# CHAPTER : 17
# ELECTRIC CURRENT

In our daily life we use electricity for various activities. The electric lamps and tubes light our houses, we listen music on a tape recorder or radio, see different programmes on television, enjoy cool breeze from electric fan or cooler, and use electric pump to irrigate fields. In fact, electricity is a unique gift of science to mankind. We can not imagine life without electricity in the modern world. At home you might have observed that as soon as you switch on an electrtc lamp, it starts glowing. Why does it happen? What is the function of a switch?

In the preceding lessons of this module, you have studied about static electric charges and forces between them. In this lesson, you will learn about electric charges in motion. You will also learn that the rate of flow of charge through a conductor depends on the potential difference across it. You will also study the distribution of current in circuits and Kirchhoff's laws which govern it. Elementary idea of primary and secondary cells will also be discussed in this lesson.

Physics is an experimental science and the progress it has made to unfold laws of nature became possible due to our ability to verify theoretical predictions or reproduce experimental results. This has led to continuous improvement in equipment and techniques. In this lesson you will learn about potentiometer, which is a very versatile instrument. It can be used to measure resistance as well as electro-motive force using null method.

## OBJECTIVES

After studying this lesson, you should be able to :

- *state Ohm's law and distinguish between ohmic and non-ohmic resistances;*
- *obtain equivalent resistance for a series and parallel combination of resistors;*
- *distinguish between primary and secondary cells;*

- *apply Kirchhoff's rules to closed electrical circuits;*
- *apply Wheatstone bridge equation to determine an unknown resistance; and*
- *explain the principle of potentiometer and apply it to measure the e.m.f and internal resistance of a cell.*

**Free and Bound Electrons**

An atom is electrically neutral, i.e. as many negatively charged electrons revolve around the nucleus in closed orbits as there are positively charged protons inside it. The electrons are bound with the nucleus through Coulomb (attractive) forces.

Farther the electrons from the nucleus, weaker is the Coulomb force. The electrons in the outermost orbit are, therefore, most loosely bound with the nucleus. These are called *valence electrons*. In metallic solids, the valence electrons become free to move when a small potential difference is applied.

## 17.1 ELECTRIC CURRENT

You have studied in the previous lesson that when a potential difference is applied across a conductor, an electric field is set up within it. The free electrons move in a direction opposite to the field through the conductor. This constitutes an electric current. Conventionally, *the direction of current is taken as the direction in which a positive charge moves*. The electrons move in the opposite direction. To define current precisely, let us assume that the charges are moving perpendicular to a surface of area $A$, as shown in Fig. 17.1. The current is the rate of flow of charge through a surface area placed perpendicular to the direction of flow. If charge $\Delta q$ flows in time $\Delta t$, the average current is defined as :

$$I_{av} = \frac{\Delta q}{\Delta t} \qquad (17.1)$$

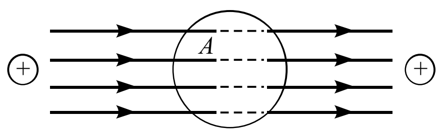



**Fig. 17.1 :** Motion of charges inside a conductor of surface area $A$

If the rate of flow of charge varies with time, the current also varies with time. The instantaneous current is expressed as :

$$I = \frac{dq}{dt} \qquad (17.2)$$

**The electric current through a conductor is the rate of transfer of charge across a surface placed normal to the direction of flow.**

The SI unit of current is ampere. Its symbol is A :

$$1 \text{ ampere} = \frac{1 \text{ coulomb}}{1 \text{ second}} \tag{17.3}$$

The smaller units of current are milliampere, 1 mA = $10^{-3}$A, and microampere, 1μA = $10^{-6}$A. The current can arise due to flow of negative charges (electrons), as in metals. In a semiconductor, flow of electrons (negative charge) and holes constitutes current. Holes are vacancies in a crystal. These are taken as positively charged particles having the same amount of charge as that on an electron. You will study about these particles in more detail in lesson 28.

Let us consider a conductor of cross sectional area $A$ shown in Fig. 17.2. The volume element for a length $\Delta x$ is $A\ \Delta x$. If $n$ is the number of electrons per unit volume, the number of electrons in this volume element will be $nA\Delta x$. The total charge in this volume

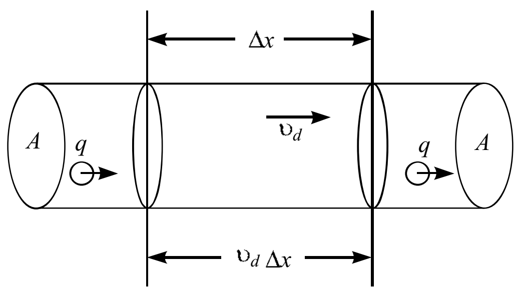



**Fig. 17.2 :** The charges move with a speed $v_d$ through a surface of area $A$. The number of charges in a length $\Delta x$ is $nA\ v_d\ \Delta t$.

element is $\Delta q = nA\Delta xe$, where $e$ is charge on the electron. If electrons drift with a speed $v_d$ due to thermal energy, the distance travelled in time $\Delta t$ is $\Delta x = v_d \Delta t$. On substituting this value of $\Delta x$ in the expression for $\Delta q$, we find that total charge in the volume element under consideration is given by

$$\Delta q = nAe\ v_d\ \Delta t$$

so that

$$\frac{\Delta q}{\Delta t} = I = nAev_d \tag{17.4}$$

You will learn more about the drift velocity in sec.17.9.

## 17.2 OHM'S LAW

In 1828, Ohm studied the relation between current in a conductor and potential difference applied across it. He expressed this relation in the form of a law, known as **Ohm's law**.

**George Simon Ohm**
**(1787-1854)**

German physicist, George Simon Ohm is famous for the law named after him. He arrived at the law by considering an analogy between thermal and electrical conduction. He also contributed to theory of sirens, interference of polarised light in crystals etc. Ohm, the practical unit of resistance, is named in his honour.

According to Ohm's law, **the electric current through a conductor is directly proportional to the potential difference across it, provided the physical conditions such as temperature and pressure remain unchanged.**

Let $V$ be the potential difference applied across a conductor and $I$ be the current flowing through it. According to Ohm's law,

$$V \propto I$$

or

$$V = RI$$

$$\Rightarrow \qquad \frac{V}{I} = R \qquad (17.5)$$

where constant of proportionality $R$ signifies the electrical resistance offered by a conductor to the flow of electric current. *Resistance is the property of a conductor by virtue of which it opposes the flow of current through it.* The $I$–$V$ graph for a metallic conductor is a straight line (Fig. 17.3(a)).

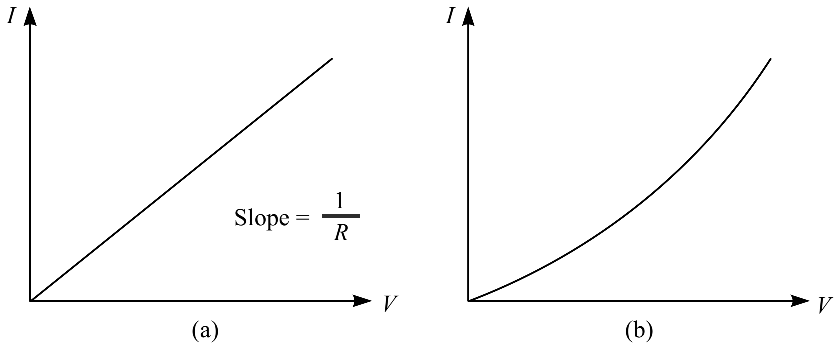



**Fig. 17.3 :** Current-voltage graph for **a)** an ohmic device, and **b)** a semiconductor diode

The SI unit of resistance is ohm. It is expressed by symbol Ω (read as omega)

1 ohm = 1 volt/1 ampere

Most of the metals obey Ohm's law and the relation between voltage and current is linear. Such resistors are called *ohmic*. Resistors which do not obey Ohm's law are called *non-ohmic*. Devices such as vacuum diode, semiconductor diode, transistors show non ohmic character. For semiconductor diode, Ohm's law does not hold good even for low values of voltage. Fig. 17.3(b) shows a non-linear *I–V* graph for a semiconductor diode.

## ACTIVITY 17.1

**Aim : To study conduction of electricity through an electrolyte.**

**Material Required** Ammeter, Voltmeter, a jar containing copper sulphate solution, two copper plates, a battery, plug key, connecting wires and a rheostat.

**How to Proceed :**

1. Set up the apparatus as shown in Fig. 17.4.
2. Plug in the key and note ammeter and voltmeter readings.
3. Change the value of ammeter reading by moving the sliding contact of rheostat and note voltmeter reading again.
4. Repeat step –3 at least five times and record ammeter and voltmeter readings each time.
5. Repeat the experiment by changing (a) seperation between $P_1$ and $P_2$, (b) plate area immersed in electrolyte, and (c) concentration of electrolyte.
6. Plot *I–V* graph in each case.

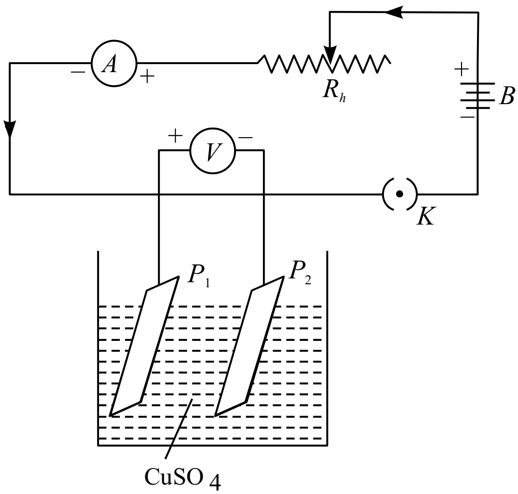


**Fig. 17.4 :** Electrical conduction through an electrolyte

**What do you conclude?**

- If *I–V* graph is a straight line passing through the orgin, as shown in Fig. 17.5, we say that ionic solution behaves as an ohmic resistor.
- The slope of the graph changes steeply with change in volume of electrolyte between the plates. It means that resistivity of an electrolyte depends not only on its nature but also on the area of the electrodes and the seperation between them.

