1.1 Electric Current

The directed rate of flow of electric charge through any cross-section of a conductor is known as electric current.

If ΔQ charge flows in time Δt, then current at any time t is $I = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt}$

Also, $I = \frac{q}{t} = \frac{ne}{t}$

$[\because q = ne]$

where, n = number of charged particles constitute the electric current.

The direction of the current is in the flow of positive charge and opposite to the direction of flow of negative charge.

SI unit of current is ampere and it is represented by A.

$$1\text{ A} = \frac{1\text{ coulomb (C)}}{1\text{ second (s)}} = 1\text{C/s}$$

NOTE Current is a scalar quantity.

Current Density

The current density at a point in a conductor is the ratio of the current at that point in the conductor to the area of cross-section of the conductor at that point.

If a current I is distributed uniformly over the cross-section A of a conductor, then the current density at that point is $J = \frac{I}{A}$.

NOTE Current density is a vector quantity.

Electric Current in Conductors

(i) In Case of a Metallic Conductor

Among the solids, all metals are good conductors of electricity. Free electrons are the cause of conductance of electricity in them.

(ii) In Case of a Solid Conductor

In case of solid conductor (i.e. Cu, Fe, Ag, etc) atoms are tightly bound to each other but there are large number of free electrons in them to conduct.

(iii) In Case of a Liquid Conductor

In case of a liquid conductor like electrolytic solution, there are positive and negative charged ions which can move on applying electric field to conduct.

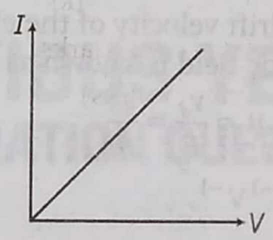
1.2 Ohm's Law

At constant temperature, the potential difference V across the ends of a given metallic wire (conductor) in an electric circuit is directly proportional to the current flowing through it.

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

where, R = resistance of conductor

The variation of current w.r.t. applied potential difference is shown with the help of following graph.



No effect of V and I on R because as V increase, I increase but R remains the same.

Resistance of a Conductor

It is defined as the ratio of potential difference applied across the ends of the conductor to the current flowing through it.

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

SI unit is ohm (Ω).

Resistance can also be written as, $R = \rho\frac{L}{A}$

where, L = length of the conductor, A = area of cross-section and ρ = constant, known as resistivity of the material. It depends upon the nature of the material and temperature of the conductor.

Effect of Temperature on Resistance

Temperature coefficient of resistance averaged over the temperature range t_1°C to t_2°C is given by

$$\alpha = \frac{R_2 - R_1}{R_1(t_2 - t_1)}$$

where, R_1 and R_2 are the resistances at t_1°C and t_2°C, respectively.

Drift Velocity

It is defined as the average velocity with which the free electrons move towards the positive end of a conductor under the influence of an external electric field applied across the conductor.

Thus, $$v_d = \frac{e\mathbf{E}}{m}\tau$$

where, τ = relaxation time, $\mathbf{E}$ = electric field, m = mass of the electron, e = electronic charge

The drift velocity of electron is of the order of $10^{-4}\,\text{ms}^{-1}$.

Mobility

The ratio of the drift velocity of the electrons to the applied electric field is known as mobility. It is expressed as, $\mu = \frac{v_d}{E} = \frac{q\tau}{m}$

Its SI unit is $m^2s^{-1}V^{-1}$.

1.3 Resistivity of Various Material

Resistivity of various material is defined as the resistance of unit cube of a material of the given conductor

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

It depends upon the following factors

(i) $\rho = \frac{1}{n}$, where n = number of free electron

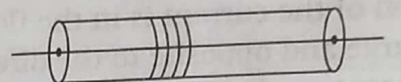
(ii) $\rho = \frac{1}{\tau}$, where τ = average relaxation time of free electron.

Colour Code of Carbon Resistance

The colour code of carbon resistor remains in the form of coaxial rings.

The first band represents the first significant figure, second band represents second significant figure and third band represents multiplier (i.e. power of ten). The fourth band represents tolerance.

