UNIT 5 THE MEMORY SYSTEM

5.0   INTRODUCTION

In the previous block, fundamentals of a computer system were discussed. These fundamentals included discussion on von-Neumann architecture based machines, instruction execution, representation of digital data and logic circuits etc. This Block explains the most important component of memory and Input/output systems of a computer. This unit covers the details of the Memory. This unit discusses issues associated with various components of the memory system, the design issues of main memory and the secondary memory. Various characteristics of secondary memory and its types that are used in a computer system, would also be discussed. The unit also defines how multiple disks can be used to create a redundant array of disks that can be used to provide a faster and reliable storage.

5.1   OBJECTIVES

After going through this Unit, you will be able to:

- explain the key characteristics of various types of memories and memory hierar-chy;
- explain and differentiate among various types of random access memories;
- explain the characteristics of secondary storage devices and technologies;
- explain the latest secondary storage technologies;
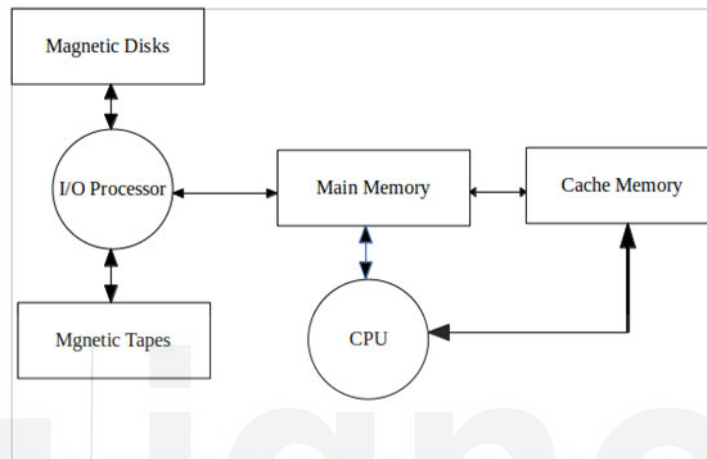- identify the various levels of RAID technologies

5.2   THE MEMORY HIERARCHY

In computers, memory is a device used to store data in binary form. Smallest unit of binary data is called 'bit'. Each bit of binary data is stored in a different cell or storage unit and collection of these cells is defined as the memory. A memory system is composed of a memory of fixed size and procedures which tells how to access the data stored in the memory. Based on the persistence of the stored data, memory is classified into two categories:

- Volatile memory: which loses its data in the absence of power.

- Non-volatile memory: Do not lose data when power is switched off.

Another classification of memory devices, which is also the objective of this unit is based on the way they interact with the CPU which can be determined from figure 5.1 Main/ Primary memory interact directly with the CPU e.g. RAM and ROM.

Auxiliary/ secondary memory need I/O interface to interact with the CPU e.g. magnetic disks and magnetic tapes. There are other memories like cache and registers, which directly interacts with the CPU. Such memories are used to speed up the program execution. For execution, a program must be loaded into the main memory and should be stored on the secondary storage when it completes its execution. Auxiliary memory is used as a backup storage, whereas main memory contains data and program only when it is required by the CPU.

Various memory devices in a computer system forms a hierarchy of components which can be visualised in a pyramidal structure as shown in Figure 5.2. As you can observe in the Figure 5.2 that at the bottom of the pyramid, you have magnetic tapes and magnetic disks; and registers are at the top of the pyramid. Main memory lies at the middle as it can interact directly with the CPU, cache memory and the secondary memory. As you go up in the pyramid, the size of the memory device decreases, the access speed, however, increases and cost per bit also increases. Different memories have different access speeds. CPU registers or simply registers are fastest among all and are used for holding the data being processed by the CPU temporarily but because of very high cost per bit they are limited in size. Instruction execution speed of the CPU is very high as compared to the data access speed of main memory. So, to compensate the speed difference between main memory and the CPU, a very high speed special memory known as cache is used. The cache memory stores current data and program plus frequently accessed data which is required in ongoing instruction execution.

You may note the following points about memory hierarchy:

✓ The size of the memory increases as you go down the memory hierarchy.

✓ The cost of per unit of memory increases as you go up in the memory hierarchy i.e. Memory tapes and auxiliary memory are the cheapest and CPU Registers are the costliest amongst the memory types.

✓ The amount of data that can be transferred between two consecutive memory layers at a time decreases as you move up in the pyramid. For example, from main memory to Cache transfer one or few memory words of size in Kilobytes are accessed at a time, whereas in a hard disk to main memory transfer, a block data of size of 1 Megabyte is transferred in a single access.

✓ One interesting question about the memory hierarchy is why having faster smaller memories does not slow down the computer? This is primarily due to the

fact that there is very high probability that a program may access the instructions and data in the closed vicinity of presently executing instruction and data. This concept is further explained in next unit.
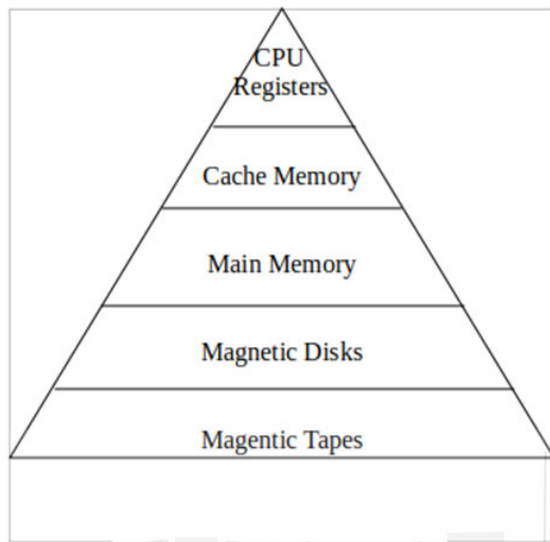

Figure 5.2: Memory Hierarchy

In subsequent sections and next unit, we will discuss various types of memories in more detail.

5.3   SRAM, DRAM, ROM, FLASH MEMORY

The main memory is divided into fixed size memory blocks called *words*. Size of the memory word may be limited by the communication path and the processing unit size. As word size/ length denotes the amount of bits that can be processed by the processor at one time. Each memory word is addressed uniquely in the memory. A 32-bit processor uses a word size of 32 bits whereas 64-bit processor uses a word of 64 bits. RAM (random access memory) is a volatile memory i.e. content of the RAM vanishes when power is switched off. RAM is a major constituent of the main memory. Both read and write operations can be performed on RAM, therefore, it is also known as read-write memory. Access time of each memory word is constant in random access memory. RAM can be constructed from two types of technologies - Static Random Access Memory (SRAM) and Dynamic Random Access Memory (DRAM). The main difference being that DRAM loses its content even if power is on, therefore requires refreshing of stored bits in DRAM. Thus, DRAM is slower than SRAM, however, the DRAM chips are cheaper. In general, DRAM is used as the main memory of the computer, while SRAM is used as the Cache memory, which is discussed in details in the next unit.

