A LEVEL PHYSICS 9702 · AS LEVEL · TOPIC 10 · ~9 MIN READ

D.C. circuits

E.m.f. and internal resistance, Kirchhoff's two laws and the conservation laws behind them, deriving series and parallel resistance, multi-loop circuits, potential dividers with sensors, and the potentiometer null method.

Circuit symbols | E.m.f. vs p.d. | Internal resistance | Kirchhoff's first law | Kirchhoff's second law | Series & parallel | Potential dividers | Sensors

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Paper tag = **where it is examined** DATA & FORMULAE given in the exam C1 A1 B1 how marks are awarded

highlight = comes up again and again Test yourself at the end

IN 30 SECONDS

- **E.m.f.** is the energy a source transfers to each unit of charge; **p.d.** is the energy each unit of charge transfers to a component. Both are measured in volts.
- **Internal resistance** wastes some of the e.m.f.: terminal p.d. V = E − Ir.
- **Kirchhoff's first law** (junctions) comes from conservation of charge; **the second law** (closed loops) from conservation of energy.
- **A potential divider** shares the supply p.d. in proportion to the resistances: $V_{out} = V_{in} \times R_2/(R_1 + R_2)$.
- **The potentiometer** compares p.d.s by a null method: when the galvanometer reads zero, no current is drawn from the cell being measured.

BY THE END YOU CAN

- Draw and interpret circuit diagrams with the standard symbols.
- Define e.m.f., distinguish it from p.d., and use internal resistance.
- State Kirchhoff's laws, link them to conservation, and use them to derive series and parallel formulas and solve circuits.
- Explain potential dividers, including thermistor and LDR sensors.
- Use a potentiometer and galvanometer to compare p.d.s by a null method.

1 E.m.f. and internal resistance

Definitions

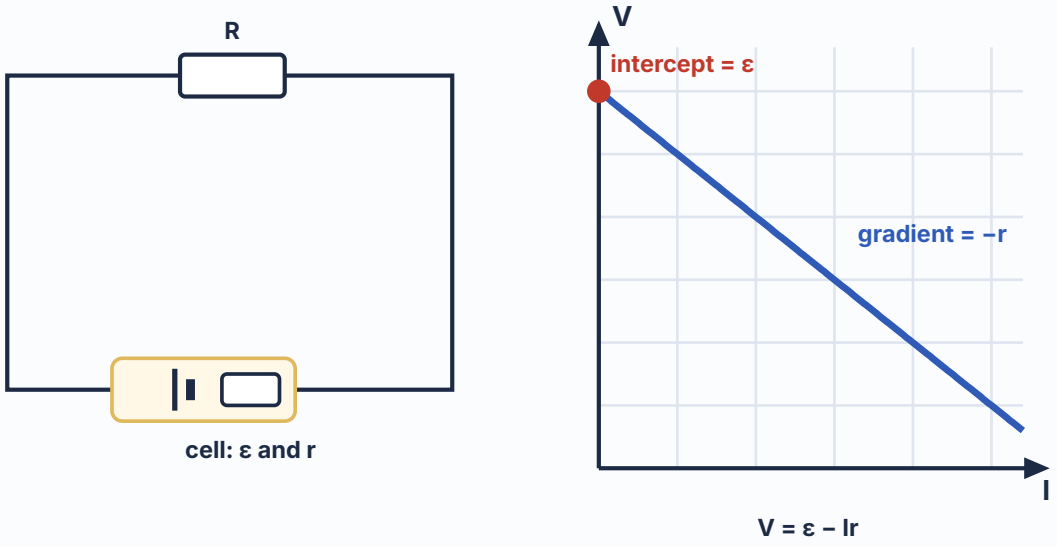
Electromotive force (e.m.f.) — the energy transferred from other forms (e.g. chemical) to electrical energy per unit charge, by a source driving charge round a complete circuit.

Potential difference — the energy transferred from electrical energy to other forms per unit charge passing between two points.

