JEE MAIN · PAPER 1 · PHYSICS

12 Current Electricity

Formula & concept sheet

Charges in motion in conductors: drift velocity, resistance and resistivity, resistor networks and heating, cells with internal resistance, Kirchhoff's laws and bridges, meters, and the charging of a capacitor through a resistor. Each idea is explained first, then the formulas, shortcuts and traps.

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READ ALONGSIDE NCERT XII · Current Electricity

HOW TO USE THIS SHEET

1. **Skim** — Read the Key ideas, then the formula cards.
2. **Memorise** — Learn the formulas and check every Trap box.
3. **Test** — Do the worked examples, then this chapter's PYQs.
4. **Revise** — Use the last-minute checklist before the exam.

Formula memorise · **Key idea** why it works · **Trap** marks lost here · **PYQ** how it is asked

Practise this chapter with real past-paper questions on Prep Vault. Written for revision, not as a first read.

CHAPTER 12

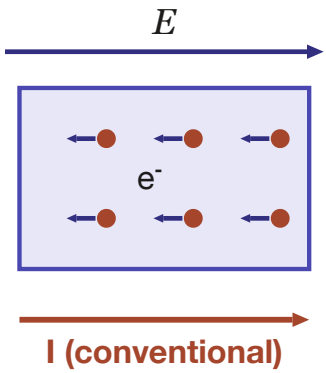
Current Electricity

NCERT XII · Current Electricity

Covers: current and drift velocity · Ohm's law and resistivity · temperature dependence · series and parallel · power and heating · cells and internal resistance · Kirchhoff's laws · Wheatstone and metre bridge · potentiometer · ammeter and voltmeter · RC circuits.

1 Electric current and drift velocity

ELECTRIC CURRENT The charge crossing a cross-section per unit time, $I = dq/dt$ (ampere, C/s). Current is a scalar: it has a sense along the wire, but currents add algebraically at a junction, not as vectors. The conventional direction is that of positive charge, **opposite** to the flow of electrons.



free electrons drift left, against E; the conventional current I runs right, with E

- The free electrons of a metal move randomly at about 10^5 m/s and collide with the lattice every $\tau \sim 10^{-14}$ s. An electric field adds a tiny steady **drift** against $\vec{E}$, of the order of 10^{-4} m/s.
- The current is carried at the drift speed, but the field that sets all the electrons moving travels along the wire at nearly the speed of light, so a lamp lights at once.
- Current density $J = I/A$ (A/m^2) is a vector along $\vec{E}$; it tells how the current is spread over the cross-section.

CURRENT AND CHARGE

$$I = \frac{dq}{dt}$$

$$q = \int I\,dt$$

charge passed = area under the I-t graph; for steady current $q = It$

CURRENT FROM DRIFT

$$I = neAv_d$$

n free electrons per m^3, A area, v_d drift speed

DRIFT SPEED AND MOBILITY

$$v_d = \frac{eE\tau}{m}$$

$$\mu = \frac{v_d}{E} = \frac{e\tau}{m}$$

mobility in m^2/(V s); $e = 1.6 \times 10^{-19}$ C

FROM THE ELECTRON PICTURE TO OHM'S LAW

$I = \frac{\Delta q}{\Delta t} = \frac{(nA\,v_d\Delta t)\,e}{\Delta t} = neAv_d$	electrons in a length $v_d\Delta t$ cross the section in time Δt
$v_d = a\tau = \frac{eE}{m}\tau$	after each collision the speed starts again from zero on average
$J = nev_d = \frac{ne^2\tau}{m}E = \sigma E$	so $\sigma = \frac{ne^2\tau}{m}$ and $\rho = \frac{1}{\sigma} = \frac{m}{ne^2\tau}$
$V = El,\ I = JA \Rightarrow R = \frac{V}{I} = \frac{\rho l}{A}$	uniform wire of length l

WHY IT WORKS

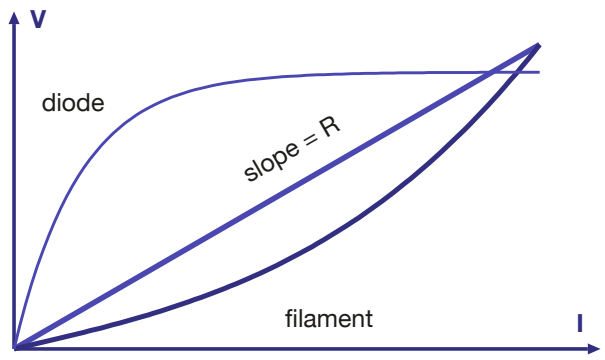
In a wire of changing cross-section the current I is the same everywhere (charge does not pile up), so J, E and v_d are all proportional to $1/A$: the electrons drift fastest where the wire is thinnest.

