UNIT 5 ELECTRICITY AND ITS EFFECTS

Structure

5.1 INTRODUCTION

In Unit 4, you studied the formation of images by mirrors and lenses. You know that a source of light is necessary for obtaining image of any object (other than the self-luminous objects such as the sun and a candle). Most of the man-made sources of light are of electrical origin. For example, an electric bulb gives light because electricity (electric current) flows through its filament.

Would not you like to know : What is electricity? How does it originate? What constitute electric current? What are the effects on matter when current flows through it? These are some of the issues we shall discuss in the present unit.

You will agree that electricity plays an important role in our lives. Be it appliances such as electric iron, electric bulbs and electric fans or transportation or communication, electricity is used in all these gadgets and activities. Electricity and its various applications became possible after the discovery of electric charge. Like mass, electric charge is an intrinsic property of matter. In Section 5.2, you will learn the laws governing the behaviour of electric charge and the concept of electric field. The electrical appliances consist of various electrical components (such as resistor, capacitor etc.) connected to each other in definite arrangements called electrical circuits. In Section 5.3, you will learn the microscopic description of electric current and the behaviour of the some common electrical components when they constitute simple electrical circuits.

You will also learn the Kirchhoff's rules which govern the distribution of currents in complex electrical circuits.

The resistance is one of the important parameters of materials used in electrical circuits. Therefore, precise measurement of resistance is necessary for designing electrical circuits and it is carried out by a variety of electrical instruments like meter bridge and potentiometer. You will learn the principle of operation of these instruments in Section 5.4. Further, a large number of applications of electricity has been possible because the flow of current through conducting materials produces heat and induces chemical changes. In Sections 5.5 and 5.6, you will learn the heating and chemical effects of electricity respectively. We end this unit with a discussion on the construction and working of a few important types of cells – a source of potential differences –which are essential components of any electrical circuit. You will learn about cells in Section 5.7.

Objectives

After studying this unit, you should be able to

- state Coulomb's law and explain the concept of electric field,
- define electric potential, current and resistance,
- state Ohm's law,
- derive an expression for the drift velocity of electrons in a conductor,
- describe the working of Wheatstone bridge, metre bridge and potentiometer,
- explain the relation between current and heat produced by it in a conductor,
- state Faraday's laws of electrolysis and explain the process of electrolysis, and
- describe the construction and working of a few cells.

5.2 ELECTRIC CHARGE AND ELECTRIC FORCE

From your school physics, you know that electric charge is an intrinsic property of matter. You also know that there are two types of electric charge : *positive charge* and *negative charge*. They are characterised by the fact that

(a) the like charges repel each other, and

(b) the unlike charges attract each other.

Generally, the amount of positive and negative charges in a material body is equal. It is, however, possible to transfer charge from one body to another. For example, when we rub a glass rod with a piece of silk cloth, the rod becomes positively charged (that is, it has excess of positive charge) and the silk cloth becomes negatively charged (that is, it has excess of negative charge). Further, the electric charge obeys the conservation principle : **electric charge can neither be created nor destroyed; it can only be transferred from one body to another**.

At the microscopic level, electric charge plays an important role in the atomic structure of matter. You know that an atom – the building block of matter – comprises three types of particles namely electron, proton and neutron. These atomic particles are distinguished from each other on the basis of the nature of their electric charges. Electron is negatively charged, proton is positively charged and neutron is an electrically neutral particle. **Since the amount of charge possessed by an electron and a proton is equal, a neutral atom comprises equal number of electrons and protons**.

The study of the behaviour of electric charge is broadly divided into two categories. When we confine our study to charges which are at rest, it is called **electrostatics**. However, when charges are in motion, they give rise to magnetic effects as well and this area of study is called **electromagnetics**. In the present unit, we shall mostly confine ourselves to electrostatics and electric current without any reference to the associated magnetic effects.

As mentioned above, like charges repel each other and unlike charges attract each other. You may like to know : What governs the strength of attraction or repulsion between the charges? To answer this question, you should know the Coulomb's law as discussed below.

5.2.1 Coulomb's Law

Experiments show that when two charged bodies are brought near each other, they either attract or repel. *This indicates that the electric charges exert force on each other*. The force between charged bodies or electric charges is called **electric force** and it is one of the fundamental forces of nature (like the gravitational force arising due to the mass of a body). The question is : What is the strength of this force? How does it depend on the amount of charge and the separation between the charges? These questions were answered by Coulomb, on the basis of a series of measurements, in the form of Coulomb's law. The Coulomb's law is :

The force of attraction or the force of repulsion between two charges is directly proportional to the product of the magnitudes of the charges and is inversely proportional to the square of the distance between them; also, the force between the two charges acts along the line joining them.

To write the expression for Coulomb's law, consider two charges q_1 and q_2 separated by a distance r (Figure 5.1). Then, according to the Coulomb's law the electric force (F) between the charges is :

$$F \propto q_1 q_2 \qquad \text{. . . (5.1)}$$

and,

$$F \propto \frac{1}{r^2} \qquad \text{. . . (5.2)}$$

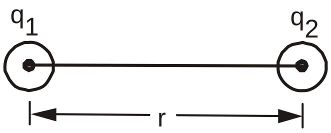


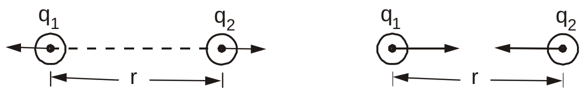
Figure 5.1 : Two Charges q_1 and q_2 Separated by a Distance r

Combining Eqs. (5.1) and (5.2), we get :

$$F \propto \frac{q_1 q_2}{r^2}$$

$$F = K \frac{q_1 q_2}{r^2} \qquad \text{. . . (5.3)}$$

where K is the proportionality constant and it is called *electrostatic force constant*.



(a) **(b)**

Figure 5.2 : (a) Force of Repulsion; and (b) Force of Attraction between Charges

You may note that the expression for the Coulomb's law (Eq. (5.3)) takes into account that like charges repel each other and *vice-versa*. When q_1 and q_2 have the same sign, the product $q_1\,q_2$ is positive and F is positive indicating repulsive force (Figure 5.2(a)). On the other hand, when q_1 and q_2 have opposite signs, F is negative indicating attractive force between charges (Figure 5.2(b)).

In SI unit, the constant of proportionality, K, is given as :

$$K = \frac{1}{4\pi\,\varepsilon_0}$$

where ε_0 is a constant called **absolute permittivity** of free space. The value of ε_0 is $8.854 \times 10^{-12}\ \mathrm{C^2\,N^{-1}\,m^{-2}}$. The SI unit of electric charge is called Coulomb (C). The magnitude of the charge on an electron (e) – the fundamental charge – is 1.602×10^{-19} C. The charge on an electron is denoted by – e and that on a proton by + e. And in SI unit the electric force is expressed in Newton (N).

The constant of proportionality, K, in Eq. (5.3) takes care of the fact that **the magnitude of the electric force depends on the medium in which the charges are located**. It is so because the permittivity is a characteristic of the medium. When the same charges q_1 and q_2 are kept at the same distance r in a medium whose permittivity is ε_m, Eq. (5.3) reduces to :

$$F_{\text{med}} = \frac{1}{4\pi\,\varepsilon_m}\,\frac{q_1\,q_2}{r^2} \qquad \text{. . . (5.4)}$$

Dividing Eq. (5.3) (which gives the electric force between q_1 and q_2 placed in free space or vacuum) by Eq. (5.4), we get :

$$\frac{F_{\text{vac}}}{F_{\text{med}}} = \frac{\dfrac{1}{4\pi\,\varepsilon_0}\,\dfrac{q_1\,q_2}{r^2}}{\dfrac{1}{4\pi\,\varepsilon_m}\,\dfrac{q_1\,q_2}{r^2}}$$

$$= \frac{\varepsilon_m}{\varepsilon_0} \qquad \text{. . . (5.5)}$$

The ratio $\dfrac{\varepsilon_m}{\varepsilon_0}$ is called the **relative permittivity** or the **dielectric constant** of the medium and is denoted by ε_r. Hence, the *relative permittivity or the dielectric constant of a medium is defined as the ratio of the magnitude of force between the two charges placed some distance apart in vacuum to the force between the same charges placed same distance apart in the medium*. Further, since the relative permittivity (ε_r) is a ratio of two same quantities, it is a dimensionless quantity.

Although the Coulomb's law enables us to determine the electric force between charged bodies, the process becomes very cumbersome if there are large number of charged bodies each having different amounts of charge on them. Analysis of such electrostatic problems becomes much easier if we define a quantity which can be associated with position only; that is, the quantity can be associated with every point in the space surrounding a charge or a group of charges. This quantity is called electric field and you will learn it now.

Electric Field

Refer to Figure 5.3 which shows a positive charge q placed at point O. The electric field due to this charge at some point, say P, is defined as the electric force experienced by a positive test charge q_0 placed at this point.

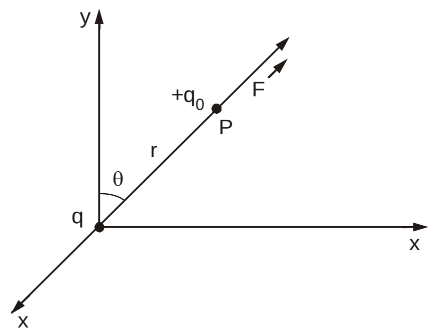


Figure 5.3 : Electric Field at Point *P* due to Charge *q*

Mathematically, we write the electric field, E as :

$$E = \frac{F}{q_0} \qquad \text{. . . (5.6)}$$

In the context of electric field, it is important to note that the *amount* of charge on the test charge should be small so that its effect (force) on the charge q is negligible. This condition must be satisfied to ensure that the electric field is independent of the magnitude of the test charge. The SI unit of electric field is NC^{-1}. It is, like electric force, a **vector** quantity. However, for simplicity, we shall mostly confine ourselves only to the magnitude of the electric field in this unit. The direction of electric field is the same as the direction of electric force (Figure 5.3).

Further, on the basis of Eqs. (5.3) and (5.6), we have :

$$E = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q}{r^2} \qquad \text{. . . (5.7)}$$

where r is the distance between the charge q and point P where field is measured. Eq. (5.7) shows that the magnitude of the field decreases as the distance increases.

