Current Electricity

Class 12 Physics · Chapter 3 · CBSE

Handwritten Notes · Sequence: NCERT + S.L. Arora

How to use these notes: Topics follow the NCERT order. Extra topics from S.L. Arora are added where they fit and marked [S.L. Arora]. Boxed formulas are the ones to remember.

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1. Electric Current NCERT 3.1–3.2

Flow of electric charge through a conductor is called **electric current**.

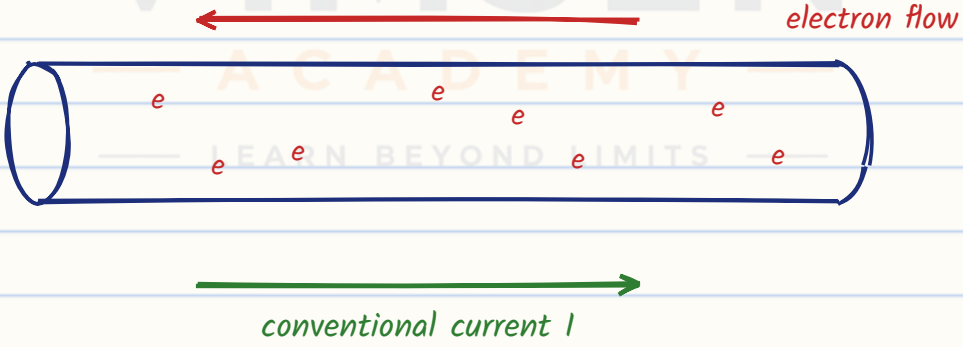
If a net charge q passes through any cross-section in time t,

$$I = q / t$$

If current is not steady, we take the **instantaneous current**:

$$I = \lim_{\Delta t \to 0} \Delta Q/\Delta t = dQ / dt$$

- **SI unit:** ampere (A). 1 A = 1 C/s
- **1 ampere:** when 1 coulomb of charge flows through a cross-section in 1 second.
- Smaller units: 1 mA = 10^{-3} A, 1 μA = 10^{-6} A
- Current is a **scalar** (it adds algebraically, does not follow vector addition), though it has a direction.
- Conventional current flows from + to − (direction of flow of positive charge), i.e. **opposite** to the flow of electrons.



Charge is quantised: $q = n e$, so the number of electrons crossing in time t is $n = I t / e$.

Example: How many electrons pass per second when the current is 1 A?

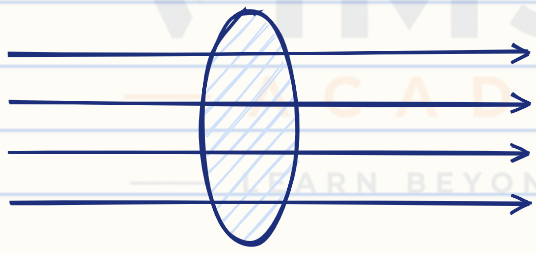
$n = I t / e = (1 \times 1) / (1.6 \times 10^{-19}) =$ **6.25×10^{18} electrons**

2. Electric Currents in Conductors NCERT 3.3

→ In metals, free electrons carry current. In electrolytes, both +ve and −ve ions carry it.
→ With **no electric field**, free electrons move randomly with thermal speeds. Their velocities are in all directions, so the net flow through any area is **zero**.
→ When a field E is applied, electrons are accelerated opposite to E, giving a **net flow of charge** → current.
→ To keep the current steady, the field must be maintained, e.g. by a cell or battery.

3. Current Density [S.L. Arora]

Current per unit area of cross-section held **normal** to the direction of current.



$J = I / A$

($A \perp$ to current)

→ **Unit:** A m^{-2}. It is a vector, along the flow of positive charge.
→ If the area makes angle θ with the normal: $I = J A \cos\theta = \mathbf{J} \cdot \mathbf{A}$
→ In terms of the field (proved in Topic 4): $J = \sigma E$

4. Ohm's Law & Resistivity NCERT 3.4

Ohm's law: At constant temperature and other physical conditions, the current through a conductor is directly proportional to the potential difference across its ends.

$$V \propto I \Rightarrow V = I R$$

R = **resistance** of the conductor. SI unit: ohm, 1 ohm = 1 V/A.

Resistance depends on



$$R = \rho l / A$$

→ $R \propto l$ (length) — doubling the length doubles R.

→ $R \propto 1/A$ (area) — a thicker wire has less resistance.

$$R = \rho l / A$$

ρ (rho) = resistivity (specific resistance). It depends only on the material and temperature, not on shape or size. Unit: ohm m.

→ **Conductance** $G = 1/R$, unit siemens (S) or mho. [S.L. Arora]

→ **Conductivity** $\sigma = 1/\rho$, unit $S\ m^{-1}$.

