Chapter 9

Electrostatics and Current Electricity

Learning Objectives

After studying this chapter, the students will be able to:

- Define and calculate electric field strength.
  [Use $F = qE$ for the force on a charge in an electric field. Use $E = \frac{\Delta V}{\Delta d}$ 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.
  $F = k\frac{q_1 q_2}{r^2}$ for the force between two point charges in free space, [where $k = \frac{1}{4\pi\varepsilon_0}$]
- Use $E = k\frac{q}{r^2}$ 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 $P = IV$, $P = I^2R$ and $P = V^2/R$.
- 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.

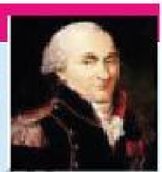
We know that magnitude of the charge on an electron is equal to that of a proton. The charge on a proton is e^+ and that on an electron is e^-. Its value is; $e = 1.6 \times 10^{-19}$ C where C (coulomb) is the SI unit of charge. This charge (e) is the smallest amount of free charge that has been discovered. Charges of larger magnitude are built up on an object by adding or removing electrons. It is the minimum amount of charge that any particle may contain. Thus, any amount of charge q is an integer multiple of e, i.e.,

$$q = Ne \qquad \text{where } N \text{ is an integer}$$

Electrostatics is the study of phenomena and properties of electric charges at rest. When charges are in motion, we call it as an electric current.

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

Coulomb's law is a fundamental principle in electrostatics that quantifies the force between two charged objects. The first measurement of the force between electric charges was made by a French Physicist Charles de Coulomb in 1874. Coulomb's law is essential in understanding the behaviour of charged particles and the interactions that govern many electrical phenomena. On the basis of these measurements, he deduced a law known as Coulomb's law. It states that:

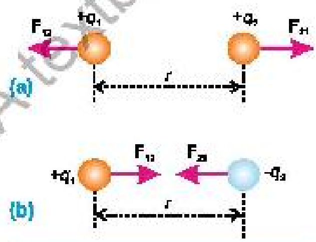


Fig. 9.1
(a) Repulsive forces between like charges and
(b) attractive forces between unlike charges.

The force between two-point charges is directly proportional to the product of the magnitudes of charges and inversely proportional to the square of the distance between them. It is mathematically expressed as

$$F \propto \frac{q_1 q_2}{r^2} \text{ or } F = k\frac{q_1 q_2}{r^2} \quad \text{.......... (9.1)}$$

where F is the magnitude of the mutual force that acts on each of the two point charges q_1, q_2, and r is the distance between them. The force **F** always acts along the line joining the two point charges (Fig. 9.1), k is the constant of proportionality. Its value depends upon the nature of medium between the two charges and system of units in which F, q and r are measured. If the medium between the two point charges is free space and the system of units is SI, then k is represented as

$$k = \frac{1}{4\pi\varepsilon_o} \quad \text{.............. (9.2)}$$

where ε_o is an electrical constant, known as permittivity of free space. In SI units, its value is $8.85 \times 10^{-12}\ C^2 N^{-1} m^{-2}$. Substituting the value of ε_o the constant

$$k = \frac{1}{4\pi\varepsilon_o} = 9 \times 10^9\ N\ m^2\ C^{-2}$$

Thus, Coulomb's force in free space is

$$F = \frac{1}{4\pi\varepsilon_o}\frac{q_1 q_2}{r^2} \quad \text{............... (9.3)}$$

Point to ponder!

Does an electrostatic force exist between a charged and an uncharged?

As stated earlier, Coulombs' force is mutual force, it means that if q_1 exerts a force on q_2, then q_2 also exerts an equal and opposite force on q_1. If we denote the force exerted on q_2 by q_1 as F_{21} and that on charge q_1 due to q_2 as F_{12} then

$$\mathbf{F}_{12} = -\mathbf{F}_{21} \quad \text{..............................(9.4)}$$

The magnitude of both these two forces is the same and is given by Eq. 9.3. To represent the direction of these forces, we introduce unit vectors. If $\hat{\mathbf{r}}_{21}$ is the unit vector directed from q_1 to q_2 and $\hat{\mathbf{r}}_{12}$ is the unit vector directed from q_2 to q_1 then

$$\mathbf{F}_{21} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}\hat{\mathbf{r}}_{21} \quad \text{.................... (9.5)}$$

$$\mathbf{F}_{12} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}\hat{\mathbf{r}}_{12} \quad \text{.................... (9.6)}$$

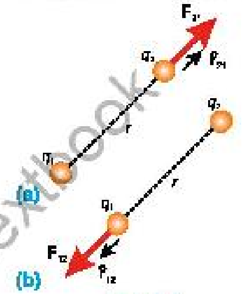


Fig. 9.2

The forces F_{21} and F_{12} are shown in Fig. 9.2 (a and b). It can be seen that $\hat{\mathbf{r}}_{21} = -\hat{\mathbf{r}}_{12}$, so Eqs. 9.5 and 9.6 show that;

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

The sign of the charges in Eqs. 9.5 and 9.6 determine whether the forces are attractive or repulsive.

We shall now consider the effect of medium between the two charges upon the Coulomb's force. If the medium is an insulator, it is usually referred as dielectric. It has been found that the presence of a dielectric always reduces the electrostatic force as compared with that in free space by a certain factor which is a constant for the given dielectric. This constant is known as relative permittivity and is represented by ε. The values of relative permittivity of different dielectrics are given in Table 9.1.

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

Thus, the Coulomb's force in a medium of relative permittivity ε_r is given by

$$F = \frac{1}{4\pi\varepsilon_0\varepsilon_r}\frac{q_1 q_2}{r^2} \quad \text{.................... (9.7)}$$

It can be seen in the table that ε_r, for air is 1.0006. This value is so close to one that with negligible error, the Eq. 9.3 gives the electric force in air.

Example 9.1 Three point charges q_1, q_2 and q_3 are lying in the same plane as shown in Fig. 9.3(a). Find the magnitude and direction of the net fore acting on q_1.

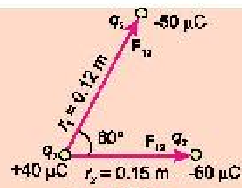


Fig. 9.3(a)

Solution

Force on q_1 exerted by q_2 is attractive. Let it be F_{12}. Its magnitude is given by

$$F_{12} = k\frac{q_1 q_2}{r_2^2} = \frac{(9\times10^9\,\text{N m}^2\,\text{C}^{-2})(40\times10^{-6}\,\text{C})(60\times10^{-6}\,\text{C})}{(0.15\ \text{m})^2} = 960\ \text{N}$$

Force on q_1 exerted by q_3 is also attractive. Let it be $\mathbf{F}_{13}$. Its magnitude is given by

$$F_{13} = k\frac{q_1 q_3}{r_2^2} = \frac{(9\times10^9\,\text{Nm}^2\,\text{C}^{-2})(40\times10^{-6}\,\text{C})(50\times10^{-6}\,\text{C})}{(0.12\ \text{m}^2)} = 1250\ \text{N}$$

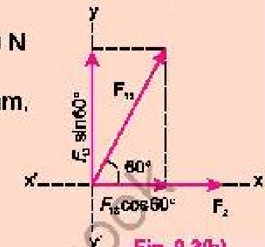


Fig. 9.3(b)

To find the resultant of $\mathbf{F}_{12}$ and $\mathbf{F}_{13}$, let us make free-body diagram, resolving $\mathbf{F}_{13}$ into its rectangular components, we have

$$F_{13x} = F_{13}\cos 60^\circ = 1250\ \text{N} \times 0.5 = 625\ \text{N}$$

$$F_{13y} = F_{13}\sin 60^\circ = 1250\ \text{N} \times 0.86 = 1075\ \text{N}$$

The x-component of resultant $\mathbf{F}$ is

$$F_x = F_{12} + F_{13}\cos 60^\circ$$

$$F_x = 960\ \text{N} + 625\ \text{N}$$

$$F_x = 1585\ \text{N}$$

y-component of $\mathbf{F}$ is:

$$F_y = F_{13}\sin 60^\circ = 1075\ \text{N}$$

Magnitude of F is given by

$$F = \sqrt{F_x^2 + F_y^2} = 1975\ \text{N}$$

For direction of $\mathbf{F}$:

$$\tan\theta = \frac{F_y}{F_x} = \frac{1075}{1585} = 0.68$$

Therefore, $\theta = 34^\circ$ with the line joining q_1 and q_2.

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 insulating 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?

9.2 ELECTRIC FIELD STRENGTH

We have learnt that a charge experiences an electrostatic force in the presence of other charges. Let us consider a positively charged object Q. If we place a small charge $+q$ at point A, it will experience an electrostatic force F due to the charge Q. Thus, an electric field is said to exist at point A. Coulomb's law suggests that the field gets stronger as the point A gets closer to Q as represented in Fig. 9.4. The strength of the field at a position is known as its intensity at that point.

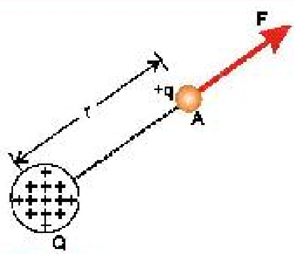


Fig. 9.4

> The electric intensity of the field or simply electric field at any point is defined as the force experienced by a unit positive charge placed at that point.

Electric intensity is a force, so it is a vector quantity and is usually denoted by $\mathbf{E}$. It can be obtained by the relation:

$$\mathbf{E} = \frac{\mathbf{F}}{q} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9.8)$$

As $\quad F = \dfrac{1}{4\pi\varepsilon_o}\dfrac{qQ}{r^2} \quad \therefore \quad E = \dfrac{1}{4\pi\varepsilon_o}\dfrac{Q}{r^2}$

In vector form: $\quad \mathbf{E} = \dfrac{1}{4\pi\varepsilon_o}\dfrac{Q}{r^2}\hat{\mathbf{r}}$

From Eq. 9.8, the unit of electric intensity is newton per coulomb N C^{-1}. The direction of **E** is the same as that of **F**. The Eq. 9.5 can also be written as:

$$\mathbf{F} = q\mathbf{E} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9.9)$$

Example 9.2 Two positive point charges q_1 = 16.0 μC and q_2 = 4.0 μC are separated by a distance of 3.0 m, as shown in Fig.9.5. Find the spot on the line joining the two charges where electric field is zero.

