ELECTRICAL CIRCUIT AND SEMICONDUCTOR PHYSICS

Unit- 1

Electric Charge:

"Electric Charge is the property of subatomic particles that causes it to experience a force when placed in an electric and magnetic field."
Electric charges are of two types: Positive and Negative, commonly carried by charge carriers protons and electrons.
Examples of the types of charges are subatomic particles or the particles of matter:
Protons are positively charged.
Electrons are negatively charged.
Neutrons have zero charge.

Coulomb is the unit of electric charge.

Overview of Electric Charge:

Definition	**Electric Charge is the property of subatomic particles that causes it to experience a force when placed in an electromagnetic field.**
Symbol	**Q**
Formula	**Q = I.t**
SI Unit	**Coulomb**
Other Units	**Faraday, Ampere-Hour**

Properties of Electric Charge:

Various properties of charge include the following:

- Additivity of Electric Charge
- Conservation of Electric Charge
- Quantization of Electric Charge

Types of electric charge:

Two kinds of electric charges are there:

- positive (+) charge
- negative (-) charge

Negative Charge:

When an object has a negative charge, it means that it has more electrons than protons.

Positive Charge:

When an object has a positive charge, it means that it has more protons than electrons.

When there is an identical number of positive and negative charges, the negative and positive charges would cancel out each other and the object would become neutral.

Coulomb's Law:

We might already know that like charges repel each other and unlike charges attract each other. But have you taken a minute to wonder how strong are these forces? Coulomb's Law provides a means to calculate the strength of the force between two points.

Coulomb's Law states that

The magnitude of the electrostatic force of attraction or repulsion between two-point charges is directly proportional to the product of the magnitudes of charges and inversely proportional to the square of the distance between them.

The Coulomb's Law is given by the expression:

$$F_e = \frac{kq_1q_2}{r^2}$$

where F_e **is the electric force,** q_1 **and** q_2 **are electric charges, k is the Coulomb's constant** 8.988×10^9 $N\cdot m^2/C^2$ **and r is the distance of separation.**

Conductors:

A metal rod brushed with wool in the hand will not exhibit any signs of being charged. A metal rod with a wooden or plastic handle, on the other hand, exhibits symptoms of charging when rubbed with wool without touching its metal section. Assume one end of a copper wire is connected to a neutral pith ball and the other end is connected to a negatively charged plastic rod. It is observed that the pith ball will acquire a negative charge. When a comparable experiment is carried out with a nylon thread or a rubber band, no charge is transferred from the plastic rod to the pith ball.

Insulators:

When a charge is transmitted to a conductor, it quickly becomes charged. Dispersed across the conductor's whole surface If, on the other hand, some When a charge is applied to an insulator, it remains stationary. This material property explains why a nylon or plastic comb is preferred. When combing dry hair or stroking it, it becomes electrified, while a metal piece does not. The charges on metal pass through our bodies to the ground. Both the ground and the body are electrical conductors.

Quantization of Electric charge:

Quantization refers to the transmission of an analog signal into a digital signal. It is the way of representing the sampled values of the amplitude by a finite set of levels. It is the process of converting a sample of continuous-amplitude signals into a discrete-time signal.

We know that electric charge is the physical property of matter which is responsible for experiencing a force when placed in an electromagnetic field. The SI unit of electric charge is Coulomb. We also know that charges can be added (additivity of electric charge), charges can be conserved (conservation of electric charges), and charges can be quantized (quantization of electric charge).

Quantization of electric charge refers to the concept that charge can take up only certain discrete values. It means that the observed value of the particle's electric charge (q) will be integral multiples of (e) 1.6 × 10-19 coulombs. Charge quantization is the principle that the charge of any object is an integer multiple of the elementary charge.

It is given by the formula:

$q = ne$

Where,

n = 0, 1, 2, ….(both positive and negative integers)

The value of e is 1.6 × 10-19 Coulomb.

Conversion of Electric charge:

A charge is a property associated with the matter due to which it produces and experiences electrical and magnetic effects. The basic idea behind the conservation of charge is that the total charge of the system is conserved. We can define it as:

Conservation of charge is the principle that the total electric charge in an isolated system never changes. The net quantity of electric charge, the amount of positive charge minus the amount of negative charge in the universe, is always conserved.

