

Higher Secondary Course **ELECTRONICS**



Government of Kerala
Department of General Education

Prepared by
State Council of Educational Research
and Training (SCERT), Kerala
2026

THE NATIONAL ANTHEM

Jana-gana-mana adhinayaka, jaya he
Bharatha-bhagya-vidhata
Punjab-Sindh-Gujarat-Maratha
Dravida-Utkala-Banga
Vindhya-Himachala-Yamuna-Ganga
Uchchala-Jaladhi-taranga
Tava subha name jage,
Tava subha asisa mage,
Gahe tava jaya gatha
Jana-gana-mangala-dayaka jaya he
Bharatha-bhagya-vidhata
Jaya he, jaya he, jaya he,
Jaya jaya jaya, jaya he.

PLEDGE

India is my country. All Indians are my brothers and sisters.

I love my country, and I am proud of its rich and varied heritage. I shall always strive to be worthy of it.

I shall give my parents, teachers and all elders, respect and treat everyone with courtesy.

To my country and my people, I pledge my devotion. In their well-being and prosperity alone, lies my happiness.

Prepared by

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FOREWORD

Dear students,

In today's digital age, electronics has become an integral part of our daily life. The rapid development of electronics greatly influences the lifestyle of every human being and helps improve facilities in all fields of life. As we look into the future, several emerging technologies are poised to further transform electronics. The advent of quantum computing, the rise of Internet of Things (IoT), the development of more efficient semiconductor materials like gallium nitride (GaN) and silicon carbide are some of the most exciting developments.

Electronics engineering and technology is therefore, a highly sought after discipline in the modern era which provides tremendous career and research opportunities. Moreover, the study of science and technology at the school level supports students in skill acquisition and develops aptitude towards entrepreneurship. These are some of the factors which led to the introduction of electronics as an optional subject at the higher secondary level.

This textbook serves as a comprehensive guide that skillfully combines analytical techniques with practical applications. The pedagogical approach adopted prioritizes understanding through experimentation and simulation. This textbook is the result of combined efforts of a team of dedicated practising teachers and experts in electronics in the state of Kerala.

I hope that the students will make effective use of the inputs offered in the book.

Dr. Jayaprakash R.K.

*Director
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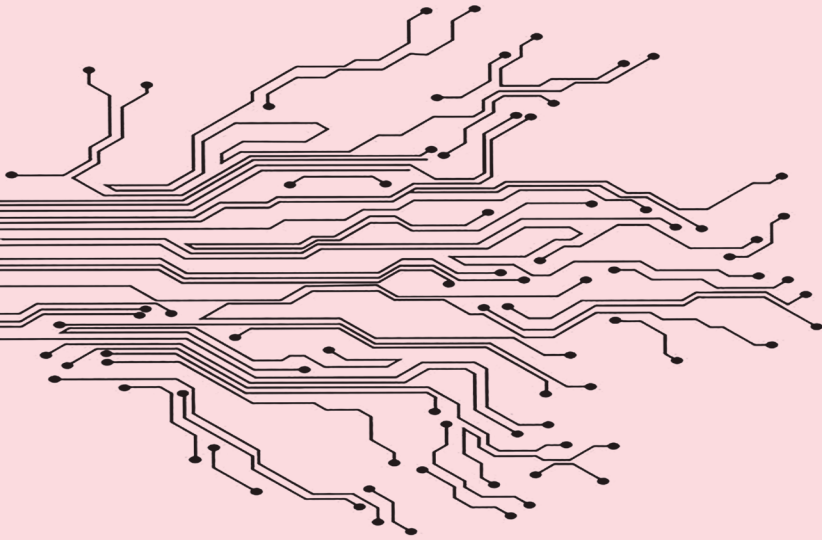
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Certain icons are used in this textbook for convenience



For further reading. Evaluation not required



Know your progress



Activity

THE CONSTITUTION OF INDIA

PREAMBLE

WE, THE PEOPLE OF INDIA, having solemnly resolved to constitute India into a ¹**[SOVEREIGN SOCIALIST SECULAR DEMOCRATIC REPUBLIC]** and to secure to all its citizens :

JUSTICE, social, economic and political;

LIBERTY of thought, expression, belief, faith and worship;

EQUALITY of status and of opportunity; and to promote among them all

FRATERNITY assuring the dignity of the individual and the ²[unity and integrity of the Nation];

IN OUR CONSTITUENT ASSEMBLY this twenty-sixth day of November, 1949 do **HEREBY ADOPT, ENACT AND GIVE TO OURSELVES THIS CONSTITUTION.**

1. Subs. by the Constitution (Forty-second Amendment) Act, 1976, Sec.2, for "Sovereign Democratic Republic" (w.e.f. 3.1.1977)
2. Subs. by the Constitution (Forty-second Amendment) Act, 1976, Sec.2, for "Unity of the Nation" (w.e.f. 3.1.1977)

The World of Electronics: An Overview

We have learned the basics of electricity and electric circuits in our previous years, and we are familiar with a lot of electronic devices including our mobile phone and television. Have you ever thought what electronics or electronics engineering is and how it differs from electricity or electrical engineering.

1.1 Significance of Electronics

Do you agree that 'electronics' today has become an integral part of our everyday life? From the beginning of the day, till the time we go to bed, we use a large number of electronic gadgets to make our work easier and solve our problems. Electronics is present everywhere. If we look around we can find a lot of electronic devices such as laptops, smartphones, headphones, smart watches and so on.

One significant area where electronics has made a remarkable impact is photography. The smart phones nowadays are equipped with digital cameras that can capture high quality pictures and videos. Surveillance cameras are largely used at homes and streets for the safety and security of civilians and their property.

Even our kitchens are equipped with electronic devices such as water coolers and microwave oven. We are familiar with electronic equipment such as ECG machines, EEG machines, X Ray machines, CT scan and MRI scanners that are used for diagnosing diseases in hospitals. Doctors depend on these to provide accurate medical care.

Why are we so dependant on electronic technology? As stated earlier the answer is so simple. They make our daily activities easier and help us to improve our lifestyle.



Fig. 1.1 Familiar electric devices

Electronics is a dynamic and rapidly evolving field that continues to shape the world in profound ways. From the simple circuits of the early 20th century to the highly sophisticated systems of today, electronics has transformed nearly every aspect of modern life. As we stand on the edge of new technological advancements, the significance of electronics will only continue to grow. Quantum computing, Internet of Things, robotics, new

semiconductor materials, and flexible electronics are just a few of the innovations that promise to drive the next stage of advancements in this field.



Activity 1.1

Check whether you are familiar with the devices shown in the Fig. 1.1.



Activity 1.2

You may be familiar with a lot of electronic devices. Similarly, you may have seen many electronic devices while visiting a hospital or an office. List out those devices and their uses.

1.2 Electronics – A distinct branch of science and engineering

It is essential to understand the basic concepts that form the foundation of electronics. The most fundamental concept is electricity itself. Electricity is a form of energy resulting from the movement of electrons through a conductor. This movement of electrons is called electric current. In electronic circuits, this current is manipulated and controlled to perform various functions such as powering a light bulb, processing data in a computer, or transmitting signals for communication. Electricity is all about making electromagnetic energy flow around a circuit so that it will drive something like an electric motor or a heating element,

powering appliances such as electric cars, kettles, lamps, etc. Generally, electrical instruments need a great deal of energy to make them work. So, they use comparatively larger electric currents. For example, a 2.5 kilowatt heating element inside an electric kettle operates on a current of almost 10 ampere. But, the electronic components use currents likely to be measured in fractions of milliamperes. In other words, a typical electric appliance is likely to be using currents tens, hundreds, or thousands of times bigger than a typical electronic one.

Electronics is a field that involves carefully controlling and directing a small amount of electric current through complex circuits to process signals, store data or control devices. Let us consider an example of a microwave oven. In a microwave oven, electricity provides the power that generates high-energy waves to cook food; electronics controls the electrical circuit that does the cooking.

Thus, Electronics is a branch of science and engineering that deals with the study and application of electrical circuits, devices, and systems that utilise the flow of electrons to perform various functions. This field includes a wide variety of components including semiconductors, diodes, and transistors, which are fundamental ones in the design of circuits for communication, computation, and control systems.

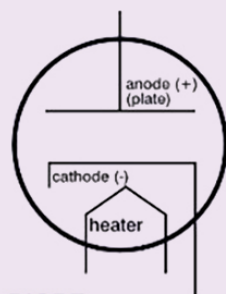


Know your progress

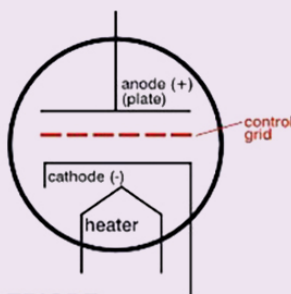
Have you ever noticed a light dimmer which controls the brightness level of an electric bulb? The dimmer is similar to an electronic regulator that controls the speed of the electric fan in our home or classroom. "The bulb and the fan are electrical devices while the dimmer and the fan regulator are electronic devices. "Do you agree with the statement?" Justify your answer.

1.3 The Origin and Evolution of Electronics

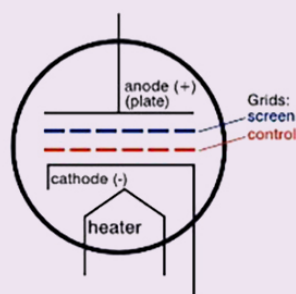
The actual history of electronics began with the invention of vacuum diode by J. A. Fleming, in 1897. Electronics in daily life evolved when a vacuum triode was invented by Lee De Forest in 1906 to amplify electrical signals. This led to the introduction of tetrode and pentode tubes in 1925 that dominated the world until World War II.



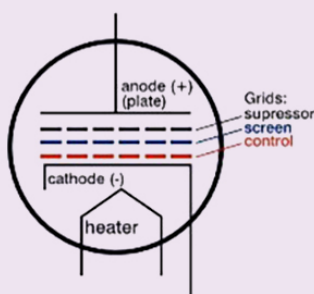
DIODE



TRIODE



TETRODE

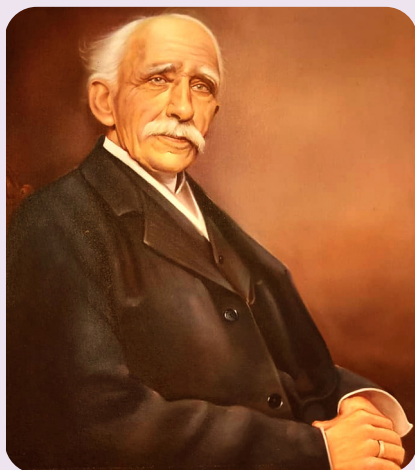


PENTODE

Vacuum tube or thermionic valve is a device that controls electric flow in a high vacuum between electrodes to which an electric potential difference has been applied. It takes the form of an evacuated tubular envelope of glass. A vacuum tube or in simple form, a diode is like an incandescent bulb with an added electrode inside. When the filament of the bulb is heated, electrons flow into the vacuum inside the bulb. If an anode or plate is there which is made more positive than the filament, a direct current flows through the vacuum to the electrode.

In vacuum tubes the current flows in one direction only. Therefore, vacuum tube was able to convert an alternating current to direct current.

Triodes with three electrodes, tetrodes with four electrodes and pentodes with five electrodes were used for various other applications.



Sir John Ambrose Fleming (1849–1945)

Sir John Ambrose Fleming invented Fleming valve, a vacuum tube in 1904. It is the first thermionic diode that is used to conduct current in one direction and block the flow of current in opposite direction. It was used as a detector in early radio receivers.

[illegible]

A collection of various integrated circuits (chips) in different packages, including DIP, SOP, and QFP, arranged on a white background.

13



The terms SSI, MSI, LSI, VLSI and ULSI represent the advancements in technology, where each subsequent technology allowed for the integration of more and more components onto a single chip. As the number of transistors increased, the complexity and functionality of the integrated circuits also grew, leading to more powerful and efficient electronic devices.

Acronym	Full Name	Approximate Transistor Count	Typical Gates per Chip	Common Applications
SSI	Small-Scale Integration	≤ 100	≤ 10	Basic logic gates (AND, OR, NOT), flip-flops, used in early computers and calculators
MSI	Medium-Scale Integration	100 to 1,000	10 to 100	Multiplexers, decoders, counters, registers, simple memory modules
LSI	Large-Scale Integration	1,000 to 10,000	100 to 10,000	Early microprocessors (e.g., Intel 4004), small memory chips (SRAM, ROM)
VLSI	Very Large-Scale Integration	10,000 to 1,000,000+	$> 10,000$	Modern microprocessors, GPUs, large memory chips (DRAM, Flash), FPGAs
ULSI	Ultra Large-Scale Integration	$> 1,000,000+$	$> 100,000$	Advanced microprocessors (e.g., Pentium series) and high-performance computing chips. Often considered an extension of VLSI, and the term VLSI is sometimes used to broadly cover both

The development of digital integrated circuits changed the overall architecture of computers. Microprocessors were introduced in 1969 by Intel. These ICs integrated the functions of CPU (Central Processing Unit) of computers onto a single chip thereby making computers compact and fast. Following the success of digital integrated circuits, analog integrated circuits were developed, for analog signal processing. A key development in the field is operational amplifier (Op - Amp), which is a versatile component used in many applications. Other important circuits include multipliers, Analog to Digital converters (ADC), Digital to Analog converters (DAC) and analog filters.

As we look into the future, several upcoming technologies are expected to further transform electronics. One of the most exciting developments is the advent of quantum computing. Unlike classical computers, which use bits to process information in binary form (0s and 1s), quantum computers use quantum bits, or qubits, which can represent and process multiple states simultaneously. This

capability has the potential to exponentially increase computing power.

Another significant trend is the rise of the Internet of Things (IoT). IoT refers to the interconnection of everyday objects via the internet, allowing them to send and receive data. This technology is rapidly expanding, with applications ranging from smart homes, where appliances can be controlled from far away, to industrial IoT, which enables real-time monitoring and optimisation of manufacturing processes.



Know your progress

Why do we prefer silicon transistors over germanium?
Give the advantages of integrated circuits.

1.4 Application of Electronics in Different Fields

Consumer Electronics

The devices and equipment meant for daily use are known as consumer electronics. We are familiar with electronic regulators used for controlling the speed of fans we use in our home, classrooms or anywhere else. Do you know the mechanism behind it? The electronic component used for regulating the speed is TRIAC. It controls the speed by controlling the electric power reaching the motor. Electronic components like Silicon Controlled Rectifiers (SCR) are used to control the speed of motors. SCRs are also used in power rectifiers and inverters. Some of its applications in the field of consumer electronics include office gadgets like computers, scanners, calculators, FAX machines, projectors, etc. They also include home appliances like washing machines, refrigerators, microwave ovens, TVs, vacuum cleaners, video games, DVD players, loudspeakers, etc.



Fig. 1.4 Consumer electronic devices

Communication and Entertainment

Electronic devices, infrastructure and digital platforms enable communication and entertainment applications. In communication sector, applications include radio/TV broadcasting, mobile communication,



Fig. 1.5 Electronic devices in communication and entertainment field

communication through internet and satellite systems. In entertainment, electronics drives everything including smart TVs, music streaming and video gaming.

Smartphones, laptops and tablets use electronics for voice and data transmission, facilitating global conversations and access to information. Radio and television broadcasting relies on electronic signals to transmit audio and video content to larger audiences. The internet, a backbone of digital communication, is built on electronic computing and network devices for

rapid information exchange. Electronic systems in satellites enable long distance communication such as live global broadcasts and telecommunications.

Electronic devices such as smart TVs, streaming services and home theatre systems provide good audio-visual experiences. Electronic components are at the heart of gaming devices and PCs. Electronics play an important role in music players, from digital streaming platforms to headphones and sound systems.

Application of Electronics in Industries

Electronics has a huge impact on the smooth functioning of various industries. The use of automatic control systems in different industries is increasing day by day. Electronic circuits are used to control the operations of automatic door openers, lighting systems, power systems, safety devices etc. Even the power stations which generate thousands of megawatts of electricity are controlled by electronic circuits.



Fig. 1.6 Electronic devices in medical field

Applications in the Medical Field

Many electronic devices are extensively used for the diagnosis and treatment of diseases in the medical field. Moreover, they help medical professionals in their research. Electron microscope, ECG, EEG, X-rays, MRI scanner, CT scanner and glucometer are some of the examples of electronic equipments used in hospitals. For data recording and physiological analysis, advanced, sophisticated instruments are being developed using the latest technologies for diagnosis and treatment of certain diseases.



Activity 1.3

When you visit a hospital, notice as much medical instruments as you can and try to identify them.

Applications in Defence and Aerospace Sectors

Electronic technology is used extensively in the defence and aeronautical systems. One of the remarkable developments during the Second World War was the invention of RADAR (Radio Detection and Ranging). The RADAR is used to detect and find the exact location of the enemy aircraft. The applications of electronics also include missile launching systems, cockpit controllers, aircraft systems, rocket launchers for space and many more.



Fig. 1.7 Electronic devices in defence and aerospace sectors

Automobiles

Electronics is widely used in the latest automobile technology. Electronic circuits used for monitoring and controlling the engine performance, for charging battery in cars and for measuring gauges and electronic ignition system are some of the most common applications of electronics in automobile sector.

The anti-collision units, anti-lock braking systems (ABS), traction controls, window regulators and several electronic control units are certain other areas of applications in this field.

Robotics and Artificial Intelligence

Electronic systems that use Artificial Intelligence and robotics are used in industrial applications such as inspection, navigation and assembly. Virtual Reality and face gesture recognition are computer-based, and these developments have been possible because of electronics engineering.



Know your progress

1. Make a list of electronic devices you have seen at home, school and places you have visited.
2. Classify the devices in your list into various fields of applied electronics.

1.5 Electronic Components

Electronic components are the elements of a circuit which help in the functioning of electronic circuits. They are the basic building blocks of electronic circuits or devices. They can control the flow of electrons in an electronic system or electronic circuit.

According to their behaviour in an electronic circuit, the electronic components are broadly classified into active and passive components. Active Components are those which require an external power source to operate. They can amplify or control electrical signals. Semiconductor devices such as diode, transistor etc. are examples of active components. Passive components cannot amplify or process electrical signals. Resistors, capacitors and inductors are examples of passive components.

Resistors

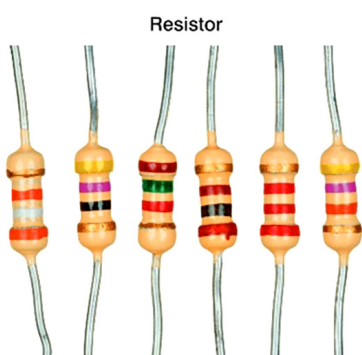


Fig. 1.8 Resistors

Resistors are passive electronic components which have a specific electrical resistance. The resistor's resistance limits the flow of electrons through a circuit. The electrical resistance of a resistor is measured in ohms (Ω).

The power rating of a resistor is the maximum power that can be dissipated without damaging the component. A $100\ \Omega$ 1W resistor means its resistance value is $100\ \Omega$ and its power rating is 1W, which means it can pass a maximum current of 100 mA.

(Calculation: Power $P = I^2R$, $1 = I^2 \times 100$, So $I^2 = \frac{1}{100}$ and therefore $I = \frac{1}{10} = 0.1\ \text{A} = 100\ \text{mA}$)

1.6 Colour Coding of Resistors

Since standard resistors are manufactured in small sizes (especially the carbon composition and the carbon film resistors) it is difficult to print their ratings on its body. So, a standard colour coding system is used to indicate the resistance value of resistors.

The colour coding system for resistors uses bands to indicate the resistance value, tolerance, and sometimes the temperature coefficient. The bands are read from left to right, usually starting with the band closest to the end, and the tolerance band (often gold or silver) is typically on the right, separated by a slightly larger gap.

In a four-banded colour code the first and second bands represent the first and second significant digits of the resistance value. The third band represents the multiplication factor, and the fourth band represents the tolerance. In a five-band code the first three bands represent the first three significant digits of the value, the fourth band represents the multiplier and the fifth band represents the tolerance. The tolerance is a measure of precision with which the resistance was manufactured. If the fourth band is absent, the tolerance is assumed to be $\pm 20\%$.

The table below shows the standard values assigned to each colour.

Colour	Digit	Multiplier	Tolerance (%)
Black	0	$10^0 (1)$	
Brown	1	10^1	
Red	2	10^2	
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	
Blue	6	10^6	
Violet	7	10^7	
Grey	8	10^8	
White	9	10^9	
Gold		10^{-1}	± 5
Silver		10^{-2}	± 10
No Colour			± 20

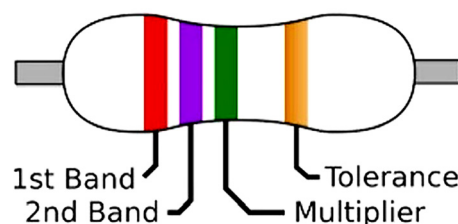


Fig. 1.9 Colour codes of resistors

As an example, let us consider a colour band sequence of Green, Blue, Orange and Silver which represents the resistance value of a resistor. Let us calculate the value of resistance.

Here, the codes of the first two bands which are 5 and 6 represent the first two significant digits of the value. The code of the third band which is 3 represents the multiplier and the code of the fourth band which is $\pm 10\%$ represents the tolerance.

So, the value of resistance is $56 \times 10^3 \Omega \pm 10\% = 56 \text{ k}\Omega \pm 10\%$.

This means that the value is in between 51.4 k Ω and 61.6 k Ω .



Know your progress

You are given a resistance with a colour band sequence of yellow, violet, orange and gold. What is the resistance value of the resistor?

1.7 Standard Values of Resistors

Manufacturing every possible value of resistance is impractical. So, the companies make preferred predetermined values of resistance with different tolerance values such as 5%, 10%, 20% etc. Such values of resistances are called the standard values of resistances. The table below shows the standard resistance values of resistor available in the market.

Ohms			Kilo Ohms			Mega Ohms	
1.0	10	100	1.0	10	100	1.0	10
1.2	12	120	1.2	12	120	1.2	12
1.5	15	150	1.5	15	150	1.5	15
1.8	18	180	1.8	18	180	1.8	18
2.2	22	220	2.2	22	220	2.2	22
2.7	27	270	2.7	27	270	2.7	
3.3	33	330	3.3	33	330	3.3	
3.9	39	390	3.9	39	390	3.9	
4.7	47	470	4.7	47	470	4.7	
5.6	56	560	5.6	56	560	5.6	
6.8	68	680	6.8	68	680	6.8	
8.2	82	820	8.2	82	820	8.2	

Table 1.1 Some standard values of resistors

1.8 Types of Resistors

Fixed resistors

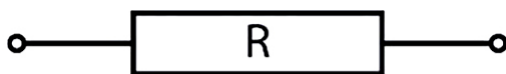


Fig. 1.10 Symbol of fixed resistors

A fixed resistor is the type of resistor which has a fixed value of resistance in the circuit. A fixed resistor cannot be changed, as it is set at a specific value.

Carbon composition and carbon film resistors are two types of fixed resistors that have distinct characteristics.

Carbon composition resistors are made from a mixture of carbon powder and a binding agent such as clay. The resistance value is determined by the ratio of carbon to the binding agent in the mixture. Carbon composition resistors have high surge current tolerance, low precision and stability and are sensitive to temperature and humidity. They are available in the range from a few Ohms to around 22 M Ω .

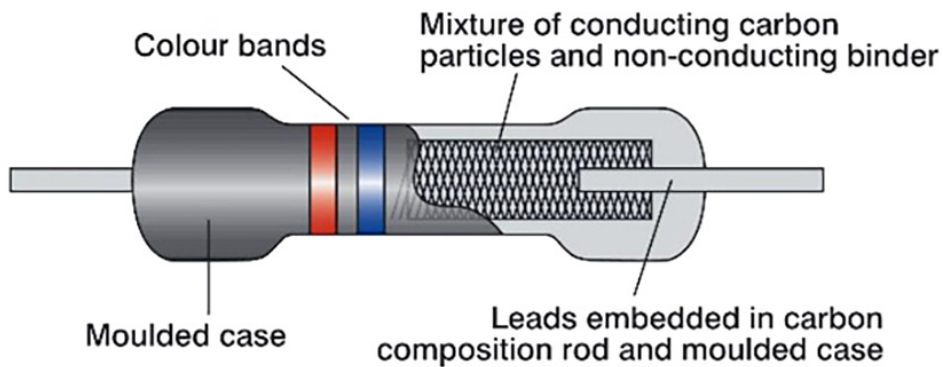


Fig. 1.11 Carbon composition resistor

Carbon Film Resistors are made by depositing a thin layer of carbon onto a ceramic substrate. The resistance values are determined by the thickness and width of the carbon film. Carbon film resistors are more precise and stable than carbon composition resistors and are less sensitive to temperature and humidity.

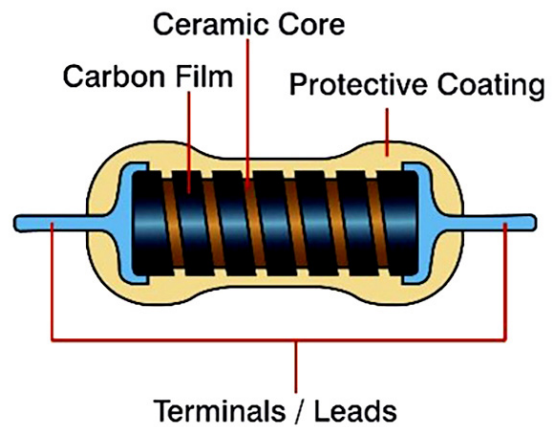
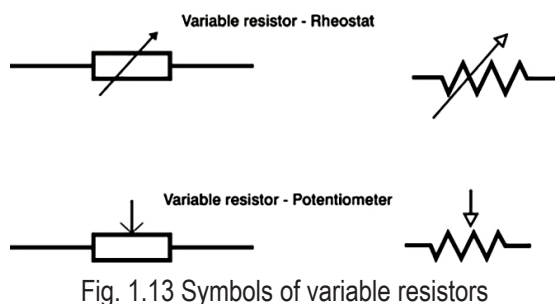


Fig. 1.12 Carbon film resistor

Variable Resistors

Suppose we need to change the values of currents and voltages while the device is working. As an example, let us take the case of adjusting the volume of radio or TV. It can be done by controlling the current or voltage of the audio signal. When the resistance value of the resistor inside the volume control device is varied, the current and thus the volume can be controlled. So, in such cases we need variable resistors. In such electronic circuits we use a variable resistor of small size which is called 'potentiometer' or simply 'pot'. The arrow in the symbol of the 'pot' represents the movable contact.



In electronic circuits we use variable resistors of small sizes which are called potentiometers. The arrow shown in the symbol of potentiometer indicates the movable contact. This moving contact is used to vary the value of resistance in the circuit. But a rheostat is a variable resistance which is comparatively larger in size. It is an adjustable resistor that is

used in applications that demand current modification or resistance variation in an electric circuit. The rheostat may control the speed of motors or modify generator characteristics.

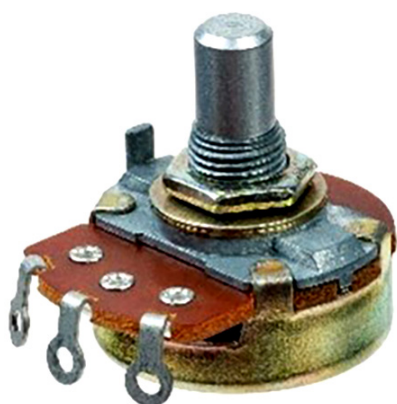


Fig. 1.14 Potentiometer

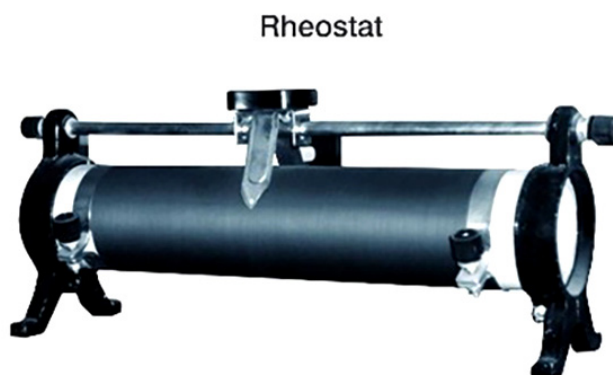


Fig. 1.15 Rheostat



Activity 1.4

1. Visit your electronics laboratory and identify the devices such as the potentiometer, different types of resistors, rheostat, etc.
2. Assemble a simple circuit using DC power supply, rheostat, ammeter, voltmeter and a resistor. Then, by adjusting the movable contact observe the variations in the current through the circuit and the voltage across it.

1.9 Capacitors

A capacitor is a passive electronic component consisting of two or more pieces for conducting materials separated by an insulating material. The capacitor is a component which has the ability to store energy in the form of an electrical charge producing a potential difference across its plates. A capacitor stores energy in its electric field and releases whenever required. The unit of capacitance of a capacitor is Farad (F).

Experiments show that the amount of charge stored in a capacitor Q is directly proportional to the electrical potential difference V between the plates.

$$Q \propto V$$

$Q = CV$, where C is the capacitance

Basic Configuration of a Capacitor

Capacitors vary in shape and size, but the basic configuration is two conductors separated by an insulating medium.

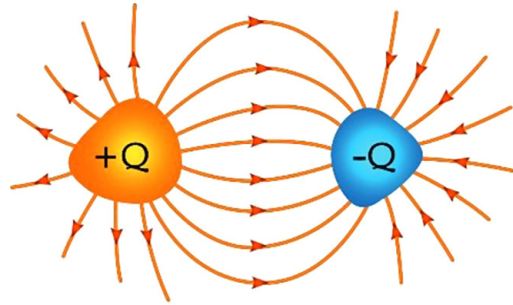


Fig. 1.16 Capacitor- Basic configuration

Two conducting plates separated by an insulating material or dielectric is called a parallel plate capacitor. In uncharged state the charge on both conductors is zero. When a battery is connected across it, the capacitor begins to charge to its maximum value. During the charging process the charge is moved from one plate to another giving one conductor a charge, say $+Q$ and the other one $-Q$. So, a potential difference is created across the capacitor. But, whether charged or not, the net charge on the capacitor is zero.



Fig. 1.17 General symbol of a capacitor

Figure below shows the structure of a parallel plate capacitor.

The capacitance of a capacitor is affected by the area of the conducting plates, the spacing between the plates and the thickness of the dielectric. If the plate area is more, the capacitance is more, which means that the capacitance of a parallel plate capacitor is directly proportional to the area of the plates. But, if the distance between the plates is more, the capacitance is less. Closer plate spacing gives higher capacitance. The higher permittivity of the dielectric gives larger capacitance and if the permittivity is less, the capacitance is less.

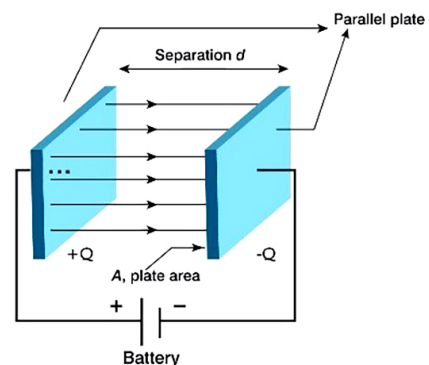


Fig. 1.18 Structure of a parallel plate capacitor

Now, let us consider a parallel plate capacitor which consists of two conducting plates each of area A separated by a distance d .

The capacitance $C \propto \frac{A}{d}$

or $C = \frac{\epsilon A}{d}$, where ϵ is the permittivity of the dielectric.

The capacitance in a circuit offers resistance to AC signal passing through it. This resistance is known as the capacitive reactance. Unlike resistance, the capacitive reactance depends on the frequency of the signal passing through it.

The expression for capacitive reactance is,

$$X_c = \frac{1}{\omega C} = \frac{1}{2\pi fC}$$

where X_c is the capacitive reactance, C is the capacitance of the capacitor, ω is the angular frequency and f is the frequency in Hertz.

Fixed Capacitors



Fig. 1.19 Electrolytic capacitor

The capacitors whose value of capacitance is fixed and cannot be varied later are known as fixed capacitors. There are polarised capacitors and non-polarised capacitors. The capacitors having the specified positive and negative polarities, are called as polarised capacitors. Electrolytic capacitors are examples of polarised capacitors. In these capacitors, some electrolyte is used as dielectric medium. These capacitors are marked with polarities as anode (+) and cathode (–).

Electrolytic Capacitor

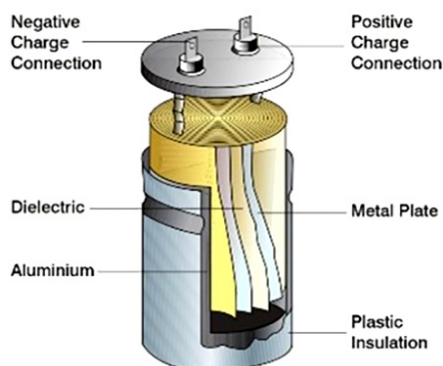


Fig. 1.20 Construction of electrolytic capacitor

The capacitors which do not have specific positive and negative polarities are called non-polarised capacitors. Examples of these types of capacitors are ceramic capacitors, paper capacitors, mica capacitors, etc. In a ceramic capacitor, ceramic material is used as its dielectric. A waxed oil or oiled paper is used in a paper capacitor. The paper is sandwiched between two thin sheets of tin foils and these sheets are rolled into a cylindrical shape and encapsulated in a plastic enclosure. A mica capacitor consists of a thin mica sheet as dielectric. In this type of capacitor, a mica sheet is sandwiched in between thin metal sheets, leads are taken out and this whole assembly is enclosed in a plastic enclosure.

Ceramic capacitor



Fig. 1.21 Ceramic capacitors

STRUCTURE OF CERAMIC CAPACITOR

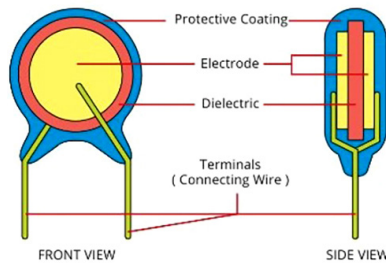


Fig. 1.22 Ceramic capacitor-structure

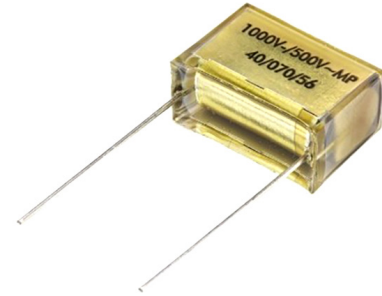


Fig. 1.23 Paper capacitor

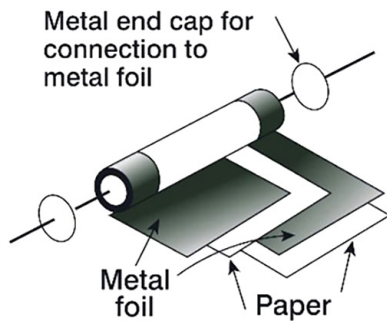


Fig. 1.24 Paper capacitor- Structure



Fig. 1.25 Mica capacitor

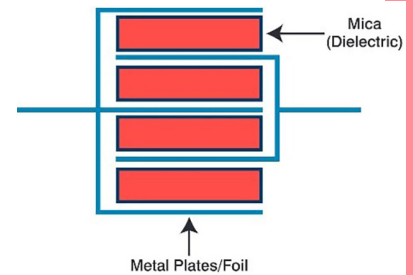


Fig. 1.26 Mica capacitor - structure

Variable Capacitors

The capacitors of which the capacitance value can be varied either electrically or mechanically are called variable capacitors. The variable capacitors consist of sets of stationary and movable plates. A shaft is attached with the movable plates and by rotating the shaft, the capacitance value can be changed.



Know your progress

If the spacing between the plates of a parallel plate capacitor having a capacitance C is reduced to half and the area of each plate is doubled, calculate the capacitance of the new capacitor.

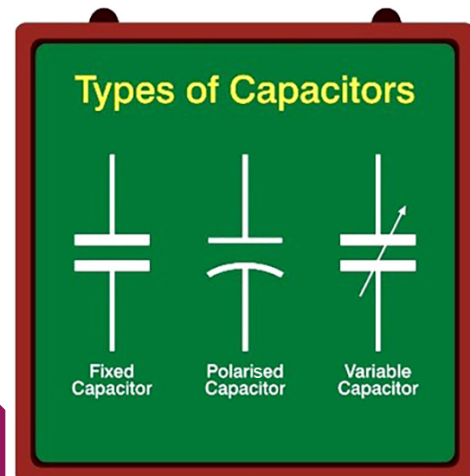


Fig. 1.27 Symbols of normal, electrolytic and variable capacitors

1.10 Inductors

An inductor is a passive electronic component, typically a coil of insulated wire, that stores energy in a magnetic field when an

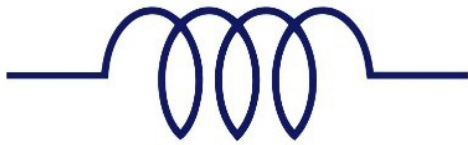


Fig. 1.28 Inductor - symbol

electric current flows through it. Its primary characteristic is inductance (L), which is its measure of opposition to a change in the electric current flowing through it. An inductor is essentially a conductor (like a wire) wound into a coil. When current flows through the coil, it generates a magnetic field around it.

The inductance of an inductor is directly proportional to the number of turns in the coil. It also depends on the radius of the coil and the type of material of the core around which the coil is wound. The unit of inductance is henry (H).

The inductance offers opposition to any change in current through it. This opposition is called the inductive reactance. The inductive reactance (X_L) can be expressed as:

$$X_L = \omega L = 2 \pi f L,$$

where ω is the angular frequency, f is the frequency in Hertz and L is the inductance.

Like resistance and capacitive reactance, the unit of inductive reactance is also ohm. From the above expression, it is clear that the inductance of an inductor increases with the frequency of the signal and therefore at zero frequency, the inductive reactance becomes zero and then the inductor acts as a short circuit. At high frequency, the reactance is very high and so the inductor acts almost as an open circuit. Therefore, it is clear that an inductor blocks AC, whereas it passes DC signal.

There are fixed and variable inductors. According to the constructional features, inductors can be classified into air core, iron core and ferrite core inductors. In air core inductors air is used as the core material. Due to the low magnetic permeability of air, these inductors have low inductance of the range of milli and micro Henry. They are suitable for high-frequency applications such as RF signals.

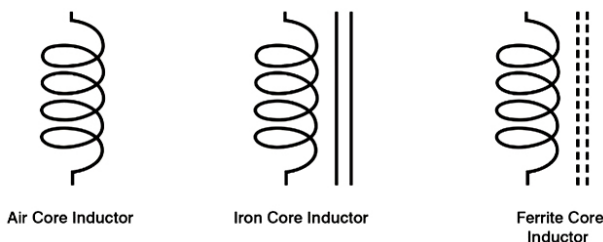


Fig. 1.29 Symbols of air core, iron core, ferrite core inductors

In iron core inductors a copper wire is wound over a laminated core. The high magnetic permeability of the core increases the inductance value. The iron core inductors are suitable for audio frequency applications.

The ferrite core Inductor is made of copper wire wound on a solid core made of ferromagnetic material called ferrite. Because of ferrite's very high magnetic permeability, the inductance value of ferrite core inductor is maximum. It is used for high frequency applications like switched mode power supplies.



Activity 1.5

In an AC circuit with a resistor, capacitor and inductor, if the AC signal frequency is varied, how does it affect the reactance of these components to the signal?

1.11 Transformers

A transformer is an electrical device that transfers electrical energy from one circuit to another through electromagnetic induction. It consists of two inductors (coils) having the same core, known as the primary and secondary coils.

When an alternating current (AC) flows through the primary coil, it generates a magnetic field that induces a voltage in the secondary coil. The voltage induced in the secondary coil is proportional to the number of turns in the secondary coil and the magnetic flux linking the two coils. In a step-up transformer, the number of turns in the secondary coil is more than the number of turns in the primary. On the other hand, in a step-down transformer, the number of turns in the secondary is less than the number of turns in the primary.

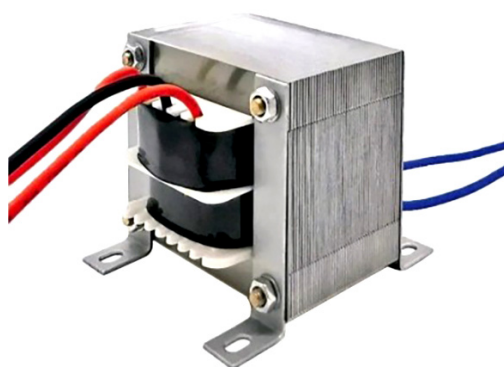


Fig. 1.30 Transformer

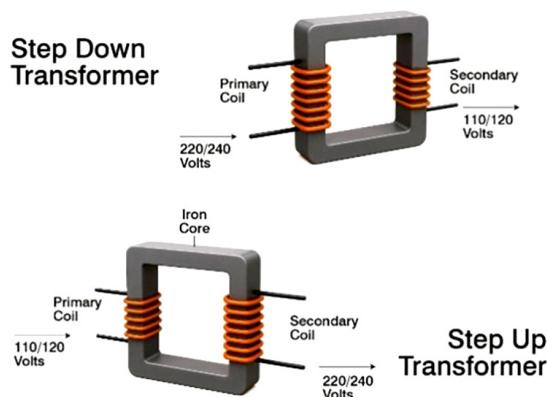


Fig. 1.31 Transformer coils

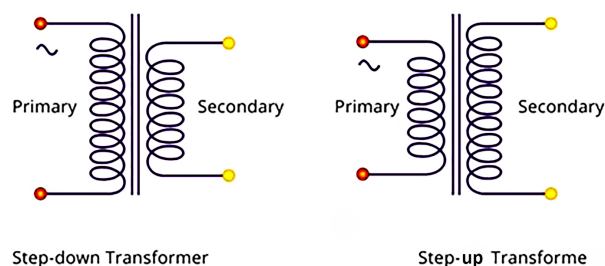


Fig. 1.32 Symbols of transformers

The ratio of the number of turns in the primary coil (N_p) to the number of turns in the secondary coil (N_s) determines the voltage transformation ratio.

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

where V_p and V_s are the primary and secondary voltages, respectively.

The current transformation ratio is the inverse of the turns ratio.

$$\frac{N_p}{N_s} = \frac{I_s}{I_p}$$

where I_p and I_s are the primary and secondary currents, respectively.

Assuming there are no power losses within the transformer, The power input to the primary coil equals the power output from the secondary coil.

$$\text{Power} = V_p \times I_p = V_s \times I_s$$

Transformer Efficiency

The efficiency of a transformer is determined by the ratio of output power to input power.

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}} \times 100$$



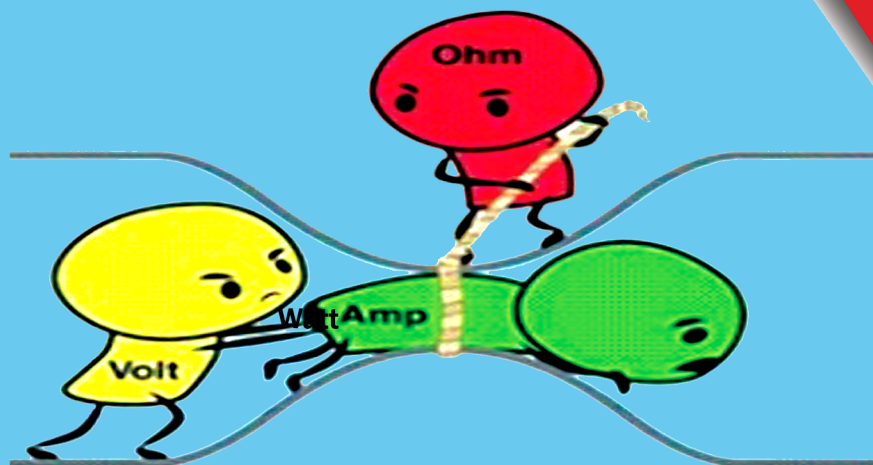
Activity 1.6

Familiarise with transformers of different ratings that are in the electronics laboratory of your school. Give 230 V AC input voltage to any one transformer such as 230/12 V or 230/6-0-6 V transformer and measure its output terminal voltages using a multimeter.



Know your progress

If the number of turns of primary and secondary windings of a transformer are 60 and 100 respectively, and if the secondary voltage is measured as 250 V, what is the voltage provided at its input terminals?



Electrical Fundamentals

Electricity is the most versatile energy source that we have; it plays a critical role in our existence. Electricity is the energy source that powers everything from home appliances to a highly sophisticated transportation systems. We know that many residential and commercial buildings generate their own renewable electric power using solar cells and wind turbines. Now, let us go through the basic concepts of electricity, which is the source of energy that makes all electronic devices work. To begin with, we shall look into what electric current, voltage and power are, how electric current is maintained through a conductor and how the electric current varies according to the change in potential difference. We shall also discuss resistors and capacitors and the effect of series and parallel combinations. Further on, we will see how to find the voltage across and the current through different components in electrical circuits with the help of Ohm's law and Kirchhoff's laws.

2.1 Electric Current



Activity 2.1

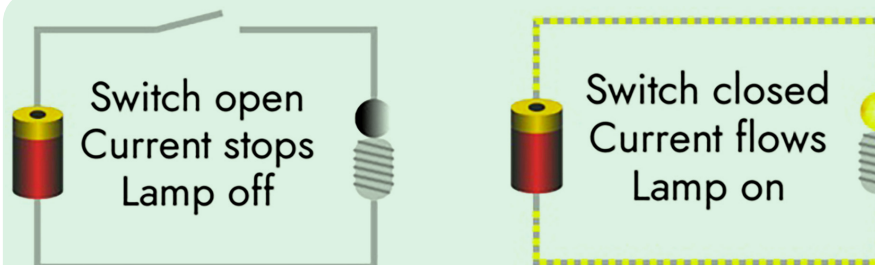


Fig. 2.1

In a flashlight, there is a simple circuit with a switch, a lamp, and a battery connected by a few short pieces of copper wire. When you turn the switch on, electricity flows around the circuit. If there is a break anywhere in the circuit, electricity cannot flow. If one of the wires is broken, the lamp will not light. Similarly, if the switch is turned off, electricity will not flow

The electric current or current intensity is defined as the rate of flow of electric charges. If 'q' is the amount of charge that crosses any section of a conductor in a time interval 't', then the current 'I' is given by

$$I = \frac{\Delta q}{\Delta t}$$

Electric current flows from a higher potential point to a lower potential point. In the case of a battery, positive terminal is considered as at a higher potential compared to negative terminal.

The unit of electric current is Ampere (A). A current of one ampere equals a flow of 1 coulomb of charge per second. Ammeter is the instrument used for measuring the electric current.

2.2 Electric Voltage

The voltage between two points is the work done (energy required) to move a unit positive charge from one point to the other. It is also called as potential difference or electromotive force (emf).

$$V = \frac{W}{Q}$$

where

V – Potential difference or Voltage in volts

W - Energy spent in joules

Q - Charge in coulombs

One volt is defined as the potential difference between two points in an electric circuit such that one joule of work must be done to move a charge of one coulomb between the points. Thus if an electric power line has a voltage of 230 V, it follows that 230 J of work has to be done to transfer each coulomb of electric charge through any apparatus connected between the two wires.

1 Volt = 1 joule/coulomb or $1V = 1 J/C$.

Voltmeter is the instrument used for measuring voltage.

2.3 Electric Power

Electric power is the time rate of doing work for moving charges from one point to another. It is represented by the symbol P and the unit of power is 'watt'. It is practically defined as the rate at which work is being done in a circuit in which a current of 1 ampere is flowing when the voltage applied is 1 volt. The electric power consumed by a resistor is determined by the voltage across it multiplied by the current flowing through it.

Power = Voltage $\times$ Current

$P = V \times I$ or $P = VI$



Activity 2.2

Build simple circuits with a variable power supply, a resistor (like a light bulb), and a voltmeter and ammeter. You can then demonstrate how does the change in voltage affects the current, showing that a higher voltage pushes more current through the circuit.

2.4 Ohm's Law

We have seen that when the potential difference increases, the current increases. It can be said that at constant temperature, the potential difference across a conductor is directly proportional to the electric current through it.

Ohm's law can be written as, $V \propto I$ at constant temperature.

$$\frac{V}{I} = \text{Constant}$$

This constant of proportionality is termed as the resistance of the conductor. Its SI unit is ohm (Ω).

$$R = \frac{V}{I}$$

2.5 Series and Parallel Combinations of Resistors

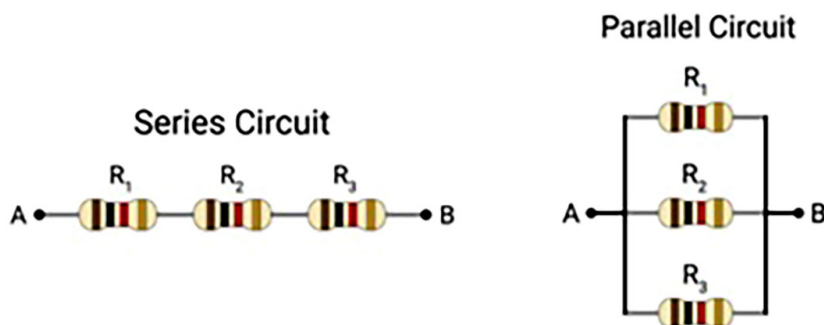


Fig. 2.2

Suppose, for a certain circuit we require a $200\ \Omega$ resistor, and for some other circuit we need a $50\ \Omega$ resistor. But, we have only $100\ \Omega$ resistors with us. How can we solve this problem? It is possible to get these values by combining the available resistors.

The two ways of combining resistors are:

1. Series Combination
2. Parallel Combination

Series Combination

Two or more resistors are said to be connected in series when they are connected in such a way that the same current flows through all those resistors. Consider three resistors R_1 , R_2 and R_3 connected in series and a voltage of V volt is applied across them as in Fig. 2.3.

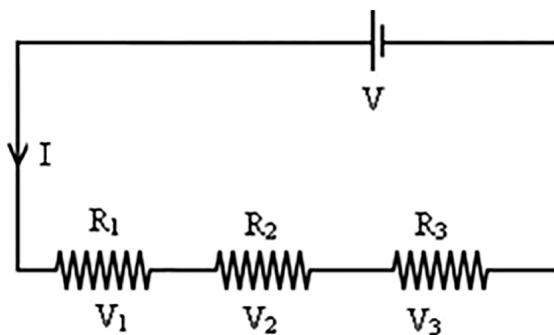


Fig. 2.3 Series combination of resistors

In this circuit the current through each resistor is the same, but the potential difference across each is different. It can be obtained using Ohm's law.

$$\text{Potential difference across } R_1, V_1 = IR_1$$

$$\text{Potential difference across } R_2, V_2 = IR_2$$

$$\text{Potential difference across } R_3, V_3 = IR_3$$

If V is the effective potential drop and R the effective resistance, then the effective potential difference across the combination is

$$V = IR$$

Total voltage across the combination is equal to the sum of the voltages across each resistor.

$$V = V_1 + V_2 + V_3$$

Substituting the values of voltage

$$IR = IR_1 + IR_2 + IR_3$$

Eliminating I from all the terms, we get

$$R = R_1 + R_2 + R_3$$

Thus, the effective resistance of the series combination of a number of resistors is equal to the sum of the resistances of individual resistors. If n number of resistors of equal value R are connected in series, the effective value $R_{\text{eff}} = nR$.

Parallel Combination

A number of resistors are said to be connected in parallel when they are connected in such a way that the same voltage appears across each of those resistors. Consider three resistors R_1 , R_2 , and R_3 are connected in parallel across a potential difference of V as in Fig. 2.4.

Here, since all the resistors are connected across the same terminals, the potential differences across all of the resistors are equal. But the current will be different in each resistor and is given by Ohm's law.

$$\text{Current through } R_1, I_1 = \frac{V}{R_1}$$

$$\text{Current through } R_2, I_2 = \frac{V}{R_2}$$

$$\text{Current through } R_3, I_3 = \frac{V}{R_3}$$

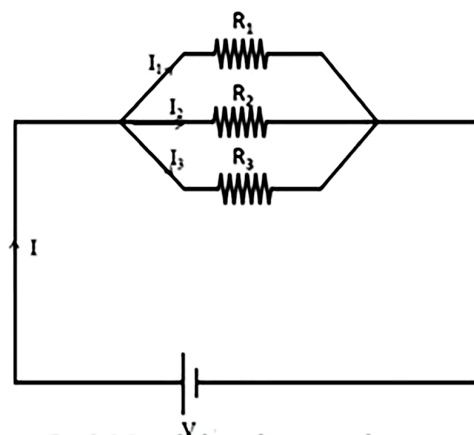


Fig. 2.4 Parallel combination of resistors

The total current through the combination is $I=V/R$ where 'R' is the effective resistance of this circuit.

The total current through the combination = the sum of the currents through each of the resistors

$$I = I_1 + I_2 + I_3$$

Substituting the values of currents, we get

$$\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

Eliminating V from all the terms we get

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Thus, in parallel combination the reciprocal of the effective resistance is equal to the sum of the reciprocals of individual resistances. The effective resistance in a parallel combination will be smaller than the value of the smallest resistance.

When only two resistors of values R_1 and R_2 are connected in parallel, the effective resistance of the combination will be:

$$R = \frac{R_1 R_2}{R_1 + R_2}$$



Know your progress

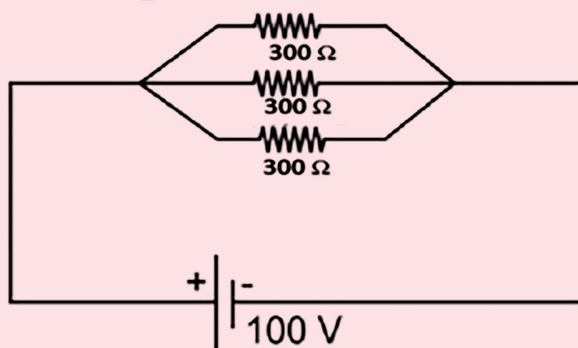


Fig. 2.5

Find the total current flowing through the circuit in Fig. 2.5 and the current through each of the resistors

Solution

The resistors each of value 300 ohms are in parallel. Effective resistance can be obtained as follows.

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$R = \frac{300}{3}$$

$$= 100 \text{ ohms}$$

$$\text{Total current in the circuit } I = \frac{V}{R} = \frac{100}{100} = 1 \text{ ampere}$$

$$\text{Since } R_1 = R_2 = R_3$$

The current through each of the resistors =

$$\text{Total current no. of resistors} = \frac{1}{3} \text{ ampere}$$

From the above problem it can be noted that if 'n' resistors each of value R ohms are connected in parallel the effective resistance of the combination, R_{eff} is

$$R_{\text{eff}} = \frac{R}{n}$$

When two 100 ohm resistors are connected in series we get a circuit resistance of 200 ohms because in series combination, $R_{\text{eff}} = R_1 + R_2$. For getting a 50 ohm effective resistance we have to combine the two 100 ohm resistors in parallel since for parallel combination $\frac{1}{R_{\text{eff}}} = \frac{1}{R_1} + \frac{1}{R_2}$. Hence, it is clear that when resistors are connected in series, the effective circuit resistance increases and when connected in parallel, the effective circuit resistance decreases.



Activity 2.3

Now try to solve the problem stated in the beginning of section 2.5 (To get effective resistances of 200 Ω and 50 Ω using 100 Ω resistors).

- Draw the circuits required.
- What happens to the effective resistance of the circuit when more resistors are added?

a) in series and b) in parallel



Activity 2.4

With hands-on circuit building, calculations, and using a simulation you can construct both types of circuits. Use a meter bridge to find the experimental resistance, and compare it to the calculated total resistance using the formulae $R_{\text{total}} = R_1 + R_2$ for series and

$$\frac{1}{R_{\text{Total}}} = \frac{1}{R_1} + \frac{1}{R_2} \text{ for parallel}$$

2.6 Combination of Capacitors

Capacitors can also be connected in series and in parallel.

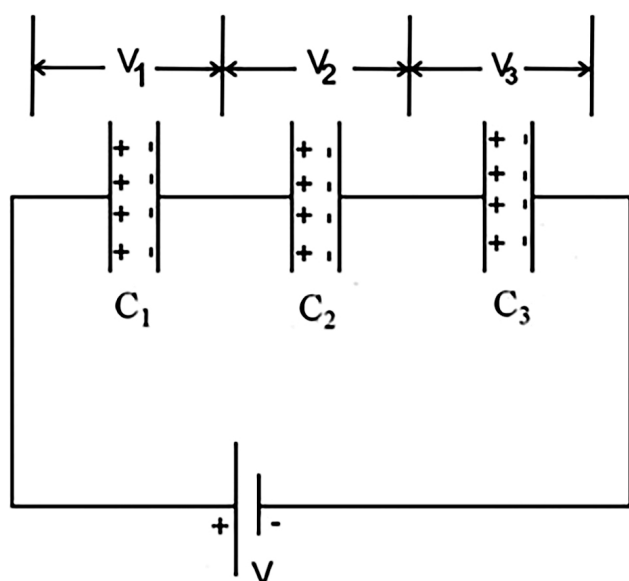


Fig. 2.6 Series combination of capacitors

equation (1) becomes

$$\frac{q}{C} = \frac{q}{C_1} + \frac{q}{C_2} + \frac{q}{C_3}$$

Eliminating 'q' from all the terms

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

If there are only two capacitors connected in series

$$C = \frac{C_1 C_2}{C_1 + C_2}$$

Capacitors in series

Consider three capacitors of capacitances C_1 , C_2 and C_3 connected in series across a potential difference of 'V' volts. Here, the same charge is stored in all the three capacitors. But, the voltage across each will be different. The total voltage across the circuit is equal to the sum of voltages across individual capacitors.

$$\text{So } V = V_1 + V_2 + V_3 \text{ -----(1)}$$

If the effective capacitance of the circuit is 'C' and since

$$\text{Voltage} = \text{Charge} / \text{Capacitance}$$

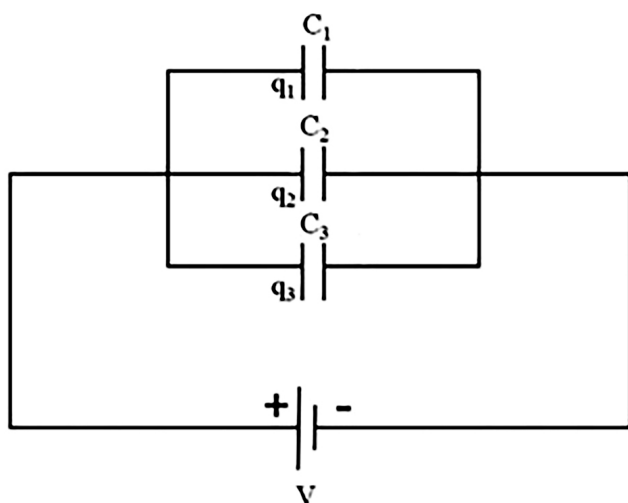


Fig. 2.7 Parallel combination of capacitors

Capacitors in parallel

If three capacitors C_1 , C_2 , and C_3 , are connected in parallel across a battery of V volts, the potential difference across each capacitor will be the same, i.e., V volts. But the charge acquired by each capacitor will be different.