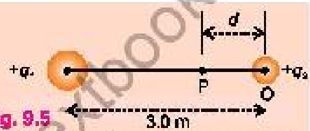


Fig. 9.5

Solution Between the two charges, the fields contributed by them have opposite directions, and electric field would be zero at a point P, where the magnitude of E_1 equals to E_2. In Fig. 9.5, let the distance of P from q_2 be d. At P, $E_1 = E_2$ which implies that:

$$\frac{1}{4\pi\varepsilon_o}\frac{q_1}{(3.0-d)^2} = \frac{1}{4\pi\varepsilon_o}\frac{q_2}{d^2}$$

or $\quad \dfrac{16.0\times10^{-6}\,\text{C}}{9.0+d^2-6d} = \dfrac{4.0\times10^{-6}\,\text{C}}{d^2} \quad$ or $d^2 + 2d - 3 = 0$, which gives d = +1 m, - 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 $\mathbf{E}_1$ and $\mathbf{E}_2$ are equal but directions are same. In this case $\mathbf{E}_1$ and $\mathbf{E}_2$ do not cancel at this spot. The positive value corresponds to the location shown in the figure and is the zero filed location, hence, d = +1.0 m.

Example 9.3 A proton experiences an electrostatic 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 x 10^{-27} kg and charge, e = 1.6 x 10^{-19} C

Solution

Using $\quad E = \dfrac{F}{q} = \dfrac{mg}{e}$

Substituting the values,

$$E = \frac{1.67\times10^{-27}\ \text{kg}\times 9.8\ \text{m s}^{-2}}{1.6\times10^{-19}\ \text{C}} = 1.0\times10^{-7}\ \text{N C}^{-1}$$

Electric Field Lines

A visual representation of the electric field can be obtained in terms of electric field lines, an idea proposed by Michael Faraday. Electric field lines can be considered as a visual map used to represent the direction and strength of an electric field around a charged object. As electric field lines provide information about the electric force exerted on a charged object, these lines are commonly called "electric lines of force".

To introduce electric field lines, we place positive test charges $+q_o$ each of magnitude q_o at different places but at equal distances from a positive charge $+q$ as shown in the Fig. 9.6. Each test charge will experience a repulsive force, as indicated by arrows in Fig. 9.6(a). Therefore, the electric field created by the charge $+q$ is directed radially outward. Figure 9.6(b) shows corresponding field lines which show the field direction. Figure 9.7 shows the electric field lines in the vicinity of a negative charge $-q$. In this case the lines are directed radially "inward", because the force on a positive test charge is now of attraction, indicating the electric field points inward.

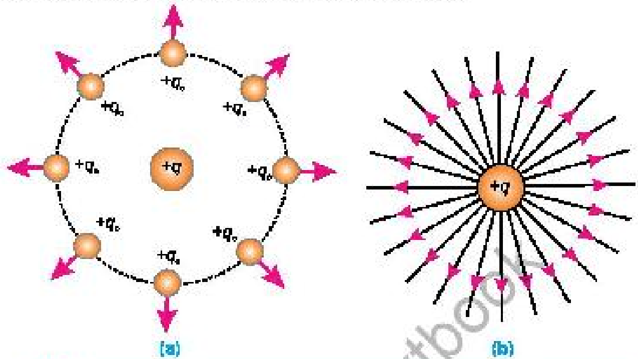


Fig 9.6

(a): A positive test charge $+q_o$ placed anywhere in the vicinity of a positive point charge $+q$ experiences a repulsive force directed radially outward.'

(b): The electric field lines are directed radially outward from the positive point charge $+q$.

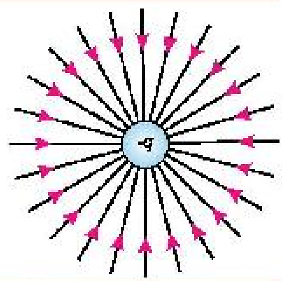


Fig 9.7: The electric field lines are directed radially inward towards a negative point charge $-q$.

Figures 9.6 and 9.7 represent two dimensional pictures of the field lines. However, electric field lines emerge from the charges in three dimensions, and an infinite number of lines could be drawn.

The electric field lines "map" also provides information about the strength of the electric field. As we notice in Figs. 9.6 and 9.7 that field lines are closer to each other near the charges where the field is strong while they continuously spread out indicating a continuous decrease in the field strength.

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

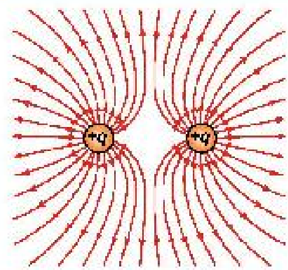


Fig.9.8: The electric field lines for two identical opposite point charges.

The electric field lines are curved in case of two identical separated charges. Figure 9.8 shows the pattern of lines associated with two identical positive point charges of equal magnitude. It reveals that the lines in the region between two like charges seem to repel each other. The behaviour of two identical negatively charges will be exactly the same. The middle region shows the presence of a zero field spot or neutral zone.

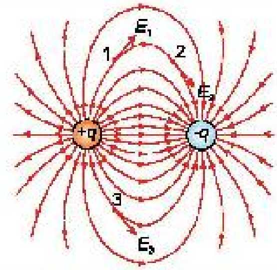


Fig 9.9: The electric field lines are directed radially inward towards a negative point charge $-q$.

Figure 9.9 shows the electric field pattern of two opposite charges of equal magnitudes. The field lines start from positive charge and end on a negative charge. The electric field at points such as 1, 2, 3 is the resultant of fields created by the two charges at these points. The directions of the resultant intensities is given by the tangents drawn to the field lines at these points.

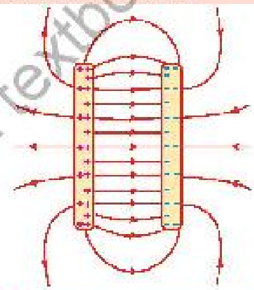


Fig.9.10: In the central region of a parallel plate capacitor, the electric field lines are parallel and evenly spaced, indicating that the electric field there has the same magnitude and direction at points.

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 on all points. Figure 9.10 shows the field lines between the plates of a parallel plate capacitor. The field is uniform in the middle region where field lines are equally spaced.

We are now in a position to summarize the properties of electric field lines.

1. Electric field lines originate from positive charges and end on negative charges.
2. The tangent to a field line at any point gives the direction of the electric field at that point.
3. The lines are closer where the field is strong and the lines are farther apart where the field is weak.
4. No two lines cross each other. This is because E has only one direction at any given point. If the lines cross E could have more than one direction.

Do you know?

There is no electric field inside the conductor.

9.3 ELECTRIC FLUX

When we place an element of area in an electric field, some of the lines of force pass through it (Fig. 9.11). The number of the field lines passing through a certain element of area is known as electric flux through that area. It is usually denoted by Greek letter ϕ_e. For example, the electric flux ϕ_e through the area A is 4 while the flux through B is 2.

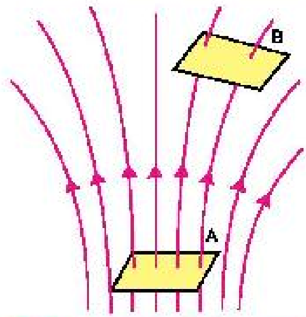


Fig.9.11: Electric flux through a surface normal to E.

In order to give a quantitative meaning to flux, the field lines are drawn such that the number of field lines passing through a unit area held perpendicular to field lines at a point represent the intensity **E** of the field at that point.

Usually, the element of area is represented by a vector area **A** whose magnitude is equal to the surface area A of the element and direction is along normal to the area.

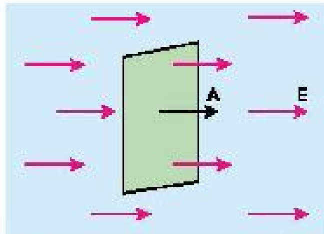


Fig.9.12(a): Maximum

In Fig.9.12 (a), area A is held perpendicular to the field lines, then EA lines pass through it. The flux ϕ_e, in this case is:

$$\phi_e = EA \text{ ....}(9.10)$$

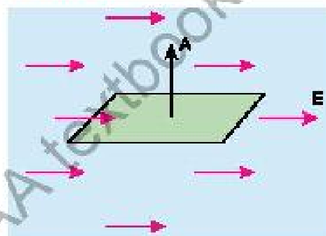


Fig.9.12(b): Minimum

In Figure 9.12 (b), area A is held parallel to field lines and, as is obvious no lines cross this area, so that flux ϕ_e, in this case is:

$$\phi_e = EA = 0 \text{ ....}(9.11)$$

Figure 9.12(c) shows the case when **A** is neither perpendicular nor parallel to field lines but is inclined at an angle θ with the field **E**. In this case, we have to find the projection of the area which is perpendicular to the field lines. The area of this projection (Fig. 9.12-c) is $A\cos\theta$. The flux ϕ_e in this case is:

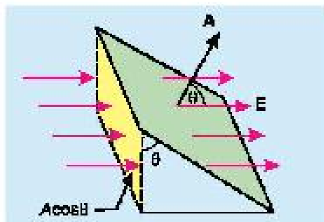


Fig.9.12 (c)

$$\phi_e = EA\cos\theta \text{ ....}(9.12)$$

The electric flux ϕ_e, through a patch of flat surface in terms of **E** and **A** is then given by

$$\phi_e = EA\cos\theta = \mathbf{E.A} \text{ ....}(9.13)$$

where θ is the angle between the field lines and the normal to the area. Electric flux being a scalar product, is a scalar quantity. Its SI unit is N m^2 C^{-1}.

Electric Flux Through a Surface Enclosing a Charge

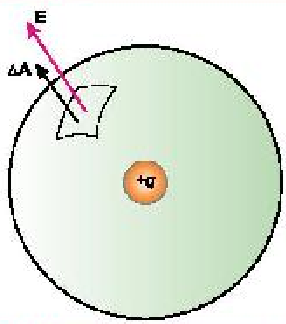


Fig.9.13: The total electric flux through the surface of the sphere due to a charge q at its centre is q/ε_o.

Let us calculate the electric flux through a closed surface, in shape of a sphere of radius r due to a point charge q placed at the centre of sphere as shown in Fig. 9.13. To apply the formula ϕ_e = **E.A** for the computation of electric flux, the surface area should be flat. For this reason the total surface area of the sphere is divided into n small patches with areas of magnitudes ΔA_1, ΔA_2, ΔA_3,………., ΔA_n, respectively as shown in Fig. 9.13. The direction of each vector area is along perpendicular drawn outward to the corresponding patch. The electric intensities at the centres of vector areas $\Delta \mathbf{A}_1$, $\Delta \mathbf{A}_2$, $\Delta \mathbf{A}_3$,……., $\Delta \mathbf{A}_n$ are $\mathbf{E}_1$, $\mathbf{E}_2$, $\mathbf{E}_3$, …….., $\mathbf{E}_n$, respectively.