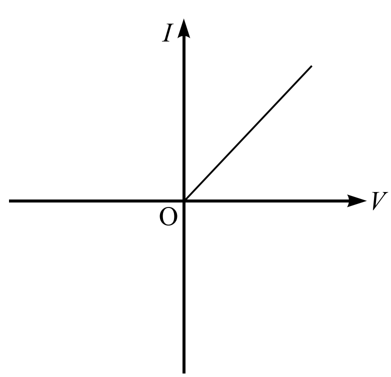


**Fig. 17.5 :** *I–V* graph for an ionic solution

### 17.2.1 Resistance and Resistivity

Let us now study the factors which affect the resistance of a conductor. You can perform two simple experiments. To do so, set up a circuit as shown in Fig. 17.6.

**ACTIVITY 17.2**

Take a long conducting wire of uniform cross section. Cut out pieces of different lengths, say $l_1$, $l_2$, $l_3$, etc from it. This makes sure that wires have same area of cross-section. Connect $l_1$ between $A$ and $B$ and note down the current through this wire. Let this current be $I$. Perform the same experiment with wires of lengths $l_2$ and $l_3$, one by one. Let the currents in the wires be $I_2$ and $I_3$ respectively.

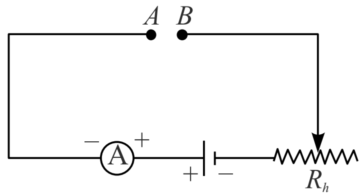



**Fig. 17.6 :** Electrical circuit to study factors affecting resistance of conductors

Plot a graph between $l^{-1}$ and $I$. You will find that the graph is a straight line and longer wires allow smaller currents to flow. That is, longer wires offer greater resistance [Fig.17.7(a)]. Mathematically, we express this fact as

$$R \propto l \tag{17.6}$$

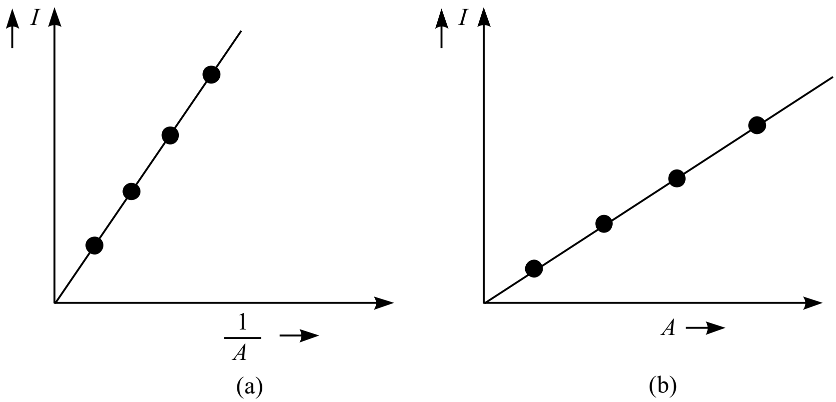



**Fig. 17.7 :** **a)** The graph between $I$ and $1/l$ for wires of uniform cross-section and **b)** the graph between current and area of cross section for wires of same length

**ACTIVITY 17.3**

Take wires of the same length of a given material but having different areas of cross section, say $A_1$, $A_2$, $A_3$ etc. Connect the wires between $A$ and $B$ one by one and note down the currents $I_1$, $I_2$, $I_3$ etc. in each case. A plot of $I$ and $A$ will give a straight line. Wires of greater cross sectional area allow greater currents to flow. You may say that wires of larger area of cross-section offer smaller resistance [Fig. 17.7 (b)]. Mathematically, we can write

$$R \propto \frac{1}{A} \qquad (17.7)$$

On combining Eqns.(17.6) and (17.7), we can write

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

or

$$R = \rho \frac{\ell}{A} \qquad (17.8)$$

where ρ is a constant for the material at constant temperature. It is called the **specific resistance** or **resistivity** of the material. By rearranging terms, we can write

$$\rho = \frac{RA}{\ell} \qquad (17.9)$$

If $\ell = 1$m and $A = 1$m$^2$, then $\rho = R$ ohm-metre. Thus *resistivity of a material is the resistance offered by a wire of length one metre and area of cross section one m$^2$*. The unit of resistivity is ohm metre (Ωm)

Reciprocal of resistivity is called conductivity (specific conductance) and is denoted by σ :

$$\sigma = \frac{1}{\rho} \qquad (17.10)$$

Unit of **conductivity** is Ohm$^{-1}$ metre$^{-1}$ or mho-metre$^{-1}$ or Sm$^{-1}$.

Resistivity depends on the nature of the material rather than its dimensions, whereas the resistance of a conductor depends on its dimensions as well as on the nature of its material.

You should now study the following examples carefully.

**Example 17.1 :** In our homes, the electricity is supplied at 220V. Calculate the resistance of the bulb if the current drawn by it is 0.2A.

**Solution :**

$$R = \frac{V}{I} = \frac{220 \text{ volt}}{0.2 \text{ amp.}} = 1100\ \Omega$$

**Example 17.2 :** A total of $6.0 \times 10^{16}$ electrons pass through any cross section of a conducting wire per second. Determine the value of current in the wire.

**Solution :** Total charge passing through the cross-section in one second is

$\Delta Q = ne = 6.0 \times 10^{16} \times 1.6 \times 10^{-19}$ C $= 9.6 \times 10^{-3}$C

$$\therefore \qquad I = \frac{\Delta Q}{\Delta t} = \frac{9.6 \times 10^{-3}\,\text{C}}{1\,\text{s}}$$
$$= 9.6 \times 10^{-3}\ \text{A}$$
$$= 9.6\ \text{mA}$$

**Example 17.3 :** Two copper wires $A$ and $B$ have the same length. The diameter of $A$ is twice that of $B$. Compare their resistances.

**Solution :** From Eqn. (17.8) we know that

$$R_A = \rho \frac{\ell}{\pi r_A^2} \quad \text{and} \quad R_B = \rho \frac{\ell}{\pi r_B^2}$$

$$\therefore \qquad \frac{R_A}{R_B} = \frac{r_B^2}{r_A^2}$$

Since diameter of $A = 2 \times$ diameter of $B$, we have $r_A = 2r_B$. Hence

Resistance of $B$ will be four times the resistance of $A$.

**Example 17.4 :** The length of a conducting wire is 60.0 m and its radius is 0.5cm. A potential difference of 5.0 V produces a current of 2.5 A in the wire. Calculate the resistivity of the material of the wire.

**Solution :** $$R = \frac{V}{I} = \frac{5.0\,V}{2.5\,A} = 2.0\ \Omega$$

Radius of the wire = 0.5 cm $= 5.0 \times 10^{-3}$ m

Area of cross section $A = \pi R^2 = 3.14 \times (5.0 \times 10^{-3})^2\ \text{m}^2 = 78.5 \times 10^{-6}\ \text{m}^2$

$$\therefore \qquad \rho = \frac{2.0 \times 78.5 \times 10^{-6}\ \Omega\text{m}^2}{60.0\ \text{m}} = 2.6 \times 10^{-6}\ \Omega\text{m}$$

## INTEXT QUESTIONS 17.1

1. (a) A current $I$ is established in a copper wire of length $\ell$. If the length of the wire is doubled, calculate the current due to the same cell.

   (b) What happens to current in an identical copper wire if the area of cross section is decreased to half of the original value?

2. The resistivity of a wire of length $l$ and area of cross section $A$ is $2 \times 10^{-8}\Omega$m. What will be the resistivity of the same metallic wire of length $2l$ and area of cross section $2A$?

3. A potential difference of 8 V is applied across the ends of a conducting wire of length 3m and area of cross section $2cm^2$. The resulting current in the wire is 0.15A. Calculate the resistance and the resistivity of the wire.
4. Do all conductors obey Ohm's law? Give examples to support your answer.
5. $5 \times 10^{17}$ electrons pass through a cross-section of a conducting wire per second from left to right. Determine the value and direction of current.

## 17.3 GROUPING OF RESISTORS

An electrical circuit consists of several components and devices connected together. Some of these are batteries, resistors, capacitors, inductors, diodes, transistors etc. (They are known as circuit elements.) These are classified as resistive and reactive. The most common resistive components are resistors, keys, rheostats, resistance coils, resistance boxes and connecting wires. The reactive components include capacitors, inductors and transformers. In addition to many other functions performed by these elements individually or collectively, they control the current in the circuit. In the preceding lesson you learnt how grouping of capacitors can be used for controlling charge and voltage. Let us now discuss the role of combination of resistors in controlling current and voltage.

Two types of groupings of resistors are in common use. These are : **series grouping and parallel grouping. We define equivalent resistance of the combination as a single resistance which allows the same current to flow as the given combination when the same potential difference is applied across it.**

### 17.3.1 Series Combination

You may connect many resistors in series by joining them end-to-end such that the same current passes through all the resistors. In Fig. 17.8, two resistors of resistances $R_1$ and $R_2$ are connected in series. The combination is connected to a battery at the ends *A* and *D*. Suppose that current *I* flows through the series combination when it is connected to a battery of voltage *V*. Potential differences $V_1$ and $V_2$ develop across $R_1$ and $R_2$, respectively. Then $V_1 = IR_1$ and $V_2 = IR_2$. But sum of $V_1$ and $V_2$ is equal to *V*, i.e.

$$\Rightarrow \qquad V = V_1 + V_2 = I R_1 + I R_2$$

If equivalent resistance of this series combination is *R*, then

$$V = IR = I (R_1 + R_2)$$

so that

$$R = R_1 + R_2$$

This arrangement may be extended for any number of resistors to obtain

$$R = R_1 + R_2 + R_3 + R_4 + \cdots \qquad (17.11)$$

That is, the equivalent resistance of a series combination of resistors is equal to the sum of individual resistances. If we wish to apply a voltage across a resistor (say electric lamp) less than that provided by the constant voltage supply source, we should connect another resistor (lamp) in series with it.

