Cambridge AS & A Level · Physics (9702) · Notes

D.C. circuits AS

Read online at pastopic.com/cambridge/physics-9702/notes/dc-circuits

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Read first: Electricity

What you need to know

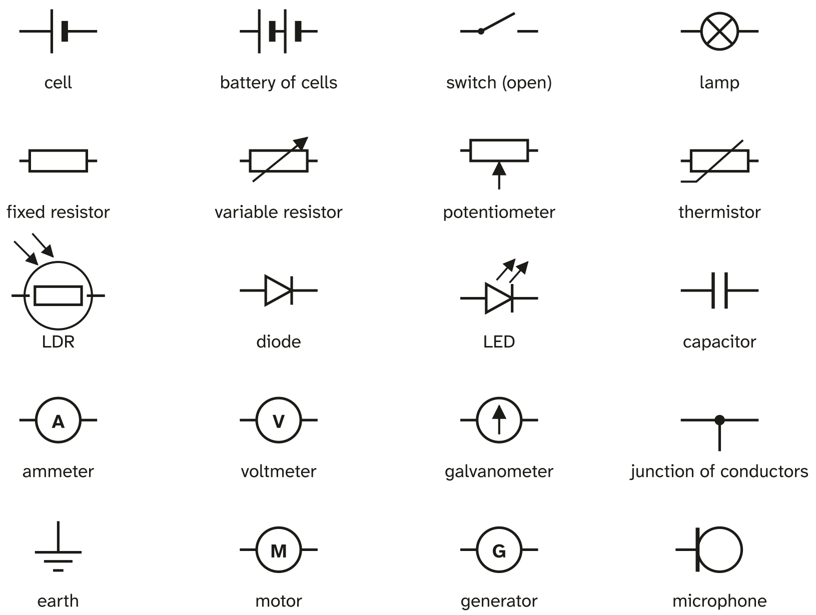
By the end of this topic you should be able to:

1. **Recall and use the circuit symbols** in the syllabus's table of symbols.
2. **Draw and interpret circuit diagrams** that use those symbols.
3. **Define and use electromotive force (e.m.f.)**: the energy transferred per unit charge by a source in driving charge round a complete circuit.
4. **Tell e.m.f. and potential difference (p.d.) apart** by what happens to the energy.
5. **Understand how the internal resistance of a source affects its terminal p.d.**
6. **Recall Kirchhoff's first law** and understand that it comes from conservation of charge.
7. **Recall Kirchhoff's second law** and understand that it comes from conservation of energy.
8. **Derive, from Kirchhoff's laws, the combined resistance of resistors in series**, and
9. **use it**: $R = R_1 + R_2 + \ldots$
10. **Derive, from Kirchhoff's laws, the combined resistance of resistors in parallel**, and
11. **use it**: $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$
12. **Use Kirchhoff's laws to solve simple circuit problems.**
13. **Understand the principle of a potential divider.**
14. **Recall and use the principle of the potentiometer** to compare potential differences.
15. **Understand how a galvanometer is used in null methods.**
16. **Explain how a thermistor or a light-dependent resistor (LDR) in a potential divider gives a p.d. that depends on temperature or light intensity.**

Current, charge, p.d., resistance, power, resistivity and the behaviour of LDRs and thermistors on their own are in the Electricity note. This note uses them without teaching them again.

Understand it

Circuit symbols and diagrams



A circuit diagram shows how components are **connected**, not where they sit on the bench. Draw wires as straight lines with square corners, and use the symbols from the syllabus's table (the chart shows the ones that come up most; the table also has a power supply, an a.c. power supply, a heater, a bell, a buzzer, a loudspeaker and an oscilloscope).

- **Cell**: the long thin line is the positive terminal, the short thick line the negative. A **battery** is two or more cells joined.
- **Variable resistor**: an arrow **through** the resistor. **Potentiometer**: an arrow **pointing onto** the resistor, the sliding contact.
- **Thermistor**: a resistor crossed by a line with a short flat foot. **LDR**: a resistor inside a circle with two arrows (light) pointing **in**. An **LED** has arrows pointing **out**.
- **Ammeter** in **series** with the component (the same current passes through both). **Voltmeter** in **parallel** across the component only (the same p.d.). A **galvanometer** is a sensitive meter used to show that the current is **zero**.
- A **dot** marks a junction where wires join. Wires that cross without a dot are not connected.

E.m.f. and potential difference

Both are measured in volts (joules per coulomb). The difference is which way the energy goes.

- **E.m.f.** E: energy transferred **to** electrical energy (from chemical energy in a cell, for example) **per unit charge** as the source drives charge round the **whole** circuit: $E = \dfrac{W}{Q}$.

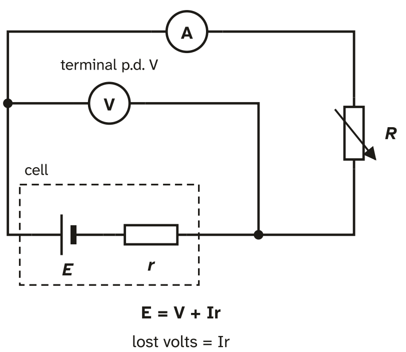
- **P.d.** V: energy transferred **from** electrical energy **to other forms** (thermal energy, light) **per unit charge** passing through a component: $V = \frac{W}{Q}$.

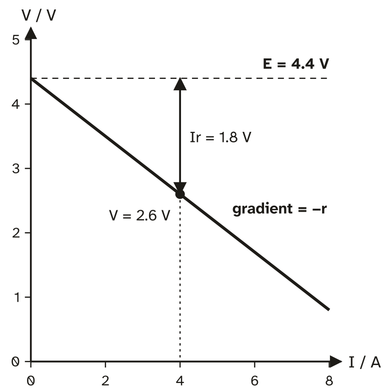
A cell of e.m.f. 1.45 V that drives 30 C round a circuit gives the charge $1.45 \times 30 = 43.5$ J of electrical energy. By conservation of energy, the same 43.5 J is transferred to other forms round the circuit, including inside the cell itself.