According to Eq. 9.13, the total flux passing through the closed surface is:

$$\Phi_e = \mathbf{E}_1.\Delta\mathbf{A}_1 + \mathbf{E}_2.\Delta\mathbf{A}_2 + \mathbf{E}_3.\Delta\mathbf{A}_3 + \ldots\ldots\ldots\ldots + \mathbf{E}_n.\Delta\mathbf{A}_n \quad \ldots\ldots\ldots\ldots (9.14)$$

The direction of electric intensity and vector area is the same at each patch. Moreover,

$$|\mathbf{E}_1| = |\mathbf{E}_2| = |\mathbf{E}_3| = \ldots\ldots\ldots = |\mathbf{E}_n| = E = \frac{1}{4\pi\varepsilon_o}\frac{q}{r^2} \quad \ldots\ldots\ldots\ldots (9.15)$$

Since **E** is parallel to vector area **A**, therefore, $\theta = 0°$ (Fig. 9.13)

so for each $\mathbf{E}.\Delta\mathbf{A} = EA\cos\theta$

$= EA\cos 0° = EA \quad (\because \cos 0° = 1)$

$$\phi_e = E\Delta A_1 + E\Delta A_2 + E\Delta A_3 + \ldots\ldots\ldots + E\Delta A_n$$

$$= E\ (\Delta A_1 + \Delta A_2 + \Delta A_3 + \ldots\ldots\ldots + \Delta A_n)$$

$$= E\ (\text{Total spherical surface area})$$

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

$$\phi_e = \frac{q}{\varepsilon_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9.16)$$

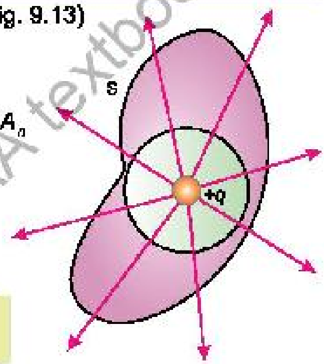


Fig: 9.14

Now Imagine that a closed surface S is enclosing this sphere. It can be seen in Fig 9.14 that the flux through the closed surface S is the same as that through the sphere. So, we can conclude that total flux through a closed surface does not depend upon the shape or geometry of the closed surface. It depends upon the medium and the charge enclosed.

9.4 GAUSS'S LAW

Suppose point charges q_1, q_2, q_3,………,q_n are arbitrarily distributed within an arbitrarily shaped closed surface, as shown in Fig. 9.15. Since $\phi_e = q/\varepsilon_o$, so the electric flux passing through the closed surface is:

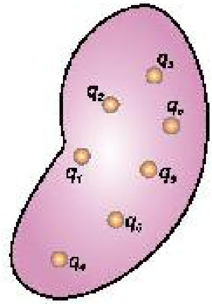


Fig: 9.15

$$\phi_e = \frac{q_1}{\varepsilon_o} + \frac{q_2}{\varepsilon_o} + \frac{q_3}{\varepsilon_o} + \ldots\ldots\ldots + \frac{q_n}{\varepsilon_o}$$

$$\phi_e = \frac{1}{\varepsilon_o} \times (q_1 + q_2 + q_3 + \ldots\ldots\ldots\ldots + q_n)$$

$$\phi_e = \frac{1}{\varepsilon_o} \times (\text{Total charge enclosed by closed surface})$$

$$\phi_e = \frac{1}{\varepsilon_o} \times Q \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9.17)$$

where $Q = q_1 + q_2 + q_3 + \ldots\ldots\ldots\ldots + q_n$, is the total charge enclosed by closed surface. Equation 9.17 is mathematical expression of Gauss's law which can be stated as:

> The total electric flux through any closed surface is $1/\varepsilon_o$ times the total charge enclosed in it.

Applications of Gauss's Law

Gauss's law can be applied to calculate the electric intensity due to different charge configurations. In all such cases, an imaginary closed surface is considered which passes through the point at which the electric intensity is to be evaluated. This closed surface is known as Gaussian surface. Its choice is such that the flux through it can be easily evaluated.

As an example, let us find the electric field at any point outside a sphere on which a charge q is placed.

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. 9.16. 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 because E is uniform over the sphere, the total flux through the whole surface will be:

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

By Gauss's law, total flux is:

$$\phi_e = \frac{q}{\varepsilon_o}$$

Therefore $\qquad E \times 4\pi r^2 = \dfrac{q}{\varepsilon_o}$

or $\qquad E = \dfrac{q}{\varepsilon_o}\dfrac{1}{4\pi r^2}$

or $\qquad E = \dfrac{1}{4\pi\varepsilon_o} \times \dfrac{q}{r^2}$

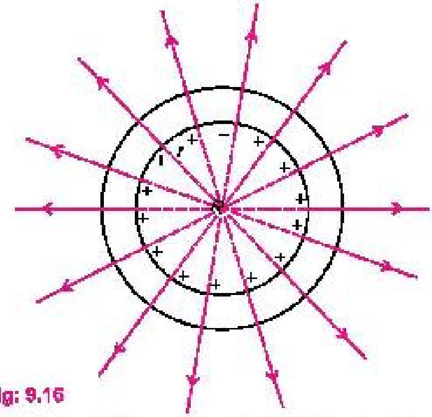


Fig: 9.16

This 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.,

$$E = \frac{1}{4\pi\varepsilon_o}\frac{q}{R^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots(9.18)$$

In vector form; $\qquad \mathbf{E} = \dfrac{1}{4\pi\varepsilon_o}\dfrac{q}{R^2}\hat{\mathbf{r}} \qquad$ where $\hat{\mathbf{r}}$ is the direction of $\mathbf{E}$.

9.5 ELECTRIC POTENTIAL

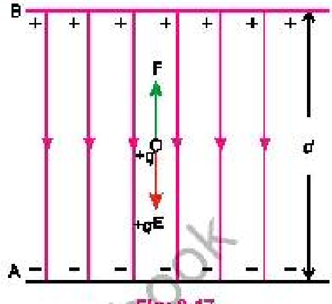


Fig: 9.17

Figure 9.17 shows two oppositely charged parallel plated which produce a uniform electric field.

Let us consider a positive charge q which is allowed to move in this uniform electric field. The positive charge will move from plate B to A and will gain $K.E.$ If it is to be moved from A to B, an external force is needed to make the charge move against the electric field and will gain $P.E.$ Let us impose a condition that as the charge is moved from A to B, it is moved keeping electrostatic equilibrium, i.e., it moves with uniform velocity. This condition could be achieved by applying a force **F** equal and opposite to qE at every point along its path. The work done by the external force against the electric field increases electrical potential energy of the charge that is moved.

Let W_{AB} be the work done by the force in carrying the positive charge q from A to B while keeping the charge in equilibrium. The change in its potential energy $\Delta U = W_{AB}$.

or $$U_B - U_A = W_{AB} \quad \text{.............................. (9.19)}$$

where U_A and U_B, are defined to be the potential energies at points A and B, respectively.

To describe electric field, we introduce the idea of electric potential difference. The **potential difference 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**, i.e.,

$$\Delta V = V_B - V_A = \frac{W_{AB}}{q} = \frac{\Delta U}{q} \quad \text{.............. (9.20)}$$

where V_A and V_B are defined as electric potentials at points A and B respectively. Electric potential energy difference and electric potential difference between the points A and B are related as:

$$\Delta U = q\Delta V \quad \text{.............................. (9.21)}$$

Thus, the potential difference between the two points can be defined as the difference of the potential energy per unit charge.

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.

As the unit of $P.E.$ is joule, Eq. 9.20 shows that the unit of potential difference is joule per coulomb. It is called volt such that,

$$1\,\text{volt} = \frac{1\ \text{joule}}{1\ \text{coulomb}} \quad \text{.......................... (9.22)}$$

That is, a potential difference of 1 volt exists between two points if work done in moving a 1 coulomb positive charge from one point to the other, keeping electrostatic equilibrium, is one joule.

In order to give a concept of electric potential at a point in an electric field, we must have a reference to which we assign zero electric potential. This point is usually taken at infinity. Thus, in Eq. 9.20, if we take point A to be at infinity and choose $V_A = 0$, the electric potential at B will be $V_B = \frac{W_{AB}}{q}$. Generally,

$$V = \frac{W}{q} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9.23)$$

Point to ponder!

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

which states that the electric potential at any point in an electric field is equal to the work done in bringing a unit positive charge from infinity to that point keeping it in electrostatic equilibrium. So, the potential at a point is always relative to potential at infinity. Both potential and potential differences are scalar quantities because both W and q are scalars.

Electric Field as Potential Gradient

In this section, we will establish a relation between electric intensity and potential difference. Let us consider the situation shown in Fig. 9.17. The electric field between the two charged plates is uniform and its value is E. The potential difference between A and B is given by the equation:

$$V_B - V_A = \frac{W_{AB}}{q} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9.24)$$

where $W_{AB} = Fd = -qEd$ (the negative sign is needed because F must be applied opposite to qE so as to keep it in equilibrium). With this, Eq. 9.24 becomes:

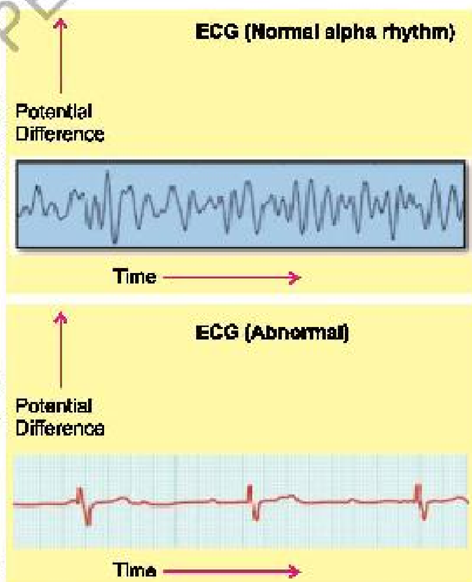
$$V_B - V_A = \frac{-qEd}{q} = -Ed$$

$$\text{or } E = -\frac{(V_B - V_A)}{d} = -\frac{\Delta V}{d} \quad \ldots\ldots\ldots (9.25)$$

If the plates A and B are separated by infinitesimally small distance Δd, the Eq. 9.25 is modified as:

$$E = -\frac{\Delta V}{\Delta d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9.26)$$

The quantity $\Delta V / \Delta d$ gives the maximum value of the rate of change of potential with distance because the charge has been moved along a field line in which the



In electroencephalography the potential deference created by the electrical activity of the brain are used for diagnosing abnormal behavior.

distance Δd between the two plates is minimum. It is known as potential gradient. Thus, the electric field intensity is equal to the negative of the gradient of electric potential. The negative sign indicates that the direction of E is along the decreasing potential.

