## Memory Organization :-

Memory is an essential part of any digital system. It stores data, instructions and results required by the processor. Memory organization describes how memory is structured, accessed and managed internally.

### Terminologies of memory organization :-

① **Memory cell :-** It is the smallest unit of memory. It stores 1 bit of information (0 or 1).

② **Memory word :-** It is a group of bits stored in memory. Ex:- 8-bit word, 16-bit word etc.

③ **Memory array :-** Memory is arranged in a 2D array of:

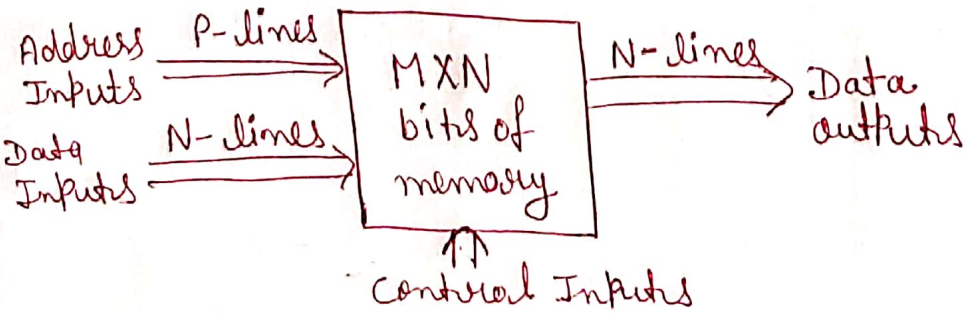
Rows → Memory words
Columns → Bits of each word (bit positions)

Ex:-

1K X 8 memory means:-

1K = 1024 rows (words)
8 = 8 bits per word

④ **Addressing :-** Each memory word is given a unique address. The CPU sends an address to the memory to read/write.
Address lines determine memory size.
If there are n address lines, it can address:-
$2^n$ memory locations




(Block Diagram of a memory device)

Read operation

write operation

① Read operation :- It is used to fetch data from memory.

Steps :-

(i) CPU places an address on address bus.
(ii) Memory decoder selects that specific word.
(iii) Memory places the stored data on data bus.
(iv) CPU reads the data.

Control signal → RD = 0 (Active Low)

② Write operation :- It is used to store new data into memory.

Steps :-

(i) CPU places the address on address bus.
(ii) CPU places data to be written on data bus.
(iii) Write control signal activates.
(iv) Memory stores the data in selected cell.

Control signal → WR = 0 (Active Low)

Important Memory parameters :-

① Memory capacity :-

Total number of bit stored.

② Access time :-

Time to read / write a memory word.

③ Cycle time :-

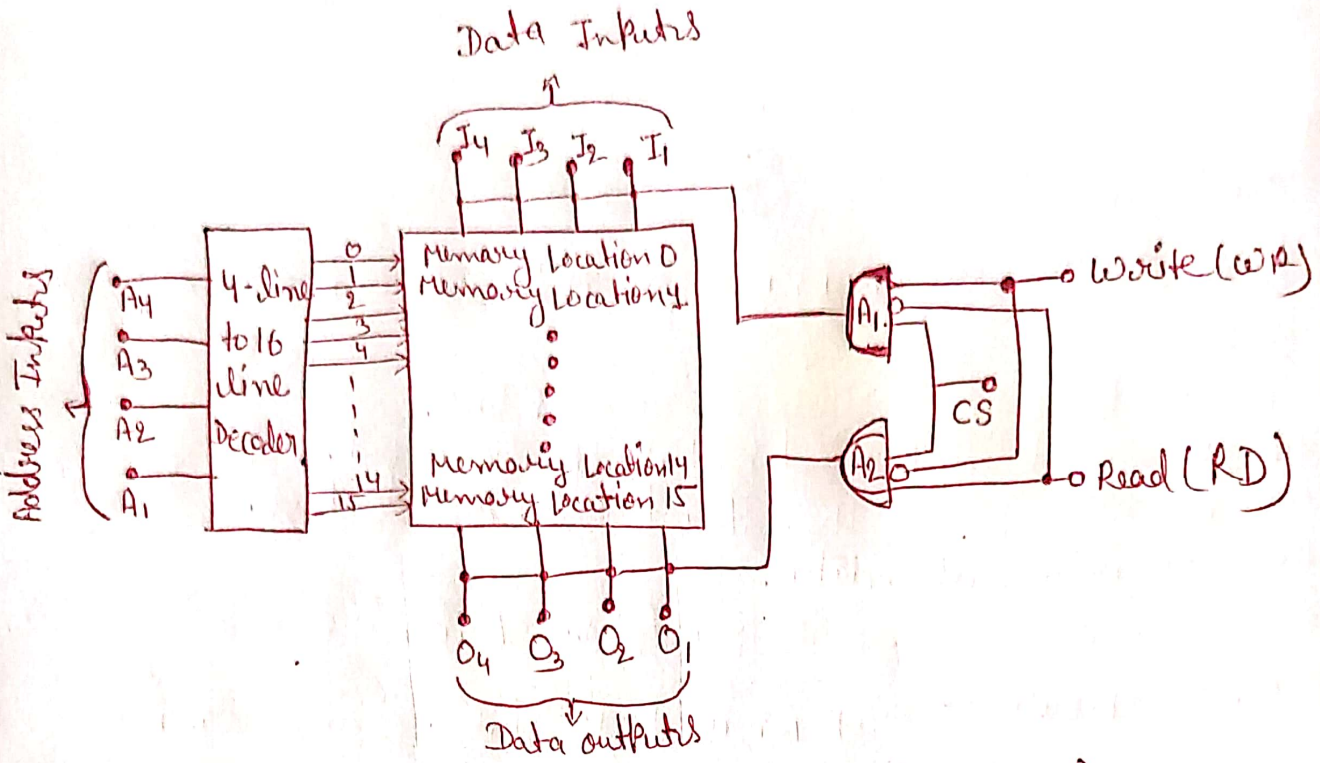
Time between two successive memory operations.

④ Bandwidth :-

Rate at which data is transferred.

⑤ Word length :-

Number of bits per word.




(Internal organization of a 16 X 4 memory Chip)

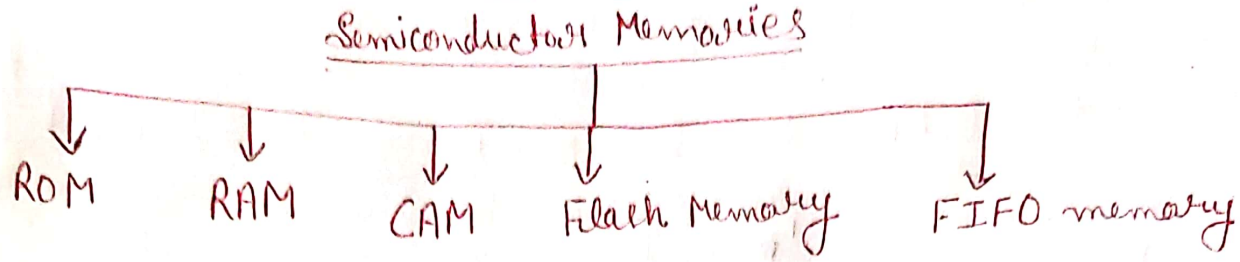
## Expanding Memory Size :-

Memory Expansion means increasing the total memory capacity of a system by connecting multiple memory chips together.

We can expand memory in two ways :-

1. Expanding word size
2. Expanding word capacity

## Classification of memories :-




## ROM (Read Only Memory) :-

ROM (Read Only Memory) is a non-volatile memory used in digital electronics to store data permanently. The contents of ROM cannot be changed during normal operation and are not lost when power is turned off.

### Why ROM is used? :-

ROM is used to store :-

(i) Programs that must not change.
(ii) Lookup tables.
(iii) System boot instructions
(iv) Fixed data for digital circuits.

### Characteristics of ROM :-

① Non-volatile :- Data remains even after power is off.