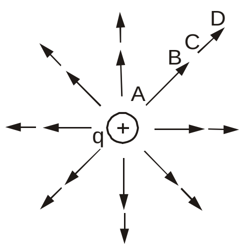
You may argue : **Since we can determine the electric force between charges using the Coulomb's law, what is the use of electric field**? There are many advantages of using the concept of electric field. Firstly, like any other field, electric field is associated with position. That is, the value of electric field at a given point in space due to a given charge or a group of charges (called *charge distribution*) is fixed. It only depends on the charge(s) producing it and on the distance of the point where it is measured. So, if you know the electric field profile of a given region in space, you can determine the electric force experienced by a given charge(s) in that region. You need not worry about the charge(s) producing the electric field.

Secondly, when charges are in motion, the electric field and the Coulomb's law descriptions of the electric forces are not the same. The Coulomb's law implies that the effect of motion of a given charge is felt *instantaneously* by other charge(s). This is not supported by the experimental observations. The effect is actually felt after some time (though very small) and this limitations of the Coulomb's law is accounted for by the electric field description of electric forces. If you persue higher studies in physics, you will learn about the implications of this aspect of electric field.

Force, as a concept, seems very familiar to all of us because we can *feel* it. Thus, when we talk about attractive or repulsive force between charges, it is not difficult to visualise. The same is not true perhaps for the field as a concept. A logical question, therefore, is : **Is there a method to visualise the abstract concept of electric field**? We can use a graphical method to do so. It involves drawing electric field lines. You will learn it now.

Electric Lines of Forces

You may recall that a vector quantity is characterised by magnitude as well as direction. Therefore, the electric field at point *A* due to positive charge *q* can be represented by vector ***AB*** as shown in Figure 5.4(a). The length of ***AB*** denotes the magnitude of the electric field at point *A* and the arrow of ***AB*** denotes the direction along which the field is acting (that is, the direction along which a unit positive test charge will experience the electric force if it is placed at point *A*). As we go away from the charge *q*, such as at point *C*, the magnitude of the field decreases (Eq. (5.7)) which is indicated by the smaller length of the vector ***CD***. However, note that the direction of the field at point *C* is same as at point *A*. Electric field in the entire space due to the positive charge *q* can similarly be represented by vectors as shown in Figure 5.4(a). And, if we join the vectors along the same line, we obtain **electric field lines** or **the lines of force** corresponding to the charge *q* as shown in Figure 5.4(b).



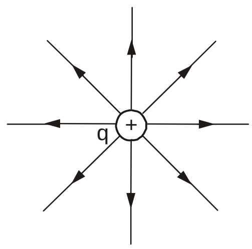


Figure 5.4 : (a) Vectors Representing Electric Field at Different Points in Space due to Positive Charge *q*; and (b) Corresponding Electric Field Lines

Similarly, the electric field lines corresponding to a negative charge, – *q*, is shown in Figure 5.5. *Note that the electric field lines are directed away from the positive charge* (*Figure 5.4*(*b*)) *and are directed towards the negative charge* (*Figure 5.5*(*c*)). Some important characteristics of the field lines are as follows :

- The direction of the field lines at any point in space indicates the direction of the electric field at that point.
- Electric field lines starts at the positive charge and terminates at the negative charge; they never start or stop except at charges.

- The number of field lines per unit cross-sectional area at a point is proportional to the magnitude of the electric field at that point. Therefore, near the charge, field lines are closer to each other indicating larger magnitude, and as we move away from the charge, field lines spread out indicating smaller magnitude of the field.

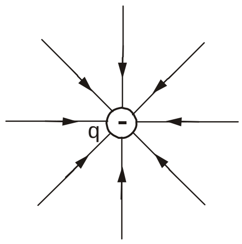


Figure 5.5 : Electric Field Lines due to a Negative Charge, – *q*

- While representing electric field by field lines, the number of field lines are drawn in proportion to the magnitude of the charge so that the density of lines truly represent the magnitude of the field at any given point.

Now, refer to Figure 5.6 which shows the electric field lines due to a system of two charges – one positive (+ q) and another negative (– q) – of equal magnitude. Before proceeding further, you must convince yourself that the field lines drawn in Figure 5.6 do have the properties listed above.

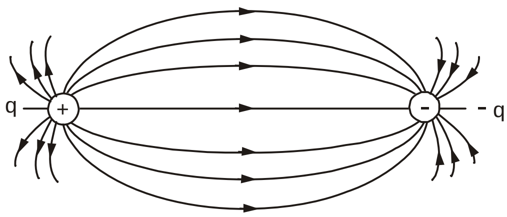


Figure 5.6 : Field Lines due to a System of Two Charges

Description of electric forces due to a complex distribution of charges in terms of a vector such as the electric field is a little tedius task. The task becomes much easier if we can define a scalar quantity which is equally effective in describing electric forces due to a charge or a charge distribution. Such a vector quantity is called electric potential and you will learn it now.

Before proceeding further, how about solving a few problems to check your understanding of the concepts you studied so far in this unit.

SAQ 1

(a) Calculate the value of the electrostatic force constant (K). Take the value of ε_0 to be $8.854 \times 10^{-12}\ \mathrm{C^2\,N^{-1}\,m^{-2}}$.

(b) Calculate the electric force between two charged spheres having charges 4×10^{-7} C and 6×10^{-7} C and placed 60 cm apart in air.

(c) What is the force of repulsion between two insulated charged copper spheres P and Q, each having charge 5×10^{-7} C and are separated by a distance of 50 cm. Also calculate the force of repulsion if both the spheres are placed in water. Take the dielectric constant of water to be 80.

(d) Calculate the magnitude of electric field due to a charge of 4×10^{-7} C at a point 2 cm from the charge.

5.2.2 Electrical Potential

As you learnt above, an electric charge produces electric field at every point in space. Similarly, we can define another field called electric (or electrostatic) potential produced by a charge or a charge distribution at every point in space.

To understand the concept of electric potential, suppose a charge Q is placed at some point in space. If we wish to bring another charge, say q, near the charge Q from a far-off distance, we will have to do work. (Recall that work is defined as force $\times$ displacement.) The electric potential at a given point in space due to the charge Q is defined as the work done in bringing a unit positive charge from infinity to that point. (The term infinity basically refers to such large distances from the charge Q where the electric force exerted by it on a unit positive charge can be considered very, very small.) The electric potential due to a charge Q at a point located at a distance r from the charge is given by :

$$V = \frac{1}{4\pi \varepsilon_0} \frac{Q}{r}$$

Now, similar to the gravitational force, the electric force is a conservative force. Therefore, the work done by the electric force can be related to electric potential energy. *Thus, electric potential can also be defined as electric potential energy per unit charge*.

Electric Potential Difference

For describing the electric forces due to charge distribution as well as for describing the motion of charges under the influence of electric forces, potential difference between two points is a more useful quantity than electric potential at a point. *If we know the potential difference between the two points, we can completely describe the motion of charge between these two points*. The best part is that in doing so, we do not require any information about electric forces and fields!

Let us consider two points, A and B, in an electric field of point charge + Q. Let V_A and V_B are the electric potentials at points A and B respectively. *Electric potential difference or the voltage between points A and B is defined as the amount of work done to move a unit positive charge from point A to the point B*. Mathematically, it can be written as :

$$V_{AB} = V_B - V_A = W_{AB}$$

$V_B - V_A$ is called electric potential difference. W_{AB} is the work done in moving the unit positive charge from A to B. If, instead of unit positive charge, a charge q is moved from point A to B, we write the potential difference between the points A and B as :

$$V_{AB} = \frac{W_{AB}}{q} \qquad \text{. . . (5.8)}$$

The unit of the electric potential difference is volt (V) and it is because of the name of its unit that is commonly called **voltage**. It is a scalar quantity.

Till now, you studied electric force, electric field and electric potential difference. Understanding of these concepts is necessary to appreciate the applications of electricity. You are now, therefore, ready to study basic electrical circuits which involves flow of electric current through a closed loop consisting of variety of electrical components. But, before that, you should solve the following SAQ.

SAQ 2

Calculate the electric potential at a point *P* due to a charge of 2×10^{-8} C situated 8 cm away. Also determine the work done in bringing a charge of 2×10^{-9} C from infinity to the point *P*.

5.3 SIMPLE ELECTRICAL CIRCUITS

When various electrical components such as resistor (or resistance) and battery are connected to each other through conducting wires in a closed loop arrangement, it is called an electrical circuit. There are two crucial considerations for any electric circuit :

(a) There must be a source of energy which provides energy to electrons so that they can move and constitute an electric current, and

(b) The wires connecting different components of the circuit must be made of conductor material so that electric current can flow uninterrupted in the circuit.

You may be aware that most of the household electrical appliances such as electric iron, radio, television etc. are basically electric circuits. The arrangement of various electric components and the values of their characteristics parameters are determined by the expected result from a particular circuit. The flow of electric current is the basic process which takes place when an electric circuit is in operation. Therefore, you should first know : **What is electric current**? **What are the basic requirements so that it flows through material wires**? Let us now learn about electric current in detail.

5.3.1 Electric Current : The Flow of Charge

Electric current is defined as the rate of flow of electric charge. It is, however, important to know that electric current cannot flow through wires made of all types of materials. Current flows only when the wire is made of a conductor. A **conductor** is a material in which there exists some *free charge carriers* (such as electrons) which can move freely and constitute the electric current when a battery (a source of electric field) is connected across the two ends of the conductor wire. Another type of materials, called **insulators**, *does not have free charge carriers* and hence electric current cannot flow through the wires made of such materials. There is yet another type of material known as **semiconductor** which behaves like a conductor under certain conditions.