Vector form of Ohm's law ($J = \sigma E$)

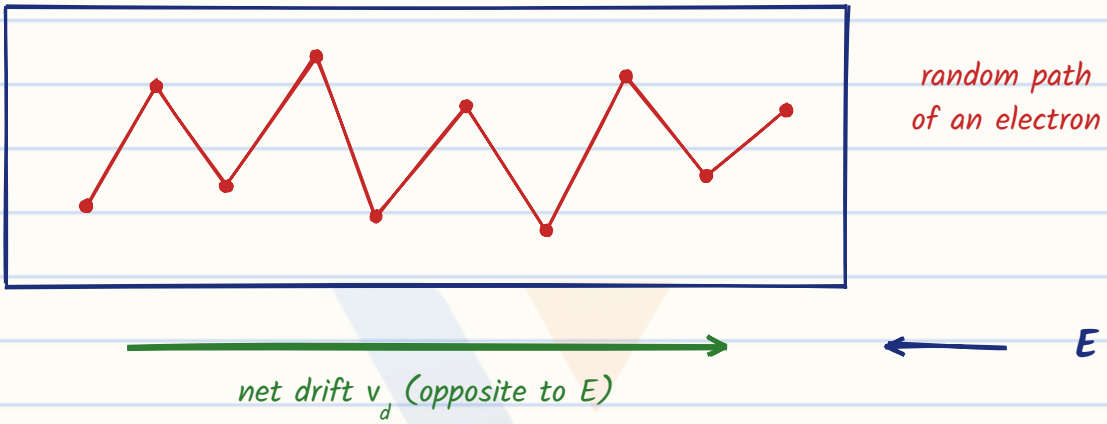
⇒ $V = I R = I \rho l / A \Rightarrow V / l = \rho (I / A)$

⇒ But $V / l = E$ (field along wire) and $I / A = J$

⇒ $\therefore E = \rho J$

$$J = \sigma E \qquad (\text{or } E = \rho J)$$

5. Drift of Electrons & Origin of Resistivity NCERT 3.5



Relaxation time (τ): average time between two successive collisions of a free electron. In metals $\tau \approx 10^{-14}$ s.

Drift velocity (v_d): average velocity with which free electrons drift opposite to the applied field. It is very small, $\approx 10^{-4}$ m/s.

Expression for drift velocity

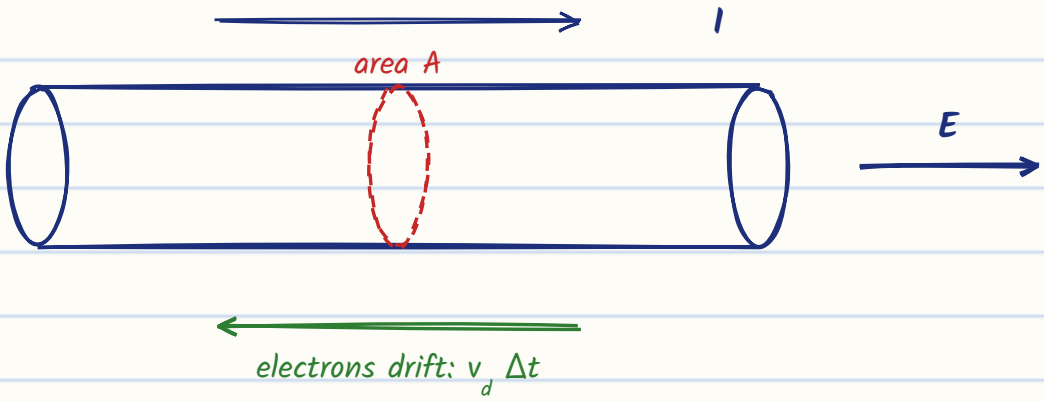
⇒ Force on electron: $F = -e\,E \Rightarrow$ acceleration $a = -e\,E / m$

⇒ Velocity of i^{th} electron: $v_i = u_i - (e\,E / m)\,t_i$

⇒ Average over all electrons: average of $u_i = 0$ (random), average of $t_i = \tau$

$$v_d = -\,e\,E\,\tau / m$$

Relation between I and v_d



⇒ In time Δt, electrons move a distance $v_d \Delta t$. Volume swept = $A\, v_d\, \Delta t$

⇒ No. of electrons = $n\, A\, v_d\, \Delta t$ (n = free electrons per m^3)

⇒ Charge crossing: $\Delta q = n\, e\, A\, v_d\, \Delta t \Rightarrow I = \Delta q/\Delta t$

$$I = n\, e\, A\, v_d \quad \text{and} \quad J = n\, e\, v_d$$

Deducing Ohm's law & resistivity

⇒ Put $|v_d| = e\, E\, \tau / m$ in $I = n\, e\, A\, v_d$: $I = (n\, e^2\, \tau\, A / m)\, E$

⇒ With $E = V / l$: $I = (n\, e^2\, \tau\, A / m\, l)\, V \Rightarrow I \propto V$ (Ohm's law!)

⇒ Compare with $V = I\, \rho\, l / A$:

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

Note: ρ depends on n (number density) and τ (relaxation time). Temperature changes τ and n, so ρ changes with T (Topic 8).

Mobility (μ) NCERT 3.5.1

Magnitude of drift velocity per unit electric field.

$$\mu = |v_d| / E = e\, \tau / m$$

SI unit: $m^2\, V^{-1}\, s^{-1}$. Practical unit: $cm^2\, V^{-1}\, s^{-1}$. Mobility is positive for both electrons and holes.

Example (NCERT 3.1): A copper wire of area $1.0 \times 10^{-7}\ m^2$ carries 1.5 A. If $n = 8.5 \times 10^{28}\ m^{-3}$, find v_d.

