3

Semiconductor Electronic Devices and Digital Circuit

3.1> Introduction

Semiconductor

→ Material's whose properties are in between a conductor and an insulator.

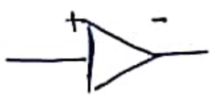
eg → Silicon & germanium.

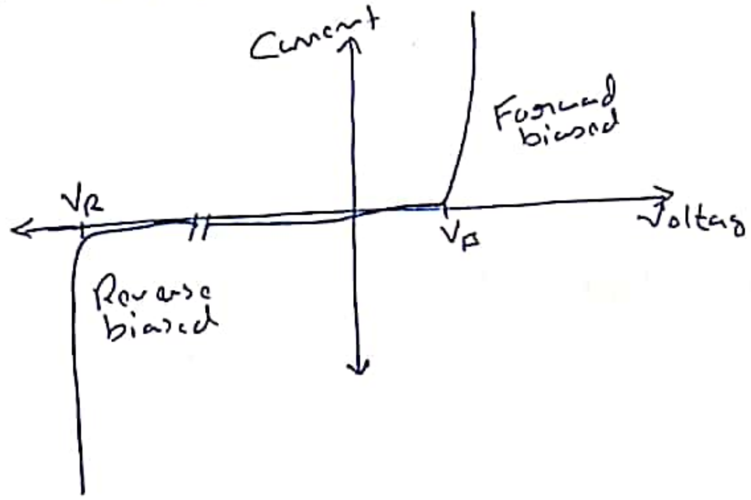
→ For use in semiconductor electronics circuits, small quantity of other elements (such as boron and phosophorus) are added. to alter their properties.

→ These properties depends on temperature, amount & direction of voltage applied to them.

3.2> Diodes

A diode is a directional element that allows current to flow in one direction.





For Silicon diod

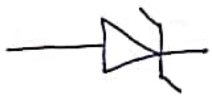
$V_F = 0.6\,V$

$V_R = 75\,V$

⇒ Regular diods are not designed to Operate with a Voltage higher than V_R Unless a Zener diode is used

⇒ Uses: → Rectification (AC → DC)
→ Voltage clamping
→ To limit voltage spikes generated when switching of inductive loads.

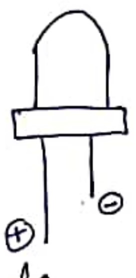
★ Zener diode

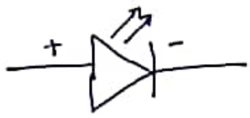


⇒ It acts as normal diode when it is forward biased but it can Conduct current without distroying itself when the reverse-biased Voltage exceeds the breakdown Voltage V_R.

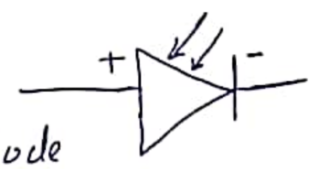
★ LED (Light emitting diod)

⇒ These diodes emits light when forward biased and amount of light they emit is proportional to the current passing through the LED.





★ Photodiode



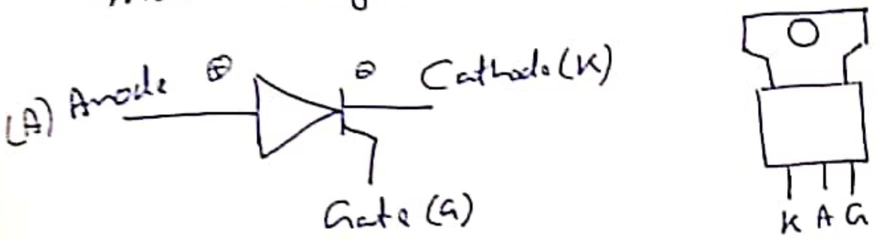
→ Amount of current that the photodiode passes is proportional to the amount of light it receives, and the current flows from ⊖ to ⊕ (reverse biased)

