

**Q.** What is the cause of an electric current?

**A.** Charges in motion constitute an electric current. Such currents occur naturally in many situations. Lightning is one such phenomenon in which charges flow from the clouds to the earth through the atmosphere's. A torch and a cell-driven clock are examples of such devices. In the present chapter, we shall study some of the basic laws concerning steady electric currents.

## **ELECTRIC CURRENT**

**Q.** Define Steady Current.

The net amount  $q$  of charge flowing across the area in the forward direction in the time interval  $t$ , is proportional to  $t$  for steady current and the quotient

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

is defined to be the *current* across the area in the forward direction. (If it turn out to be a negative number, it implies a current in the backward direction.)

In SI units, the unit of current is ampere(A).

**Note-** An ampere is typically the order of magnitude of currents in domestic appliances. An average lightning carries currents of the order of tens of thousands of amperes and at the other extreme, currents in our nerves are in microamperes.

**Note-** Currents are not always steady and hence more generally, we define the current as follows. Let  $\Delta Q$  be the net charge flowing across a cross section of a conductor during the time interval  $\Delta t$  [i.e., between times  $t$  and  $(t + \Delta t)$ ]. Then, the current at time  $t$  across the cross-section of the conductor is defined as the value of the ratio of  $\Delta Q$  to  $\Delta t$  in the limit of  $\Delta t$  tending to zero,

$$I(t) \equiv \lim_{\Delta t \rightarrow 0} \frac{\Delta Q}{\Delta t}$$

### **Flow of electric charges in a metallic conductor**

**Q.** Briefly explain the phenomenon of flow electric chares in metal

**A.** An electric charge will experience a force if an electric field is applied. If it is free to move, it will thus move contributing to a current. In some materials, the electrons will still be bound, i.e., they will not accelerate even if an electric field is applied. In other materials, notably metals, some of the electrons are practically free to move within the bulk material. These materials, generally called conductors, develop electric currents in them when an electric field is applied. If we consider solid conductors, then of course the atoms are tightly bound to each other so that the current is carried by the negatively charged electrons. Consider first the case when no electric field is present. The electrons will be moving due to thermal motion during which they collide with the fixed ions. An electron colliding with an ion emerges with the same speed as before the collision. However, the direction of its velocity after the collision is completely random. At a given time, there is no preferential direction for the velocities of the electrons. Thus on the average, the number of electrons travelling in any direction will be equal to the number of electrons travelling in the opposite direction. So, there will be no net electric current.

Let us now see what happens to such a piece of conductor if an electric field is applied. The electrons will be accelerated due to this field towards  $+Q$ . They will thus move to neutralise the charges. The electrons, as long as they are moving, will constitute an electric current. Hence in the situation considered, there will be a current for a very short while and no current thereafter. We can also imagine a mechanism where the ends of the cylinder are supplied with fresh charges to make up for any charges neutralised by electrons moving inside the conductor. In

that case, there will be a steady electric field in the body of the conductor. This will result in a continuous current rather than a current for a short period of time. Mechanisms, which maintain a steady electric field are cells or batteries that we shall study later in this chapter. In the next sections, we shall study the steady current that results from a steady electric field in conductors.

**Q.** State Ohm's law

**A.** Consider a conductor through which a current  $I$  is flowing and let  $V$  be the potential difference between the ends of the conductor.

Then Ohm's law states that

$$V \propto I$$

or,  $V = RI$

where the constant of proportionality  $R$  is called the *resistance* of the conductor. The SI units of resistance is *ohm*, and is denoted by the symbol  $\Omega$ .

### Dependence of resistance

**Q.** On what factors do the resistance depends?

**A.** Resistance  $R$  is inversely proportional to the cross-sectional area,

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

Combining Eqs.

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

and hence for a given conductor

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

where the constant of proportionality  $\rho$  depends on the material of the conductor but not on its dimensions.  $\rho$  is called *resistivity*.

Using the last equation, Ohm's law reads

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

### Current density

**Q.** Define current density. How it is related with electric field and conductivity?

**A.** Current per unit area (taken normal to the current),  $I/A$ , is called *current density* and is denoted by  $j$ . The SI units of the current density are  $A/m^2$ .

The current density is a vector as it is directed along  $\mathbf{E}$ , therefore  $\mathbf{j} (\equiv j \mathbf{E}/E)$ .

If  $E$  is the magnitude of uniform electric field in the conductor whose length is  $l$ , then the potential difference  $V$  across its ends is  $El$ .

$$El = j\rho l$$

or,  $E = j\rho$

Also

$$\mathbf{E} = \mathbf{j}\rho$$

or,  $\mathbf{j} = \sigma \mathbf{E}$

where  $\sigma \equiv 1/\rho$  is called the *conductivity*.