$v_d = I / (n\ e\ A) = 1.5 / (8.5 \times 10^{28} \times 1.6 \times 10^{-19} \times 10^{-7})$

$v_d = 1.1 \times 10^{-3}$ m/s (about 1 mm/s)

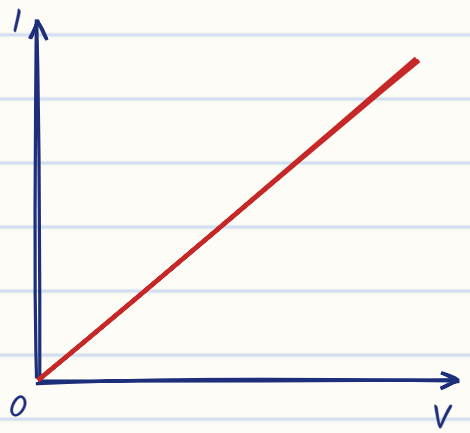
Why does a bulb glow instantly if v_d is so small? The electric field is set up along the whole wire at nearly the speed of light, so electrons everywhere start drifting at once.

6. Limitations of Ohm's Law NCERT 3.6

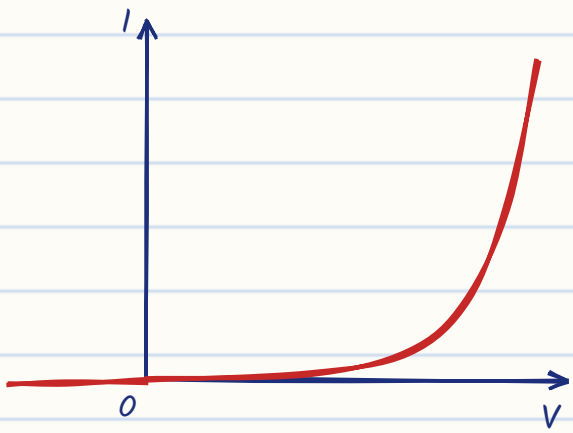
Materials that obey Ohm's law are **ohmic**; others are **non-ohmic**.

Deviations:

1. V stops being proportional to I (graph is non-linear), e.g. a filament at high current.
2. The relation depends on the sign of V: reversing V changes the size of I, e.g. a diode.
3. The relation is not unique: more than one V for the same I, e.g. GaAs.



(a) Ohmic: straight line



(b) Diode: non-linear

7. Resistivity of Various Materials NCERT 3.7

Type	ρ (ohm m)	Examples
Conductors	$10^{-8} - 10^{-6}$	Ag, Cu, Al
Semiconductors	$10^{-5} - 10^{6}$	Si, Ge
Insulators	$10^{11} - 10^{19}$	glass, rubber, mica

→ Silver has the least resistivity; copper is used for wires as it is cheap and a good conductor.

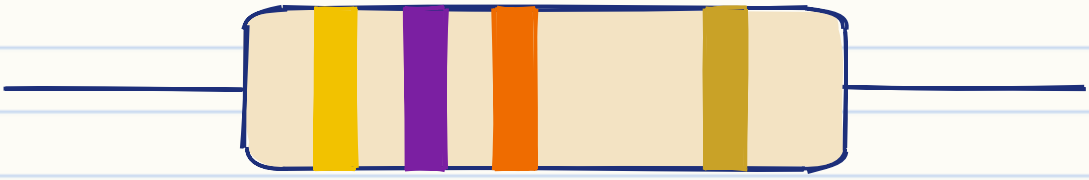
→ Alloys (nichrome, manganin, constantan) have high ρ and low temperature coefficient ⇒ used in heaters and standard resistors.

Colour code of carbon resistors [S.L. Arora]

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

Trick: B B ROY of Great Britain had a Very Good Wife.
Tolerance: Gold ± 5%, Silver ± 10%, no band ± 20%.

First two bands = digits, 3rd = multiplier (power of 10), 4th = tolerance.



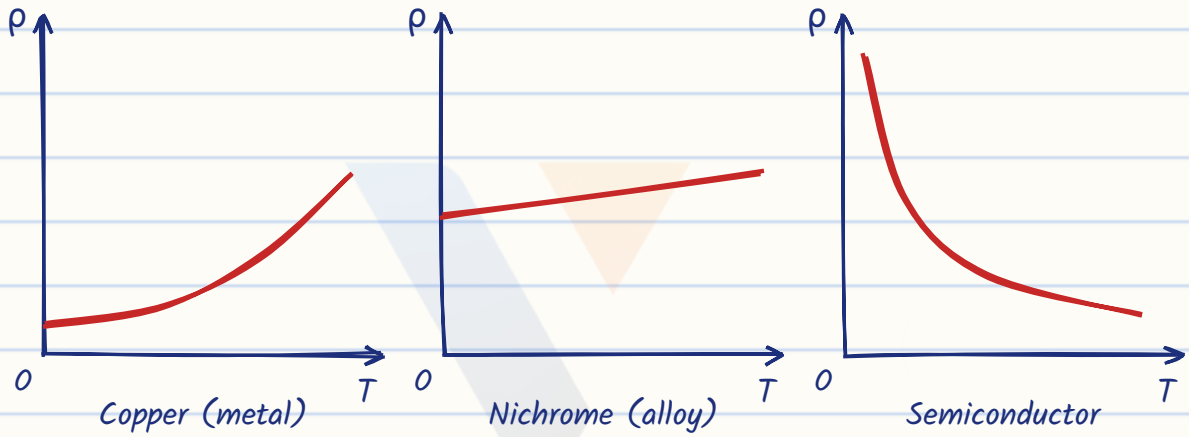
4 7 × 10^3 ohm ± 5% = 47 k ohm ± 5%

8. Temperature Dependence of Resistivity NCERT 3.8

Over a limited range of temperature, for metals:

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

α = **temperature coefficient of resistivity**, unit K^{-1} or $°C^{-1}$. Similarly, $R_T = R_0[1 + \alpha(T - T_0)]$.



