

THEME B · THE PARTICULATE NATURE OF MATTER

SL & HL ≈ 35 min read

IB Physics B.5 Current and Circuits — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). B.5 has no additional higher level content: everything on this page is examinable at both SL and HL.

Alternating current is not required — every circuit here is direct current (dc).

 SL B.5 questions HL B.5 questions Flashcards DC circuits simulation

What this page covers

- ✓ Cells as sources of emf; chemical and solar cells as the energy supply for a circuit, with their advantages and disadvantages
- ✓ Reading and drawing circuit diagrams with the data-booklet symbols
- ✓ Direct current as a flow of charge carriers, $I = \frac{\Delta q}{\Delta t}$
- ✓ Potential difference as work done per unit charge, $V = \frac{W}{q}$
- ✓ Conductors and insulators explained by how mobile their charge carriers are
- ✓ What resistance is and where it comes from; $R = \frac{V}{I}$ and resistivity $\rho = \frac{RA}{L}$
- ✓ Ohm's law, ohmic and non-ohmic conductors, and the heating effect of a current
- ✓ Power dissipated in a resistor, $P = IV = I^2 R = \frac{V^2}{R}$
- ✓ Resistors in series and in parallel
- ✓ Emf and internal resistance of a cell, $\varepsilon = I(R + r)$

- ✓ Variable resistors: thermistors, light-dependent resistors (LDRs) and potentiometers, including potential dividers

In one minute

- Current is the rate of flow of charge, $I = \Delta q / \Delta t$. In a metal the charge carriers are free electrons; conventional current is drawn from + to -.
- A source's **emf** is the energy it gives each coulomb; the **pd** across a component is the energy each coulomb transfers there. Both are measured in volts (J C^{-1}).
- Resistance $R = V/I$ comes from collisions of the charge carriers with the vibrating lattice ions. For a wire, $R = \rho L/A$.
- An ohmic conductor has constant R (straight-line I-V graph through the origin). A filament lamp is non-ohmic: its resistance rises as it heats up.
- Series: same current, pds add, $R_s = R_1 + R_2 + \dots$. Parallel: same pd, currents add, $1/R_p = 1/R_1 + 1/R_2 + \dots$.
- A real cell has internal resistance: the terminal pd $V = \varepsilon - Ir$ falls as the current rises.

Contents

- | | |
|---|---|
| 1. Cells, emf and energy sources | 9. Emf and internal resistance |
| 2. Circuit diagrams and meters | 10. Variable resistors and potential dividers |
| 3. Electric current and charge carriers | 11. Exam tips |
| 4. Potential difference | 12. Common misconceptions |
| 5. Resistance and resistivity | 13. How this topic connects |
| 6. Ohm's law and I-V characteristics | 14. Key equations |
| 7. Electrical power | 15. Check your understanding |
| 8. Series and parallel circuits | |

What provides the energy in a circuit?

Charge does not get “used up” in a circuit: the same charge carriers go round and round. What a circuit needs is a **source of energy** that does work on the charges, pushing them round the complete loop. In IB Physics that source is a **cell** (or a battery of cells), which is described by its **electromotive force** (emf).

The emf ε of a source is the work done per unit charge by the source in moving charge around a complete circuit — the energy transferred from another form (chemical, light) into electrical energy for each coulomb that passes through the source.

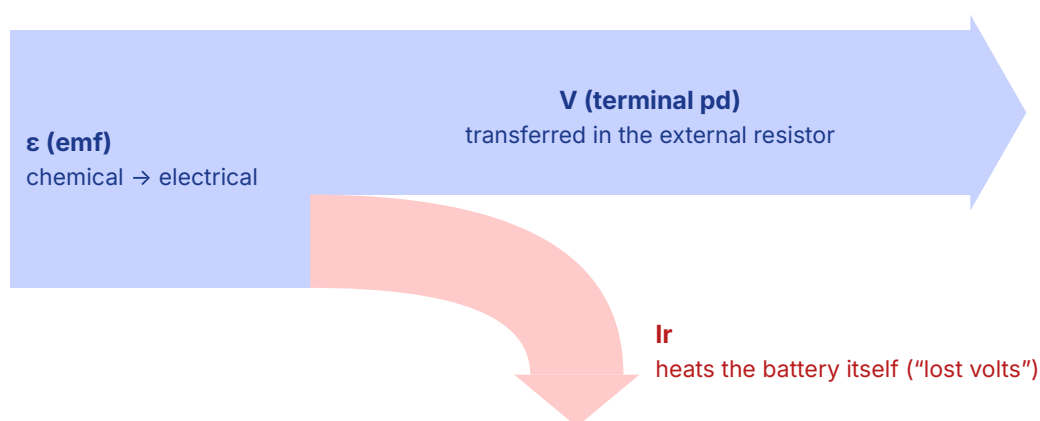
- Emf is measured in volts: $1 \text{ V} = 1 \text{ J C}^{-1}$. A 1.5 V cell gives 1.5 J to every coulomb that passes through it.
- Despite its name, emf is **not a force**; it is energy per unit charge.
- A **battery** is two or more cells connected together. Cells in series (+ to –) have a total emf equal to the sum of their emfs.

Chemical cells and solar cells

- In a **chemical cell**, chemical reactions between the electrodes and the electrolyte separate charge, transferring chemical energy into electrical energy. **Primary** cells are used once; **secondary** (rechargeable) cells, such as lithium-ion cells, can have their reactions reversed by pushing a current through them in the opposite direction.
- In a **solar (photovoltaic) cell**, light absorbed in a semiconductor junction releases charge carriers, transferring light energy directly into electrical energy. A single cell has a small emf (well under 1 V), so cells are connected in series and parallel to make panels. The current a panel can deliver increases with the intensity of the light falling on it.

Source	Advantages	Disadvantages
Primary chemical cell	portable; cheap; ready to use; long shelf life; steady emf for most of its life	stores little energy for its mass; cannot be recharged, so many are discarded; toxic or scarce materials; emf falls near the end of its life
Secondary (rechargeable) cell	portable; can be recharged hundreds of times, so less waste and lower running cost; can store energy from renewable sources	higher initial cost; capacity falls with each charge cycle; mining of lithium/cobalt has environmental and social costs; can overheat if damaged
Solar cell / panel	no fuel and no emissions while operating; renewable; little maintenance; useful in remote places	no output at night and reduced output in cloud; low efficiency, so large areas are needed; needs storage (cells) for a steady supply; energy and materials used in manufacture
Mains supply (from power stations)	delivers large powers continuously; low cost per joule	not portable; supplies ac; the power stations may burn fossil fuels (B.2 greenhouse effect)

