mechanical counter for carrying operations like addition and subtraction. It consisted of two sets of gears with teeth (counter wheels) for representing decimal numbers. Each gear had 10 decimal digits engraved on it. The position of the dial indicated the decimal value. Each set of dials was used to temporarily hold a number like a register. One special register was considered like an accumulator which held the running total. There was one more register which was used to enter a number to be added or subtracted from the accumulator. Thus when the machine was set in motion, the numbers in the two sets of dials were added, with the result appearing in the accumulator. Two main technical innovations were:

1. A ratchet device to transfer a carry automatically from one place to next.
2. A means of storing a negative number referred as complement representation.

By means of complement number representation the machine could accomplish both addition and subtraction.

In 1671, the German mathematician and philosopher **Gottfried Leibniz** constructed a calculator that could perform multiplication and division along with addition and subtraction. Leibniz's machine could perform additional operations in a repetitive step by step fashion using chains and pulleys. This machine was the forerunner of many machines that was also called as four function calculator.

In 1750, the punch cards were developed to specify the pattern in the technology of weaving. Symbols stored on punch cards were used to represent instructions. There were series of modifications and finally in 1801, Joseph Marie Jacquard made an improvement to the textile loom. The machine used a series of punched paper cards. He produced a very successful loom in which all the power was supplied mechanically and all the control through the punch card. And the cards were moved through loom apparatus. The presence or absence of a hole dictated the movements of parts of the loom to create the desired pattern. Thus this loom was a programmable process control machine with the 'program' supplied on punch cards were used as a template to allow his loom to weave intricate patterns automatically.. The resulting Jacquard loom was an important step in the development of computers because the use of punched cards to define woven patterns can be viewed as an early, albeit limited, form of programmability.

The ideas behind the general purpose programmable computer were developed by **Charles Babbage** in the 19th century. He designed two machines: **Difference Engine and Analytical Engine**.

Difference Engine: The difference engine was designed to calculate the entries of a table automatically and transfer them via steel punches to an engineer's plate from which the tables could be printed. The only arithmetic operation performed by this machine was addition. However using a mathematical technique called ***method of finite difference***, a large number of useful formulas could be computed either exactly or approximately using only additions. The formulas included polynomials and trigonometric functions like sine functions. The structure of Babbage's Difference Engine is as shown in figure 3.1 below.

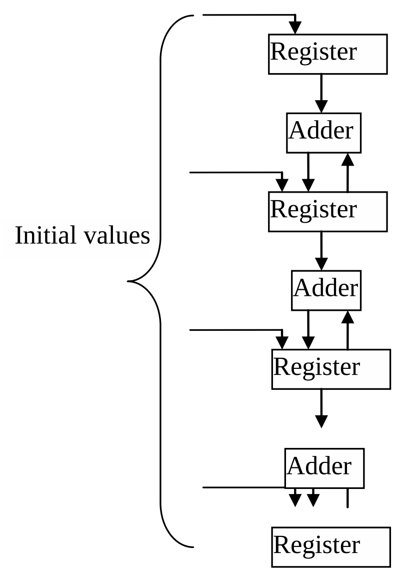

Figure 3.1: Structure of Babbage's Difference Engine

The difference engine consisted of a number of mechanical registers. Each register consisted of a set of counter wheels and could store a decimal number. Pairs of adjacent registers were connected by an adding mechanism. To compute results, initial values were loaded into the registers. When the difference engine was driven by a suitable motor it could then perform a series of steps to give an answer. This machine could accommodate third degree polynomials and 15-digit numbers. Babbage proposed to build a machine that would accommodate sixth degree polynomials and 20-digit numbers but could not succeed as the British government withdrew its support. In the mean time he came up with a more powerful and ambitious machine which he called an **Analytical engine**.

Analytical engine: This machine was designed to be a general purpose device that is capable of performing any mathematical operation automatically. The Analytical engine's structure is as shown in Figure 3.2 below.

