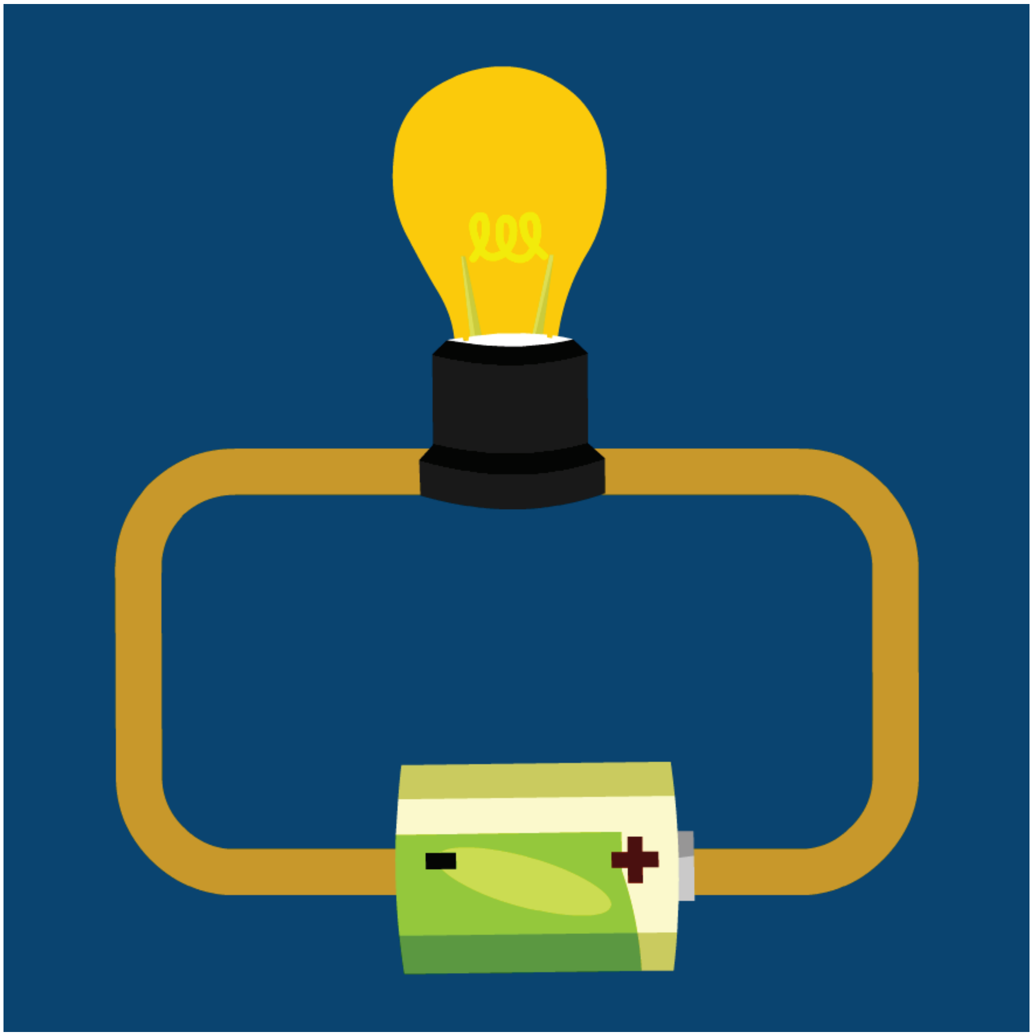
CURRENT ELECTRICITY



Current Electricity

Charges in motion constitute an **electric current**. A conductor offers a path for current. Application of potential difference across a conductor causes current. Potential difference can be provided using a cell or a battery (group of cells).

Current in a circuit in a single direction is called a direct current (dc), while a current whose direction keeps reversing at regular intervals and whose magnitude keeps changing continuously is called alternating current (ac).

Current carriers (mobile charge carriers): The charged particles whose drift in a definite direction constitutes the electric current are called current carriers.

Conventional current in a metallic conductor: In metallic conductors, negatively charged particles, namely electrons, drift under the influence of applied potential difference. This constitutes an **electron current**.