SRAM

SRAM can be constructed using flip-flops. It is a sequential circuit. A SRAM cell using SR flip flop is shown in figure 5.3. As you can observe, this sequential circuit has three inputs: *select, read/write, and input* and single output: *output*. When s*elect* input is high "1" circuit is selected for read/write operation and when *select* input is low "0" neither read nor write operation can be performed by the binary cell. Thus, *select* input must be high in order to perform read/write operation by the binary cell. Binary cell reads a bit when *read/write* input is low "0" and writes when read/write input is high "1". Third input *input* is used to write into the cell. The only caution over here is that when *read/write* input is low "0" i.e. we want to perform a read operation, then read operation must not be affected by the input *input*. This is ensured by

inverted *input* to the first AND gate which guarantees the input to both R and S to be low and thus prevents any modification to the flip flop value. The characteristic table of SR flip flop is given in Unit 4 Block 1 for better understanding of the functioning of the binary cell.
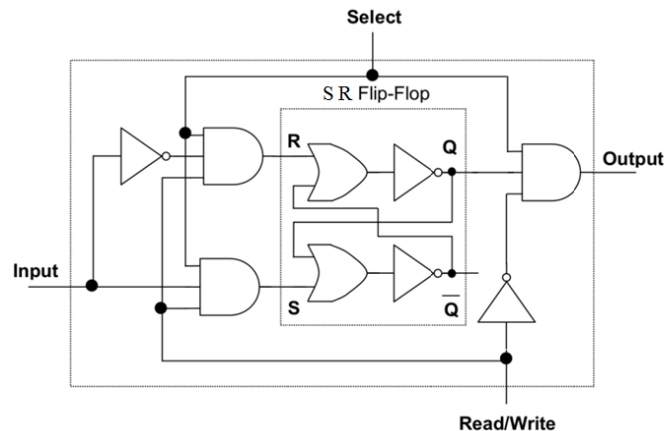

Figure 5.3: Logic Diagram of RAM cell

Read operation: *select* is high "1", *read/write* is low "0" and *input* is either low "0" or high "1" then input to R and S will be 0 and flip flop will keep its previous state and that will be the output.

Write operation: select is high "1", *read/write* is high "1" and if *input* is low "0" then R will be high "1" and S will be low "0" and flip flop will store "0" and if *input* is high "1" then R will go low"0" and S will go high "1" and flip flop will store "1".

A RAM chip is composed of several read/write binary cells. A block diagram of 2^m x n RAM is shown in Figure 5.4. The RAM shown has a total capacity of 2^m words and each word is n bits long e.g. in 64 x 4 RAM, the RAM has 64 words and each word is 4 bits long. To address 64 i.e. 2^6 words, we need 6 address lines. So in a $2^m \times n$ RAM, we have 2^m words where each word has n bits and RAM has m-bit address which requires m address lines. The RAM is functional only when chip select (CS1) signal =1 and $\overline{CS2}$ = 0. If chip select signal is not enabled or chip select signal is enabled and neither read nor write input is enabled then data bus will in high impedance state and no operation can be performed. During high impedance state, other input signals will be ignored which means output has no logical significance and does not carry a signal
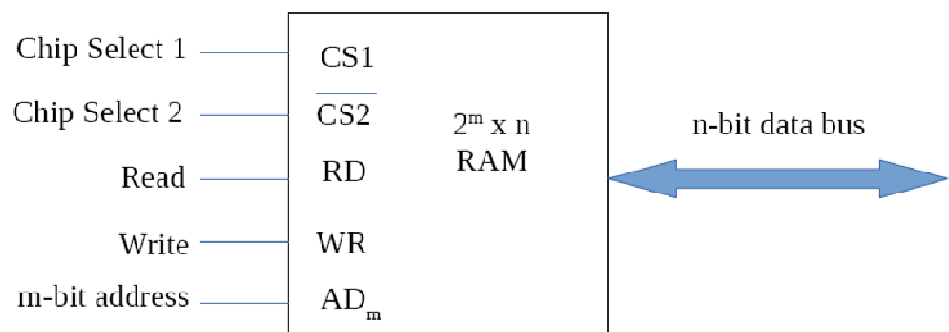

Figure 5.4: Block Diagram of 2^m x n RAM

DRAM

Dynamic Random Access Memory (DRAM) is a type of RAM which uses 1 transistor and 1 capacitor (1T1C cell) for storing one bit. A block diagram of a single DRAM cell is shown in Figure 5.5. In DRAM, transistor is used as a gate which opens and closes the circuit and thus stops and allows the current to flow. Charging level of the capacitor is used to represent the bit "1" and bit "0". As capacitors tends to discharge in a very short time period DRAM cells need to be refreshed periodically to store the binary information despite continuous power supply. Hence they are called dynamic random access memory. With low power consumption and very compact in size because of 1T1C architecture DRAM offers larger storage capacity in a single chip. Each DRAM cell in the memory is connected with Word Line (Rows) and Bit Line (Columns) as shown in Figure 5.5. Word line (rows) controls the gates of the transfer lines while Bit lines (columns) are connected to sense amplifiers i.e. to determine "0" or "1".
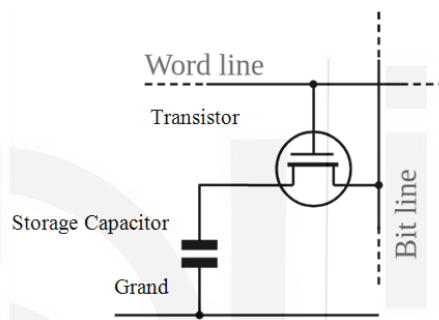

Figure 5.5: A DRAM cell

Figure 5.6 presents the general block diagram of $2^M \times 2^M \times N$ DRAM, where binary cells are arranged in a square of $2^M \times 2^M$ words of N bit each. For example, 4 megabit DRAM is represented in a square arrangement of (1024×1024) or $(2^{10} \times 2^{10})$ words of 4 bit each. Thus, in the given example we have 1024 horizontal/ word lines and 1024×4 column/ bit lines. In other words, each element, which consists of 4 bits of array, is connected by horizontal row lines and vertical column lines.
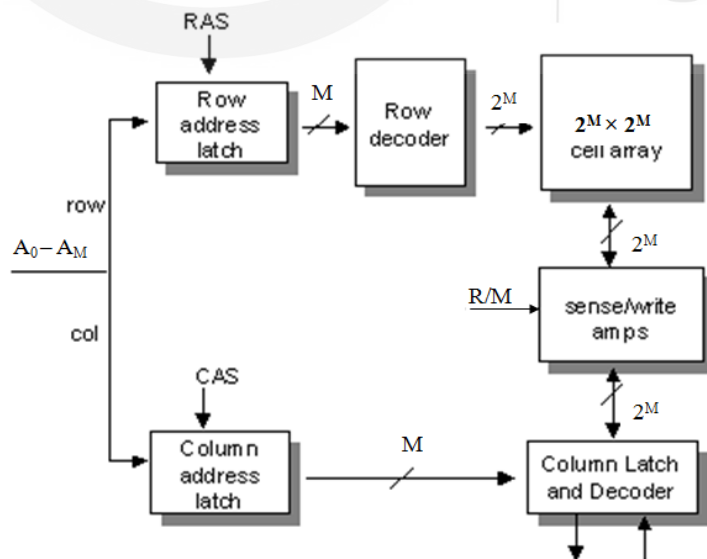

Figure 5.6: Block Diagram of DRAM

Selection and role of various signals for read and write operation is as follows:
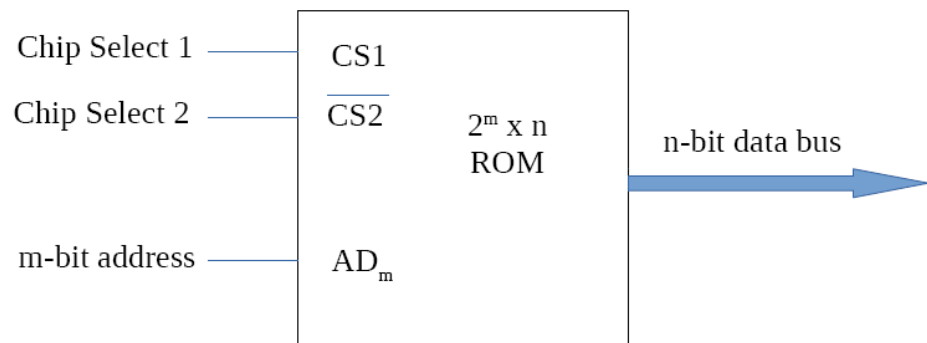
1. RAS (Row Address Strobe): On the falling edge of RAS signal, it opens or strobe the address lines (rows) to be addressed.