The unit of electric intensity from Eq.9.26 is volt/metre ($V\ m^{-1}$) which is equal to $N\ C^{-1}$ as given below:

$$1\frac{\text{volt}}{\text{metre}} = 1\frac{\text{joule/coulomb}}{\text{metre}} = 1\frac{\text{newton}\times\text{metre}}{\text{metre}\times\text{coulomb}} = 1\frac{\text{newton}}{\text{coulomb}} = 1\ N\ C^{-1}$$

Example 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.

Solution

Here, $\Delta V = 12\,V$, $\Delta d = 1.0\,cm = 1\times10^{-2}\,m$, $E = ?$

Using the equation $E = \dfrac{\Delta V}{\Delta d}$

Substituting the values,

$$E = \frac{12\ V}{1\times10^{-2}\ m} = 1200\ V\ m^{-1}$$

Example 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 = $q = e = 1.6\times10^{-19}$ 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*

$$\Delta V\times e = \frac{1}{2}mv^2$$

Submitting the values,

$$12\ V\times1.6\times10^{-19}\ C = \frac{1}{2}\times9.1\times10^{-31}\ kg\times v^2$$

$$v^2 = 4.2\times10^{12}\ m^2\ s^{-2}$$

or $$v = 2.1\times10^{6}\ m\ s^{-1}$$

9.6 ELECTRON VOLT

We know that when a particle of charge q moves from point A at potential V_A to a point B at potential V_B keeping electrostatic equilibrium, the change in potential energy ΔU of particle is:

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

If no external force acts on the charge to maintain equilibrium, this change in *P.E.* appears in the form of change in *K.E.*

Suppose charge carried by the particle is $q = e = 1.6 \times 10^{-19}$C.

Thus, in this case, the energy acquired by the charge will be:

$$\Delta K.E. = q\Delta V = e\Delta V = (1.6 \times 10^{-19}\,C)(\Delta V)$$

Moreover, assume that ΔV = 1 volt, hence,

$$\Delta K.E. = q\Delta V = (1.6 \times 10^{-19}\,C) \times (1\,volt)$$

$$\Delta K.E. = (1.6 \times 10^{-19}) \times (C \times V) = 1.6 \times 10^{-19}\,J$$

The amount of energy equal to 1.6×10^{-19} J is called one electron-volt and is denoted by 1 eV. It is defined as "the amount of energy acquired or lost by an electron as it traverses a potential difference of one volt". Thus,

$$1\,eV = 1.6 \times 10^{-19}\,J \ldots\ldots\ldots\ldots\ldots\ldots (9.28)$$

Example 9.6 A particle carrying a charge of $2e$ falls through a potential difference of 3.0 V. Calculate the energy required by it.

Solution $q = 2e$, $\Delta V = 3.0$ V

The energy acquired by the particle is:

$$\Delta U = q\Delta V = (2e)(3.0\,V) = 6.0\,eV$$

$$\Delta U = 6.0 \times 1.6 \times 10^{-19}\,J = 9.6 \times 10^{-19}\,J$$

9.7 MOTION OF CHARGED PARTICLES IN A UNIFORM 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. The magnitude of electric force acting on a charge q is represented in Fig 9.18 given by

$$F = qE \ldots\ldots\ldots\ldots\ldots (9.29)$$

where E is the electric intensity of the uniform electric field. If V is the potential difference between the plates and d is the separation of plates, then

$$E = \frac{V}{d} \ldots\ldots\ldots\ldots\ldots (9.30)$$

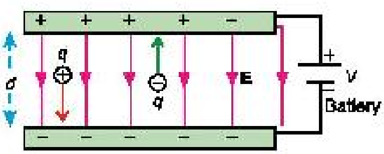


Fig. 9.18

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 $V = 20\,V$, $d = 2.0\,cm = 2 \times 10^{-2}\,m$, the magnitude of E will be:

$$E = \frac{V}{d} = \frac{20\,V}{2 \times 10^{-2}\,m^{-1}} = 1000\,V\,C^{-1}$$

The acceleration for the electron will be given by

$$F = ma$$

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

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

$$a = \frac{1.6 \times 10^{-19}\,C \times 1000\,V\,C^{-1}}{9.1 \times 10^{-31}\,kg} = 1.76 \times 10^{14}\,m\,s^{-2}$$

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 $S = d = 2 \times 10^{-2}\,m$, $v_i = 0$, $v_f = v = ?$

Putting the values in the above equation

$$2 \times 1.76 \times 10^{14}\,m\,s^{-2} \times 2 \times 10^{-2}\,m = v^2$$

or $$v^2 = 7.04 \times 10^{12}\,m^2\,s^{-2}$$

or $$v = 2.65 \times 10^{6}\,m\,s^{-1}$$

9.8 PATH OF A CHARGED PARTICLE

The path of a charged particle is determined by the electric field in the region. The path is typically straight if the field is uniform and the charged particle is moving along the field. However, if a charged particle enters perpendicularly to the uniform field between the oppositely charged parallel plates with a certain velocity as shown in Fig. 9.19, it will not go straight. Its path will be parabolic just like a projectile thrown horizontally in the gravitational field. The horizontal component of the velocity of the charged particle remains constant whereas vertical component is accelerated due to the electric force.

Figure 9.19 shows that a positivity charged particle is attracted towards the negatively charged plate and thus undergoes deflection in that direction.

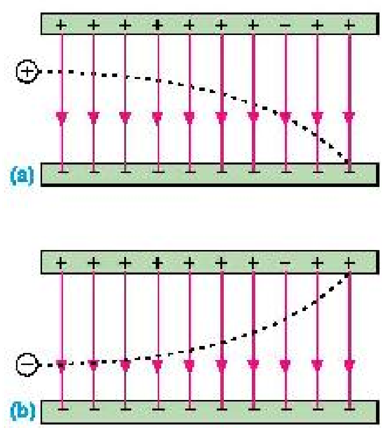


Fig. 9.19

On the other hand, a negatively charged particle is attracted towards the positively charged plate and experiences deflection in that direction.

9.9 SHIELDING FROM EXTERNAL ELECTRIC FIELD

An English scientist Michael Faraday invented a structure in 1836, called Faraday cage or Faraday shield. Faraday cage is an enclosure that blocks the external electric fields in conductive materials. It acts like a hollow conductor where devices or objects can be put for protection from electrical external fields. Any electrical shock received by the cage runs through its outer surface without causing any harm inside. The electric field inside the hollow conductor remains zero.

To understand the working of Faraday cage, suppose that a piece of conductor (say copper) carries a number of free electrons. Each electron will experience a force of repulsion because of the electric field of its neighbouring electrons. As a consequence, all the electrons rush to the surface of the conductor. Once static equilibrium is established with all of the excess charges on the surface, no further movement of charge occurs. If some electrons shift from the conductor to another object due to friction etc., a net positive charge appears on the surface of the conductor. We can say,

At equilibrium under electrostatic conditions, any excess charge resides on the surface of a conductor.

Now consider the interior of the hollow conductor. The excess charges arrange themselves on the conductor's surface precisely in the manner that the total field within the interior becomes zero. In other words,

The conductor shields any charge within it from electric fields outside the conductor.

To eliminate the interference of external fields, circuits are often enclosed within metal boxes that provide shielding from such fields.

Figure 9.20 shows another aspect of how conductors alter the electric field lines created by external charges.

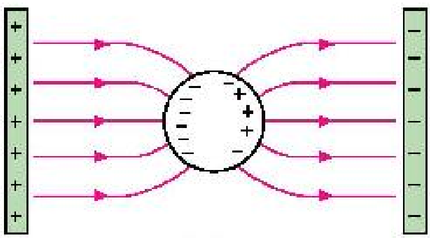


Fig. 9.20

The lines are altered because the electric field just outside the surface of a conductor is perpendicular to the surface at equilibrium under electrostatic conditions. If the field were not perpendicular, there would be a component of the field parallel to the surface. Since the free electrons on the surface of the conductor can move, they would do so under the force exerted by the parallel component. But in reality, no electron flow occurs at equilibrium. Therefore, there can be no parallel component, and the electric field is perpendicular to the surface.

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 the insulators can not be used to construct Faraday cage.

A good example of Faraday cage in our daily life is that of cars. The chassis and bodies of cars protect people inside due to its metal framed structure during the thunderstorms. The electrical charge travels over the metal surface of the vehicle into the ground and prevent the passengers inside.

A metal body of the microwave oven acts as a Faraday cage. Thus, they prevent the microwaves in an oven from expanding into the environment. Metal frame of an airplane also acts as a Faraday cage. When lightning strikes an airplane, electricity is distributed along its metal frame surface that keeps passengers and all devices inside the airplane safe.

9.10 ELECTRIC CURRENT

Usually, it is said that electric current is the flow of charge. Let us see what actually flows in a conductor. The charge carriers are the free electrons. When the ends of a conductor are connected to a battery or some other source of potential, an electric field is set up at every point within the conductor. The free electrons experience a force in the direction of $-\mathbf{E}$ and they start moving. As the free electrons are bumping among the atoms, so they are not accelerated in a straight line under this force. They keep on colliding with the atoms of the conductor. The overall effect of these collisions is to transfer the energy of accelerated eletrons to the lattice with the result that the electrons acquire an average velocity, called the drift velocity in the direction of $-\mathbf{E}$. The drift velocity is of the order of $10^{-3}\, m\, s^{-1}$. This drift velocity of electrons forms the electric current. The slow drift velocity does not mean that it takes long time for an electric current to set up. We know that as soon as we switch ON a bulb, it lit up immediately.

The reason is that on turning the switch ON, all the free electrons in the circuit start drifting. They repel the neighbouring ones and the disturbance propagates along the wire almost instantaneously. That is why, the electric current is set up very rapidly.

If a net charge Q passes through any cross-section of a conductor in time t, the current I flowing through it is:

$$I = \frac{Q}{t} \quad \text{..............} \quad (9.31)$$

The SI unit of current is ampere (A) and it is the current due to flow of one coulomb charge per second through any cross-section of a conductor. 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. 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. The electricity supplied to our homes, offices, factories etc., by power stations is an A.C.