The direction of drift of positive charges is the direction of current. This current is called conventional current. The direction of conventional current is opposite to that of drift of electrons.

Strength of electric current: Electric current is the net flow of charge per second across a surface.

If ΔQ is the amount of charge that passes through an area in a time interval Δt, then the average current in the given time interval is, $I_{av} = \frac{\Delta Q}{\Delta t}$.

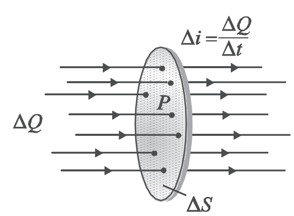
The instantaneous current is given by $I = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt}$

If the current is steady, then $I = \frac{Q}{t}$ where Q is the charge flowing across a section of a conductor in an interval of time t.

- The SI unit of current is ampere (A). 1 ampere = 1 coulomb per second.
- Since 1 coulomb = 6.25×10^{18} electrons, a flow of 6.25×10^{18} electrons per second is equal to 1 ampere of current.

Material	Mobile charge carriers
• Metallic conductors	Free electrons
• Liquid conductors	Positive ions and Negative ions
• Semiconductors	Free electrons and Holes
• Gaseous conductors	Positive ions and free electrons
• Super conductors	Cooper pairs (a pair of electrons with opposite spins)

Current density $(\vec{J})$



- If current i is uniformly distributed over an area S and is perpendicular to it, then $j = \frac{i}{S}$.
- Current density is a vector quantity. The direction of current density is the same as the direction of motion of positive charges.
- SI unit of current density is Am^{-2}.
- Relation between current and current density is $i = \int di = \int_S \vec{j} \cdot \overrightarrow{dS}$ over a finite area S.

Drift velocity of free electrons

- Drift velocity of **electrons** is given by $\vec{v}_d = -\frac{e\vec{E}}{m}\tau$ where $e \to$ charge on the electron, $m \to$ mass of the electron, $E \to$ electric field, $\tau \to$ relaxation time.
- The random speed of free electrons in a metallic conductor depends on the temperature and is of the order of 10^6 ms^{-1}. The drift speed of the free electrons is of the order of 10^{-4} ms^{-1}.

Relaxation time and mean free path: The average time elapsed between two successive collisions of a free electron with the metal ions in a conductor is called **relaxation time**, denoted by τ. The average distance traveled by an electron between two successive collisions is called the **mean free path**, denoted by λ.

Mobility (μ)

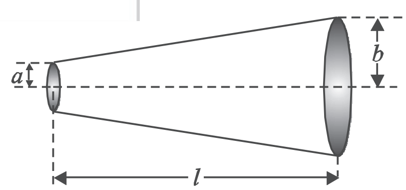
- The mobility (μ) of charge carriers is given by $\mu = v_d / E$ and its unit is $m^2V^{-1}s^{-1}$.
- The mobility of electrons and conductivity of a material are related by the expression $\sigma = ne\mu$ for a metallic conductor and $\sigma = n_e e\, \mu_e + n_h e\, \mu_h$ for a semiconductor
  where n_e is electron density, n_h is hole density, μ_e is electron mobility, μ_h is hole mobility.

Expression for current and current density in terms of drift speed

- $I = nAev_d$ and $\vec{J} = ne\vec{v}_d$
  where n is the number of electrons per unit volume of a metallic conductor of cross sectional area A and e is the charge on the electron.

Ohm's law: Mathematically Ohm's law is expressed as $V = IR$
where, R is a constant of proportionality called resistance of the conductor.

- We have $R = \frac{V}{I}$. The SI unit of resistance is ohm (Ω). 1 ohm = 1 volt per ampere.
- The dimensional formula is $[I^{-2}ML^2T^{-3}]$.
  At a given temperature, $R \propto \frac{1}{A}$ or $R = \rho\frac{l}{A}$ where ρ = specific resistance or resistivity of the material of the conductor.
  $R = \frac{m}{ne^2\tau} \times \frac{l}{A} = \frac{\rho l}{A}$ where ρ is the specific resistance of the material and



- For a conductor of length l having a circular cross-section, the resistance of the conductor is $R = \frac{\rho l}{\pi ab}$
  (Here the radius of cross-section varies linearly from a to b and (b – a) << l).