→ **Metals:** α is +ve. As T rises, collisions increase ⇒ τ decreases ⇒ ρ increases.

→ **Alloys (nichrome, manganin):** ρ high, increases only slightly with T (very small α).

→ **Semiconductors:** α is −ve. As T rises, n increases (more carriers) faster than τ falls ⇒ ρ decreases.

→ **Superconductors** [S.L. Arora]: ρ becomes zero below a critical temperature, e.g. mercury below 4.2 K.

Example: A silver wire has R = 2.1 ohm at 27.5 °C and 2.7 ohm at 100 °C. Find α.

$\alpha = (R_2 - R_1) / [R_1(T_2 - T_1)] = 0.6 / (2.1 \times 72.5) = 3.9 \times 10^{-3}$ $°C^{-1}$

9. Electrical Energy, Power NCERT 3.9

⇒ Charge ΔQ moves through p.d. V in time Δt: loss of P.E. $= V\,\Delta Q = V\,I\,\Delta t$

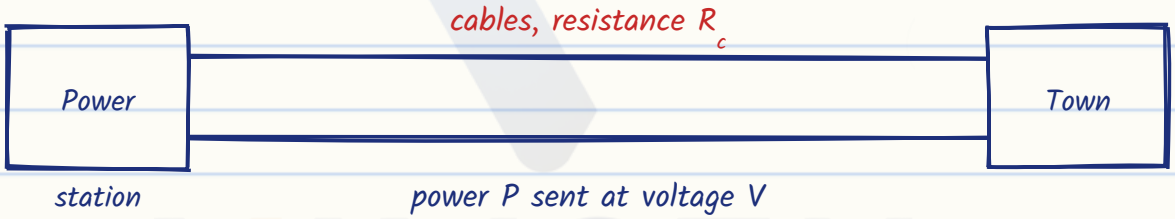
⇒ This energy is dissipated as heat in the conductor (Joule heating).

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

→ SI unit of power: watt (W). Energy $W = P\,t$, commercial unit 1 kWh $= 3.6 \times 10^6$ J.

→ Heat produced $H = I^2\,R\,t$ (Joule's law of heating).

Power transmission



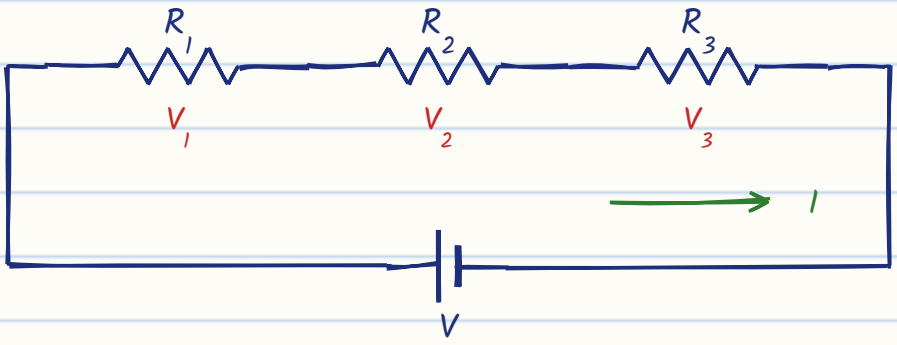
⇒ Current in cables $I = P / V$ ⇒ power wasted $P_c = I^2\,R_c$

$$P_c = P^2\,R_c / V^2$$

$P_c \propto 1/V^2$, so power is transmitted at very high voltage to reduce losses, then stepped down by transformers.

10. Combination of Resistors [S.L. Arora]

(a) Series combination



same I
V divides

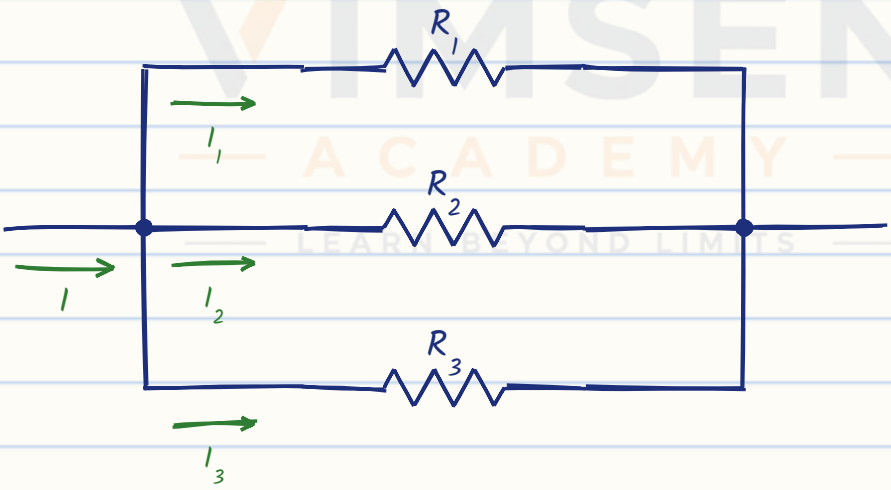
⇒ Same current I through each. $V = V_1 + V_2 + V_3$

⇒ $I R_s = I R_1 + I R_2 + I R_3$

$$R_s = R_1 + R_2 + R_3$$

R_s is greater than the largest resistance.