Internal resistance and terminal p.d.

A real source has **internal resistance** r: the charge has to pass through the materials of the cell too, and some energy is turned into thermal energy **inside** the cell. The p.d. across that internal resistance, Ir, is sometimes called the **lost volts**. What is left appears across the terminals: the **terminal p.d.** V.

$$E = V + Ir \qquad \text{and, with an external resistance } R, \qquad E = IR + Ir = I(R + r)$$





A cell with $E = 4.4$ V and $r = 0.45$ Ω connected to $R = 5.05$ Ω:

- current $I = \frac{E}{R + r} = \frac{4.4}{5.50} = 0.80$ A;
- lost volts $Ir = 0.80 \times 0.45 = 0.36$ V;
- terminal p.d. $V = 4.4 - 0.36 = 4.04$ V (the same as $IR = 0.80 \times 5.05$).

What the internal resistance does:

- **Terminal p.d. is less than the e.m.f.** whenever there is a current. With **no current** (an open circuit, or a very high-resistance voltmeter alone across the cell) there are no lost volts, and $V = E$.
- **Smaller external resistance → larger current → more lost volts → smaller terminal p.d.** This is the chain to write for any "explain" question. Adding a resistor **in parallel** lowers the external resistance, so it does the same.
- **The graph of V against I** is a straight line, $V = E - rI$: its intercept on the V axis is E, and its gradient is $-r$. The largest possible current (a short circuit, $V = 0$) is $\frac{E}{r}$, where the line meets the I axis; for the cell above, $\frac{4.4}{0.45} = 9.8$ A.
- **Power**: the cell's total power output is EI; the external circuit gets VI and the cell wastes I^2r. At 0.80 A: $EI = 3.52$ W, $VI = 3.232$ W, $I^2r = 0.288$ W, and $3.232 + 0.288 = 3.52$.

- **The e.m.f. itself does not change** when the current changes (unless told otherwise).

Kirchhoff's first law: charge is conserved

The sum of the currents into a junction equals the sum of the currents out of it. Charge cannot pile up at a junction or disappear, so every coulomb that arrives each second must leave each second.

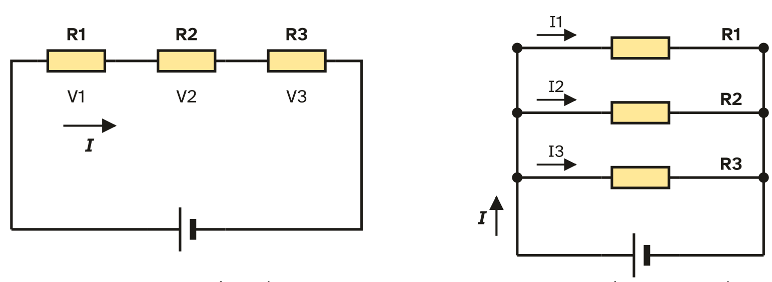
- Currents of 0.75 A and 0.40 A flow into a junction and one wire leaves it: that wire carries 1.15 A out.
- In a single loop (no junctions) the current is the same at every point.
- Writing each current **into** the junction as positive and each **out** as negative, the currents add up to zero ("the algebraic sum of the currents at a junction is zero").

Kirchhoff's second law: energy is conserved

Round any closed loop of a circuit, the sum of the e.m.f.s equals the sum of the p.d.s. Each coulomb that goes once round a loop gains energy E per coulomb from each source and loses energy V per coulomb in each component, and it ends where it started, so the gains equal the losses.

- Go round the loop in one direction. An e.m.f. counts **positive** if the source pushes current the way you are going, **negative** if it pushes against it. A p.d. IR counts positive if the current in that resistor is in your direction, negative if against it.
- **Cells in series**: e.m.f.s pointing the same way add; a cell turned round subtracts. Two cells of 6.5 V and 2.0 V facing opposite ways give a net e.m.f. of 4.5 V.
- **Components in parallel have the same p.d.**: the loop through one of them and back through the other contains no e.m.f., so their p.d.s must be equal.
- A loop may run through the internal resistance of a cell: include its Ir.

Resistors in series and in parallel



same current I in each
V = V1 + V2 + V3
R = R1 + R2 + R3

same p.d. V across each
I = I1 + I2 + I3
1/R = 1/R1 + 1/R2 + 1/R3

Series (derivation). There are no junctions, so by Kirchhoff's first law the current I is the same in every resistor. By Kirchhoff's second law, the total p.d. across the combination equals the sum of the p.d.s across the resistors:

$$V = V_1 + V_2 + V_3 \;\Rightarrow\; IR = IR_1 + IR_2 + IR_3 \;\Rightarrow\; R = R_1 + R_2 + R_3$$

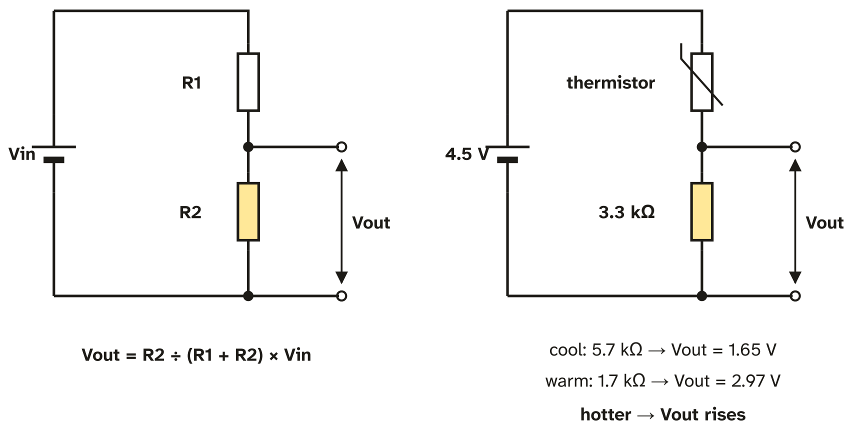
Parallel (derivation). By Kirchhoff's second law each resistor has the same p.d. V across it. By Kirchhoff's first law the current into the combination is the sum of the currents in the branches:

$$I = I_1 + I_2 + I_3 \Rightarrow \frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \Rightarrow \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Using them:

- 33 Ω and 22 Ω in series: 55 Ω. In parallel: $\frac{1}{R} = \frac{1}{33} + \frac{1}{22}$, so $R = 13.2$ Ω. For **two** resistors, $R = \frac{R_1 R_2}{R_1 + R_2} = \frac{726}{55} = 13.2$ Ω.
- **A parallel combination is always smaller than its smallest resistor.** Adding another branch always **lowers** the total resistance.
- n identical resistors R in parallel give $\frac{R}{n}$: four 36 Ω resistors in parallel give 9.0 Ω.
- **Networks**: combine the innermost groups first (parallel groups to one value, then add series parts), redrawing the circuit if it helps.
- **Don't forget to turn $\frac{1}{R}$ upside down** at the end.

Potential dividers



Two resistors in series across a p.d. V_{in} **share** it. They carry the same current, so each p.d. is proportional to its resistance:

$$\frac{V_1}{V_2} = \frac{R_1}{R_2} \qquad \text{and} \qquad V_{out} = \frac{R_2}{R_1 + R_2} \times V_{in}$$

where V_{out} is the p.d. across R_2. The bigger resistor gets the bigger share. Make R_2 larger (or R_1 smaller) and V_{out} rises. Scaling both resistances by the same factor changes nothing.

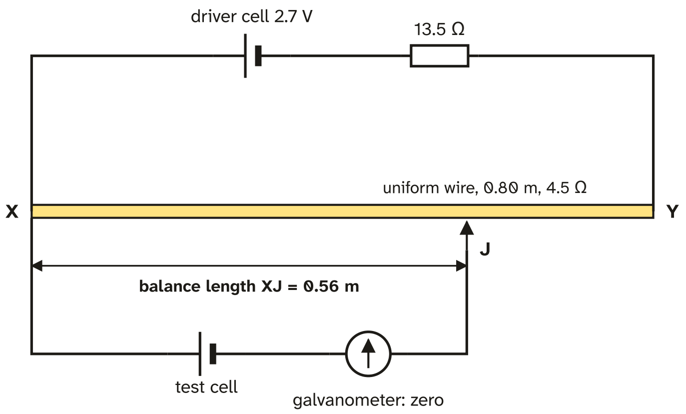
Sensors in a potential divider. Replace one resistor with a **thermistor** or an **LDR**, and the output depends on temperature or light:

- In the diagram, the thermistor is on top and V_{out} is across the 3.3 kΩ fixed resistor. When cool (thermistor 5.7 kΩ): $V_{out} = \frac{3.3}{9.0} \times 4.5 = 1.65$ V. When warm (thermistor 1.7 kΩ): $V_{out} = \frac{3.3}{5.0} \times 4.5 = 2.97$ V.

- **Warmer → thermistor's resistance falls → it takes a smaller share → the fixed resistor's p.d. rises.** Equivalently: total resistance falls, current rises, IR across the fixed resistor rises.
- **Swap the two components** and the output goes the other way: V_{out} across the thermistor **falls** as it warms.
- With an **LDR**: **brighter → LDR's resistance falls → the p.d. across the LDR falls**, and the p.d. across the fixed resistor rises.
- The p.d.s across the two parts always add up to V_{in} (negligible internal resistance).

A **potentiometer used as a variable potential divider**: a resistor with a sliding contact across a supply. The p.d. between one end and the contact can be set anywhere from 0 to the full supply p.d.

The potentiometer and null methods



E = (p.d. per metre of wire) × XJ

The potentiometer compares p.d.s using a **uniform resistance wire** carrying a steady current. For a uniform wire, $R = \frac{\rho L}{A}$ with ρ and A the same all along, so the resistance of a length is proportional to the length. With the same current I everywhere in the wire, the p.d. $V = IR$ between two points is **proportional to the length between them**:

$$\frac{V_1}{V_2} = \frac{L_1}{L_2}$$

Measuring an e.m.f. by a null method. A test cell and a **galvanometer** are connected from end X to a sliding contact J. Move J until the **galvanometer reads zero**: the **balance point**. Then:

- there is **no current in the test cell**, so no lost volts in it; the p.d. across XJ equals its **e.m.f.**, and its internal resistance does not matter;
- in the diagram, the p.d. across the wire is $2.7 \times \frac{4.5}{13.5+4.5} = 0.675$ V, which is $\frac{0.675}{0.80} = 0.844$ V per metre, so the test cell's e.m.f. is $0.844 \times 0.56 = 0.47$ V.

A **null method** is any method where you adjust the circuit until a meter reads **zero** and take the reading at that point. The galvanometer only has to show zero, so it does not need an accurate scale, but it must be **sensitive**.

For a balance point to exist:

- the **positive terminals** of the driver cell and the test cell must be joined to the **same end** of the wire;
- the **p.d. across the whole wire must be larger** than the p.d. being measured;
- the wire must be uniform (resistance proportional to length).

Comparing two e.m.f.s: balance each in turn on the same wire (same current): $\frac{E_1}{E_2} = \frac{L_1}{L_2}$.