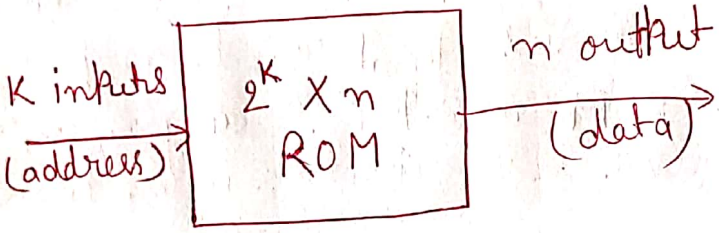
② Permanent storage :- Data is written once and mostly used for reading.

③ Fast read operation :- ROM provides data very quickly since it is pre-programmed.

④ Secure data :- It cannot be accidentally changed.

## Block Diagram of ROM :-

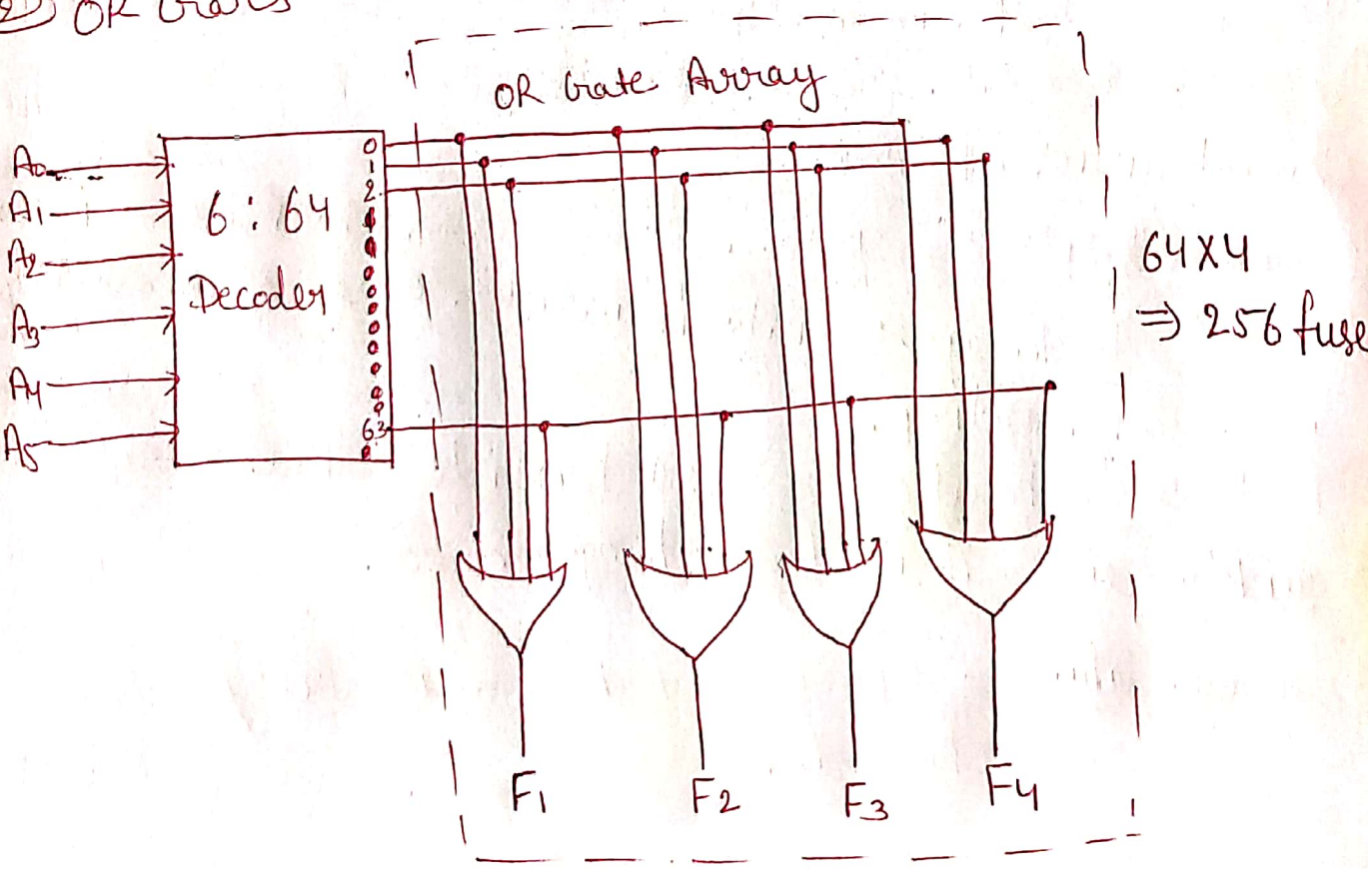
In ROM system, there are K input lines and 'n' output lines. The input address from which we wish to retrieve the ROM content is taken using the K input lines. Since each of the K-input lines can have a value of 0 or 1, there are total of $2^K$ addresses that can be referred to by these input lines and each of these addresses contains 'n' bits of information that is output from the ROM.




## Internal Structure of ROM :-

The internal structure of ROM has two basic components :—

1. Decoder
2. OR Gates




(Internal construction of 64X4 ROM)

Working :-

(1) C.P.U sends an address to ROM through address lines.
(2) The decoder inside ROM activates one row corresponding to the address.
(3) The selected memory row contains fixed stored data.
(4) The stored word appears on the data output lines.

Types of ROM :-

(1) Masked ROM (MROM) :- In MROM, data is permanently written at manufacturing time. It is cheapest in bulk. It cannot be reprogrammed.
Uses :- Calculators, simple embedded devices.

(2) Programmable ROM (PROM) :-
User can program it once. It uses fuse links that are permanently burned to store data.
Once programmed → cannot be erased.

(3) Erasable Programmable ROM (EPROM) :-
It can be erased using ultraviolet light.
It has a transparent quartz window on top.
After erasing, it can be reprogrammed.
It is useful for repeated testing.

(4) Electrically Erasable PROM (EEPROM) :-
It can be erased electrically.
Erasing can be done byte by byte.
Slower write speed but very flexible.

(5) Flash Memory :-
It is a type of EEPROM.
Erased in blocks, not byte by byte.
Very fast and widely used.
Used in USB drives, SSD, memory cards.

## ROM operation :-

### Read operation

1. CPU sends address to ROM.
2. Decoder selects the corresponding memory cell.
3. Stored data appears on the output lines.

### Advantages of ROM :-

1. Permanent and Reliable Storage
2. Non-volatile
3. Low cost
4. Faster access than secondary memory
5. Ideal for firmware and embedded systems.

### Disadvantages of ROM :-

1. Cannot be modified easily.
2. Limited flexibility compared to RAM.
3. Slow write/erase speed.

## RAM (Read and Write Memory) :-

RAM stands for Random Access Memory. It is a type of read/write memory where any memory location can be accessed directly using its address.
It is volatile memory, that is data is lost when power is turned off.
It is used by CPU for temporary storage of data and instructions during program execution.

### Why is it called "Random Access"?

Because any location in the memory can be accessed in the same time regardless of its physical position.

## Basic operations in RAM :-

### ① Write operation :-

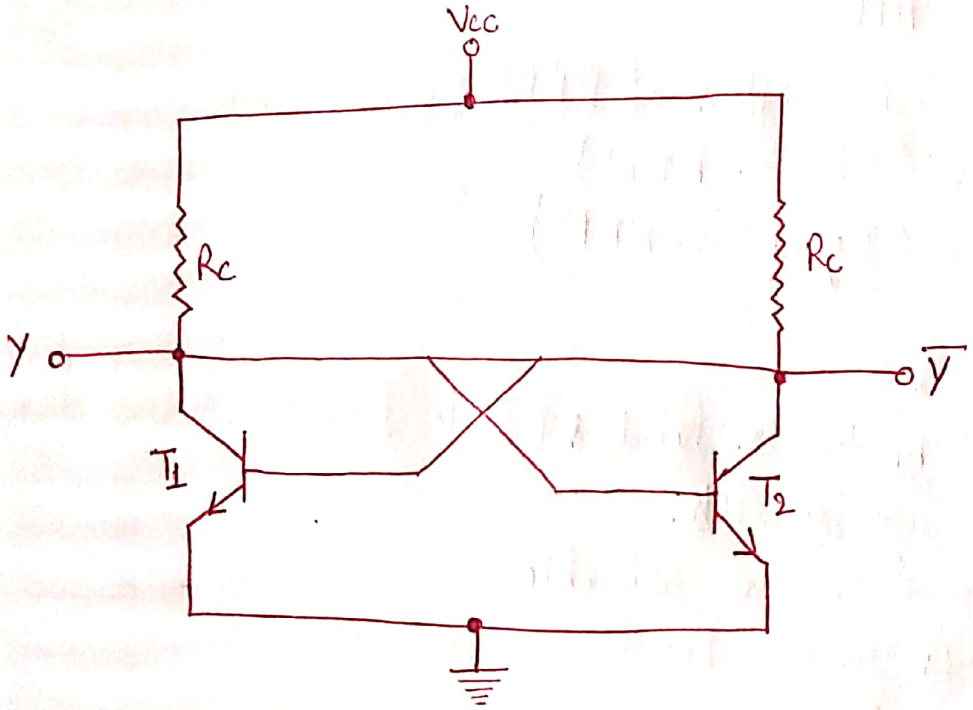
(i) CPU places address on address bus.
(ii) Places data on data bus.
(iii) Write enable signal is activated.
(iv) Data gets stored in the selected cell.