Energy per coulomb of charge passing through the battery

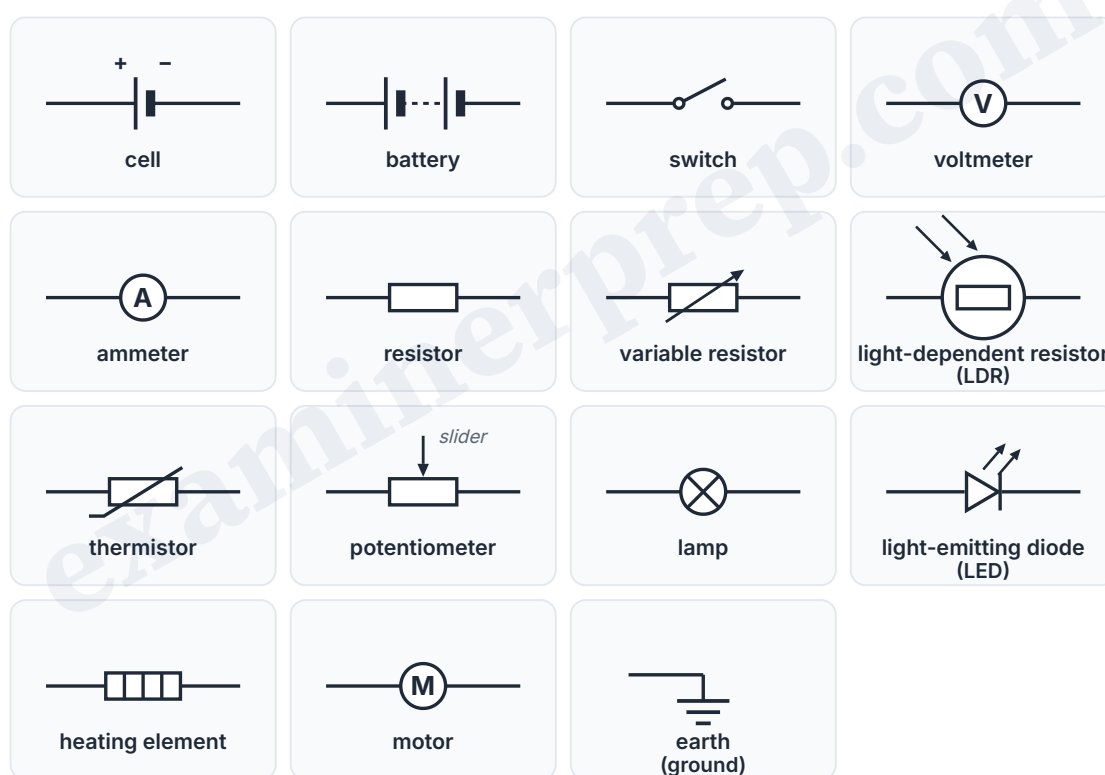


Energy flow in a circuit, per coulomb of charge, for the battery in worked example 5. For each coulomb the battery converts ϵ joules of chemical energy into electrical energy (its emf). Of this, V joules are transferred in the external resistor (the terminal pd) and Ir joules heat the battery's own internal resistance. Band widths are to scale.

How are circuits drawn, and where do meters go?

A circuit diagram shows how the components of a circuit are connected, using standard symbols joined by straight lines that represent connecting wires of negligible resistance.

The diagram shows the *arrangement* of the components — what is connected to what — not their physical positions. Two diagrams that look different are the same circuit if they have the same connections. The symbols you are expected to recognise and draw are the ones listed in the data booklet:



The electrical circuit symbols listed in the IB Physics data booklet. For a cell, the long thin line is the positive terminal. A potentiometer has a third terminal, the sliding contact shown by the arrow.

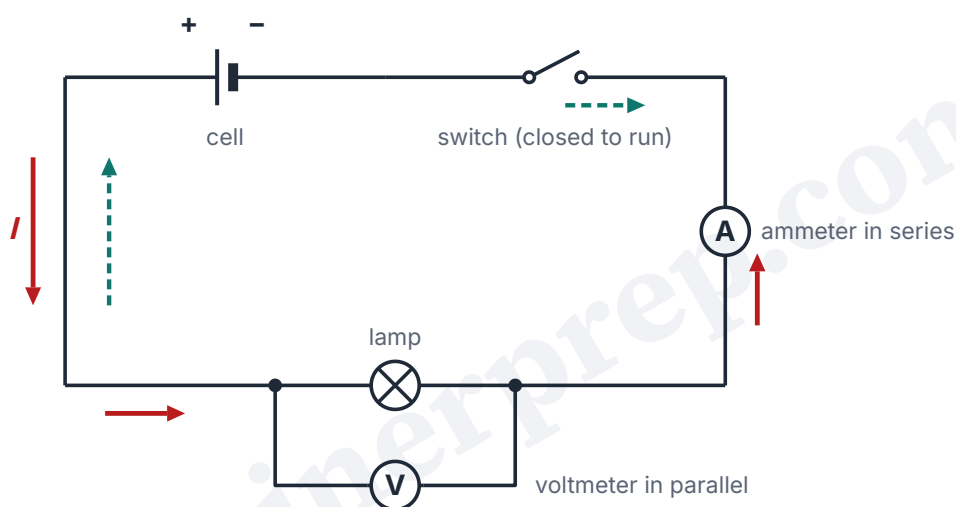
- Draw wires as straight lines with right-angled corners. Mark a junction where wires join with a dot.
- An **ammeter** measures the current *through* a component, so it is connected in **series** with it.
- A **voltmeter** measures the pd *across* a component, so it is connected in **parallel** with it, one lead on each side.

An ideal ammeter has zero resistance, so there is no pd across it. An ideal voltmeter has infinite resistance, so it draws no current from the circuit.

- Unless a question says otherwise, meters are ideal. If a meter is non-ideal, its resistance is constant: treat it as an ordinary resistor in the circuit (see worked example 6).

→ **conventional current I: from + to – round the external circuit**

→ **electron flow: from – to + (opposite direction)**



A cell, switch, ammeter and lamp in series, with a voltmeter in parallel with the lamp. Conventional current (solid red arrows) leaves the positive terminal; the electrons (dashed teal arrows) actually drift the other way round the circuit.

What is electric current?

Electric current is the rate of flow of charge carriers past a point in a circuit:

$I = \frac{\Delta q}{\Delta t}$. A direct current (dc) is one in which the charge carriers flow in one direction only.

- I = current (A), Δq = charge passing the point (C), Δt = time taken (s). In the data booklet.
- The ampere is an SI base unit; the coulomb is defined from it: $1 \text{ C} = 1 \text{ A s}$.
- Charge is quantised: every charge is a whole-number multiple of the elementary charge $e = 1.60 \times 10^{-19} \text{ C}$ (data booklet). The number of

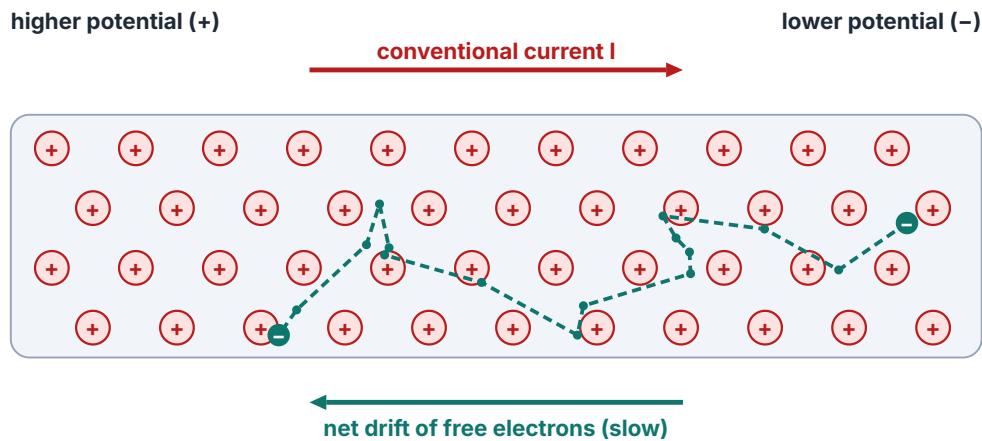
electrons that make up a charge q is $N = q/e$.

- **Charge carriers** are free particles that carry charge: electrons in metals, positive and negative ions in electrolytes and molten salts.
- **Conventional current** is drawn from the positive terminal to the negative terminal round the external circuit — the direction in which positive charges would flow. In a metal, the electrons flow the opposite way.

Conductors and insulators

Whether a material conducts depends on how many charge carriers it has that are **free to move** (mobile).

Material	Charge carriers	Result
Conductor (metals, graphite)	a very large number of delocalised electrons that are free to move through the lattice	a small pd produces a large current
Semiconductor (e.g. silicon; thermistors, LDRs and solar cells are made of semiconducting materials)	few free carriers at room temperature; more are released when the temperature or the light intensity increases	resistance falls sharply as temperature or light increases
Insulator (plastics, glass, rubber)	electrons are bound to their atoms; almost no mobile carriers	negligible current even with a large pd



Free electrons in a metal wire. Without a pd they move randomly and there is no net flow. With a pd, a slow net drift is added towards the higher-potential end — opposite to the conventional current. Collisions with the lattice ions are the origin of resistance.