When something changes, work out the p.d. per metre of wire first.

- More resistance in series with the driver cell (or a driver cell with internal resistance) → less current in the wire → **smaller** p.d. per metre → the balance length gets **longer**.
- A wire of **greater resistance** with the same driver circuit → it takes a **bigger share** of the driver's e.m.f. → larger p.d. per metre → balance length **shorter**.
- The balance length does not depend on the test cell's internal resistance.

Balanced potential dividers. Two potential dividers across the same supply, with a galvanometer (or voltmeter) joining their middle points, show zero when the two middle points are at the same potential, which happens when **the ratios of the resistances are equal**: $\frac{R_1}{R_2} = \frac{R_3}{R_4}$ (top-to-bottom in each divider). If one resistance is unknown, adjust a known one until the meter reads zero, then use the ratio.

Key facts and formulas

"Given" means it is on the data sheet in the exam. "Learn it" means you must remember it.

Formula	Status
E.m.f. $E = \frac{W}{Q}$ (energy to electrical, per unit charge)	Learn it
P.d. $V = \frac{W}{Q}$ (electrical energy to other forms, per unit charge)	Learn it
$E = V + Ir = I(R + r)$	Learn it
Terminal p.d. $V = E - Ir$; V-I graph: intercept E, gradient $-r$	Learn it
Power: total EI, external VI, wasted in the cell I^2r	Learn it
Kirchhoff's first law: $\sum I_{\text{in}} = \sum I_{\text{out}}$ (conservation of charge)	Learn it
Kirchhoff's second law: round a closed loop, $\sum E = \sum IR$ (conservation of energy)	Learn it
Resistors in series $R = R_1 + R_2 + \ldots$	Given
Resistors in parallel $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$	Given
Potential divider $V_{\text{out}} = \frac{R_2}{R_1 + R_2} V_{\text{in}}$, $\frac{V_1}{V_2} = \frac{R_1}{R_2}$	Learn it
Potentiometer (uniform wire, same current) $\frac{V_1}{V_2} = \frac{L_1}{L_2}$	Learn it
Balanced dividers $\frac{R_1}{R_2} = \frac{R_3}{R_4}$	Learn it

From the Electricity topic, used all the time here (all **Learn it**): $Q = It$, $V = IR$, $P = VI = I^2R = \frac{V^2}{R}$, $W = QV$, $R = \frac{\rho L}{A}$. $I = Anvq$ is given.

How to do it

In the Paper 1 and Paper 2 questions we have tagged for this topic (179 different questions, 2021–2025; 5 more appear on two papers), the types came up this often. 23 of the 179 questions mix two or more types, so the counts add up to more than 179. Many Paper 2 questions also have parts on the Electricity topic.

Question type	Questions
Kirchhoff's laws and circuit calculations	61
E.m.f., internal resistance and terminal p.d.	50
Potential dividers, thermistors and LDRs	35
Resistors in series and parallel	27
Potentiometers and null methods	23
Circuit symbols and diagrams	10

1. Kirchhoff's laws and circuit calculations (61 questions)

1. **Label every current** on the diagram, using Kirchhoff's first law at each junction so you need as few unknowns as possible.
2. **Choose a closed loop** and write Kirchhoff's second law round it: sum of e.m.f.s $=$ sum of IR terms (with signs).
3. **Solve**, then check with a second loop or junction.

Variations you will meet:

- **"State Kirchhoff's first law"**: the **sum** of the currents into a **junction** equals the sum of the currents out of it. **"State Kirchhoff's second law"**: round any **closed loop**, the **sum** of the e.m.f.s equals the **sum** of the p.d.s.
- **Which quantity is conserved?** First law: **charge**. Second law: **energy**. (Not current, voltage, power or mass.)
- **Which equation is (or is not) correct?** A junction equation must balance at one junction; a loop equation must follow a real closed loop. An equation that mixes currents from branches that are not in one loop is wrong.
- **Currents in parallel branches** with a battery of negligible internal resistance: each branch has the full e.m.f. across it, so $I_{\text{branch}} = \frac{E}{R_{\text{branch}}}$; the battery current is their sum.
- **An unknown resistor in a branch**: p.d. across it $=$ branch p.d. minus the p.d.s across the other resistors in that branch, then $R = \frac{V}{I}$.

- **Several cells**: add e.m.f.s that face the same way and subtract those that face the other way, then $I = \frac{\text{net e.m.f.}}{\text{total resistance}}$.
- **P.d. between two points**: add up the rises and falls along any path from one point to the other.
- **A second battery of the same e.m.f. in parallel** (negligible internal resistance) across a resistor: the p.d. across the resistor is still the one e.m.f., so its current and power are unchanged.
- **Power in a network of identical resistors or lamps**: find the current in (or p.d. across) each one, then $P = I^2R$ or $\frac{V^2}{R}$. The component in the main line, carrying the whole current, usually dissipates most.
- **Energy from the source**: total power $= EI$ equals the sum of the powers in all resistors (including the internal resistance). Energy left in a battery $=$ starting energy $-EIt$.
- **Component in series read from a graph** (lamp, thermistor): same current, so read its p.d. at that current and add.
- **Diodes in a circuit**: a diode passes current only when its triangle points the way conventional current would flow; otherwise its branch carries no current.

2. E.m.f., internal resistance and terminal p.d. (50 questions)

1. **Write** $E = V + Ir$ (or $E = I(R + r)$).
2. **Find the current** in the source first (Kirchhoff's first law if the circuit branches).
3. **Solve** for the unknown: $r = \frac{E-V}{I}$, $E = V + Ir$, $I = \frac{E}{R+r}$.