Resistivity or specific resistance (ρ)

- The resistivity of a material is defined as numerically equal to the resistance across the opposite faces of a cube of the given material of unit length and unit area of cross section.
- $\rho = \frac{RA}{L}$, R is in ohm, A is in square meter and L is in meter.
- The SI unit of ρ is ohm meter (Ω m). The dimensional formula for ρ is $[I^{-2}M^1L^3T^{-3}]$.
- The resistivity of a material is related to microscopic quantities by the relation, $\rho = \frac{m}{ne^2\tau}$.
- Resistivity of a conductor depends on the nature of the material and temperature.

- Resistivity is independent of the physical dimensions (i.e., size and shape) of the conductor. Its value is different for different materials.
- Good conductors have low resistivity while insulators have very high resistivity. Semiconductors have resistivity lying between that of good conductors and insulators.
- Alloys have resistivity which is greater than the resistivity of its constituent metals.

Conductivity (σ)

- It is the reciprocal of resistivity. The SI unit of σ is siemen m^{-1}
- The dimensional formula for σ is $[I^2M^{-1}L^{-3}T^3]$.

Conductance (G)

- It is the reciprocal of resistance i.e. $G = \frac{1}{R} \Rightarrow G = \frac{A}{\rho l} = \frac{\sigma A}{l}$. The SI unit of G is siemen (S).
- The dimensional formula is $[I^2M^{-1}L^{-2}T^3]$.

Relation between J, σ and E (Ohm's law in vector form)

Current density, conductivity and electric field are related by $J = \sigma E$. In vector form, $\vec{J} = \sigma\vec{E}$.

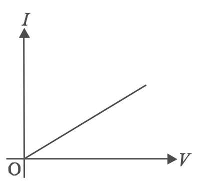
Limitations of Ohm's Law

1. Ohm's law is applicable only to metallic conductors at moderate temperatures and moderate potential differences.
2. Ohm's law cannot be applied

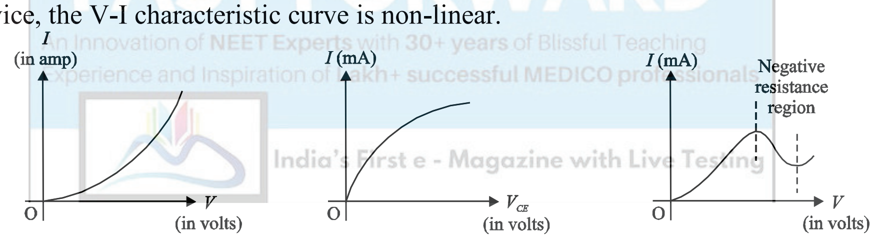
- to conductors maintained at very high temperatures or very low temperatures.
- to semiconductors and semi conducting devices.
- to conductors across which very high pd or very low pd is applied.

V-I characteristics

- The variation of current (I) with voltage (V) at various temperatures for any device is called its V-I characteristics.
- For an ohmic device, V-I characteristic is linear.
- For a non-ohmic device, the V-I characteristic curve is non-linear.



V-I characteristic of Ohmic device – Metal conductor



V-I characteristic of some non-ohmic devices

Effect of temperature on resistance

- The resistivity ρ of a material depends on its temperature. For a small variation of temperature, $\rho = \rho_0(1+\alpha(T-T_0))$, where α = temperature coefficient of resistance of the material.
- The resistance of a conductor at absolute temperature T is given by the relation $R_T = R_0(1+\alpha(T-T_0))$
- $\alpha = \frac{(R_T - R_0)}{R_0(T-T_0)} = \frac{1}{R_0}\left(\frac{\Delta R}{\Delta T}\right)$
- SI unit of α is $\frac{1}{kelvin}$ (K^{-1}).
- R versus t (°C) graph; y-intercept → R_0, slope = $R_0\alpha$

$$\Rightarrow \alpha = \frac{slope}{y\text{-}intercept}$$