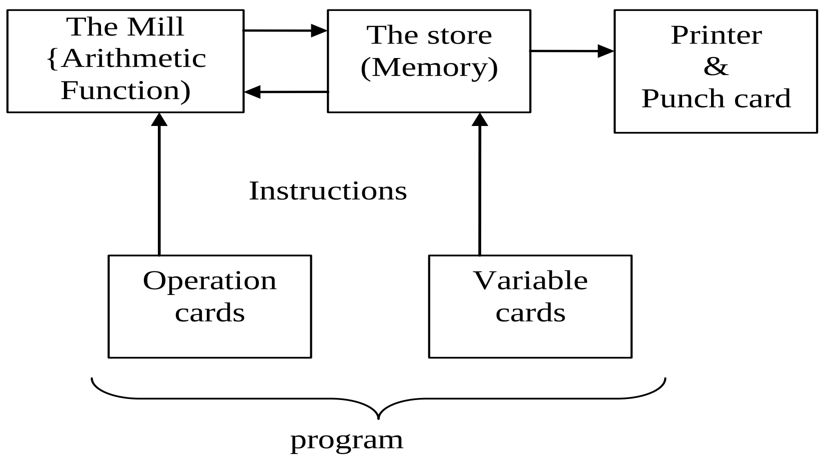

Figure 3.2: Structure of Babbage's analytical engine

The Analytical engine consists of five units of which two main units are the **Store** and the **Mill**. To control the sequence of operations, punch cards were used which were of the type developed earlier for Jacquard's loom. Each of these components are described below:

- **The Store:** Is a memory unit comprising sets of counter wheels
- **The Mill:** It corresponds to a modern Arithmetic Logic Unit. It was capable of performing four basic arithmetic operations. It operated on pairs of mechanical registers and produced a result stored in another mechanical register, all of which were stored in the store (a memory as defined above)
- **The punch cards:** It constituted a computer program and were divided into two groups:

  - **90 Operation cards:** These cards were used to control the operation of the Mill. Each operation card selected one of the four possible operations (that is addition, subtraction, multiplication and division) at each step in the program.
  - **Variable cards: I**t is used to select the memory locations to be used by a particular operation, that is the source of the input operands and the destination of the results.
- **Output:** Is a printer or a card punch device so that output data either printed on a printer or punched on cards.

Large-scale automated data processing of punched cards was performed for the US Census in 1890 by tabulating machines designed by Herman Hollerith and manufactured by the Computing Tabulating Recording Corporation, which later became IBM.

During the first half of the 20th century, many scientific computing needs were met by increasingly sophisticated analog computers. However, these were not programmable and generally lacked the versatility and the accuracy of modern digital computers.

Computers take numerous physical forms. Early electronic computers were the size of a large room, consuming as much power as several hundred modern personal computers. Today, computers can be made small enough to fit into a wrist watch and be powered from a watch battery. Society has come to recognize personal computers and, the laptop computer as icons of the information age. However, the most common form of computer in use today is by far the embedded computer. Embedded computers are small, simple devices that are often used to control other devices. For example, they may be found in machines ranging from fighter aircraft to industrial robots, digital cameras, and even children's toys.

The ability to store and execute programs makes computers extremely versatile. Computers can range from personal computers to supercomputers which are all able to perform same computational tasks so long as time and storage capacity are not considerations. The use of digital electronics and more flexible programmability were important steps, in the development of digital electronic computer.

EDSAC ***(Electronic Delay Storage Automatic Calculator)*** was one of the first computers to implement the stored program (von Neumann) architecture. Several developers came up with a far more flexible and elegant design, which came to be known as the ***stored program architecture*** **or** ***von Neumann architecture***. This design was first formally described by John von Neumann in the paper "First Draft of a Report on the EDVAC", published in 1945. Nearly all modern computers implement some form of the stored program architecture.

The modern definition of a ***computer*** **is an electronic device that performs calculations on data, presenting the results to humans or other computers in a variety of useful ways.** A computer is a complex system that contains millions of elementary electronic components. Hence computer can be considered to have hierarchic nature. A hierarchic system is a set of interrelated subsystems each again hierarchical in nature until we reach some lowest level of elementary subsystem. A hierarchic nature of a complex system is essential to both their design and their description. At each level the designer is concerned with the structure and function.

Definitions of few terms used in this course

- **Structure:** It defines the way in which the components of a computer are interrelated.
- **Function:** It defines the operation of each individual component as a part of the structure.

- **Architecture:** It refers to those attributes of a computer system which are visible to a programmer.
- **Organization:** It refers to the operational units of a computer and their interconnections, and how they implement the architecture of the system.

Classification of Computers

Computers can be classified into many types based on their **size, speed and cost.**

- The smallest machines are called as ***microcomputers***. For example a personal computer, that is widely used in schools, homes and business offices.
- The next higher level machine is called a ***minicomputer***. Minicomputers are widely used in payroll, scientific computing applications etc.
- ***Mainframes*** are used for business data processing, when computing and storage capacity is larger than what the minicomputers can handle.
- ***Supercomputers*** are used for large scale numerical calculations such as weather forecasting, missile launching, aircraft and simulation.

We usually describe the computer system using top down approach which is clearest and most effective. In this unit we describe the structure and function of the major components of a computer system, and then proceed successively to the lower layers of the hierarchy in the next coming units of this book.

