1. **Electric current:** It is defined as the rate of flow of electric charge with time.

   Mathematically, average current $I = \frac{\text{Charge}}{\text{time}} = \frac{q}{t}$.

   It is a scalar with ampere as SI unit.

   Instantaneous current $I = \lim_{\Delta t \to 0} \frac{\Delta q}{\Delta t} = \frac{dq}{dt}$

2. **Current carriers:** In metals, the current flows due to drift of electrons. In electrolytes, the flow of current is caused by motion of positive and negative ions whereas in gases, the current flows due to motion of ions and free electrons.

   Metals are better conductors than electrolytes because of following two reasons:

   (*i*) The number density of free electrons in metals is very large as compared to that of ions in the electrolytes.

   (*ii*) The mass of electrons being very small; they drift very fast.

   By convention, the direction of current is taken to be that of motion of positive charge (Higher potential to lower potential). So the electrons move in a direction opposite to that of conventional current.

3. **Types of current:**

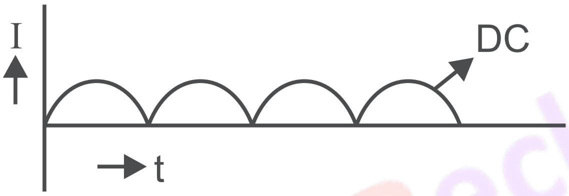
   (*a*) **Direct current (DC):** It is the current which continuously flows in the same direction. Source of dc is a cell, a battery or a dc generator.

(*b*) **Alternating current (AC):** It is the current which repeatedly reverses its direction of flow.

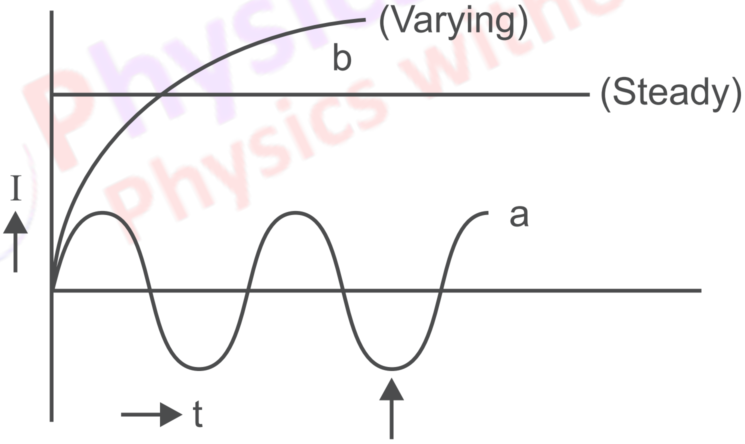
Source: AC generator; Invertor.

(*c*) **Steady current:** The current in a circuit is said to be steady if its value does not change with time.

(*d*) **Varying current:** It is the current whose value changes with time. The above currents are graphically represented as shown.



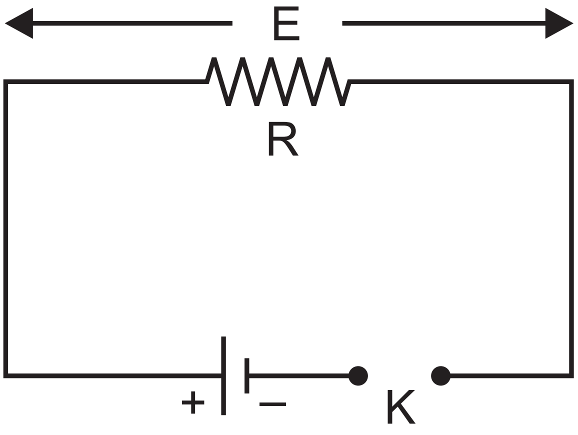
(*a*) and (*b*) are also varying currents.