It is known that every atom is electrically neutral, containing as many electrons as the number of protons in the nucleus. Bodies can also have any whole multiples of the elementary charge:

Electrical charge resides in electrons and protons, and the smallest charge that a body can have is the charge of one electron or proton. [ie. – 1.6 x 10-19 C or + 1.6 x 10-19 C]

<u>Electric Field:</u>

Electric field can be considered as an electric property associated with each point in the space where a charge is present in any form. An electric field is also described as the electric force per unit charge.

The formula of electric field is given as;

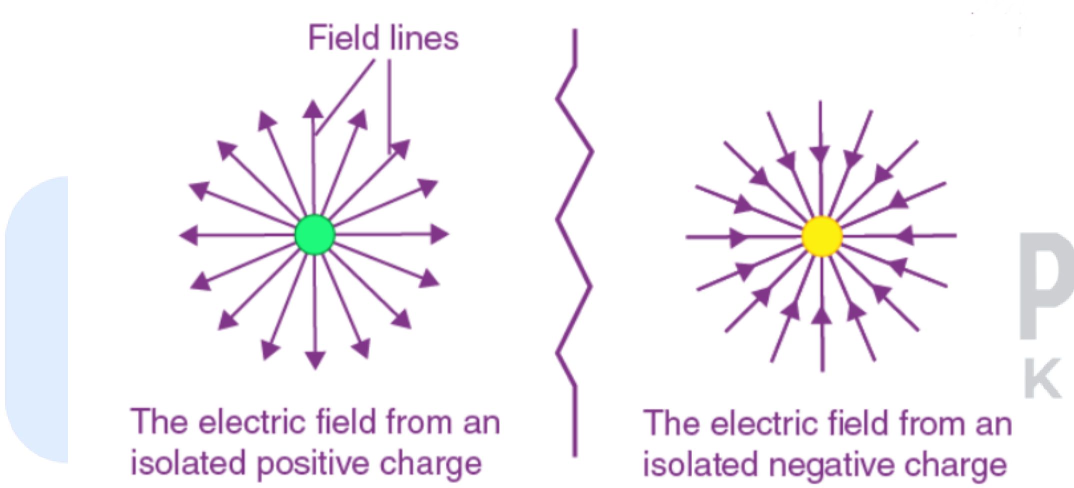
$E = F/Q$

Where,

E is the electric field.
F is a force.
Q is the charge.

Electric fields are usually caused by varying magnetic fields or electric charges. Electric field strength is measured in the SI unit volt per meter (V/m).

The direction of the field is taken as the direction of the force which is exerted on the positive charge. The electric field is radially outwards from positive charge and radially in towards negative point charge.



Gauss Law:

According to the Gauss law, the total flux linked with a closed surface is $1/\varepsilon_0$ times the charge enclosed by the closed surface.

$$\oint \vec{E} \cdot d\vec{s} = \frac{1}{\epsilon_0} q$$

For example, a point charge q is placed inside a cube of edge ‘a’. Now, as per Gauss law, the flux through each face of the cube is $q/6\varepsilon_0$.

The electric field is the basic concept of knowing about electricity. Generally, the electric field of the surface is calculated by applying Coulomb’s law, but to calculate the electric field distribution in a closed surface, we need to understand the concept of Gauss law. It explains the electric charge enclosed in a closed or the electric charge present in the enclosed closed surface.

As per the Gauss theorem, the total charge enclosed in a closed surface is proportional to the total flux enclosed by the surface. Therefore, if ϕ is total flux and ϵ_0 is electric constant, the total electric charge Q enclosed by the surface is;

$Q = \phi \epsilon_0$

The Gauss law formula is expressed by;

$\phi = Q/\epsilon_0$

Where,

Q = total charge within the given surface,

ε_0 = the electric constant.

Electric Potential Energy:

The electric potential energy of any given charge or system of changes is termed as the total work done by an external agent in bringing the charge or the system of charges from infinity to the present configuration without undergoing any acceleration.

Definition: Electric potential energy is defined as the total potential energy a unit charge will possess if located at any point in the outer space.

There are two key elements on which the electric potential energy of an object depends.

- Its own electric charge.
- It's relative position with other electrically charged objects.