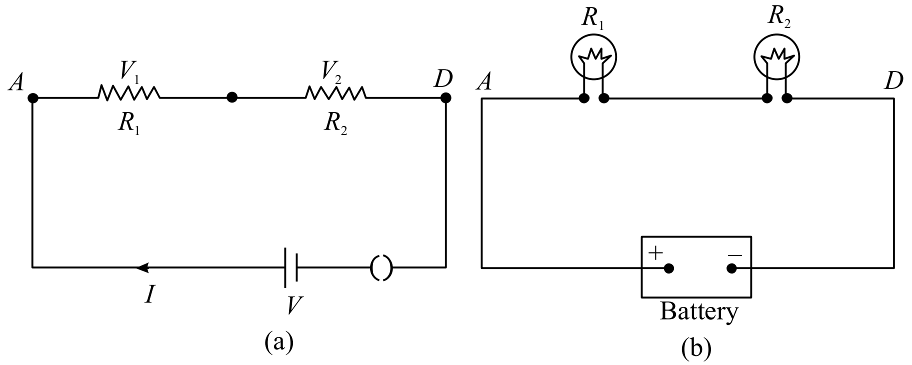



**Fig. 17.8 :** **a)** Two resistors connected in series to a battery, and **b)** two lamps joined in series connected to *a dc* source.

### 17.3.2 Parallel Combination

You may connect the resistors in parallel by joining their one end at one point and the other ends at another point. In parallel combination, **same potential difference exists across all resistors.** Fig. 17.9 shows a parallel combination of two resistors $R_1$ and $R_2$. Let the combination be connected to a battery of voltage $V$ and draw a current $I$ from the source.

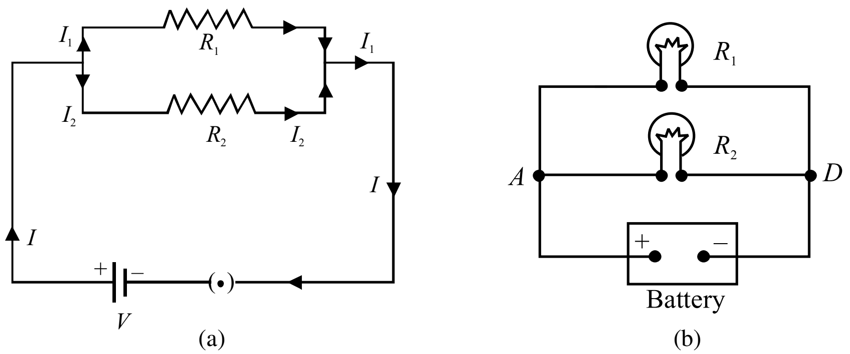



**Fig. 17.9 :** **a)** Two resistors connected in parallel. The battery supplies the same voltage to both resistors, and **b)** lamps connected in parallel to a battery.

The main current divides into two parts. Let $I_1$ and $I_2$ be the currents flowing through resistors $R_1$ and $R_2$, respectively. Then $I_1 = V/R_1$ and $I_2 = V/R_2$.

The main current is the sum of $I_1$ and $I_2$. Therefore, we can write

$$\Rightarrow \qquad I = I_1 + I_2 = \frac{V}{R_1} + \frac{V}{R_2}$$

If the equivalent resistance of combination is $R$, we write $V = IR$ or $I = V/R$:

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

$$\therefore \qquad \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \qquad (17.12a)$$

or

$$R = \frac{R_1 R_2}{R_1 + R_2} \qquad (17.12b)$$

From Eqn. (17.12a) we note that **reciprocal of equivalent resistance of parallel combination is equal to the sum of the reciprocals of individual resistances.** The process may be extended for any number of resistors, so that

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \ldots \qquad (17.13)$$

Note that the equivalent resistance of parallel combination is smaller than the smallest individual resistance. You may easily see this fact by a simple electrical circuit having a resistor of 2 Ω connected across a 2V battery. It will draw a current of one ampere. When another resistor of 2 Ω is connected in parallel, it will also draw the same current. That is, total current drawn from the battery is 2A. Hence, resistance of the circuit is halved. As we increase the number of resistors in parallel, the resistance of the circuit decreases and the current drawn from the battery goes on increasing.

In our homes, electrical appliances such as lamps, fans, heaters etc. are connected in parallel and each has a separate switch. Potential difference across each remains the same and their working is not influenced by others. As we switch on bulbs and fans, the resistance of the electrical circuit of the house decreases and the current drawn from the mains goes on increasing (Fig.17.10).

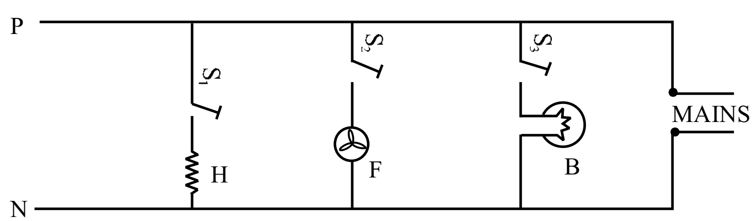



**Fig. 17.10 :** Arrangement of appliances in our homes. These are connected in parallel so that every appliance is connected to 220 V main supply. The total current drawn from the mains is the sum of the currents drawn by each appliance.

**Example 17.5 :** For the circuit shown in Fig. 17.11, calculate the value of resistance $R_2$, and current $I_2$ flowing through it.

**Solution:** If the equivalent resistance of parallel combination of $R_1$ and $R_2$ is $R$, then

$$R = \frac{R_1 R_2}{R_1 + R_2} = \frac{10\, R_2}{10 + R_2}$$

According to Ohm's law,

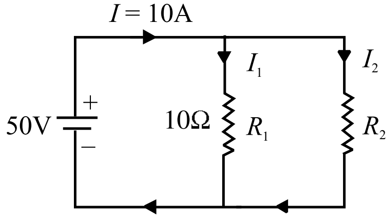



Fig. 17.11 : Two resistors in parallel

$$R = \frac{50}{10} = 5\Omega$$

$$\therefore \qquad \frac{10\,R_2}{10 + R_2} = 5$$

$\Rightarrow$ $10\,R_2 = 50 + 5\,R_2$ or $R_2 = 10\,\Omega$

Since $R_1$ and $R_2$ are equal, current will be equally divided between them. Hence, $I_2 = 5$A

**Example 17.6 :** For the circuit shown in Fig. 17.12, calculate the equivalent resistance between points *a* and *d*.

**Solution :** 15Ω and 3Ω resistors are connected in parallel. The equivalent resistance of this combination is

$$R_1 = \frac{15 \times 3}{15 + 3}\Omega = \frac{45}{18} = \frac{5}{2} = 2.5\Omega$$

Now we can regard the resistances 5Ω, $R_1$ = 2.5Ω and 7Ω as connected in series. Hence, equivalent resistance between points *a* and *d* is

$$R = (5 + 2.5 + 7) = 14.5\ \Omega$$

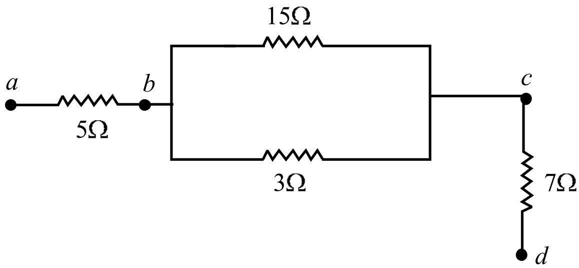



**Fig. 17.12:** A combination of series and parallel groupings

**Example 17.7 :** Refer to the network shown in Fig. 17.13. Calculate the equivalent resistance between the points (i) *b* and *c* (ii) *c* and *d*, and (iii) *a* and *e*.

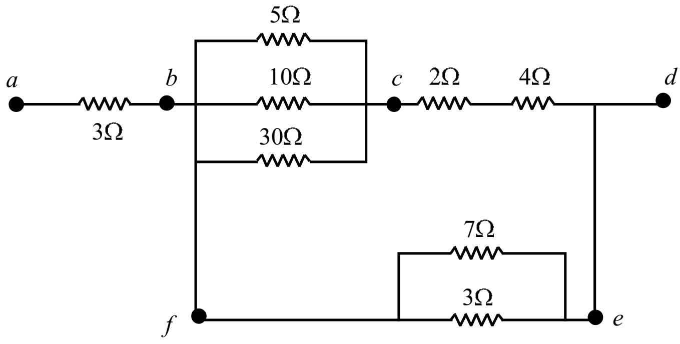



**Fig. 17.13 :** A combination of series and parallel groupings of resistors

**Solution :**

(i) Three resistors (5Ω, 10Ω and 30Ω) are connected in parallel. Therefore, equivalent resistance is given by

$$\frac{1}{R_1} = \frac{1}{5} + \frac{1}{10} + \frac{1}{30} = \frac{6+3+1}{30} = \frac{10}{30}\Omega$$

or $$R_1 = 3\ \Omega$$

(ii) The resistors with resistances 2Ω and 4Ω are in series. The equivalent resistance

$$R_2 = (2 + 4) = 6\Omega$$

(iii) The resistances 7Ω and 3Ω are in parallel. So equivalent resistance

$$\frac{1}{R_3} = \left(\frac{1}{7} + \frac{1}{3}\right) = \frac{3+7}{21} = \frac{10}{21}$$