Let *Q* be the total charge that flows through a conductor wire in time *t*. The electric current (*I*) in the wire can be expressed as :

$$I = \frac{Q}{t} \qquad \text{. . . (5.9)}$$

If the total charge Q consists of n electrons, each of charge e, we can write :

$$Q = n\, e \qquad \text{. . . (5.10)}$$

Thus, from Eqs. (5.9) and (5.10), we get :

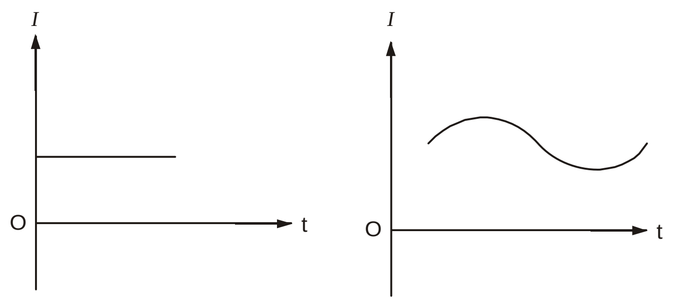
$$I = \frac{n\,e}{t} \qquad \text{. . . (5.11)}$$

The SI unit of electric current is Ampere (A). Thus, a current is said to be of 1 Ampere, if one Coulomb (C) charge flows through the wire in one second; that is :

$$1 \text{ Ampere} = \frac{1 \text{ Coulomb}}{1 \text{ second}}$$

There are two types of electric current :

(a) When electric charge flows only in one direction, the resulting current is called **direct current (DC)**. Refer to Figure 5.7 which shows the current-time plot for direct current. Note that the crucial fact about direct current is its direction of flow; its magnitude may or may not change with time.



(a) **(b)**

Figure 5.7 : Current-time Plots for Direct Current of (a) Constant Magnitude; and (b) Variable Magnitude

(b) When the direction of the flow of charges changes **periodically**, the resulting current is called **alternating current (AC)**. Refer to Figure 5.8 which shows the current-time graph for alternating current.

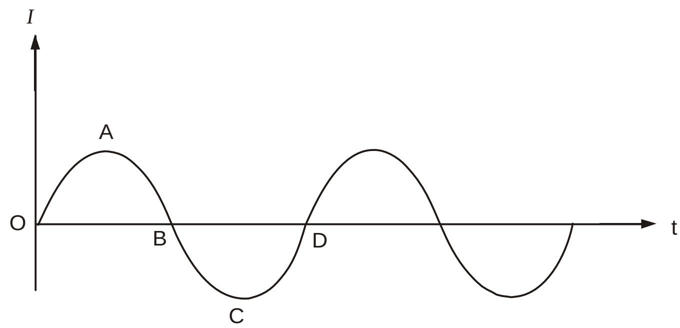


Figure 5.8 : Variation of Current with Time for Alternating Current

Note that in alternating current, the value of current increases from zero (point O), reaches a maximum value (point A) and then again becomes zero (point B). Subsequently, it changes direction, again reaches a maximum value (point *C*) in the reverse direction and becomes zero (point *D*) as time passes.

Direct currents are produced by cells and batteries; generators can produce AC as well as DC. We shall confine our discussion in this unit to DC only.

Further, as mentioned above, there must be a source of electrical energy in any electric circuit if current is to flow in it. The source of electrical energy creates a potential difference (or, equivalently, creates an electric field) across the circuit and forces electric charges to move along the conductor wire. So, when a potential difference V is applied across a conductor, a current I flows in it. Now, suppose that you want a current of given magnitude to flow in a conductor. **What parameters do you think you have to know**? Well, apart from applied potential difference, the magnitude of current in a conductor depends on its resistance. Let us now learn about resistance of a conductor.

SAQ 3

A potential difference of 400 volts is applied across a conductor whose resistance is 200 Ω. Calculate the number of electrons flowing through the conductor in 2 seconds. Take the value of charge on electron, e to be 1.6×10^{-19} C.

5.3.2 Resistance : Ohm's Law

When a potential difference is applied across a conductor, the free electrons in the conductor are accelerated. The accelerated motion of electrons is restrained (or resisted) due to their collisions with ions in the conductor. The opposition to the motion of electrons in a conductor is characterised by a parameter of the conductor called resistance (R).

The mathematical expression for the resistance of a conductor is obtained on the basis of Ohm's law. According to this law, *the current* (I) *flowing through a conductor is directly proportional to the potential difference* (V) *across its two ends if its temperature and other physical conditions remain the same*. Mathematically, we write :

$$V \propto I$$

or,

$$V = RI \qquad \text{. . . (5.12)}$$

where R is called resistance of the conductor.

Refer to Figure 5.9 which depicts the variation of current with the applied potential difference across a conductor. The linear variation of I with V implies (Eq. 5.12)) a constant value of resistance ($R = V/I$) of the conductor. Such conductors (which obey Ohm's law) are called **ohmic conductors**. But, there are

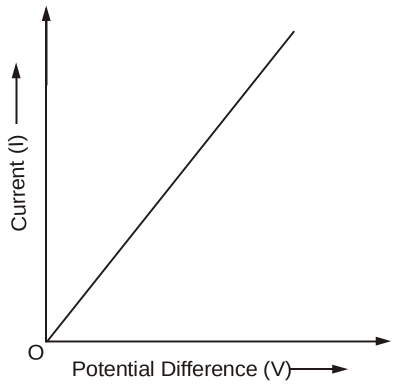


Figure 5.9 : Voltage-Current Plot for Ohmic Conductors

conductors which do not obey Ohm's law and they are called **non-ohmic conductors**. The non-linear variation of *I* with *V* (Figure 5.10) for non-ohmic conductors is caused due to increase in the resistance of the conductor as the current increases.

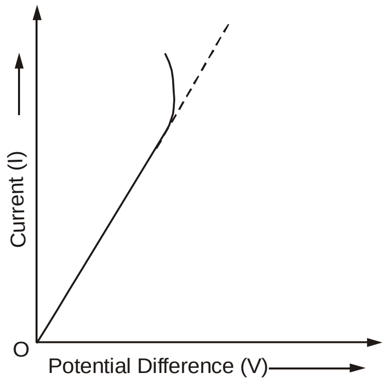


Figure 5.10 : Current-voltage Plot for Non-ohmic Conductors

The SI unit of resistance is ohm (Ω). One ohm resistance of a conductor is defined as the resistance offered by it when a potential difference of one volt is applied and one ampere of current flows through the conductor.

Combination of Resistors

Resistance of conductors is gainfully used in a variety of electric appliances such as electric bulb, electric iron etc. In fact, the heating effects of current, which you will learn in Section 5.5, is based on the resistance of materials. Further, resistor – a piece of conductor which has a fixed value of resistance for a given potential difference – is one of the important components of electric circuit. When more than one resistors are to be connected in a circuit, it can be done in two ways :

(a) they can be connected in series, and

(b) they can be connected parallel to each other.

The net or the equivalent resistance offered in the circuit by a group of resistors depends on the way they are combined to each other. **The equivalent resistance of a combination of resistors is the resistance of a single resistor, which, if used in place of the combination of resistors, will carry the same current for the given potential difference**. Let us now discuss the series and parallel combinations of resistors.

Resistors in Series

Refer to Figure 5.11 which shows two resistors R_1 and R_2 connected to each other in series. A source (E) of potential difference is also connected to this series combination.

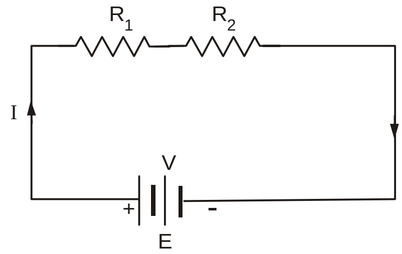


Figure 5.11 : Circuit Diagram Comprising Two Resistors R_1 and R_2 Connected in Series

Let R_{es} is the equivalent resistance of the series combination of resistors. You may note that the current through both the resistors is same. However, the potential difference across any resistor is proportional to its resistance. If the values of the potential differences are V_1 and V_2 across R_1 and R_2 respectively, we can write, using Ohm's law :

$$V_1 = IR_1$$

$$V_2 = IR_2 \qquad \ldots (5.13)$$

Further, the potential difference across the two resistors must be equal to the potential difference (V) applied in the circuit. That is :

$$V = V_1 + V_2$$

$$= I\ (R_1 + R_2) \qquad \ldots (5.14)$$

using Eq. (5.13). From the definition of equivalent resistance, we can write :

$$V = I\,R_{es} \qquad \ldots (5.15)$$

Comparing Eqs. (5.14) and (5.15), we get :

$$R_{es} = R_1 + R_2 \qquad \ldots (5.16)$$

Eq. (5.16) shows that the total (or equivalent) resistance offered by two or more resistors connected in series is the algebraic sum of the resistances of the individual resistors.

Resistors in Parallel

Refer to Figure 5.12 which shows two resistors R_1 and R_2 connected to each other in parallel. In this case, the potential difference across both the resistors is same as the applied voltage. However, the current through each of them is different and their sum is equal to the total current I. Therefore, we can write :

$$I = I_1 + I_2 \qquad \ldots (5.17)$$

Also, $\quad V = I_1\,R_1$ and $V = I_2\,R_2$

or, $$I_1 = \frac{V}{R_1} \text{ and } I_2 = \frac{V}{R_2} \qquad \ldots (5.18)$$

Let R_{ep} is the equivalent resistance of this parallel combination of resistors.

Thus, from the definition of equivalent resistance, we have :

$$I = \frac{V}{R_{ep}} \qquad \text{. . . (5.19)}$$

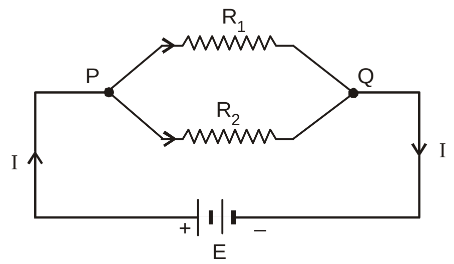


Figure 5.12 : Resistors Connected in Parallel to Each Other

Substituting Eqs. (5.17) and (5.18) in Eq. (5.19), we get :

$$\frac{V}{R_{ep}} = \frac{V}{R_1} + \frac{V}{R_2}$$

or,

$$\frac{1}{R_{ep}} = \frac{1}{R_1} + \frac{1}{R_2} \qquad \text{. . . (5.20)}$$

Eq. (*5.20*) *shows that the reciprocal of the total (or equivalent) resistance of the parallel combination of resistors is equal to the sum of the reciprocals of the resistances of the individual resistors*.

It is important to note that when the resistors are connected **in series, the equivalent resistance is always greater than the largest resistance in the combination but in the parallel combination of resistors, the equivalent resistance is always less than the smallest resistance in the combination**. Therefore, the resistors are connected in series combination to increase the effective or the net resistance in the circuit whereas they are connected in parallel to decrease the effective resistance in the circuit.

