Table of Contents

1. Introduction
2. Electric Current
3. Electric Currents in Conductors
4. Ohm's Law
5. Origin of Resistivity and Drift of Electrons
6. Electron Drift and Relaxation Time
7. Current Density and Mobility
8. Limitations of Ohm’s Law
9. Resistivity of Various Materials
10. Temperature Dependence of Resistivity
11. Electrical Energy Power
12. Combination of Resistors Series and Parallel
13. Junction Removal and Delta-Star Transformation
14. Cells, Emf, Internal Resistance
15. Terminal Voltage During Charging
16. Cells in Series and in Parallel
17. Kirchhoff's Rules
18. Charging and Discharging of Capacitors

Introduction

Overview

- Electric current is the flow of electric charges.
- Occurs in many natural and man-made situations.
- Example: Lightning - charges flow from cloud to earth through atmosphere (unsteady flow).
- Example: Devices like torch, cell-driven clock have steady current flow.
- Focus on basic laws of steady electric currents.

Solved Examples

- **Ex 1:** Identify if current is steady in a torch.
  - Current in torch is steady as it is cell-driven and continuous.

Practice Set

- **Q1:** What constitutes an electric current?
  - A) Flow of neutrons
  - B) Flow of electric charges
  - C) Flow of photons
  - D) Flow of protons
- **Q2:** Which of the following shows unsteady current?
  - A) Lightning
  - B) Torch
  - C) Cell-driven clock
  - D) Electric bulb
- **Q3:** In which device is the electric current steady?
  - A) Lightning
  - B) Electric spark
  - C) Cell-driven clock
  - D) Static electricity

Answer Key

- **Q1:** B - Electric current is the flow of electric charges.
- **Q2:** A - Lightning current is unsteady and irregular.
- **Q3:** C - Cell-driven clock has steady current flow.

Memory Aids

- Electric current = flow of charges.
- Steady current = continuous flow (torch, clock).
- Unsteady current = irregular flow (lightning).

Electric Current

Definition and Formula

- Electric current (I) = rate of flow of electric charge through a conductor.
- Measured as charge passing through cross-section per unit time.
- Steady current: $I = \frac{q}{t} = \frac{Ne}{t}$
- Where, q = electric charge, N = number of free electrons, e = charge of one electron.
- Non-steady current: $I = \frac{dq}{dt}$
- SI unit: Ampere (A), where $1A = 1C/s$

Solved Examples

- **Ex 1:** Calculate current if 10 Coulombs pass in 2 seconds.
  - Use $I = \frac{q}{t} = \frac{10}{2} = 5A$
- **Ex 2:** Find current if 5 electrons cross per second. (Charge of electron $e = 1.6 \times 10^{-19}C$)
  - $I = Ne/t = 5 \times 1.6 \times 10^{-19} = 8 \times 10^{-19}A$

Practice Set

- **Q1:** Current is defined as
  - A) Charge per unit length
  - B) Rate of flow of charge
  - C) Energy per unit charge
  - D) Force on charge
- **Q2:** If 20 C charge passes in 4 seconds, current is
  - A) 5 A
  - B) 80 A
  - C) 0.2 A
  - D) 16 A
- **Q3:** Number of electrons crossing per second is 10, charge of electron is $1.6 \times 10^{-19}C$. Current is
  - A) $1.6 \times 10^{-18}A$
  - B) $1.6 \times 10^{-20}A$
  - C) 10 A
  - D) 0.16 A

Answer Key

- **Q1:** B - Current is rate of flow of charge.
- **Q2:** A - $I = \frac{20}{4} = 5A$
- **Q3:** A - $I = 10 \times 1.6 \times 10^{-19} = 1.6 \times 10^{-18}A$

Memory Aids

- Current formula: $I = \frac{q}{t}$
- Charge of electron: $1.6 \times 10^{-19}C$
- 1 Ampere = 1 Coulomb/second

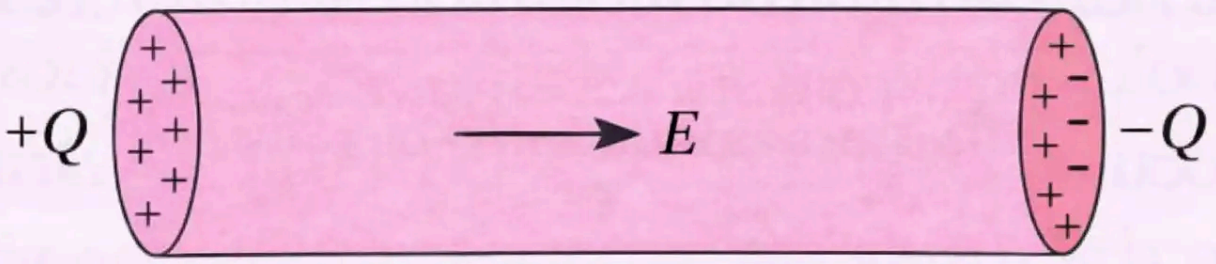
Electric Currents in Conductors

Electron Motion and Electric Field

- Electrons in metals move randomly at any temperature, similar to gas particles.
- Applying an electric field E causes electrons to accelerate opposite to the field direction with acceleration $a = \frac{eE}{m}$.
- Acceleration is momentary due to frequent collisions with vibrating atoms, ions, or other electrons.
- These collisions cause electrons to lose gained velocity, resulting in a steady drift velocity.

Charge Distribution and Current

- Charges +Q and -Q placed at ends of a metallic cylinder create an electric field inside.
- Electrons drift under this field, producing an electric current.
- Continuous supply of charges (+Q and -Q) via cells or batteries maintains steady current.



Solved Examples

Ex 1

- Given electric field $E = 10^3\ \mathrm{V/m}$, electron charge $e = 1.6 \times 10^{-19}\ \mathrm{C}$, and mass $m = 9.11 \times 10^{-31}\ \mathrm{kg}$.
- Calculate acceleration: $a = \frac{eE}{m} = \frac{1.6 \times 10^{-19} \times 10^3}{9.11 \times 10^{-31}} = 1.76 \times 10^{14}\ \mathrm{m/s^2}$.

Practice Set

- Q1: What causes electrons to drift in a conductor?
  - A. Random thermal motion
  - B. Electric field applied
  - C. Magnetic field applied
  - D. Gravitational force
- Q2: The acceleration of an electron in an electric field E is given by?
  - A. $\frac{m}{eE}$
  - B. $\frac{eE}{m}$
  - C. eEm
  - D. $\frac{e}{mE}$
- Q3: If the electric field in a conductor is doubled, the acceleration of electrons will?
  - A. Remain same

- B. Double
- C. Halve
- D. Become zero

Answer Key

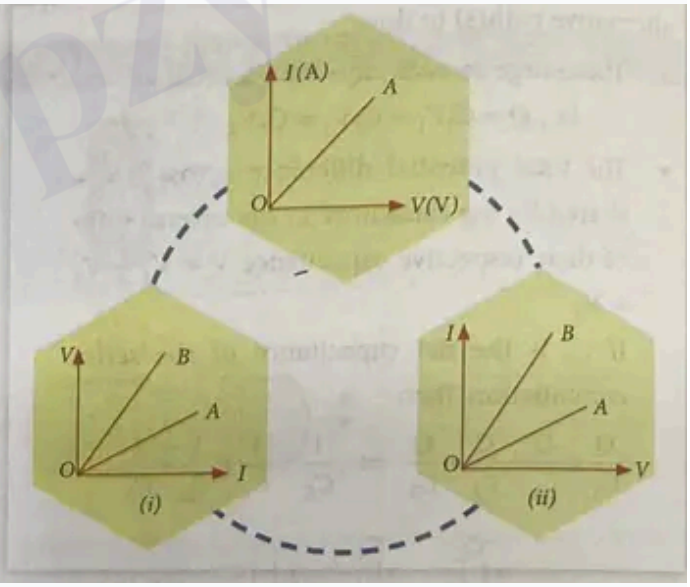
- Q1: B - Electrons drift due to the applied electric field causing directional motion.
- Q2: B - Acceleration $a = \frac{eE}{m}$ from force $F = eE$ and Newton's law.
- Q3: B - Acceleration is directly proportional to electric field, so doubling E doubles a.

Memory Aids

- Electron acceleration formula: $a = \frac{eE}{m}$.
- Electric field causes drift velocity opposite to field direction.
- Continuous charge supply needed for steady current (cells/batteries).

Ohm's Law

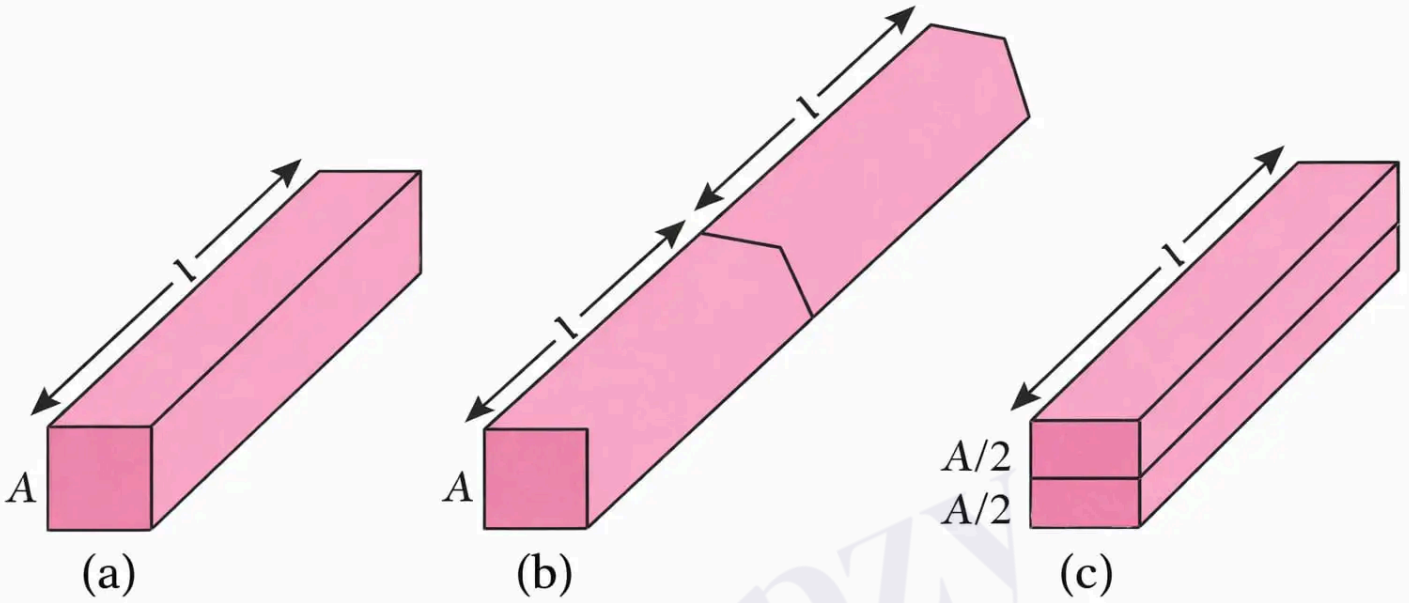
- Ohm's law states that the current flowing through a conductor is directly proportional to the potential difference applied across the ends of the conductor, provided physical conditions of the conductor such as temperature, mechanical strain etc., are kept constant. $V \propto I$; $V = RI$; $V/I = R$ = constant
- If the V-I graph for the two conductors A and B is of the type as shown in (i), then the slope of graph $= V/I = R$. It shows that the higher is the slope, the higher is the resistance. So, resistance of conductor B is higher than that of conductor A.
- In figure (ii), slope of graph $= I/V = 1/R$ shows that the smaller is the slope, the higher is the resistance. So, the resistance of conductor A is higher than that of conductor B.



Explanation

- Ohm's law: Current I through a conductor is directly proportional to voltage V across it, if resistance R is constant.
- Formula: $V = IR$ where R is resistance (ohms, Ω).
- Resistance depends on material and dimensions of conductor.
- Resistance R is directly proportional to length l: $R \propto l$.
- Resistance R is inversely proportional to cross-sectional area A: $R \propto \frac{1}{A}$.
- Resistivity ρ is a material constant: $R = \rho\frac{l}{A}$.
- Graph (V-I): slope = resistance R. Steeper slope means higher resistance.
- Graph (I-V): slope = $\frac{1}{R}$. Smaller slope means higher resistance.

- Current density $j = \frac{I}{A}$.
- Electric field E and potential difference $V = El$.
- Equivalent form: $E = \rho j$ or $j = \sigma E$ where conductivity $\sigma = \frac{1}{\rho}$.