Conventional Current

As we now understand, the electric current is due to flow of electrons through the metal wires, but early scientists believed that electric current was due to flow of positive charges. The scientists have kept the convention and take the direction of current flow to be the direction in which positive charges would move. We call it conventional current.

Conventional current is hypothetical flow of positive charges that would have the same effect in the circuit as the flow of negative charges that actually does occur.

In Fig. 9.21, negative electrons arrive at the positive terminal of the battery. The same effect would have been achieved if an equivalent amount of positive charge has left the positive terminal. Therefore, we can say that the conventional current flows from positive terminal towards the negative terminal of a battery. A conventional current is consistent with our earlier use of a positive test charge for defining electric fields and potential. The direction of conventional current is always from a point of higher potential towards a point of lower potential that is from the positive terminal towards the negative terminal. Now onward the current I always means the conventional current.

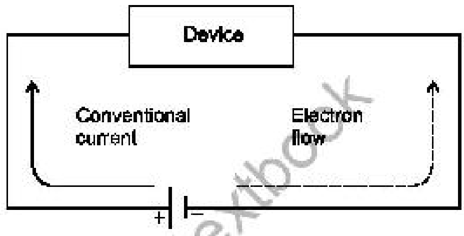


Fig. 9.21

9.11 CURRENT THROUGH A CONDUCTOR

Consider a segment of the current carrying conductor having length L and area of cross-section A. The volume of the segment is AL, as represented in Fig. 9.22. Let n be the number of charge carriers per unit volume, then total number of charge carriers in the segment at any time are nAL. If the charge on a charge carrier is q, the total change present inside the segment at any instant is:

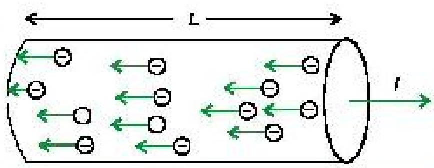


Fig. 9.22: Negative charge carriers

$$Q = nALq \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9.32)$$

Usually, the charge carriers in a conductor are free electrons which have negative charge.

Suppose that charge carriers move towards left face of the segment when a potential difference is applied across the conductor. Then electric current is set up in the conductor directed towards right face. Assuming that drift velocity of the charge carries to be v, the time taken t by all the charge carriers originally present in the

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.

segment to exit through the left face will be:

$$t = \frac{L}{v}$$

By definition of the current

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

Putting the value of Q and t in the above equation, we have

$$I = \frac{nALq}{\frac{L}{v}}$$

or $$I = nAvq \quad \text{..................} (9.33)$$

Example 9.7 A copper wire has a cross-sectional area of $2 \times 10^{-6}\ m^2$ and carries a current of 3 A. If the number of elections 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.

Solution

$I = 3$ A, $A = 2 \times 10^{-6}\ m^2$, $n = 8.5 \times 10^{28}\ m^{-3}$, $q = 1.6 \times 10^{-19}$ C, $v = ?$

Using equation,

$$I = Anvq$$

$$3 = (2 \times 10^{-6}\ m^2)(8.5 \times 10^{28}\ m^{-3})\,v\,(1.6 \times 10^{-19}\ C)$$

$$v = 1.1 \times 10^{-4}\ m\,s^{-1}$$

9.12 OHM'S LAW

When a potential difference V is applied across the ends of a conductor, a current I starts flowing through it. The Ohm's law states that:

> The current flowing through a conductor is directly proportional to the potential difference applied across the conductor, provided there is no charge in the physical state of the conductor.

Mathematically,

$$I \propto V \quad \text{or} \quad V \propto I$$

or $$V = IR \quad \text{..................} (9.34)$$

where R is a constant of proportionality known as resistance of the conductor. The SI unit of resistance is ohm denoted by the Greek capital letter omega (Ω), and is defined as:

> The resistance of a conductor is 1 ohm if a current of 1 ampere flows through it when a potential difference of 1 volt is applied across its ends.

9.13 RESISTIVITY AND ITS DEPENDENCE UPON TEMPERATURE

It has been experimentally seen that the resistance R of a wire is directly proportional to its length L and inversely proportional to its cross sectional area A. Mathematically,

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

or $$R = \rho \frac{L}{A} \quad \text{.............} \quad (9.35)$$

where ρ (rho) is a constant of proportionality known as resistivity or specific resistance of the material of the wire. It may be noted that resistance is the characteristic of a particular wire whereas the resistivity is the property of the material of which the wire is made. From Eq. 9.35, we have

$$\rho = \frac{RA}{L} \quad \text{.............} \quad (9.36)$$

The above equation gives the definition of resistivity as **the resistance of a metre cube of a material.** The SI unit of resistivity is ohm-metre (Ω m)

Conductance is another quantity used to describe the electrical properties of materials. In fact, conductance is the reciprocal of resistance, i.e.,

$$\text{Conductance} = \frac{1}{\text{Resistance}} \;, \; G = \frac{1}{R}$$, G is the conductance.

Mathematically, conductivity, σ (sigma) is the reciprocal of resistivity (ρ), i.e.

$$\sigma = \frac{1}{\rho} \text{.........................} (9.37)$$

The SI unit of conductivity is $\text{ohm}^{-1}\text{m}^{-1}$ or mho m^{-1}. Resistivity of various materials is given in Table 9.2. It may be noted from Table 9.2 that silver and copper are two best conductors. That is the reason, most of electric wires are made of copper.

The resistivity of a substance depends upon the temperature also. It can be explained by recalling that the resistance offered by a conductor to the flow of electric current is due to collisions, which the free electrons encounter with atoms of the lattice. As the temperature of the conductor rises, the amplitude of vibration of the atoms in the lattice increases and hence, the probability of their collision with free electrons also increases. One may say that the atoms then offer a bigger target, that is the collision cross-section of the atoms increases with temperature. This makes the collisions between free electrons and the atoms in the lattice more frequent and hence, the resistance of the conductor increases.

Table 9.2

Substance	$\rho(\Omega\,m)$	$\alpha(K^{-1})$
Silver	1.52×10^{-8}	0.00380
Copper	1.69×10^{-8}	0.00390
Gold	2.27×10^{-8}	0.00340
Aluminum	2.63×10^{-8}	0.00390
Tungsten	5.00×10^{-8}	0.00460
Iron	11.00×10^{-8}	0.00520
Platinum	11.00×10^{-8}	0.00520
Constanton	49.00×10^{-8}	0.00001
Mercury	94.00×10^{-8}	0.00091
Nichrome	100.0×10^{-8}	0.00020
Carbon	3.5×10^{-5}	-0.00005
Germanium	0.5	-0.05
Silicon	20-2300	-0.07

Experimentally, the change in resistance of a metallic conductor with temperature is found to be nearly linear over a considerable range of temperature above and below 0°C (Fig.9.23). Over such a range the fractional change in resistance per kelvin is known as the temperature coefficient (α) of resistance, i.e.

$$\alpha = \frac{R_t - R_o}{R_o t} \quad \text{.........................} \quad (9.38)$$

where R_o and R_t are resistances at temperatures 0°C and t°C respectively. As resistivity ρ depends upon the temperature, Eq. 9.35 gives

$$R_t = \rho_t \frac{L}{A} \quad \text{and} \quad R_o = \rho_o \frac{L}{A} \quad \text{.......} \quad (9.39)$$

Substituting the values of R_t and R_o in Eq. 9.39, we have

$$\alpha = \frac{\rho_t - \rho_o}{\rho_o t} \quad \text{.........................} \quad (9.40)$$

where ρ_o is the resistivity of a conductor at 0 °C and ρ_t is the resistivity at t°C. Values of temperature coefficients of resistance of some substances are also listed in Table 9.2. There are some substances like germanium, silicon, etc. whose resistance decreases with increase in temperature, these substances have negative temperature coefficients.

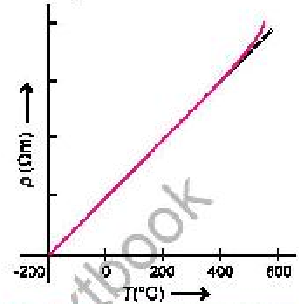


Fig. 9.23: Variation of resistivity of Cu with temperature

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.

Example 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.

Solution

The resistance R of the wire can be calculated by Eq. 9.34 i.e.,

$$R = \frac{V}{I} = \frac{1.5V}{0.75A} = 2.0 \, V A^{-1} = 2.0 \, \Omega$$

The resistivity ρ of iron of which the wire is made of is given by

$$\rho = R\frac{A}{L} = \frac{2.0\,\Omega \times 2.5 \times 10^{-7} \, m^2}{5.0 \, m} = 1.0 \times 10^{-7} \, \Omega \, m$$

Example 9.9 A platinum wire has resistance of 10 Ω at 0°C and 20 Ω at 193°C. Find the value of temperature coefficient of resistance of platinum.

Solution $R_o = 10\,\Omega$, $R_t = 20\,\Omega$, $t = 466\,K - 273\,K = 193\,K$

Temperature coefficient of resistance can be found by

$$\alpha = \frac{R_t - R_o}{R_o t} = \frac{20\,\Omega - 10\,\Omega}{10\,\Omega \times 193\,K} = \frac{1}{193\,K} = 5.18 \times 10^{-3} K^{-1}$$

9.14 ELECTRICAL POWER

Consider a circuit consisting of a battery of emf ε connected in series with a resistance R (Fig. 9.24). A steady current I flows through the circuit and a steady potential difference V exists between the terminals A and B of the resistor R. Terminal A, connected to the positive pole of the battery, is at a higher potential than the terminal B. 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

Work done $= W = V \times Q$..................(9.41)

This is the energy supplied by the battery.

The rate at which the battery is supplying electrical energy is the power output or electrical power of the battery. Using the definition of power, we have

$$\text{Electrical power} = \frac{\text{Energy supplied}}{\text{Time taken}} = V\frac{Q}{t}$$

Since $\qquad I = \frac{Q}{t}$

The above equation can also be written as:

Electrical power $= VI$......................(9.42)

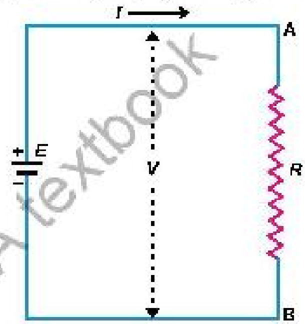


Fig. 9.24: The power of a battery appears as the power dissipated in the resistance R.

Equation 9.42 is a general relation for power delivered from a source of current I operating on a voltage V. In the circuit shown in Fig. 9.24 the power supplied by the battery is expended or dissipated in the resistor R. The principle of conservation of energy tells us that the power dissipated in the resistor is also given by Eq. 9.42.

