

D.C. circuits

A-Level Physics 9702 · Topic 10 revision notes · AS

Real circuits with real batteries: e.m.f. and internal resistance, Kirchhoff's laws, combining resistors, potential dividers and the potentiometer.

11 definitions to learn word for word, 12 equations in their own column, 8 diagrams and graphs. Read it, cover it, test yourself.

1. 10.1 E.m.f. and internal resistance
2. 10.2a Kirchhoff's laws
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Definitions (mark-scheme wording) Equations Exam traps

10.1 E.m.f. and internal resistance

Definitions

Electromotive force (e.m.f.): the energy transferred from other forms (e.g. chemical) to electrical energy per unit charge in driving charge round a complete circuit.

Potential difference: the energy transferred from electrical to other forms per unit charge.

Internal resistance (r): the resistance of the source itself, which causes energy to be dissipated inside the source when it delivers current.

Terminal p.d.: the p.d. across the terminals of a source when it delivers a current: $V = E - Ir$.

Equations

$$E = I(R + r)$$

e.m.f. = current $\times$ total resistance
V

$$V = E - Ir$$

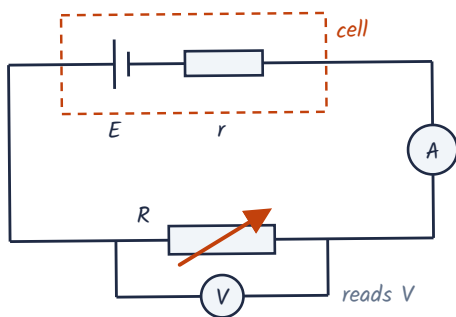
terminal p.d. = e.m.f. - lost volts
V

$$V = IR$$

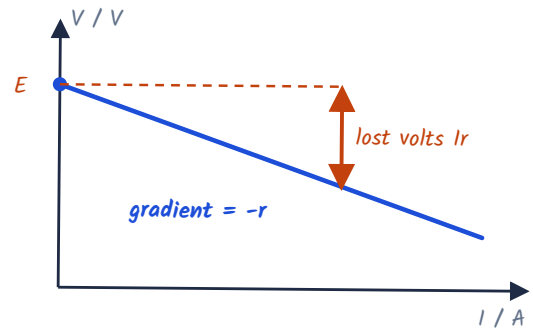
terminal p.d. across the external load R
V

Key points

- ✓ e.m.f.: energy **into** electrical form; p.d.: energy **out of** electrical form. Both in V (J C^{-1}).
- ✓ Ir is the **lost volts**: energy per coulomb wasted as heat inside the source.
- ✓ As current increases, lost volts rise and the **terminal p.d. falls**.
- ✓ On open circuit ($I = 0$), terminal p.d. = e.m.f.; a high-resistance voltmeter alone reads close to E .
- ✓ Experiment: vary the load resistor, record V and I ; plot **V against I** : y-intercept = E , gradient = $-r$.
- ✓ Low r matters for large currents (car starter battery); high r is a safety feature for EHT supplies.



A real cell = ideal e.m.f. E in series with internal resistance r (dashed box). The voltmeter across the load reads the terminal p.d. V (ideal ammeter).



Terminal p.d. against current: the y-intercept is the e.m.f. E and the gradient is $-r$. The gap below E is the lost volts Ir .

Watch out!

- ! A voltmeter across a cell in use reads the **terminal p.d.**, not the e.m.f.
- ! Gradient of V against I is $-r$: quote r as a positive value.

10.2a Kirchhoff's laws

Definitions

Kirchhoff's first law: the sum of the currents into a junction equals the sum of the currents out of the junction.

Kirchhoff's second law: around any closed loop in a circuit, the sum of the e.m.f.s equals the sum of the p.d.s.

Key points

- ✓ First law is a consequence of **conservation of charge**.
- ✓ Second law is a consequence of **conservation of energy**.
- ✓ Choose a direction round the loop; an e.m.f. counts **positive** if the loop passes through it from $-$ to $+$.
- ✓ An IR term is positive if the loop goes **with** the assumed current through that resistor.
- ✓ A current that comes out **negative** just flows the opposite way to the one assumed.
- ✓ Parallel branches have the **same p.d.**; series components carry the **same current**.