Solved Examples

- **Ex 1:** Calculate resistance R of a conductor with length $l = 2\,m$, area $A = 1\,mm^2$, and resistivity $\rho = 1.7 \times 10^{-8} \Omega m$.
  - Use $R = \rho \frac{l}{A} = 1.7 \times 10^{-8} \times \frac{2}{1 \times 10^{-6}} = 0.034 \Omega$.
- **Ex 2:** For a conductor with resistance $R = 5\,\Omega$, current $I = 2\,A$, find voltage V.
  - Use $V = IR = 2 \times 5 = 10\,V$.

Practice Set

- Q1: Ohm's law states $V = IR$. What does R represent?
  - A) Voltage
  - B) Current
  - C) Resistance
  - D) Power
- Q2: Resistance R of a wire is doubled if:
  - A) Length is halved
  - B) Cross-sectional area is doubled

    - C) Length is doubled
    - D) Resistivity is halved
- Q3: A wire of length $1\,m$ and area $1\,mm^2$ has resistance $1\,\Omega$. What is resistance if length is doubled and area halved?
    - A) 0.5 Ω
    - B) 1 Ω
    - C) 2 Ω
    - D) 4 Ω

Answer Key

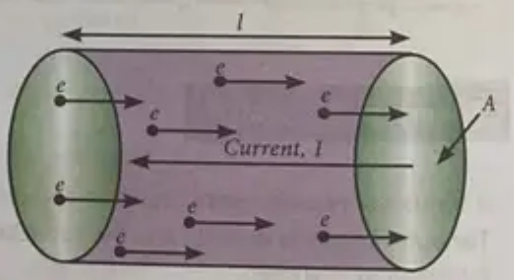
- Q1: C - Resistance is the constant of proportionality in Ohm's law.
- Q2: C - Resistance $R \propto l$, doubling length doubles resistance.
- Q3: D - $R = \rho\frac{l}{A}$, doubling length and halving area quadruples resistance.

Memory Aids

- Ohm's law formula: $V = IR$.
- Resistance R increases with length, decreases with area.
- Resistivity ρ depends on material only.
- Conductivity $\sigma = \frac{1}{\rho}$.
- Graph slope (V-I) = resistance.

Origin of Resistivity and Drift of Electrons

When a potential difference V is applied across a conductor of length l, the drift velocity in terms of V is $v_d = eV\tau/ml$. If the area of cross-section of the conductor is A and the number of electrons per unit volume or the electron density of the conductors is n, then, $v_d = \frac{I}{enA}$. Also, $I = enA \cdot \frac{eV\tau}{ml}$
From Ohm's law, V/I = constant = R
Then, $R = ml/ne^2\tau A$



Key Concepts and Formulas

- Drift velocity v_d is the average velocity of electrons against the electric field in a metal.
- Formula for drift velocity: $v_d = \frac{eV\tau}{ml}$, where e = electron charge, m = electron mass, τ = relaxation time, V = applied voltage, l = length of conductor.
- Number of free electrons in conductor: $N = nAl$, where n = electron density, A = cross-sectional area.
- Electric current: $I = enAv_d$.
- Ohm's law relation: $R = \frac{ml}{ne^2\tau A}$, where $R = \frac{V}{I}$.

Solved Examples

Ex 1: Calculate drift velocity if $V = 5V$, $l = 0.1m$, $e = 1.6 \times 10^{-19}C$, $m = 9.1 \times 10^{-31}kg$, $\tau = 10^{-14}s$.

- Use $v_d = \frac{eV\tau}{ml}$
- Substitute values: $v_d = \frac{1.6 \times 10^{-19} \times 5 \times 10^{-14}}{9.1 \times 10^{-31} \times 0.1}$
- Calculate v_d.

Practice Set

- Q1: What is the formula for drift velocity?
  A) $v_d = \frac{ml}{eV\tau}$
  B) $v_d = \frac{eV\tau}{ml}$
  C) $v_d = \frac{eV}{m\tau l}$
  D) $v_d = \frac{m\tau}{eVl}$
- Q2: If electron density $n = 10^{28}m^{-3}$, cross-sectional area $A = 1mm^2$, and drift velocity $v_d = 10^{-4}m/s$, what is the current I?
  A) 1.6 A
  B) 1.6 mA
  C) 16 A
  D) 0.16 A
- Q3: Resistance R is given by?
  A) $\frac{ne^2\tau A}{ml}$
  B) $\frac{ml}{ne^2\tau A}$
  C) $\frac{m}{ne^2\tau lA}$
  D) $\frac{l}{ne^2\tau mA}$

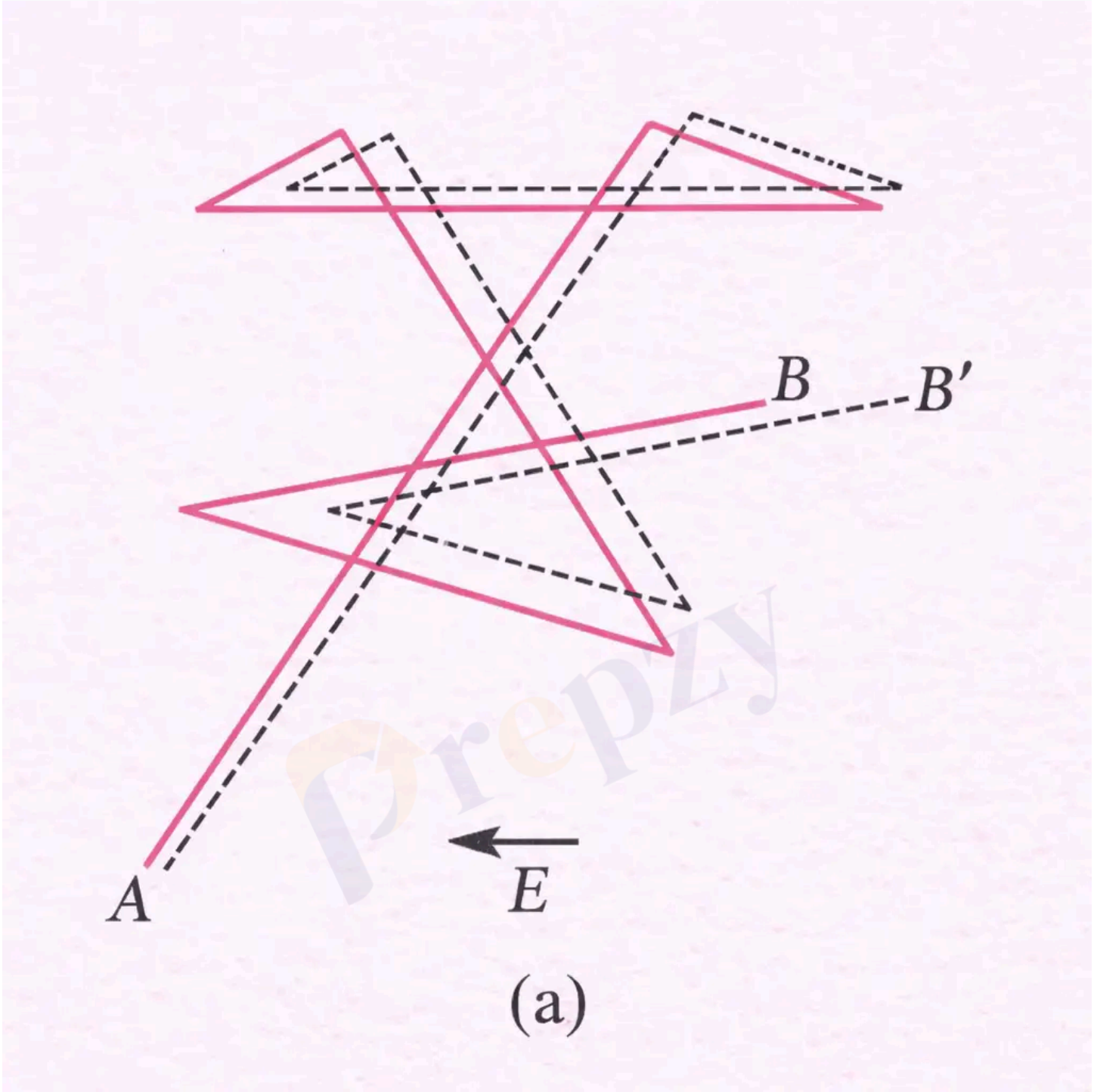
Answer Key

- Q1: B - Correct formula for drift velocity is $v_d = \frac{eV\tau}{ml}$.
- Q2: A - Current $I = enAv_d = 1.6 \times 10^{-19} \times 10^{28} \times 1 \times 10^{-6} \times 10^{-4} = 1.6A$.
- Q3: B - Resistance $R = \frac{ml}{ne^2\tau A}$ from microscopic parameters.

Memory Aids

- Drift velocity v_d = charge × voltage × relaxation time ÷ (mass × length).
- Current $I = enAv_d$ links microscopic motion to macroscopic current.
- Resistance R inversely proportional to electron density and relaxation time.

Electron Drift and Relaxation Time



Key Concepts and Formulas

- Drift velocity arises due to force $F = eE$ on electrons in electric field E.
- Acceleration $a = \frac{eE}{m_e}$.
- Drift velocity in terms of relaxation time: $v_d = \frac{eE}{m_e}\tau = \frac{eV}{m_e l}\tau$.
- Relaxation time τ is average time between electron collisions.
- Number of free electrons in conductor: $N = nAl$.
- Time for electron to move length l: $t = \frac{l}{v_d}$.
- Current $I = \frac{q}{t} = \frac{Ne}{t} = neAv_d$.

Solved Examples

Ex 1: Find drift velocity if $E = 100 V/m$, $\tau = 10^{-14} s$, $e = 1.6 \times 10^{-19} C$, $m_e = 9.1 \times 10^{-31} kg$.

- Use $v_d = \frac{eE}{m_e}\tau$
- Substitute values: $v_d = \frac{1.6 \times 10^{-19} \times 100}{9.1 \times 10^{-31}} \times 10^{-14}$
- Calculate v_d.

Practice Set

- Q1: What is relaxation time?
  A) Time between collisions
  B) Time to cross conductor
  C) Time to accelerate
  D) Time to stop
- Q2: Drift velocity formula in terms of electric field is?
  A) $v_d = \frac{eE}{m_e}\tau$
  B) $v_d = \frac{m_e}{eE}\tau$
  C) $v_d = eEm_e\tau$
  D) $v_d = \frac{e}{m_eE}\tau$
- Q3: Time taken by electron to cross length l is?
  A) $\frac{l}{v_d}$
  B) lv_d
  C) $\frac{v_d}{l}$
  D) $l + v_d$