or, $$R_3 = \frac{21}{10}\Omega = 2.1\ \Omega$$

Now we can treat equivalent resistance $R_1$ and $R_2$ to be in series. Therefore

$$R_4 = R_1 + R_2 = (3 + 6) = 9\Omega$$

Now $R_4$ and $R_3$ are in parallel. Therefore equivalent resistance

$$\frac{1}{R_5} = \frac{1}{R_4} + \frac{1}{R_3}$$

$$= \frac{1}{9} + \frac{1}{2.1}$$

$$= \frac{1}{9} + \frac{10}{21} = \frac{37}{63}$$

$$R_5 = \frac{63}{57}\Omega = 1.70\ \Omega$$

(iv) Finally $R_5$ and 3Ω (between *a* and *b*) are in series. Hence

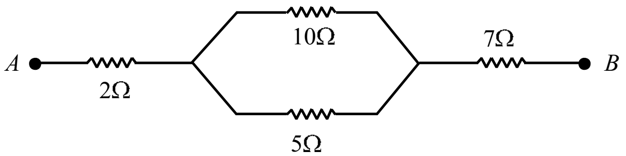
$$R = (1.70 + 3) = 4.79\ \Omega$$

**Note :** For ease and convenience, you should draw a new equivalent circuit after every calculation.

## INTEXT QUESTIONS 17.2

1. There are two bulbs and a fan in your bed room. Are these connected in series or in parallel? Why?

2. The electric supply in a town is usually at 220 V. Sometimes the voltage shoots upto 300 V and may harm your T V set and other gadgets. What simple precaution can be taken to save your appliances?
3. Calculate the equivalent resistance between points *A* and *B* for the following circuit :




## 17.4 TYPES OF RESISTORS

We use resistors in all electrical and electronic circuits to control the magnitude of current. Resistors usually are of two types :

- carbon resistors
- wire wound resistors

In a wire wound resistor, a resistance wire (of manganin, constantan or nichrome) of definite length, which depends on the required value of resistance, is wound two-fold over an insulating cylinder to make it non-inductive. In carbon resistors, carbon with a suitable binding agent is molded into a cylinder. Wire leads are attached to the cylinder for making connections to electrical circuits. Resistors are colour coded to give their values :

$$R = AB \times 10^{C}\ \Omega,\ D$$

where *A*, *B* and *C* are coloured stripes. The values of different colours are given in Table 17.1. As may be noted,

– first two colours indicate the first two digits of the resistance value;

– third colour gives the power of ten for the multiplier of the value of the resistance; and

– fourth colour (the last one) gives the tolerance of the resistance, which is 5% for golden colour, 10% for silver colour and 20% for body colour.

**Table 17.1 : Colour codes of resistors**

| Colour | Number | Multiplier |
|---|---|---|
| Black | 0 | 1 |
| Brown | 1 | $10^1$ |
| Red | 2 | $10^2$ |
| Orange | 3 | $10^3$ |

| | | |
|---|---|---|
| Yellow | 4 | $10^4$ |
| Green | 5 | $10^5$ |
| Blue | 6 | $10^6$ |
| Violet | 7 | $10^7$ |
| Grey | 8 | $10^8$ |
| White | 9 | $10^9$ |

Suppose that four colours on a resistor are Blue, Grey, Green and Silver. Then

The first digit will be 6 (blue)

The second digit will be 8 (Grey)

The third colour signifies multiplier $10^5$ (Green)

The fourth colour defines tolerance = 10% (Silver)

Hence value of the resistance is

$$68 \times 10^5 \pm 10\%$$
$$= 68 \times 10^5 \pm (68 \times 10^5 \times 10/100)$$
$$= 68 \times 10^5 \pm 68 \times 10^4$$
$$= (6.8 \pm 0.68)\ \text{M}\Omega$$

## 17.5 TEMPERATURE DEPENDENCE OF RESISTANCE

The resistivity of a conductor depends on temperature. For most metals, the resistivity increases with temperature and the change is linear over a limited range of temperature :

$$\rho = \rho_0 [1 + \alpha (T - T_0)] \qquad (17.14)$$

where $\rho$ and $\rho_0$ are the resistivities at temperatures $T$ and $T_0$, respectively. The temperatures are taken in °C and $T_0$ is the reference temperature. $\alpha$ is called the temperature co-efficient of resistivity. Its unit is per degree celcius.

### Superconductors

Temperature dependence of resistivity led scientists to study the behaviour of materials at very low temperatures. They observed that certain metals and their alloys lost their resistivity completely below a certain temperature, called **transition temperature,** which is specific to the material. In such materials, current, once set up, remained, unchanged for ever without the use of an external source to maintain it. Such materials were termed as **superconductors.**

It was soon realised that superconductors, if they may exist near room temperature, will bring in revolutionary changes in technology. (These have been termed as *high temperature superconductors*.) For example, energy efficient powerful electromagnets made of superconducting coils may levitate vehicles above a magnetic track and make a high speed transportation system possible.

Efforts are being made to develop high temperature superconductors. The work done so far suggests that oxides of copper, barium and ytterium are showing good possibilities. A superconductor ($T_2$ $Ba_2$ $Ca_2$ $Cu_3O_{10}$) which can exist at –153°C has been developed. India is a front runner in this area of research.

Eqn. (17.14) can be rearranged to obtain an expression for temperature coefficient of resistivity :

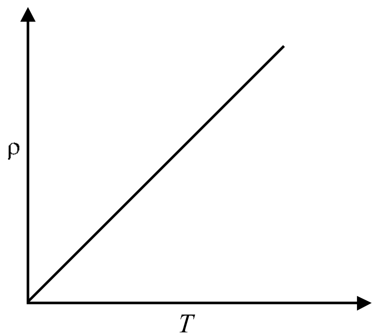
$$\rho = \rho_0 + \rho_0 \alpha (T - T_0)$$

or

$$\alpha = \frac{(\rho - \rho_0)}{\rho_0 (T - T_0)} = \frac{1}{\rho_0} \frac{\Delta\rho}{\Delta T}$$

where $\Delta\rho = (\rho - \rho_0)$ and $\Delta T = T - T_0$.

The resistivity versus temperature graph for a metal like copper is shown in Fig. 17.14(a). The curve is linear over a wide range of temperatures.



(a)

**Fig. 17.14 :** Typical resistivity–temperature graph for a metal

You may recall that resistance of a conductor is proportional to its resistivity. Therefore, temperature variation of resistance can written as :

$$R = R_0 [1 + \alpha (T - T_0)] \qquad (17.15)$$

The resistances corresponding to two different temperatures $T_1$ and $T_2$ are given by

$$R_1 = R_0 [1 + \alpha (T_1 - T_0)] \qquad (17.16)$$

and

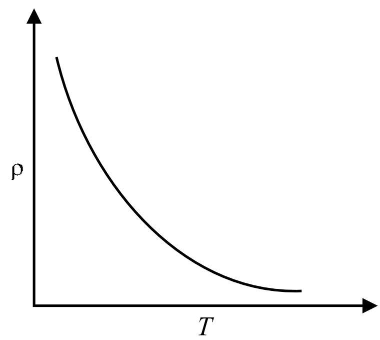
$$R_2 = R_0 [1 + \alpha (T_2 - T_0)] \qquad (17.17)$$

On combining these equations, we can write an expression for temperature coefficient ofresistivity :

$$\alpha = \frac{(R_2 - R_1)}{R_0 (T_2 - T_1)} = \frac{1}{R_0} \frac{\Delta R}{\Delta T} \qquad (17.18)$$

If $R_0 = 1\Omega$ and $(T_2 - T_1) = 1°C$, then $\alpha = (R_2 - R_1)$. Thus **temperature coefficient of resistance is numerically equal to the change in resistance of a wire of resistance 1Ω at 0° C when the temperature changes by 1° C. This property of metals is used in making resistance thermometers.**

The resistivity of alloys also increases with increase in temperature. But the increase is very small compared to that for metals. For alloys such as **manganin, constantan** and **nichrome,** the temperature coefficient of resistivity is vanishingly small ($\sim 10^{-6}\ °C^{-1}$ )and resistivity is high. That is why these materials are used for making resistance wires or standard resistances.



(b)

**Fig. 17.14(b) :** Resistivity of semiconductors decreases with temperature

Semiconductors such as germanium and silicon have resistivities which lie between those of metals and insulators. The resistivity of semiconductors usually decreases with increase in temperature [Fig.17.14(b)]. This gives a negative temperature coefficient of resistance. This will be discussed in detail in the lesson on semiconductors.

## 17.6 ELECTROMOTIVE FORCE (EMF) AND POTENTIAL DIFFERENCE

EMF is the short form of electromotive force. EMF of a cell or battery equals the potential difference between its terminals when these are not connected (open circuit) externally. You may easily understand the difference between e.m.f. and potential difference of a cell by performing the following activity.

### ACTIVITY 17.4

Connect a cell in a circuit having a resistor $R$ and key $K$. A voltmeter of very high resistance is connected in parallel to the cell, as shown in Fig.17.15. When key $K$ is closed, voltmeter reading will decrease. Can you give reasons for this decrease in the voltmeter reading? Actually when key $K$ is open, no current flows through the loop having cell and voltmeter: (The resistance in the circuit is infinite.) Hence the voltmeter reading gives e.m.f. $E$ of the cell, which is the potential difference between the terminals of the cell when no current is drawn from it. When key $K$ is closed, current flows outside and inside the cell. The cell

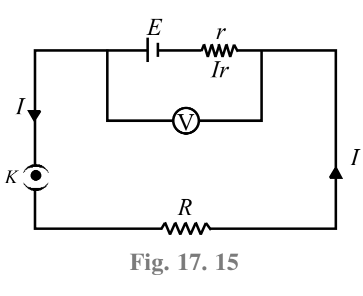



**Fig. 17. 15**

introduces a resistance $r$, called **internal resistance** of the cell. Let current $I$ be flowing in the circuit. Potential drop $Ir$ across internal resistance $r$ due to current flow acts opposite to the e.m.f. of the cell. Hence, the voltmeter reading will be

$$E - Ir = V$$

or $$E = V + Ir \qquad \{17.19)$$

Thus while drawing current from a cell, e.m.f. of the cell is always greater than the potential difference across external resistance, unless internal resistance is zero.