Power dissipated $P = VI$

Alternative equation for calculating power can be found by substituting $V = IR$, $I = V/R$ in turn in Eq. 9.42.

$$P = VI = (IR)I = I^2R$$

or $\qquad P = VI = V(V/R) = V^2/R$

Thus, we have three equations for calculating the power dissipated in a resistor.

$$P = VI \quad , \qquad P = I^2R$$

$$P = V^2/R \quad .... \quad (9.43)$$

If V is expressed in volts and I in amperes, the power is expressed in watts.

9.15 ELECTROMOTIVE FORCE (EMF) AND POTENTIAL DIFFERENCE

We know that a source of electrical energy, say a cell or a battery, when connected across a resistance, maintains a steady current through it Fig. 9.25. The cell continuously supplies energy which is dissipated in the resistance of the circuit. Suppose when a steady current has been established in the circuit, a charge Q passes through any cross-section of the circuit in time t. During the course of motion, this charge enters the cell at its low potential end and leaves at its high potential end. The source must supply energy W to the positive charge to compel it to go to the point of high potential. The emf E of the source is defined as the energy supplied to unit charge by the cell.

Fig. 9.25: Electromotive force of a cell

i.e., $$E = \frac{W}{Q} \quad \text{.................(9.44)}$$

It may be noted that electromotive force is not a force and we do not measure it in newtons. The unit of emf is joule/coulomb which is volt (V). The energy supplied by the cell to the charge carriers is derived from the conversion of chemical energy into electrical energy inside the cell.

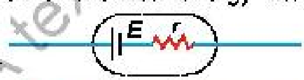


Fig. 9.26: An equivalent circuit of a cell of emf E and internal resistance r.

Like other components in a circuit, a cell also offers some resistance. This resistance is due to the electrolyte present between the two electrodes of the cell and is called the internal resistance of the cell. Thus, a cell of emf E having an internal resistance r is equivalent to a source of pure emf E with a resistance r in series as shown in Fig. 9.26.

Let us consider the performance of a cell of emf E and internal resistance r as shown in Fig.9.27. A voltmeter of infinite resistance measures the potential difference across the external resistance R or the potential difference V across the terminals of the cell. The current I flowing through the circuit is given by

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

or $$E = IR + Ir \quad \text{...........(9.45)}$$

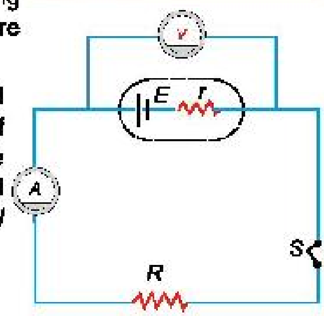


Fig. 9.27: The terminal potential difference V of a cell is $E - Ir$.

Here $IR = V$ is the terminal potential difference of the cell in the presence of current I. When the switch S is open, no current passes through the resistance. In this case, the voltmeter reads the emf E as terminal voltage. Thus, terminal voltage in the presence of the current (switch ON) would be less than the emf E by Ir.

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

Let us interpret the Eq. 9.45 on energy considerations. The left side of this equation is the emf E of the cell which is equal to energy gained by unit charge as it passes through the cell from its negative to positive terminal. The right side of the equation gives an account of the utilization of this energy as the current passes the circuit. It states that, as a unit charge passes through the circuit, a part of this energy equal to Ir is dissipated into the cell and the rest of the energy is dissipated into the external resistance R. It is given by potential drop IR. Thus, the emf gives the energy supplied to unit charge by the cell and the potential drop across the various elements account for the dissipation of this energy into other forms as the unit charge passes through these elements.

The emf is the "cause" and potential difference is its "effect". The emf is always present even when no current is drawn through the battery or the cell, but the potential difference across the conductor is zero when no current flows through it.

Example 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.

Solution

$$E = 2.2\,\text{V}, \qquad R = 5.0\,\Omega, \qquad V = 1.8\,\text{V}$$

We have to calculate I and r

Using

$$V = IR \quad \text{or} \quad I = \frac{V}{R} = \frac{1.8\,\text{V}}{5.0\,\Omega} = 0.36\,\text{A}$$

Internal resistance r can be calculated by using

$$E = V + Ir$$

$$2.2\,\text{V} = 1.8\,\text{V} + 0.36\,\text{A} \times r$$

or $$r = 1.1\,\Omega$$

9.16 KIRCHHOFF'S RULES

Kirchhoff's rules are two fundamental principles in circuit analysis that help to determine the current and voltage in electrical circuits. They are particularly useful for analysing complex circuits that cannot be simplified by Ohm's law and series or parallel combinations.

Kirchhoff's First Rule

It states that the sum of all the currents meeting at a point in the circuit is zero.

i.e., $\Sigma I = 0$ ....(9.46)

It is a convention that a current flowing towards a point is taken as positive and that flowing away from a point is taken as negative.

For your information

A node is a point in an electric circuit which joins the two or more branches.

Consider a situation where four wires meet at a point A (Fig.9.28). The currents flowing into the point A are I_1 and I_2 and currents flowing away from the point are I_3 and I_4.

According to the convention, currents I_1 and I_2 are positive and currents I_3 and I_4 are negative. Applying Eq. 9.46, we have

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

or $$I_1 + I_2 = I_3 + I_4 \quad \ldots\ldots\ldots\ldots (9.47)$$

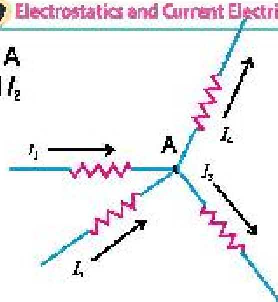


Fig. 9.28: According to Kirchhoff's 1st rule $I_1 + I_2 = I_3 + I_4$

Using Eq.9.47, Kirchhoff's first rule can be stated in other words as:

> The sum of all the currents flowing towards a point is equal to the sum of all the currents flowing away from the point.

Do you know?

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

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

Kirchhoff's Second Rule

It states that the algebraic sum of voltage changes in a closed circuit or a loop must be equal to zero. Consider a closed circuit shown in Fig. 9.29. The direction of the current I flowing through the circuit depends on the cell having the greater emf. Suppose E_1 is greater than E_2, so the current flows in counter clockwise direction. We know that a steady current is equivalent to a continuous flow of positive charges through the circuit. We also know that a voltage change or potential difference is equal to the work done on a unit positive charge or energy gained or lost by it in moving from one point to the other. Thus, when a positive charge Q due to the current I in the closed circuit (Fig.9.29), passes through the cell E_1 from low (-ve) to high potential (+ve), it gains energy because work is done on it. Using Eq. 9.44 the energy gain is E_1Q. When the current passes through the cell E_2, it loses energy equal to $-E_2Q$ because here the charge passes from high to low potential. In going through the resistor R_1, the charge Q loses energy equal to $-IR_1Q$ where IR_1 is potential difference across R_1. The minus sign shows that the charge is passing from high to low potential. Similarly, the loss of energy while passing through the resistor R_2 is $-IR_2Q$. Finally, the charge reaches the negative terminal of the cell E_1, from where we started. According to the law of conservation of energy, the total change in energy of our system is zero. Therefore, we can write:

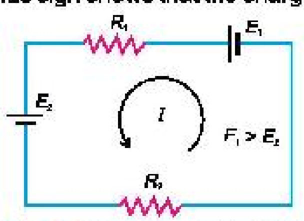


Fig. 9.29: According to Kirchhoff's 2nd rule $E_1 - IR_1 - E_2 - IR_2 = 0$

$$E_1Q - IR_1Q - E_2Q - IR_2Q = 0$$

or $$E_1 - IR_1 - E_2 - IR_2 = 0 \quad \ldots\ldots\ldots (9.48)$$

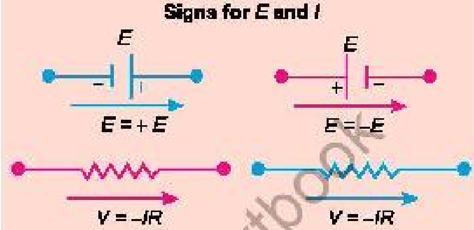
which is Kirchhoff's second rule and it states that:

The algebraic sum of potential changes in a closed circuit is zero.

We have seen that this rule is simply a particular way of stating the law of conservation of energy in electrical problems.

For your information

Signs for E and I

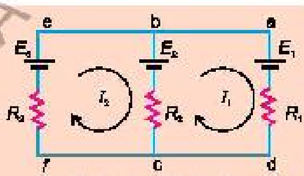


Before applying this rule for the analysis of complex network, it is worthwhile to thoroughly understand the rules for finding the potential changes.

(i) If a source of emf is traversed from positive to negative terminal, the potential change is positive. It is negative in the opposite direction.

(ii) If a resistor is traversed in the direction of current, the change in potential is positive. It is negative in the opposite direction.

Example 9.11 Calculate the currents in the three resistances of the circuit shown in Fig. 9.30.



R_1 = 10 Ω, R_2 = 30 Ω, R_3 = 15 Ω,
E_1 = 40 V, E_2 = 60 V, E_3 = 50V

Fig. 9.30

Solution

First we select two loops abcda and ebcfe. The choice of loops is quite arbitrary, but it should be such that each resistance is included at least once in the selected loops.

After selecting the loops, suppose a current I_1 is flowing in the first loop and I_2 in the second loop, all flowing in the same sense. These currents are called loop currents. The actual currents will be calculated with their help. It should be noted that the sense of the current flowing in all loops should essentially be the same. It may be clockwise or anticlockwise. Here we have assumed it to be clockwise.