### ② Read operation :-

(i) CPU puts address on address bus.
(ii) Read Enable (RE) signal is activated.
(iii) Stored data appears on data bus.

## Characteristics of RAM :-

① Valatile :- Data last when power off.
② Fast access :- Quick read / write cycles.
③ Temporary storage :- Halds active data and programs.
④ Random Access :- Any location accessed directly.
⑤ Read/write :- Both operations possible.

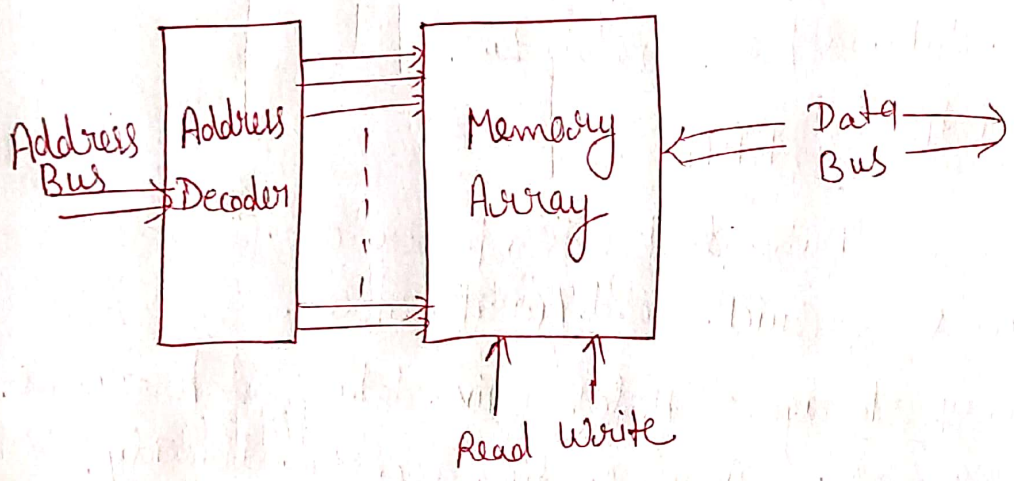



(Basic Bipolar RAM Storage Cell)

## Internal structure of RAM :-

RAM consists of :-

(i) Memory cells arranged in rows and columns.
(ii) Row decoder and column decoder
(iii) Sense amplifiers (for reading data)
(iv) Address lines ($A_0, A_1 \ldots$)
(v) Data lines ($D_0, D_1, \ldots$)
(vi) Control Signals (Read/write, chip select).




(Block Diagram of RAM)

## Types of RAM :-

There are two types of RAM :-

(1) SRAM (Static RAM)
(2) DRAM (Dynamic RAM)

### (1) SRAM :-

- It uses bistable latches (flip-flop) to store data.
- No need for refresh.
- Faster and more reliable.
- Consumes more power.
- More expensive
- Lower memory density.

Application :- It is used in cache memory (L1, L2, L3).

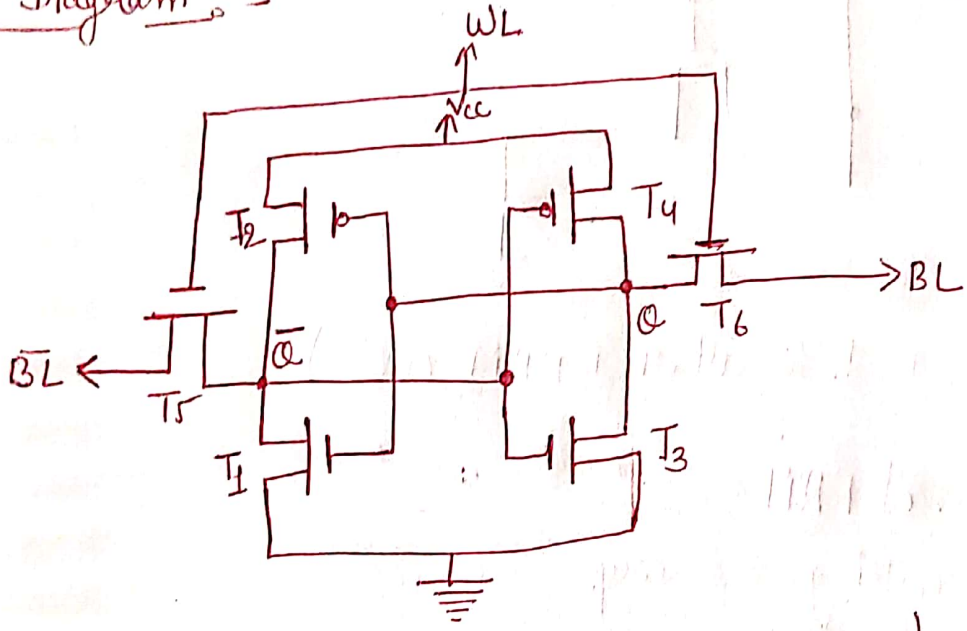
SRAM cell circuit :-

A typical SRAM cell is made of 6 transistors :-

4 transistors form two cross-coupled inverters.

2 access transistors connect the cell to the bit lines ($BL, \overline{BL}$)

Circuit Diagram :-




(A Six-Transistor CMOS SRAM cell)

(2) DRAM :-

⇒ It stores data as charge in a capacitor.
⇒ Charge leaks → needs periodic refreshing.
⇒ Slower than SRAM.
⇒ Low power consumption.
⇒ Cheap and high memory density.

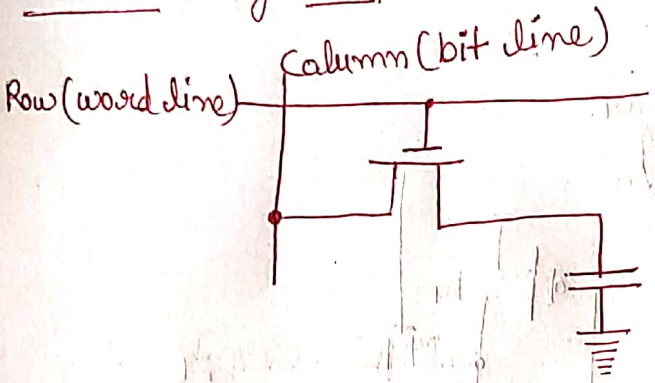
Applications :-

It is used in main memory (primary memory) of computer.

## DRAM cell circuit :-

A DRAM cell uses 1 transistor + 1 capacitor.
Capacitor stores charge (logic 1 or 0).
MOSFET access transistor control read / write.