- The net drift of the electrons is slow (typically less than a millimetre per second), but a lamp lights almost instantly because the electric field is set up all round the circuit at once, and electrons everywhere in the circuit start drifting together.

WORKED EXAMPLE 1 Easy · Calculate

A phone battery is charged with a steady current of 1.8 A for 45 minutes. The pd across the battery while it is charging is 5.0 V.

Calculate (a) the charge that flows into the battery, (b) the number of electrons that this charge corresponds to and (c) the energy transferred to the battery.

(a) Convert the time to seconds: $\Delta t = 45 \times 60 = 2700 \text{ s}$.

$$\Delta q = I \Delta t = 1.8 \times 2700 = 4.9 \times 10^3 \text{ C (4860 C)}$$

$$\textbf{(b)} \quad N = \frac{\Delta q}{e} = \frac{4860}{1.60 \times 10^{-19}} = 3.0 \times 10^{22} \text{ electrons}$$

$$\textbf{(c)} \quad W = qV = 4860 \times 5.0 = 2.4 \times 10^4 \text{ J}$$

What is potential difference?

The potential difference V between two points is the work done per unit charge when a positive charge is moved from one point to the other along the current path: $V = \frac{W}{q}$.

- V = potential difference (V), W = work done, i.e. energy transferred (J), q = charge moved (C). In the data booklet.
- 1 volt = 1 joule per coulomb. If 2.0 C flows through a lamp with a pd of 9.0 V across it, $9.0 \times 2.0 = 18$ J of electrical energy is transferred to internal energy and light.
- Positive charge moves from high to low potential through a resistor, transferring energy to it. Inside a source the charge is moved from low to high potential, gaining energy.

	Emf ϵ	Potential difference V
Energy transfer	other forms $\rightarrow$ electrical energy	electrical energy $\rightarrow$ other forms
Where	in a source (cell, solar cell)	across a component (resistor, lamp, motor)
Definition	work done by the source per unit charge in moving charge round the whole circuit	work done per unit charge moving between two points along the current path
Unit	V (= J C ⁻¹)	V (= J C ⁻¹)

What is resistance and where does it come from?

The resistance of a component is the ratio of the potential difference across it to the current through it: $R = \frac{V}{I}$.

- R in ohms (Ω); $1 \Omega = 1 \text{ V A}^{-1}$. In the data booklet.

- $R = V/I$ defines resistance at **every** point, for every component — ohmic or not. It is the ratio of the coordinates, never the gradient of a graph.

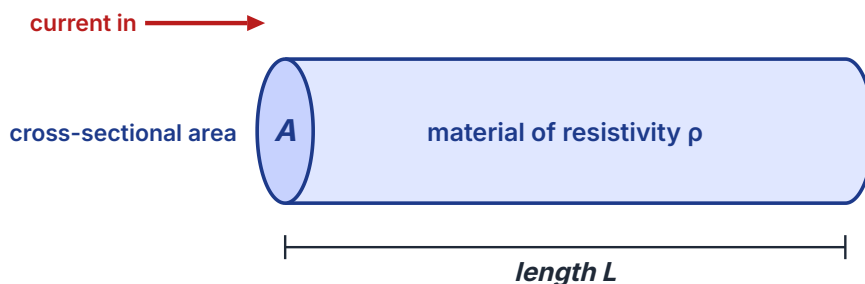
The origin of resistance

- The pd sets up an electric field in the conductor. Between collisions the field accelerates the free electrons, increasing their kinetic energy.
- The electrons repeatedly collide with the positive lattice ions (and with impurities and defects), transferring that energy to the lattice. The ions vibrate with larger amplitude: the **internal energy** and the **temperature** of the conductor increase. This is the **heating effect** of a current.
- The collisions limit the drift speed, which is why the current is finite for a given pd. More frequent collisions mean a smaller current for the same pd — a larger resistance.
- In a metal, a higher temperature means larger lattice vibrations and more frequent collisions, so **the resistance of a metal increases with temperature**.

Resistivity

The resistivity ρ of a material is defined by $\rho = \frac{RA}{L}$, where R is the resistance of a uniform sample of length L and cross-sectional area A . It is a property of the material (at a given temperature), not of the particular sample.

- ρ = resistivity ($\Omega \text{ m}$), A = cross-sectional area (m^2), L = length (m). In the data booklet; rearranged, $R = \frac{\rho L}{A}$.
- For a wire of diameter d , $A = \pi \left(\frac{d}{2}\right)^2 = \frac{\pi d^2}{4}$. Remember to halve the diameter and convert mm to m *before* squaring.



$$R = \rho L / A : \text{doubling } L \text{ doubles } R; \text{ doubling } A \text{ halves } R$$

(halving the diameter quarters A , so R becomes four times larger)

A longer conductor gives the electrons more lattice to collide with, so $R \propto L$. A wider conductor provides more parallel paths, so $R \propto 1/A$.

Material	Approximate resistivity at room temperature / $\Omega \text{ m}$	Typical use
Copper	1.7×10^{-8}	connecting wires
Constantan (alloy)	4.9×10^{-7}	wire-wound resistors (resistivity almost independent of temperature)
Nichrome (alloy)	1.1×10^{-6}	heating elements
Pure silicon (semiconductor)	about 10^3	solar cells and other semiconductor devices
Glass, plastics	10^{10} to 10^{16}	insulation

WORKED EXAMPLE 2 Medium · Calculate / Determine

A $5.0 \, \Omega$ resistor is to be made from constantan wire of diameter 0.32 mm . The resistivity of constantan is $4.9 \times 10^{-7} \, \Omega \text{ m}$.

(a) Calculate the length of wire needed. (b) The wire is then cut into two equal halves and the halves are connected side by side, in parallel. Determine the resistance of the combination. (c) Suggest why copper wire is not used to make this resistor.

$$\text{(a)} \quad A = \pi \left(\frac{0.32 \times 10^{-3}}{2} \right)^2 = 8.04 \times 10^{-8} \text{ m}^2$$

$$L = \frac{RA}{\rho} = \frac{5.0 \times 8.04 \times 10^{-8}}{4.9 \times 10^{-7}} = \mathbf{0.82 \text{ m}}$$

(b) Each half has half the length, so $R = 2.5 \, \Omega$. Two equal resistors in

parallel: $\frac{1}{R_p} = \frac{1}{2.5} + \frac{1}{2.5} \Rightarrow R_p = \mathbf{1.25 \, \Omega \approx 1.3 \, \Omega}$

(Equivalently: a wire of half the length and twice the area has $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$ of the resistance.)