Electric Potential:

Electric potential is defined as the amount of work needed to move a unit charge from a reference point to a specific point against the electric field. When an object is moved against the electric field, it gains some amount of energy which is defined as the electric potential energy. The electric potential of the charge is obtained by dividing the potential energy by the quantity of charge.

Strength of the electric field depends on the electric potential. It is independent of the fact of whether a charge should be placed in the electric field or not. Electric potential is a scalar quantity. At point charge +q, there is always the same potential at all points with a distance r. Let us learn to derive an expression for the electric field at a point due to a system of n point charges.

The electric potential of an object depends on these factors:

- Electric charge the object carries.
- The relative position with other electrically charged objects.

Electrical power:

Electric power is the rate at which electrical energy is transferred by an electric circuit. The SI unit of power is the **watt**, one joule per second. Standard suffixes apply to watts as with other SI units: thousands, millions and billions of watts are called kilowatts, megawatts and gigawatts respectively.

Capacitor:

The capacitor is a device in which electrical energy can be stored. It is an arrangement of two-conductor generally carrying charges of equal magnitudes and opposite sign and separated by an insulating medium. The non-conductive region can either be an electric insulator or vacuum such as glass, paper, air or semi-conductor called as a dielectric.

Capacitor vary in shape and size, they have many important applications in electronics.

Charge on the capacitor is Q.

Total charge/ the net charge on the capacitor is –Q + Q = 0.

Capacitance:

The charge on the capacitor (Q) is directly proportional to the potential difference (V) between the plates i.e.

QαV

or Q = CV

The constant of proportionality (C) is termed as the capacitance of the capacitor.

Dimensional Formula and Unit of Capacitance:

Unit of Capacitance: Farad (F)

The capacitor value can vary from a fraction of pico-farad to more than a micro-Farad. Voltage level can range from a couple to a substantial couple of hundred thousand volts.

Dimensional Formula: M-1L-2I2T4

Types of Capacitors:

1. Parallel Plate Capacitor
2. Spherical capacitor
3. Cylindrical capacitor

1. Parallel Plate Capacitor

The parallel plate capacitor consists of two metal plates of Area, A and is separated by a distance d. The plate on the top is given a charge +Q and that at the bottom is given the charge –Q. A potential difference of V is developed between the plates.

The separation is very small compared to the dimensions of the plate so that the effect of bending outward of electric field lines at the edges and the non-uniformity of surface charge density at the edges can be ignored.

The charge density on each plate of parallel plate capacitor has a magnitude of σ

$\sigma = Q/A$

2. Spherical Capacitor:

Let's consider a spherical capacitor that consists of two concentric spherical shells. Suppose the radius of the inner sphere, Rin = a and radius of the outer sphere, Rout = b. The inner shell is given a positive charge +Q and the outer shell is given –Q.

3. Cylindrical Capacitor:

Consider a solid cylinder of radius, a surrounded by a cylindrical shell, b. The length of the cylinder is l and is much larger than a-b to avoid edge effects. The capacitor is charged so that the charge on the inner cylinder is +Q and the outer cylinder is –Q.

Dielectrics and Capacitance:

Dielectrics:

It is an insulating material (non-conducting) which has no free electrons. But a microscopic displacement of charges is observed in the presence of an electric field. It is found that the capacitance increases as the space between the conducting plates are filled with dielectrics.

Polar and Non-polar Dielectrics:

Each atom is made of a positively charged nucleus surrounded by electrons. If the center of the negatively charged electrons does not coincide with the center of the nucleus, then a permanent dipole (separation of charges over a distance) moment is formed. Such molecules are called *polar molecules*. If a polar dielectric is placed in an electric field, the individual dipoles experience a torque and try to align along the field.

In non-polar molecules, the centers of the positive and negative charge distributions coincide. There is no permanent dipole moment created. But in the presence of an electric field, the centers are slightly displaced. This is called *induced dipole moments*.

Polarization of a Dielectric Slab:

It is the process of inducing charges on the dielectric and creating a dipole moment. Dipole moment appears in any volume of a dielectric.

The polarization vector p→ is defined as the dipole moment per unit volume.