### Circuit Diagram :-




(1-transistor DRAM cell)

### Applications of RAM :-

1. CPU working memory
2. Caches (SRAM)
3. Main memory in computers
4. Routers and switches
5. Microcontrollers
6. Mobile phones

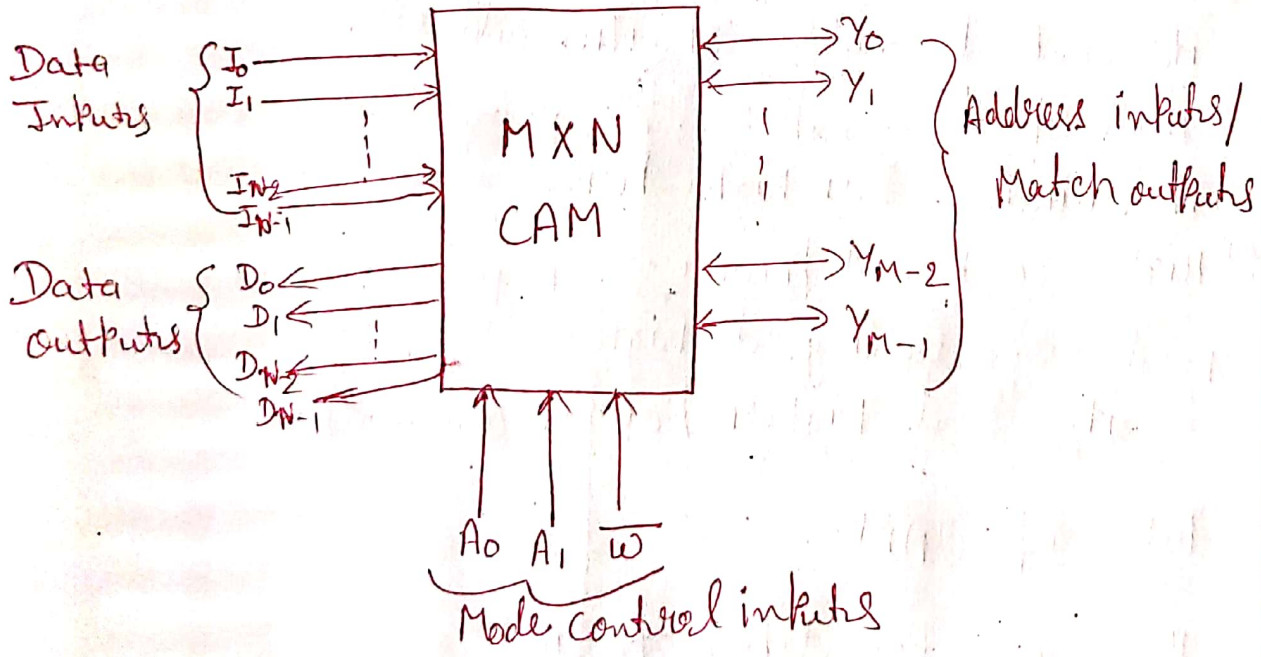
## Content Addressable Memory (CAM) :-

Content Addressable Memory is a type of memory that searches for data by its contents, not by its address and return the corresponding address. This is different from traditional RAM which requires a specific address to access data. CAM performs a parallel search, comparing an input word to all stored data simultaneously in a single clock cycle, making it very fast and ideal for high speed applications like network routing and database lookup.

A CAM can perform three basic operations read, write and associate.

CAM is also called associative memory and parallel search memory.

## Block Diagram :-




Here, (Block Diagram of a CAM)

Storage capacity = M X N (M words of N bits each)

## Working :-

Input :- A data word to be searched

CAM operation :-

① It compares the input data simultaneously with all stored words.
② Each memory cell has comparison logic.
③ If a match is found → Match Line (ML) becomes 1
④ Output gives the address of matching word.

CAM output :-

① Match Signal
② Address of matched data

Characteristics of CAM :-

① Parallel Search :- It compares the input word with all entries in the memory simultaneously.
② Content based access :- Data is retrieved based on its content, not a specific address.
③ High Speed :- Capable of very fast lookups, making it suitable for high-performance applications.
④ Higher cost and power :- Requires more complex hardware, leading to higher cost, lower storage density and higher power consumption.

## Types of CAM :-

There are two types of CAM :-

① Binary CAM :- It stores and searches for binary data (0 and 1).
② Ternary CAM :- It stores 0, 1 and dont care (X) where X allows matching of multiple patterns.

## Application of CAM:-

(1) Networking :-
- Routing tables
- Packet filtering
- Switching

(2) Cache memory :-
- Associative mapping
- Tag comparison

(3) Data Searching :-
- Keyword matching
- Search engines

(4) Pattern Recognition :-
- Image and Signal processing

## Advantages of CAM :-

1. Very fast searching
2. Efficient for lookup operations
3. Ideal for networking and cache

## Disadvantages of CAM :-

1. High cost
2. More power consumption
3. Lower memory density.

## Charge Coupled Device Memory (CCD) :-

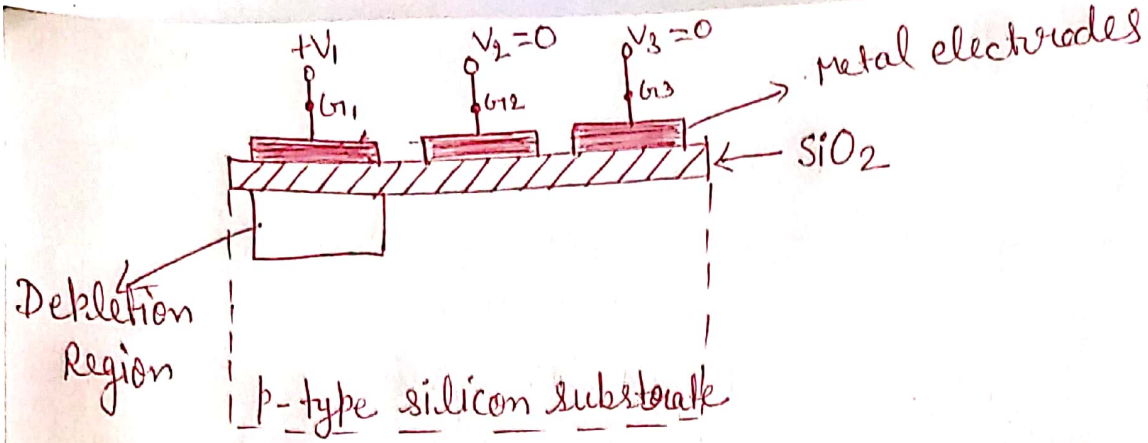
A CCD is a type of serial access memory where information is stored as electric charges and transferred (shifted) from one cell to another.

CCD memory is based on MOS capacitor technology and it is mainly used for imaging sensors and analog memory applications.

A CCD stores data in the form of electrical charges in tiny capacitors. The charges are moved (coupled) from one capacitor to the next when clock signals are applied.

Data is accessed serially → one bit after another.

Data is stored as charge packets.




(Basic CCD structure)

## Working principle of CCD Memory :-

① CCD memory is made of a chain of MOS capacitors.

② Each capacitor can hold an electric charge representing :-
- 1 → if charge stored
- 0 → if no charge stored

③ When a clock pulse is applied :-
- Charge in one capacitor moves to the next
- This continues step by step.

④ The output is obtained at the end of the capacitor chain.

This process is called charge shifting or charge transfer.

## Characteristics :-

① Serial access
② Low power consumption
③ High packing density
④ Used mainly for sensing

## Applications of CCD memory :-

① Digital cameras
② Camcorders
③ Medical imaging
④ Astronomy telescopes
⑤ Barcode readers
⑥ Optical scanners

## Advantages of CCD :-

① High density
② Low power
③ Low noise
④ High sensitivity

## Disadvantages of CCD :-

① Slow access
② Not suitable for random access.
③ Requires multiple clock signals.
④ Charge leakage occurs over time.

## ROM as a PLD :-

A PLD (Programmable Logic Device) is a digital IC whose logic function can be programmed by the user.
ROM (Read Only Memory) can also be used as a PLD because it can implement any combinational logic function.