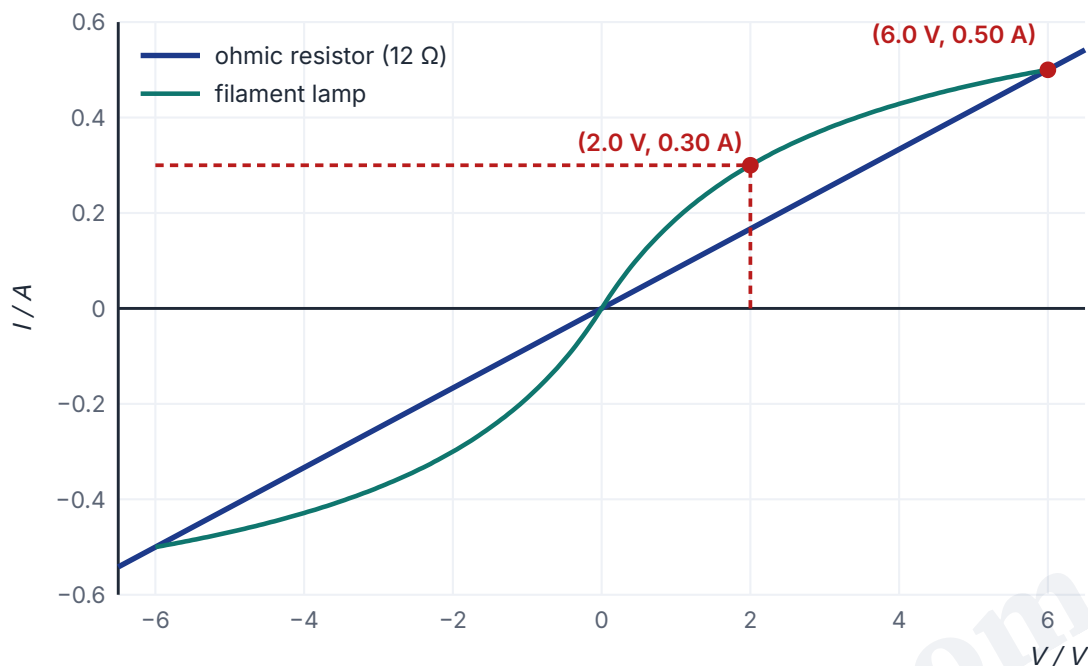
(c) Copper has a resistivity about 30 times smaller, so the same $5.0 \, \Omega$ would

need $L = \frac{5.0 \times 8.04 \times 10^{-8}}{1.7 \times 10^{-8}} \approx 24 \text{ m}$ of wire — far too long to be practical.

What is Ohm's law, and which conductors obey it?

Ohm's law: the current in a conductor is directly proportional to the potential difference across it, provided that the temperature and other physical conditions stay constant.

- A conductor that obeys Ohm's law is **ohmic**: its resistance is constant, and its I–V graph is a straight line through the origin. A metal conductor at constant temperature is treated as ohmic.
- A conductor whose resistance changes with the current is **non-ohmic**. The standard example is a **filament lamp**.
- $R = V/I$ is the *definition* of resistance and applies to everything. Ohm's law is the *experimental observation* that, for some conductors, R does not depend on V or I .



I-V characteristics of a $12\ \Omega$ ohmic resistor (straight line through the origin) and a filament lamp rated $6.0\ \text{V}$, $0.50\ \text{A}$. Reversing the pd reverses the current but does not change the shape. Both pass through $(6.0\ \text{V}, 0.50\ \text{A})$, where their resistances are equal.

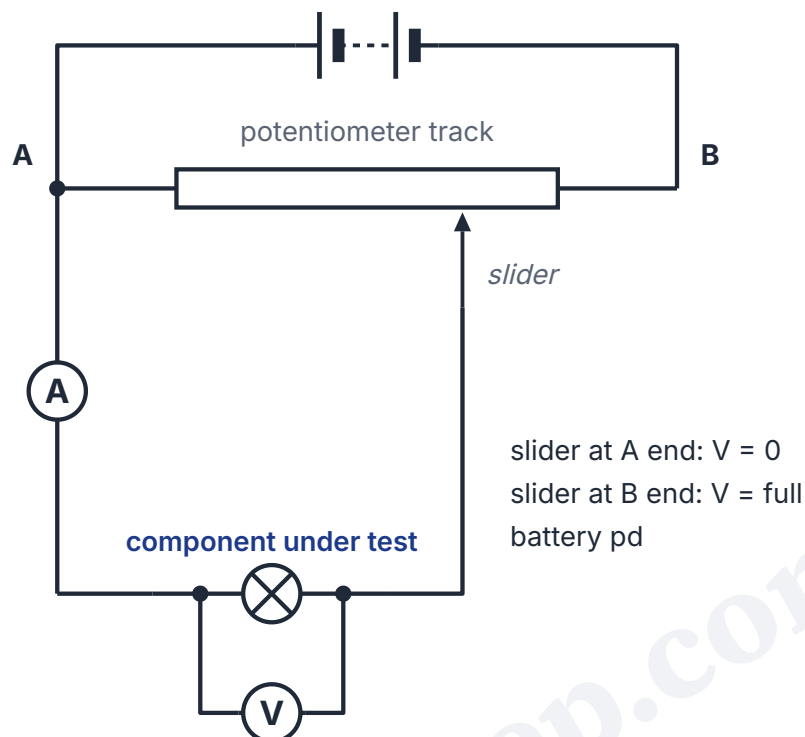
Why the filament lamp is non-ohmic

- As the pd increases, the current increases and the power I^2R dissipated in the filament increases, so the filament's temperature rises (to well over $2000\ ^\circ\text{C}$ in normal use).
- The lattice ions vibrate with larger amplitude, the electrons collide with them more frequently, and the resistance increases.
- So equal increases in V produce smaller and smaller increases in I : the I-V curve bends towards the V axis.

The heating effect of resistors

Every resistor that carries a current warms up. A resistor designed for a circuit stays ohmic because it is made of a material such as constantan, whose resistivity hardly changes with temperature, and because it can lose energy to its surroundings fast enough to stay cool. If the current becomes large enough for its temperature to rise significantly, even a metal resistor stops being ohmic.

Two circuits are used to obtain I-V characteristics: a variable resistor in series with the component, or — better — a **potentiometer** used as a potential divider, which allows the pd to be varied all the way from zero.



Measuring the I - V characteristic of a component (here a filament lamp). Moving the slider along the potentiometer varies the pd across the component continuously from 0 to the full battery pd. Reversing the battery gives the negative half of the graph.

WORKED EXAMPLE 3 Medium · Determine / Explain (graph)

Use the I - V graph of the filament lamp above.

(a) Determine the resistance of the lamp when the pd across it is 2.0 V and when it is 6.0 V. (b) Explain the difference between your two answers. (c) Calculate the power dissipated in the lamp at 6.0 V. (d) A student draws the tangent to the curve at 2.0 V, finds its gradient to be 0.090 A V^{-1} and states that the resistance is $1/0.090 = 11 \text{ } \Omega$. Comment on this answer.

(a) Read the current at each pd. At 2.0 V, $I = 0.30 \text{ A}$: $R = \frac{2.0}{0.30} = \mathbf{6.7 \text{ } \Omega}$.

At 6.0 V, $I = 0.50 \text{ A}$: $R = \frac{6.0}{0.50} = \mathbf{12 \text{ } \Omega}$

(b) At the larger pd the current is larger, so more power is dissipated and the filament is hotter. Its lattice ions vibrate with larger amplitude, so the electrons collide with them more often and the resistance is greater.

(c) $P = IV = 0.50 \times 6.0 = \mathbf{3.0 \text{ W}}$

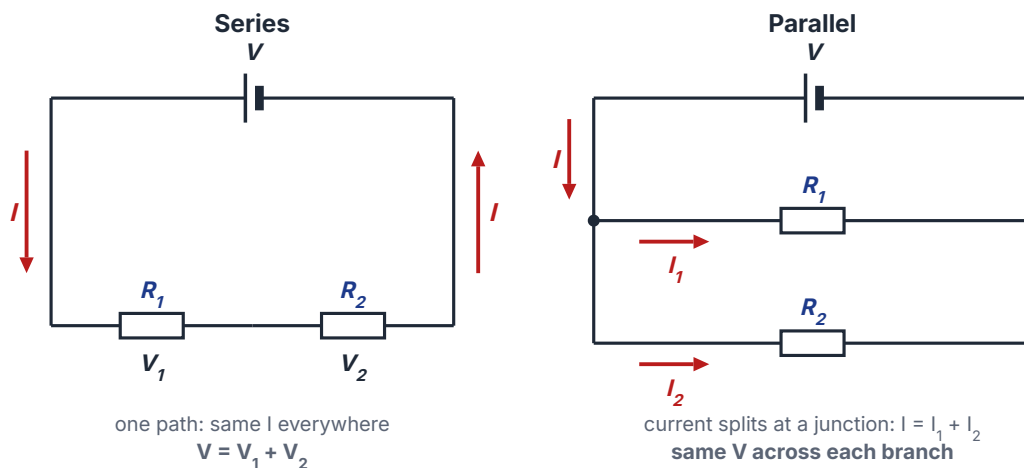
(d) The answer is wrong. Resistance is defined as V/I at that point (6.7Ω), not as the reciprocal of the gradient. The two agree only for an ohmic conductor, whose graph is a straight line through the origin.