TRAP

Drift speed is not the speed of the signal and not the thermal speed. For the same field, a hotter wire has a smaller τ, hence a smaller v_d and a larger resistivity.

2 Ohm's law, resistance and resistivity

OHM'S LAW For many conductors at constant temperature the potential difference is proportional to the current, $V = IR$. R is the **resistance** of that particular piece (ohm, Ω); the **resistivity** ρ (Ω m) belongs to the material, and the conductivity is $\sigma = 1/\rho$.



ohmic: straight line, slope R · filament: curves up as R rises when it heats · diode: V rises steeply at small I, then stays almost flat

OHMIC AND NON-OHMIC

- **Ohmic**: a straight V-I line through the origin, constant R (metals at constant temperature).
- **Non-ohmic**: a curved or one-way graph. A lamp filament curves because it heats and R rises; a diode conducts one way, with a threshold voltage.
- For a non-ohmic device $R = V/I$ at the working point, not dV/dI.

RESISTANCE OF A WIRE

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

l in m, A in m^2; $A = \pi r^2 = \dfrac{\pi d^2}{4}$ for a round wire

CONDUCTANCE, CONDUCTIVITY

$$G = \frac{1}{R}, \quad \sigma = \frac{1}{\rho}$$

siemens (S) and S/m; $\vec{J} = \sigma \vec{E}$ is Ohm's law at a point

RESISTIVITY OF A METAL

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

copper 1.7×10^{-8} Ω m; nichrome about 10^{-6} Ω m

STRETCHING AND CUTTING A WIRE (VOLUME AND MATERIAL FIXED)

CHANGE	RESISTANCE	WHY
Length $\times n$	$R \to n^2 R$	area falls to A/n, so $R \propto l/A \propto l^2$
Small stretch by $x\%$	R rises by about $2x$	$(1+x)^2 \approx 1 + 2x$
Radius scaled by k	$R \to R/k^4$	$l \propto 1/r^2$ and $A \propto r^2$
Cut into n equal pieces, pieces in parallel	R/n^2	each piece R/n, then n in parallel
Two wires of the same material and mass	$R \propto l^2$	same volume, so $A \propto 1/l$

KEY IDEA

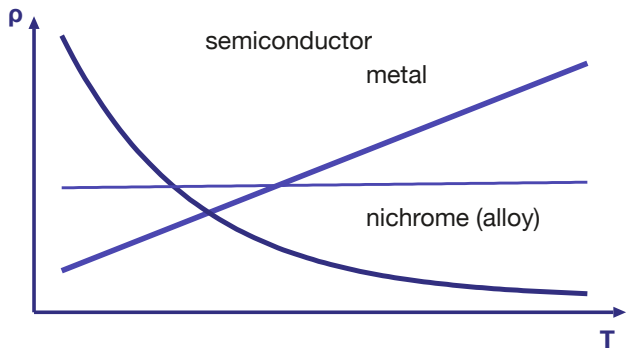
Resistance depends on shape; resistivity does not. Heaters use nichrome (high ρ, high melting point, resists oxidation); standard resistors use manganin or constantan (almost no change with temperature).

QUICK CHECK

Two wires of the same material and mass have lengths l and $2l$. Ratio of their resistances?

Answer: same volume, $A \propto 1/l$, so $R \propto l^2$: $1 : 4$.

3 Temperature and the colour code



metal: ρ rises almost linearly with T · semiconductor: ρ falls steeply · nichrome: nearly constant

- **Metals**: more lattice vibration at higher T shortens τ, so ρ **rises** ($\alpha > 0$).
- **Semiconductors**: more carriers are freed at higher T (larger n), so ρ **falls** ($\alpha < 0$).
- **Alloys** (manganin, constantan, nichrome): ρ nearly constant, $\alpha \approx 0$.