Colour	Black	Brown	Red	Orange	Yellow	Green	Blue	Violet	Grey	White
Mnemonic	B	B	R	O	Y	of Great	Britain	had Very	Good	Wife
Digit	0	1	2	3	4	5	6	7	8	9



Carbon resistor

Tolerance	Unit
Gold	5%
Silver	10%
No colour	20%

1.4 Conductance and Conductivity

Conductance

It is defined as the reciprocal of resistance of conductor.

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

Its SI unit is mho (Ω^{-1}) or siemen (S). The dimensional formula of conductance is $[M^{-1}L^{-2}T^{-3}A^2]$.

Conductivity

It is defined as the reciprocal of resistivity of a conductor. It is expressed as, $\sigma = \frac{1}{\rho}$

Its SI unit is mho per metre (Ω^{-1}/m).

Relation between J, σ and E

The relation between the current flowing through the conductor and drift velocity of electron is given by

$$J = \sigma E$$

It is microscopic form of Ohm's law.

Superconductivity

The resistivity of certain metals or alloys drops to zero when they are cooled below a certain temperature. This is called superconductivity. It was observed by Prof. Kamerlingh in 1911.

Some Important Units

(i) Resistance - Ohm (Ω)

(ii) Resistivity - Ohm-metre (Ω-m)

(iii) Conductance $\left(\frac{1}{R}\right)$ - Mho or Ω^{-1} or Siemen (S)

(iv) Current density - A/m^2

NOTE If a conductor is stretched or compresses to n times of original length, then

$$l' = nl \Rightarrow R' = n^2 R$$

where, R' = new resistance and R = original resistance.

1.5 Combinations of Resistors

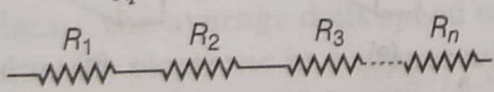
There are two types of combinations of resistors

Series Combination

In this combination, different resistors are connected end to end.

Equivalent resistance can be obtained by the formula,

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



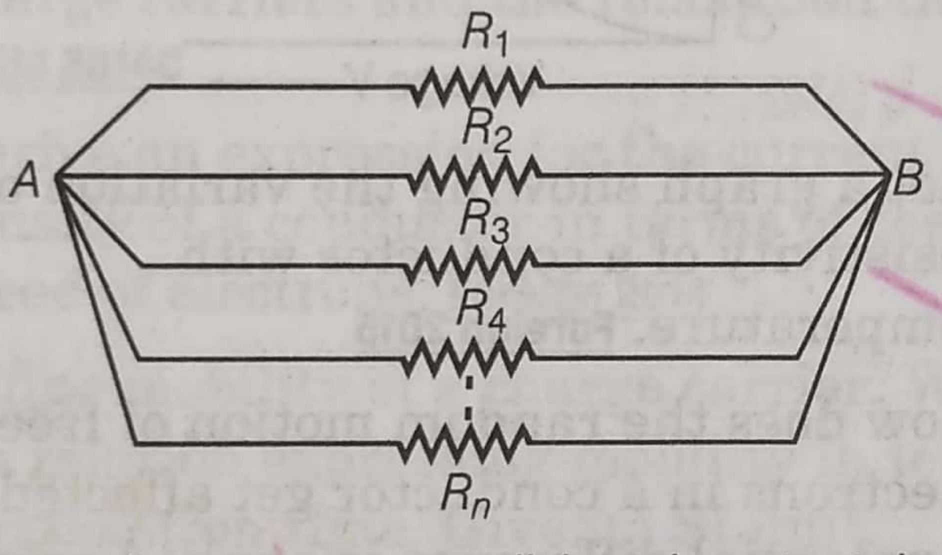
NOTE The total resistance in the series combination is more than the greatest resistance in the circuit.

Parallel Combination

In this combination, first end of all the resistors are connected to one point and last end of all the resistors are connected to other point.

Equivalent resistance can be obtained by the formula,

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



NOTE The total resistance in parallel combination is less than the least resistance of the circuit.