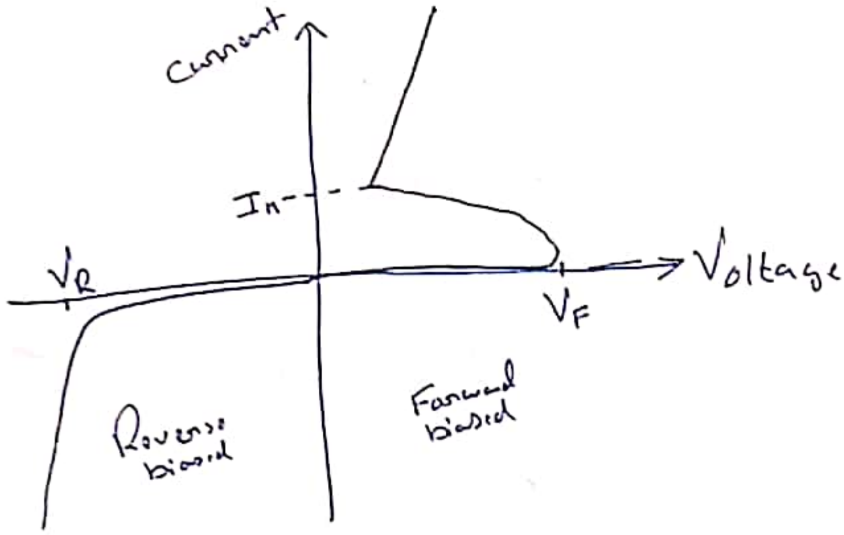
⇒ Commonly used as light sensor.

3.2) Thyristor

⇒ Three terminal semiconductor device that behaves like a diode but with an additional terminal.

⇒ The additional terminal is called gate, and when small current flows into the gate, it allows a much larger current to flow from ~~...~~ ⊕ to ⊖.





⇒ Forward Voltage (V_F) of a thyristor is quite large (50 – Several thousand Volts), unlike singular diod.

⇒ Note: If the current to the gate is cut off, the thyristor continues to conduct as long as the voltage applied causes it to forward biased.

→ Thyristor is turned off only when ~~voltage~~ ~~applied~~ current between the anode & the cathode drops below a certain level. (holding current)

↳ This effect is called Latching.

3.4) Bipolar Junction Transistor

→ Transistor is a Solid-State Switch that opens or closes a circuit.

{Switching action is done by change in the electrical characteristics of the device.}

→ 3 terminal device.

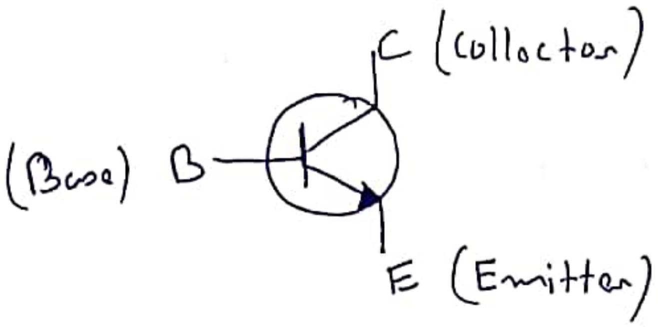
Transistors

- BJT {Bipolar Junction transistor} ✓
- FET {Field Effect Transistor}
- MOSFET {Metal oxide Semiconductor Field effect transistor} ✓

Widely Used

BJT

- npn type ✓ → Most widely used
- pnp type



Let us further define :-

$$V_{BE} = V_B - V_E$$

$$V_{CE} = V_C - V_E$$

Some general characteristics of BJT are :-

- BJT is active device
- BJT is <u>Current - Controlled device</u> whose operation depends on the magnitude of the Current Supplied to the base.
- Small base Current allows a much larger current to flow between Collector & Emitter.
- BJT has 3 states of operation.
    - → Non - Conducting State
    - → Linear State
    - → Saturation state.

⇒ States are Set by Current Supplied to the base.