E.M.F. of a cell depends on :

- the electrolyte used in the cell;
- the material of the electrodes; and
- the temperature of the cell.

Note that the e.m.f. of a cell does not depend on the size of the cell, i.e. on the area of plates and distance between them. This means that if you have two cells of different sizes, one big and one small, the e.m.f.s can be the same if the material of electrods and electrolyte are the same. However, cells of larger size will offer higher resistance to the passage of current through it but can be used for a longer time.

**Example 17.8 :** When the current drawn from a battery is 0.5A, potential difference at the terminals is 20V. And when current drawn from it is 2.0A, its voltage reduces to 16V. Calculate the e.m.f. and internal resistance of the battery.

**Solution :** Let $E$ and $r$ be the e.m.f. and internal resistance of battery. When current $I$ is drawn from it, the potential drop across internal resistance of the cell is $Ir$. Then we can write

$$V = E - Ir$$

For $I = 0.5$A and $V = 20$ volt, we have

$$20 = E - 0.5\,r \qquad \text{(i)}$$

For $I = 2.0$A and $V = 16$ volt, we can write

$$16 = E - 2r \qquad \text{(ii)}$$

We can rewrite Eqns. (i) and (ii) as

$$2E - r = 40$$

and $$E - 2r = 16$$

Solving these,we get

$$E = 21.3 \text{ V and } r = 2.67\Omega$$

### 17.6.1 Elementary Idea of Primary and Secondary cells

We have seen that to pass electric current through a conductor continuously we have to maintain a potential difference between its ends. For the purpose, generally, we use a device called chemical cell.

Chemical calls are of two types :

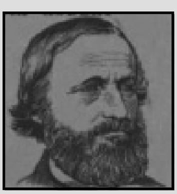
(i) **Primary Cells** : In these cells, the chemical energy is directly converted into electrical energy. The material of a primary cell is consumed as we use the cell and, therefore, it cannot be recharged and reused. Dry cell, Daniel Cell, Voltaic Cell etc are examples of primary cells.

(ii) **Secondary Cells** : These are chemical cells in which electrical energy is stored as a reversible chemical reaction. When current is drawn from the cells the chemical reaction runs in the reverse direction and the original substances are obtained. These cells, therefore, can be charged again and again. Acid-accumulator, the type of battery we use in our inverter or car, is a set of secondary cells.

## 17.7 KIRCHHOFF'S RULES

You now know that Ohm's law gives current–voltage relation for resistive circuits. But when the circuit is complicated, it is difficult to know current distribution by Ohm's law. In 1842, Kirchhoff formulated two rules which enable us to know the distribution of current in complicated electrical circuits or electrical networks.

**Gustav Robert Kirchhoff**
**(1824-1887)**



The fundamental contributions of German physicist Kirchhoff were in the fields of black body radiation and spectroscopy. But he also contributed in many other fields. His rules that you will study in this lesson enable us to analyse complex electric networks. With the help of Bunsen spectrum analysis, he discovered elements Rubidium and Cesium.

(i) **Kirchhoff's First Rule (Junction Rule)** : It states that *the sum of all currents directed towards a junction (point) in an electrical network is equal to the sum of all the currents directed away from the junction.*

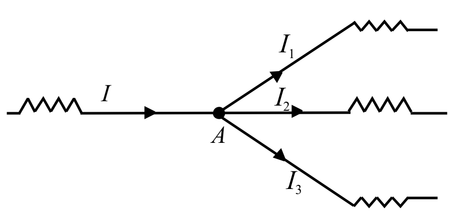



**Fig. 17.16 :** Kirchhoff's first rule : Sum of currents coming to a junction is equal to the sum of currents going away from it.

Refer to Fig. 17.16.If we take currents approaching point $A$ as positive and those leaving it as negative, then we can write

$$I = I_1 + I_2 + I_3$$

or $$I - (I_1 + I_2 + I_3) = 0 \qquad (17.20)$$

In other words, the algebraic sum of all currents at a junction is zero.

Kirchhoff's first rule tells us that there is no accumulation of charge at any point if steady current flows in it. The net charge coming towards a point should be equal to that going away from it in the same time. In a way, it is an extension of continuity theorem in electrical circuits.

(ii) **Kirchhoff's Second Rule (Loop Rule)** : This rule is an application of law of conservation of energy for electrical circuits. It tells us that *the algebraic sum of the products of the currents and resistances in any closed loop of an electrical network is equal to the algebraic sum of electromotive forces acting in the loop.*

While using this rule, we start from a point on the loop and go along the loop either clockwise or anticlockwise to reach the same point again. The product of current and resistance is taken as positive when we traverse in the direction of current. The e.m.f is taken positive when we traverse from negative to positive electrode through the cell. Mathematically, we can write

$$\sum IR = \sum E \qquad (17.21)$$

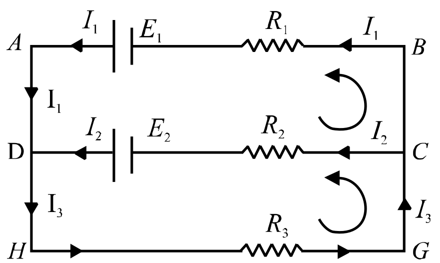



**Fig. 17.17 :** A network to illustrate Kirchhoff's second rule

Let us consider the electrical network shown in Fig. 17.17. For closed mesh *ADCBA*, we can write

$$I_1R_1 - I_2R_2 = E_1 - E_2$$

Similarly, for the mesh *DHGCD*

$$I_2R_2 + (I_1 + I_2)\, R_3 = E_2$$

And for mesh *AHGBA*

$$I_1R_1 + I_3\, R_3 = E_1$$

At point *D* $$I_1 + I_2 = I_3$$

In more general form, Kirchhoff's second rule is stated as : *The algebraic sum of all the potential differences along a closed loop in a circuit is zero.*

**Example 17.9 :** Consider the network shown in Fig. 17.18. Current is supplied to the network by two batteries. Calculate the values of currents $I_1$, $I_2$ and $I_3$. The directions of the currents are as indicated by the arrows.

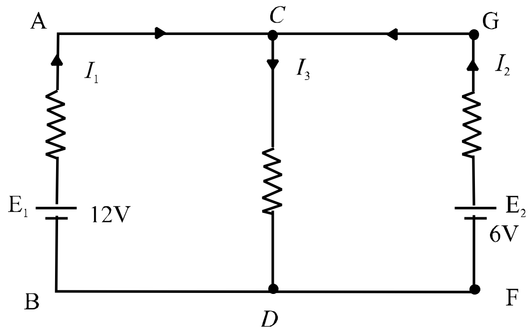



**Fig. 17.18 :** Calculation of currents in a network of resistors and batteries.

**Solution :** Applying Kirchhoff's first rule to junction *C*, we get

$$I_1 + I_2 - I_3 = 0 \qquad \text{(i)}$$

Applying Kirchhoff's second rule to the closed loops *ACDBA* and *GCDFG*, we get

$$5I_1 + 2I_3 = 12 \qquad \text{(ii)}$$

and $$3I_2 + 2I_3 = 6 \qquad \text{(iii)}$$

On combining these equations, we get

$$5I_1 - 3I_2 = 6 \qquad \text{(iv)}$$

Multiply (i) by 2 and add to (ii) to obtain

$$7I_1 + 2I_2 = 12 \qquad \text{(v)}$$

On multiplying Eqn. (iv) by 2 and Eqn. (v) by 3 and adding them, we get

$$31I_1 = 48$$

or $$I_1 = 1.548\text{A}$$

Putting this value of $I_1$ in eqn. (v), we get

$$I_2 = 0.582\text{A}$$

And from (i), we get

$$I_3 = I_1 + I_2 = 2.13\text{A}$$

### 17.7.1 Wheatstone Bridge

You have learnt that a resistance can be measured by Ohm's law using a voltmeter and an ammeter in an electrical circuit. But this measurement may not be accurate for low resistances. To overcome this difficulty, we use a wheatstone bridge. It is an arrangement of four resistances which can be used to measure one of them in terms of the other three.

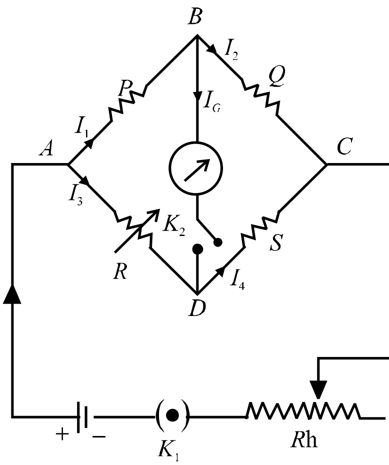



**Fig. 17.19 :** A wheatstone bridge.

Consider the circuit shown in Fig. 17.19 where

(i) *P* and *Q* are two adjustable resistances connected in arms *AB* and *BC*.

(ii) *R* is an adjustable known resistance.

(iii) *S* is an unknown resistance to be measured.

(iv) A sensitive galvanometer *G* along with a key $K_2$ is connected in the arm *BD*.

(v) A battery *E* along with a key $K_1$ is connected in the arm *AC*.

On closing the keys, in general, some current will flow through the galvanometer and you will see a deflection in the galvanometer. It indicates that there is some potential difference between points *B* and *D*. We now consider the following three possibilities:

(i) **Point *B* is at a higher potential than point *D* :** Current will flow from *B* towards *D* and the galvanometer will show a deflection in one direction, say right

(ii) **Point *B* is at a lower potential than point *D* :** Current will flow from point *D* towards *B* and the galvanometer will show a deflection in the opposite direction.