If q_1 , q_2 and q_3 are the charges acquired by C_1 , C_2 and C_3 respectively, the total charge drawn from the battery will be:

$$q = q_1 + q_2 + q_3$$

If 'C' is the effective capacitance of the combination

$$CV = C_1V + C_2V + C_3V$$

OR

$$C = C_1 + C_2 + C_3$$

So, the effective capacitance of a number of capacitors connected in parallel is equal to the sum of the individual capacitances.

In a series combination, the effective capacitance is smaller than the smallest in the combination while in a parallel connection the effective capacitance is larger than the largest in the combination.

? Know your progress

Three Capacitors each of value 9 pF are connected a) in series and b) in parallel. If the combinations are connected to a 30V DC supply, find out the effective capacitance and the total charge in each case.

Solution

Effective capacitance in parallel

$$C = C_1 + C_2 + C_3 = 9 + 9 + 9 = 27 \text{ pF}$$

Charge on a 9 pF Capacitor

$$CV = 9 \times 10^{-12} \times 30$$

$$= 27 \times 10^{-11} \text{ Coulomb}$$

$$\text{Total charge } q = q_1 + q_2 + q_3$$

$$= C_1V + C_2V + C_3V$$

$$= 3 \times 27 \times 10^{-11} \text{ Coulomb}$$

$$= 81 \times 10^{-11} \text{ Coulomb}$$

Effective capacitance in series

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

$$\frac{1}{C} = \frac{1}{9} + \frac{1}{9} + \frac{1}{9}$$

$$\text{or } C = \frac{9}{3} = 3 \text{ pF}$$

In a series combination, the charge on each capacitor will be the same: $q = CV$

$$= 3 \times 10^{-12} \times 30$$

$$= 9 \times 10^{-11} \text{ Coulomb}$$

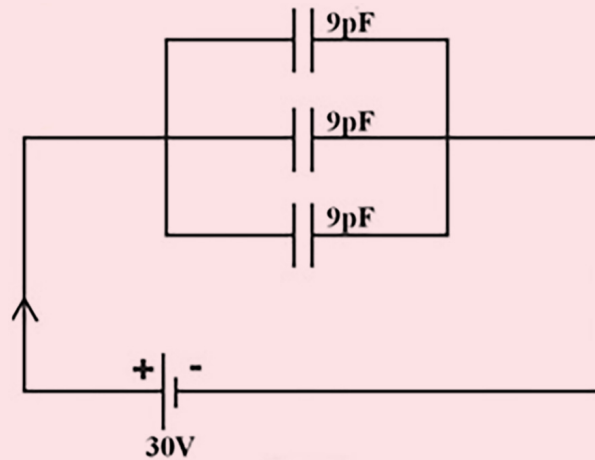


Fig. 2.8

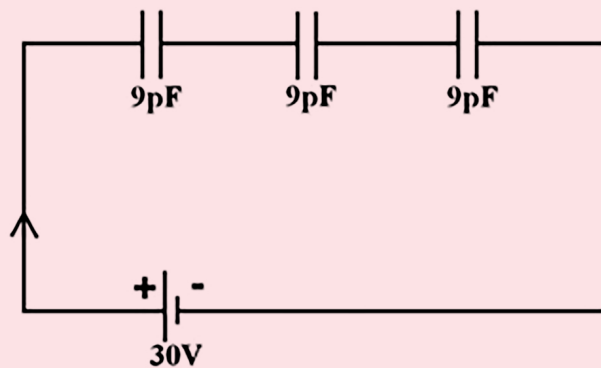


Fig. 2.9

2.7 Kirchhoff's Laws

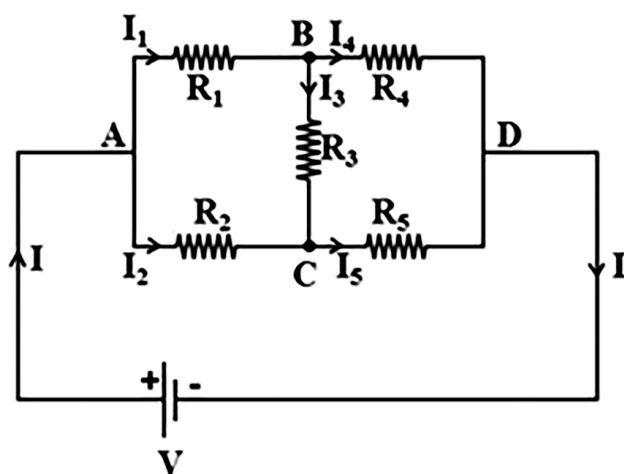


Fig. 2.10 Demonstration of Kirchhoff's law

Analyse the circuit given in Fig 2.10.

The above circuit cannot be reduced to a simple parallel or series combination as the resistors are neither in series nor in parallel with each other. So such circuits cannot be solved simply using Ohm's law. Gustav Robert Kirchhoff proposed two general rules for solving such networks.

Kirchhoff's Current Law (KCL)

Kirchhoff's current law says that at any junction, "the sum of the currents entering a junction must be equal to the sum of the currents leaving the junction".

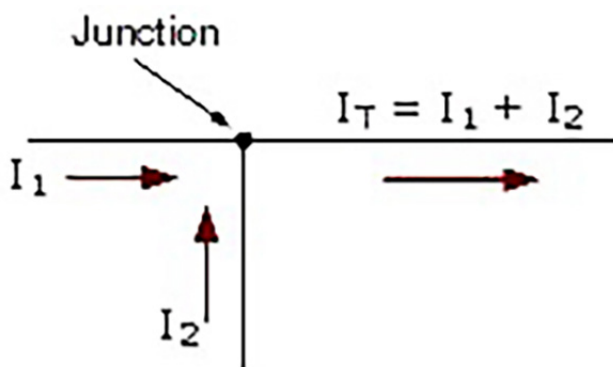


Fig. 2.11 Kirchhoff's current law (KCL)

Consider the circuit given in Fig. 2.11. In this example, the current I_T leaving the junction is the algebraic sum of the two currents, I_1 and I_2 entering the same junction. That is $I_T = I_1 + I_2$.

If the current entering a junction is taken as positive and the current

leaving the junction as negative then Kirchhoff's current law can be stated as "The algebraic sum of the currents meeting a junction is zero".

Consider the diagram shown in Fig. 2.12 in which the current I_1 and I_2 are entering the junction O and the currents I_3 , I_4 , and I_5 are leaving the junction.

Using Kirchhoff's current law (KCL)

$$I_1 + I_2 - I_3 - I_4 - I_5 = 0$$

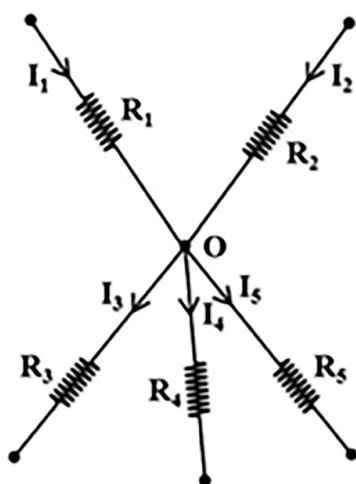


Fig. 2.12 Demonstration of KCL

Kirchhoff's Voltage Law (KVL)



Activity 2.5

Assemble two circuits as shown in Fig. 2.13 and Fig. 2.14.

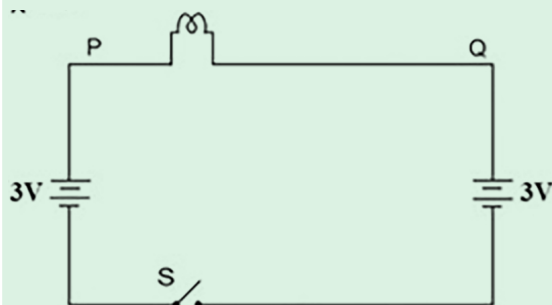


Fig. 2.13 Same potentials applied at both the ends

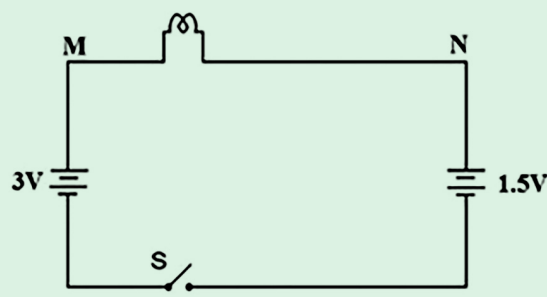


Fig. 2.14 Unequal potentials applied at the ends

- What do you observe?
- When the switches are closed, which bulb glows and which does not?
- Think why do these circuits behave differently.
- Justify your observation.

The bulb in the Fig. 2.13 does not glow since there is no potential difference between the points P and Q. In Fig. 2.14, the potential applied at the terminals of bulb (points M and N) are different. So, the current flows through the bulb and it glows. Thus, we can conclude that electric current can be established through a conductor only if there is a potential difference across its ends. Now, if the potential at M is increased, the bulb glows more and more brightly due to higher current flow. Try to do that.

Kirchhoff's voltage law can be stated as The algebraic sum of all voltages around any closed loop in an electrical circuit must be zero.

Illustration

Consider the following circuit. The following illustration will help you to understand it.

Here, the assumed current I causes a +ve drop of voltage when flowing from +ve to -ve potential while, -ve drop of voltage when current flows from -ve to +ve.

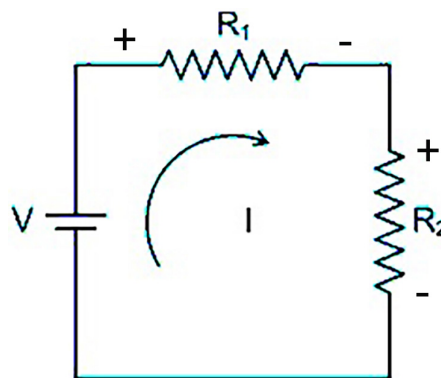
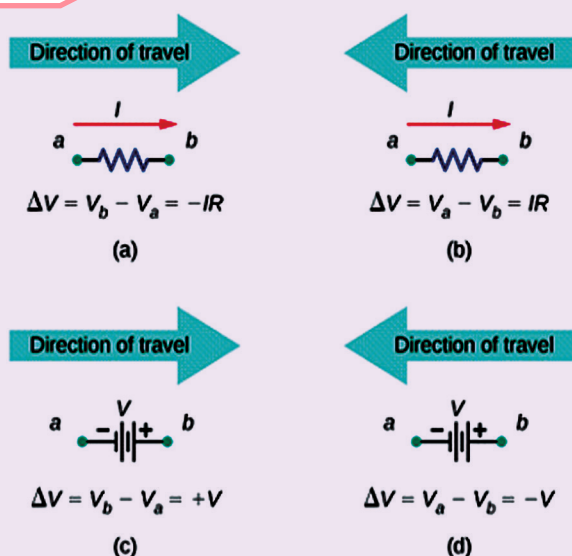


Fig. 2.15



Here, each of these resistors and voltage sources is traversed from a to b. (a) When moving across a resistor in the same direction as the current flow, subtract the potential drop. (b) When moving across a resistor in the opposite direction of the current flow, add the potential drop. (c) When moving across a voltage source from the negative terminal to the positive terminal, add the potential drop. (d) When moving across a voltage source from the positive terminal to the negative terminal, subtract the potential drop.

For the above circuit, if we apply KVL,

$$V - IR_1 - IR_2 = 0$$

$$V = IR_1 + IR_2$$

Here, the assumed current I causes potential drop across the resistor with the polarity as indicated in Fig. 2.15.



Know your progress

Find the current through each resistor in the following circuit.

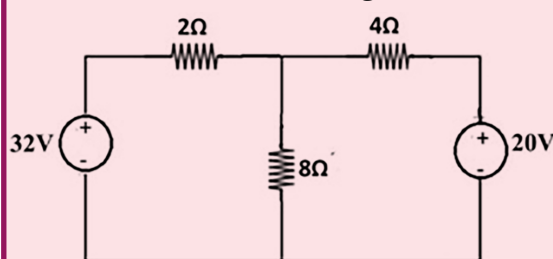


Fig 2.16

Solution

Let us solve this problem using KVL.

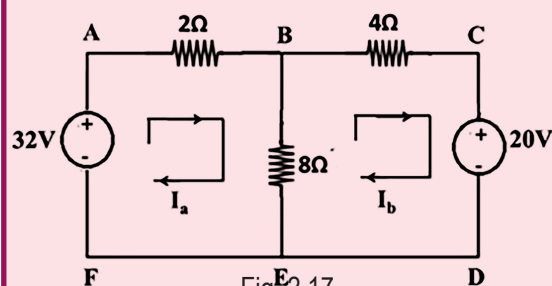


Fig 2.17

Applying KVL to loop ABEFA, $-2I_a - 8(I_a - I_b) + 32 = 0$

Applying KVL to loop BCDEB, $-4I_b - 20 - 8(I_b - I_a) = 0$

we can rewrite these equations as, $10I_a - 8I_b = 32$; $-8I_a + 12I_b = -20$

which can be solved to get, $I_a = 4A$, $I_b = 1A$

Current through $2\Omega = I_a = 4A$

Current through $8\Omega = I_a - I_b = 3A$

Current through $4\Omega = I_b = 1A$



Activity 2.6

Performing a physical lab experiment is a classic and effective way to verify Kirchhoff's laws using real components.

Verification of KCL and KVL: Connect a multi-loop circuit using resistors, a DC power supply, a breadboard, and connecting wires.

Measure currents at junctions (KCL): Use an ammeter to measure the currents entering and leaving a junction. Students can compare the measured values with theoretical calculations, observing minor deviations due to factors like component tolerances.

Measure voltages around a loop (KVL): Use a voltmeter to measure the voltage drops across each component in a closed loop. The sum of these voltages should be equal to the voltage of the power supply.

2.8 Voltage Sources and Current Sources

Voltage sources

Ideal voltage source

Consider a perfect voltage source whose internal resistance is zero. If there is no internal voltage drop in the voltage source, full voltage will appear across the load connected across it. Such a voltage source is an example of an ideal voltage source.

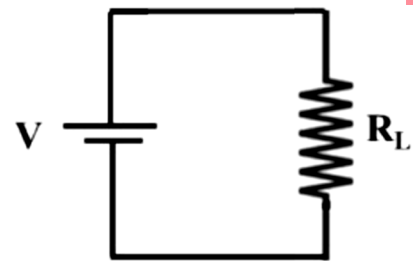


Fig. 2.18 Ideal voltage source

Practical voltage source

A practical voltage source is a more realistic model that includes an internal resistance R_s in series with an ideal voltage source V_s , causing the terminal voltage to decrease as more current is drawn from the source. Therefore, it should be understood that a real voltage source has some internal resistance.

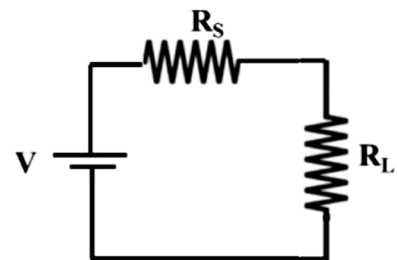


Fig. 2.19 Practical voltage source

Current sources

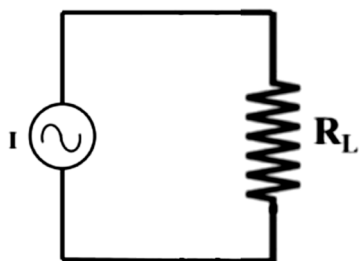


Fig. 2.20 Ideal current source

Ideal Current source

An ideal current source is a circuit that provides a constant, unvarying current to the load.

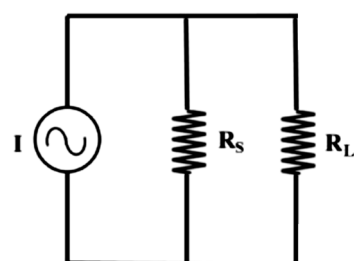


Fig. 2.21 Practical current source

Practical current source

A voltage source has a very small internal resistance while a current source has a very large internal resistance. Ideally, the internal resistance is infinity and hence the output current produced by a current source does not depend on the value of the load resistor.

The internal resistance of a real current source is always shown in parallel with the ideal current source.

Direct current (DC) and Alternating current (AC)

Electricity can move around a circuit in two different ways. In Fig 2.22(a), you can see electrons always going in the same direction. This type of electricity is called direct current (DC). Low-voltage DC powers most electronic gadgets, from smart phones to laptops, enabling a steady, consistent flow of power.

Direct current (DC)

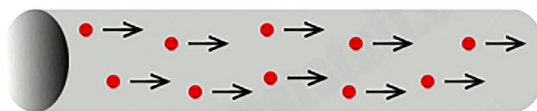


Fig 2.22(a)

Alternating current (AC)

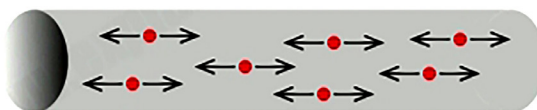


Fig 2.22(b)

The bigger appliances in your home including ceiling fans and electric ovens use a different kind of electricity called alternating current (AC). In AC circuits the electrons constantly reverse direction Fig 2.22(b)—about 50–60 times every second. AC is used for long-distance power transmission because high voltages result in lower currents, which reduce energy loss due to heat.

Alternating current (AC)

We know that the voltage supplied by a battery is DC voltage and that supplied by the house-hold distribution system is AC voltage. Alternating Current or Voltage varies in magnitude and its terminal polarity reverses periodically. It means that the alternating current will flow first in one direction and then in the opposite direction.

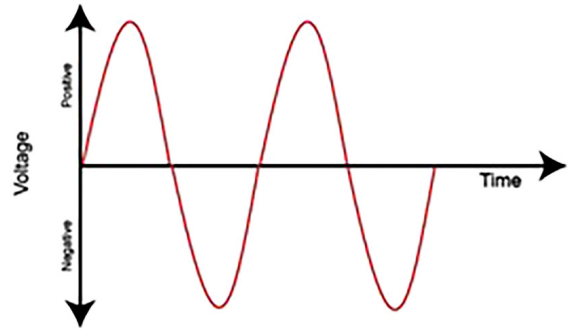


Fig. 2.23

2.9 Amplitude, Frequency and Phase

Graphical representation of sine wave

An alternating voltage or alternating current can be characterised by amplitude, frequency and phase

Amplitude

The maximum value (V_m) of an alternating quantity on either the positive side or the negative side is known as its amplitude.

Peak To Peak Value (V_{pp})

It is the sum of positive peak and negative peak values

$$V_{pp} = 2V_m$$

Cycle

One complete set of positive and negative half cycles can be termed as a cycle.

Time Period

The time taken by an alternating current or voltage to complete one cycle is known as time period (T).

$$\text{Time Period } T = \frac{1}{f}$$

where f is the frequency

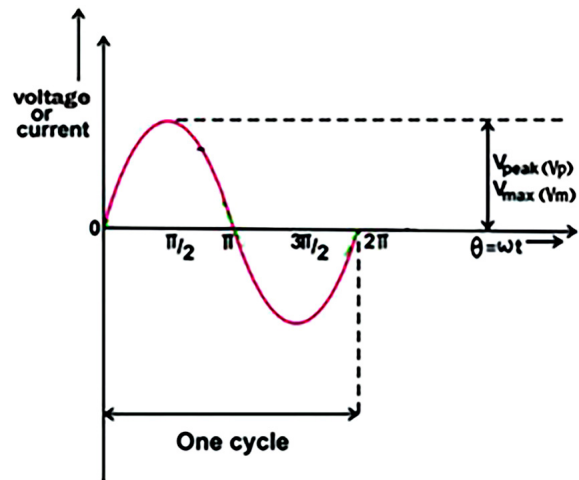


Fig 2.24 Sinusoidal waveform

Frequency

The number of cycles completed by an alternating current in one second is known as the frequency (f) of AC.

It is generally expressed in Hertz (Hz) or in cycles per second.

$$\text{Frequency } F = \frac{1}{T}$$

As we know, the household AC supply has a frequency of 50 Hz.

Phase

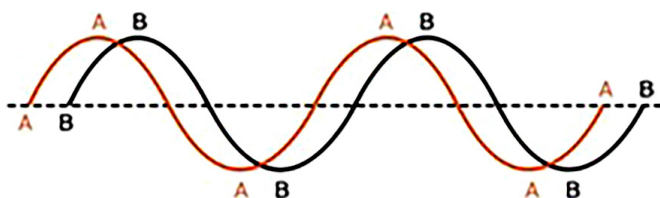
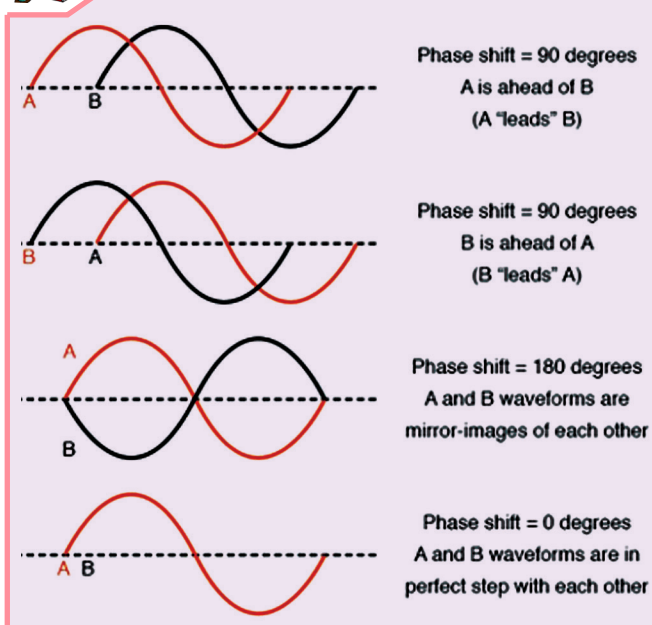


Fig. 2.25 Phase shift between two signals



Phase describes the position of a point in a cycle of a repeating waveform or motion, and it is often expressed as an angle, in degrees or radians. It represents a wave's state at a specific time and location, indicating its position within a cycle, whether it's at a crest, trough, or some point in between.

The two waves shown in Fig. 2.25 (A versus B) are of the same amplitude and frequency, but they are out of step with each other. In technical terms, this is called a phase shift. Phase can also describe the relative difference between two waves of the same frequency, indicating how one wave is shifted in time or space compared to the other.

A sine wave can be represented by the expression $v = V_m \sin (2\pi ft + \theta)$ where V_m is the peak or maximum amplitude, f is the frequency of the wave and θ is the phase angle. If the waveform starts at zero amplitude

at zero time the phase is zero. If it starts at any other value the corresponding angle will be the phase angle of the waveform.

2.10 Average and RMS Values of AC

Instantaneous value of AC

It is the value of the alternating signal at any instant of time measured

from some reference point. It can be any value between positive maximum value and negative maximum value. It is represented by 'i' or 'v' and is mathematically represented as:

$$i = I_m \sin \theta$$

$$v = V_m \sin \theta$$

$$i = I_m \sin \omega t$$

$$v = V_m \sin \omega t$$

$$i = I_m \sin 2\pi f t$$

$$v = V_m \sin 2\pi f t$$

$$\theta = \omega t = 2\pi f t$$

Average value of AC

AC voltage varies with time. The average value will give the DC equivalent voltage corresponding to the AC voltage. The average value of a sine wave over a cycle is zero. It can be found over a half cycle.

$$V_{\text{average}} = \frac{1}{T/2} \int_0^{T/2} V_0 \sin \omega t \, dt$$

On integration and then by substituting $\omega = 2\pi/T$ it can be seen that

$$V_{\text{average}} = \frac{2V_m}{\pi}$$

But, the average value or mean value of AC does not give accurate values when used to calculate energy changes associated with AC. So, it is needed to go for a more suitable value. It will be more accurate if we define the effective value of AC in terms of heating effect because for both the half cycles the amount of heat developed are equal for a full cycle and it does not average to zero.

Root Mean Square (RMS) values of AC

The RMS or Root Mean Square values of AC is defined as the DC equivalent which produces the same amount of heat energy in the same time as that of an AC, while flowing through a resistance. The heat developed for a small interval of time dt is $dH = p \, dt$, where p is the power developed in time dt .

Total heat energy developed for a full cycle of AC is

$$\begin{aligned} H &= \int_0^{T/2} P \, dt \\ &= \int_0^{T/2} I^2 R \, dt \\ &= \int_0^{T/2} I_m^2 (\sin^2 \omega t) R \, dt \end{aligned}$$

On integration, it can be seen that

$$H = I_m^2 \frac{T}{2} R \dots\dots\dots(1)$$

If a DC current I_{rms} produces the same amount of heat

$$H = I_{rms}^2 RT \dots\dots\dots(2)$$

Equating (1) & (2)

$$I_{rms} = \frac{I_m}{\sqrt{2}}$$

Rms value of current or voltage of AC can also be defined as the square root of the mean of the squares of all instantaneous values over one complete cycle.

? Know your progress

The instantaneous value of an AC voltage is represented by $V = 141 \sin(314t)$. Find its frequency and rms values.

Solution

$$V_o = 141 \text{ V}$$

$$2\pi f = 314$$

$$f = \frac{314}{2\pi} = 50 \text{ Hz}$$

$$V_{rms} = \frac{V_o}{\sqrt{2}} = \frac{141}{1.41} = 100 \text{ V}$$



Activity 2.7

Try to get a 6V output from the 230V 50 Hz supply using a 230/6V transformer in your school electronics laboratory. Use a CRO to measure and analyse this 6V AC. Observe the AC waveform obtained & measure the maximum value of voltage and its frequency. Calculate the rms value.

- How do you calculate the exact value of maximum voltage, from the waveform obtained on the CRO?
- Is the maximum value greater than the transformer secondary voltage which is 6 V?
- Which among the following is the AC voltage (6 V) obtained from the secondary terminals of the transformer?
(a) rms (b) average (c) maximum
- Measure transformer secondary voltage using a multi meter and note down the value observed.



Know your progress

What is the significance of rms value of AC?

2.11 Concept of Impedance

As you know, AC is preferred for all commercial and domestic purposes because AC can be economically transmitted over long distances. Other than ohmic resistance (R) the presence of inductances (L) or capacitances (C) significantly affects the flow of alternating current. Similar to the ohmic resistance (R) the opposition to the current flow offered by the inductance (L) of an inductor is called the inductive reactance (X_L) and that offered by the capacitance of a capacitor is called the capacitive reactance (X_C). Resistance, inductive reactance and capacitive reactance are measured in ohms.

Impedance is a measure of overall opposition of a circuit to the current flow through it. It is like resistance but it also takes into account, the effects of capacitance and inductance.

AC circuit with resistance only

Consider the circuit in Fig. 2.26 in which only ohmic resistance is present.

As you have already studied the instantaneous value of voltage

$$V = V_m \sin \omega t \text{-----(1)}$$

Since $I = V/R$, the instantaneous value of current through this circuit

$$I = V_m \sin \omega t / R$$

Since $\frac{V_m}{R} = I_m$, the maximum value of current.

the above equation can be written as

$$I = I_m \sin \omega t \text{-----(2)}$$

From equation (1) and (2), it can be noted that the current and voltage are in the same phase.

Now, let us analyse an AC circuit with an inductor of inductance L only.

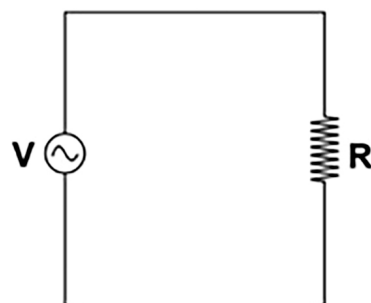


Fig. 2.26 AC circuit with resistance only

AC circuit with inductance only

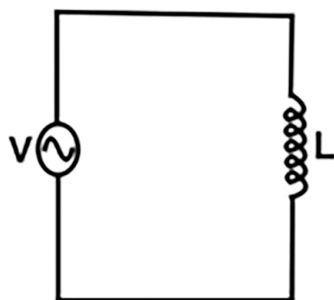


Fig. 2.27 AC circuit with inductance only

In the circuit given in Fig. 2.27, a potential difference of $v = V_m \sin \omega t$ is applied across an inductor of inductance 'L' Henry. You know that according to Faraday's law of electromagnetic induction, coil produces an induced emf

$$e = -\frac{d\phi}{dt}$$

Where ϕ is flux

$$\phi = -L \frac{di}{dt}$$

since $\phi = LI$

For the above loop as per KVL

$$V_m \sin \omega t - L \frac{di}{dt} = 0$$

$$\frac{di}{dt} = \left(\frac{V_m}{L} \right) \sin \omega t$$

$$\text{Therefore, } I = \int \left(\frac{V_m}{L} \right) \sin \omega t dt$$

$$I = \frac{V_m}{\omega L} (-\cos \omega t)$$

But, using trigonometric identity

$$\sin (90 - \omega t) = \cos \omega t$$

$$\text{Or } \sin (\omega t - 90) = -\cos \omega t$$

If I_m is the maximum value of current through the inductor

$$I = I_m \sin (\omega t - 90) \text{ where } I_m = \frac{V_m}{\omega L}$$

The equations for current and voltage show that the current through the inductor lags behind the voltage by 90 degree or $\frac{\pi}{2}$ radians.

The ratio of the peak value of voltage across the inductor to the peak value of current through it is a constant and is called the inductive reactance (X_L) which is similar to the resistance.

$$X_L = \frac{V_m}{I_m} = L\omega = 2\pi fL \text{ where } \omega = 2\pi f$$

Therefore, it is seen that the inductive reactance depends on the supply frequency. i.e., X_L is directly proportional to the frequency. The unit of inductive reactance X_L is ohm itself. It can be concluded that for a purely inductive circuit the current lags behind the voltage by 90 degrees or $\pi/2$ radians.

AC circuit with capacitance only

In the circuit in Fig. 2.28 the supply voltage $V = V_m \sin \omega t$ is applied across a capacitor of capacitance C .

The charge on the capacitor at any instant

$$q = CV_m \sin \omega t$$

You have already studied that the current through a capacitor is equal to the rate of change of charge on it.

$$i = \frac{dq}{dt} = \frac{d}{dt} (CV_m \sin \omega t)$$

using differentiation it can be seen that

$$i = CV_m \omega \cos \omega t$$

Using trigonometric relations

$$\cos \omega t = \sin \left(\omega t + \frac{\pi}{2} \right)$$

Therefore, the above equation becomes

$$i = CV_m \omega \sin \left(\omega t + \frac{\pi}{2} \right)$$

$$i = I_m \sin \left(\omega t + \frac{\pi}{2} \right)$$

Where
$$I_m = \frac{V_m}{\left(\frac{1}{\omega C} \right)}$$

From the above expression for voltage and current it is clear that the current through the capacitor leads the voltage by $\frac{\pi}{2}$ radians or 90 degrees.

Now, for a given frequency, the ratio of the maximum value of voltage to the maximum value of current for a capacitor is a constant and is called the capacitive reactance X_C .

Now, let us discuss how the combination of L , C and R behaves in an AC circuit.

AC circuit with resistance, capacitance and inductance

Try to analyse the circuit in Fig. 2.29.

Here, inductor, capacitor and resistor are connected in series across a supply of E volts.

The amplitude of voltage across R , $V_R = I_m R$ and as seen earlier, it is in phase with the current.

The amplitude of voltage across C , $V_C = I_m X_C$, leads the current by $\pi/2$ radians.

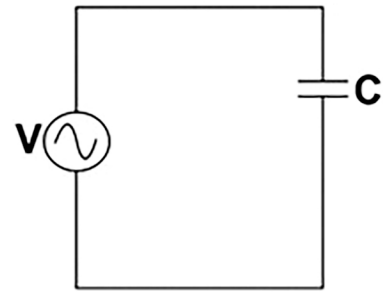


Fig. 2.28 AC circuit with capacitance only

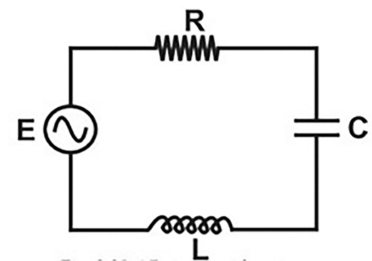


Fig. 2.29 AC circuit with resistance, capacitance and inductance

The amplitude of voltage across L, $V_L = I_m X_L$, which lags the current by $\pi/2$ radians

The effective potential difference

$$V = V_R^2 + (V_C - V_L)^2$$

Therefore, the peak value of this voltage

$$\begin{aligned} V &= \sqrt{I_m R^2 + (I_m X_C - I_m X_L)^2} \\ &= I_m \sqrt{R^2 + (X_C - X_L)^2} \end{aligned}$$

From this equation it can be noted that the ratio of peak value of voltage to the peak value of current is a constant for a given frequency. This constant is called the impedance of the circuit whose unit is ohm itself.

$$\text{So, impedance } Z = \frac{V_m}{I_m} = \sqrt{R^2 + (X_C - X_L)^2}$$

If $X_C = X_L$ the circuit is purely resistive.

Impedance (Z) can also be indicated in the complex form with a real part R (resistor) in series with an imaginary part $+jX_L$ for inductor and $-jX_C$ for capacitor.

$Z = R + jX_L$ if the circuit contains a resistor R and a coil which offers a reactance X_L

$Z = R - jX_C$ if the circuit contains a resistor R and a capacitance which offers a reactance X_C .

In an RLC series circuit what should be the frequency of supply so that the inductive reactance is equal to the capacitive reactance? In such a condition, what will be the impedance of the circuit?

For Inductive reactance = Capacitive reactance

$$X_L = X_C \quad \text{ie, } 2\pi fL = \frac{1}{2\pi fC}$$

$$f^2 = \frac{1}{(2\pi)^2 \times LC} \quad \text{or } f = \frac{1}{2\pi\sqrt{LC}}$$

At this frequency

$$Z = \sqrt{R^2 + (X_C - X_L)^2}$$

$$Z = \sqrt{R^2 + 0}$$

$$Z = R$$

So, the impedance of the circuit is minimum and is equal to the resistance of the circuit. In this case, when the inductive reactance becomes equal to the capacitive reactance at a particular frequency, the RLC circuit is said to be at **resonance**.

Semiconductor Fundamentals

We are familiar with electronic devices like calculator, television and mobile phone. If we examine electronic devices, we can see diodes, transistors, resistors, capacitors, inductors, transformers and ICs. We have already studied about resistors, capacitors, inductors and transformers. But, diodes and transistors which are made from semiconductors are new to us. An integrated circuit (IC), or simply a chip, is a tiny electronic device that combines a complete circuit, including many diodes, resistors, transistors, capacitors, etc., on to a single, small piece of semiconductor material, usually silicon. ICs are the fundamental building blocks of almost all modern electronic devices from computers and smartphones to cars and toasters.

Semiconductors are the basic materials used in constructing electronic devices like junction diodes, transistors and integrated circuits. Research on semiconductor materials started in the early nineteenth century. The most commonly used semiconductor materials are Silicon (Si) and Germanium (Ge). Also, there are compound semiconductors like Gallium Arsenide (GaAs) and Gallium Phosphide (GaP). Such composite semiconductors have special electrical or optical properties.

In the 1950s, Ge was the most commonly used material. However, it is not suitable for high temperature applications. Later Si was more preferred to Ge because of its better temperature stability, lower cost, strong crystal structure and availability.

3.1 Energy Level Diagram

In Bohr's atomic model, each electron orbit is associated with a specific fixed energy. An electron moving in a particular orbit has the quantity of energy corresponding to the orbit (Fig. 3.1). The farther an orbit is from the nucleus, the greater is its energy. Therefore, electrons in the outer orbits have more energy than those in the inner orbits. In an isolated atom, the different energy levels of electrons in various orbits can be represented by each corresponding to a specific energy level. This diagram which visually represents the quantized energy level of an atom, is called an Energy Level Diagram (ELD). Fig. 3.2 shows the energy level diagram of an isolated atom. In this diagram, E_1 represents the energy of the first orbit, E_2 that of the second orbit, and so on.

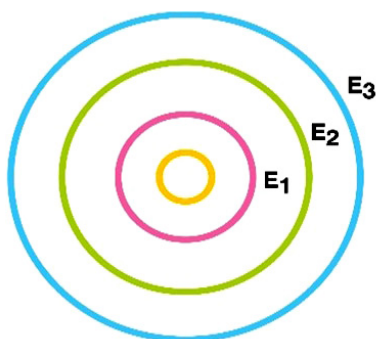


Fig. 3.1 Structure of an atom

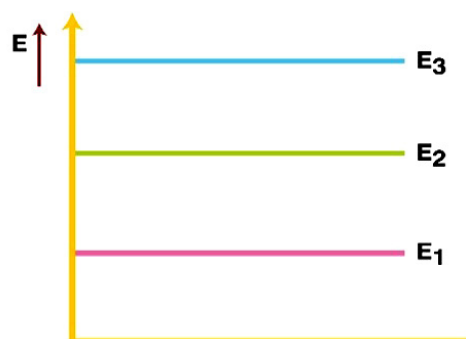


Fig. 3.2 Energy level diagram



NIELS BOHR

In 1913, Niels Bohr, a Danish physicist gave the explanation of atomic structure. According to him an atom consists of a positively charged nucleus surrounded by negatively charged electrons revolving in different fixed orbits. The number of electrons in each orbit is fixed. Hence, the number of electrons in an isolated atom that can possess a particular energy value is also fixed.

3.2 Energy Bands in Solids

So far, we have considered the energy levels of electrons in a single, isolated atom. Atoms of gases can be considered isolated because of their greater spacing under normal pressure and temperature. Hence, the energy levels of such atoms are not affected by other distant atoms. But, there are significant changes in the energy levels when atoms exist close together as in solids. In a solid, the orbit of an electron is influenced not only by the charges in its own atom, but by electrons of every atom in the solid. When atoms come

closer, the electrons also come closer and even overlap. Because of this interaction, the energy levels are split up. These energy levels are discrete, but closely spaced forming almost a continuous range of energy called energy band. We also know that the number of electrons in the outermost orbit decides valency. These valence electrons are not free to move about from one point to another. If they get sufficient energy, they can reach higher energy levels so that they become free to move about. This results in electrical conduction.

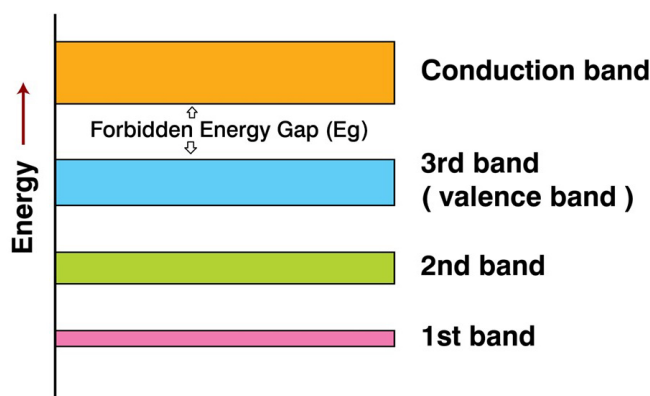


Fig. 3.3 Energy band diagram

Valence Band

The electrons in the outermost orbit of an atom are called valence electrons. The energy band occupied by the valence electrons is called valence band. The valence band may be either completely filled or partially filled, but can never be empty.

The range of energies possessed by valence electrons is known as valence band.

Conduction Band

The electrons which have left the valence band are called conduction (free) electrons. The range of energy occupied by these electrons is called conduction band. This band lies next to the valence band. It may be either empty or partially filled with electrons. In a conduction band, electrons move freely and conduct current through the solid.

The range of energies possessed by conducting electrons is known as conduction band.

If a substance has an empty conduction band, it means that the current conduction is not possible in that substance. Generally, in insulators the conduction band is empty. On the other hand, in conductors it is partially filled.

Forbidden Energy Gap

Electrons cannot take the energy level in between valence band and conduction band. The separation between the conduction band and valence band in the energy band diagram is known as forbidden energy gap, band gap or ' E_g '.

The width of the energy gap is a measure of the bondage of valence electrons to the atom. The greater the energy gap, the more tightly the valence electrons are bound to the nucleus. In order to push an electron from the valence band to the conduction band, external energy equal to the forbidden energy gap must be supplied.

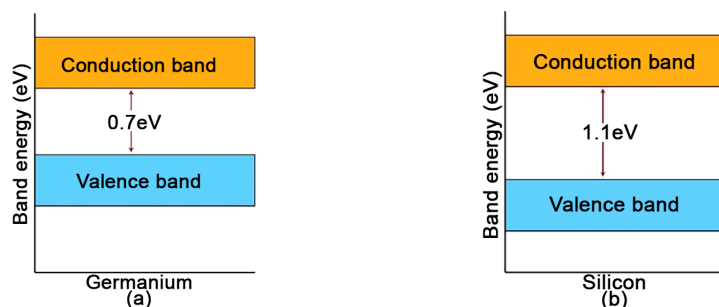


Fig. 3.4 Energy band diagram of (a) Germanium and (b) Silicon



Know your progress

1. Explain why the discrete energy levels of an isolated atom is split into a band of energy when atoms combine together to form a solid.
2. Define valence band, conduction band and forbidden energy gap.

3.3 Classification of Solids

The electrical conduction properties of solids can be explained on the basis of forbidden energy gap. Based on this, materials can be classified into three - conductors, semiconductors and insulators. Fig. 3.5 shows the energy band diagram of different solids.

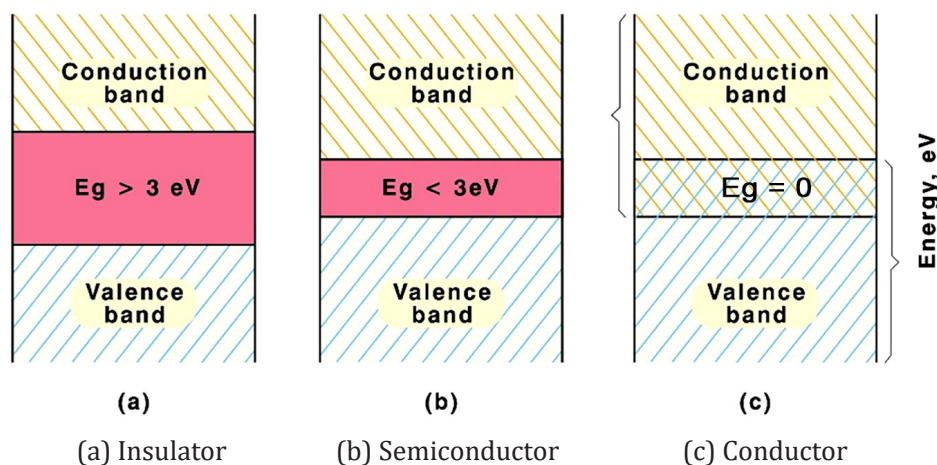


Fig. 3.5 Energy band diagrams of solids

Insulators

An insulator (e.g., wood, glass) has a large forbidden energy gap (usually $> 3\text{eV}$) as shown in Fig. 3.5 (a). The electrons are found only in the valence band at room temperature.

To achieve conductivity, electrons from the valence band have to move into the conduction band. This is not possible in insulators because of a large forbidden energy gap.

Conductors

Conductors (e.g., copper, aluminium) have

- overlapping valence and conduction bands
- plenty of free electrons in the conduction band

In conductors there is no band gap between the valence band and conduction band. Due to this, even a slight potential difference across the conductor is enough to move the free electrons, resulting in electric current.

Semiconductors

A semiconductor is one whose electrical properties lie in between insulators and conductors (e.g., Silicon and Germanium).

Semiconductors at room temperature have a very narrow forbidden energy gap (for Germanium, $E_g = 0.7\text{ eV}$; and for Silicon, $E_g = 1.1\text{ eV}$). At zero kelvin, there are no electrons in the conduction band of semiconductors, whereas their valence band is completely filled. Therefore, at absolute zero temperature, a semiconductor behaves as an insulator. However, with increase in temperature, electrons get lifted from the valence band to the conduction band. These free electrons can move towards the conduction band, since the energy gap is small. Therefore, at room temperature, semiconductors are capable of conducting some electrical current.



Activity - 3.1

Create a table of matching words using the following terms

Plastic, Energy gap very small ($< 3\text{ eV}$), Conductor, Energy gap very large ($> 3\text{ eV}$), Valence band & Conduction band overlap, Gold, Silicon, Insulator, Semiconductor, Continuous current flow, No current flow, Partial conductivity

- From the table, note down your observations based on what you have learned in the above section.
- Among rubber, copper or silicon, which material needs the highest amount of energy to move an electron from the valence band to the conduction band? Why is it so?

Now, check whether your table matches with that given below.

Insulator	Semiconductor	Conductor
Plastic	Silicon	Gold
Energy gap very large (>3 eV)	Energy gap very small (<3 eV)	Valence band and conduction band overlap
No current flow	Partial conductivity	continuous current flow



Know your progress

Distinguish between conductors, insulators and semiconductors on the basis of energy band diagram.

3.4 Bonds in Semiconductors

The atoms of every element are held together in a molecule by the bonding action of valence electrons. This bonding action is due to the fact that there is a tendency for each atom to complete its outermost orbit by acquiring 8 electrons in it. However, in most of the elements, the outermost orbit is incomplete. In order to acquire 8 electrons in the outermost orbit, atoms share electrons with other

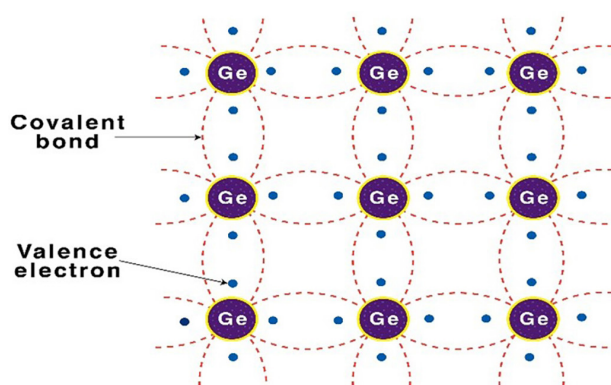


Fig. 3.6 Germanium Bond structure

atoms. To do so, the atom may donate, accept or share valence electrons with other atoms. In semiconductors, bonds are formed by sharing valence electrons. Such bonds are called covalent bonds. In the formation of a covalent bond, each atom contributes an equal number of valence electrons and the contributed electrons are shared by the atoms engaged in the formation of the bond.

Fig. 3.6 shows the covalent bonds among Germanium atoms. A Germanium atom has four valence electrons. There is a tendency in each Germanium atom to have eight electrons in the last orbit. To do so each Germanium atom positions itself between four other

Germanium atoms as shown in Fig. 3.6. Each neighboring atom shares one valence electron with the central atom. In this way, the atom completes its outermost orbit by having eight electrons revolving round the nucleus.

3.5 Commonly Used Semiconductors

There are many semiconductors available, but very few of them have practical applications in electronics. The two commonly used materials are Germanium (Ge) and Silicon (Si). In Ge and Si, the energy required to break the covalent bond (energy required to release an electron) is very small. For Ge, it is 0.7 eV and for Si it is 1.1 eV.

(i) Germanium

Germanium is a metalloid and is recovered from the ash of certain coals. Generally Germanium is recovered in the form of germanium dioxide powder which is then purified by chemical reduction techniques.

The atomic number of Germanium is 32. Therefore, it has 32 protons and 32 electrons. Two electrons are in the first orbit, eight electrons in the second, eighteen electrons in the third and four electrons in the outer or valence orbit (See Fig. 3.7). It is clear that a Germanium atom has four valence electrons making it a tetravalent element.

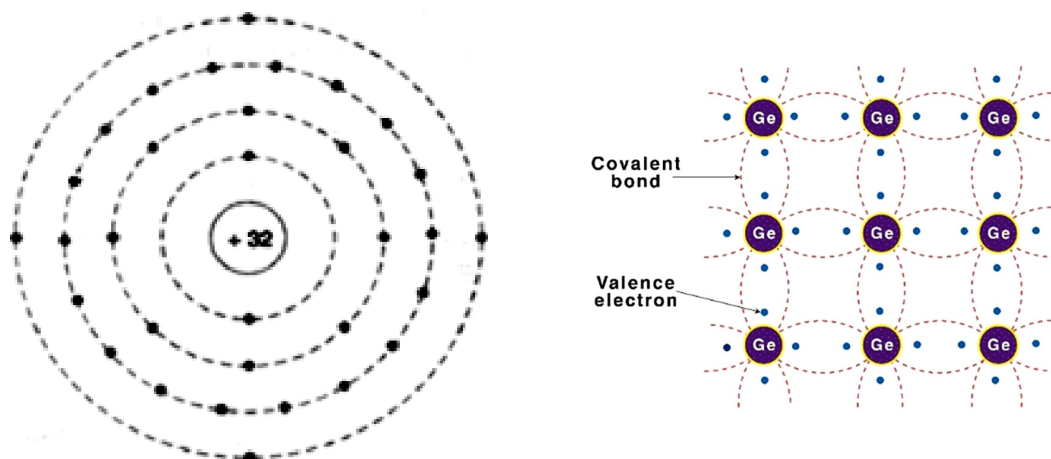


Fig. 3.7 (a) Atomic structure and (b) bonding of Germanium

(ii) Silicon

Silicon compounds are commonly available in the form of sand (silicon dioxide). Silicon is obtained by purifying Silicon dioxide by chemical reduction techniques.

The atomic number of Silicon is 14. Two electrons are there in the first orbit, eight electrons in the second orbit and four electrons in the valence orbit. It is clear that the Silicon atom has four valence electrons, that is, it is tetravalent. Fig. 3.8 shows how various Silicon atoms form covalent bonds.

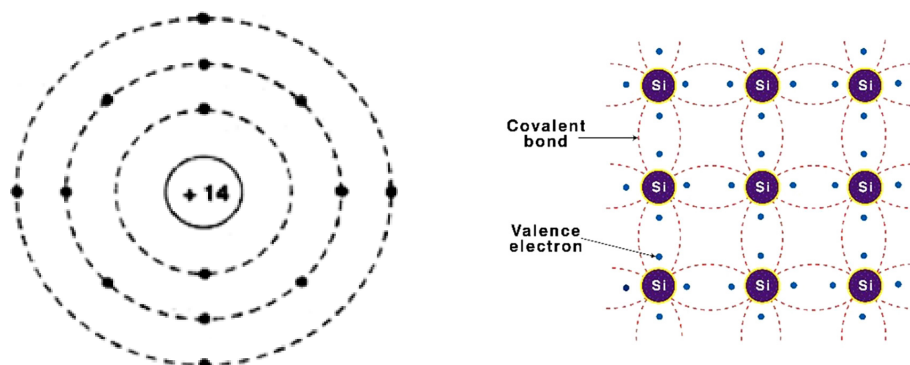


Fig. 3.8 (a) Atomic structure and (b) bonding of silicon

Silicon is preferred over Germanium for making semiconductor components because it is more stable, cheaper, and easily available in nature. It can operate efficiently at higher temperatures without getting damaged, while Germanium devices produce more leakage current and become less reliable when heated. Silicon also forms a strong layer of silicon dioxide (SiO_2) on its surface, which is very useful in making transistors and integrated circuits. These advantages make silicon the best choice for most of the semiconductor devices.

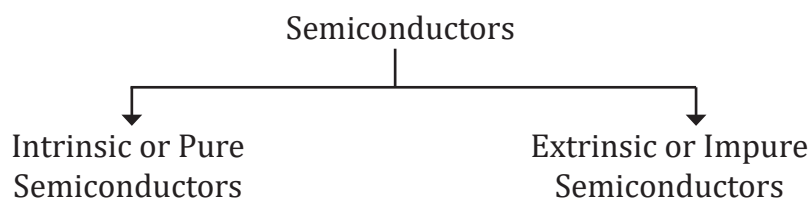


Know your progress

1. Name two commonly used semiconductors. Write the values of forbidden energy gaps of those semiconductors.
2. Explain the reason why the conductivity of Germanium is more than that of Silicon at room temperature.

3.6 Types of Semiconductors

Semiconductors may be classified as shown below.



Intrinsic Semiconductors

Semiconductors in their extremely pure form are called intrinsic semiconductors. At 0 K they behave as insulators because there are no free electrons. At room temperature a few electrons get sufficient energy to break the covalent bond. These electrons can move freely and act as charge carriers. A vacancy is created in the covalent bond when a free electron is formed and this vacancy is called a hole. Holes in the valence band can be filled by other electrons in the valence band. This results in the movement of holes in the valence band. These holes can be viewed as positive charge carriers.

In intrinsic semiconductors the number of holes is equal to the number of free electrons. The free electrons exist in the conduction band and holes exist in the valence band.



Know your progress

Why do semiconductors behave as insulators at absolute zero temperature?

Movement of Holes in Semiconductors

If an electron in the valence band gets sufficient energy, it can jump across the forbidden energy gap and enter the conduction band. Suppose covalent bond A breaks due to the external energy received by the atom and an electron is released. A hole is left behind in the valence band. Under favourable conditions, the electron from another covalent

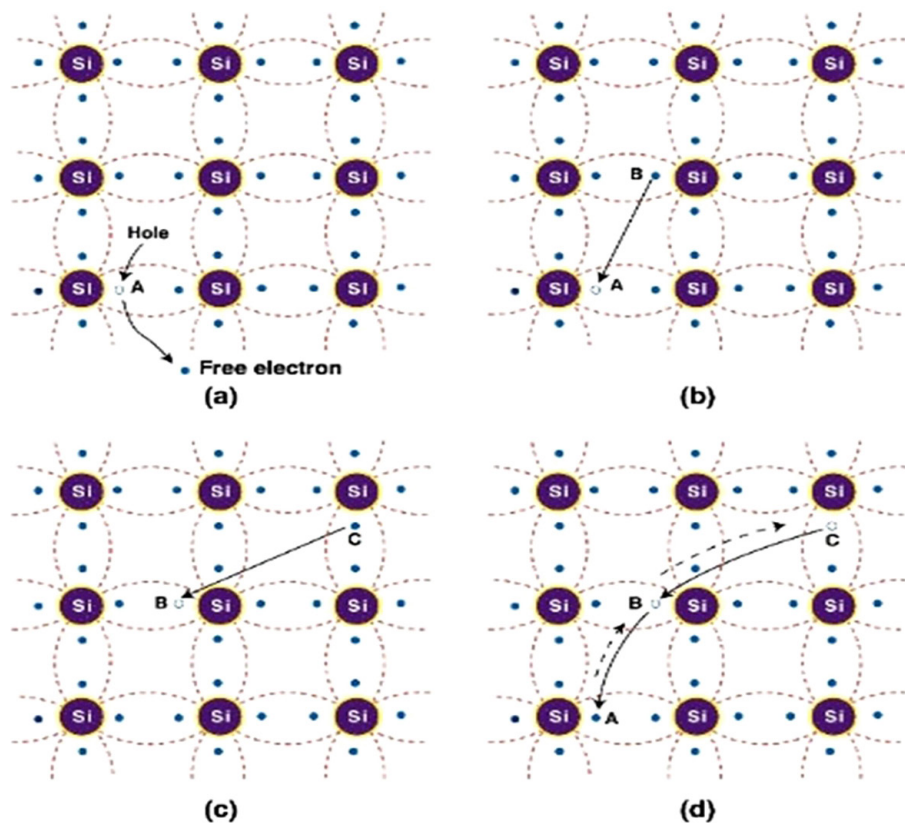


Fig. 3.9 Movement of Holes in Semiconductors

bond B jumps into the hole in A. This fills the original hole but creates a new hole in B. Then an electron from another bond C jumps into the hole in B and so on. In this way, a succession of electron movement takes place. So, we can say that the hole is moved from A to C. Even if the actual movement is by electrons, for convenience we will consider it as hole movement.

It should be noted that holes are filled by electrons which move from adjacent atoms without passing through the forbidden energy gap. It means that the hole movement takes place in valence band only. No additional hole is created if an existing hole is filled by an adjacent electron.

Let us conclude the above facts as follows:

1. Holes exist in and flow in the valence band.
2. Conduction electrons are found in and flow in the conduction band.
3. Hole current is in the valence band and electronic current is in the conduction band.
4. Conduction electrons move twice as fast as the holes.



Know your progress

Define a hole. Explain how hole movement takes place in a semiconductor.

Extrinsic Semiconductors

As you have seen earlier, a pure form of semiconductor is a bad conductor of electricity because of the small number of thermally generated charge carriers which are free to move about. Therefore, in order to have conduction, more free charge carriers have to be created in the crystal structure. This can be achieved by adding suitable materials (impurity) to pure semiconductors. Impurity added semiconductors are called extrinsic semiconductors. The process of adding impurities to a semiconductor is known as **doping**. Now let us discuss how these free charge carriers are formed when impurity atoms are added.

The purpose of adding impurity is to increase either the number of free electrons or holes in the semiconductor. If a pentavalent impurity (having 5 valence electrons) is added to a semiconductor,

free electrons are produced in the semiconductor. On the other hand, addition of trivalent impurity (having 3 valence electrons) creates holes in the crystal. Depending on the type of impurity added, extrinsic semiconductors are classified into:

- (i) N- type semiconductor
- (ii) P- type semiconductor

N-Type Semiconductors

N - type semiconductors are obtained by adding pentavalent impurities (Bismuth, Antimony, Arsenic and Phosphorous) to a pure semiconductor. The four valence electrons of impurity atom form covalent bond with four neighbouring semiconductor atoms and the fifth electron is free to move in the crystal. Thus, the addition of pentavalent impurity atom provides free electrons to the semiconductor.