- **Energy view:** e.m.f. = energy given to each coulomb by the source; p.d. = energy each coulomb gives up in a component. Round a loop, energy in = energy out.

$$E = I(R + r) \; ; \; V = E - Ir$$ LEARN IT

V = terminal p.d.; Ir = "lost volts" inside the source



Measuring E and r: plot terminal p.d. V against current I. Intercept = E, gradient = −r.

WORKED EXAMPLE

A cell of e.m.f. 9.0 V and internal resistance 1.5 Ω is connected to a 6.0 Ω resistor. Find the current, the terminal p.d. and the power wasted inside the cell.

1. I = E/(R + r) = 9.0/7.5 = **1.2 A** C1 A1
2. V = E − Ir = 9.0 − 1.8 = **7.2 V** A1
3. **power in r = I^2r = 1.2^2 × 1.5 = 2.2 W** A1

COMMON MISTAKE

Using the e.m.f. where the terminal p.d. is needed, or confusing the p.d. across r with the terminal p.d. These were the most common circuit errors in the 2024 Paper 2 reports.

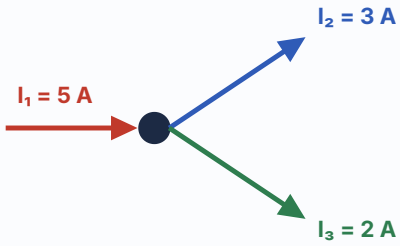
- **When does terminal p.d. fall?** When the current increases (smaller external resistance), more volts are lost inside: V = E − Ir decreases.

2 Kirchhoff's laws

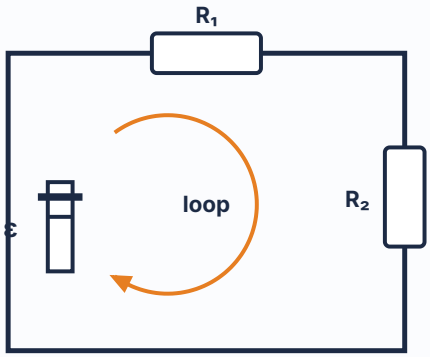
The two laws

Kirchhoff's first law — the sum of the currents entering a junction equals the sum of the currents leaving it. (Conservation of charge.)

Kirchhoff's second law — in any closed loop of a circuit, the sum of the e.m.f.s equals the sum of the p.d.s. (Conservation of energy.)



Junction (1st law):
$I_1 = I_2 + I_3$
charge is conserved



Loop (2nd law):
$\varepsilon = IR_1 + IR_2$
energy is conserved

Junction rule (charge) and loop rule (energy).

- **Write "sum of" and "closed loop".** The 2024 reports penalised answers without them.

Deriving series and parallel resistance

- **Series:** the same current I flows through each resistor. By the second law, $V = V_1 + V_2 + \ldots$, so $IR = IR_1 + IR_2 + \ldots$, giving **$R = R_1 + R_2 + \ldots$**
- **Parallel:** each resistor has the same p.d. V. By the first law, $I = I_1 + I_2 + \ldots$, so $V/R = V/R_1 + V/R_2 + \ldots$, giving **$1/R = 1/R_1 + 1/R_2 + \ldots$**

$$R = R_1 + R_2 + \ldots \; ; \; 1/R = 1/R_1 + 1/R_2 + \ldots$$ DATA & FORMULAE

series; parallel

- **Parallel combination is always less than the smallest resistor.** Adding a resistor in parallel decreases the total resistance and increases the supply current (2024 Paper 1).

WORKED EXAMPLE

A 4.0 Ω resistor is in series with a 6.0 Ω and a 3.0 Ω resistor in parallel, across a 12 V supply of negligible internal resistance. Find the current in each resistor.