Dielectric Constant:

Let E0→ be the electric field due to external sources and Ep→

be the field due to polarization (induced). The resultant field is:

E→=E0→+Ep→

The induced electric field is opposite in direction to the applied field. But the resultant field is in the direction of the applied field with reduced magnitude.

E→=E0→K

K is called the dielectric constant or relative permittivity of the dielectric. For vacuum,

Ep→=0,K=1

It is also denoted by ε.

Effect of Dielectric in Capacitance:

Dielectric Slabs in Series:

A parallel plate capacitor contains two dielectric slabs of thickness d_1, d_2 and dielectric constant k_1 and k_2 respectively. The area of the capacitor plates and slabs is equal to A.

Considering the capacitor as combination of two capacitors in series, the equivalent capacitance C is given by:

1C=1C1+1C2

1C=d1k1ε0A+d2k2ε0A

C=ε0Ad1k1+d2k2

Dielectric Slabs in Parallel:

Consider a capacitor with two dielectric slabs of same thickness d placed inside it as shown. The slabs have dielectric constants k_1 and k_2 and areas A_1 and A_2 respectively. Treating the combination as two capacitors in parallel,

$C = C_1 + C_2$

Electric current:

- Electric Current is the rate of flow of electrons in a conductor. The SI Unit of electric current is the Ampere.
- Electrons are minute particles that exist within the molecular structure of a substance.

Unit of Electric Current:

The magnitude of electric current is measured in coulombs per second. The SI unit of electric current is Ampere and is denoted by the letter A. Ampere is defined as one coulomb of charge moving past a point in one second. If there are 6.241 x 1018 electrons flowing through our frame in one second, then the electrical current flowing through it is 'One Ampere.'

Conventional Current flow Vs Electron Flow:

There is a lot of confusion around conventional current flow and electron flow. In this section, let us understand their differences.

Conventional Current Flow

The conventional current flow is from the positive to the negative terminal and indicates the direction in which positive charges would flow.

Electron Flow

The electron flow is from negative to positive terminal. Electrons are negatively charged and are therefore attracted to the positive terminal as unlike charges attract.

Properties of Electric Current:

After we define electric current, let us learn the properties of electric current. Electric current is an important quantity in electronic circuits. We have adapted electricity in our lives so much that it becomes impossible to imagine life without it. Therefore, it is important to know what is current and the properties of the electric current.

- We know that electric current is the result of the flow of electrons. The work done in moving the electron stream is known as electrical energy. Electrical energy can be converted into other forms of energy such as heat energy, light energy, etc. For example, in an iron box, electric energy is converted to heat energy. Likewise, the electric energy in a bulb is converted into light energy.
- There are two types of electric current known as alternating current (AC) and direct current (DC). The direct current can flow only in one direction, whereas the alternating direction flows in two directions. Direct current is seldom used as a primary energy source in industries. It is mostly used in low voltage applications such as charging batteries, aircraft applications, etc. Alternating current is used to operate appliances for both household and industrial and commercial use.
- The electric current is measured in ampere. One ampere of current represents one coulomb of electric charge moving past a specific point in one second.

1 ampere = 1 coulomb / 1 second

- The conventional direction of an electric current is the direction in which a positive charge would move. Henceforth, the current flowing in the external circuit is directed away from the positive terminal and toward the negative terminal of the battery.

Resistance:

Resistance is a measure of the opposition to current flow in an electrical circuit.

Resistance is measured in ohms, symbolized by the Greek letter omega (Ω). Ohms are named after Georg Simon Ohm (1784-1854), a German physicist who studied the relationship between voltage, current and resistance. He is credited for formulating Ohm's Law.

All materials resist current flow to some degree. They fall into one of two broad categories:

Conductors: Materials that offer very little resistance where electrons can move easily. Examples: silver, copper, gold and aluminum.

Insulators: Materials that present high resistance and restrict the flow of electrons. Examples: Rubber, paper, glass, wood and plastic.

Gold wire serves as an excellent conductor.

Resistance measurements are normally taken to indicate the condition of a component or a circuit.

The higher the resistance, the lower the current flow. If abnormally high, one possible cause (among many) could be damaged conductors due to burning or corrosion. All conductors give off some degree of heat, so overheating is an issue often associated with resistance.

The lower the resistance, the higher the current flow. Possible causes: insulators damaged by moisture or overheating.