The pentavalent impurities which produce N-type semiconductor are known as donor impurities because they donate or provide free electrons to the semiconductor crystal.

In an N- type semiconductor, a large number of free electrons are created by doping that improves its conductivity. But, there will be a very small number of free holes created because of thermal agitation. Free electrons are much more in number and so they can be termed as majority carriers and holes are comparatively much less. Hence, they can be termed as minority carriers. Therefore, in N-type semiconductor electrons are the majority charge carriers and holes are the minority charge carriers.

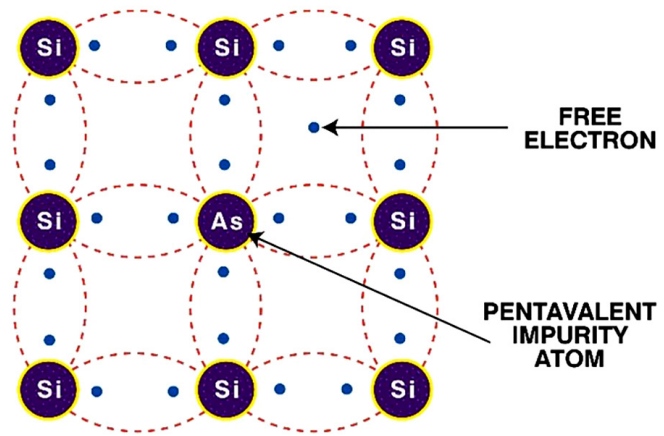


Fig. 3.10 N type semiconductor

P - Type Semiconductors

P-type semiconductors are obtained by adding trivalent impurities (Boron, Gallium, Indium, Aluminum) to a pure semiconductor. The three valence electrons of the impurity atom form covalent bonds with four neighbouring semiconductor atoms and the fourth covalent bond has a vacancy. This gives rise to a hole in the semiconductor. Thus, the addition of a trivalent impurity atom creates holes in the

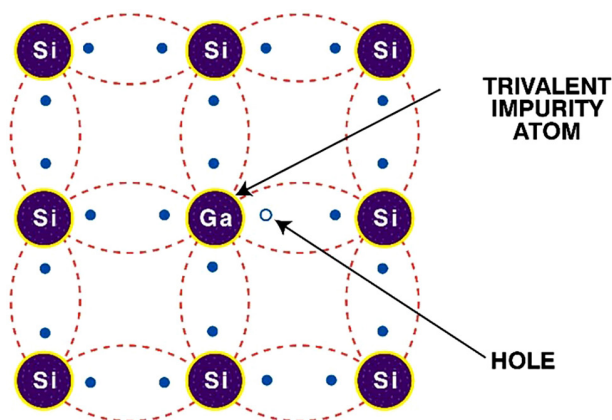


Fig. 3.11 P type semiconductor

semiconductor. The trivalent impurities that produce P-type semiconductors are known as acceptor impurities, because the holes created can accept electrons.

In a P-type semiconductor, a large number of free holes are created by doping which improves its conductivity. However, there will be a very small number of free electrons created because of thermal

agitation. Free holes are much more in number and so, they can be termed as majority carriers. Here, free electrons are comparatively less. Hence, they can be termed as minority carriers. Therefore, in P-type semiconductors holes are the majority charge carriers and electrons are the minority charge carriers.

As discussed earlier, the N-type semiconductor has an excess of electrons and the P-type semiconductor has an excess of holes. Do you think that the N-type semiconductor has a net negative charge and P-type semiconductor has a net positive charge? The term excess in this context means that the number of electrons is more than that required to fill the valence band. It does not mean that the total number of electrons is more than the number of protons. So, P type and N type semiconductors are electrically neutral.



Know your progress

1. Explain the need of adding an impurity to an intrinsic semiconductor.
2. What are the majority carriers in an N-type semiconductor?
3. What do you understand by intrinsic and extrinsic semiconductors?

Properties of P-Type and N - Type Materials

P – type material	N – type material
- Semiconductor material is doped with acceptor (trivalent) impurity atoms. - Material has high hole concentration. - Concentration of free electrons in P-type material is very low. - Contains negatively charged acceptor ions (immobile) and positively charged holes.	- Semiconductor material is doped with donor (pentavalent) impurity atoms. - Material has high electron concentration. - Concentration of holes in N-type material is very low. - Contains positively charged donor ions (immobile) and negatively charged electrons (free).

3.7 Charge Carrier Transportation in Semiconductors

The movement of charge carriers in a semiconductor material is classified as diffusion and drift. Diffusion is a charge transportation mechanism taking place because of the concentration gradient. On the other hand, the drift in a charge carrier movement is under the influence of an electric field. Majority carriers have both drift and diffusion transportation whereas minority carriers undergo only drift.

The majority charge carriers are created by doping and the minority charge carriers are formed due to other reasons such as thermal agitation.



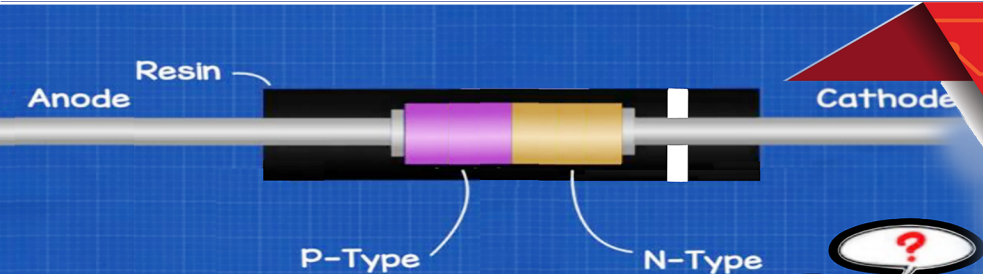
Activity 3.2

Complete the following table.

N type semiconductors	P type semiconductors
	Trivalent impurity atoms are added to intrinsic semiconductors.
Excess electrons improve conductivity.	
	Electrons are minority carriers.

- Due to doping which type of carriers are created - majority or minority?
- Give examples for the two types of impurity atoms mentioned in the table. Now, you can verify whether your solution matches with the following.

N type semiconductors	P type semiconductors
Pentavalent impurity atoms are added to intrinsic semiconductors.	Trivalent impurity atoms are added to intrinsic semiconductors.
Excess electrons improve conductivity.	Excess holes improve conductivity.
Holes are minority carriers.	Electrons are minority carriers.



4

How does it work?



Semiconductor Diode

Introduction

In the previous unit, we studied about N-type and P-type semiconductors. Now, let us see what happens when we join a P-type semiconductor to an N-type semiconductor. This can be done by a special fabrication technique. When a P-type semiconductor is suitably joined to an N-type semiconductor, the contact surface is called P-N junction. Most semiconductor devices contain one or more P-N junctions. The P-N junction is very important as it controls the behaviour of semiconductor devices.

4.1 Formation of P-N Junction

In a semiconductor, the P-N junction is created by the method of doping. The P-side or the positive side of the junction has an excess of holes, and the N-side or the negative side has an excess of electrons. A P-N junction diode is a semiconductor device that is formed by combining P and N type semiconductors and used in allowing the flow of electric current in one direction and blocking the flow of current in the opposite direction. Fig. 4.1 shows a P-N junction just formed with no external voltage applied. As soon as the P-N junction is formed, the following processes are initiated.

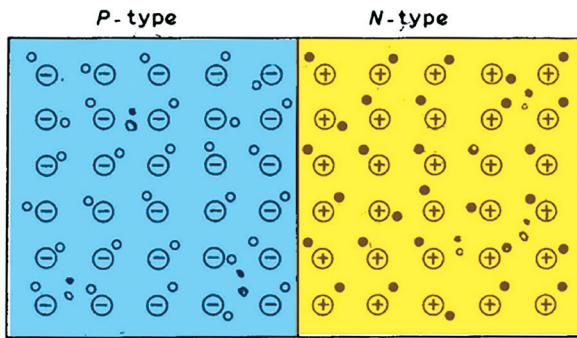


Fig. 4.1 PN junction with no external voltage applied

1. Holes from the P region diffuse into the N region. Then they combine with the free electrons in the N region.
2. Free electrons from the N region diffuse into the P region. These electrons combine with the holes in the P region.
3. When a hole is moved from the P-side towards the junction, there forms a net negative charge at the P-side due to the presence of immobile negative ions.
4. When an electron moves from the N-side towards the junction, there forms a net positive charge at the N-side due to the presence of immobile positive ions.
5. Negative charge at the P-side stops electrons from further diffusion.
6. Positive charge at the N-side stops holes from further diffusion.
7. This process results in the formation of a barrier region which prevents the corresponding majority carriers from crossing the junction.

Depletion Region

When a P-N junction is formed, a few electrons from the N-type diffuse through the junction and combine with the holes in the P-side and leaves behind positive ions in the N-side. Similarly, a few holes from the P-side moves towards the junction and combines with electrons in the N-side and leaves the negative ions in the P-side. The positive ions try to stop further movement of electrons and negative ions try to stop the movement of holes. This results in the formation of the depletion layer, which acts as a barrier and does not allow any further flow of electrons from the N region to the P region. This region is called depletion region or space charge region.

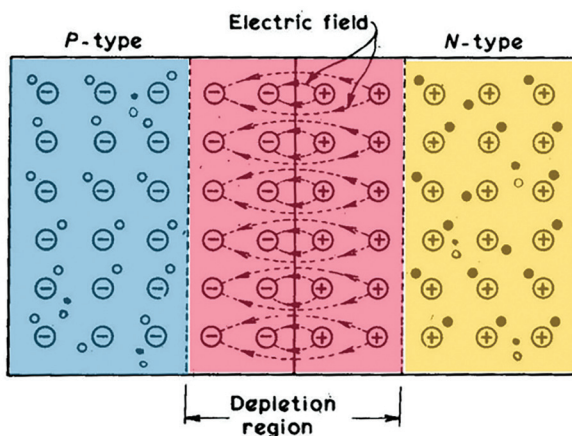


Fig. 4.2 Depletion region is formed in the junction

Fig. 4.2 shows the depletion layer when a P-type and N-type material are joined. The region contains immobile ions which are electrically charged. The physical distance from one side of the barrier to the other side is referred to as the width of the barrier. With no external batteries connected, the barrier potential is of the

order of fractions of a volt. For a Silicon P-N junction, the barrier potential is about 0.7 V, whereas for Germanium P-N junction it is approximately 0.3 V.

4.2 Semiconductor Diode

A semiconductor diode is an electronic device which is basically a PN junction. Fig. 4.3 shows the PN junction, the schematic symbol of a diode and a physical image of a typical diode. The diode has two terminals called the Anode and the Cathode. The P side (P type) is called Anode and N side is called Cathode.

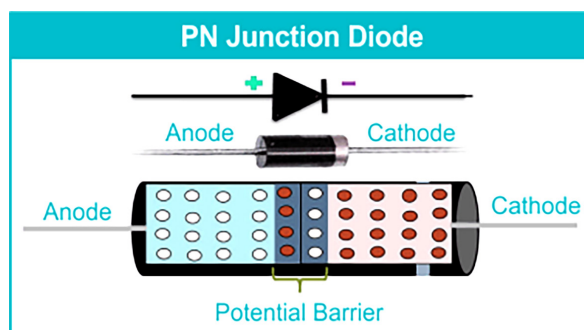


Fig. 4.3 Diodes

4.3 P-N Junction Biasing



Activity 4.1

Take a semiconductor diode and connect with a battery of 5 V and DC bulb (torch bulb) in series as shown in the Fig. 4.4.

- Does the bulb glow in the circuit?
- If yes, do you agree that the diode connected in this manner conducts current, or it acts as a closed switch?

When the diode is connected in this manner, the lamp glows. This means the diode is conducting and the current is flowing in the circuit.

Now, connect the diode in the circuit with its terminals reversed as shown in Fig. 4.5.

- Does the bulb glow in this circuit?
- If not, what does it mean?

When the diode is connected as in Fig. 4.5 the lamp does not glow. It means no current is flowing in the circuit although the battery is present. The diode does not permit the current flow.

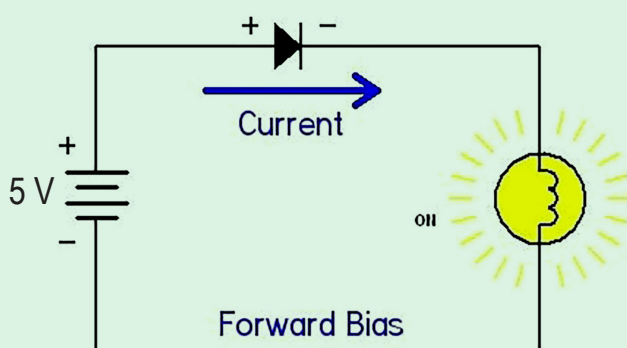


Fig. 4.4 Forward biased diode

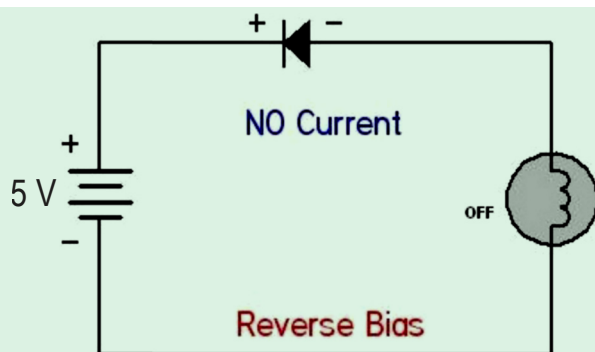


Fig. 4.5 Reverse biased diode

From the above activities we find that a diode conducts in one direction only. The unidirectional conduction property of a diode finds much applications in electronics. The diode has different electrical properties depending on the polarity of voltage across its terminals. The voltage given to the diode to control its characteristics is called the bias voltage of the diode.

P-N Junction with Forward Bias

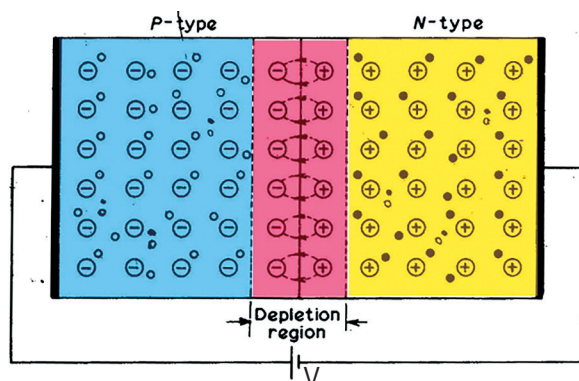


Fig. 4.6 Forward biased P-N junction

Suppose we connect a battery to the P-N junction diode in such a way that the positive terminal of the battery is connected to the P side and the negative terminal to the N side as shown in Fig. 4.6. In this condition the P-N junction is said to be forward biased.

When the P-N junction is forward biased, the holes are repelled due to the positive potential of the battery and are forced to move towards the junction. The electrons are repelled from the negative

terminal of the battery and drift towards the junction. Because of their extra energy (due to the applied voltage) some of the holes and free electrons penetrate the depletion region. This will reduce the potential barrier. Then more majority carriers drift across the junction. Once the potential barrier is eliminated (i.e., when the applied voltage becomes equal to the barrier potential) by the applied voltage, junction resistance becomes almost zero and a low resistance path is established. This results in a flow of current in the circuit. This is called the forward current.

P-N Junction with Reverse Bias

When the positive terminal of a DC source is connected to the N side of the diode and the negative terminal to the P side, the diode is said to be reverse biased. Fig. 4.7 shows a reverse biased P-N junction.

The holes in the P region are attracted towards the negative terminal of the battery. The electrons in the N region are attracted towards the positive terminal of the battery. Thus, the majority carriers are drawn away from the junction. This action widens the depletion region and increases the barrier potential. i.e., the potential barrier widens. The increased barrier potential makes it more difficult for the majority carriers to diffuse across the junction.

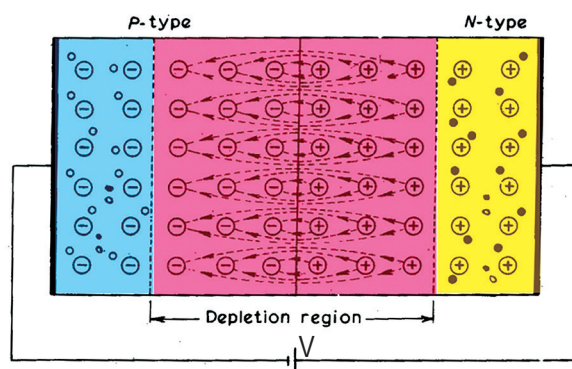


Fig. 4.7 Reverse biased P-N junction

In earlier chapters we have seen that a few minority carriers are also generated due to thermal agitation. As soon as a minority carrier is generated it is drifted across the junction because of the applied voltage. The rate of generation of minority carriers depends upon the temperature. If the temperature is fixed, the rate of generation of minority carriers remains constant. Therefore the current, due to the flow of minority carriers remains the same whether the battery voltage is low or high. For this reason this current is called reverse saturation current. This current is very small as the number of minority carriers is less and is of the order of nano amperes in silicon diode and micro amperes in germanium diode. This is one of the reasons for which silicon diodes are more preferred to germanium diodes.



Know your progress

1. Explain the formation of a depletion region in an open circuited P-N junction.
2. What do you understand by an ideal diode? Draw its V-I characteristics.
3. Describe the action of P-N junction under forward bias and reverse bias.

4.4 V-I Characteristics of a P-N Junction Diode

Fig. 4.8 shows the V-I Characteristics of a P-N junction diode. It is the graphical representation of the relation between the voltage across the junction and the current through the diode. Usually voltage is taken along the x-axis and current along the y-axis.

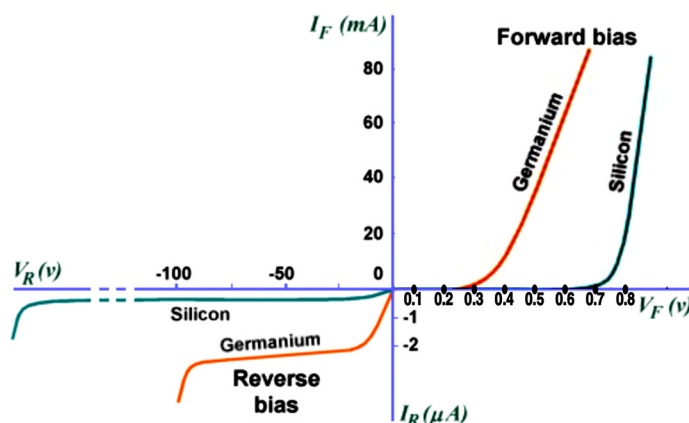


Fig. 4.8 V-I Characteristics of a P-N junction diode

Fig. 4.9 shows the circuit arrangement for determining the V-I characteristics of a P-N junction.

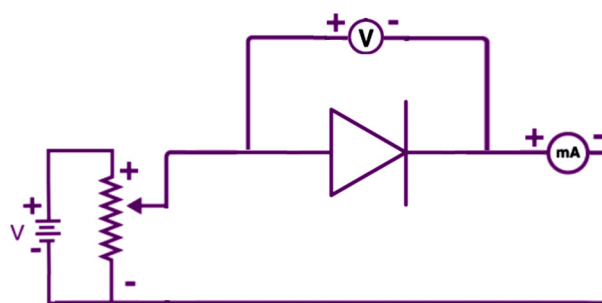


Fig. 4.9 Circuit arrangement for forward characteristics



Activity 4.2

Select meters of appropriate ratings and assemble a circuit in your school laboratory as shown in Fig. 4.9. Increase the input voltage from zero onwards and note down the corresponding meter readings and draw the forward characteristic curve of the Si diode.

- What are the voltage and current ratings of voltmeter and ammeter selected respectively? Can you select a 0-250 V voltmeter and 0 - 10 A ammeter? Why?
- Verify whether the curve obtained matches with that given in the following section.

In the above circuit the maximum voltage across the diode to be measured is less than 1 V. For this, if we select a 0-250 V voltmeter it is difficult for us to note the reading. The current expected through the diode is only of the order of milli ampere. So, if we select 0-10 A ammeter, the reading on the ammeter may not be properly readable. That is why we should select meters of appropriate range.

Forward Bias Characteristics

From Fig. 4.10 we find that the diode current is very small for the first few tenths of a volt. The diode does not conduct well until the external voltage overcomes the barrier potential. As we approach 0.3 V for Ge and 0.7 V for Si, a larger number of free electrons and holes start crossing the junction. Above that voltage even a small increase in the voltage produces a sudden increase in the current. The voltage at which the current starts to increase rapidly is called cut in voltage or knee voltage. Here, the P-N junction behaves as an ordinary conductor.

From the graph (Fig. 4.10) it is noted that for a silicon diode the cut in voltage is approximately 0.7 V whereas for a germanium diode it is about 0.3 V.

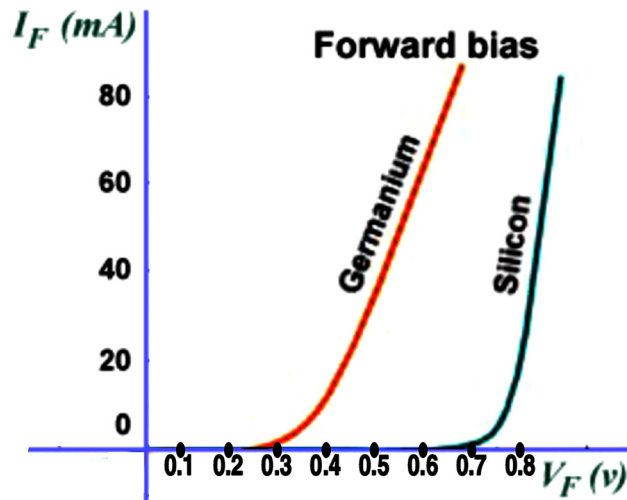


Fig. 4.10 Cut in voltage of Si and Ge

Ideal Diode

We have seen that a diode has a very important property that it permits only unidirectional conduction. It conducts well in the forward direction and poorly in the reverse direction. It would have been ideal if a diode acted as a perfect conductor when forward biased and as a perfect insulator when reverse biased. The V-I characteristics of such an ideal diode would be as shown in Fig. 4.11. An ideal diode acts like a switch. The forward biased diode acts as a closed switch and offers zero resistance whereas the reverse biased diode acts as an open switch and offers infinite resistance.

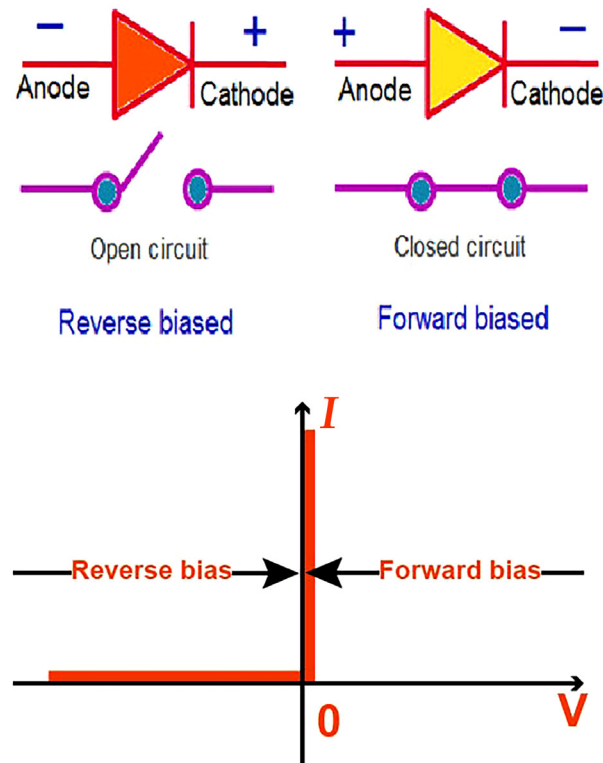


Fig. 4.11 Ideal diode characteristics

Static and Dynamic Resistance of a Diode

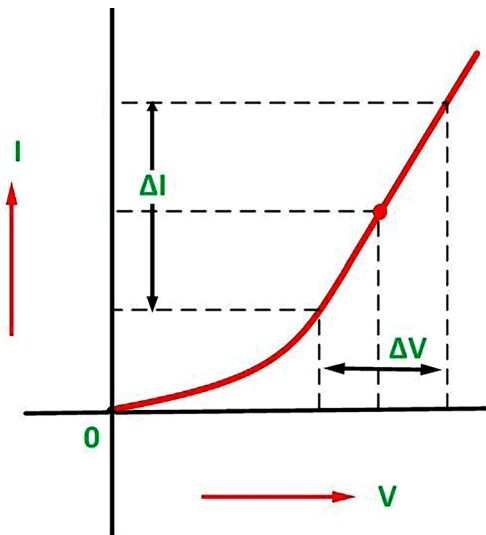


Fig. 4.12 forward characteristics of a silicon diode

No diode can act as an ideal diode. A diode does not behave as a perfect conductor when forward biased. It offers small resistance when it is forward biased. Fig. 4.12 shows the forward characteristics of a typical silicon diode.

DC Resistance or Static Resistance

When forward biased, a diode offers a definite resistance in the circuit. This resistance is known as the forward resistance of the diode. DC resistance or static resistance is simply the ratio of the DC voltage across the diode to the DC current flowing through it.

$$R_{dc} = \frac{V}{I}$$

It is clear from Fig. 4.13 that the DC resistance of a diode varies as the current changes.

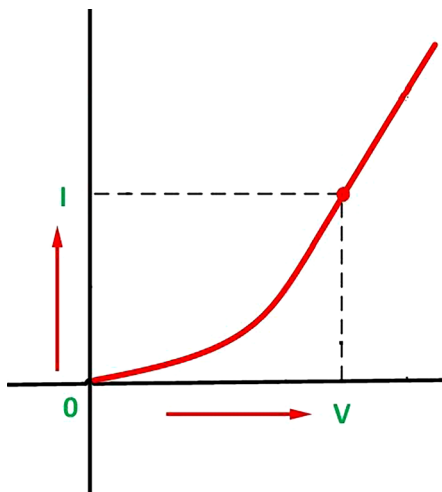


Fig. 4.13

AC Resistance or Dynamic Resistance

The resistance offered by the diode to the AC signal is called dynamic resistance. It is the ratio of change in voltage to the change in current.

R_{ac} = Change in Voltage / Change in Current

$$= \frac{\Delta V}{\Delta I} = \frac{V_2 - V_1}{I_2 - I_1}$$

Note:- The Greek letter Δ (Delta) means: a change of. So, ΔI is the change in current.

Generally, it indicates a small scale.

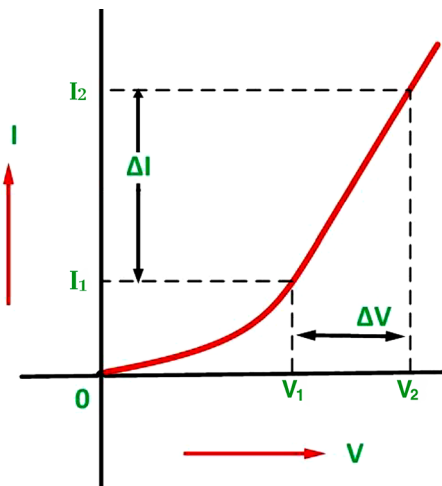


Fig. 4.14

Reverse Bias Characteristics

In order to obtain the reverse bias characteristics we use the same circuit with a few changes as shown in Fig. 4.15. Now, we reverse the terminals of the diode and the milli ammeter is replaced by a micro ammeter.

With reverse bias to the P-N junction i.e., the semiconductor for P-type connected to the negative terminal of the battery and N-type connected to the positive terminal, the potential barrier at the junction is increased. Therefore, the junction resistance becomes very high and hence theoretically no current flows through the circuit. However in practice a very small current flows in the circuit as shown in Fig. 4.16 and it is due to the minority carriers.

If the reverse voltage is increased continuously, the kinetic energy of electrons may become high enough to detach electrons from the semiconductor atoms. At this stage, a breakdown of the junction occurs, characterised by a sudden rise of reverse current and a sudden fall of the resistance of the barrier region. This may destroy the junction permanently.

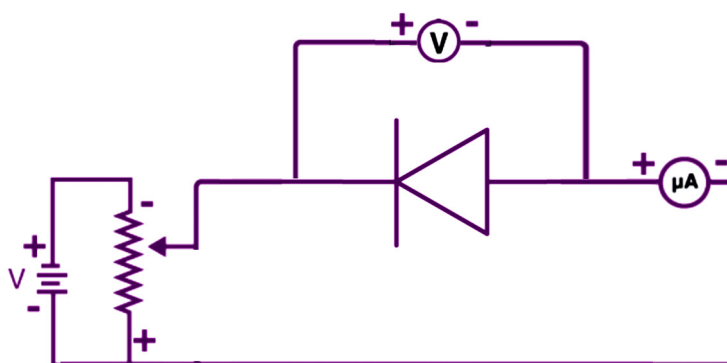


Fig.4.15 Circuit arrangement for reverse characteristics

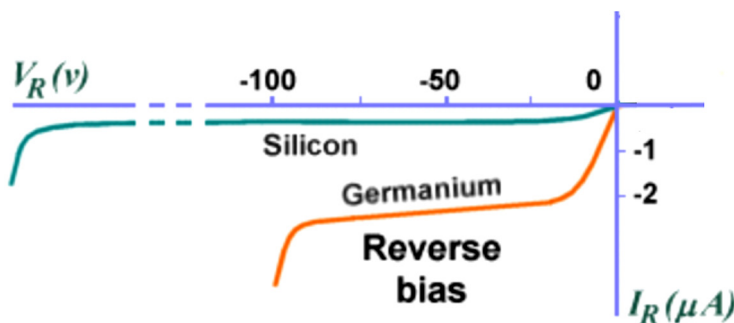


Fig. 4.16 Reverse characteristics of silicon diode and germanium diode



Know your progress

1. Explain how unidirectional current flow is possible through a diode.
2. Explain the V-I characteristics of a diode.

4.5 Junction Breakdown

If the reverse voltage applied to the P-N junction is increased, a point is reached when the junction breaks down and the reverse current rises sharply. This critical value of the voltage is known as the break down voltage. The junction offers zero resistance at this point.

The breakdown voltage depends on the width of the depletion region which depends on the doping level.

There are two processes which can cause junction breakdown.

1. Avalanche breakdown
2. Zener breakdown

Avalanche Breakdown

Avalanche break down occurs in the junction which is lightly doped and have a wide depletion region. Due to the applied voltage, there forms an electric field in the depletion region. The minority carriers which are thermally generated acquire energy from this electric field and collide with the electrons in the covalent bond. Due to this collision with the valence electrons, covalent bonds are broken and electron hole pairs are generated. These newly generated charge carriers also acquire energy from the same field and collide with the covalent bonds and produce new charge carriers. This leads to an avalanche of charge carriers and the junction offers very low resistance. This cumulative phenomenon is called avalanche multiplication. This leads to the breakdown of the P-N junction and hence the breakdown process is known as avalanche breakdown.

Zener Breakdown

Zener breakdown occurs in the junction which is heavily doped and has a narrow depletion region. Because of this the breakdown voltage sets up a very strong electric field across this narrow region and this field is strong enough to break the covalent bonds, thereby generating electron hole pairs. This can cause a large current flow. This mechanism of breakdown is called Zener breakdown. A comparison of the two types of junction breakdown processes are given in Table 4.1.

Avalanche breakdown	Zener breakdown
1. This breakdown occurs at junctions which are lightly doped and have wide depletion layers. 2. Here electric field is not strong enough to produce Zener breakdown. 3. Here minority carriers collide with semiconductor atoms in the depletion region, which breaks the covalent bonds and electron-hole pairs are generated. Newly generated charge carriers are accelerated by the electric field which results in more collision and generates an avalanche of charge carriers. This results in avalanche breakdown. 4. This breakdown occurs above 6 V.	1. This breakdown occurs at junctions which are heavily doped and have narrow depletion layers. 2. The breakdown voltage sets a very strong electric field across this narrow depletion layer. 3. Here, the electric field is very strong to rupture (break) the covalent bonds thereby generating electron hole pairs. So, even a small increase in reverse voltage is capable of producing a large number of charge carriers. Hence, the junction now has a very low resistance. This leads to Zener breakdown. 4. Zener breakdown occurs below 6 V.

Table 4.1 Comparison of Avalanche breakdown and Zener breakdown

4.6 Zener Diode

As seen earlier, a P-N junction diode under reverse biased condition breaks down at a particular reverse voltage after which the diode becomes damaged. But, if it becomes possible for a diode to be properly used even under breakdown condition, it will help us to improve several electronic devices and circuits. Such a specially designed diode is called the Zener diode.

Zener diodes are special diodes designed to operate in the breakdown region without damage. Zener diodes have a heavily doped P-N junction which is operated in the breakdown region. Zener breakdown occurs due to the breaking of covalent bonds by the strong electric field set up in the depletion region. It produces extremely large number of holes and electrons which constitute the reverse saturation current called Zener current I_z . The reverse voltage at which Zener breakdown takes place is called the Zener voltage (V_z).



The satisfactory explanation of reverse breakdown in diode was first given by the American Scientist C. Zener. This breakdown is known by his name as Zener breakdown.

A properly doped crystal diode which has a sharp breakdown voltage is known as a zener diode.

Appearance



Schematic Symbol



Fig 4.17 Symbol of Zener diode

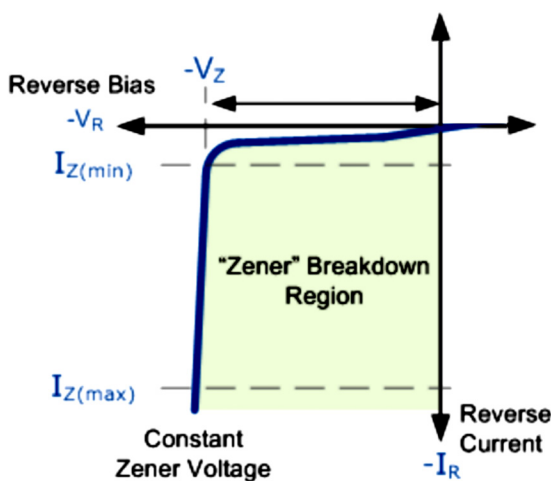


Fig 4.18 V-I Characteristics of a Zener diode

The symbol of a Zener diode is the same as that of an ordinary diode except that the bar is turned in to Z shape as in Fig. 4.17. From the graph, it can be understood that for a large variation of current the voltage across the diode is almost constant.

The following points may be noted about Zener diode:-

1. A Zener diode is like an ordinary diode except that it is doped heavily so as to have a sharp break down voltage.
2. A Zener diode has a sharp breakdown voltage called Zener voltage V_z .
3. When forward biased, its characteristics are the same as that of an ordinary diode.
4. The reverse breakdown voltage of a Zener diode is small compared to an ordinary diode and it can be operated in the breakdown region.



Know your progress

1. Explain the mechanism of Avalanche breakdown and Zener breakdown.
2. Explain any one application of a Zener diode.



ZENER DIODE AS VOLTAGE REGULATOR

Zener diodes are widely used as voltage regulators to regulate the voltage across circuits. A Zener diode can be used as a voltage regulator to provide a constant voltage from a source whose voltage may vary over the specified range. The circuit arrangement is shown in Fig. 4.19. It consists of a resistor connected in series with the input voltage and a Zener diode connected in parallel with the load.

The working of this circuit is explained below.

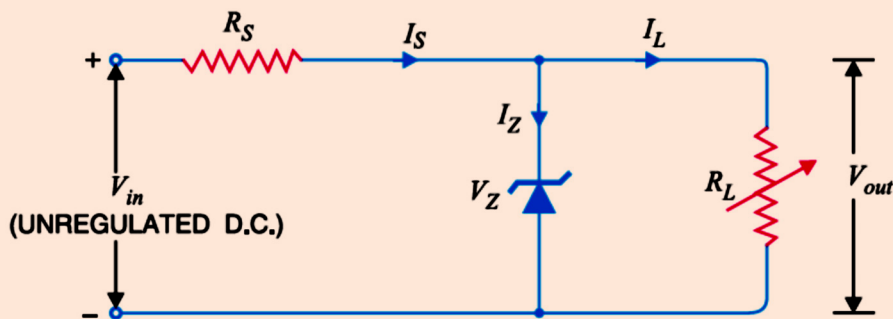


Fig. 4.19 Zener Voltage Regulator

The voltage regulator utilises the property of the Zener diode that when the breakdown is reached the voltage remains constant. At the same time, the current through it varies as the applied voltage changes. When the input voltage varies above V_Z of the Zener diode, it will be in the reverse break down and the output voltage [which is same as V_Z] remains constant. The voltage $V_{in} - V_Z$ drops across the series resistor R_s . When the input voltage increases, the output voltage remains constant at V_Z and the current I_s increases.

$$I_s = \frac{V_{in} - V_Z}{R_s}$$

But $I_s = I_z + I_L$. As I_s increases, I_z increases keeping I_L constant. Thus, the output voltage remains constant as $V_o = I_L \times R_L$. When the input voltage decreases, the current I_s decreases. Hence I_z decreases keeping I_L constant. As I_L is kept constant, the output voltage remains constant. So the Zener diode keeps the output voltage constant by varying the current through it accordingly while keeping the voltage V_z constant in the breakdown region. This voltage regulation is called line regulation.

In this circuit, an input voltage V_{in} is regulated down to a stable output voltage V_o . The breakdown voltage of a diode is stable over a wide range of currents and holds V_o relatively constant even though the input voltage may fluctuate over a fairly wide range.

Transistors

Transistors are the fundamental building blocks of all modern electronic systems. They are semiconductor devices with three terminals. Following their development in the early 1950s, the transistors have led to the fast development of electronics. A transistor is a small semiconductor device used to control, switch, or amplify electrical signals. It works by using a small input current or voltage to regulate a much larger current flowing through it. Because of this ability, transistors act like electronic switches and signal amplifiers.

Transistors are used in most of the electronic devices from simple gadgets to advanced computers, where millions or even billions of transistors are integrated into microchips. In essence, the transistor is the key component that allowed electronic circuits to become smaller, faster, and more efficient, driving the entire digital revolution.

Have you ever seen a transistor? Do you know how many terminals a transistor has? In Fig. 5.1 different types of transistors, and their symbols are shown. We can observe from Fig. 5.1 that a transistor is a three-terminal device.

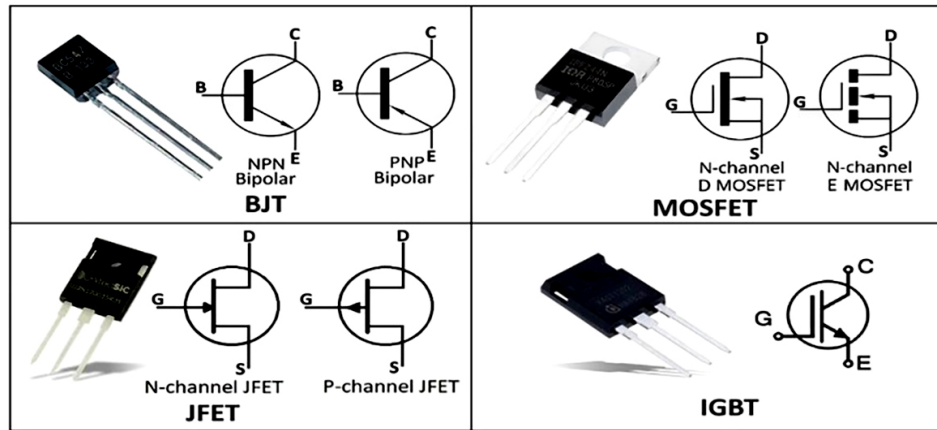


Fig. 5.1 Different types of transistors

Although several companies produce over a billion individually packaged (known as discrete) transistors every year, a vast majority of transistors are now produced in integrated circuits (ICs), along with diodes, resistors, capacitors and other electronic devices. We know that a diode is a two terminal device and has two semiconductor regions.

The word transistor was developed from the terms 'trans' which means transfer and 'istor' which means resistor. Therefore transistor means transfer of resistance from input terminals to the output terminals. The resistance across the input terminals (input resistance) and that between the output terminals (output resistance) can be controlled by changing the voltage given to the transistor terminals. This feature allows us to use transistors for various applications like amplification, switching, etc.

Transistors are commonly used for amplification and switching. Amplifiers are used to increase the amplitude of a signal (e.g. in public address system amplifiers are used to increase the loudness of sound or audio signal). Switches are used to make a device or system ON or OFF using an electrical signal.

5.1 Bipolar Junction Transistor (BJT)

When a P-type semiconductor and an N-type semiconductor are joined together, they form a PN junction or a diode. This diode behaves differently when current flows forward and backward. A bipolar junction transistor (BJT) has two PN junctions. In a P-type material, holes are the majority charge carriers, and in an N-type material, electrons are the majority carriers. In a BJT, both electrons and holes help carry the current, which is why it is called a bipolar device.

Structure of BJT

Based on the types of semiconductor layers used, BJTs are classified into

1. NPN Transistor
2. PNP Transistor

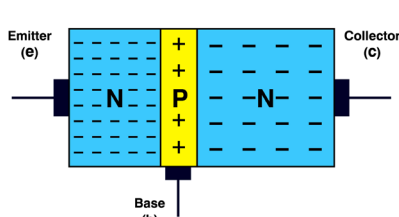


Fig. 5.2 (a) NPN Transistor

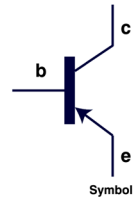
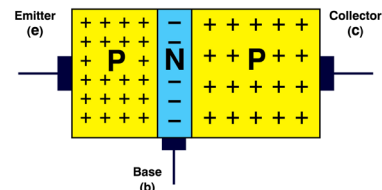
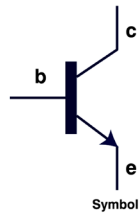


Fig. 5.2 (b) PNP Transistor

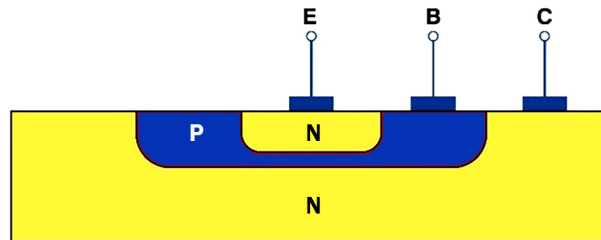


Fig. 5.2 (c) NPN Transistor (Cross section)

When a P type semiconductor layer is sandwiched between two N type layers, the transistor is known as NPN transistor (Fig. 5.2 (a)). Similarly, when an N-layer is sandwiched between two P-layers, the transistor is known as PNP transistor (Fig. 5.2 (b)). Fig. 5.2 (c) shows the cross section of an NPN transistor. Transistors are made either from Silicon (Si) or Germanium (Ge) crystal.

A transistor (NPN or PNP) has the following regions.

- (i) **Emitter:** This region of the transistor emits charge carriers. It is more heavily doped in comparison to the other regions. The physical size of this region is in between that of collector and base regions.
- (ii) **Base:** Base is the middle region of the transistor which is lightly doped and physically very thin. This region accepts some of the charge carriers by recombination and passes most of the carriers to the collector region.
- (iii) **Collector:** The collector region collects majority of the charge carriers from the emitter region through the base. This region is moderately doped. The collector region is made physically larger than the emitter region. This is due to the fact that the collector has to dissipate more heat.



'The name diode is derived from the fact that it has two electrodes - 'di' means two and 'ode' means electrode. Transistor is the semiconductor version of triode (vacuum tube), which is derived from 'tri' and 'ode'.

In the transistor symbol, arrow head is there at the emitter, which indicates the direction of the conventional current flow. i.e., in the case of NPN transistor it is from the base to the emitter (base is positive with respect to the emitter), while in the case of PNP it is from the emitter to the base (emitter is positive with respect to the base).

- The junction between collector layer and base layer is called Collector-Base junction or C-B junction.
- The junction between base layer and emitter layer is called Emitter-Base junction or E-B junction.



Activity 5.1

Make a matching table of the structure of a BJT using the following words.

Emitter, lightly doped, moderately doped, collector, heavily doped, largest physical size, very thin, moderate size, supplies charge carriers, passes most of the carriers, accepts most of the carriers, Base.

- Do you agree that the recombination occurring in the base region is very less? If so, why?
- Which region is with the largest area? Why? Verify whether your table matches with the following.

Emitter	Base	Collector
Heavily doped	Lightly doped	Moderately doped
Supplies charge carriers	Passes most of the carriers	Accepts most of the carriers
Moderate size	Very thin	Largest physical size

The base region is lightly doped and very thin. So, it has very less number of carriers for recombination and therefore, it passes most of the carriers to the collector region. The collector region is made physically large as this region has to dissipate more heat energy.

5.2 Transistor Biasing

A PN junction diode can work in two ways depending on how do we connect the battery. If the positive side of the battery is connected to the diode's anode, and the negative side is connected to the cathode, the diode is said to be forward biased. In this condition, the diode allows current to flow. If we reverse the battery connections, the diode is said to be reverse biased and the diode does not allow current to flow through it.

Since the diode behaves differently during forward and reverse bias, it is known as a unidirectional device.

A transistor also needs proper biasing (proper connection of voltages) to work correctly.

A transistor has two PN junctions: Emitter-Base junction and Collector-Base junction. To use a transistor in different applications (like amplification or switching), both these junctions must be biased. Depending on how these two junctions are biased, the transistor works in three different modes of operation; active, saturation and cut off.

Emitter- Base (E-B) Junction	Collector- Base (C-B) Junction	Mode of Operation
Forward	Reverse	Active
Forward	Forward	Saturation
Reverse	Reverse	Cut-Off

First, we shall see the active mode of operation, which is used when the transistor acts as an amplifier. Amplification is the most common use of a BJT. Transistor biasing for active mode of operation is as shown in Fig. 5.3. The Emitter-Base (E-B) junction is forward biased and the Collector-Base (C-B) junction is reverse biased. For this purpose, a battery V_{EE} is connected between the emitter and the base and a battery V_{CC} is connected between the collector and the base'.

In the case of a PNP transistor, Fig. 5.3 (a) the emitter base junction of PNP is forward biased by connecting the positive terminal of V_{EE} to the emitter and the negative terminal to the base. The collector base junction is reverse biased by connecting the negative terminal of V_{CC} to the collector and the positive terminal to the base.

Similarly, for an NPN transistor, Fig. 5.3 (b) the emitter base junction of NPN is forward biased by connecting the negative terminal of V_{EE} to the emitter and positive terminal to the base. The collector base

junction is reverse biased by connecting the positive terminal of V_{CC} to the collector and negative terminal to the base. The forward biasing of the emitter base junction makes the resistance in the emitter circuit low and the reverse-biasing of the collector-base junction makes the resistance in the collector circuit high.

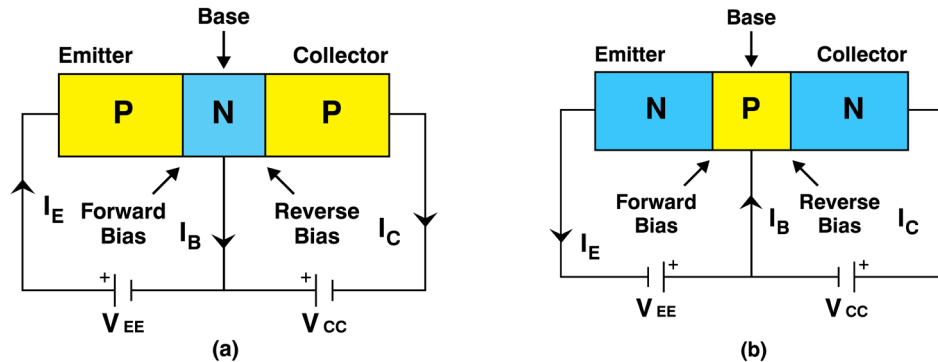


Fig.5.3 Transistor biasing

Fig. 5.3 shows the conventional flow of currents in a transistor. The emitter terminal of the transistor emits charges which results in the emitter current (I_E). Some of these carriers are recombined in the base region which causes the base current (I_B) to flow. Most of the carriers are collected by the collector region which constitutes the collector current (I_C).

5.3 Working of NPN Transistor

In the N-P-N transistor the emitter is connected to the negative terminal of the battery V_{EE} for making it forward biased and the collector terminal is connected to the positive terminal of the battery V_{CC} for making it reverse biased (Fig. 5.4). I_E is the current flowing through the emitter terminal of the transistor, I_B is current flowing through the base and I_C is the current flowing through the collector.

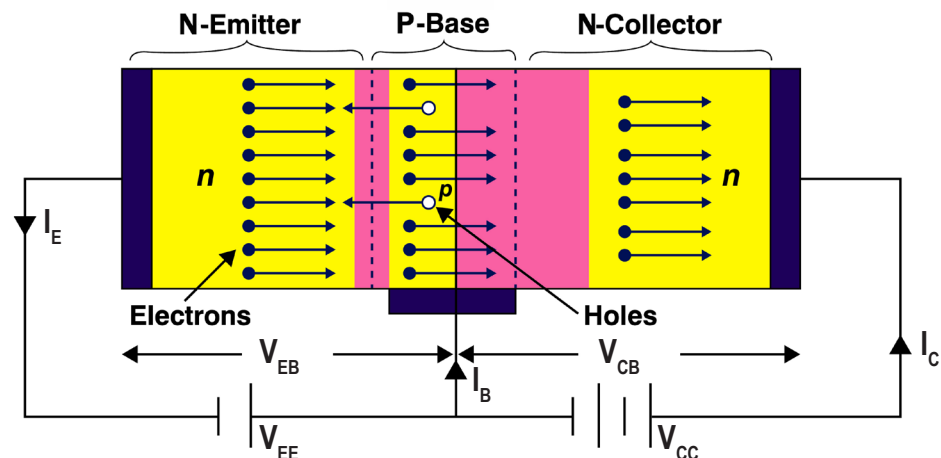


Fig.5.4 N-P-N Transistor

In the N-Type emitter, the majority carriers are free electrons. So, the negative terminal of V_{EE} repels the electrons of the emitter region and the positive terminal of the battery (V_{CC}) attracts the electrons emitted by the emitter. Since the emitter junction is forward biased, the potential barrier at this junction is reduced and so the electrons supplied by the emitter start moving towards the base. This constitutes the emitter current I_E . As the base region is very thin and lightly doped, only some of the electrons emitted from the emitter recombine with the holes, which are the majority carriers in the base region. This constitutes the base current I_B . The injected majority carriers from emitter to base become the minority carriers in the base region. These minority carriers can drift through the reverse biased collector - base junction and reach the collector region and constitute the collector current I_C .

$$I_E = I_C + I_B$$



Supply voltage is named according to which terminal it is connected to and is denoted by double subscripts. For example, V_{EE} means it is a source voltage and it is connected in the emitter terminal. Similarly, V_{CC} means source voltage which is connected in the collector. The voltage across the junction is also denoted by double subscripts, and the more positive terminal is written first. In a transistor, the voltage across the emitter and the base junction is written as V_{BE} which denotes the base voltage with reference to the emitter. Similarly, the voltage across the collector and the base junction is written as V_{CB} which denotes the voltage at collector with reference to the base.

5.4 Working of a PNP Transistor

In the PNP transistor, the emitter is connected to the positive terminal of the battery V_{EE} for making it forward biased and the collector terminal is connected to the negative terminal of the battery V_{CC} for making it reverse biased as shown in Fig. 5.5. I_E is the current flowing through the emitter terminal, I_B is the current flowing through the base and I_C is the current flowing through the collector region.

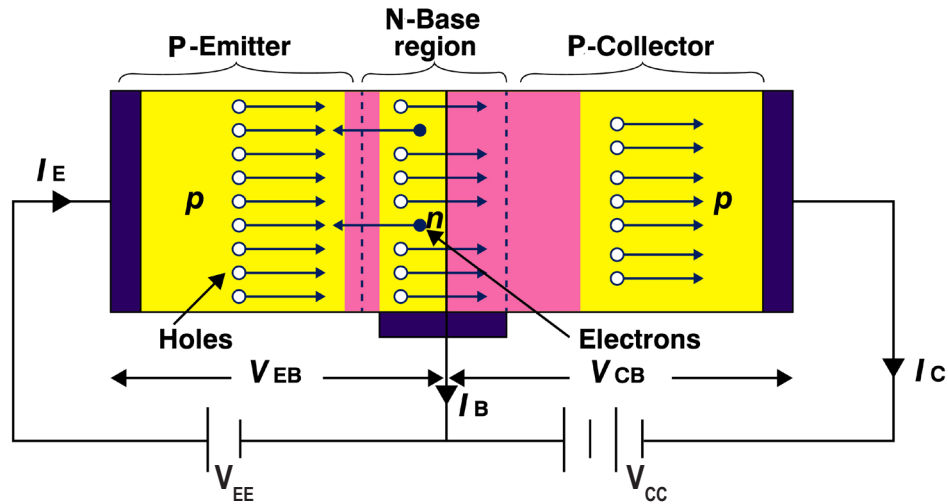


Fig.5.5 P-N-P Transistor

In the P-type emitter the majority carriers are holes. So, the positive terminal of the supply V_{EE} repels the holes of the emitter and negative terminal of the battery V_{CC} attracts the holes emitted by the emitter. So, holes start moving from the emitter to the collector. This constitutes the emitter current I_E . During the motion from emitter to collector, holes will pass through the base region where some of the holes may recombine with electrons. A very small percentage of the holes emitted by the emitter recombine with the electrons in base region and this constitutes base current I_B . The rest of the holes are able to reach the collector which produces the collector current I_C .

5.5 Transistor Configurations

When a device is used in a circuit, we need two terminals each to connect the input signal and the output signal. As the transistor is a three-terminal device, one terminal has to be common to the input and the output. There are three possible ways to connect the transistor, within an electronic circuit with one terminal being common to both the input and output. In each method of connection, the circuit responds differently to the input signal, because the characteristics of each configuration is different. The three transistor configurations are

- Common Base Configuration (CB configuration)
- Common Emitter Configuration (CE configuration)
- Common Collector Configuration (CC configuration)

Common Base (CB) Configuration

In Common Base configuration the base is common to both the input and the output (Fig. 5.6). The input signal is applied between

the emitter and the base terminals and the output is taken between the collector and the base terminals. The base terminal is grounded or connected to a fixed reference voltage.

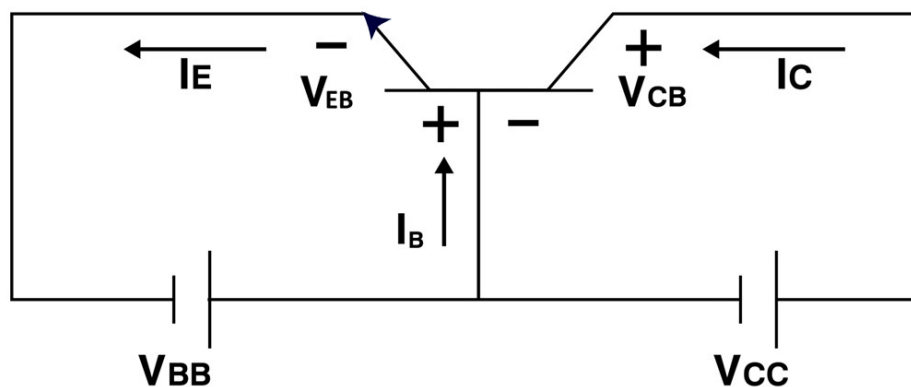


Fig. 5.6 Common Base (CB) Configuration

Input voltage	$= V_{BE}$	Output voltage	$= V_{CB}$
Input current	$= I_E$	Output current	$= I_C$
Input resistance (R_i)	$= \frac{V_{BE}}{I_E}$	Output resistance (R_o)	$= \frac{V_{CB}}{I_C}$

In the expression for input resistance, numerator V_{BE} is the voltage across a forward biased junction which is very small, whereas denominator is the total current I_E and it is comparatively large. Therefore, the input resistance is very low. The output resistance of CB configuration is very high because of its reverse biased junction.

Current amplification factor or current gain α (Alpha)

Current amplification factor or current gain is the ratio of the output current to the input current. In a common base configuration the emitter current (I_E) is the input current and the collector current (I_C) is the output current. Therefore, in CB configuration current gain is the ratio of the collector current (I_C) to the emitter current (I_E). It is denoted as alpha (α).

$$\alpha = \frac{I_C}{I_E}$$

As we know, the emitter current is always greater than the collector current. So, the value of alpha (α) is always less than unity. The practical values in the commercial transistors range from 0.9 to 0.99.

Expression for total collector current

From the above equation for α , collector current I_C is α times I_E . We know that when a transistor is in its active mode of operation, the

collector base (CB) junction is reverse biased. So even when $I_E = 0$ some current will flow through the collector because of the presence of minority charge carriers and this current is called the reverse saturation current I_{CBO} . I_{CBO} is the reverse saturation current in CB configuration and it is the current between the Collector and the Base when the Emitter is Open. Therefore, total collector current,

$$I_C = \alpha I_E + I_{CBO}$$

The current I_{CBO} is very small and for practical cases it may be neglected.

Solved Problem 5.1

A transistor in a common base configuration has the following parameters. I_B is $20 \mu\text{A}$ and I_C is 2mA . Calculate the value of α .

$$\begin{aligned} \text{Ans: } I_C &= 2\text{mA} \\ I_B &= 20\mu\text{A} = 20 \times 10^{-3} \text{ mA} \\ \text{But } \alpha &= \frac{I_C}{I_E} \end{aligned}$$

We know that in a transistor $I_E = I_B + I_C$

$$\begin{aligned} I_E &= 20 \mu\text{A} + 2 \text{ mA} \\ &= 20 \times 10^{-3} \text{ mA} + 2 \text{ mA} = 2.02 \text{ mA} \end{aligned}$$

Therefore

$$\begin{aligned} \alpha &= \frac{I_C}{I_E} = \frac{2\text{mA}}{2.02\text{mA}} \\ &= 0.99 \end{aligned}$$

Solved Problem 5.2

In a transistor in CB configuration the emitter current is 5 mA and the collector current is 4.92 mA , calculate the value of α .

$$\begin{aligned} \text{Ans: } I_E &= 5\text{mA} \\ I_C &= 4.92\text{mA} \\ \alpha &= \frac{I_C}{I_E} \\ &= \frac{4.92\text{mA}}{5\text{mA}} \\ &= 0.984 \end{aligned}$$

Solved Problem 5.3

In a transistor in common base configuration, the emitter current is 1 mA. When the emitter circuit is open, the collector current is 50 μ A. Find the total collector current, given that $\alpha = 0.92$.

$$I_E = 1 \text{ mA}$$

$$I_{CBO} = 50 \text{ } \mu\text{A} = 0.05 \text{ mA}$$

$$\alpha = 0.92$$

Therefore, the total collector current

$$\begin{aligned} I_C &= \alpha I_E + I_{CBO} \\ &= 0.92 \times 1 + 0.05 \\ &= 0.92 + 0.05 = 0.97 \text{ mA} \end{aligned}$$



Know your progress

In a transistor in CB configuration the emitter current is 1 mA and the collector current is 0.956 mA, calculate the value of α .

