Given

Refracted index of water = n = 1.33

To Find

Angle of incidence = angle of polarization = θ_p = ?

By using Brewster's law

$\tan\theta_p = n$

$\theta_p = \tan^{-1}n$

$\theta_p = \tan^{-1}(1.33)$

$\theta_p = 53°$

8.9 **A beam of unpolarized light is incident on a stack of four polarizing sheets that are lined up so that the characteristic direction of each is rotated by 30° clockwise with respect to the preceding sheet. What fraction in percentage of the incident intensity be transmitted?**

Given

Intensity of unpolarized light = I_o

intensity of light becomes half after passing through first polarized filter

so $I_1 = \frac{I_o}{2}$

polarization angle between first and second sheet = $\theta_1 = 30°$

To Find

Intensity of transmitted light after passing through second sheet = I_2 = ?

Solution

Now using Malus's law

$I_2 = I_1 \cos^2\theta_1$

$$I = \frac{I_o}{2}\cos^2 30 = \frac{I_o}{2}\left(\frac{\sqrt{3}}{2}\right)^2 = \frac{I_o}{2}\left(\frac{3}{4}\right) = \frac{3}{8}I_o\ \text{W m}^{-2}$$

polarization angle between second and third sheet = $\theta_2 = 30°$

Intensity of transmitted light after passing through second sheet = I_3 = ?

Now using Malus's law

$I_3 = I_2 \cos^2\theta_2$

$$I_3 = \frac{3}{8}I_o \cos^2 30 = \frac{3}{8}I_o\left(\frac{\sqrt{3}}{2}\right)^2$$

$$= \frac{3}{8}I_o\left(\frac{3}{4}\right) = \frac{9}{32}I_o\ \text{W m}^{-2}$$

polarization angle between third and fourth sheet = $\theta_3 = 30°$

Intensity of transmitted light after passing through second sheet = I_4 = ?

Now using Malus's law

$I_4 = I_3 \cos^2\theta_3$

$$I_4 = \frac{9}{32}I_o \cos^2 30 = \frac{9}{32}I_o\left(\frac{\sqrt{3}}{2}\right)^2$$

$$= \frac{9}{32}I_o\left(\frac{3}{4}\right) = \frac{27}{128}I_o\ \text{W m}^{-2}$$

$$\frac{I_4}{I_o} = \frac{27}{128}$$

In percentage

$$\frac{I_4}{I_o} = \frac{27}{128}\times 100 = 21\%$$

8.10 **A polarizer and an analyzer have their axes aligned at 60°. What is the fraction of the initial intensity that emerges?**

Given

Angle of polarization = 60°

To Find $\frac{I}{I_o}$ = ?

Solution

Now using Malus's law

$I = I_o \cos^2\theta$

$$\frac{I}{I_o} = \cos^2 60 = \left(\frac{1}{2}\right)^2 = \left(\frac{1}{4}\right) = 0.25$$

8.11 **If the gravitational waves have a wavelength of 3000 km, then find their frequency assuming it moves with the speed of light?**

Given

Wavelength of GW's = 3000 km = 3×10^6 m

Speed = c = 3×10^8 m s^{-1}

To Find

Frequency of GW's = ?

Solution:

$c = f\lambda$

$3 \times 10^8 = f\,(3 \times 10^6)$

f = 100 Hz

◆ ◆ ◆

CHAPTER 9

ELECTROSTATIC AND CURRENT ELECTRICITY

STUDENT LEARNING OBJECTIVES

Here are the learning objectives extracted from the image, presented in a clear, bulleted format:

- Define and calculate electric field strength [Use F=qE for the force on a charge in an electric field. Use E=ΔV/Δd to calculate the field strength of the uniform field between charged parallel plates]
- Describe the effect of a uniform electric field on the motion of charged particles
- State that, for a point outside a spherical conductor, the charge on the sphere may be considered to be a point charge at its centre.
- Explain how a Faraday cage works [by inducing internal electric fields that work to shield the inside from the influence of external electric fields]
- State and apply Coulomb's law $F = \frac{kq_1q_2}{r^2}$ for the force between two point charges in free space. [where $k = \frac{1}{4\pi\varepsilon_o}$)
- Use $E = \frac{kq}{r^2}$ for the electric field strength due to a point charge in free space.
- Use, for a current-carrying conductor, the expression I=Anvq, where n is the number of charge carriers per unit volume.
- State and use V=W/Q.
- State and use P=IV, P=I²R and P=V²/R
- State and use $R = \rho\frac{L}{A}$
- State that the resistance of a light dependent resistor (LDR) decreases as the light intensity increases.
- State Kirchhoff's first law and describe that it is a consequence of conservation of charge
- State Kirchhoff's second law and describe that it is a consequence of conservation of energy
- Use Kirchhoff's laws to solve simple circuit problems
- State and use the principle of the potentiometer as a means of comparing potential differences.
- Explain the use of a galvanometer in null methods
- Explain the use of thermistors and light-dependent resistors in potential dividers [to provide a potential difference that is dependent on temperature and light intensity]
- Explain the internal resistance of sources and its consequences for external circuits.
- Explain how inspectors can easily check the reliability of a concrete bridge with carbon fibres as the fibres conduct electricity.

INTRODUCTION TO ELECTROSTATICS

What is the smallest amount of free charge?

The smallest amount of free charge discovered is the charge on an electron (e^-) or a proton (e^+). Its value is $e=1.6\times10^{-19}$ C (Coulomb, the SI unit of charge).

How are larger charges formed?

Charges of larger magnitude are built up on an object by adding or removing electrons. Any amount of charge 'q' is always an integer multiple of 'e', meaning $q=Ne$, where N is an integer.

What is Electrostatics?

Electrostatics is the study of phenomena and properties related to electric charges that are at rest (static charges). When charges are in motion, it is called an electric current.

Do you know about Charles de Coulomb?

Charles de Coulomb (1736-1806) was a French Physicist who made major contributions to electrostatics and magnetism by quantifying the force between electric charges. He also researched material strengths, forces on beams (structural mechanics), and ergonomics (how people can best do work).

Q. **Define Electricity and Electrostatics.**

Ans

ELECTRICITY:

A physical phenomenon which is used to study the interaction of charges or charged particles is called electricity.

Examples:

- Sky lightning
- Attracting of paper pieces with comb by rubbing with hairs.
- Wall Painting
- Writing by a board marker on board
- Maintaining of human body

TYPES OF ELECTRICITY:

There are two types of electricity:

i. Electrostatic Electricity
ii. Current Electricity

ELECTROSTATICS:

The word "ELECTROSTATICS" combined by two words which are electro and statics.

- Electro means charges.
- Static means in rest.

Definition:

"The study of electric charges at rest under the action of electric forces is known has ELECTROSTATICS."

What is Electric Charge?

In **1752, Benjamin Franklin** discovers the electric charge.

"Charge is the intrinsic property of fundamental particles".

-OR-

"Efficiency or deficiency of electrons is called charge".

- Fundamental particles are electrons, protons, neutrons etc....
- Protons have Positive charge
- Electrons have Negative charge
- Neutrons have no charge

TYPES OF ELECTRIC CHARGE:

There are two types which are followings:

i. Positive charge
ii. Negative charge

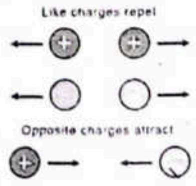
Mass can exist without charge, but Charge cannot exist without

Masses of Fundamental particles are:

Neutron: 1.67×10^{-27} kg
Electron: 9.10×10^{-31} kg
Proton: 1.67×10^{-27} kg

Charges on Fundamental Particles are:

Neutron: No Charge
Electron: -1.6×10^{-19} C
Proton: $+1.6\times10^{-19}$ C



i. **Positive Charge:**

- Positive charge is on protons.
- It is produced by loss of electrons.
- It is denoted by +e.
- $+e = +1.6\times10^{-19}$ C

ii. **Negative charge:**

- Negative charge is on electrons.
- It is produced by gaining electrons.
- It is denoted by – e.
- $-e = -1.6\times10^{-19}$ C

Basic Laws of Electrostatics:

i. Like charges repel each other
ii. Dislike charges attract each other.
iii. Charged bodies always attract a neutral body.

PROPERTIES OF ELECTRIC CHARGE:

Quantity:

Charge is a scalar quantity which is completely describe by its magnitude and SI unit.

It has no direction. i.e., 15 C, here 15 is the magnitude of the charge and C is the coulomb, unit of charge.

SI Unit:

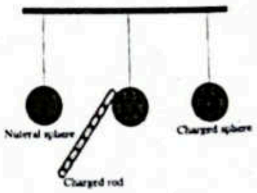
- The SI unit of charge is coulomb.
- It is represented by C.
- $1\text{ C} = 1\text{ A}\times1\text{ sec}$
- $1\text{ C} = 6.25\times10^{18}$ electrons

Dimension:

The dimension of charge is [AT]

Smallest Charge:

- Charge on electron and proton is the smallest charge in the universe.
- Charge on electron is -1.6×10^{-19} C and
- Charge on proton is $+1.6\times10^{-19}$ C



Quantization:

Charge is quantized; a body can only have charge multiply by e.

$$Q = ne \qquad (n = 1,2,3,4,5,6,\ldots\ldots\ldots\ldots)$$

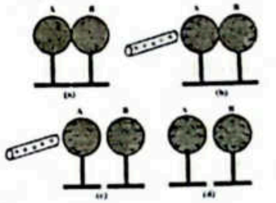
Half charge does not exist. (Fraction of charge)

Conservation of charge:

In Isolated system, total charge remains same.

"Charge cannot be created, nor be destroyed but transfer from one body to another body.

${}_{1}^{0}n\rightarrow P^{+1} + e^{-1}$



How to charge the objects:

There are three basic processes to charge a body:

i. **By Rubbing or By Friction:**

In this process two neutral bodies brought in contact and rub each other then they charged.

Example.

Two Balloons rub by cloth and then repel each other.

Rubbing of comb with hairs.

ii. **By conduction:**

In this process a charge body is brought in contact with neutral body and charge neutral object.

Example:

Charging of capacitor

iii. **By Induction:**

In this process a charge body is brought near to a neutral body and charges it.

Table 9.1

Material	ϵ_r
Vacuum	1
Air (atm)	1.0006
Ammonia (liquid)	22-25
Bakelite	5-15
Benzene	2.284
Germanium	16
Glass	4.8-10
Mica	3-7.5
Paraffined paper	2
Plexiglass	3.40
Rubber	2.94
Teflon	2.1
Transformer oil	7.1
Water (distilled)	78.5

Example:

Making dipoles with charged particles

ELECTRIC FORCE:

"The force which holds the positive and negative charge to make up atoms and molecules is called an electric force."

- The attraction or repulsion is due to electric force.
- Our body is composed of atoms and molecules and our existence is result of electric force.

CHARLES DE COULOMB (1736-1806)

Coulomb's major contribution to science was in the field of electrostatics and magnetism. During his lifetime, he also investigated the strengths of material and determined the forces that effect on beams, thereby, contributing to the field of structural mechanics. In the field of ergonomics, his research provided a fundamental understanding of the ways in which people can best do work.

9.1 COULOMB'S LAW

Q. State and explain the coulombs law?

Ans

COULOMBS LAW

In **1784**, the first attempt to the quantitative measurement of force between electric charges was made by a French military engineer **Charles Coulomb**. He deduced a law known as Coulomb's law.

- This law is also called empirical law.
- Coulomb's law only applicable on point charges at rest.

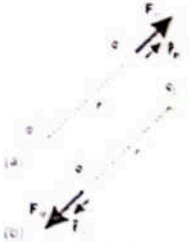


Fig 9.2

Statement:

"The electric force of (attraction and repulsion) between two points charge is **directly proportional** to the product of the magnitude of charges and **inversely proportional** to the square of the distance between them."

Explanation:

Consider two point charges "q_1" and "q_2" placed at a distance "r" from each other. Then magnitude of mutual force according to coulomb law is given by"

$$F \propto q_1q_2 \quad \text{.............. i}$$

$$F \propto \frac{1}{r^2} \quad \text{.............. ii}$$

Combining (i) and (ii)

$$F \propto \frac{q_1q_2}{r^2}$$

$$F = K\frac{q_1q_2}{r^2} \quad \text{.............. iii}$$

Where

- k is constant of proportionality which is called electrostatic constant. It is also called coulombs constant.
- F is the electrostatic force between two charges. it is always line joining force.
- q_1, q_2 are two point charges.
- r is the distance between point charges.

Dependence of K:

Its value depends upon

- The system of units.
- Nature of medium between the charges.

Point charge

"A charge is said to be point charge if its size is very small as compared to the distance from any other charge."

For free space

If the medium between two point charges is free space,

Than

$$K = \frac{1}{4\pi\varepsilon_o}$$

Here ε_o is an electrical constant, known as permittivity of free space.

$$K = \frac{1}{4\pi\varepsilon_o}$$

$$K = \frac{1}{4\times3.14\times8.85\times10^{-12}}$$

$$K = 9\times10^9\ Nm^2C^{-2}$$

Thus coulomb's force for free space is:

$$F = \frac{1}{4\pi\varepsilon_o}\frac{q_1q_2}{r^2} \quad \text{.............. iv}$$

Permittivity

"The ability of a medium to allow the electric force to pass through it is determined by a factor known as permittivity."

ε_o = Permittivity of free space

$\varepsilon_o = 8.85\times10^{-12}\ C^2N^{-1}m^{-2}$

Mutual force:

- F is the magnitude of mutual forces that act on each of two point charges.
- The force F always acts along the line joining the two point charges.
- As column is mutual force thus the charge q_1 and q_2 exerts equal

and opposite force on each other.

Effect of medium on Coulomb force:

- If an insulating medium called as dielectric is placed between the two charges, then is it experimentally observed that the force is reduced as compared to free space.
- The factor by which the force is a reduced is called a **relative permittivity** and is denoted by ε_r

Unit of K.

$$F = K\frac{q_1q_2}{r^2}$$

$$K = F\frac{r^2}{q_2q_2}$$

$$K = N\frac{m^2}{C.C}$$

$$K = Nm^2C^{-2}$$

Thus the coulomb's force between two point charges in the presence of dielectric is:

$$F_{med} = K\frac{q_1q_2}{r^2}$$

$$F_{med} = \frac{1}{4\pi\varepsilon_o\varepsilon_r}\frac{q_1q_2}{r^2}$$

$$F_{med} = \frac{1}{\varepsilon_r}\left(\frac{1}{4\pi\varepsilon_o}\frac{q_1q_2}{r^2}\right) \quad \text{.............. V}$$

$$F_{med} = \frac{1}{\varepsilon_r}(F_{air})$$

$$F_{med} = \frac{F_{air}}{\varepsilon_r}$$

Relative permittivity

"It is ratio between permittivity of medium to the permittivity of free,

- The value of relative permittivity is different dielectric.
- The value of ε_r is always greater than one.
- For air ε_r is 1.0006.
- The value of ε_r is infinity for all metals.
- It has no unit.
- It is a dimensionless quantity.

Vector form:

If the force exerts on q_2 by q_1 is denoted by $\vec{F}_{21}$ and that on charge q_1 due to q_2 as $\vec{F}_{12}$ then,

$$\vec{F}_{12} = -\vec{F}_{21}$$

The magnitude of these two forces the same but negative sign show that they point in opposite direction.

If

$\hat{r}_{21}$ is the unit vector a directed from q_1 to q_2

$\hat{r}_{12}$ is the unit vector directed from q_2 to q_1

Then Coulomb forces are given as;

$$\overrightarrow{F_{21}} = \frac{1}{4\pi\varepsilon_o}\frac{q_1q_2}{r^2}\hat{r}_{21} \quad \text{.............. vi}$$

$$\overrightarrow{F_{12}} = \frac{1}{4\pi\varepsilon_o}\frac{q_1q_2}{r^2}\hat{r}_{12} \quad \text{.............. vii}$$

But $\hat{r}_{21} = -\hat{r}_{12}$

Do you know?

A Van de Graaff generator is an electrostatic generator which uses a moving belt to accumulate electric charge on a hollow metal globe on the top of an insulated column, creating very high voltage direct current (DC) at low current levels. It was invented by an American physicist Robert J. Van de Graff in 1929.

The potential difference achieved in modern Van de Graaff generators can reach 5 megavolts. A tabletop version can produce of the order of 100,000 volts and can produce enough energy to produce a visible spark.

A pulley drives an insulting belt by a sharply pointed metal comb which has been given a positive charge by a power supply. Electrons are removed from the belt, leaving it positively charged. A similar comb at the top allows the net positive charge to spread to the dome.

Why do the hairs lift when VAN DE GRAAFF GENERATOR is touched?

Thus Eq. vi becomes,

$$F'_{21} = \frac{1}{4\pi\epsilon_o}\frac{q_1q_2}{r^2}(-\hat{r}_{12})$$

$$F'_{21} = -\frac{1}{4\pi\epsilon_o}\frac{q_1q_2}{r^2}\hat{r}_{12} \quad F'_{12} = \frac{1}{4\pi\epsilon_o}\frac{q_1q_2}{r^2}\hat{r}_{12}$$

$$F'_{21} = -F'_{12}$$

- The sign of charges represents either the forces are attractive or repulsive
- They are also implying that coulomb law obeys the Newton's third law.

MULTIPLE CHOICE QUESTIONS

- **Coulomb's Law states that the force between two point charges is inversely proportional to the:**

  (a) Distance between them (b) Square of the distance between them

  (c) Product of their charges (d) Permittivity of free space

Answer: (b) Square of the distance between them

Explanation: Coulomb's Law is an inverse square law, meaning the force decreases proportionally to the square of the distance, $F \propto 1/r^2$

- **If the distance between two point charges is doubled, the electrostatic force between them will become:**

  (a) Twice as strong (b) Half as strong (c) Four times as strong (d) One-fourth as strong

Answer: (d) One-fourth as strong

Explanation: Since force is inversely proportional to the square of the distance ($F \propto 1/r^2$), doubling 'r' to '2r' makes the force $1/(2r)^2 = 1/(4r^2)$, so it becomes one fourth.

- **The constant 'k' in Coulomb's Law, when the medium is free space and units are SI, has a value of:**

  (a) $8.85 \times 10^{-12}\ C^2N^{-1}m^{-2}$ (b) $9 \times 10^9\ N\ m^2C^{-2}$ (c) $1.6 \times 10^{-19}\ C$ (d) 1 C

Answer: (b) $9 \times 10^9\ N\ m^2C^{-2}$

Explanation: This is the numerical value of $k = 1/(4\pi\epsilon_o)$ in SI units for free space.

- **If an insulating medium (dielectric) is placed between two charges, the electrostatic force between them will:**

  (a) Increase (b) Decrease (c) Remain the same (d) Become zero

Answer: (b) Decrease

Explanation: The presence of a dielectric always reduces the electrostatic force compared to free space by a factor of its relative permittivity (ϵr), which is always greater than 1.

- **The force between two point charges acts along:**

  (a) A line perpendicular to the charges (b) A curved path between the charges

  (c) The line joining the two point charges (d) Any arbitrary direction

Answer: (c) The line joining the two point charges

Explanation: Coulomb's force is a central force, always acting along the straight line connecting the centers of the two charges.

SLO BASED SHORT QUESTIONS & ANSWERS

- **State Coulomb's Law.**

Ans: Coulomb's Law states that the force between two point charges is directly proportional to the product of the magnitudes of the charges' and inversely proportional to the square of the distance between them.

- **What is permittivity of free space (ϵ_o), and what is its approximate value in SI units?**

Ans: Permittivity of free space (ϵ_o) is an electrical constant that describes the ability of a vacuum to permit electric field lines. Its approximate value in SI units is $8.85 \times 10^{-12}\ C^2N^{-1}m^{-2}$

- **How does the force between two charges change if the medium between them is replaced by an insulator with relative permittivity ϵ_r?**

Ans: If the medium is replaced by an insulator with relative permittivity ϵr, the force between the charges will decrease by a factor of ϵr compared to the force in free space.

- **If charge q_1 exerts a force F_{12} on q_2, what is the force exerted by q_2 on q_1?**

Ans: According to Newton's third law and Coulomb's law, charge q_2 exerts an equal and opposite force $F_{21} = -F_{12}$ on q_1

- **What is the smallest amount of free charge that has been discovered?**

Ans: The smallest amount of free charge discovered is the elementary charge 'e', which is approximately $1.6 \times 10^{-19}\ C$ (the magnitude of the charge on an electron or proton).

Do You Know

A Van de Graaff generator is an electrostatic generator that uses a moving belt to accumulate electric charge on a hollow metal globe, creating very high voltage DC at low current levels. It was invented by Robert J. Van de Graaff in 1929. Modern generators can reach 5 megavolts, and tabletop versions can produce about 100,000 volts, enough for a visible spark. Electrons are removed from the belt by a charged metal comb, leaving it positively charged. A similar comb at the top transfers the positive charge to the dome.

Why do the hairs lift when a VAN DE GRAAFF GENERATOR is touched?

When a person touches a Van de Graaff generator, their body becomes charged with the same type of charge (usually positive) as the dome. Since like charges repel, each hair strand on the person's head becomes positively charged and tries to repel all other positively charged hair strands, causing them to stand on end and spread out.

9.2 ELECTRIC FIELD STRENGTH

Q. Define and explain the concept of electric field strength?

Ans

Forces are two types:

i. Contact forces

ii. Non-Contact Forces

Contact Forces:

The forces which need to contact for transformation of things from one place to another place.

- Tension force
- Frictional force
- Reaction force
- Air resistance force

Non-Contact Forces:

The forces which no need to contact for transformation of things from one place to another place.