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**Note-** Metals have low resistivities in the range of  $10^{-8}\Omega\text{m}$  to  $10^{-6}\Omega\text{m}$ . At the other end are insulators like ceramic, rubber and plastics having resistivities  $10^{18}$  times greater than metals or more. In between the two are the semiconductors. These, however, have resistivities characteristically decreasing with a rise in temperature.

### Drift velocity

**Q.** What is 'drift velocity'? Derive an expression for drift velocity in terms of material parameters.

**A.** An electron will suffer collisions with the heavy fixed ions, but after collision, it will emerge with the same speed but in random directions. If we consider all the electrons, their average velocity will be zero since their directions are random. Thus, if there are  $N$  electrons and the velocity of the  $i$ th electron ( $i = 1, 2, 3, \dots N$ ) at a given time is  $\mathbf{v}_i$ , then

$$\frac{1}{N} \sum_{i=1}^N \mathbf{v}_i = 0$$

when an electric field is present. Electrons will be accelerated due to this field by

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

If  $\mathbf{v}_i$  was the velocity of the electron immediately after the last collision, then its velocity  $\mathbf{V}_i$  at time  $t$  is

$$\mathbf{V}_i = \mathbf{v}_i - \frac{e\mathbf{E}}{m} t_i$$

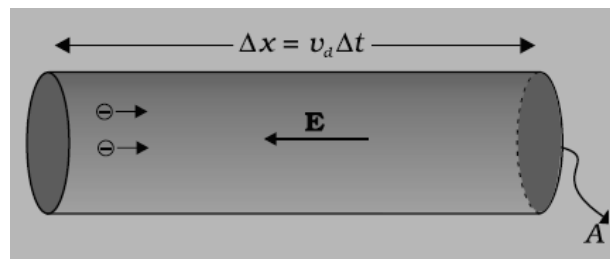
The average velocity of the electrons at time  $t$  is the average of all the  $\mathbf{V}_i$ 's. The average of  $\mathbf{v}_i$ 's is Zero.

The collisions of the electrons do not occur at regular intervals but at random times. Let us denote by  $\tau$ , the average time between successive collisions.

Averaging  $\mathbf{V}_i$  over the  $N$ -electrons at any given time  $t$  gives us for the average velocity  $\mathbf{v}_d$

$$\mathbf{v}_d \equiv (\mathbf{V}_i)_{\text{average}} = (\mathbf{v}_i)_{\text{average}} - \frac{e\mathbf{E}}{m} (t_i)_{\text{average}},$$

$$= 0 - \frac{e\mathbf{E}}{m} \tau = -\frac{e\mathbf{E}}{m} \tau$$



The electrons move with an average velocity which is independent of time, although electrons are accelerated. This is the phenomenon of drift and the velocity  $\mathbf{v}_d$  is called the *drift velocity*.

If  $n$  is the number of free electrons per unit volume then the amount of charge crossing the area  $A$  in time  $\Delta t$  is by definition  $I \Delta t$ , where  $I$  is the magnitude of the current. Hence,

$$I \Delta t = +n e A |\mathbf{v}_d| \Delta t$$

Substituting the value of  $|\mathbf{v}_d|$

$$I \Delta t = \frac{e^2 A}{m} \tau n \Delta t |\mathbf{E}|$$

By definition  $I$  is related to the magnitude  $|\mathbf{j}|$  of the current density by

$$I = |\mathbf{j}| A$$

$$|\mathbf{j}| = \frac{ne^2}{m} \tau |\mathbf{E}|$$

The vector  $\mathbf{j}$  is parallel to  $\mathbf{E}$

$$\mathbf{j} = \frac{ne^2}{m} \tau \mathbf{E}$$

This is exactly the Ohm's law, if we identify the conductivity  $\sigma$  as

$$\sigma = \frac{ne^2}{m} \tau$$

### Mobility and their relation with electric current

**Q.** Define mobility. Write its relation with current.

**A.** Mobility  $\mu$  defined as the magnitude of the drift velocity per unit electric field

$$\mu = \frac{|\mathbf{v}_d|}{E}$$

The SI unit of mobility is  $\text{m}^2/\text{Vs}$

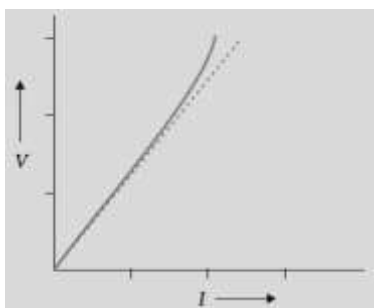
Also

$$\mu = \frac{v_d}{E} = \frac{e\tau}{m}$$

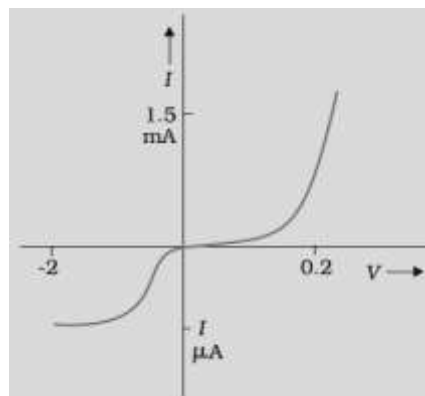
### V-I characteristics (linear and nonlinear)