Voltage gain

The ratio of the output voltage to the input voltage is called voltage gain. In CB configuration, the output current is almost equal to the input current. At the same time, the output impedance is high and the input impedance is low. So, the voltage developed across the output will be high. Therefore, the voltage gain of CB configuration is also high.

Common Emitter (CE) Configuration

In Common Emitter configuration the emitter is common to both the input and the output. The input signal is applied between the base and the emitter terminals and the output is taken between the collector and the emitter terminals. As shown in Fig.5.7 the emitter terminal is grounded or connected to a fixed voltage point.

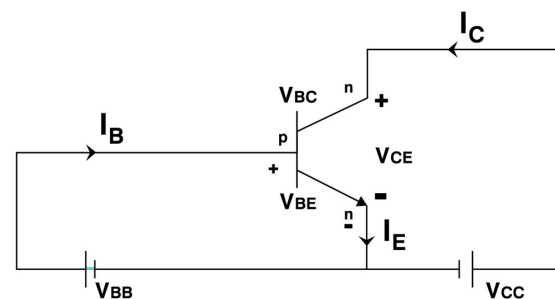


Fig.5.7 : Common emitter configuration

Input Voltage	= V_{BE}	Output Voltage	= V_{CE}
Input Current	= I_B	Output Current	= I_C
Input impedance (R_i)	= $\frac{V_{BE}}{I_B}$	Output impedance (R_o)	= $\frac{V_{CE}}{I_C}$

The input current I_B in CE configuration is very small compared to the input current I_E in CB configuration. Therefore, the input impedance of the transistor is medium. But since the output voltage V_{CE} and the output Current I_C are large compared to those of CB configuration, the output impedance is medium.

Current amplification factor or Current gain β (Beta)

Current amplification factor or current gain is the ratio of output current to input current. In a common emitter configuration (CE configuration) the base current (I_B) is the input current and the collector current (I_C) is the output current. Therefore, in a CE configuration current gain is the ratio of the collector current (I_C) to the base current (I_B). It is denoted as beta (β). Value of β is very much greater than 1.

Expression for total collector current

As per the equation for β , the collector current I_C is β times I_B . We know that when a transistor is in its active mode of operation, the collector junction is reverse biased. So, even when $I_B = 0$, some current will flow through the collector because of the presence of minority charge carriers and this current is called reverse saturation current I_{CEO} . I_{CEO} is the reverse saturation current in CE configuration and it is the current between the collector and the emitter when the base is open. Therefore, the total collector current,

$$I_C = \beta I_B + I_{CEO}$$

The current I_{CEO} is small and so may be neglected in practical cases.

Relationship between α and β

We know that $\alpha = \frac{I_C}{I_E}$

Since $I_E = I_C + I_B$ the above equation becomes $\alpha = \frac{I_C}{I_C + I_B}$

Dividing both numerator and denominator of RHS by I_C ,

$$\text{we get } \alpha = \frac{1}{1 + \frac{I_B}{I_C}}$$

$$I_{e, \alpha} = \frac{1}{1 + \frac{1}{\beta}}$$

$$I_{e, \alpha} = \frac{\beta}{\beta + 1}$$

Therefore,

$$\alpha (\beta + 1) = \beta$$

$$\alpha + \alpha\beta = \beta$$

$$\alpha = \beta - \alpha\beta$$

$$\alpha = \beta (1 - \alpha)$$

$$\text{Therefore, } \beta = \frac{\alpha}{1 - \alpha}$$



Know your progress

Define α and β parameters and state the relation between them.

Voltage gain

The ratio of the output voltage to the input voltage is called voltage gain. In CE configuration, the output impedance is high, and the input impedance is low and also the output current I_c is very large compared to the input current I_B . So, the voltage developed across the output will be high. Therefore, the voltage gain of CE configuration is high. The CE configuration has high voltage gain and current gain. So, the power gain in CE configuration is high. Hence, it is widely used as power amplifiers.

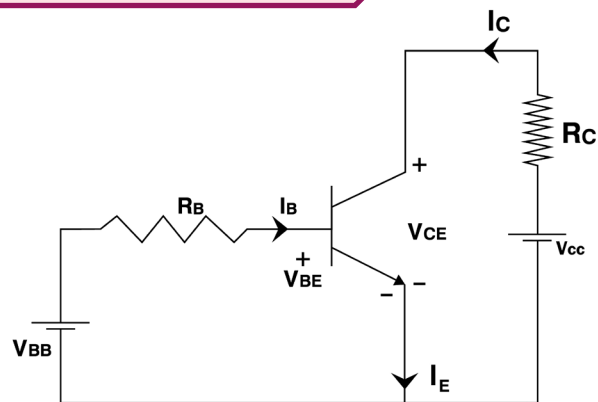


Fig. 5.8 CE Amplifier

Fig. 5.8 shows a CE configuration which is used as an amplifier. The input is applied between the emitter and the base and the output is taken from the collector and the emitter. A small change in the base current results in a large change in the collector current ($I_c = \beta I_B$). The output resistance of this configuration is high. The voltage is the product of current and resistance. So, an amplified output is obtained across the collector.

Solved problem 5.4

In a transistor CE configuration, the emitter current is 2 mA and collector current is 1.95 mA, calculate the value of β .

$$\begin{aligned}
 I_E &= 2 \text{ mA} \\
 I_C &= 1.95 \text{ mA} \\
 \beta &= \frac{I_C}{I_B} \\
 I_B &= 2 - 1.95 = 0.05 \text{ mA} \\
 \beta &= \frac{I_C}{I_B} \\
 &= 1.95 \text{ mA} / 0.05 \text{ mA} = 39
 \end{aligned}$$

Solved problem 5.5

In a transistor CE configuration, the base current is 50 μA . Calculate the value I_E . (β is given as 50)

$$\begin{aligned}
 I_B &= 50 \mu\text{A} = 0.05 \text{ mA} \\
 \beta &= \frac{I_C}{I_B} \\
 I_C &= \beta I_B \\
 &= 50 \times 0.05 \text{ mA} = 25 \text{ mA} \\
 I_E &= I_C + I_B \\
 &= 0.05 + 25 = 25.05 \text{ mA}
 \end{aligned}$$

Common Collector (CC) Configuration

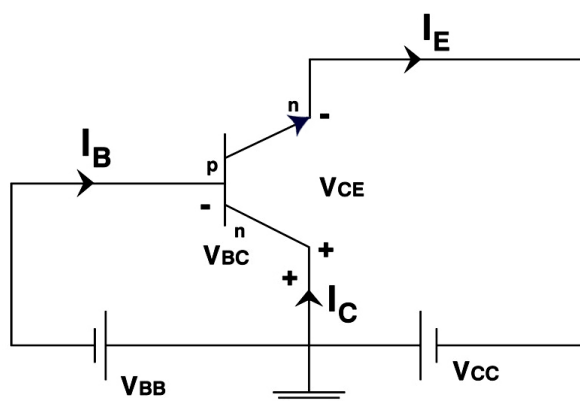


Fig.5.9 Common collector configuration

In this Common Collector configuration collector is common to both the input and the output (Fig. 5.9). The input signal is applied between the base and the collector terminals and the corresponding output is taken between the emitter and the collector terminals.

$$\begin{aligned}
 \text{Input voltage} &= V_{BC} \\
 \text{Output voltage} &= V_{CE}
 \end{aligned}$$

$$\begin{aligned}
 \text{Input Current} &= I_B \\
 \text{Output Current} &= I_E
 \end{aligned}$$

$$\text{Input impedance } (R_i) = \frac{V_{BC}}{I_B} \quad \text{Output impedance } (R_o) = \frac{V_{CE}}{I_E}$$

Since the collector base junction is reverse biased the input impedance is very high and the output impedance is very low. This configuration is also called emitter follower.

In Fig. 5.9 we can see that $V_{BC} = V_{CE} - V_{BE}$. Since V_{BE} is very small compared to V_{CE} , $V_{BC} \approx V_{CE}$. So the voltage gain of this circuit is unity. This implies that the emitter voltage (Output voltage) follows the input voltage and hence this circuit is known as an emitter follower.

Current amplification factor or current gain γ (Gama)

$$\gamma = \frac{I_E}{I_B}$$

γ is high since $I_E \gg I_B$

Relationship between α , β and γ

From the above equation for γ , we have

$\gamma = \frac{I_B + I_C}{I_B}$, dividing both the numerator and denominator by I_B , we get

$$\gamma = \frac{1 + \frac{I_C}{I_B}}{1}$$

$$\gamma = 1 + \beta \quad \beta = \frac{I_C}{I_B}$$

$$\text{Also } \gamma = 1 + \beta = 1 + \frac{\alpha}{1 - \alpha} = \frac{1}{1 - \alpha}$$



Know your progress

1. What are the configurations of a BJT?
2. What are the applications of an emitter follower?
Why is this circuit referred to as emitter follower?
3. Which transistor configuration has the highest power gain?

5.6 Characteristics of a Transistor in CE Configuration

The V-I characteristics gives the graphical representation of the input voltage and the input current as well as the output voltage and the output current variations. In order to measure these variations ammeters are connected in series

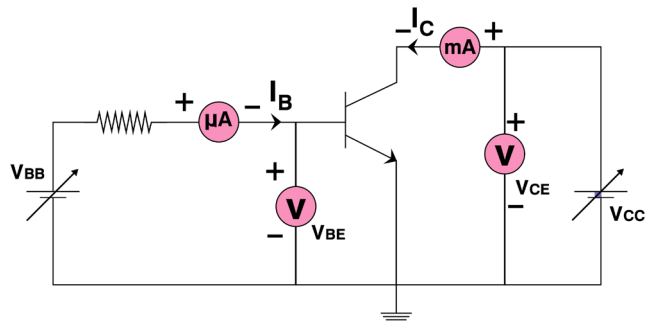


Fig.5.10 Circuit arrangements for CE characteristics

with the base and the collector to measure the base current and the collector current respectively. Voltmeters are connected in parallel to measure the input voltage (V_{BE}) and the output voltage (V_{CE}).

Input characteristics

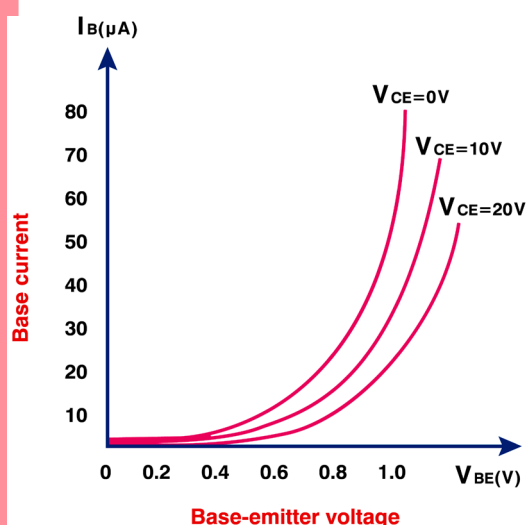


Fig.5.11 CE input characteristics

To study the input characteristics, the output voltage, V_{CE} is made constant and the changes of the input current (I_B) for the variations in the input voltage (V_{BE}) is measured and plotted in the graph. A family of curves may be drawn for different values of V_{CE} .

From the graph the following points can be noted.

1. The input characteristics resemble the forward characteristics of a PN junction diode.
2. For small changes of V_{BE} there will be a large change in base current I_B . i.e., input impedance will be small.
3. Input impedance, $r_i = \frac{\Delta V_{BE}}{\Delta I_B}$ for $V_{CE} = \text{constant}$.



Activity 5.2

Draw the forward characteristics of an ordinary PN Junction diode and observe the similarities and differences with the input characteristics of a CE configuration.

As already stated, the input characteristics of a CE configuration resemble the forward characteristics of a PN junction diode. In both the cases, the current is zero till the input voltage is increased above the cut in voltage of the PN junction. After that, for a very small change in voltage the current increases rapidly.

Since there is a large change in the current flow for a small change in the input voltage, the input impedance which is equal to $\Delta V_{BE} / \Delta I_B$ is very small for a CE transistor configuration.

Output characteristics

It is the curve between the output current (I_C) and the output voltage (V_{CE}) at constant input current (I_B). To study the output characteristics, the input current, I_B is kept constant and the change in the output current with the variation of output voltage is measured and the same is plotted in the graph (V_{CE} versus I_C). The curve is as shown in Fig. 5.12. From the graph we can observe the following:

1. **Cut off Region:** Region below the curve ($I_B = 0$) is called the cut-off region. In this region the emitter base and the collector base junction are reverse biased. Since $I_B = 0$ only reverse saturation current I_C flows through the transistor. This current is negligible. So, the transistor is off in this region.

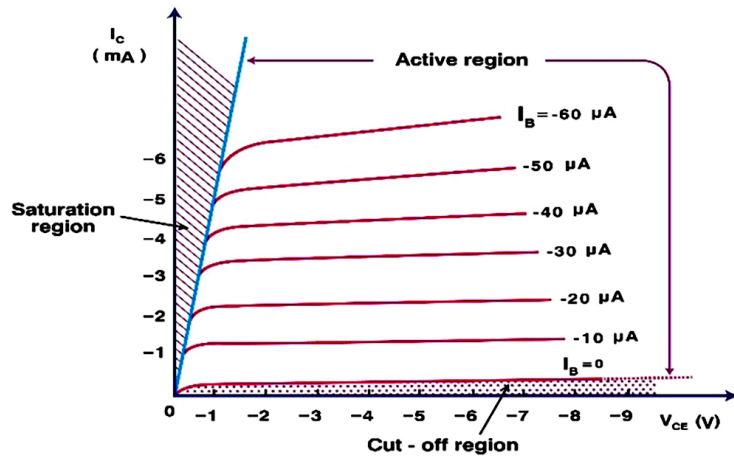


Fig.5. 12 CE output characteristics

2. **Saturation Region:** In this region the emitter base (EB) and the collector base (CB) junctions are forward biased. In the saturated region, the base current I_B does not produce a corresponding change in the collector current I_C .
3. **Active Region:** In this region the emitter base (EB) junction is forward biased and the collector base (CB) junction is reverse biased.
4. Very large changes of V_{CE} produce a small change in I_C i.e. the output impedance is high.
5. Output impedance $r = \frac{\Delta V_{CE}}{\Delta I_C}$ at constant I_B



Know your progress

Sketch the input and output characteristics of a transistor in CE configuration and explain the shape of these characteristics qualitatively.

5.7 Comparison Among CB, CE and CC Configuration

Characteristics	CB	CE	CC
1) Input impedance (r_i)	Very low (about 25Ω)	Moderate (about $1k\Omega$)	Very high
2) Output impedance (r_o)	Very high (about $400 K\Omega$)	High (about $50 K\Omega$)	Low (about 50Ω)
3) Current amplification factor	$\alpha = \frac{I_C}{I_E}$	$\beta = \frac{I_C}{I_B}$	$\gamma = \frac{I_E}{I_B}$
4) Current gain	Less than unity	High	High
5) Voltage gain	High	High	Less than unity

5.8 DC Load Line

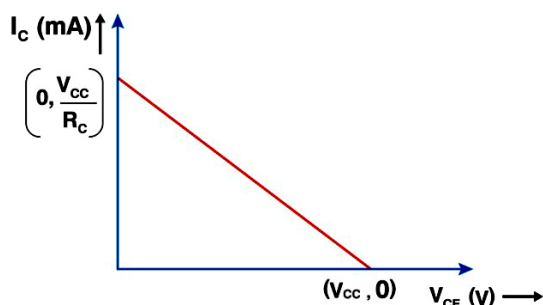


Fig. 5.13 DC load line

In the common emitter configuration with collector resistance R_C , as shown in Fig. 5.8, the relation between the collector to the emitter voltage V_{CE} and the collector current I_C is $V_{CE} = V_{CC} - I_C R_C$. Suppose that we mark the different values of V_{CE} and I_C for a given R_C in a CE circuit. When we join these points together, we get a straight line which corresponds to the equation $V_{CE} = V_{CC} - I_C R_C$. This line is called the DC load line.

Two points on this line is enough to draw the line. This can be done by knowing the maximum values of the output voltage $V_{CE'}$ and the output current I_C . When $I_C = 0$ mA the collector-emitter voltage V_{CE} is maximum and when $V_{CE'} = 0$ the collector current I_C becomes maximum.

DC load line is a straight line on a transistor's output characteristics curve that shows all possible combinations of DC collector current (I_C) and collector-emitter voltage (V_{CE}).

The output side of a transistor in CE configuration can be represented by the equation.

$$V_{CE} = V_{CC} - I_C R_C$$

When the collector current $I_C = 0$, then the collector-emitter voltage is maximum and equal to V_{CC} .

$$\begin{aligned} V_{CC} \\ \text{i.e. } V_{CE} = V_{CC} \end{aligned}$$

This gives a point on x-axis. The co-ordinates of this point is $(V_{CC}, 0)$.

This point is known as the **cut-off point**.

When $V_{CE} = 0$, we get a point on the y-axis

$$\begin{aligned} V_{CE} &= V_{CC} - I_C R_C \\ 0 &= V_{CC} - I_C R_C \end{aligned}$$

Therefore, $I_C = V_{CC}/R_C$. The co-ordinates on y-axis is $(0, V_{CC}/R_C)$. This point is known as **saturation point**. The current is maximum at this point.

The load line establishes the relation between the output voltage and the output current when the load is varied from zero to infinity.

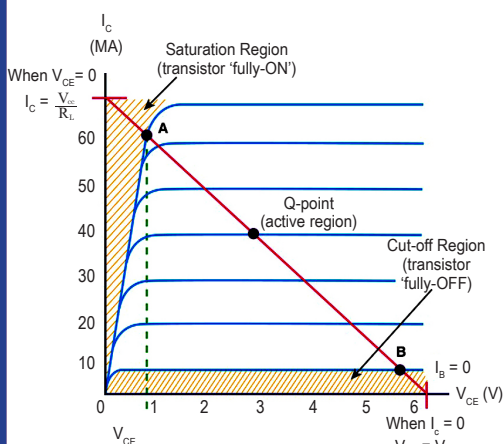


Fig. 5.14 shows the DC load line of a transistor connected in CE configuration



Activity 5.3

Draw the DC load line for the following circuit

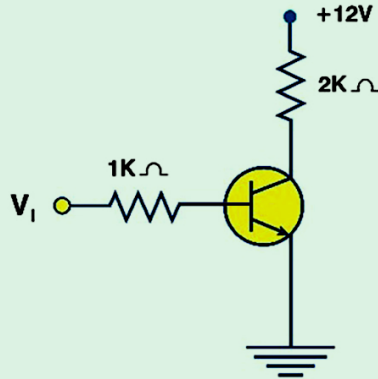


Fig. 5.15

Operating Point (Q - Point)

The operating point is a point on the DC load line which represents the values of the output voltage V_{CE} and the output current I_C of the transistor for a given input current I_B when no ac signal is applied. When an AC signal is applied to the base of the transistor (for amplification) the collector current and the collector emitter voltage will both vary around these values. Therefore, this operating point is much important in the design of transistors for particular applications. This is also known as Quiescent point or working point. This is the intersection of DC load line and input current I_B in the output characteristics curve in Fig. 5.14.

5.9 Transistor as a Switch

When used as an amplifier, the transistor's base biasing voltage is applied in such a way that it always operates within its "active" region. However, bipolar transistors can be made to work as "ON/OFF" type solid state switches by biasing the transistor to operate in cut-off and saturation regions.

Solid state switches are one of the main applications for the use of transistors. Transistor switches can be used for controlling high power devices such as motors, lamps, and can also be used in digital electronics and logic gate circuits.

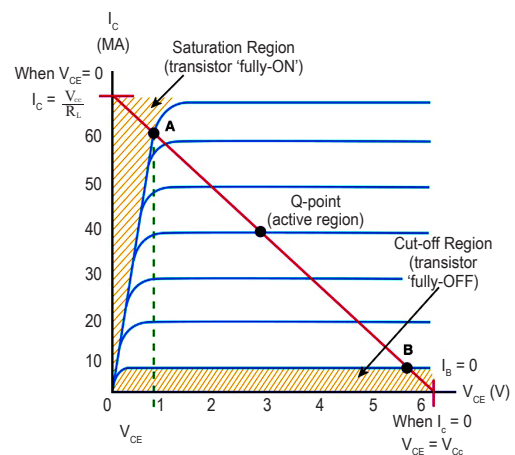


Fig. 5.16 Operating Regions

A transistor acts as a switch by driving it back and forth between its cut-off (OFF) and saturation (ON) regions. The operating regions are shown in Fig. 5.15

Cut-off Region

In this region, the emitter base and collector base junctions are reverse biased. Therefore, the transistor is switched OFF.

- Base-Emitter voltage $V_{BE} < 0.7V$
- Base-Emitter junction is reverse biased.
- Collector base junction is reverse biased.
- Transistor is in OFF state.
- Zero collector current flows.
- $V_{CE} = V_{CC}$
- Transistor operates as an open switch.

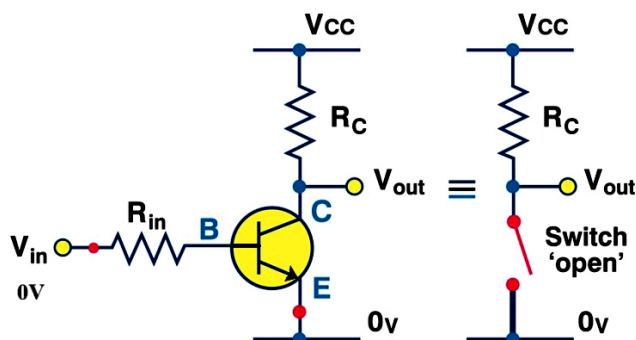


Fig.5. 17 : Transistor as an open switch

Saturation Region

In this region the emitter base (EB) and the collector base (CB) junctions are forward biased. So, maximum amount of base current (I_B) is applied, resulting in the maximum collector current (I_C). Therefore, the transistor is switched "Fully-ON".

- Base-Emitter voltage $V_{BE} > 0.7V$
- Base-Emitter junction is forward biased.
- Base-Collector junction is forward biased.
- Transistor is "fully-ON" (saturation region)
- Max Collector current flows. ($I_C = V_{CC}/R_C$)
- $V_{CE} = 0$ (ideal saturation)
- $V_o = V_{CE} = 0$
- Transistor operates as a "closed switch".

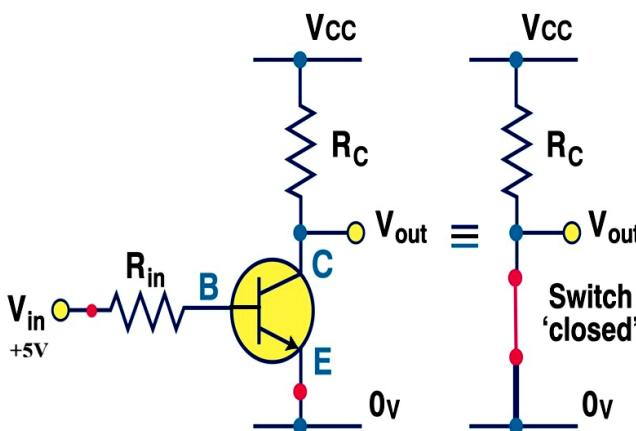


Fig. 5. 18 : Transistor as a closed switch

SCR

(Silicon Controlled Rectifier)



Water Heater & Electric Stove

FET

(Field Effect Transistor)



TV & Audio Systems

MOSFET

(Metal Oxide Semiconductor FET)



Computers & Mobile Devices

LED

(Light Emitting Diode)



LED Lamp & Flashlight

Photodiode

Motion Sensors & Remote Control

Solar Cell

Solar Panels & Garden Lamp

Special Purpose Electronic Devices

In the last chapter we studied the working of Bipolar Junction Transistors (BJT). We know that transistor is a semiconductor device that can be used for amplification, switching, etc. Transistors may be roughly grouped into two major divisions: bipolar and field-effect. In this chapter, we can study the general concept of the field-effect transistor (FET). FETs are low power consuming devices than BJT and hence, it makes them ideal for use in integrated circuits (IC's).

The electronic devices used in high power applications such as motor control are called power electronic devices. The symbols and applications of power electronic devices such as SCR, TRIAC, DIAC and UJT are also included in this chapter.

Another type of special electronic device is the photo sensor (photo detector) which is used to sense light energy and produce corresponding electrical energy. Photo diodes, photo transistors and solar cells are examples. Light dependent resistors (LDR) are also photo sensors, whose resistance vary when light falls on them.

We are familiar with different types of displays used in electronic devices, home appliances, electronic speedometers, etc. In this chapter we will discuss the operation of LED (light emitting diode), a commonly used component in display. Thermistors are temperature sensing electronic components which will change its resistance in

accordance with temperature applied to it. Varactor diode is a kind of diode which acts as variable capacitor when its biasing voltage is changed. In this chapter we will also discuss integrated circuits (ICs), their classification, typical examples and advantages.

6.1 FET (Field Effect Transistors)

Field Effect Transistor (FET) was developed in the early 1960s. FET is a voltage controlled device whereas BJT is current controlled. FETs are broadly classified into two:

1. Junction Field Effect Transistor (JFET)
2. Metal Oxide Semiconductor FET (MOSFET)

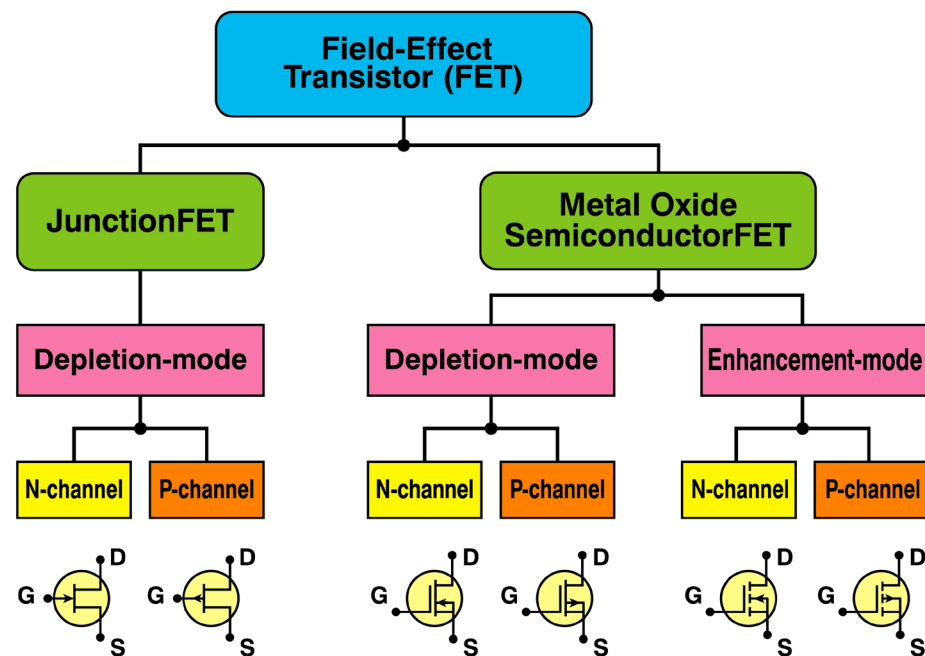


Fig. 6.1 Classifications of FET and its symbols

Junction Field Effect Transistor (JFET)

Construction of JFET

A JFET consists of a P-type or N-type silicon bar containing a PN junction as shown in Fig. 6.2 (a). The bar forms the conducting channel for the charge carriers. If the bar is of N-type, it is called N-channel JFET, and if the bar is of P-type, it's called a P-channel JFET. As shown in Fig. 6.2 (a), the two PN- junctions forming diodes are connected internally and a common terminal called Gate is taken out. The symbols of N-channel & P-channel JFET are shown in Fig. 6.2 (b).

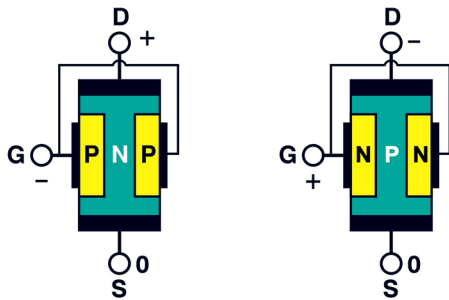


Fig. 6.2 (a)

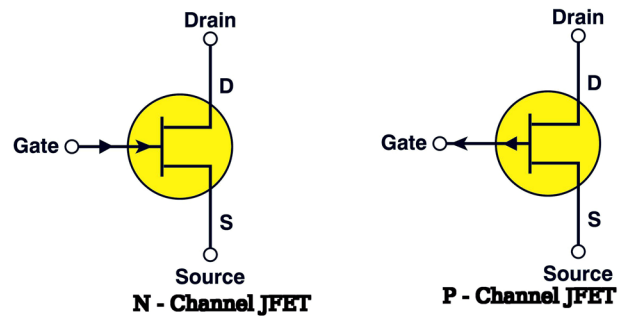


Fig. 6.2 (b)

A field effect transistor has three terminals which are called source, drain and gate. Drain and Source are similar in function to the collector and the emitter respectively of the bipolar transistor. The current path between these two terminals is called the channel which may be made of either a P-type or an N-type semiconductor material. The control of current flowing in this channel is achieved by varying the voltage applied to the Gate.

1. **Source (S):-** The terminal through which majority carriers enter the channel.
2. **Drain (D):-** The terminal through which majority carriers leave the channel.
3. **Gate (G):-** The terminal formed by joining the two other semiconductor regions on either side of the channel internally. It controls the flow of majority carriers from Source to Drain.

Working Principle of JFET

Generally, the semiconductor channel of the JFET is a resistive path through which a drain current I_D flows when a voltage is applied between the drain and the source (V_{DS}). The JFET can conduct current equally well in either direction. The magnitude of the current flowing through the channel between the Drain and the Source terminals is controlled by a voltage applied to the Gate terminal, which is reverse biased. In an N-channel JFET this Gate voltage is negative while for a P-channel JFET the Gate voltage is positive.

In JFET, under normal working condition, the Gate junction is reverse biased and hence the Gate current is practically zero.

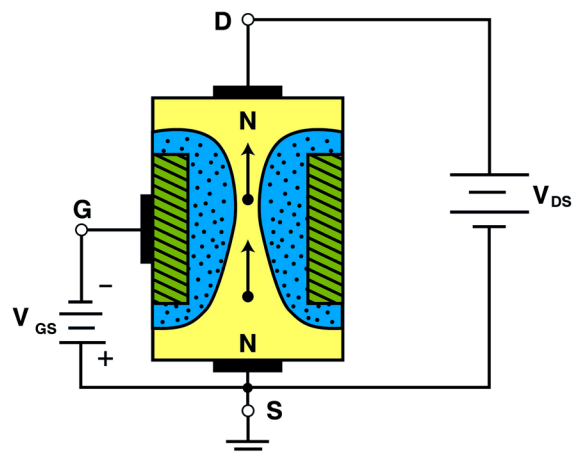


Fig. 6.2 (c)

The reverse biased junction forms a depletion region around the Gate area. JFETs are therefore known as depletion mode devices. If a small negative voltage ($-V_{GS}$) is applied to the Gate, the size of the depletion region begins to increase reducing the effective area of the channel and thus reducing the current flowing through it as shown in Fig. 6.2 (c). When the applied reverse voltage is increased the width of the depletion region increases, which in turn reduces the width of the channel and this causes the current to decrease.

Since the PN junction is reverse biased, only a little current will flow through the gate terminal. As the Gate voltage ($-V_{GS}$) is made more negative, the width of the channel decreases until no more current flows between the Drain and the Source and the FET is said to be pinched-off (similar to the cut-off region for a BJT). The gate voltage at which the channel closes is called the pinch-off voltage (V_p).

Comparison between BJT and FET

	JFET	BJT
1	Unipolar device - current conduction is due to majority carriers only.	Bipolar device - current conduction is due to both majority and minority carriers.
2	High input impedance (of the order of $100\text{ M}\Omega$) since the input side is reverse biased.	Low input impedance since the input side is forward biased.
3	Voltage controlled device - Gate voltage (V_g) controls the drain current I_D .	Current controlled device - Base current (I_B) controls the collector current I_C .
4	Better thermal stability - Current conduction is due to majority carriers only.	Less thermal stability - Current conduction is due to majority and minority carriers.
5	Less noisy - No junctoins in the current path of JFET.	More noisy - In BJT there are two junctoins in the current path (EB junction and CB junction).

Applications of JFET

The junction field effect transistor has many applications in the field of electronics and communication. Some of these applications are stated below.

1. Low noise and high input impedance amplifier
2. Switching applications
3. Voltage Variable Resistance (VVR)

MOSFET

The second type of FET is Metal - Oxide Semiconductor FET (MOSFET). Like JFET, it also has a source, gate and drain. However, unlike JFET, the gate of a MOSFET is insulated from the channel. Because of this, the MOSFET is sometimes known as IGFET which stands for Insulated Gate Field Effect Transistor.

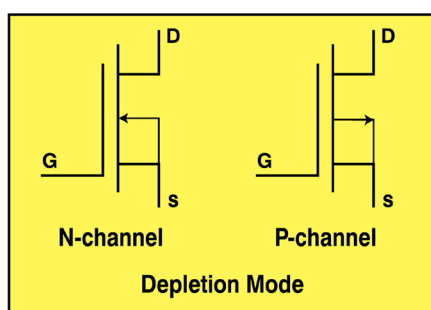


Fig. 6.3 : Symbols of depletion mode MOSFETs

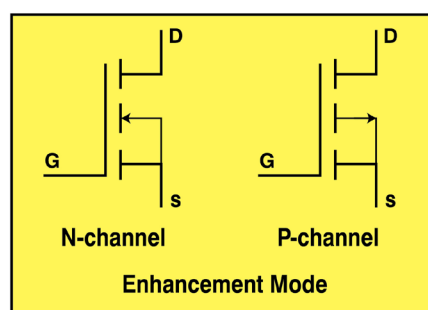


Fig. 6.4 : Symbols of enhancement mode MOSFETs

MOSFETs are further classified into two - Depletion type MOSFET and Enhancement type MOSFET. The primary difference between the two types of MOSFETs lies in their construction and mode of operation. Fig. 6.3 shows the symbols of N-channel and P-channel depletion mode MOSFETs and Fig. 6.4 shows the symbols of N-channel and P-channel Enhancement mode MOSFETs.

Application of MOSFET

1. Used in digital ICs, Microprocessors, memories, etc.
2. High input impedance amplifiers
3. UPS and Inverters



Fig.6 5. Typical FET and MOSFET Packages

Complementary MOS (CMOS)

Have you heard about CMOS technology? CMOS means Complementary Metal-Oxide-Semiconductor and it is a technology used for constructing very low power digital ICs. CMOS uses a combination of P-channel and N-channel Enhancement-mode MOSFETs (PMOS and NMOS), wired in series.

The main advantage of CMOS design is its extremely low power consumption. The total power dissipation of the circuit is in nano watts. Hence, CMOS ICs are normally used in calculators, digital watches, computers and satellites.



Know your progress

1. How is the drain current controlled in JFET?
2. What is the importance of Pinch-off Voltage (V_p) in JFET?
3. Give some differences between JFET & BJT

6.2 Power Electronic Devices

Power electronic devices are those, that can handle currents up to several thousand amperes and voltages up to kilovolt range.

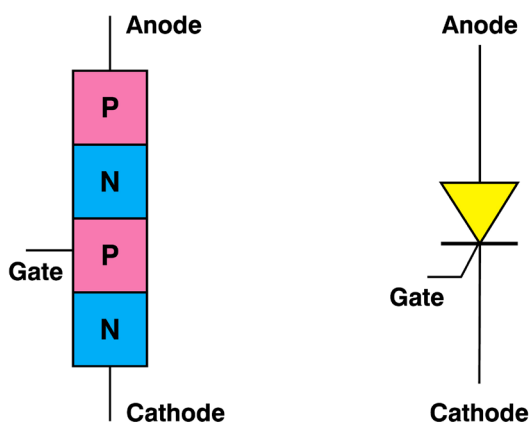


Fig. 6.6 SCR - Structure and symbols

SCR (Silicon Controlled Rectifiers)

The SCR is a three terminal semiconductor switching device which is probably the most important circuit element other than diode and transistor. SCR can change AC to DC and at the same time it can control the amount of power to the load. Apart from a normal diode, SCR has a third terminal called the gate for controlling the rectification. SCR consists of four semiconductor layers and three PN junctions. It can be considered as

an ordinary rectifier (PN junction) and a junction transistor (NPN) combined in one unit to form PNPN device as shown in Fig. 6.6.

Fig. 6.6 shows the symbol of SCR. Three terminals are taken- the first from the outer P-type material called Anode (A), second from the outer N-type material called Cathode (K) and the third from the internal P-layer called Gate (G). In normal operating conditions of SCR, anode is held at a high positive potential with respect to cathode and the gate at a small positive potential with respect to cathode.

Working of SCR

In a silicon controlled rectifier, load is connected in series with anode. The anode is always kept at positive potential with respect to cathode. The working of SCR is as follows:

(1) **When the Gate is open:** Fig. 6.7

shows the SCR circuit with gate open i.e. no voltage is applied to the gate. Under this condition, junction J_2 is reverse biased while junction J_1 and J_3 are forward biased. Hence, the situation in the junctions J_1 and J_3 are just as in NPN transistor with base open. Consequently, no current flows through the load and the SCR is Cut-off. However, if the applied voltage is gradually increased, a stage is reached when reverse biased junction J_2 breaks down. The SCR now conducts heavily and is said to be in the ON state. The applied voltage at which SCR conducts heavily without gate voltage is called breakover voltage. Commercially available SCRs have breakover voltages from about 50 V to 800 V.

(2) **When the gate is positive with respect to cathode:** The SCR can be made to conduct heavily at a smaller applied voltage by applying a small positive potential to the gate as shown in Fig. 6.8. Now the junction J_3 is forward

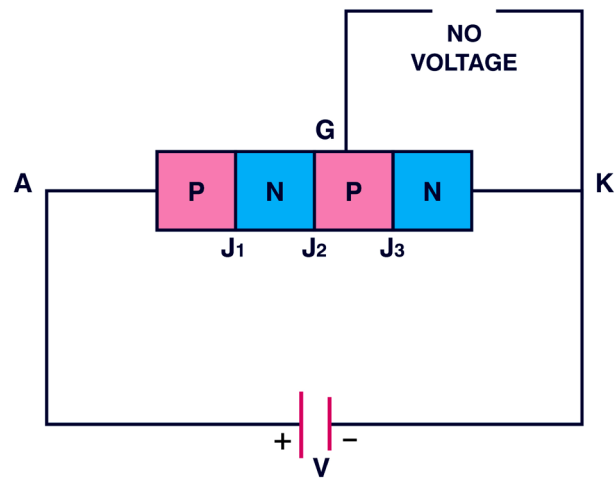


Fig.6.7 SCR with gate open

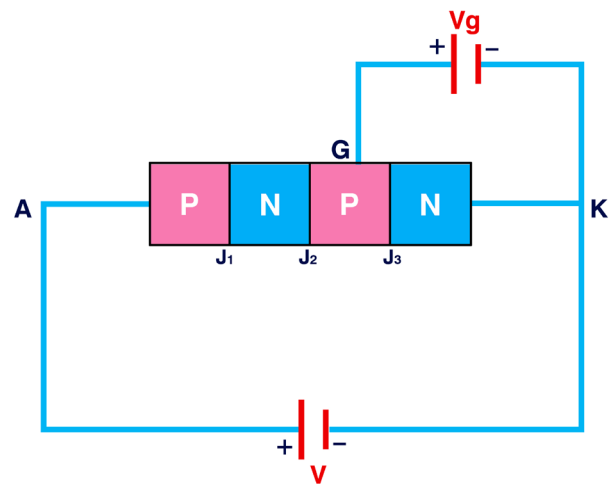


Fig. 6.8 SCR with gate voltage applied

biased and junction J_2 is reverse biased. The electrons from N-type material start moving across the junction J_3 towards left whereas holes from the P-type move towards right. Consequently, the electrons from the junction J_3 are attracted across the junction J_2 and gate current starts flowing. As soon as the gate current flows, the anode current increases. The increased anode current in turn makes more electrons available at the junction J_2 . This process continues and in an extremely small duration, junction J_2 breaks down and SCR starts conducting heavily. Once SCR starts conducting, the gate loses its control. Even if the gate voltage is removed, the anode current does not decrease at all. The only way to stop conduction (i.e. to bring SCR in the off state) is to reduce the applied voltage.

Applications of SCR

1. Heat control
2. Speed control of motor
3. Battery charger
4. UPS

TRIAC

The TRIAC is a three terminal device, with terminals MT1, MT2 (Main terminal) and G (gate) which can conduct in either direction, when triggered by a positive or a negative pulse irrespective of the polarity of the voltage across its main terminals. The TRIAC behaves like two SCRs connected in parallel but in opposite directions, with a common gate terminal i.e., the anode of one SCR is connected to the cathode of the other and their gates are connected together. Thus, anode and gate voltage applied in either direction will trigger the TRIAC. It is due to the fact that the applied voltage will trigger at least one of the SCRs connected in the opposite directions.

The TRIACs are available with very high current ratings and high voltage. When voltage in the positive half cycle of AC exceeds the positive break over voltage (break over voltage of the SCR in that direction), the TRIAC conducts in that direction. Similarly, when the voltage in the negative half cycle of AC exceeds the negative break over voltage (break over voltage of the SCR in that direction), the TRIAC conducts in that direction. These conducting voltages in either direction can be varied by varying the gate current.

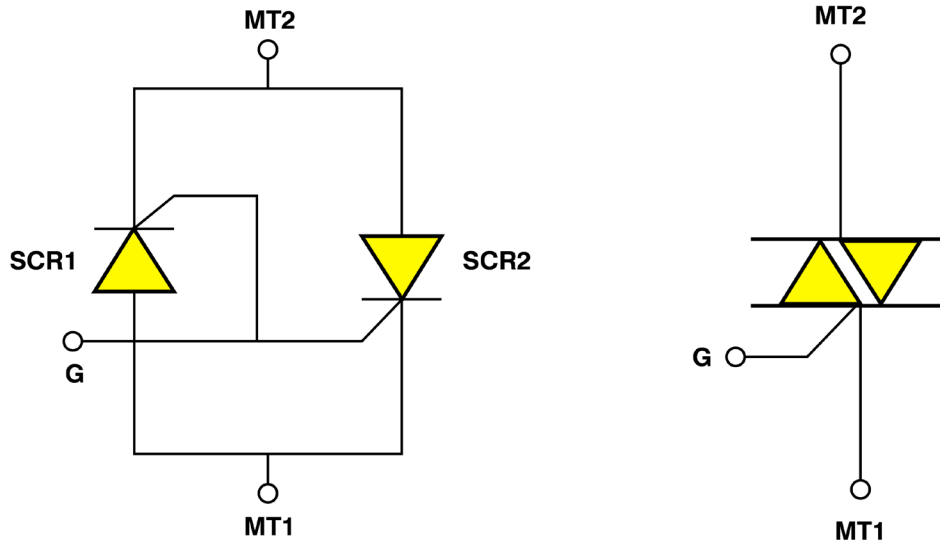


Fig. 6.9 TRIAC Equivalent circuit and symbol

Applications of TRIAC

The TRIAC has an important property that it can conduct current in either forward or reverse direction, depending upon the polarity of the voltage across its terminals. This property makes the TRIAC very useful to control AC machines. Some applications of TRIAC are given below:

1. Electronic Fan Regulators
2. Motor speed control
3. Battery charger & UPS

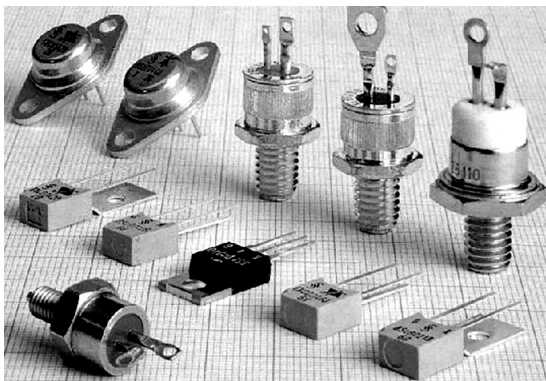


Fig. 6.10 Typical SCR and TRIAC Packages



DIAC

The DIAC (Diode for Alternating Current) is a two terminal device. The basic construction of DIAC is similar to a TRIAC, but without a gate terminal as shown in Fig. 6.11.

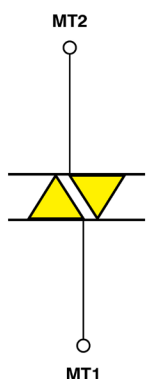


Fig. 6.11
DIAC Symbol

The working of the DIAC is similar to that of the TRIAC except that it has no gate terminal. Because of this, the conducting voltage (break over voltage) of the DIAC cannot be varied.

Applications of DIAC

DIAC is normally used with a TRIAC in control circuits such as light dimming, heat control, motor speed control, etc.



Activity - 6.1

Consider the circuit shown in Fig. 6.12 (a). The load may be a light or a fan. What happens to the load when the potentiometer is varied?

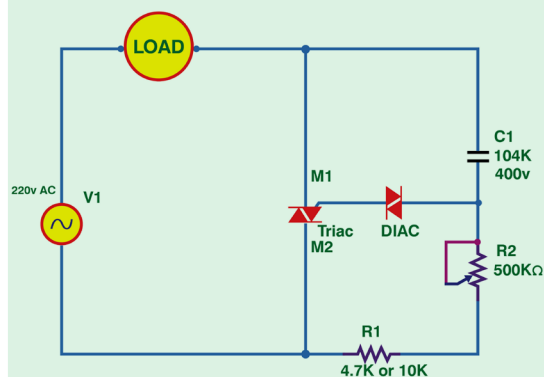


Fig. 6.12 (a) Fan /Light Regulator circuit



Fig. 6.12 (b) Typical Electronic Fan Regulator

Unijunction Transistor (UJT)

UJT (Unijunction Transistor) is a three terminal semi conductor device with one junction. Since the device has only one (P-N) junction, it is called a Unijunction device.

UJT Symbol and Construction

Fig. 6.13 (a) shows the basic structure of a unijunction transistor. It consists of a lightly doped N-type silicon bar with a small piece of heavily doped P-type material alloyed to its one side to produce single P-N junction. The UJT has three terminals: an emitter (E) and two Bases (B_1 and B_2). The two base leads are taken from the N-type silicon bar. The emitter is of P-type and it is heavily doped. The emitter (E) junction is usually located closer to base-2 (B_2) than base-1 (B_1). Fig. 6.13 b shows the symbol of UJT.

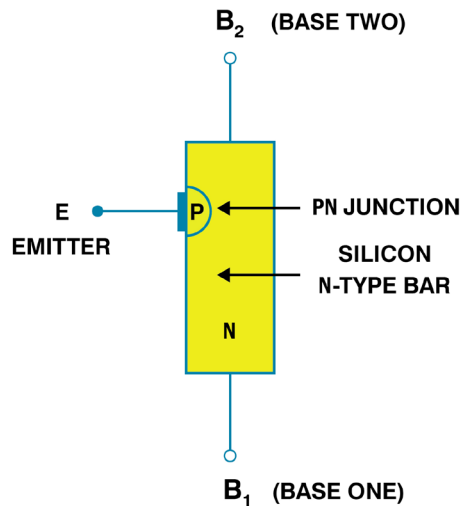


Fig. 6.13 (a) UJT Construction

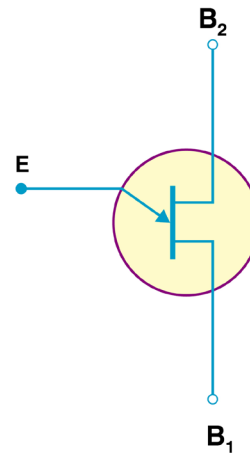


Fig. 6.13 (b) UJT Symbol

Applications

1. Sawtooth waveform generator
2. Phase and Timing control circuits

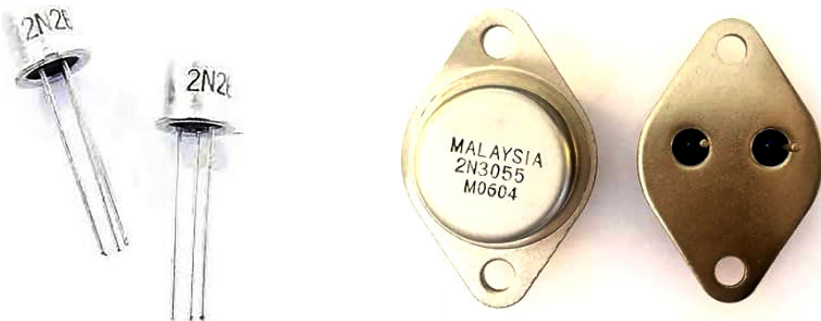


Fig. 6.14 UJT Packages

6.3 Light Emitting Diode (LED)

Have you heard about LED? Where is it used?

An LED (Light Emitting Diode) is a diode that gives visible light when forward biased. It is mainly used as a source of light, for displays and as indicators.

In an LED electrical energy is converted into optical energy. These are examples of electro-luminescence, the process in which emission of photons takes place by the recombination of excess electrons and holes in a direct band gap semiconductor. The main advantages of using these are low energy consumption, longer lifetime (more than 20 years), faster switching, smaller size, etc. Fig. 6.15 shows the symbol of LED and some commonly used LEDs.

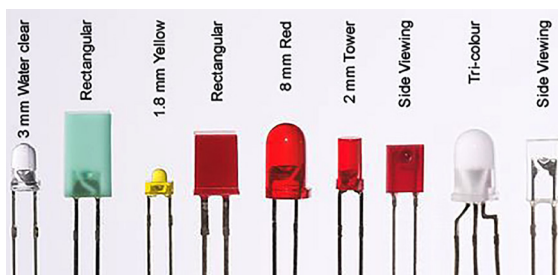
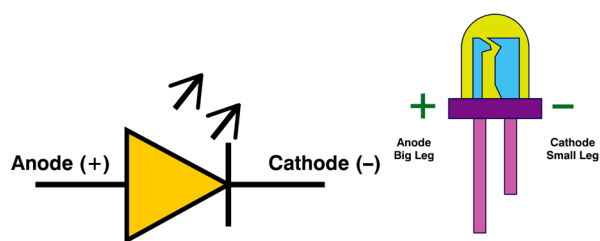


Fig. 6.15 Symbol of LED, its construction and some commonly used LEDs

Working of LED

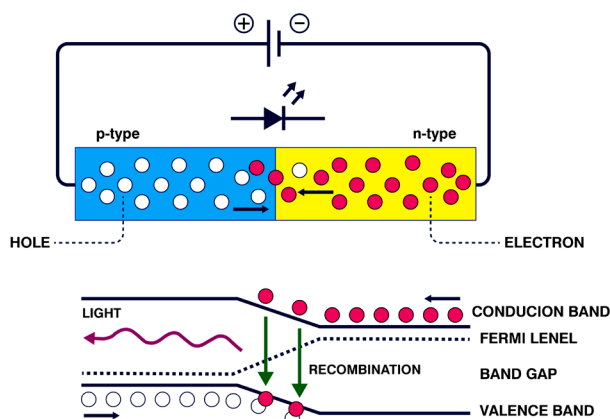


Fig. 6.16 Working of LED

When a PN junction is forward biased, recombination of holes and electrons will occur at the junction. During recombination, a large amount of energy is released in the form of heat or light.

How does a PN junction generate light?

Consider a simple semiconductor, which is forward biased. When an electron from the bottom of the conduction band falls into a hole at the

top of the valence band, an energy equal to band gap energy (E_g) is released in the form of EM radiations whose frequency is given by

$$\nu = \frac{E_g}{h}$$

Here h is Plank's constant. In Silicon and Germanium, the band gap energy is small (0.7eV and 1.1eV) so that the frequency of the generated EM radiation is small and a great percentage of this energy is given off in the form of heat (thermal energy). As a result, no light is emitted.

In some semiconductor materials like Gallium Arsenide (GaAs) or Gallium Phosphide (GaP), the band gap energy is large so that the frequency of emitted radiation falls in the visible range. The colour emitted from the LED depends on the frequency of emission which in turn depends on the band gap energy of the material used. Thus, we can say that the colour of the LED depends on the nature of materials used. The wavelength of output optical signals depends upon the band gap energy. The output wavelength can be made to be within certain limits by using compound semiconductors, so that a particular color can be observed, provided the output is in

visible range. The forward voltage rating of most LEDs is from 1V to 3 V and the forward current rating ranges from 5 mA to 100 mA.

Bicolour LED

An LED that emits one colour when forward biased and another colour when reverse biased is called bicolour LED. Fig. 6.17 shows the working of a typical Red-Green bicolour LED. A typical bicolour LED contains two PN junctions that are connected in reverse - parallel i.e., they are in parallel, with anode of one being connected to the cathode of the other. If positive potential is applied to the top terminal as shown in Fig. 6.17 (i), the PN junction on the led will glow in red colour. If the polarity of the voltage source is reversed as shown in Fig. 6.17 (ii), the PN junction on the right will glow in green colour.

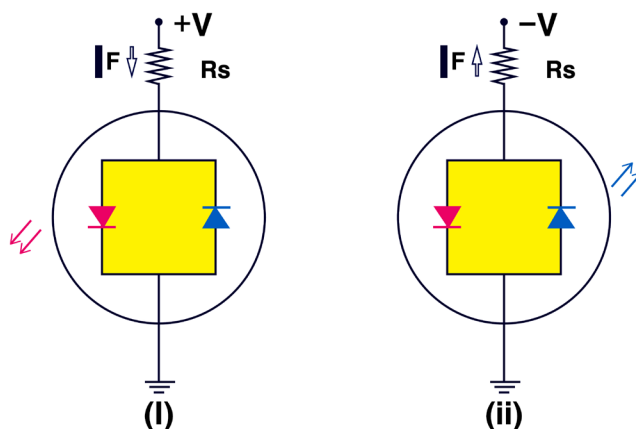


Fig. 6.17 Working of Red & Green multi colour LED

Bicolour LEDs are typically red when biased in one direction and green when biased in the other. If a bicolour LED is switched fast enough between two polarities, the LED will produce a third colour. A red /green LED will produce a yellow light when rapidly switched back and forth between biasing polarities.

Applications of LED

Light emitting diodes are used in applications such as power indicator, seven segment display, automotive lighting, advertising LED boards, dot matrix display, background light source in LED TV and traffic signals. Infrared LEDs are also used in the remote control units of many commercial products including televisions. LED lamps are used for household applications.

The table below shows different colours of LEDs and the names of materials used.



	Color	Wavelength [nm]	Semiconductor material
	Infrared	$\lambda > 760$	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
	Red	$610 < \lambda < 760$	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
	Orange	$590 < \lambda < 610$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
	Yellow	$570 < \lambda < 590$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
	Green	$500 < \lambda < 570$	Traditional green: Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP) Pure green: Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN)
	Blue	$450 < \lambda < 500$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate—under development
	Violet	$400 < \lambda < 450$	Indium gallium nitride (InGaN)
	Purple	multiple types	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
	Ultraviolet	$\lambda < 400$	Diamond (235 nm) Boron nitride (215 nm) Aluminium nitride (AlN) (210 nm) Aluminium gallium nitride (AlGaN) Aluminium gallium indium nitride (AlGaInN)—down to 210 nm
	Pink	multiple types	Blue with one or two phosphor layers: yellow with red, orange or pink phosphor added afterwards, or white with pink pigment or dye.
	White	Broad spectrum	Blue/UV diode with yellow phosphor



Know your progress

1. Discuss the construction of SCR & UJT
2. Give some important applications of SCR & TRIAC
3. How do LEDs work?

6.4 Photo Detectors (Photo Sensors)

Photo detectors (Photo sensors) are used for detecting light signals. The Photo detector devices can be classified as follows.

1. Photoresistors [Light Dependent Resistors (LDR)]
2. Photodiode
3. Phototransistor
4. Photovoltaic cells (solar cells)

Photo Resistors or Light Dependent Resistors (LDR)

A photoresistor or light dependent resistor (LDR) is a resistor whose resistance decreases with increasing incident light intensity. In other words, it exhibits photo conductivity. LDR is used in automatic light sensing circuits, safety systems, amusement, etc.

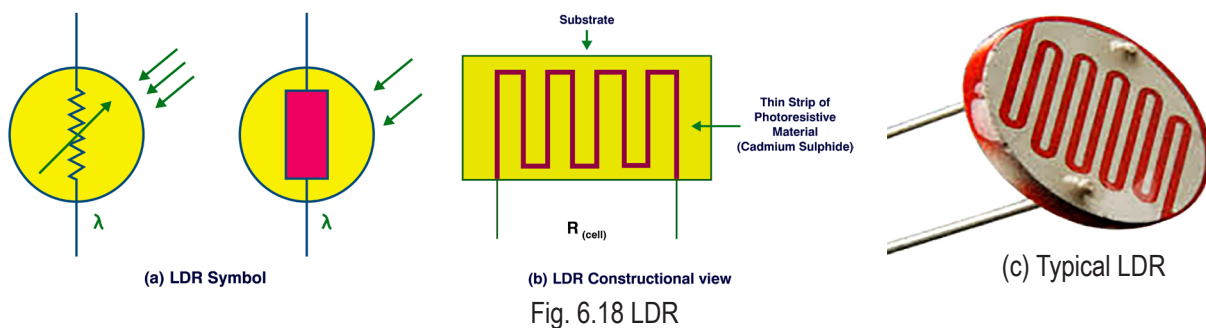


Fig. 6.18 LDR

Fig. 6.18 (a) shows the symbol of LDR. Photo resistors are of various types. Fig. 6.18 (b) shows the constructional view of LDR. In this, a strip of photosensitive material is made by cadmium sulphide. This material is inexpensive, so it is used in many consumer items such as camera light meters, alarm devices, outdoor clocks, solar street lamps, bed lamps, etc. Fig. 6.18 (c) shows a typical LDR. A photoresistor is made of a high resistance semiconductor. If light falls on the device, photons absorbed by the semiconductor give bound electrons enough energy to jump into the conduction band. The resulting free electron (and its hole partner) conducts electricity, thereby lowering resistance. Normally, the resistance of an LDR is very high, sometimes as high as $1\text{M}\Omega$, but when they are illuminated with light, the resistance drops drastically.