(iii) **Both points *B* and *D* are at the same potential:** In this case, no current will flow through the galvanometer and it will show no deflection, i.e. the galvanometer is in null condition. In this condition, the Wheatstone bridge is said to be in the *state* of *balance.*

The points $B$ and $D$ will be at the same potential only when the potential drop across $P$ is equal to that across $R$. Thus

$$I_1 P = I_3 R \quad (1\ 7.22)$$

But $$I_1 = I_2 + I_G$$

and $$I_4 = I_3 + I_G \quad (17.23)$$

Applying Kirchhoff's first rule at junctions $B$ and $D$ in the null condition ($I_G = 0$), we get

$$I_1 = I_2$$

and $$I_3 = I_4 \quad (1\ 7.24)$$

Also potential drop across $Q$ will be equal to that across $S$. Hence

$$I_2 Q = I_4 S \quad (17.25)$$

Dividing Eqn. (17.22) by Eqn. (17.25), we obtain

$$\frac{I_1 P}{I_2 Q} = \frac{I_3 R}{I_4 S} \quad (17.26)$$

Using Eqn. (17.24), we get

$$\frac{P}{Q} = \frac{R}{S} \quad (17.27)$$

This is the condition for which a Wheatstone bridge will be balanced. From Eqn. (17.27), we find that the unknown resistance $S$ is given by

$$S = \frac{QR}{P}$$

You can easily see that measurement of resistance by Wheatstone bridge method has the following merits.

*(i) The balance condition given by Eqn.* (17.27) *at null position is independent* of *the applied voltage V. In other words, even if you change the e.m.f* of *the cell, the balance condition will not change.*

*(ii) The measurement* of *resistance does not depend on the accuracy of calibration* of *the galvanometer. Galvanometer is used only* as a *null indicator (current detector).*

The main factor affecting the accuracy of measurement by Wheatstone bridge is its sensitivity with which the changes in the null condition can be detected. It has been found that the bridge has the greatest sensitivity when the resistances in all the arms are nearly equal.

**Example 17.9:** Calculate the value of $R$ shown in Fig.17.20. when there is no current in 50Ω resistor.

**Solution:** This is Wheatstone bridge where galvanometer has been replaced by 50Ω resistor. The bridge is balanced because there is no current in 50Ω resistor. Hence,

$$\frac{20}{10} = \frac{40}{R}$$

or $$R = \frac{40 \times 10}{20} = 20\Omega$$

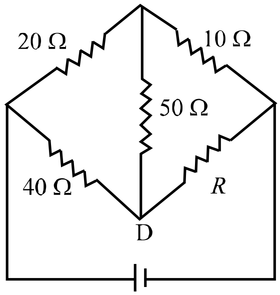
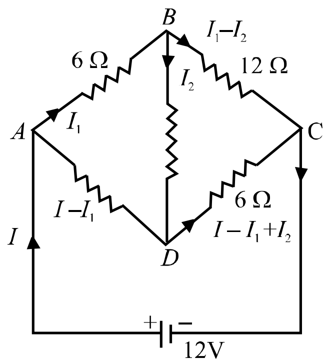


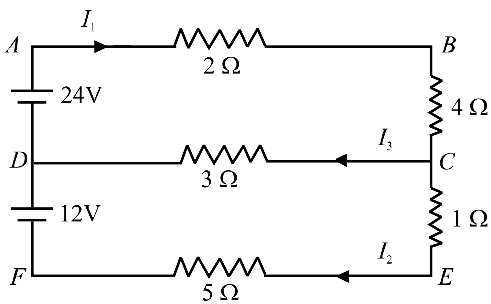

**Fig. 17.20 :** When there is no current through 50Ω resistor, the bridge is balanced.

## INTEXT QUESTIONS 17.3

1. Refere to figure below. Calculate the value of currents in the arms $AB$, $AD$ and $BD$.




2. Examine the following circuit containing resistors and batteries. Calculate the current $I_1$, $I_2$ and $I_3$.



## POTENTIOMETER

You now know how to measure e.m.f. of a source or potential difference across a circuit element using a voltmeter. (An ideal voltmeter should have infinite resistance so that it does not draw any current when connected across a source of e.m.f.) Practically it is not possible to manufacture a voltmeter which will not draw any current. To overcome this difficulty, we use a potentiometer, which draws no current from it. It employs a null method. The potentiometer can also be used for measurement of internal resistance of a cell, the current flowing in a circuit and comparison of resistances.

### 17.8.1 Description of a Potentiometer

A potentiometer consists of a wooden board on which a number of resistance wires (usually ten) of uniform cross-sectional area are stretched parallel to each other. The wire is of maganin or nichrome. These wires are joined in series by thick copper strips. In this way, these wires together act as a single wire of length equal to the sum of the lengths of all the wires. The end terminals of the wires are provided with connecting screws.

A metre scale is fixed on the wooden board parallel to wires. A jockey (a sliding contact maker) is provided with the arrangement. It makes a knife edge contact at any desired point on a wire. Jockey has a pointer which moves over the scale. It determines the position of the knife edge contact. In Fig. 17.21 a ten wire potentiometer is shown. *A* and *B* are ends of the wire. *K* is a jockey and *S* is a scale. Jockey slides over a rod *CD*.

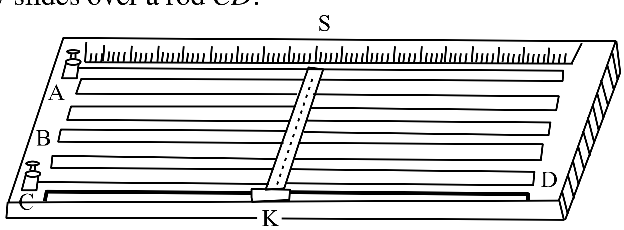



**Fig. 17.21 :** An illustrative diagram of a potentiometer

### 17.8.2 Measurements with a Potentiometer

Let us suppose that a steady source of e.m.f. *E* (say an accumulator) is connected across a uniform wire *AB* of length *l*. Positive terminal of the accumulator is connected at end *A* (Fig.17.22). A steady current *I* flows through the wire. The potential difference across *AB* is given by

$$V_{AB} = RI$$

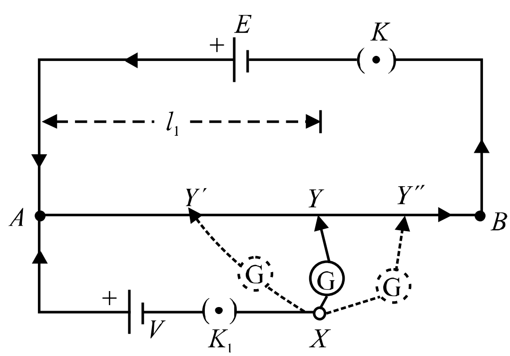



**Fig. 17.22 :** Potentiometer circuit to measure potential difference between the terminals of a cell.

If $r$ is the resistance per unit length of the wire, and $k$ is the potential drop across unit length of the wire, then

$$R = r\ell$$

and $$E = k\,\ell$$

or $$k = \frac{E}{\ell}$$

For length $\ell_1$ of wire, potential drop is given by

$$V_1 = k\ell_1 = \frac{E}{\ell}\ell_1 \qquad (17.28)$$

Thus potential falls linearly with distance along the wire from the positive to the negative end.

We wish to measure an unknown voltage $V$. The positive terminal of the cell is connected to end $A$ of the wire and negative terminal through a galvanometer to the jockey having variable contact $Y$. Note that for $V > E$, it will not be possible to obtain a null point. So we use a standard cell of emf $E$ (> $V$), as shown in Fig.17.22. To check this, insert keys $K$ and $K_1$ and tap at ends $A$ and $B$. The galvanometer should show deflection in opposite directions. If so, all is well with the circuit.

Insert key $K_1$ and start moving jockey from $A$ towards $B$. Suppose that at position $Y'$ potential drop across the length $AY$ of the wire is less than voltage $V$. The current in the loop $AY'XA$ due to voltage $V$ exceeds the current due to potential difference across $AY'$. Hence galvanometer shows some deflection in one direction. Then jockey is moved away, say to $Y''$ such that potential drop across $AY''$ is greater than the voltage $V$. If galvanometer shows deflection in the other direction, the voltage drop across $AY''$ is greater than that across $AY'$. Therefore, the jockey is moved slowly between $Y'$ and $Y''$. A stage is reached, say at point $Y$, where potential drop across $AY$ is equal to voltage $V$. Then points $X$ and $Y$ will be at the same potential and hence the galvanometer will not show any deflection, i.e. null point is achieved. If $l_1$ is the length between $A$ and $Y$, then

$$V = k\ell_1 = \frac{E\ell_1}{\ell} \qquad (17.29)$$

Thus, the unknown voltage $V$ is measured when no current is drawn

The measurements with potentiometer have following advantages :

- When the potentiometer is balanced, no current is drawn from the circuit on which the measurement is being made.
- It produces no change in conditions in a circuit to which it is connected.
- It makes use of null method for the measurement and the galvanometer used need not be calibrated.

### 17.8.3 Comparison of E.M.Fs of two Cells

You have learnt to measure the e.m.f. of a cell using a potentiometer. We shall now extend the same technique for comparison of e.m.fs of two cells. Let us take, for example, a Daniel cell and a Leclanche cell and let $E_1$ and $E_2$ be their respective e.m.fs.

Refer to circuit diagram shown in Fig.17.23. The cell of e.m.f. $E_1$ is connected in the circuit through terminals 1 and 3 of key $K_1$. The balance point is obtained by moving the jockey on the potentiometer wire as explained earlier. Note that e.m.f of cell E should be greater than the emfs of $E_1$ and $E_2$ seperately. (Otherwise, balance point will not be obtained.) Let the balance point on potentiometer be at point $Y_1$ and length $AY_1 = l_1$. The cell of e.m.f. $E_2$ is connected in the circuit through terminals 2 and 3 of the key $K_2$. Suppose balance is obtained at point $Y_2$ and length $AY_2 = l_2$.