- Gravitational force
- Electric force

Newton's Law OR Gravitational Law:

$$F = G\frac{m_1m_2}{r^2} \qquad F = G\frac{mM}{r^2}$$

It tells about the magnitude and Direction of

Coulomb's Law:

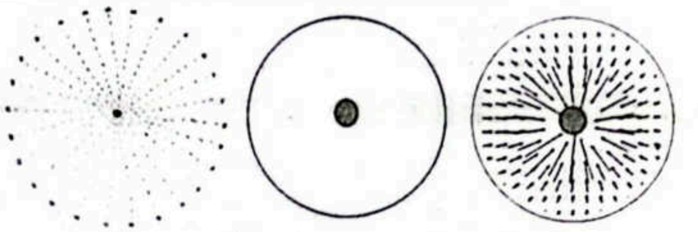
$$F = K\frac{q_1q_2}{r^2}$$

It tells about the magnitude and Direction of

Electric Field or Field of Force:

"The place of region around a point charge with in which another charge experiences a force is called **electric field.**"

- The origin of electric force still unknown that is why these all forces are basic forces of nature.
- According to **Faraday,** it is **intrinsic property** of nature that an electric field exists in space around the electric charge.
- A charge produces an electric field in this space surrounding it in the form of a sphere.
- This field is tested only by talking another charge in field.



TEST CHARGE:

A test charge is a charge with a magnitude so small that placing it at a point has a negligible affect on the field around the point.

- Test charge is always positive (+ve).
- Denoted by q.
- Test charge has very small value.

ELECTRIC FIELD STRENGTH:

"The magnitude of force experienced by a unit positive charge placed at a point in the electric field is called electric field strength or electric intensity of that point."

-OR-

"Force per Unit test charge is called electric field intensity"

Mathematically,

$$\vec{E} = \frac{F}{q_o}$$

Explanation:

Consider a charge q which produces a field. When a charge q_o is placed in the field, the charge q interacts with q_o to produce an electric force.

Then electric field intensity is given by:

$$\vec{E} = \frac{F}{q_o}$$

Here $\vec{F}$ is the force experienced by positive test charge q_o.

The test charge q_o should be very small so that it does not disturb the feel to be measured.

The strength of field is proportional to density of dots.

Unit:

Electric field is a force per unit charge is:

$$\vec{E} = \frac{F}{q_o}$$

$$\vec{E} = \frac{N}{C}$$

$$\vec{E} = NC^{-1}.$$

So, the SI Unit of Electric field intensity is NC^{-1}.

Quantity:

It is vector quantity and its direction is in the direction of force.

Electric intensity due to a point charge:

Consider a point charge q placed in vacuum producing its own electric field.

A charge q_0 is placed in the field at a distance 'r' from the point charge.

Then the force experience by the charge q_o due to charge q, according to **coulomb's force**, is given by:

$$\vec{F} = \frac{1}{4\pi\epsilon_o}\frac{qq_o}{r^2}\hat{r}$$

Where $\hat{r}$ is a vector directed from the point charge q to test charge q_o.

But **Electric intensity** at that point, where q_o is placed, is given by:

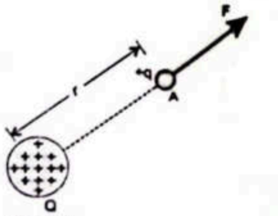


Fig. 9.4

$$\vec{E} = \frac{\vec{F}}{q_o} \text{ But}$$

Where $\hat{r}$ is the unit vector directed from q to q_o. Now putting the value of $\vec{F}$ in above equation, electric intensity is:

$$\vec{E} = \frac{\vec{F}}{q_o} = \frac{1}{q_o}\frac{1}{4\pi\epsilon_o}\frac{qq_o}{r^2}\hat{r} = \frac{1}{4\pi\epsilon_o}\frac{q}{r^2}\hat{r}$$

This relation shows that electric intensity at a point is inversely proportional to square of its distance from the charge. If the points charge q is placed in some dielectric of dielectric constant ϵ_r, then

$$\vec{E}' = \frac{1}{4\pi\epsilon_o\epsilon_r}\frac{q}{r^2}\hat{r}$$

This equation shows the vector form of electric field intensity which directed from the point charge q to test charge q_o

The magnitude of electric intensity in vacuum due to point charge is given by,

$$E = \frac{1}{4\pi\epsilon_o}\frac{q}{r^2}$$

Electric field intensity depends on

The electric field intensity depends on that three factors which are below

i. Magnitude of charge
ii. Medium
iii. Distance from charge

ELECTRIC FIELD LINES:

"The path followed by a unit positive charge in the electric field is called electric field line."

-OR-

"The imaginary lines on which a unit positive test charge moves in an electric field are called electric field lines."

Faraday's Concept:

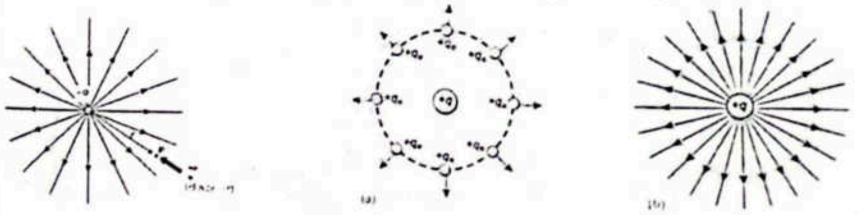
- The electric field lines of force or electric field lines were introduced by Michael Faraday.
- He states that, Electric field exist in the form of lines which gives the visual representation of field and terms as electric field lines.
- Electric field lines give the information about the direction of the electric field.
- Electric field lines give the information about the strength or magnitude of the electric field at different points.

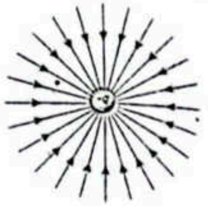
TYPICAL TYPES OF ELECTRIC FIELD LINES:

Electric filed lines due to positive point charge:

Consider a positive charge +q and place positive charges each of magnitude q_o at equal distance but at different points from charge $+q$ each test charge experiences a repulsive force which is directed outwards as shown in fig.

- Electric field lines due to +ve charge are radially outward.
- Electric field lines due to +ve charge are straight.
- Other test charge will follow straight path in +ve charge electric field.
- Electric field lines due to +ve charge is non-uniform electric field.
- Electric field is strong near change (radius) and weak away form charge





Electric filed lines due to negative point charge:

The field due to negative charge $-q$ is directed inwards because the force on a positive test charge q_o is now of attraction. This is shown in the Fig.

- Electric field lines due to -ve charge are radially inward.
- Electric field lines due to -ve charge are straight.
- Other test charge will follow straight path in -ve charge electric field.
- Electric field lines due to -ve charge is non-uniform electric field.
- Electric field is strong near change (radius) and weak away form charge.

Electric filed lines due to two same point charges:

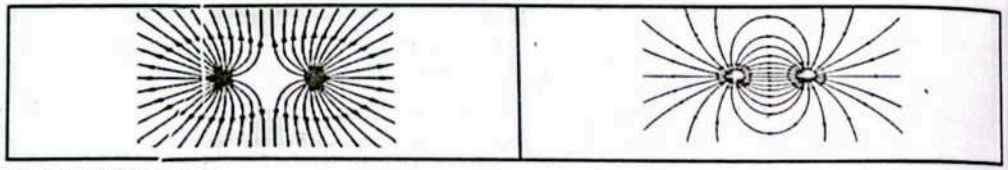
In case of two identical point charges of equal magnitudes, the electric field lines are:

- Electric field lines due to same charges repel each other.
- Electric field lines are curved due to same charges.
- Another test charge q_o will follow curved path in electric field of same charges.
- Electric field is non-uniform due to same charges.
- The middle portion has no line which shows a zero field spot or neutral zone where the $\vec{E}$ (Electric intensity) is Zero.

Electric filed lines due to two opposite point charges:

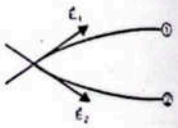
The electric field lines of two opposite charges of same magnitudes are:

- Electric field lines due to two opposite charges starts from +ve charge and end on -ve charge.
- Electric field lines are curved due to opposite charges.
- Another test charge q_o will follow curved path in electric field of opposite charges.
- Electric field is non-uniform due to opposite charges.
- E (Electric field intensity) is maximum at Centre.
- The direction of resultant intensities is tangent to curved path at these points.



Electric field strength:

"The number of lines per unit area passing perpendicularly through an area is proportional to the magnitude of the electric field."



- The above figs show the two dimensional image (pictures) of field lines however they are three dimensional and are infinite in number.
- The electric fields lines map also indicates the strength of electric field
- The field lines are closer to each other near the charges as a result electric field strong.
- The field lines are spread out continuously away from the charges as a result electric field weak

Uniform field:

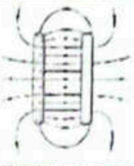
The electric field between two oppositely charged parallel plates of capacitor of finite length is shown in fig. In the regions where the field lines are parallel and equally spaced, the same number of lines pass per unit area and therefore field is uniform.

The field in the middle is **uniform** but at the ends, the field lines becomes **curved** called **"Fringing Field"**.

CHARACTERISTICS OF ELECTRIC FIELD LINES:

1 Electric field lines start from positive charges and end on negative charges
2 The tangent to a field at any point gives the direction of the electric field at that point.

3 The lines are closer near the charge thus the field is strong
4 The field is weak away from charge because lines are farther apart
5 No two lines intersect each other because $\vec{E}$ has only one direction at a given point, if the lines cross $\vec{E}$ could have more than one directions, it is physically not possible
6 These lines are imaginary having no physical significance
7 Electric field lines may be straight or curved
8 They contact longitudinally and expand laterally (sideways)
9 They can pass easily through a conducting medium



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MULTIPLE CHOICE QUESTIONS

- **Electric field strength (E) at a point is defined as the force experienced by a:**

(a) Unit negative charge placed at that point (b) Unit positive charge placed at that point
(c) Any charge placed at that point (d) Two unit charges placed at that point

Answer: (b) Unit positive charge placed at that point

Explanation: Electric field strength is defined as the force per unit positive test charge

- **The SI unit of electric intensity (electric field strength) is:**

(a) Volt (V) (b) Joule per Coulomb (J/C)
(c) Newton per Coulomb (N/C) (d) Coulomb per Newton (C/N)

Answer: (c) Newton per Coulomb (N/C)

Explanation: Since $E=F/q$, its unit is Newton per Coulomb

- **Electric field lines around a positive point charge are directed:**

(a) Radially inward (b) Radially outward (c) Tangential to the charge (d) Parallel to each other

Answer: (b) Radially outward

Explanation: A positive test charge would be repelled by a positive source charge, so the field lines point away from it

- **Where are electric field lines typically drawn closer together?**

(a) Where the field is weak (b) Where the field is uniform
(c) Near the charges where the field is strong (d) Far from the charges

Answer: (c) Near the charges where the field is strong

Explanation: The density of electric field lines (number of lines per unit area) is proportional to the magnitude of the electric field strength.

- **Which of the following statements about electric field lines is INCORRECT?**

(a) They originate from positive charges and end on negative charges.
(b) No two lines cross each other.
(c) The tangent to a field line gives the direction of the electric field.
(d) They form closed loops.

Answer: (d) They form closed loops

ation: Electric field lines do not form closed loops; they start on positive charges and end on negative charges (or extend to infinity). Magnetic field lines form closed loops.

SLO BASED SHORT QUESTIONS & ANSWERS

- **Define electric field strength (or electric intensity).**

Ans: Electric field strength at any point is defined as the electrostatic force experienced by a unit positive test charge placed at that point.

- **What is the direction of the electric field lines for a negative point charge?**

Ans: The electric field lines for a negative point charge are directed radially inward, towards the charge, because a positive test charge would be attracted to it

- **How can electric field lines visually represent the strength of an electric field?**

Ans: Electric field lines visually represent field strength by their density, where the lines are closer together, the electric field is stronger, and where they are farther apart, the field is weaker

- **Why can no two electric field lines ever cross each other?**

Ans: No two electric field lines can ever cross each other because if they did, it would imply that the electric field at that point has more than one direction, which is physically impossible. The electric field at any given point must have a unique direction.

- **What does a uniform electric field look like in terms of field lines?**

Ans: A uniform electric field is represented by parallel and equally spaced electric field lines, indicating that the field has the same magnitude and direction at all points in that region.

- **How are Electric Field Lines Constructed (Conceptual)?**

Ans: To visualize electric field lines, imagine placing small, positive test charges (+qo) at various points around a source charge. The direction of the repulsive force experienced by each test charge indicates the direction of the electric field at that point.

9.3 ELECTRIC FLUX:

Q. Define electric flux and also discuss their special cases for maximum, minimum flux?

Ans

"Total number of electric field lines passing normally through a certain area is called Electric Flux."

-OR-

"The scalar or dot product of electric intensity $\vec{E}$ and the vector area $\vec{A}$ is called electric flux"

- It is denoted by Greek letter ϕ
- Flux is Latin word, which means to flow
- It is a scalar quantity

Mathematically:

$$\varphi_e = \vec{E}\cdot\vec{A} = EA\cos\theta$$

The electric flux depends upon

- Electric intensity
- surface Area
- orientation of surface

Unit:

$$\varphi_e = \vec{E}\cdot\vec{A}$$
$$\varphi_e = NC^{-1}\cdot m^2$$
$$\varphi_e = Nm^2C^{-1}$$

So, in SI system, its unit is $\mathbf{Nm^2C^{-1}}$

Do you know?

There is no electric field inside the conductor

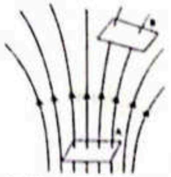
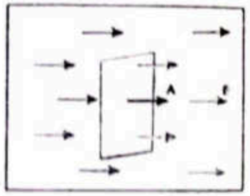


Fig.9.11: Electric flux through a surface normal to E.

EXPLANATION:

When we place an element of area 'A' and 'B' in the electric field, then the flux through aria A is 4 and the flux through area B is 2



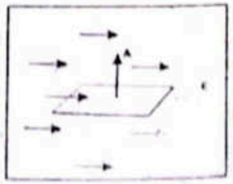
Case: 1 (Maximum flux):

When area A is held perpendicular to the field lines having uniform electric field of intensity then electric flux φ_e in this case is given by:

$$\varphi_e = EA_\perp$$
$$\varphi_e = \vec{E}\cdot\vec{A} = EA\cos\theta(\theta = 0)$$
$$\varphi_e = EA\cos 0$$
$$\varphi_e = EA$$

Where $A\perp$ denotes the area held perpendicular to field lines. It is the maximum flux.

$$\varphi_e = EA$$



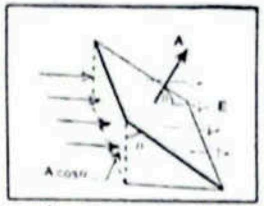
Case: 2 (Minimum flux):

When area A is placed parallel to the field lines in this case no line cross this area so that flux φ_e in this case is given by:

$$\varphi_e = EA_{||}$$
$$\varphi_e = \vec{E}\cdot\vec{A} = EA\cos\theta \qquad (\theta = 90)$$
$$\varphi_e = EA\cos 90$$
$$\varphi_e = 0$$

Where $A_{||}$ shows that A is held parallel to the field lines.

In this case flux is zero.



Case: 3 (Inclined area):

When A is inclined at an angle θ with the lines then we will take the projection of the area which is perpendicular to the field lines.

The area of projection is this case is equal to $A\cos\theta$, thus flux φ_e is given by:

$$\varphi_e = EA\cos\theta$$
$$\varphi_e = \vec{E}\cdot\vec{A}$$

θ is the angle between field lines and normal to the area.

Vector Area:

"It is an area whose magnitude is equal to the surface area A of the element but its direction is normal to this area."

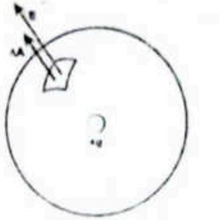
Determine an expression for the Electric Flux through a Surface Enclosing a Charge.

ELECTRIC FLUX THROUGH A SURFACE ENCLOSING A CHARGE

Consider a close surface in the form of a sphere of radius r due to a point charge q at its centre. In order to calculate the electric flux through whole surface of sphere, we divided this close surface into n number of small elements $\Delta A_1, \Delta A_2 \ldots\ldots \Delta A_n$ which are magnitudes of the area of each element. If n is very large then each element would be a flat element.

The corresponding vector areas are $\Delta\vec{A}_1, \Delta\vec{A}_2 \ldots\ldots \Delta\vec{A}_n$ respectively with direction normal to each patch.

Let the electric intensities at the centre of vector areas $\Delta\vec{A}_1, \Delta\vec{A}_2 \ldots\ldots \Delta\vec{A}_n$ are $\vec{E}_1, \vec{E}_2, \ldots\ldots \vec{E}_n$ respectively, then flux is given by:



Electric Flux through area A₁:

$$\varphi_1 = \vec{E}_1\cdot\Delta\vec{A}_1$$
$$\varphi_1 = E_1\Delta A_1\cos\theta$$

Since $\vec{E}$ and $\vec{A}$ are pointing in the same direction, so, $\theta = 0$.

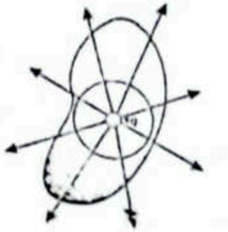
$$\varphi_1 = E_1\Delta A_1\cos 0$$
$$\varphi_1 = E_1\Delta A_1$$

Electric Flux through area A₂:

$$\varphi_2 = \vec{E}_2\cdot\Delta\vec{A}_2$$
$$\varphi_2 = E_2\Delta A_2\cos\theta$$

Since $\vec{E}$ and $\vec{A}$ are pointing in the same direction, so, $\theta = 0$

$$\varphi_2 = E_2\Delta A_2\cos 0$$
$$\varphi_2 = E_2\Delta A_2$$



Electric Flux through area A₃:

$$\varphi_3 = \vec{E}_3\cdot\Delta\vec{A}_3$$
$$\varphi_3 = E_3\Delta A_3\cos\theta$$

Since $\vec{E}$ and $\vec{A}$ are pointing in the same direction, so, $\theta = 0$.

$$\varphi_3 = E_3\Delta A_3\cos 0$$
$$\varphi_3 = E_3\Delta A_3$$

up to so on ....

. . . . .

. . . . .

Electric Flux through area Aₙ:

$$\varphi_n = \vec{E}_n\cdot\Delta\vec{A}_n$$
$$\varphi_n = E_n\Delta A_n\cos\theta$$

Since $\vec{E}$ and $\vec{A}$ are pointing in the same direction, so, $\theta = 0$.

$$\varphi_n = E_n\Delta A_n\cos 0$$
$$\varphi_n = E_n\Delta A_n$$

The magnitude of electric intensity $\mathbf{E}$ is same for each element because they are equidistant from the centre of sphere.

$$\therefore |E_1| = |E_2| = |E_3| \ldots\ldots = |E_n|$$

$$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}$$

Thus total flux passing through the closed surface is:

$$\Phi_e = \varphi_1 + \varphi_2 + \varphi_3 + \ldots\ldots\ldots\ldots + \varphi_n$$
$$\Phi_e = \vec{E}_1 \cdot \Delta\vec{A}_1 + \vec{E}_2 \cdot \Delta\vec{A}_2 + \cdots \ldots\ldots \vec{E}_n \cdot \Delta\vec{A}_n$$
$$\Phi_e = E_1\Delta A_1 + E_2\Delta A_2 + \cdots \ldots\ldots E_n\Delta A_n \qquad \therefore \cos 0 = 1$$
$$\Phi_e = E(\Delta A_1 + \Delta A_2 + \cdots \ldots\ldots + \Delta A_n)$$
$$\Phi_e = E(\text{ Total area of sphere })$$
$$\Phi_e = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2}4\pi r^2$$
$$\Phi_e = \frac{q}{\varepsilon_0}$$

INDEPENDENT OF SHAPE OF THE SURFACE:

Now consider a closed surface S enclosing the same sphere with a charge 'q' at its centre. The flux through this surface S is the same as that through the sphere.

- Thus flux through a closed surface does not depend upon shape of the closed surface.
- It only depends upon the medium and the charge enclosed.
- If a surface encloses a positive as well as a negative charge of same magnitude, then net flux through that surface is zero.

9.4 GAUSS'S LAW

Q. State and explain the Gauss's Law?

Ans

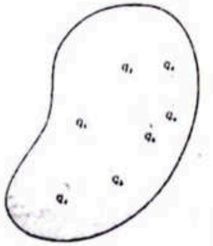
GAUSS'S LAW

The flux through any closed surface is $\frac{1}{\varepsilon_0}$ times the total charge enclosed in it.

$$\Phi_e = \frac{1}{\varepsilon_0}(Q)$$

DERIVATION:

Consider a closed surface in which point charges $q_1, q_2, q_3, \ldots\ldots\ldots q_n$ are distributed arbitrary.



Each charge will act as an independent source of electric flux.

The flux through the surface due to point charge q_1 is:

$$\Phi_1 = \frac{q_1}{\varepsilon_0}$$

The flux through the surface due to point charge q_2 is:

$$\Phi_2 = \frac{q_2}{\varepsilon_0}$$

The flux through the surface due to point charge q_3 is:

$$\Phi_3 = \frac{q_3}{\varepsilon_0}$$

$$\vdots \qquad \vdots$$

The flux through the surface due to point charge q_n is:

$$\Phi_n = \frac{q_n}{\varepsilon_0}$$

Thus total electric flux passing through the whole closed surface will be:

$$\Phi_e = \Phi_1 + \Phi_2 + \Phi_3 + \ldots\ldots\ldots\ldots + \Phi_n$$
$$\Phi_e = \frac{q_1}{\varepsilon_0} + \frac{q_2}{\varepsilon_0} + \frac{q_3}{\varepsilon_0} + \ldots\ldots\ldots\ldots + \frac{q_n}{\varepsilon_0}$$
$$\Phi_e = \frac{1}{\varepsilon_0}(q_1 + q_2 + q_3 + q_4 + \ldots\ldots\ldots\ldots + q_n)$$
$$\Phi_e = \frac{1}{\varepsilon_0}\sum_{i=1}^{n} q$$
$$\Phi_e = \frac{1}{\varepsilon_0}(Q)$$
$$\sum_{i=1}^{n} q = Q$$

Where Q is the total charge enclosed by closed surface.