RESISTANCE AND TEMPERATURE

$$R_T = R_0\,[1 + \alpha(T - T_0)]$$

α in K^{-1}, taken from the reference T_0; the same form holds for ρ; valid over a modest range

RATIO AT TWO TEMPERATURES

$$\frac{R_2}{R_1} = \frac{1 + \alpha t_2}{1 + \alpha t_1}$$

with t measured from the reference (usually 0°C)

ZERO NET CHANGE WITH T

$$R_1\alpha_1 + R_2\alpha_2 = 0$$

two resistors in series with opposite-sign α: the total R stays almost constant

FOUR-BAND RESISTOR COLOUR CODE

BLACK	BROWN	RED	ORANGE	YELLOW	GREEN	BLUE	VIOLET	GREY	WHITE
0	1	2	3	4	5	6	7	8	9

Bands: first digit, second digit, multiplier 10^n, tolerance (gold 5%, silver 10%, none 20%). Red-violet-orange-gold reads $27 \times 10^3\ \Omega = 27\ \mathrm{k\Omega} \pm 5\%$. Mnemonic: B B ROY of Great Britain had a Very Good Wife.

TRAP

A semiconductor's resistance **falls** as it warms; α is negative. A cold lamp filament has a much lower resistance than a glowing one, so a bulb is most likely to fail at the moment it is switched on.

SANITY CHECK

For a small temperature change, $\Delta R = R\alpha\,\Delta T$. If $R\alpha\,\Delta T$ comes out larger than R itself, the linear formula is being pushed too far.

4 Resistor networks, power and heating

SERIES

- same current I through each
- V divides in proportion to R: $V_1 = V\dfrac{R_1}{R_1 + R_2}$
- $R = R_1 + R_2 + \ldots$ (larger than any one)
- power $\propto R$: the bigger R is hotter

PARALLEL

- same potential difference V across each
- I divides inversely to R: $I_1 = I\dfrac{R_2}{R_1 + R_2}$
- $\dfrac{1}{R} = \dfrac{1}{R_1} + \dfrac{1}{R_2} + \ldots$ (smaller than any one)
- power $\propto 1/R$: the smaller R is hotter

TWO IN PARALLEL

$$R = \frac{R_1 R_2}{R_1 + R_2}$$

n equal resistors R: series nR, parallel R/n

ELECTRIC POWER

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

watt; use I^2R in series, V^2/R in parallel

HEAT PRODUCED

$$H = I^2Rt = VIt = \frac{V^2 t}{R}$$

joule; $1\ \mathrm{kWh} = 3.6 \times 10^6$ J

RATED BULB

$$R = \frac{V^2}{P}$$

from the rated V and P; at another voltage V' the power is $P(V'/V)^2$, R held fixed

BULBS IN SERIES

$$P = \frac{P_1 P_2}{P_1 + P_2}$$

bulbs rated for the same voltage; the lower-wattage bulb has the larger R and glows brighter

BULBS IN PARALLEL

$$P = P_1 + P_2$$

each gets the full rated voltage; the higher-wattage bulb glows brighter

STANDARD EQUIVALENT RESISTANCES

NETWORK	EQUIVALENT RESISTANCE
A wire of resistance R bent into a circle, between diametrically opposite points	$R/4$
The same ring, between points subtending angle θ at the centre	$R\theta(2\pi - \theta)/4\pi^2$
Cube of 12 equal resistors R: across an edge, a face diagonal, a body diagonal	$7R/12$, $3R/4$, $5R/6$
Infinite ladder: each section a series R and a shunt R	$(1+\sqrt{5})R/2$, from $x = R + Rx/(R+x)$
Symmetric star of three R_Y replaced by a delta	$R_\Delta = 3R_Y$

REDUCING A NETWORK

1. Mark points that must be at the same potential (a symmetry, or a balanced bridge). Join them with a wire, or delete a resistor joining them.
2. Find series and parallel groups, replace them, redraw after each step.
3. If the network still will not reduce, use Kirchhoff's laws or the node-voltage method (section 6).