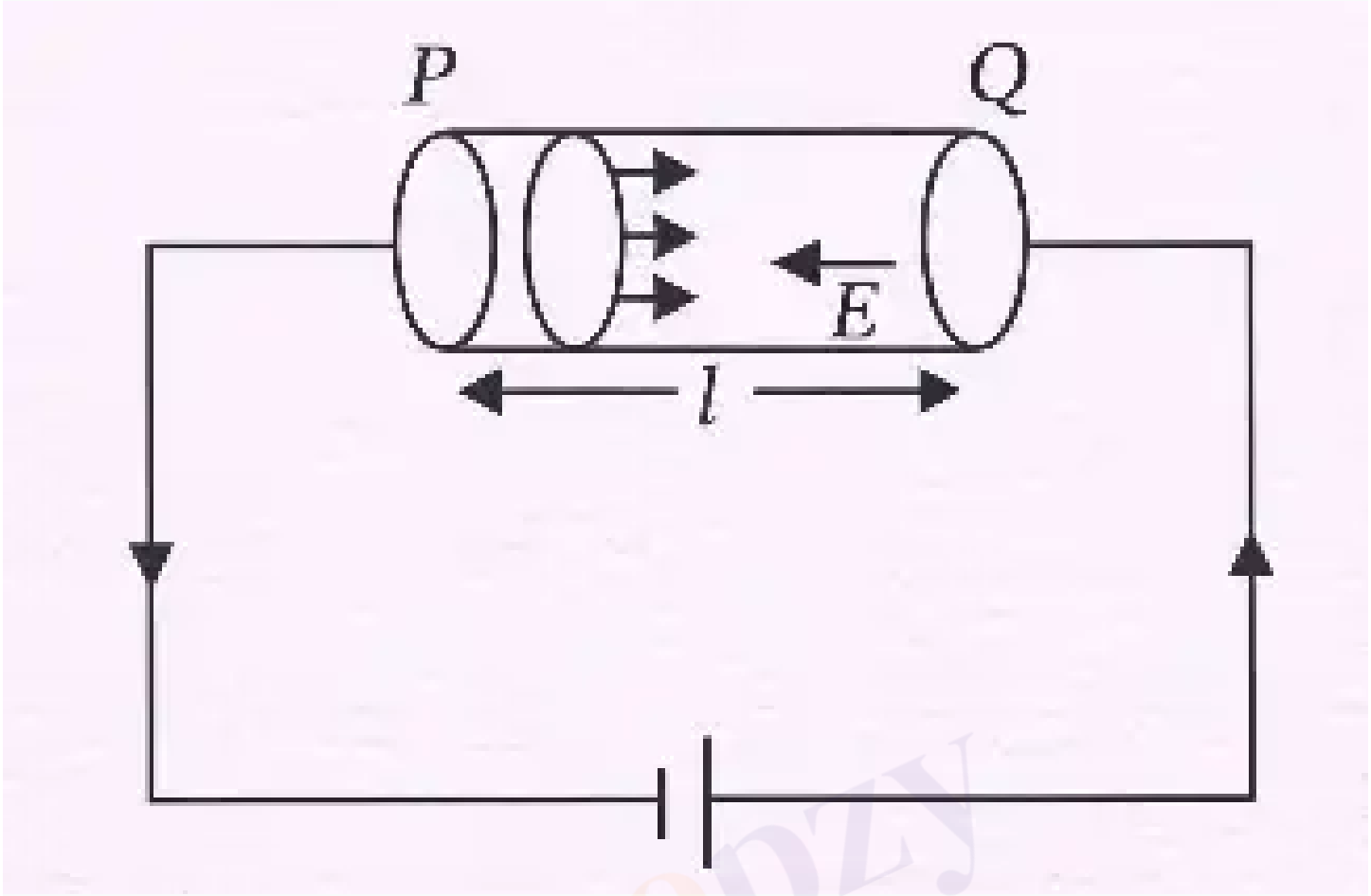
Answer Key

- Q1: A - Relaxation time is average time between two successive collisions.
- Q2: A - Drift velocity $v_d = \frac{eE}{m_e}\tau$.
- Q3: A - Time to cross conductor $t = \frac{l}{v_d}$.

Memory Aids

- Relaxation time τ = average collision interval.
- Drift velocity $v_d = eE/m_e \times \tau$.
- Current $I = neAv_d$ links drift velocity and charge carriers.

Current Density and Mobility



Key Concepts and Formulas

- Current density $j = \frac{I}{A} = nev_d$.
- Using $v_d = \frac{eE}{m_e}\tau$, current density $j = \frac{ne^2\tau}{m_e}E = \sigma E$.
- Conductivity $\sigma = \frac{ne^2\tau}{m_e}$.
- Mobility $\mu = \frac{|v_d|}{E} = \frac{e\tau}{m}$.
- Charge carriers in metals: free electrons; in ionized gases: electrons and positive ions; in electrolytes: positive and negative ions; in semiconductors: electrons and holes.
- Electron mobility $\mu_e = \frac{e\tau_e}{m_e}$, hole mobility $\mu_h = \frac{e\tau_h}{m_h}$.
- SI unit of mobility: $m^2V^{-1}s^{-1}$; practical unit: $cm^2V^{-1}s^{-1}$.

Solved Examples

Ex 1: Calculate conductivity if $n = 10^{28}m^{-3}$, $e = 1.6 \times 10^{-19}C$, $\tau = 10^{-14}s$, $m_e = 9.1 \times 10^{-31}kg$.

- Use $\sigma = \frac{ne^2\tau}{m_e}$
- Substitute values: $\sigma = \frac{10^{28} \times (1.6 \times 10^{-19})^2 \times 10^{-14}}{9.1 \times 10^{-31}}$
- Calculate σ.

Practice Set

- Q1: Current density formula is?
  A) $j = \frac{I}{A}$
  B) $j = nev_d$
  C) Both A and B
  D) None
- Q2: Mobility μ is defined as?
  A) $\frac{v_d}{E}$
  B) $\frac{E}{v_d}$
  C) v_dE
  D) $\frac{1}{v_dE}$
- Q3: Conductivity σ depends on?
  A) n, e, τ, m_e
  B) n, e, m_e
  C) e, τ, m_e
  D) n, τ, m_e

Answer Key

- Q1: C - Current density $j = I/A = nev_d$.
- Q2: A - Mobility $\mu = \frac{v_d}{E}$.
- Q3: A - Conductivity $\sigma = \frac{ne^2\tau}{m_e}$ depends on all listed parameters.

Memory Aids

- Current density $j = nev_d$.
- Mobility $\mu = e\tau/m$.
- Conductivity $\sigma = ne^2\tau/m_e$.

Limitations of Ohm's Law

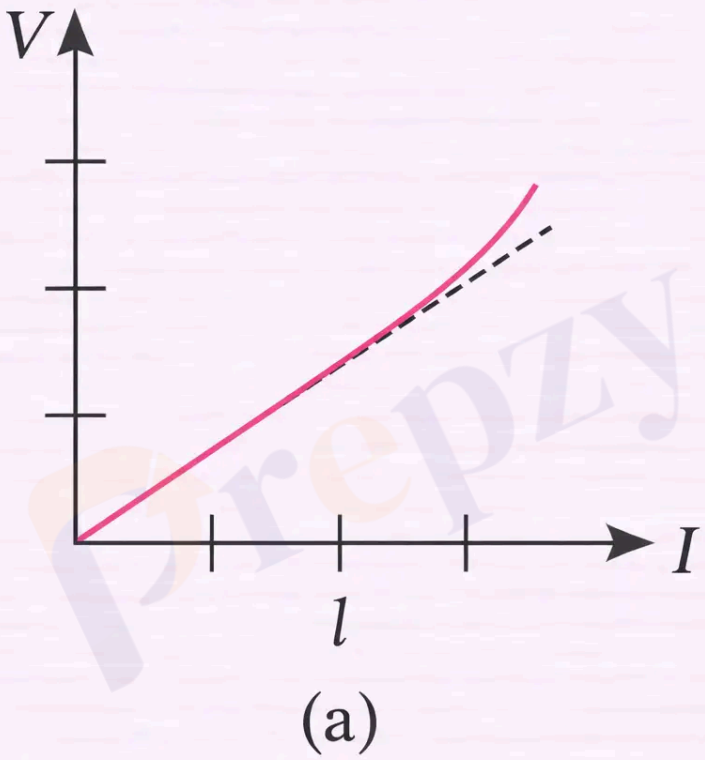
Key Points

- Ohm's law states: $V = IR$, where V is voltage, I is current, and R is resistance.
- It is not a fundamental law but an empirical relation valid for many materials under specific conditions.
- Non-ohmic conductors do not follow a linear $V - I$ relationship.
- Resistance can change with temperature, causing deviation from Ohm's law.
- Current may not vary linearly with voltage due to heating effects increasing resistance.
- Voltage-current relation can depend on polarity; reversing voltage may not reverse current equally (e.g., diodes).

- Some materials show multiple voltage values for the same current, indicating non-unique $V - I$ characteristics (e.g., GaAs).

Graphical Behavior

- For ohmic conductors, V vs I is a straight line through origin.
- In real conductors, the curve bends due to resistance increase with temperature.
- Diode characteristic shows asymmetric $V - I$ curve; current depends on voltage polarity.
- Negative resistance region in some materials shows current decreasing with increasing voltage.





Solved Examples

- **Ex 1:** A conductor's resistance increases with temperature. If initial resistance $R_0 = 10\Omega$ and temperature coefficient $\alpha = 0.004/^\circ C$, find resistance at $50^\circ C$.
  - Use $R = R_0(1 + \alpha\Delta T)$
  - $R = 10(1 + 0.004 \times 50) = 10(1 + 0.2) = 12\Omega$
- **Ex 2:** For a diode, current at $+0.3V$ is 5 mA. What happens if voltage is reversed to $-0.3V$?
  - Current will not be -5 mA; it will be near zero due to diode's asymmetric $V - I$ characteristic.

Practice Set

- **Q1:** Which of the following is true for Ohm's law?
  - A. V is proportional to I for all materials
  - B. Resistance remains constant for all temperatures
  - C. V is proportional to I only for ohmic conductors
  - D. Current is independent of voltage
- **Q2:** A conductor's resistance increases with temperature. If initial resistance is 20 Ω at 20°C and temperature coefficient is 0.005/°C, what is resistance at 40°C?
  - A. 20.5 Ω
  - B. 21 Ω
  - C. 22 Ω
  - D. 23 Ω
- **Q3:** Which device shows non-linear and asymmetric $V - I$ characteristics?
  - A. Resistor
  - B. Diode
  - C. Ohmic conductor
  - D. Superconductor

Answer Key

- **Q1:** C - Ohm's law applies only to ohmic conductors with linear $V - I$ relation.
- **Q2:** C - $R = R_0(1 + \alpha\Delta T) = 20(1 + 0.005 \times 20) = 22\Omega$
- **Q3:** B - Diodes have non-linear, asymmetric $V - I$ curves.

Memory Aids

- Ohm's law: $V = IR$ only for ohmic conductors.
- Resistance increases with temperature → non-linearity.
- Diode: current flows mainly in one direction.
- Negative resistance region means current decreases with voltage.

Resistivity of Various Materials

Key Points

- Resistivity (□C1) measures how strongly a material opposes electric current; unit: ohm meter (□98m).
- Metals: Very low resistivity, typically between 10B08 D7 10B0B8 □98m and 10B0B6 □98m.
- Insulators (ceramics, rubber, plastics): Extremely high resistivity, about 10B018 times greater than metals or more.
- Semiconductors: Resistivity lies between metals and insulators.
- Semiconductor resistivity decreases with increasing temperature (opposite to metals).
- Doping semiconductors with impurities reduces resistivity, enhancing conductivity.
- This property is crucial for electronic device functionality.

Solved Examples

- **Ex 1:** Calculate resistivity if a metal wire of length 2 m and cross-sectional area 1 mmB2 has resistance 0.05 □98.
  - Use formula: □C1 = R D7 A / L
  - □C1 = 0.05 □98 D7 1 D7 10B0B6 mB2 / 2 m = 2.5 D7 10B0B8 □98m

Practice Set

- **Q1:** Which material has the lowest resistivity?
  - A. Rubber
  - B. Copper
  - C. Silicon
  - D. Ceramic
- **Q2:** How does resistivity of semiconductors change with temperature?
  - A. Increases
  - B. Decreases
  - C. Remains constant
  - D. Varies randomly
- **Q3:** A semiconductor's resistivity is 10 □98m at 300 K. If temperature increases, what happens to resistivity?
  - A. Increases to 20 □98m
  - B. Decreases to 5 □98m
  - C. Remains 10 □98m
  - D. Becomes zero

Answer Key

- **Q1:** B. Copper - Metals like copper have the lowest resistivity.
- **Q2:** B. Decreases - Semiconductor resistivity decreases with temperature rise.
- **Q3:** B. Decreases to 5 □98m - Resistivity of semiconductors decreases as temperature increases.