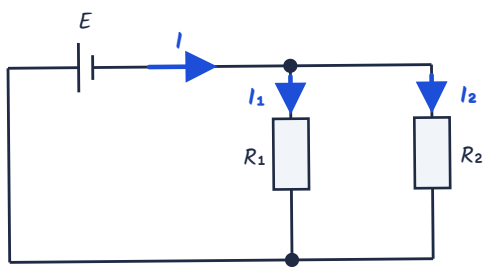
Equations

$$\sum I_{\text{in}} = \sum I_{\text{out}}$$

first law: charge conservation at a junction
 A

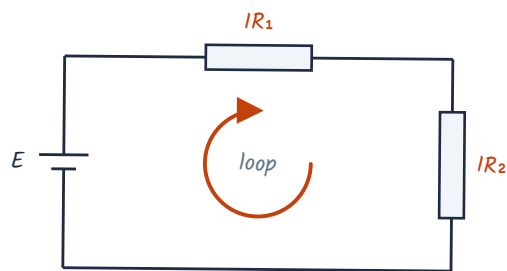
$$\sum E = \sum IR$$

second law: energy conservation round a closed loop
 V



junction: $I = I_1 + I_2$

First law: the current I arriving at the junction splits so that $I = I_1 + I_2$.



$E = IR_1 + IR_2$

Second law round a single loop: the e.m.f. equals the sum of the p.d.s, $E = IR_1 + IR_2$.

Watch out!

- ! Going round a loop against the assumed current, the IR term is **subtracted**.
- ! Count each e.m.f. once per loop, with the correct sign for its direction.

10.26 Resistors in series and in parallel

Definitions

Combined (equivalent) resistance: the single resistance that would draw the same current from the same p.d. as the combination.

Key points

- ✓ Series: same current I ; p.d.s add (second law), $V = IR_1 + IR_2$, so $R = R_1 + R_2$.
- ✓ Parallel: same p.d. V ; currents add (first law), $I = V/R_1 + V/R_2$, giving the reciprocal rule.
- ✓ Parallel combination is always **less than the smallest** branch resistance.
- ✓ n equal resistors R in parallel: R/n . Two equal in parallel: half of one.
- ✓ Adding a branch in parallel **lowers** total resistance and increases the supply current.
- ✓ Solve networks from the inside out: combine parallel groups first, then add series parts.

Equations

$R = R_1 + R_2 + \dots$

resistors in series

Ω

$1/R = 1/R_1 + 1/R_2 + \dots$

resistors in parallel

Ω^{-1}

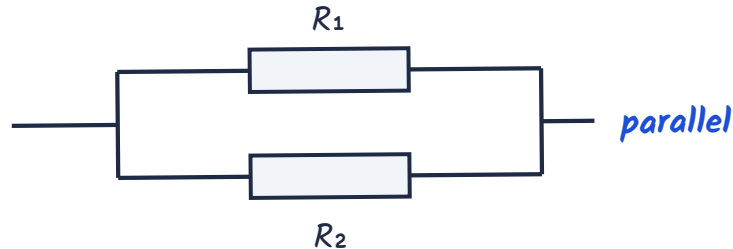
$R = R_1 R_2 / (R_1 + R_2)$

shortcut for exactly two in parallel

Ω



$$R = R_1 + R_2$$



$$1/R = 1/R_1 + 1/R_2$$

Series: resistances add. Parallel: reciprocals add, so the total is below the smallest branch.

Watch out!

- ! After adding reciprocals, remember to **invert**: $1/R = 0.5 \Omega^{-1}$ means $R = 2 \Omega$.
- ! Two 10Ω resistors in parallel make 5Ω , not 20Ω .

10.3a Potential dividers and sensor circuits

Definitions

Potential divider: two or more resistors in series across a supply, so that the supply p.d. is shared between them in the ratio of their resistances.