3.3 Structure of a Computer System

A computer is an entity that interacts in some or the other way with its external environment. **All of its linkages to external environment are classified as peripheral devices or communication lines**. In particular, the basic model of a computer is as shown in figure 3.3. It consists of four main components, **Central Processing Unit (CPU), Memory, Input /**

Output and a **Bus**. Bus can also be a wire or a communication line or in general it can be referred to as a system interconnection.

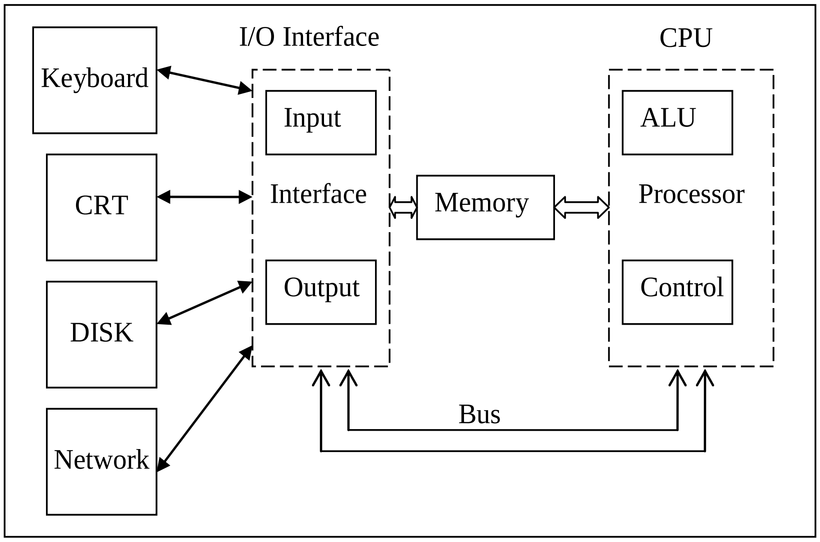

Figure 3.3: Functional units of a computer

- **CPU:** This is the computational unit and is the computer's heart. This entity controls the operations of the computer and performs its data processing functions. It is usually referred to as a processor. All the actions of all components are controlled by the control unit of CPU. CPU comprises two units called **Arithmetic Logic Unit (ALU),** where all the arithmetic and logical operations are performed and the **Control Unit (CU)** which coordinates with all other units for proper system operation.
- **Memory:** Memory is used to store the instructions, data and the result as well. Memory unit is an integral part of a computer system. The main function of a memory unit is to store the information needed by the system.

- **Input/output interface:** They are used to move data from the computer and from its external environment. The external environment may be an input or an output device like Printer, displays, keyboard etc.
- **System interconnection:** This constitutes some mechanism that provide for communication among CPU, Memory & I/O. These can be referred to as a system BUS.

Traditionally the computer system consists of a single CPU. But some machines like multiprocessing involves the use of multiple CPU's and share a single memory.

Central Processing Unit

It is the heart or core component of CPU. Figure 3.4 shows the basic functional components of Central Processing Unit.

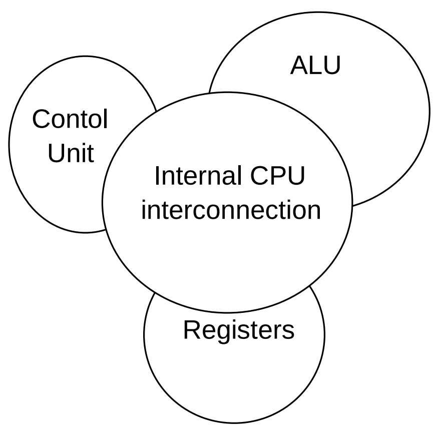

Figure 3.4: Basic Block diagram of CPU

Its major structural components are Control unit, ALU, Registers and CPU interconnections.

- **Control Unit:** It controls the operations of the CPU and hence the computer system.
- **Arithmetic logic unit (ALU):** It performs the computers data processing functions

- **Registers:** It forms the internal memory for CPU. It provides storage, internal to the CPU.
- **CPU interconnections:** It provides means for communication among the control unit, ALU and registers of the CPU.

The CPU must carry out the tasks given below:

1. Read the given instructions
2. Decode them
3. Get operands for execution
4. Process the instruction
5. Give out / store the result

To carry out these tasks the CPU needs to temporarily store some data. It must remember the location of the last instruction so that it can know where to get the next instruction. It needs to store instruction and data temporarily while an instruction is being executed. In general the CPU needs an internal memory for all store, either instruction or data.