KEY IDEA

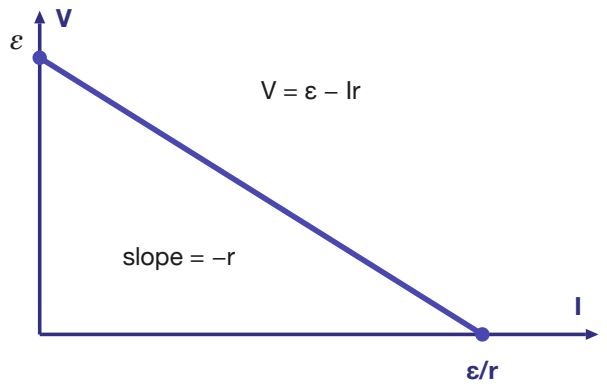
Two bulbs in series: the **dimmer-rated** (lower watt) one shines brighter. In parallel: the **higher-watt** one does. The same bulb can be either, depending on the wiring.

TRAP

Ideal ammeter: $R = 0$ (a wire). Ideal voltmeter: $R = \infty$ (an open gap). Replace them that way before simplifying a circuit; a voltmeter branch carries no current.

5 Cells: emf and internal resistance

EMF AND INTERNAL RESISTANCE The emf ε of a cell is the work it does per unit charge in driving charge round the whole circuit; it equals the terminal voltage when no current flows. The chemicals inside also resist the current, so a real cell is an ideal emf ε in series with an internal resistance r.



$V = \varepsilon - Ir$: intercept ε on the V axis, slope $-r$, short-circuit current ε/r on the I axis

TERMINAL VOLTAGE

discharging: $V = \varepsilon - Ir = \dfrac{\varepsilon R}{R + r}$

charging: $V = \varepsilon + Ir$

$V = \varepsilon$ only when $I = 0$; $V = 0$ at short circuit, $I = \varepsilon/r$

INTERNAL RESISTANCE FROM READINGS

$$r = R\left(\frac{\varepsilon}{V} - 1\right)$$

V measured across the external resistance R

CURRENT IN THE CIRCUIT

$$I = \frac{\varepsilon}{R + r}$$

R = total external resistance

POWER TO THE LOAD

$$P = I^2 R = \frac{\varepsilon^2 R}{(R + r)^2}$$

the cell also wastes $I^2 r$ inside

EFFICIENCY

$$\eta = \frac{V}{\varepsilon} = \frac{R}{R + r}$$

rises with R

MAXIMUM POWER TRANSFER (R VARIED, R FIXED)

$P = \dfrac{\varepsilon^2 R}{(R + r)^2}$	power in the load
$\dfrac{dP}{dR} = 0 \Rightarrow (R + r) - 2R = 0 \Rightarrow R = r$	condition for the maximum
$P_{max} = \dfrac{\varepsilon^2}{4r},\ \eta = 50\%$	half the power is lost inside the cell

COMBINATIONS OF CELLS (EACH OF EMF ε, RESISTANCE r)

ARRANGEMENT	EQUIVALENT EMF	EQUIVALENT RESISTANCE	BEST WHEN
n in series, aiding	$n\varepsilon$	nr	$R \gg nr$
m in parallel	ε	r/m	$R \ll r/m$
m rows of n cells (mixed)	$n\varepsilon$	nr/m	$R = nr/m$ (most current)
Two unequal cells in parallel	$\dfrac{\varepsilon_1 r_2 + \varepsilon_2 r_1}{r_1 + r_2}$	$\dfrac{r_1 r_2}{r_1 + r_2}$	reverse the sign of ε for a reversed cell
Two cells in series, opposing	$\varepsilon_1 - \varepsilon_2$	$r_1 + r_2$	the stronger cell sets the current direction

TRAP

Maximum power in the load occurs at $R = r$ but the efficiency is then only 50%. If instead R is fixed and r varies, the load power is largest at $r = 0$.