An important aspect of the resistance of a conductor is that it depends on the dimensions (size and shape) of the conductor. To understand the size and shape dependence of resistance, note that, for a given potential difference, if we increase the thickness of the conductor, current will increase because the charge passing through the cross-sectional area of the conductor per unit time will increase. Thus, resistance of the conductor will decrease. This implies that R is inversely proportional to the area of cross-section, A of the conductor. Further, suppose the length, l of the conductor is reduced and same potential difference is applied. In this case, resistance will decrease, that is, R is directly proportional to the length of the conductor.

In view of the above, we may write :

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

The dependence of resistance on the material composition of a conductor is incorporated in the above expression as proportionality constant ρ, called **resistivity**. Thus, we can write :

$$R = \rho \frac{l}{A} \qquad \ldots (5.21)$$

The SI unit of resistivity is ohm metre (Ω m). In Eq. (5.21), if A = 1 m^2, and l = 1 m, then

$$\boxed{\rho = R}$$

That is, *the resistivity of a conductor is numerically equal to the resistance offered by the unit length of the conductor having unit area of cross-section*. **Resistivity is the characteristic of the material of the wire**. For a given material at a fixed temperature, only length and area of cross-section of a wire are important parameters influencing the resistance of a conductor specimen. **Thick wires have lower resistance compared to thin ones**.

On comparing the resistivities of the conductors, insulators and semiconductors, it is noted that the insulators have high resistivity (i.e. glass ~ $10^{10} - 10^{14}$ Ω m; wood ~ $10^8 - 10^{11}$ Ω m) in comparison to conductors (i.e. copper ~ 1.7×10^{-8} Ω m; silver ~ 1.6×10^{-8} Ω m) and semiconductor (germanium ~ 0.46 Ω m; silicon ~ 2300 Ω m) at 0^oC. The resistivity of alloys like constantan is 49×10^{-8} Ω m and that of nichrome is 100×10^{-8} Ω m at 0^oC which is of the order of the resistivity of the conductors.

Yet another important term related to the resistance is called **conductivity** (σ). It is defined as the reciprocal of resistivity, that is :

$$\sigma = \frac{1}{\rho} \qquad \ldots (5.22)$$

The SI unit of conductivity is ohm^{-1} m^{-1} or mho m^{-1}.

Till now, you studied electric current and the resistance offered by the conductor. Though we have said that current is the flow of electric charge, we have not described the motion of these charges. You will learn it now.

SAQ 4

(a) Calculate the resistivity of the material of a wire 2 m long, 0.2 mm in diameter and having a resistance of 4 ohm.

(b) Three resistors 2 Ω, 3 Ω and 5 Ω are combined in series and the combination is connected to a battery of 20 volt. Calculate the total resistance of the series combination and potential drop across each resistors. What would be the total resistance if the resistances are connected in parallel?

5.3.3 Drift Velocity

You may be aware that in a metallic conductor such as copper and silver, the electrons in the outermost orbit of its atoms, called *valence electrons*, are very loosely bound with their parent atoms and can be detached leaving behind a positive ion. The valence electrons in a conductor are called *free electrons* or *conduction electrons*, which move randomly inside the conductor due to thermal energy. The velocity of the free electrons due to the thermal energy is called **thermal velocity**. In the absence of an applied electric field, the average flow of charge along a given direction is zero. *It is understandable because the average thermal velocity of free electrons in a conductor is zero.*

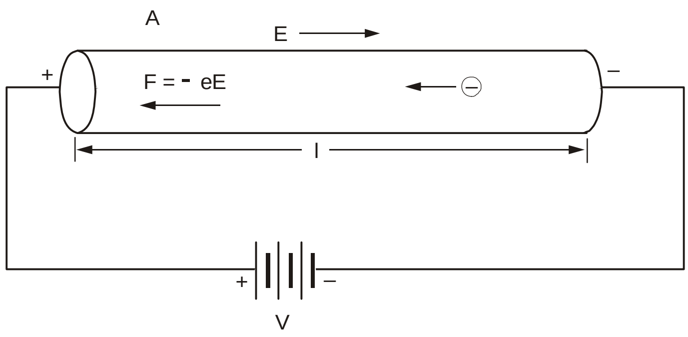


Figure 5.13 : Electric Potential Difference *V* Applied across a Conductor of Length *l*

Now, refer to Figure 5.13, which depicts a conductor of length l across which a potential difference V is applied. As a result, a constant electric field E acts on the randomly moving electron and cause them to accelerate along a given direction. The constant electric field accelerates the electrons continuously. *However, we know from the Ohm's law that for a given conductor, current is proportional to the applied voltage*! So, the question is : **What causes these accelerated electrons to attain a steady or constant velocity**?

The accelerated electrons interact or collide with other particles (such as positive ions) of the conductor and loose some of its energy. Thus, the combined effect of the applied electric field and collisions with ions on the electrons is that they attain a constant average velocity called the **drift velocity**. These drifting electrons constitute the electric current.

You may ask : **How is an electron accelerated in an electric field**? To answer this question, note that the force experienced by an electron due to electric field E can be written as :

$$F = - e\,E \qquad \ldots (5.23)$$

The negative sign indicates that the force is in opposite direction to the field. According to the Newton's second law of motion :

$$F = m\,a \qquad \ldots (5.24)$$

where m is mass of the electron and a is its acceleration in the field E.

From Eqs. (5.23) and (5.24), we get :

$$m\,a = - e\,E$$

or,

$$\boxed{a = -\frac{e\,E}{m}} \qquad \ldots (5.25)$$

Eq. (5.25) shows that, under the influence of an electric field, the free electrons are accelerated. You may further ask : **How is the microscopic parameter v_d and macroscopic parameter *I* associated with the motion of electrons related with each other**? To express v_d in terms of I, note that the total charge in the conductor of length l and area of cross-section A is :

$$q = n\,A\,l\,e \qquad \ldots (5.26)$$

where n is the number of electrons per unit volume of the conductor and e is the charge on each electron. Note that lA gives the volume of the conductor specimen shown in Figure 5.13. If this amount of charge passes through the length l of the conductor in time t, we have :

$$t = \frac{l}{v_d} \qquad \ldots (5.27)$$

where v_d is the drift velocity of electrons. From Eqs. (5.26) and (5.27), we can write the expression for the electric current as :

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

$$= \frac{n\ A\ l\ e}{\dfrac{l}{v_d}}$$

$$= n\ A\ e\ v_d \qquad \ldots (5.28)$$

Eq. (5.28) shows that the current in a conductor is proportional to the drift velocity of free electrons.

For dealing with simple electrical circuits, ohm's law is quite useful. The analysis of complicated electrical circuits, such as the one in television set which contain large number of electrical components in a variety of configurations, is a rather difficult process. The difficulty is reduced considerably due to two basic rules followed by currents and voltages in DC circuits. These rules, formulated by Kirchhoff, are known as Kirchhoff 's rules and you will learn them now. But, before proceeding further, you should answer an SAQ.

SAQ 5

If a current of 15 A is maintained in a conductor of cross-sectional area 10^{-4} m^2, calculate the drift velocity of electrons. Take the number of electrons per unit volume to be 5×10^{28} m^{-3} and the charge on an electron, *e* to be 1.6×10^{-19} C.

5.3.4 Kirchhoff's Rules

Kirchhoff's First Rule (Junction Rule)

This rule states that in an electrical circuit, the algebraic sum of the currents meeting at a point is always zero.

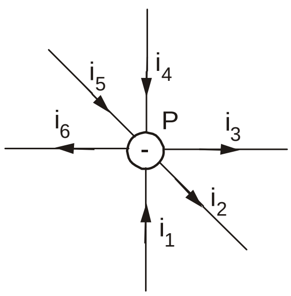


Figure 5.14 : Currents Entering and Leaving a Junction

Refer to Figure 5.14 which shows currents i_1, i_2, . . . etc. meeting at a point *P*. Then, according to the junction rule, we have :

$$i_1 - i_2 - i_3 + i_4 + i_5 - i_6 = 0$$

$$i_1 + i_4 + i_5 = i_2 + i_3 + i_6 \qquad \ldots (5.29)$$

Eq. (5.29) implies that the junction rule can also be stated as : *the sum of the currents flowing in a conductor towards the junction is equal to the sum of the currents flowing away from the junction*. The junction rule is basically a consequence of the **principle of conservation of charge**, which says that the quantity of charge arriving at a point must equal the amount of charge leaving the point.

Kirchhoff 's Second Rule (Loop Rule)

According to this rule, around any closed path of an electric circuit, the algebraic sum of the potential changes or electromotive forces (*emfs*) *is zero*. Another statement of this rule is : the algebraic sum of the emfs around a closed path in a circuit is equal to the algebraic sum of the products of resistances and the currents flowing in them.

To apply this rule in an electric circuit, the following sign conventions are followed :

(a) The current flowing in anticlockwise direction is taken as positive.

(b) If the current due to a cell flows in the clockwise directions, the emf of the cell is taken as negative and *vice-versa*.

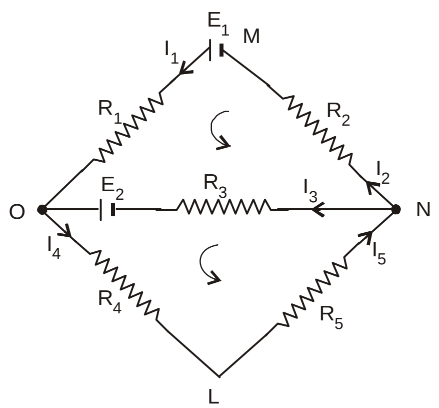


Figure 5.15 : Electric Current Comprising Resistances and Cells

Refer to Figure 5.15 which shows a circuit comprising resistances and cells. Let us consider the closed path *MONM*. Using the sign convention for emfs of the cells, we can write their algebraic sum *E* in the loop as :

$$E = E_1 - E_2 \qquad \text{. . . (5.30)}$$

And, we can write the algebraic sum of the products of resistances and currents in the closed path *MONM* as :

$$I_1 R_1 + I_2 R_2 + (-I_3 R_3) \qquad \text{. . . (5.31)}$$

Therefore, according to the loop rules, we have from Eqs. (5.30) and (5.31) :

$$E_1 - E_2 = I_1 R_1 + I_2 R_2 - I_3 R_3$$

The electric current, potential difference (voltage) and resistance are some of the parameters of practical importance in the electrical circuits. Generally, measurement of these parameters are done to ascertain whether or not a given circuit will produce the desired result. These measurements are done by electrical instruments. Therefore, it is important for you to know the principles and working of the basic instruments. You will learn it now.