## Why ROM can ACT as a PLD?

ROM contains :-

① Decoder → Generates all minterms
② Fixed OR array → Combines minterms to produce outputs

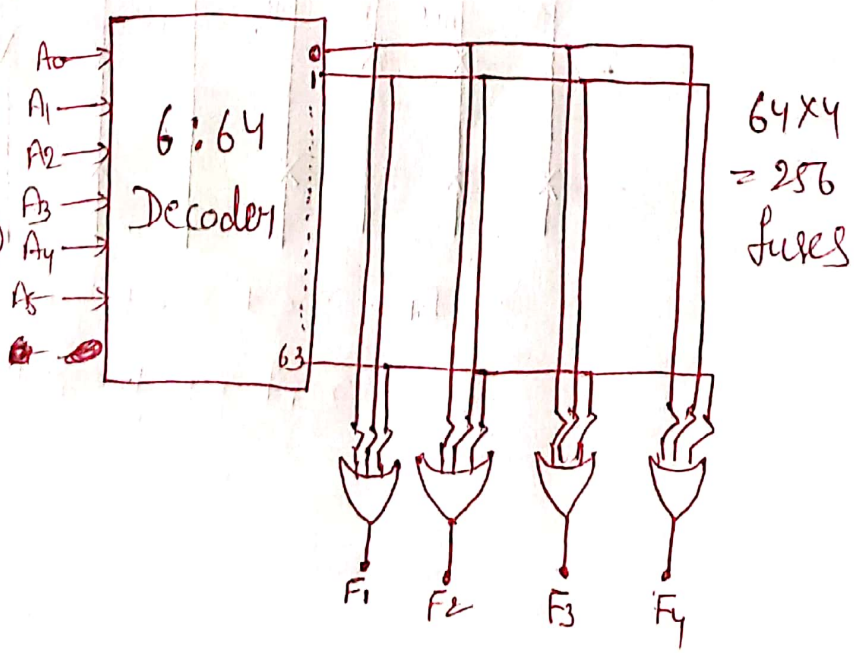
This is exactly what we need to realize any combinational circuit.


Thus ROM behaves like a programmable logic array.

## Structure of ROM as a PLD :-

### 64X4 PROM :-

64 words
4 bits
$2^6 = 64$ words
$n = 6$ (no. of inputs)



## Decoder :-

If ROM has n inputs, the decoder generates $2^n$ minterms.

Ex:- For 3 inputs → 8 minterms.

OR Array :- Each output line selects a combination of minterms using OR gates.

The OR gates determine which minterms produce a logic 1 output.

Ex:- Using PROM realize the function expressions:-

$F_1(A,B,C) = \Sigma m(0,1,3,5,7)$

$F_2(A,B,C) = \Sigma m(1,2,5,6)$

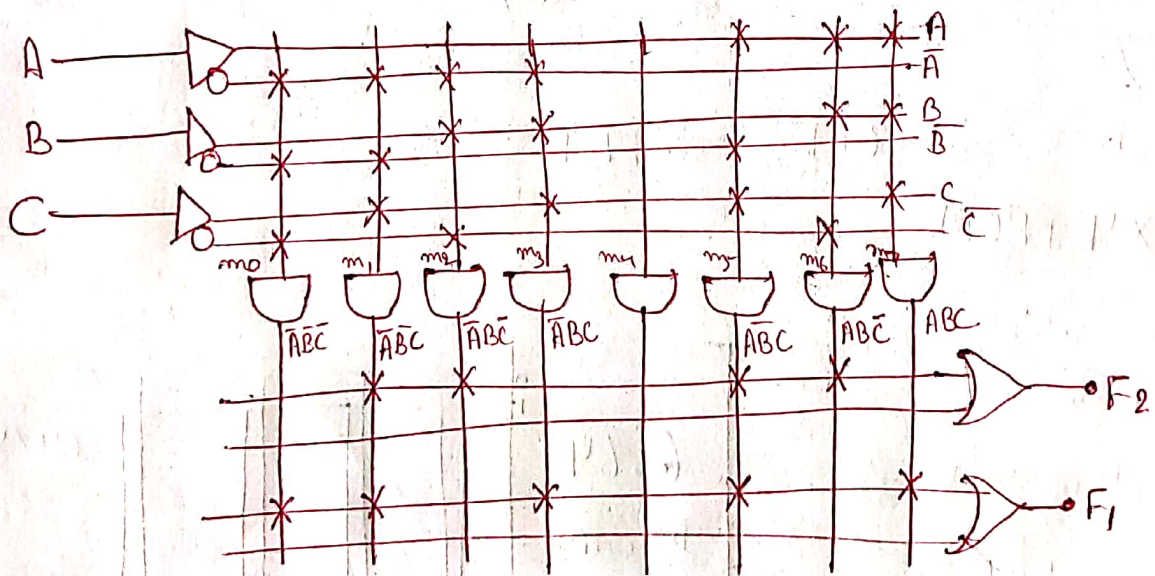
$m_0 = \bar{A}\bar{B}\bar{C}$ $\quad m_4 = A\bar{B}\bar{C}$

$m_1 = \bar{A}\bar{B}C$ $\quad m_5 = A\bar{B}C$

$m_2 = \bar{A}B\bar{C}$ $\quad m_6 = AB\bar{C}$

$m_3 = \bar{A}BC$ $\quad m_7 = ABC$

Implementation :-




So, $F_1 = m_0 + m_1 + m_3 + m_5 + m_7$

$F_2 = m_1 + m_2 + m_5 + m_6$

Advantages of using ROM as PLD :-

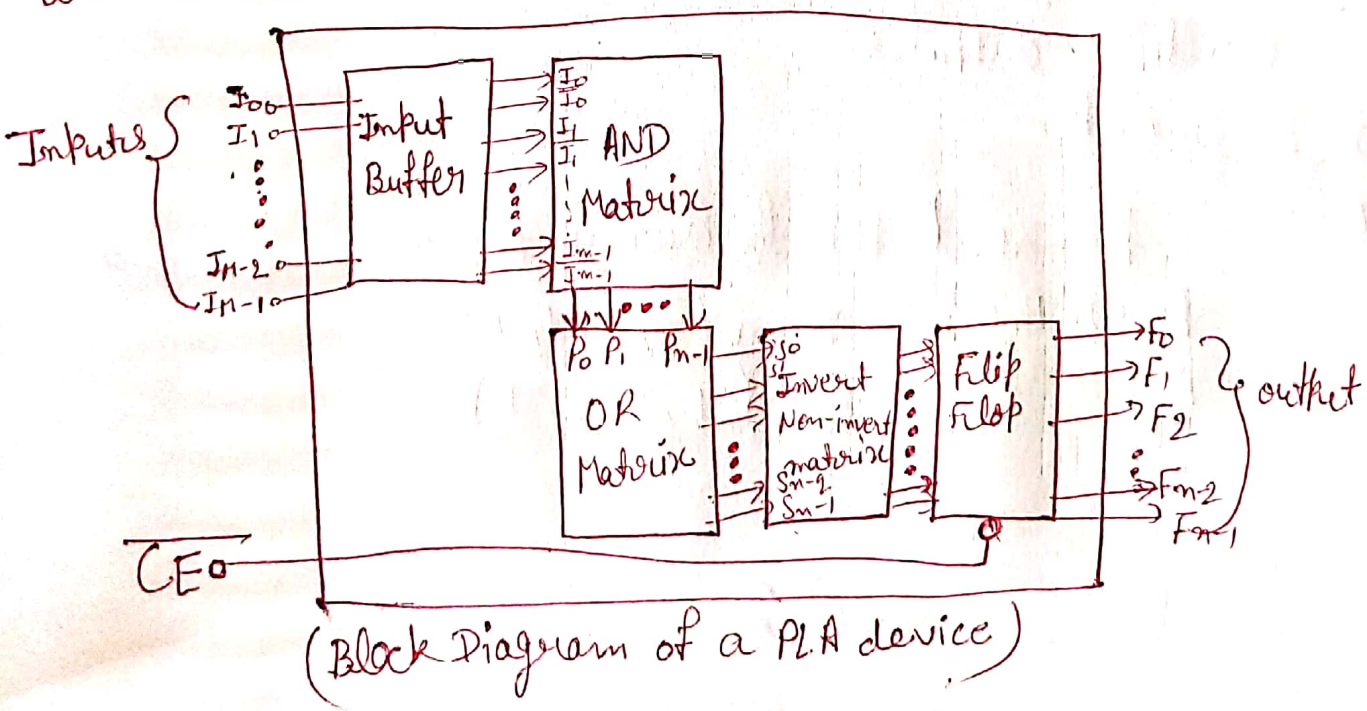
1. Implements any combinational function
2. Simple Programming
3. Universal device
4. Reliable & stable

Disadvantages :-

1. Wastes memory
2. Slower than PLA/PAL

## Programmable Logic Array (PLA) :-

A PLA is a type of Programmable Logic Device used to implement combinational logic circuits.
PLA usually consists of programmable array of logic gates and interconnections with array inputs and outputs connected to the device pins through fixed logic elements such as inverting / non-inverting buffers and flip-flops.
A PLA consists of two-level AND-OR circuits on a single chip. The number of AND and OR gates and their inputs are fixed for a given PLA chip.
The AND gates provide the product terms and the OR gates logically sum these product terms and generate a SOP expression.
It has M inputs, n product terms and N outputs with $n < 2^M$.