2. /CAS (Column Address Strobe): Similar to /RAS, on the falling edge, this enables a column to be selected as mentioned in the column address from the rows opened by the /RAS to complete the read-write operation.

3. R/(/W), Write enable: This signal determines whether to perform a read operation or a write operation. While the signal is low, write operation is enabled and data input is also captured on falling edge of /CAS whereas high enables the read operation.

4. Sense amplifier compares the charge of the capacitor to a threshold value and returns either logic "0" or logic "1".

For a read operation once the address line is selected, transistor turns ON and opens the gate for the charge of the capacitor to move to the bit line where it is sensed by the sense amplifier. Write operation is performed by applying a voltage signal to the bit line followed by the address line allowing a capacitor to be charged by the voltage signal.

ROM (Read-Only Memory)

Another constituent of the main memory is ROM (read only memory). Unlike RAM, which is read-write memory and volatile, ROM's are read only and non-volatile memory i.e. content of the ROM persist even if power is switched-off. Once data is stored at the time of fabrication, it cannot be modified. This is why, ROM is used to store the constants and the programs that are not going to change or get modified during their lifetime and will reside permanently in the computer. For example, bootstrap loader, which loads the part of the operating system from secondary storage to the main memory and starts the computer system when power is switched on, is stored in ROM.

A block diagram of $2^m \times n$ ROM looks similar to that of RAM. As ROM is a read-only memory there is no need of explicit read and write signals. Once the chip is selected using chip select signals a data word is read and placed on to the data bus. Hence, in the case of ROM, you need an unidirectional data bus i.e. only in output mode as shown in figure 5.7. Another interesting fact about ROM is that, ROM offers more memory cells and thus, memory as compared to the RAM for same size chip.

Figure 5.7: Block Diagram of 2^m x n ROM

As shown in Figure 5.7, $2^m \times n$ ROM has 2^m words of n bits each for which it has *m* address lines and *n* output data lines. For example, in 128×8 ROM, you have 128 memory words of 8-bit each. For 128×8 ROM i.e. $2^m = 2^7$, m = 7, you need 7 address lines (minimum number of bits required to represent 128) and 8-bit output data bus. Figure 5.8 shows a 32×8 ROM.
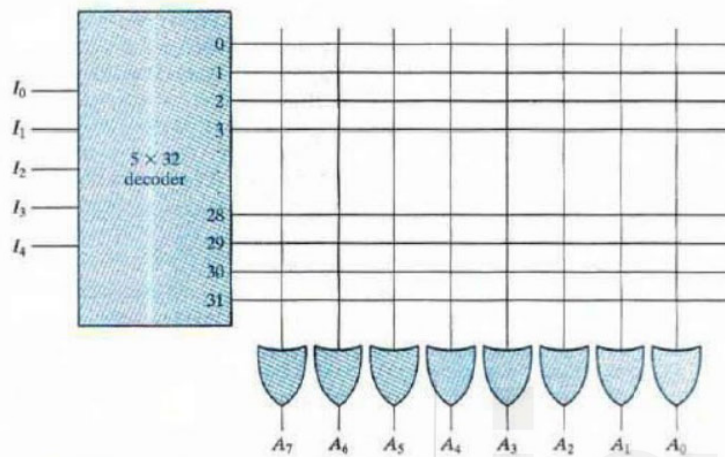

Figure 5.8: Internal diagram of 32x8 ROM

Unlike RAMs, which are sequential circuits, ROMs are combinational circuits. Typically, to design a RAM of specific size you need a decoder and OR gates. For example, to design a ROM of size 32 x 8 bits you need a decoder of size 5×32 and 8 OR gates. 5×32 decoder will have 5 input lines, which will act as 5 address lines of the ROM, the decoder will convert 5-bit input address to 32 different outputs. Figure 5.8 shows the construction of 32×8 ROM using 5×32 decoder and eight OR gates for data output. ROMs of other sizes can be constructed similarly. For example, to construct a ROM of 64×4 ROM, you need a 6×64 decoder and four OR gates and to construct a ROM of size 256×8, you need 8×256 decoder and 8 OR gates.

As discussed, ROMs are non-volatile memory and content of the ROM once written, cannot be changed. Therefore, ROMs are used to store the look-up tables for constants to speed up the computation. In addition, ROM can store the boot loader programs and gaming programs. All this requires, zero error in writing of such programs and therefore, ROM device fabrication requires very high precision. Constructing a ROM, as shown in figure 5.8, requires decision about which interconnections in the circuit should be open and which interconnections should be closed. There are four ways you can program a ROM which are as follows:

1. Mask ROM (MROM): Masking of ROM is done by the device manufacturer in the very last phase of the fabrication process on customers special request. Mask ROMs are customised as per the user requirements, thus, are very costly as different masks are required for different specifications. Because of very high cost of masking, this customization is generally used in manufacturing of ROM at very large scale.

2. Programmable ROM (PROM): MROMs are not cost effective for small productions, PROMs are preferred for small quantities. PROMs are programmed using a special hardware which blow fuses with a very high voltage to produce logic "0" and intact fuse defines logic "1". The content of PROM is irreversible once programmed.

3. Erasable PROM (EPROM): EPROMs are third type of ROMs which are restructured or reprogrammed using shortwave radiations. An ultraviolet light for

a specific duration is applied to the EPROM, which destroys/ erases the internal information and after which EPROMs can be programmed again by the user.

4. Electrically EPROM (EEPROM) : EEPROMs are similar to EPROMs except of using ultraviolet radiations for erasing PROM, EEPROM uses electrical signals to erase the content. EEPROM can be erased or reprogrammed by the user without removing them from the socket.

Flash Memory

Flash memory is a non-volatile semiconductor memory which uses the programming method of EPROM and erases electrically like EEPROM. Flash memory was designed in 1980s. Unlike, EEPROM where user can erase a byte using electrical signals, a section of the memory or a set of memory words can be erasable in flash memory and hence the name flash memory i.e. which erases a large block of memory at once. Flash memory is easily portable and mechanically robust as there is no mechanical movement in the memory to read-write data. Flash memory is widely used in USB memory, SD and micro SD memory cards used in cameras and mobile phones respectively.

There are two types of flash memory, viz. NAND flash memory, where read operation is performed by paging the contents to the RAM i.e. only a block of data is accessed not an individual byte or word; and NOR flash memory, which are able to read an individual memory byte/word or cell.

The features of various semiconductor memories are summarised in the Table 1.

Memory	Type	Erase Mechanism/ Level	Write Mechanism	Volatile/ Non- Volatile
Random-access Memory (RAM)	Read–Write	Electrical/ Byte	Electrical	Volatile
Read –only Memory (ROM)	Read–Only	Not Applicable	Masks	Non-volatile
Programmable ROM (PROM)	Read–Only	Not Applicable	Electrical	Non-volatile
Erasable PROM (EPROM)	Read-mostly	UV light/ Chip	Electrical	Non-volatile
Electrically Erasable (EEPROM)	Read-mostly	Electrical/ Byte	Electrical	Non-volatile
Flash memory	Read-mostly	Electrical/ Block	Electrical	Non-volatile

Table 1: Features of Semiconductor Memories

Check Your Progress 1

1. Differentiate among RAM, ROM, PROM and EPROM.

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2. What is a flash memory? Give a few of its typical uses.