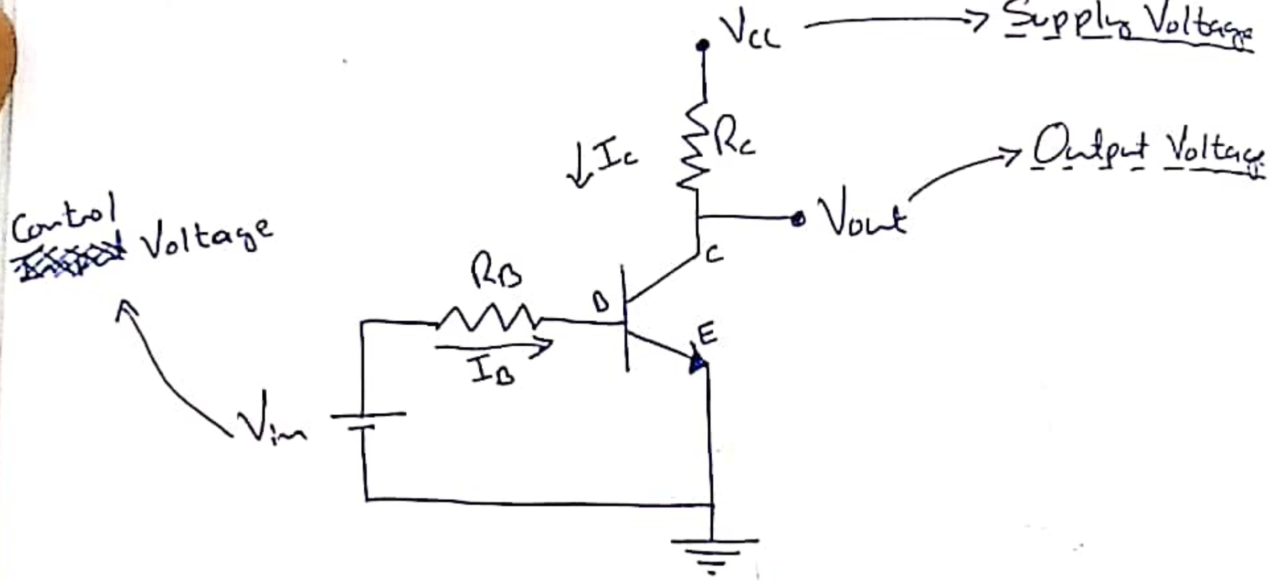
- Voltage at the emitter is always lower than the Voltage at the base by about 0.6V.
- The Collector Voltage (V_c) has to be more positive than the emitter voltage.
- If AC Voltages are applied to the base input, then a DC Offset Voltage needs to be applied in series to the AC Voltage to enable the transistor to be Controlled by both the positive & negative Part of AC Signal.

⇒ Two most Common Standard BJT Circuits are :-

① Transistor Switch (Common emitter circuit)

② Emitter follower Circuit.

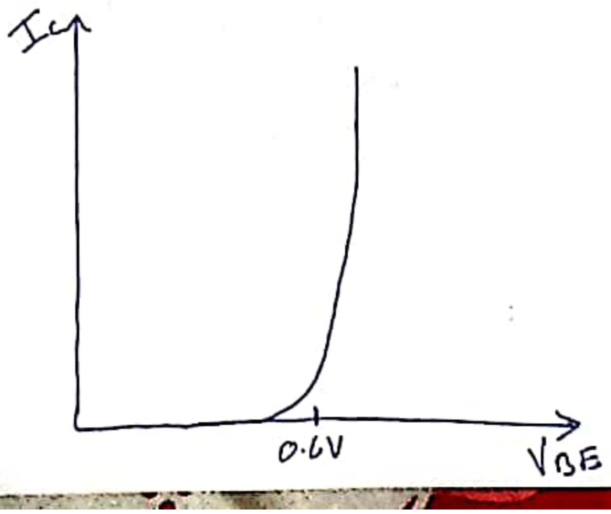
★ Transistor Switch Circuit

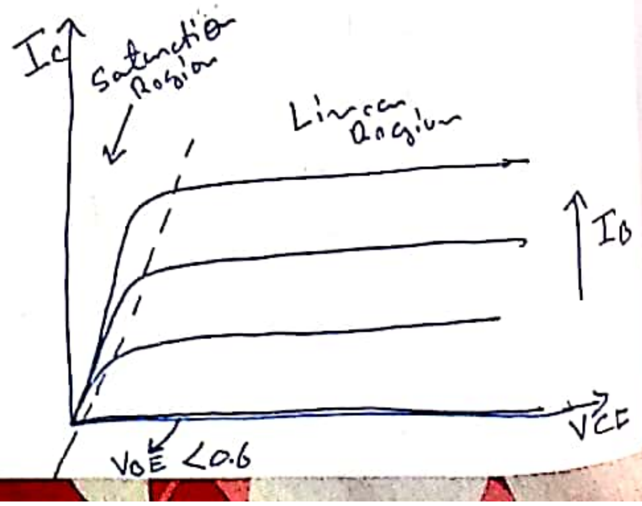


⇒ This Circuit is called Common emitter Circuit, because both the emitter & the Supply Voltage grounds are Connected to the Same common point

⇒ In practice Rc represents lode resistance.