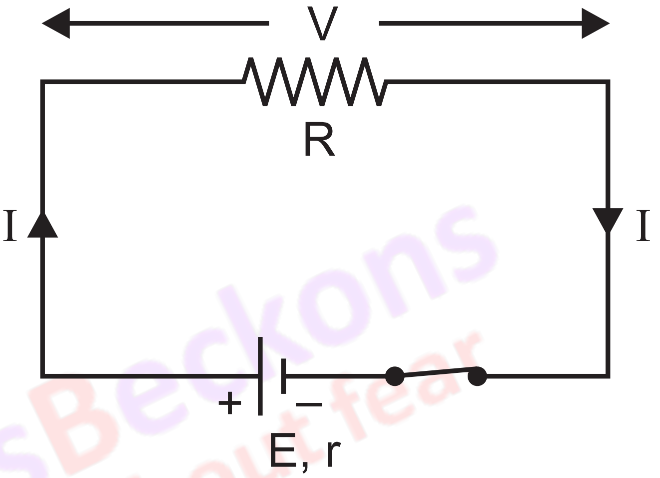


To make current flow, a potential difference has to be maintained between two points.

4. **Electromotive force (E M F):** It is the potential difference across the terminals of cell in an open circuit, i.e. when no current is being drawn from it. It is denoted by *E* and is measured in volts.

5. **Potential difference (V):** It is the difference of potential across the terminals of a cell in use, i.e. when current is drawn from it. It is generally less than E M F.





V exceeds E when the cell is being charged.

6. **Internal resistance of a cell:** It is the resistance offered by the electrolyte in the cell.

7. **Relation between *E* and *V*:** Consider a cell of emf 'E' and internal resistance r used to drive a current I through an external resistance R.

   The emf drives current I through the external resistance R as well as the internal resistance 'r'.

$$\therefore \quad E = I(R + r) = IR + Ir = V + Ir$$

$$\therefore \quad V < E \text{ or } E > V$$

   E exceeds V because a part of the emf is lost in overcoming the internal resistance of the cell. The term Ir is called lost volts.

We have $$r = \frac{E-V}{I} = \frac{E-V}{V/R} = \left(\frac{E-V}{V}\right)R$$

Note: The terminal potential difference across a cell exceeds its EMF during the charging of the cell. We have $V = E + Ir$.

8. **Ohm's Law:** For a conductor under fixed physical conditions (temperature, stress etc); the potential difference across its terminals is directly proportional to the current flowing through it.

   i.e. $V \propto I \Rightarrow V = IR$ where R is constant of proportionality called resistance of the conductor.

9. **Resistance**: It is defined as the property of a conductor by which it opposes the flow of current through itself. It is a scalar. Its SI unit is ohm (Ω).

   1Ω = 1 volt / ampere. One ohm is resistance of a conductor which allows one ampere current through itself when a potential difference of one volt is applied across its ends. The value of resistance of a conductor depends on dimensions of the conductor and also on nature of its material.

10. **Factors affecting resistance:** For a given conductor, resistance

$$R \propto l \text{ (length of the conductor)}$$

$$\propto \frac{1}{A} \text{ (A is area of the conductor).}$$

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

where ρ is a constant called resistivity of the material of the conductor.

If l = 1m; A = 1 sq m; then $\rho = R$.

Hence resistivity of the material of a conductor is the resistance offered by 1 m long conductor with uniform area of cross-section 1 sq. m. Its SI unit is ohm-m. Resistivity depends on nature and temperature of the material and is independent of shape and size. The value of resistivity varies from very low for good conductors (e.g. $1.6 \times 10^{-8}\ \Omega$ m for silver) to very high for insulators (e.g. ~ $10^{14}\ \Omega$ m for rubber).

11. **Conductance:** It is reciprocal of resistance of the conductor. Its SI unit is ohm^{-1} or mho (℧) or siemen (S).
12. **Electrical conductivity:** It is reciprocal of resistivity of the (material of the) conductor.

    It is denoted by $\sigma\left(=\frac{1}{\rho}\right)$. Its SI unit is Sm^{-1}.
13. **Mechanism of current flow through a metallic conductor:**

    Metals have free electrons in them. These electrons are in constant random motion colliding with each other as well as with atoms in the lattice. This random motion of electrons does not contribute to current.
14. **Drift velocity:** A potential difference applied across the ends of a conductor develops electric field in the conductor. The free electrons in the conductor drift under the action of the electric field force against the direction of the electric field. This drift velocity $\left(\text{Drift speed } \left|\vec{v}_d\right| = \frac{eE}{m}\tau\right)$

    causes the flow of current.

In the above expression; $E\left(=\frac{V}{l}\right)$ is electric field intensity; m is the mass of the electron and τ is the average time between successive collisions of the free electrons with the atoms or ions of the conductor. It is known as mean free time or relaxation time of the electrons. The drift speed in good conductors is of the order of 10^{-5} ms^{-1} to 10^{-4} ms^{-1}.