We now apply Kirchhoff's second rule to obtain the equations required to calculate the currents through the resistances. We first consider the loop abcda. Starting at point a we follow the loop clockwise. The voltage change while crossing the battery E_1 is $-E_1$ because the current flows through it from positive to negative. The voltage change across R_1 is $-I_1R_1$. The resistance R_2 is common to both the loops I_1 and I_2, therefore, the currents I_1 and I_2 simultaneously flow through it. The directions of currents I_1 and I_2 as flowing through R_2 are opposite, so we have to decide that which of these currents is to be assigned a positive sign. The convention regarding the sign of the current is that if we are applying the Kirchhoff's second rule in the first loop, then the current of this loop i.e., I_1 will be assigned a positive sign and all currents flowing opposite to I_1 have a negative sign. Similarly, while applying Kirchhoff's second rule in the second loop, the current I_2 will be considered as positive and I_1 as negative. Using this convention the current flowing through R_2 is (I_1 - I_2) and the voltage change across is -(I_1 - I_2)R_2. The voltage change across the battery E_2 is E_2. Thus, the Kirchhoff's second rule as applied to the loop abcda gives

$$-E_1 - I_1 R_1 - (I_1 - I_2)R_2 + E_2 = 0$$

Substituting the values, we have

$$-40\text{ V} - I_1 \times 10\ \Omega - (I_1 - I_2) \times 30\ \Omega + 60\text{ V} = 0$$

$$20\text{ V} - 10\ \Omega \times [I_1 + 3(I_1 - I_2)] = 0$$

or $$4I_1 - 3I_2 = 2\text{ V}\ \Omega^{-1} = 2\text{ A}\ \ldots\ldots\ldots\ldots\text{(i)}$$

Similarly, applying Kirchhoff's second rule to the loop ebcfe, we have

$$-E_2 - (I_2 - I_1)R_2 - I_2 R_3 + E_3 = 0$$

Substituting the values

$$-60\text{ V} - (I_2 - I_1) \times 30\ \Omega - I_2 \times 15\ \Omega + 50\text{ V} = 0$$

$$-10\text{ V} - 15\ \Omega \times [I_2 + 2(I_2 - I_1)] = 0$$

$$6I_1 - 9I_2 = 2\text{ V}\ \Omega^{-1} = 2\text{ A}\ \ldots\ldots\ldots\ldots\text{(ii)}$$

Solving Eq.(i) and Eq. (ii) for I_1 and I_2, we have

$$I_1 = 0.66\text{ A and } I_2 = 0.22\text{ A}$$

Knowing the value of loop currents I_1 and I_2 the actual current flowing through each resistance of the circuit can be determined. Fig. 9.29 shows that I_1 and I_2 are the actual currents through the resistances R_1 and R_3. The actual current through R_2 is the difference of I_1 and I_2 and its direction is along the larger current. Thus,

The current through $R_1 = I_1 = 2/3\text{ A} = 0.66\text{ A}$ flowing in the direction of I_1 i.e., from a to d.

The current through $R_2 = I_1 - I_2 = 2/3\text{ A} - 2/9\text{ A} = 0.44\text{ A}$ flowing in the direction of I_1 i.e., from c to b.

The current through $R_3 = I_2 = 2/9\text{ A} = 0.22\text{ A}$ flowing in the direction of I_1 i.e., from f to e.

Procedures of Solution of Circuit Problems

After solving the above problem, we are in a position to apply the same procedure to analyse other direct current complex networks. While using Kirchhoff's rules in other problems, it is worthwhile to follow the approach given below:

(i) Draw the circuit diagram.

(ii) The choice of loops should be such that each resistance is included at least once in the selected loops.

(iii) Assume a loop current in each loop. All the loop currents should be in the same sense. It may be either clockwise or anticlockwise.

(iv) Write the loop equations for all the selected loops. For writing each loop equation, the voltage change across any component is positive if traversed from low to high potential and it is negative if traversed from high to low potential.

(v) Solve these equations for the unknown quantities.

9.17 WHEATSTONE BRIDGE

It is an electric circuit. The Wheatstone bridge circuit shown in Fig. 9.31 consists of four resistances R_1, R_2, R_3 and R_4 connected in such a way so as to form a mesh ABCDA. A battery is connected between points A and C. A sensitive galvanometer of resistance R_g is connected between points B and D. If the switch S is closed, a current will flow through the galvanometer. We have to determine the condition under which no current flows through the galvanometer even after the switch is closed. For this purpose, we analyse this circuit using Kirchhoff's second rule. We consider two loops ABDA and BCDB and assume anticlockwise loop currents I_1 and I_2 through the loops respectively. The Kirchhoff's second rule as applied to loop ABDA gives:

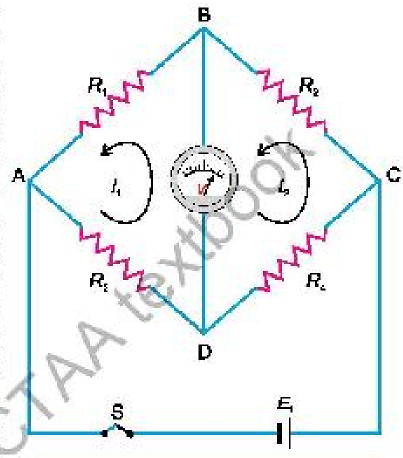


Fig. 9.31: Wheatstone bridge circuit

$$-I_1R_1-(I_1-I_2)R_g-I_1R_3=0 \qquad (9.49)$$

Similarly, by applying the Kirchhoff's second rule to loop BCDB, we have

$$-I_2R_2-I_2R_4-(I_2-I_1)R_g=0 \qquad (9.50)$$

The current flowing through the galvanometer will be zero if, $I_1-I_2=0$ or $I_1=I_2$. With this condition Eq. 9.51 and Eq. 9.52 reduce to:

$$-I_1R_1=I_1R_3 \qquad (9.51)$$

and

$$-I_2R_2=I_2R_4 \qquad (9.52)$$

Dividing Eq. 9.48 by Eq. 9.49, we have

$$\frac{-I_1R_1}{-I_2R_2}=\frac{I_1R_3}{I_2R_4} \qquad (9.53)$$

Point to ponder!

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

As $I_1=I_2$, therefore,

$$\frac{R_1}{R_2}=\frac{R_3}{R_4} \qquad (9.54)$$

Thus, whenever the condition of Eq. 9.54 is satisfied, no current flows through the galvanometer and it shows no deflection, or conversely when the galvanometer in the Wheatstone bridge circuit shows no deflection, Eq. 9.54 is satisfied. If we connect three resistances R_1, R_2 and R_3 of known adjustable values and a fourth resistance R_4 of unknown value and the resistances R_1, R_2 and R_3 are so adjusted that the galvanometer shows no deflection, then from the known resistances R_1, R_2 and R_3 , the unknown resistance R_4 can be determined by using Eq. 9.54.

9.18 POTENTIOMETER

A potentiometer is mainly used to compare potential differences and to find the value of an unknown resistance. It works on the principle of Wheatstone Bridge.

Working of Potentiometer

Potential difference is usually measured by an instrument called a voltmeter. The voltmeter is connected across the two points in a circuit between which potential difference is to be measured. It is necessary that the resistance of the voltmeter be large compared to the circuit resistance across which the voltmeter is connected. Otherwise, an appreciable current will flow through the voltmeter which will alter the circuit current and the potential difference to be measured. Thus, the voltmeter can read the correct potential difference only when it does not draw any current from the circuit across which it is connected. An ideal voltmeter would have an infinite resistance.

However, there are some potential measuring instruments such as digital voltmeter and cathode-ray oscilloscope which practically do not draw any current from the circuit because of their large resistance and are thus very accurate potential measuring instruments. But these instruments are very expensive. A very simple instrument which can measure and compare potential differences accurately is a potentiometer.

A potentiometer consists of a resistor R in the form of a wire on which a terminal C can slide (Fig. 9.32-a). The resistance between A and C can be varied from 0 to R as the sliding contact C is moved from A to B. If a battery of emf E is connected across R (Fig. 9.32-b) the current flowing through it is $I = E/R$. If we represent the resistance between A and C by r, the potential drop between these points will be $r\,I = r\,E/R$. Thus, as C is moved from A to B, r varies from 0 to R and the potential drop between A and C changes from 0 to E.

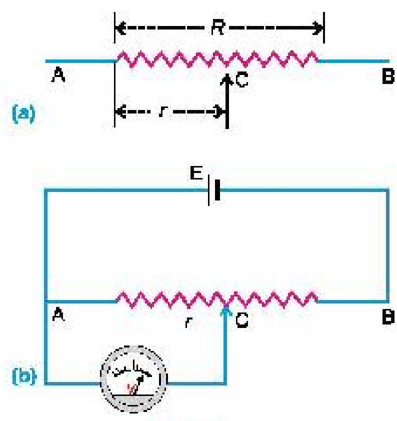


Fig. 9.32

Such an arrangement also known as potential divider can be used to measure the unknown emf of a source by using the circuit shown in Fig. 9.33. Here R is in the form of a straight wire of uniform area of cross-section. A source of potential, say a cell whose emf E_x is to be measured, is connected between A and the sliding contact C through a galvanometer G. It should be noted that the positive terminal of E_x and that of the potential divider are connected to the same point A. If, in the loop AGCA, the point C and the negative terminal of E_x are at the same potential, then the two terminals of the galvanometer will be at the same potential and no current will flow through the galvanometer. Therefore, 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 equal to the potential difference between A and C whose value Er/R is known. In case of a wire of uniform cross-section, the resistance is proportional to the length of the wire. Therefore, the unknown emf is also given by

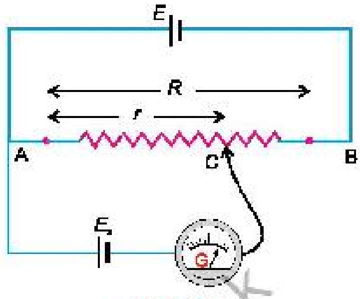


Fig. 9.33

$$E_x = E\frac{r}{R} = E\frac{\ell}{L} \quad \text{.....................(9.55)}$$

where L is the total length of the wire AB and ℓ is its length from A to C, after C has been adjusted for no deflection. As the maximum potential that can be obtained between A and C is E, so the unknown emf E_x should not exceed this value, otherwise the null condition will not be obtained. It can be seen that the unknown emf E_x is determined when no current is drawn from it and therefore, potentiometer is one of the most accurate methods for measuring potential.

The method for measuring the emf of a cell as described above can be used to compare the emfs E_1 and E_2 of two cells. The balancing lengths ℓ_1 and ℓ_2 are found separately for the two cells. Then,

$$E_1 = E\frac{\ell_1}{L} \text{ and } E_2 = E\frac{\ell_2}{L}$$

Dividing these two equations, we have

$$\frac{E_1}{E_2} = \frac{\ell}{\ell_2} \text{..................................(9.56)}$$

So, the ratio of the emfs is equal to ratio of the balancing lengths.

9.19 USE OF A GALVANOMETER

A galvanometer is an instrument for detecting a current. We are not going to discuss its internal structure and how does it work. We focus only on its use. It is often used in null methods to achieve precise measurements in electrical circuits. The null method involves adjusting the circuit until the galvanometer shows no deflection i.e., a zero reading. This indicates that certain required conditions are met in the circuit. In this state, the electric potentials at both ends of the galvanometer are the same. Although a galvanometer has its own resistance, but at the null reading, its resistance does not come into play. The reason is that, in this condition no current is passing through it. The null method is widely used in bridge circuits such as Wheatstone and potentiometer setups.