(b) Parallel combination



same V
I divides

⇒ Same V across each. $I = I_1 + I_2 + I_3$

⇒ $V/R_p = V/R_1 + V/R_2 + V/R_3$

$$1/R_p = 1/R_1 + 1/R_2 + 1/R_3$$

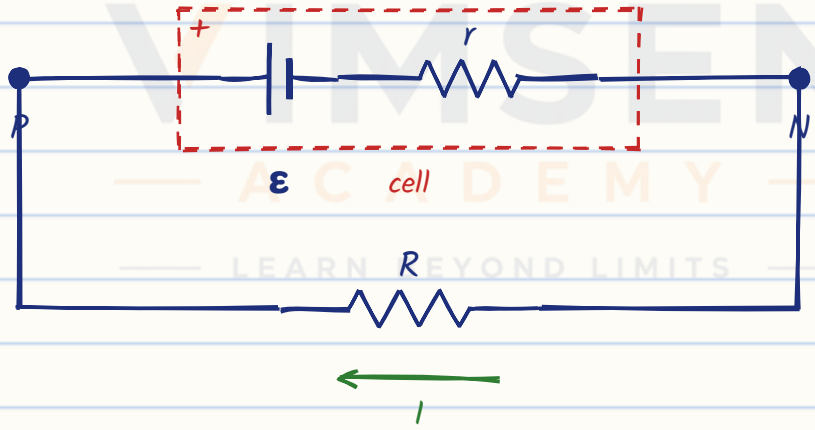
R_p is less than the smallest resistance. For two: $R_p = R_1R_2 / (R_1 + R_2)$.

Example: 2 ohm, 4 ohm and 5 ohm are joined (a) in series (b) in parallel. Find R_{eq}.
(a) $R_s = 2 + 4 + 5 =$ **11 ohm** (b) $1/R_p = 1/2 + 1/4 + 1/5 = 19/20$
$\Rightarrow R_p =$ **20/19 ohm ≈ 1.05 ohm**

11. Cells, EMF, Internal Resistance NCERT 3.10

EMF (ε): potential difference between the terminals of a cell when **no current** is drawn (open circuit). It is the work done by the cell per unit charge.

Internal resistance (r): resistance offered by the electrolyte and electrodes of the cell to the flow of current inside it.



$V = \varepsilon - I r$

⇒ Current through the circuit: $I = \varepsilon / (R + r)$
⇒ Terminal p.d. $V = I R = \varepsilon - I r$ (cell **discharging**)

$$I = \varepsilon / (R + r) \qquad V = \varepsilon - I r$$

→ While **charging** (current forced in): $V = \varepsilon + I r$.
→ Maximum current (short circuit, $R = 0$): $I_{max} = \varepsilon / r$.
→ Internal resistance: $r = R (\varepsilon/V - 1)$. [S.L. Arora]

Example (NCERT 3.1): A car battery has $\varepsilon = 12$ V, $r = 0.4$ ohm. Maximum current?

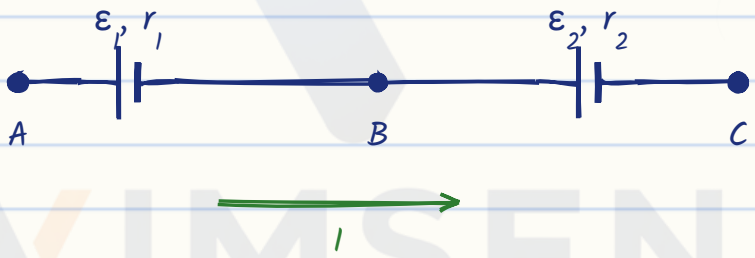
$I_{max} = \varepsilon / r = 12 / 0.4 =$ **30 A**

Example (NCERT 3.2): $\varepsilon = 10$ V, $r = 3$ ohm, current 0.5 A. Find R and terminal voltage.

$0.5 = 10/(R + 3) \Rightarrow R =$ **17 ohm**; $V = I R = 0.5 \times 17 =$ **8.5 V**

12. Cells in Series and in Parallel NCERT 3.11

(a) Series



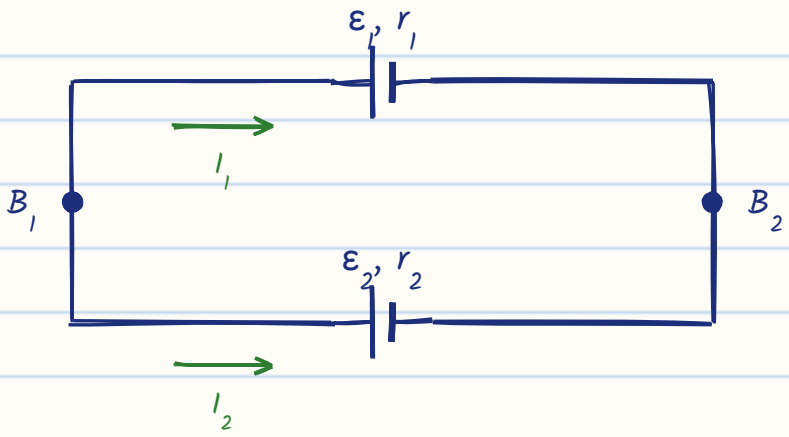
$\Rightarrow V_{AB} = \varepsilon_1 - I r_1$, $V_{BC} = \varepsilon_2 - I r_2$

$\Rightarrow V_{AC} = (\varepsilon_1 + \varepsilon_2) - I (r_1 + r_2) = \varepsilon_{eq} - I r_{eq}$

$$\varepsilon_{eq} = \varepsilon_1 + \varepsilon_2 \qquad r_{eq} = r_1 + r_2$$

If one cell is reversed: $\varepsilon_{eq} = \varepsilon_1 - \varepsilon_2$ (r_{eq} still adds). For n identical cells: $\varepsilon_{eq} = n\varepsilon$, $r_{eq} = nr$.