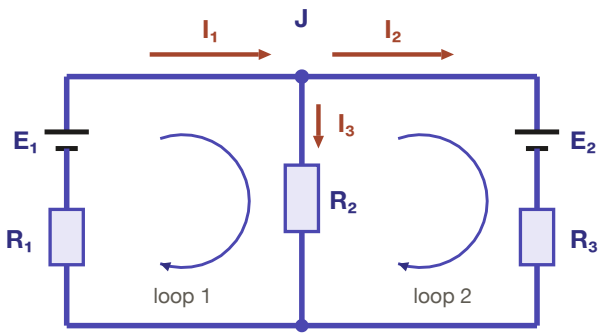
QUICK CHECK

A cell of emf 2 V gives 1.8 V across a $9\ \Omega$ resistor. Its internal resistance?

Answer: $r = R\left(\dfrac{\varepsilon}{V} - 1\right) = 9\left(\dfrac{2}{1.8} - 1\right) = 1\ \Omega.$

6 Kirchhoff's laws and the Wheatstone bridge

KIRCHHOFF'S LAWS **Junction rule**: the currents into a node sum to zero, $\sum I = 0$ (charge does not pile up). **Loop rule**: the potential changes around any closed loop sum to zero, $\sum \Delta V = 0$ (the electrostatic field is conservative; energy is conserved).



at J: $I_1 = I_2 + I_3$

each loop: $\sum E = \sum IR$ · at the junction J: $I_1 = I_2 + I_3$

USING THE LOOP RULE

1. Guess a current in every branch. A negative answer later just means the true direction is opposite.
2. Write junction equations (one fewer than the number of nodes).
3. Go round each loop: crossing a resistor **with** the current gives $-IR$, **against** it $+IR$; crossing a cell from $-$ to $+$ gives $+\varepsilon$, from $+$ to $-$ gives $-\varepsilon$ (internal r counts as a resistor).
4. Use as many independent loops as there are unknown currents left; solve and check on a loop not used.

NODE-VOLTAGE SHORTCUT

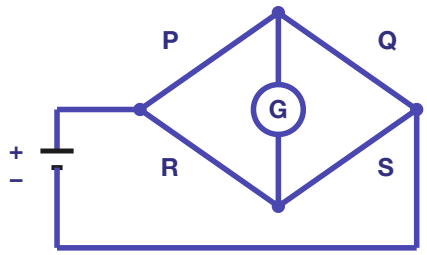
$$V_J = \frac{\sum \varepsilon_i/R_i}{\sum 1/R_i}$$

branches meeting at node J, their other ends at 0 V; ε_i taken with sign towards J. Current in a branch $= (\varepsilon_i - V_J)/R_i$

COUNTING EQUATIONS

b branches, n nodes: $n-1$ junction and $b-n+1$ loop equations

these are all independent; a drawn-out circuit often needs only one extra equation



balance: P/Q = R/S (no current in G)

the bridge is balanced when G shows no deflection; the cell feeds the bridge across its two outer corners

WHEATSTONE BRIDGE

- Four resistors in a diamond, a galvanometer G across the middle, a cell across the other corners.
- **Balanced** when $\frac{P}{Q} = \frac{R}{S}$ (that is, $PS = QR$): the two middle corners are at the same potential and G reads zero, so it may be removed (or replaced by a wire) without changing anything.
- With the bridge balanced the cell and the galvanometer can be interchanged and it stays balanced.
- If it is not balanced, solve with Kirchhoff's laws, or look for a symmetry.

TRAP

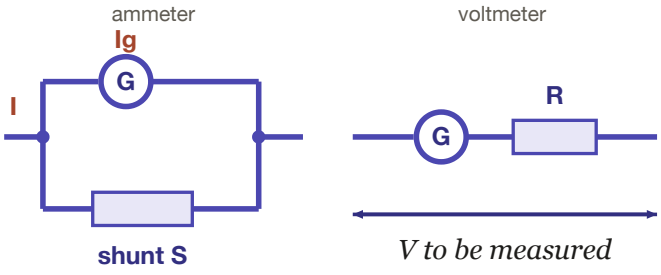
Do not guess signs inside a loop. Choose a direction round it, then apply the sign rule to every element. A wrong sign on one cell is the commonest error in two-cell circuits, especially when one cell turns out to be **charging**.

SANITY CHECK

After solving, check the junction rule at a node you did not use, and check that the power given out by the cells equals the heat $\sum I^2R$ in the resistors.