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3.	A memory has a capacity of 16K $\times$ 16
	(a)	How many data input and data output lines does it have?
	(b)	How many address lines does it have?

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4.	A DRAM that stores 4K bytes on a chip and uses a square register array. Each array is of size 4 bits. How many address lines will be needed? If the same configuration is used for a chip which does not use square array, then how many address lines would be needed?

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5.	How many RAM chips of size 256K $\times$ 4 bit are required to build 1M Byte memory?

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## 5.4	SECONDARY MEMORY AND CHARACTERISTICS

In previous section, we have discussed various types of random access and read only memories in detail. RAM and ROM together make the main memory of the computer system. You know that a program is loaded into main memory to complete its execution. Computational units or CPU can directly interact with the main memory. Hence, faster main memory, which can match with the speed of CPU, is always desirable. In the previous section configuration of two types of RAMs, viz SRAM and DRAM were discussed. As you may observe the SRAM consists of flip-flop based circuits, therefore, is quite fast in comparison to DRAM However, the cost per bit of DRAM is much less than the SRAM. Thus, you may observe the size of main memory is much more than cache. It is discussed in more details in the next unit. To achieve high speed, cost per bit of main memory is generally high which also limits its size.

On the other hand, as we have discussed, RAM, which is a major constituent of the main memory, is volatile i.e. content of the main memory is lost when power is switched off. Because of above mentioned issues, you need a low cost and high capacity, non-volatile memory to store program files and the data for later use. Secondary memory devices which are at the bottom of the memory hierarchy pyramid are ideal for the said purpose. We will discuss various secondary storage devices in this section.

### 5.4.1	Hard Disk Drive

In the era of Big Data, in which variety of data is generated rapidly, large secondary storage has become an important component of every computer system. Today, hard disk drives (HDD) is the primary type of secondary storage. The size of hard disk drives in modern computer system ranges from Gigabytes (GB) to Terabytes (TB). Internal hard drives extends the internal storage of a computer system whereas external hard drives are used for back up storage.

HDD are electro-mechanical storage devices, which store digital data in the form of small magnetic fields induced on the surface of the magnetic disks. Data recorded on the surface of magnetic disks is read by disks read/write head, which transforms magnetic signal to electrical signal for reading and electrical signal to magnetic field

for writing. HDD is composed of many concentric magnetic disks mounted on a central shaft as shown in Figure 5.8.
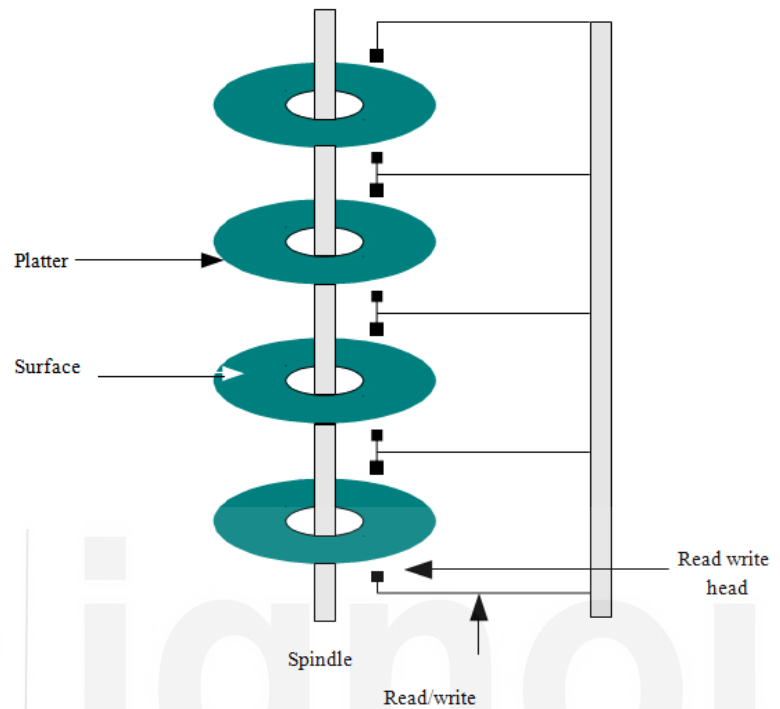

Figure 5.8: Internal structure of Hard disk drives (HDD)

Figure 5.8 shows the internal structure of an HDD. An HDD is made of several concentric magnetic disks mounted on a central shaft called spindle. Each magnetic disk is made of either glass or an aluminium disk called platter. Each platter is coated with ferromagnetic material for storing data. Platter itself is made of non-ferromagnetic material so that its own magnetic field should not interfere the magnetic field of the data. Generally, both sides of the platter is coated with magnetic material for good storage capacity at low cost.

Data recorded on the disk is accessed through a read/write head. Each side of the disk has its own read write head. Each read/write head is positioned at a distance of tens of nanometer called flying height to the platter so that it can easily sense or detect the polarization of the magnetic field.
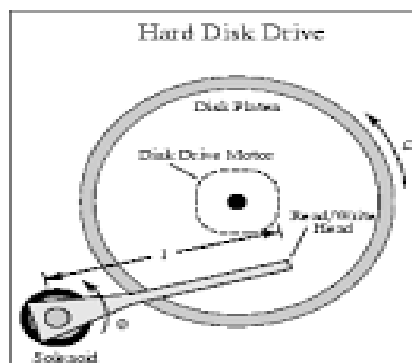

Figure 5.9: Read/ Write Head

Two motors are used in HDD. First one is called the spindle motor, which is used to rotate the spindle on which all the platters are mounted. Second motor is used to move

the read/write heads across the entire surface of the platter radially and is called actuator or access arm.

Magnetic Read and Write Mechanisms

During a read/ write operation, read/write head is kept stationary while platter is rotated by the spindle motor. As you know, data on the disk is recorded in the form of magnetic field. The current is passed through the read/write head which induces a magnetic field on the surface of platter and thus, records a bit on the surface. Different directions of current generates magnetic fields with different polarities and hence are used for storing "1" and "0". Similarly, to read a bit from the surface, the magnetic field is sensed by the read/write head which produces an electric current of the same polarity and hence the bit value is read.

Data Organization and Formatting

As discussed and shown in figure 5.8, hard disk drives consists of number of concentric platters which are mounted on a spindle forming a cylindrical structure. Data is written in the form of magnetic fields on both surfaces of these platters and is read by read/write head which is connected to an actuator. In this section, we will discuss structure of magnetic disk in detail.

Structure of the disk is shown in figure 5.10. As you know, each magnetic disk is a circular disk mounted on a common spindle but entire disk space is not used for data. Disk surface is divided in to thousands of concentric circular regions called *tracks*. The width of every track is kept the same. Data is stored in these tracks. Magnetic field of one track should not affect the magnetic region in the other track thus two tracks are kept apart with each other by a constant distance. Further, each track is divided into number of sectors and two sectors are kept apart using inter-sector gap. Data is stored in these sectors. Each track forms a cylindrical structure with other tracks on other platters below or above it. For example, an outer most cylinder will have outer most track of all the platters. So, if we have n tracks in a platter then there will be n concentric cylinders too.

Components of the drive are controlled by a disk controller. Now a days, disk controllers are built in to the disk drive. A new or blank magnetic disk is divided into sectors. Each sector has three components: header, 512 byte (or more) data area and a trailer. This process of is called physical / low level formatting. Header and trailer contains metadata about the sectors e.g. sector number, error correcting code etc. Disk controller uses this information whenever it writes or reads a data item on to a sector.