APPLICATIONS OF GAUSS'S LAW

By applying Gauss's law we can calculate the electric intensity $\vec{E}$ due to different charge configurations. For this purpose, following steps must be followed:

- Draw an imaginary, closed surface which passes through the point at which the electric intensity is to be measured. This closed surface is known as "**Gaussian Surface**".
- Calculate the electric flux enclosed by the Gaussian surface $\Phi_e = EA\cos\theta$
- Calculate the electric flux using Gauss's law $\Phi_e = \frac{1}{\varepsilon_0}(Q)$
- Compare both electric fluxes to calculate the electric intensity $\vec{E}$.

GAUSSIAN SURFACE:

"A Gaussian surface is an imaginary closed surface of arbitrary shape which passes through the point where we want to calculate electric intensity."

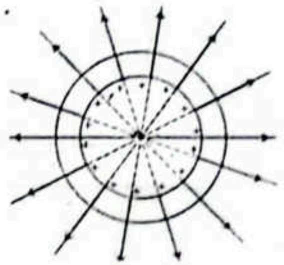
-OR-

"A closed surface in three dimensional spaces such that flux of a vector field is calculated."

Gaussian surfaces included:

- The surface of sphere
- The surface of a torus
- The surface of cube

THE FIELD OF A CHARGED CONDUCTING SPHERE:



Consider a conducting sphere of radius R containing a charge q we know that all the charge is distributed uniformly over the surface of sphere as shown in Fig. We can also conclude from the spherical symmetry that the electric field is radial everywhere and that its magnitude depends only on the distance r from the centre of the sphere. Thus, the magnitude E is uniform over a spherical surface with any radius r concentric with the spherical conductor. Therefore, we take our Gaussian surface as an imaginary sphere with radius r greater than the radius R of the conducting sphere.

The area of the Gaussian sphere is $4\pi r^2$, and E is uniform over the sphere, the total flux through the whole surface will be:

Electric flux $= \phi_e = EA = E \times 4\pi r^2$

By Gauss's law, total flux is:

Electric flux $= \phi_e = \frac{q}{\varepsilon_0}$

Comparing both electric fluxes

$$E \times 4\pi r^2 = \frac{q}{\varepsilon_0}$$
$$E = \frac{q}{\varepsilon_0} \times \frac{1}{4\pi r^2}$$
$$E = \frac{1}{4\pi\varepsilon_0} \times \frac{q}{r^2}$$

This equation shows that the field at any point outside the sphere is the same as though the entire charge were concentrated at its centre. Just outside of the sphere, where $r = R$, i.e.

$$E = \frac{1}{4\pi\varepsilon_0} \times \frac{q}{R^2}$$

Vector Form :

$$E = \frac{1}{4\pi\varepsilon_0} \times \frac{q}{R^2}\hat{r}$$

Where $\hat{r}$ is the direction of the Electric field E.

MULTIPLE CHOICE QUESTIONS

- **Electric flux (Φe) through an area is quantitatively defined as:**
  (a) The strength of the electric field
  (b) The number of electric field lines passing through that area.
  (c) The dot product of the electric field vector and the area vector.
  (d) The magnitude of the area.

Answer: (c) The dot product of the electric field vector and the area vector.

Explanation: Quantitatively, electric flux is defined as $\Phi e = E \cdot A = EA\cos\theta$.

- **If an area is held parallel to the electric field lines, the electric flux through it is:**
  (a) Maximum (b) Minimum (c) Equal to EA (d) Non-zero

Answer: (b) Minimum (which is zero)

Explanation: If the area is parallel to the field lines, the normal to the area is perpendicular to the field lines ($\theta=90°$), and $\cos 90°=0$, so $\Phi_E=0$

- **Gauss's Law states that the total electric flux through any closed surface is proportional to:**
  (a) The total charge outside the surface
  (b) The total charge enclosed within the surface
  (c) The electric field strength (d) The area of the surface

Answer: (b) The total charge enclosed within the surface.

Explanation: Gauss's Law states $\Phi_E = Q_{enclosed}/\varepsilon_0$

- **The total electric flux through a closed surface enclosing a point charge 'q' depends on:**
  (a) The shape of the closed surface (b) The size of the closed surface
  (c) The magnitude of the charge enclosed and the permittivity of the medium
  (d) The position of the charge inside the surface.

Answer: (c) The magnitude of the charge enclosed and the permittivity of the medium

Explanation: According to Gauss's Law, for a given medium, the flux only depends on the total charge enclosed, not the shape, size, or specific position of the charge within the closed surface.

- **The imaginary closed surface chosen to apply Gauss's Law for calculating electric intensity is known as a:**
  (a) Coulombian surface (b) Faraday surface (c) Gaussian surface (d) Maxwellian surface

Answer: (c) Gaussian surface

Explanation: A Gaussian surface is an imaginary closed surface used in the application of Gauss's Law, chosen to simplify the calculation of electric flux.

SLO BASED SHORT QUESTIONS & ANSWERS

- **Define electric flux.**

Ans: Electric flux is the measure of the number of electric field lines passing through a given surface area.

- **What is the SI unit of electric flux?**

Ans: The SI unit of electric flux is Newton-meter squared per Coulomb ($N\,m^2/C$) or Volt-meter ($V\,m$).

- **State Gauss's Law in words.**

Ans: Gauss's Law states that the total electric flux through any closed surface is equal to $1/\varepsilon_0$ times the total electric charge enclosed within that surface.

- **What is a "Gaussian surface," and why is its choice important when applying Gauss's Law?**

Ans: A Gaussian surface is an imaginary closed surface used to calculate electric fields using Gauss's Law. Its choice is important because selecting a surface with appropriate symmetry (matching the charge distribution) greatly simplifies the calculation of electric flux and intensity.

- **If a point charge is placed outside a closed surface, what is the total electric flux through that surface, according to Gauss's Law?**

Ans: If a point charge is placed outside a closed surface, the total electric flux through that surface is zero because the net charge enclosed within the surface is zero.

9.5 ELECTRIC POTENTIAL

Q. **State and explain the electric potential?**

Ans

THE ELECTRIC POTENTIAL

"The electric potential energy per unit charge is called electric potential of that point."

Electric Potential Difference:

"The difference of the electric potential energy per unit charge between two points is called electric Potential difference."

-OR-

"Work done in moving a unit positive charge from one point to other point against the electric field keeping the charge in electrostatics equilibrium is called electric Potential Difference."

Formula:

$$\Delta V = \frac{W_{AB}}{q_o}$$

Quantity:

Absolute potential is scalar quantity and it has no direction.

Explanation:

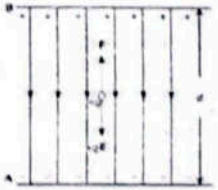


Fig: 9.17

Electric potential is a scalar quantity that represents the amount of potential energy per unit charge at a given point in an electric field. It's related to the work done in moving a charge. Consider two oppositely charged parallel plates (forming a uniform electric field E). If a positive charge 'q' is moved from plate A to plate B against the uniform electric field, an external force is needed to do work.

The work done by the external force (W_{AB}) in moving a charge 'q' from A to B while keeping the charge in equilibrium is:

$$W_{AB} = q(V_B - V_A)$$

Or, the change in electric potential energy $\Delta U_{AB}=U_B-U_A=q(V_B-V_A)$.

Where V_A and V_B are the electric potentials at points A and B, respectively.

Definition of Electric Potential Difference (ΔV):

The potential difference (ΔV) between two points (A and B) in an electric field is defined as the work done in carrying a unit positive charge from A to B while keeping the charge in equilibrium.

$$\Delta V = V_B - V_A = \frac{W_{AB}}{q_o} = \frac{\Delta U}{q_o} = \frac{U_B}{q_o} - \frac{U_A}{q_o} \qquad \text{(Equation 9.20)}$$

Where U_A and U_B are the potential energies at points A and B respectively but the potential difference between two points in an electric field is the work done on unit positive charge keeping the charge in equilibrium. Here V_A and V_B are the electric potential of points A and B respectively.

The electric potential energy and electric potential difference between the points A and B are related as

$$\Delta U = q_o \Delta V = W_{AB}$$

Unit:

The unit of P.E. is Joule and that of charge is Coulomb.

Thus unit of potential difference is **Joule per Coulomb** (JC^{-1}) which is equal to one Volt.

$$1\ \text{Volt} = \frac{1\ \text{Joule}}{1\ \text{Coulomb}}$$

Volt:

"The potential difference between two points will be one Volt if one Joule of work is done to move a positive charge of one Coulomb from one point to other point keeping the charge in equilibrium."

Potential at a point (Absolute Potential V):

Electric potential at a point at a point is defined as amount of work done in bringing a unit positive charge infinity up to that point by keeping it in electrostatics equilibrium"

Formula:

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

Quantity:

- Absolute potential is scalar quantity
- It has no direction

To calculate the electric potential at any point we must have a reference point where potential is supposed to be zero. This point is usually taken at infinity. Let A be point I i.e., at infinity where electric field is zero.

$$V_B - V_A = \frac{W_{AB}}{q}$$

$$V_B - 0 = \frac{W_B}{q}$$

$$V_B = \frac{W_B}{q}$$

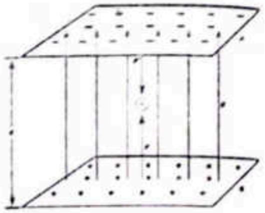
Electric Potential Energy:

"It is the amount of energy stored in a charge inside an electric field"

Formula

$$W_{AB} = \Delta V \times q_o$$

$$\Delta U = q_o \Delta V = q_o V = \frac{kqq_o}{r}$$



Quantity:

- Absolute potential is scalar quantity
- It has no direction.

ELECTRIC FIELD AS POTENTIAL GRADIENT

(Relation between Electric Intensity and Potential Difference)

The relationship between electric intensity (E) and potential difference (ΔV) for a uniform electric field (e.g., between two charged parallel plates separated by distance ('d') is:

$$E = -\Delta V/\Delta d \quad \text{(Equation 9.26)}$$

- The negative sign indicates that the electric field points in the direction of decreasing potential (i.e., from higher to lower potential).
- The quantity ΔV/Δd is called the **potential gradient**. It gives the maximum value of the rate of change of potential with distance.
- Units of E can also be Volts per meter (V/m), which is equivalent to N/C. 1 Volt/meter=1 Joule / (Coulomb × meter)=1 Newton / Coulomb=1 N C^{-1}
- $1\frac{V}{m} = \frac{J/C}{m} = 1\frac{Nm}{Cm} = 1\frac{N}{C}$

Proof

The potential difference between points A and B is given by,

$$V_B - V_A = \frac{W_{AB}}{q} \quad \ldots\ldots\ldots\ldots \text{(1)}$$

Work done in moving the charge from A to B is,

$$W_{AB} = \vec{F} \cdot \vec{d} = q_o\vec{E} \cdot \vec{d} = qEd\cos\theta$$

$$W_{AB} = q_o \cdot Ed\cos 180 = q \cdot Ed(-1)$$

$$W_{AB} = -q_o Ed \quad \ldots\ldots\ldots\ldots \text{(2)}$$

Force is applied opposite to q_oE to keep the charge in equilibrium.

Putting the value from Eq. (2) in Eq. (1),

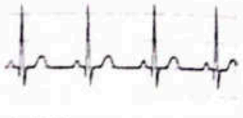
$$V_B - V_A = -\frac{qEd}{q} = -Ed$$

$$E = -\frac{V_B - V_A}{d} = -\frac{\Delta V}{d}$$

When the plates A and B are separated by infinitesimally small distance Δr then,

$$E = -\frac{\Delta V}{\Delta r}$$

Do you know?



An ECG records the "voltage" between points on human skin generated by electrical process in the heart. This ECG is made in running position providing information about the heart's performance under stress

Explanation: An ECG (Electrocardiogram) records the voltage between points on the human body, generated by electrical processes in the heart. This provides vital information about heart performance.

9.6 ELECTRON VOLT

Q. Prove that ev = 1.6×10^{-19}J ?

Ans

"It is the amount of energy acquired or lost by an electron as it moves through a potential difference of one volt."

$$1ev = 1.6 \times 10^{-19}J$$

Explanation:

When a particle of charge q moves from a point A with potential V_A to a point B with potential V_B keeping electrostatic equilibrium, the change in potential energy of the partr5icle is given by

$$\Delta U = q(V_B - V_A) = q\Delta V$$

If no external force acts on the charge to maintain the equilibrium, this change is P.E. appears as a change in its K.E.

$$\Delta(K.E) = q\Delta V$$

∴ q = e = Charge on electron,

$$e = 1.6 \times 10^{-19}C$$

$$\Delta(K.E) = e\Delta V$$

But

$$\Delta V = 1K$$

$$\Delta(K.E) = (e)(1V)$$

$$= (1.6 \times 10^{-19}C) \times (1\text{Volt})$$

$$= (1.6 \times 10^{-19})(C \times V)$$

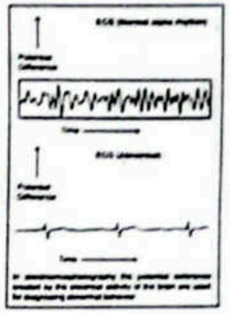
$$= 1.6 \times 10^{-19}J$$

The amount of energy is equal to 1.6×10^{-19}J is called one electron volt and is denoted by 1 eV

$$\therefore 1ev = 1.6 \times 10^{-19}J$$

Point to ponder!

Why is it advised to wear rubber soled shoes while handling electric appliances?



Electric Potential Energy (EPE)

When a charge 'q' moves from point A with potential V_A to point B with potential V_B in an electric field, the change in its electric potential energy (ΔU) is given by

$$\Delta U = q(V_B - V_A) = q\Delta V \text{ (Equation 9.27)}$$

If no external force acts on the charge to maintain equilibrium, this change in EPE appears in the form of change in kinetic energy.

Point to Ponder!

"Why is it advised to wear rubber soled shoes while handling electric appliances?"

Explanation:

It is advised to wear rubber-soled shoes while handling electric appliances because rubber is an excellent electrical insulator. This means it does not conduct electricity easily. In case of an accidental electric shock, the rubber soles provide a barrier between your body and the ground, preventing the electricity from flowing through you to the ground. This significantly reduces the risk of serious injury or electrocution.

MULTIPLE CHOICE QUESTIONS

- **Electric potential difference (ΔV) between two points is defined as:**
  - (a) The electric field strength between the points
  - (b) The force per unit charge to move a charge between the points
  - (c) The work done per unit charge to move a charge between the points
  - (d) The potential energy of a charge

Answer: (c) The work done per unit charge to move a charge between the points

Explanation: Potential difference is defined as the work done (W) per unit positive test charge (Q) in moving it from one point to another, ΔV=W/Q

- **The SI unit of potential difference is:**

(a) Joule (J) (b) Coulomb (C) (c) Volt (V) (d) Ampere (A)

Answer: (c) Volt (V)

Explanation: One volt is defined as one joule of work done per one coulomb of charge.

- **The relationship between electric field intensity (E) and potential difference (ΔV) in a uniform field is given by:**

(a) E = ΔV×Δd (b) E = ΔV/Δd (c) E = Δd/ΔV (d) E = ΔV + Δd

Answer: (b) E = ΔV/Δd

Explanation: For a uniform electric field, the magnitude of the field is the potential difference per unit distance, E = ΔV/Δd. The full relationship is E = −∇V

- **One electron-volt (1 eV) is defined as the energy acquired by an electron when it is accelerated through a potential difference of:**

(a) 1 Joule (b) 1 Coulomb (c) 1 Volt (d) 1 Ampere

Answer: (c) 1 Volt

Explanation: The electron-volt is a unit of energy commonly used in atomic and nuclear physics; 1 eV is the energy gained by an electron (or proton) when it moves through a potential difference of 1 Volt.

- **Potential difference and electric potential are scalar quantities because:**
  (a) They only have magnitude
  (b) They are related to force, which is a vector
  (c) They are defined as work done per unit charge, and work is a scalar
  (d) They are independent of direction

Answer: (c) They are defined as work done per unit charge, and work is a scalar

Explanation: Work (energy) is a scalar quantity, and potential difference is fundamentally a measure of energy per unit charge, making it a scalar.

SLO BASED SHORT QUESTIONS & ANSWERS

- **Define electric potential difference.**

Ans: Electric potential difference between two points is defined as the work done per unit positive test charge in moving it from one point to another in an electric field.

- **What is the relationship between electric field intensity (E) and the potential gradient ($\Delta V/\Delta d$)?**

Ans: The electric field intensity (E) is equal to the negative of the potential gradient ($\Delta V/\Delta d$), indicating that the electric field points in the direction of decreasing potential.

- **Define one electron-volt (eV) and provide its approximate value in Joules.**

Ans: One electron-volt (eV) is the amount of energy gained or lost by a single elementary charge (like an electron) when it moves through an electric potential difference of one volt. Its approximate value is $1\ eV = 1.6\times10^{-19}\ J$.

- **Why is it advised to wear rubber-soled shoes while handling electric appliances?**

Ans: Rubber is an excellent electrical insulator. Wearing rubber-soled shoes creates a high resistance path between your body and the ground, reducing the risk of electric shock by preventing current from flowing through you to the Earth if you come into contact with a live appliance.

- **How is electric potential at a point defined, assuming zero potential at infinity?**

Ans: Electric potential at a point is defined as the work done in bringing a unit positive charge from infinity to that point in an electric field, assuming electric potential at infinity is zero.

9.7 MOTION OF CHARGED PARTICLES IN A UNIFORM ELECTRIC FIELD

Q. **Discuss motion of charged particles in an electric field.**

Ans

MOTION OF CHARGED PARTICLES IN AN ELECTRIC FIELD

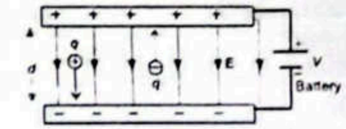
Two oppositely charged parallel metal plates produce uniform electric field between them. The direction of electric field is from positive to negative plate.

- A positive charge +q placed in the field will move in the direction of electric field whereas
- A negative charge -q will move opposite to the electric field.

Force on a Charge in a Uniform Electric Field:

The magnitude of electric force acting on a charge q is represented in Fig. given by

$$F = qE$$



Where,

- E is the electric intensity of the uniform electric field.
- q is the charge which placed in electric field.
- F is the force exerted by electric filed

If V is the potential difference between the plates and *d* is the separation of plates, then

$$E = \frac{V}{d}$$

Hence $$F = q\frac{V}{d}$$

Example of Electron

To understand the effect of uniform electric field on the motion of charged particles, let us consider an electron placed between the two plates. The electron accelerates towards the positive plate due to a force *F* acting on it.

For example, let V = 20 V, d = 2.0 cm = 2×10^{-3} m, the magnitude of E will be:

$$E = \frac{V}{d} = \frac{20\ V}{2\times10^{-3}} = 1000\ VC^{-1}$$

Acceleration: The acceleration for the electron will be given by

$$F = ma$$

Or $$a = \frac{F}{m} = \frac{qE}{m}$$

The charge on an electron q = e = 1.6×10^{-19} C and mass of electron m = 9.1×10^{-31} kg.

So,

$$a = \frac{1.6\times10^{-19}\times1000}{9.1\times10^{-31}} = 1.76\times10^{14}ms^{-1}$$
$$a = 1.76\times10^{14}ms^{-2}$$

Velocity of electron: If the electron is released from the negative plate, the velocity gained by it when it reaches positive plate can be found by the third equation of motion

$$2aS = V_f^2 - v_i^2$$

Here $$S = d = 2\times10^{2}m,\ v_i = 0,\ v_f = v = ?$$

- Putting the values in the above equation

$$2aS = V_f^2 - v_i^2$$
$$2\times1.76\times10^{14}\times2\times10^{2} = v^2 - 0^2$$
$$v^2 = 2\times1.76\times10^{14}\times2\times10^{2}$$
$$v^2 = 2.65\times10^{6}ms^{-1}$$
$$v = \sqrt{2.65\times10^{6}} = 1.6\times10^{3}ms^{-1}$$

For Your Information

Force on a Charge in a Uniform Electric Field:

The magnitude of the electric force (F) acting on a charge 'q' in a uniform electric field 'E' is: F=qE (Equation 1)

In the case of parallel plates, the electric field is related to the potential difference (V) between the plates and their separation (d) by E=V/d. So, F=qV/d (Equation 2)

Motion of a charged in a Uniform Electric Field:

Consider a charge placed between two parallel plates. The charge accelerates towards the plate due to the force acting on it.

From Newton's second law, F=ma. So, ma=qE or a=qE/m. For an electron: a=eE/m. If the electron is released from the negative plate (initial velocity v_i=0), its final velocity (v_f) after moving through a distance 'S' (which is 'd', the separation between plates) can be found using the third equation of motion.

$$2aS = v_f^2 - v_i^2$$
$$2ad = v_f^2$$

Substitute $$a = eE/m$$
$$2(eE/m)d = v_f^2$$

Since $$V = Ed \text{ (for uniform field)},\ Ed = V$$
$$v_f^2 = 2eV/m$$
$$v_f = \sqrt{\frac{2eV}{m}}$$

9.8 PATH OF A CHARGED PARTICLE:

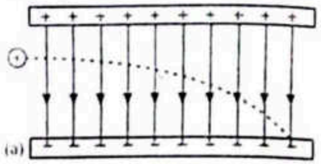
Q. **Discuss the path of charged particle in an electric field.**

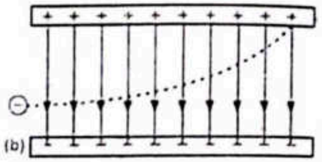
Ans

PATH OF CHARGED PARTICLE

The path of a charged particle determined by the electric field in the region is called an electric trajectory.

- If a charged particle enters an electric field parallel to the field lines, its trajectory will be a straight line (accelerating or decelerating).
- If a charged particle enters a uniform electric field **perpendicular** to the field lines (like an electron entering the region between parallel plates horizontally), its path will be a **parabola**.
  - The horizontal component of the velocity remains constant (no force in that direction).
  - The vertical component of the velocity changes (accelerates) due to the electric force. This is analogous to projectile motion in a gravitational field, where gravity provides a constant downward force.