Resistivity:

The electrical resistivity is a measure of opposition to the flow of electric current through a given conductor. It allows us to compare how efficiently different materials allow or restrict the flow of current through them. Resistivity is also known as “specific resistance.” It gives us an idea of the resistance offered to the current flow through a conductor. Higher is the resistivity of a conductor; higher will be the resistance offered by it.

The resistivity of a substance can be defined as the resistance offered by a cube made of that substance having edges of unit length with the current flowing normally through the opposite faces of the cube and distributed uniformly all over them.

Or in simple words, the electrical resistivity is the electrical resistance per unit length and per unit cross-sectional area offered by a conductor at a specific temperature. Mathematically,

$$\rho = \frac{RA}{l} = \frac{ohm \times (metre)^2}{metre}$$

The SI unit of Resistivity is Ohm-metre.

Materials that allow the electric current to pass through them easily are called conductors. These have a low value of resistivity, for example, copper is a conductor, and its resistivity is $1.72 \times 10^{-8} \Omega - m$, making copper and aluminium ideal materials to make electric wires and cables. Although silver and gold have much lower values of resistivity, these metals are too expensive to be used as electrical wires.

Conductivity:

The conductivity of a material is a measure of the ease with which electric current can flow through a material. It is also known as specific conductance. The conductivity of a substance is the inverse of its resistivity. Higher is the value of resistivity; lower will be the value of conductivity and vice versa.

It is represented by σ.

$$\sigma=\frac{1}{\rho}$$

Where ρ is the resistivity.

The SI unit of conductivity is the inverse of the SI unit of resistivity. Thus, the SI unit of conductivity is $\Omega^{-1}m^{-1}$ or Siemens/metre or S/m.

The conductivity of a material is closely related to the property of conductance, and the conductance of a given material is the reciprocal of electrical resistance.

We know that the electrical resistance R and specific resistance ρ depend on the physical nature of the given material; its dimensions or physical shape are expressed in terms of its length L and area of cross-section A. Thus, the conductance of a material is a function of the nature and physical properties of the given substance.

The conductance of a substance is equal to the reciprocal of electrical resistance. It is represented by G.

$$G=\frac{1}{R}$$

Where R is the resistance.

The SI unit of conductance is Seimens (S) and is represented by an inverted ohm and is represented by ℧ (mho).

Just as resistance gives an idea about the resistance to the flow of current, conductance gives an idea regarding the ease of current flow through a substance. Thus, good conductors like copper and aluminium have large conductance values, while insulators like plastic and wood have low conductance values.

Ohm’s Law and Resistance:

Ohm’s law states that the voltage or potential difference between two points is directly proportional to the current or electricity passing through the resistance, and directly proportional to the resistance of the circuit. The formula for Ohm's law is **V=IR**. This relationship between current, voltage, and relationship was discovered by German scientist Georg Simon Ohm. Let us learn more about Ohms Law, Resistance, and its applications.

Ohm's Law Definition:

Most basic components of electricity are voltage, current, and resistance. Ohm's law shows a simple relation between these three quantities. **Ohm's law** states that the current through a conductor between two points is directly proportional to the voltage across the two points.

Ohm's Law Formula:

Voltage= Current× Resistance

V= I×R

V= voltage, I= current and R= resistance

The SI unit of resistance is **ohms** and is denoted by **Ω**

This law is one of the most basic laws of electricity. It helps to calculate the power, efficiency, current, voltage, and resistance of an element of an electrical circuit.

Applications of Ohm's Law:

Ohm's law helps us in determining either voltage, current or impedance or resistance of a linear electric circuit when the other two quantities are known to us. It also makes power calculation simpler.

How do we establish the current-voltage relationship

In order to establish the current-voltage relationship, the ratio V / I remains constant for a given resistance, therefore a graph between the potential difference (V) and the current (I) must be a straight line.

How do we find the unknown values of resistance?

It is the constant ratio that gives the unknown values of resistance, For a wire of uniform cross-section, the resistance depends on the length l and the area of cross-section A. It also depends on the temperature of the conductor. At a given temperature the resistance,

where ρ is the specific resistance or resistivity and is characteristic of the material of wire. The specific resistance or resistivity of the material of the wire is,

If 'r' is the radius of the wire, then the cross-sectional area, $A = \pi r^2$. Then the specific resistance or resistivity of the material of the wire is,

Limitations of ohms law

1. Ohm's law is not applicable to unilateral networks. Unilateral networks allow the current to flow in one direction. Such types of networks consist elements like a diode, transistor, etc.