Data is stored in series of logical blocks. The disk controller maps the logical blocks on to the physical disk space and also manages sectors which have been used for storing data and which are still free. This is done by the operating system after partitioning the disk in to one or more groups of cylinders. Disk controller stores the initial data structure file of every sector on to the disk. This data structure file contains a list of used and free sectors, list of bad sectors etc. Windows uses File Allocation Table (FAT) for the said purpose.
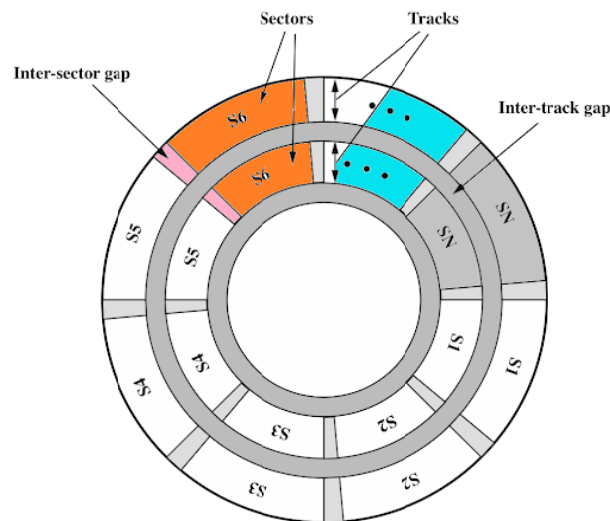
Figure 5.10: Magnetic Disk Structure of CAV

There are two arrangements with which platters are divided into tracks and sectors. The first arrangement is called as *constant linear velocity (CLV)*, in which the density of bits per track is kept uniform, i.e. outer tracks are longer than the inner tracks and hence contains more number of sectors and data. Outermost tracks are generally 40% longer than the innermost track. In this arrangement, in order to maintain uniform bit/data rate among tracks, the rotation speed is increased from outermost to inner most track. This approach is used by CD-ROM and DVD-ROM drives.

In another approach called as *constant angular velocity (CAV)*, the density of bits / data per track is decreasing as we move from innermost track to outermost track by keeping the disk rotation speed constant. As disk is moving at a constant speed, the width of the data bits increases in the outer tracks, which results in the constant data rate. Figure 5.10 shows that the width of sectors in outer tracks is increasing and density of bits is decreasing.

Disk Performance

Data is read and written on the disks by the operating system for usage at later stage. A disk stores the programs and related data. However, disk is a much slower device and the programs stored on it cannot be executed by the processing unit directly. Therefore, the programs and its related data, which are not in the main memory, are loaded in the main memory from the secondary storage. Since, the speed of disk read/write is very slow in compared to RAM, time to read or write a byte from or on to the disk affects the computer overall efficiency. Therefore, *in a single read/write operation on disk data of one or more sectors is transferred to/from the memory*. An operating system, in general, request for read/write to one or more sectors on the disk. The time taken by the disk to complete a read/ write request of the operating system is known as disk access time. There are number of factors which affect the performance of the disk. These factors are:

1. Seek Time: It is defined as a time taken by the read/write head, or simply as a head, to reach the desired track on which the requested sector is located. Head should reach the desired track in minimum time. Shorter seek time leads to faster I/O operation.

2. Rotational Latency: Since, every track consists of a number of sectors, therefore, the read/write operation can be completed only when the desired sector is available under the read/write head for the I/O operation. It depends on the

rotational speed of the spindle and is defined as a time taken by a particular sector to get underneath the read/write head.

3. Data Transfer Rate: Since, large amount of data is transferred in one read/write operation, therefore, the data transfer rate is also a factor for I/O operation. It is defined as the amount of data read or written by the read/write head per unit time.

4. Controller overhead: It is the time taken by the disk controller for mapping logical blocks to physical storage and keep track of which sectors are free and which are used.

5. Queuing Delay: time spent waiting for the disk to be free.

The disk access time is defined as the summation of seek time, rotational latency, data transfer rate, controller overhead and queuing delay and is given by the equation.

$$access_{time} = seek_{time} + rotational_{latency} + data_{tranferrate} + controller_{overhead} + queuing_{delay}$$

Out of the five parameters mentioned in the above equation, most of the time of the disk controller goes in moving the read/write to the desired location and thus seeking the information. If the disk access requests are processed efficiently then performance of the system can be improved. The aim of disk scheduling algorithm is to serve all the disk access requests with least possible head movement. There are number of disk scheduling algorithms which are presented here in brief.

First Come First Serve (FCFS) scheduling: This approach serves the disk access request in the order they arrived in the queue.

Shortest Seek Time First (SSTF) scheduling: Shortest Seek Time First disk scheduling algorithm selects the request from the queue which requires least movement of the head.

SCAN scheduling: The current head position and the head direction is the necessary input to this algorithm. Disk access requests are serviced by the disk arm as disk arm starts from one end of the disk and moves towards the other end. On reaching the other end the direction of the head is reversed and requests are continued to be serviced.

C-SCAN scheduling: Unlike SCAN algorithm, C-SCAN does not serve any request in the return trip. Instead, on reaching to the end, it reverses back to the beginning of the disk and then serves the requests.

LOOK scheduling: LOOK is similar to SCAN algorithm with only a single difference, after serving the last request, LOOK algorithm does not go till the end instead it immediately reverses its direction and moves to the beginning of the other end.

5.4.2   Optical Memories

So far, the storage devices you have studied are based on either electric charge or magnetic field. Magnetic memories are primarily used as a secondary storage device, but they can easily be damaged. However they have lower cost per bit than solid state devices.

First laser based memory was developed in 1982 by Phillips and Sony. Laser based storage devices uses a laser beam to read or write data and are called as optical memories or optical storage devices. As laser beams can be controlled more precisely and accurately than magnetic read/write heads. Data stored on optical drives remains unaffected by the magnetic disturbances in its surrounding.

Initially, these optical storage devices commonly known as compact disk (CD) or CD-DA (Digital Audio) were used to store only audio data of 60 minute duration. Later, huge commercial success of CD lead to development of low cost optical disk technology. These CDs can be used as auxiliary storage and can store any type of digital data. A variety of optical-disk devices have been introduced. We briefly review some of these types.

Compact Disk ROM (CD-ROM)

Compact Disk or CD-ROM are made of a 1.2 mm thick sheet of a polycarbonate material. Each disk surface is coated with a reflective material generally aluminium. The standard size of a compact disk is 120 mm in diameter. An acrylic coat is applied on top of the reflective surface to protect the disk from scratches and dust.
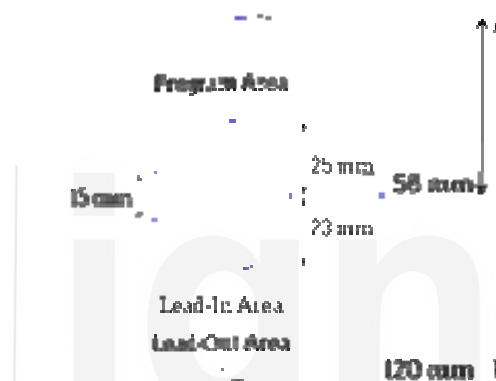