(b) Parallel



$\Rightarrow I = I_1 + I_2 = (\varepsilon_1 - V)/r_1 + (\varepsilon_2 - V)/r_2$

$\Rightarrow$ Rearranging: $V = \varepsilon_{eq} - I\, r_{eq}$, where

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

Or: $\varepsilon_{eq}/r_{eq} = \varepsilon_1/r_1 + \varepsilon_2/r_2$, $1/r_{eq} = 1/r_1 + 1/r_2$.

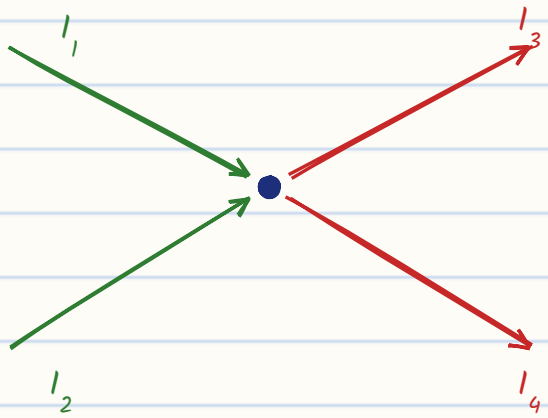
(c) Mixed grouping [S.L. Arora]

n cells in series in each row, m such rows in parallel (total mn cells), external R:

$$I = \frac{n\,\varepsilon}{R + nr/m}$$ I is maximum when $R = nr/m$

13. Kirchhoff's Rules NCERT 3.12

Junction rule (KCL): At any junction, the sum of currents entering = the sum of currents leaving. **(Conservation of charge)**



$I_1 + I_2 = I_3 + I_4$
($\Sigma I = 0$ at a junction)

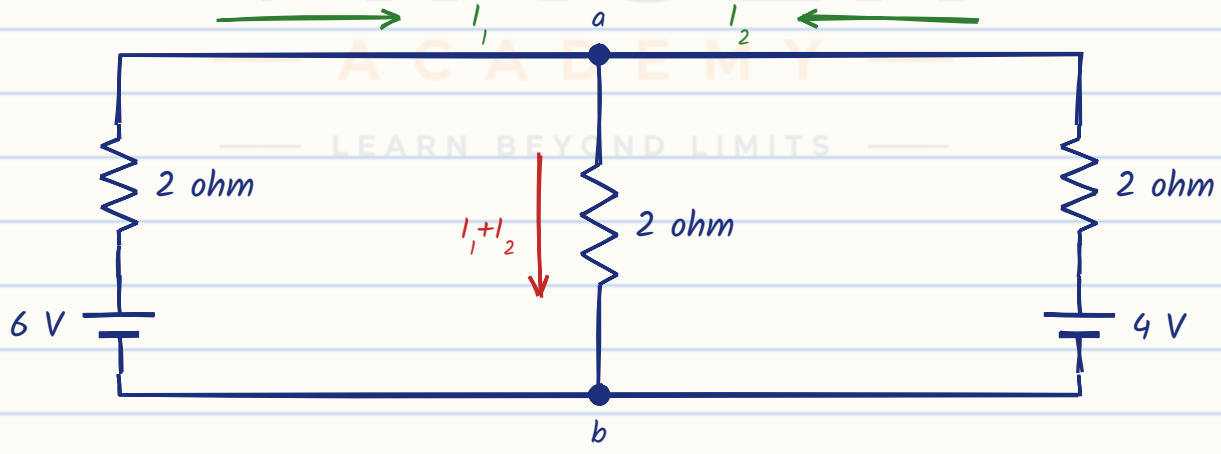
Loop rule (KVL): The algebraic sum of changes in potential around any closed loop is zero. **(Conservation of energy)**

Sign convention

→ Across a resistor, going **along** the current: change = $-IR$; against the current: $+IR$.

→ Across a cell from − to +: change = $+\varepsilon$; from + to −: $-\varepsilon$.

Example: Find the current in each branch.