The CPU contains a handful of registers which act like local variables. The CPU runs instructions and performs computations, mostly by the ALU. The registers are the only memory the CPU has. Register memory is very fast for the CPU to access, since it resides in the CPU itself.

However, the CPU has rather limited memory. All the local memory it uses is in registers. It has very fast access to registers, which are on-board on the CPU. It has much slower access to RAM.

- **Arithmetic logic unit (ALU)**

  The ALU is a collection of logic circuits designed to perform arithmetic (addition, subtraction, multiplication, and division) and logical operations (not, and, or, and exclusive-or). It's basically the calculator of the CPU. When an arithmetic or logical operation is required, the values and command are sent to the ALU for processing.

- **Control Unit:**

  The purpose of control unit is to control the system operations by routing the selected data items to the selected processing hardware at the right time. Control unit acts as nerve centre for the other units.

- **Instruction decoder:**

  All instructions are stored as binary values. The instruction decoder receives the instruction from memory, interprets the value to see what instruction is to be performed, and tells the ALU and the registers which circuits to energize in order to perform the function.

- **Registers:**

  The registers are used to store the data, addresses, and flags that are in use, by the CPU.

Memory Units

Memory is basically a large array of bytes. The main function of a memory unit is to store the information needed by the system. Information stored can be data, an instruction that is nothing but programs and may be some garbage. Memory locations that do not contain any valid data may store some arbitrary values and hence they are termed as garbage data. Memory unit is an integral part of a computer system.

The system performance is largely dependent on the organization, storage capacity and speed of operation of the memory system. The CPU can read or write to the memory, but it's much slower than accessing registers. Nevertheless, you need memory because registers simply hold too little information.

Most of the memory is in RAM, which can be thought of as a large array of bytes as shown in figure 3.5. In an array, we can refer to individual elements using an index. In computer organization, indexes are more commonly referred to as addresses. Addresses are the numbers used to identify successive locations. Specifying its address and a command that performs the storage or retrieval process can access a word.

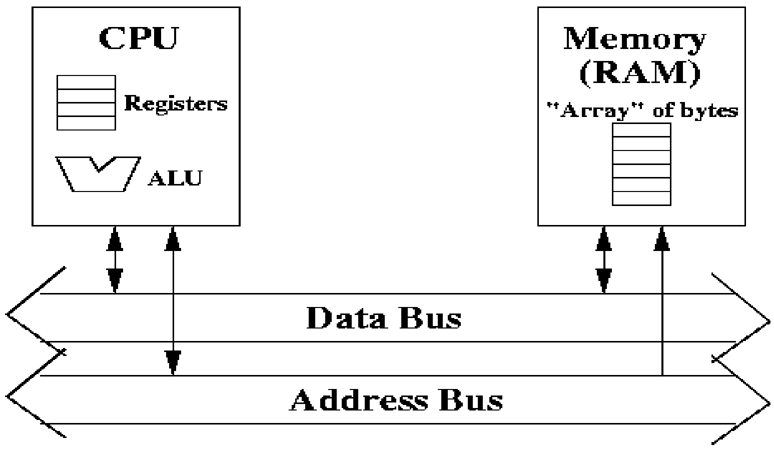

Figure 3.5: System showing the registers and memory as array of bytes

The number of bits in each word is called as ***word length*** of the computer. Large computers usually have 32 or more bits in a word. Word length of microcomputers ranges from 8 to 32 bits. The capacity of the memory is one factor that decides the size of the computer. Data are usually manipulated within the machine in units of words, multiples of words or parts of words. During execution the program must reside in the main memory. Instructions and data are written into the memory or read out from the memory under the control of a processor. Most memory is byte-addressable, meaning that each address refers to one byte of memory.

The bulk of the memory is stored in a separate device called RAM usually called ***physical memory***. RAM stores programs as well as data. The CPU fetches an instruction in RAM to a register, which is referred as an instruction register. This register then determines what instruction it has, and executes the instruction. Executing the instruction may require loading data from RAM to the CPU or storing data from the CPU to RAM.

The time required to access one word is called the ***memory access time****.*

Classification of Memory system of a Computer

Memory system of a computer can be broadly classified into four groups.

- **Internal Memory**

  Internal memory refers to a set of CPU registers. These serve as working memory, storing temporary results during the computation process. They form a general purpose register file for storing the data as it is processed. Since the cost of these registers is very high only few registers can be used in the CPU.

- **Primary Memory**

  Primary memory is also called as ***main memory***, which operates at electronic speeds. CPU can directly access the program stored in the primary memory. Main memory consists of a large number of semiconductor storage cells. Each cell is capable of storing one bit of information*. Word* is a group of these cells. Main memory is organized so that the contents of one word, containing n bits, can be stored or retrieved in one basic operation.