7 Galvanometer, ammeter and voltmeter

GALVANOMETER A sensitive instrument that deflects fully for a small current I_g and has its own resistance G. Alone it can measure only tiny currents and voltages; a **shunt** or a **series resistance** converts it.



ammeter: small S in parallel, most of I bypasses G · voltmeter: large R in series, I_g flows when V is full scale

AMMETER OF RANGE I

$$S = \frac{I_g G}{I - I_g} = \frac{G}{n-1}$$

$n = I/I_g$; shunt S in parallel with G; $R_A = \frac{GS}{G+S} \approx S$ (small)

VOLTMETER OF RANGE V

$$R = \frac{V}{I_g} - G = G(n-1)$$

$n = V/(I_g G)$; R in series; $R_V = G + R$ (large)

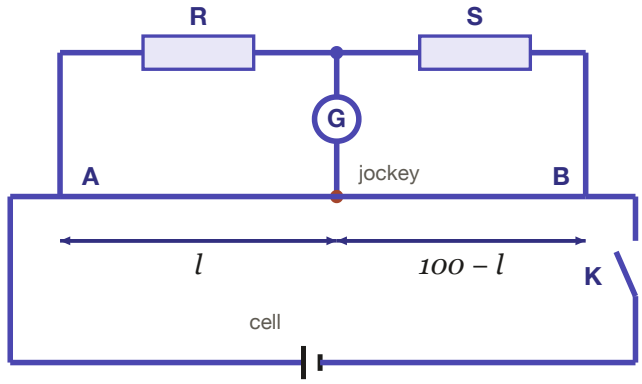
WHY IT WORKS

The shunt must carry nearly all the current, so it is small; the voltmeter must draw almost no current from the circuit, so it is large. A real ammeter adds its resistance in series; a real voltmeter shunts the element it measures. Both therefore disturb the circuit a little.

TRAP

Do not swap the two formulas. Check the size of the answer: a shunt is far smaller than G, a series resistance far larger. The ammeter range goes up when S goes down.

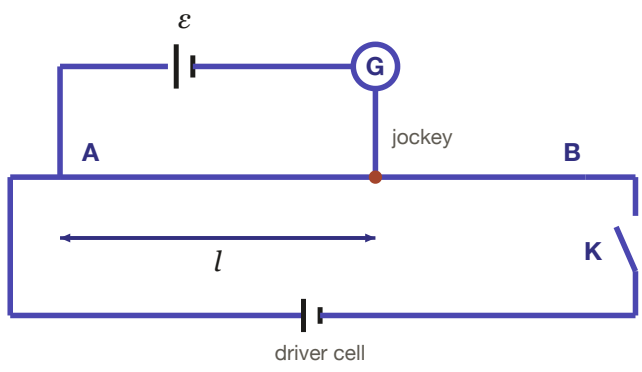
8 Metre bridge and potentiometer



balance: $\frac{R}{S} = \frac{l}{100 - l}$, with l the jockey length from A and $100 - l$ the length from B

METRE BRIDGE

- A Wheatstone bridge whose two lower arms are the two parts of one uniform 100 cm wire, so their resistances are proportional to their lengths.
- At balance (no deflection in G): $\frac{R}{S} = \frac{l}{100 - l}$, so $S = \frac{R(100 - l)}{l}$. Here l is the length from the end A on the side of R, in cm. If the unknown X is in that gap instead, $X = \frac{Rl}{100 - l}$: read off which resistor sits on which side.
- Take l near 50 cm for the least error. Interchange R and S and average the two readings to cancel the end errors.
- Only the length ratio matters; the cell's emf and the wire's resistance drop out.



at balance no current flows in G, so $\varepsilon = k\,l$: the emf is proportional to the balance length l

POTENTIOMETER

- A long uniform wire carrying a steady current has a potential difference proportional to length. The **potential gradient** is $k = \frac{V_{AB}}{L} = \frac{I\rho}{A}$ (V/m).
- At balance no current flows through the test cell, so $\varepsilon = kl$ and $\frac{\varepsilon_1}{\varepsilon_2} = \frac{l_1}{l_2}$: it reads the true emf, as an ideal voltmeter would.
- A smaller gradient (a longer wire, or a series resistance in the driver circuit) gives a longer balance length and greater sensitivity. The driver emf must exceed the emf measured, with matching polarity.