Activity - 6.2

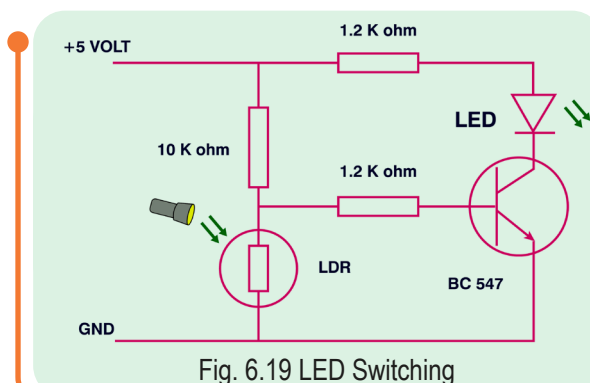


Fig. 6.19 LED Switching

Set up this circuit and observe the status of LED when the torch is ON and OFF.

Photodiode

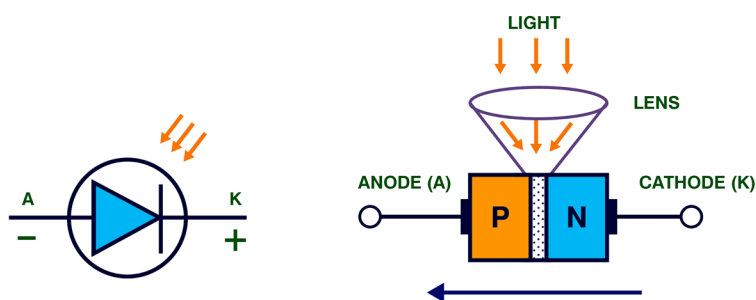


Fig. 6.20 Photo diode symbol and structure

A photodiode is a reverse biased silicon PN junction in which the reverse current increases when the junction is exposed to light. The reverse current in a photo diode is directly proportional to the intensity of light falling on its PN junction. This means that the greater the intensity of

light falling on the PN junction of photo diode, the greater will be the reverse current. Fig. 6.20 shows the symbol of photodiode. The inward arrows represent the incoming light. Fig. 6.20 also shows the typical structure of a photo diode. It consists of a PN junction and a glass window mounted on the top of the case to allow light to enter and strike the PN junction. The two leads extending from the case are labelled anode and cathode.

Applications of Photodiode

1. Burglar alarm - Security alarms protect against burglary (theft).
2. Photodiodes are often used for measurement of light intensity. For e.g., camera light meters
3. They are also widely used in various medical applications such as detectors for Computer Tomography.
4. It is often used for optical communications and in lighting regulation.

Photo Transistor

The photo transistor is a semiconductor light sensor formed from a basic transistor with a transparent cover that allows light to fall on the base of the transistor. The principle of working of a photo transistor is the same as that of a photodiode. A photo transistor, however, is much more sensitive to light and produces more output current for a given light intensity than a photodiode does. A photo transistor has a photosensitive collector base PN junction. The current induced by the photoelectric effects is the base current I_B of the transistor. The resulting amplified collector current is given as $I_c = \beta I_B$. Fig. 6.21 shows the symbol and Fig. 6.22 below shows the physical appearance of a phototransistor.

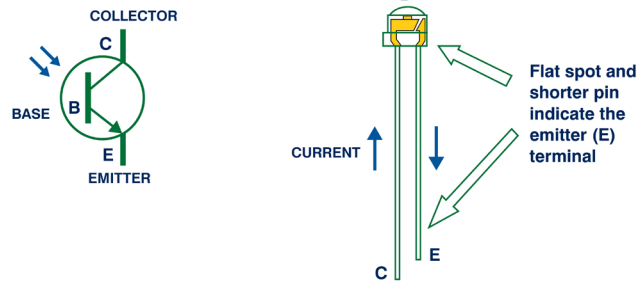


Fig.6.21 Phototransistor

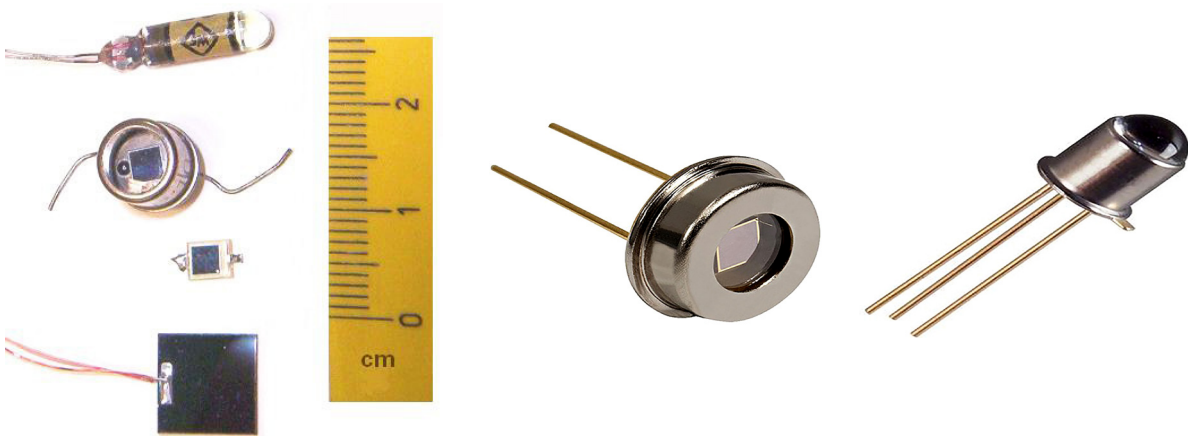


Fig. 6.22 Typical photo diode and photo transistor packages

Application

They are used in light controllers in highways, level indicators and counting system.

Solar Cell (Photovoltaic Cell)

Solar cell (a photovoltaic cell) is a device which converts light energy into electrical energy. It is a form of photoelectric cell (the electrical characteristics - e.g., current, voltage, or resistance vary when light is incident upon it) which, when exposed to light, can generate and support an electric current without being attached to any external voltage source.

Photovoltaics is the field of technology and research related to the practical application of photovoltaic cells in producing electricity from light. Cells can be described as photovoltaic even when the light source is not necessarily sunlight (lamplight, artificial light, etc.).

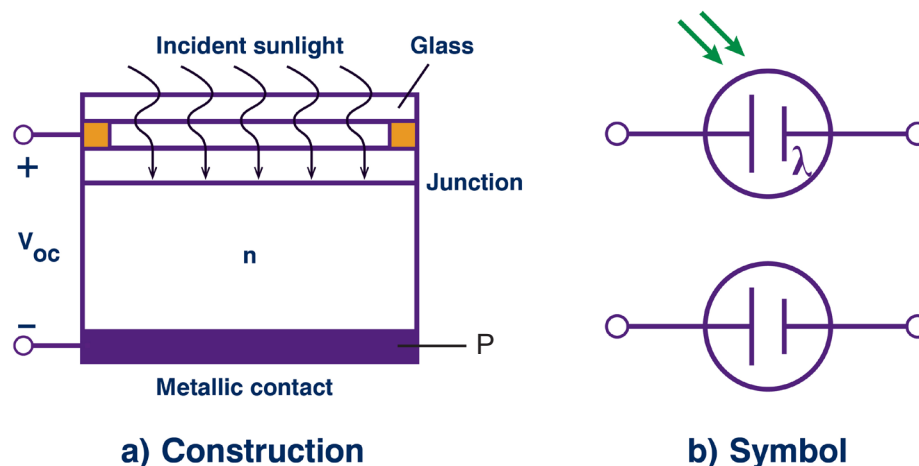


Fig. 6.23 Solar cell Symbol & Construction

A PN junction of suitable material like silicon, germanium, selenium etc., can be used as a solar cell. Fig. 6.23 (a) shows the basic construction of a silicon PN junction solar cell. The top surface area must be perpendicular to sunlight to ensure maximum power. The metallic conductor connected to the P-type material and thickness of the P-type material is such that a maximum number of photons of light energy will reach the junction.

Light from the sun is allowed to fall on an unbiased PN junction as shown in Fig. 6.23 (a). Photons of light energy in this region collide with the valence electrons and generate conduction band electrons and holes. This phenomenon will occur on either side of the junction.



Fig. 6.23 (c) Typical Solar Panel

In the P region, newly generated electrons are minority carriers. As in an ordinary diode, these minority electrons will move freely across the junction to the N region. Similarly, the minority holes from the N region will move to the P region. This results in reverse current due to minority carriers in the PN crystal. If an external resistor is connected between the contacts on P and N regions, current will flow through it. The voltage across the diode terminal is photovoltaic emf and is of the order of 0.5 V for silicon cell and 0.1 V for germanium cell.

6.5 Thermistors

Have you ever thought how does a sensor detect the temperature?

We can sense (detect) temperature using a thermistor. This is a type of resistor whose resistance varies significantly with temperature, more than that in standard resistors. Thermistor is the combination of the words thermal and resistor. The typical package and symbol of a thermistor is as shown in Fig. 6.24.

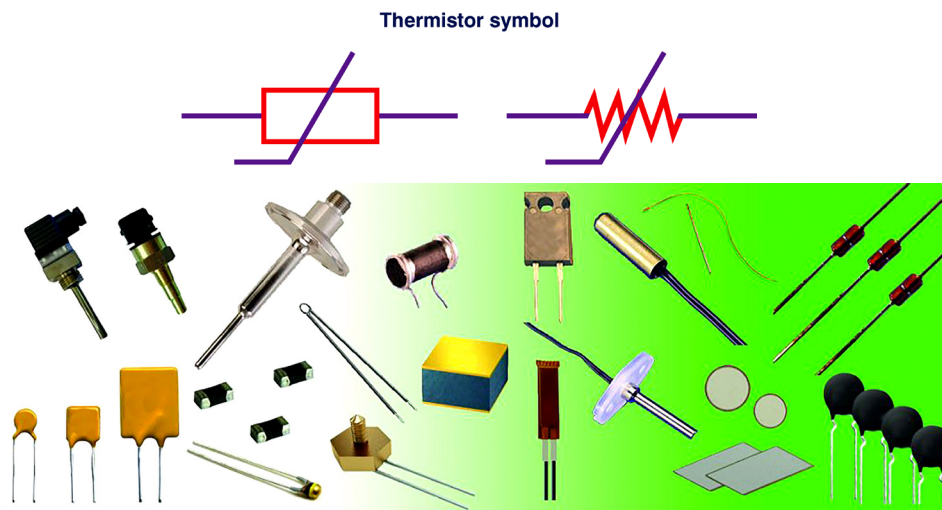


Fig. 6.24 Thermistor symbol – Typical packages

Thermistor is a temperature sensitive resistor; that is its terminal resistance is related to its body temperature. It is not a junction device and is made of Ge, Si or a mixture of oxides of cobalt, nickel, strontium or manganese. The compound employed will determine whether the device has positive or negative temperature coefficient. They have great resistance at low temperatures but when they warm up their resistance decreases rapidly. Current can then flow through them. This makes them ideal for a temperature sensor. Thermistors achieve a higher precision within a limited temperature range, typically -90°C to 130°C .

Applications of Thermistor

Thermistors are widely used as current limiters, temperature sensors, resistance thermometers, and self-regulating heating elements.

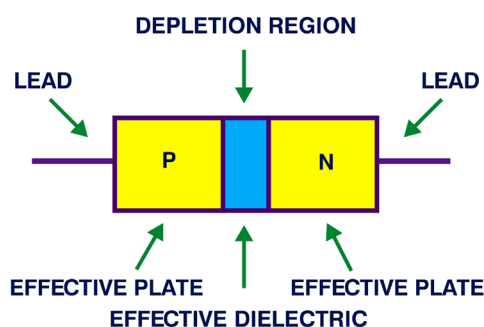


The first NTC (Negative Temperature Co-efficient) thermistor was discovered in 1833 by Michael Faraday, who reported the semiconducting behaviour of silver sulphide. Faraday noticed that the resistance of silver sulphide decreases drastically as temperature is increased. Since early thermistors were difficult to be produced and technology were limited, commercial production of thermistors began only after 1930s.

- The thermistor was invented by Samuel Ruben in 1930.

6.6 Varactor Diode (Varicap)

We have studied about variable capacitors. But a Junction diode



(a)



(b)

Fig. 6.25 Varicap -Construction and Symbol

which acts as a variable capacitor under the influence of varying reverse bias voltage is known as varactor diode. The varactor diode is also called varicap diode and variable capacitance diode.

The capacitance is formed with P and N regions as conducting plates and the depletion region as dielectric. When the reverse voltage is varied, the width of the depletion region varies. So, the capacitance varies as the separation between the conducting plates changes. Thus, the varactor acts as a voltage controlled capacitance.

Application

Varactors are used as voltage-controlled capacitors. They are commonly used in voltage-controlled oscillators, and frequency multipliers. Voltage-controlled oscillators have many applications such as frequency modulation for FM transmitters.



Know your progress

1. Give two applications of (i) Photo diode (ii) Varactor Diode.
2. Draw the symbols of (i) Photo resistor, (ii) Thermistor and (iii) Solar Cell.

6.7 Integrated Circuit (IC)

The most advanced electronic circuits contain millions of diodes, transistors, resistors and capacitors. These components are fabricated onto wafers, or chips, of semiconductor material, usually silicon. The chips are enclosed in little boxes or cans with pins for connection to external components.

IC - Classification

An integrated circuit consists of various electronic components and their interconnections in a single small semiconductor chip. There are four basic types of constructions employed in the manufacturing of integrated circuit, namely

1. **Monolithic IC:-** In this IC all electronic components (resistors, capacitors, diodes and transistors) are made on a single wafer (substrate) of semiconductor. Such ICs are used widely.
2. **Thin - film IC:-** In this IC, the thickness of the substrate is kept 0.001 inch or 0.0025 cm only.
3. **Thick - film IC:-** Thickness of substrate material is kept more in this type of IC, in comparison to a thin film IC.
3. **Hybrid:-** These ICs are formed either by combining two or more monolithic IC's or by combining monolithic IC's with thick film or thin film components.

IC -Package type

There are four popular IC packages that are available.

1. The Metal Can (TO) package
2. The Dual Inline Package (DIP)
3. The Single Inline Package (SIP)
4. The Flat package or Flat pack

Advantages of IC technology

Integrated circuits have several advantages over individual, or discrete, components.

1. Compactness-extremely small size
2. High speed
3. Low power requirement
4. Reliability

Evolution of ICs

In the early days of integrated circuits, only a few transistors could be placed on a chip. So, the degree of integration was small and the design process was relatively simple. Now-a-days with a good design and thorough planning millions and billions of transistors could be placed on one chip.



Fig. 6.26 First IC

First Integrated circuit

In 1958 - Jack Kilby - Texas Instruments developed Integrated circuit.

A device having multiple electrical components and their interconnections manufactured on a single substrate. This is shown in the photograph.

Typical examples of - IC

Integrated circuits can be divided into two further groups: analog (linear) and digital. The output voltage of linear circuits is continuous and follows changes in the input.

OP AMP - IC - 741

A typical representative of a linear IC is an Operational Amplifier (OP AMP-741). Fig. 6.27 below shows symbol and DIP package of IC-741. Operational amplifier is also termed as OP AMP. Basically, it is a differential amplifier having two inputs and the output is the amplified form of the difference of the two signals applied to these two inputs. Out of these two inputs, one input is known as inverting input and the other is called non inverting input. The main features of this IC are its very high gain and very large bandwidth.

This IC is widely used for performing various mathematical operations such as addition, subtraction, multiplication, division, integration, differentiation, logarithm, antilogarithm, etc. This is the reason why the IC is known as operational amplifier.

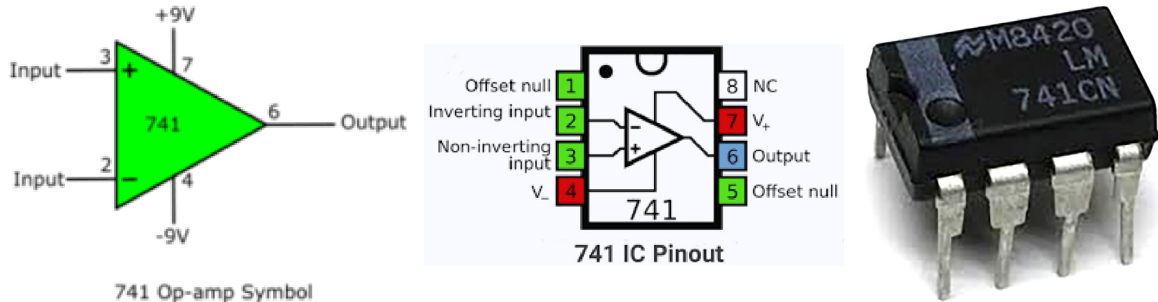


Fig. 6.27 Op-amp symbol, Pinout diagram and package

Timer IC-555

One of the most popular and widely used IC in electronic circuits is IC-555, which is called Timer. The IC is mainly used as monostable and astable multivibrators. It can produce accurate and highly stable timing pulses or time delays.

Important features of IC-555

1. It operates on +5 V to + 18 V DC supply voltage.
2. Adjustable duty cycle.
3. The timing of the pulse can be varied from micro seconds to hours.

The pin-out diagram and NE-555 with DIP- package are shown in Fig. 6.28 (a) and (b).

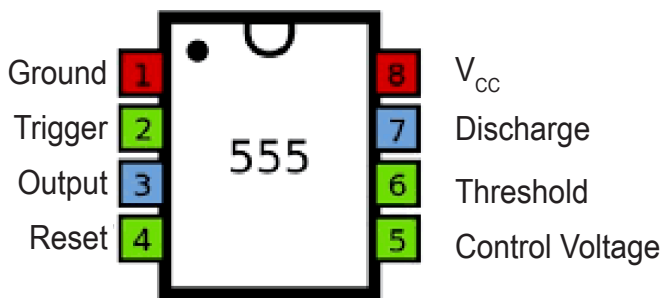


Fig. 6.28 (a) IC-555 Pin diagram

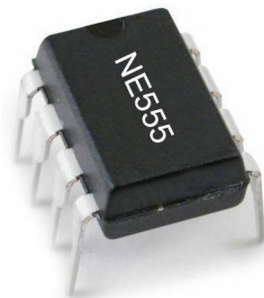


Fig. 6.28 (b) IC-555 package

Application of IC-555

1. Rectangular/square wave generator: A 555 astable multivibrator is used to generate a rectangular wave of any duty cycle. It can be modified to generate square waves. Also, the circuit can be modified as a ramp generator. The 555 Timer

IC is widely used in decorative displays and various security systems.

2. Timer circuit
3. Music generation



Activity - 6.3

Try These Circuits

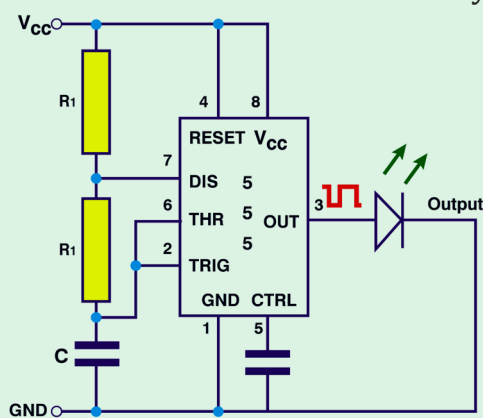


Fig. 6.29 Astable multivibrator

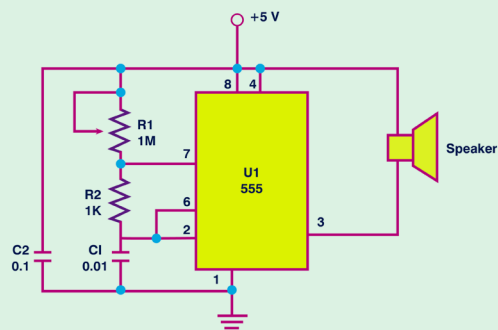


Fig. 6.30 Tone Circuit

Digital ICs

About 80 percent of the ICs in the market are digital ICs. Their output voltage is not continuous. It is either LOW or HIGH and it changes from one state to the other very quickly, i.e., switching functions. Digital ICs include circuits such as logic gates, memory chips, calculators, microprocessors etc. Typical examples for digital ICs are IC 7404 (NOT gate), IC 7402 (NOR gate), IC 7400 (NAND gate), etc.

Inverter or NOT Gate 7404

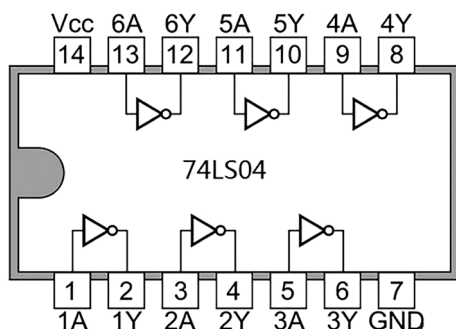
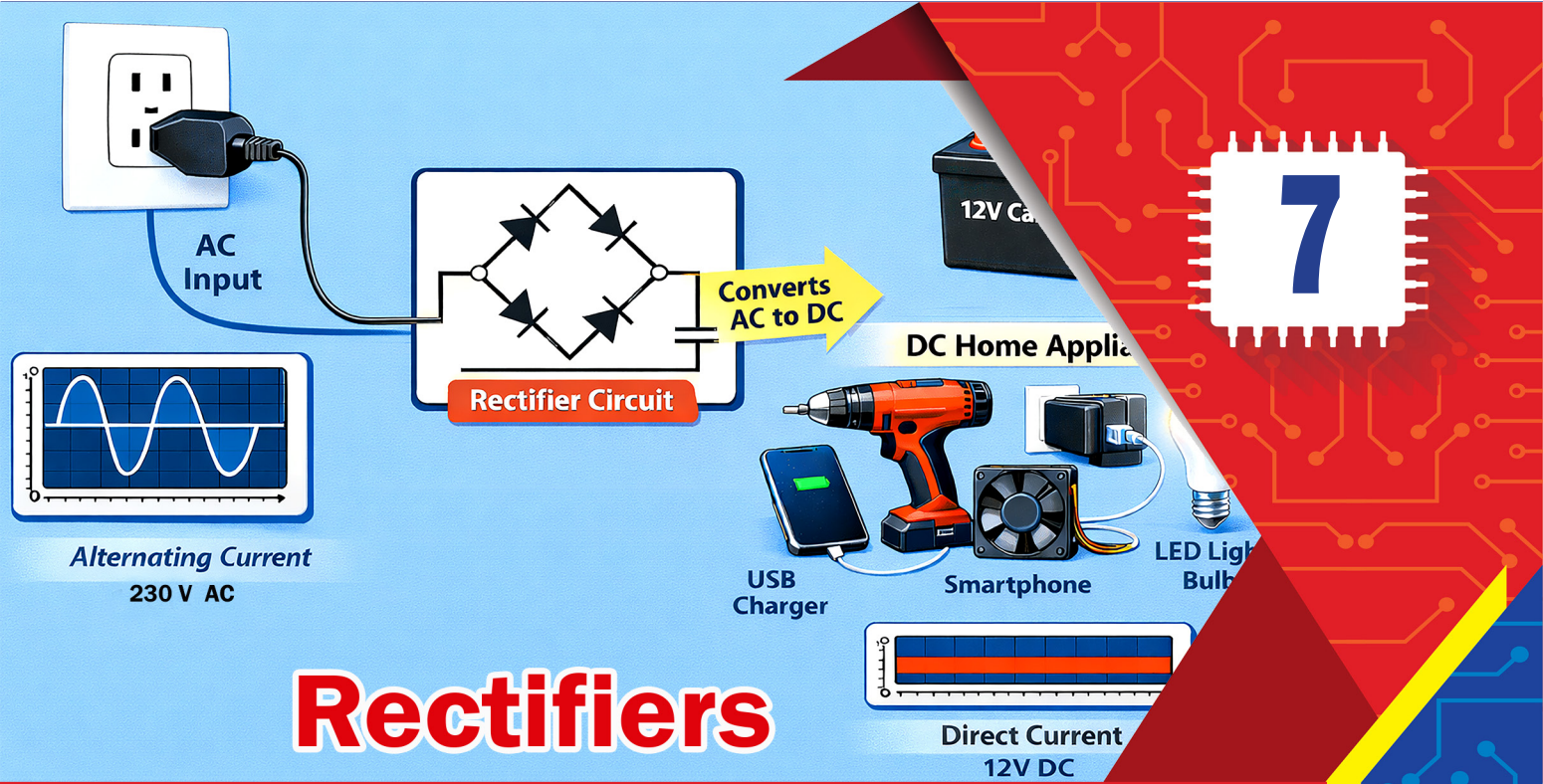


Fig. 6.31 IC- 74LS04 Pin diagram and package

The Logic NOT Function is simply a single input inverter that changes the input of a logic level 1 to an output of logic level 0 and vice versa. The logic NOT function is so called because its output state is not the same as its input state. Commonly available

logic NOT gates are of two types i.e., TTL Logic Types and CMOS Logic Types. Fig. 6.31 shows pin diagram and package of NOT gate.



Rectifiers

Most of the electricity supplied to homes and industries is in the form of alternating current (AC), which constantly changes direction. In India, the standard AC supply from the mains is 230 volts with a frequency of 50 Hz. However, electronic devices such as mobile phones, laptops, televisions and LED lights require DC supply for their operation.

Batteries can provide DC power, which are costly and suitable only for short term use. Therefore, we need a way to convert the AC voltage from the mains into DC voltage. This conversion is done using rectifier circuits-devices that transform alternating voltage or current into unidirectional (DC) voltage or current. But, the output from a rectifier is not so smooth as DC from a battery. It contains unwanted AC components known as ripples, which cause fluctuations in the voltage. If this fluctuating DC is supplied directly to an electronic device, it may not work properly. In order to eliminate these ripples and produce a more stable DC output, filter circuits are used.

There are various types of rectifiers and filters, based on their design. Without rectifiers, the modern digital world would struggle to function, as they play a vital role in powering the devices we rely on every day. In this chapter, we will explore how these circuits work and why they are essential in electronic systems.

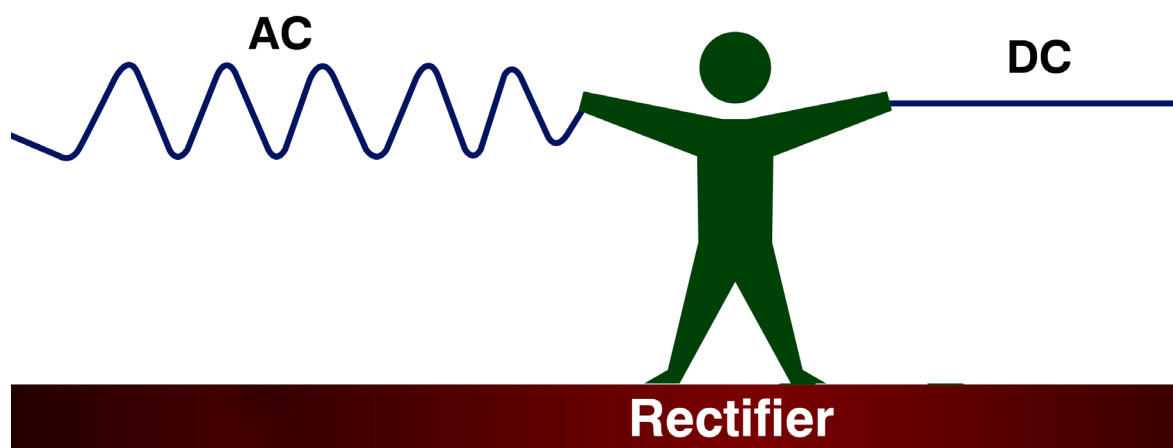


Fig. 7.1 Rectifier Action: Transforming AC into DC



Activity 7.1

Below is a list of household items. Your task is to sort them into two categories: AC/DC powered devices. (Refrigerator, Laptop, Ceiling fan, Smartphone, Microwave oven, Washing machine, LED bulb, Clock)

AC-powered devices	DC-powered devices

- Do you know how a mobile charger converts electricity from your wall socket to charge your phone?
- What type of current is supplied by your home socket – AC or DC?
- Why do electronic devices like phones and laptops need adapters?
- Can you explain the difference between AC and DC in simple terms?

7.1 Diode as a Rectifier

Can you suggest an electronic component that converts bidirectional or alternating current (AC) into a unidirectional or direct current (DC)? A PN junction diode is such a device. We have already studied that a PN junction diode conducts only in one direction. It conducts when forward biased while it practically does not conduct when reverse biased. Hence, it can be used to convert AC voltage to DC voltage. In other words, a diode can be used for rectification. This unique property makes the diode an essential component in power supplies, chargers and almost all electronic circuits that require DC voltage derived from an AC source. Let us now see how diode acts as a rectifier.

7.2 Types of Rectifiers

Rectifiers are broadly classified into Half wave and Full wave rectifiers based on how much of the AC input waveform is converted to DC. Half wave rectifiers convert only one half of the AC cycle, while full wave rectifiers convert both the halves, offering higher efficiency. Let's dive deeper into this topic and explore how it really works.

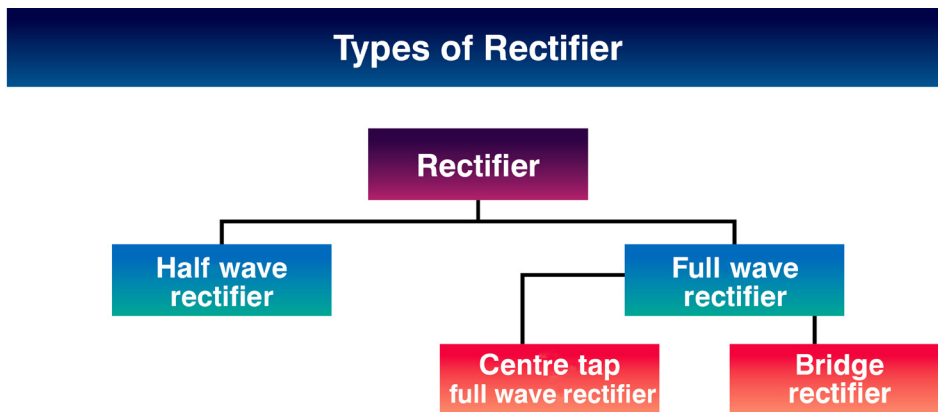


Fig. 7.2 Classification of rectifiers

7.3 Half Wave Rectifier

A half-wave rectifier is one of the simplest types of rectifiers used in electronics to convert alternating current (AC) into direct current (DC). The unidirectional conducting property of a diode finds great application in rectifiers.

Figure 7.3 shows the circuit of a half wave rectifier. Generally, AC supply (230 V, 50 Hz) is given through a transformer. Here the transformer is used for two purposes. To step down the AC input

voltage and to isolate the rectifier circuit from the power line for reducing the risk of electric shock. The output of the transformer is applied in series with the diode and the load resistance R_L .

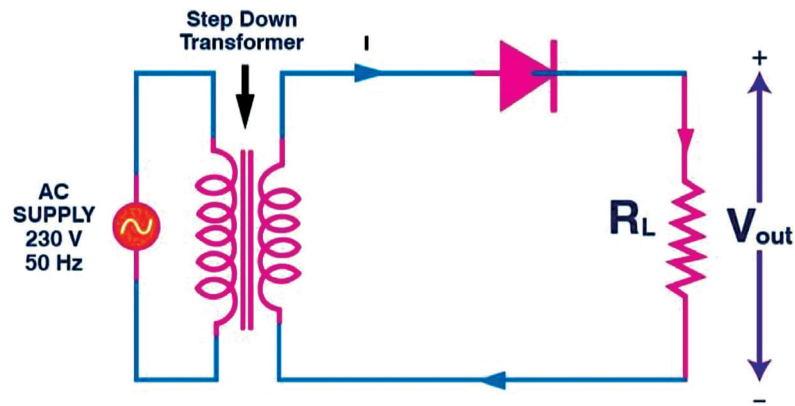


Fig. 7.3 Circuit diagram of Half wave rectifier

Operation

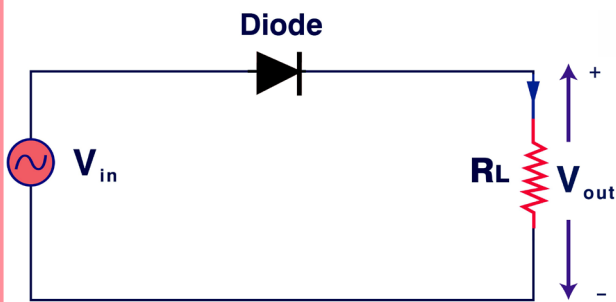


Fig. 7.3 (a) Simplified Half-Wave Rectifier Circuit

The primary winding of the transformer is connected to the power mains. Voltage across the secondary winding of the transformer changes polarity after every half cycle, since the primary is connected to an AC voltage.

For better understanding, let us simplify the half-wave circuit by replacing the secondary transformer coils with a voltage source as shown in Fig. 7.3 (a) below.

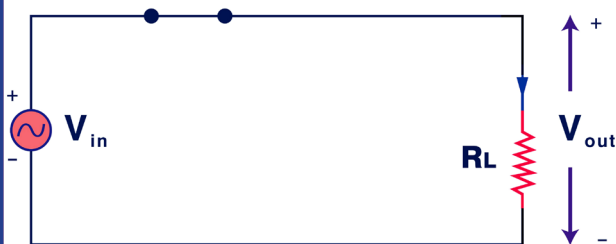


Fig. 7.3 (b) Working of Half Wave Rectifier during the Positive Half Cycle

During the positive half of the AC input waveform, the top end of the transformer's secondary coil becomes positive relative to the bottom end as shown in Fig. 7.3 (b). This causes the diode to be forward-biased, i.e., it acts like a closed switch and allows current to flow through it to the load resistor. This creates an output voltage across the load that follows the shape of the positive half of the input AC signal.

During the negative half of the AC input, the polarity reverses, and the bottom end of the secondary coil becomes positive as shown in Fig. 7.3 (c). The diode is now reverse biased and acts like an open switch, blocking the flow of current. As a result, no current flows to the load, and the output voltage is zero.

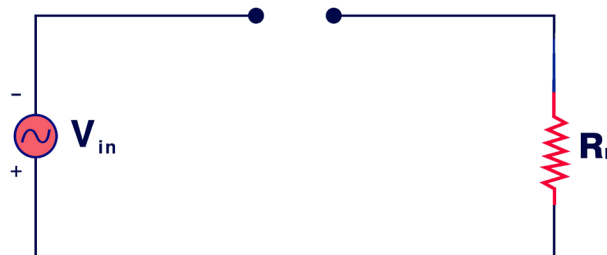


Fig. 7.3(c) Working of Half Wave Rectifier in Negative Half Cycle

This process repeats with each cycle, allowing only the positive half cycles of the AC signal to pass through. The resulting waveform is a series of positive voltage pulses separated by periods of zero voltage. This is not a pure DC like that from a battery, but a pulsating DC as shown in Fig. 7.4. It can be considered as the sum of a DC component (constant voltage) and an AC component (varying voltage). These undesired AC components are called ripples. The DC value is obtained by taking the average value of instantaneous voltages (voltage at each instant of time).

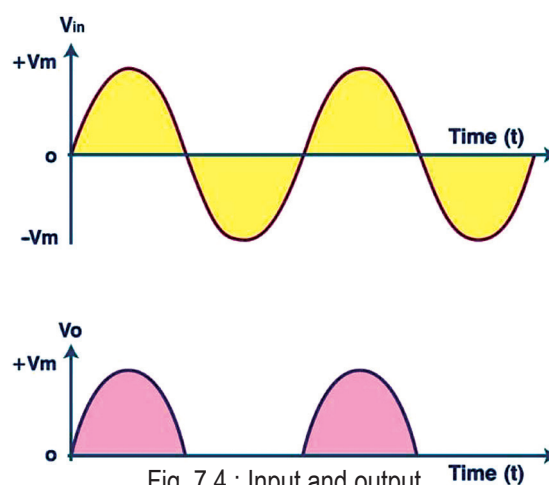


Fig. 7.4 : Input and output waveforms of half wave rectifier

? Know your progress

1. Which property of a diode is used in rectifiers?
2. What is the purpose of a transformer in a rectifier circuit?
3. What would happen if the diode in a half-wave rectifier were replaced by a short circuit?
4. Why is filtering necessary in rectifier circuits?



Activity 7.2

Construct a half wave rectifier circuit using a diode and a resistor. Use an oscilloscope in your school laboratory to observe and sketch both the input AC waveform and the output waveform.

- Compare the shapes of the input and output waveforms.
- Explain the function of the diode in the circuit.
- Describe what happens during the negative half-cycle of the AC input.
- Draw the output waveform of the circuit when the diode is reversed.

7.4 Full Wave Rectifier

A full-wave rectifier is an electronic circuit that converts the entire alternating current (AC) waveform into direct current (DC), making it more efficient than a half-wave rectifier. Unlike half-wave rectifiers that delivers only one half of the AC cycle, full-wave rectifiers deliver both the positive and negative halves, resulting in a smoother and more continuous DC output. The following two circuits are commonly used for full wave rectification.

1. Centre-tap full wave rectifier
2. Bridge rectifier

Centre-tap Full Wave Rectifier

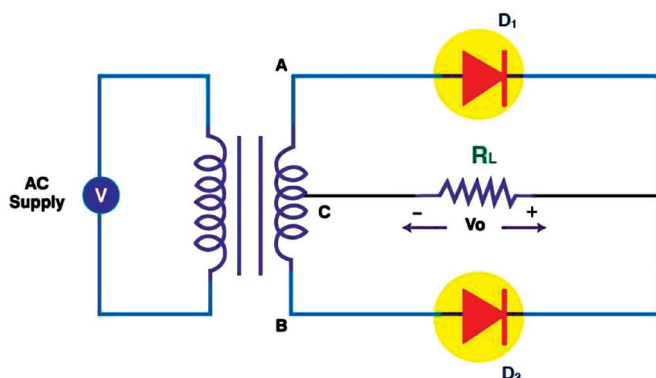


Fig. 7.5 Circuit diagram of a Centre-tap Full wave rectifier

The circuit of a centre tap full wave rectifier is shown in Fig. 7.5. It uses two diodes D_1 and D_2 and a Centre-tap transformer.

Operation

During the positive half cycle of the AC input, terminal A of the secondary becomes positive and terminal B becomes negative

with respect to point C as shown in Fig. 7.5 (a). Due to this, diode D_1 becomes forward-biased and diode D_2 reverse-biased. So, the diode D_1 conducts while diode D_2 does not. The current flows from terminal A through the diode D_1 , load resistor R_L and the upper half of the secondary winding.

During the negative half cycle of the AC input, terminal A of the secondary winding becomes negative and terminal B becomes positive with respect to the point C. This makes the diode D_2 forward-biased and diode D_1 reverse-biased. So, the diode D_2 alone conducts while diode D_1 does not. The current flows from terminal B through diode D_2 , load resistor R_L and the lower half of the secondary winding.

We can see that the current enters the load from the same direction during both the half cycles of the input AC voltage. Therefore, DC output is obtained across load R_L .

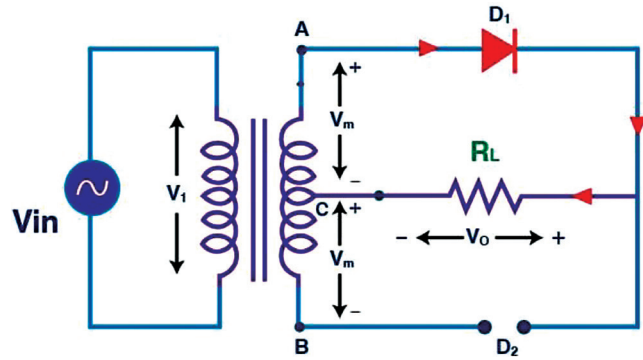


Fig. 7.5 (a) Operation of a Centre-tap Full-Wave Rectifier during the Positive Half Cycle

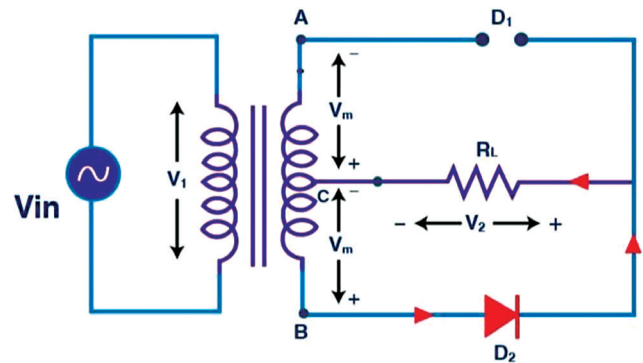


Fig. 7.5 (b) Operation of a Centre-tap Full-Wave Rectifier during the Negative Half Cycle

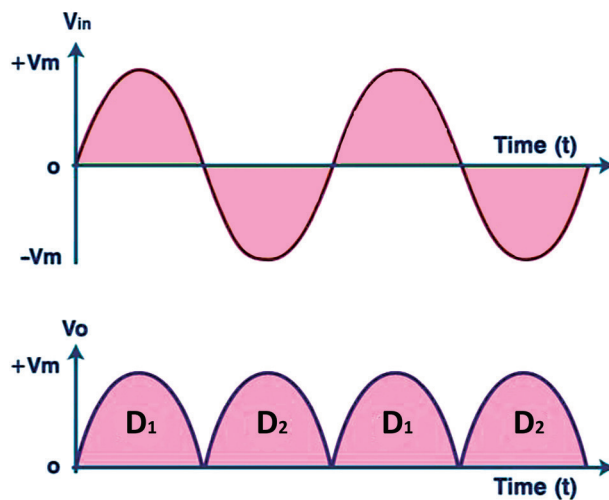


Fig. 7.5 Input and Output Waveforms for a Centre tap Rectifier

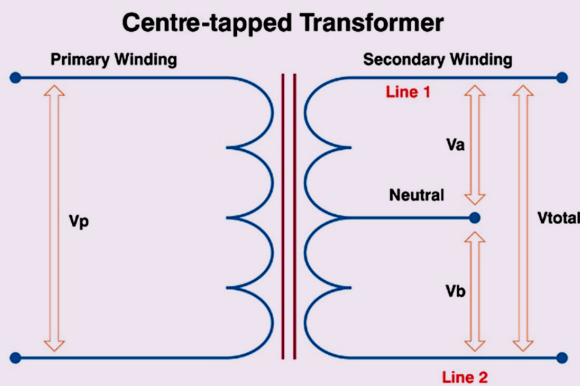
? Know your progress

1. How does a full-wave rectifier differ from a half-wave rectifier in terms of AC cycle usage?
2. What is the role of the centre-tap transformer in the rectifier circuit?



A Centre-tap transformer is a type of transformer where the secondary winding has a connection at its midpoint, known as the centre tap. This tap divides the winding into two equal halves, allowing the transformer to deliver two equal voltages with respect to the centre point. The centre tap is often connected to the ground or used as a neutral reference. In practical circuits like full-wave rectifiers,

this configuration is especially useful because it enables the use of both halves of the AC cycle. During each half cycle, one half of the winding supplies current through one diode, while the other half supplies current through the other diode. This results in a continuous flow of current in the same direction through the load, producing a smoother DC output.



Full wave bridge rectifier

A more widely used full wave rectifier circuit is the bridge rectifier. Here, an ordinary transformer is used in the place of a centre-tap transformer. The circuit forms a bridge connecting the four diodes D_1 , D_2 , D_3 and D_4 as shown in Fig. 7.6. The AC supply which is to be rectified is applied to the diagonally opposite ends of the bridge, whereas the load resistor R_L is connected across the other diagonally opposite ends of the bridge.

Operation

When an AC supply is switched ON, the alternating voltage appears across the terminals A and B of the secondary winding of the transformer, which needs rectification.

During the positive half cycle of the secondary voltage, end A becomes positive, and end B becomes negative as shown in the Fig. 7.6 (a). The diodes D_1 and D_3 are forward biased and the diodes D_2 and D_4 are reverse biased. Therefore, diode D_1 and D_3 conduct, and diodes D_2 and D_4 do not conduct. The current flows through diode D_1 , load resistor R_L (from L to M), diode D_3 , and the transformer secondary.

During the negative half cycle, end A becomes negative and end B positive as shown in Fig. 7.6 (b). This makes the diodes D_2 and D_4 forward biased, while diodes D_1 and D_3 are reverse biased. Therefore, diodes D_2 and D_4 conduct while diodes D_1 and D_3 do not conduct. Thus, current flows through the diode D_4 , load resistor R_L (from L to M), diode D_2 and the transformer secondary. The current flow through the load resistor R_L is in the same direction (L to M) during both the half cycles. Hence, a DC output voltage is obtained across the load resistor.

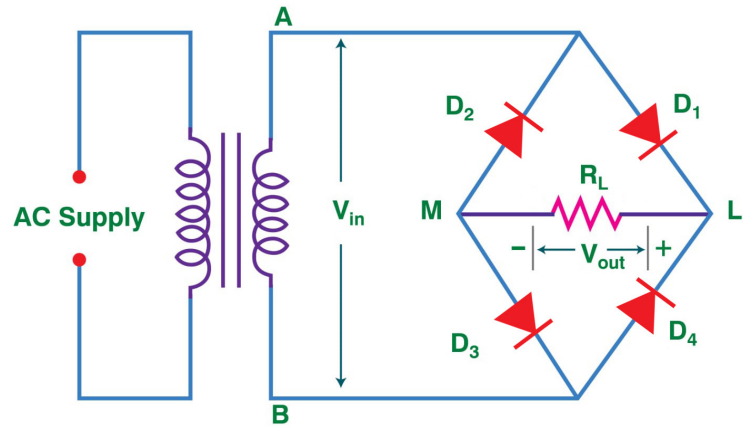


Fig. 7.6 Circuit diagram of Bridge rectifier

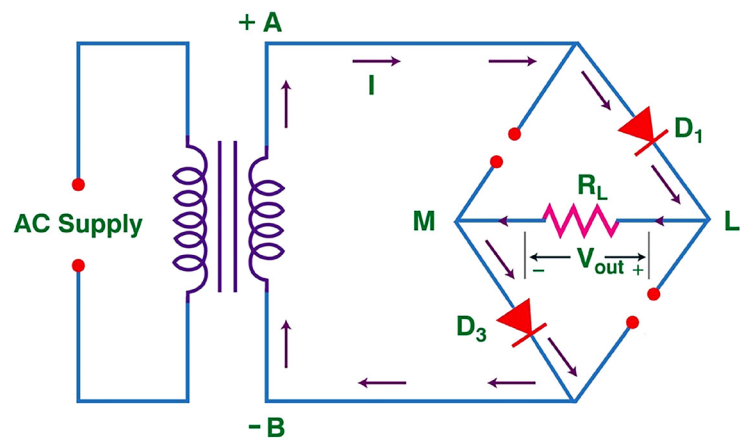


Fig. 7.6 (a) Operation of a Bridge Rectifier during the Positive Half Cycle

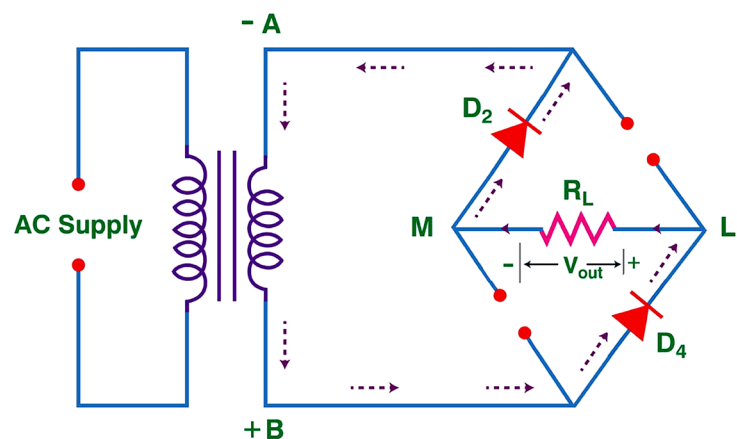


Fig. 7.6 (b) Operation of a Bridge Rectifier during the Negative Half Cycle

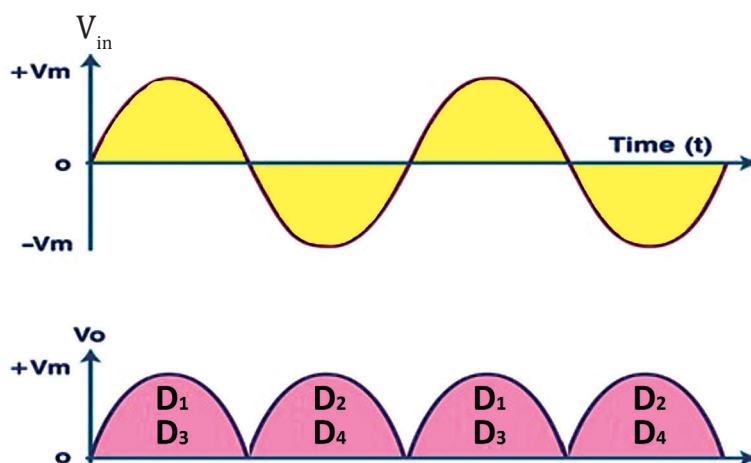


Fig. 7.6 (c) Input and Output Waveforms for a Bridge Rectifier Time (t)



Activity 7.3

Comparison of Half Wave and Full Wave Rectifiers

Set up both half wave and full wave bridge rectifier circuits using a 230 V/6 V transformer, diodes (1N 4007) and a $1\text{k}\Omega$ load resistor. Connect the primary of the transformer to the AC mains supply. Observe the input and output waveforms on a CRO for both the circuits.

Note that in a half-wave rectifier, the output occurs only during one half cycle, whereas in a full-wave rectifier, the output appears during both the half cycles, giving a smoother DC output.



Know your progress

1. Why does a full wave rectifier circuit work better than a half wave rectifier?
2. What happens if one of the diodes stops working or gets damaged? Draw the output waveform?
3. Which rectifier would you choose for a battery charger and why?

7.5 Peak Inverse Voltage (PIV)

The maximum value of reverse voltage that a PN junction diode can withstand without damaging itself is known as its Peak Inverse Voltage. The PIV rating indicates the maximum reverse voltage a diode can handle safely. Exceeding this voltage can cause a breakdown, leading to high reverse currents and potential failure.

Peak Inverse Voltage of a Half Wave Rectifier

The peak inverse voltage of a half wave rectifier is equal to the peak voltage (V_m) of the AC input, as shown by the formula,

$$PIV = V_m$$

This is because during the negative half-cycle of the AC input, the diode is reverse biased, and the entire peak voltage is developed across the diode (as there is no voltage across the load resistance). When the input reaches its peak value V_m , in the negative half-cycle, the voltage across the diode is also maximum. This maximum voltage is known as the peak inverse voltage. It represents the maximum voltage appearing across the diode, when the diode is reverse biased. Thus, for a half wave rectifier the peak inverse voltage is V_m .

Peak Inverse Voltage of a Centre-tap Full Wave Rectifier

The circuit diagram in Fig. 7.7 shows the instant when the secondary voltage attains its maximum value $+V_m$.

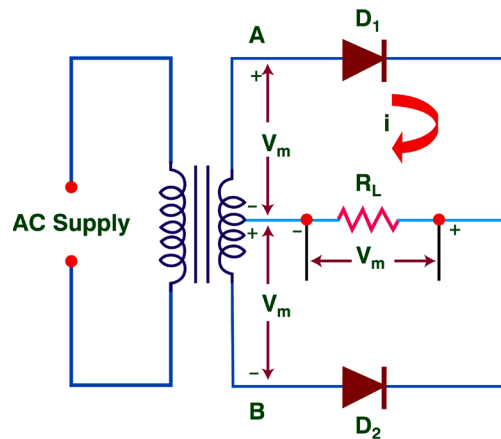


Fig. 7.7 Centre-tap full wave rectifier when input voltage is maximum

At this instant, V_m developed in the upper half of the secondary winding of the transformer will forward bias the diode D_1 . This diode conducts, and the current flows through R_L , developing V_m voltage across it. The diode D_2 at this instant is reverse biased, and the voltage that appears across the non conducting diode is the sum of the maximum value of voltage developed by the lower half of the secondary winding and the voltage developed across the load R_L . Hence, the peak inverse voltage across the diode D_2 is $2V_m$.

$$PIV = V_m + V_m = 2V_m$$

Peak Inverse Voltage of a Full Wave Bridge Rectifier

When the secondary voltage attains its maximum positive value, the terminal A is positive and B is negative as shown in Fig. 7.8.

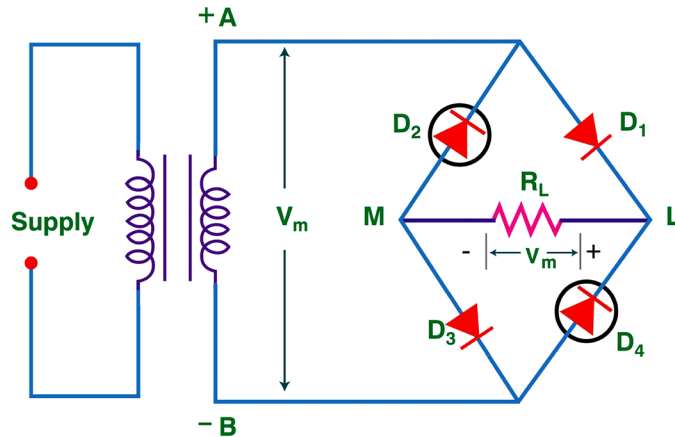


Fig. 7.8 Full wave bridge rectifier when input voltage is maximum

At this instant the diodes D_1 and D_3 are forward biased and conducts current, whereas the diode D_2 and D_4 are reverse biased and are non-conducting. The entire voltage V_m across the secondary winding appears across the load resistor R_L . Also, we can see that the potentials at the points A and B are almost similar to the potentials at the points L and M respectively. The reverse voltage or PIV across the non conducting diode (D_2 or D_4) is equal to maximum secondary voltage. Therefore,

$$PIV = V_m$$

7.6 Ripple Factor

The ripple current is undesirable and its value should be the smallest possible in order to make the rectifier effective. Ripple factor 'r' is a measure of how much AC content remains in the output of a rectifier. It is defined as the ratio of the RMS value of the AC component to the DC component of the output voltage. The smaller the value of this factor, the lesser is the AC component in comparison to DC component.

$$r = \frac{\text{(rms value of AC component in the rectified output)}}{\text{(DC component)}}$$

The general expression for ripple factor is
(derivation not needed)

$$r = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}$$

For a half wave rectifier, it can be derived that ,

$$V_{dc} = \frac{V_m}{\pi}$$

$$V_{rms} = \frac{V_m}{2}$$

Where V_{rms} = rms value of output voltage

V_{dc} = average value of output voltage

V_m = peak or maximum voltage

By substituting the above values in the general expression,

$$\text{We get } r = 1.21$$

The output of a half wave rectifier contains more ripples than the DC component. Hence half wave rectifiers are poor converters of AC to DC.

For a full wave rectifier (centre- tap and bridge)

$$V_{dc} = \frac{2V_m}{\pi}$$

$$V_{rms} = \frac{V_m}{\sqrt{2}}$$

By substituting the above values in the general expression,

$$\text{we get } r = 0.48$$

The output of a full wave rectifier contains a lesser percentage of ripples than a half wave rectifier. Hence, full wave rectifiers are better converters of AC to DC, compared to half wave rectifiers.

7.7 Efficiency (η)

Rectifier efficiency is a measure of how effectively a rectifier converts alternating current (AC) power into direct current (DC) power. It indicates the percentage of total AC input power that is converted into useful DC output power. In other words, it tells us how efficiently the rectifier performs the conversion with minimum energy loss.

Thus, rectifier efficiency is defined as the ratio of DC output power to the AC input power.

Mathematical Expression

$$\eta = \frac{P_{dc}}{P_{ac}}$$

where

η = Rectifier efficiency (in percentage)

P_{dc} = DC output power (watts)

P_{ac} = AC input power (watts)

For a half wave rectifier,

$$I_{dc} = \frac{I_m}{\pi} \text{ and } I_{rms} = \frac{I_m}{2}$$

$$\begin{aligned} P_{dc} &= (I_{dc})^2 R_L \\ &= \left(\frac{I_m}{\pi}\right)^2 R_L \end{aligned}$$

$$\begin{aligned} P_{ac} &= (I_{rms})^2 R_L \\ &= \left(\frac{I_m}{2}\right)^2 R_L \end{aligned}$$

substitute these values

$$\begin{aligned} \text{Efficiency } (\eta) &= \frac{P_{dc}}{P_{ac}} \\ &= \left(\frac{I_m}{\pi}\right)^2 R_L \div \left(\frac{I_m}{2}\right)^2 R_L = 0.406 \end{aligned}$$

$$\text{Efficiency}(\eta) = 40.6 \%$$

Theoretically, the maximum value of rectifier efficiency of a half wave rectifier is 40.6 percent. This shows that a half wave rectifier can convert a maximum of 40.6% of AC power into DC power.

For full wave rectifier,

$$I_{dc} = \frac{2I_m}{\pi} \text{ \& } I_{rms} = \frac{I_m}{\sqrt{2}}$$

$$\begin{aligned} P_{dc} &= (I_{dc})^2 R_L \\ &= \left(\frac{2I_m}{\pi}\right)^2 R_L \end{aligned}$$

$$P_{ac} = (I_{rms})^2 R_L = \left(\frac{I_m}{\sqrt{2}}\right)^2 R_L$$

substitute these values

$$\begin{aligned}\text{Efficiency } (\eta) &= \frac{P_{dc}}{P_{ac}} \\ &= \left(\frac{2I_m}{\pi} \right)^2 R_L \div \left(\frac{I_m}{\sqrt{2}} \right)^2 R_L \\ &= 0.812\end{aligned}$$

$$\text{Efficiency}(\eta) = 81.2 \%$$

Theoretically, the maximum value of rectifier efficiency of a full wave rectifier is 81.2%.