{This need to be Switched ON & OFF}





- **Off State** ⇒ When $V_{BE} < \sim 0.6V$

→ In this state, no current flows between the collector & the emitter ($I_c = 0$).

→ $V_{out} = V_{cc}$

linear operation state ⇒ When $\boxed{0.7V > V_{BE} \geq 0.6V}$ & $\boxed{V_{CE} > 0.2V}$

⇒ In the linear operation state, the collector current I_c is linearly related to the base current I_b

$$\boxed{I_c = \beta I_B = h_{FE} I_B}$$

Saturation State ⇒ $V_{BE} \geq 0.7V$

→ Current flows between collector & emitter.

→ $V_{CE} = 0.2V$.

→ $V_{out} = V_{CE}$

⇒ In the transistor switch circuit the transistor is normally designed to operate in either the off state or the on state (saturation) state.

↳ But not in the linear state.

⇒ The question is what is V_{in} voltage needed to cause the transistor to saturate.

$$V_{in} = I_B R_B + V_{BE} \quad \text{—} ①$$

$$I_B = I_c / \beta \quad \text{—} ②$$

$$I_c = \frac{(V_{cc} - V_{CE})}{R_C} \quad \text{—} ③$$

Eq. ①, ② & ③ can be used to find V_{in} for saturation.

Scanned by CamScanner

Example: Voltage Saturation Calculations for the (2N3904) Transistor

$R_C = 1K\Omega \quad R_B = 5K\Omega \quad , V_{cc} = 10V$

From data sheet

$V_{CE} = 0.2V$ at saturation

So $I_C = \frac{V_{cc} - V_{CE}}{R_C} = \frac{10 - 0.2}{1000} = 9.8\,mA$

$I_{C,max} = 200\,mA$

$h_{FE} = \beta = 100$

$V_{BE} > 0.65\,V$ for saturation

We set $V_{BE} = 0.7V$

$$I_B = I_C/\beta = {9.8}/{100} = 0.098\,mA$$

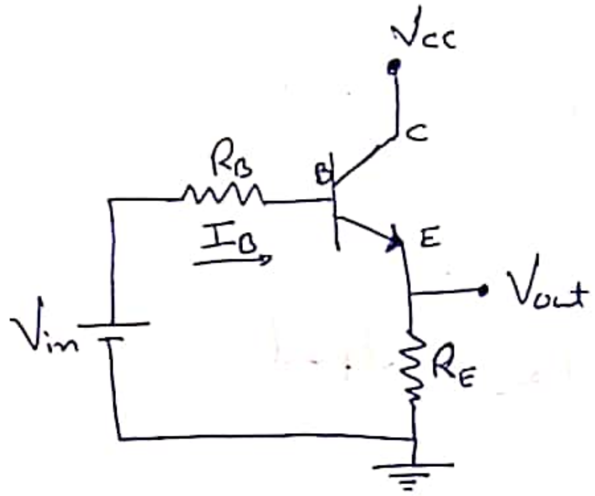
$$V_{in} = (I_B R_B) + V_{BE}$$
$$= (0.098 \times 10^{-3} \times 5 \times 10^{3}) + 0.7$$
$$= 1.19V$$

⇒ To insure saturation V_{in} has to be greater than 1.19V.

↳ This can be achived easily if we let $V_{in} = 2V$ {for example}

⇒ When transistor is off, V_{in} has to be less than V_{BE}.