(Block Diagram of a PLA device)

## Programmable AND Array :-

① Generates product terms (minterms).
② User can choose which inputs to connect to each AND gate.

## Programmable OR Array :-

Combines selected product terms to form output functions.

## Optional inverters :-

Provide both true and complemented inputs.

## Working of PLA :-

① Inputs go to AND array :-
AND array forms required product terms.

② Product terms go to OR array :-
OR array selects which product terms form each output.

③ Outputs generated :-
Each output = OR of selected product terms.

## Features of PLA :-

① Two programmable arrays
② High flexibility
③ multiple outputs
④ Efficient

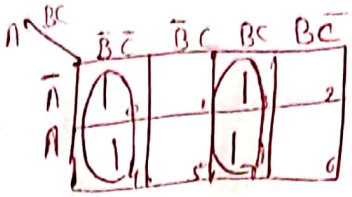
Ex :- Implement the following function using PLA

$F_1(A, B, C) = \Sigma m(0, 3, 4, 7)$

$F_2(A, B, C) = \Sigma m(1, 2, 5, 7)$

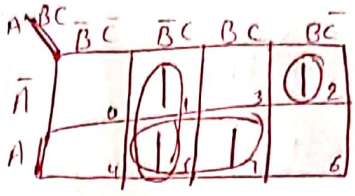
$F_1(A,B,C) = \Sigma m(0,3,4,7)$

$\Rightarrow \bar{B}\bar{C} + BC$

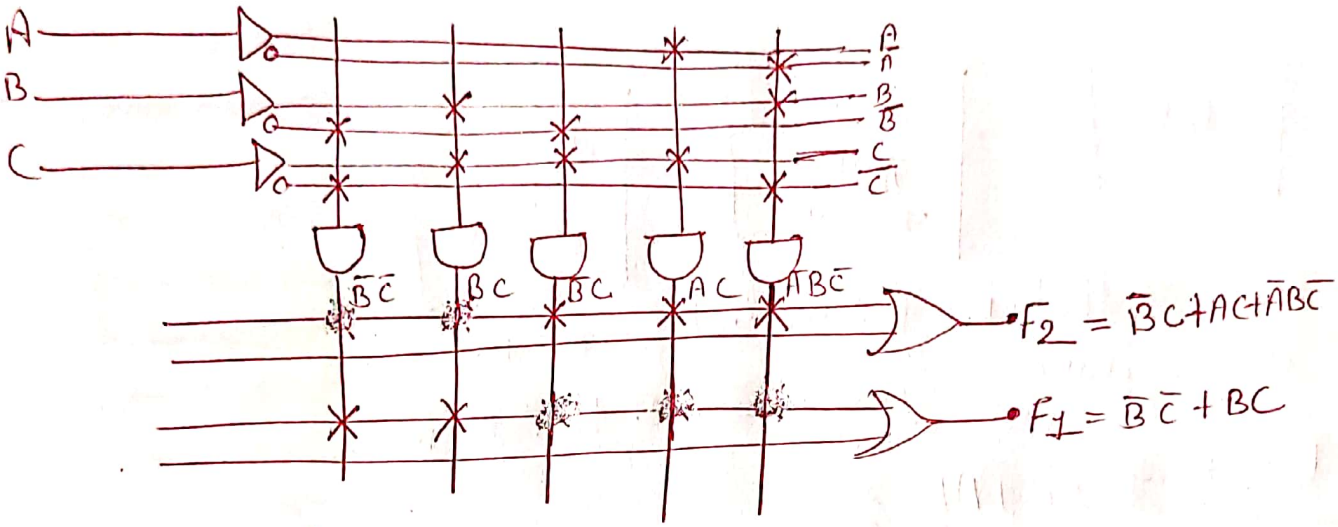



$F_2(A,B,C) = \Sigma m(1,2,5,7)$

$\Rightarrow \bar{B}C + AC + \bar{A}B\bar{C}$




Implementation :-




Advantages of PLA :-

1. It can implement any combinational circuit (logic).
2. Flexible due to two programmable arrays
3. Can implement complex functions
4. Reduced hardware compared to individual gates
5. Product terms can be shared among outputs.

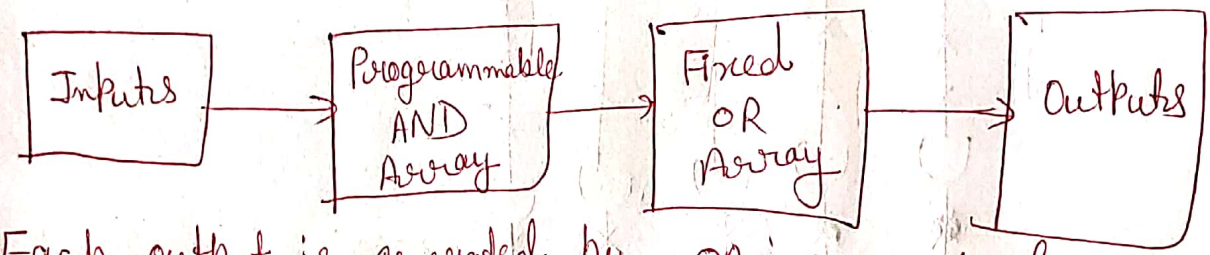
Disadvantages of PLA :-

1. Slower than PAL due to more programmability
2. More expensive and complex
3. Larger size compared to PAL
4. Programming in slightly difficult

## Programmable Array Logic (PAL) :-

Programmable Array Logic is a type of programmable logic device that uses a programmable AND gate array followed by a fixed OR gate array to implement boolean functions.

## Block Diagram :-




Each output is generated by OR-ing a set of AND terms already fixed inside the device.

## Working of PAL :-

### ① Programmable AND Array :-

The user selects which input combinations form product terms.

### ② Fixed OR Array :-

Each OR gate receives a set of predefined product terms.

We cannot change which AND terms go to which OR gate.

### ③ Outputs :-

Each OR gate generates one function.

Optional output flip-flops may give sequential functionality.

## Features of PAL :-

(1) Programmable AND :- Flexible generation of product terms.

(2) Fixed OR :- Faster and simpler structure.

(3) High Speed :- Because OR structure is fixed.

(4) less flexible :- Cannot change OR connections.

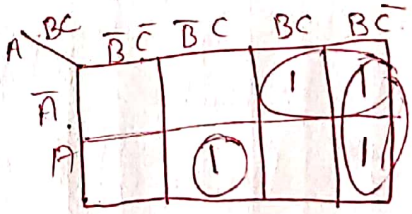
Ex :- Generate the following boolean function with a PAL with 4 inputs and 4 outputs

$$Y_0 = ABCD$$
$$Y_1 = \bar{A}B\bar{C} + \bar{A}BC + A\bar{B}C + AB\bar{C}$$
$$Y_2 = \bar{A}BC\bar{D} + \bar{A}BCD + ABCD$$
$$Y_3 = \bar{A}B\bar{C}D + \bar{A}BC\bar{D} + AB\bar{C}D$$