15. The drift speed and current are related as $\boldsymbol{I} = neAv_d$ where n is number density (number per unit volume) of free electrons; A is area of cross-section of the conductor. By convention, current I and drift velocity are in opposite directions.

16. **Current density (J):** The current per unit area of cross-section of the conductor is called current density. The SI unit of current density is A m^{-2}.

$$J = \frac{I}{A} \text{ or } \vec{J} = -\frac{neA\vec{v}_d}{A} = -ne\vec{v}_d$$

and $$I = \vec{J}\cdot\vec{A}$$

17. In terms of the conductor and its material parameters; the resistance of a conductor of length 'l' and area of cross-section 'A' is given by

$$R = \frac{m}{e^2n\tau}\cdot\frac{l}{A}\text{. Also } R = \rho\frac{l}{A}.$$

$\therefore$ We get $\rho = \dfrac{m}{e^2n\tau}$.

Hence the resistivity of the material of a conductor varies inversely as the number density of free electrons and the relaxation time.

18. Ohm's law can also be expressed in terms of current density.

We have $$I = \frac{V}{R} = \frac{E\,.\,l}{\rho\,\frac{l}{A}} = \frac{E\,.\,A}{\rho} \Rightarrow \frac{I}{A} = \frac{E}{\rho}$$

or in vector form $$\vec{J} = \frac{\vec{E}}{\rho} = \sigma\vec{E}\,.$$

Hence current density and electric field vector are in same direction.

19. The mobility (μ) of a charge carrier is defined as the drift velocity per unit electric field intensity.

Mathematically, for electron $\mu_e = \frac{v_d}{E} = \frac{1}{E}\left(\frac{eE}{m}\tau\right) = \frac{e}{m}\tau\,.$

The SI unit of mobility is m^2 / V–s.

20. The resistivity and hence the resistance of all metallic conductors increases with increase in temperature. For small temperature variation near room temperature; the variation is linear and is given by

$$\rho_T = \rho_o\,[1 + \alpha\,(T - T_o)]$$

and $$R_T = R_o\,[1 + \alpha\,(T - T_o)]$$

where ρ_o; R_o represent the corresponding values of resistivity at a certain lower reference temperature T_o and ρ_T; R_T the values at temperature T.

α is called temperature co-efficient of resistivity or resistance.

21. Metals have positive value of α. Hence resistance of a metallic conductor increases with rise in temperature. The resistance of semiconductors decreases with rise in temperature as α for semiconductors is negative. Some alloys like manganin and constantan have low value of α. These alloys are used to make standard resistances.

22. The value of carbon resistances is expressed in terms of three coloured rings with a fourth band for quality or tolerance according to the following code.

Black	Brown	Red	Orange	Yellow	Green	Blue	Violet	Grey	White
0	1	2	3	4	5	6	7	8	9

In addition following bands are used for quality; Gold (± 5%); Silver (± 10%); No band (± 20%). The first two colours marked on a resistance give significant digits and third is a multiplier power of ten. For a resistance with Violet; Blue; Yellow and Gold bands; we have

$$\boxed{R = \overset{\text{Violet}}{\overset{\downarrow}{7}}\;\overset{\text{Blue}}{\overset{\downarrow}{6}} \times 10^{\underset{\uparrow}{4}}\;\underset{\text{Yellow}}{} + \overset{\text{Gold}}{\overset{\uparrow}{5\%}}} = 760\ \text{k}\Omega \pm 5\%.$$

23. The effective resistance R of a series combination of a number of resistances is given by their sum i.e.

$$R = R_1 + R_2 + R_3 + R_4 + \ldots$$

The resistance increases in series combination.

24. The effective resistance R of a parallel combination of a number of resistances is given by the relation;

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

The resistance decreases in parallel combination.

25. When a potential difference V is applied across the ends of a conductor of resistance R; a current I is caused by the electrons drifting against the direction of the electric field. The energy gained by the electrons under the action of external field is lost when these electrons undergo collision against the atoms or ions in the conductor. The heat produced in the process is given by $H = I^2Rt = \frac{V^2}{R}t = VIt$ joule. This is known as Joule's law of heating.