★ Emitter Follower Circuit



⇒ This circuit is called the emitter follower, because the output voltage follows the input voltage with a difference of about 0.6V.

$$V_{out} = V_{in} - I_B R_B - V_{BE}$$

$$\boxed{V_{out} = V_{in} - I_B R_B - 0.6} \quad \{\forall\ V_{in} > 0.6V\}$$

$$\boxed{I_E = I_C + I_B}$$

$$\boxed{I_E = \frac{V_{out}}{R_E}} \qquad \boxed{I_C = \beta I_B}$$

$$\Rightarrow \boxed{I_B = \frac{I_E}{1+\beta} = \frac{V_{out}}{(1+\beta)R_E}}$$

$$\boxed{V_{out} = (V_{in} - 0.6)\frac{(1+\beta)R_E}{R_B + (1+\beta)R_E}}$$

{Output is independent of supply voltage}

⇒ The above equation is valid as long as transistor is not saturated.

⇒ When transistor is saturated $\boxed{V_{out} = V_{cc} - 0.2}$

⇒ BJT transistors have certain parameters that should not be exceeded.

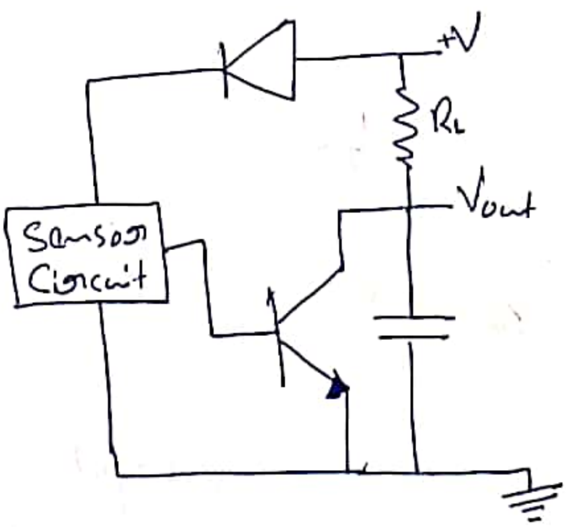
- ↳ Maximum Collector Current
- ↳ Power dissipation Capability.

→ BJT is typically used for low-power application

3.4.3) Open Collector Output

⇒ Many sensors used in mechatronic applications such as proximity sensor, have electronic circuits that use an internal BJT transistor as in interface.

⇒ To gen an output from these sensors, an appropriate "pull-up" resistor or load and the supply voltage needs to be applied to the terminals of the sensor.



⇒ When the proximity sensor is off, the transistor is not in saturation, and there will be no voltage drop across load.

$V_{out} = V$

⇒ When an object is detected by the proximity sensor, the transistor conducts and a voltage drop develops across the load resistance.

3.4.4 > Phototransistor, Photo Interrupter & Opto-Isolator

Phototransistor

→ Instead of using a voltage source to saturate the transistor, a phototransistor uses light to do the same thing.

⇒ Typically a phototransistor and LED are packaged together to make optical sensors that can detects the presence of object called Photo interrupters.

⇒ Opto-isolator/optocoupler combines two elements similar to a photo interrupter but in an enclosed package.

3.5 > Metal-Oxide Semiconductor Field Effect Transistor

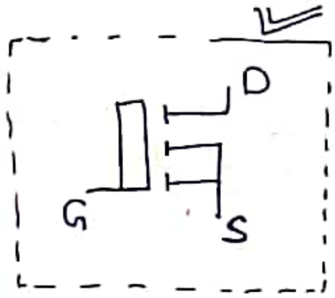
→ They are also 3-terminal device as BJT but they have different names for the terminals, and they operate differently.

Three terminals

- → Gate (Similar to base)
- → drain (Similar to collector)
- → Source (Similar to emitter)

⇒ Naming of the terminal comes from the flow of electrons between the source & drain when the transistor is conducting.

⇒ The most commonly used MOSFET is the enhanced type and is available as n- or p type.