2. Ohm's law is also not applicable to non – linear elements. Non-linear elements are those which do not have current exactly proportional to the applied voltage that means the resistance value of those elements' changes for different values of voltage and current. Examples of non – linear elements are the thyristor.

Electromotive Force:

Electromotive force is defined as the electric potential produced by either electrochemical cell or by changing the magnetic field. EMF is the commonly used acronym for electromotive force.

A generator or a battery is used for the conversion of energy from one form to another. In these devices, one terminal becomes positively charged while the other becomes negatively charged. Therefore, an electromotive force is a work done on a unit electric charge.

- Electromotive force is used in the electromagnetic flowmeter which is an application of Faraday's law.
- The electromotive force symbol is ε.

- Following is the formula for electromotive force:

ε = V + Ir

Where,

V is the voltage of the cell

I is the current across the circuit

r is the internal resistance of the cell

ε is the electromotive force

The unit for electromotive force is Volt.

EMF is numerically expressed as the number of Joules of energy given by the source divided by each Coulomb to enable a unit electric charge to move across the circuit.

$$Volts = \frac{}{Coulombs}$$

Resistance in series and parallel:

Resistor connections that are more sophisticated are sometimes simply series and parallel combinations. This is common, particularly when considering wire resistances. Wire resistors are linked in series with other resistors connected in parallel.

Consider an example, where R1 is connected in series with two parallel resistors R2 and R3. In such cases, the total resistance in series and parallel is calculated as:

R(combined) = (R2xR3/R2+R3) + R1

Comparison between series and parallel resistors:

Comparison element	Series Circuit	Parallel Circuit
Component Orientation	Here, the resistors are connected one after the other	Here, the resistors are connected from head to head or tail to tail
Current	Same current flows across all the components	Each component have different current value

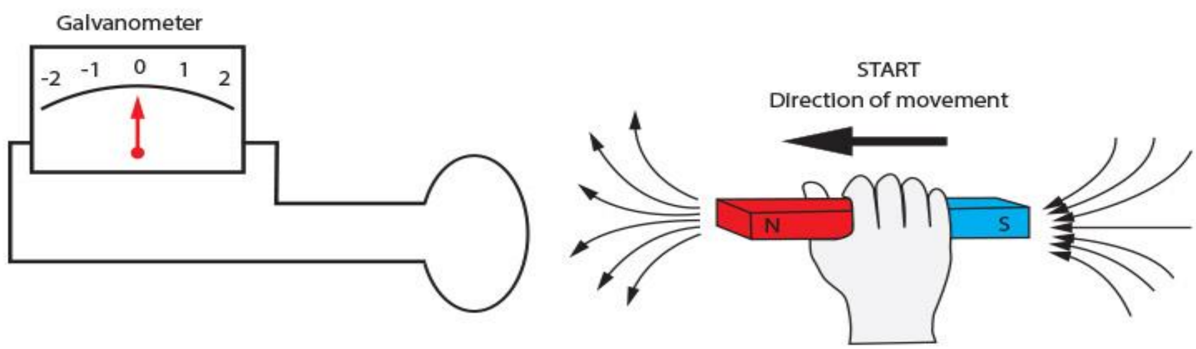
Voltage	Different voltage across different components	The voltage existing across all the components in the circuit is the same
Number of paths	Single	Multiple
Equivalent resistance	The equivalent resistance in a series connection is always greater than the highest value of resistance.	The equivalent resistance is always less than the sum of the independent resistors connected in parallel

AN ELECTRIC CURRENT IN A SINGLE LOOP:

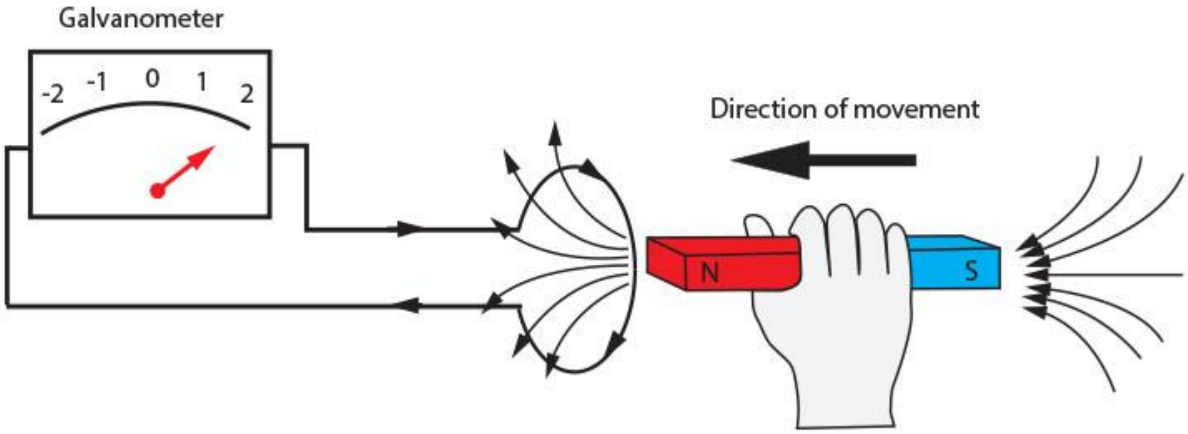
Even with a single loop of wire, passing a magnet into it will create an electric current. The single loop will still have all the characteristics of how a solenoid interacts with magnets.

A single loop is still a solenoid

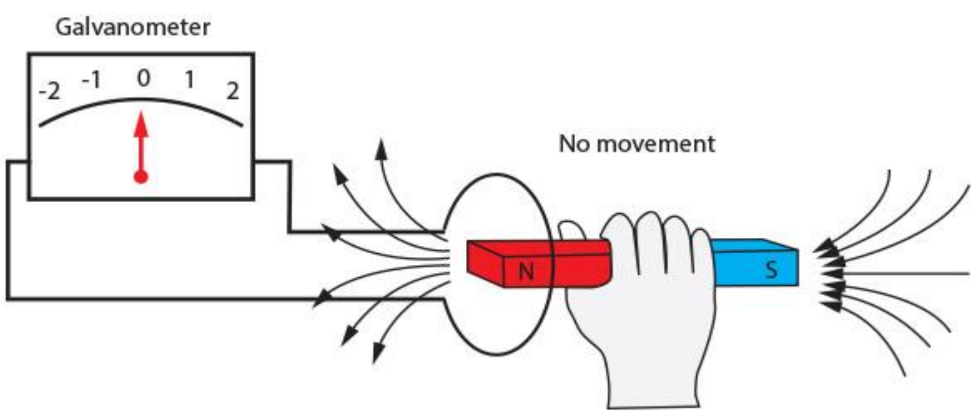
Follow the movement of a magnet into one loop:



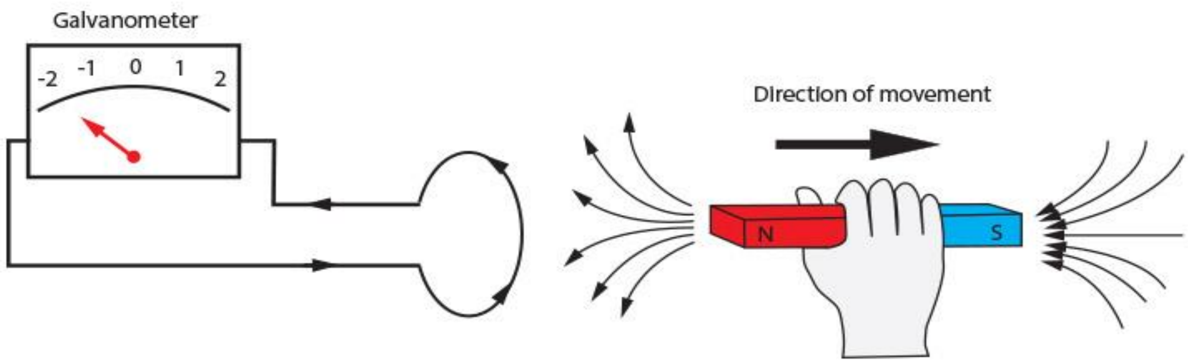
Below, a current is induced in the loop when a motion exists between the bar magnet and the loop.