How much power is dissipated in a resistor?

The electrical power dissipated in a resistor is the rate at which electrical energy is transferred to internal energy in it: $P = IV = I^2R = \frac{V^2}{R}$.

- P = power (W), I = current through the resistor (A), V = pd across it (V), R = its resistance (Ω). All three forms are in the data booklet.
- $P = IV$ follows from $V = W/q$ and $I = q/t$: $P = \frac{W}{t} = \frac{Vq}{t} = VI$.
Substituting $V = IR$ gives the other two forms.
- Energy transferred in time t : $W = Pt = VIt$.
- Choose the form that uses what is shared: in **series** the current is the same, so compare with I^2R (the larger resistor dissipates more power); in **parallel** the pd is the same, so compare with V^2/R (the *smaller* resistor dissipates more power).
- A lamp labelled "12 V, 24 W" dissipates 24 W when the pd across it is 12 V. Its operating resistance is $R = V^2/P = 6.0 \Omega$. When cold, its resistance is much smaller, so the current at switch-on is larger than the operating current — which is why filament lamps often fail at the moment they are switched on.

How do you combine resistors in series and in parallel?



Series: one path, so the same current flows through each resistor and the cell's pd is shared.

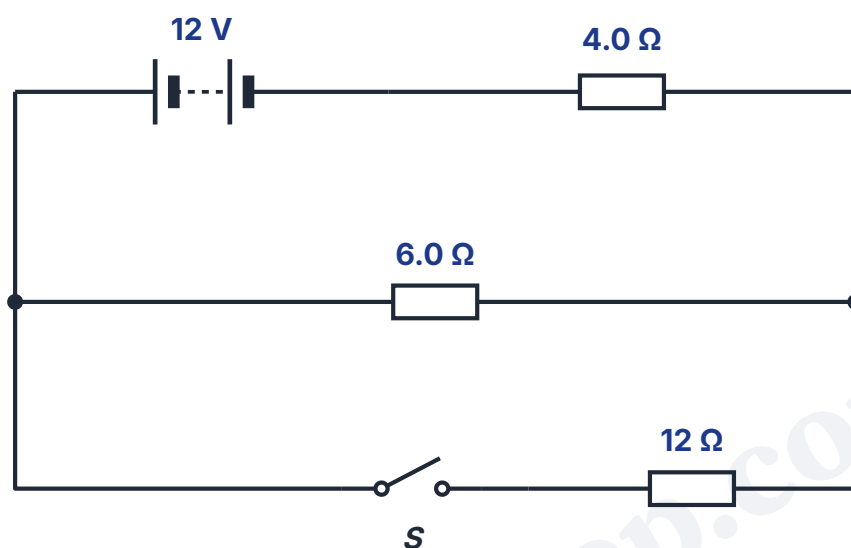
Parallel: each branch is connected directly across the cell, so each has the same pd and the current divides between the branches.

	Series	Parallel
Current	$I = I_1 = I_2 = \dots$	$I = I_1 + I_2 + \dots$
Potential difference	$V = V_1 + V_2 + \dots$	$V = V_1 = V_2 = \dots$
Combined resistance	$R_s = R_1 + R_2 + \dots$	$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \dots$
Physics behind it	charge cannot build up anywhere, so the same charge passes each point per second; the energy given to each coulomb by the source is shared between the components	charge is conserved at a junction, so the current in equals the current out; each coulomb passes through only one branch and transfers all its energy there

- All of these are in the data booklet.
- The combined resistance of a parallel combination is **always smaller than the smallest** resistance in it. Adding another branch in parallel always decreases the total resistance.
- n identical resistors R : series nR ; parallel R/n . For two resistors in parallel,

$$R_p = \frac{R_1 R_2}{R_1 + R_2}$$
 ("product over sum").
- In series the pds divide in the ratio of the resistances: the larger resistor takes the larger share of the pd.

- **Method for a network:** reduce each parallel group to a single resistance, add the series resistances, find the total current from the source, then work back outwards to find each pd and current.



S closed in parts (a)–(b); opened in part (c)

Circuit for worked example 4. The battery has negligible internal resistance. Switch S is in series with the 12 Ω resistor only.

WORKED EXAMPLE 4 Medium · Determine / Explain

In the circuit above, switch S is closed.

(a) Determine the current in the battery. (b) Determine the current in the 6.0 Ω resistor and the power dissipated in the 4.0 Ω resistor. (c) Switch S is now opened. Explain, without detailed calculation, what happens to the pd across the 6.0 Ω resistor, then calculate its new value.

(a) Parallel pair: $\frac{1}{R_p} = \frac{1}{6.0} + \frac{1}{12} \Rightarrow R_p = 4.0 \Omega$. Total: $R = 4.0 + 4.0 = 8.0 \Omega$.

$$I = \frac{V}{R} = \frac{12}{8.0} = \mathbf{1.5 \text{ A}}$$

(b) pd across the parallel pair = $IR_p = 1.5 \times 4.0 = 6.0 \text{ V}$ (the other 6.0 V is across the 4.0 Ω resistor).

Current in 6.0 Ω: $\frac{6.0}{6.0} = \mathbf{1.0 \text{ A}}$ (and 0.50 A in the 12 Ω resistor: $1.0 + 0.50 =$

1.5 A ✓).

Power in $4.0\ \Omega$: $P = I^2 R = 1.5^2 \times 4.0 = \mathbf{9.0\ W}$

(c) Opening S removes a parallel branch, so the resistance of that section rises from $4.0\ \Omega$ to $6.0\ \Omega$ and the total resistance increases. The current from the battery decreases, so the pd across the $4.0\ \Omega$ resistor (IR) decreases. The battery pd is unchanged, so the pd across the $6.0\ \Omega$ resistor **increases**.

New current $= \frac{12}{4.0 + 6.0} = 1.2\ \text{A}$; pd across $6.0\ \Omega = 1.2 \times 6.0 = \mathbf{7.2\ V}$

TRY IT YOURSELF

B.5 DC Circuits simulation: build series and parallel circuits, add meters and watch how the currents and pds change when you add or remove a branch.

What are emf and internal resistance?

A real cell is not a perfect source. The charge carriers must also pass through the materials inside the cell (the electrolyte and electrodes), which have resistance. This is the cell's **internal resistance** r .