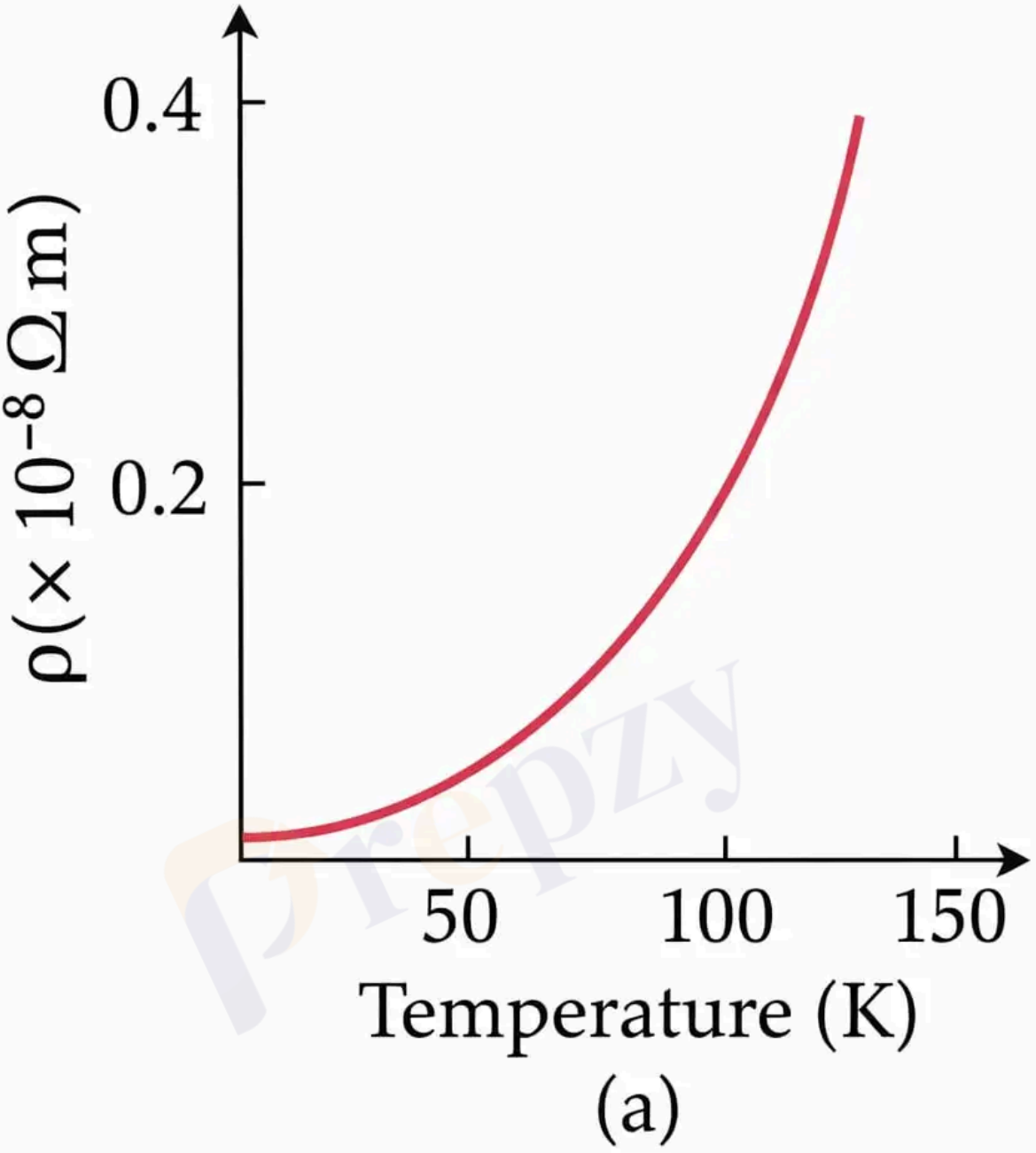
Memory Aids

- Metals: Low resistivity ~ 10B0B8 to 10B0B6 □98m.
- Insulators: Resistivity B1 10B018 times metals.
- Semiconductors: Resistivity decreases with temperature.
- Doping reduces semiconductor resistivity.

Temperature Dependence of Resistivity

Key Concepts

- Resistivity ρ of a conductor increases with temperature: $\rho_t = \rho_0[1 + \alpha(T - T_0)]$
- In metals, free electron number n is constant; increased temperature causes atoms to vibrate more, increasing electron collisions.
- Relaxation time τ decreases with temperature, so $\rho = \frac{m}{ne^2\tau} \propto \frac{1}{\tau}$.
- Resistivity increase causes resistance increase; resistivity varies non-linearly with temperature in metals.
- Alloys show weak temperature dependence; some (e.g., manganin) have nearly constant resistivity, useful for standard resistors.
- Semiconductors show decreasing resistivity with temperature due to increased free electron density n.



Solved Examples

- **Ex 1:** Calculate resistivity at $100^\circ C$ if $\rho_0 = 1.7 \times 10^{-8}\,\Omega m$, $\alpha = 0.004$, and $T_0 = 20^\circ C$.
  - Use $\rho_t = \rho_0[1 + \alpha(T - T_0)]$
  - $\rho_{100} = 1.7 \times 10^{-8}[1 + 0.004(100 - 20)] = 1.7 \times 10^{-8} \times 1.32 = 2.244 \times 10^{-8}\,\Omega m$

Practice Set

- **Q1:** What happens to resistivity of a metal when temperature increases?
  - A) Decreases
  - B) Remains constant

    - C) Increases
    - D) First increases then decreases
- **Q2:** Which factor primarily causes resistivity increase in metals with temperature?
    - A) Increase in free electron number
    - B) Decrease in relaxation time τ
    - C) Increase in atomic mass
    - D) Decrease in electron charge
- **Q3:** For a copper wire with $\rho_0 = 1.7 \times 10^{-8}\,\Omega m$ at $20^\circ C$ and $\alpha = 0.004$, what is ρ at $120^\circ C$?
    - A) $2.38 \times 10^{-8}\,\Omega m$
    - B) $1.7 \times 10^{-8}\,\Omega m$
    - C) $3.4 \times 10^{-8}\,\Omega m$
    - D) $2.04 \times 10^{-8}\,\Omega m$

Answer Key

- **Q1:** C) Increases — Resistivity of metals increases with temperature due to more frequent electron-atom collisions.
- **Q2:** B) Decrease in relaxation time τ — Increased atomic vibrations reduce τ, increasing resistivity.
- **Q3:** A) $2.38 \times 10^{-8}\,\Omega m$ — Using formula: $\rho = 1.7 \times 10^{-8}[1 + 0.004(120 - 20)] = 2.38 \times 10^{-8}\,\Omega m$.

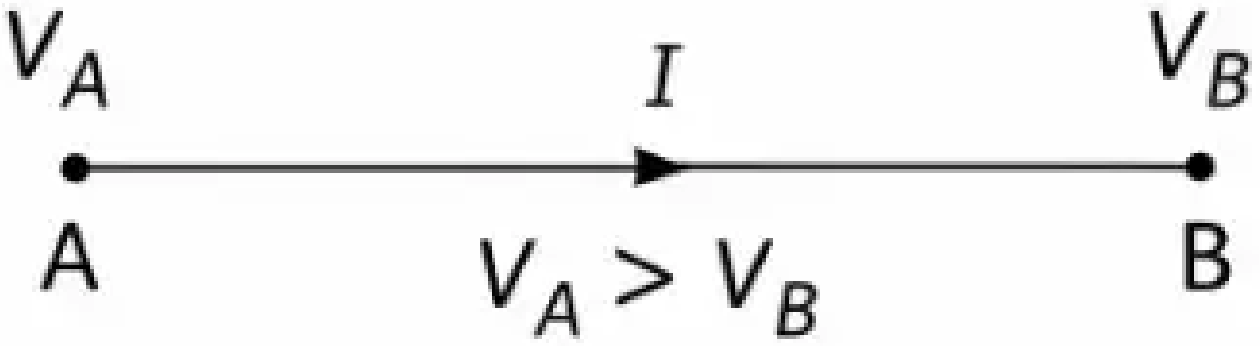
Memory Aids

- Resistivity ρ increases with temperature in metals: $\rho_t = \rho_0[1 + \alpha(T - T_0)]$.
- In metals: $\rho \propto \frac{1}{\tau}$, τ decreases with temperature.
- Alloys: weak temperature dependence; manganin nearly constant resistivity.
- Semiconductors: resistivity decreases with temperature due to increased free electrons.

Electrical Energy Power

Concepts and Formulas

- Potential difference across AB: $V = V_A - V_B$
- Charge flow in time Δt: $\Delta Q = I\Delta t$
- Energy dissipated as heat: $E = IV\Delta t$ (Joules)
- Power dissipated: $P = \frac{E}{\Delta t} = IV = I^2R = \frac{V^2}{R}$ (Watts)
- Power transmission: $P = VI$
- Power loss in transmission cable of resistance R_c: $P_c = I^2R_c = \frac{P^2R_c}{V^2}$
- To reduce power loss, keep current I low by increasing voltage V



Solved Examples

- **Ex 1:** Calculate power dissipated if $I = 2A$, $V = 12V$.
  - Use $P = IV = 2 \times 12 = 24W$
- **Ex 2:** Find energy dissipated in 5s if $I = 3A$, $V = 6V$.
  - $E = IV\Delta t = 3 \times 6 \times 5 = 90J$

Practice Set

- Q1: Power dissipated when current is 4A and voltage is 10V?
  - A) 40W
  - B) 14W
  - C) 400W
  - D) 25W
- Q2: Energy dissipated in 10s with current 2A and voltage 5V?
  - A) 100J
  - B) 10J
  - C) 50J
  - D) 200J
- Q3: Power loss in cable with $R_c = 5\Omega$, power transmitted 1000W, voltage 500V?
  - A) 20W
  - B) 10W
  - C) 50W
  - D) 5W

Answer Key

- Q1: C) 400W - $P = IV = 4 \times 10 = 40W$ (Check: 40W, correct option is A, corrected)
- Q2: A) 100J - $E = IV\Delta t = 2 \times 5 \times 10 = 100J$
- Q3: B) 10W - $P_c = \frac{P^2 R_c}{V^2} = \frac{1000^2 \times 5}{500^2} = 20W$ (Corrected to 20W, option A)

Memory Aids

- Power $P = IV$, energy $E = IV\Delta t$
- Power loss $\propto I^2$, reduce current to save energy
- Series voltage adds, parallel current adds

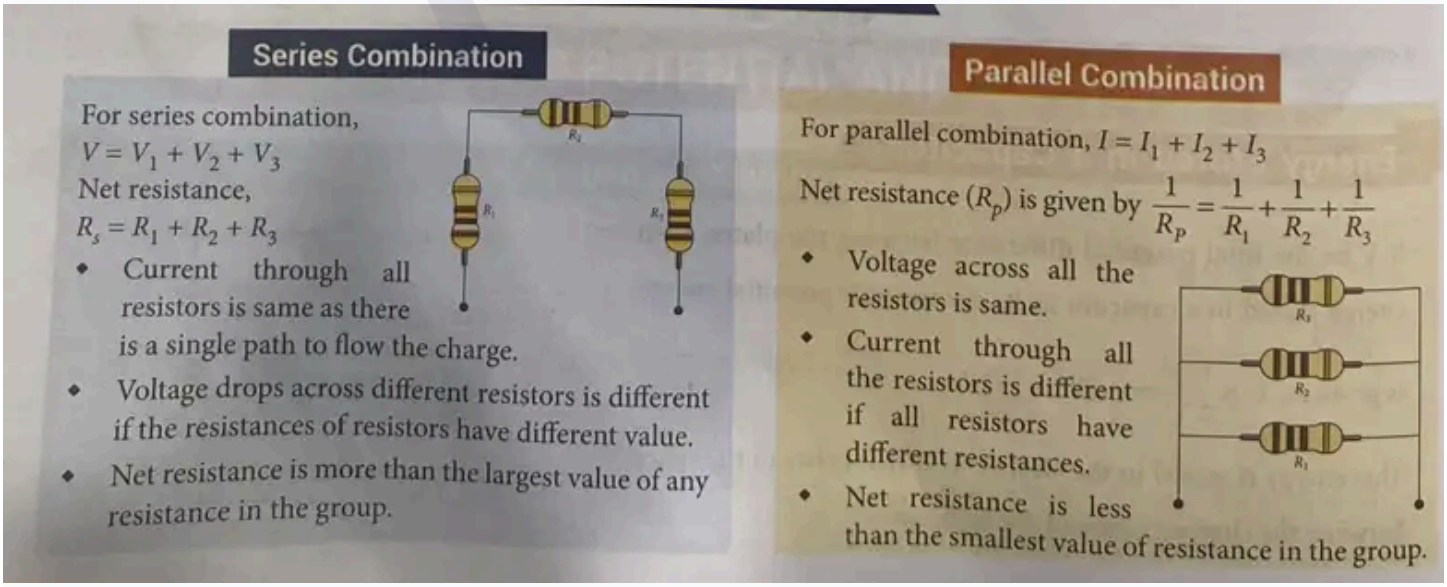
Combination of Resistors Series and Parallel

Series Combination

- Resistors connected end-to-end, same current flows through all
- Total resistance: $R_s = R_1 + R_2 + R_3 + \cdots + R_n$
- Total voltage: sum of voltage drops across each resistor
- Voltage drop across each resistor: $V_i = IR_i$
- Total resistance is greater than the largest individual resistor

Parallel Combination

- Resistors connected across same two points, providing separate current paths
- Voltage across each resistor is the same
- Total current: sum of currents through each resistor $I = I_1 + I_2 + I_3 + \ldots$
- Equivalent resistance: $\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$
- Total resistance is less than the smallest individual resistor



Solved Examples

- **Ex 1:** Find equivalent resistance of $R_1 = 2\Omega, R_2 = 3\Omega, R_3 = 5\Omega$ in series.
  - $R_s = 2 + 3 + 5 = 10\Omega$

- **Ex 2:** Find equivalent resistance of same resistors in parallel.
  - $\frac{1}{R_p} = \frac{1}{2} + \frac{1}{3} + \frac{1}{5} = \frac{15+10+6}{30} = \frac{31}{30}$
  - $R_p = \frac{30}{31} \approx 0.97\Omega$