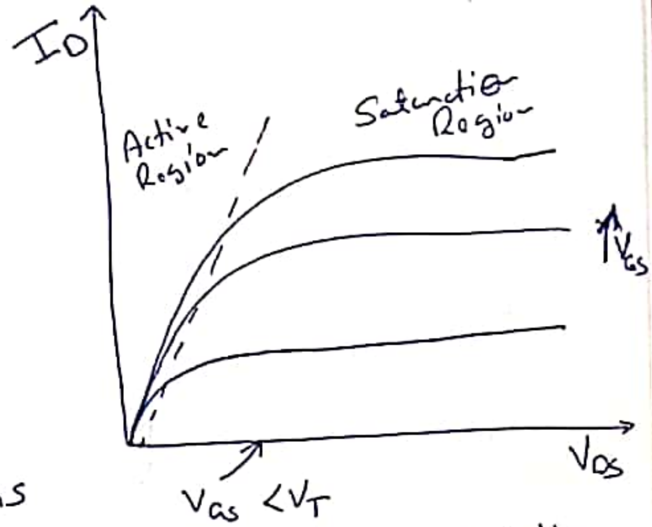


⇒ MOSFETs have the following characteristics :-

- The voltage applied to the gate is the signal that controls the operation of the transistor and hence the name field effect transistor.
  - ↳ This is in contrast to a BJT where the current applied to the base controls its operation.
- The gate is insulated from the drain-source circuit. (Indicated in the symbol)
  - ↳ The gate has a high internal resistance ($R_{gate} = 10^{14}\Omega$)
    - ↳ Almost no current flows through the gate. (leakage current in nanoampere range)
  - ↳ This high impedance of mosfet give it an advantage in interfacing with other logic circuit.
- Mosfet have three states:
  1. Cutoff
  2. active
  3. Saturation

- They acts as Voltage-Controlled resistors.
  - ↳ when off, drain Source resistance is very high
  - ↳ when fully on, drain Source resistance is very low
    - ↳ Current flows from drain to source.
- N-type enhancement Mosfet operates with a positive Voltage applied to the gates.
- MOSFETs have higher power rating & generates less heat than BJTs.

Transfer Characteristics



Output characteristics

→ V_T is between 2V to 5V.

⇒ MOSFETs are typically used for Switching applications (ON/OFF) to drive motors or LED.

⇒ Mosfets are mounted on heat sink.

3.6) Combinational Logic Circuit

⇒ The invention of the transistor had led to the development of digital circuits in which transistors form the building blocks.

Digital logic

- Combinational Logic — Output is not dependent on history of the input
- Sequential logic — Signal history is important & determines the output of the system.

Basic Combinational logic devices :-

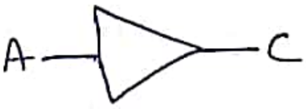
① AND gate →  → $C = A \cdot B$

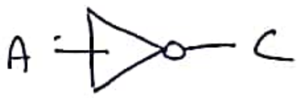
② NAND Gate →  → $C = \overline{A \cdot B}$

③ OR Gate →  → $C = A + B$

④ NOR Gate →  → $C = \overline{A + B}$

⑤ XOR Gate →  → $C = A \otimes B$

⑥ Buffer →  → $C = A$

⑦ Inverter →  → $C = \overline{A}$

★ Boolean Algebra

↳ Rules governing operations of binary variables.

1. $A + A = A$
2. $A + 1 = 1$
3. $A + 0 = A$
4. $A \cdot A = A$
5. $A + B = B + A$
6. $A \cdot (B + C) = AB + A \cdot C$
7. $A + (B \cdot C) = (A + B) \cdot (A + C)$
8. $A + \overline{A} = 1$
9. $A \cdot \overline{A} = 0$
10. $A \cdot 0 = 0$
11. $A \cdot 1 = A$
12. $\overline{A + B + C + \cdots} = \overline{A} \cdot \overline{B} \cdot \overline{C} \cdots$
13. $\overline{A \cdot B \cdot C \cdots} = \overline{A} + \overline{B} + \overline{C} + \cdots$

{ De Morgan rules }

★ Bollean Function generation from true table

"Hear we look at problem of finding a logic gate system with the minimum number of gates that can be used to realize a logic circuit operation that is specified in terms of a true table"

⇒ The basic approach is to manipulate the logic function into one of two equivalent forms:-