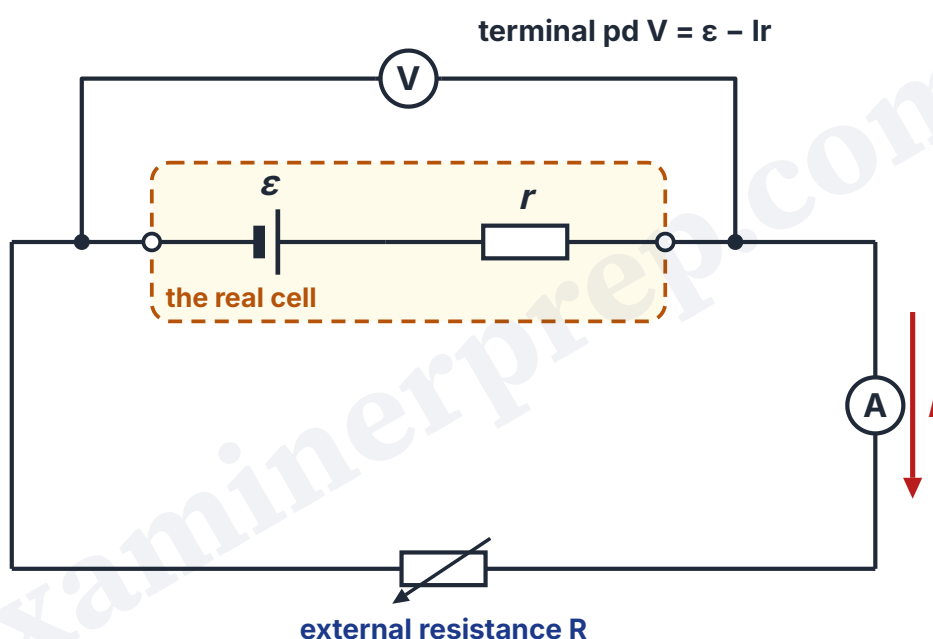
An electric cell is characterised by its emf ε and its internal resistance r : $\varepsilon = I(R + r)$, where I is the current and R is the total external resistance.

- ε = emf (V), I = current (A), R = external resistance (Ω), r = internal resistance (Ω). In the data booklet.
- Expanding: $\varepsilon = IR + Ir$. The **terminal pd** (the pd across the external circuit) is $V = IR$, so

$$V = \varepsilon - Ir$$

- Ir is the pd across the internal resistance — the energy per coulomb transferred to internal energy *inside* the cell, sometimes called the “lost volts”. A cell with a large current warms up.

- When no current flows ($I = 0$), $V = \varepsilon$: an ideal voltmeter connected directly across an isolated cell reads its emf.
- If the terminals are joined by a thick wire ($R \approx 0$), the current is limited only by r : the maximum (short-circuit) current is $I = \varepsilon/r$.
- A car battery needs a very small internal resistance to deliver the hundreds of amperes needed by the starter motor; a high-voltage supply is given a large internal resistance on purpose, so that the current in an accidental short circuit is small (safety).



A real cell drawn as an ideal emf ε in series with its internal resistance r (inside the dashed box). The voltmeter is connected across the terminals, so it reads the terminal pd $V = \varepsilon - Ir$, not the emf.

WORKED EXAMPLE 5 Hard · Show that / Determine

A student uses the circuit above, with the cell replaced by a battery (still drawn as a single emf ε in series with an internal resistance r), to investigate the battery. With the variable resistor at one setting the meters read 0.35 A and 5.72 V; at a second setting they read 1.15 A and 4.10 V. The meters are ideal.

- (a) Show that the internal resistance of the battery is about $2\ \Omega$. (b) Determine the emf of the battery. (c) For the second setting, determine the power delivered to the variable resistor, the power dissipated inside the

battery, and the fraction of the energy converted by the battery that reaches the external circuit.

(a) $V = \varepsilon - Ir$ for both readings. Subtracting: $5.72 - 4.10 = (1.15 - 0.35)r$

$$r = \frac{1.62}{0.80} = \mathbf{2.03\ \Omega} \approx 2\ \Omega \text{ (= -gradient of the V-I graph below)}$$

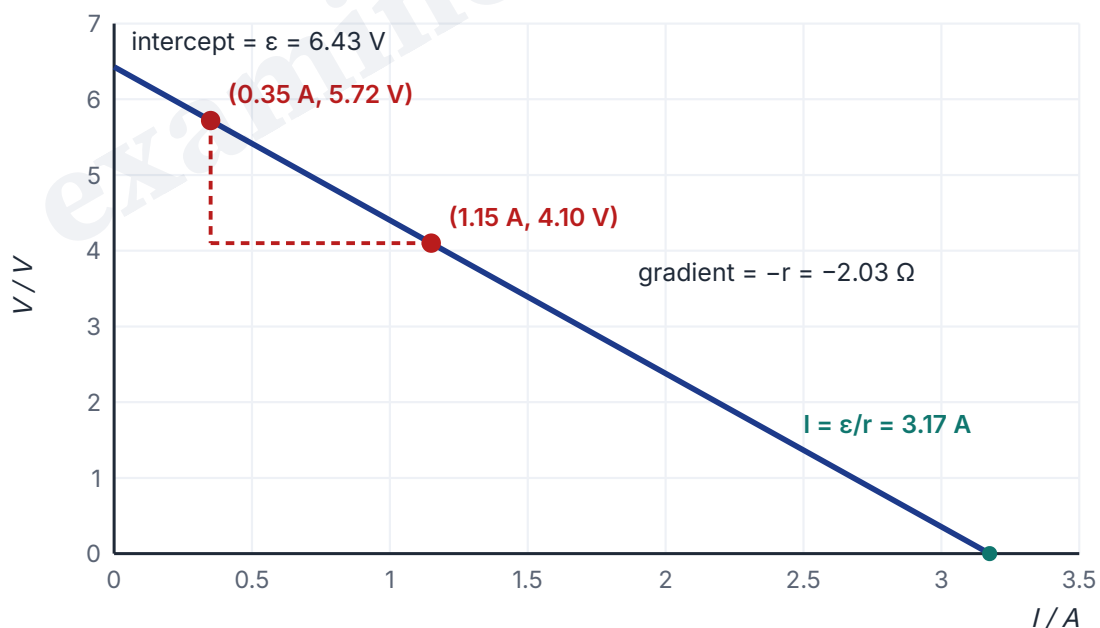
(b) $\varepsilon = V + Ir = 5.72 + 0.35 \times 2.025 = \mathbf{6.4\ V}$ (6.43 V; the second reading gives the same: $4.10 + 1.15 \times 2.025 = 6.43\ \text{V}$)

(c) To the variable resistor: $P = IV = 1.15 \times 4.10 = \mathbf{4.7\ W}$

Inside the battery: $P = I^2r = 1.15^2 \times 2.025 = \mathbf{2.7\ W}$

$$\text{Fraction reaching the external circuit} = \frac{IV}{I\varepsilon} = \frac{V}{\varepsilon} = \frac{4.10}{6.43} = \mathbf{0.64\ (64\ \%)}$$

Check: total power converted $= I\varepsilon = 1.15 \times 6.43 = 7.39\ \text{W} = 4.71 + 2.68\ \text{W}$. The energy-flow diagram in the first section shows the same split per coulomb: $6.43\ \text{J} = 4.10\ \text{J} + 2.33\ \text{J}$.

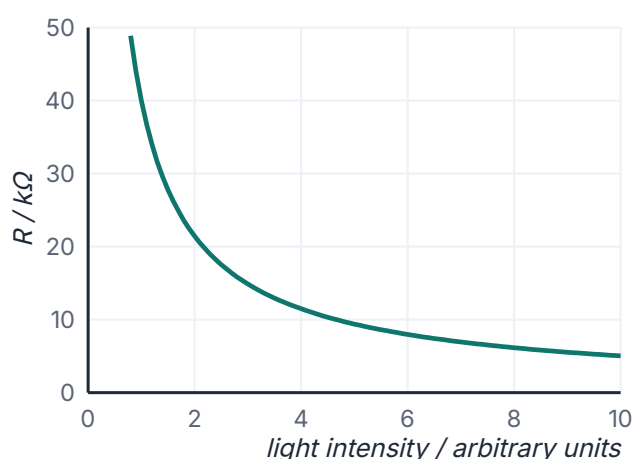
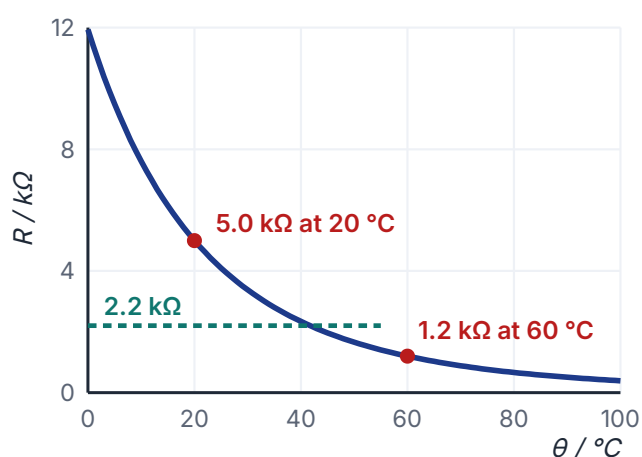


Terminal pd against current for the battery in worked example 5, obtained by varying R . The graph is a straight line $V = \varepsilon - Ir$: the intercept on the V axis is the emf and the gradient is $-r$. The intercept on the I axis is the short-circuit current ε/r .