**Q.** Sketch V-I graphs for (i) good conductor (ii) Diode (iii) for GaAs

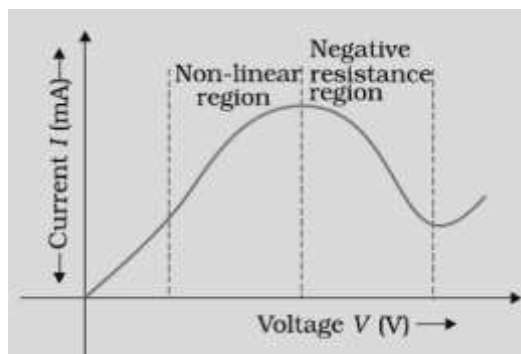
**A.**



The dashed line represents the linear Ohm's law. The solid line is the voltage  $V$  versus current  $I$  for a good conductor.



Characteristic curve of a diode.

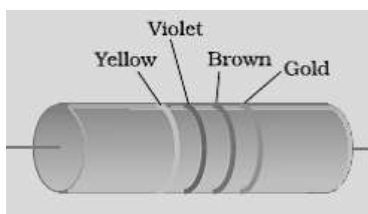


Variation of current versus voltage for GaAs

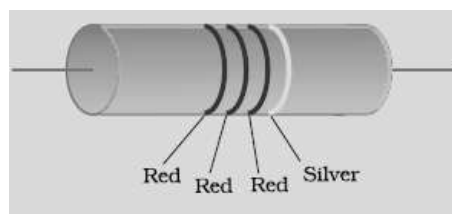
### Carbon resistors, colour code for carbon resistors

**Q.** What is advantage of using Carbon resistor? Below fig shows the carbon resistors with colored rings, calculate the value of the resistance.

**A.** Resistors in the higher range are made mostly from carbon. Carbon resistors are compact, inexpensive and thus find extensive use in electronic circuits. Carbon resistors are small in size and hence their values are given using a colour code.



$$(47 \times 10 \Omega) \pm 5\%$$



$$(22 \times 10^2 \Omega) \pm 10\%$$

**BB ROY** Great **B**ritain **V**ery **G**ood **W**ife

Colour	Number	Multiplier	Tolerance (%)
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	$10^7$	
Gray	8	$10^8$	
White	9	$10^9$	
Gold		$10^{-1}$	5
Silver		$10^{-2}$	10
No colour			20

### Temperature dependence of resistance

**Q.** How resistivity is effected by temperature.

**A.** The resistivity of a metallic conductor is approximately given by,

$$\rho_T = \rho_0 [1 + \alpha (T - T_0)]$$

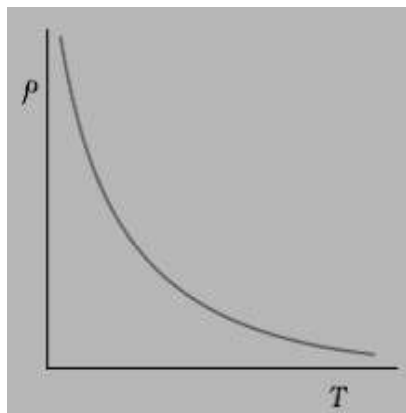
where  $\rho_T$  is the resistivity at a temperature  $T$  and  $\rho_0$  is the same at a reference temperature  $T_0$ .  $\alpha$  is called the temperature co-efficient of resistivity. For metals,  $\alpha$  is positive.

**Q.** Define the temperature co-efficient of resistivity

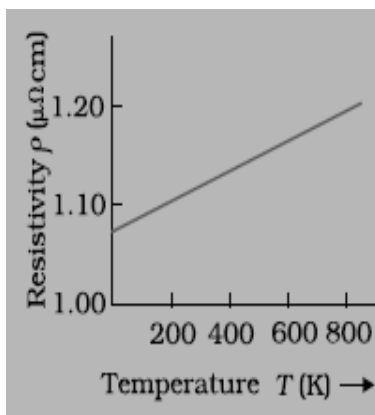
**A.** The *temperature coefficient of resistivity*  $\alpha$  is defined as the fractional increase in resistivity per unit increase in temperature

**Q.** Sketch a graph (i) variation of resistivity of metal with temperature (ii) resistivity of alloy (nichrome) with temperature (iii) resistivity of semiconductor with temperature.