(a)


(b)

MULTIPLE CHOICE QUESTIONS

- **A positively charged particle placed in a uniform electric field will experience a force in the direction:**
  (a) Opposite to the electric field (b) Perpendicular to the electric field.
  (c) Parallel to the electric field (d) Depends on the particle's velocity

Answer: (c) Parallel to the electric field

Explanation: The force on a positive charge in an electric field is given by $F=qE$, so the force vector is in the same direction as the electric field vector.

- **The acceleration (a) of a charged particle in a uniform electric field (E) is given by (where q is charge and m is mass):**
  (a) $a = qmE$ (b) $a = mE/q$ (c) $a = qE/m$ (d) $a = E/qm$

Answer: (c) $a = qE/m$

Explanation: From Newton's second law, $F = ma$. Since $F = qE$, then $ma = qE$, leading to $a = qE/m$.

- **If a negatively charged particle is placed in a uniform electric field, it will accelerate:**
  (a) In the direction of the electric field (b) Opposite to the direction of the electric field
  (c) Perpendicular to the electric field. (d) In a circular path

Answer: (b) Opposite to the direction of the electric field

Explanation: For a negative charge, the force $F=qE$ will be in the direction opposite to E because 'q' is negative.

- **A charged particle projected into a uniform electric field perpendicular to its initial velocity will follow a path that is:**
  (a) A straight line (b) A parabola. (c) A circle (d) An ellipse

Answer: (b) A parabola

Explanation: The electric force provides a constant acceleration in the direction of the field (or opposite for negative charge), similar to gravitational acceleration on a horizontally projected object, resulting in a parabolic trajectory.

- **In a parallel plate capacitor, the electric field in the central region is:**
  (a) Non-uniform and diverging (b) Non-uniform and converging
  (c) Uniform and directed from positive to negative plate (d) Zero

Answer: (c) Uniform and directed from positive to negative plate

Explanation: The field lines between parallel plates are straight, parallel, and equally spaced, indicating a uniform field directed from the higher potential (positive) plate to the lower potential (negative) plate.

SLO BASED SHORT QUESTIONS & ANSWERS

- **Describe the motion of a positive charge in a uniform electric field if it starts from rest.**

Ans: A positive charge starting from rest in a uniform electric field will accelerate linearly in the direction of the electric field, as the force on it is parallel to the field.

- **How does a uniform electric field affect the kinetic energy of a charged particle moving within it?**

Ans: A uniform electric field will change the kinetic energy of a charged particle if there is a component of the electric force along the direction of motion, as the field does work on the particle.

- **Describe the path of a charged particle when it enters a uniform electric field perpendicular to its initial velocity.**

Ans: When a charged particle enters a uniform electric field perpendicular to its initial velocity, its path will be parabolic, similar to a projectile under gravity, as it experiences a constant acceleration component perpendicular to its initial velocity.

- **What is the force on an electron in a uniform electric field?**

Ans: The force on an electron in a uniform electric field is $F=(-e)E$, meaning the force is equal in magnitude to eE and directed opposite to the electric field.

- **What happens to a charged particle that is accelerated by a potential difference in an evacuated tube?**

Ans: A charged particle accelerated by a potential difference gains kinetic energy equal to its charge times the potential difference ($K.E = q\Delta V$), and its speed increases as it moves through the potential difference.

9.9 SHIELDING FROM EXTERNAL ELECTRIC FIELD (Faraday Cage)

Q. What is a Faraday Cage? How a Faraday Cage Works:

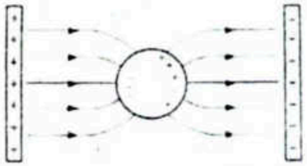
Ans

FARADAY CAGE

An English scientist Michael Faraday invented a phenomenon (in 1836) now known as a Faraday cage. It is an enclosure made of conductive material that blocks external electric fields, protecting its contents from electrical influence.

How a Faraday Cage Works:

1. **Induction of Internal Fields:** When an external electric field is applied to a hollow conductor (like a Faraday cage), it causes the free electrons within the conductor to redistribute themselves.
2. **Charge Redistribution:** Electrons in the conductor are mobile. They will move in response to the external field until the electric field they create inside the conductor exactly cancels out the external electric field.
3. **Zero Internal Field:** Once this charge redistribution reaches electrostatic equilibrium, there is **no net electric field inside the hollow conductor**. The internal electric field becomes zero.
4. **Shielding:** This means that anything inside the Faraday cage is shielded from the influence of external electric fields, preventing any electrical phenomena from occurring inside.



Do you know?

At equilibrium under electrostatic conditions, any excess charge resides on the surface of a conductor, and the electric field inside a conductor is zero.

Example:

- The chassis and bodies of cars protect people inside during thunderstorms by diverting lightning strikes over the metal surface to the ground.
- The metal body of a microwave oven acts as a Faraday cage, preventing microwaves from escaping and harming the environment.
- When lightning strikes an airplane, electricity is distributed along its metal frame, keeping passengers safe.

MULTIPLE CHOICE QUESTIONS

- **A Faraday cage works by:**
  (a) Absorbing all external electric fields.
  (b) Allowing electric fields to pass through its interior freely.
  (c) Inducing internal electric fields that cancel external ones, shielding the inside.
  (d) Converting electric fields into magnetic fields.

Answer: (c) Inducing internal electric fields that cancel external ones, shielding the inside.

Explanation: Free charges within the conducting cage redistribute themselves to create an internal electric field that precisely opposes and cancels the external field, making the net field inside zero.

- **Inside a hollow conductor, in electrostatic equilibrium, the electric field is:**
  (a) Very strong (b) Non-uniform (c) Perpendicular to the surface (d) Zero

Answer: (d) Zero. **Explanation:** A fundamental property of conductors in electrostatic equilibrium is that the electric field inside them is zero, and any excess charge resides entirely on the outer surface.

- **Which of the following is a real-world example of a Faraday cage?**
  (a) A wooden box. (b) A plastic container.
  (c) The metal frame of an airplane. (d) A glass bottle.

Answer: (c) The metal frame of an airplane.

Explanation: The metal body of an airplane acts as a Faraday cage, shielding passengers and electronics from external lightning strikes by conducting the charge over its surface.

- **The principle of a Faraday cage relies on the fact that charge placed on a conductor:**
  (a) Spreads throughout its volume. (b) Concentrates at its center.
  (c) Resides entirely on its outer surface. (d) Radiates outward.

Answer: (c) Resides entirely on its outer surface.

Explanation: In electrostatic equilibrium, free charges in a conductor repel each other and move to the outer surface to maximize their separation, resulting in zero electric field inside.

- **If an external electric field is applied to a Faraday cage, the free electrons within the conductor:**
  (a) Remain stationary. (b) Move to the center of the conductor.
  (c) Redistribute themselves on the surface. (d) Are ejected from the conductor.

Answer: (c) Redistribute themselves on the surface.

Explanation: The free electrons in the conductor move under the influence of the external field until their redistribution creates an opposing internal field that cancels the external field inside.

SLO BASED SHORT QUESTIONS & ANSWERS

- **What is a Faraday cage?**

Ans: A Faraday cage is an enclosure made of a conducting material that blocks external static electric fields, shielding its interior from the influence of those fields.

- **Explain the basic principle behind how a Faraday cage works.**

Ans: When an external electric field is applied, the free charges (electrons) within the conductor of the Faraday cage redistribute themselves on its surface, creating an induced electric field inside that is equal in magnitude and opposite in direction to the external field, thus canceling it out and making the net electric field inside zero.

- **Why is the electric field inside a conductor zero in electrostatic equilibrium?**

Ans: The electric field inside a conductor is zero in electrostatic equilibrium because any excess charge on the conductor resides entirely on its outer surface, and the free charges within the conductor redistribute themselves to cancel out any internal electric field.

- **Give a practical example of a Faraday cage in everydav life.**

Ans: Examples include the metal body of a car or airplane (protecting occupants from lightning), or the metal mesh inside a microwave oven door (shielding from microwaves while allowing visibility).

- **If a Faraday cage were made of an insulator, would it still work? Explain.**

Ans: No, a Faraday cage would not work if it were made of an insulator. Insulators do not have free charges that can redistribute themselves to cancel out an external electric field, so the field would penetrate the material.

9.10 ELECTRIC CURRENT:

Q. **Define current electricity. What is Electric Current?**

Ans

CURRENT ELECTRICITY:

The branch of Physics which deals with the study of moving charges is called electrodynamics. It is also known as current electricity.

ELECTRIC CURRENT:

Time rate of flow of electric charges through any cross section of conductor is called electric current.

Formula:

If ΔQ charge is passing through any cross section of wire in time Δt, then electric current I is given by

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

Units and dimensions:

Electric current is a **scalar** quantity.

Its S.I unit is **ampere (A)**.

The dimension of current is **[A]**.

One ampere:

Electric current is equal to one ampere if charge of **one coulomb** is passing through any cross section of conductor in **one second**.

$$1A = \frac{1C}{1s}$$

Do you know?

- Flow of current is directly proportional to the potential difference.
- Flow of heat is directly proportional to the temperature difference.
- Flow of fluid is directly proportional to the pressure difference.

For your information

Current is a flow of charge, pressured into motion by voltage and hampered by resistance.

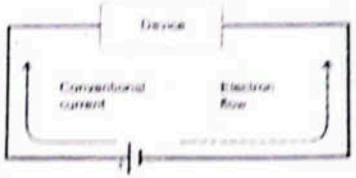
Fig. 9.22: Negative charge carriers

What is the cause of current in materials?

CHARGE CARRIERS IN DIFFERENT MEDIUMS:

Electric current is due to the flow of charge particles which are called **charge carriers**.

- **Metals:** In metals, charges carriers are negatively charge **electrons**.
- **Electrolytes:** In electrolytes, charge carriers are **positive** and **negative** ions, e.g. Cu^{++} and SO_4^{--} ions.
- **Gases:** In gases, charge carriers are **electrons** and **ions**.
- **Semiconductors:** In semiconductors, the charge carriers are **free electrons** and **holes**.



What is the difference between electronic and conventional current?

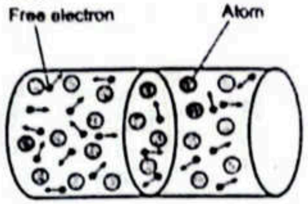
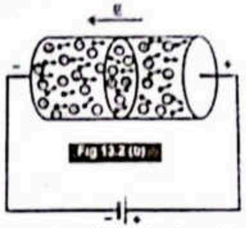
DIFFERENCE BETWEEN ELECTRONIC AND CONVENTIONAL CURRENT:

ELECTRONIC CURRENT	CONVENTIONAL CURRENT
• The electronic current in a circuit is defined as that current which passes from a point of low potential to a point of high potential as if it represents the movement of negative charges.	• The conventional current in a circuit is defined as that equivalent current which passes from a point of high potential to a point of low potential as if it represents the movement of positive charges.
• Electronic current represents the flow of negative charge (electrons).	• Conventional current represents the flow of positive charge.
• The flow of electronic current is directed from low potential (negative) to high potential (positive).	• The flow of conventional current is directed from high potential (positive) to low potential (negative).

Explain passage of current in metallic conductor.

CURRENT FLOW THROUGH A METALLIC CONDUCTOR

Let us discuss the flow of charges through metallic conductor in two different situations

When Battery is not Connected	When Battery is Connected
- When battery is not connected to a metal conductor, no electric field will be developed inside the metallic conductor. - As no field is present, free electrons will move randomly i.e. the rate of flow of charge through the wire is zero.	- When ends of the wire are connected to a battery, an electric field $\vec{E}$ will be set up at every point within the wire. - As electric field is present the free electrons will now experience a force in the direction opposite to $\vec{E}$. As a result of this force the free electrons acquire a motion in the direction of $-\vec{E}$
	 Fig 13.2 (b)
- The speed of randomly moving electrons depends upon temperature. The velocity of free electrons at room temperature due to their thermal motion is several hundred kilometers per second.	- The force experienced by the free electrons does not produce a net acceleration because of collision with the atoms, the electrons acquire an average velocity of the order of $10^{-3}ms^{-1}$ which is called the drift velocity in the direction of $-\vec{E}$.

DRIFT VELOCITY:

The **average uniform velocity** of electrons under the influence of an electric field is called drift velocity. It is of the order of $10^{-3}ms^{-1}$.

Steady Current:

A steady current is established in a wire when a **constant** potential difference maintains across the wire which generate the necessary electric field $\vec{E}$ along the wire.

SOURCE OF CURRENT:

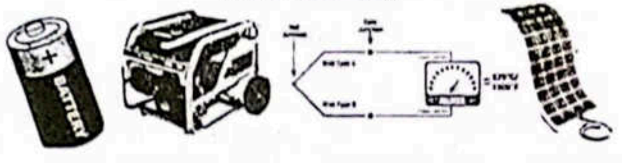
A source which produces a potential difference across the ends of a conductor is called a **source of current**.

TYPES OF SOURCES:

Every source of current converts some non-electrical energy such as chemical, mechanical, heat or solar energy into electrical energy. There are many types of sources of current. A few examples are mentioned below:

- **Cell:** It converts chemical energy into electrical energy.
- **Electric Generator:** It converts mechanical energy into electrical energy.
- **Thermo Couples:** It converts heat energy into electrical energy.
- **Solar Cell:** It converts light energy into electrical energy.

Sources of Current



TYPES OF CURRENT:

There are two types of current:

(i) Direct Current (DC)

(ii) Alternating current (DC)

DIRECT CURRENT (DC):

If the charges move around a circuit in the same direction at all times, the current is said to be direct current (D.C).

For example, batteries produce direct current.

ALTERNATING CURRENT (AC):

If the charges move first one way and then the opposite way, changing direction in regular intervals, the current is said to be alternating current (A.C).

Mostly the electric generators produce A.C

Note: The electricity supplied to our homes, offices, factories etc., by power stations is an A.C

9.11 CURRECT THROGH A CONDUCTOR:

Q. **Derive the expression for the current in a conductor.**

Ans

Consider a segment of a current-carrying conductor with length 'L' and cross-sectional area 'A'. Let 'n' be the number of charge carriers per unit volume, and 'q' be the charge on each carrier.

The volume of this segment is $A \times L$.

The total number of charge carriers in this segment is $N_{total} = n \times A \times L$.

The total charge in this segment is $Q = N_{total} \times q = nALq$.

If these charge carriers move with a drift velocity v_d, the time it takes for all of them to pass through a cross-section of the conductor is $t = L/v_d$.

The current (I) is $I = Q/t$:

$$I = (nALq)/(L/v_d)$$

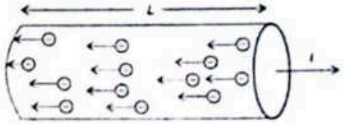
$$I = nAqv_d \qquad \text{(Equation 9.33)}$$

This equation relates current to the properties of the charge carriers and the conductor.

Define and explain drift velocity.

Drift Velocity:

- Electrons in a conductor move randomly at high speeds (around 10^6 m/s).
- When an electric field is applied, these electrons experience a net force in the direction opposite to the electric field (towards the positive terminal). This causes them to drift slowly in that direction, with an average speed called **drift velocity**.
- The drift velocity is very small, typically of the order of 10^{-4} m/s. This means it takes a long time for an individual electron to travel the length of a wire.
- However, the electric field itself propagates through the conductor at nearly the speed of light, which is why current seems to flow almost instantaneously when a switch is turned on



MULTIPLE CHOICE QUESTIONS

- **Electric current is defined as the:**
  (a) Flow of charge carriers.
  (b) Amount of charge per unit time passing through a cross-section of a conductor
  (c) Velocity of charge carriers. (d) Force on charge carriers

Answer: (b) Amount of charge per unit time passing through a cross-section of a conductor

Explanation: Current (I) is formally defined as the rate of flow of charge (Q) through a cross-sectional area per unit time (t): $I = Q/t$.

- **The SI unit of electric current is:**
  (a) Coulomb (C) (b) Volt (V) (c) Ampere (A) (d) Watt (W)

Answer: (c) Ampere (A)

Explanation: One Ampere is defined as one Coulomb of charge flowing per second (1 A = 1 C/s).

- **Conventional current is defined as the flow of:**

(a) Electrons from negative to positive
(b) Positive charges from positive to negative
(c) Neutral particles
(d) Any charge in any direction

Answer: (b) Positive charges from positive to negative

Explanation: Historically, conventional current was defined as the direction a positive charge would flow, from higher potential (positive terminal) to lower potential (negative terminal).

- **In a current-carrying conductor, the drift velocity of free electrons is typically:**

(a) Very high, close to the speed of light
(b) Very slow
(c) Equal to the speed of sound
(d) Zero

Answer: (b) Very slow

Explanation: While the electric field propagates very quickly, individual electrons have a very slow average drift velocity due to frequent collisions with atoms in the conductor.

- **The expression I=Anvq for current in a conductor relates current to:**

(a) Area, number of turns, voltage, charge
(b) Area, number of charge carriers per unit volume, drift velocity, charge
(c) Ampere, number of particles, voltage, quantity.
(d) Area, number of electrons, velocity, quantum

Answer: (b) Area, number of charge carriers per unit volume, drift velocity, charge.

Explanation: In the formula I=Anvq, 'A' is cross-sectional area, 'n' is charge carriers per unit volume, 'v' is drift velocity, and 'q' is the charge of each carrier.

SLO BASED SHORT QUESTIONS & ANSWERS

- **Define electric current.**

Ans: Electric current is the rate of flow of electric charge through a cross-section of a conductor per unit time

- **What is the difference between electron flow and conventional current?**

Ans: Electron flow describes the actual movement of negatively charged electrons from the negative terminal to the positive terminal, while conventional current is a historical convention defining current flow as the direction a positive charge would move, from the positive terminal to the negative terminal

- **What factors determine the current (I) in a conductor, according to the expression I=Anvq?**

Ans: The current (I) is determined by the cross-sectional area (A) of the conductor, the number of charge carriers per unit volume (n), the drift velocity (v) of the charge carriers, and the charge (q) of each carrier

- **Why does it take time for light to switch on after flipping a switch, even though electrons move very slowly?**

Ans: While the individual electrons move very slowly (drift velocity), the electric field (which propagates at nearly the speed of light) is established almost instantaneously throughout the circuit, pushing electrons already present in the filament to light up the bulb.

- **What is the SI unit of charge, and what is its value for an electron?**

Ans: The SI unit of charge is the Coulomb (C). The charge on an electron is $e = -1.6 \times 10^{-19}$ C

9.12 OHM'S LAW

Q. Explain Ohm's Law?

Ans

OHM'S LAW

- This law was given by German physicist "George Simon Ohm".
- Ohm's law gives a relationship between **voltage and current**.

STATEMENT:

The current flowing through a conductor is directly proportional to potential difference across its ends

Limitations of Ohm's law:

Ohm's law is only applicable when:

- **Temperature** is kept constant.
- **Dimensions** (length and area) of wire are constant.
- **Physical state** of the conductor is kept constant.

Mathematical form:

The Ohm's law can be expressed as;

$$I \propto V$$

$$I = \frac{1}{R}V$$

$$V = IR$$

Here,

R = Resistance
I = Current
V = Potential Difference

The opposition offered by the atoms of the conductor to the flow of electric current is called **resistance**.

Factor affecting resistance:

Resistance of the conductor depends upon the following factors:

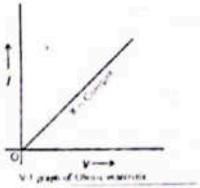
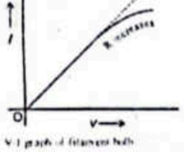
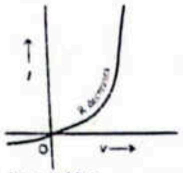
i. Nature of the material
ii. Length of the conductor ($R \propto L$)
iii. Area of the conductor $\left(R \propto \frac{1}{A}\right)$
iv. Temperature of the conductor ($R \propto T$)

Unit:

The SI unit of resistance is "Ohm". It is denoted by the symbol " Ω ".

1 Ohm: The resistance of the conductor is said to be 1ohm if a potential difference of 1 volt produces a current of 1 ampere in it.

Mathematically: $1\,\text{ohm} = \frac{1\,\text{volt}}{1\,\text{ampere}}$

OHMIC DEVICES	NON-OHMIC DEVICES
• The devices which **obey** Ohm's law are called Ohmic • For Ohmic devices, current is **directly** proportional to the voltage($I \propto V$). • In this type of devices, resistance **remains constant**. • V-I graph for ohmic devices is **straight line** • **Metallic conductors** are ohmic like **copper, silver, gold** etc.  V-I graph of Ohmic materials	• The devices which do **not obey** Ohm's law are called Non-Ohmic devices. • For non-ohmic devices current is **not directly proportional** to voltage • In this type of devices, resistance **does not remain constant**. • V-I graph for non-ohmic devices is **not straight** line. • **Semiconductor diode, tungsten filament** etc. are non-ohmic  V-I graph of filament bulb  V-I graph of diode

9.13 RESISTIVITY AND ITS DEPENDENCE UPON TEMPERATURE

Q. **What is the mathematical expression of resistance? Write its unit and on which factors it dependence?**

Ans

RESISTIVITY AND ITS DEPENDENCE UPON TEMPERATURE

It has been experimentally seen that the resistance of a conductor is directly proportional to its length 'L' and inversely proportional to its area of cross – section 'A'.

Mathematically:

$$R \propto L$$

$$R \propto \frac{1}{A}$$

Now, $$R \propto \frac{L}{A}$$

$$R = \rho\frac{L}{A} \qquad \text{..........(1)}$$

Where 'ρ' is the constant of proportionality which is called "Resistivity" or "Specific resistance" of the conductor. The resistance of a meter cube of a material is called **Resistivity**.