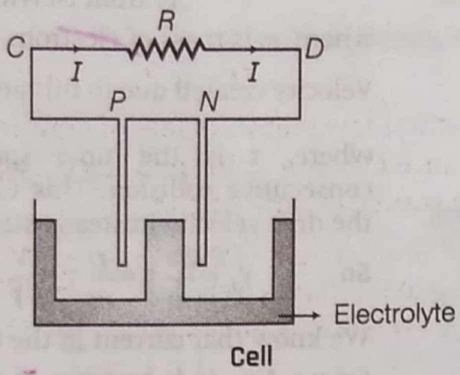
- If n identical resistors each of resistance r are connected in

  (i) series combination, $R_{eq} = nr$

  (ii) parallel combination, $R_{eq} = \frac{r}{n}$

2.1 Cell

A device which is used to maintain a steady current in an electric circuit is called cell or electrolytic cell. It has two electrodes positive (P) and negative (N) as shown in figure above.



Terms Related to Cell

EMF of a Cell

It is the maximum potential difference between two terminals of circuit, when circuit is open.

EMF of the cell , $E = \dfrac{W}{q}$.

Internal Resistance (r)

Internal resistance of a cell is defined as the resistance offered by the electrolyte of the cell to the flow of current through it. It is denoted by r. Its SI unit is ohm (Ω).

Terminal Potential Difference (V)

The maximum potential difference between two terminals of circuit when the circuit is closed it, is known as terminal voltage or terminal potential difference (V) of cell.

Relation between r, R, E and V

$$r = R\left(\frac{E}{V} - 1\right) \quad \dots\text{(i)}$$

$\frac{r}{R} = \frac{E}{V} - 1$

$\frac{r}{R} + 1 = \frac{E}{V}$

where, r = internal resistance,
R = external resistance,
E = emf of cell,
V = terminal voltage of cell

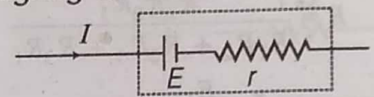
Also, $V = E - Ir$ $\quad \dots$(ii)

and $V = \left(\dfrac{E}{R+r}\right)R$ or $V = \dfrac{E}{\left(1 + \dfrac{r}{R}\right)}$ $\quad \dots$(iii)

The terminal voltage increases with the increase of external resistance R.

Charging of a Cell

During charging of the cell, $V = E + Ir$



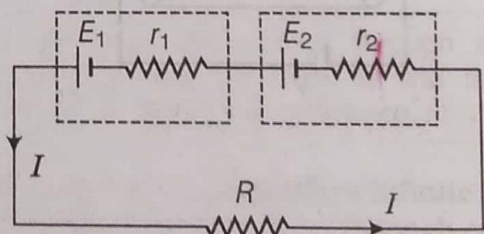
So, $V < E$, when current is drawn from the cell i.e. discharging.
and $V > E$ when charging of cell takes place.

2.2 Cells in Series and Parallel

Series Combination

In series combination, current is given by,

$$I = \frac{nE}{(R + nr)}$$

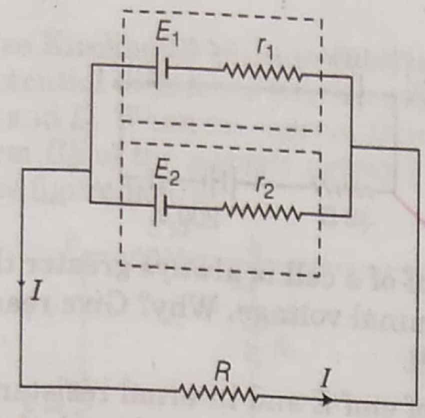


where, $\quad r_{eq} = r_1 + r_2$

Parallel Combination

In parallel combination, current is given by,

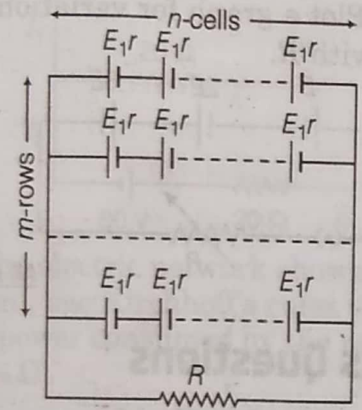
$$I = \frac{mE}{(r + mR)}$$



Mixed Grouping

It consists of m-rows in parallel combination such that each row contains n-cells of each of emf E and internal resistance r, then current in the circuit is given by

$$I = \frac{mnE}{mR + nr}$$



and maximum current is drawn from the battery, when external resistance matches with net internal resistance i.e.