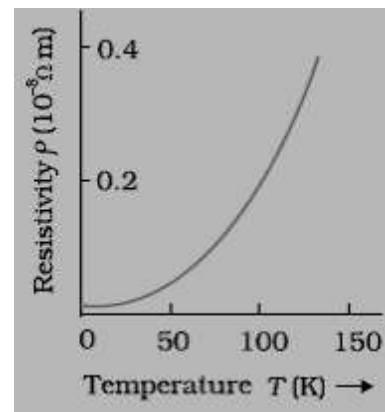
**A.**



Resistivity  $\rho_T$  of copper as a function of temperature  $T$   
(i)



Resistivity  $\rho_T$  of nichrome as a function of absolute temperature  $T$ .  
(ii)



Temperature dependence of resistivity for a typical semiconductor  
(iii)

**Q.** How alloys are different from metals with variation of temperature? Why resistivity of metal increases with the temperature?

**A.** Materials like Nichrome, Manganin and constantan (which are an alloy) exhibit a very weak dependence of resistivity with temperature. Also, resistivity of a material is given by

$$\rho = \frac{1}{\sigma} = \frac{m}{n e^2 \tau}$$

$\rho$  thus depends inversely both on the number  $n$  of free electrons per unit volume and on the average time  $\tau$  between collisions. As we increase temperature, average speed of the electrons, which act as the carriers of current, increases resulting in more frequent collisions. The average time of collisions  $\tau$ , thus decreases with temperature, hence  $\rho$  increases.

For insulators and semiconductors, however,  $n$  increases with temperature. This increase more than compensates any decrease in  $\tau$  for such materials,  $\rho$  decreases with temperature.

### Electrical energy and power

**Q.** Show that energy dissipated as heat in the conductor connected across potential difference  $V$ , current  $I$  for a time interval  $\Delta t$  is given by  $\Delta W = I V \Delta t$

**A.** Consider a conductor with end points A and B, in which a current  $I$  is flowing from A to B. The electric potential at A and B are denoted by  $V(A)$  and  $V(B)$  respectively. Since current is flowing from A to B,  $V(A) > V(B)$  and the potential difference across AB is  $V = V(A) - V(B) > 0$ .

The change in potential energy

$$\begin{aligned} \Delta U_{\text{pot}} &= \text{Final potential energy} - \text{Initial potential energy} \\ &= \Delta Q [V(B) - V(A)] = -\Delta Q V \\ &= -I V \Delta t < 0 \end{aligned}$$

If charges moved without collisions through the conductor, their kinetic energy would also change so that the total energy is unchanged. Conservation of total energy would then imply that,

$$\Delta K = -\Delta U_{\text{pot}}$$

that is,

$$\Delta K = I V \Delta t > 0$$

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Thus, in case charges were moving freely through the conductor under the action of electric field, their kinetic energy would increase as they move.

Thus, in an actual conductor, an amount of energy dissipated as heat in the conductor during the time interval  $\Delta t$  is,

$$\Delta W = I V \Delta t$$

The energy dissipated per unit time is the power dissipated

$P = \Delta W / \Delta t$  and we have,

$$P = I V$$

Using Ohm's law  $V = IR$ , we get

$$P = I^2 R = V^2 / R$$

**Note-** Consider a device  $R$ , to which a power  $P$  is to be delivered via transmission cables having a resistance  $R_c$  to be dissipated by it finally. If  $V$  is the voltage across  $R$  and  $I$  the current through it, then

$$P = V I$$

The connecting wires from the power station to the device has a finite resistance  $R_c$ . The power dissipated in the connecting wires, which is wasted is  $P_c$  with

$$P_c = I^2 R_c \\ = \frac{P^2 R_c}{V^2}$$

Thus, to drive a device of power  $P$ , the power wasted in the connecting wires is inversely proportional to  $V^2$ . The transmission cables from power stations are hundreds of miles long and their resistance  $R_c$  is considerable. To reduce  $P_c$ , these wires carry current at enormous values of  $V$  and this is the reason for the high voltage danger signs on transmission lines

### Series and Parallel combinations of resistors

**Q.** Two resistances  $R_1, R_2$  are connected in series; derive a relation for the equivalent resistance of the two.

**A.** Consider two resistors  $R_1$  and  $R_2$  in series. The charge which leaves  $R_1$  must be entering  $R_2$ . Since current measures the rate of flow of charge, this means that the same current  $I$  flows through  $R_1$  and  $R_2$ . By Ohm's law:

Potential difference across  $R_1$ ,  $V_1 = I R_1$ ,  
and Potential difference across  $R_2$ ,  $V_2 = I R_2$ .



The potential difference  $V$  across the combination is  $V_1 + V_2$ . Hence,

$$V = V_1 + V_2 = I (R_1 + R_2)$$

This is as if the combination had an equivalent resistance  $R_{eq}$ , which by Ohm's law is

$$R_{eq} \equiv \frac{V}{I} = (R_1 + R_2)$$

$$R_{eq} = (R_1 + R_2)$$

If we had three resistors connected in series, then similarly

$$V = I R_1 + I R_2 + I R_3 = I (R_1 + R_2 + R_3)$$

This obviously can be extended to a series combination of any number  $n$  of resistors  $R_1, R_2, \dots, R_n$ . The equivalent resistance  $R_{eq}$  is

$$R_{eq} = R_1 + R_2 + \dots + R_n$$

**Q.** Two resistances  $R_1, R_2$  are connected in parallel; derive a relation for the equivalent resistance of the two.