1. parallel: 1/R = 1/6 + 1/3 ⇒ R = 2.0 Ω; total 6.0 Ω C1
2. I = 12/6.0 = **2.0 A** through the 4.0 Ω A1
3. **p.d. across the parallel pair = 2.0 × 2.0 = 4.0 V ⇒ 0.67 A in 6.0 Ω and 1.3 A in 3.0 Ω** A1

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Two-loop circuits

- **Label unknown currents** in each branch with arrows (guess directions). Use the first law to reduce the unknowns, then write one second-law equation for each independent loop. A negative answer just means the current flows the other way.

WORKED EXAMPLE

A 12 V cell in series with 2.0 Ω, and a 6.0 V cell in series with 3.0 Ω, are both connected across a 6.0 Ω resistor (positive terminals joined at the top). Find the current in each branch.

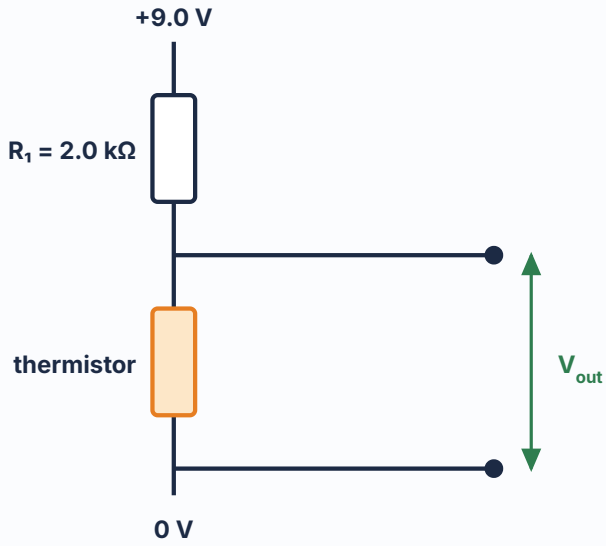
1. let I_1 (12 V branch) and I_2 (6.0 V branch) flow up into the top junction; then 6.0 Ω carries $I_1 + I_2$ B1
2. loop 1: $12 = 2.0I_1 + 6.0(I_1 + I_2)$; loop 2: $6.0 = 3.0I_2 + 6.0(I_1 + I_2)$ C1
3. solving: **$I_1 = 2.0$ A, $I_2 = -0.67$ A**: the 6.0 V cell is being charged, with 0.67 A flowing into its positive terminal A1
4. **current in 6.0 Ω = 1.3 A** A1

3 Potential dividers

Sharing the p.d.

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

p.d. across R_2 when no current is drawn from the output



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

thermistor at 1.0 kΩ:

$V_{out} = 9.0 \times 1/3 = 3.0$ V

warmer ⇒ R_2 falls

⇒ V_{out} falls

A thermistor in a potential divider: as temperature rises, R falls and its share of the p.d. falls.

- **Sensors:** put a thermistor or LDR as one resistor. As temperature or light changes, its resistance changes, so the output p.d. changes. Swap the positions to make the output rise instead of fall.
- **Explain in steps:** temperature rises ⇒ thermistor resistance falls ⇒ its share of the total resistance falls ⇒ the p.d. across it falls (and across the fixed resistor rises).

WORKED EXAMPLE

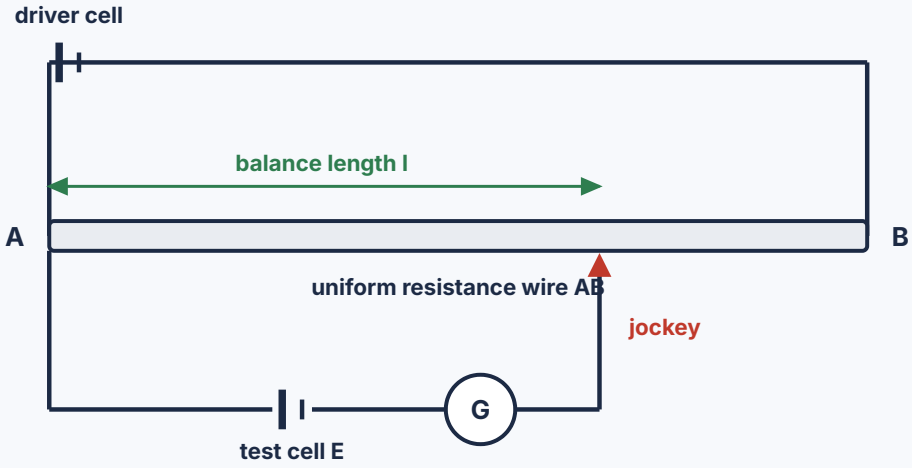
A 2.0 kΩ resistor and a thermistor are in series across 12 V. The thermistor's resistance is 4.0 kΩ at 20 °C and 1.0 kΩ at 60 °C. Find the p.d. across the thermistor at each temperature.