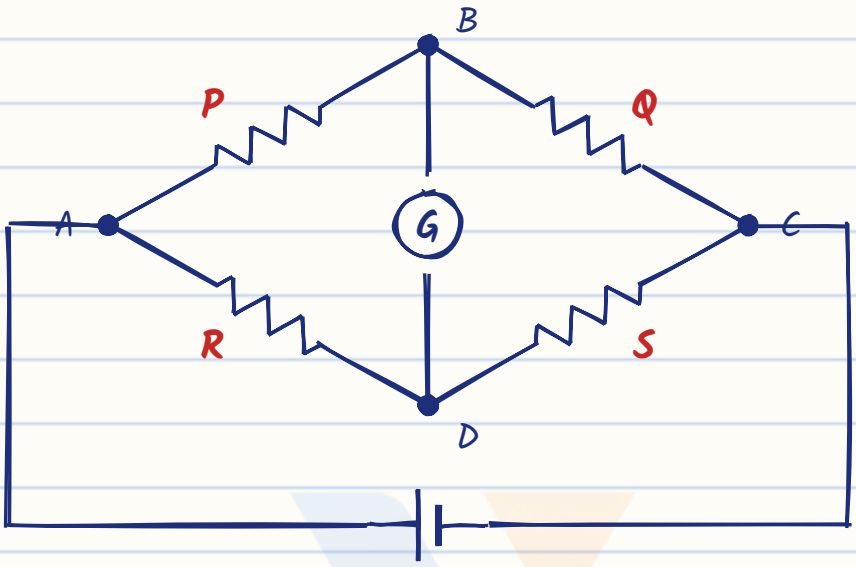
⇒ Junction a: $I_3 = I_1 + I_2$

⇒ Left loop: $6 - 2I_1 - 2(I_1 + I_2) = 0 \Rightarrow 4I_1 + 2I_2 = 6$

⇒ Right loop: $4 - 2I_2 - 2(I_1 + I_2) = 0 \Rightarrow 2I_1 + 4I_2 = 4$

⇒ Solving: $I_1 = 4/3$ A, $I_2 = 1/3$ A, $I_3 = 5/3$ A

14. Wheatstone Bridge NCERT 3.13



$I_g = 0$ at balance

Four resistances P, Q, R, S with a galvanometer between B and D and a cell between A and C. Bridge is balanced when $I_g = 0$.

Balance condition (using Kirchhoff)

⇒ $I_g = 0$ ⇒ current I_1 in P and Q, current I_2 in R and S

⇒ Loop ABDA: $-I_1P + I_2R = 0 \Rightarrow I_1P = I_2R$

⇒ Loop BCDB: $-I_1Q + I_2S = 0 \Rightarrow I_1Q = I_2S$

⇒ Dividing the two equations:

$$P / Q = R / S$$

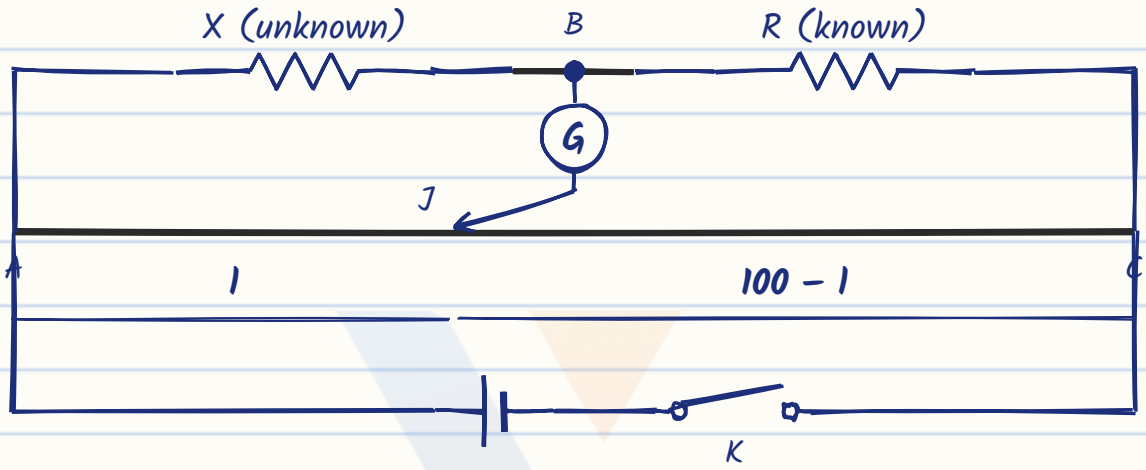
→ Used to find an **unknown resistance**: $S = R\,Q / P$.

→ Bridge is most sensitive when all four resistances are of the same order.

→ Balance is not affected by interchanging the cell and the galvanometer.

15. Meter Bridge [S.L. Arora]

A practical Wheatstone bridge: a uniform wire AC of length **1 m** stretched on a scale; the jockey J slides on it.



⇒ At balance point J (length l from A): $P \propto l$, $Q \propto (100 - l)$

⇒ $X / R = l / (100 - l)$

$$X = R\, l / (100 - l)$$

→ Specific resistance of the wire: $\rho = X \pi r^2 / L$ (r = radius, L = length of wire X).

→ Balance point should be near the middle to reduce end errors.

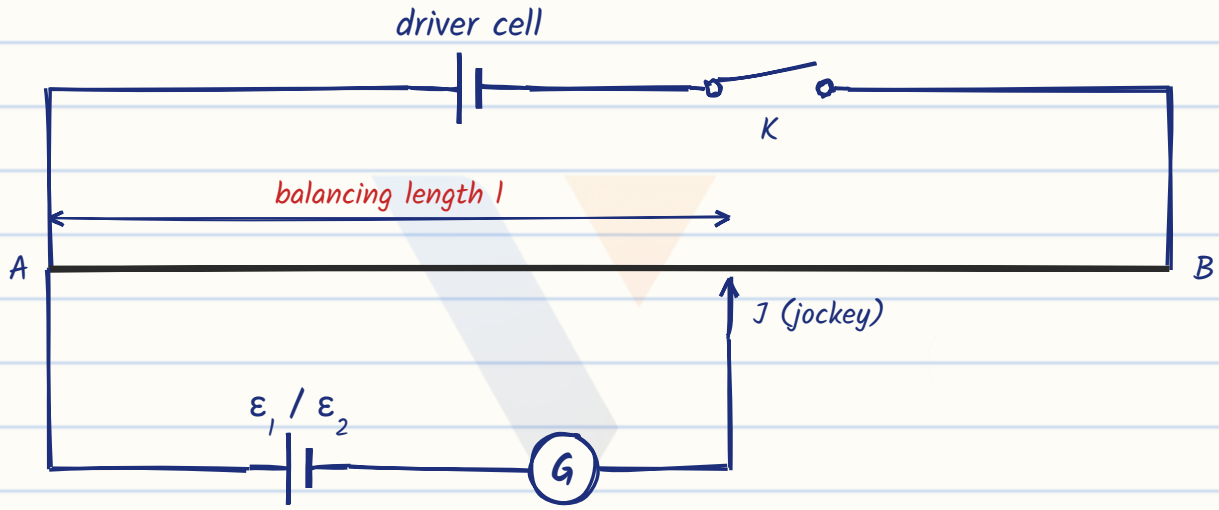
Example: With R = 3 ohm in the right gap, balance is at 40 cm. Find X.