5.4 ELECTRICAL INSTRUMENTS

You might have seen electrician using an instrument called multimeter. Multimeter is a handy instrument designed in such a manner that it can measure a large number of electrical quantities in circuits involving both the direct current and the alternating current. There are some simpler instruments for the measurement of current, resistance and voltage. The measurement of current is done by the instrument called ammeter and the measurement of voltage is done by voltmeter. Both these instruments are modified forms of an instrument called galvanometer. To understand the working of a galvanometer requires the knowledge of the magnetic effects of current. Since you will learn this concept in the next unit, we shall discuss galvanometer, ammeter and voltmeter there only.

In the following, we discuss circuit arrangements for measuring resistance and potential difference to a very high degree of accuracy. The measurement of these quantities is done by instruments called meter bridge and potentiometer respectively. Both these instruments are the modified forms of Wheatstone bridge. Let us, therefore, discuss the Wheatstone bridge first.

5.4.1 Wheatstone Bridge

A Wheatstone bridge is an electric circuit used to measure resistance with high accuracy. Refer to Figure 5.16 which shows the circuit of a Wheatstone bridge comprising four resistances P, Q, R and X, arranged in a quadrilateral shape, and a source of emf, E. If we know the values of three resistances, say, P, Q and R, the value of the fourth resistance (the *unknown resistance*) X can be determined using this circuit.

You may ask : **How do we determine the value of the unknown resistance (X)?** To understand the principle, note that the resistances P, Q and R (a variable resistance) are known. The sensitive galvanometer G is attached with key K_1, called galvanometer key, between points M and O. The key K_2, called battery key, is attached with battery connected between points L and N of the circuit.

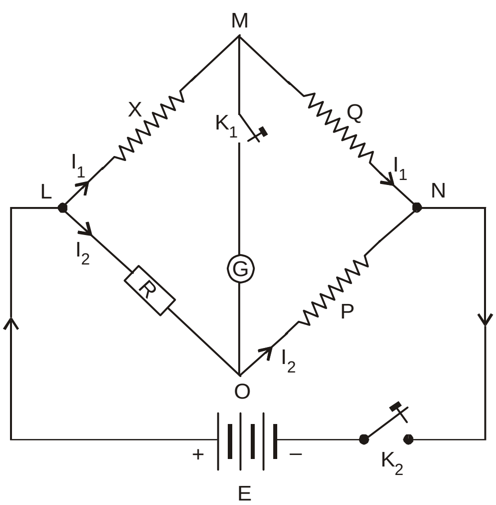


Figure 5.16 : Circuit Diagram of the Wheatstone Bridge

When key K_2 is connected, current flows in the circuit. Now, the value of variable resistance R is adjusted in such a way that the current through G becomes zero. This implies that point M and O are at the same potential. This condition is known as the **null condition** and the Wheatstone bridge is said to be balanced. Using the Kirchhoff's rules, we can show (we have not given the derivation for this relation; you will study it in higher classes) that :

$$\frac{P}{Q} = \frac{R}{X}$$

or, $$X = \frac{RQ}{P}$$

The measurement of unknown resistance using the Wheatstone bridge is very accurate if all the four resistances are of the same order of magnitude. Let us now discuss meter bridge which works on the principle of the Wheatstone Bridge.

5.4.2 Meter Bridge (or Slide Wire Bridge)

It is an instrument which is used for the measurement of an unknown resistance or to compare the values of two unknown resistances. The circuit diagram of the meter bridge is shown in Figure 5.17. It consists of a 100 cm long constantan wire *LN* whose two ends are attached to two copper strips *LA* and *ND*. Parallel to the length of the wire, a meter scale is fitted on the wooden board. The resistance box *R* and unknown resistance *X* are attached respectively in two gaps *AB* and *CD*. One end of the galvanometer is attached to the terminal *O* on the central copper strip *BC* and other end is connected to a jockey (*J*) which can be moved over the wire.

Can you see the similarity between the circuits of the meter bridge and the Wheatstone bridge? Similarity becomes obvious if you note that the resistance of wire between points *L* and *M* represents one arm and that of the wire length between *M* and *N* represents another arm of the Wheatstone bridge. And, variable resistance *R* and unknown resistance *X* represent the remaining two arms of the Wheatstone bridge. Thus, the circuit of meter bridge is equivalent to that of the Wheatstone bridge.

Now, if position *M* of the jockey on the wire *LN* represents the null condition, we can write :

$$\frac{P}{Q} = \frac{R}{X} \qquad \text{. . . (5.32)}$$

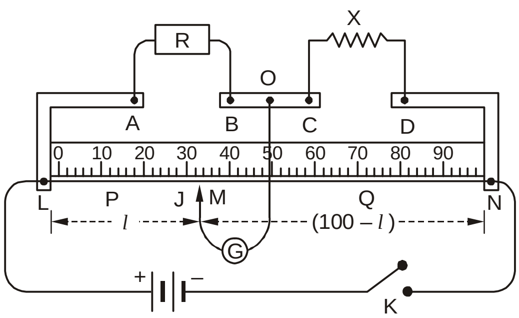


Figure 5.17 : Circuit Diagram of the Meter Bridge

To obtain the null condition, the value of resistance in the resistance box *R* is adjusted and the jockey is moved over *MN* until we obtain zero deflection (that is, zero current) in the galvanometer *G*. Let, for the null condition, the jockey is at the point *M* at distance *l* from the point *L*. Thus, $LM = l$ and $MN = (100 – l)$. It is assumed that the resistance for length *l* is *P* (between point *L* and *M*) and resistance for length (100 – *l*) is *Q* (between point *M* and *N*). Thus, we can write :

$$P \propto l \text{ and } Q \propto (100 - l)$$

Substituting for *P* and *Q* in Eq. (5.32), we get :

$$X = R\left(\frac{100 - l}{l}\right)$$

So, knowing the value of *R* (from the resistance box), the value of unknown resistance (*X*) can be calculated.

5.4.3 Potentiometer

Potentiometer is a multipurpose instrument used for measuring or comparing electromotive force (emf) of cells as well as for the measurement of resistance. This instrument also works on the principle of the Wheatstone bridge.

Refer to Figure 5.18 which shows the circuit diagram of a potentiometer. It consists of a long thin constantan or manganin (high resistance) wire of length 4 or 5 m of uniform area of cross-section. This wire is stretched over a wooden board. The length of wire is divided into number of equal segments of 1 m length and each segment is connected to other in series with the help of copper strips.

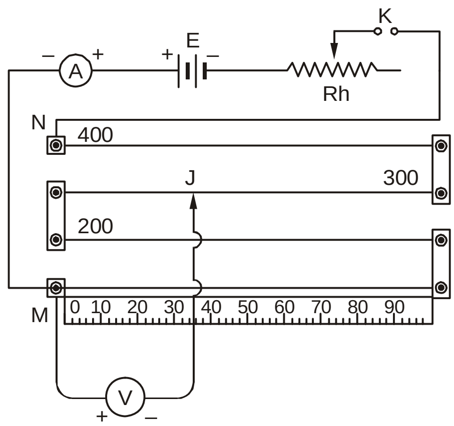


Figure 5.18 : The Circuit Diagram of a Potentiometer

A battery (*E*) is connected across two end terminals *M* and *N* of the wire and the value of the current through the wire is kept constant by using a rheostat (Rh). A meter scale is fixed parallel to the length of the wire to determine the length of the wire used for obtaining the null condition during a measurement. The null point is obtained by moving a jockey or a sliding key over the length of the wire.

Potentiometer works on the principle that for a constant current, the potential difference across a given length segment of the wire is directly proportional to the length of that segment. To check the validity of this assumption, suppose the resistance and potential difference across a given length segment *l* of wire are *R* and *V* respectively and *I* is the current through the wire. According to the Ohm's law, we can write :

$$V = I\,R$$

And from Eq. (5.21), we have :

$$R = \rho\,\frac{l}{A}$$

where ρ is the resistivity of the wire, and *A* is its area of cross-section. Thus, we get :

$$V = I\,\rho\,\frac{l}{A} \qquad \text{. . . (5.33)}$$

Eq. (5.33) shows that if ρ, *I* and *A* are constant, we have :

$$V \propto l \qquad \text{. . . (5.34)}$$

Now, let us discuss how a potentiometer is used for measuring small resistances such as the internal resistance of a cell and for comparing the emfs of two cells.

Measurement of the Internal Resistance of a Cell

The circuit diagram for this measurement is shown in Figure 5.19. *B* is the battery of emf *E* whose internal resistance (*r*) is to be measured. *E ′* is the emf of the auxiliary battery *B ′*. The rheostat helps to maintain the constant current, *I*, through the potentiometer.

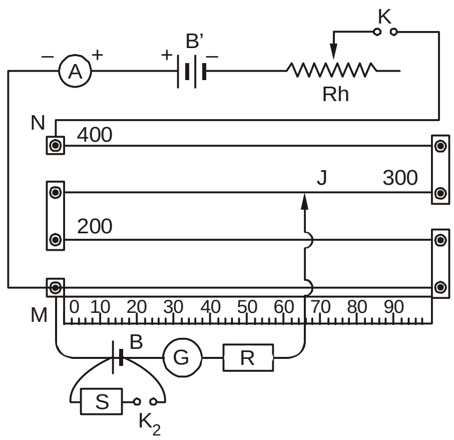


Figure 5.19 : Circuit Diagram for the Measurement of Internal Resistance of a Cell

Let l_1 is the balancing length between point *M* and jockey *J* when the cell *B* is in the circuit. Thus, from Ohm's law, we can write :

$$E = (x\,l_1)\,I \qquad \text{. . . (5.35)}$$

where *x* is the resistance per unit length of the wire.