- ***Secondary Memory***

  This memory type is much larger in capacity and also much slower than the main memory. Secondary memory stores system programs, large data files and the information which is not regularly used by the CPU. When the capacity of the main memory is exceeded, the additional information is stored in the secondary memory. Information from the secondary memory is accessed indirectly through the I/O programs that transfer the information between the main memory and secondary memory. Examples for secondary memory devices are magnetic hard disks and CD-ROMs.

- ***Cache Memory***

  The performance of a computer system will be severely affected if the speed disparity between the processor and the main memory is significant. The system performance can be improved by placing a small, fast acting buffer memory between the processor and the main memory. This buffer memory is called as ***cache memory***. Cost of this memory is very high.

Input / Output and I/O Interface

Any movement of information from or to the computer system is considered as Input/Output. The CPU and its supporting circuitry provide I/O methods. Input and output unit is usually combined under the term input-output unit (I/O). For example consider the keyboard of a video terminal, which consists of key- board for input and a cathode ray tube display for output.

There are a wide variety of peripherals which deliver different amounts of data, run at different speeds and present data in different formats. All the I/O peripherals are slower than CPU and RAM. Hence I/O units need proper I/O interfaces.

Input Devices:

Computer accepts the coded information through the input unit. It has the capability of reading the instructions and data to be processed. The most commonly used input device is the keyboard of a video terminal. This is electronically connected to the processing part of a computer. The keyboard is wired such that whenever a key is pressed the corresponding letter or digit is automatically translated into its corresponding code and is directly sent either to memory or the processor.

Output Devices

Output unit displays the processed results. Examples are video terminals and graphic displays.

I/O devices do not alter the information content or the meaning of the data. Some devices can be used as output only e.g. graphic displays.

Following are the Input / Output techniques

- Programmed
- Interrupt driven
- Direct Memory Access (DMA)

System Interconnection / BUS

"A bus is a communication pathway connecting two or more devices."

A key characteristic of a bus is that it is a **shared transmission medium**. Multiple devices connect to the bus, and a signal transmitted by any one device is available for reception by all other devices attached to the bus. If two devices transmit during the same time period, their signals will overlap and become garbled. Thus, only one device at a time can successfully transmit. The communication between the external environment and CPU is established through the System Bus. System bus is classified into three different types, depending on whether it carries Data, Control, or Address information and are indicated in figure 3.5.

3.4 ALU

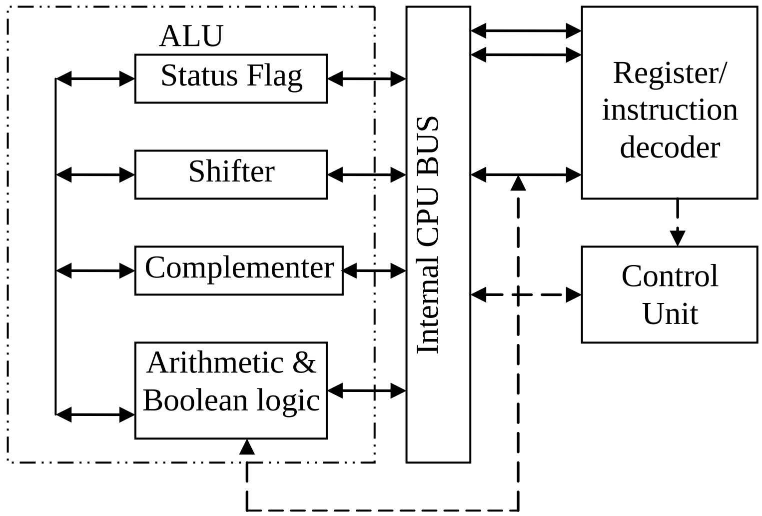

Figure 3.6: CPU showing internal components of ALU

Basic components of ALU are as shown in figure 3.6. The Arithmetic and Logic Unit is the core of any processor. It performs the calculations on the input data given. ALU is needed to transfer data between the various registers. Always ALU operates only on data in the internal CPU memory. ALU is capable of performing any arithmetic and boolean operations.

An Arithmetic-Logic Unit or ALU can be considered as a combination of various circuits in a single circuit that are used to execute data processing instructions. The complexity of ALU is determined by the way in which its arithmetic instructions are realized. Simple ALUs that perform fixed point addition and subtraction, as well as logical operations can be realized by combinational circuits.

The ALU that realized using a combinational logic that are basically constructed from AND, OR, and NOT gates. It is basically an implementation of a Boolean function. A generic diagram for a combinational logic circuit of ALU is as shown in figure 3.7. In general, a combinational logic circuit has inputs, which are divided into data inputs and control inputs, and outputs. Control inputs tell the circuit what to do with the data inputs.