How do variable resistors and potential dividers work?

A resistor can have a variable resistance. In IB Physics the variable resistors are limited to three: the **thermistor**, the **light-dependent resistor** and the **potentiometer**. The data-booklet “variable resistor” symbol used in worked example 5 is simply a potentiometer track with only one end and the slider connected, so that it acts as an adjustable resistance.

Component	Its resistance changes with...	Why	Typical use
Thermistor (NTC)	temperature: resistance decreases as temperature increases	it is a semiconductor; a higher temperature frees more charge carriers, which outweighs the extra lattice collisions	temperature sensors, fire alarms, thermostats
Light-dependent resistor (LDR)	light intensity: resistance decreases as light intensity increases	absorbed light frees more charge carriers in the semiconductor	automatic street lights, light meters
Potentiometer	the position of a sliding contact along a resistive track	moving the slider changes the length of track between the terminals, and $R \propto L$	volume controls, supplying a variable pd



Left: an NTC thermistor whose resistance falls from $5.0 \text{ k}\Omega$ at 20°C to $1.2 \text{ k}\Omega$ at 60°C (used in worked example 6; the dashed line marks $2.2 \text{ k}\Omega$ for part (c)). Right: the resistance of an LDR falls steeply as the light intensity increases. Both curves are non-linear.

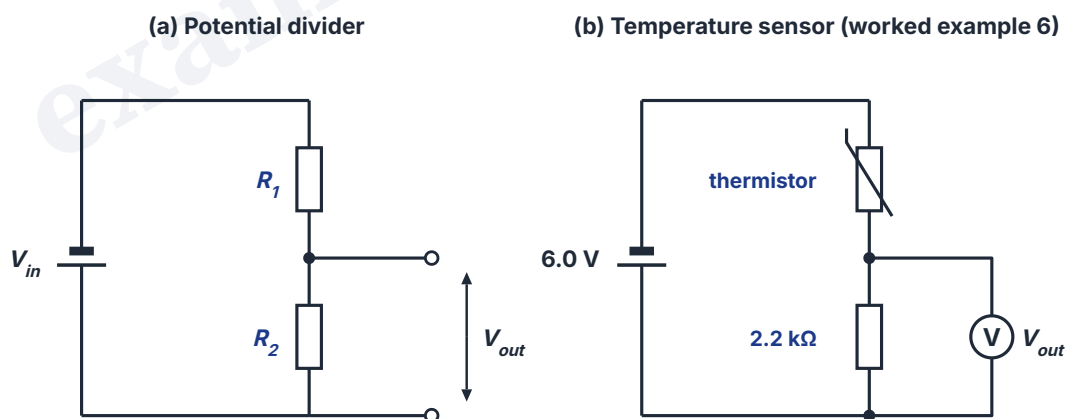
Potential dividers

Two resistors in series across a supply share its pd in the ratio of their resistances. Taking the output across one of them gives a **potential divider**.

Because the same current $I = \frac{V_{in}}{R_1 + R_2}$ flows through both (with nothing drawing current from the output):

$$V_{out} = IR_2 = V_{in} \frac{R_2}{R_1 + R_2}$$

- V_{in} = supply pd (V), V_{out} = output pd across R_2 (V). This is **not** in the data booklet — derive it from the series rules each time, as here.
- If one of the resistors is a thermistor or an LDR, V_{out} changes with temperature or light level: the circuit becomes a **sensor**.
- A potentiometer connected across a supply is a continuously adjustable potential divider: the two parts of the track either side of the slider act as R_1 and R_2 .
- If a meter or other load with a finite resistance is connected across the output, it is in parallel with R_2 , lowering the resistance of that part and so lowering V_{out} . A voltmeter used here should have a resistance much larger than R_2 .



(a) A potential divider: the output pd is the share of V_{in} across R_2 . (b) A thermistor in series with a fixed $2.2 \text{ k}\Omega$ resistor across a 6.0 V supply of negligible internal resistance; the voltmeter reads the pd across the fixed resistor.

WORKED EXAMPLE 6 Hard · Determine / Explain

In circuit (b) above, the thermistor has the resistance–temperature graph shown earlier ($5.0 \text{ k}\Omega$ at 20°C , $1.2 \text{ k}\Omega$ at 60°C). Assume first that the

voltmeter is ideal.

(a) Determine V_{out} at 20 °C and at 60 °C. (b) Explain why V_{out} increases as the temperature rises. (c) Use the graph to estimate the temperature at which $V_{out} = 3.0$ V. (d) At 20 °C the ideal voltmeter is replaced by one of resistance 10 k Ω . Determine its reading.

$$\text{(a) } 20^\circ\text{C: } V_{out} = 6.0 \times \frac{2.2}{2.2 + 5.0} = \mathbf{1.8\text{ V}} \text{ (1.83 V)}$$

$$60^\circ\text{C: } V_{out} = 6.0 \times \frac{2.2}{2.2 + 1.2} = \mathbf{3.9\text{ V}} \text{ (3.88 V)}$$

(b) As the temperature rises, the resistance of the thermistor decreases, so the total resistance decreases and the current increases. The pd across the fixed resistor, IR , therefore increases. (Equivalently: the fixed resistor becomes a larger fraction of the total resistance, so it takes a larger share of the 6.0 V.)

(c) $V_{out} = 3.0$ V is half of 6.0 V, so the two resistances must be equal: the thermistor's resistance is 2.2 k Ω . From the graph this happens at about **42 °C** (accept 40–44 °C).

(d) The voltmeter is in parallel with the 2.2 k Ω resistor: $\frac{1}{R_p} = \frac{1}{2.2} + \frac{1}{10} \Rightarrow$

$$R_p = 1.80 \text{ k}\Omega.$$

$V_{out} = 6.0 \times \frac{1.80}{1.80 + 5.0} = \mathbf{1.6\text{ V}}$ (1.59 V) — lower than the 1.83 V an ideal voltmeter would read, because the meter draws current and reduces the resistance of the lower part of the divider.

Exam tips for B.5

EXAM TIP 1 — SAY WHAT “IDEAL” MEANS

A question asking what an ideal ammeter or voltmeter is gives an easy mark that many students miss by writing “it is accurate”. Give the physics: an ideal

ammeter has **zero resistance** (no pd across it); an ideal voltmeter has **infinite resistance** (it draws no current).

EXAM TIP 2 — RESISTANCE IS V/I , NOT A GRADIENT

On an I-V (or V-I) graph of a non-ohmic component, read off one point and divide V by I . Using the gradient of a tangent is a very common error and earns nothing. Also check which quantity is on which axis before you interpret a gradient at all.

EXAM TIP 3 — EXPLAIN CHANGES AS A CHAIN

When a resistance in a circuit changes (an LDR in brighter light, a thermistor warming up, a switch opening), explain step by step: what happens to the **total resistance** → the **current** from the source → the **pd** across the component in question. Each link is usually a marking point; jumping straight to the conclusion loses marks even when it is correct.