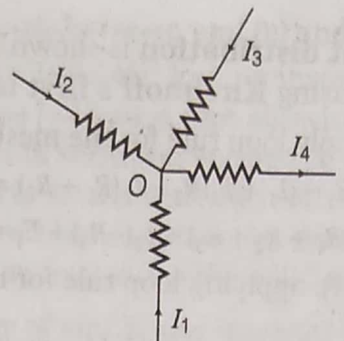
$$R = \frac{nr}{m} \text{ and } I_{max} = \frac{nE}{2\left(\frac{nr}{m}\right)} = \frac{mnE}{2nr} = \frac{mE}{2r}$$

2.3 Kirchhoff's Laws

Kirchhoff has given two rules based on conservation of electric charge and of energy, these are known as **Kirchhoff's laws.**

Kirchhoff's First Law (Junction Rule)

The algebraic sum of electric currents at any junction of electric circuit is equal to zero i.e. the sum of current entering into a junction is equal to the sum of current leaving the junction



$$\Sigma I = 0,\ I_4 = I_1 + I_2 + I_3$$

Junction law supports law of conservation of charge because this is a point in a circuit which cannot act as a source or sink of charge(s).

NOTE The current flowing towards the junction of conductors is considered as positive and the current flowing away from the junction is taken as negative.

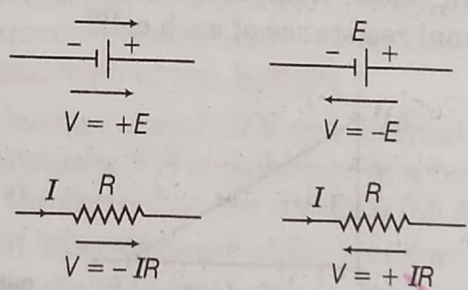
Kirchhoff's Second Law (Loop Rule)

In any closed loop of electrical circuit, the algebraic sum of emf's of cell and the product of currents and resistance is always equal to zero i.e.

$$\Sigma \Delta V = 0 \text{ or } \Sigma E = \Sigma I R$$

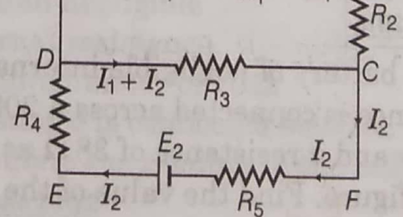
Kirchhoff's second law supports the law of conservation of energy, because the net change in the energy of a charge, after completing a closed path must be zero.

NOTE Sign convention for Kirchhoff's second law.



An Application based on Kirchhoff's Law

Let us consider a circuit diagram



Current distribution is shown in given circuit using **Kirchhoff's first law.**

Now, apply loop rule for the mesh $DCBAD$

$$E_1 - (I_1 + I_2)R_3 - I_1 (R_1 + R_2) = 0$$

$$\Rightarrow -I_1 (R_1 + R_2 + R_3) + I_2(-R_3) + E_1 = 0 \quad \ldots(\text{i})$$

Similarly, applying loop rule for the mesh $CDEFC$

$$E_2 - I_2R_4 - (I_1 + I_2)R_3 - I_2R_5 = 0$$

$$\Rightarrow I_1 (R_3) + I_2(R_3 + R_4 + R_5) = E_2$$

$$\Rightarrow I_1 (R_3) + I_2(R_3 + R_4 + R_5) - E_2 = 0 \quad \ldots(\text{ii})$$

By Eqs. (i) and (ii), we can calculate I_1 and I_2.

3.1 Potentiometer

It is an electrical device which can

(i) measure the potential difference with greater accuracy.