Figure 5.11: Outer Layout of a CD

Unlike magnetic disks, data on an optical disk is recorded in a spiral shape tracks. Each track is separated by a distance of 1.6 mm. Data in a track is recorded in the form of land and pit as shown in Figure 5.13. When a focused laser beam in incident on to the optical disk, the disk is burned as per the digitally recorded data forming a pit and land structure. The data is read from the surface by measuring the intensity of the reflected beam. The pit area scatters the incident beam, whereas the land reflects the incident beam, which are read as "0" and "1" respectively.
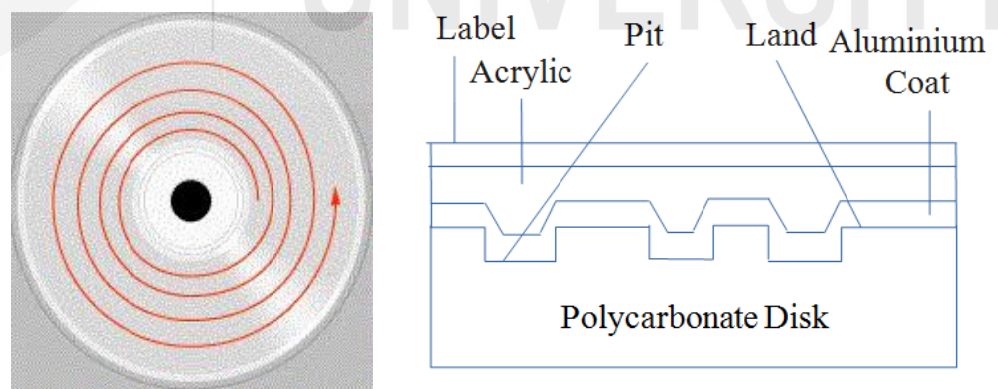

Figure 5.12: Spiral track of CD   Figure 5.13: Land & Pit formation in CD track

As shown in Figure 5.12, the tracks in CD are in spiral shape. The tracks in CDs are further divided into sectors. All sectors in CDs are equal in length. This means that density of data recorded on the disk is uniform across all the tracks. Inner tracks have less number of sectors whereas outer tracks have more sectors. CD-ROM devices uses constant linear velocity (CLV) method for reading the disk content. In this method, the

disk is rotated at lower velocity as we move away from the center of the disk. This ensures a constant linear velocity at each track of the CD. The format of a sector of CD is show in Figure 5.14.

SYNC	HEADER	DATA	L-ECC

12 Bytes	4 Bytes	2048 Bytes	288 Bytes

Figure 5.14: Sector format of CD

Data on the CD-ROM are stored in a track as a sequence of sectors. As shown in the Figure 5.14 each sector has four fields *viz.* sync, header, user data followed by error correcting codes. Each part of the sector is described below:

- Sync: It is the first field in every sector. The sync field is 12 byte long. The first byte of sync field contains a sequence of 0s followed by 10 bytes of all 1s and 1 byte of all 0s.

- Header: Header is four byte field in the sector. Three bytes are used to represent the sector address and one byte is used to represent the mode i.e. how subsequent fields in the sector are going to use. There are 3 modes:

  - Mode Zero: Specifies a no user data i.e. blank data field.
  - Mode One: Specifies an user data of 2048 bytes followed by 288 bytes of error correcting code.
  - Mode Two: No error correcting code will be used thus subsequent field will contain 2336 bytes of user data.

- Data: Data field contains the user 2048 byte of user data when mode is 1 or mode 2.

- L-ECC: Layered error correcting code field is 288 byte long field which is used for error detection and correction in mode 1. In mode 2, this field is used to carry an additional 288 bytes of user data.

Compact Disk Recordable (CD-R)

CD-Recordable are the compact disks which are capable of storing any type of digital data. The physical structure of CD-R is same as that of CD-ROM as discussed in previous section except that polycarbonate disk has a very thin layer of an organic dye before the Aluminum coating. CD- R can record user data only once but user can read the data many times thus these are also known as CD-WO (write once), or WORM (write once read many). Many CD writers allow the users to write CD-R in multiple session until CD is full. In each writing session, a partition is created in the CD- R. But once written, data on CD-R cannot be changed or deleted. There are three types of organic dyes used in CD-R.

Cyanine dyes are the most sensitive dye amongst the three types. CD-Rs have cyanine dyes are green in color. Very sensitive to UV rays and even can lose the data if exposed to direct sunlight for few days.

Phthalocyanine dye does not need a stabilizer as compared to cyanine dyes. They are silver, gold or light green in color. They are very less sensitive as compared to cyanine dyes but if exposed to direct sunlight for few weeks, it may lose the data.

Azo dye is the most stable among all types. It is most resistant to UV rays but if exposed to direct sunlight for 3-4 weeks, the CD -R may lose the data.

Compact Disk Rewritable (CD-RW)

The CD-RW are re-writable optical disks. The data on CD-RW can be read or written multiple times. But for writing again on the already written CD-RW, the disk data must be erased first. There are two approaches of erasing the data written on CD-RW. In the first approach, the entire disk data is erased completely i.e. all traces of any previous data is erased. This is called full blanking. Whereas in another approach called as fast blanking, only the meta data is erased. The later approach is faster and allows rewriting the disk. The first approach is used for confidentiality purposes.

The phase change technology is used in CD-RW. The phase change disk uses a material that has significantly different reflectivity in two different phase states. There is an amorphous state, in which the molecules exhibit a random orientation and which reflects light poorly; and a crystalline state, which has a smooth surface that reflects light well. A beam of laser light can change the material from one phase to the other. The phase change technology of CD-RW uses a 15-25 % degree of reflection whereas CD-R works on 40-70 % degree of reflection.

Digital Versatile Disk (DVD)

Digital versatile disk commonly known as DVD is also an optical storage device like CD, CD-R, CD-WR. Among the three DVDs have highest storage capacity ranges from 1.4 GB to 17 GB on a single side. The higher storage capacity is enabled by the use of laser beams of shorter wavelength as compared to compact disks. DVD uses a laser beam of 650 nm whereas compact disk uses a laser beam of 780 nm. Shorter wavelength laser beam creates shorter pits on the polycarbonate disk, thus offers higher storage capacity for similar dimensions. DVD-Audio and DVD-video are a standard format for recording audio and video data on DVDs. Like compact disks, DVD also comes in various variants like DVD-ROM, DVD-R, DVD-WR etc.

Blue Ray Disk

A blue ray disk is a digital disk that can store several hours high definition videos. Blue ray disks is of the same size of DVD, but can store 25 GB to 128 GB of data. A blue ray disk is designed to replace DVD technology. It has its applications in gaming applications, which uses very high quality animations.

5.4.3 Charge-coupled Devices, Bubble Memories and Solid State Devices

Charge-coupled Devices CCDs (CCDs)

Charge couple devices are photo sensitive devices which are used to store digital data. CCD is an integrated circuit of MOS-capacitors called cells, which are arranged in an array like structure in which each cell is connected with its neighbouring cell. Each capacitor can hold the charge which is used to represent the logic "1". While reading the array of capacitors, the capacitor moves its charge to the neighbouring capacitor with next clock pulse. CCD arrays are mainly used in representing images and video data, where presence and absence of charge in the capacitor represents the corresponding pixel intensity.

As mentioned, CCD are highly photo-sensitive in nature and thus, produces a good quality picture even if light is dim or in low illumination intensity. Now a days, CCDs are widely used in digital cameras, satellite imagery, radar images and other high resolution imagery applications.

Magnetic Bubble Memories

Working principle of magnetic bubble memory is similar to that of charge coupled devices (CCD) discussed in the previous section. Magnetic bubble memory is an

arrangement of small magnetic area called bubble on a series of parallel track made of magnetic material. Each bubble represents a binary "1" and absence of a bubble on magnetic material is interpreted as "0". Binary data is read from the memory by moving these bubbles towards the edge of a track under the influence of external magnetic field. Magnetic field produces as bubbles remain persistent and do not demagnetise by its own. So, magnetic bubble memories are non-volatile type memories.