EXAM TIP 4 — PREFIXES AND DIAMETERS

Circuit questions are full of $k\Omega$, $M\Omega$ and mA . Convert to base units before substituting, or keep the prefixes consistent ($k\Omega$ with mA gives V). In resistivity questions, use the *radius*, convert mm to m , and only then square: $A = \pi(0.16 \times 10^{-3})^2$, not $\pi(0.32)^2$.

EXAM TIP 5 — EMF IS NOT TERMINAL PD

A voltmeter across the terminals of a cell that is delivering current reads $V = \mathcal{E} - Ir$, which is *less* than the emf. When asked why the terminal pd falls as the current rises, refer to the pd Ir across the internal resistance increasing with I . Define emf in terms of **energy per unit charge**, never as a force.

Common misconceptions

Misconception	Why it is wrong	Correct idea
Current is used up as it goes round the circuit.	Charge is conserved; carriers cannot vanish or pile up.	The current is the same all round a series loop. It is <i>energy</i> that is transferred in the components.
A battery always supplies the same current.	The current depends on the total resistance, $I = \varepsilon / (R + r)$.	A battery has a (nearly) fixed emf; the current is set by the circuit.
Electrons travel round the circuit at nearly the speed of light.	Their net drift is very slow.	The <i>field</i> is established almost instantly, so all the electrons start drifting at once.
Adding a resistor in parallel increases the total resistance.	It adds an extra path for the current.	Any extra parallel branch decreases the total resistance and increases the current from the source.
A larger resistance always dissipates more power.	True only when the current is the same (series).	In parallel the pd is the same, so $P = V^2 / R$: the <i>smaller</i> resistance dissipates more.
Ohm's law is $V = IR$.	$R = V / I$ is a definition that holds for every component.	Ohm's law is the statement that $I \propto V$ at constant temperature — true only for ohmic conductors.

How this topic connects

Why resistors warm up: electrical work becoming internal energy

The pd does work on the charge carriers ($W = qV$), giving them kinetic energy between collisions. In collisions they pass this energy to the lattice ions, which vibrate with larger amplitude. In the kinetic model of B.1, this is an increase in the **internal energy** of the resistor, seen as a rise in temperature. The resistor then

loses energy to its surroundings by conduction, convection and radiation (B.1), and it reaches a steady temperature when the rate of loss equals $I^2 R$. The same energy chain — work done $\rightarrow$ internal energy — is the one used for friction in A.3.

Electrons colliding with ions: a particle picture of resistance

Modelling a metal as a lattice of positive ions with a “gas” of free electrons explains resistance as collisions between the drifting electrons and the ions. The model correctly predicts that $R \propto L$ (more collisions along a longer path), $R \propto 1/A$ (more parallel paths), that resistance rises with temperature (larger lattice vibrations), and that a current heats a conductor. Like every model it has limits: on its own it cannot explain why semiconductors behave the opposite way, which requires the extra idea that their number of free carriers rises with temperature — a good example of a model being extended when it meets new evidence.

Heat flow and charge flow: two conduction laws with the same shape

Thermal conduction obeys $\frac{\Delta Q}{\Delta t} = kA \frac{\Delta T}{\Delta x}$ (B.1); electrical conduction obeys $I = \frac{\Delta q}{\Delta t} = \frac{A}{\rho} \cdot \frac{V}{L}$. In both, a flow rate (of energy or of charge) is proportional to the area and to a “driving difference” per unit length (temperature gradient or potential gradient), with a material constant (k or $1/\rho$). Metals are good at both for the same reason: their free electrons carry charge and also transport energy quickly through the lattice. Insulators such as plastic are poor at both.

Tools & inquiry — circuit experiments (NOS: measurement and uncertainty)

- **Resistivity of a wire:** measure the resistance of different lengths of the same wire and plot R against L . The gradient is ρ/A . Measure the diameter with a micrometer at several places and in two perpendicular directions, and average. Because $A \propto d^2$, the percentage uncertainty in d is doubled in A — usually the largest uncertainty in ρ . A non-zero intercept reveals a systematic error such as contact resistance.
- **I–V characteristics:** use a potentiometer so that readings can start from 0 V; take more readings where the curve bends; reverse the supply to obtain the negative quadrant.

- **Emf and internal resistance:** vary the external resistance, record V and I , and plot V against I . The gradient is $-r$ and the intercept is ε . Keep the currents modest and switch off between readings, so that the cell does not warm up and change r during the experiment.
- **Safety:** a short circuit across a cell of small internal resistance produces a large current that heats wires and the cell rapidly; high-voltage supplies must have a high internal resistance or a current limit.

Key equations

examinerprep.com

Equation	Use	In data booklet?
$I = \frac{\Delta q}{\Delta t}$	current as rate of flow of charge	yes
$V = \frac{W}{q}$	potential difference (and emf) as energy per unit charge	yes
$R = \frac{V}{I}$	definition of resistance	yes
$\rho = \frac{RA}{L}$	resistivity	yes
$P = IV = I^2 R = \frac{V^2}{R}$	power dissipated in a resistor	yes
$R_s = R_1 + R_2 + \dots$	resistors in series (same I , pds add)	yes
$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \dots$	resistors in parallel (same V , currents add)	yes
$\varepsilon = I(R + r)$	emf and internal resistance	yes
$V = \varepsilon - Ir$	terminal pd of a cell	no — rearrange $\varepsilon = I(R + r)$
$V_{out} = V_{in} \frac{R_2}{R_1 + R_2}$	potential divider	no — derive from the series rules
$e = 1.60 \times 10^{-19} \text{ C}$	elementary charge	yes (constants)

Check your understanding

1. A current of 250 mA flows for 2.0 minutes through a lamp that has a pd of 6.0 V across it. Calculate the charge that passes through the lamp and the energy transferred.

$$q = It = 0.250 \times 120 = 30 \text{ C. } W = qV = 30 \times 6.0 = 180 \text{ J.}$$

2. Wire Y is made of the same metal as wire X but is twice as long and has twice the diameter. Determine the ratio resistance of Y : resistance of X.

Doubling the diameter multiplies A by 4. $R = \rho L/A$, so $R_Y/R_X = 2/4 = 0.5$: wire Y has **half** the resistance of X.

3. You have three 6.0Ω resistors. Show how to connect all three to obtain (a) 9.0Ω and (b) 4.0Ω .

(a) Two in parallel (3.0Ω) in series with the third: $3.0 + 6.0 = 9.0 \Omega$. (b) Two in series (12Ω) in parallel with the third: $\frac{6.0 \times 12}{6.0 + 12} = 4.0 \Omega$. (All three in series give 18Ω ; all three in parallel give 2.0Ω .)

4. A filament lamp is labelled “12 V, 24 W”. Calculate its resistance at normal brightness, and state and explain whether its resistance at 3.0 V is larger or smaller.

$R = \frac{V^2}{P} = \frac{12^2}{24} = 6.0 \Omega$ (current 2.0 A). At 3.0 V the current and power are smaller, so the filament is cooler; its lattice ions vibrate less, electrons collide less often, and its resistance is **smaller** than 6.0Ω .

5. A cell of emf 1.5 V and internal resistance 0.50Ω is connected to a 2.5Ω resistor. Calculate the current, the terminal pd and the energy per coulomb transferred inside the cell.

$I = \frac{\epsilon}{R + r} = \frac{1.5}{2.5 + 0.50} = 0.50 \text{ A}$. Terminal pd $V = IR = 0.50 \times 2.5 = 1.25 \text{ V}$ ($\approx 1.3 \text{ V}$). Inside the cell: $Ir = 0.50 \times 0.50 = 0.25 \text{ V}$, i.e. 0.25 J per coulomb ($1.25 + 0.25 = 1.5 \checkmark$).

Practise B.5 with exam-style questions

Original Paper 1A, 1B and 2 questions on current, resistance, circuits and internal resistance, with full mark schemes. Tick the questions you want and print them as your own test.

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SL students: the previous SL page is [B.3 Gas laws](#).