Unit: The SI unit of resistivity is **Ohm – meter** (Ωm).

DIFFERENCE BETWEEN RESISTANCE AND RESISTIVITY:

RESISTANCE	RESISTIVITY
i. The opposition offered to the flow of charge carriers by the conductor is called **resistance**. $R = \frac{V}{I}$	i. The resistance of the cubic meter of the material is called resistivity. $\rho = R\frac{A}{L}$
ii. Resistance is the characteristic of particular wire.	ii. Resistivity is the property of the material of which the wire is made of.
iii. Resistance depends upon the **nature, dimensions** (length and width) and **temperature** of conductor.	iii. Resistivity depends upon the **nature** and **temperature** of conductor, but independent of **dimensions** (length and width) of wire.

CONDUCTANCE:

The reciprocal of resistance is called conductance.

Mathematically,

It is denoted by G.

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

Unit: The SI unit of conductance is ohm^{-1}, which is also known as "mho" or "siemen"

CONDUCTIVITY:

The reciprocal of resistivity is called conductivity.

Mathematically,

It is denoted by 'σ'

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

Unit: The SI unit of conductivity is $ohm^{-1}m^{-1}$, Which is also known as "$mho - m^{-1}$"

DEPENDENCE OF RESISTANCE ON TEMPERATURE

The resistance of conductor is due to the **collisions** of electrons with the atoms of the conductor. As the temperature of the conductor rises, the K.E of the atoms increases and they vibrant with **greater amplitude**. Hence the probability of their collisions with free electrons also increases. So the electrons find it more difficult to pass through them. Thus the current in the circuit, which is due to the flow of electrons, decreases and we say that the resistance of the conductor has been increased.

TEMPERATURE COEFFICIENT OF RESISTANCE

"The fractional change in resistance per kelvin is called temperature co-efficient of resistance"

It is denoted by 'α'

Explanation:

Suppose,

R_0 = Resistance of conductor at 0°C

R_t = Resistance of conductor at t°C

$(R_t - R_0)$ = Change in resistance.

Experimentally,

It has been found that the change in resistance is directly proportional to the original resistance and the rise in temperature.

Mathematically,

$$(R_t - R_0) \propto R_0$$

$$(R_t - R_0) \propto t$$

Combine both above relations

$$(R_t - R_0) \propto R_0 t$$

$$(R_t - R_0) = \alpha R_0 t$$

$$\alpha = \frac{(R_t - R_0)}{R_0 t} \qquad \text{..........(1)}$$

Table 13.1

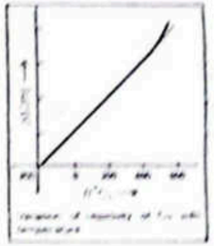
Substance	$\rho(\Omega m)$	$\alpha(K^{-1})$
Silver	1.52×10^{-8}	0.00380
Copper	1.54×10^{-8}	0.00393
Gold	2.27×10^{-8}	0.00340
Aluminium	2.63×10^{-8}	0.00390
Tungsten	5.25×10^{-8}	0.00450
Iron	11.00×10^{-8}	0.00500
Platinum	11.00×10^{-8}	0.00392
Constantan	49.00×10^{-8}	0.00001
Mercury	94.00×10^{-8}	0.00091
Nichrome	100.0×10^{-8}	0.00040
Carbon	3.5×10^{5}	-0.0005
Germanium	0.5	-0.05
Silicon	20-2300	-0.07

Since resistivity is directly proportional to the resistance, therefore, eq (1) in terms of resistivity can be expressed as

$$\alpha = \frac{(\rho_t - \rho_0)}{\rho_0 t}$$

In above equation 'α' is called the "**Temperature co-efficient of resistivity**"

Unit: The SI unit of temperature coefficient of resistivity 'α' is K^{-1}


Variation of resistivity of Cu with temperature

TYPES OF TEMPERATURE COEFFICIENT OF RESISTANCE:

i. **Positive Temperature coefficient (PTC):** Some substances have positive temperature coefficient. Its means that their resistance increases with increase in temperature.

$$(R \propto T)$$

For example: "α" is positive for metallic conductors like **copper, silver, gold** etc.

ii. **Negative Temperature coefficient (NTC):** Some substances have negative temperature coefficient. Its means that their resistance decreases with increase in temperature.

$$(R \propto \frac{1}{T})$$

For example: "α" is negative for semi-conductors like germanium, silicon etc.

iii. There are some substances whose resistance does not change with the temperature. That is why they are used to make standard resistors.

For example: "$\alpha = 0$" for alloys like **manganin** and **constantan** etc. Due to this property, constantan is used to make **standard resistors**.

For your information

Inspectors can easily check the reliability of a concrete bridge made with carbon fibers. The fibers conduct electricity. If sensors show that electrical resistance is increasing over time the fibers are separating because of cracks.

MULTIPLE CHOICE QUESTIONS

- Ohm's Law states that for a conductor, the current flowing through it is directly proportional to the:

(a) Resistance (b) Length

(c) Potential difference applied across its ends (d) Cross-sectional area

Answer: (c) Potential difference applied across its ends

Explanation: Ohm's Law is V∝I, or V=IR, where V is the potential difference and I is the current, implying direct proportionality between V and I for a given R.

- The SI unit of resistance is:

(a) Volt (V) (b) Ampere (A) (c) Ohm (Ω) (d) Watt (W)

Answer: (c) Ohm (Ω)

Explanation: The Ohm (Ω) is the SI unit of electrical resistance.

- **The resistance of a metallic conductor generally:**

  (a) Decreases as temperature increases. (b) Increases as temperature increases.

  (c) Remains constant with temperature (d) Depends only on its length.

Answer: (b) Increases as temperature increases.

Explanation: For most metallic conductors, increased thermal vibrations of atoms at higher temperatures hinder the flow of electrons, leading to increased resistance.

- **Resistivity (ρ) of a material is defined as resistance of a conductor with:**

  (a) Any length and area. (b) Unit length and unit area.

  (c) Unit length and any area. (d) Any length and unit area.

Answer: (b) Unit length and unit area

Explanation: Resistivity is an intrinsic property of a material, representing the resistance of a 1-meter cube of that material (R=ρL/A).

- **Which of the following materials typically has a resistance that decreases as light intensity increases?**

  (a) Thermistor (b) Light Dependent Resistor (LDR)

  (c) Copper wire (d) Nichrome wire

  ○ **Answer:** (b) Light Dependent Resistor (LDR)

  ○ **Explanation:** LDRs are semiconductors whose resistance decreases significantly when exposed to light, due to increased free charge carriers.

SLO BASED SHORT QUESTIONS & ANSWERS

- **State Ohm's Law.**

Answer: Ohm's Law states that for a given conductor at constant temperature, the current flowing through it is directly proportional to the potential difference applied across its ends.

- **Define 1 Ohm (Ω).**

Answer: 1 Ohm (Ω) is defined as the resistance of a conductor through which a current of 1 Ampere flows when a potential difference of 1 Volt is applied across its ends.

- **What factors determine the resistance of a wire, as given by its resistivity formula?**

Answer: The resistance (R) of a wire is directly proportional to its resistivity (ρ) and length (L), and inversely proportional to its cross-sectional area (A), given by R=ρL/A.

- **Explain why the resistance of a metallic conductor generally increases with temperature.**

Answer: As the temperature of a metallic conductor increases, the atoms within its lattice vibrate more vigorously. These increased vibrations cause more frequent collisions with the flowing free electrons, impeding their movement and thus increasing the material's electrical resistance.

- **What is a Light Dependent Resistor (LDR) and how does its resistance change with light intensity?**

Answer: A Light Dependent Resistor (LDR) is a semiconductor device whose resistance decreases as the intensity of light falling on it increases. This is because more light provides more energy for electrons to break free and become charge carriers.

9.14 ELECTRICAL POWER

Q. **What is Electrical Power (P)? Explain and derive its relations.**

Ans

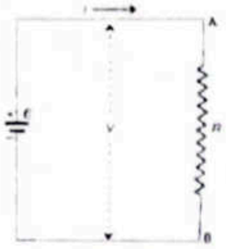
ELECTRICAL POWER (P)

The rate at which the battery is supplying electrical energy is called **power output** or **electrical power** of the battery -OR-

The rate at which work is done to maintain the steady current in a circuit is called **Electric power**

MATHEMATICAL EXPRESSION:

$$\text{Electric power} = \frac{\text{Energy supplied}}{\text{Time taken}} \qquad \text{.......... -i-}$$



Consider a circuit consisting of a battery E connected in series with a resistance R as shown in Fig. In this circuit the battery is continuously **lifting charge** uphill through the potential difference V.

Using the meaning of potential difference, the work done in moving a **charge Q** up through the potential difference V is given by.

$$\text{Work done} = \Delta W = V \times \Delta Q \qquad \text{.......... -ii-}$$

This is the energy supplied by the battery.

By putting the value of equation (ii) in equation (i)

$$\text{Electric power} = \frac{\text{Energy supplied}}{\text{Time taken}}$$

$$P = \frac{\Delta W}{\Delta t}$$

$$P = \frac{V \times \Delta Q}{\Delta t} \qquad \text{.......... -iii-}$$

As we know that;

$$\therefore I = \frac{\Delta Q}{\Delta t}$$

so, equation (iii) becomes;

$$P = V \times I$$

POWER DISSIPATION:

The power supplied by the battery is **expended or dissipated in the resistor R** this is called Power dissipation.

According to law of conservation of energy;

$$\text{Dissipated power} = \text{Electrical power}$$

$$\mathbf{P = VI}$$

According to ohm's law; $\therefore V = IR$

Therefore, above equation becomes,

$$P = (IR)I$$

$$P = I^2R \qquad \text{.......... -iv-}$$

From ohm's law, $I = \frac{V}{R}$

therefore, equation no. iv becomes;

$$P = \left(\frac{V}{R}\right)^2 R$$

$$P = \frac{V^2}{R} \qquad \text{.......... -v-}$$

UNIT: SI unit of electric power is watt.

ONE WATT: If **one ampere current** passes through a conductor due to applied potential difference of **one volt**, then the power would be **one watt**.

9.15 ELECTROMOTIVE FORCE (EMF) AND POTENTIAL DIFFERENCE

Q. **What is Electromotive Force (EMF, E)?**

Ans

ELECTROMOTIVE FORCE (EMF):

The energy supplied to a unit positive charge by the cell in moving it from negative to positive electrode inside the source is called electromotive force (EMF).

FORMULA:

$$E = \frac{\Delta W}{\Delta Q}$$

EXPLANATION:

When a source of electrical energy i.e. a cell or battery is connected across a resistance "R", it maintains a steady current through it.

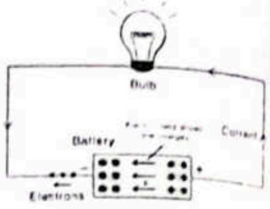
The cell supplies energy which is used in the resistance of the circuit.

Suppose "ΔQ" charge passes through the circuit in a time " Δt ".

This charge enters the cell at its **lower potential end** and leaves at its **high potential end**.

The source supplies the energy "ΔW" to positive charge to move the charge from **low potential** to the **high potential** which is given by,

$$E = \frac{\Delta W}{\Delta Q}$$



SOURCE OF EMF:

The energy supplied by the cell to the charge carriers comes from the conversion of chemical energy into electrical energy.

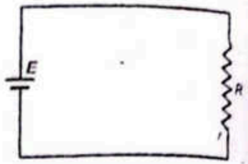
UNIT:

It may be noted that electromotive force is not a force and we do not measure it in 'Newton'.

$$E = \frac{\Delta W}{\Delta Q}$$

$$E = \frac{\text{Joule}}{\text{Coulomb}}$$

$$E = \text{Joule Per Coulomb} = \textbf{Volt}$$



So, the unit of EMF is **joule/coulomb**.

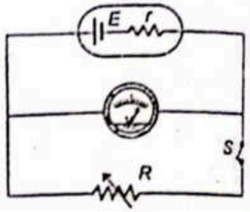
Which is also called **volt.**

It is denoted by(V).

INTERNAL RESISTANCE

"This resistance offered by electrolyte present between two electrodes of a cell to the flow of ions is called internal resistance of the cell.

It is denoted by "r"



It is defined as "The potential difference between the terminals of battery or cell when it is giving current to an external circuit is called terminal potential difference".

RELATION BETWEEN EMF & POTENTIAL DIFFERENCE:

Voltmeter measures the potential difference across the external resistance " R ".

The current " I " flowing through the circuit is given by,

$$I = \frac{E}{R+r} \qquad \therefore V = E \text{ and } V = IR$$

So,

$$E = I(R+r)$$

$$E = IR + Ir$$

Here,

"IR" is the terminal potential difference of the cell when current "I " is flowing in the circuit

"Ir" is the potential difference across the internal resistance of the cell.

$$E = V_t + Ir$$

EXPLANATION OF THE EQUATION ON THE BASIS OF ENERGY:

$$E = V_t + Ir$$

- The left side of the above equation is the EMF of the cell.

(This is equal to the energy gained by the unit charge as it passes through the cell from negative to positive terminal)

- The right side states that "Ir" is **energy dissipated** into the cell as **heat**.
- "IR" is rest of **energy is dissipated** into the external resistance "R "

SPECIAL CASES:

Open Circuit:

When switch " S " is open no current passes through the resistance, so the voltmeter read the EMF as terminal potential difference

Means internal resistance of cell is zero.

$$E = V_t + I(0)$$

$$E = v_t$$

Closed Circuit:

When switch "S" is closed, current "I" is passing through the resistance, so the terminal potential difference is less than the EMF by the factor of "Ir".

$$V_t = E - Ir$$

$$V_t < E$$

Charging of a Battery:

When battery is being charged, then the current flows in opposite direction to the current produced by the battery.

So,

$$V_t = E - (-Ir)$$

$$V_t = E + Ir$$

So, the **terminal potential difference is greater** than the EMF of battery

$$V_t > E$$

Consequences of Internal Resistance:

- The terminal potential difference (V) is always less than the EMF (E) when current is drawn from the source
- The terminal potential difference equals the EMF only when the current 'I' is zero (open circuit)
- When a source is short-circuited (R = 0), the current can become very large (I=E/r), potentially damaging the source.

COMPARISON BETWEEN ELECTROMOTIVE FORCE (EMF) AND POTENTIAL DIFFERENCE:

ELECTROMOTIVE FORCE (EMF)	POTENTIAL DIFFERENCE
• It is a **gain** of energy per unit charge when charge move through the battery $E = \frac{\Delta W}{\Delta Q}$	• It is a **loss** of energy per unit charge when charge move through the resistor. $V = \frac{\Delta W}{\Delta Q}$
• EMF pushes the charge from **low** potential to the **high** potential.	• Potential difference pushes the charge from **high** potential to the **low** potential.
• EMF is measured in "**volt**".	• Potential difference is also measured in "**volt**".
• EMF is **independent** of the **resistance**.	• Potential difference **depends upon resistance**.
• EMF is the **cause**.	• Potential difference is the **effect**.

MAXIMUM OUTPUT POWER:

In the circuit as shown, as the current "I" flow through "R", the charges flows from a point of **higher potential** to a point of **lower potential**, they **lose potential energy**.

If " V " is the potential difference across "R" the **loss** of potential energy per second (power) is "VI".

The loss of energy per second appears in the other forms of energy and is known as **power delivered** to "R" by current "I".

Power delivered to " R "

$$P_{out} = VI$$

$$P_{out} = (IR)I$$

So,

$$P_{out} = I^2 R$$

As

$$I = \frac{E}{R+r}$$

So,

$$P_{out} = \left(\frac{E}{R+r}\right)^2 R$$

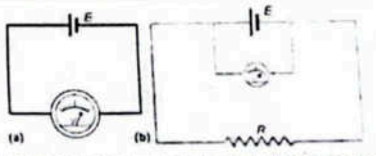
$$P_{out} = \frac{E^2 R}{(R+r)^2}$$

As the square of $(R+r)^2 = R^2 + r^2 + 2Rr$

Now,

If $\qquad (R-r)^2$ then $(R-r)^2 = R^2 + r^2 - 2Rr$

Do you know?



A voltmeter connected across the terminals of a cell measures
(a) the emf of the cell on open circuit.
(b) the terminal potential difference on a closed circuit

Add 4Rr in both sides $(R-r)^2 + 4\mathbf{Rr} = R^2 + r^2 - 2Rr + 4\mathbf{Rr}$

Now, $(R-r)^2 + 4\mathbf{Rr} = R^2 + r^2 + 2Rr$

So $(R-r)^2 + 4\mathbf{Rr} = (R+r)^2$

So,

$$P_{out} = \frac{E^2R}{(R-r)^2+4Rr}$$

Condition for Maximum Power:

When R = r (load resistance is equal to the internal resistance of battery) then the power output becomes maximum.

$$P_{out} = \frac{E^2R}{(R-r)^2+4Rr}$$

$$P_{out} = \frac{E^2R}{(r-r)^2+4R(R)}$$

$$P_{out} = \frac{E^2R}{(0)^2+4R^2}$$

$$P_{out} = \frac{E^2}{4R} = \frac{E^2}{4r}$$

This is the maximum output power delivered to a load resistance.

Ponder upon!

Does a dry cell have internal resistance?

Answer: Yes, all real power sources, including a dry cell, have internal resistance. This resistance comes from the chemical processes and materials within the cell itself, which oppose the flow of charge.

MULTIPLE CHOICE QUESTIONS

- **Electrical power (P) consumed by a resistor is given by all of the following expressions EXCEPT:**
  (a) P=IV (b) P=I²R (c) P=V²/R (d) P=V/I

Answer: (d) P=V/I

Explanation: V/I is resistance (R), not power. The other three are correct formulas for electrical power.

- **The electromotive force (EMF) of a battery is defined as the:**
  (a) Voltage across its terminals when a current is flowing
  (b) Maximum potential difference it can provide when no current is drawn
  (c) Energy dissipated in its internal resistance (d) Current it can supply.

Answer: (b) Maximum potential difference it can provide when no current is drawn.

Explanation: EMF is the work done by the source per unit charge to move charge from its lower potential to its higher potential terminal, representing the maximum potential difference available when the circuit is opens (no current)

- **The SI unit of electrical power is:**
  (a) Joule (J) (b) Volt (V) (c) Ampere (A) (d) Watt (W)

Answer: (d) Watt (W)

Explanation: One Watt (W) is defined as one Joule per second (1 W=1 J/s).

- **The terminal potential difference (V) of a battery is always less than its EMF (E) when:**
  (a) The battery is being charged. (b) No current is flowing through the external circuit.
  (c) Current is being drawn from the battery. (d) The external resistance is zero.

Answer: (c) Current is being drawn from the battery.

Explanation: When current flows, there's a voltage drop across the battery's internal resistance (Ir), so the terminal potential difference is E−Ir, which is less than E.

- **The electrical energy consumed by a bulb connected to a battery comes from:**
  (a) The resistance of the bulb (b) The current flowing through the bulb.
  (c) The work done by the battery in moving charge
  (d) The potential difference across the bulb

Answer: (c) The work done by the battery in moving charge.

Explanation: The battery does work (energy supplied per unit charge) to push charges through the external circuit, and this energy is consumed (dissipated as heat and light) by the bulb.

SLO BASED SHORT QUESTIONS & ANSWERS

- **Define electrical power.**

Ans: Electrical power is the rate at which electrical energy is supplied by a source or dissipated by a component in an electrical circuit.

- **Write down the three common formulas for calculating electrical power.**

Ans: The three common formulas are P=IV, P=I²R, and P=V²/R

- **What is the electromotive force (EMF) of a source?**

Ans: The electromotive force (EMF) of a source (like a battery) is the maximum potential difference it can provide across its terminals when no current is flowing through the external circuit (i.e., when the circuit is open). It's the energy supplied per unit charge.

- **Explain the concept of internal resistance of a source.**

Ans: Internal resistance is the opposition to the flow of current within the source itself (e.g., within a battery due to its electrolyte). It causes a voltage drop when current flows, meaning the terminal potential difference is less than the EMF.

- **Under what condition is the terminal potential difference of a battery equal to its EMF?**

Ans: The terminal potential difference of a battery is equal to its EMF when no current is flowing through the external circuit (i.e., the circuit is open or the external resistance is infinite), because there is no voltage drop across the internal resistance (Ir=0).

9.16 KIRCHHOFF'S RULES

Q. State and explain Kirchhoff's Rules.

Ans

KIRCHHOFF'S RULES

A simple electrical circuit may consist of more than one resistances but a single voltage source. A simple circuit can be solved by using:

- Ohm's Law
- Rules of series and parallel combinations of resistance.

When an electrical circuit consists of number of resistances and a number of electrical voltage sources, then such circuit is called complex network.

- A complex network can be solved by using the "**Kirchhoff's Rules**".

There are two types:

- Kirchhoff's 1st Rule and
- Kirchhoff's 2nd Rule

Do you know?

The node at which potential is taken as zero is called datum node or reference node.

KIRCHHOFF'S FIRST RULE (KCL):

Statement: "Sum of all the currents meeting at a point in the circuit is zero".

It is also called "**Kirchhoff's current law**".

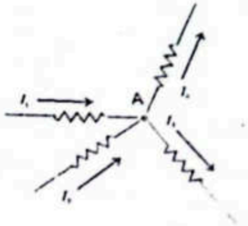
Mathematically:

$\Sigma I = 0$"The sum of all the current flowing towards a point is **equal** to the sum of all the currents flowing away from the point." 1" rule

$$I_1 + I_2 = I_3 + I_4$$

EXPLANATION:

Consider a circuit where four wires meet at a point A as shown in fig. The currents I_1 and I_2 are flowing towards the point A and current



According to the convention current flowing towards a point is taken as **positive** and that flowing away from a point A taken as **negative**.