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**A.** Consider now the parallel combination of two resistors Fig. The charge that flows in at A from the left flows out partly through  $R_1$  and partly through  $R_2$ . The currents  $I$ ,  $I_1$ ,  $I_2$  shown in the figure are the rates of flow of charge at the points indicated. Hence,

$$I = I_1 + I_2$$

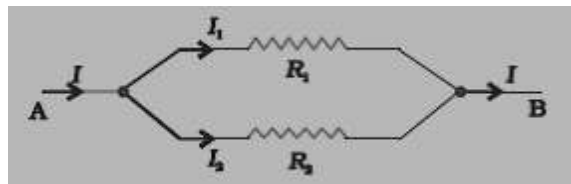
The potential difference between A and B is given by the Ohm's law applied to  $R_1$

$$V = I_1 R_1$$

Also, Ohm's law applied to  $R_2$  gives

$$V = I_2 R_2$$

$$\therefore I = I_1 + I_2 = \frac{V}{R_1} + \frac{V}{R_2} = V \left( \frac{1}{R_1} + \frac{1}{R_2} \right)$$



If the combination was replaced by an equivalent resistance  $R_{eq}$ , we would have, by Ohm's law

$$I = \frac{V}{R_{eq}}$$

Hence,

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$

### Internal resistance of a cell, potential difference and emf of a cell

**Q.** Differentiate between electromotive force and potential difference of a cell. Show that during discharging of a cell  $V = \epsilon - Ir$ , where  $\epsilon$  is emf,  $V$  is the potential difference,  $I$  is the current drawn,  $r$  is the internal resistance of the cell.

**A.** When there is no current, the electrolyte has the same potential throughout, so that the potential difference between P and N is  $V_+ - (-V_-) = V_+ + V_-$ . This difference is called the *electromotive force* (emf) of the cell and is denoted by  $\epsilon$ . Thus

$$\epsilon = V_+ + V_- > 0$$

$\epsilon$  is, actually, a potential difference and *not a force* consider a resistor  $R$  connected across the cell Fig. A current  $I$  flows across  $R$  from C to D.

**Note-** a steady current is maintained because current flows from N to P through the electrolyte. Clearly, across the electrolyte the same current flows through the electrolyte but from N to P, whereas through  $R$ , it flows from P to N. emf  $\epsilon$  is the potential difference between the positive and negative electrodes in an open circuit, i.e., when no current is flowing through the cell.

If however  $R$  is finite,  $I$  is not zero. In that case the potential difference between P and N is

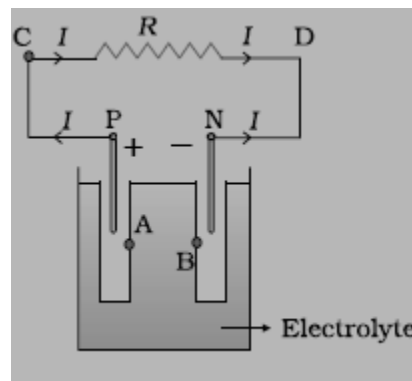
$$V = V_+ - V_- - Ir$$

$$= \epsilon - Ir$$

**Note** -The negative sign in the expression  $(Ir)$  for the potential difference between A and B. This is because the current  $I$  flows from B to A in the electrolyte.

**Note-** internal resistances of cells in the circuit may be neglected when the current  $I$  is such that  $\epsilon \gg Ir$ . The actual values of the internal resistances of cells vary from cell to cell. The internal resistance of dry cells, however, is much higher than the common electrolytic cells.

From Ohm's law





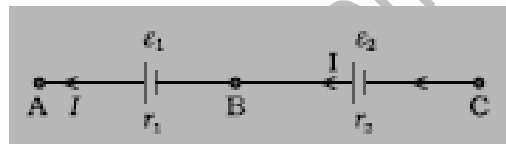
$V = IR$  therefore  $I R = \varepsilon - I r$

$$\text{Or, } I = \frac{\varepsilon}{R + r}$$

**Note** - The maximum current that can be drawn from a cell is for  $R = 0$  and it is  $I_{\max} = \varepsilon/r$ . However, in most cells the maximum allowed current is much lower than this to prevent permanent damage to the cell.

### CELLS IN SERIES AND IN PARALLEL

**Q.** Two cells of emf  $\varepsilon_1, \varepsilon_2$  and internal resistance  $r_1, r_2$  respectively are connected in series as shown in the fig. Calculate the equivalent emf and internal resistance of the combination.