1. Sum of product forms: ⟵ {More commonly used}

$A \cdot B + A \cdot C$

2. Product of sums form:

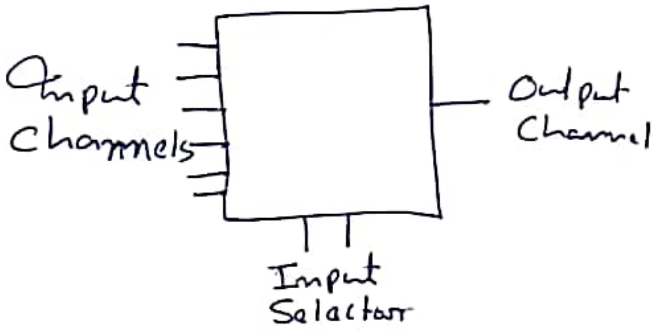
$(A + B) \cdot (A + C)$

⇒ Karnaugh map is a graphical method that can be used to produce simplified Boolean expressions from sum of product obtained from true table.

★ Multiplexers & Decoders

Multiplexer

→ Circuit that selects one input out of the several available to be connected to the output.



→ Commonly used in the design of ADC converters & in microcontroller circuit to select the timing source.

→ Multiplexer with 2^n input chanels, need n channel selector input.

Decoders or Demultiplexer

→ A decoder with n input & m outputs will activate only one of the m output for a specified pattern of the n inputs.

→ Operate in opposite fashion to a multiplexer.

3.7> Sequential Logic Circuit

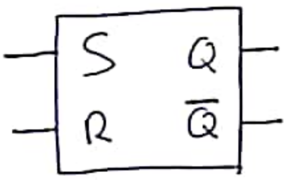
⇒ Sequential logic can be thought of as Combinational logic circuit and memory.

\# **flip-flop** ⇒ A Sequential logic device that can store and switch between two binary states.

eg of other Sequential logic Circuit ⇒ Counter, Shift register & microprocessors.

flip-flop
- → SR
- → Clocked SR
- → JK
- → D
- → T

★ **SR Flip flop**



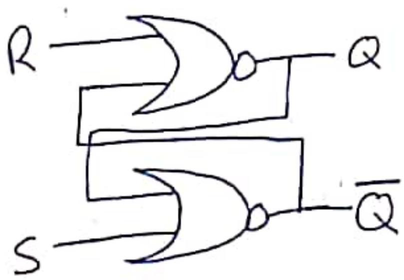
Operation

① $S=0$ & $R=0$ ⟹ Output of flip-flop does not change.

② $S=1$ & $R=0$ ⇒ flip-flop is set to $Q=1$ $\overline{Q}=0$

③ $S=0$ & $R=1$ ⇒ flip-flop is reset to $Q=0$ & $\overline{Q}=1$

④ S & R are not allowed to be 1 simultaneously, since the output will not be predictable.

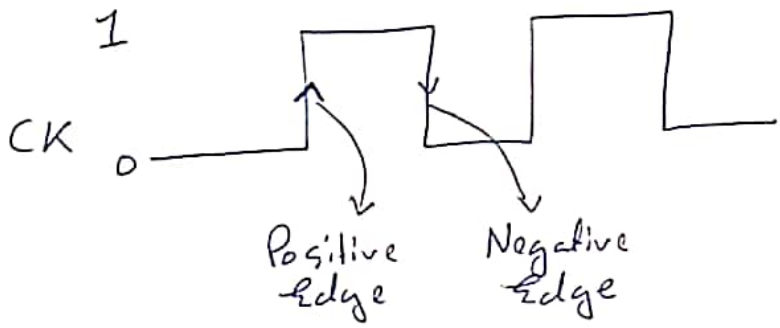


{Equivalent circuit}

★ Clocked SR Flip-Flop

Clock signal

- Two stage signal
- Generally square & periodic but can be non-periodic



Positive Edge trigger device

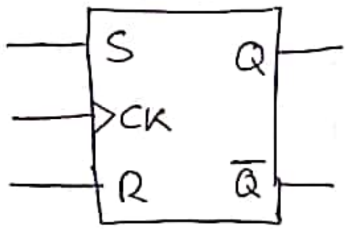
"Responds to low to high"

Negative edge trigger device

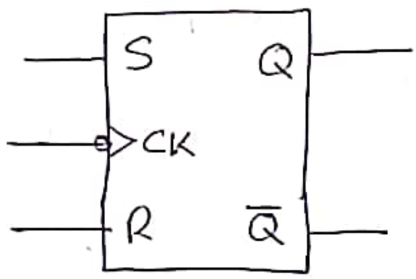
"Responds to high to low"

⇒ In a clocked SR flip-flop, the output changes state at clock transition.