Apply Kirchhoff's 1st rule, we have

$$I_1 + I_2 + (-I_3) + (-I_4) = 0$$

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

$$I_1 + I_2 = I_3 + I_4$$

CONVENTION

i. The current flowing **towards** a point is taken as **positive**.
ii. The current flowing **away** from a point is taken as **negative**

LAW OF CONSERVATION OF CHARGE:

Kirchhoff's first law is also known as **Kirchhoff's point rule** which verify the law of **conservation of charge**. "If there is no sink or source of charge at the point, then total charge flowing towards the point **must be equal to** the total charge flowing away from the point

$$I_1 + I_2 = I_3 + I_4$$

As we know that

$$\because I = \frac{Q}{t}$$

$$\frac{Q_1}{t} + \frac{Q_2}{t} = \frac{Q_3}{t} + \frac{Q_4}{t}$$

$$\frac{1}{t}(Q_1 + Q_2) = \frac{1}{t}(Q_3 + Q_4)$$

$$Q_1 + Q_2 = Q_3 + Q_4$$

KIRCHHOFF'S SECOND RULE (KVL):

Statement: "The algebraic sum of all potential changes (voltage drops and gains) in a closed circuit loop is zero."
Mathematically: $\sum\Delta V = 0$ (Equation 9.48)

Consequence: Kirchhoff's second rule is a direct consequence of the conservation of energy. For any closed loop, the total energy gained by a unit charge from sources of EMF must be equal to the total energy lost by that unit charge as it passes through resistors and other components.

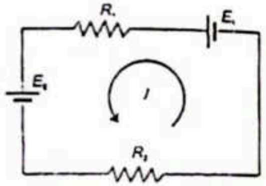
"The algebraic sum of voltage changes in a closed circuit or a loop must be equal to zero".

It is also called "**Kirchhoff's Voltage law**".

Mathematically:

$$\sum V = 0$$

EXPLANATION:



Consider a closed circuit as shown in figure. The direction of current I flowing through the circuit depends upon the cell having the greater EMF. Suppose E_1 is greater than E_2 ($E_1>>E_2$) so, the current flows in the anti-clockwise direction.

- When a positive charge **ΔQ** due to the current I in the closed circuit passes through the cell E_1 from **low to high potential, it gains energy,** because the work is done on it.
  ∴ The gained energy is $\mathbf{E_1\Delta Q}$
- When the current passes through the cell $\mathbf{E_2}$ it **loses energy** equal to $-\mathbf{E_2\Delta Q}$, because here charge passes from **high potential to low potential**.
- In going through the resist or $\mathbf{R_1}$ the charge **ΔQ** loses energy equal to $-\mathbf{IR_1\Delta Q}$.
- Similarly, the loss of energy while passing through the resistor $\mathbf{R_2}$ is $-\mathbf{IR_2\Delta Q}$.

Finally, the charge reaches the **negative** terminal of the cell $\boldsymbol{E_1}$ from where we started.

According to the **law of conservation of energy** the total charge in energy of system is zero.

So, we can write

$$E_1\Delta Q + (-IR_1\Delta Q) + (-E_2\Delta Q) + (-IR_2\Delta Q) = 0$$
$$\Delta Q\,(E_1 - IR_1 - E_2 - IR_2) = 0$$
$$(E_1 - IR_1 - E_2 - IR_2) = 0 \text{ and } \Delta Q \neq 0$$
$$\mathbf{(E_1 - IR_1 - E_2 - IR_2) = 0}$$

Kirchhoff's 2nd rule is the manifestation (explanation) of **law of conservation of energy**.

SIGN CONVENTION FOR KIRCHHOFF'S SECOND RULE:

When traversing a closed loop:

○ **For an EMF source (battery):** If you travel from the negative terminal to the positive terminal (a voltage gain), the EMF is taken as **positive (+E)**.

○ If you travel from the positive terminal to the negative terminal (a voltage drop), the EMF is taken as **negative (-E)**.

○ **For a Resistor (R):** If you travel in the **same direction as the assumed current (I)** (a voltage drop, as current flows from high to low potential), the potential change is taken as **negative (-IR)**.

○ If you travel in the **opposite direction to the assumed current (I)** (a voltage gain, moving from low to high potential), the potential change is taken as **positive (+IR)**.

Question: Explain procedure of solution of circuit problems.

Procedures for Solution of Circuit Problems using Kirchhoff's Rules:

Following steps are used to analyze the direct current complex circuits.

1. **Draw Circuit Diagram:** Draw a clear circuit diagram.
2. **Assign Currents:** Assume a direction for the current in each branch. If your assumed direction is wrong, the calculated current will be negative.
3. **Apply KCL:** At each junction, apply Kirchhoff's Current Law ($\sum I=0$).
4. **Apply KVL:** For each selected closed loop (choose enough loops to include all components), apply Kirchhoff's Voltage Law ($\sum\Delta V=0$) using the sign conventions.
5. **Solve Equations:** Solve the simultaneous equations obtained from KCL and KVL to find the unknown currents or voltages.

9.17 WHEATSTONE BRIDGE

Q. **What is a Wheatstone Bridge? Explain its construction and working.**

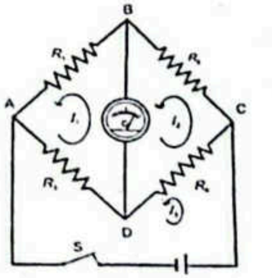
Ans

WHEATSTONE BRIDGE

It is an electric circuit that is used to measure the value of an unknown resistance accurately.

It was first suggested by **Charles Wheatstone** in **1833**.

CONSTRUCTION:



- The **Wheatstone bridge** circuit consists of four resistances R_1, R_2, R_3 *and* R_4 connected in such a way so as to form a loop ABCDA as shown in figure.
- A battery of EMF is connected between points *A* and *C*
- A **sensitive galvanometer** of resistance $\boldsymbol{R_g}$ is connected between points B and D.

WORKING:

When the switch S is closed a current will flow through the galvanometer.

We are to determine the condition under which **no current** will flow through the galvanometer even after the key is closed.

We consider the loops ABDA, BCDB and ADCA

We assume anti-clockwise loop currents

- I_1 through the loop ABDA
- I_2 through the loop BCDB
- I_3 through the loop ADCA

BALANCED CONDITION:

Adjust the resistances in such a way that galvanometer shows no deflection.

This null deflection is known as the **principle of Wheatstone bridge**.

LOOP ABDA	LOOP BCDB
By applying Kirchhoff's 2nd rule $-I_1R_1-(I_1-I_2)R_g-(I_1-I_1)R_3=0$ ..... i According to balanced condition $I_1=I_2=I$ So, equation (i) becomes; $-IR_1-(I-I_1)R_3=0$ $-IR_1=(I-I_1)R_3$ iii	By applying Kirchhoff's 2nd rule $-I_2R_2-(I_2-I_1)R_g-(I_2-I_1)R_4=0$ .... ii According to balanced condition $I_1=I_2=I$ So, equation (ii) becomes, $-IR_2-(I-I_1)R_4=0$ $-IR_2=(I-I_1)R_4$ iv

By dividing equation (iii) and equation (iv)

$$\frac{-IR_1}{-IR_2}=\frac{(I-I_1)R_3}{(I-I_1)R_4}$$

$$\frac{R_1}{R_2}=\frac{R_3}{R_4}$$

DETERMINATION OF UNKNOWN RESISTANCE:

- ✓ If one of the resistances say R_4 is unknown
- ✓ The other resistances R_1, R_2 and R_3 of known adjustable values.
- ✓ Known resistances R_1, R_2 and R_3 are so adjusted that the galvanometer shows no deflection
- ✓ The unknown resistance R_4 can be determined by;

$$R_4=\frac{R_2}{R_1}\times R_3$$

Point to ponder!

Why is a three-pin plug used in domestic electric appliances?

Answer: A three-pin plug is used for safety reasons. The third (longer) and thicker pin is the earth wire (ground wire). It is connected to the metal casing of the appliance. In case of a fault where a live wire touches the metal casing, the earth wire provides a low-resistance path for the current to flow directly to the ground. This prevents the casing from becoming live and delivering an electric shock to anyone who touches it. It also causes a large current to flow, tripping a circuit breaker or blowing a fuse, thus disconnecting the power.

Point to ponder!

Why is a three pin plug used in some electric appliances?

MULTIPLE CHOICE QUESTIONS

- **Kirchhoff's First Rule (Junction Rule or Current Law) is a consequence of the conservation of:**
  (a) Energy (b) Momentum (c) Charge (d) Mass

Answer: (c) Charge

Explanation: The Junction Rule states that the sum of currents entering a junction equals the sum of currents leaving it, directly reflecting that charge cannot accumulate or be lost at a junction.

- **Kirchhoff's Second Rule (Loop Rule or Voltage Law) is a consequence of the conservation of:**
  (a) Charge (b) Energy (c) Power (d) Current

Answer: (b) Energy

Explanation: The Loop Rule states that the algebraic sum of potential changes around any closed loop in a circuit is zero, which is a statement of energy conservation for charges moving around a closed path.

- **The Wheatstone bridge circuit is primarily used to:**
  (a) Amplify voltage signals. (b) Measure an unknown resistance
  (c) Convert AC to DC. (d) Store electrical energy.

Answer: (b) Measure an unknown resistance

Explanation: The Wheatstone bridge is designed to precisely measure an unknown electrical resistance by balancing it against known resistances.

- **According to Kirchhoff's First Rule, the sum of all currents meeting at a point in the circuit is:**
  (a) Constant (b) Zero (c) Maximum (d) Minimum

Answer: (b) Zero

Explanation: The rule states that ΣI=0 at any junction (currents entering are positive, leaving are negative, or sum of entering = sum of leaving)

- **In a balanced Wheatstone bridge, the galvanometer shows:**
  (a) Maximum current (b) No deflection (zero current)
  (c) A fluctuating current (d) A large voltage

Answer: (b) No deflection (zero current)

Explanation: A Wheatstone bridge is balanced when the potential difference across the galvanometer is zero, leading to no current flow through it.

SLO BASED SHORT QUESTIONS & ANSWERS

- **State Kirchhoff's First Rule (Junction Rule).**

Ans: Kirchhoff's First Rule (Junction Rule) states that the algebraic sum of all currents meeting at any junction (point) in an electrical circuit is zero (i.e., total current entering equals total current leaving)

- **State Kirchhoff's Second Rule (Loop Rule).**

Ans: Kirchhoff's Second Rule (Loop Rule) states that the algebraic sum of the changes in potential (voltages) around any closed loop in an electrical circuit is zero.

- **Why is the Wheatstone bridge considered a "null method" for measuring resistance?**

Ans: It is considered a "null method" because it determines the unknown resistance by adjusting known resistances until a null (zero) deflection is observed on a galvanometer, indicating a balanced condition and precise measurement.

- **What fundamental conservation law is the basis for Kirchhoff's First Rule?**

Ans: Kirchhoff's First Rule (Current Law) is based on the law of **conservation of electric charge** .

- **What fundamental conservation law is the basis for Kirchhoff's Second Rule?**

Ans. Kirchhoff's Second Rule (Voltage Law) is based on the law of **conservation of energy**.

9.18 POTENTIOMETER

Q. **What is a Potentiometer? What is its Working Principle? Why is it preferred over a Voltmeter? What are Applications of Potentiometer?**

Ans

POTENTIOMETER:

A potentiometer is a simple instrument, which can be used to measure and compare potential differences accurately without drawing current from the circuit.

Principle:

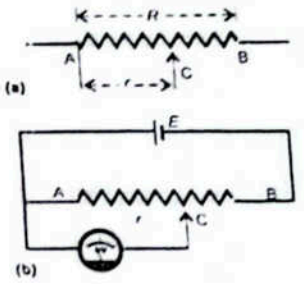
The potentiometer is based on the principle that:

If constant current flows through a wire of uniform cross sectional area, then potential difference between any two points is directly proportional to its length.($V \propto l$)

Construction:

A potentiometer consists of a long wire AB in the form of four segments stretched over a wooden board on which a sliding contact C can slide as shown in the figure.

The wire AB has a resistance R while the resistance between A and C can be varied from 0 to R as the sliding contact C is moved from A to B. A battery of emf is connected across R.



Q: What are the uses of potentiometer?

Uses Of Potentiometer:

i. The potentiometer is used to measure and compare potential differences.

ii. The potentiometer is used as a potential divider.

iii. The potentiometer is used to find the unknown emf of a source.
iv. The potentiometer is used to compare emf's of two sources.
v. The potentiometer is used to find the internal resistance of the cell or battery.

Potentiometer as a Potential Divider:

If a battery of EMF E is connected across R, as shown in the fig;

Then current flowing through R, $I = \frac{E}{R}$

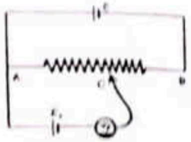
If resistance between points A and C is 'r', then;

Potential drop across, $V = Ir$

Or $V = \frac{E}{R}r = \frac{Er}{R}$

Thus as C is moved from A to B, 'r' varies from 0 to R and potential drop between A and C changes from 0 to E such arrangement is known as potential divider.

Measurement Of Unknown EMF Of A Source:



The circuit to measure the unknown emf E_x is shown in figure, the E_x is connected between the points A and C through a galvanometer 'G'.

To measure the potential E_x, the position of C is so adjusted that the galvanometer shows no deflection. Under this condition, the emf E_x of the cell is $V_{AC} = \frac{l}{L}V$

If $V_{AC} = Ex$

And $V = E$

Then,

$$E_x = \frac{l}{L}E$$

Where l = length of wire from A to C

And L = total length of wire AB

Comparison Of Emf's Of Sources:

The method for measuring the emf of a cell can be used to compare the emfs of two cells.

Let l_1 be the balancing length corresponding to a cell of emf E_1, then;

$$E_1 = \frac{El_1}{L}$$

Similarly, l_2 be the balancing length corresponding to other cell of emf E_2, then;

$$E_2 = \frac{El_2}{L}$$

Dividing these equations, we get;

$$\frac{E_1}{E_2} = \frac{l_1}{l_2}$$

So the ratio of the emf is equal to the ratio of the balancing lengths.

Q: Why ordinary voltmeter cannot measure accurate potential difference and which device is used for the purpose?

Ordinary voltmeter cannot measure accurate potential difference because it draws current from circuit for its working.

For accurate measurement of potential, we need a device which has its operating voltage or battery such devices are:

(1) Oscilloscope **(Complex device)**
(2) Digital voltmeter **(Complex device)**
(3) Potentiometer **(simple device)**

COMPARISON OF POTENTIOMETER AND VOLTMETER:

POTENTIOMETER	VOLTMETER.
• It measures the unknown **emf very accurately**.	• It measures the unknown **emf approximately**.
• While measuring emf it **does not draw** any current from the driving source of known emf.	• While measuring emf **it draws** some current from the source of emf.
• While measuring unknown potential difference the resistance of potentiometer becomes **infinite**.	• While measuring unknown potential difference the resistance of voltmeter is **high but finite**.
• It is based on **zero deflection** method.	• It is based on **deflection** method.
• It has a **high sensitivity**.	• Its sensitivity is **low.**
• It is used for various applications like measurement of **internal resistance of cell, calibration** of **ammeter** and **voltmeter,** measurement of thermo emf, **comparison of emf's** etc.	• It is only used to measure emf or unknown potential difference.

Why is potentiometer preferred over a Voltmeter?

A potentiometer is generally considered a more accurate measuring instrument than a voltmeter, especially for small potential differences. This is because a potentiometer uses a null method, meaning it draws no current from the circuit under test when a balance is achieved. A voltmeter, on the other hand, draws a small current, which can alter the potential difference being measured, leading to inaccuracies. An ideal voltmeter would have infinite resistance, while a potentiometer effectively has infinite resistance at the null point.

9.19 USES OF GALVANOMETER:

What is a Galvanometer? What is its role in null Method? Write down null method applications.

GALVANOMETER

A galvanometer is an instrument designed for detecting and measuring small electric currents. It is often used in null methods in circuits.

Role in Null Methods:

- In null methods (like with a Wheatstone bridge or potentiometer), the galvanometer is used to indicate a **zero deflection**.
- When the galvanometer shows no deflection, it indicates that no current is flowing through it. This implies that the electrical potentials at both ends of the galvanometer are the same, establishing a condition of balance.
- Although a galvanometer has its own resistance, at the null reading, its resistance does not come into play because no current is passing through it. This makes null methods very precise.

Null Method Applications:

- **Wheatstone Bridge:**
    - Measures unknown resistance.
    - Galvanometer connected between mid-points of opposite sides.
    - Variable resistance adjusted until galvanometer shows no deflection (balanced bridge).
    - Unknown resistance calculated using ratio of known resistances.
- **Potentiometer:**
    - Measures unknown voltage by comparison with a known reference voltage.
    - Galvanometer and jockey used to make contact along the resistance wire.
    - At null point, potential difference between jockey and wire end equals unknown voltage.
    - Jockey's position gives the unknown voltage measurement.

Advantages of Galvanometer in Null Method:

1. **Accuracy:** Eliminates the effect of the galvanometer's internal resistance, leading to more accurate readings.
2. **Sensitivity:** Highly sensitive, capable of detecting very small currents (order of 10-6 ampere).
3. **Clarity:** "No deflection" provides a direct and clear indication of balance, simplifying null point identification.

MULTIPLE CHOICE QUESTIONS

- **A potentiometer is primarily used to:**
  (a) Measure current directly.
  (b) Compare potential differences or measure unknown EMFs.
  (c) Measure resistance. (d) Convert AC to DC.

Answer: (b) Compare potential differences or measure unknown EMFs.

Explanation: Potentiometers are null-method devices used for very accurate measurements of potential differences and EMFs without drawing current from the source.

- **The principle of a potentiometer relies on:**
  (a) Ohm's Law.
  (b) The voltage drop along a uniform wire being proportional to its length.
  (c) Kirchhoff's current law.
  (d) The resistance of a conductor being proportional to its area.

Answer: (b) The voltage drop along a uniform wire being proportional to its length.

Explanation: A potentiometer works by comparing an unknown potential difference to a known potential difference across a precisely measured length of a uniform resistance wire.

- **In null methods, a galvanometer is used to:**
  (a) Measure precise current values.
  (b) Detect the presence of a current or zero current.
  (c) Provide a variable resistance. (d) Amplify voltage.

Answer: (b) Detect the presence of a current or zero current.

Explanation: In null methods (like the Wheatstone bridge or potentiometer), the galvanometer indicates when the current is zero, signifying a balanced condition.

- **An ideal voltmeter would have:**
  (a) Zero resistance. (b) Infinite resistance.
  (c) Very low resistance. (d) Resistance equal to the circuit being measured.

Answer: (b) Infinite resistance.

Explanation: An ideal voltmeter has infinite resistance so that it draws no current from the circuit branch it is measuring, thereby not altering the potential difference it is meant to measure.

- **When a potentiometer is in balance (null deflection), the current drawn from the unknown source is:**
  (a) Maximum. (b) Minimum but non-zero. (c) Zero. (d) Variable.

Answer: (c) Zero.

Explanation: The key advantage of a potentiometer is that it measures potential difference or EMF when no current is being drawn from the source, making the measurement highly accurate.

SLO BASED SHORT QUESTIONS & ANSWERS

- **What is the primary function of a potentiometer?**

Ans: The primary function of a potentiometer is to accurately compare potential differences or to measure the electromotive force (EMF) of a cell without drawing any current from it.

- **Explain the basic principle behind the working of a potentiometer.**

Ans: The potentiometer works on the principle that the potential difference across any portion of a uniform wire carrying a constant current is directly proportional to the length of that portion of the wire.

- **Why is a galvanometer often used in "null methods" in electrical measurements?**

Ans: A galvanometer is used in "null methods" to detect the presence or absence of a very small current. When the galvanometer shows zero deflection (the "null point"), it indicates that no current is flowing through that part of the circuit, which is crucial for accurate measurements (e.g., in a balanced bridge or potentiometer).

- **What is an "ideal voltmeter," and what is its resistance?**

Ans: An ideal voltmeter is a hypothetical voltmeter that would have infinite resistance, allowing it to measure potential difference across a component without drawing any current from the circuit branch.

- **What advantage does a potentiometer offer over a simple voltmeter for measuring EMF?**

Ans: A potentiometer offers the advantage of measuring the EMF of a source without drawing any current from it (a null method). This avoids any voltage drop across the source's internal resistance, leading to a more accurate measurement of its true EMF compared to a voltmeter that draws some current.

9.20 THERMISTORS

Q. What are Thermistors?

Ans

THERMISTORS

Thermistors are heat-sensitive resistors. They are made of semiconducting materials whose resistance changes significantly with temperature.

TYPES OF THERMISTORS:

1. **Negative Temperature Coefficient (NTC) Thermistors:** Most common type. Their resistance **decreases** as temperature increases. This is because rising temperature provides more thermal energy to the charge carriers (electrons and holes), enabling them to move more freely and thus reducing resistance.
2. **Positive Temperature Coefficient (PTC) Thermistors:** Their resistance **increases** as temperature increases.

Fig. 9.34 Thermistors symbols

Manufacturing

Thermistors are made by heating under high pressure semiconductor ceramic made from mixtures of metallic oxides of **manganese, nickel, cobalt, copper, iron** etc.

Shapes:

- These are pressed into desired shapes and then baked at high temperature.
- They may be in the form of **beads, rods or washers**.
- Different types of thermistors are shown in Fig.

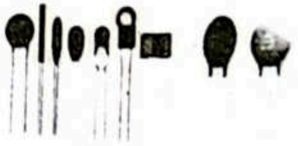
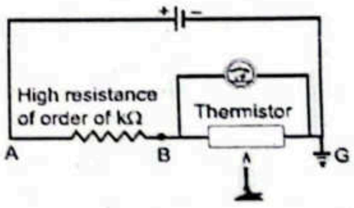


Fig. 9.35 Types of thermistors

Applications of Thermistors:

- **Temperature Measurement:** Used in thermometers, air conditioners, refrigerators, ovens, and microwave ovens. They convert changes in temperature into electrical signals, which can be processed to display temperature.
- **Temperature Control (Temperature Compensation):** Used in circuits where temperature changes need to affect electrical performance. Examples include oscillators, battery charging circuits, and power systems.
- **Current Limiters (Inrush current limiting):** Used to limit the initial flow of current when a device is first turned on.