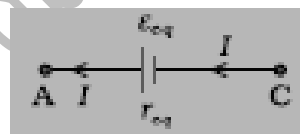


**A.** Consider two cells of emf's  $\varepsilon_1$  and  $\varepsilon_2$  in the series.  $r_1, r_2$  are their internal resistances. For connections across A and C, the combination can be considered as one cell of emf  $\varepsilon_{eq}$  and an internal resistance  $r_{eq}$ .

$$V_{AB} \equiv V_{(A)} - V_{(B)} = \varepsilon_1 - I r_1 \text{ and } V_{BC} \equiv V_{(B)} - V_{(C)} = \varepsilon_2 - I r_2$$

the potential difference between the terminals A and C of the combination is

$$\begin{aligned} V_{AC} &= V(A) - V(C) = [V(A) - V(B)] + [V(B) - V(C)] \\ &= (\varepsilon_1 + \varepsilon_2) - I(r_1 + r_2) \end{aligned}$$



But

$$V_{AC} = \varepsilon_{eq} - I r_{eq}$$

Comparing the last two equations, we get

$$\varepsilon_{eq} = \varepsilon_1 + \varepsilon_2$$

$$\text{and } r_{eq} = r_1 + r_2$$

Therefore

- (i) The equivalent emf of a series combination of  $n$  cells is just the sum of their individual emf's,
- (ii) The equivalent internal resistance of a series combination of  $n$  cells is just the sum of their internal resistances.

**Note**- If instead we connect the two negatives, eqn change to  $V_{BC} = -\varepsilon_2 - I r_2$  and we will get  $\varepsilon_{eq} = \varepsilon_1 - \varepsilon_2$  ( $\varepsilon_1 > \varepsilon_2$ ). If in the combination, the current leaves any cell from the *negative* electrode, the emf of the cell enters the expression for  $\varepsilon_{eq}$  with a *negative* sign.

**Q.** Two cells of emf  $\varepsilon_1, \varepsilon_2$  and internal resistance  $r_1, r_2$  respectively are connected in parallel as shown in the fig. Calculate the equivalent emf and internal resistance of the combination.



**A.** Consider a parallel combination of the cells Fig.  $I_1$  and  $I_2$  are the currents leaving the positive electrodes of the cells. At the point B1,  $I_1$  and  $I_2$  flow in whereas the current  $I$  flows out. Since as much charge flows in as out, we have  $I = I_1 + I_2$



Then, considering the first cell

$$V \equiv V(B_1) - V(B_2) = \varepsilon_1 - I_1 r_1$$

and second cell

$$V \equiv V(B_1) - V(B_2) = \varepsilon_2 - I_2 r_2$$

$$I = I_1 + I_2$$

$$= \frac{\varepsilon_1 - V}{r_1} + \frac{\varepsilon_2 - V}{r_2} = \left( \frac{\varepsilon_1}{r_1} + \frac{\varepsilon_2}{r_2} \right) - V \left( \frac{1}{r_1} + \frac{1}{r_2} \right)$$

Hence,  $V$  is given by,

$$V = \frac{\varepsilon_1 r_2 + \varepsilon_2 r_1}{r_1 + r_2} - I \frac{r_1 r_2}{r_1 + r_2}$$

But

$$V = \varepsilon_{\text{eq}} - I r_{\text{eq}}$$

Hence

$$\varepsilon_{\text{eq}} = \frac{\varepsilon_1 r_2 + \varepsilon_2 r_1}{r_1 + r_2}$$

$$r_{\text{eq}} = \frac{r_1 r_2}{r_1 + r_2}$$

**Note-** If the negative terminal of the second is connected to positive terminal then

$\varepsilon_2 \rightarrow -\varepsilon_2$  rest is same.

### KIRCHHOFF'S RULES-

#### Q. State Kirchhoff's rules

- (a) Junction rule: At any junction, the sum of the currents entering the junction is equal to the sum of currents leaving the junction (conservation of charge).  
(b) Loop rule: The algebraic sum of changes in potential around any closed loop involving resistors and cells in the loop is zero (conservation of energy).

#### Guidelines to apply Kirchhoff's law with sign convention-

1. Choose any closed loop in the network, and designate a direction (clockwise or counter-clockwise) to transverse the loop in applying the loop rule.
2. (a) Go round the loop in the designated direction adding emf's and potential differences. An emf is counted as **+ve** when it is traversed from (-) to (+) and **-ve** when traversed from (+) to (-)  
(b) An IR term is counted -ve if the resistor is traversed in the same direction of the assumed current, and +ve if in the opposite direction.

Equate the sum of step 2 to zero.

Example-

At junction a the current leaving is  $I_1 + I_2$  and current entering is  $I_3$ .

The junction rule says  $I_3 = I_1 + I_2$ . -----(i)

(At point h current entering is  $I_1$ . There is only one current leaving h and by junction rule that will also be  $I_1$ .)