Variations you will meet:

- **"Define e.m.f."**: the energy transferred (to electrical energy) **per unit charge** in driving charge round a complete circuit. **"What does a 3.7 V label mean?"**: 3.7 J of energy transferred to electrical energy for each coulomb that passes through the cell, shared between the whole circuit including the internal resistance.
- **E.m.f. or p.d.?** E.m.f.: other forms → electrical, per unit charge, in the source. P.d.: electrical → other forms, per unit charge, in a component. Units of e.m.f.: J C^{-1} $=$ V.
- **Two readings** (V_1 at I_1, V_2 at I_2): $r = \frac{V_1 - V_2}{I_2 - I_1}$, then $E = V_1 + I_1 r$. Or with two external resistances, write $E = I(R + r)$ twice and solve.
- **Voltmeter reads E with no load, less with a load**: $r = \frac{E-V}{I}$ with $I = \frac{V}{R}$.
- **V–I graph**: E is the intercept on the V axis (extend the line if needed); $r = -$gradient; the largest current is where the line meets the I axis. A graph of the p.d. across the internal resistance, Ir, against V is a straight line of gradient -1: $Ir = E - V$.
- **Switch closed / resistor added in parallel / variable resistance reduced**: external resistance down → current up → lost volts Ir up → terminal p.d. (voltmeter across the source or the external circuit) **down**.
- **Load resistance increased**: current down, lost volts down, terminal p.d. up; the power wasted in r goes down.
- **Internal resistance grows as a cell ages** (e.m.f. constant): current down, terminal p.d. down, less power in the external resistor.
- **Power and energy**: power wasted in the cell I^2r; efficiency $= \frac{VI}{EI} = \frac{V}{E}$. The whole energy per coulomb is E; the external circuit gets only V per coulomb.

- **Cells in parallel**: identical cells in parallel have the e.m.f. of **one** cell and an internal resistance of $\frac{r}{n}$.
- **Removing a cell from a parallel set**: the combined internal resistance goes up, the current falls, and the p.d. across the load falls.
- **Replacing a source with one of negligible internal resistance** (same e.m.f.): the whole e.m.f. is across the load, so its current and power rise.

3. Potential dividers, thermistors and LDRs (35 questions)

1. **Identify the two parts** in series and which one the output (or voltmeter) is across.
2. **Use the ratio**: $V_{\text{out}} = \frac{R_{\text{across}}}{R_{\text{total}}} V_{\text{in}}$, or find the current $I = \frac{V_{\text{in}}}{R_{\text{total}}}$ and then $V = IR$.
3. **For a sensor**, say how its resistance changes, then what that does to the **share** of the p.d. (or to the current).

Variations you will meet:

- **Resistance of the sensor from a voltmeter reading**: p.d. across the fixed resistor $\rightarrow$ current $I = \frac{V}{R}$; p.d. across the sensor $= V_{\text{in}} - V$; sensor resistance $= \frac{V_{\text{in}} - V}{I}$.
- **Sensor resistance from its graph** (resistance against temperature or light intensity): read it at the given value, then use the divider.
- **After a change** (a new temperature or light level): find the new resistance, then the new share. A resistance that rises by a quarter is multiplied by 1.25; one that falls by a quarter is multiplied by 0.75.
- **Which circuit gives an output that rises with temperature (or light)?** The output must be across the **fixed** resistor, since the sensor's share falls as its resistance falls.
- **Which changes increase V_{out}?** Anything that increases $\frac{R_{\text{across}}}{R_{\text{total}}}$: a larger resistance across the output, or a smaller one in the other part. Doubling both changes nothing.
- **A voltmeter between the middles of two dividers**: find the potential at each middle point (the p.d. from the same supply rail), then subtract. A positive reading means the + terminal is at the higher potential.
- **A divider along a uniform wire** (slider on a resistance wire): the p.d. between one end and the slider is proportional to that length.
- **Power ratio in series** (same current): $\frac{P_1}{P_2} = \frac{R_1}{R_2}$.
- **"By reference to the current"**: say that the total resistance changes, so the current changes, and so the p.d. IR across the fixed resistor changes, naming each resistance.

4. Resistors in series and parallel (27 questions)

1. **Find groups**: resistors in one line with nothing branching off between them are in **series**; resistors joined at both ends to the same two points are in **parallel**.
2. **Combine from the inside out**: each parallel group to one value, then add series parts.
3. **Check**: a parallel result must be less than its smallest resistor.

Variations you will meet:

- **"Show that $R = R_1 + R_2 + \ldots$" or "$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$" using Kirchhoff's laws**: state which quantity is the same (current in series, p.d. in parallel), write the Kirchhoff sum ($V = V_1 + V_2$ or $I = I_1 + I_2$), substitute $V = IR$ or $I = \frac{V}{R}$, and cancel.
- **Networks of identical resistors** R: express the answer as a fraction of R, then, if the total is given, solve for R.
- **Series and parallel totals given** for two resistors: $R_1 + R_2 = S$ and $\frac{R_1 R_2}{R_1 + R_2} = P$, so $R_1 R_2 = SP$; test the options, or solve the quadratic.
- **Least or greatest resistance**: parallel is always smaller than either resistor; series is always larger than either.
- **Wires in parallel** (with the Electricity topic): find each wire's resistance with $R = \frac{\rho L}{A}$ as a multiple of the original, then combine. Doubling the radius makes the resistance a quarter.
- **Adding a branch** lowers the total resistance, so the current from the supply rises; with negligible internal resistance, the current in the existing branches does not change.
- **Switches**: a closed switch across a resistor shorts it out (no current through the resistor); an open switch removes its branch.
- **Total power** from a supply of p.d. V into a network of resistance R: $P = \frac{V^2}{R}$, so find R first.