Thermistors in Voltage Dividers

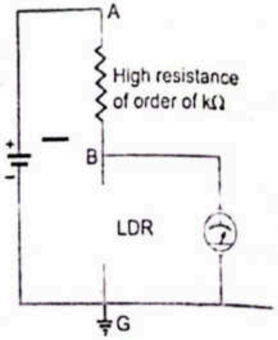
Thermistors are often used as part of a **potential divider circuit** to provide a voltage output that depends on temperature.

- As the temperature changes, the thermistor's resistance changes.
- This change in resistance alters the voltage across the thermistor in the potential divider circuit.
- This variable voltage can then be fed to a micro-controller or other control circuit to perform actions based on temperature levels, such as turning on a fan if the temperature is high or triggering a fire alarm.

9.21 LIGHT DEPENDENT RESISTOR

Q. **What is a Light Dependent Resistor (LDR) Explain?**

Ans



LIGHT DEPENDENT RESISTOR (LDR)

A Light Dependent Resistor (LDR), also known as a photoresistor, is a resistor whose resistance decreases as the intensity of light falling on it increases.

Working Principle:

- LDRs are typically made from semiconductor materials like cadmium sulfide.
- In darkness, the semiconductor material has a very high resistance because there are very few free electrons (charge carriers).
- When light falls on the LDR, the photons provide enough energy to the electrons in the outer orbits of the semiconductor atoms, causing them to break free.
- Thus increases the number of free charge carriers, which in turn increases the material's conductivity and reduces its resistance.

Applications of LDRs:

- **Light Sensors:** Used in automatic lighting systems in homes and streetlights (turning lights ON at dusk, OFF at dawn).
- **Exposure Control in Cameras:** LDRs help adjust the exposure time in cameras based on ambient light.
- **Security Systems:** Used in burglar alarms and other security applications where changes in light intensity need to trigger an action.
- **Toys and Novelties:** Used in various gadgets that react to light.

LDR in Voltage Dividers

Similar to thermistors, LDRs are commonly used in potential divider circuits to provide a voltage that varies with light intensity.

- As light intensity changes, the LDR's resistance changes.
- This changes the voltage drop across the LDR in the potential divider.
- This variable voltage can then be read by a micro-controller or other electronic circuit to perform tasks based on light levels (e.g., turning on outdoor lights when it gets dark, or a light-activated switch).

Working as an ON-OFF Switch:

- **During Daytime (High Light Intensity):**
  - The light intensity on the LDR is high.
  - The resistance of the LDR **decreases** significantly.
  - In the potential divider, if the output is taken across the LDR, the voltage across the LDR will be low. This low voltage can be used to keep the switching device (e.g., a transistor acting as a switch) in an "OFF" state, thus keeping the lights off.
- **During Nighttime (Low Light Intensity/Darkness):**
  - The light intensity on the LDR is low (or zero).
  - The resistance of the LDR **increases** dramatically (to very high values).
  - In the potential divider, the voltage across the LDR will be high. This high voltage can be used to activate the switching device (turn it "ON"), which in turn switches on the lights.

This setup automatically turns lights on when it gets dark and turns them off when it gets light, without human intervention.

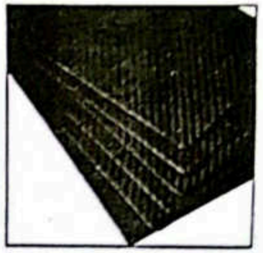


Fig. 9.38: Carbon fibre sheets

Reliability of a Concrete Bridge with Carbon Fibers

How can inspectors check the reliability of a concrete bridge with carbon fibers?

A concrete bridge embedded with carbon fibers can have its reliability easily checked by inspectors because the carbon fibers conduct electricity.

Method:

1. **Electrical Properties:** First, the electrical properties of carbon fibers in good condition are known (their conductivity/resistance).
2. **Embedding:** During construction, carbon fibers are embedded within the concrete structure.
3. **Measurement:** Inspectors can apply small electric currents and measure the resistance of the carbon fiber network within the bridge.
4. **Monitoring Integrity:**
   - If the concrete develops cracks or structural damage, the carbon fibers within those damaged regions will also likely experience stress, elongation, or even breakage.
   - Such damage to the fibers would change their electrical resistance.
   - An increase in resistance would indicate that the concrete bridge is deteriorating or that the carbon fibers themselves are damaged.
5. **Early Detection:** This method allows for the non-destructive detection of internal flaws, such as micro-cracks or voids, which might not be visible from the outside.
6. **Other Methods:** Other methods like ultrasound waves can also be used to detect internal flaws and monitor structural integrity.

MULTIPLE CHOICE QUESTIONS

- **Carbon fibers are embedded in concrete bridges for reliability checks because they:**

(a) Are very strong mechanically. (b) Conduct electricity
(c) Are lightweight. (d) Change color when stressed

Answer: (b) Conduct electricity.

Explanation: The method described relies on the electrical conductivity of carbon fibers to monitor the structural integrity of the concrete.

- **If carbon fibers embedded in a concrete bridge conduct electricity, how can inspectors easily check its reliability?**

(a) By measuring its temperature. (b) By checking for changes in its electrical resistance.
(c) By observing its color. (d) By measuring its weight.

Answer: (b) By checking for changes in its electrical resistance.

Explanation: Damage (cracks, deterioration) in the concrete can affect the electrical path through the carbon fibers, leading to a change in resistance, which can be easily measured.

- **A decrease in the electrical resistance of the carbon fibers in a concrete bridge might indicate:**

(a) The bridge is strengthening. (b) There are no structural issues
(c) A crack is forming, increasing contact.
(d) Some form of damage that alters the conductive path.

Answer: (d) Some form of damage that alters the conductive path.

Explanation: Changes in resistance (either increase or decrease, depending on the nature of damage and fiber distribution) would signal structural changes. The text implies that changes in resistance are monitored to check reliability. While typically damage increases resistance by breaking connections, complex interactions could lead to other changes. The core idea is that *any* change signals an issue.

- **The method of using carbon fibers in concrete for reliability checks is analogous to:**

(a) Using a thermometer to measure temperature. (b) Using a strain gauge to measure deformation
(c) Using a light meter to measure brightness. (d) Using a pH meter to measure acidity

Answer: (b) Using a strain gauge to measure deformation.

Explanation: The principle is similar to a strain gauge where mechanical deformation causes a change in electrical resistance. Here, structural changes in the concrete are indirectly measured by changes in the fiber's electrical properties.

- **What does the integrity of the concrete bridge determined by measuring the resistance of the network of carbon fibers indicate?**

(a) The overall weight of the bridge.
(b) The traffic flow over the bridge.
(c) The presence of structural deterioration or damage.
(d) The atmospheric pressure.

Answer: (c) The presence of structural deterioration or damage.

Explanation: Any changes to the concrete's structural integrity (like cracks or degradation) would affect the electrical pathways of the embedded carbon fibers, thus changing their measured resistance and signaling potential damage.

- **A thermistor is a heat-sensitive resistor whose resistance:**

(a) Always increases with temperature.
(b) Always decreases with temperature.
(c) Can either increase or decrease depending on its type (NTC/PTC).
(d) Is unaffected by temperature.

Answer: (c) Can either increase or decrease depending on its type (NTC/PTC).

Explanation: While NTC (Negative Temperature Coefficient) thermistors (whose resistance decreases with temperature) are common, PTC (Positive Temperature Coefficient) thermistors (whose resistance increases) also exist.

- **The resistance of a Light Dependent Resistor (LDR) typically:**

(a) Increases as light intensity increases.
(b) Decreases as light intensity increases.
(c) Remains constant regardless of light intensity.
(d) Increases as light intensity decreases.

Answer: (b) Decreases as light intensity increases.

Explanation: LDRs are semiconductor devices where increased light provides more energy, freeing more charge carriers and thus decreasing resistance.

- **Thermistors and LDRs are commonly used in:**

(a) Current amplifiers.
(b) Simple switches and sensors in potential dividers.
(c) High-power circuits.
(d) Voltage regulators.

Answer: (b) Simple switches and sensors in potential dividers.

Explanation: Their resistance changes significantly with environmental factors (temperature, light), making them ideal for converting these changes into a variable potential difference in a potential divider circuit to activate switches or sensors.

- **A common application of an LDR is in:**

(a) Household heating systems.
(b) Temperature compensation circuits.
(c) Automatic street lighting systems.
(d) Medical imaging.

Answer: (c) Automatic street lighting systems.

Explanation: LDRs are often used as light sensors to automatically turn lights on when it gets dark and off when it gets bright.

- **Which type of thermistor is typically used for temperature compensation and has a resistance that decreases as temperature increases?**

(a) PTC (Positive Temperature Coefficient)
(b) NTC (Negative Temperature Coefficient)
(c) Linear
(d) Constant coefficient

Answer: (b) NTC (Negative Temperature Coefficient)

Explanation: NTC thermistors are very common and their resistance decreases as temperature rises, making them suitable for sensing and temperature compensation.

SLO BASED SHORT QUESTIONS & ANSWERS

- **Why are carbon fibers embedded in concrete bridges for reliability checks?**

Ans: Carbon fibers are embedded in concrete bridges for reliability checks because they are electrically conductive, allowing inspectors to monitor the structural integrity of the bridge by measuring changes in their electrical resistance.

- **How can monitoring the electrical resistance of carbon fibers indicate structural issues in a concrete bridge?**

Ans: Changes in the concrete's structural integrity, such as the formation of cracks or internal deterioration, can alter the electrical conductivity path of the embedded carbon fibers, leading to measurable changes in their overall electrical resistance, which signals potential damage

- **What is the initial step inspectors take to check the reliability of a concrete bridge with carbon fibers?**

Ans: The initial step is to understand the electrical properties of the carbon fibers themselves, as carbon fibers are known to be good conductors of electricity

- **Besides resistance measurement, what other methods can be used to check the strength of concrete bridges?**

Ans: Other methods include continuously monitoring strain, vibration, and temperature. or using ultrasound waves to detect internal flaws, cracks, or voids.

- **How do the carbon fibers allow inspectors to determine the integrity of the concrete bridge?**

Ans: Inspectors can determine the integrity of the concrete bridge by applying small electric current to the carbon fiber network and measuring the resistance. Any change in resistance compared to a baseline indicates that the concrete is deteriorating or that the carbon fibers are being damaged, thus compromising structural integrity.

- **What is a thermistor, and how does its resistance respond to temperature changes for an NTC thermistor?**

Ans: A thermistor is a heat-sensitive resistor. For an NTC (Negative Temperature Coefficient) thermistor, its resistance decreases as the temperature increases.

- **Describe the working principle of a Light Dependent Resistor (LDR).**

Ans: An LDR is made of a semiconductor material whose conductivity increases when light falls on it. This means that as the light intensity increases, more free electrons are generated, and its electrical resistance decreases.

- **How are thermistors used in temperature measurement or control?**

Ans: Thermistors are used in temperature measurement or control by placing them in a potential divider circuit. As temperature changes, their resistance changes, causing the voltage across them (or another component in the divider) to change, which can then be used to activate a circuit or display a temperature reading

- **Give two applications of Light Dependent Resistors (LDRs).**

Ans: Two applications of LDRs include automatic street lighting systems (to turn lights on at dusk and off at dawn) and camera exposure control (to adjust shutter speed based on ambient light)

- **Briefly explain how thermistors and LDRs can be used in potential divider circuits.**

Ans: Thermistors and LDRs are used in potential divider circuits by connecting them in series with a fixed resistor across a voltage supply. As their resistance changes due to temperature or light, the voltage drop across them (or the fixed resistor) also changes, providing a variable voltage output dependent on the environmental factor.

* * *

TEXT BOOK EXERCISE WITH SOLUTION

MULTIPLE CHOICE QUESTIONS

Tick the correct answer.

9.1 **Two point charges A and B are separated by 10 m. If the distance between them is reduced to 5m, the force exerted on each:**

(a) decreases to half its original value
(b) increases to twice the original value
(c) decreases to one quarter of its original value
(d) increases four times to its original value

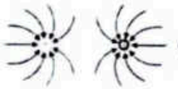
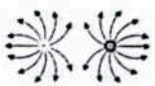
Answer: (d) increases four times its original value (According to Coulomb's Law, $F \propto 1/r^2$. If r is halved, $r \to r/2$, then $F \propto 1/(r/2)^2 = 1/(r^2/4) = 4/r^2$. So, force becomes 4 times.)

9.2 **Which electric charge is possible on a particle?**

(a) 2.5×10^{-19} C (b) 3.2×10^{-19} C
(c) 1.6×10^{-19} C (d) 6.02×10^{23} C

Answer: (c) 1.6×10^{-19} C (This is the elementary charge 'e'. All charges must be integer multiples of 'e'. 3.2×10^{-19} C is 2e, which is also possible. However 1.6×10^{-19} C is the most fundamental possible charge. 2.5×10^{-19} C is not an integer multiple of 1.6×10^{-19} C.)

9.3 **Which diagram best represents the electric field lines around two oppositely charged particles?**

(a) 
(b) 
(c) 
(d) 

Answer: (d) (This corresponds to the electric field of an electric dipole, with lines starting from positive and ending on negative.)

9.4 **What is the work done on an election by potential difference of 100 volts?**

(a) 1.6×10^{-19} eV **(b) 1.6×10^{-17} eV**
(c) 6.25×10^{-17} eV (d) 100 eV

Answer: (d) 100 eV (Work done = $q\Delta V$. For an electron moving through 100 V, the energy is 100 electron volts, or $100 \times 1.6 \times 10^{-19}$ J.)

9.5 **The potential at a point situated at a distance of 50 cm from a charge of 50 μC is:**

(a) 9×10^{-1} volts (b) 18×10^{-4} volts
(c) 9×10^{5} volts (d) 18×10^{4} volts

Answer: (c) 9×10^5 V (Potential $V = kQ/r$. $r = 50$ cm $= 0.5$ m $Q = 50\mu C = 50 \times 10^{-6}$ C
$V = (9 \times 10^9) \times (50 \times 10^{-6})/0.5$
$= 9 \times 10^9 \times 100 \times 10^{-6} = 9 \times 10^5$ V.)

9.6 **A ball of weight 0.1 N having a charge of 100 μC remained suspended between two oppositely charged horizontal metal plates. The electric intensity between the plates is:**

(a) 10 N C^{-1} (b) 100 N C^{-1}
(c) 1000 N C^{-1} (d) 10000 N C^{-1}

Answer: (c) 1000 N C^{-1} (For suspension, electrostatic force = weight. $qE = W$. $E = W/q = 0.1$ N$/(100 \times 10^{-6}$ C$) = 0.1/10^{-4} = 1 \times 10^3$ N $C^{-1} = 1000$ N C^{-1}.)

9.7 **A piece of wire has resistance of 4 Ω. It is doubled on itself so that its length becomes half but area of cross-section is doubled. Its resistance now will be:**

(a) 8 Ω (b) 4 Ω
(c) 2 Ω **(d) 1 Ω**

Answer: (d) 1Ω (Original resistance $R = \rho L/A = 4\Omega$. New length $L' = L/2$. New area $A' = 2A$. New resistance $R' = \rho L'/A' = \rho(L/2)/(2A) = \rho L/(4A) = (1/4)(\rho L/A) = (1/4)$ R. $R' = (1/4) \times 4\Omega = 1\Omega$.)

9.8 **The current through a conductor is 3.0 A when it is attached across a potential difference of 6.0 V. How much power is used?**

(a) 0.5 W (b) 2.0 W
(c) 9.0 W **(d) 18 W**

Answer: (d) 18 W (Power $P = VI = (6.0 \text{ V}) \times (3.0 \text{ A}) = 18$ W.)

9.9 **The algebraic sum of potential changes for a complete circuit is zero. It is the statement of:**

(a) Ohm's law (b) Gauss's law
(c) Kirchhoff's first law
(d) Kirchhoff's second law

Answer: (d) (statement of Kirchhoff's second Law)

9.10 **The radius of curvature of the path of a charged particle in a uniform magnetic field is directly proportional to:**

(a) the particle's charge
(b) the particle's momentum
(c) the particle's energy
(d) the flux density of the field

Answer: (b) the particle's momentum (In a uniform magnetic field, the magnetic force provides the centripetal force: $qvB = mv^2/r$. So, $r = mv/(qB)$, mv is momentum.)

SHORT ANSWER QUESTIONS

9.1 **How does a moving conductor like an aeroplane acquire charge as it flies through the air? Describe briefly.**

Ans: An airplane has conducting body, the charge acquires by airplane while flying through air due to friction between the airplane surface and the air. The molecules of air have loosely bound electron which transfer to body airplane and the plane acquired negative charge. This leads to a static electric charge, which can sometimes be felt as a shock if we touch the body of airplane. ~~Define electric intensity and electric potential.~~

9.2 **Define electric intensity and electric potential.**

Answer:

- **Electric Intensity (Electric Field Strength):** Electric intensity (E) at any point is defined as the electrostatic force experienced by a **unit positive charge** placed at that point. It is a vector quantity, measured in Newton per Coulomb (N C^{-1}) or Volts per meter (V m^{-1}).
- **Electric Potential (V):** Electric potential at a point is defined as the work done per unit positive charge in bringing a tiny positive test charge from infinity (where potential is considered zero) to that point, without accelerating it. It is a scalar quantity, measured in Volts (V) or Joules per Coulomb (J C^{-1}).

1.3 **A battery is rated at 100 A h (ampere-hour). How much charge can this battery supply?**

Given: Battery rating = 100 Ah. Ampere-hour (Ah) is a unit of electric charge, where
1 Ah = 1 Ampere for 1 hour
We know that current $I = Q/t$.
So, Charge $Q = I \times t$
$Q = 100$ A × 1 h. To convert to SI unit (Coulombs), convert hours to seconds
1 h = 3600 s
$Q = 100$ A × 3600 s
$Q = 360{,}000$ C
$Q = 3.6 \times 10^5$ C

9. 4

Ans: This battery can supply 3.6×10^5 C of charge.

Is electron-volt a unit of potential difference or energy? Explain.

Ans: Electron-volt (eV) is a unit of energy.

Explanation: It is defined as the amount of kinetic energy gained (or potential energy lost) by a single electron when it accelerates through an electric potential difference of one volt.

Mathematically, energy (E) is charge (q) multiplied by potential difference (ΔV), i.e., $E = q\Delta V$.
For an electron with charge $e = 1.602 \times 10^{-19}$ C moving through 1 V:

$$1 \text{ eV} = (1.602 \times 10^{-19} \text{ C}) \times (1 \text{ V}) = 1.602 \times 10^{-19} \text{ J}$$

While it relates to potential difference, its unit is fundamentally energy (Joules).

9.5 Q3 **A copper wire of length L has resistance R. It is stretched to double of its length. What will be the resistance of the new length of wire?**

Ans: Length of wire = L
Resistance of wire of length L = R
Length of stretched wire = L' = 2L
Resistance of stretched wire = ?
Initial volume of wire = AL
Volume of stretched wire = A'L'
The volume should remain constant
So $AL = A'L'$
Or $AL = A'(2L)$ $\frac{\rho L}{2L} = \frac{\rho'(L}{L}$
$A' = \frac{A}{2}$
Now $R = \rho \frac{L}{A}$
And $R' = \rho \frac{L'}{A'}$
$R' = \rho \frac{2L}{\frac{A}{2}} = 4\rho \frac{L}{A}$
$R' = 4R$

6
9.4 **Why does the resistance of a conductor rise with increase in temperature?**

Ans: The resistance of a conductor rises with an increase in temperature because of increased thermal vibrations of the atoms within the conductor's crystal lattice. The change in resistance of a conductor is directly proportional to the temperature, i.e.

$$R_t - R_o = \alpha R_o t \text{ and } \Delta R \propto t$$

The resistance offered by a conductor to flow of electric current is due to the collision of free electrons with the lattice atoms, which are in thermal vibration. When temperature of the conductor rises, the thermal vibration of atoms and the amplitudes of vibration increases. Hence, the chance of collisions between free electrons and atoms increases. Thus, the resistance of conductor increases with the rise in temperature.

7
9.5 **Is the filament resistance lower or higher in a 500 W - 220 V light bulb than in a 100 W - 220V bulb?**

Ans: We know that power dissipated in a resistor is given by,

$$P=\frac{V^2}{R}$$

So $$R=\frac{V^2}{P}$$

For the 500-W bulb

$R_{500W}=(220\ V)^2/500\ W=48400/500=96.8\Omega$

For the 100-W bulb

$R_{100W}=(220\ V)^2/100$

$W=48400/100=484\Omega$

Thus resistance of light bulb having 500W is lower than the light bulb having power 100W.

Why does resistance of a thermistor changes as temperature increases?

Ans: A thermistor is a heat sensitive resistor. Most thermistors have negative temperature coefficient of resistance, i.e., the resistance of such thermistors decreases when the rise in temperature. Thermistors with positive temperature coefficient are also available.

In the thermistors, resistance decreases as temperature increases. This is because increasing temperature provides more energy to the charge carriers (electrons or holes), enabling them to move more freely and thus reducing resistance.

Which materials can be used to construct Faraday's cage and why?

Ans: Faraday cages can be constructed using conductive materials.

Examples: Metals like copper, aluminum, steel, or even conductive mesh or fabric.

Reason: The principle of Faraday cage demands a material that contains a lot of free electrons that can move freely to the surface of the material. Only the conductors have free electrons whereas insulators do not contain free electron, so we required conductors to construct Faraday cage.

CONSTRUCTED RESPONSE QUESTIONS

9.1 Electric lines of force never cross each other. Why?

Ans: Electric lines of force (electric field lines) never cross each other because if they did, it would mean that the electric field at the point of intersection has more than one direction simultaneously which is not possible physically. $\vec{E}=K\frac{q}{r^2}\hat{r}$ the relation also shows single unit vector for single point.