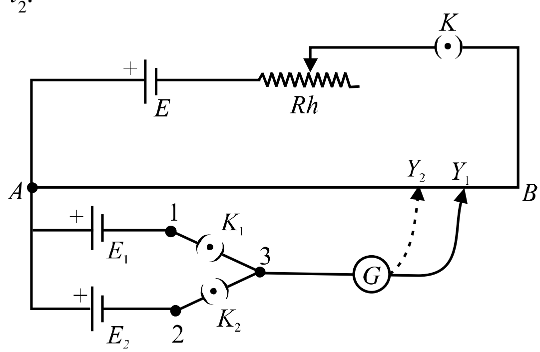



**Fig. 17.23 :** Circuit diagram for comparison of e.m.fs of two cells $E_1$ and $E_2$.

Applying potentiometer principle, we can write

$$E_1 = kl_1 \quad \text{and} \quad E_2 = kl_2$$

where $k$ is the potential gradient along the wire $AB$. Hence

$$\frac{E_1}{E_2} = \frac{\ell_1}{\ell_2} \qquad (17.30)$$

### 17.8.4 Determination of Internal Resistance of a Cell

You have learnt that cells always offer resistance to the flow of current through them, which is often very small. This resistance is called the internal resistance of the cell and depends on the size of the cell, i.e. the area of the plates immersed in the liquid, the distance between the plates and strength of electrolyte used in the cell.

Let us now learn how to measure internal resistance of a cell using a potentiometer. Refer to Fig. 17.24, which shows the circuit diagram for measuring internal resistance '$r$' of a cell of emf $E_1$. A resistance box $R$ with a key $K_1$ is connected in parallel with the cell. The primary circuit has a standard cell, a rheostat and a one way key $K$. As soon as key $K$ is closed, a current $I$ begins to flow through the wire

$AB$. The key $K_1$ is kept open and on moving the jockey, a balance is obtained with the cell $E_1$ at point, say $Y_1$. Let $AY_1 = l_1$. Then we can write

$$E_1 = kl_1 \tag{17.31a}$$

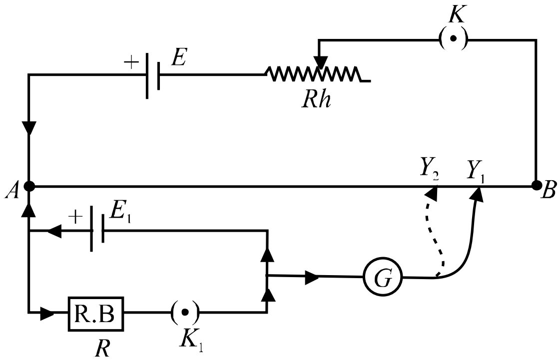



**Fig. 17.24 :** Measurement of the internal resistance $r$ of a cell

Now key $K_1$ is closed. This introduces a resistance across the cell. A current, say $I_1$, flows in the loop $E_1RK_1E_1$ due to cell $E$. Using Ohm's law, we can write

$$I_1 = \frac{E_1}{R+r}$$

where $r$ is internal resistance of the cell. It means that terminal potential difference $V_1$ of the cell will be less than $E_1$ by an amount $I_1r$. The value of $V_1$ is

$$V_1 = I_1R = \frac{E_1}{R+r}R$$

Then, potential difference $V_1$ is balanced on the potentiometer wire without change in current $I$. Let the balance point be at point $Y_2$ such that $AY_2 = l_2$. Then

$$V_1 = kl_2$$

(17.31b)

Using Eqns. (17.31a,b) we get

$$\frac{E_1}{V_1} = \frac{\ell_1}{\ell_2} = \frac{R+r}{R}$$

or

$$r = R\left(\frac{l_1}{l_2} - 1\right) \tag{17.32}$$

Thus by knowing $R_1$, $l_1$ and $l_2$, the value of $r$ can be easily calculated.

**Example 17.10 :** Length of a potentiometer wire is 5 m. It is connected with a battery of fixed e.m.f. Null point is obtained for the Daniel cell at 100 cm. If the length of the wire is kept 7 m, what will be the position of null point?

**Solution:** Let e.m.f. of battery be $E$ volt. The potential gradient for 5 m length is

$$k_1 = \frac{E}{5} \text{ Vm}^{-1}$$

When the length of potentiometer wire is 7 m, potential gradient is

$$k_2 = \frac{E}{7} \text{ Vm}^{-1}$$

Now, if null point is obtained at length $l_2$, then

$$E_1 = k_2 \ell_2 = \frac{E}{7} \ell_2$$

Here same cell is used in two arrangements. Hence

$$\frac{E}{5} = \frac{E}{7} \ell_2$$

$$\Rightarrow \qquad \ell_2 = 7 / 5 = 1.4 \text{m}$$

## 17.9 DRIFT VELOCITY OF ELECTRONS

Let us now understand the microscopic picture of electrical conduction in a metal. The model presented here is simple but its strength lies in the fact that it conforms to Ohm's law.

We assume that a metallic solid consists of atoms arranged in a regular fashion. Each atom usually contributes free electrons, also called conduction electrons. These electrons are free to move in the metal in a random manner, almost the same way as atoms or molecules of a gas move about freely in the a container. It is for this reason that sometimes conduction electrons are referred to as **electron gas**. The average speed of conduction electrons is about $10^6 \text{ms}^{-1}$.

We know that no current flows through a conductor in the absence of an electric field, because the **average velocity** of free electrons is zero. On an average, the number of electrons moving in $+x$ direction is same as number of electrons moving in $-x$ direction. There is no net flow of charge in any direction.

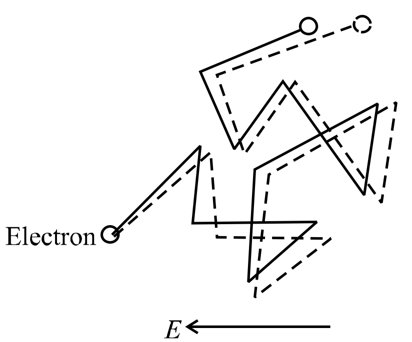


**Fig. 17.25 :** Motion of electrons in a conductor placed in an electric field.

The conduction electrons frequently collide with the atoms in the solid. The free electrons drift slowly in a direction opposite to the direction of the applied electric field. The average drift velocity is of the order of $10^{-4} \text{ms}^{-1}$. This is very small compared to the average speed of free electrons between two successive collisions ($10^6 \text{ms}^{-1}$). On applying an electric field, the conduction electrons get accelerated.

The excess energy gained by the electrons is lost during collisions with the atoms. The atoms gain energy and vibrate more vigorously. The conductor gets heated up. Fig. 17.25 shows how the motion of electrons is modified when an electric field is applied is applied.

Let us now obtain an expression for the drift velocity of conduction electrons. Let $e$ and $m$ be the charge and mass respectively of an electron. If $E$ is the electric field, the force on the electron is $eE$. Hence acceleration experienced by the electron is given by

$$\mathbf{a} = \frac{e\mathbf{E}}{m}$$

If $\tau$ is the average time between collisions, we can write the expression for velocity of drifting electrons in terms of electric field as

$$\boldsymbol{v}_{\mathrm{d}} = \frac{e\mathbf{E}}{m}\tau$$

On combining this result with Eqn. (17.4), we obtain the expression for current :

$$I = -\, neAv_d$$

$$= -neA\,\frac{eE}{m}\tau$$

$$= -\frac{Ane^2E}{m}\tau$$

Since electric field is negative spatial gradient of potential $\left(E = -\frac{\partial V}{\partial r}\right)$ we can rewrite the expression for current as

$$I = +\frac{ne^2A}{m}\frac{V}{\ell}\tau \qquad (17.33)$$

$$\Rightarrow \qquad \frac{V}{I} = \frac{m}{ne^2\tau}\frac{\ell}{A} = R \qquad (17.34)$$

Eqn. (17.34) implies that conduction current obeys Ohm’s law.

On combining this result with Eqn. (17.9), we get

$$\rho = \frac{1}{\sigma} = \frac{m}{ne^2\tau} \qquad (17.35)$$

## 17.10 POWER CONSUMED IN AN ELECTRICAL CIRCUIT

Let us examine the circuit in Fig. 17.26 where a battery is connected to an external resistor $R$ . The positive charges (so to say) flow in the direction of the current in the resistor and from negative to positive terminal inside the battery. The potential difference between two points gives kinetic energy to the charges. These moving charges collide with the atoms (ions) in the resistor and thus lose a part of their kinetic energy. This energy increases with the temperature of the resistor. The loss of energy by moving charges is made up at the expense of chemical energy of the battery.

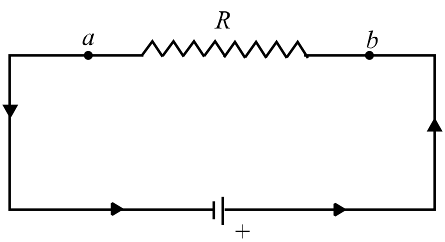



**Fig. 17.26 :** A circuit containing a battery and a resistor. The power consumed depends on the potential difference between the points *a* and *b,* the current through the resistor.

The rate of loss of potential energy by moving charge $\Delta Q$ in going through the resistor is

$$\frac{\Delta U}{\Delta t} = V\frac{\Delta Q}{\Delta t} = VI \qquad (17.\ 36)$$

where $I$ is the current in the circuit and $V$ is potential difference between the ends of the resistor.