Now a known value of resistance *S* is introduced using a resistance box and again the key K_2 is inserted. Let l_2 be the balancing length for the terminal potential difference *V* between two poles of cell. Thus, we can write :

$$V = (x\,l_2)\,I \qquad \text{. . . (5.36)}$$

From Eqs. (5.35) and (5.36), we get :

$$\frac{E}{V} = \frac{l_1}{l_2} \qquad \text{. . . (5.37)}$$

The expression for the internal resistance of the cell is given by :

$$r = \left(\frac{E}{V} - 1\right) S$$

Substituting the value of $\frac{E}{V}$ from Eq. (5.37) in the above equation, we get :

$$r = \left(\frac{l_1}{l_2} - 1 \right) S$$

or,
$$r = \left(\frac{l_1 - l_2}{l_2} \right) S \qquad \ldots (5.38)$$

Eq. (5.38) gives the internal resistance (r) of the cell in terms of the known quantities l_1, l_2 and S.

Comparing the emfs of Two Cells

The circuit diagram for this purpose is shown in Figure 5.20. The negative poles of the two cells, whose emfs are to be compared, are connected to a two-way key and their positive poles are connected to the terminal M of the potentiometer. The common end of two-way key is attached with jockey, J, through a galvanometer G. The driver battery of emf E (whose emf is greater than the emf of the either of two cells E_1 and E_2), rheostat (Rh), one way key (K) and an ammeter (A) are attached between the end terminals M and N of the potentiometer. A constant current is passed through the potentiometer wire between points M and N.

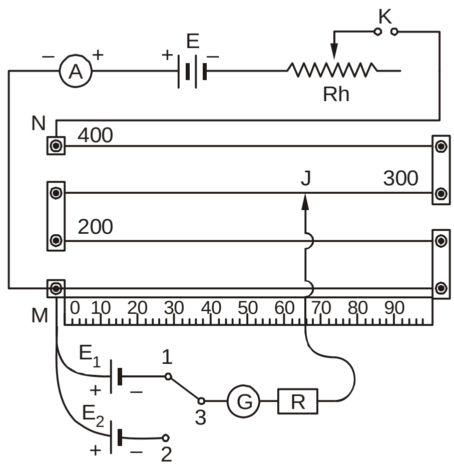


Figure 5.20 : Circuit Diagram to Compare emfs of Two Cells

First, the key is pluged in between the terminals 1 and 3 of the two-way key so that the cell of emf E_1 becomes the part of the circuit. Let the balancing length is l_1, x is the resistance per unit length of the potentiometer wire, and I is the constant current flowing through it. Thus, we can write :

$$E_1 = (x\, l_1)\, I \qquad \ldots (5.39)$$

Now the key between the terminal 1 and 3 is removed and it is inserted between the terminals 2 and 3 so that the cell of emf E_2 becomes the part of the circuit. Let l_2 is the balancing length for this condition. So, we can write :

$$E_2 = (x\, l_2)\, I \qquad \ldots (5.40)$$

Divide Eq. (5.39) by Eq. (5.40), we get :

$$\frac{E_1}{E_2} = \frac{l_1}{l_2} \qquad \ldots (5.41)$$

Eq. (5.41) gives the ratio of the emfs of the two cells in terms of known quantities l_1 and l_2. In this Section, you have studied the construction and working of some electrical instruments such as the meter bridge and the potentiometer.

You must have observed that electric bulb or the element of a heater or an electric iron becomes hot when electric current flows through them. Do you know why it happens? They become hot due to conversion of electrical energy into heat energy and this is an example of the heat produced by electric current. Let us now discuss the heating effect of current.

5.5 HEATING EFFECTS OF CURRENT

When electric current flows in a conductor, the electrons collide with the ions and transfer its energy to them (ions and atoms). This leads to increase in the average energy of the ions and the temperature of the conductor rises, that is, the conductor is heated. It is *termed as heating effect of electric currents*. This phenomenon was extensively studied by Joule who formulated a law relating the current flowing in a conductor and the heat produced. You will learn it now.

5.5.1 Joule's Law

According to this law, the amount of heat (Q) produced in a conductor due to the flow of current (I) is directly proportional to the square of the current, resistance (R) of the conductor and to the time (t) for which the current flows. Mathematically, the law can be written as :

$$Q \propto I^2 R t$$

$$\boxed{Q = \frac{I^2 R t}{J}} \qquad \text{. . . (5.42)}$$

where J is called Joule's **mechanical equivalent of heat**. J is a conversion factor given as :

$$J = 4.18 \text{ J cal}^{-1}$$

In SI units, the heat (Q) produced (in Joule) due to flow of current (I) through a conductor of resistance (R) for time (t) is given by :

$$Q = I^2 R t \qquad \text{. . . (5.43)}$$

You may be aware that the household or industrial use of electricity invariably involves conversion of electrical energy into one or the other form of energy such as heat, light and mechanical motion. The consumption of electrical energy in all these activities is measured in terms of electric power. Let us now define it.

Electric Power

The electric power of a circuit is defined as *the rate at which work is done by the source of emf in maintaining the electric current in the circuit*. Let W is the amount of work done in maintaining electric current in a circuit for time t. Then, the electric power (P) of the circuit is given as :

$$P = \frac{W}{t} \qquad \text{. . . (5.44)}$$

You may ask : **How do we determine the work done by the source of emf**? Let R is the resistance of a resistor across which a potential difference V is applied (Figure 5.21). The current (I) flowing through the resistor is :

$$I = \frac{V}{R} \qquad \text{. . . (5.45)}$$

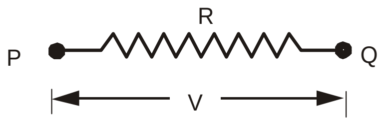


Figure 5.21 : Current *I* Flowing through Resistor *R*

Further, the current through the resistor can also be written in terms of total charge q and time t as :

$$I = \frac{q}{t} \qquad \text{. . . (5.46)}$$

Eq. (5.46) means that, if current I flows for time t, total charge q is It. Now, suppose the current flows from end P to Q of the resistor R. It means that the potential at P is higher than Q by an amount V. If a unit charge flows from end P to Q, energy equal to V will be consumed from the source of emf and it will appear as heat energy across the resistor. Thus, if charge q passes through R, the work done or, equivalently, the electrical energy dissipated by the source of emf can be written as :

$$W = q\,V$$

$$= V\,I\,t \qquad \text{. . . (5.47)}$$

using Eq. (5.46). Substituting Eq. (5.47) in Eq. (5.44), we get

$$P = \frac{V\,I\,t}{t}$$

$$= V\,I \qquad \text{. . . (5.48)}$$

Substituting Eq. (5.45) in Eq. (5.48), we get :

$$P = \frac{V^2}{R}$$

$$= I^2\,R \qquad \text{. . . (5.49)}$$

The SI unit of electric power is watt (W). If $V = 1$ volt and $I = 1$ ampere, power, $P = 1$ Watt. That is, if one ampere of current flows through a circuit in which a constant potential difference of one volt is applied, one watt electric power is consumed.

Further, from Eq. (5.44), we can write the work done or the electrical energy as :

$$W = P \times t$$

Electric Energy = Electric Power × Time

The SI unit of electric energy is **Joule**. *Commercial unit of electric energy is kilowatt hour*. If an electric device or appliance of power one kilowatt is used for one hour, one kilowatt hour electrical energy is consumed. The relation between the two units of electrical energy is :

$$1\ \text{kWh} = 3.6 \times 10^6\ \text{J}$$

In all the electrical circuits, there is a common component called cell or battery (a group of cells) or a source of emf or a source of potential difference. All these are basically the same thing with respect to their roles in the circuit : they provide electrical energy so that a continuous current can flow in the circuit. You may be aware that potential difference in a DC circuit is provided by cells. Cells convert chemical energy into electrical energy. You will now learn the chemical effects of current. But before that how about solving an SAQ!

SAQ 6

An electric bulb of 40 W works at 220 volts. Calculate its resistance and current carrying capacity.

5.6 CHEMICAL EFFECTS OF CURRENT

Chemical effects of electric current are observed in liquids when an electric current flows through it. Liquids which dissociate into ions (a radical having charge, i.e. Cu^{++}, Na^{+}, Cl^{-}) when current flow through them are called *electrolytes*. *The process of dissociation of a liquid into ions due to the flow of current is called electrolysis*. For example, when electric current flows in sodium chloride (NaCl) solution, the following chemical reaction takes place :

$$NaCl \rightarrow Na^{+} + Cl^{-}$$

Here Na^{+} is a positive ions called **cation**. *The cation has less electron than what it would have in its normal state*. During electrolysis, they would collect at the **cathode**. On the other hand, Cl^{-} is a negative ion called **anions**. *The anion has more electrons than what it would have in its normal state*. During electrolysis, the negative ions collect at the **anode**. Let us now discuss the electrolysis of copper sulphate and the Faraday's laws which govern the process of electrolysis.

Electrolysis : Faraday's Law

To carry out the electrolysis of copper sulphate solution, an apparatus called copper voltmeter (Figure 5.22) is used. It is made up of a glass-vessel in which two copper electrodes *P* (anode) and *Q* (cathode) are dipped in copper sulphate solution. The two electrodes are connected with a rheostat, battery, ammeter and a one-way key. Anode is connected to the positive pole of the battery and cathode is connected to the negative pole. The rheostat is used to adjust the current in the circuit.

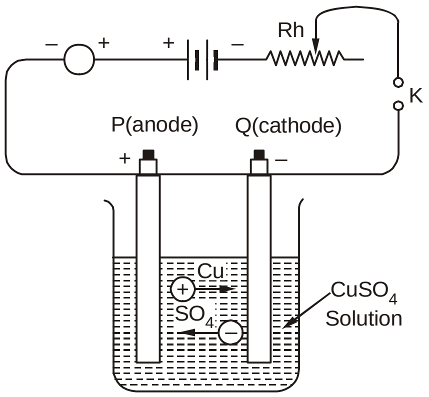


Figure 5.22 : A Copper Voltmeter

When the key (*K*) is inserted, the current flows through the copper sulphate solution and it breaks into Cu^{++} and SO^{4--} ions. The chemical reaction is :

$$CuSO_4 \rightarrow Cu^{++} + SO_4^{--}$$

The copper ion (Cu^{++}) reaches the cathode and two electrons from the negative pole of the battery combine with the Cu^{++} ion and a neutral Cu atom is produced and deposited at the cathode. The following reaction takes place at the cathode :

$$\mathrm{Cu}^{++} + 2e \rightarrow \mathrm{Cu}$$

As soon as a Cu^{++} ion discharges at the cathode, a Cu atom at the anode releases two electrons and the resulting Cu^{++} ion goes into the $CuSO_4$ solution. The two electrons flow from the anode to the positive pole of the battery. The reaction taking place at the anode is :

$$\mathrm{Cu} \rightarrow \mathrm{Cu}^{++} + 2e$$

Therefore, there is no accumulation of charge anywhere in the voltmeter. **The continuous flow of current in the circuit is achieved by the flow of ions inside the electrolyte and flow of electrons in the metallic connecting wires outside the voltmeter**.