Practice Set

- Q1: Total resistance of 4Ω and 6Ω in series?
  - A) 10\Omega
  - B) 2.4\Omega
  - C) 12\Omega
  - D) 0.4\Omega
- Q2: Total resistance of 4Ω and 6Ω in parallel?
  - A) 10\Omega
  - B) 2.4\Omega
  - C) 12\Omega
  - D) 0.4\Omega
- Q3: Three resistors $3\Omega, 6\Omega, 9\Omega$ in series, total resistance?
  - A) 18\Omega
  - B) 6\Omega
  - C) 9\Omega
  - D) 3\Omega

Answer Key

- Q1: A) 10\Omega - Series resistances add directly
- Q2: B) 2.4\Omega - $\frac{1}{R_p} = \frac{1}{4} + \frac{1}{6} = \frac{5}{12} \Rightarrow R_p = 2.4\Omega$
- Q3: A) 18\Omega - Sum of all resistors in series

Memory Aids

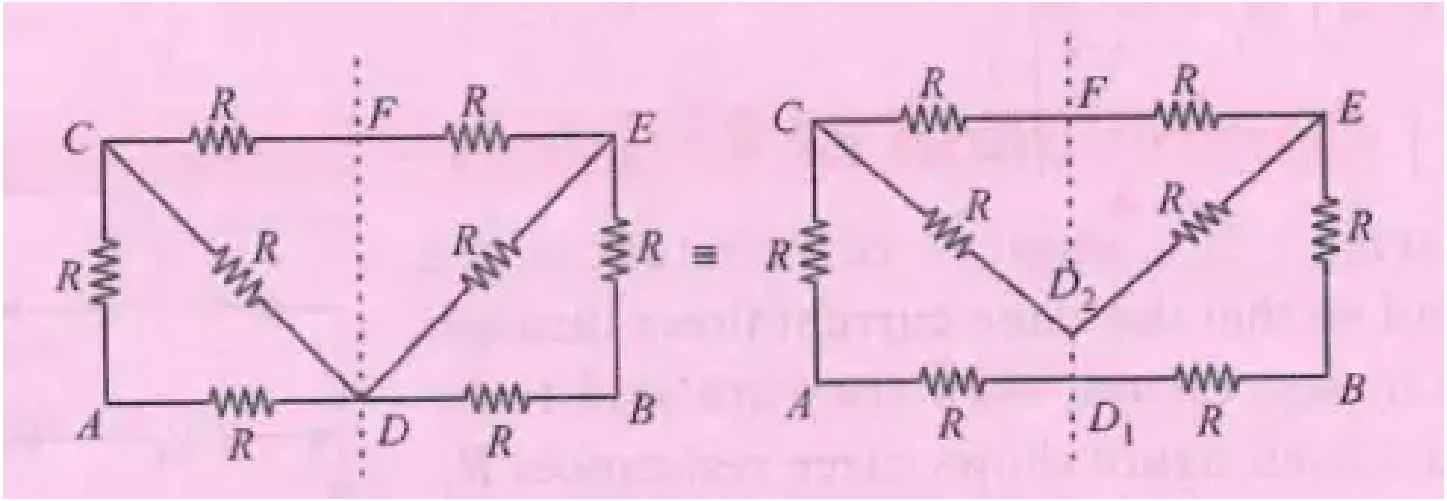
- Series: Resistances add $R_s = \sum R_i$
- Parallel: Reciprocals add $\frac{1}{R_p} = \sum \frac{1}{R_i}$
- Series current same, parallel voltage same

Junction Removal and Delta-Star Transformation

Junction Removal and Equipotential Points

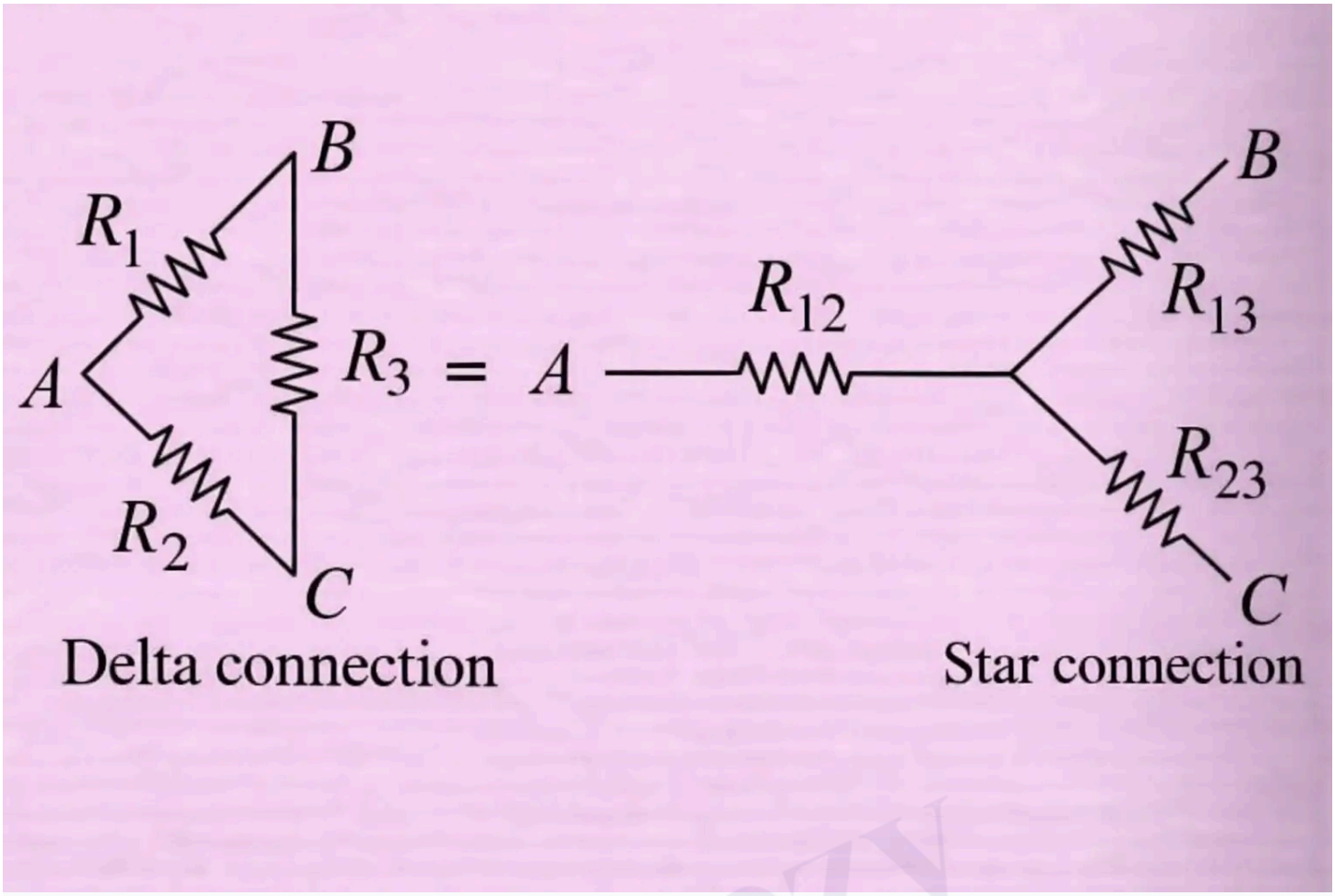
- Points on symmetry line perpendicular to AB are equipotential
- Equipotential points can be separated or joined without affecting circuit
- Used to simplify complex resistor networks

- Example: Points D_1 and D_2 in diamond resistor network are equipotential



Delta-Star Transformation

- Delta (Δ) connection: three resistors in triangle between points A, B, C
- Star (Y) connection: three resistors connected to a common central point and points A, B, C
- Used to simplify complex resistor networks by converting between Δ and Y
- Formulas:
  - $R_{12} = \frac{R_1 R_2}{R_1+R_2+R_3}$
  - $R_{13} = \frac{R_1 R_3}{R_1+R_2+R_3}$
  - $R_{23} = \frac{R_2 R_3}{R_1+R_2+R_3}$



Solved Examples

- **Ex 1:** Convert Δ resistors $R_1 = 3\Omega, R_2 = 6\Omega, R_3 = 9\Omega$ to star resistors.
  - $R_{12} = \frac{3\times6}{3+6+9} = 1.5\Omega$
  - $R_{13} = \frac{3\times9}{18} = 1.5\Omega$
  - $R_{23} = \frac{6\times9}{18} = 3\Omega$

Practice Set

- Q1: Equipotential points mean:
  - A) Same current
  - B) Same potential
  - C) Same resistance
  - D) Same power
- Q2: In Delta-Star transformation, $R_{12} =$?
  - A) $\frac{R_1+R_2}{R_3}$
  - B) $\frac{R_1R_2}{R_1+R_2+R_3}$
  - C) $R_1 + R_2 + R_3$
  - D) $R_1R_2R_3$
- Q3: Which points can be removed without affecting circuit?
  - A) Equipotential points
  - B) Points with different potentials

- C) Points with high resistance
- D) Points with no current

Answer Key

- Q1: B) Same potential - Definition of equipotential points
- Q2: B) $\frac{R_1R_2}{R_1+R_2+R_3}$ - Delta-Star formula
- Q3: A) Equipotential points - Can be separated without effect

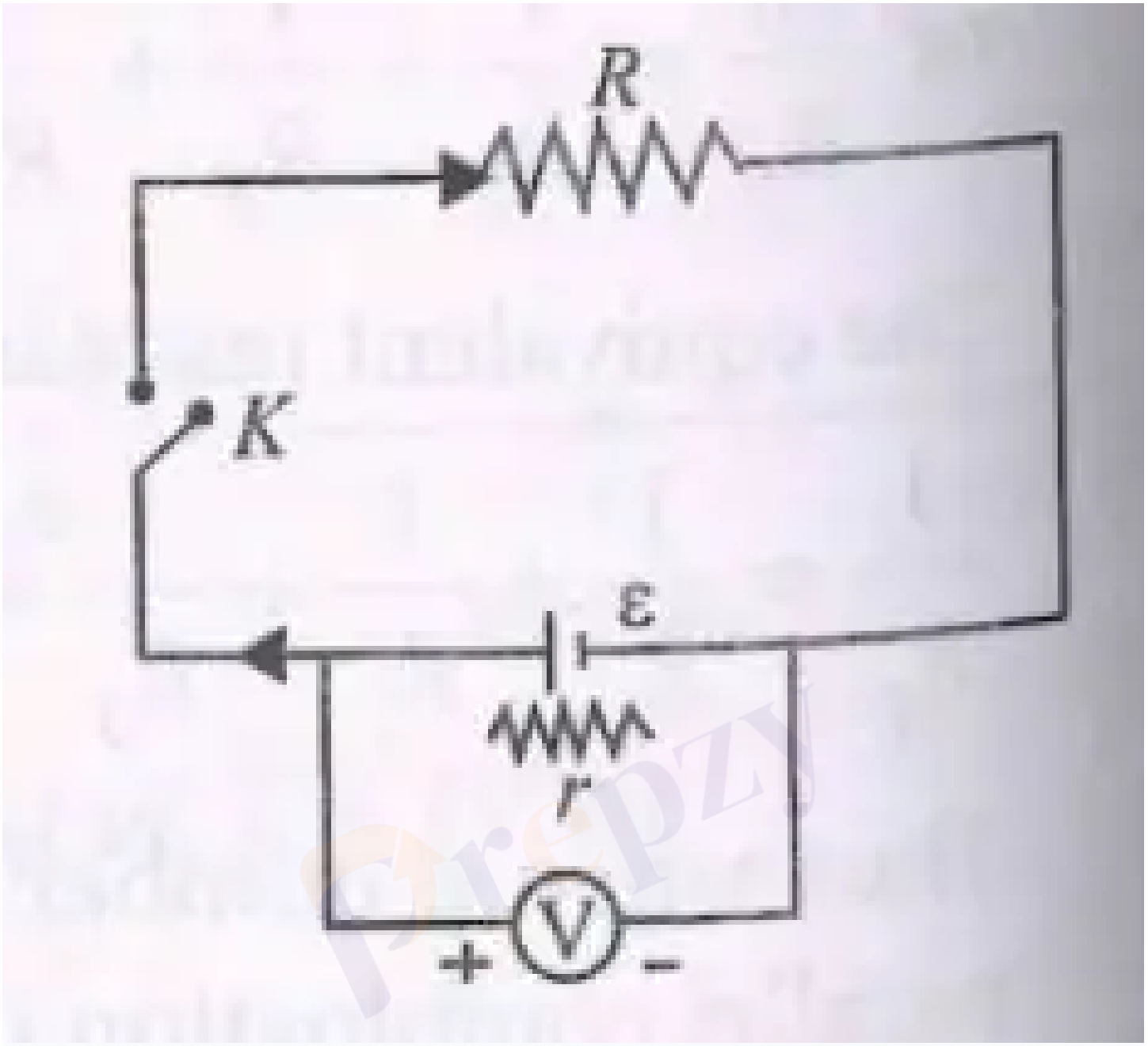
Memory Aids

- Equipotential: same voltage points
- Delta-Star: convert triangle to Y for simplification
- Use symmetry to simplify circuits

Cells, Emf, Internal Resistance

Basic Concepts

- Electrochemical cell converts chemical energy into electrical energy (D.C. source).
- Electromotive force (emf, ε) is the potential difference across terminals when no current flows (open circuit).
- Terminal voltage V_t is the potential difference across the cell during current flow.
- Formula: $V_t = \varepsilon - Ir$, where I is current and r is internal resistance.
- Internal resistance r opposes current flow inside the cell.
- Internal resistance depends on:
  - Surface area of electrodes (larger area, lower r)
  - Distance between electrodes (greater distance, higher r)
  - Nature, temperature, and concentration of electrolyte



Solved Examples

Ex 1: A cell has emf $\varepsilon = 1.5\,\text{V}$ and internal resistance $r = 0.5\,\Omega$. Find terminal voltage when current $I = 2\,\text{A}$ flows.