When the bar magnet is stationary with respect to the loop, no current is registered on the galvanometer.



The galvanometer is moved in one direction as you go towards the loop, but moving it in the opposite direction causes the galvanometer to also move in the opposite direction, which means there is a change in the direction of the induced current in the wire.

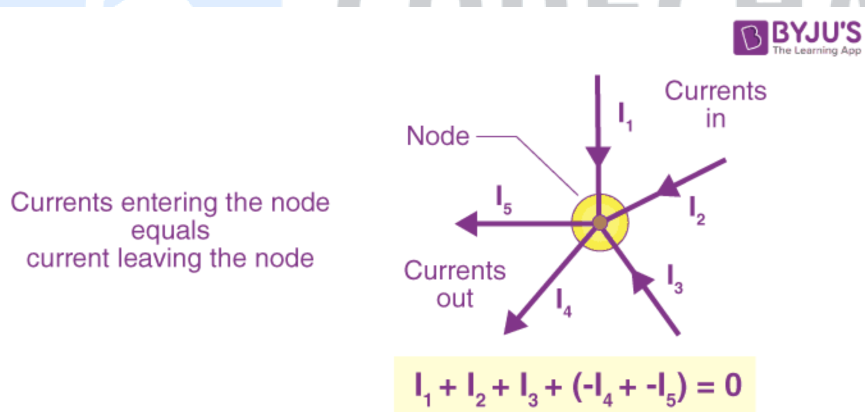


Kirchhoff's First Law or Kirchhoff's Current Law:

According to Kirchhoff's Current Law,

The total current entering a junction or a node is equal to the charge leaving the node as no charge is lost.

Put differently, the algebraic sum of every current entering and leaving the node has to be null. This property of Kirchhoff law is commonly called Conservation of charge wherein, I(exit) + I(enter) = 0.



In the above figure, the currents I_1, I_2 and I_3 entering the node is considered positive, likewise, the currents I_4 and I_5 exiting the nodes is considered negative in values. This can be expressed in the form of an equation:

I1 + I2 + I3 – I4 – I5 = 0

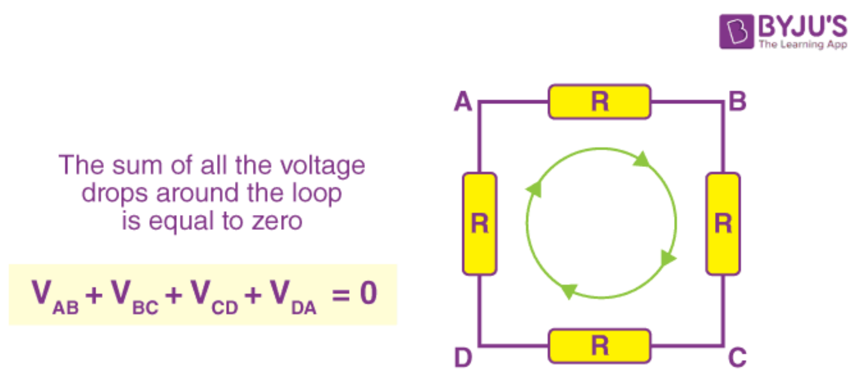
A node refers to a junction connecting two or more current-carrying routes like cables and other components. Kirchhoff's current law can also be applied to analyze parallel circuits.

Kirchhoff’s Second Law or Kirchhoff’s Voltage Law:

According to Kirchhoff’s Voltage Law,

The voltage around a loop equals the sum of every voltage drop in the same loop for any closed network and equals zero.

Put differently, the algebraic sum of every voltage in the loop has to be equal to zero and this property of Kirchhoff’s law is called conservation of energy.



When you begin at any point of the loop and continue in the same direction, note the voltage drops in all the negative or positive directions and returns to the same point. It is essential to maintain the direction either counterclockwise or clockwise; otherwise, the final voltage value will not be zero. The voltage law can also be applied in analyzing circuits in series.

When either AC circuits or DC circuits are analyzed based on Kirchhoff’s circuit laws, you need to be clear with all the terminologies and definitions that describe the circuit components like paths, nodes, meshes, and loops.