? Know your progress

1. Among the different types of rectifiers, which one offers the highest efficiency and why?
2. Explain how the term ripple factor is used to compare the performance of rectifiers.
3. In a centre-tap full wave rectifier, if the peak voltage from centre tap to one end is 60V, what is the maximum reverse voltage across a diode?
4. The efficiency of a half wave rectifier is 40%. What happens to the remaining 60% power?

7.8 Comparative Study of Rectifier Circuits

Sl No	Parameter	Half wave rectifier	Centre tap full wave rectifier	Full wave bridge rectifier
1	No of diodes	1	2	4
2	PIV	V_m	$2V_m$	V_m
3	I_{dc}	$\frac{I_m}{\pi}$	$\frac{2I_m}{\pi}$	$\frac{2I_m}{\pi}$
4	I_{rms}	$\frac{I_m}{2}$	$\frac{I_m}{\sqrt{2}}$	$\frac{I_m}{\sqrt{2}}$
5	V_{dc}	$\frac{V_m}{\pi}$	$\frac{2V_m}{\pi}$	$\frac{2V_m}{\pi}$
6	V_{rms}	$\frac{V_m}{2}$	$\frac{V_m}{\sqrt{2}}$	$\frac{V_m}{\sqrt{2}}$
7	Ripple factor	1.21	0.48	0.48
8	Efficiency	40.6%	81.2%	81.2%
9	Output frequency	f_{in}	$2 f_{in}$	$2f_{in}$

Table 7.1 : Comparison of rectifier circuits

A full wave rectifier has several advantages over a half wave rectifier because it utilises both halves of the AC input signal. As a result, it has much higher efficiency and a greater average DC output voltage. The ripple content in the output is significantly reduced, and the ripple frequency is doubled, which makes the output smoother and easier to filter. This leads to better transformer utilisation and a more continuous power delivery. Due to reduced ripple, smaller filter components are sufficient, and the overall DC output is steadier, making full-wave rectifiers more suitable for practical and reliable power supply applications.



Activity 7.4

With the help of your teacher, set up the circuit of a centre-tap full wave rectifier in your lab and observe the input and output waveforms using a CRO. Measure the maximum value of voltage across the load resistor and calculate the following parameters.

$$V_m = \dots\dots\dots V$$

Parameters	Equation	Result
PIV		
V_{rms}		
V_{dc}		
Ripple factor		
Ripple Voltage		

Solved problem 7.1

A half wave rectifier has a transformer secondary voltage $v=30\sin\omega t$ and a load resistance of $R_L = 600 \Omega$. Find the value of peak current (I_m), average (DC) value of current (I_{dc}), RMS value of current (I_{rms}), DC output voltage (V_{dc}), AC input power (P_{ac}), DC output power (P_{dc}) and rectification efficiency.

Solution

Given

$$V_m = 30 V$$

$$R_L = 600 \Omega$$

$$\begin{aligned}
 1. \quad \text{Peak Current, } I_m &= \frac{V_m}{R_L} \\
 &= \frac{30}{600} = 0.05 A = 50 \text{ mA}
 \end{aligned}$$

2. Average (DC) Current, $I_{dc} = \frac{I_m}{R_L}$
 $= \frac{50}{600} = 0.0159 \text{ A} = 15.9 \text{ mA}$
3. RMS Current, $I_{rms} = \frac{I_m}{2}$
 $= \frac{0.05}{2} = 0.025 \text{ A} = 25 \text{ mA}$
4. DC Output Voltage, $V_{dc} = I_{dc} \times R_L$
 $= 15.9 \text{ mA} \times 600 = 9.55 \text{ V}$
5. AC Input Power and DC Output Power
 $P_{dc} = (I_{dc})^2 \times R_L = (0.0159)^2 \times 600 = 0.1518 \text{ W}$
 $P_{ac} = (I_{rms})^2 \times R_L = (0.025)^2 \times 600 = 0.375 \text{ W}$
6. Efficiency (η) = $\frac{P_{dc}}{P_{ac}} \times 100$
 $= \frac{0.1520}{0.375} \times 100 = 40.5\%$

Solved problem 7.2

A full wave rectifier is supplied with an AC voltage having a peak value of 20 V. The load resistance is 1 k Ω . Find the average (DC) output voltage, RMS value of output voltage, DC output current, RMS output current, ripple factor and the ripple voltage.

Solution

Given

$$V_m = 20 \text{ V}$$

$$R_L = 1 \text{ k}\Omega = 1000 \Omega$$

1. Average (DC) Output Voltage, $V_{dc} = \frac{2V_m}{\pi}$
 $= \frac{2 \times 20}{3.14} = 12.73 \text{ V}$
2. RMS Output Voltage, $V_{rms} = \frac{V_m}{\sqrt{2}}$
 $= \frac{20}{\sqrt{2}} = 14.14 \text{ V}$
3. DC Output Current, $I_{dc} = \frac{V_{dc}}{R_L}$
 $= \frac{12.73}{1000} = 12.73 \text{ mA}$
4. RMS Output Current, $I_{rms} = \frac{V_{rms}}{R_L}$

- $$= \frac{14.14V}{1000}$$
- $$= \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}$$
- $$= 0.48$$
5. Ripple factor, r
6. Ripple voltage = ripple factor $\times V_{dc} = 0.48 \times 12.73 = 6.11$

Solved problem 7.3

A centre-tap full wave rectifier has a transformer secondary voltage given by $v = 50\sin\omega t$ and load resistance $R_L = 800$. Calculate.

1. Peak load current (I_m)
2. DC current (I_{dc})
3. RMS current (I_{rms})
4. DC output voltage (V_{dc})
5. Peak Inverse Voltage (PIV)

Solution

Given

$$V_m = 50 \text{ V}$$

$$R_L = 800 \Omega$$

1. Peak Load Current, $I_m = \frac{V_m}{R_L} = \frac{50}{800} = 0.0625 \text{ A}$
 $= 50/(800) = 0.0625 \text{ A} = 62.5 \text{ mA}$
2. Average (DC) Current, $I_{dc} = \frac{2I_m}{\pi}$
 $= \frac{2 \times 62.5}{3.14} = 39.8 \text{ mA}$
3. RMS Current, $I_{rms} = \frac{I_m}{\sqrt{2}}$
 $= \frac{62.5}{\sqrt{2}} = 44.2 \text{ mA}$
4. DC Output Voltage, $V_{dc} = I_{dc} \times R_L$
 $= 0.0398 \times 800 = 31.84 \text{ V}$
5. Peak Inverse Voltage (PIV)
 For centre-tap full wave rectifier,
 $PIV = 2V_m = 2 \times 50 = 100 \text{ V}$

7.9 Filter Circuits

The purpose of rectification is to produce a steady DC voltage, like that from a battery. However, the output from a rectifier is not pure DC, it still has some unwanted AC ripples. If this pulsating DC is sent directly to electronic devices, they may not work properly. So, it is important to reduce these ripples. This is done using a filter circuit, which removes the AC components and allows only the DC components to reach the load. Filter circuits are connected between the rectifier and the load Fig. 7.9 shows the schematic diagram of a filter circuit. The input to the filter circuit is the output of the rectifier. At the output of the filter, we get a signal of pure DC avoiding ripples.

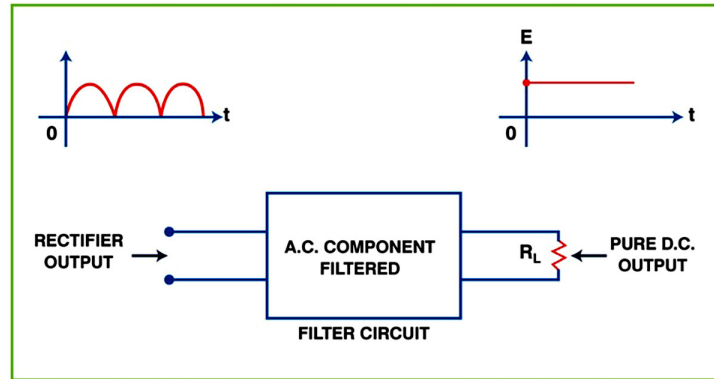


Fig. 7.9 Schematic diagram of Filter circuit

Capacitor Filter

This is the simplest and cheapest filter. The capacitor (C) is placed across the rectifier output, in parallel with the load resistor (R_L) shown in Fig. 7.10. The rectifier gives a pulsating DC voltage, which is applied to the capacitor. The capacitor helps to remove the AC components of the signal by giving it an easy path to flow through. So the AC does not reach the load. This works because a capacitor behaves differently for AC and DC. The resistance offered by a capacitor is called capacitive reactance, and it depends on the frequency of the signal. The expression for capacitive reactance is

$$X_C = \frac{1}{2\pi fC}$$

For DC ($f = 0$), the capacitive reactance becomes infinity, so the capacitor acts like an open circuit and blocks DC. But for AC, as the frequency increases, the reactance decreases allowing AC to pass through easily.

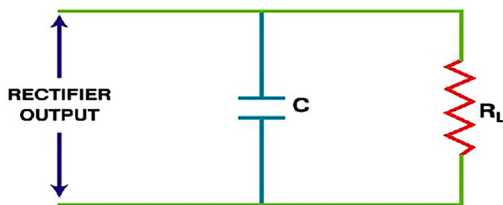


Fig. 7.10 Capacitor Filter

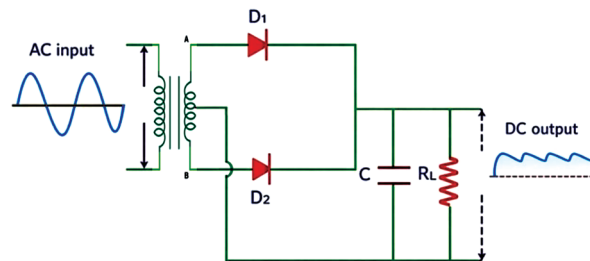


Fig. 7.11 Full wave rectifier with capacitor filter

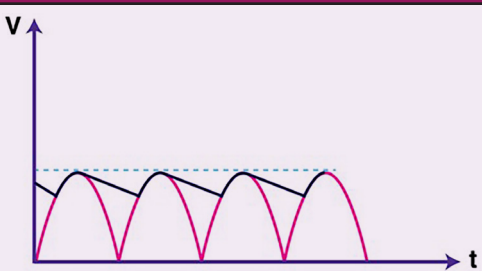
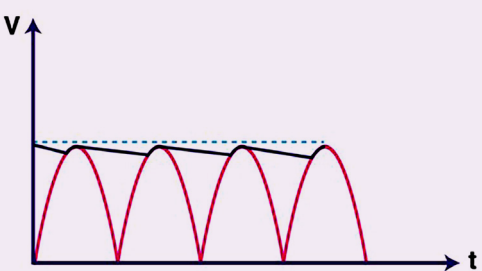
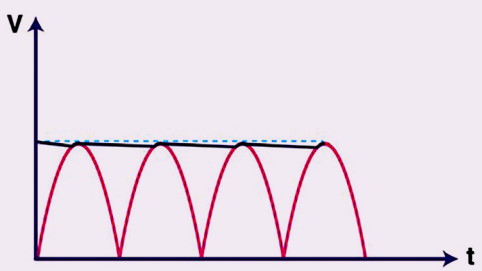
In short, a capacitor blocks DC but gives AC a low-resistance path. DC components will flow through the load R_L . Only a small part of the AC components passes through the load, producing a small ripple voltage. The ripple voltage depends on the value of the capacitor.



Activity - 7.5

Assemble a bridge rectifier and observe its output wave form using a CRO. Then connect the capacitors with values $1\ \mu\text{F}$, $10\ \mu\text{F}$ and $100\ \mu\text{F}$ one by one at the output of the rectifier and observe the output wave forms in each case.

Now verify whether the waveforms obtained on your CRO resembles the following diagrams.

Case	Capacitance Value	Output Waveform
CASE 1	$C=1\ \mu\text{F}$	
CASE 2	$C=10\ \mu\text{F}$	
CASE 3	$C=100\ \mu\text{F}$	

From the above activity, it is observed that the ripple in the rectifier output decreases as the value of the capacitor increases. A larger capacitor has a greater ability to store electric charge and a lower capacitive reactance. This allows it to charge quickly during the peak of the rectified voltage and discharge slowly when the voltage falls. As a result, the voltage across the load remains almost constant and the ripple content is greatly reduced. The capacitor therefore acts

as an energy reservoir, maintaining a steady DC output by supplying current to the load during the nonconducting periods of the rectifier.

Capacitor filters are widely used in DC power supply circuits because of their simple design, low cost, compact size, light weight, and efficient performance. They are particularly suitable for applications where a smooth and stable DC voltage is required such as in radios, amplifiers, and microcontroller based electronic circuits. Such filters can be used effectively with both half wave and full wave rectifiers to improve the quality and stability of the DC output.



Know your progress

1. How can we reduce the ripple contents in a rectifier output?
2. Point out certain real world applications of rectifiers.
3. A large value capacitor is connected at the output of a rectifier. Why?



Devices that need very smooth DC

Device/ Application	Why Smooth DC is needed	What happens if ripple is present
Mobile phones and laptops	Stable voltage ensures reliable performance	Processor errors, Screen flicker
Audio amplifiers	Clear power gives clear sound	Buzzing or humming in Speakers
Medical equipment (eg : ECG)	Ensure accurate diagnostics in patient monitoring	Distorted readings, inaccurate diagnostics
Digital clocks / Timers	Accurate timing requires stable voltage	Incorrect time
Microcontrollers	Consistent logic operation	Random resets and unpredictable behaviour
Communication Devices	Clear transmissions and receptions	Signal noise, data corruption
Sensors and Measurement Systems	Reliable data collection	Fluctuating readings



Types of Filters

Filters are used in rectifier circuits to reduce the ripple in the output and obtain a smooth DC voltage. Several types of filters can be used, depending on the level of ripple reduction required and circuit design.

Type of Filter	Components Used	Connection	Function	Remarks
Capacitor Filter	Capacitor (C)	Parallel with load	Reduces voltage ripple by charging and discharging	Simple and low-cost
Inductor Filter (Choke Filter)	Inductor (L)	Series with load	Smooths current by opposing rapid changes	Bulky and costly
LC Filter	Inductor (L) + Capacitor (C)	L in series, C in parallel	Improves both current and voltage smoothing	Used in medium-power supplies
π Filter (C-L-C)	Capacitor (C_1), Inductor (L), Capacitor (C_2)	C-L-C arrangement	Provides excellent ripple reduction	Used in high-quality DC supplies



Have you seen someone speaking to a large audience using a microphone? Why do we need a microphone or mic? You know that if he doesn't use mic, his voice may not be heard to all. So, we need a system to increase the strength of the voice signal. The enhancement of audio signal can be done with the help of a megaphone. But it is insufficient to address a large audience. If we can convert the voice signal or audio signal to an electrical signal, we can increase the amplitude or strength of the signal using electronic amplifiers. A device which converts one form of energy into another is called a transducer. So, we need a transducer which can convert an audio signal into the corresponding electrical signal. Microphone is such a device. The electrical signal obtained from the microphone is strengthened or amplified using an electronic circuit called amplifier. Now we need another transducer to convert the amplified electrical signal back to the form of sound. A loud speaker can be used to serve this purpose. The system which contains a microphone, a loudspeaker and an amplifier is called a public address system (PA system) which can be used to deliver sound to a large gathering. The microphone and loudspeaker convert energy from one form to another. But amplifier is a device which increases the energy or loudness of sound. Let us study the basics of amplifiers in this chapter.

8.1 Concept of Amplification

An amplifier is an electronic device which increases the amplitude of a given signal. See Fig. 8.1 Here a 2 mV input signal is amplified to a signal of the same shape with an amplitude of 100 mV. This implies that the amplitude is increased by 50 times. The amount of increase is called gain of the amplifier. It is the ratio of the output amplitude (amplitude of the output signal) to the input amplitude (amplitude of the input signal). Thus, gain is 50.

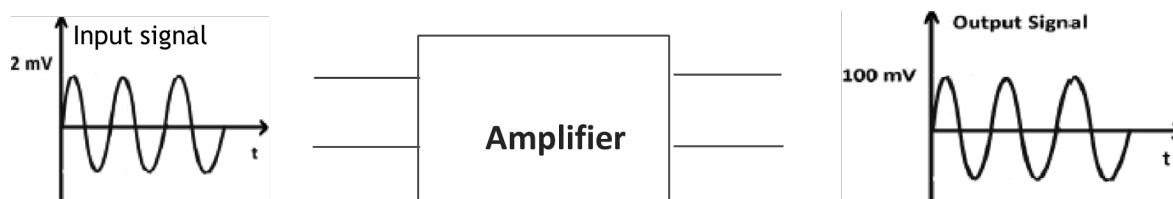


Fig. 8.1 Amplifier showing input and output waveform

Amplifiers are mainly of three types—voltage amplifiers, current amplifiers and power amplifiers. In voltage amplifiers, the output voltage is greater than the input voltage which means that the voltage is amplified. Similarly in current amplifiers, the current is amplified and in power amplifiers, the power is amplified.

$$\text{Gain of voltage amplifier, } A = \frac{\text{Output voltage}}{\text{Input voltage}}$$

Amplifiers have wide applications in communication systems, control systems and instrumentation systems. For example, our TV and radio receivers have amplifiers to increase the amplitude of the signal received. Do you know that when we rotate the knob of the volume control of a radio, we actually change the gain of an amplifier inside?

8.2 Transistor as an Amplifier

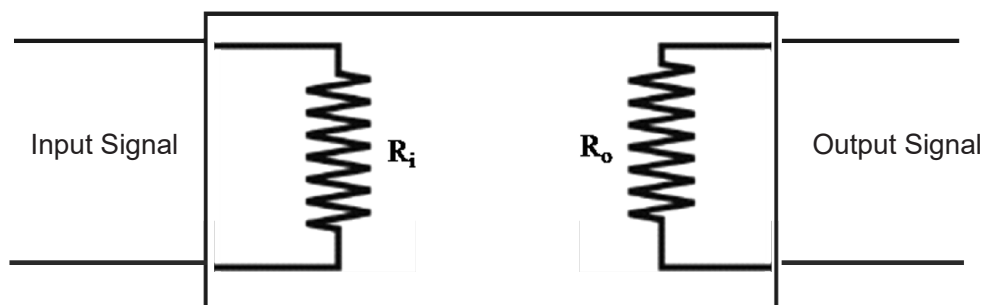


Fig. 8.2 Amplifier showing Input resistance R_i and output resistance R_o

As we have studied in chapter 5, when a transistor is operated in the active region, the input junction is forward biased and the output junction is reverse biased. Hence it has low input resistance and high output resistance. The transistor can function as an amplifier, because of the transfer of current from a low resistance junction to a high resistance junction without reducing its value. In both common emitter and common base configurations, since the resistance values have the above features, these can be used for voltage amplification. At the same time, in the common collector configuration, the input resistance is high and the output resistance is low. Hence the common collector configuration cannot be used for voltage amplification.

The transistor is a current-controlled device. The base current I_B controls the collector current I_C . In CE configuration, the input current is I_B and the output current is I_C . Since I_C is β times I_B , CE configuration can provide current amplification. Similarly, CC configuration can also provide current amplification. However, in CB configuration current gain is less than unity.

Among the three transistor configuration-CE, CB and CC, the CE configuration is commonly used for amplification due to its ability to provide high voltage gain and high current gain. So, CE configuration is the focus of our further discussion.



Know your progress

1. Why CE configuration is commonly used in amplifiers?
2. Why CB configuration has current gain less than one?

8.3 Biasing of Transistor for Amplification

Usually, the input signal of an amplifier is AC. The AC signals have both positive and negative values. To keep the transistor in the ON condition and to have the base current flowing, the base to emitter voltage of the transistor should be kept around 0.7 V. This happens for the positive values above 0.7V of the input signal. But for the input voltages below 0.7V (including the entire negative half cycle), the transistor can be made conducting by applying a positive DC voltage of sufficient value at the base of the transistor and it is called biasing. This positive DC voltage keeps the base emitter voltage at +0.7V during the whole cycle of the input signal. This makes the transistor active all the time and it amplifies the entire input signal without any distortion. Transistor biasing is the process of applying

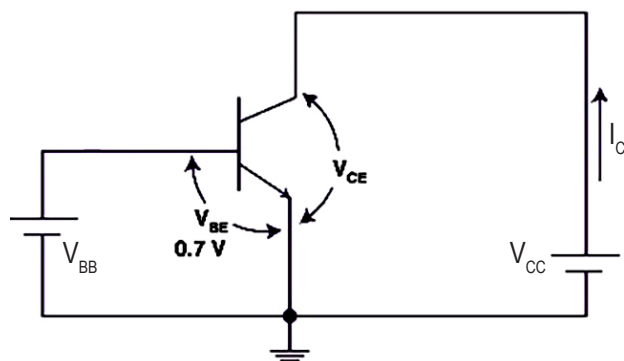


Fig. 8.3 (a) Emitter base junction forward biased and collector base junction reverse biased

external DC voltage and current to a transistor to get its operating point in the active region (at the centre of DC load line).

Consider the circuit shown in Fig. 8.3 (a). It can also be drawn conveniently as in Fig. 8.3 (b). The emitter base junction is forward biased by V_{BB} and the collector base junction is reverse biased by V_{CC} , for operating the transistor in an active

region. The V_{CC} should be greater than V_{BB} in order to reverse bias the collector-base junction.

To keep the transistor in the active region, the value of V_{BE} should be between 0.6 V to 0.7 V. To get the desired base current the value of V_{BB} must be fixed precisely. A resistor of proper value can be used in series with the voltage source V_{BB} , to get the required base current (Fig. 8.3 (c)). To fix the operating point (I_C and V_{CE}) at the required value, a resistor R_C is placed at the collector terminal.

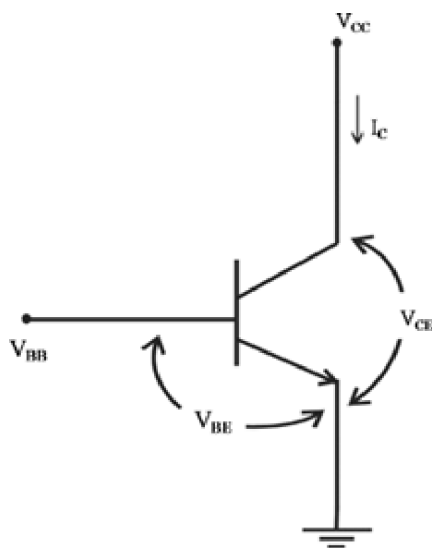


Fig. 8.3 (b) circuit in Fig. 8.3 (a) - simplified.

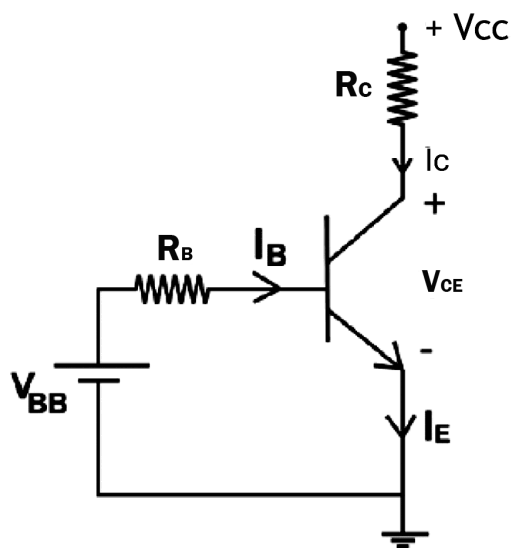


Fig. 8.3 (c) Circuit showing resistors R_B and R_C

The biasing circuit can be redrawn as in Fig. 8.3 (d).

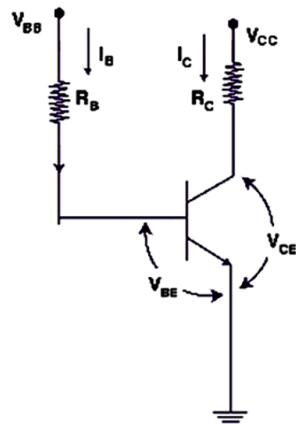


Fig. 8.3 (d) Circuit of Fig. 8.3 (c) Redrawn

Instead of using two separate power supplies V_{BB} and V_{CC} , we can combine them to get a single supply.

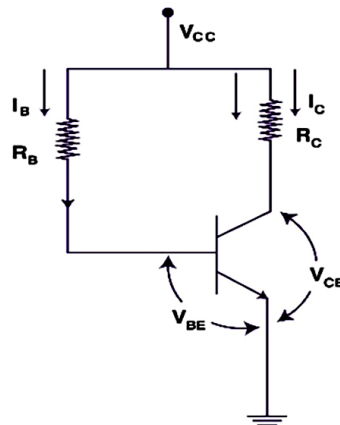


Fig. 8.3 (e) Fixed biasing circuit of Fig. 8.3 (d) Redrawn with a single voltage source

Considering the input section and applying Ohm's law.

$$V_{CC} = I_B R_B + V_{BE}$$

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

Since $V_{BE} \ll V_{CC}$, it can be neglected.

$$I_B = \frac{V_{CC}}{R_B}$$

Here V_{CC} is constant. Once R_B is selected, I_B becomes fixed.

Considering the output side of the circuit

$$V_{CC} = I_C R_C + V_{CE}$$

$$I_C = \frac{V_{CC} - V_{CE}}{R_C}$$

When I_B is fixed, I_C is also fixed ($I_C = \beta I_B$). Once I_C is fixed, V_{CE} is also fixed. When these two are fixed, the operating point is also fixed. This biasing is called fixed biasing.

But fixed biasing has the following disadvantages.

- 1) The operating point depends on β of the transistor
- 2) Thermal runaway.

These two cases are explained below.

The flow of collector current produces heat in the collector junction. This increases the temperature. Hence more minority carriers are generated in CB junction. This increases the reverse leakage current and hence the collector current is also increased. As the collector current increases, it will again result in increased temperature. And as said earlier, this will increase collector current. This process goes on and finally the temperature at the collector junction increases to such an extent causing the junction to breakdown. This process is called thermal runaway.

Also, it is significant to note that the values of I_C and V_{CE} depend on β of the transistor. When the transistor in an amplifier is damaged, we replace it with a new one. In this case, the β will change. This will change the values of I_C and V_{CE} and hence the operating point.

Now we look forward for a biasing circuit which can avoid the two undesirable factors affecting an amplifier mentioned above. In other words, the biasing circuit should be able to make the operating point independent of β as well as it should be able to stop thermal runaway. A biasing called voltage divider biasing is able to solve both these issues. Fig. 8.3 (f) shows a voltage divider or potential divider biasing circuit.

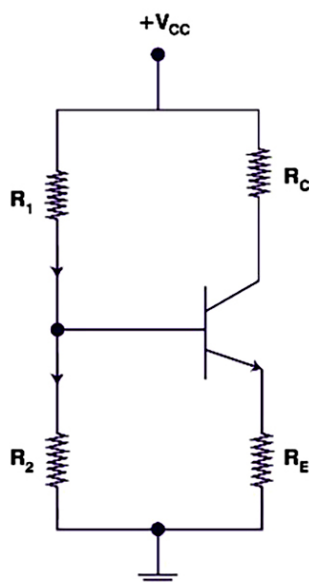


Fig. 8.3 (f)
Voltage divider biasing circuit

Voltage Divider biasing circuit

Voltage divider biasing circuit is the most widely used biasing circuit. It contains resistors R_1 and R_2 which forms the potential divider circuit. By suitably selecting the values of R_1 and R_2 , we can fix the base voltage and hence the operating point of the transistor will also be fixed.

I_1 is the current through R_1 and I_2 is the current through R_2 . Therefore $I_1 = I_2 + I_B$ and since I_B is very small, it can be neglected. So

$$I_1 = I_2$$

Consider the input side in Fig. 8.4,

Applying ohm's law to the input circuit,

$$V_{CC} = I_1 R_1 + I_2 R_2$$

$$\text{Since } I_1 = I_2$$

$$V_{CC} = I_2 (R_1 + R_2)$$

$$\text{Voltage drop across } R_2 = V_B = V_{CC} \times R_2 \div (R_1 + R_2)$$

$$V_B = \frac{V_{CC} R_2}{(R_1 + R_2)} \dots\dots\dots(1)$$

$$\text{But } V_B = V_{BE} + V_{RE}$$

$$\text{So } V_{RE} = V_B - V_{BE}$$

$$I_E = \frac{V_{RE}}{R_E} \dots\dots\dots(2)$$

Since I_E is approximately equal to I_C

$$I_C = \frac{V_E}{R_E}$$

Considering the output side,

$$V_{CC} = I_C R_C + V_{CE} + V_E$$

$$V_{CC} = I_C R_C + V_{CE} + I_E R_E$$

$$V_{CC} = I_C R_C + V_{CE} + I_C R_E$$

$$V_{CC} = I_C (R_C + R_E) + V_{CE}$$

$$V_{CE} = V_{CC} - I_C (R_C + R_E) \dots\dots\dots(3)$$

From equations 2 and 3, it can be seen that I_C and V_{CE} are independent of beta. Thus, the operating point remains where it is fixed. Also changing the transistor does not affect the operating point. Due

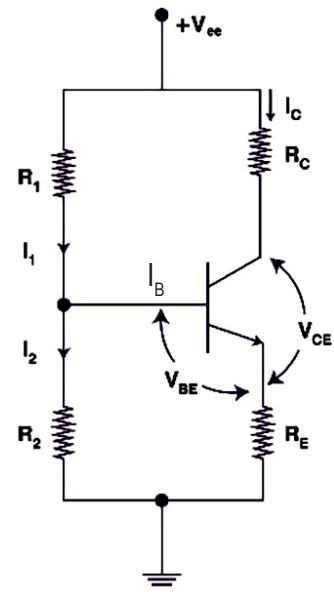
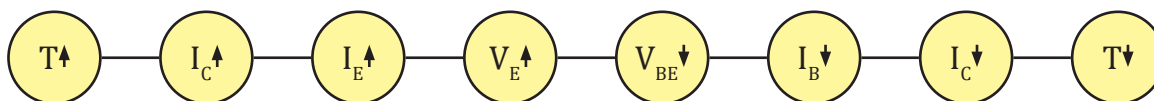


Fig. 8.4
Voltage divider biasing circuit
with various currents and
voltages shown

to these reasons, potential divider biasing circuit is also called the universal biasing circuit.

Now let us discuss the effect of the emitter resistor R_E . It avoids thermal runaway by reducing the collector current that occurs due to temperature rise. When I_C increases, I_E also increases, thereby increasing V_E .

Since V_B is a constant as seen in equation (1), increase in V_E results in a decrease in V_{BE} . This results in a decrease in I_B , which in turn reduces I_C . Thus, I_C is not allowed to rise to a high value causing a rise in temperature in the collector junction. Thus, thermal runaway is avoided. The figure below shows diagrammatically how an increase in temperature T changes the values of I_C , I_E , V_E , V_{BE} and I_B and how the rise in temperature is automatically stopped. The process is explained in the following figure.



Solved problem 8.1

For the circuit in Fig. 8.5, find V_{CE} and V_E values neglecting the value of V_{BE} . Given $R_1 = 10 \text{ k}\Omega$,

$R_2 = 5 \text{ k}\Omega$, $R_E = 10 \text{ k}\Omega$, $R_C = 5 \text{ k}\Omega$, $V_{CC} = 15 \text{ V}$.

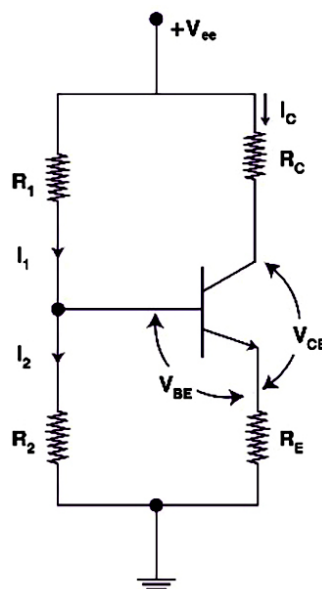


Fig. 8.5

Voltage divider biasing circuit with various currents and voltages shown

SOLUTION:

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

$$V_E = V_B \text{ (if } V_{BE} \text{ is neglected)}$$

Voltage at the emitter, $V_E = V_{CC} \times R_2 \div (R_1 + R_2)$

$$= \frac{5 \times 5}{(10 + 5)}$$

$$= 5 \text{ V}$$

$$I_E = \frac{V_E}{R_E}$$

$$= 5\text{V}/10 \text{ k}\Omega$$

$$= 0.5 \text{ mA}$$

$$I_C = I_E = 0.5 \text{ mA}$$

$$V_{CE} = V_{CC} - I_C (R_C + R_E)$$

$$= 15 - (0.5 \times 15) = 7.5 \text{ V}$$

**Activity 8.1**

Set up a voltage divider biasing circuit as shown in Fig. 8.4. Use the values as $R_1 = 40 \text{ k}$, $R_2 = 5 \text{ k}$, $R_C = 5 \text{ k}$, $R_E = 1 \text{ k}$, $V_{CC} = 12 \text{ V}$, $V_{BE} = 0.3 \text{ V}$. Calculate V_B , V_E , V_{CE} , I_C . Also verify these values using voltmeter and ammeter.

The main requirements of a biasing circuit are:

1. To establish the operating point at the center of the active region so that on applying the input signal, the instantaneous (varying) operating point does not shift towards saturation or cut off.
2. To stabilize the collector current against temperature variations.
3. To make the operating point independent of transistor parameters so that the operating point does not shift when the transistor is replaced by a new one.

**Know your progress**

- 1) Thermal runaway is largely observed in semiconductor devices. Find reason.
- 2) If biasing of an amplifier is not done, how does it affect amplification?

8.4 Single Stage RC Coupled Amplifier

We have now understood how we can bias a transistor for working as an amplifier. Now let us discuss the circuit diagram of an amplifier. A typical amplifier circuit is shown in Fig. 8.6.

The input signal to be amplified is given at the base. The output voltage is taken from the collector terminal. C_b is the input coupling capacitor which is used to couple the AC input signal to the base. At the same time it ensures that, biasing is properly maintained. In the absence of C_b , DC bias voltage at the base will reduce drastically, since it gets grounded through the source (source resistance is very low). C_c is the output coupling capacitor which passes the AC voltage to the output (or next stage) blocking the DC components.

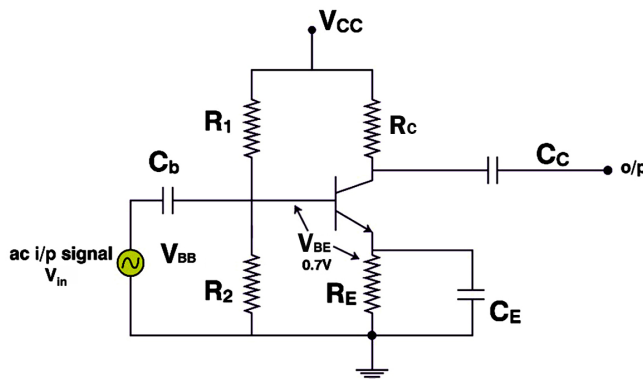


Fig. 8.6 Single stage RC coupled amplifier

As we have seen, R_E is a stabilizing resistor that prevents thermal runaway by developing a voltage whose polarity is opposite to the forward bias applied to the base. In the absence of AC input signal, the variation in the collector current is due to temperature variations.

The change in DC bias voltage due to this is prevented by the voltage V_E developed across R_E . The input voltage to transistor base $V_{BE} = V_B - V_E$. When the value of V_E is increased, the input voltage to transistor base is reduced which reduces the collector current. Thus, any unwanted variation in collector current is suppressed by the presence of R_E . At the same time the collector current variations due to an input signal which is necessary for amplification will also be reduced by the effect of R_E . So, a part of the output AC voltage is dropped across the R_E , which will not be available across R_C . The voltage across R_C is the final output. Thus, output voltage and in turn the gain of the amplifier is reduced. To prevent this, we place a capacitor C_E across R_E . As we know, a capacitor offers only a low impedance to AC. The effective emitter resistance is thus very low for AC. That means C_E will prevent AC voltage developing across R_E which would otherwise oppose the input signal voltage and reduce the gain of the amplifier. At the same time for DC, it acts as an open circuit.

and will not affect the DC bias. C_E thus bypasses the AC components without being dropped across R_E . Hence it is called emitter bypass capacitor. The output of the amplifier is coupled to the load using the coupling capacitor C_C and the collector resistor R_C , hence the amplifier is named RC coupled amplifier.

? Know your progress

- 1) The emitter resistance helps to avoid thermal runaway. Explain.
- 2) How does the removal of emitter bypass capacitor affect the gain of the amplifier?

Gain

The expression for voltage gain of a CE amplifier is

$$\text{Voltage gain, } A = \frac{\text{Output voltage } (V_{\text{out}}) \text{ at the collector terminal}}{\text{Input voltage } (V_{\text{in}})}$$

Gain of an amplifier is usually expressed in decibel (dB).

$$\text{Gain in dB} = 20 \log_{10} (V_{\text{out}} / V_{\text{in}}) = 20 \log_{10} (A)$$

Solved problem 8.2

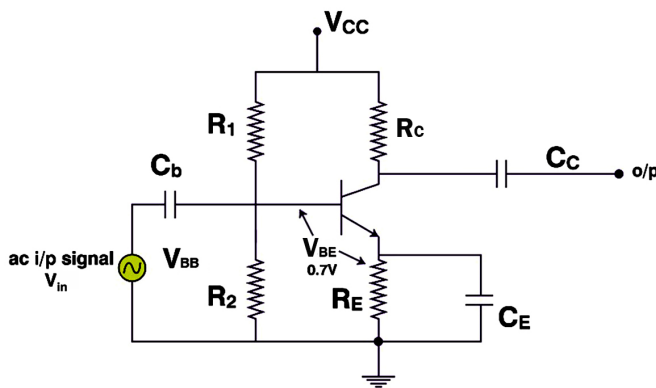
If the gain of an amplifier is 10, find the gain in dB.

$$\text{Gain in dB} = 20 \log_{10} (V_o / V_i) = 20 \log_{(10)} = 20 \times 1 = 20 \text{ dB}$$



Activity 8.2

Set up a single stage transistor amplifier circuit using the following components and analyze the results obtained.



$$R_1 = 33 \text{ k}\Omega$$

$$R_C = 1.5 \text{ k}\Omega$$

$$R_2 = 3.3 \text{ k}\Omega$$

$$R_E = 330 \text{ k}\Omega$$

Fig. 8.7 Single stage RC coupled amplifier

- 1) Measure the collector current and collector to emitter voltage using CRO.
- 2) Measure the maximum signal voltage that can be amplified by the amplifier without having output clipped.
- 3) Measure the voltage gain of the amplifier at 1kHz.
- 4) Measure the voltage gain of the amplifier for different values of load resistor.



Decibel System

Logarithmic scale is used to compare two powers. This is because an individual's power of vision or hearing varies non linearly. The number of bels by which a power P_2 exceeds power P_1 is defined as

$$\text{Number of bels} = \log_{10} (P_2/P_1)$$

Decibel is a smaller unit than bel, decibel is one -tenth of a bel
 Number of dB (decibel) = 10 x Number of bels

$$= 10 \log_{10} (P_2/P_1) \text{ dB}$$

For an amplifier P_1 represents the input power and P_2 the output power. If V_1 and V_2 are the input and output voltage of the amplifier

$$P_1 = \frac{V_1^2}{R_1}$$

$$P_2 = \frac{V_2^2}{R_2}$$

R is the resistance across which the power is developed.

$$\text{Number of dB} = 10 \log_{10} \left(\frac{V_2^2}{V_1^2} \right)$$

$$= 2 \times 10 \times \log_{10} (V_2/V_1)$$

$$\text{Or (Voltage gain) dB} = 20 \log_{10} (\text{Voltage gain})$$

8.5 Multistage Amplifier

A single stage amplifier may not be sufficient to provide the desired gain in certain cases. In order to increase the gain, more than one stage can be connected in series (cascaded). Such a cascade of amplifiers is known as a multistage amplifier or cascaded amplifier.

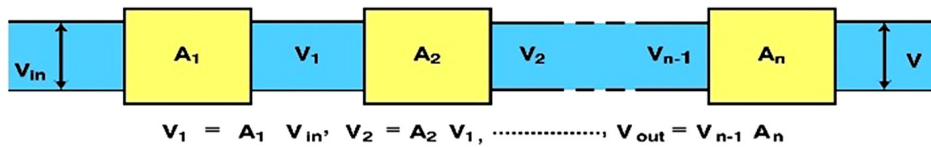


Fig. 8.8 Multistage amplifier

Overall voltage gain $A = A_1 \times A_2 \times \dots \times A_n$ where $A_1, A_2, \dots, A_n$ represent the individual amplifier gains

Gain of Multistage amplifier in dB

$$20 \log_{10} A = 20 \log_{10} A_1 + 20 \log_{10} A_2 + \dots + 20 \log_{10} A_n$$

$$AdB = A_1 dB + A_2 dB + \dots + A_n dB$$

When individual amplifier gains are in dB, we have to add them to get the total gain of the cascaded amplifier in dB. When individual gains are in ratio, we have to multiply them to get the total gain.

Solved problem 8.3

A multistage amplifier consists of three stages with voltage gain 30, 50 and 80 respectively. Calculate the overall voltage gain in dB.

$$\text{Overall gain } AdB = A_1 dB + A_2 dB + A_3 dB$$

$$A_1 dB = 20 \log_{10} 30 = 29.54 \text{ dB}$$

$$A_2 dB = 20 \log_{10} 50 = 33.98 \text{ dB}$$

$$A_3 dB = 20 \log_{10} 80 = 38.06 \text{ dB}$$

$$\begin{aligned} AdB &= 29.54 + 33.98 + 38.06 \\ &= 101.58 \text{ dB} \end{aligned}$$

Alternatively,

$$\begin{aligned} A &= A_1 \times A_2 \times A_3 \\ &= 30 \times 50 \times 80 \\ &= 120000 \end{aligned}$$

Overall voltage gain in dB

$$\begin{aligned} &= 20 \log_{10} 120000 \\ &= 101.58 \text{ dB} \end{aligned}$$

8.6 Frequency Response of an Amplifier

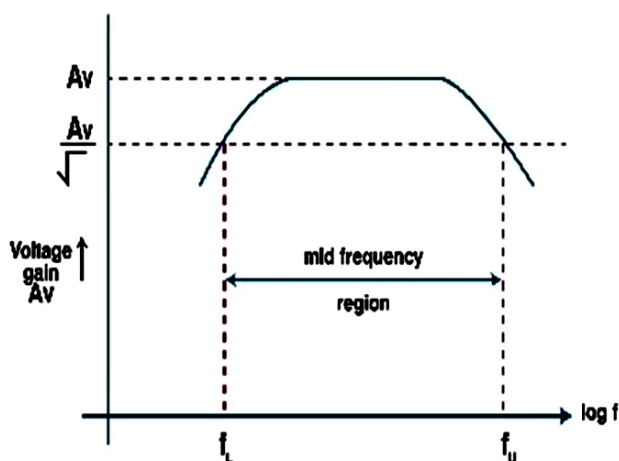


Fig. 8.9 (a) Frequency response of amplifier

Frequency response is the response of the amplifier to different frequencies. In order to draw the frequency response graph, we have to input sine waves of constant amplitude but with different frequencies. In each case, the output voltage is noted and gain is calculated. Then graph is plotted with frequency along the x-axis and voltage gain along the y-axis. Fig. 8.9 (a) shows the typical frequency response curve of a single stage RC coupled amplifier.

From the frequency response curve, it can be seen that the gain remains constant only at mid frequencies. The gain decreases at low and high frequencies. Mid frequency region is defined as the range of frequencies between lower cut off frequency (f_L) and upper cut off frequency (f_H).

The lower and upper cut off frequencies are defined as those frequencies where the power gain of the amplifier decreases to half the mid frequency gain. These points are also called half power points. In decibels, the power decreases by 3dB at cut off frequencies. Correspondingly at half power points, the voltage gain falls to $1/\sqrt{2}$ (or 0.707) of the mid frequency gain.

Bandwidth

The mid frequency range of an amplifier is specified by the parameter bandwidth. It is the difference between the cut off frequencies f_H and f_L . The bandwidth specifies the range of frequencies over which the amplifier can provide constant and better gain. Within the bandwidth, amplifier amplifies all frequencies equally well. When we amplify a signal, the frequency range of this signal must be within the bandwidth of the amplifier.

Fall of gain at low frequencies

The coupling and bypass capacitors are provided to offer almost zero impedance to AC signals. In other words, they should act as short circuit to AC. But the capacitive reactance is inversely proportional to frequency.

$$X_c = \frac{1}{2\pi fC}$$

So as frequency decreases, the capacitive reactance increases. Hence, they cannot be replaced by short circuits at low frequencies.

The input coupling capacitance offers a high reactance at low frequencies. Due to this a significant input voltage is dropped across the input coupling capacitance. Thus, only a portion of the input signal to be amplified reaches the transistor base. This causes gain reduction at low frequency. Similarly, the coupling capacitor connected at the output side also cannot couple the signal completely to the next stage. C_E which is used to bypass R_E also cannot do the bypassing action effectively due to its high reactance to AC. This causes a voltage drop across R_E resulting in gain reduction.

Fall of gain at high frequencies

We know that the depletion layer is formed at the base-emitter and the base-collector junctions. The depletion layer does not have any charge carriers, whereas in either side of the region there are charge carriers. This results in a capacitive effect.

The capacitance C_{bc} between the base and the collector connects the output with the input. (See Fig. 8.9 (b)). At low frequencies, since the reactance is high it is almost an open circuit and hence there is no effect. But at high frequencies since the capacitive reactance is small, it provides a conducting path between the input and the output. This will effectively reduce the input and thereby the gain.

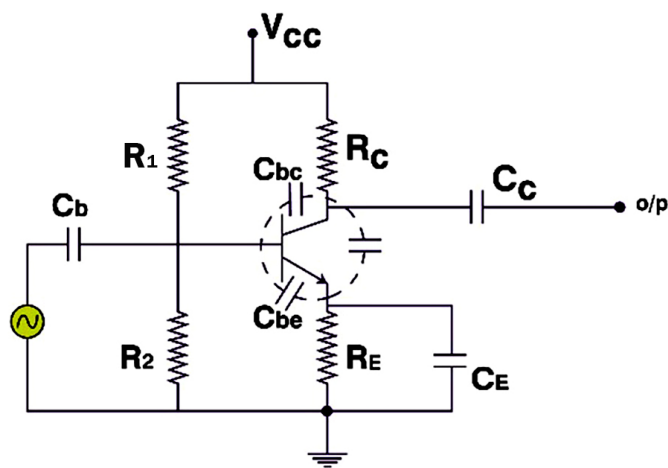


Fig. 8.9 (b) Diagram showing junction capacitances at high frequencies



Activity 8.3

- Set up a single stage RC coupled amplifier referring Fig. 8.7 and
 1. Measure the Q point values using CRO.
 2. Measure the voltage gain of the amplifier for different frequencies like 200 Hz, 600 Hz, 1 kHz, 1500 Hz, 2 kHz, 3 kHz, 1 MHz etc.
 3. Plot the frequency response curve.
 4. Measure the bandwidth.

Based on the frequency of operation, amplifiers can be broadly classified as audio frequency amplifier, radio frequency amplifier and video amplifier. Audio frequency amplifier is for frequencies between 15 Hz and 20 kHz, radio frequency amplifier for frequencies between 10 kHz and 1000 GHz and video amplifier for frequencies between DC to 6 MHz.



Know your progress

Specify the significance of frequency response curve in the design of amplifiers.

8.7 Audio Power Amplifiers

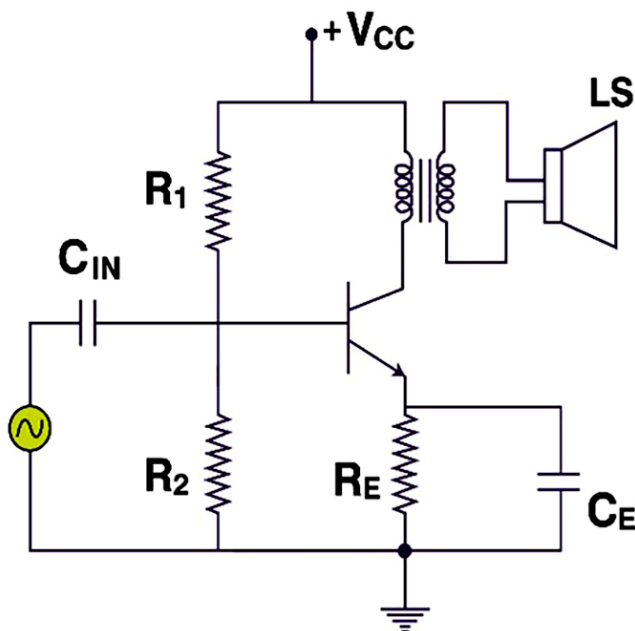


Fig. 8.10 (a)

As the name implies, audio amplifiers are used to amplify the audio signals. It is an essential component in public address systems, radio, tape recorder, TV etc. The RC coupled amplifier can be used as an audio amplifier. As discussed earlier, it is a voltage amplifier. In many systems, we need multistage amplifiers to get the desired gain. The initial stages will be voltage amplifiers, whereas the final stage will be a power amplifier, so as to deliver the maximum power to the output device (e.g., loud speaker).

Let us now look at a typical audio power amplifier that can be used at the final stage of a public address system Fig. 8.10 (a). The output device connected to an audio amplifier is a loud speaker.

The impedance of a typical loud speaker is 8 ohms.

So, if it is connected directly the effective load resistance will be very low. This in turn makes the gain very low. This problem can be solved by using a transformer to couple the output to the loud speaker. This arrangement is hence called transformer coupled amplifier. The transformer functions as an impedance matching element, which converts the low impedance of the output device into an effective high impedance.

Fig. 8.10 (b) shows the block diagram of a simple public address system (PA System)

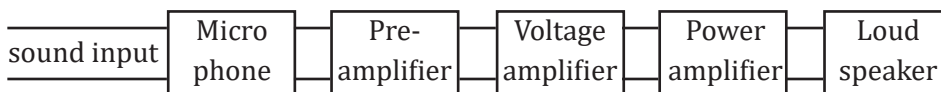


Fig. 8.10 (b)

8.8 Operational Amplifiers

Operational Amplifiers, or **Op-amps** as they are more commonly called, are one of the basic building blocks of analog electronic circuits. Operational amplifiers are devices used extensively for signal conditioning, filtering and for performing mathematical operations such as addition, subtraction, multiplication, division, integration and differentiation. It consists of several circuits, with many stages of amplification, built specifically to attain ideal characteristics required for an amplifier on a single silicon chip. The main characteristics of an op-amp are

- Very high gain (ideally infinite)
- Very high input impedance (ideally infinite) and very low output impedance (ideally zero)
- Very high bandwidth (ideally infinite)

An Operational Amplifier consists of two high impedance inputs, one called the Inverting input, marked with a negative or “minus” sign (–) and the other one called the Non-inverting input, marked with a positive or “plus” sign (+) and one output.

An operational amplifier only responds to the difference between the voltages on its two input terminals, known commonly as the “Differential Input Voltage”. Then if the same voltage is applied to both the input terminals the resultant output will be zero. So, a noise voltage which appears common to both inverting and non-inverting inputs can be eliminated.

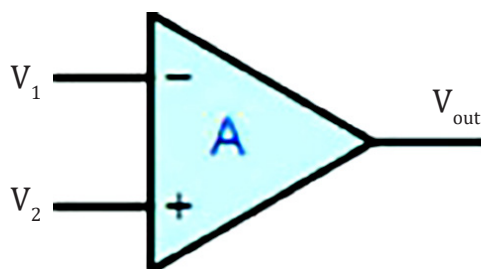


Fig. 8.11 (a) Symbolic representation of op-amp

The input to the Op-amp can be given either to the inverting terminal or to the noninverting terminal. If the input is given to the inverting terminal, the output will be inverted in comparison with the input, whereas when it is given to the non-inverting terminal, it will be in phase with the input. 741 C is a popular operational amplifier which is an 8 pin IC.

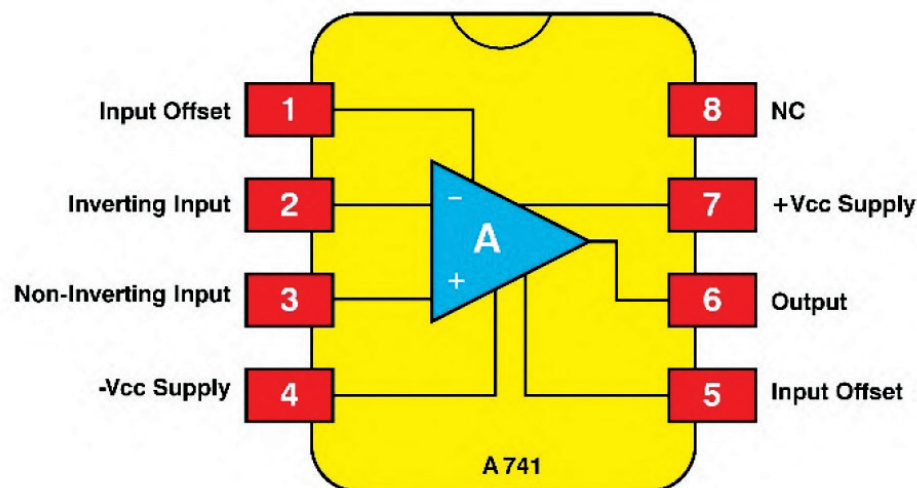


Fig. 8.11 (b) Pin-out of IC 741 C

Inverting Amplifier

When the Op-amp is used as inverting amplifier, the input signal is given to the inverting input. Now the output signal is 180° out of phase with the input signal.

The gain of the inverting amplifier is given by $A = \frac{-R_F}{R_i}$

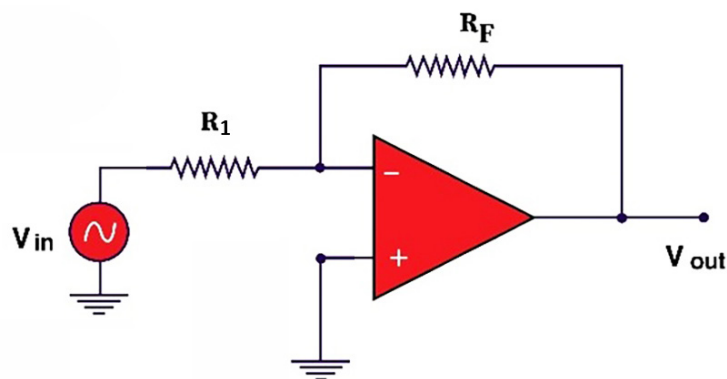


Fig. 8.11 (c) Inverting Amplifier

Non Inverting Amplifier

When the Op-amp is used as non-inverting amplifier, the input signal is given to the non-inverting input. Now the output signal is in phase with the input signal.

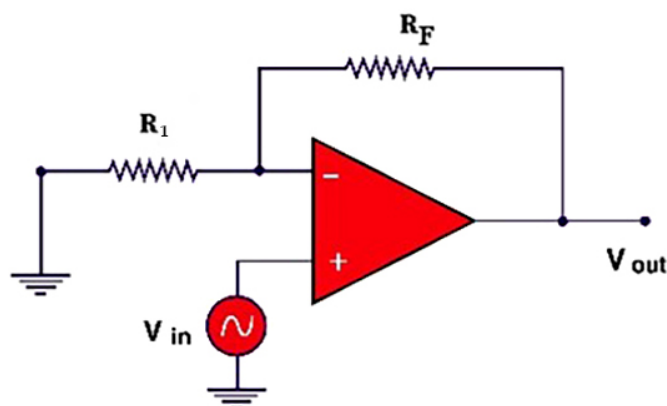


Fig. 8.11 (d) Non Inverting Amplifier Circuit

The gain of the non-inverting amplifier is given by;

$$A = 1 + \frac{R_F}{R_1}$$



Activity 8.4

Set up an integrator Circuit and a differentiator circuit with $R = 1\text{ K}$ and $C = 0.02\text{ }\mu\text{F}$. Set up a square wave of 1 KHz frequency and 1 V peak to peak value as input V_{in} . Observe the output waveform on the CRO.

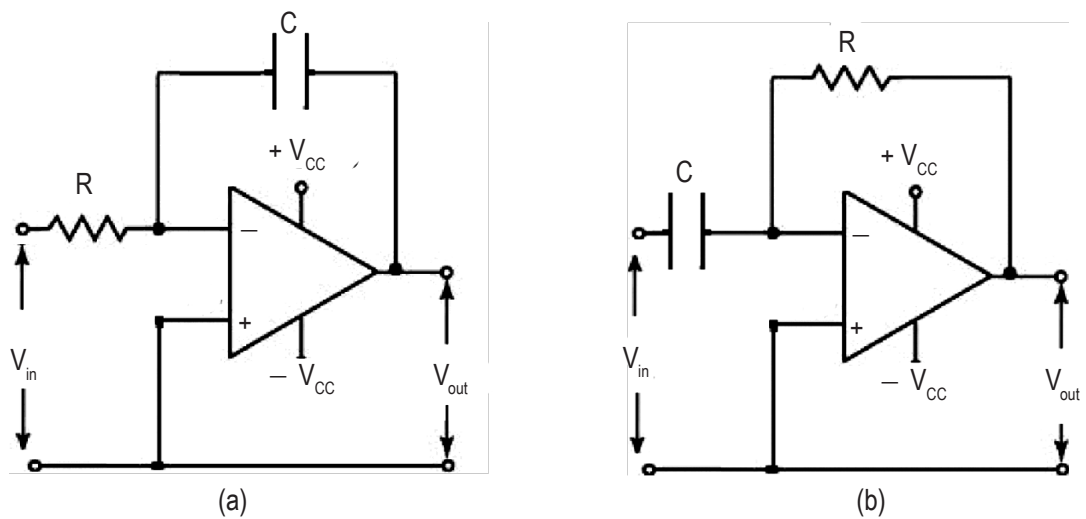
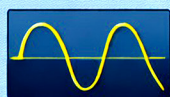
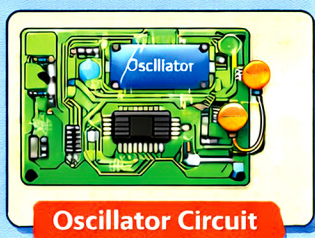


Fig. 8.12



Know your progress

1. State the ideal characteristics of op-amp.
2. Design an inverting amplifier for unit voltage gain
3. Design a non inverting amplifier for gain 10.