1. 20 °C: 12 × 4.0/(2.0 + 4.0) = **8.0 V** C1 A1
2. **60 °C: 12 × 1.0/(2.0 + 1.0) = 4.0 V** A1

COMMON MISTAKE

Neglecting part of the circuit's resistance or rounding the current early. The 2024 Paper 2 report flagged both in potential-divider calculations.

The potentiometer and null method



Slide the jockey until G reads zero (null): then E ∝ l. Compare two cells: $E_1/E_2 = l_1/l_2$.

At balance, no current flows through the galvanometer or the test cell.

- **Principle:** a driver cell maintains a steady current in a uniform wire, so the p.d. along the wire is proportional to length. A test cell is connected via a galvanometer to a sliding contact (jockey).
- **At balance (null),** the galvanometer reads zero: the p.d. across the length l of wire equals the e.m.f. of the test cell. Because no current flows from the test cell, its internal resistance doesn't matter: the potentiometer measures the e.m.f. itself.
- **Comparing two cells:** $E_1/E_2 = l_1/l_2$ (same driver current).

WORKED EXAMPLE

A standard cell of e.m.f. 1.018 V balances at 50.9 cm. A test cell balances at 75.0 cm on the same wire. Find the e.m.f. of the test cell.

1. E/1.018 = 75.0/50.9 C1
2. **E = 1.50 V** A1

- **Why a galvanometer?** It is a very sensitive ammeter that shows small currents in either direction, so it detects the exact null point.

LINKING QUESTION

Electrical definitions start in Electricity; capacitors add to these circuits in Capacitance; and rectifier circuits use diodes in Alternating currents.

Test yourself — cover the answers first

QUICK CHECK

1. Define e.m.f.
2. Kirchhoff's first law follows from the conservation of what?
3. A battery of e.m.f. 6.0 V has terminal p.d. 5.4 V when the current is 0.30 A. Find r.
4. Find the combined resistance of 10 Ω and 15 Ω in parallel.
5. Why does a potentiometer measure the e.m.f. of a test cell, not its terminal p.d.?

EXAM-STYLE

6. A light sensor uses an LDR and a 10 kΩ resistor across 6.0 V. The output is taken across the 10 kΩ resistor. Explain what happens to the output as the room gets darker.
7. Derive the formula for the combined resistance of two resistors in parallel using Kirchhoff's laws.
8. A student measures V and I for a cell with a variable resistor. When I = 0.20 A, V = 1.42 V; when I = 0.50 A, V = 1.30 V. Find E and r.

Show answers

1. energy transferred from other forms to electrical energy per unit charge, by a source driving charge round a complete circuit
2. charge
3. 2.0 Ω
4. 6.0 Ω
5. at balance no current flows from the test cell, so there are no lost volts
6. darker ⇒ LDR resistance increases ⇒ larger share of the 6.0 V across the LDR ⇒ output across 10 kΩ decreases
7. same p.d. V across each (2nd law); $I = I_1 + I_2$ (1st law); $V/R = V/R_1 + V/R_2 \Rightarrow 1/R = 1/R_1 + 1/R_2$
8. gradient $-r = -0.12/0.30 \Rightarrow r = 0.40\ \Omega$; $E = 1.42 + 0.20 \times 0.40 = 1.50$ V

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