It is assumed that the resistance of the connecting wires is negligible. The total loss is in the resistor $R$ only. Rate of loss of energy is defined as power :

$$P = VI$$

Since $V = IR$, we can write

$$P = I^2R = V^2/R \qquad (17.37)$$

The SI unit of power is watt (W).

The electrical power lost in a conductor as heat is called *joule heat*. The heat produced is proportional to : (i) square of current ($I$), (ii) resistance of conductor ($R$), and (iii) time for which current is passed ($t$).

The statement $Q = I^2 Rt$, is called Joule's law for heating effect of current.

**Example: 17.11 :** A 60W lamp is connected to 220V electricity supply in your home. Calculate the power consumed by it, the resistance of its filament and the current through it.

**Solution :** We know that $I = P/V$

$$\therefore \qquad = \frac{60\text{W}}{220\text{V}} = \frac{3}{11}\text{A} = 0.27\text{A}$$

Resistance of the lamp

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

$$= \frac{220V}{3/11A}$$

$$= \frac{220 \times 11}{3}\Omega = 807\Omega$$

The lamp consumes 60J of energy per second. It will consume 60 Wh energy in one hour and $60 \times 24 = 1440$ Wh energy in one day.

Energy consumed per day = 1.440 kWh

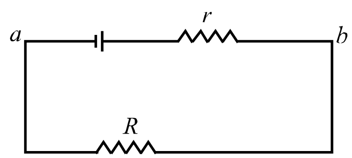
In common man's language, it is known as 1.4 unit of energy.

## INTEXT QUESTIONS 17.4

1. When current drawn from a cell increases, the potential difference between the cell electrodes decreases. Why?

2. A metallic wire has a resistance of 30Ω at 20° C and 30.16Ω at 40° C. Calculate the temperature coefficient of resistance.

3. The e.m.f of a cell is 5.0 V and *R* in the circuit is 4.5Ω. If the potential difference between the points *a* and *b* is 3.0 V, calculate the internal resistance *r* of the cell.




4. In a potentiometer circuit, balance point is obtained at 45 cm from end *A* when an unknown e.m.f is measured. The balance point shifts to 30 cm from this end when a cell of 1.02 V is put in the circuit. Standard cell *E* always supplies a constant current. Calculate the value of unknown e.m.f.

5. A potentiometer circuit is used to compare the e m.f. of two cells $E_1$ and $E_2$. The balance point is obtained at lengths 30 cm and 45 cm, respectively for $E_1$ and $E_2$. What is the e.m.f of $E_1$, if $E_2$ is 3.0 V?

6. A current of 0.30 A flows through a resistance of 500Ω. How much power is lost in the resistor?

7. You have two electric lamps. The printed specifications on them are 40W, 220V and 100W, 220 V. Calculate the current and resistance of each lamp when put in a circuit of 220 V supply line.

## WHAT YOU HAVE LEARNT

- Drift velocity is the average velocity with which electrons move opposite to the field when an electric field exists in a conductor.
- Electric current through any cross-sectional area is the rate of transfer of charge from one side to other side of the area. Unit of current is ampere and is denoted by A.
- Ohm's law states that the current flowing through a conductor is proportional to the potential difference when physical conditions like pressure and temperature remain unchanged.
- Ratio $V/I$ is called resistance and is denoted by $R$. Unit of resistance is ohm (denoted by $\Omega$)
- Resistivity (or specific resistance) of a material equals the resistance of a wire of the material of one metre length and one $m^2$ area of cross section. Unit of resistivity is ohm metre.
- For a series combination of resistors, the equivalent resistance is sum of resistances of all resistors.
- For a parallel combination of resistors, inverse of equivalent resistance is equal to the sum of inverses of all the resistances.
- Primary cells cannot be recharged and reused, whereas, secondary cells can be charged again and again.
- Kirchhoff's rules help us to study systematically the complicated electrical circuits. The first rule states that the sum of all the currents directed towards a point in an electrical network is equal to the sum of all currents directed away from the point. Rule II : The algebraic sum of all potential differences along a closed loop in an electrical network is zero.
- The Wheatstone bridge circuit is used to measure accurately an unknown resistance ($S$) by comparing it with known resistances ($P$, $Q$ and $R$). In the balance condition,

  $P/Q = R/S.$
- The e.m.f. of a cell is equal to the potential difference between its terminals when a circuit is not connected to it.
- A potentiometer measures voltages without drawing current. Therefore, it can be used to measure e.m.f. of a source that has appreciable internal resistance.
- Drift velocity of electrons in a conductor is given by $\upsilon_d = -\frac{eE}{m}\tau$.
- Power consumed in an electrical circuit through Joule heating is given by

$$p = VI = I^2R = \frac{V^2}{R}.$$

## ANSEWERS TO INTEXT QUESTIONS

**17.1**

1. (a) The current reduces to half as resistance of the wire is doubled.

   (b) The current is doubled as resistance is halved.

2. Resistivity is a property of the material of wire. It will not change with change in length and area of cross-section.

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

3. $R = \frac{V}{I} = \frac{8}{0.15} = \frac{800}{15} = 53.3\ \Omega$

   $R = \frac{P\ell}{A} \Rightarrow \frac{800}{15} = \rho \frac{3}{2 \times 10^{\ 4}} \Rightarrow \rho = \frac{800 \times 2 \times 10^{-4}}{15 \times 3} = 35.5 \times 10^{-4}\ \Omega\text{m}.$

4. No. Only metallic conductor obey Ohm's law upto a certain limit. Semiconductors and electrolytes do not obey Ohm's law.

5. $I = \frac{q}{\tau} = \frac{n|e|}{t} = \frac{5 \times 10^{17} \times 1.6 \times 10^{-19}}{1}\text{A} = 0.8 \times 10^{-3}\text{A} = 0.8\ \text{mA}$

   The direction of current is opposite to the direction of flow of electrons, i.e., from right to left.

**17.2**

1. In parallel. They may draw different currents needed for their operation and are operated separately using different switches.

2. We use a voltage stablizer

3. $R = R_1 + \frac{R_2 R_3}{R_2 + R_3} + R_4$

   $= 2 + \frac{10}{3} + 7$

   $= 12.\ 3\ \Omega$

**17.3**

1. Applying Kirchhoff's second rule on loop *ABCDA,* we get

$2I_1 + 4I_1 + 3I_3 = 24$

$6I_1 + 3I_3 = 24 \quad ...(1) \quad \Rightarrow \quad 2I_1 + I_3 = 8 \quad ....(1)$

Similarly, for loop *DCBFD,* we can write

$-3I_3 + 6I_2 = 12 \quad \Rightarrow \quad 2I_2 - I_3 = 4 \quad ...(2)$

Also applying Kirchoff's first rule at junction *D* we get

$I_2 + I_3 = I_1$

Substituting in (1) we get

$2I_2 + 3I_3 = 8$

$2I_2 - I_3 = 4$

$4I_3 = 4$

$I_3 = 1A$

Substituting in (2)

$2I_2 = 5 \quad \Rightarrow \quad I_2 = 2.5$ A

2. $\frac{P}{Q} = \frac{6}{12} = \frac{1}{2}$ and $\frac{R}{S} = \frac{3}{6} = \frac{1}{2}$

$\frac{}{Q} = \frac{}{S}$ $\therefore$ bridge is balanced

Hence $V_B = V_D$ and $I_2 = 0$

$$I_1 = \frac{V}{I} = \frac{12}{18} = \frac{2}{3}\text{A}$$

and

$$I - I_1 = \frac{12}{9} = \frac{4}{3}\text{A}$$

**17.4**

1. $V = E - Ir$ as $I$ increases $V$ decreases.

2. $R_{20} = R_0 (1 + 20\alpha)$

$R_{40} = R_0 (1 + 40\alpha)$

$$\frac{R_{40}}{R_{20}} = \frac{1 + 40\alpha}{1 + 20\alpha}$$

$$\frac{1 + 40\alpha}{1 + 20\alpha} = \frac{30.16}{30} = 1 + \frac{0.16}{30}$$

$$1+\frac{20\,\alpha}{1+20\,\alpha}=1+\frac{0.16}{30}$$

$$\frac{20\,\alpha}{1+20\,\alpha}=\frac{0.16}{30}$$

On cross-multiplication, we get $600\alpha = 0.16 + 3.2\alpha$

$$\Rightarrow \quad \alpha \simeq \frac{0.16}{600} = 2.67 \times 10^{\ 4}\text{K}^{\ 1}$$

3. $I = \dfrac{V}{R} = \dfrac{3}{4.5} = \dfrac{30}{45} = \dfrac{2}{3}\text{A}$

$$V = \Sigma - Ir \;\Rightarrow\; 3 = 5 - \frac{2}{3}r$$

$$\therefore\; r = \frac{2\times 3}{2} = 3\Omega$$

4. $\dfrac{E_2}{E_1} = \dfrac{\ell_2}{\ell_1} \Rightarrow \dfrac{1.02}{E_1} = \dfrac{30}{45} \;\Rightarrow\; E_1 = 0.51 \times \dfrac{3}{2} = 1.53\text{V}$

5. $\dfrac{E_2}{E_1} = \dfrac{\ell_2}{\ell_1}$

$$\frac{E_1}{3} = \frac{2}{3}$$

$E_1 = 2\ V$

6. $P = IV$

$= 3 \times 0.3 \times 500$

$= 45$ WaH.

7. $I = \dfrac{P}{V} \Rightarrow I_1 = \dfrac{40}{220} = \dfrac{2}{11}\text{A}$ and $I_2 = \dfrac{100}{220} = \dfrac{5}{11}\text{A}$

$$R = \frac{V^2}{P} \Rightarrow I_1 = \frac{40}{220} = \frac{2}{11}\text{A}\ \frac{V^2}{P} \Rightarrow R_1 = \frac{220\times 220}{40} = 1210\Omega$$

and $R_2 = \dfrac{220\times 220}{100} = 484\Omega$