Sine Wave



Sine Wave



Mechanical Oscillation



Audio Amplifier

Tone Generator

Power Inverter

Oscillators

You might have noticed that an FM channel is specified by its frequency along with its name. What is this frequency? It is the frequency of the carrier signal which carries the program to the destination. The carrier is usually a high frequency signal produced by an oscillator. An electronic oscillator is a circuit that produces a repetitive, oscillating electric signal, often a sine wave or a square wave. Oscillators generate AC signals of different frequencies ranging from a few Hz to several MHz by drawing power from a DC power supply. They are mainly used in electronic communication circuits such as radio, television, RADAR etc. In various communication circuits, oscillators are used to generate high frequency signals to carry messages. Oscillators are often characterized by the frequencies of their output signal.

- An audio frequency (AF) oscillator produces frequencies in the audio range (20 Hz - 20 kHz).
- A radio frequency (RF) oscillator produces frequencies in the radio frequency range. (above 100 kHz)

Square waves are generated with the help of multivibrators. The other wave forms such as triangular waves can be obtained by shaping the square waves.

9.1 Alternating Signal Generators

We are familiar with the electric supply voltage provided in our houses which is of sine wave having a frequency of 50 Hz. It is produced by an alternator (AC generator). An alternator is a mechanical device having rotating parts. It converts mechanical energy into electrical energy. But an alternator cannot produce very high frequencies, since the mechanical parts cannot be moved at a faster rate. An oscillator differs from an alternator in the following aspects.

1. An oscillator is not a mechanical device; so the operation is quite silent.
2. It can produce wide range of frequencies.
3. The frequency of the signal can be easily changed when required.



The carrier is a high frequency signal used in a long-distance communication where the message is added in the carrier (or modulated) for transmission. If the message is contained in the amplitude of the carrier, it is Amplitude Modulation (AM) and if it is contained in the frequency, it is called Frequency Modulation (FM).

FM channel	Frequency
Ananthapuri FM	101.8 MHz
Kochi AIR FM	102.3 MHz
Kannur AIR FM	101.5 MHz

AM channel	Frequency
Thrissur AIR	630 KHz
Alappuzha AIR	550 KHz
Kozhikkode AIR	684 KHz



Activity 9.1

Find the frequencies of FM channels in your locality.

9.2 Types of Oscillations

Sinusoidal oscillations can be damped or undamped. The electrical oscillations whose amplitude goes on decreasing with time are called damped oscillations see Fig 9.1 (a). This happens because the circuit in which oscillations are generated has ohmic losses and energy is being lost as oscillations are produced.

In undamped oscillations Fig 9.1 (b), the maximum amplitude of sine wave does not change with time. In this case, right amount of energy is being supplied to overcome the energy losses in the circuit. In electronic oscillators, an amplifier is used to supply energy to compensate losses.

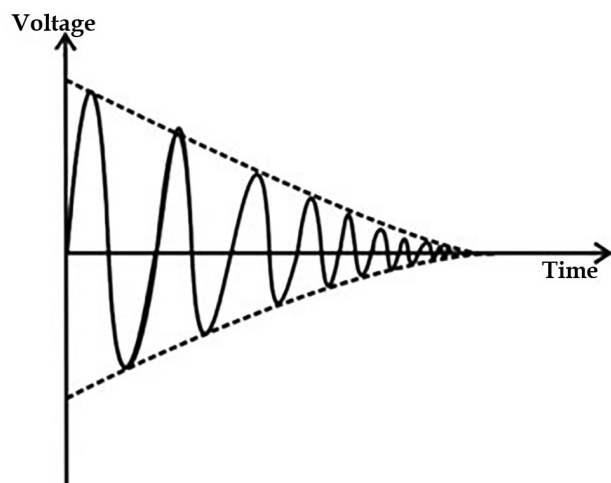


Fig. 9.1 (a) Damped Oscillations

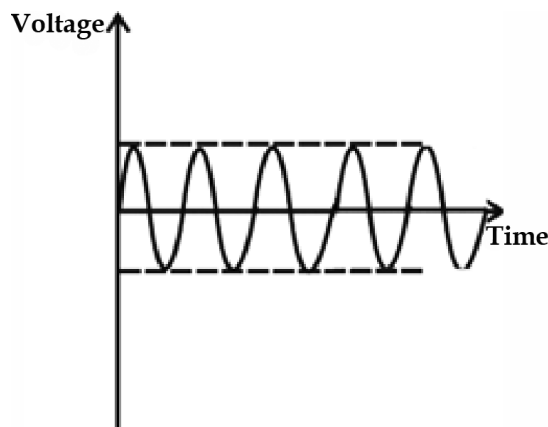


Fig. 9.1 (b) Undamped Oscillations



Activity 9.2

Take a long piece of rope and fix its one end. Hold the other end in your hand and move your hand up and down.

If you make only one move, then you can see oscillations in the rope and these oscillations die soon. It is an example of damped oscillation.

Instead of making one move, if you continuously move your hand up and down, you can see sustained oscillations in the rope. In this case you are giving energy continuously to keep the oscillations in the rope. These oscillations are undamped or sustained oscillations.

9.3 Generation of Sine Waves

In an electronic oscillator, the circuit which produces oscillations of any desired frequency is known as tank circuit. To understand the generation of oscillations, we shall have a look into the mechanical oscillations produced by a simple pendulum.

A pendulum consists of a mass (known as a bob) attached by a string to a pivot point. If we push the bob to one side, the pendulum moves and it sweeps out a circular arc, moving back and forth in a periodic fashion (or it oscillates). During the oscillation, the bob goes to the extreme position at one side, stops there for a while and returns to the mean position. It does not stop at the mean position, but moves towards the other extreme position and returns from

there to go to the previous extreme position. The oscillation continues in this way. The potential energy of the pendulum is maximum at the extreme positions but the kinetic energy is zero since the pendulum rests there for a while. When the bob returns from there, the potential energy decreases and kinetic energy increases and the kinetic energy is maximum at the mean position. The pendulum oscillates because of the energy transfer between potential and kinetic forms. The oscillations continue in this way for any long time and we get undamped oscillations if there is no loss of energy during this transfer. But due to air friction, the energy of the pendulum decreases and oscillation decreases or the amplitude of the oscillation decreases gradually and it dies out finally. If we give energy to compensate this loss, the oscillation becomes steady and we get sustained oscillations.

The oscillation produced in the tank circuit of an oscillator is analogous to the oscillation of the pendulum. In the LC tank circuit, the oscillations are produced when the energy changes between the magnetic and the electric forms. The magnetic energy is stored in the inductor and the electric energy is stored in the capacitor. The working of the tank circuit is discussed in the next section.

Tank circuit

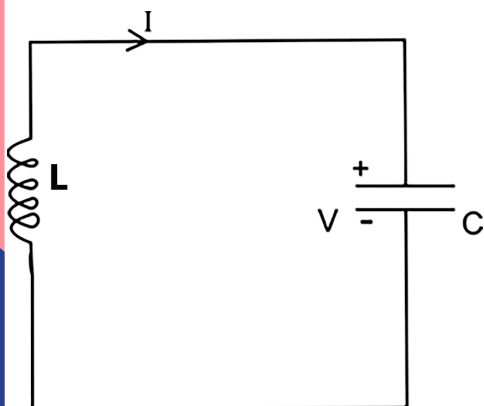


Fig. 9.2 Tank circuit

An LC circuit, also called a resonant circuit, tank circuit, or tuned circuit, consists of an Inductor L and a Capacitor C (Fig 9.2). When connected together, they can act as an electrical resonator. LC circuits are used either for generating signals at a particular frequency, or picking out a signal at a particular frequency from a more complex signal. They are the key components in the LC oscillators.

The LC circuit that is discussed earlier is an idealized model since it is assumed that, there is no dissipation of energy due to resistance. But the practical implementation of an LC circuit always includes loss of energy resulting from a small but non-zero resistance within the components (L and C) and the connecting wires. The purpose of an LC circuit is usually to oscillate with minimal damping, so the resistance is made as low as possible. The operation of a tank circuit is explained below.

The capacitor stores energy in its electric field E and the inductor stores energy in its magnetic field B . If a charged capacitor is

connected across an inductor, charge will start to flow through the inductor, building up a magnetic field around it. The voltage across the capacitor decreases due to the discharging of the capacitor. Eventually all the charge on the capacitor is lost and the voltage across it reaches zero. However, the current continues to flow, because the inductors resist changes in current. The energy to keep the current flowing is extracted from the magnetic field. So the magnetic field begins to decline. As current flows, the capacitor will start charging, developing a voltage of opposite polarity. When the magnetic field is completely dissipated, the capacitor will be fully charged. The capacitor now starts discharging and the current flows charging the magnetic field. Then the cycle will begin again, with the current flowing in the opposite direction.

The charge flows back and forth between the plates of the capacitor, through the inductor. The energy oscillates back and forth between the capacitor and the inductor. These oscillations gradually decrease, as the energy is lost in the internal resistances and the oscillations die out soon. This action is similar to a pendulum swinging back and forth. The frequency of oscillations generated in the tank circuit is the resonant frequency of the LC circuit. If we plot the variation of the current in the inductor or the variation of voltage across the capacitor with respect to time, we get a sinusoidal graph. This changing voltage or current is the output of the oscillator.

Similar to the air friction that causes loss of energy during the oscillation of the pendulum, the electrical resistances of the inductor and the capacitor cause loss of energy in oscillator. In order to get sustained oscillation, we need to supply energy continuously to the system. We give this energy to a pendulum in the form of regular external push, whereas it is given to an oscillator with the help of an amplifier in the circuit.

Basically, we have two types of oscillators. They are LC oscillators and RC oscillators. An oscillator has two parts - an amplifier and a feedback network. If the feedback circuit is an LC circuit, the oscillator is called LC oscillator and if the feedback circuit is an RC circuit, the oscillator is called an RC oscillator.

RC oscillators are used in integrated circuits since inductors used in LC oscillators are difficult to integrate in ICs.

The generation of oscillations in RC oscillators will be discussed later in this unit after studying the Barkhausen criterion for oscillations.

Frequency Selectivity

You might have heard about tuning a radio. We can select programs from different radio stations by tuning them. Such tuner circuits have frequency selectivity. The ability of a circuit to select a signal of a particular frequency from a group of large number of signals having different frequencies is known as frequency selectivity. An LC tank circuit is a tuner which can select a frequency which is equal to its resonant frequency.

How is a particular frequency selected by an LC circuit? It is explained below. The total impedance of LC circuit is given by

$$Z = R + j (X_L - X_C)$$

where R is the total internal resistance of the inductor and the capacitor.

X_L is the reactance of the inductor.

X_C is the reactance of the capacitor.

Now the impedance of the circuit is minimum or the current in the circuit is maximum when X_L is equal to X_C . So, $Z = R$. Thus, at a particular frequency for which X_C becomes equal to X_L , the circuit produces maximum response or current. This frequency is known as resonant frequency (f_o). In this condition, the circuit is said to be in resonance. For other frequencies, the response of the circuit will be less. The tank circuit thus selects its resonant frequency from all other frequencies by providing maximum response to this frequency. At resonant frequency,

$$\begin{aligned} X_L &= X_C \\ 2\pi f_o L &= \frac{1}{2\pi f_o C} \\ \text{We get, } f_o &= \frac{1}{2\pi\sqrt{LC}} \end{aligned}$$

It is seen that different frequencies can be selected by varying the value of L or C . Usually C is varied with a variable capacitor and this process is called tuning.

An LC oscillator has an LC tank as its feedback circuit. When the DC power supply of the oscillator is switched ON, a very large number of different frequencies are produced in the circuit (refer the content given in the box). The LC tank circuit of the oscillator is a resonant circuit and it selects only one frequency which is equal to its resonant frequency from these different frequencies. This frequency will be amplified by the amplifier and sustained

oscillation of that particular frequency is obtained. Thus, frequency of oscillation is determined by the LC tank circuit.

A sudden change in voltage contains a large number of sine waves having different amplitudes and different frequencies. These frequencies occur as harmonics. The frequencies range from a few Hz to several MHz.

The LC oscillators are not used for generating low frequencies below 20 kHz. Why?

The frequency of oscillation of an LC oscillator is given by

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

They are good for generating high frequencies. But for low frequencies, (say audio frequencies), the LC oscillators are impractical since high value of inductance and capacitance are required according to the above equation. The size of the inductor and the capacitor are very large, if the value of capacitance or inductance is high. In this case RC oscillators are suitable, since large value resistance is not large in size. Also, with the advancement of IC technology, RC oscillators are more feasible since it is very difficult to make large value inductance in ICs. Therefore, RC oscillators are becoming increasingly popular.



Know your progress

1. How will you compare the oscillations in a LC circuit with the oscillations in a simple pendulum?
2. What is the need of an amplifier in an oscillator?
3. How does an LC tank circuit determine the frequency of oscillation?

9.4 Concept of Feedback

Feedback is the process of providing a fraction of output back to the input of a system. It is used to control or improve the performance of the system. In electronic circuits, we use two types of feedback - positive feedback and negative feedback. In positive feedback, the feed back voltage is in the same phase as that of the input voltage and hence when it is added, the effective input increases. On the other hand, in the negative feedback, the feed back voltage has a phase difference of 180° (180 degree) with input voltage and hence when it is added, the effective input decreases.

Positive Feedback

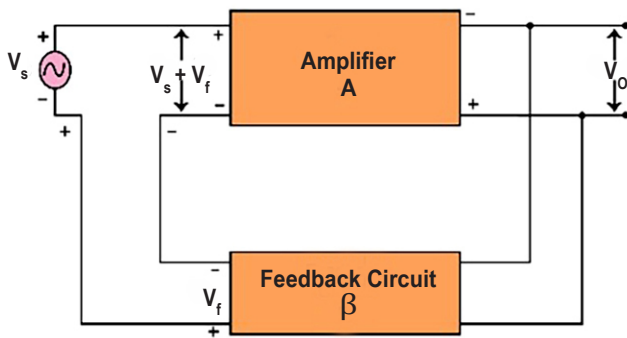


Fig. 9.3 Positive feedback

In Fig. 9.3, the amplifier has gain 'A' and the feedback factor is ' β '. Now a part of the output voltage is taken back to the input side so that this feedback voltage V_f supports the actual input signal V_s . Note the polarity of the signals V_f and V_s . Now the input of the amplifier is

$V_s + V_f$. The type of feedback here is positive feedback.

Analyze Figure 9.4 and note the difference in gain without feedback and with positive feedback.

Without feedback

Input voltage = V_s

Output voltage, $V_o = AV_s$

With feedback

Input voltage = $V_s + V_f$

Output voltage, $V_o = A(V_s + V_f)$

It is clear that the output voltage is greater with feedback. The positive feedback given has resulted in the increase in the gain of the amplifier system. Thus positive feedback is mainly used in oscillators for obtaining sustained oscillations.

Negative Feedback

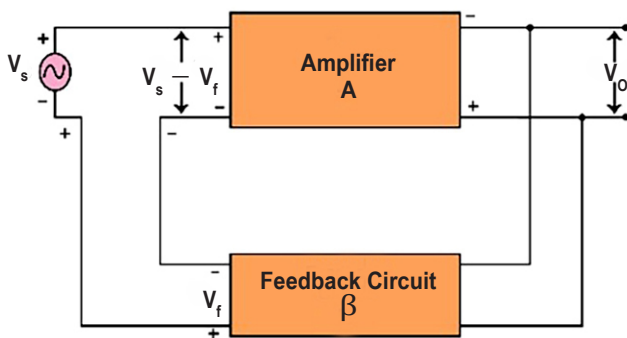


Fig. 9.4 Negative feedback

Here the feedback voltage V_f opposes the input signal V_s . Note the polarities of the voltages V_s and V_f (V_f is 180° out of phase with V_s , hence negative polarity). Now the effective input to the amplifier is $V_s - V_f$. This type of feedback is known as negative feedback.

The input voltage without feedback is V_s and the corresponding output voltage is $V_o = AV_s$. With feedback, the effective input voltage is $V_s - V_f$. So the output voltage is $V_o = A(V_s - V_f)$.

Clearly the output voltage decreases when there is negative feedback in the system. In other words, the negative feedback reduces the gain of the system. Negative feedback is mainly used in amplifiers to reduce the noise effects and to increase the bandwidth.



Know your progress

What is feedback? Compare positive and negative feedback.

9.5 Barkhausen Criterion for Oscillation

Consider the block diagram of an oscillator containing amplifier and feedback circuit.

The gain of the amplifier is A and the gain of the feedback network (or feedback factor) is β . We know that an oscillator generates an AC signal, taking energy from a DC source voltage. It does not require any AC input signal.

Then from where does the oscillator get sine wave? As we have discussed in section 9.4, when the DC voltage source is switched ON, the voltage changes or voltage spike is the source of sinusoidal oscillation.

From Fig. 9.5, we can see that a fraction of the output voltage βV_o reaches the input of the amplifier as V_i .

$$\begin{aligned}\text{Thus we have} \quad V_o &= AV_i \\ V_i &= \beta V_o \\ \text{or } V_o &= A\beta V_o\end{aligned}$$

This is possible only if $A\beta = 1$.

If the output of the system has to remain constant at V_o with time (sustained oscillation), then $A\beta$ should be unity.

What happens if $A\beta$ is not unity? We shall discuss it with an example. Consider that at a particular time, the output sine wave of the oscillator has an amplitude of 1V.

Case I, $A\beta < 1$

Take $A\beta = 0.8$, $A = 2$, $\beta = 0.4$ (see Figure 9.5)

If $V_o = 1V$

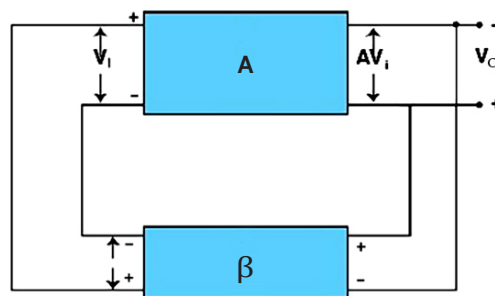


Fig. 9.5 Block diagram of an oscillator

$$\text{Input } V_i = \beta V_o = 0.4 \times 1 = 0.4 \text{ V.}$$

Now output voltage $V_o = V_i \times A = 0.4 \times 2 = 0.8$ ie, output voltage is decreased from 1V to 0.8 V

What happens next?

$$\text{Now } V_o = 0.8 \text{ volts.}$$

$$V_i = \beta V_o = 0.4 \times 0.8 = 0.32 \text{ V}$$

$$\text{So output } V_o = 2 \times 0.32 = 0.64.$$

In this way, the amplitude of the output voltage continuously decreases and after sometime the oscillations die out. Such an oscillation is called a damped oscillation. Refer Figure 9.6 (a).

Case II, $A\beta > 1$

$$\text{Take } A = 2, \beta = 0.6 \text{ or } A\beta = 1.2$$

$$\text{we have output } V_o = 1 \text{ volt.}$$

$$\text{So the input } V_i = \beta V_o = 0.6 \times 1 = 0.6 \text{ V}$$

$$\text{Now output } V_o = AV_i = 2 \times 0.6 = 1.2 \text{ V}$$

Now output voltage is increased from 1 V to 1.2 V. What happens next?

$$\text{Now } V_o = 1.2 \text{ V}$$

$$\text{Input } V_i = \beta V_o = 0.6 \times 1.2 = 0.72 \text{ V}$$

$$\text{So output } V_o = AV_i = 2 \times 0.72 = 1.44 \text{ V}$$

In this way the amplitude of the output voltage continuously grows and such oscillations are called growing oscillations. Refer Figure 9.6 (b).

Case III, $A\beta = 1$

$$\text{Take } A = 2, \beta = 0.5 \text{ we have } V_o = 1 \text{ V}$$

$$\text{So the input } V_i = \beta V_o = 0.5 \times 1 = 0.5 \text{ V}$$

$$\text{With this input, output } V_o = AV_i = 2 \times 0.5 = 1 \text{ V}$$

We see that the output voltage remains the same in this case and such oscillations are called sustained oscillations. Refer Fig. 9.6 (c). We need sustained oscillation at the output of an oscillator.

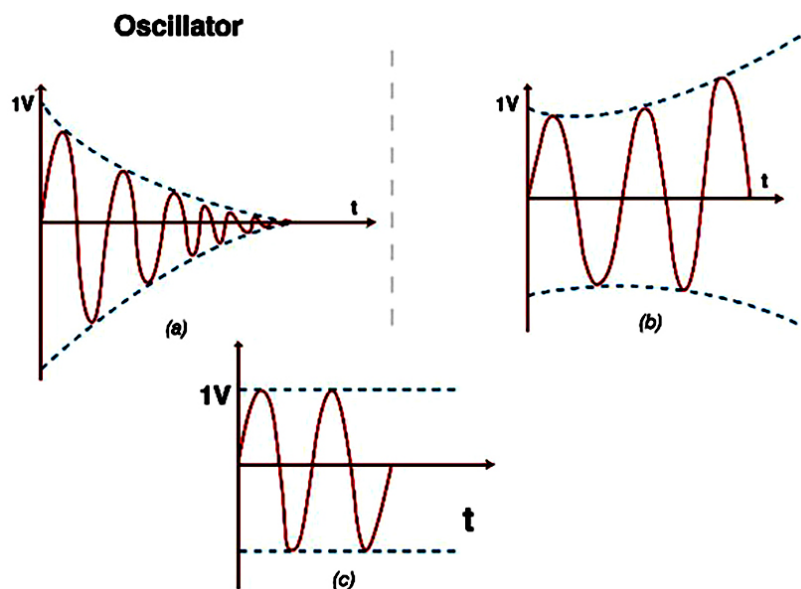


Fig. 9.6

Now we have learned that the magnitude of $A\beta$ should be unity ($|A\beta| = 1$) to get a sustained oscillation. The second condition is that the total phase shift introduced in the signal when it moves around the closed loop containing amplifier and feedback network must be 360° or 0° ($V_i = \beta V_o$, so the polarity of V_i and βV_o should be the same). In other words, we can say that the phase angle of $A\beta$ should be 360° or 0° . If the amplifier introduces a phase shift, the feedback network should produce an additional phase shift, so that the total phase shift becomes 360° . For example, if a CE amplifier is used, then it introduces 180° phase shift between its input and output. So, the feedback network should introduce 180° phase shift or the phase of β should be 180° .

Thus, we can conclude that the conditions for sustained oscillations are;

**Magnitude of $A\beta = 1$ and
Phase of $A\beta = 0^\circ$ or 360°**

These two conditions are known as Barkhausen criterion for oscillation.



The gain of an amplifier with positive feedback is given by $A_F = \frac{A\beta}{1 - A\beta}$. When the loop gain $A\beta = 1$, the gain of positive feedback system becomes infinity. Thus, an oscillator has infinite gain. In other words, we can say that an oscillator produces an output signal without an input because it has infinite gain.

9.6 Oscillation in RC Oscillators

RC oscillators have feedback circuit containing RC network. The phase shift produced by an RC network depends on the frequency of the signal. The phase shift produced by an RC network is given by

$$\theta = \tan^{-1} \left[\frac{1}{2\pi fRC} \right]$$

Thus, if the amplifier produces 180° phase shift, then the RC network must produce another 180° phase shift. So, the sustained oscillation will be produced in the oscillator at that particular frequency for which the RC network makes 180° phase shift. Thereby an RC network selects the frequency of oscillation.



Know your progress

1. Write Barkhausen criterion for oscillation.
2. How is the frequency of oscillation selected in RC oscillator?

9.7 RC Oscillators

The two most important RC oscillators are

1. Phase shift oscillator
2. Wien bridge oscillator

Phase Shift Oscillators

Let us discuss an oscillator for which Op-amp acts as amplifier stage and three RC sections function as feedback circuit (Fig. 9.7).

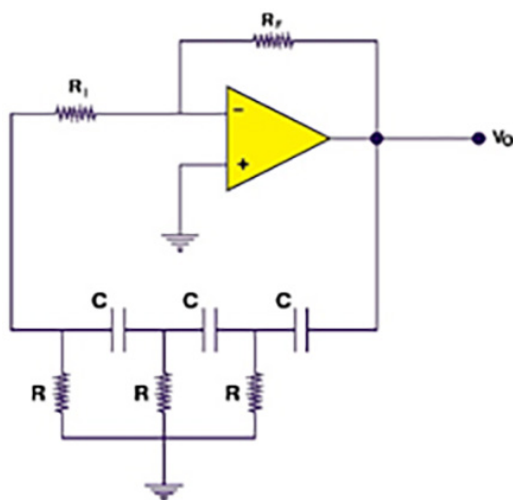


Fig. 9.7 : Phase shift oscillator

The Op-amp used is in inverting mode and hence there is 180° phase shift between its input and output. The three cascaded RC sections should provide the additional 180° phase shift for the oscillation to start. Since we have used three identical RC sections, each RC section must provide 60° phase shifts.

As we have already seen, a large number of different frequency sine waves are generated when the DC supply is switched ON. At a specific frequency when the phase shift of one RC section is 60° , the phase shift of three RC sections becomes 180° and the circuit will oscillate at that frequency (Fig 9.8).

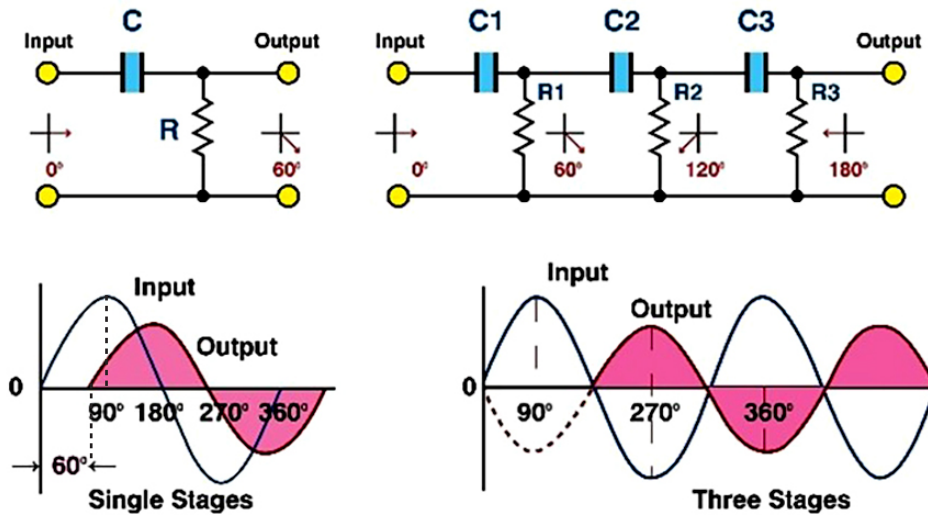


Fig. 9.8 : RC stages and corresponding phase shifts

The frequency of oscillation is given by

$$f_0 = \frac{1}{2\pi RC\sqrt{6}}$$

If we calculate the value of feedback factor β at this frequency, we get

$$\beta = 1/29$$

(Note: derivation is out of the scope of this textbook)

So as per Barkhausen criteria $A = 29$

For the inverting configuration, $A = \frac{-R_F}{R_1}$

$$|A| = \frac{R_F}{R_1}$$

$$\text{or } R_F = 29 R_1$$

To obtain a desired frequency of oscillation, choose a particular value for the capacitor, C and then calculate the value of R from equation for 'f'.

Solved Problem 9.1

Design a phase shift oscillator for 400 Hz.

Solution

Let $C = 0.1 \mu\text{F}$, then from equation

$$f_0 = \frac{1}{2\pi RC\sqrt{6}}$$

we have

$$\begin{aligned}
 R &= \frac{1}{2\pi f_0 C \sqrt{6}} \\
 &= 1/(2\pi \times 400 \times 0.1 \times 10^{-6} \times \sqrt{6}) \\
 &= 1.63 \text{ k}\Omega
 \end{aligned}$$

$$\text{Take } R_F = 29 R_1$$

? Know your progress

Design a phase shift oscillator for i) 1 kHz and ii) 600 Hz

Wien Bridge Oscillator

Figure 9.9 shows the circuit of a Wien bridge oscillator. Here a Wien bridge circuit is connected between the input and the output terminals of the Op-amp. The bridge has series RC circuit in one arm and parallel RC circuit in the adjoining arm. The resistors R_1 and R_F are connected in the remaining two arms of the bridge.

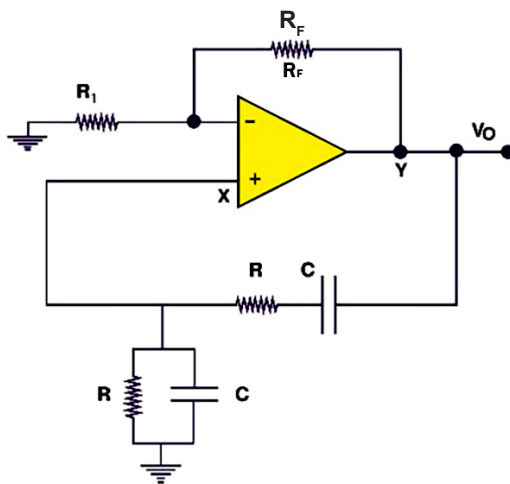


Fig. 9.9 : Wien Bridge Oscillator

For sustained oscillation, the total phase shift around the network must be 0° or 360° . In this circuit, the Op-amp is in non inverting mode and hence there is no phase shift between its input and output. So the feedback network should not introduce any phase shift in the signal. This condition occurs only when the bridge is balanced or when it is at resonance.

The frequency of oscillation is the same as the resonant frequency of the balanced Wien bridge and it is given by

$$f_0 = \frac{1}{2\pi RC}$$

If we calculate the feedback factor, β at this frequency, we get

$$\beta = \frac{1}{3}$$

To satisfy the Barkhausen criterion, the gain of the amplifier

$$A = \frac{1}{\beta} = 3$$

So the gain of the non inverting amplifier, $A = 1 + \frac{R_F}{R_1} = 3$ or $\frac{R_F}{R_1} = 2$.

$$\text{ie., } R_F = 2R_1$$

Wien bridge oscillator has a very good frequency stability and the frequency can be varied easily to a large range.



Activity 9.3

Design a Wien bridge oscillator for i) 950 Hz and ii) 1.5 kHz.



Know your progress

1. What is the purpose of using three RC stages in a phase shift oscillator?
2. What should be the gain of the amplifier in a phase shift oscillator and that in a wien bridge oscillator?

9.8 Astable Multivibrator

It is a square wave generator and its output waveform has only two voltage levels; either HIGH state or LOW state. Here the Op-amp operates in saturated regions - positive saturation ($+V_{sat} = +V_{CC}$) and negative saturation ($-V_{sat} = -V_{CC}$). The output of the Op-amp swings between $+V_{sat}$ and $-V_{sat}$, continuously resulting in a square wave output. An astable multivibrator circuit using Op-amp is shown in Fig. 9.10.

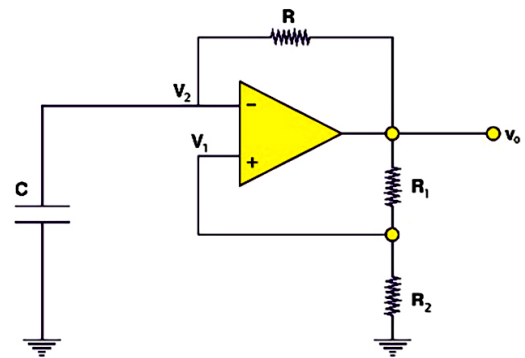


Fig. 9.10 Astable Multivibrator

The operation of the circuit is explained below.

The differential input voltage of the Op-amp, $V_{id} = V_1 - V_2$

If V_{id} is positive, or $V_1 > V_2$, the output of the Op-amp goes to positive saturation, $+V_{CC}$. If V_{id} is negative, or $V_1 < V_2$, then output of the Op-amp goes to negative saturation, $-V_{CC}$.

Assume that the capacitor, C is initially uncharged and voltage across it is zero. So $V_2 = 0$. Now, when DC supply is switched ON, there will be a small output offset voltage, V_{offset} . If we assume that, this V_{offset} is positive, then this voltage is divided between resistors R_1 and R_2 . Hence there will be a small positive voltage V_1 . Now V_{id} is positive, and so the output of the Op-amp becomes $+V_{CC}$.

$$S_o V_o = +V_{CC}$$

At the same time, the capacitor, C starts charging through R with the voltage $+V_{CC}$. The voltage across the capacitor gradually builds up and when this voltage slightly goes above V_1 .

$V_{id} = V_1 - V_2$ becomes negative.

The output now switches to $-V_{cc}$.

$$S_o V_o = -V_{cc}$$

V_1 is now a negative voltage.

Now the capacitor discharges and charges negatively through 'R'. So, the voltage across the capacitor increases negatively. When this voltage V_2 goes more negative than V_1 , V_{id} becomes positive and the output of the Op-amp goes to $+V_{cc}$. This process repeats and the output of the Op-amp switches between $+V_{cc}$ and $-V_{cc}$ after fixed time intervals. Thus, we get square wave output.

The time period of the output square wave, $T = 2RC \ln [(2R_2 + R_1)/R_1]$

To simplify this equation, take $R_1 = 1.16R_2$. Then we get

$$T = 2RC$$

or frequency, $f = 1/T = 1/(2RC)$

Thus, the frequency of the square wave can be easily varied by a variable resistor or a variable capacitor. The square waveform with variable ON and OFF time can be used for different timing applications.

Solved problem 9.2

Design a square wave generator for 1 kHz.

Solution

Take $R_1 = 1.16R_2$ so that we can use simplified equation,
 $f_o = 1/2RC$

Let $R_2 = 10 \text{ k}\Omega$, So $R_1 = 1.16 \times 10 = 11.6 \text{ k}\Omega$

Let $C = 0.01 \text{ }\mu\text{F}$

So $R = 1/(2f_o C) = 1/(2 \times 1 \times 10^3 \times 0.01 \times 10^{-6})$
 $= 50 \text{ k}\Omega$



Know your progress

Design an astable multivibrator of frequency

i) 15 kHz ii) 100 Hz

9.9 Crystal Oscillator

The most important feature of an oscillator is its frequency stability. The frequency of the signal produced by an oscillator should remain constant irrespective of time and ambient conditions. The frequency stability of LC and RC oscillators is not superior. But a crystal oscillator has a very precise frequency. It uses a piezoelectric crystal which can produce mechanical vibrations when excited with an AC signal. The most common type of piezoelectric material used is the quartz crystal, so the oscillator circuits incorporating them came to be known as crystal oscillators. Quartz crystals are manufactured for frequencies from a few tens of kilohertz to tens of megahertz. They are used for consumer devices such as wrist watches, clocks, radios, computers, and cell phones.

Piezoelectricity

When a crystal of quartz is properly cut and mounted, it can be distorted in an electric field by applying a voltage to an electrode near to or on the crystal. When the field is removed, the quartz will generate an electric field as it returns to its previous shape, and this can generate a voltage. If an AC voltage is applied to the crystal, it will vibrate (contract and expand) at a frequency equal to that of the applied voltage. Otherwise, if the crystal is made to vibrate mechanically, it will generate an AC voltage at a frequency equal to that of the vibration. This property is known as piezo electricity. The result is that a quartz crystal behaves like a circuit composed of an inductor, a capacitor and a resistor, with a precise resonant frequency. The resonant frequency of a crystal is determined by the cut and size of the crystal. The symbol and equivalent circuit of the crystal is given in Fig. 9.11.

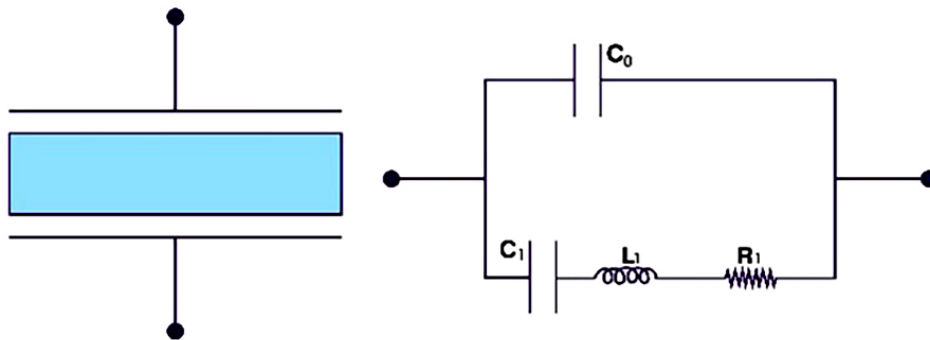


Fig. 9.11 : Quartz crystal symbol and equivalent circuit

A quartz crystal provides both series and parallel resonance. The series resonant frequency is a few kilohertz lower than the parallel

resonant frequency. Crystals below 30 MHz are generally operated between series and parallel resonance. Crystals above 30 MHz (up to 200 MHz) are generally operated at series resonance where the impedance is at its minimum and equal to the series resistance. To obtain higher frequencies, a crystal can be made to vibrate at one of its overtone modes, which occur near multiples of the fundamental resonant frequency. Only odd numbered overtones are used. Such a crystal is referred to as a 3rd, 5th, or even 7th overtone crystal. To accomplish this, the oscillator circuit usually includes additional LC circuits to select the desired overtone produced by the crystal. Also, the frequency produced by the crystal oscillator is almost independent of temperature.



Activity 9.4

Set up an astable multivibrator to switch an LED ON and OFF- with a time period of one second.

Solution

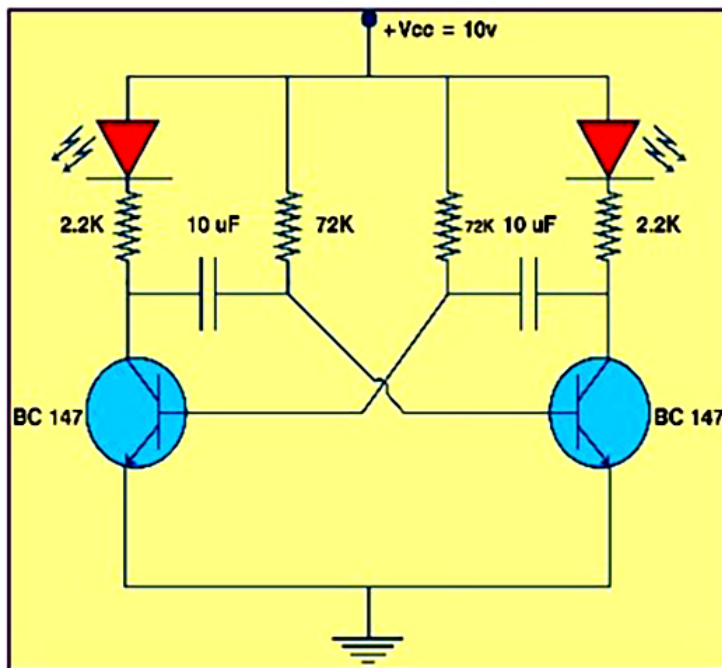


Fig. 9.12

Connect the LEDs in the collector of the multivibrator as shown in Fig. 9.12.

The time period of an astable multivibrator is $T = 1.38R_B C$. We have to generate a square waveform with a time period of 1 second.

$$\text{Let } C = 10 \mu\text{F}$$

$$\begin{aligned} \text{Now } T &= 1.38 R_B \times 10 \times 10^{-6} \\ \text{or } R_B &= 72 \text{ k}\Omega \end{aligned}$$

The LEDs will be ON and OFF alternately; ie when one LED is ON, the other will be OFF and vice versa. The ON and OFF durations of LEDs are 0.5 second each.

Digital Electronics

Analog signals are continuously varying signals that have infinite number of values within any specified interval of time. Alternating current or voltage wave forms which are of sinusoidal shape are examples of analog signals.

Digital signals represent information using discrete values usually in the form of binary 0 and 1. For example: Data inside a computer or smartphone.

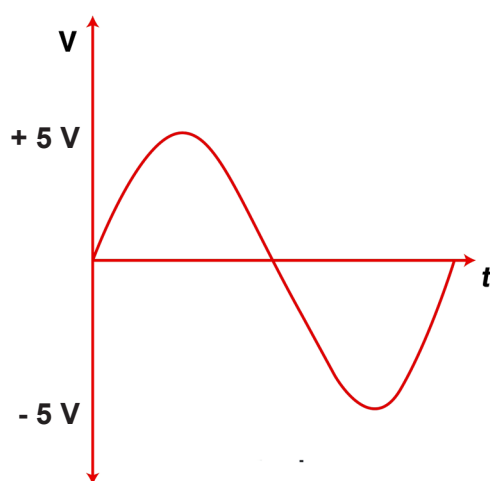


Fig. 10.1 Analog Signal

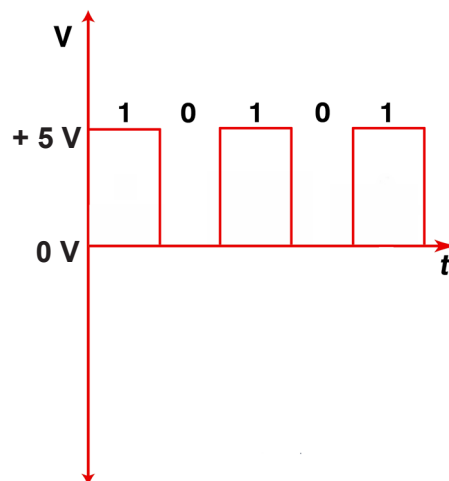


Fig. 10.2 Digital Signal

In digital signals, a logic 1 can be represented by a + 5 V and logic 0 can be represented by a 0 V. In analog circuits or devices, the electrical variable such as current or voltage is continuous. That means an analog circuit processes continuously varying signals or analog signals. But, in a digital circuit only discrete values of variables are recognised. A digital circuit or device processes digital signal.

10.1 Number System

Do you know the name of the number system which you use in your daily life? This number system which uses digits from 0 to 9 i.e., 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9 is called decimal number system. Deci means 10. This number system is termed as decimal system because the base of this system is 10. Similarly, we have a wide variety of number systems. Each of this is based on a specific base or radix. The binary number system applies base 2, octal number system applies base 8 and hexadecimal number system applies base 16.



Activity 10.1

Let us examine the formation of the number $(429)_{10}$ in a decimal number system.

$$(429)_{10} = 4 \times 10^2 + 2 \times 10^1 + 9 \times 10^0$$

$$\text{i.e } 429 = 400 + 20 + 9$$

Here 4 is in the hundredth position, 2 is in the tenth position and the digit 9 is in its one's position. Similarly, we can represent numbers in other number systems.

10.2 Binary Number System

Binary number system is the soul of digital electronics. The base of this number system is 2. A number in this system is represented by 0s and 1s.

As shown in the above activity (10.1), let us discuss the formation of the binary number 10110. Starting from the least significant bit 0 towards left in the above binary number 10110, 0 is in the one's position, 1 is in the two's position, the next 1 is in the four's position, next 0 is in the eights position and the next 1 is in the sixteens' position. Digital signals are represented by the binary number system.

In the system 0 is equivalent to 0 in the decimal system and 1 is equivalent to 1 in the decimal system. The next number is 10 in the binary number system which is equivalent to 2 in the decimal system. Similarly, the following number is 11 which is equivalent to 3 in the decimal system.

Conversion of a Binary number to Decimal number

Try to analyse the following table.

Binary	Equivalent decimal
0	0
1	1
10	2
11	3
100	4

Table 10.1

The representation of a binary number and its meaning has been illustrated above. Keeping these in mind the binary number $(10110)_2$ can be converted into a decimal number as follows.

The representation of a binary number and its meaning has been illustrated in the previous section. Keeping these in mind the binary number $(10110)_2$ can be converted into decimal as follows.

$$\begin{array}{ccccc}
 1 & 0 & 1 & 1 & 0 \\
 \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\
 2^4 & 2^3 & 2^2 & 2^1 & 2^0
 \end{array}$$

$$\begin{aligned}
 (10110)_2 &= 1 \times 2^4 + 0 \times 2^3 + 1 \times 2^2 + 1 \times 2^1 + 0 \times 2^0 \\
 &= 1 \times 16 + 0 \times 8 + 1 \times 4 + 1 \times 2 + 0 \times 1 \\
 &= (22)_{10}
 \end{aligned}$$

$$\text{So } (10110)_2 = (22)_{10}$$

Where 22 is the decimal equivalent value of binary number 10110.



Know your progress

Convert the following numbers into decimal system

a) $(11110)_2$

b) $(10101)_2$

Conversion from Decimal to Binary

To convert a number in the decimal system into binary, first we have to divide the number by 2. If it is exactly divisible write 0 against the number on its right hand side. If not exactly divisible put 1 against the number. Again divide the result obtained by 2 and proceed until the result is 1. Then, read the number starting from the last resultant digit through all digits on the right hand side. As an example, let us convert $(53)_{10}$ to binary.

The arrow shown represents how to read up the binary

ie: 110101

2	53	1
2	26	0
2	13	1
2	6	0
2	3	1
	1	

So $(53)_{10} = (110101)_2$



Know your progress

Convert the following numbers into binary number system.

(a) $(76)_{10}$ (b) $(99)_{10}$

Decimal and Binary Fraction

To understand the meaning of representation of decimal fractions, let us consider such a number say $(36.2012)_{10}$

The expansion for this number is

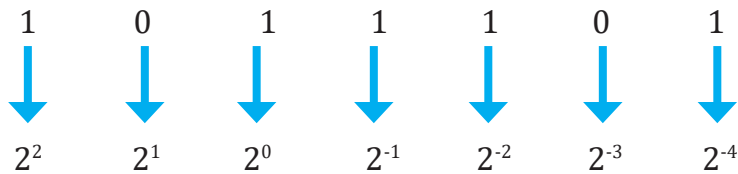
$$(36)_{10} = 3 \times 10^1 + 6 \times 10^0 \text{ and}$$

$$(0.2012)_{10} = 2 \times 10^{-1} + 0 \times 10^{-2} + 1 \times 10^{-3} + 2 \times 10^{-4}$$

So the positional values of the above number can be shown as below:

3	6	2	0	1	2
↓	↓	↓	↓	↓	↓
10^1	10^0	10^{-1}	10^{-2}	10^{-3}	10^{-4}

Similarly, the positional values of a binary fraction 101.1101 can be shown as



Conversion of Binary Fraction to Decimal

Let us consider the binary fraction $(101.1101)_2$. This may be written as follows:

$$(1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0) + (1 \times 2^{-1} + 1 \times 2^{-2} + 0 \times 2^{-3} + 1 \times 2^{-4})$$

So the decimal equivalent of this binary becomes

$$5 + (1/2 + 1/4 + 1/16) = (5.8125)_{10}$$

Conversion from Decimal Fraction to Binary

We have studied in the earlier sections that to convert a decimal whole number to binary whole number, a division by 2 has to be performed. To convert decimal fractions to binary fractions we have to multiply by 2. If the product of each number is greater than 1 put a 1 below that number otherwise put a 0. To understand this, let us consider the following example.

Conversion of decimal fraction $(0.8125)_{10}$ into binary:

Number	0.8125	0.625	0.25	0.5
Base	2	2	2	2
	1.6250	1.250	0.50	1.0
Remainder	1	1	0	1

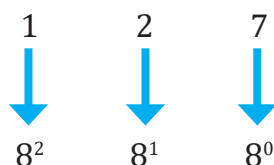
$$\text{Therefore } (0.8125)_{10} = (0.1101)_2$$

10.3 Octal Number System

The octal number system uses digits 0, 1, 2, 3, 4, 5, 6 & 7 ie, eight digits. So, the base of this number system is 8.

$(127)_8$ which is in octal number system can be represented as

$$(127)_8 = 1 \times 8^2 + 2 \times 8^1 + 7 \times 8^0$$



Conversion from Octal to Decimal

Keeping the above representation in mind, let us find the decimal equivalent of the octal number $(127)_8$

$$\begin{aligned}(127)_8 &= 1 \times 8^2 + 2 \times 8^1 + 7 \times 8^0 \\ &= 64 + 16 + 7 \\ &= (87)_{10}\end{aligned}$$

So, the decimal equivalent of $(127)_8$ is $(87)_{10}$.

Conversion from Decimal to Octal

We have already studied how to convert a decimal number into binary. Similarly we can convert a decimal number to an octal number by dividing the given number by 8 repeatedly, until the result is less than 8.

Let us convert $(87)_{10}$ to the octal number system.

$$\begin{array}{r|l} 8 & 87 & 7 \\ & 10 & 2 \\ & 1 & \end{array}$$

So $(87)_{10} = (127)_8$



Know your progress

Convert the following decimal numbers into octal numbers.

- (i) $(256)_{10}$ (ii) $(728)_{10}$

Octal to Binary Conversion

To convert an octal number into binary we should first proceed to convert the octal number to decimal. Then the decimal number obtained is to be converted to binary. Consider the octal number $(127)_8$. Let us try to convert this number into a binary number.

For this, first, we have to convert $(127)_8$ to decimal

$$\begin{aligned}\text{ie, } (127)_8 &= 1 \times 8^2 + 2 \times 8^1 + 7 \times 8^0 \\ &= 1 \times 64 + 2 \times 8 + 7 \times 1 \\ &= (87)_{10}\end{aligned}$$

Now, $(87)_{10}$ may be converted to binary.

$$(87)_{10} = (1010111)_2$$

2	87	1
2	43	1
2	21	1
2	10	0
2	5	1
2	2	0
1		

Therefore, $(127)_8 = (1010111)_2$.

So, the binary equivalent to the octal number 127 is 1010111.

10.4 Hexa Decimal Number System

The number system with base 16 is called hexadecimal number system. The 16 characters including numbers and alphabets used in this system are 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E and F.

The following table illustrates the above fact

Decimal	Hexadecimal
0	0
1	1
2	2
3	3
4	4
5	5
6	6
7	7
8	8
9	9
10	A
11	B
12	C
13	D
14	E
15	F

Table -10.2

According to this system the next hexadecimal number is 10 which is equivalent to 16 in the decimal system.

$$\text{i.e.,} \quad (10)_{16} = (16)_{10}$$

$$\text{Similarly,} \quad (11)_{16} = (17)_{10}$$

$$(12)_{16} = (18)_{10} \text{ and so on.}$$

Similar to the methods adopted in the earlier sessions we can convert a decimal number to hexa decimal number and vice versa. Let us convert the decimal number $(269)_{10}$ to a hexa decimal number.

$$\begin{array}{r|l} 16 & 269 \quad 13 \\ 16 & 16 \quad 0 \\ & 1 \end{array}$$

13 is denoted as D in hexadecimal numbers system.

$$\text{Therefore, } (269)_{10} = (10D)_{16}$$

Let us now convert the hexadecimal number F9 into decimal. We know that F is equivalent to 15 in the decimal system. So,

$$\begin{aligned} (F9)_{16} &= 15 \times 16^1 + 9 \times 16^0 \\ &= 240 + 9 = (249)_{10} \end{aligned}$$

Therefore, the decimal equivalent of the hexadecimal F9 is 249.



Know your progress

(a) Convert the following decimal numbers to hexadecimal numbers.

i) $(148)_{10}$

ii) $(84)_{10}$

(b) Convert the following hexadecimal numbers to decimal numbers.

i) $(19)_{16}$

ii) $(2C)_{16}$

10.5 Binary Addition

Binary addition follows the same basic rules of addition. In binary addition two or more corresponding bits are added. If the result has more than one bit, the second bit becomes the carry. For example, $1 + 1 = 10$, Here Sum = 0 and Carry = 1

A B	Carry	Sum
0 + 0	0	0
0 + 1	0	1
1 + 0	0	1
1 + 1	1	0
1 + 1 + 1	1	1

The single bits are added together and 0+0, 0+1, or 1+0 results in a sum of 0 or 1. When you do 1+1, the sum is equal to 2 in the decimal system. In binary, it is 10. Here, the bit '0' is the sum bit and bit 1 is the carry bit. When you do 1+1+1 = 11, Sum = 1 and Carry = 1

Examples: 2 - Bit Binary addition

$$\begin{array}{r}
 00+ \\
 01 \\
 \hline
 01
 \end{array}
 \quad
 \begin{array}{r}
 10+ \\
 01 \\
 \hline
 11
 \end{array}
 \quad
 \begin{array}{r}
 01+ \\
 01 \\
 \hline
 10
 \end{array}
 \quad
 \begin{array}{r}
 11+ \\
 10 \\
 \hline
 101
 \end{array}$$



Know your progress

Add the given binary numbers.

(a) 100 + 101 (b) 1001 + 0111 (c) 1101 + 1010 (d) 10010 + 01110

10.6 Logic Gates

A logic gate is the primary building block of a digital circuit. It is a circuit with one or more inputs and one output. At any given moment, logic gate takes one of the two binary conditions 0 (low) or 1 (high) depending upon its function and the input values. Low and High states are represented by different voltage levels. For example +5V may represent logic 1 and 0 V may represent a logic 0.

There are three primary logic gates namely, AND, OR and NOT. Also we have other logic gates like NAND, NOR, XOR and XNOR. Out of these, NAND and NOR gates are called the universal gates, because these gates alone could be used to realise the primary logic gates. The circuit symbol and the truth table of these logic gates are explained below.

AND Gate

The AND gate is so named because the gate acts as in the same way as the logical 'AND' operator. The output will be 1 if both inputs are 1; otherwise the output is 0. In other words, if 0 is called 'LOW' and

1 is called 'HIGH', the output is 'HIGH' only when both the inputs are 'HIGH', otherwise, the output is 'LOW'.



Activity 10.2

In the circuit shown in figure 10.3 can be used to explain the function of an AND gate. Here a bulb is connected to supply through two switches connected in series. Let us try to explain the operation.

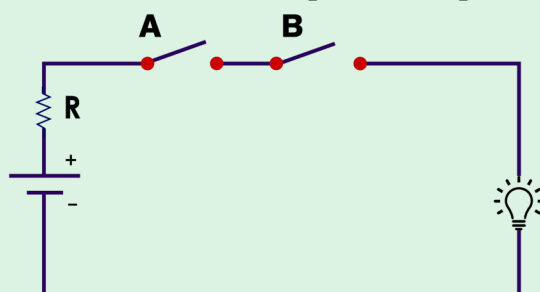


Fig. 10.3 Switch representation of AND gate

Here the two switches, A and B are connected together to form a series circuit. These switches are considered as the inputs to the AND gate and the condition of the bulb as output. Therefore, in the circuit above, both the switches A and B must be closed (Logic 1) in order to put the lamp ON (Logic 1). If any or

both of the switches are open (Logic 0), the bulb will be OFF (Logic 0). Thus, the working of this circuit clearly reveals the function of an AND gate.

Here A and B are used to represent the two input Boolean variables and the output is represented by the variable Y. In Boolean algebra, a variable can take any of the values 0 or 1. The logical symbol of the AND gate is shown in Fig. 10.4.

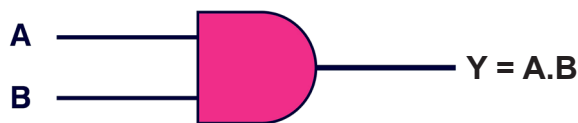


Fig. 10.4 Symbol of AND gate

The action of AND gate is represented by writing the Boolean expression as follows.

$$Y = A \text{ AND } B$$

In Boolean algebra the multiplication sign stands for the AND operation. Therefore, the output of the AND gate is also represented as

$$Y = A.B$$

or simply as $Y = AB$

Here, we have considered a two input AND gate. Therefore, there are four possible input combinations: 00, 01, 10 and 11. For example, if the inputs are 0 & 1, then the output will be

$$Y = A.B$$

$$Y = 0.1$$

$$Y = 0$$

The input and the output information of any logic gate or circuit can be plotted into a table to give a visual representation of the switching function of the circuit, and this is commonly called a Truth Table. The truth table of a logic gate shows each possible input combination to the gate with the resultant output depending upon the combination of these inputs.

The truth table for AND gate is shown below:

Inputs		Output
A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

Table 10.3 Truth table for AND gate

Figure 10.5 shows the circuit implementation of AND gate using diodes and resistor. Can you explain how does this circuit act as an AND gate?

The working of the above circuit can be explained as follows. Here, logic 0 is represented by a voltage near to 0 V and logic 1 is represented by the voltage near to +Vcc.

Case 1: $A=0, B=0$: In this case, both the diodes D_1 and D_2 are forward biased by the supply V_{cc} . Hence, at the output Y , there will be a voltage of 0.7 V (which is the voltage drop of the forward biased diode). Since 0.7 V is near to 0V, the output is treated as logic 0.

Case 2: $A=0, B=1$: Here, the diode D_1 is forward biased and D_2 is reverse biased. As one of the diodes is forward biased, the voltage at Y is 0.7 V. Again the output is treated as logic 0.

Case 3: $A=1, B=0$: Here the diode D_1 is reverse biased and D_2 is forward biased. As one of the diodes is forward biased, the voltage at Y is 0.7 V. Again the output is treated as logic 0.

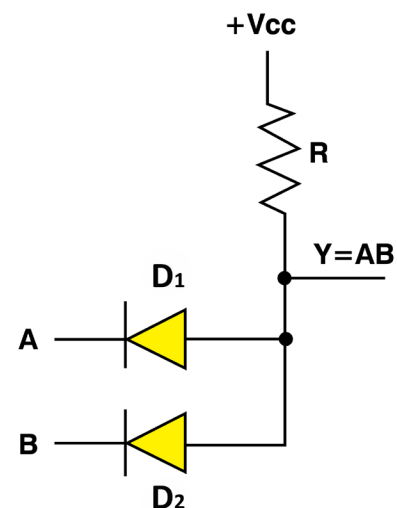


Fig. 10.5 AND gate using diodes and resistor

Case 4: $A=1, B=1$: Here both the diodes D_1 and D_2 are not in conducting state as voltages are equal at either sides of these diodes. Since both the diodes are not conducting, the voltage at point Y is $+V_{cc}$. Now, the output Y is at logic 1.