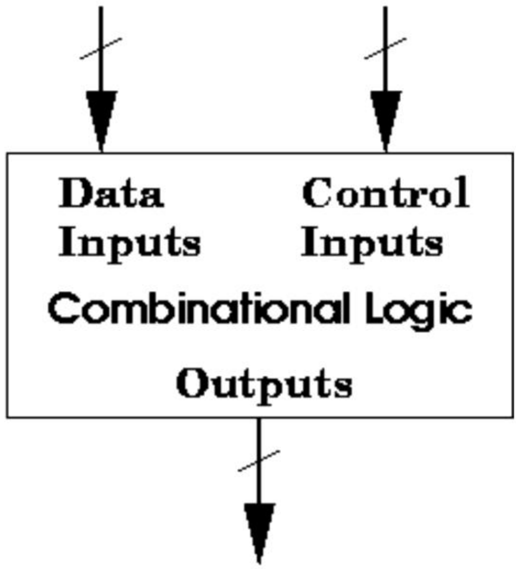

Figure 3.7: A generic ALU that has 2 inputs and 1 output

A typical ALU will have two input ports and a result port. It will also have a control input telling it which operation to perform. For example add, subtract, and, or, etc. It also consists of additional output bits for condition codes. Basically, these bits indicate some facts about the computation. For example carry, overflow, negative, zero result. Additional output bits are together called as the ***status bits***. The status bits are used for branching operations.

ALUs may be simple and perform only a few operations: Integer arithmetic like add and subtract and Boolean logic like and, or, complement and left Shift, right Shift, rotate. Such simple ALUs may be found in small 4- and 8-bit processors.

Example: Consider a 32 bit ALU as shown in figure 3.8. It consists of source 1 labeled as SRC1 and source 2 labeled as SRC2 as the two 32-bit data inputs. It also has a control input, labeled C which is a signal for addition. These control bits tell the ALU to perform addition operation on the data inputs.

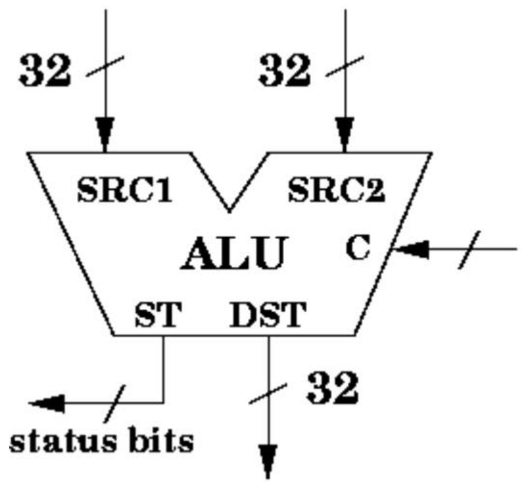

Figure 3.8: A 32 bit ALU

The result of the computation is sent to the output labeled **DST**. It is also 32 bits. There are some additional output bits labeled **ST**. In our example they may indicate whether the output is zero, or has overflowed.

More complex ALUs will support a wider range of integer operations like multiplication and division, floating point operations like add, subtract, multiply, divide. It can even compute mathematical functions like square root, sine, cosine, log, *etc.*

To perform arithmetic and logic operations necessary operands are transferred from the memory location to ALU where one of the operand is stored temporarily in some register. This register is called ***temporary register***. Each register stores one word of data.

3.5 Control Unit

The control unit is the portion of the processor that actually causes things to happen. The purpose of control unit is to control the system operations by routing the selected data items to the selected processing hardware at the right time. Control unit acts as nerve centre for the other units. This unit decodes and translates each instruction and generates the necessary enable signals for ALU and other units. Control unit has two responsibilities i.e., ***instruction interpretation and instruction sequencing***.

In ***instruction interpretation*** the control unit reads instruction from the memory and recognizes the instruction type, gets the necessary operand and sends them to the appropriate functional unit. The signals necessary to perform desired operation are taken to the processing unit and results obtained are sent to the specified destination.

In ***instruction sequencing*** control unit determines the address of the next instruction to be executed and loads it into program counter.

In general the I/O transfers are controlled by the software instructions that identify both the devices involved and the type of transfer. But the actual timing signals that govern the transfers are generated by the control circuits. Similarly the data transfer between a processor and the memory is controlled by the control circuits.

The operation of the computer can be summarized as below:

- The computer accepts information through the input unit and transfers it to the memory.
- Information stored in the memory is fetched into arithmetic and logic unit to perform the desired operations.
- Processed information is transferred to the output unit.
- All activities inside the machine are controlled by a control unit.