For the loops 'ahdcba'

$$-30I_1 - 41 I_3 + 45 = 0 \text{ -----(ii)}$$

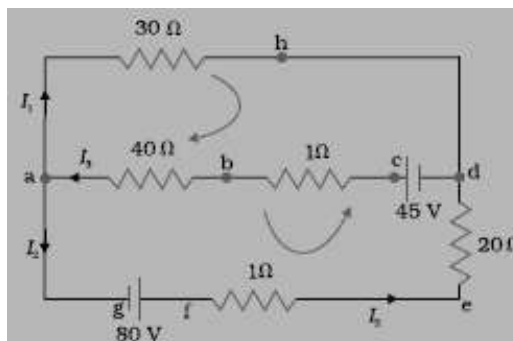
and 'ahdefga', the loop rules give

$$-30I_1 + 21 I_2 - 80 = 0. \text{ -----(iii)}$$

Three equations three unknown solve them.

Using  $V=IR$ , get the potential across each

branch or resistor or cells ( $V = e-ir$ ).



### Wheatstone bridge

**Q.** What is a Wheatstone bridge? What do you mean by balanced bridge condition? With the help of circuit diagram briefly explain how will you determine an unknown resistance using it.

**A.** The *Wheatstone bridge* is an arrangement of four resistances  $R_1, R_2, R_3, R_4$  as shown in the fig. The null-point condition is given by

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

using which the value of one resistance can be determined, knowing the other three resistances. In case of a *balanced* bridge where the resistors are such that  $I_g = 0$ . We can easily get the balance condition, such that there is no current through  $G$ . In this case, the Kirchhoff's junction rule applied to junctions  $D$  and  $B$  immediately gives us the relations  $I_1 = I_3$  and  $I_2 = I_4$ .

Next, we apply Kirchhoff's loop rule to closed loops  $ADBA$  and  $CBDC$ . The first loop gives

$$-I_1 R_1 + 0 + I_2 R_2 = 0 \text{ (} I_g = 0 \text{)}$$

and the second loop gives, upon using  $I_3 = I_1, I_4 = I_2$

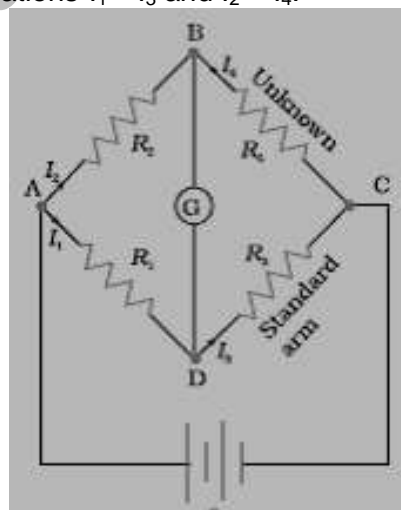
$$I_2 R_4 + 0 - I_1 R_3 = 0$$

we obtain,

$$\frac{I_1}{I_2} = \frac{R_2}{R_1} \quad \text{and} \quad \frac{I_1}{I_2} = \frac{R_4}{R_3}$$

hence

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



### METER BRIDGE-

**Q.** State the principal of meter-bridge. Using it briefly explain with the help of circuit diagram, how you will determine an unknown resistance and specific resistance.

**A. Principle-** It is based on the principle of Wheatstone bridge

#### To determine unknown Resistance-

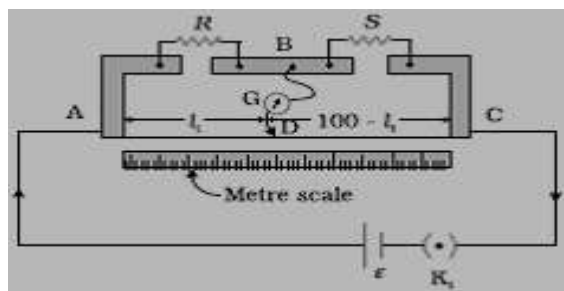
$R$  is an unknown resistance whose value we want to determine. It is connected across one of the gaps.

Across the other gap, we connect a standard known resistance  $S$ . The portion  $AD$  of the wire has a resistance  $R_{cm}l$ , where

$R_{cm}$  is the resistance of the wire per unit centimetre.

The portion  $DC$  of

the wire similarly has a resistance  $R_{cm} (100-l)$ .



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The four arms AB, BC, DA and CD [with resistances  $R$ ,  $S$ ,  $R_{cm} l$  and  $R_{cm}(100-l)$ ] obviously form a Wheatstone bridge

The balance condition, no deflection on the galvanometer or null point

$$\frac{R}{S} = \frac{R_{cm} l_1}{R_{cm} (100 - l_1)} = \frac{l_1}{100 - l_1}$$

the unknown resistance  $R$  is known in terms of the standard known resistance  $S$  by

$$R = S \frac{l_1}{100 - l_1}$$

**To determine Specific Resistance-** The above steps remaining same and now knowing the value of unknown resistance say  $R$ , we can calculate specific resistance of the material of  $R$  as  $R = \rho l / A$ , where  $l$  is the length of the resistance wire and  $A = \pi r^2$  is the area of cross-section of the wire ( $r$  is to be measured by screw – gauge)

Note- It can be shown that the percentage error in  $R$  can be minimized by adjusting the balance point near the middle of the bridge, i.e., when  $l_1$  is close to 50 cm.