Solid State Devices (SSD)

Solid state drives also known as solid state storage devices are based on flash memory. As discussed, flash memory, a non-volatile type memory uses semiconductor devices to store the data. The major advantage of SSD is that it is purely an electronic device i.e. unlike HDD, SSD does not have mechanical read/ write head other mechanical components. Hence, reading and writing through SSD is faster than HDD. Now a days, SSD have replaced HDD in computer systems, however, SSD disks are more expensive than HDDs.

Check Your Progress 2

1. What will be the storage capacity of a disk, which has 8 recording surfaces, 32 tracks with each track having 64 sectors. Also, what would be the size of one cylinder of the disk? You may assume that each sector can store 1 MB data.

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   ………………………………………………………………………………

2. What would be the rotation latency time for the disk specified above, if it has a rotational speed of 6000 rpm?

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   ………………………………………………………………………………

3. What are the advantages and disadvantages of using SSD over HDD?

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4. What are the differences between CLV and CAV disks?

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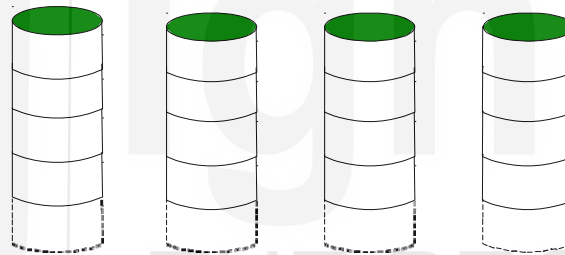   ………………………………………………………………………………

5.5 RAID AND ITS LEVELS

Continuous efforts have been made by researchers to enhance the performance of the secondary storage devices. As pointed out in previous sections performance of the secondary storage is inversely affected by disk access time. Lower the disk access time higher would be the performance. What about an idea of providing parallel access to a group of disks? With the use of parallel access the amount of data that can be accessed per unit time can be enhanced by a significant factor. A mechanism which splits the data on multiple disk is known as data striping. Data access through parallel access allows users to access data stored at multiple disks simultaneously, thus reduces effective reading time. Does data striping ensure protection of data against disk failure?

Another important factor for secondary storage is the reliability of data storage system. Storing same data on more than one disks enhances reliability. If one disk fails, then data can be accessed through another disk. Replicating data on multiple disks is called mirroring. Mirroring brings redundancy in data. So many schemes have been employed to enhance the performance and reliability of data and collectively they are called as redundant arrays of inexpensive disks (RAID). Based on the trade-off between reliability and performance RAID schemes have been categorises into various RAID levels.

Data striping increases the data transfer speed as different data bytes are accessed in parallel from different disks in a single disk access time. Whereas mirroring protects data from disk failures. If one disk fails then same data is accessed from the copy of the data stored in other disk.
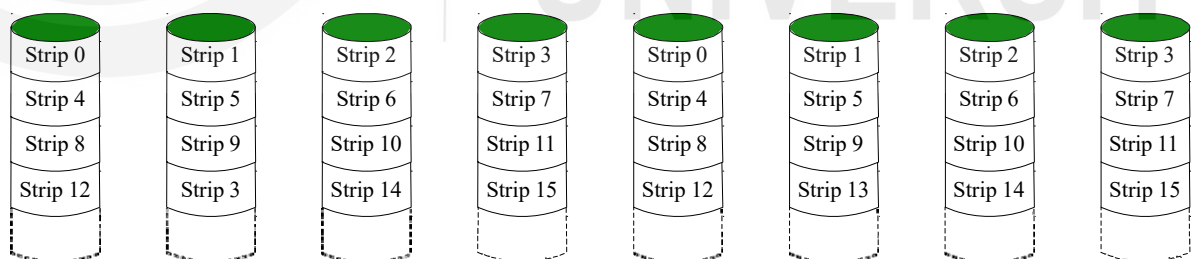
RAID Levels

RAID Level-0: RAID level-0 implements block splitting of data with no protection against disk failures. In block splitting, each block is stored in a different disk in the array. For example, i^{th} block of a file will be store in $(i \bmod n) + 1$ disk, where n is the total number of disks in the array. In this case, a significant enhancement on the performance can be observed as *n blocks* can be accessed (one each from each disk) in a single disk access time.
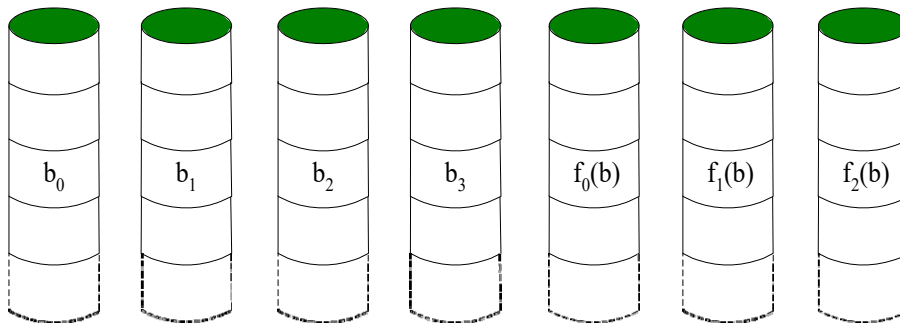

(a) RAID Level 0

RAID Level-1: This level protects data by implementing mirroring. If a system has 2 disks then each block of information will be stored in both of the disks. This ensures, if one disk fails then same copy of the block is accessed from the second disk. Mirroring introduces redundancy unlike level-0 which increases the data transfer rate.
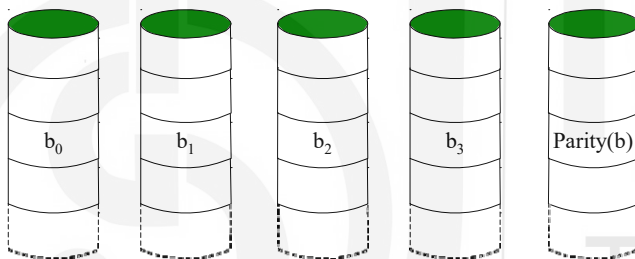

(b) RAID Level 1

RAID Level-2: This level uses error detection and correction bits, which are extra bits used for detection and correction of a single bit error in a byte. This is why this level is also known as memory-style error correction code organization. If one of the disk fails then parity bits and remaining bits of the byte are used to recover the bit value.
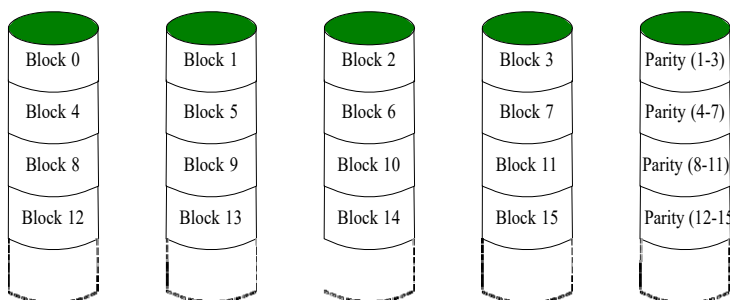
(c)   RAID 2 (Redundancy through Hamming Code)