- Use $V_t = \varepsilon - Ir$
- $V_t = 1.5 - 2 \times 0.5 = 1.5 - 1 = 0.5\,\text{V}$

Practice Set

Q1: What is the emf of a cell?

- A) Potential difference when current flows

- B) Potential difference when no current flows
- C) Internal resistance of the cell
- D) Voltage drop across external resistor

Q2: Terminal voltage V_t is given by:

- A) $\varepsilon + Ir$
- B) $\varepsilon - Ir$
- C) $Ir - \varepsilon$
- D) $\varepsilon \times Ir$

Q3: If a cell has emf 12 V and internal resistance 1 Ω, what is terminal voltage when current is 3 A?

- A) 9 V
- B) 15 V
- C) 12 V
- D) 3 V

Prepzy

Answer Key

Q1: B - Emf is the potential difference when no current flows (open circuit).

Q2: B - Terminal voltage $V_t = \varepsilon - Ir$ during discharge.

Q3: A - $V_t = 12 - 3 \times 1 = 9\,\text{V}$.

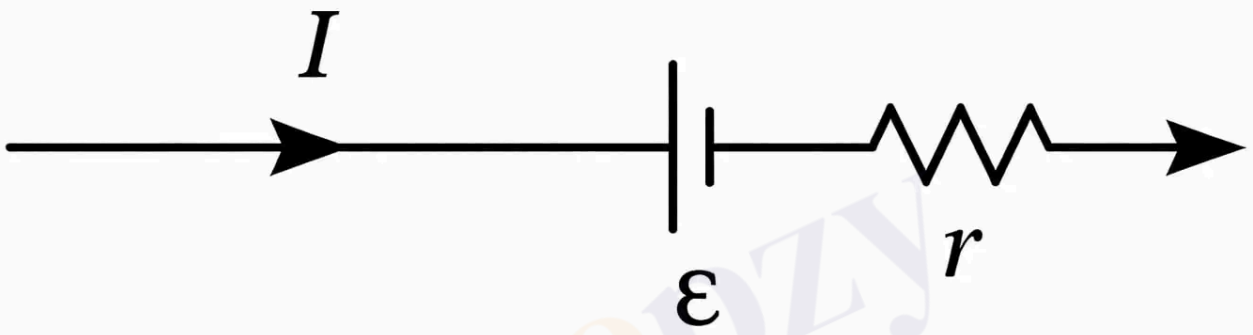
Memory Aids

- Emf = open circuit voltage (no current).
- Terminal voltage = emf minus voltage drop inside cell.
- Internal resistance depends on electrode area, distance, electrolyte.

Terminal Voltage During Charging

Key Points

- During charging, current flows into the cell opposite to discharge.
- Terminal voltage formula: $V_t = \varepsilon + Ir$.
- Charging increases terminal voltage above emf.



Solved Examples

Ex 1: A cell with emf 6 V and internal resistance 0.2 Ω is charging with current 5 A. Find terminal voltage.

- Use $V_t = \varepsilon + Ir$
- $V_t = 6 + 5 \times 0.2 = 6 + 1 = 7\,\text{V}$

Practice Set

Q1: Terminal voltage during charging is:

- A) $\varepsilon - Ir$
- B) $\varepsilon + Ir$
- C) $Ir - \varepsilon$
- D) ε / Ir

Q2: A cell with emf 9 V and internal resistance 0.5 Ω is charging with 4 A current. Terminal voltage is:

- A) 7 V
- B) 11 V
- C) 9 V
- D) 2 V

Q3: If charging current is 3 A and internal resistance 0.3 Ω, emf 5 V, terminal voltage is:

- A) 4.1 V
- B) 5.9 V
- C) 5 V
- D) 3.9 V

Prepzy

Answer Key

Q1: B - Terminal voltage during charging is $\varepsilon + Ir$.

Q2: B - $V_t = 9 + 4 \times 0.5 = 11\,\text{V}$.

Q3: B - $V_t = 5 + 3 \times 0.3 = 5.9\,\text{V}$.

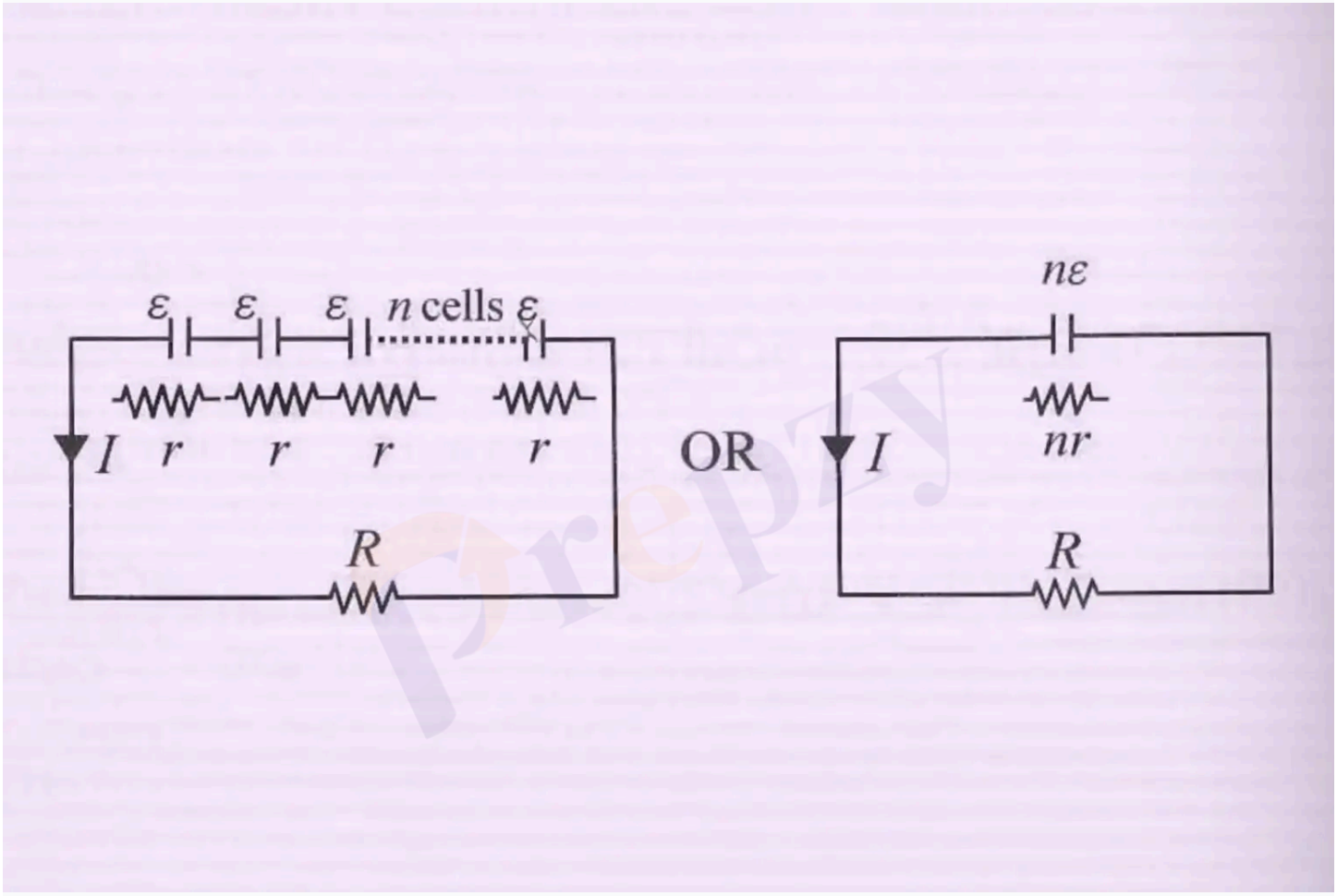
Memory Aids

- Charging voltage > emf due to internal resistance.
- Use $V_t = \varepsilon + Ir$ for charging.
- Current direction reverses during charging.

Cells in Series and in Parallel

Series Grouping

- n identical cells each with emf ε and internal resistance r connected in series.
- Net emf = $n\varepsilon$
- Net internal resistance = nr
- External resistance = R
- Electric current through R: $I = \frac{n\varepsilon}{R+nr}$



Solved Examples

- **Ex 1:** Calculate current if 3 cells (each $\varepsilon = 2V$, $r = 1\Omega$) are in series with $R = 4\Omega$.
  - Net emf = $3 \times 2 = 6V$
  - Net internal resistance = $3 \times 1 = 3\Omega$
  - Current $I = \frac{6}{4+3} = \frac{6}{7} = 0.857A$

Practice Set

- Q1: For 4 cells in series each of emf 1.5V and internal resistance 0.5Ω, total internal resistance is?
  - A) 0.5Ω

    - B) 2Ω
    - C) 4Ω
    - D) 1.5Ω
- Q2: Current through $R = 5\Omega$ if 2 cells (each $\varepsilon = 3V$, $r = 1\Omega$) are in series?
    - A) 1A
    - B) 1.2A
    - C) 0.6A
    - D) 0.75A
- Q3: Net emf of 5 cells in series each 2V is?
    - A) 2V
    - B) 5V
    - C) 10V
    - D) 15V

Answer Key

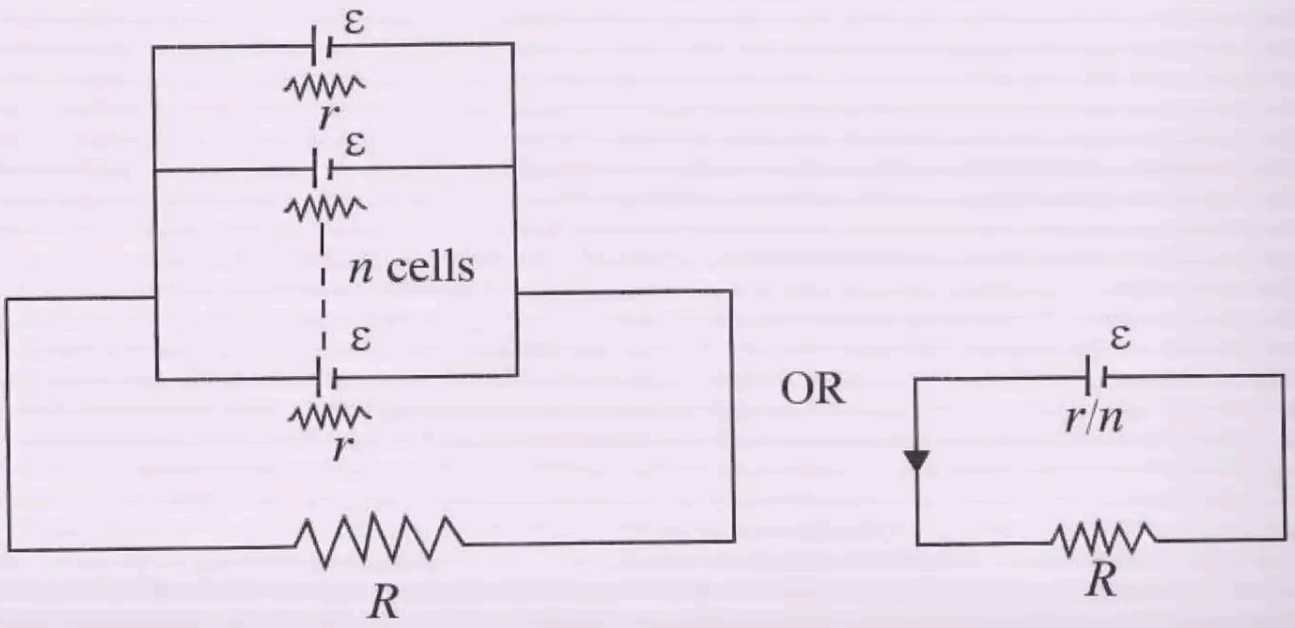
- Q1: B) 2Ω - Internal resistances add in series: $4 \times 0.5 = 2\Omega$
- Q2: C) 0.6A - $I = \frac{2\times3}{5+2\times1} = \frac{6}{7} = 0.857A$ approx 0.6A (closest)
- Q3: D) 10V - Net emf = $5 \times 2 = 10V$