26. The relations for electric power of an electric device are $P = VI = I^2R = \frac{V^2}{R}$ watt.

27. For n identical cells each of emf E and internal resistance 'r' each joined in series to send a current I through an external resistance R; we have

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

Cells are joined in series when the external resistance is large as compared to the internal resistance.

28. For n identical cells each of emf E and internal resistance r each joined in parallel to send a current I through an external resistance R; we have

$$I = \frac{nE}{nR + r}.$$

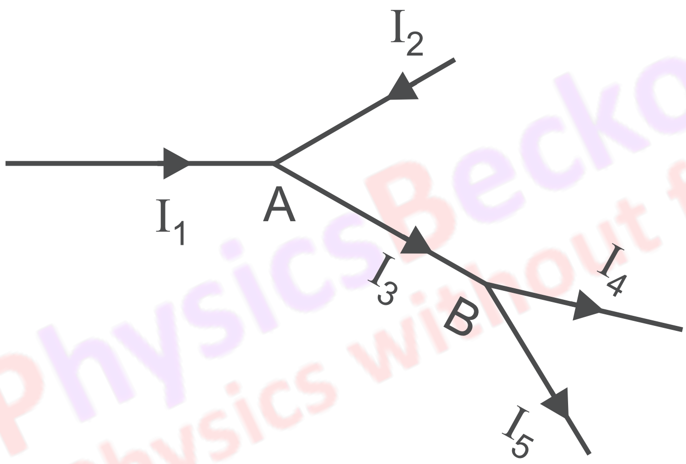
A parallel combination of cells is useful when the cells have a very large internal resistance.

29. The power drawn from a cell or a battery is maximum when its total internal resistance is equal to the total external resistance.

30. **Kirchhoff's laws:** The laws are useful in complicated electrical circuits where Ohm's law fails to gives results. The two laws are;

(*a*) **Junction rule or current rule:** It states that the algebraic sum of the currents meeting at any junction of an electrical circuit is zero.

The law is based on principle of conservation of electric charge.



In the given diagram; at *A*: $I_1 + I_2 - I_3 = 0$ and at *B*;

$$I_3 - I_4 - I_5 = 0$$

Sign convention: The current entering a junction is taken as positive and that leaving the junction is taken as negative.

(*b*) **Loop rule or voltage rule:** It states that the algebraic sum of the potential drops across various parts and emf's encountered in a **closed current loop** is always zero.

$$\Sigma (E + IR) = 0$$

The law is based on the principle of conservation of energy.

Sign Conventions*:

1. The product IR is taken positive if we move against current and negative if we move along the direction of current.
2. The emf of a cell is taken as positive if we travel from negative to positive terminal of battery. It is taken as negative if we travel from positive to negative terminal of the battery in the loop.

31. A wheatstone bridge is a combination of four resistances P, Q, R and S used to determine any one in terms of the other three. When the bridge is balanced; ($I_g = 0$) we have $\frac{P}{Q} = \frac{R}{S}$.

The bridge is most sensitive when all the four resistances in the bridge are equal.

32. A slide wire bridge is a practical form of Wheatstone bridge. It is used to find the value of an unknown resistance X by using the formula $X = R.\frac{(100 - L)}{L}$.

where R is the known resistance and 'L' is the balancing length, i.e. position of the null point from the side of resistance R.

** NOTE: Different books make use of different sign conventions.*

33. A potentiometer is a device used to accurately measure small potential difference and to compare emf's of two given cells. The principle of potentiometer states that **for a wire of uniform area of cross-section carrying a steady current, the potential difference across a given length of the wire is directly proportional to the length.**

34. For comparing emfs E_1 and E_2 of two cells we have

$\frac{E_1}{E_2} = \frac{l_1}{l_2}$ where l_1 and l_2 are the balancing lengths of the potentiometer wire for the two cells.

35. The potential gradient of a potentiometer is defined as the fall of potential per unit length along the potentiometer wire. Potential gradient $k = \frac{V}{l}$. Its SI unit is Vm^{-1}.

36. The internal resistance 'r' of a cell can be measured by a potentiometer using the formula

$$r = \frac{l_1 - l_2}{l_2} . \text{S}$$

where l_1 is balancing length when no current is drawn from the cell and l_2 is the balancing length when an external resistance 'S' is connected across the cell.

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