5. Potentiometers and null methods (23 questions)

1. **Find the p.d. across the whole wire**, as a potential divider with anything in series with it.
2. **Divide by the wire's length** to get the p.d. per metre.
3. **At balance**, the e.m.f. (or p.d.) being measured $=$ p.d. per metre $\times$ balance length. For two sources on the same wire, $\frac{E_1}{E_2} = \frac{L_1}{L_2}$.

Variations you will meet:

- **"What is meant by a null method?"**: the circuit is adjusted until the reading on the galvanometer (meter) is **zero**.
- **Why the test cell's internal resistance doesn't matter**: at balance there is no current in it, so no lost volts.
- **Which circuit works?** The driver cell across the **whole** wire; positive terminals to the **same end**; the galvanometer in series with the **test** cell, going to the sliding contact; the driver's p.d. across the wire larger than the test e.m.f.
- **Explain why** $V \propto L$ along the wire: $V = IR = \frac{I\rho L}{A}$ with I, ρ and A constant.
- **Which way does the balance point move?** Work out whether the p.d. per metre goes up (balance point moves **towards** the start, X) or down (moves away). A driver cell with non-negligible internal resistance, or a larger series resistance, lowers it.
- **Measuring a very small e.m.f.** (millivolts) precisely: put a **large resistor in series with the driver cell** so the p.d. across the wire is only a little larger than the e.m.f. being measured; then the balance length is long and its percentage uncertainty is small.
- **Balanced bridge**: two dividers with a galvanometer (or voltmeter) between their middle points read zero when $\frac{R_1}{R_2} = \frac{R_3}{R_4}$. Use it to find an unknown resistor, or the resistance of an LDR or thermistor.

- **A voltmeter along a potentiometer**: the reading rises in proportion to the distance from the end it is measured from, a straight line through the origin.

6. Circuit symbols and diagrams (10 questions)

1. **Use only the syllabus symbols**, with square corners and no gaps in the wires.
2. **Put meters in the right place**: ammeter in series, voltmeter in parallel across the component.
3. **Check the circuit is a closed loop** that does what the question says.

Variations you will meet:

- **Name the symbol**: know the ones that are easy to mix up: variable resistor (arrow through) and potentiometer (arrow onto); thermistor (foot) and LDR (circle and arrows); diode and LED (arrows out); microphone (circle and bar) and loudspeaker; ammeter, voltmeter and galvanometer.
- **Draw the circuit to measure resistance**: cell, ammeter and component in one loop, voltmeter across the component only.
- **Complete a circuit** with a thermistor or LDR in series with a resistor: use the correct symbol, and connect the voltmeter across the component the question names.
- **Redraw series as parallel**: each resistor must connect directly across the same two points.
- **Match a picture of connected components to a circuit diagram**: follow each wire from terminal to terminal.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

A student connects a cell in series with an ammeter and a variable resistor, and puts a voltmeter across the terminals of the cell. When the current is 0.40 A the voltmeter reads 2.52 V. When the resistance is reduced, the current is 1.00 A and the voltmeter reads 2.10 V.

(a) Explain why the voltmeter reading falls as the current increases. **[2]**

(b) Calculate the internal resistance r and the e.m.f. E of the cell. **[3]**

(c) For a current of 1.00 A, calculate the power wasted inside the cell and the percentage of the cell's total power output that reaches the variable resistor. **[3]**

Solution

(a) The cell has internal resistance, so part of its e.m.f. is lost across it: the lost volts Ir. **B1** As the current increases, Ir increases, so the terminal p.d. $V = E - Ir$ decreases. **B1**

(b) $E = V + Ir$ for both readings: $2.52 + 0.40r = 2.10 + 1.00r$ **C1** $r = \dfrac{2.52 - 2.10}{1.00 - 0.40} = 0.70$ Ω **A1** $E = 2.52 + 0.40 \times 0.70 = 2.80$ V **A1**

(c) $P = I^2 r = 1.00^2 \times 0.70 = 0.70$ W **A1** Percentage to the resistor $= \dfrac{VI}{EI} = \dfrac{2.10}{2.80}$ **C1** $= 75\%$. **A1**

Example 2

A light-dependent resistor (LDR) and a fixed resistor of resistance 2.2 kΩ are connected in series across a battery of e.m.f. 5.0 V and negligible internal resistance. The LDR is connected to the positive terminal. A voltmeter of very high resistance measures the p.d. V_{out} across the fixed resistor.

(a) In dim light the LDR has resistance 8.8 kΩ. Calculate V_{out}. **[2]**

(b) In bright light V_{out} is 3.5 V. Calculate the resistance of the LDR. **[3]**

(c) By reference to the current in the circuit, explain why V_{out} is larger in bright light. **[3]**

Solution

(a) $V_{\text{out}} = \dfrac{2.2}{2.2 + 8.8} \times 5.0$ **C1** $= 1.0$ V **A1**

(b) Current $I = \dfrac{3.5}{2200} = 1.59 \times 10^{-3}$ A **C1** p.d. across the LDR $= 5.0 - 3.5 = 1.5$ V **C1** $R = \dfrac{1.5}{1.59 \times 10^{-3}} = 940$ Ω (or from the ratio: $2200 \times \frac{1.5}{3.5} = 943$ Ω) **A1**

(c) In brighter light the resistance of the **LDR** decreases, so the **total** resistance of the circuit decreases. **B1** The current in the circuit increases (the e.m.f. is unchanged). **B1** The p.d. across the fixed resistor, IR with R constant, increases. **B1**

Example 3

A battery of e.m.f. 7.2 V and internal resistance 0.44 Ω is connected to a 2.2 Ω resistor in series with a parallel pair of resistors of 5.6 Ω and 8.4 Ω.