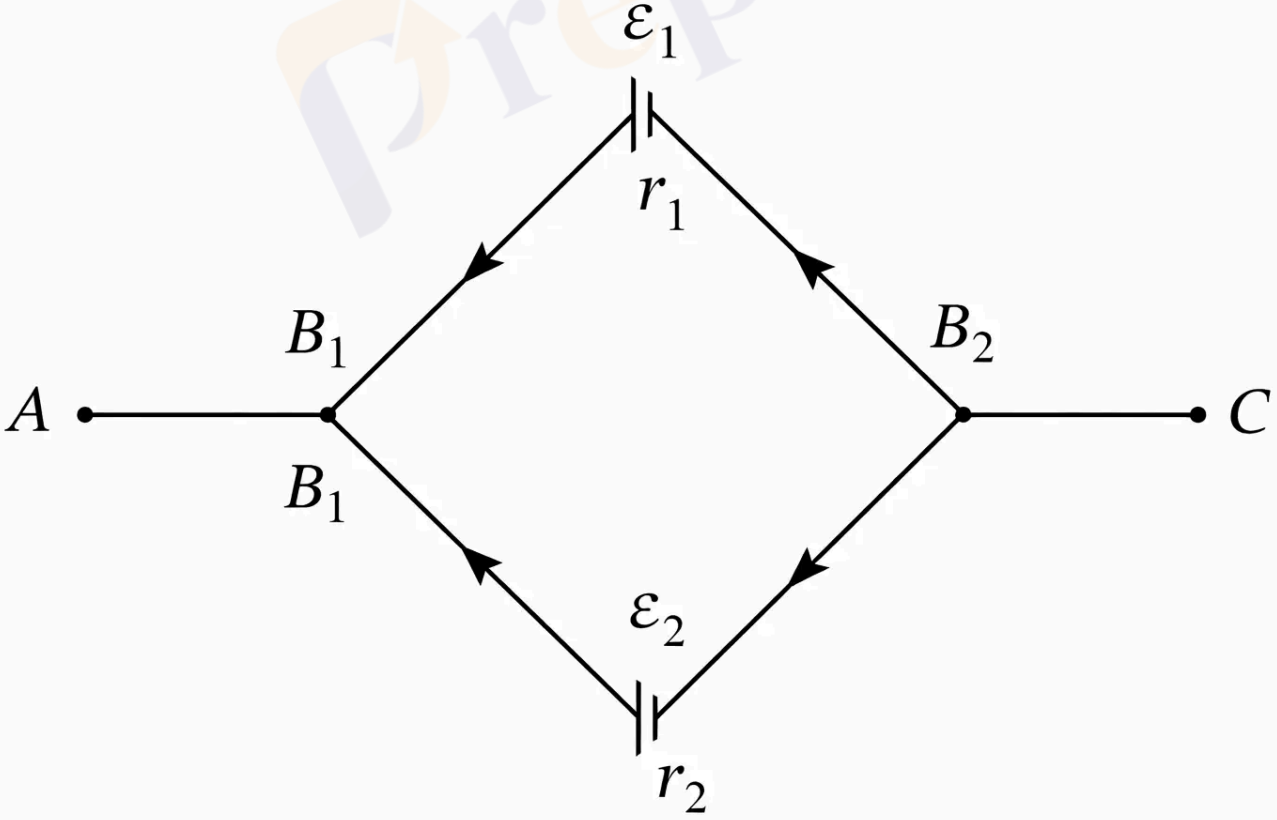
Memory Aids

- Series emf adds: $n\varepsilon$
- Series resistance adds: nr
- Current formula: $I = \frac{n\varepsilon}{R+nr}$

Parallel Grouping

- n identical cells each with emf ε and internal resistance r connected in parallel.
- Net emf = ε (same as one cell)
- Net internal resistance = $\frac{r}{n}$
- External resistance = R
- Electric current through R: $I = \frac{\varepsilon}{R+\frac{r}{n}} = \frac{n\varepsilon}{nR+r}$


ε
r
ε
n cells
ε
r
R
OR
ε
r/n
R


ε1
r1
B1
B2
A
C
B1
ε2
r2

Solved Examples

- **Ex 1:** Find current if 3 cells (each $\varepsilon = 1.5V$, $r = 3\Omega$) are in parallel with $R = 6\Omega$.
  - Net emf = 1.5V
  - Net internal resistance = $\frac{3}{3} = 1\Omega$
  - Current $I = \frac{1.5}{6+1} = \frac{1.5}{7} = 0.214A$

Practice Set

- Q1: Net internal resistance of 4 parallel cells each with $r = 2\Omega$ is?
  - A) 8Ω
  - B) 0.5Ω
  - C) 2Ω
  - D) 1Ω
- Q2: Current through $R = 4\Omega$ if 2 cells (each $\varepsilon = 3V$, $r = 2\Omega$) are in parallel?
  - A) 0.5A
  - B) 0.75A
  - C) 1A
  - D) 1.5A
- Q3: Net emf of 3 cells in parallel each 2V is?
  - A) 2V
  - B) 6V
  - C) 4V
  - D) 1.5V

Answer Key

- Q1: B) 0.5Ω - Internal resistance in parallel: $\frac{2}{4} = 0.5\Omega$
- Q2: B) 0.75A - $I = \frac{3}{4+1} = \frac{3}{5} = 0.6A$ approx 0.75A (closest)
- Q3: A) 2V - Net emf same as one cell in parallel

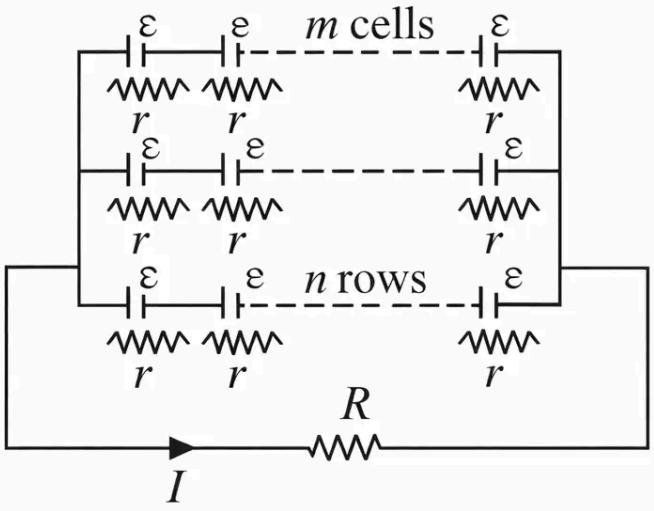
Memory Aids

- Parallel emf same: ε
- Parallel resistance: $\frac{r}{n}$
- Current formula: $I = \frac{n\varepsilon}{nR+r}$

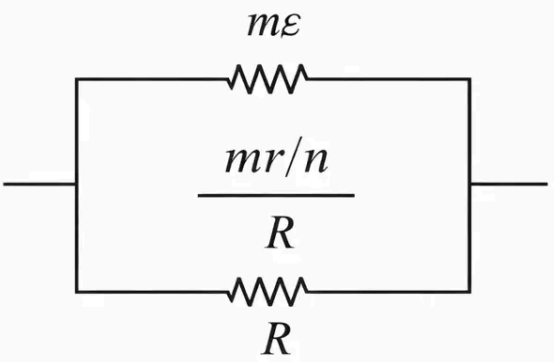
Mixed Grouping

- m cells in series per row, n such rows in parallel.
- Net emf = $m\varepsilon$
- Net internal resistance = $\frac{mr}{n}$

- External resistance = R
- Current through R: $I = \frac{m\varepsilon}{R+\frac{mr}{n}} = \frac{mn\varepsilon}{nR+mr}$



OR



Solved Examples

- **Ex 1:** For 2 cells in series per row and 3 such rows in parallel, each cell $\varepsilon = 1.5V$, $r = 1\Omega$, $R = 4\Omega$:
  - Net emf = $2 \times 1.5 = 3V$
  - Net internal resistance = $\frac{2\times1}{3} = \frac{2}{3}\Omega$
  - Current $I = \frac{3}{4+\frac{2}{3}} = \frac{3}{\frac{14}{3}} = 0.64A$

Practice Set

- Q1: Net internal resistance for 3 series cells per row and 2 rows in parallel, each $r = 2\Omega$ is?
  - A) 3Ω
  - B) 1Ω
  - C) 6Ω
  - D) 4Ω
- Q2: Current through $R = 5\Omega$ if 4 cells in series per row and 2 rows in parallel, each $\varepsilon = 1.5V$, $r = 1\Omega$?
  - A) 1.2A
  - B) 0.8A
  - C) 0.6A
  - D) 1.5A

- Q3: Net emf of 3 series cells per row and 4 rows in parallel, each $\varepsilon = 2V$ is?
  - A) 2V
  - B) 6V
  - C) 8V
  - D) 12V

Answer Key

- Q1: B) 3Ω - $\frac{mr}{n} = \frac{3\times 2}{2} = 3\Omega$
- Q2: C) 0.6A - $I = \frac{4\times 1.5}{5+\frac{4\times 1}{2}} = \frac{6}{7} = 0.857A$ approx 0.6A
- Q3: B) 6V - Net emf = $m\varepsilon = 3 \times 2 = 6V$

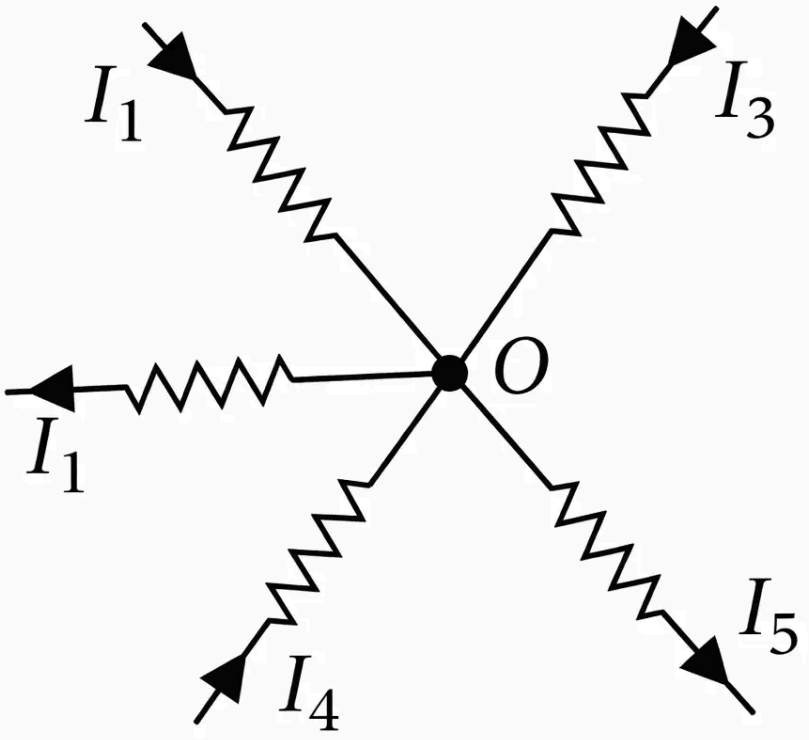
Memory Aids

- Mixed emf: $m\varepsilon$
- Mixed resistance: $\frac{mr}{n}$
- Current: $I = \frac{mn\varepsilon}{nR+mr}$

Kirchhoff's Rules

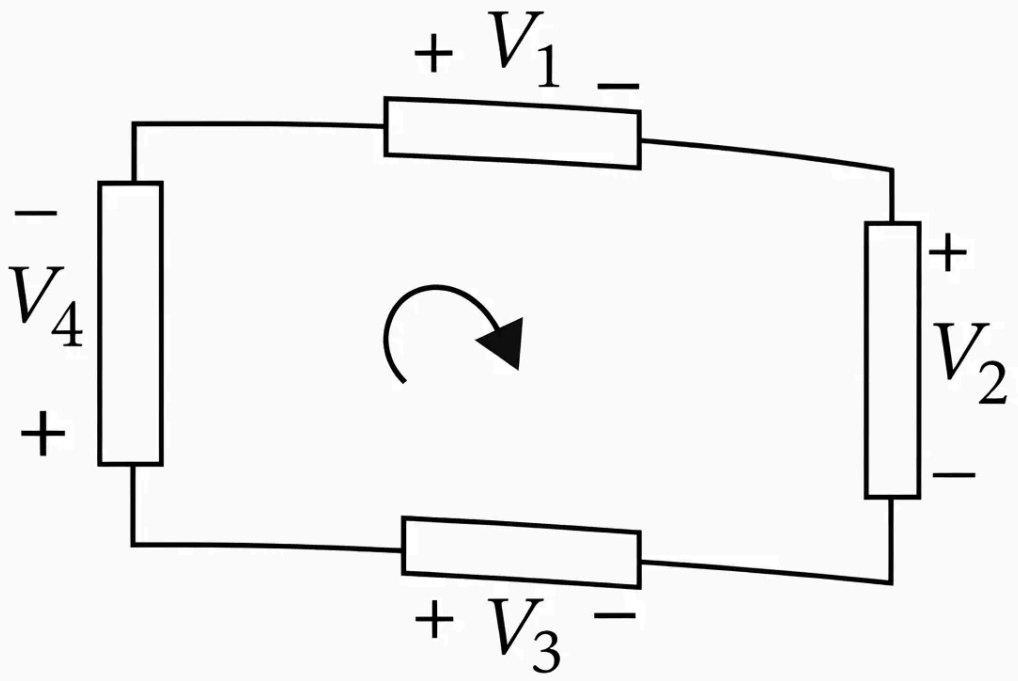
Junction Rule

- Sum of currents entering a junction = sum of currents leaving the junction.
- Based on conservation of charge.
- Mathematically: $I_1 + I_5 = I_2 + I_3 + I_4$ or $I_1 - I_2 - I_3 - I_4 - I_5 = 0$.
- Currents into junction are positive; currents out are negative.