(ii) compare the emfs of two cells.

(iii) measure the emf of a cell.

(iv) be used to determine the internal resistance of a primary cell.

Working Principle

The potentiometer works on the principle that potential difference across any two points of uniform current carrying conductor is directly proportional to the length between the two points i.e. $V \propto l$

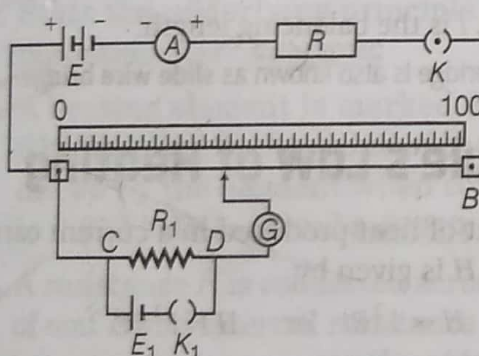
Potential Gradient

It is the potential drop per unit length of wire of potentiometer

i.e. $K = \dfrac{V}{l}$, where V and l are potential difference applied by driving cell and length of wire of potentiometer, respectively.

Application of Potentiometer

Measurement of Potential Difference Using Potentiometers



If r is the resistance of potentiometer wire of length L, then current through potentiometer wire is $I = \dfrac{E}{R+r}$

Potential drop across potentiometer wire $= Ir = \left(\dfrac{E}{R+r}\right)r$

Potential gradient of potentiometer wire

$$K = \left(\frac{E}{R+r}\right)\frac{r}{L} \Rightarrow V = Kl = \left(\frac{E}{R+r}\right)\frac{r}{L}l$$

The potentiometer is a better device to measure potential difference than a voltmeter as null point method is used and hence, it can measure even the emf of cell but voltmeter cannot. It measures potential difference with greater accuracy.

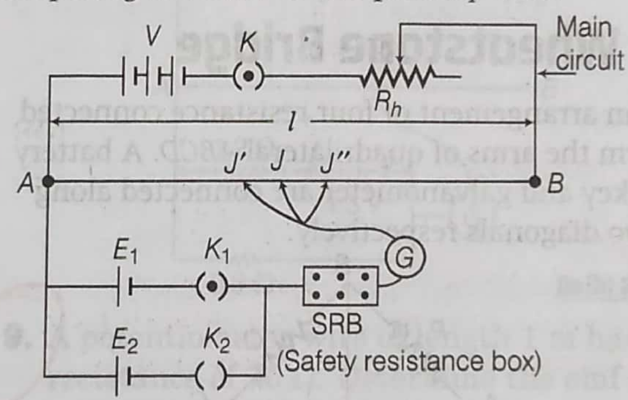
Comparing EMF of Two Cells

The emfs of two primary cells can be compared using potentiometer as $\dfrac{E_1}{E_2} = \dfrac{l_1}{l_2}$

where, l_1 and l_2 are the balancing lengths corresponding to cells of emf's E_1 and E_2 respectively.

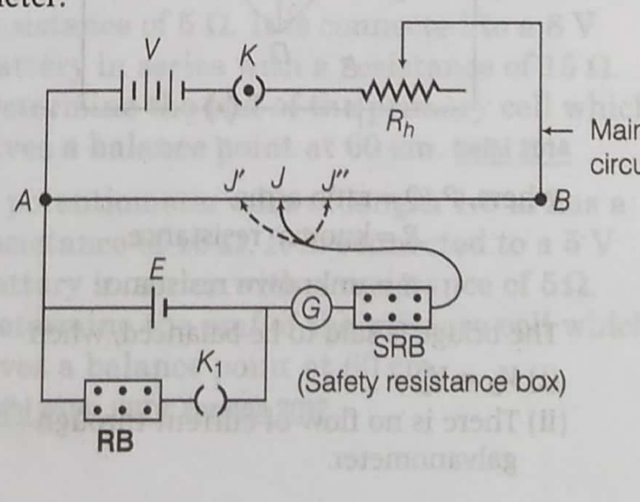
Circuit diagram

For comparing the emfs of two primary cells.