3.6 Bus Structure

A bus consists of 1 or more wires. There's usually a bus that connects the CPU to memory and to disk and I/O devices. Real computers usually have several busses, even though the simple computer we have modeled only has one bus where we consider the data bus, the address bus, and the control bus as part of one larger bus.

The size of the bus is the number of wires in the bus. We can refer to individual wires or a group of adjacent wires with subscripts. A bus can be drawn as a line with a dash across it to indicate there's more than one wire. The dash in it is then labeled with the number of wires and the designation of those wires.

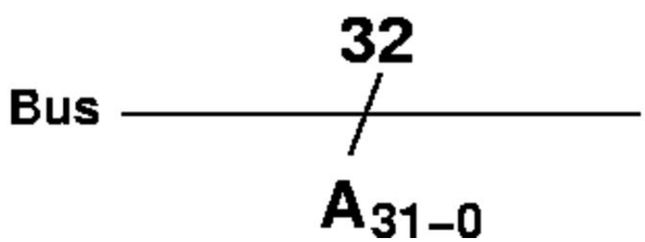

Figure 3.9: Representation of a 32 bit Bus

For example, consider a bus as shown in figure 3.9. It consists of a slant dash on the horizontal line that represents it is a bus that carries more wires. Also the slant dash is labeled 32 which indicates that the number of wires in that bus is 32 and the dash is also labeled $\mathbf{A_{31-0}}$ which indicates individual 32 wires from $\mathbf{A_0}$ to $\mathbf{A_{31}}$. We can then refer to, say $\mathbf{A_{10-0}}$ or $\mathbf{A_{15-9}}$ to refer to some subset of the wires.

A bus allows any number of devices to hook up to the bus. Devices connected to the bus must share the bus. Only one device can write to it at a time. One alternative to using a bus is to connect each pair of devices directly. Unfortunately, for N devices, this requires about N^2 connections, which may be too many. Most devices have a fixed number of connections which doesn't permit dedicated connections to other devices. A bus doesn't have this problem.

Data, Address, and Control Busses

There are usually 3 kinds of buses. There's a 32-bit data bus, which is used to write or read 32 bits of data to or from memory. There's a 32-bit address bus for the CPU to specify which address to read or write from or to memory. Finally, there's a control bus which may consist of a single wire or multiple wires to allow the CPU and memory to communicate

For example a control signal is required to indicate when and whether a read or write is to be performed. To support two 32-bit busses, both the CPU and memory require 64 pins or connections 32 for data and 32 for address. Earlier there was shortage of pins and hence it was necessary to multiplex the address and data bus. Multiplexing uses the same bus as both address and data bus.

There are other kinds of busses that are used primarily for I/O devices like USB. These are mostly high-speed busses for external devices.

3.7 Von Neumann Architecture

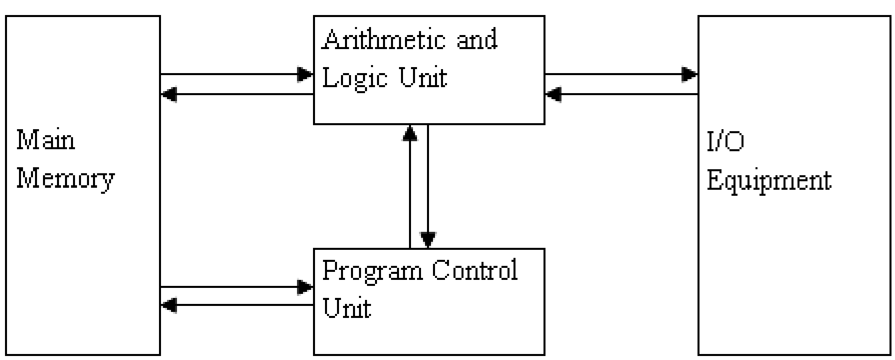

Figure 3.10: Structure of the IAS Computer

IAS is the first digital computer in which the von Neumann Architecture was employed. The general structure of the IAS computer is as shown in figure 3.10:

- A main memory, which stores both instructions and data
- An arithmetic and logic unit (ALU) capable of operating on binary data
- A control unit, which interprets the instructions in memory and causes them to be executed
- Input and Output (I/O) equipment operated by the control unit

The **von Neumann Architecture** is based on three key concepts:

1. Data and instructions are stored in a single read-write memory.
2. The content of this memory is addressable by location, without regard to the type of data contained therein.
3. Execution occurs in a sequential fashion unless explicitly modified from one instruction to the next.