- This is done to provide Synchronization of the output change in Complex system.



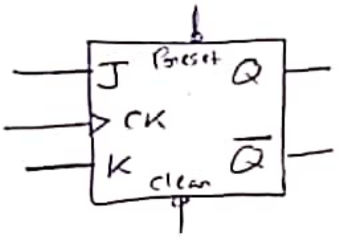
Positive edge triggered Clocked SR flip flop



Negative edge triggered Clocked SR flip flop

★ JK Flip flop

⇒ A JK flip flop is similar to an SR flip-flop, but allows a simultaneous input J=1 & K=1.

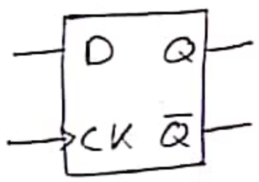


⇒ Preset input sets the output Q to 1 & Clear input sets the output Q to zero.

⇒ J=1, K=1 & CK=1 ⇒ ~~No State Change~~ Output flips

★ D Flip Flop (Data flip flop)

⇒ Typically used to represent data registers.



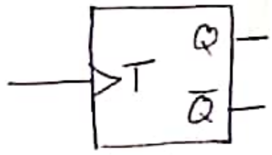
→ Set of memory elements that are used to hold information until it is needed

Latch → Similar to D flip flop but its clock input is not edge triggered

→ Commonly used to maintain the output in DAC.

★ T Flip flop

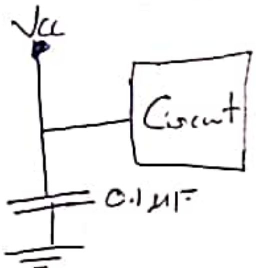
⇒ If J & K input of the flip-flop are permanently set to 1 and the input is applied at the clock or T or Toggle input, we get what is called T flip flop.



⟹ A characteristic of the T flip flop is that the output changes its state at a frequency that is half of the input clock frequency.

↳ This feature is utilized in the construction of → Binary Counter
→ Frequency divider.

⟹ It is very important in digital circuits to reduce the noise in the power supplied to the circuit.



↳ This can be done by bypass Capacitor as shown.

(Purpose)

{To damper AC Component in the DC signal}

3.8) Circuit Families {Digital}

TTL
Transistor-Transistor Logic
↓
{Based on BJT Technology}

CMOS
Complementary metal-oxide Semiconductor
↓
{based on FET Technology}

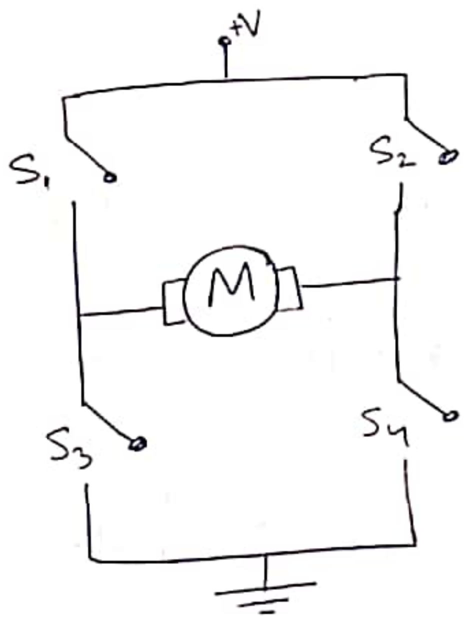
TTL & CMOS Voltage levels

Operations	Low State Voltage Range TTL	Low State Voltage Range CMOS	High state Voltage Range TTL	High state Voltage Range CMOS
Input	0-0.8V	0 – 1.5V	2.0 – 5V	3.5 – 5V
Output	0 – 0.5V	0 – 0.05V	2.7 – 5V	4.95 – 5V

3.9> H-Bridge driver

→ A very Common application of transistors is to Construct drivers to drive motors.

↳ One Such Circuit is H-bridge drive Circuit.



⇒ Switching elements used are transistors.

↳ Transistor Can be BJT or MOSFET depending upon Power requirement.