RAID Level-3: Single parity disk is used in this scheme. Parity bit for a sector is computed and stored in a parity disk. During the access, parity bit of the sector is computed and if computed parity bit is equal to the stored parity, the missing bit is 0 otherwise it is 1. This RAID level is also known as bit-interleaved parity organization. Thus has an advantage over level-2 that only single parity disk is used as compare to number of parity disks in level-2. The biggest drawback of this approach is that all the disks are used for single I/O operation in computation of the parity bit which slows down the disk access and also restricts parallel access.
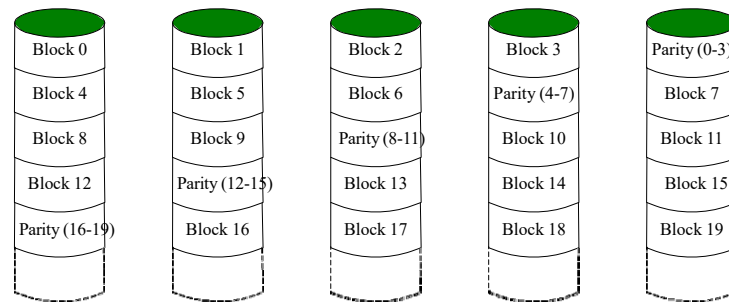

(d) RAID Level 3

RAID Level-4: This level uses block striping and one disk is used to keep parity block. This is also called block-interleaved parity organization. The advantage of block interleaving is that parity block along with corresponding blocks on other disks is used to retrieve the damaged block or the blocks of the failed disk. Unlike in level-3, block access reads one disk which allows parallel access to other blocks stored in other disks in the array.
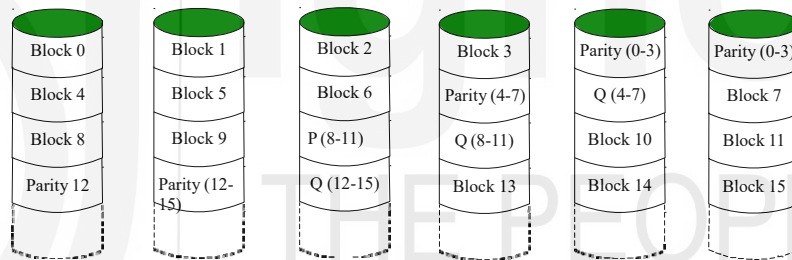

(e) RAID 4 (Block level Parity)

RAID Level-5: This level stores block of data and parity in all the disks in the array. One disk store the parity while data is spread out on different disks in the array. This structure is also known as block-interleaved distributed parity.

(f) RAID 5 (Block-level Distributed Parity)

RAID Level-6: Level-6 uses error correcting codes for recovery of damaged data while other levels uses parity. It also provides protection against multiple disks failures. For the recovery purposes, this arrangement is used to store redundant data on some of the disks, hence it is also called as p + q redundancy scheme. Here, p is the number of disks that store the error correcting codes while q is the number of disks that store redundant data.

(g) RAID Level 6

Table below summarises characteristics of various RAID levels.

RAID Level	Category	Features	I/O Request Rate (Read /write)	Data Transfer Rate (Read /write)	Typical Application
0	Striping	a) The disk is divided into blocks or sectors. b) Non-redundant.	Large Blocks: Excellent	Small Blocks: Excellent	Applications which requires high performance for non-critical data
1	Mirroring	a) Mirror disk which contains the same data is associated with every disk. b) Data Recovery is simple. On failure, data is recovered from the mirror disk.	Good / fair	Fair /fair	May be used for critical files

2	Parallel Access	a) All member disks participate in every I/O request. b) Synchronizes the spindles of all the disks to the same position. c) The blocks are very small in size (Byte or word). d) Hamming code is used to detect double-bit errors and correct single-bit error.	Poor	Excellent	Not useful for commercial purposes.
3	Parallel Access	a) Parallel access as in level 2, with small data blocks. b) A simple parity bit is computed for the set of data for error correction.	Poor	Excellent	Large I/O request size application, such as imaging CAD
4	Independent access	a) Each member disk operates independently, which enables multiple input/output requests in parallel. b) Block is large and parity strip is created for bits of blocks of each disk. c) Parity strip is stored on a separate disk.	Excellent/ fair	Fair / poor	Not useful for commercial purposes.
5	Independent access	a) Allows independent access as in level 4. b) Parity strips are distributed across all disks. b) Distribution avoids potential input/output bottleneck found in level 4.	Excellent / fair	Fair / poor	High request rate read intensive, data lookup
6	Independent access	Also called the p+q redundancy scheme, is much like level 5, but stores extra redundant information to guard against multiple disk failures.	Excellent/ poor	Fair / poor	Application requiring extremely high availability

Check Your Progress 3

1. What is the need of RAID?

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2. Which RAID levels provide good data transfer rate?

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3. Which RAID level is able to fulfil large number of I/O requests?

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5.6 SUMMARY

This unit introduces the concept of memory hierarchy, which is primarily required due to the high cost per bit of high speed memory. The processing unit have register, cache, main memory and secondary or auxiliary memory. The main memory consists of RAM or ROM. This unit explains the logic circuit and organisation of RAM and ROM. The unit also explains several different types of secondary storage memories. The unit provide details on hard disk and its characteristics. It also gives details of different kind of optical disk. The concept of access time and constant linear and angular velocity has also been explained in details. For larger computer systems simple hard disk is not sufficient, rather an array of disks called RAID are used for such systems to provide good performance and reliability. The concept of RAID and various levels of RAID has been defined in this unit. The next unit will introduce you to the concept of high speed memories.

5.7 ANSWERS

Check Your Progress 1

1. RAM is a sequential circuit, volatile, requires refreshing (DRAM) and is a read/write memory; ROM, PROM and EPROM are mostly non-volatile memories. ROM is a combinational circuits. All these ROMs are written mostly once and read many times.
2. Flash memory is a non-volatile semiconductor memory, where a section of the memory or a set of memory words can be erased. They are portable and mechanically robust as there is no mechanical movement in the memory to read-write data. Flash memory is used in USB memory, SD and micro SD memory cards used in cameras and mobile phones respectively.
3. (a) Since a word of data is 16 bits, it will have 16 data input and 16 data output lines, if not multiplexed.
   (b) The number of words are 16K, which is 2^{14}. Thus, 14 address lines would be required.
4. The memory must select one of the 4K bytes, which is 2^{12}. In case a square array is used (as shown in Figure 5.6), then 6 row address and 6 column address lines would be needed, which can be multiplexed. So just 6 address lines be sufficient. However, for a non square memory you may require all 12 address lines.
5. Two chips will be required to make 256×8 memory. 4 such combinations would be required to make 1 MB memory. Thus, you will require 8 such chips.

Check Your Progress 2

1. Storage capacity of a disk = recording surfaces × tracks per surface × sectors per track × size of each sector

   Storage capacity of a disk = $8 \times 32 \times 64 \times 1$ MB $= 2^3 \times 2^5 \times 2^6 \times 2^{20} = 2^{34} = 16$ GB

   One cylinder will have = = $8 \times 64 \times 1$ MB $= 2^3 \times 2^6 \times 2^{20} = 512$ MB

2. The time of one rotation = 1/6000 min = 60/6000 sec = 1/100 sec= 10 millisec
   Rotational latency = on an average time of half rotation = 5 ms

3. SSD drives does not require any mechanical rotation, therefore are less prone to failure. In addition, they are much faster than HDD. But they are more expensive than HDD

4. The size of sectors on CLV disks is same on the entire disk, therefore, these disks are rotated a different speed. Density of data is same in all the sectors. In CAV disks the rotation speed is same, thus, sector size is more in the outer tracks. However, reading/writing process, in general, is faster.

Check Your Progress 3

1. RAID are a set of storage devices put together for better performance and reliability. Different kind of RAID levels have different objectives.

2. Good data transfer rate are provided by RAID level 0, 2 and 3.

3. Large number of I/O requests are fulfilled by RAID level 0, 1, 4,5 ,6.