9.2 Is E necessarily zero inside a charged rubber balloon if the balloon is spherical? Assume that charge is distributed uniformly over the surface.

Ans: Yes, the electric field (E) is necessarily zero inside a charged rubber balloon, even if the balloon is spherical and the charge is distributed uniformly over its surface. This is a direct consequence of Gauss's Law and the properties of conductors/insulators.

According to Gauss's law

$$\phi=\frac{q}{\epsilon_o}=0$$

And $\phi=\vec{E}.\vec{A}=0$

Since $\vec{A}\neq 0$

Hence $\vec{E}=0$

9.3 Electrostatic force is 10^{38} times stronger than gravitational force. Argue that our galaxy should be almost electrically neutral.

Ans: Gravity depends on how much stuff (mass) something has, while the electrostatic force depends on its electrical charge. If galaxies had a lot of electrical charge, the huge pushes or pulls from the electrostatic force would be so strong that they'd rip the galaxy apart. The fact that galaxies *don't* fly apart tells us they have very little electrical charge, meaning they're almost electrically neutral. The gravitational force is mass dependent and the electrostatic force is charge dependent.

9.4 An uncharged conducting hollow sphere is placed in the field of a positive charge *q*. What will be the net flux through the shell?

Ans: The net flux through the uncharged conducting hollow sphere will be zero.

Explanation: An uncharged metal sphere is in an electric field of positive charge "q", no net electric flux passes through it. This is because the sphere itself has no overall charge inside it, and according to Gauss's Law, flux only passes when there's charge *inside* a closed surface. The electric field lines just go in one side and out the other.

$\Phi_e=Q_{enclosed}/\epsilon_o$ but $Q_{total}=0$ so $\Phi_e=0/\epsilon_o=0$.

9.5 A potential difference is applied across the ends of a copper wire. What is the effect on the drift velocity of free electrons by:

(i) increasing the potential difference?

(ii) decreasing the length and the temperature of the wire?

Ans: **(i) Increasing the potential difference:**

Effect: Increasing the potential difference across the ends of the copper wire will increase the drift velocity of the free electrons. $v_d\propto E\propto V$

Explanation: A larger potential difference creates a stronger electric field ($E=\Delta V/L$) inside the wire. A stronger electric field exerts a greater electric force ($F=qE$) on the free electrons, causing them to accelerate more effectively between collisions with the lattice ions. This leads to a higher average drift velocity in the direction opposite to the electric field.

(ii) Decreasing the length and the temperature of the wire:

Effect: By decreasing length and temperature of the wire, its resistance decreases and hence collisions of free electrons with the lattice atom also decrease which causes an increase in drift velocity. I.e.

$$v_d\propto I\propto\frac{1}{R}\propto\frac{1}{t}$$

Explanation for decrease of length: With a shorter length for the same potential difference, the electric field strength ($E=\Delta V/L$) inside the wire increases. A stronger electric field leads to a greater force on electrons and thus a higher drift velocity.

Explanation for decrease of temperature: As temperature decreases, the thermal vibrations of the atoms in the copper wire reduce. This means there are fewer and less energetic collisions between the free electrons and the vibrating atoms. With fewer obstacles, the electrons can achieve a higher average drift velocity under the influence of the electric field. (This is why resistance decreases with decreasing temperature for conductors).

Note: (Explanation is for information only, you may skip it while memorizing the answer)

9.6 Why the terminal potential difference of a battery decreases when the current drawn from it is increased?

Ans: We know that emf of a source and the terminal potential difference is related as;

$E=V_t+Ir$

or $V_t=E-Ir$

where Ir = Potential drop across internal resistance of the source and called lost voltage.

When the current drawn from the battery increases, then lost voltage increases. As a result, the terminal potential difference decreases.

COMPREHENSIVE QUESTIONS

9.1 Explain the electric potential and prove that electric field intensity is equal to the negative of potential gradient.

9.2 State and explain Kirchhoff's rules.

9.3 What is a Wheatstone bridge? Explain its working with the help of a diagram.

9.4 What is a light dependent resistor (LDR)? How can this be used as ON-OFF switch for lighting?

9.5 What is a potentiometer? Describe its working.

SOLVED EXERCISE

9.1. Three-point charges q_1, q_2 and q_3 are lying in the same plane as shown in Fig. Find the magnitude and direction of the net fore acting on q_1.

Given:

From figure,

$q_1=+40\times10^{-6}C$

$q_2=-60\times10^{-6}C$

$q_3=-50\times10^{-6}C$

$r_1=0.12\ m$

$r_2=0.15\ m$

To Find:

Force on q_1 due to q_2 & q_3 = $\vec{F}$ = ?

Solution:

Force on q_1 due to q_2 is attractive. Let it be F_{12}. Its magnitude is calculated as

$$F_{12}=\frac{1}{4\pi\varepsilon_o}\frac{q_1q_2}{r_2^2}$$

$$=9\times10^9\times\frac{40\times10^{-6}\times60\times10^{-6}}{(0.15)^2}$$

$F_{12}=960\ N$

Force on q_1 due to q_3 is also attractive. Let it be F_{13}. Its magnitude is calculated as

$$F_{13}=\frac{1}{4\pi\varepsilon_o}\frac{q_1q_3}{r_1^2}$$

$$=9\times10^9\times\frac{40\times10^{-6}\times50\times10^{-6}}{(0.12)^2}$$

$F_{13}=1250\ N$

To find the resultant of F_{12} and F_{13}, let us make free-body diagram, resolving F_{13} into its rectangular components, we have

$F_{x13}=F_{13}\cos 60=1250\cos 60=625\ N$

$F_{y13}=F_{13}\sin 60=1250\sin 60=1075\ N$

x-component of resultant force

$F_x=F_{12}+F_{x13}=960+625=1585\ N$

y – component of resultant force

$F_y=F_{y13}=1075\ N$

$E = \sqrt{E_x^2 + E_y^2}$

$E = \sqrt{(1085)^2 + (1075)^2} = $ [illegible]

$\theta = \tan^{-1}\frac{E_y}{E_x}$

$\theta = \tan^{-1}\frac{1075}{1085} = 45°$

9.2: **Two positive point charges $q_1 = 16.0\ \mu C$ and $q_2 = 4.0\ \mu C$ are separated by a distance of 3.0 m, as shown in Fig. Find the spot on the line joining the two charges where electric field is zero.**

To Find: Zero field location $d = ?$ [illegible]

Calculation:

Let at a point P the electric field is zero. Distance of the point P from $q_2 = d$

$E_1 = E_2$

$\frac{1}{4\pi\varepsilon_o}\frac{q_1}{(3-d)^2} = \frac{1}{4\pi\varepsilon_o}\frac{q_2}{d^2}$

$\frac{16\mu C}{(3-d)^2} = \frac{4\mu C}{d^2}$

$4(3-d)^2 = 16d^2$

$(3-d)^2 = 4d^2$

$(3-d)^2 = (2d)^2$

Taking square root

$3 - d = \pm 2d$

Either $3 - d = 2d$ or

$3 - d = -2d$

$d = 1\ m$ or

$d = -3\ m$

There are two values of d. the negative value corresponds to a location off to the right of both the charges where magnitudes of E_1 and E_2 are equal but directions are same. In this case E_1 and E_2 do not cancel at this spot. The positive value corresponds to the location shown in the figure and is the zero field location, hence, $d = +1.0\ m$.

Example 9.3: A proton experiences an electric force equal to its weight at a particular point in an electric field. What is the field intensity at that point?

Mass of proton = 1.67×10^{-27} kg and charge, $e = 1.6 \times 10^{-19}$ C

Solution: Using

$E = \frac{F}{q} = \frac{mg}{e}$

$E = \frac{1.67 \times 10^{-27} \times 9.8}{1.6 \times 10^{-19}} = 1 \times 10^{-7}\ N\ C^{-1}$

9.4: **Two parallel metal plates are 1.0 cm apart. These are connected to a battery of 12 volts. Find the magnitude of electric field intensity between them.**

Given:

Here, potential difference = $\Delta V = 12\ V$

Distance between the plate = $\Delta d = 1.0\ cm = 1 \times 10^{-2}\ m$

To find:

$E = ?$

Solution: $E = \frac{12}{1 \times 10^{-2}} = 1200\ V\ m^{-1}$

9.5: **Two horizontal parallel metal plates are connected to a 12 volt battery. An electron is released from the negative plate. Determine its velocity as it reaches the positive plate. Mass of electron = 9.1×10^{-31} kg and charge = $q = e = 1.6 \times 10^{-19}$ C.**

Solution:

The electron is repelled by the negative plate and attracted by the positive plate. It will be accelerated towards positive plate. Therefore, its P.E. will be lost that will be converted into its K.E.

Loss of P.E = Gain in K.E

$\Delta V e = \frac{1}{2}mv^2$

Substituting the values:

$(12\ V \times 1.6 \times 10^{-19}\ C) = \frac{1}{2}(9.1 \times 10^{-31}\ kg) \times v^2$

$v^2 = 4.2 \times 10^{12}\ m^2 s^{-2}$

$v = 2.1 \times 10^{6}\ m\ s^{-1}$

9.6: **A particle carrying a charge of 2e falls through a potential difference of 3.0 V. Calculate the energy acquired by it.**

Solution:

$q = 2e$

$\Delta V = 3.0\ V$

$K.E = q\Delta V$

$= (2e)(3\ V)$

$K.E = 6\ eV$

As $1\ eV = 1.6 \times 10^{-19}\ J$

$K.E = 6 \times 1.6 \times 10^{-19}\ J$

$K.E = 9.6 \times 10^{-19}\ J$

9.7: **A copper wire has a cross sectional area of $2 \times 10^{-6}\ m^2$ and carries a current of 5 A. If the number of electrons per unit volume is $8.5 \times 10^{28}\ m^{-3}$, calculate the drift velocity of the electrons in the wire. Charge on an electron is 1.6×10^{-19} C.**

Given:

$I = 5\ A$

$A = 2 \times 10^{-6}\ m^2$

$n = 8.5 \times 10^{28}\ m^{-3}$

$q = 1.6 \times 10^{-19}\ C$

To find:

$v = ?$

Solution:

$I = Anvq$

$5 = (2 \times 10^{-6}\ m^2)(8.5 \times 10^{28}\ m^{-3})\ v\ (1.6 \times 10^{-19}\ C)$

$v = 1.1 \times 10^{-4}\ m\ s^{-1}$

9.8 **0.75 A current flows through an iron wire when a battery of 1.5 V is connected across its ends. The length of the wire is 5.0 m and its cross-sectional area is $2.5 \times 10^{-7}\ m^2$. Compute the resistivity of iron.**

Current = I = 0.75 A

Potential difference = V = 1.5 V

Length of wire = L = 5.0 m

Area of cross-section = $A = 2.5 \times 10^{-7}\ m^2$

Required:

Resistivity = $\rho = ?$

Solution:

$R = \frac{\rho L}{A}$

$\rho = \frac{RA}{L}$ ... (i)

$V = IR$ (Ohm's law)

$R = \frac{V}{I} = \frac{1.5}{0.75} = 2.0\ \Omega$

$\rho = R\frac{A}{L}$

$\rho = 2 \times \frac{2.5 \times 10^{-7}}{5}$

$\rho = 1.0 \times 10^{-7}\ \Omega\ m$

9.9 **A platinum wire has resistance of 10 Ω at 0 °C and 20 Ω at 273 °C. Find the value of temperature coefficient of resistance of platinum.**

Given: Resistance at 0°C = R_o = 10 Ω

Resistance at 273°C = R_t = 20 Ω

$T_1 = 0°C = 273 = 273\ K$

$T_2 = 273\ °C = 273 + 273\ K$

$T_2 = 546\ K$

$\Delta T = T_2 - T_1 = 546 - 273 = 273\ K$

$\alpha = ?$

$\alpha = \frac{R_t - R_o}{R_o t}$

$\alpha = \frac{20 - 10}{10 \times 273} = \frac{10}{10 \times 273}$

$\alpha = \frac{1}{273}$

$\alpha = 3.66 \times 10^{-3}\ K^{-1}$ Ans.

9.10 **The potential difference between the terminals of a battery in open circuit is 2.2 V. When it is connected across a resistance of 5.0 Ω, the potential falls to 1.8 V. Calculate the current and the internal resistance of the battery.**

Given: EMF = E = 2.2 V

Resistance = R = 5.0 Ω

Potential difference = V = 1.8 V

Required:

Current = I = ?

Internal resistance = r = ?

Solution:

$V = IR$

$I = \frac{V}{R} = \frac{1.8}{5} = 0.36\ A$

$E = V + Ir$

$Ir = E - V$

$r = \frac{E - V}{I}$

$r = \frac{2.2 - 1.8}{0.36} = 1.1\ \Omega$

$r = 1.1\ \Omega$ Ans.

Calculate the current in the three resistances of the circuit shown in fig.

Apply Kirchhoff's 2nd rule to loop(1) and loop(2).

Loop 1: [illegible]

[illegible]

Loop 2: [illegible]

[illegible]

Solving equations [illegible]

Multiplying by [illegible]

[illegible]

Putting in [illegible]

[illegible]

So, Current through R_1 = [illegible]

Current through R_2 = [illegible]

Current through R_3 = [illegible]

NUMERICAL PROBLEMS

9.1 **Two unequal point charges repel each other with a force of 0.4 N when they are 5.0cm apart. Find the force which each charge exerts on the other when they are (a) 2.5 cm apart (b) 15.0 cm apart.**

Given:

Let q_1 and q_2 be the charges

The force between the charge = F = 0.4 N

Distance between the charges = r = 5.0 cm = 0.05 m

(a) Force between the charges = F' = ?

If distance between the charge = r' = 2.5 cm = 0.025

Solution:

$$\frac{F'}{F} = \frac{r^2}{r'^2}$$

As all other factors are constant

$$\frac{F'}{0.4} = \frac{0.05^2}{0.025^2}$$

$$F' = \frac{0.05^2}{0.025^2} \times 0.4 = 1.6\ N$$

(b) Force between the charges = F' = ?

If distance between the charge = r' = 15 cm = 0.15

Solution:

$$\frac{F'}{F} = \frac{r^2}{r'^2}$$

As all other factors are constant

$$\frac{F'}{0.4} = \frac{0.05^2}{0.15^2}$$

$$F' = \frac{0.05^2}{0.15^2} \times 0.4 = 0.04\ N$$

9.2 **A particle of charge +20 μC is placed between two parallel plates, 10 cm apart and having a potential difference of 0.5 kV between them. Calculate the electric field between the plates, and the electric force exerted on the charged particle.(Ans: 5 kN/C, 100 mN)**

Given

Charge on particle = q = +20 μC = $+20 \times 10^{-6}$ C

Distance between the plates = Δr = 10 cm = 0.10 m

Potential difference between the plates = ΔV = 0.5 kV = 0.5×10^{3} V

To find

Electric Filed between plates = ?

Electric Force on charge particle = ?

Solution:

$$E = \frac{\Delta V}{\Delta r}$$

$$E = \frac{0.5 \times 10^{3}}{0.10} = 5 \times 10^{3}\ N\ C^{-1} = 5\ kN\ C^{-1}$$

$F = qE$

$F = 20 \times 10^{-6} \times 5 \times 10^{3} = 100 \times 10^{-3} = 100 \times 10^{-3}$

$= 100$ mN

9.2 **The electron and proton in a hydrogen atom are separated (on the average) by a distance of approximately 5.3×10^{-11} m. Find the ratio of the electric force and the gravitational force between the electron and proton in this state.**

Given:

Charge on electron = q_1 = -1.6×10^{-19} C

Charge on proton = q_2 = $+1.6 \times 10^{-19}$ C

Mass of electron = m_1 = 9.1×10^{-31} kg

Mass of electron = m_2 = 1.673×10^{-27} kg

Separation between electron and proton = r = 5.3×10^{-11} m

$G = 6.67 \times 10^{-11}\ N\ m^2\ kg^{-2}$

$$K = \frac{1}{4\pi\varepsilon_o} = 9 \times 10^{9}\ N\ m^2\ C^{-2}$$

To Find:

$$\frac{F_e}{F_g} = ?$$

Solution:

$$\frac{F_e}{F_g} = \frac{\frac{kq_1q_2}{r^2}}{\frac{Gm_1m_2}{r^2}} = \frac{kq_1q_2}{Gm_1m_2}$$

$$\frac{F_e}{F_g} = \frac{1}{4p\varepsilon_o} \times \frac{1}{G} \times \frac{q_1q_2}{m_1m_2}$$

$$= 9 \times 10^{9} \times \frac{1}{6.67 \times 10^{-11}} \times \frac{1.6 \times 10^{-19} \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31} \times 1.673 \times 10^{-27}}$$

$$\frac{F_e}{F_g} = \frac{9 \times 1.6 \times 1.6 \times 1.6 \times 10^{9-19-19}}{6.67 \times 9.1 \times 1.673 \times 10^{-11-31-27}}$$

$$\frac{F_e}{F_g} = \frac{23.04 \times 10^{-29}}{101.54 \times 10^{-69}} = 0.23 \times 10^{-29+69}$$

$$= 0.23 \times 10^{40} = 2.3 \times 10^{39}$$

9.3 **After a pleasant showering, a water droplet of mass 1.2×10^{-11} kg is located in the air near the ground. An atmospheric electric field of magnitude 6.0×10^{3} N C^{-1}points vertically downward in the vicinity of the water droplet. The droplet remains suspended at rest in the air. Find the electric charge on the droplet**

Given

Mass of droplet = m = 1.2×10^{-11} kg

Atmospheric electric field = E = 6.0×10^{3} N C^{-1}(downward)

To Find

Electric charge on droplet = ?

Solution

$F_e = F_g$

As the droplet is suspended

$qE = mg$

$q(6.0 \times 10^{3}) = 1.2 \times 10^{-11}(9.8) = (11.76/6) \times 10^{-11-3}$

$q = 1.96 \times 10^{-11-3} = 1.96 \times 10^{-14}$ C

Since the electric field points vertically downward and the electric force must be upward to balance gravity, the charge on the droplet must be negative (because a negative charge experiences a force opposite to the electric field direction).

So, $q = -1.96 \times 10^{-14}$ C.

9.4 **An electron enters the region of a uniform electric filed, with $v_i = 2.99 \times 10^{6}$ m $s^{-1}$and E = 300 N C^{-1}. The horizontal length of the plates is 10.0 cm. Find the acceleration of the electron while it is in the electric field. How long will it take to pass through the field?**

Given

Terminal velocity = $v_i = v_i = 2.99 \times 10^{6}$ m s^{-1}

Electric field = E = 300 N C^{-1}

Horizontal length of plates = S = 10 cm = 0.1 m

Mass of electron = 9.1×10^{-31} kg

Charge on electron = q = 1.6×10^{-19} C

To Find

Acceleration of electron = a = ?

Time taken to pass the field = t = ?

Solution

Force on electron = $F_e = qE$

$F_e = 1.6 \times 10^{-19} \times 300 = 4.8 \times 10^{-17}$ N

$$\text{Acceleration of electron} = a = \frac{F_e}{m}$$

$$a = \frac{4.8 \times 10^{-17}}{9.1 \times 10^{-31}}$$

$$= 0.53 \times 10^{31-17} = 5.27 \times 10^{13}\ m\ s^{-1}$$

for the time to pass the electric field

$S = v_i t$

$0.1 = 2.99 \times 10^{6}\ t$

$t = 0.0344 \times 10^{-6}$

$t = 3.44 \times 10^{-8}$ s

9.5 **A disc of 10 cm² area is placed in a vertical electric field $E = 5 \times 10^{5}$ N C^{-1}.If the plane of the disc makes an angle of 30° with the horizontal, determine the electric flux through the disc.**

Given

Area of disc = A = 10 cm² = 1×10^{-3} m²

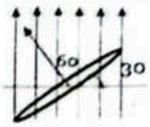
Electric field = E = 5×10^{5} N C^{-1}

Angle disc with horizontal = α = 30°

Angle between vector area and electric field lines = θ = 90°-30° = 60°

Angle of the plane of the disc with the horizontal = 30°

The formula for electric flux is $\Phi_e = EA\cos\theta$, where θ is the angle between the electric field lines and the normal to the area



If the plane of the disc makes an angle of 30° with the horizontal, and the electric field is vertical, then the normal to the disc makes an angle of 90°−30°=60° with the vertical electric field

So, θ=60°

To Find

Electric Flux = ϕ_e = ?

Solution

$\phi_e = EA\ Cos\ \theta$

$\phi_e = (5 \times 10^{5})(1 \times 10^{-3})\ Cos\ 60°$

$\phi_e = 500\ (0.5) = 250\ N\ m^2\ C^{-1}$

(Note: Answer to this question in the text book is $250\sqrt{3}$ which is according to statement is not correct)

9.6 **A circular copper rod is 50 cm long and has 1 cm diameter. Find the resistance across its ends. What should be the side of square cross-section of a 50 cm long tungsten rod if its resistance is the same? [Resistivity of copper is 1.69×10^{-8} Ω m and that of tungsten is 5.0×10^{-8} Ω m.]**

Given

Length of copper rod = L_C = 50 cm = 0.5 m

Diameter of copper rod = D_C = 1 cm = 0.01 m

Area of cross section of copper rod = A_C

$$= \pi\left(\frac{D_C}{2}\right)^2 = 3.14\left(\frac{0.01}{2}\right)^2 = 7.85 \times 10^{-5}\ m^2$$

Resistance of copper rod = $R_C = R_T$ = ?

Length of tungsten rod = L_T = 50 cm = 0.5 m

Length of square cross section of rod = L = ?

Resistivity of copper = $\rho_C = 1.69 \times 10^{-8}$ Ω m

Resistivity of tungsten = $\rho_T = 5 \times 10^{-8}$ Ω m

Solution

$$R_C = \rho_C \frac{L_C}{A_C}$$

$$R_C = 1.69 \times 10^{-8} \frac{0.5}{7.85 \times 10^{-5}} = 1.08 \times 10^{-4}\ \Omega$$

Now