(a) Show that the total resistance of the circuit, including the battery, is 6.0 Ω. **[2]**

(b) Calculate the current in the battery and the terminal p.d. of the battery. **[3]**

(c) Calculate the current in the 8.4 Ω resistor. **[2]**

(d) The $8.4\ \Omega$ resistor is removed. State and explain the effect on the terminal p.d., and calculate its new value. **[4]**

Solution

(a) Parallel pair: $\frac{5.6 \times 8.4}{5.6 + 8.4} = 3.36\ \Omega$ **C1** Total $= 0.44 + 2.2 + 3.36 = 6.00\ \Omega$ **A1**

(b) $I = \frac{E}{R + r} = \frac{7.2}{6.0} = 1.2$ A **A1** $V = E - Ir = 7.2 - 1.2 \times 0.44$ **C1** $= 6.67$ V **A1**

(c) p.d. across the pair $= 1.2 \times 3.36 = 4.03$ V (Kirchhoff's second law: the same p.d. across both branches) **C1** $I = \frac{4.032}{8.4} = 0.48$ A (and 0.72 A in the $5.6\ \Omega$ resistor; $0.48 + 0.72 = 1.2$ A by Kirchhoff's first law) **A1**

(d) Removing a parallel branch increases the external resistance, so the current in the battery decreases. **M1** The lost volts Ir decrease, so the terminal p.d. **increases**. **A1** New current $= \frac{7.2}{0.44 + 2.2 + 5.6} = 0.874$ A **C1** $V = 7.2 - 0.874 \times 0.44 = 6.82$ V **A1**

Example 4

A driver cell of e.m.f. 2.6 V and negligible internal resistance is connected in series with a $22\ \Omega$ resistor and a uniform resistance wire XY of length 1.00 m and resistance $4.0\ \Omega$. A thermocouple, whose e.m.f. is to be measured, is connected with a galvanometer between end X and a sliding contact J on the wire, with its positive terminal towards X.

(a) Calculate the p.d. across the wire XY. **[2]**

(b) The galvanometer reads zero when XJ is 0.635 m. Calculate the e.m.f. of the thermocouple. **[2]**

(c) Explain why the internal resistance of the thermocouple does not affect this value. **[1]**

(d) The $22\ \Omega$ resistor is replaced by a $48\ \Omega$ resistor. Explain why the e.m.f. of the thermocouple can no longer be measured with this circuit. **[3]**

Solution

(a) Potential divider: $V_{\mathrm{XY}} = \frac{4.0}{22 + 4.0} \times 2.6$ **C1** $= 0.40$ V **A1**

(b) $E = 0.40 \times \frac{0.635}{1.00}$ **C1** $= 0.254$ V **A1**

(c) At balance the galvanometer reads zero, so there is no current in the thermocouple and no p.d. across its internal resistance. **B1**

(d) New p.d. across the wire $= \frac{4.0}{48 + 4.0} \times 2.6 = 0.20$ V **C1** The thermocouple's e.m.f., 0.254 V, is larger than the p.d. across the whole wire, **M1** so no point on the wire gives a zero reading: the balance length would have to be $\frac{0.254}{0.20} = 1.27$ m, longer than the wire. **A1**

Common mistakes

- **Stating Kirchhoff's first law for one current.** The March 2021 and June 2022 reports describe statements about a single current, or about currents "equal" without the word **sum**, or about a loop instead of a junction. Say "the **sum** of the currents into a **junction** equals the **sum** of the currents out".
- **Leaving "closed loop" out of the second law.** The June 2021 and November 2022 reports both note answers that missed "round a **closed loop**" or "the **sum** of". Several reports (March 2021, June 2021, June 2022) also mention candidates mixing up the first and second laws.
- **Using the e.m.f. as the p.d. across a component.** The June 2021, November 2021, June 2022 and November 2022 reports all describe candidates putting the battery's e.m.f. in place of a voltmeter reading or the p.d. across one part. Only with negligible internal resistance, and only across the whole external circuit, is the p.d. equal to the e.m.f.
- **$\frac{E}{I}$ is not the internal resistance.** The March 2021 report describes candidates dividing the e.m.f. by the current: that gives the **total** resistance $R + r$. Subtract the external resistance, or use $r = \frac{E-V}{I}$.
- **Wrong current in the internal resistance.** The November 2022 report describes candidates who used the current in one branch; the current in the source is the **sum** of the branch currents (first law).
- **E.m.f. and terminal p.d. mixed up.** The March 2025 report describes this as the most popular wrong answer; the June 2021 report adds that a battery's label is its e.m.f., not the energy per coulomb given to the external circuit. The terminal p.d. equals the e.m.f. only when there is no current.
- **Reading a V–I graph.** The June 2021 report says candidates took the last plotted p.d. instead of the intercept for E, and very few saw that the internal resistance is the magnitude of the gradient.
- **The wrong resistor's share.** The June 2021, June 2022 and June 2023 reports describe candidates finding the p.d. across the wrong resistor of a potential divider, or assuming a different current in resistors in series. In series the current is the same; the bigger resistance has the bigger p.d.
- **Forgetting to invert $\frac{1}{R}$.** The June 2022 report describes candidates who stopped at the reciprocal of the parallel resistance. Also convert kΩ to Ω before combining with values in Ω.
- **Forgetting that parallel branches share the p.d.** The June 2022 report describes candidates who thought the larger resistor had the larger p.d. in parallel, or used $P = I^2R$ to say it had more power without noticing that the currents differ. In parallel use $P = \frac{V^2}{R}$: the **smaller** resistance dissipates more.
- **Vague "resistance" and missing the current.** The June 2022 report stresses naming **which** resistance changes (the thermistor's, the combination's, the whole circuit's) and commenting on the current when the question says "by reference to the current".
- **The p.d. across a potentiometer wire is not the driver's e.m.f.** The June 2021 and November 2021 reports describe this. Anything in series with the wire (a resistor, internal resistance) takes a share. The November 2021 report adds that many candidates were not used to equating a ratio of lengths to a ratio of p.d.s.
- **Wrong direction for the balance point.** The November 2021 and June 2023 reports say only the strongest candidates could explain the change. Always go: resistance → current in the wire → p.d. per metre → balance length.
- **Potentiometer circuits with the cells the wrong way round.** The June 2022 report notes that the "familiar-looking" circuit had the wrong polarity. Positive terminals go to the same end of the wire.