At this stage, you may like to know : **How much copper is deposited at the cathode for a given current in the circuit**? These and other similar issues were investigated by Faraday who formulated laws on the basis of experiments.

Now you will study the Faraday's laws of electrolysis.

Faraday's Laws of Electrolysis

The process of electrolysis is governed by the two laws proposed by Faraday.

First Law

According to this law, the mass of the substance deposited at the cathode during electrolysis is directly proportional to the quantity of electricity (total charge) passed through the electrolyte. Mathematically, it is expressed as :

$$m \propto q$$

where q is the charge (or current) flowing through the electrolyte and m is the mass of the substance liberated in the process. Thus, we can write :

$$m = z\,q$$

or $$m = z\,I\,t \qquad \text{. . . (5.50)}$$

where z is called **electrochemical equivalent** (ECE) of the substance, and I is the constant current passed through the electrolyte for time t. If q = 1 C, $m = z$. Thus, the electrochemical equivalent of a substance is defined as *the mass of the substance deposited at the cathode when 1 Coulomb of charge passes through the electrolyte*. The SI unit of electrochemical equivalent of a substance is kg C^{-1}.

Second Law

According to this law, if same quantity of electricity is passed through different electrolytes, masses of the substances deposited at the respective cathodes are directly proportional to their chemical equivalents.

Chemical equivalent of an electrolyte is the ratio of its atomic weight to its valency. Let m is the mass of the ions of a substance liberated in the electrolysis and its chemical equivalent is E. Then, according to the second law :

$$m \propto E$$

or
$$\frac{m}{E} = \text{constant} \qquad \text{. . . (5.51)}$$

Faraday's Constant

It is the quantity of charge required to liberate one gram equivalent of the substance of an electrode during the process of electrolysis. It has a fixed value of 96500 C mol^{-1}. The relation between the Faraday's constant (F), chemical equivalent (E) and the electrochemical equivalent (z) is given as :

$$F = \frac{E}{z} \qquad \text{. . . (5.52)}$$

Faraday's constant is also given by :

$$F = N\,e$$

where N is the Avogadro number and e is the electronic charge.

Application of Electrolysis

There are various applications of electrolysis. It has been put to many technical and commercial uses like purification of metals, extraction of metals from the ores, medical application (for nerve stimulation, for removing unwanted hair on any part of the body etc.), purification of metals, electroplating etc.

5.7 SOURCES OF EMF : BATTERY

A battery is a number of cells connected to each other in series. Generally, the cells are categorized into two types : primary cell and secondary cell. **This classification is based on the chemical reaction taking place inside the cell**. *If the chemical reaction inside a cell is reversible in nature or the cell can again be put into use by recharging, that is, passing current from an external source, the cell is called* **secondary cell** or **storage cell**. Some common examples of secondary cell are Lead-acid accumulator, NiFe cell etc. *On the other hand, electrochemical cell that cannot be put to use again by recharging is called* **primary cell**. Once a primary cell gets discharged, the chemicals inside the cell have to be replaced completely. Some examples of the primary cell are the Voltaic cell, Daniel cell and Laclanche cell. Let us now briefly discuss the working of some primary and secondary cells.

5.7.1 Primary Cells

Voltaic Cell

This cell was invented by Volta and hence the name *voltaic cell*. A schematic diagram of a simple voltaic cell is shown in Figure 5.23. It consists of a glass vessel containing dilute sulphuric acid as electrolyte in which two rods, one of copper and other of zinc are placed. Due to the chemical reactions inside the cell, the zinc rod acquires negative charge and becomes a negative terminal and the copper rod acquires positive charge which becomes a positive terminal and hence a potential difference is established between the copper and zinc rods.

Due to positive charges building up on copper rod and negative charges on the zinc rod, the potential difference between the two rods gradually increases, and continues till the potential gradient along the electrolyte between the copper and zinc rods just restricts the further drift of H^+ ions to the copper rod.

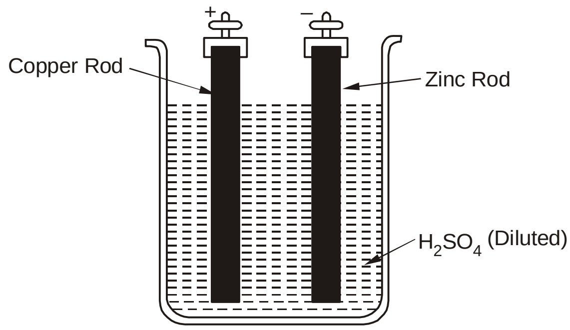


Figure 5.23 : Schematic Diagram of a Simple Voltaic Cell

The maximum emf developed in voltaic cell is found to be **1.08 V**. The simple voltaic cell suffers from the defects of *local action* and *polarization*. But later, another cell was invented by Daniel, called Daniel cell. In this cell, the defect of polarization was avoided by using $CuSO_4$ solution as depolariser.

Daniel Cell

This cell consists of a copper vessel which itself acts as a positive pole, Anode of the cell and contain copper sulphate ($CuSO_4$) solution (Figure 5.24). A porous pot containing an amalgamated zinc rod cathode and dilute sulphuric acid (H_2SO_4) is placed inside the $CuSO_4$ solution. The porous pot prevents the dilute H_2SO_4 and the $CuSO_4$ solution from mixing with each other; however, it allows the H^+ ions, produced in the porous pot, to diffuse through and mix with the $CuSO_4$ solution. The amalgamated zinc rod is used to avoid the defect of local action. Both $CuSO_4$ solution (serves as depolariser) and dil. H_2SO_4 serves as an electrolyte. The crystal of $CuSO_4$ are placed on the perforated shelf along the walls of the copper vessel. When the cell works, the concentration of $CuSO_4$ solution falls. The crystals of $CuSO_4$ keep this concentration constant.

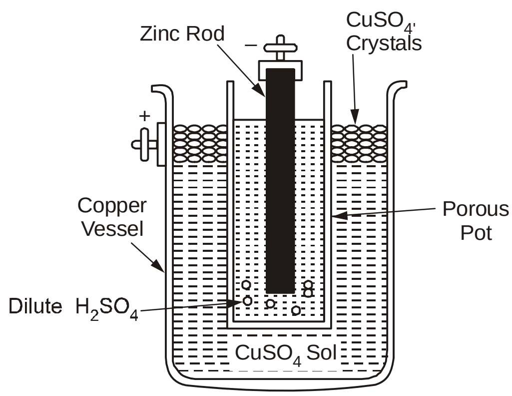


Figure 5.24 : Schematic Diagram of A Daniel Cell

As the positive charge build up on the copper vessel and negative charge on the zinc rod, the potential difference between the two poles of the cell goes on increasing. The cell develops an e.m.f. of **1.1 V**, when equilibrium is attained.

Dry Cell

It consists of a moist paste of ammonium chloride containing zinc chloride as an electrolyte. This paste is contained in a small cylindrical zinc vessel, which acts as the cathode of the cell. A carbon rod fitted with a brass cap is placed in the middle of the zinc vessel. It acts as the anode of the cell. The carbon rod is surrounded by a closely packed mixture of MnO_2 and charcoal powder in a muslin bag. While the MnO_2 acts as depolariser, the charcoal powder reduces the internal resistance of the cell. The zinc container and its contents are sealed at the top with pitch or shellac. A small hole is provided at the top, so as to allow ammonia gas, formed during chemical reactions, to escape the cell.

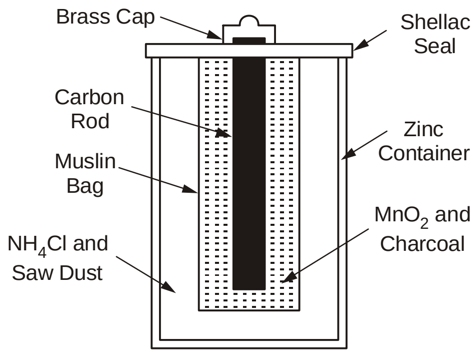


Figure 5.25 : A Dry Cell

The emf of the cell is nearly **1.5 V**. Its internal resistance may vary from 0.1 Ω to 10 Ω. Further, an electric current of about 0.25 A can be continuously drawn from a dry cell.

5.7.2 Secondary Cells

The secondary cell, also known as **storage cell**, is characterised by the fact that it can be **recharged** by passing current from an external source into it in the direction opposite to that in which current is supplied by the cell. Batteries used in cars, buses, trucks etc. are examples of secondary cells.

The commonly used secondary cells like the lead-acid accumulator, the nickel-iron (NiFe) or nickel-cadmium cells are available in several designs like button cells, cylindrical cells used in quartz wrist watches. Study carefully the important parameters of some of these cells given in Table 5.1.

Table 5.1 : Different Types of Secondary Cell

Types of Cell	Positive Pole (Anode)	Negative Pole (Cathode)	Electrolyte	Container	EMF of a Cell as Output
Lead-acid accumulator	PbO_2	PbO	Dil. sulphuric acid (H_2SO_4)	Hard rubber/ Glass/plastic vessel	2.05
NiFe cell	Nickel	Iron	Potassium hydroxide	Steel	1.2
Nickel-cadmium alkaline cell	Nickel	Cadmium	Potassium hydroxide	Steel	1.2

5.8 SUMMARY

- According to the Coulomb's law, the force of attraction or the force of repulsion between the two charges q_1 and q_2 is given by :

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$$

  where r is the distance between the two charges.