Equations

$$V_{out} = V_{in} \times R_2 / (R_1 + R_2)$$

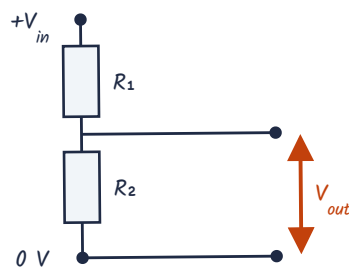
p.d. across R_2 (unloaded output)
V

$$V_1 / V_2 = R_1 / R_2$$

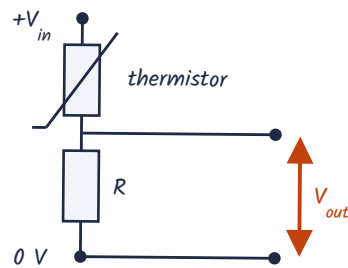
p.d.s share in the ratio of resistances
-

Key points

- ✓ Series resistors share the supply p.d. in the **ratio of their resistances**: $V_1/V_2 = R_1/R_2$.
- ✓ The **larger** resistor takes the larger share of the p.d.
- ✓ Replace one resistor with a **thermistor or LDR** to make a temperature or light sensor.
- ✓ Output across the fixed resistor **rises** when the sensor resistance falls (hotter, or brighter).
- ✓ A variable resistor or rotary potentiometer gives a continuously variable output from 0 to V_{in} .
- ✓ Formula assumes the output draws **no current**; a low-resistance load lowers V_{out} .



Potential divider: R_2 gets its share of the input, $V_{out} = V_{in} \frac{R_2}{R_1 + R_2}$.



hotter: thermistor R falls, V_{out} rises

Temperature sensor: when the thermistor warms, its resistance falls, so a larger share of the p.d. appears across the fixed resistor and V_{out} rises.

Watch out!

- ! Check which resistor the output is across: swapping the sensor and fixed resistor **reverses** the response.
- ! V_{out} depends on the **ratio** $R_2/(R_1 + R_2)$, not on either resistance alone.

10.36 The potentiometer and null methods

Definitions

Potentiometer: a uniform resistance wire with a steady current in it, so that the p.d. between two points is proportional to the length of wire between them.

Null method: a method in which the length is adjusted until a galvanometer shows zero current (balance).

Balance length: the length of potentiometer wire at which the galvanometer reads zero.

Equations

$$E_1 / E_2 = L_1 / L_2$$

ratio of e.m.f.s from balance lengths

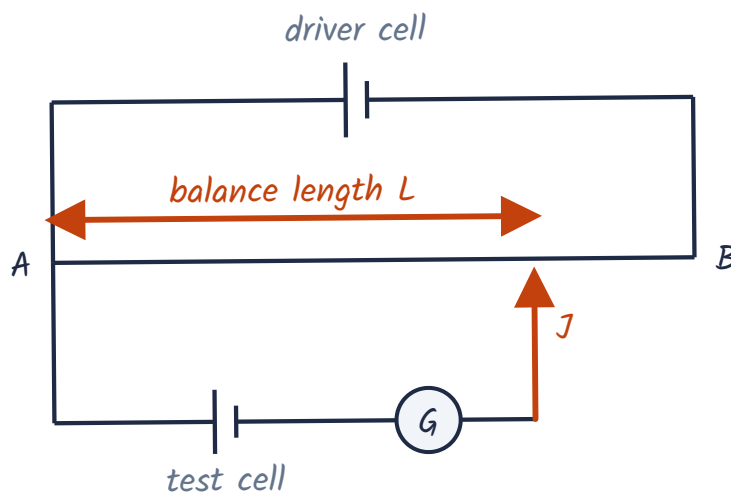
$$V = (L / L_0) \times V_{AB}$$

p.d. across length L of a wire of total length L_0

V

Key points

- ✓ Driver cell sets a steady current along the wire; p.d. per unit length is **constant**, so $V \propto L$.
- ✓ Connect **like terminals** (+ to +) of driver and test cell to the same end A of the wire.
- ✓ At balance the galvanometer reads zero: **no current in the test cell**, so no lost volts and it measures the **e.m.f.**
- ✓ Compare two e.m.f.s: find the balance length for each; $E_1/E_2 = L_1/L_2$.
- ✓ Can also compare two p.d.s, e.g. across two resistors carrying the same current, to compare resistances.
- ✓ If no balance point exists: driver e.m.f. is too small, or a cell is connected the wrong way round.



Potentiometer: slide the jockey J until G reads zero. The balance length AJ is proportional to the e.m.f. of the test cell.

Watch out!

- ! At balance the test cell delivers no current, so the reading is its **e.m.f.**, not a terminal p.d.
- ! The driver cell must have a larger e.m.f. than the cell being tested, or no balance point is found.