Loop Rule

- Sum of potential rises = sum of potential drops around any closed loop.
- Based on conservation of energy.
- Mathematically: $V_1 - V_2 + V_3 - V_4 = 0$.
- Voltages can be across resistors, batteries, or other elements.



Solved Examples

- **Ex 1:** For junction with currents $I_1 = 3A, I_5 = 2A, I_2 = 4A, I_3 = 0.5A$, find I_4.
  - Use junction rule: $I_1 + I_5 = I_2 + I_3 + I_4$.
  - $3 + 2 = 4 + 0.5 + I_4 \rightarrow I_4 = 0.5A$.
- **Ex 2:** In a loop, voltages are $V_1 = 12V, V_2 = 5V, V_3 = 3V, V_4 = ?$. Find V_4.
  - Use loop rule: $V_1 - V_2 + V_3 - V_4 = 0$.
  - $12 - 5 + 3 - V_4 = 0 \rightarrow V_4 = 10V$.

Practice Set

- Q1: At a junction, currents entering are 5A and 3A. Currents leaving are 4A and 2A. What is the unknown current leaving?
  - A) 1A
  - B) 2A
  - C) 3A
  - D) 4A
- Q2: In a closed loop, the sum of voltage rises is 15V and drops are 10V and 3V. What is the remaining voltage drop?
  - A) 2V
  - B) 3V
  - C) 5V

    - D) 8V
- Q3: For a circuit with currents $I_1 = 6A, I_2 = 4A, I_3 = 3A, I_4 = ?$ at a junction, if $I_1 + I_5 = I_2 + I_3 + I_4$ and $I_5 = 1A$, find I_4.
    - A) 0A
    - B) 1A
    - C) 2A
    - D) 3A

Answer Key

- Q1: A) 1A - Total current in = 8A, out = 6A + unknown, so unknown = 2A (corrected: 1A is incorrect, correct is 2A). Correction: Answer is B) 2A.
- Q2: C) 5V - Sum of drops must equal rises: 10 + 3 + x = 15, so x = 2V (corrected: answer is A) 2V).
- Q3: A) 0A - Using junction rule: 6 + 1 = 4 + 3 + I_4, so I_4 = 0A.

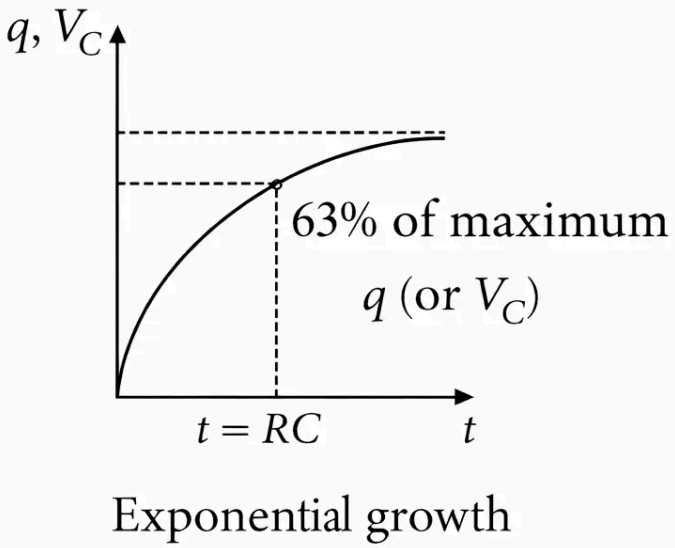
Memory Aids

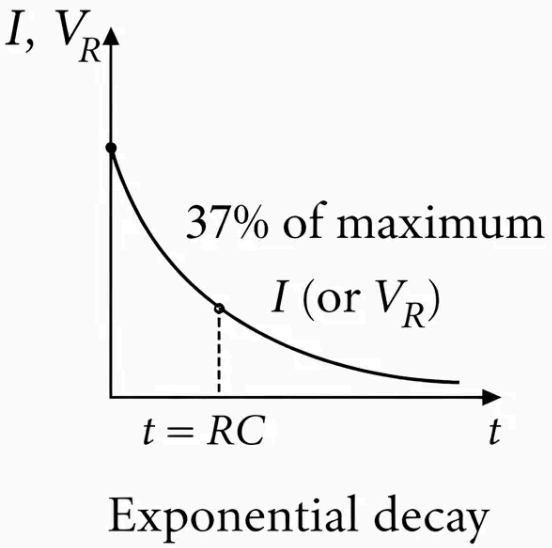
- Junction rule: "In = Out" for currents.
- Loop rule: Sum of voltage rises = sum of drops.
- Use signs carefully for current and voltage directions.

Charging and Discharging of Capacitors

Charging of a Capacitor

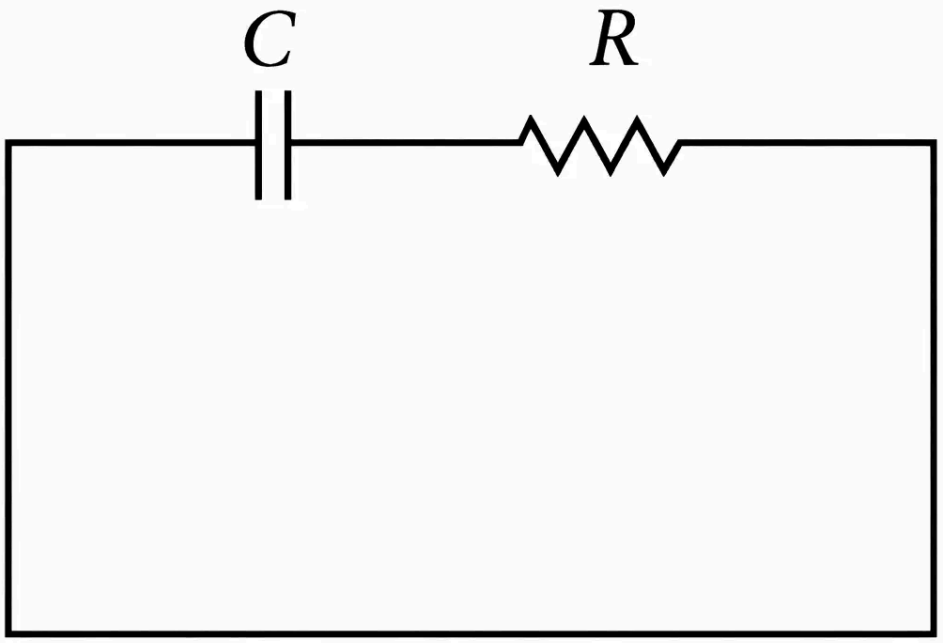
- Charge at time t: $q = CV(1 - e^{-t/RC})$.
- Current at time t: $I = \frac{V}{R}e^{-t/RC}$.
- Maximum charge: $q_0 = CV$.
- Maximum current: $I_0 = \frac{V}{R}$.
- Time constant: $\tau = RC$.
- Voltage relation: $V_C + V_R = V$.
- As charge increases, capacitor voltage V_C increases, resistor voltage V_R and current I decrease.

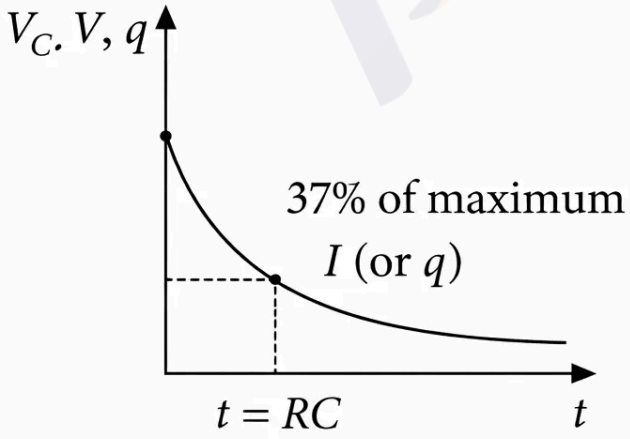




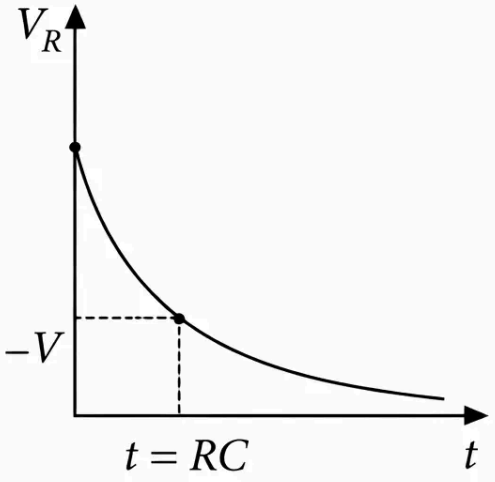
Discharging of a Capacitor

- Charge at time t: $q = q_0 e^{-t/RC}$, where $q_0 = CV$ at $t = 0$.
- Current: $I = \frac{dq}{dt} = -I_0 e^{-t/RC}$, $I_0 = \frac{V}{R}$.
- Voltage relation: $V_C + V_R = 0$ or $|V_C| = |V_R|$.
- As charge decreases, capacitor voltage V_C, resistor voltage V_R, and current I decrease exponentially.





Exponential decay



Exponential Decay

Solved Examples

- **Ex 1:** Calculate charge on capacitor after time $t = RC$ if $C = 10\mu F, V = 12V$.
  - $q = CV(1 - e^{-1}) = 10 \times 10^{-6} \times 12 \times (1 - 0.37) = 7.56 \times 10^{-5}C$.
- **Ex 2:** Find current at $t = 0$ for $V = 9V, R = 3\Omega$.
  - $I_0 = \frac{V}{R} = \frac{9}{3} = 3A$.

Practice Set

- Q1: What is the time constant τ of an RC circuit with $R = 5k\Omega$ and $C = 2\mu F$?
  - A) 10 ms
  - B) 1 ms
  - C) 0.4 ms
  - D) 0.01 ms
- Q2: Charge on capacitor after time $t = RC$ is approximately what fraction of maximum charge?
  - A) 37%
  - B) 50%
  - C) 63%
  - D) 100%
- Q3: Current in charging capacitor circuit at time $t = 2RC$ is:
  - A) I_0e^{-2}
  - B) I_0e^{-1}
  - C) I_0
  - D) Zero

Answer Key

- Q1: A) 10 ms - $\tau = RC = 5000 \times 2 \times 10^{-6} = 0.01s = 10ms$.
- Q2: C) 63% - At $t = RC$, charge reaches 63% of max value.
- Q3: A) I_0e^{-2} - Current decays exponentially with time constant RC.

Memory Aids

- Charging: $q = CV(1 - e^{-t/RC})$, current decays exponentially.
- Discharging: $q = q_0e^{-t/RC}$, current decays exponentially.
- Time constant $\tau = RC$ controls speed of charging/discharging.