- **Energy left in a battery.** The June 2023 report describes candidates giving the energy transferred instead of subtracting it from the initial energy; the March 2021 report notes the same slip and also candidates ignoring the power wasted in the internal resistance.
- **Cells in the wrong direction.** The November 2021 report mentions candidates confused by the polarities of cells, and the June 2021 report says the key to a two-battery question was noticing that they faced opposite ways. A cell that faces the other way **subtracts** its e.m.f.
- **Batteries in parallel.** The March 2022 report describes candidates who thought a second identical battery in parallel would raise the p.d. across a resistor. Kirchhoff's second law round the loop gives the same p.d., so the current and power are unchanged.

How to get the marks

- **Definitions and laws** (key words):
  - E.m.f.: energy transferred **per unit charge** (to electrical energy) in driving charge **round a complete circuit**.
  - Kirchhoff's first law: **sum** of currents into a **junction** $=$ sum of currents out. Conservation of **charge**.
  - Kirchhoff's second law: round a **closed loop**, **sum** of e.m.f.s $=$ **sum** of p.d.s. Conservation of **energy**.
  - Null method: the reading on the galvanometer is **zero**.
- **Calculations (C1 then A1)**: write the equation ($E = V + Ir$, $V_{\text{out}} = \frac{R_2}{R_1+R_2}V_{\text{in}}$, $\frac{E_1}{E_2} = \frac{L_1}{L_2}$), substitute, then give the answer with a unit. A correct intermediate value (a current, a p.d. across one resistor) usually earns a mark by itself.
- **"Show that"**: show every step and give one more significant figure than the value printed (6.00 Ω, not 6 Ω). Mark schemes also accept a correct route through a different intermediate quantity.
- **Derivations with Kirchhoff's laws**: state what is the same (current or p.d.), write the Kirchhoff sum, substitute $V = IR$, cancel. The mark scheme needs each step; skipping "$V = V_1 + V_2$" loses a mark.
- **"State and explain" chains**: one link per mark. For example: LDR resistance increases (**B1**) → total resistance increases → current in the battery decreases (**M1**) → lost volts decrease → terminal p.d. increases (**A1**).
- **"By reference to the current"**: the current must appear in your answer.
- **Increase / decrease / no change**: give a reason for each, and name the resistance or current you mean.
- **Circuit diagrams**: correct symbols, a closed loop, no gaps, meters in the right places.
- **Multiple choice**: work it out first. Wrong options often use the e.m.f. as the terminal p.d., forget to invert $\frac{1}{R}$, swap the divider ratio (p.d. across the other resistor), or get the conservation law the wrong way round.

Quick check

1. Calculate the combined resistance of a 1.9 Ω resistor in series with a parallel pair of 28 Ω and 7.0 Ω.
2. A cell of e.m.f. 1.55 V and internal resistance 0.46 Ω is connected to a lamp of resistance 2.64 Ω. Calculate the current, the terminal p.d., and the energy transferred to thermal energy inside the cell for each coulomb that passes.

3. A single loop contains a cell of e.m.f. 8.5 V and a cell of e.m.f. 2.5 V facing the opposite way, both with negligible internal resistance, and resistors of $1.6\ \Omega$ and $2.4\ \Omega$. Calculate the current and the p.d. across the $2.4\ \Omega$ resistor.
4. An LDR and a fixed resistor are connected in series across a battery of negligible internal resistance. A voltmeter is connected across the LDR. The light gets brighter. State and explain what happens to the voltmeter reading.
5. On a potentiometer wire, a cell of known e.m.f. 1.08 V balances at 0.720 m. A second cell balances at 0.515 m on the same wire with the same current. Calculate the e.m.f. of the second cell.

Answers

1. Parallel pair: $\frac{28 \times 7.0}{28 + 7.0} = 5.6\ \Omega$. Total $= 1.9 + 5.6 = 7.5\ \Omega$.
2. $I = \frac{1.55}{2.64 + 0.46} = \frac{1.55}{3.10} = 0.50$ A. $V = 1.55 - 0.50 \times 0.46 = 1.32$ V (check: $0.50 \times 2.64 = 1.32$ V).
   Energy per coulomb in the cell $=$ lost volts $= 0.23$ J C^{-1}, i.e. 0.23 J.
3. Net e.m.f. $= 8.5 - 2.5 = 6.0$ V. $I = \frac{6.0}{1.6 + 2.4} = 1.5$ A. p.d. $= 1.5 \times 2.4 = 3.6$ V.
4. The LDR's resistance decreases, so the total resistance decreases and the current increases. The p.d. across the fixed resistor (IR) increases, and the two p.d.s add up to the constant e.m.f., so the p.d. across the LDR, the voltmeter reading, **decreases**.
5. $E = 1.08 \times \frac{0.515}{0.720} = 0.773$ V.

Past questions to try

- **9702/23/O/N/25 Q5**: Kirchhoff's first law, a thermistor in parallel with a resistor, and finding currents with internal resistance.
- **9702/21/O/N/24 Q7**: terminal p.d. and internal resistance, then the same resistors redrawn in parallel.
- **9702/22/M/J/23 Q7**: an LDR potential divider, then a potentiometer wire balanced against it.
- **9702/23/O/N/21 Q6**: internal resistance of a cell, a potentiometer measurement of an e.m.f., and how the balance length changes with a thinner wire.