Simplification by k-map :-

$$Y_0 = ABCD$$

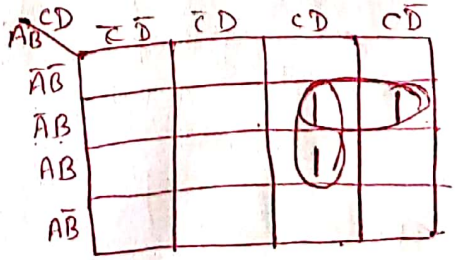
$$Y_1 = A\bar{B}\bar{C} + \bar{A}BC + A\bar{B}C + AB\bar{C}$$




$$\Rightarrow \bar{A}B + A\bar{B}C + B\bar{C}$$

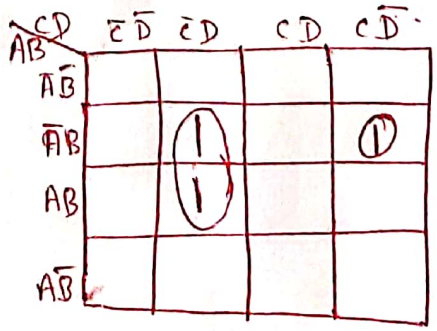
$$Y_2 = \bar{A}BC\bar{D} + \bar{A}BCD + ABCD$$

$$\Rightarrow \bar{A}BC + BC\bar{D}$$

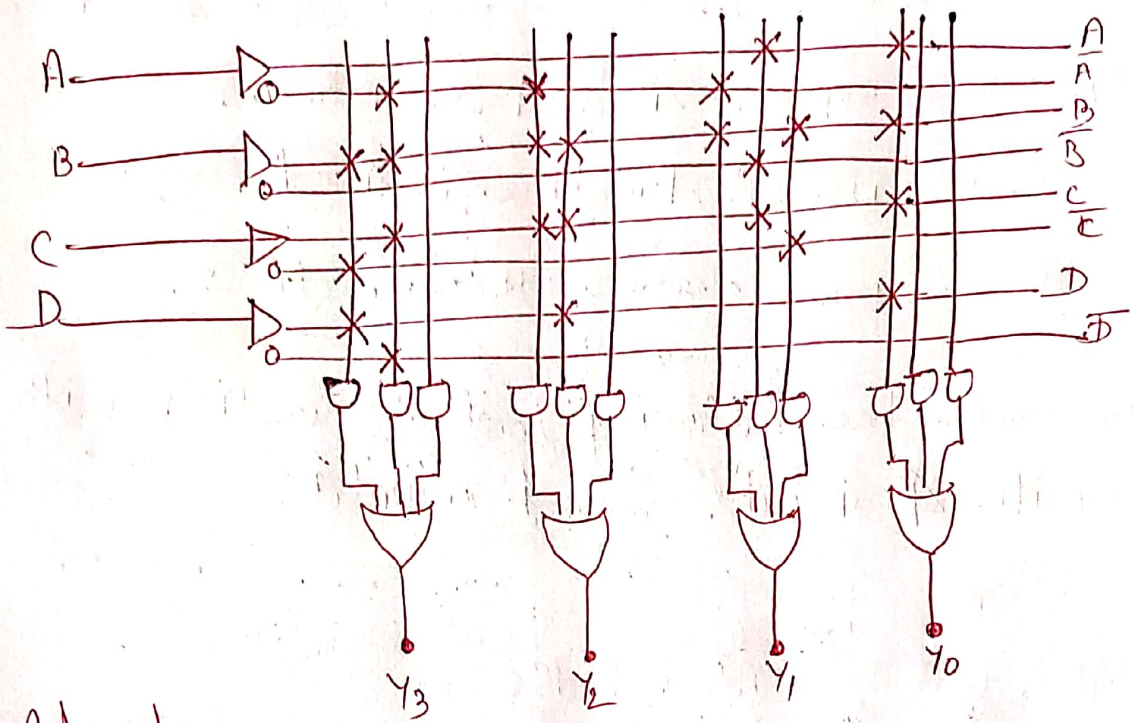



$$Y_3 = \bar{A}B\bar{C}D + \bar{A}BC\bar{D} + AB\bar{C}D$$

$$\Rightarrow B\bar{C}D + \bar{A}BC\bar{D}$$



## Implementation using PAL :-




## Advantages of PAL :-

1. Very fast due to fixed OR array
2. Simple and easy to program
3. Low cost than PLA
4. Reliable
5. Ideal for small to medium logic circuits.

## Disadvantages of PAL :-

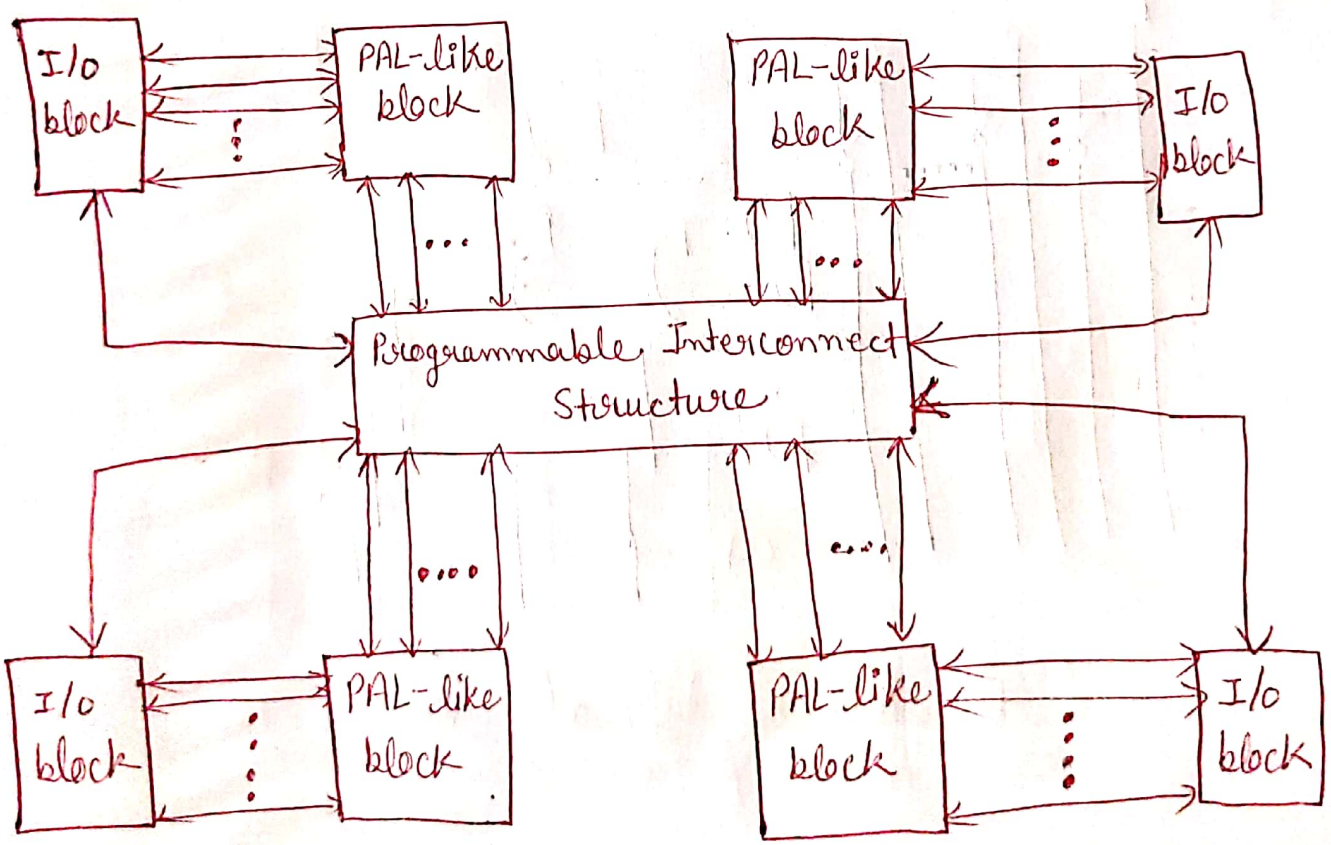
1. Less flexible compared to PLA
2. Cannot implement all logic function
3. Limited number of product terms available per output.

## Complex Programmable Logic Device (CPLD):-

A CPLD is a type of programmable logic device used to implement digital logic circuits. It lies between PLA/PAL and FPGA in terms of complexity, capacity and cost.

A CPLD is a digital integrated circuit that implements a variety of logic functions, from simple address decoding to more complex tasks like boot loaders or signal processing. It consists of programmable logic blocks and a global interconnection matrix.