- The electric field (E) at a point due to a charge or a charge distribution is defined as the force experienced by a unit positive charge placed at that point. That is,

$$E = \frac{F}{q}$$

- Electric potential difference or voltage between two points is defined as the amount of work done to move a unit positive charge from one point to another.

- The rate of flow of electric charges is called current (I), that is :

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

- According to Ohm's law :

$$V = I\,R$$

  where R is the resistance.

- Resistance of a conductor is a measure of the opposition offered by the conductor to the flow of charge. Its units is ohm (Ω).

- If two resistances R_1 and R_2 are connected in series, the equivalent resistance (R_e) of the combination is given by :

$$R_e = R_1 + R_2$$

  and when these resistances are connected in parallel, the equivalent resistance is given by :

$$\frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2}$$

- At a given temperature, the resistance of a wire is given by :

$$R = \rho\,\frac{l}{A}$$

  where ρ is the resistivity of the material of the wire, l is the length and A is area of cross-section of the wire. The unit of resistivity is Ω m.

- Drift velocity is the average velocity of the free electrons in a conductor under the influence of an external electric field (E) applied across the conductor. It is expressed as :

$$v_d = \frac{I}{n\,A e}$$

where e is the charge on an electron, I is the current, n is the number density of electrons and A is the area of cross-section of the conductor wire.

- The Wheatstone bridge and metre bridge are used for accurate measurements of resistances. The potentiometer is used for the measurement of electric potentials.
- According to Joule's law, the heat produced by current (I) flowing through a resistance R for time t is given by :

$$Q = I^2 R t$$

- Electric power (P) of a circuit is the rate at which work is done by the source of emf in maintaining the electric current in the circuit. It is expressed as

$$P = \frac{V^2}{R} = I^2 R$$

- The process of dissociation of a liquid into ions, as a result of the flow of electric current through it, is called **electrolysis**.
- According to the Faraday's laws of electrolysis :

  (i) The mass of the substance deposited at the cathode during electrolysis is directly proportional to the quantity of charge passed through the electrolyte, that is,

  $$m = z q$$

  where z is the electrochemical equivalent.

  (ii) If same quantity of electricity is passed through different electrolytes, masses of the substances deposited at the respective cathodes are directly proportional to their chemical equivalents, that is,

  $$\frac{m}{E} = \text{Constant.}$$

- A cell or a battery is used to provide potential difference in DC circuits. Cells are of two types : primary cell and secondary cell. The underlying principle is same in both types of the cell : chemical energy is converted into electrical energy.
- The primary cells are simple voltaic cell, Daniel cell and Leclanche cell. The lead-acid accumulator is an example of secondary cell.

5.9 ANSWERS TO SAQs

SAQ 1

(a) The electrostatic force constant, K is given by :

$$K = \frac{1}{4\pi\,\varepsilon_0}$$

$$= \frac{1}{4 \times 3.14 \times (8.854 \times 10^{-12}\ \mathrm{C^2\,N^{-1}\,m^{-2}})}$$

$$= 9 \times 10^9 \ \text{Nm}^2\,\text{C}^{-2}$$

(b) We have from the problem

$q_1 = 4 \times 10^{-7}\,\text{C}$; $q_2 = 6 \times 10^{-7}\,\text{C}$; and $r = 60$ cm $= 0.6$ m.

The electric force between the two charged spheres is given by :

$$F = \frac{1}{4\pi\,\varepsilon_0}\frac{q_1 q_2}{r^2}$$

$$= \frac{(9 \times 10^9 \ \text{Nm}^2\,\text{C}^{-2}) \times (4 \times 10^{-7}\,\text{C}) \times (6 \times 10^{-7}\,\text{C})}{(0.6\ \text{m})^2}$$

$$= 6 \times 10^{-3}\,\text{N}$$

(c) Charge on sphere *P*, $q_p = 5 \times 10^{-7}\,\text{C}$, and the charge on sphere *Q*, $q_Q = 5 \times 10^{-7}\,\text{C}$; separation between the spheres, $r = 50$ cm $= 0.5$ m.

Force of repulsion when the spheres are placed in air is,

$$F_{\text{air}} = \frac{1}{4\pi\,\varepsilon_0}\frac{q_P\, q_Q}{r^2}$$

$$= \frac{(9 \times 10^9\ \text{Nm}^2\,\text{C}^{-2}) \times (5 \times 10^{-7}\,\text{C}) \times (5 \times 10^{-7}\,\text{C})}{(0.5\ \text{m})^2}$$

$$= 9 \times 10^{-3}\,\text{N}$$

And the force of repulsion when the two spheres are placed in water is,

$$F_{\text{water}} = \frac{1}{4\pi\,\varepsilon_0}\frac{q_P\, q_Q}{r^2}$$

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

$$\therefore \qquad = \frac{9 \times 10^{-3}\,\text{N}}{80}$$

$$= 1.12 \times 10^{-4}\,\text{N}$$

(d) Given, $q = 4 \times 10^{-7}\,\text{C}$; and $r = 2$ cm $= 0.02$ m.

The electric field due to a point charge is given by Eq. (5.7) :

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

$$= \frac{(9 \times 10^9\ \text{Nm}^2\,\text{C}^{-2}) \times \ (4 \times 10^{-7}\,\text{C})}{(0.02\ \text{m})^2}$$

$$= 9 \times 10^6\,\text{N}\,\text{C}^{-1}$$

SAQ 2

As per the problem, charge, $q = 2 \times 10^{-8}\,\text{C}$; and distance of the point *P* where potential is to be calculated, $r = 8$ cm $= 0.08$ m.

The electric potential at a point P due to charge q is given by :

$$V_P = \frac{1}{4\pi\,\varepsilon_0}\,\frac{q}{r}$$

$$= \frac{(9\times10^9\ \text{Nm}^2\ \text{C}^{-2})\times(2\times10^{-8}\ \text{C})}{0.08\ \text{m}}$$

$$= 2.25\times10^3\ \text{V}$$

The potential at point P is equal to the work done in bringing a unit positive charge from infinity to the point P. Thus, the work done in bringing a charge of 2×10^{-9} C from infinity to P can be written as :

$$W = (2\times10^{-9}\ \text{C})\times(2.25\times10^3\ \text{V})$$

$$= 4.50\times10^{-6}\ \text{J}$$

SAQ 3

As given in the problem,

$$R = 200\ \Omega;\ V = 400\ \text{volts};\ t = 2\,s;\ \text{and}\ e = 1.6\times10^{-19}\ \text{C}.$$

Using Ohm's law,

$$V = I\,R$$

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

$$= \frac{400\ \text{V}}{200\ \Omega}$$

$$= 2\,\text{A}$$

However, we know that the current can also be written as :

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

or,
$$q = I\,t$$

$$= (2\ \text{A})\times(2\ \text{s})$$

$$= 4C$$

But, we know that,

$$q = n\,e$$

or,
$$n = \frac{q}{e}$$

$$= \frac{4\ \text{C}}{1.6\times10^{-19}\ (\text{C})}$$

$$= 2.5\times10^{19}$$

SAQ 4

(a) As per the problem, length of the wire, l = 2 m, diameter of the wire, $d = 0.2\ \text{mm} = 2\times10^{-4}\ \text{m}$, and its resistance, $R = 4\ \Omega$.

Thus, we have the area of cross-section of the wire,

$$A = \pi r^2$$

$$= \pi \left(\frac{d}{2}\right)^2$$

$$= \frac{1}{4} \times 3.14 \times (2 \times 10^{-4}\ \text{m})^2$$

$$= 3.14 \times 10^{-8}\ \text{m}^2$$

And, the resistivity of the wire is given by Eq. (5.21) :

$$\rho = \frac{R \times A}{l}$$

$$= \frac{(4\ \Omega) \times (3.14 \times 10^{-8}\ \text{m}^2)}{2\ \text{m}}$$

$$= 6.28 \times 10^{-8}\ \Omega\,\text{m}$$

(b) We have three resistors $R_1 = 2\ \Omega$; $R_2 = 3\ \Omega$; and $R_3 = 5\ \Omega$

The equivalent resistance of the series combination of R_1, R_2 and R_3 is given by Eq. (5.16) :

$$R_{es} = R_1 + R_2 + R_3$$

$$= 2 + 3 + 5$$

$$= 10\ \Omega$$

The voltage applied across this series combination, E = 20 volt. Thus, the current through the combination is,

$$(I) = \frac{V}{R_{es}}$$

$$= \frac{20}{10}$$

$$= 2\,\text{A}$$

In the series combination, same current I flows through each resistor. Therefore,

Potential difference (P. D.) across R_1

$$= I\,R_1$$

$$= 2 \times 2 = 4\ \text{volts}$$

Similarly, P. D. across $R_2 = I\,R_2 = 2 \times 3 = 6$ volts and

P. D. across $R_3 = I\,R_3 = 2 \times 5 = 10$ volts

When the resistances are connected in parallel, the expression for the equivalent resistance R_{ep} is given by Eq. (5.20) :

$$\frac{1}{R_{ep}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$= \frac{1}{2\Omega} + \frac{1}{3\Omega} + \frac{1}{5\Omega}$$

or, $$R_{ep} = \frac{30}{31}\,\Omega$$

$$\approx 0.97\ \Omega$$

SAQ 5

As per the problem, $I = 15\,\text{A}$; $A = 10^{-4}\ \text{m}^2$; $n = 5 \times 10^{28}\ \text{m}^{-3}$ and $e = 1.6 \times 10^{-19}\ \text{C}$.

The drift velocity of electrons is given by Eq. (5.28) :

$$v_d = \frac{I}{n\,e\,A}$$

$$= \frac{15\,\text{A}}{(5 \times 10^{28}\ \text{m}^{-3}) \times (1.6 \times 10^{-19}\,\text{C}) \times (10^{-4}\ \text{m}^2)}$$

$$= 1.88 \times 10^{-5}\ ms^{-1}$$

SAQ 6

As per the problem, P = 40 W; and V = 220 volts.

From Eq. (5.48), we have :

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

$$= \frac{40\,\text{W}}{220\,\text{V}}$$

$$\approx 0.182\ \text{A}$$

And the resistance of the filament of the bulb can be written as Eq. (5.49) is,

$$R = \frac{V^2}{P}$$

$$= \frac{(220\ \text{V})^2}{40\ \text{W}}$$

$$= 1210\ \Omega.$$