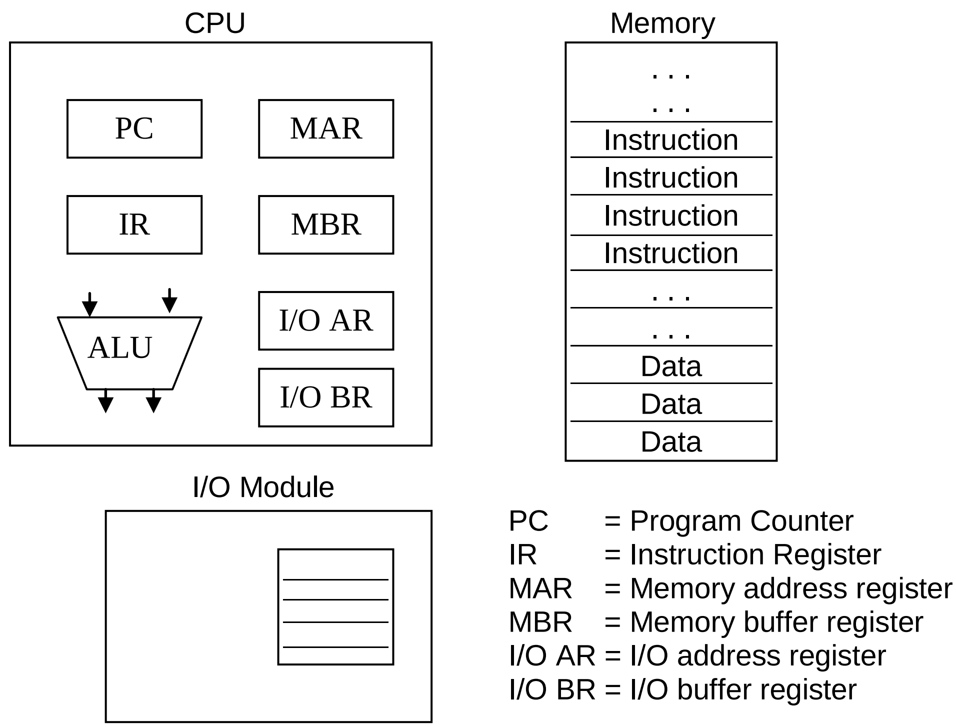

Figure 3.11: Computer components Von Neumann architecture

The CPU consists of various registers as listed in figure 3.11. They are

1. **Program Counter (PC):** It contains an address of an instruction to be fetched.
2. **Instruction Register (IR):** It contains the instruction most recently fetched.
3. **Memory Address Registers (MAR):** Contains the address of a location in memory.
4. **Memory Buffer Register (MBR):** It contains a word of data to be written to memory or the word most recently used.
5. **I/O Address Register (I/O AR):** Contains the address of a I/O.
6. **I/O Buffer Register (I/O BR):** It contains a word of data to be written to I/O device.

Any instruction to be executed must be present in the System Memory. The instruction is read from a location pointed by PC of the memory, and then transferred it to IR through the data bus. The instruction is decoded and then the data is brought to the ALU either from memory or register etc. Then ALU computes the required operation on the data and stores the result in a special register called Accumulator. All the sequence of actions is controlled by the control signals generated by the control unit. Thus ***Accumulator*** is a special purpose register designated to hold the result of an operation performed by the ALU.

3.8 Summary

This unit begins with providing a historical perspective of computers. It, then provides sufficient discussion on classification of computers, various components of the computers, followed by memory which is considered to be the crucial component. Finally this unit concludes with a brief discussion on ALU and Bus Architecture.

Self Assessment Questions:

1. ____________ are used for business data processing, when computing and storage capacity are larger than what the minicomputers can handle.
2. ____________ refers to those attributes of a computer system which are visible to a programmer.
3. A ____________ is an entity that interacts in some or the other way with its external environment.
4. Bus can also be a wire or a communication line or in general it can be referred to as a ____________.
5. ____________ performs the calculations on the input data.

3.9 Terminal Questions

1. Explain the functional units of a basic computer with a neat diagram
2. Explain Von Neumann Architecture.
3. Explain the functions of ALU.
4. Explain the System Bus structure.
5. Give a brief account of early days of computers.
6. Discuss on various types of memories.

3.10 Answers

Self Assessment Questions:

1. mainframes
2. architecture
3. computer
4. system interconnection
5. arithmetic logic unit (ALU)

Terminal Questions:

1. Refer Section 1.3
2. Refer Section 1.7
3. Refer Section 1.4
4. Refer Section 1.6
5. Refer Section 1.2
6. Refer Section 1.3.2