As we have studied in the previous section, the null method is used to measure an unknown resistance in the Wheatstone bridge circuits. The galvanometer is connected between the mid-points of opposite sides. The variable resistance is adjusted until the galvanometer shows no deflection. At this point, the bridge is balanced and the unknown resistance can be calculated using the ratio of the known resistances.

In a potentiometer, null method is used to measure an unknown voltage by comparison with a known reference voltage applied across the resistance wire of the potentiometer. A galvanometer and a jockey are used to make contact along the wire. At null point, the potential difference between the jockey and the end of the wire equals the unknown voltage. The position of the jockey gives the measure of the unknown voltage.

There are some advantages of using a galvanometer in null method.

1. Null method, eliminates the effect of the galvanometer's internal resistance on the measurement resulting in more accurate readings.
2. Galvanometers are highly sensitive and can detect very small currents of the order of 10^{-6} ampere.
3. "No deflection" indicates a direct and clear condition of balance making it easier to identify the null point.

9.20 THERMISTORS

A thermistor is a heat sensitive resistor. Most thermistors have negative temperature coefficient of resistance, i.e., the resistance of such thermistors decreases when their temperature is increased. Thermistors with positive temperature coefficient are also available.

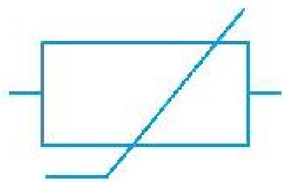


Fig. 9.34: Thermistors sysmbols

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.

Fig. 9.35: Types of thermistors

Thermistors are made by heating under high pressure semiconductor ceramic made from mixtures of metallic oxides of manganese, nickel, cobalt, copper, iron, etc. These are pressed into desired shapes and then baked at high temperature. Different types of thermistors are shown in Fig. 9.34. They may be in the form of beads, rods or washers.

Applications of Thermistors

Temperature Measurement

Thermistors are used in thermometers, and electric devices such as air conditioners, refrigerators, heaters, microwave ovens, incubators, etc.to monitor temperature.

Thermistors with high negative temperature coefficient are very accurate for measuring low temperatures especially near 10 K. The higher resistance at low temperature enables more accurate measurement possible.

Thermistors have wide applications as temperature sensors, i.e. they convert changes of temperature into electrical voltage which is duly processed. For example, these are used in coolant temperature sensors in automobile engines to prevent the engine overheating and in digital thermometers.

Temperature Compensation

Thermistors are used in circuits where temperature changes could affect performance. Such as in oscillators, battery charging circuits and power systems.

Inrush Current Limiting

Thermistors are used to limit the initial flow of current when a device is first turned on.

Voltage Divider

Thermistors are widely used as voltage divider. As shown in Fig. 9.36 when temperature of a thermistor increases, its resistance decreases. This decreases the voltage drop across the thermistor. As a result, the potential at point B increases that can be used to trigger a circuit connected to it. In case of a fire alarm, the use of a thermistor turns the NOT gate low when it gets heated. The output of NOT gate goes high and turns the siren ON.

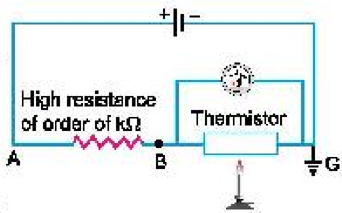


Fig. 9.36

9.21 LIGHT DEPENDENT RESISTOR

Light dependent resistor (LDR) is a resistor whose resistance decreases with increasing light intensity. Due to this property, it is also known as photo resistor. The LDRs are typically made from semiconductor material like cadmium sulphide. The material is deposited in a special pattern on an insulating plate.

Working Principle

The principle used in an LDR is the increase in the conductivity of the material on exposing it to light. In darkness, the semiconductor material has a few free electrons (charge carriers) resulting in high resistance. When light photons hit the material, they transfer energy to electrons in the outer orbits, thus, making them free to conduct electricity. This decreases the resistance of LDR. The amount of light hitting the LDR's surface determines the number of free elections. Conversely, less light results in lowering the free elections, thus, making higher resistance. This change in resistance can be measured and used in circuits to sense light levels.

Applications of LDRs

Light Sensors

LDRs are commonly used in light sensing circuits such as automatic lighting systems in homes and street lights. An LDR works just like a switch that turns ON at dusk and OFF at dawn.

Camera Exposure Control

LDRs help in adjusting the exposure time in cameras based on the amount of available light.

Voltage Divider

In a typical circuit, an LDR can be a part of voltage divider, that converts the resistance change into measurable voltage change. This voltage can then be read by a micro-controller or other control circuitry to perform actions based on light levels. A circuit is shown in Fig. 9.37 in which an LDR is used as voltage divider. In the dark, the LDR has a very high resistance as compared to the standard resistance (100 kΩ) in the circuit. Therefore the voltage drop across the LDR is very large as registered by a voltmeter. When the LDR is exposed to light, the resistance of LDR decreases to very low. Now, the voltmeter registers a lower reading. Hence, the change in light intensity gives rise to change in voltage. Therefore, by connecting mid-point B to a NOT gate, LDR can be used as a switch.

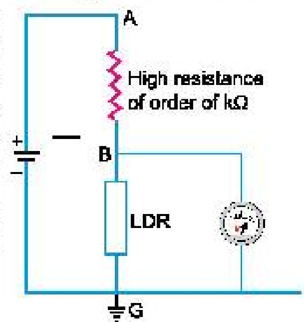


Fig. 9.37

Reliability of A Concrete Bridge

Inspectors can easily check the reliability of concrete bridge with the help of carbon fibers embedded in its slab. This is possible because of the conducting property of the carbon fibers. Let us know step by step how does it work?

1. First step is to know the electrical properties of carbon fibers. Carbon fibers are known to be good conductors of electricity due to their high carbon content.
2. Secondly, we can embed the carbon fibers within the slab of the concrete bridge during its construction.

Fig. 9.38: Carbon fibre sheets

Then we can connect them to form a conductors network.

3. Inspectors can check the reliability of the concrete bridge by applying small electric current to the carbon fiber network. They can determine the integrity of the concrete structure by measuring the resistance of the network.

4. The sensor installed into the network can show whether the electric resistance is changing or not. If the resistance remains the same over time, it indicates that the concrete bridge is maintaining its structural integrity. However, if the resistance increases, it means that the concrete is deteriorating or that the carbon fibers are being damaged.

   Some other methods are also used to check the strength of the concrete bridge. For example, a type of sensors continuously monitor strain, vibration and temperature. Internal flaws, such as cracks or voids are detected by using ultrasound waves.

QUESTIONS

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

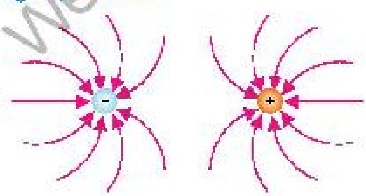
(d) increases four times to its original value

9.2 Which electric charge is possible on a particle?

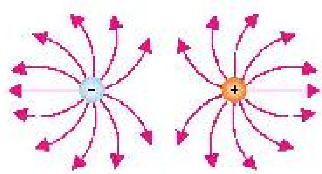
(a) 2.5×10^{-19} C (b) 3.2×10^{-19} C (c) 1.6×10^{-19} C (d) 6.02×10^{23} C

9.3 Which diagram best represents the electric field lines around two oppositely charged particles?

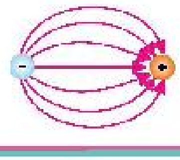
(a)



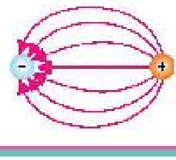
(b)



(c)



(d)



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

9.5 The potential at a point situated at a distance of 50 cm from a charge of 50 μC is:

(a) 9×10^{-4} volts (b) 18×10^{-4} volts (c) 9×10^{5} volts (d) 18×10^{4} volts

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}

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

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

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

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

Short Answer Questions

9.1 How does a moving conductor like an aeroplane acquire charge as it flies through the air? Describe briefly.

9.2 Define electric intensity and electric potential.

9.3 A battery is rated at 100 A h (ampere-hour). How much charge can this battery supply?

9.4 Is electron-volt a unit of potential difference or energy? Explain.

9.5 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?

9.6 Why does the resistance of a conductor rise with increase in temperature?

9.7 Is the filament resistance lower or higher in a 500W-220V light bulb than in a 100 W-220V bulb?

9.8 Why does resistance of a thermistor changes as temperature increases?

9.9 Which materials can be used to construct Faraday's cage and why?

Constructed Response Questions

9.1 Electric lines of force never cross each other. Why?

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.

9.3 Electrostatic force is 10^{38} times stronger than gravitational force. Argue that our galaxy should be almost electrically neutral.

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?

9.5 A potential difference is applied across the ends of a copper wire. What is the effect on the drift velocity of free elections by

(i) increasing the potential difference?

(ii) decreasing the length and the temperature of the wire?

9.6 Why the terminal potential difference of a battery decreases when the current drawn from it is increased?

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.

Numerical Problems

9.1 Two unequal point charges repel each other with a force of 0.4 N when they are 5.0 cm apart. Find the force which each charge exerts on the other when they are (a) 2.5 cm apart (b) 15.0 cm apart. [Ans: (a) 1.6 N (b) 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^{-1}, 100 mN)

9.3 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.

(Ans: $\approx 2.3 \times 10^{39}$)

9.4 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.

(Ans: -1.96×10^{-14} C)

9.5 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? (Ans: 5.27×10^{13} m s^{-2}, 3.34×10^{-8} s)

9.6 A disc of 10 cm^2 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. (Ans: $250\sqrt{3}$ N m^2 C^{-1})

9.7 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.] (Ans: 1.08×10^{-4} Ω, 1.52 cm)

9.8 The copper winding of an electric fan has a resistance of 50 Ω at 30 °C. After running for some time, the resistance becomes 52 Ω. How much is the increase in temperature of the winding? [For copper $\alpha = 0.0039$ K^{-1}] (Ans: 10.3 °C)

9.9 During an experiment, a copper wire of 50 m long and 150 μm thick is hung vertically. Then a current of 1 A is passed across its ends for 50 s. Find the resistance of the wire and the heat dissipated during this process. [Resistivity of copper is 1.69×10^{-8} Ω m.] (Ans: 47.8 Ω, 2390 J)

9.10 The emf of a battery is 12 V. It is connected to a 3.6 Ω resistor. If the internal resistance of the battery is 0.2 Ω, what will be the terminal voltage across the battery? (Ans: 11.4 V)