INTERNAL RESISTANCE OF A CELL

$$\varepsilon = kl_1$$

open circuit: no current, balance length l_1

$$V = \frac{\varepsilon R}{R + r} = kl_2$$

cell closed through R: balance length l_2

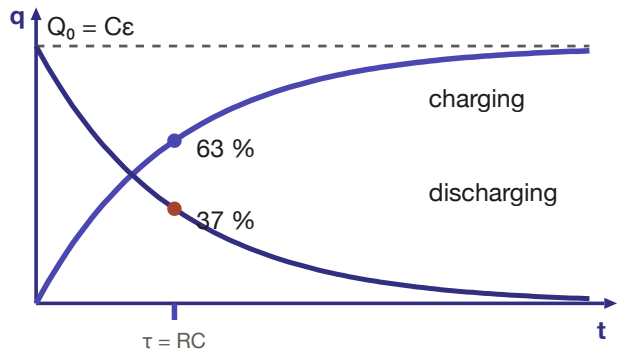
$$\frac{l_1}{l_2} = \frac{R + r}{R} \Rightarrow r = R\left(\frac{l_1}{l_2} - 1\right)$$

SYLLABUS NOTE

The metre bridge is named in the NTA topic list; the potentiometer is in older lists and may have been dropped, so it is here for completeness. Learn the formulas, but the circuit-solving sections above carry the most weight.

9 Charging a capacitor through a resistor

TIME CONSTANT $\tau = RC$ (seconds) sets the pace of every charge or discharge through a resistor R of a capacitor C. After time τ a charging capacitor holds 63% of its final charge, and a discharging one is down to 37% $(1/e)$.



both curves are exponentials with the same time constant $\tau = RC$: after τ the charge is 63% of its final value when charging and 37% of its start value when discharging

CHARGING (BATTERY ε)

$$q = C\varepsilon\left(1 - e^{-t/RC}\right)$$

$$I = \frac{\varepsilon}{R}e^{-t/RC}$$

the current starts at ε/R and falls to zero

DISCHARGING

$$q = Q_0 e^{-t/RC}$$

$$I = \frac{Q_0}{RC}e^{-t/RC}$$

half the charge is left after $t = RC\ln 2 = 0.693\,RC$

ENERGY DURING CHARGING

battery gives $C\varepsilon^2$; stored $\frac{1}{2}C\varepsilon^2$; heat $\frac{1}{2}C\varepsilon^2$

half is always lost in the resistor, whatever its value; on discharge all the stored energy becomes heat

TWO LIMITING INSTANTS

MOMENT	CAPACITOR ACTS AS
$t = 0$ (uncharged)	a wire (short circuit)
$t \to \infty$ (steady state)	a gap: no current in its branch

KEY IDEA

In a steady d.c. network, delete every capacitor branch, solve the resistors, then read the capacitor's voltage as the potential difference between its two ends in that solved circuit.

CONNECTS TO

The energy $\frac{1}{2}CV^2$ and the series and parallel rules for C come from **Electrostatics**. The same exponential reappears for an L-R circuit in **Electromagnetic Induction**.

SYLLABUS NOTE

NCERT treats capacitors and resistors separately and the transient formulas are outside its text; they are included because RC time-constant questions are asked.

10 Worked examples

DRIFT SPEED

A wire of cross-section $1\ \text{mm}^2$ carries 1 A. Take $n = 8.5 \times 10^{28}\ \text{m}^{-3}$. Find v_d.

$v_d = \dfrac{I}{neA} \approx 7.4 \times 10^{-5}$ m/s (with $A = 10^{-6}\ \text{m}^2$)

STRETCHED, THEN BENT

A $3\ \Omega$ wire is stretched to twice its length, then bent into a circle. Resistance between two diametrically opposite points?

stretch: $4 \times 3 = 12\ \Omega$; two halves of $6\ \Omega$ in parallel: $3\ \Omega$

SERIES OR PARALLEL CELLS

Four cells, each 1.5 V and $0.5\ \Omega$, drive an external $2\ \Omega$. Current for all in series, and all in parallel?

series: $6/(2+2) = 1.5$ A; parallel: $1.5/(2+0.125) \approx 0.71$ A

AIDING AND OPPOSING

Cells 10 V ($1\ \Omega$) and 4 V ($2\ \Omega$) with a $7\ \Omega$ resistor in one loop. Current if they aid, and if they oppose?