## Block Diagram:-



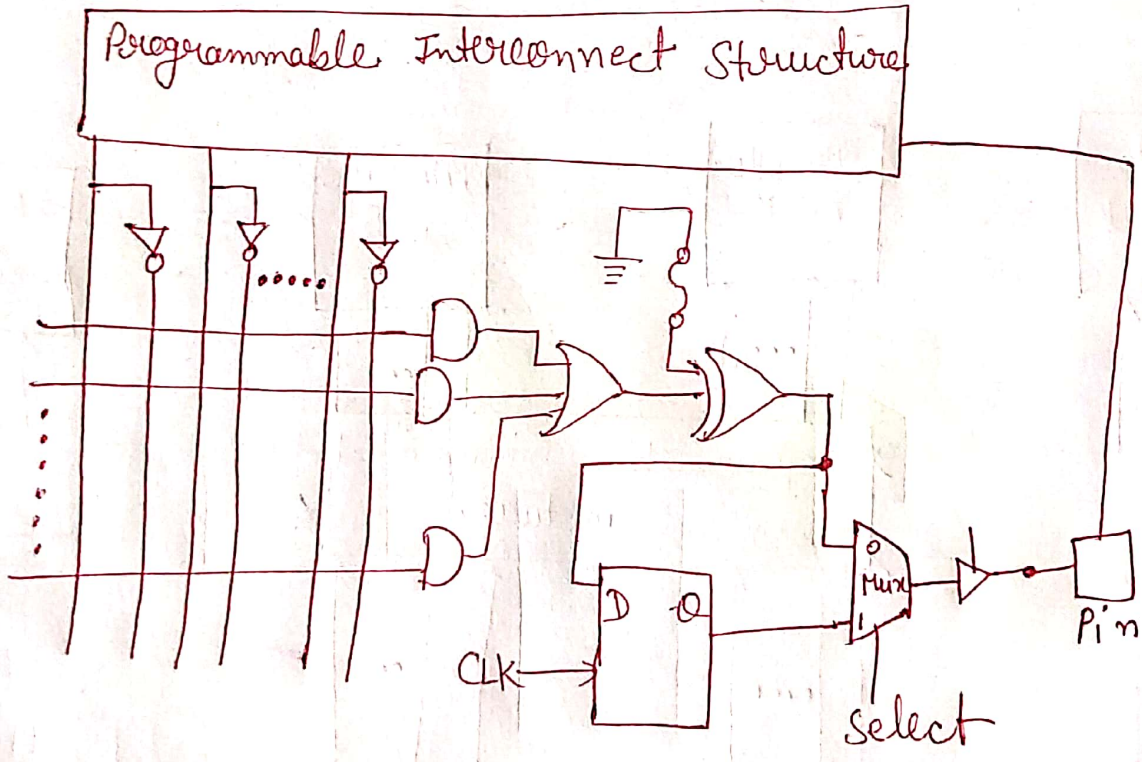

(Block Diagram of CPLD)

It consists of collection of PAL like blocks, I/o blocks and a set of interconnection wires, called programmable interconnection structure.

The PAL like blocks are connected to the programmable interconnect structure and to the I/O blocks. The chip input-output pins are attached to the I/O blocks.

A PAL like block in the CPLD usually consists of about 16 macrocells. Like other macrocells, the macrocells in CPLD consists of AND-OR configuration, an EX-OR gate, a flip-flop, a Mux and a tri-state buffer.

## Circuit Diagram :-




(Structure of typical macrocell of a CPLD)

## Characteristics of CPLD :-

1. Non-volatile memory.
2. Fast and predictable timing due to fixed, deterministic routing.
3. Moderate logic density.
4. Low power consumption than FPGA.
5. Used for control logic, glue logic and medium scale digital circuits.

## Advantages of CPLD :-

1. Reprogrammable.
2. Easy to design compared to FPGA.
3. Deterministic timing → easier for timing analysis.
4. Non-volatile.
5. Suitable for simple to medium-complex design.

## Disadvantages of CPLD :-

1. Lower logic capacity than FPGA.
2. Less routing flexibility compared to FPGA.
3. Not suitable for very high performance or data intensive designs.

## Applications of CPLD :-

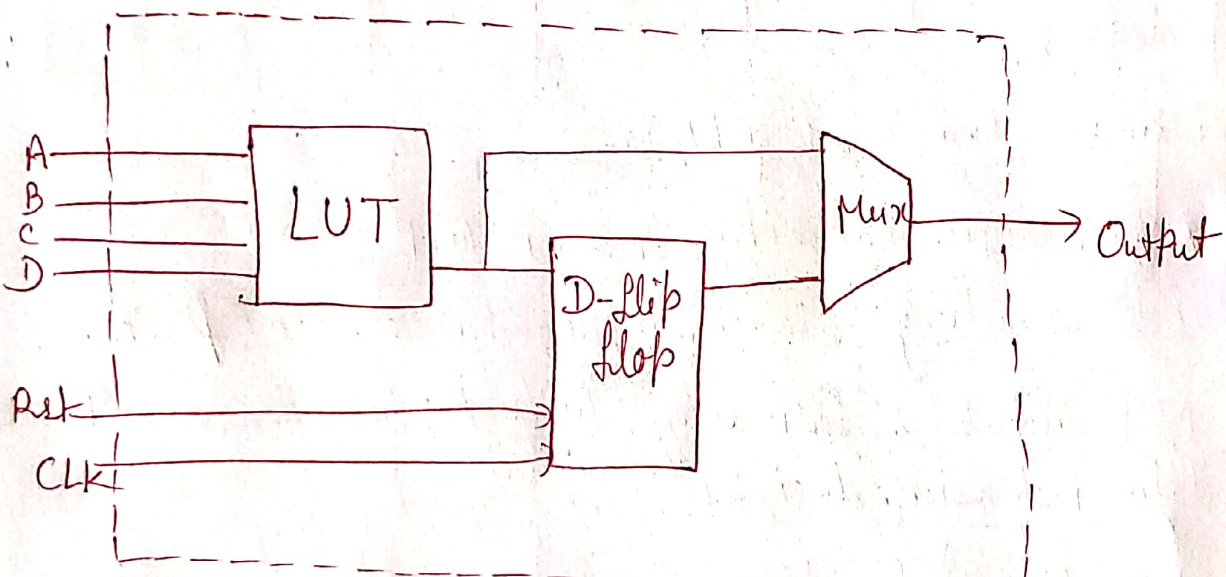
1. Digital decoders / Encoders
2. Address decoding in microprocessors.
3. Control units for digital systems.
4. State machine.

## Field Programmable Gate Array (FPGA) :-

A FPGA is a reprogrammable digital IC that allows designers to implement any digital circuit or system by configuring logic blocks and interconnections. It is the most powerful type of programmable logic device (PLD), used for complex and high speed applications.

An FPGA is a semiconductor device that contains a large array of configurable logic blocks (CLBs) connected through a programmable routing network along with programmable I/O blocks allowing the user to implement digital logic functions after manufacturing.

## Internal structure of FPGA :-




(FPGA Logic Block)

### ① Configurable Logic blocks (CLBs) :-

It is the main building blocks of FPGA.

Each CLB contains :-

LUT (Look up Table), Flip-flops, multiplexers.

(2) Programmable interconnect :-
It connects CLBs, I/O blocks and other resources.

(3) I/O blocks :-
Interface between FPGA and external devices.

Additional components in Modern FPGAs :-
(1) Block RAM → Internal memory.
(2) DSP blocks → for multiplication, MAC operations
(3) Clock management units → PLL, DLL.
(4) Embedded processors → ARM cores
(5) High-speed transceivers

Features of FPGA :-
(1) Highly reprogrammable
(2) Parallel Processing
(3) It can implement both combinational logic and sequential logic.
(4) Scalable
(5) Supports hardware-level debugging.

Advantages of FPGA :-
(1) Reprogramming in the field.
(2) Very high speed due to hardware level parallelism.
(3) Massive logic capacity.
(4) Suitable for both prototype and final product.
(5) It can integrate multiple functions on the same chip.

Disadvantages of FPGA :-
(1) More expensive than CPLDs and microcontrollers.
(2) High power consumption
(3) Complex design process.

Applications :-

1. Digital Signal Processing (DSP)
2. communication systems.
3. Image and video processing
4. Embedded systems
5. Cryptography
6. Robotics.