## POTENTIOMETER

**Q.** State the principle of potentiometer. Using it briefly explain with the help of circuit diagram how you will 1. compare the emf of two cells 2. Find the internal resistance of a primary cell.

**A.** Principal-The potential difference across any length of a wire of uniform cross-section and uniform composition is proportional to its length when a constant current flows through it.

1. **To compare the emf of two cells-** Consider first a position of the key where 1 and 3 are connected so that the galvanometer is connected to  $\epsilon_1$ . The jockey is moved along the wire till at a point  $N_1$ , at a distance  $l_1$  from  $A$ , there is no deflection in the galvanometer. We can apply Kirchhoff's loop rule to the closed loop  $AN_1G31A$  and get,

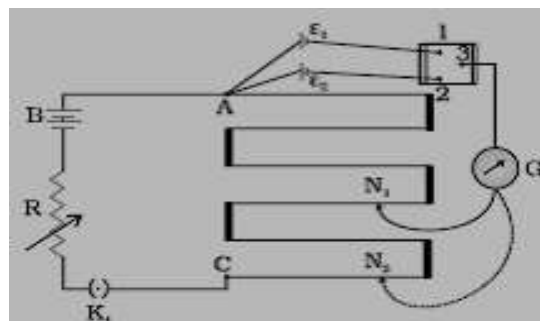
$$\phi_{l_1} + 0 - \epsilon_1 = 0$$

Similarly, if another emf  $\epsilon_2$  is balanced against  $l_2$  ( $AN_2$ )

$$\phi_{l_2} + 0 - \epsilon_2 = 0$$

From the last two equations

$$\frac{\epsilon_1}{\epsilon_2} = \frac{l_1}{l_2}$$



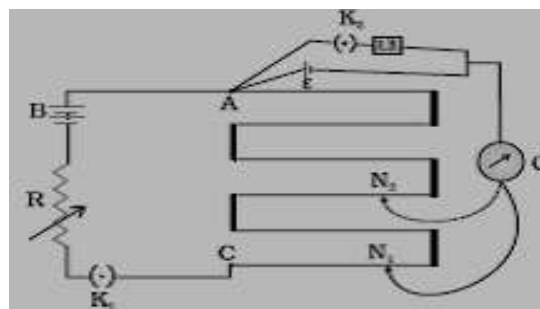
2. **To measure internal resistance of a cell-** The cell (emf  $\epsilon$ )

whose internal resistance ( $r$ ) is to be determined is connected across a resistance box through a key  $K_2$ , as shown in the figure. With key  $K_2$  open, balance is obtained at length  $l_1$  ( $AN_1$ ). Then,

$$\epsilon = \phi_{l_1}$$

When key  $K_2$  is closed, the cell sends a current ( $I$ ) through the resistance box ( $R$ ). If  $V$  is the terminal potential difference of the cell and balance is obtained at length  $l_2$  ( $AN_2$ ),

$$V = \phi_{l_2}$$



So, we have  $\varepsilon/V = l_1/l_2$

But,  $\varepsilon = I(r + R)$  and  $V = IR$ . This gives

$$\varepsilon/V = (r+R)/R$$

Hence we get

$$(R+r)/R = l_1/l_2$$

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

**Note-** The sensitivity of the potentiometer depends upon the value of potential gradient  $\phi$ . ( $\phi$ =Potential supplied by main battery divided by length of wire) Smaller the value of  $\phi$ , smaller the potential difference that a potentiometer can measure and more is the sensitivity of the potentiometer. Thus, for a given potential difference, the sensitivity of the potentiometer increases with the increase in length of potentiometer wire.

**Note-** When Voltmeter is used, current flows through the circuit, and because of the internal resistance of the cell, always terminal potential will be less than the actual cell potential. But in a potentiometer circuit, when the potential difference is balanced, no current flows in the circuit, so terminal potential will be equal to actual cell potential. i.e, Voltmeter measures the terminal potential of a cell, but Potentiometer measures actual cell potential.

### **Kirchhoff's rules made visual**

1. <http://www.phys.hawaii.edu/~teb/optics/java/kirch5/index.html>
2. <http://www.phys.hawaii.edu/~teb/optics/java/kirch4/index.html>
3. <http://www.phys.hawaii.edu/~teb/optics/java/kirch3/index.html>
4. <http://www.phys.hawaii.edu/~teb/optics/java/kirch2/index.html>
5. <http://www.phys.hawaii.edu/~teb/optics/java/kirch1/index.html>
6. <http://www.phys.hawaii.edu/~teb/optics/java/resist4/index.html>
7. <http://www.phys.hawaii.edu/~teb/optics/java/resist2/index.html>