$X = 3 \times 40 / 60 =$ **2 ohm**

16. Potentiometer [S.L. Arora]

Principle: When a steady current flows through a wire of uniform area, the p.d. across any length is proportional to that length: $V \propto l \Rightarrow V = k\,l$, where k = potential gradient (V/m).

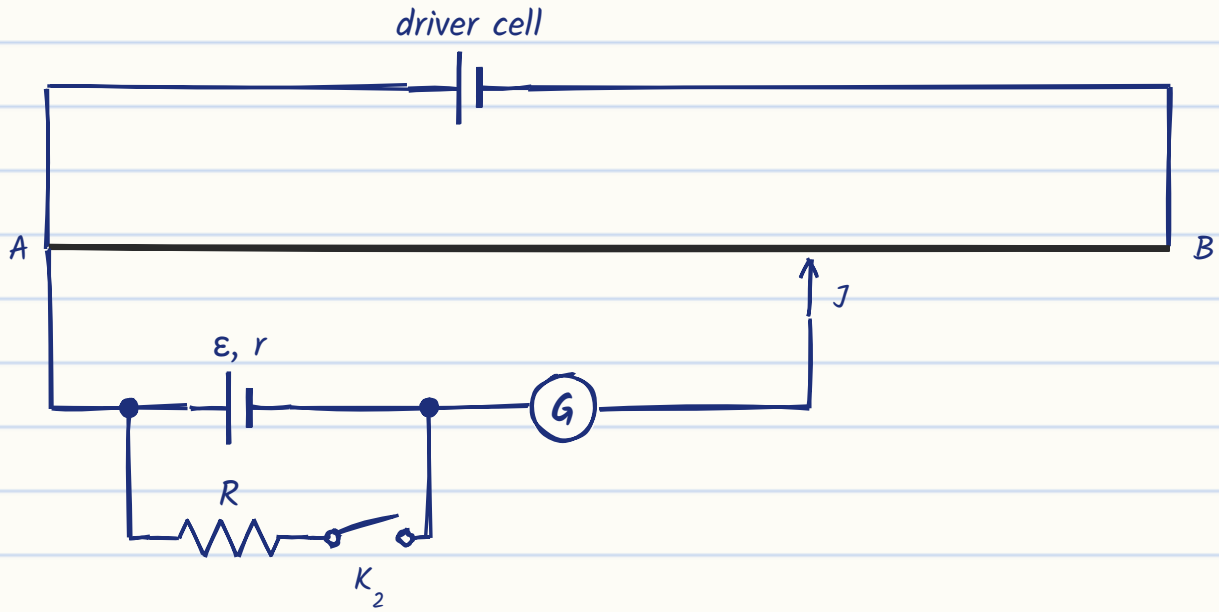
(a) Comparing EMFs of two cells



$\Rightarrow$ Cell ε_1 balances at l_1: $\varepsilon_1 = k\,l_1$; cell ε_2 balances at l_2: $\varepsilon_2 = k\,l_2$

$$\frac{\varepsilon_1}{\varepsilon_2} = \frac{l_1}{l_2}$$

(b) Internal resistance of a cell



⇒ K_2 open: $\varepsilon = k\, l_1$. K_2 closed (R in circuit): $V = k\, l_2$

⇒ $r = R\,(\varepsilon/V - 1)$

$$r = R\,(l_1 - l_2)\,/\,l_2$$

Why better than a voltmeter? At balance no current is drawn from the cell, so it measures the true EMF. A voltmeter always draws some current.

Example: Open-circuit balance 76.3 cm; with $R = 9.5$ ohm, balance 64.8 cm. Find r.

$r = 9.5 \times (76.3 - 64.8)/64.8 = 9.5 \times 11.5/64.8 =$ **1.7 ohm**

17. Formula Sheet — Quick Revision

Current	$I = q/t = dQ/dt,\ n = It/e$
Drift	$v_d = eE\tau/m,\ I = neAv_d$
Current density	$J = I/A = nev_d = \sigma E$
Resistance	$R = \rho l/A,\ \rho = m/(ne^2\tau)$
Mobility	$\mu = v_d/E = e\tau/m$
Temperature	$\rho_T = \rho_0[1 + \alpha(T - T_0)]$
Power	$P = VI = I^2R = V^2/R$
Transmission loss	$P_c = P^2R_c/V^2$
Series / Parallel	$R_s = \Sigma R,\ 1/R_p = \Sigma 1/R$
Cell	$I = \varepsilon/(R + r),\ V = \varepsilon - Ir$
Cells in parallel	$\varepsilon_{eq} = (\varepsilon_1 r_2 + \varepsilon_2 r_1)/(r_1 + r_2)$
Wheatstone	$P/Q = R/S$
Meter bridge	$X = R\,l/(100 - l)$
Potentiometer	$\varepsilon_1/\varepsilon_2 = l_1/l_2,\ r = R(l_1 - l_2)/l_2$