OR Gate

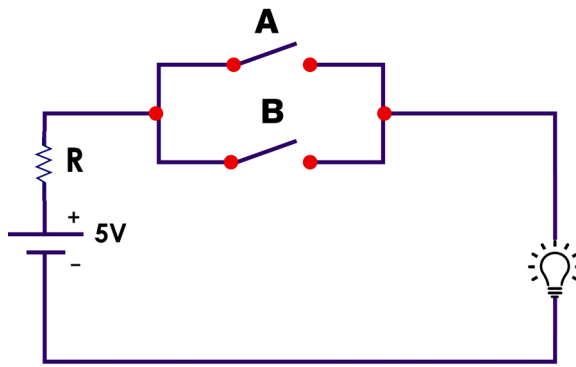


Fig. 10.6 Switch representation of OR gate

The OR gate is so named because the gate acts in the sameway as the logical “OR” operator. The output is 1 if one or both of the inputs are 1; otherwise the output is 0.

As in the case of AND gate, the function of an OR gate can be explained by using the circuit shown in Fig.10.6. Here, a bulb is connected to supply through two switches connected in parallel. Let us try to explain the operation.

Here, the two switches A and B are connected in parallel. Here switch A alone switch B alone or both A and B can be closed (logic 1) in order to put the lamp ON. The lamp will be OFF only if both the switches are open (logic ‘0’). These switches are considered as the inputs to the OR gate and the condition of the bulb as output.

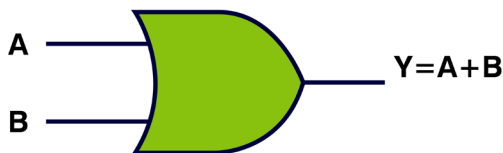


Fig. 10.7 Symbol of OR gate

The logic symbol of the OR gate is shown in Fig. 10.7.

The output of the OR gate can be expressed as

$$Y = A \text{ OR } B$$

The symbol used for OR operation is ‘+’. Therefore,

$$Y = A + B$$

For example, if the inputs are 1 and 0, then the output is

$$Y = 1 + 0$$

$$Y = 1$$

The truth table for OR gate is given in Table 10.4.

Inputs		Output
A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

Table 10.4 Truth table for OR gate

Similar to AND gate, the function of an OR gate can also be implemented using the following circuit. It consists of two diodes and one resistor. Let us try to explain its working.

The working of the circuit shown in fig. 10.8 can be briefly explained as follows.

Case 1: $A=0, B=0$: Now both the diodes are unbiased and hence, no current flows through the resistor R . So, the output voltage is zero and Y is at logic 0.

Case 2 : $A=0, B=1$: Here, the diode D_1 is unbiased and D_2 is forward biased. Now, the current flows through R , since D_2 is conducting and a high voltage appears at the output. So, the output is at logic 1.

Case 3 : $A = 1, B = 0$: In this case D_1 is forward biased and D_2 is unbiased. The current flows through R as D_1 is conducting and a high voltage appears at output. So, the output is at logic 1.

Case 4 : $A = 1, B = 1$: Here, both the diodes are forward biased and both of them conduct and the current flows through R resulting in a high voltage at the output. So, the output is at logic 1.

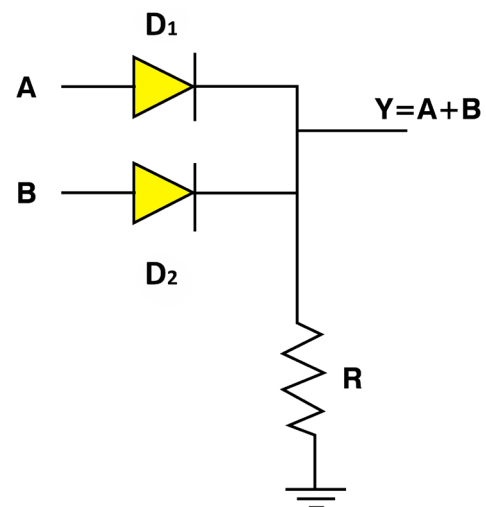


Fig. 10.8 OR gate using diodes and resistor

NOT Gate

The NOT gate is also called as logical inverter. It has only one input. It reverses the logical state. In other words, the output Y is always the complement of the input. If the input is 0, output will be 1 and if the input is 1, the output will be 0. The logical symbol of the NOT gate is shown in Fig. 10.9.

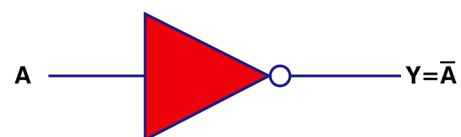


Fig. 10.9 Symbol of NOT gate

The NOT operation is expressed as

$$Y = \text{NOT } A$$

In Boolean algebra the NOT operation is represented by an over bar.

Therefore $Y = \bar{A}$

If $A = 0$, $Y = \bar{0} = 1$

If $A = 1$, $Y = \bar{1} = 0$

It can also be represented as $Y = A'$.

The truth table for NOT gate is given below.

Input	Output
A	Y
0	1
1	0

Table 10.5 Truth table for NOT gate

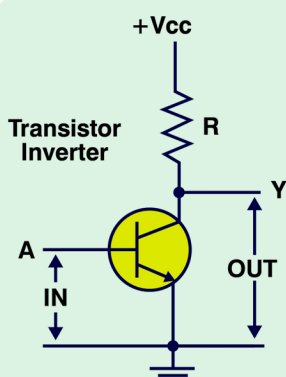


Fig 10.10 NOT gate using transistor



Activity-10.3

A very simple NOT gate can be made using just a single transistor switching circuit as shown in Fig. 10.10. Can you explain how does this circuit acts as an inverter (NOT gate)?

When the transistor's base input 'A' is HIGH, the transistor goes to saturation and the collector voltage is nearly zero. Therefore, the output Y is LOW.

Similarly, when the transistor's base input 'A' is LOW (0V), the transistor goes to cut off and no collector current flows through the resistor. This results in an output voltage at 'Y' with a value near to +Vcc (HIGH).

Thus, with an input voltage 'A' HIGH, the output Y will be LOW and with an input voltage A LOW the resulting output voltage 'Y' will be HIGH producing the complement or inversion of the input signal.

NOR Gate

The NOR gate circuit is an OR gate followed by an inverter as shown in Fig.10.11. Its output is HIGH only if both of the inputs are LOW, otherwise the output is LOW.

The logic symbol for the NOR gate is given in 10.12.

Note: From the above figure, it is clear that the bubble in the symbol for NOR gate represents NOT gate. Thus, in the digital logic circuits, this bubble represents NOT (inversion) operation.

The output of the NOR gate can be expressed as

$$Y = \overline{A+B}$$

For example, if both of the inputs are 1

The output will be $Y = (\overline{1+1}) = \overline{1} = 0$

The truth table for the NOR gate is given below.

Input			Output
A	B		$Y = \overline{A+B}$
0	0	0	1
0	1	1	0
1	0	1	0
1	1	1	0

Table 10.6 Truth table for NOR gate

NAND Gate

The NAND gate circuit is formed by an AND gate followed by a NOT gate as shown in Fig. 10.14. It acts in the manner of the logical operation AND followed by inversion. The output is LOW only if both of the inputs are HIGH, otherwise, the output is 'HIGH'. In other words, the output of the NAND gate is 0 if and only if both of the inputs are 1, otherwise the output is 1.

The logic symbol for NAND gate is shown in Fig. 10.14.

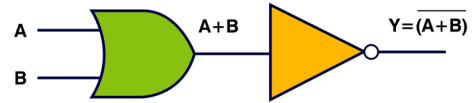


Fig. 10.11 NOR gate using OR and NOT gate

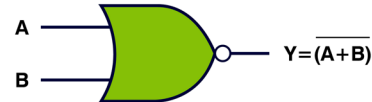


Fig. 10.12 Symbol of NOR gate

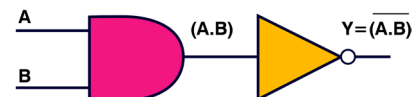


Fig. 10.13 NAND gate using AND and NOT gate

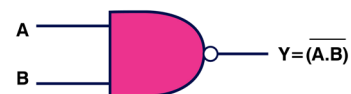


Fig. 10.14 Symbol of NAND gate

The output for the NAND gate is expressed as $Y = \overline{A.B}$

For example, if both of the inputs are '0', the output will be 1

$$Y = (\overline{0+0}) = \overline{0} = 1$$

The truth table for NAND gate is given in table 10.7.

Input		$A . B$	Output
A	B		$Y = \overline{A.B}$
0	0	0	1
0	1	0	1
1	0	0	1
1	1	1	0

Table 10.7 Truth table for NAND gate

EX - OR (XOR) Gate

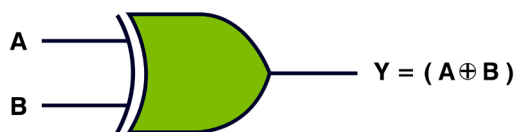


Fig. 10.15 Symbol of XOR gate

The XOR (EX-OR) gate will give a logic 1 at the output if both of the inputs are different and a logic 0 if the inputs are the same. The output is HIGH if either, but not both, of the inputs are HIGH. The output is LOW if both of the inputs are LOW or if both of the inputs

are HIGH. The logic symbol for XOR gate is shown in Fig. 10.15.

The output of the XOR gate is $Y = A\overline{B} + \overline{A}B$

In Boolean algebra the XOR operation is represented by $\oplus$

$$Y = A \oplus B$$

The truth table of the XOR gate is shown below:

Inputs		Output
A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

Table 10.8 Truth table for XOR gate

XNOR Gate

The XNOR (EX-NOR) gate is formed by placing a NOT gate at the output of XOR gate as shown in Fig. 10.16. Its output is HIGH if the inputs are the same and LOW if the inputs are different. In simple words, the output is 1 if the inputs are the same, otherwise the output is 0.

The logic symbol of XNOR gate is given below.

The output of the XNOR gate is $Y = \overline{(A \oplus B)}$

$$Y = \overline{A} \overline{B} + AB$$

The XNOR operation is represented by

$$Y = A \odot B$$

The truth table of the XNOR gate is shown below:

Inputs		Output
A	B	Y
0	0	1
0	1	0
1	0	0
1	1	1

Table 10.9 Truth table for XNOR gate

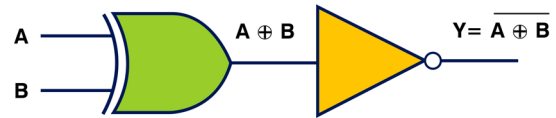


Fig. 10.16 XNOR gate using XOR and NOT gate

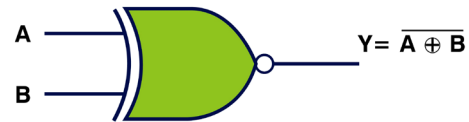


Fig. 10.17 Symbol of XNOR gate

10.7 Boolean Algebra

Digital circuits perform binary arithmetic operations with binary digits 1 and 0. These operations are called logic functions or logical operations. The algebra used to describe logic functions symbolically is called Boolean algebra. Boolean algebra is a set of rules and theorems by which logical operations can be expressed symbolically in equation form which can be manipulated mathematically.

The theorems of Boolean algebra are known as the Laws of Boolean. We can use these Laws of Boolean to reduce the number of logic gates and analyse digital circuits. As with the ordinary algebras, the alphabet (e.g. A, B, C etc) can be used to represent the variables. Boolean algebra differs from the ordinary algebra in that Boolean constant and variables can have only two values; 0 and 1.

Certain basic Laws of Boolean algebra such as commutative law, associative law and distributive law are similar to those in the ordinary algebra.

10.8 Description of the Laws and Theorems

1. Laws of Complementation

The term complements imply means to change 1s to 0s and 0s to 1s.

Theorem 1 : If $A = 0$, then $Y = \bar{A} = 1$

Theorem 2 : If $A = 1$, then $Y = \bar{A} = 0$

Theorem 3 : The complement to the complement of A is A itself.

$$Y = \overline{\bar{A}} = A$$

2. Basic properties of AND operator

Theorem 4 : $A.1 = A$

If A equals 0 and the other input is 1, the output is 0.

If A equals 1 and the other input is 1, the output is 1.

Thus the output is always equal to the input A.

Theorem 5 : $A.0 = 0$

As one input is always 0, irrespective of A, the output is always 0.

Theorem 6 : $A.A = A$

The output is always equal to the input A.

Theorem 7 : $Y = A. \bar{A} = 0$

Regardless of the value of A, the output is 0.

3. Basic properties of OR operator

Theorem 8 : $A + 1 = 1$

If A equals 0 and the other input is 1, the output is 1.

If A equals 1 and the other input is 1, the output is 1.

Thus the output is always equal to 1 regardless of what value A takes on

Theorem 9 : $A + 0 = A$

The output assumes the value of A

Theorem 10 : $A + A = A$

The output is always equal to the input A

Theorem 11 : $Y = A + \overline{A} = 1$

Regardless of the value of A, the output is 1

4. Commutative Law

Theorem 12:

A mathematical operation is commutative if it can be applied to its operands in any order without affecting the result. Addition and multiplication operations are commutative.

Example: $A + B = B + A$

$$AB = BA$$

Subtraction is not commutative:

$$A - B \neq B - A$$

There is no subtraction operation in Boolean algebra.

5. Associative Law

Theorem 13:

A mathematical operation is associative if its operands can be grouped in any order without affecting the result. In other words, the order in which one does the OR operation does not affect the result.

$$(A + B) + C = A + (B + C) = (A + C) + B$$

Similarly, the order in which one does the AND operation does not affect the result.

$$(AB) C = A (BC) = (AC) B$$

6. Distributive Law

Theorem 14:

The distributive property allows us to distribute an AND across several OR functions.

Example : $A (B + C) = AB + AC$

The following distributive law is worth mentioning because it differs from what we would find in ordinary algebra.

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

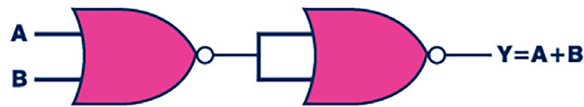
$$A + (B \cdot C) = (A + B) \cdot (A + C)$$

10.9 Universal Gates - NAND, NOR

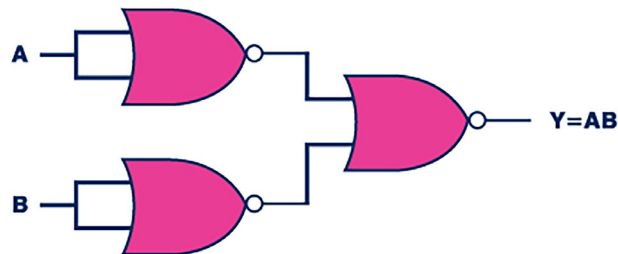
We have already seen that all the boolean functions can be expressed in terms of the fundamental gates namely AND, OR and NOT. In fact, these fundamental gates can be expressed in terms of either NAND gates or NOR gates only. That is, only NAND or NOR gates can be used to perform all the Boolean and other logic gate functions. Therefore, these gates are known as universal gates. Some of the gate functions implemented only using NOR gates are shown in fig.10.18.



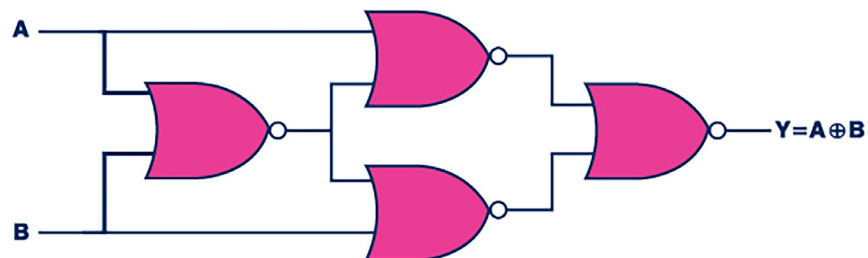
(a) NOT using NOR



(b) OR using NOR



(c) AND using NOR



(d) EXNOR using NOR

Fig. 10.18 Fundamental gates using NOR only

Like the NOR gate seen now, the NAND gate is also a Universal type gate. NAND gates can be used to produce any other type of logic gate function just like the NOR gate. Some of the gate functions implemented using only NAND gates are shown in figure 10.19.

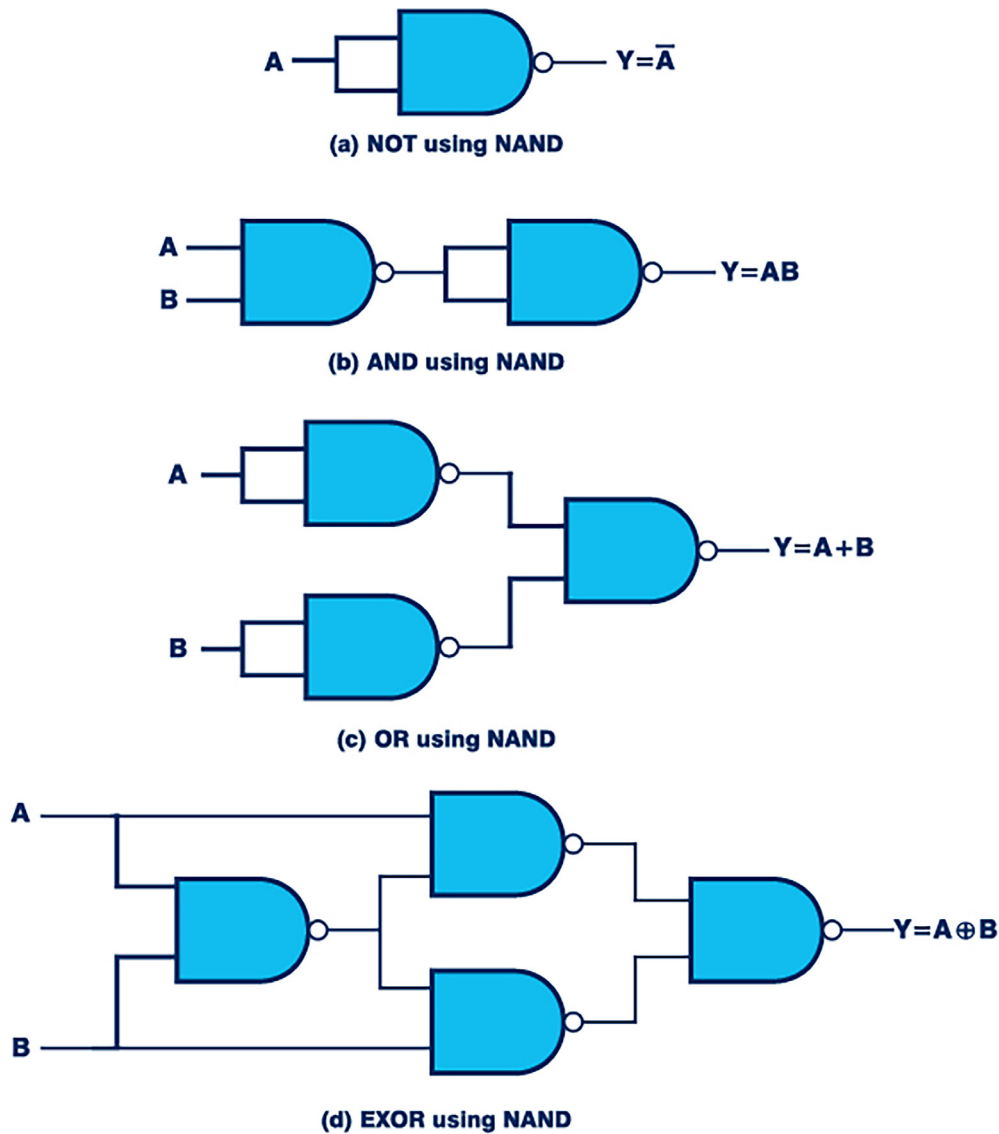


Fig. 10.19 Fundamental gates using NAND only



Activity 10.4

Now, you try to design a logic circuit to implement the function of EXOR gate using NOR only and EXNOR using NAND only.

10.10 De-Morgan's Theorem

A mathematician named De-Morgan developed a pair of important rules regarding group complementation in Boolean algebra.

Theorem - 1

The theorem states that the complement of a product is equal to the sum of the complements. That is, if the variables are A and B, then $\overline{A \cdot B} = \overline{A} + \overline{B}$

A	B	$\overline{A}$	$\overline{B}$	$\overline{A \cdot B}$	$\overline{A} + \overline{B}$
0	0	1	1	1	1
0	1	1	0	1	1
1	0	0	1	1	1
1	1	0	0	0	0

Table 10.10

A study of the above table makes clear that the last two columns are equal. Therefore, De - Morgans 1st theorem is proved.

Theorem - 2

The theorem states that, the complement of a sum is equal to the product of complements. It can be written as:

$$\overline{A + B} = \overline{A} \cdot \overline{B}$$



Activity-10.5

Complete the columns as per De-Morgan's theorem

A	B	$\overline{A}$	$\overline{B}$	$\overline{A \cdot B}$	$\overline{A} + \overline{B}$
0	0	1		1	
0	1		0		0
1	0	0		0	
1	1		0		0

Table 10.11

These theorems are illustrated using logic gates in Fig. 10.20.

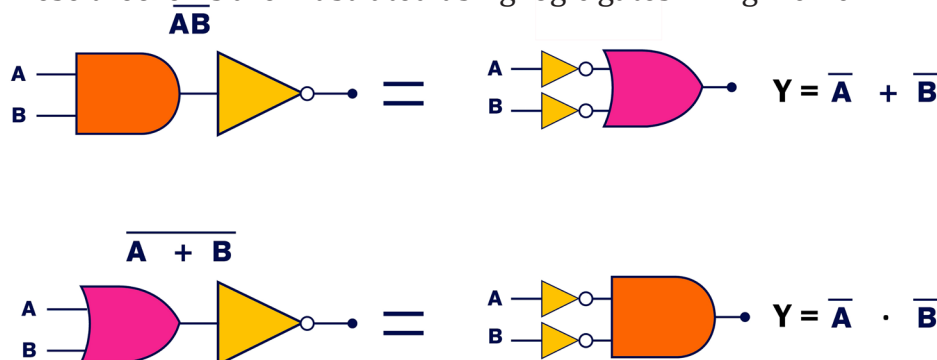


Fig10.20



Boolean Expression	Description	Equivalent Switching Circuit
$A + 1 = 1$	A in parallel with closed = "CLOSED"	
$A + 0 = A$	A in parallel with Open = "A"	
$A \cdot 1 = A$	A in series with closed = "A"	
$A \cdot 0 = 0$	A in series with open = "OPEN"	
$A + A = A$	A in parallel with A = "A"	
$A \cdot A = A$	A in series with A = "A"	
$\overline{\overline{A}}$	NOT NOT A (Double negative) = "A"	
$A + \overline{A} = 1$	A in parallel with not A = "CLOSED"	
$A \cdot \overline{A} = 0$	A in series with not A = "OPEN"	
$A + B = B + A$	A in parallel with B = B in parallel with A	
$A \cdot B = B \cdot A$	A in series with B = B in series with A	
$\overline{A+B} = \overline{A} \cdot \overline{B}$	Invert & replace OR with AND	De-Morgan's theorem
$\overline{A \cdot B} = \overline{A} + \overline{B}$	Invert & replace AND with OR	De-Morgan's theorem

Table 10.12

Solved problem 10.1

Obtain the logic equations and the truth tables for the circuits in Fig. 10.21. Fig. 10.22 shows the how the logic equation are obtained.

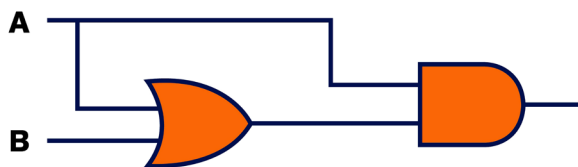


Fig. 10.21 Logic Circuit

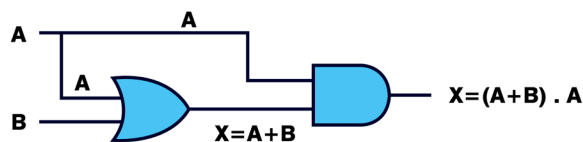


Fig. 10.22 Logic Circuit with output expression marked

Input		Output	
A	B	X	Y
0	0	0	0
0	1	1	0
1	0	1	1
1	1	1	1

Table 10.13

The circuit consists of only 2 inputs. So, there can be four possible combinations of the input. The truth table of logic circuit is given below.

It is seen that the columns Y and A are the same or $(A + B) . A = A$

So, the above logic circuit can be simplified as a circuit without any gate.

Solved problem 10.2

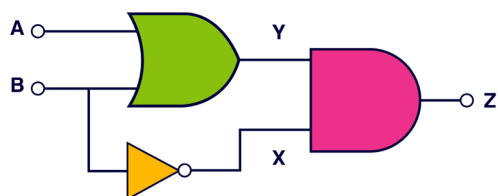


Fig. 10.23 Logic Circuit

Write down the Boolean expression and truth table for the following logic circuit in Fig. 10.23.

The circuit consists of only 2 inputs A and B. First observation tells us that the circuit consists of a 2 input OR gate and one NOT gate and finally a 2 input AND gate. X represents

the output of NOT gate and Y represents the output of OR gate. Both of these two outputs (X and Y) then becomes the input condition for the AND gate.

The Boolean expression for

$$X = \bar{B} \quad \text{and} \quad Y = A + B$$

$$Z = X.Y = \bar{B} . (A + B)$$

Inputs		Outputs		
A	B	X	Y	Z
0	0	1	0	0
0	1	0	1	0
1	0	1	1	1
1	1	0	1	0

Table 10.14

Solved problems 10.3

Write down the Boolean expression and the truth table for the following logic circuit in Fig. 10.24.

The circuit consists of only 2 inputs A and B. The first observation tells us that the circuit consists of a 2 input AND gate, one NOT gate, one OR gate and finally a 2 input OR gate. X represents the output of AND gate and Y represents the output of OR gate. Both of these two outputs (X and Y) then become the input condition for the OR gate.

The Boolean expression for $X = A.B$

$$Y = \bar{A} + B$$

and

$$Z = X + Y = (A.B) + (\bar{A} + B)$$

A	B	$\bar{A}$	X	Y	Z
0	0	1	0	1	1
0	1	1	0	1	1
1	0	0	0	0	0
1	1	0	1	1	1

Table 10.15

Solved problem 10.4

Draw the logic circuit corresponding to the equation $Y = AB + BC + \bar{B}'C$ using basic gates. Simplify the equation and again implement the logic circuit corresponding to the simplified expression.

The logic gate circuit for the above equation is shown in Fig. 10.25 (a)

Using Boolean law we can simplify it

$$\begin{aligned} AB + BC + B'C &= AB + C(B + B_1) \\ &= AB + C.1 \\ &= AB + C \end{aligned}$$

We can implement the simplified equation as shown in Fig. 10.25 (b).

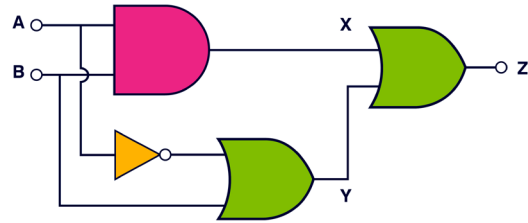


Fig 10.24 Logic Circuit

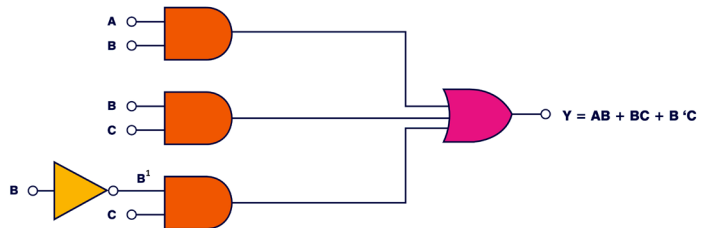


Fig. 10.25 (a) : Logic Circuit

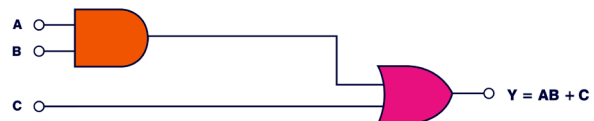


Fig. 10.25 (b) Simplified Circuit

From the above example, we can see that by using Boolean algebra the size of the circuit is reduced. In direct implementation, we have used three AND gates, one NOT and one OR gate. But, in the second case we use only one AND and one OR gate since the logic expression is simplified.

Solved problem 10.5

Draw the logic circuit for the Boolean expression $Z = (A + \bar{B}).(\bar{A}.B)$

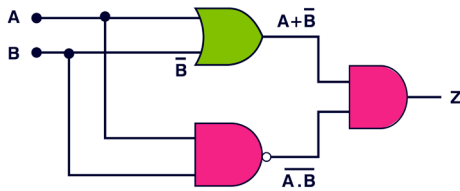


Fig. 10.26 Logic Circuit

Solved problem 10.6

Draw the logic circuit for the Boolean expression $Z = (A.B) + (C.\bar{D})$

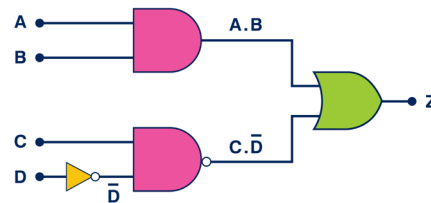


Fig. 10.27 Logic Circuit

Solved problem 10.7

Using the Boolean law
simplify the following expression :

$$Y = (A + B)(A + C)$$

$$AA + AC + AB + BC - \text{Distributive law}$$

$$A + AC + AB + BC - \text{Identity AND law } (A.A=A)$$

$$A(1 + C) + AB + BC - \text{Distributive law}$$

$$A.1 + AB + BC - \text{Identity OR law } (1 + C = 1)$$

$$A(1 + B) + BC - \text{Distributive law}$$

$$A.1 + BC - \text{Identity OR law } (1 + B = 1)$$

$$Y = A + BC - \text{Identity AND law } (A.1 = A)$$

Then the expression : $(A + B)(A + C)$ can be simplified to $A + BC$

Solved problem 10.8

Simplify the given expression : $Y = A + A.\bar{B} + \bar{A}.B$

$$Y = A + A.\bar{B} + \bar{A}.B$$

$$= A(1 + \bar{B}) + \bar{A}.B = A.1 + \bar{A}.B$$

$$= A + \bar{A}.B = A + B$$



Know your progress

- 1) Write down the Boolean expression and the truth table for the following logic circuit in figure 10.
- 2) Draw the logic circuit for the Boolean expression $Y = \overline{A.B} + CD$
- 3) Draw the logic circuit for the Boolean expression $Y = (\overline{A} + B).(C.\overline{D})$
- 4) Simplify the given expression : $Y = A.\overline{B} + (A.B).C$

10.11 Digital Systems

The digital systems consist of two types -Combinational logic circuits and Sequential Logic Circuits.

1. Combinational Logic Circuits

The outputs of Combinational Logic Circuits are determined only by the logical function and their current input state, logic '0' or logic '1', at any given instant of time as they have no feedback and any changes applied to their input signals will immediately have an effect on the output. In other words, in a Combinational logic circuit, the output is dependant at all times only on the combination of its inputs. If the state of inputs is changed, the output will also be changed as the combinational circuits have 'no memory'. These logic gates are the building blocks of combinational logic circuits. The combinational logic circuits can be classified as shown in Fig. 10.28.

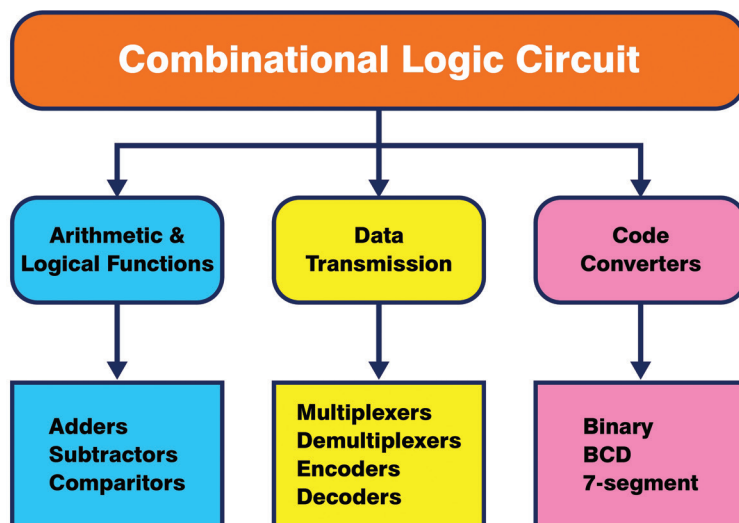


Fig 10.28 Classification of Combinational Logic Circuits

2. Sequential Logic Circuits

Sequential Logic Circuits depend on their present inputs as well as their previous output states, giving them some form of memory.

10.12 Half Adder



Fig. 10.29 Logic Symbol of Half-Adder

The circuits that perform addition within the Arithmetic and Logic Unit (ALU) of the Central Processing Unit (CPU) of a computer or within a calculator are called adders. A unit that adds two binary digits is called a half adder and the one that adds

together three binary digits is called a full adder. A half adder sums two binary digits to give a sum and a carry.

Fig. 10.29 shows the logic symbol of a half-adder. The two inputs are designated as A and B and the two outputs are designated as sum (S) and carry (C). The half-adder performs binary addition operation for the two binary inputs as shown in the table 10.16.

The Boolean realisation of binary addition is shown in the truth table. Here A and B are the inputs to give a sum S and a carry C.

Inputs		Outputs	
A	B	SUM	CARRY
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

Table 10.16 Truth Table of Half Adder

The Boolean functions corresponding to the sum and carry are

$$\text{SUM} = A \oplus B$$

$$\text{CARRY} = A.B$$

This can be realized using the logic circuit as shown in Fig. 10.30.

In a half adder, an AND gate is added in parallel to the XOR gate to generate the carry and sum respectively. The 'sum' column of the truth table represents the output of the XOR gate and the 'carry' column represents the output of the AND gate.

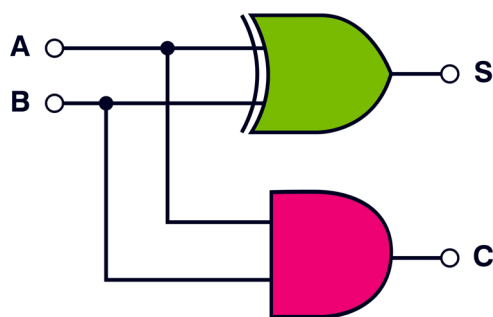


Fig. 10.30 Logic Circuit of Half-Adder

10.13 Full Adder

A half adder logic circuit is a very important component of the computing systems. As this circuit cannot accept a carry bit from a previous addition, it is not enough to perform additions for binary number greater than 1. A full adder sums three input bits. It consists of three inputs and two outputs. Two of the inputs represent the two significant bits to be added and the third one represents the carry from the previous significant position. The Logic Symbol of Full Adder is shown in figure 10.31.

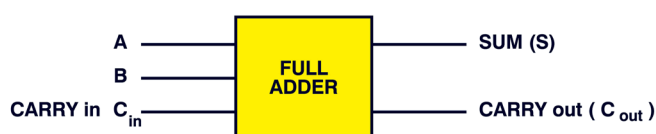


Fig. 10.31 Logic Symbol of Full-Adder

Here A and B are referred to as the inputs, C_{in} is the carry from the previous stage, C_{out} is the carry output and S is the sum. The truth table of Full Adder is shown in table 10.17.

Inputs			Output	
C_{in}	A	B	S	C_{out}
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Table 10.17 Truth Table of Full-Adder

The sum bit S is 1 if there exists odd number of 1s in the three inputs. S is the XOR of the three inputs. Hence, the logic equations for the output of the full adder are;

$$\text{SUM} = A \oplus B \oplus C_{\text{in}}$$

$$C_{\text{out}} = (A.B) + (C_{\text{in}}. (A \oplus B))$$

Logic circuit of a full adder is shown in Fig. 10.32.

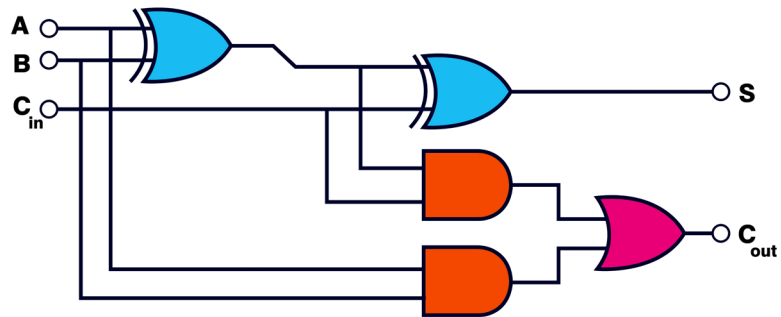


Fig 10.32 Logic Circuit of Full-Adder

Introduction to Robotics

The term 'Robot' may bring different images to our mind. Most of us might have imagined a humanoid robot that can talk, walk, or perform tasks like a human being. However, robots are not limited to this. Robots are machines that are designed to carry out a variety of tasks, from assembling cars in factories to performing intricate surgeries in hospitals. As technology advances, robots are becoming an integral part of our everyday lives. For example, robot vacuum cleaner can clean our houses all by itself. Sophia, a humanoid robot, can hold conversations and even show emotions, making her one of the most famous robots in the world. ASIMO is a robot created by Honda that can walk, dance, and even recognise faces! Drones, that can fly and carry out tasks like delivering packages or capturing aerial footage, are also a type of robot. From NASA's Mars rovers exploring the surface of Mars to industrial robots that help make products faster and more efficient, robotics is revolutionising the world around us.

This chapter will introduce the fascinating world of robots – how they work, their types, their uses, and how we can build them using tools like Arduino, sensors and actuators.

Pictures of some popular robots



Fig. 11.1 SOFIA-The humanoid Robot

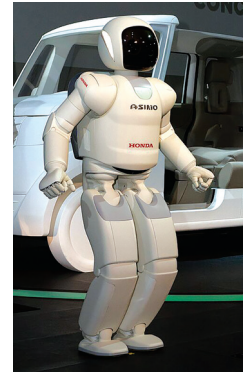


Fig. 11.2 ASIMO-The humanoid Robot created by Honda



Fig. 11.3 NASA's Mars rover

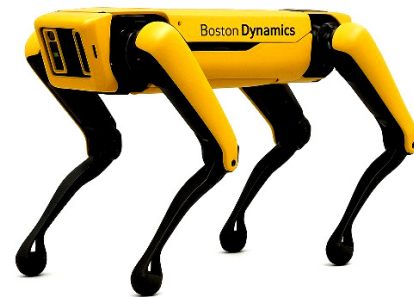


Fig. 11.4 SPOT - A four-legged robot that can easily navigate diverse terrains

11.1 Definition and Origin of Robotics

Robotics is the field of technology that involves designing, building, and operating robots. The idea of robots has fascinated people for centuries. Long ago, people imagined machines that could move on their own. In Greek mythology, there were stories about mechanical creatures like the bronze giant Talos, who could guard the island of Crete. These myths showed how much people dreamed about machines that could work for them.

The industrial revolutions of the 18th and 19th centuries ignited the idea of machines that could perform repetitive tasks. This led to the rise of automation. However, this was not yet robotics because those machines did not automatically do tasks.

The word 'robot' was first introduced in a play by a Czech writer named Karel Čapek, called R.U.R. (Rossum's Universal Robots), written in 1920. The term 'robot' comes from the Czech word 'robota', which means 'forced labour'. In the 1950s, real robots

began to appear. Unimate is the first industrial robot created by George Devol in 1956. It was initially used to remove and stack hot metal parts in General Motors plants as part of the automobile manufacturing process. This marked the beginning of robots being used in factories to move heavy items, helping workers and making tasks easier. As technology improved, robots became more useful, and today, they help in many areas of life.

The definition of a robot, as per The Robot Institute of America (1979), is:

“A reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialised devices through various programmed motions for the performance of a variety of tasks”.

This means that a robot is a programmable machine designed to perform a variety of tasks by moving materials, parts, or tools through different motions. It can be reprogrammed to carry out multiple functions, making it versatile and useful in many industries.



Fig. 11.5 Unimate



Know your progress

What is the significance of robotics?

11.2 Types of Robots

Based on evolution, robots are classified into 5 types:

Generation	Time Period	Key Features
First Generation	1950s - 1960s	Simple mechanical robots used for repetitive tasks in industries. With minimal automation and no sensors or intelligence.
Second Generation	1970s - 1980s	Programmable robots: Capable of performing various tasks with improved actuators and sensors. Mainly used in industrial applications like welding and assembly.
Third Generation	1990s - 2000s	Autonomous robots with advanced sensors and AI. Able to make decisions and adapt to their environment (e.g., autonomous mobile robots for material transport).

Fourth Generation	2010s – Present	Collaborative robots (cobots) designed to work alongside humans safely. With flexible programming and advanced safety features, enhancing industrial efficiency.
Fifth Generation	Future	Highly intelligent robots with the ability to make decisions autonomously and adapt to their surroundings. Perform complex tasks with enhanced sensors and mobility.

Based on applications robots are classified into 5 types:

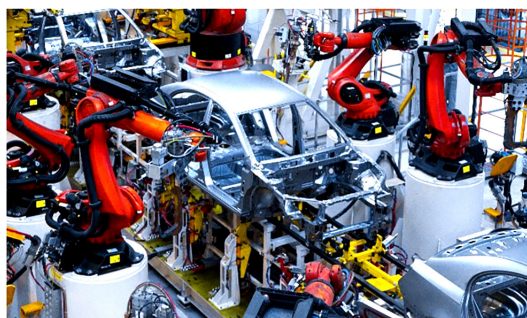


Fig. 11.6 Robots in automobile industry



Fig. 11.7 Service robot



Fig. 11.8 TESLA optimus humanoid robot



Fig. 11.9 AMRs in warehouse

- a) **Industrial Robots:** These are used in factories to perform repetitive tasks like assembling products, welding, painting, and packaging. They are very fast, precise, and can work 24/7 without getting tired. Examples: robotic arms used in automotive assembly lines.
- b) **Service Robots:** These robots are used to assist humans in non-manufacturing environments like hospitals, homes, or customer service. For example, a robot vacuum cleaner that cleans your house or a robot used in surgery to help doctors perform operations.
- c) **Humanoid Robots:** These robots are designed to look and behave like humans. They can move like humans and sometimes even mimic human actions. They are used mainly in research and entertainment.
- d) **Autonomous Mobile Robots (AMRs):** These robots are designed to navigate and perform tasks independently without direct human intervention. Examples include delivery robots and warehouse automation robots. Delivery robots in hospitals or warehouses transport goods from one place to another.

- e) Collaborative Robots (Cobots): These robots are designed to work together with humans. They help workers in factories by lifting heavy objects or performing tasks that are difficult for humans to do alone.



Know your progress

Give examples for industrial and service robots.



Fig. 11.10 : COBOT for welding

11.3 Components of Robots

A robot is made up of several parts that work together to make it function.

The main components of robots include:

1. Manipulator

The manipulator is the part of the robot responsible for performing manipulations. It consists of links, joints, and other structural elements, which provide the necessary movement for the robot. The manipulator acts as the 'arm' or 'leg' of the robot. It allows it to carry out tasks such as lifting, moving, or placing objects within its workspace.

2. End Effector

The end effector is the part attached to the last joint of the manipulator. It is primarily responsible for interacting with objects or connecting to machines. It functions as the 'hand' of the robot. End effectors can include grippers, which are used to pick up and hold objects, or specialised tools like welding torches and paint guns, depending on the robot's intended task.

3. Actuators

Actuators are the components that drive the movement of the robot. Common types of actuators in robots include electric motors, pneumatic actuators or hydraulic actuators.

4. Sensors

Sensors are used in robots to gather information about its environment and to monitor the state of their joints and actuators. These sensors are analogous to human senses, allowing robots to 'see', 'hear', and 'feel'. For instance, tactile

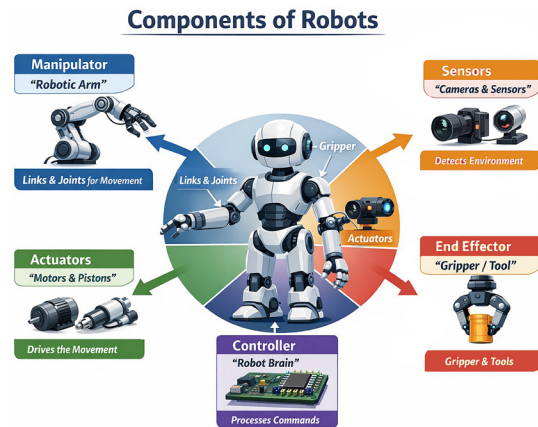


Fig. 11.11

sensors enable the robot to detect if it has made contact with an object, while vision sensors (such as cameras or LIDAR) allow the robot to perceive and interpret its surroundings. Sensors are critical for enabling robots to make decisions based on real-time data.

5. **Controller**

The controller is the 'brain' of the robot. It processes the information gathered by the sensors and sends commands to the actuators to perform the desired actions. Essentially, the controller interprets the inputs from the environment and translates them into instructions that guide the robot's movements. The controller is typically a microcontroller that executes the robot's program, enabling it to perform tasks autonomously.



Know your progress

What are the functions of the controller and sensors in robots?

11.4 Robotic Arm: Components and Structure

The most developed robot in practical use today is the robotic arm. A robotic arm is a key part of many industrial robots. It is designed to perform tasks such as picking, placing, assembling, and packaging items. It is made up of five parts:

1. **Waist**

The waist is the base of the robotic arm. It supports the rest of the arm and allows it to rotate around a vertical axis, providing the robot with a wide range of motion within its workspace.

2. **Shoulder**

The shoulder joint is located at the top of the waist and allows the arm to move in a wide arc. It provides flexibility for the robot to extend and move its arm, much like the human shoulder.

3. **Elbow**

The elbow joint is situated between the shoulder and wrist. This joint allows the arm to bend, similar to how a human elbow allows for bending and straightening of the arm. It provides further flexibility in positioning the end of the arm for specific tasks.

4. Wrist

The wrist joint provides the arm with the ability to rotate and position the tool or end effector precisely. It acts similar to a human wrist, allowing for finer adjustments and control of the tool.

5. Tool

The tool (also called the end effector) is the part at the end of the robotic arm used to interact with objects in its environment. Common tools include grippers, welding tips, or suction cups. These tools perform specific tasks like picking up objects or welding parts together.

Each of these components work together in a coordinated fashion, allowing the robotic arm to perform various tasks with high precision and speed.

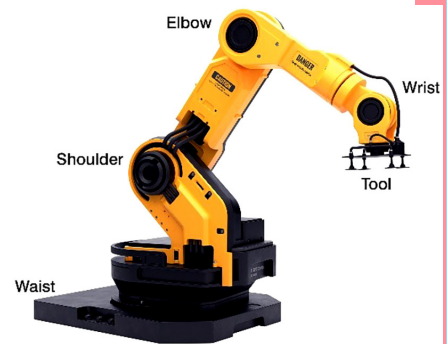


Fig. 11.12 Robotic arm

11.5 Benefits of Using Robots

- Robots can work faster and more efficiently than humans, especially when performing repetitive tasks. This helps industries produce more goods in a lesser time.
- Robots can be used in dangerous environments where human workers might be at risk such as in space, underwater, or handling toxic materials.
- Although installation cost of robots are high, they can help companies save money in the long run by reducing labour costs and increasing production.
- Robots are capable of performing tasks with high precision, such as assembling small parts in electronics or performing delicate surgery.
- Robots do not get tired, so they can work continuously without rest, making them ideal for jobs that require constant attention.

11.6 Areas of Applications

- **Auto industry:** The auto industry is the largest user of robots. These robots automate the production of vehicle parts and help assemble them into finished vehicles. Tasks such as welding, painting, and assembling car parts are performed by robots.

- **Material Transfer:** Robots handle basic tasks like moving materials from one location to another and loading/unloading machines in production processes.
- **Healthcare:** Robots are used in hospitals for surgeries, helping doctors make accurate incisions, and in rehabilitation, helping patients recover from injuries. Robotic devices can assist individuals with paralysis by helping them walk and perform daily tasks.
- **Agriculture:** In farming, robots can help plant seeds, water crops, and even pick fruits and vegetables.
- **Teaching:** Robots can assist in teaching by providing personalised learning experiences.
- **Space Exploration:** Robots are sent to space to explore planets, moons, and asteroids. They help collect data and send it back to the Earth for scientists to analyse.
- **Military:** Robots are used in the military for tasks like surveillance, bomb disposal, and reconnaissance. They keep soldiers safe by performing dangerous jobs.

11.7 Basic Components for Building a Simple Robotic Project

Now that we have looked into the basics of robotics, we will study some of the components required to build your first robot.

Arduino

A control unit is required to control the actions of a robot. Arduino is an open-hardware platform which can be used as a robotic controller in simple projects. Arduino is a small, inexpensive microcontroller that can be used to build and control robots. It is easy to use and helps you control various sensors, motors, and other components required to build a basic robot. The main parts of an Arduino board are:

- **Microcontroller:** It is the brain of the Arduino. It processes all the instructions and controls the sensors and actuators. Popular microcontrollers used in Arduino boards include the ATmega328 (used in the Arduino Uno) and the ATmega2560 (used in the Arduino Mega).

- **Input Pins:** These pins receive signals. These pins are used to connect sensors to the Arduino. Arduino has both analogue and digital pins, to receive analogue and digital signals.
- **Output Pins:** These pins are used to send signals from the microcontroller to actuators like motors. This allows the robot to perform actions.
- **USB Port:** This is used to upload instructions (programs) from a computer to the Arduino.
- **Power Supply:** Power supply can be given to the Arduino board either through USB or an external power source. The board can typically operate on a voltage range of 7 to 12 volts.

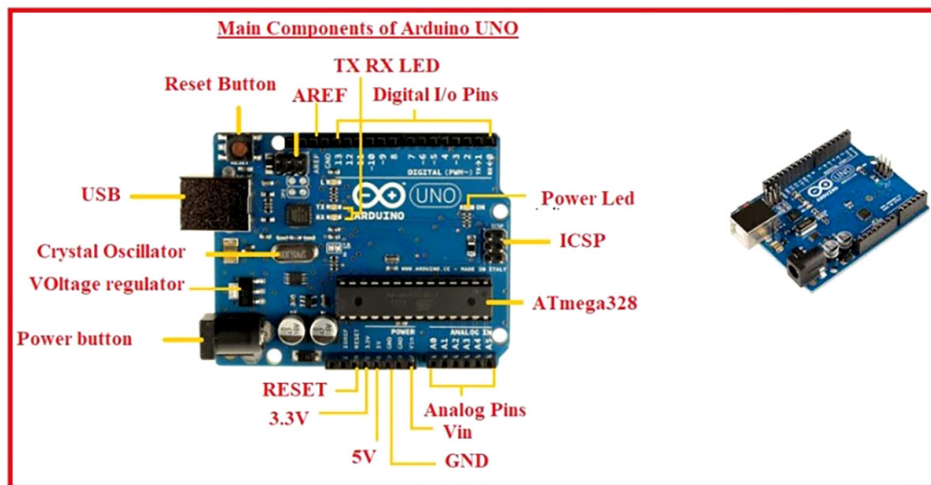
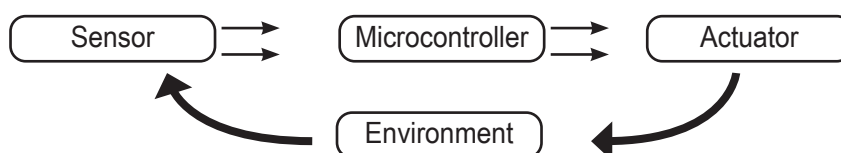


Fig. 11.13 Arduino Uno

11.8 Actuators and Sensors

In robotics, the interaction between a robot and its environment is essential for performing a wide range of tasks. This interaction is achieved through the use of sensors and actuators. Sensors serve as the robot's sensory organs, providing real-time data on various parameters such as distance, temperature, or light intensity. Actuators, on the other hand, are responsible for executing physical actions based on the information received from the sensors, such as moving a robotic arm, adjusting a position, or controlling speed.



Actuators Used in Robotics

Actuators are devices that are responsible for transforming the output of microcontroller into physical motion, to move or control the parts of a system. Three types of actuators are used in Robotics: electrical, hydraulic and pneumatic.

A hydraulic actuator converts pressurised fluid energy into mechanical motion. These actuators are known for their high power output and are often used in industrial robots or heavy-duty tasks that require high force and torque. They use pressurised fluid to move a piston inside a cylinder, which then drives the robot's arm or other components.

Pneumatic actuators use compressed air to produce linear or rotational motion. These actuators are fast, lightweight, and provide high torque with minimal energy consumption. Pneumatic actuators are common in robotic systems that require quick and lightweight movements like pick-and-place manipulators.

Electrical actuators convert electrical energy into mechanical motion. In robots, motors are the most common actuators. They enable the movements of robots. The selection of a motor type is crucial and depends entirely on the specific application requirements of the robot. The selection is based on the application's speed, torque, precision, and control needs. Robots commonly utilise three main types of motors, each offering distinct operational characteristics:

- **DC Motors (Direct Current Motors):** DC motors provide continuous rotation at a set speed. They are used for applications that require sustained, non-stop movement, such as turning the wheels of a mobile robot. They are valued for their simplicity, high speed, and efficiency in continuous motion tasks.
- **Stepper Motors:** Stepper motors are designed to rotate in discrete, fixed steps. They provide precise control over the rotation angle. They can be used when exact positioning and controlled, repeatable movements are required.
- **Servo motors:** Servo motors are specialised motors that provide precise control over angular position. They are equipped with a feedback mechanism that ensures accurate movement to a specific angle.

Sensors Used In Robotics

Sensors are transducers that convert physical phenomena (distance, temperature, light, etc.) into electrical signals that an Arduino can read.

a. Ultrasonic sensors:

Ultrasonic sensors operate based on the principle of sound wave reflection. They emit ultrasonic sound of 40 kHz and measure the time it takes for the pulse to reflect off from an object and return to the sensor. By calculating the time-of-flight, the distance to the object is determined.

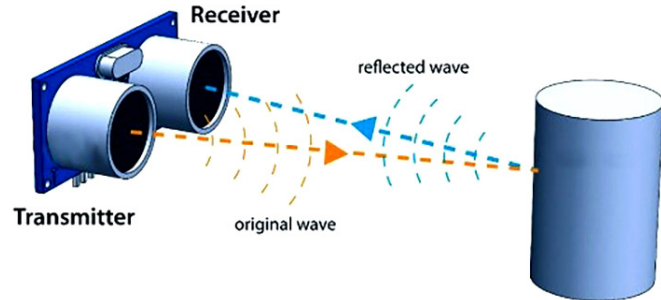


Fig. 11.14 HC SR04 Ultrasonic Sensor

They are used in obstacle detection, distance measurement, mapping, and navigation in mobile robots.

b. Infrared (IR) Sensors : IR sensors consist of an IR LED that emits infrared light and a photodetector that detects the reflected light. The intensity of the reflected IR light is used to determine the presence or absence of an object or to measure proximity. They are used in proximity sensing, obstacle detection and sensing in line-following robots.

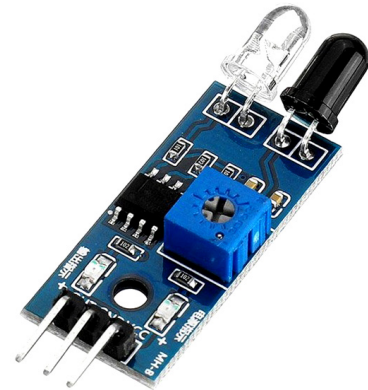


Fig. 11.15 IR Sensor module

c. Temperature Sensors: Temperature sensors measure the surrounding temperature by utilising properties such as voltage or resistance that change predictably with temperature. The LM35 is an analogue, linear temperature sensor whose output voltage changes linearly with temperature. It operates on the principle of a diode, where the voltage across the diode increases at a known rate as the temperature rises. By precisely amplifying this voltage change, the LM35 generates an analogue signal that is directly proportional to the temperature.

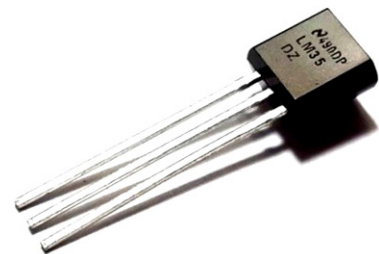


Fig. 11.16 LM 35 temperature sensor

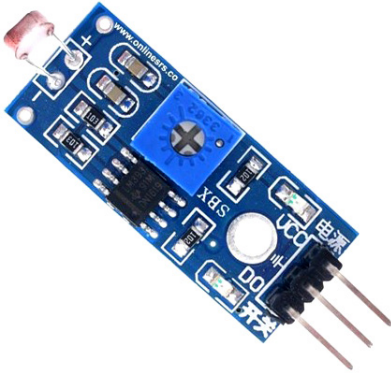


Fig. 11.17 LDR sensor

d. LDR (Light Dependent Resistor) sensors: LDRs (Light Dependent Resistors) are semiconductor sensors. LDRs are made from semiconductor materials such as cadmium sulphide (CdS), which exhibit a change in electrical resistance when exposed to light. They are used in light-sensing projects, such as light-following robots, automated lighting systems, or solar tracking systems. GL5528 Light Dependent Resistor is one of the most commonly used LDR sensors with Arduino projects. It has a wide range of resistance, typically between $1\text{k}\Omega$ to $10\text{M}\Omega$, depending on the intensity of the light falling on it.

e. Other Sensors: In robotic projects, a variety of other sensors are used to enable robots to interact with and perceive their environment. Gas sensors detect the presence of gases like CO_2 , CO, and methane. This allows the robots to monitor air quality and detect hazardous gases in industrial or environmental settings. Gyroscope sensors measure angular velocity and rotational movement, helping robots maintain orientation and stability. Accelerometer sensors detect acceleration which is crucial for navigation and balancing tasks. Magnetic field sensors (magnetometers) measure magnetic flux density to determine the robot's orientation, often used in navigation systems. Proximity sensors are used to detect the presence of objects or obstacles without physical contact, making them ideal for collision avoidance and safe navigation. Force and torque sensors measure the force or torque applied to parts of the robot, such as robotic arms, allowing for precise manipulation and feedback control.

The future of robotics involves more AI driven, adaptable robots that will find wide applications in homes, healthcare, manufacturing and agriculture sectors. These systems will handle complex, dynamic and delicate tasks that older machines could not manage. However, there are certain challenges and considerations in connection with the rapidly growing robotic industry. The increased use of automation raises concerns about the impact on human workforce and the high initial investment costs. The energy consumption of robots are also significant concerns. As robots collect more data, there are growing ethical concerns about privacy implications. The development of robots must also consider environmental impact including energy consumption.