$I = \dfrac{\varepsilon_1 \pm \varepsilon_2}{R + r_1 + r_2}$: aiding $14/10 = 1.4$ A; opposing $6/10 = 0.6$ A

METER CONVERSIONS

A galvanometer ($G = 50\ \Omega$, $I_g = 2$ mA) is to read 1 A, and separately 10 V. Find S and R.

$S = \dfrac{I_g G}{I - I_g} = 0.1/0.998 \approx 0.10\ \Omega$ (parallel); $R = 10/0.002 - 50 = 4950\ \Omega$ (series)

METRE BRIDGE

$R = 10\ \Omega$ in the left gap; balance at $l = 40$ cm. Find the unknown resistance.

$R/S = l/(100 - l) = 40/60$, so $S = 10 \times 60/40 = 15\ \Omega$

POTENTIOMETER

Open-circuit balance at 60 cm; with $2\ \Omega$ across the cell, balance at 50 cm. Internal resistance?

$r = R(l_1/l_2 - 1) = 2(60/50 - 1) = 0.4\ \Omega$

BULBS IN SERIES

A 100 W and a 60 W bulb, both rated 220 V, are in series across 220 V. Which is brighter, and what does the 60 W bulb dissipate?

$R = 484\ \Omega$ and $807\ \Omega$; $I = 220/1291 = 0.17$ A; the 60 W bulb gives $I^2 R = 23$ W (the 100 W one only 14 W)

TWO CELLS, THREE RESISTORS

Branches meet at J: 12 V with $2\ \Omega$, 6 V with $1\ \Omega$ (other ends at 0 V, cells pushing towards J), and $3\ \Omega$ from J to 0 V. Find V_J and the three currents.

$V_J = \dfrac{12/2 + 6/1}{1/2 + 1 + 1/3} = \dfrac{72}{11} \approx 6.5$ V; currents $30/11$ A, $-6/11$ A (the 6 V cell is being charged) and $24/11$ A in the $3\ \Omega$

CAPACITOR DISCHARGE

A $2\ \mu$F capacitor discharges through $1\ \text{M}\Omega$. How long until its voltage halves?

$\tau = RC = 2$ s; $t = \tau \ln 2 = 1.39$ s

11 Last-minute checklist

BEFORE YOU ANSWER

Is the circuit in steady state (capacitors open) or switching on (capacitors short)? Is a cell charging or discharging? Is a meter ideal? Are lengths in cm for the metre bridge and in m for $\rho l/A$?

- $I = neAv_d$, $v_d = eE\tau/m$, $\rho = m/ne^2\tau$; $R = \rho l/A$; stretching to n times the length multiplies R by n^2.
- $R_T = R_0(1 + \alpha \Delta T)$: metals $\alpha > 0$, semiconductors $\alpha < 0$, alloys about 0.
- Series: same I, R adds. Parallel: same V, $1/R$ adds. Power I^2R in series, V^2/R in parallel.
- Cell: $V = \varepsilon - Ir$; maximum load power at $R = r$ ($\varepsilon^2/4r$, 50% efficient); series adds ε and r, parallel keeps ε and divides r.
- Kirchhoff: $\sum I = 0$ at nodes, $\sum \Delta V = 0$ round loops; balanced bridge $P/Q = R/S$ means delete the galvanometer.
- Shunt $S = I_g G/(I - I_g)$, series $R = V/I_g - G$; metre bridge $R/S = l/(100 - l)$; potentiometer $\varepsilon_1/\varepsilon_2 = l_1/l_2$, $r = R(l_1/l_2 - 1)$.
- RC: $\tau = RC$; 63% charged after τ; half the charge left after $0.693\,\tau$; half the battery's energy is lost as heat.

Now test it. Practise this chapter with past-paper and bank questions on Prep Vault. **Practice this chapter →**