To Measure Internal Resistance of a Cell

The internal resistance can be determined using potentiometer.



If l_1, l_2 are the balancing lengths when key K_1 is opened and closed respectively and resistance R is applied in Safety Resistance Box (SRB), then internal resistance of primary cell of emfs is given by

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

The potentiometer works only when

(i) the terminal voltage applied by driving cell is greater than the emf of primary cell.

(ii) the positive terminals of driving cell and primary cell are connected at the zero end of potentiometer wire.

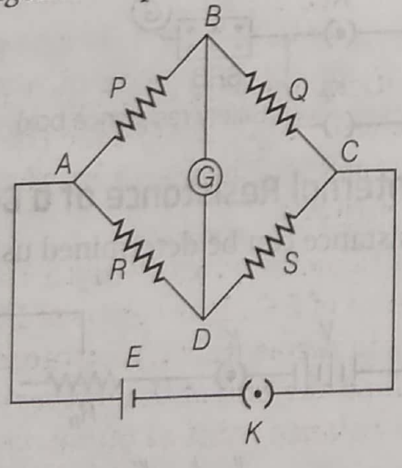
Sensitivity of a Potentiometer

It refers to the capability of measuring very small potential difference and exhibit change in balancing length even on very small change in potential difference.

The sensitivity of potentiometer can be increased by increasing the number of wires of potentiometer and hence, decreasing the value of potential gradient.

3.2 Wheatstone Bridge

It is an arrangement of four resistance connected to form the arms of quadrilateral *ABCD*. A battery with key and galvanometer are connected along its two diagonals respectively.



where, P, Q = ratio arms,

R = known resistance,

S = unknown resistance

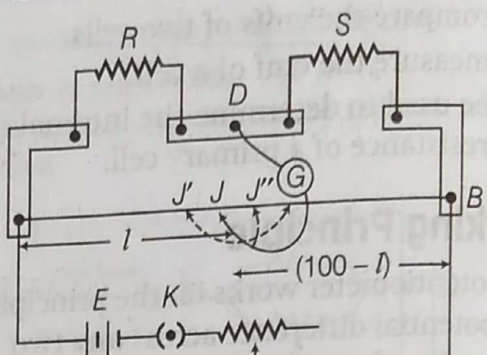
The bridge is said to be balanced, when

(i) $V_B = V_D$

(ii) There is no flow of current through galvanometer.

The Wheatstone bridge is said to be sensitive, if it gives ample deflection in the galvanometer even on slight change of resistance. For sensitivity of galvanometer, the magnitude of four resistances P, Q, R, S should be of same order.

3.3 Meter Bridge



It is an electrical device used to determine the resistance and hence, specific resistance of material of given wire/conductor.

It is based on the principle of balanced Wheatstone bridge.

For uniform wire,

resistance of wire ∝ length of conductor

At balanced situation of bridge,

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

or $$\frac{l}{100 - l} = \frac{R}{S}$$

$$\Rightarrow \quad S = \left(\frac{100 - l}{l}\right) \times R$$

where, l is the balancing length.

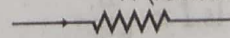
NOTE Meter bridge is also known as **slide wire bridge**.

3.4 Joule's Law of Heating

The amount of heat produced in a current carrying conductor, H is given by

$$H \propto I^2 Rt \quad \text{or} \quad H = I^2 Rt$$

$$H = VIt \quad \text{or} \quad H = \frac{V^2}{R} t$$



Electric Power

The rate of consumption of electrical energy or production of heat energy is known as electric power. SI unit of electric power is watt (W).

Electric power, $P = I^2R = \frac{V^2}{R} = VI$

- Unit in the commercial unit of electric energy, 1 unit $= 1\text{kWh} = 3.6\times 10^6$ J
- If V_s = specified voltage and W is wattage of bulb or appliance, then resistance of bulb of appliance, $R = \frac{V_s^2}{W}$

  If V_a is applied voltage, then actual power consumed, $P_a = \frac{V_a^2}{R} = \frac{V_a^2}{V_s^2}W$