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

Electricity AS

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

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Read first: Work, energy and power

What you need to know

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

1. **Understand that an electric current is a flow of charge carriers**: electrons in a metal, or any other charged particles that move.
2. **Understand that charge is quantised**: the charge on any carrier is a whole number of elementary charges e.
3. **Recall and use $Q = It$.**
4. **Use $I = Anvq$** for a conductor carrying a current, where n is the number density of charge carriers (the number per unit volume).
5. **Define the potential difference across a component** as the energy transferred per unit charge.
6. **Recall and use $V = \dfrac{W}{Q}$.**
7. **Recall and use $P = VI$, $P = I^2R$ and $P = \dfrac{V^2}{R}$.**
8. **Define resistance** and **recall and use $V = IR$.**
9. **Sketch the I–V characteristics** of a metallic conductor at constant temperature, a semiconductor diode and a filament lamp.
10. **Explain why the resistance of a filament lamp increases as the current increases**: the filament gets hotter.
11. **State Ohm's law.**
12. **Recall and use $R = \dfrac{\rho L}{A}$.**
13. **Understand that the resistance of a light-dependent resistor (LDR) decreases as the light intensity increases.**
14. **Understand that the resistance of a thermistor decreases as the temperature increases** (all thermistors here have a negative temperature coefficient).

Electromotive force, internal resistance, Kirchhoff's laws, resistors in series and parallel and potential dividers belong to the D.C. circuits topic. Many Paper 2 questions mix the two topics; this note uses only the simple facts it needs from there.

Understand it

Current is a flow of charge carriers

An **electric current** is a flow of **charge carriers**: charged particles that move. In a metal the carriers are **free (conduction) electrons**, which can drift between the fixed positive ions. In a salt solution they are positive and negative ions. A beam of protons, alpha particles or electrons is also a current. Neutrons and photons carry no charge, so they can never make a current.

The **current** is the rate of flow of charge:

$$I = \frac{Q}{t} \qquad \text{so} \qquad Q = It$$

Current is measured in amperes (A), charge in coulombs (C) and time in **seconds**. One **coulomb** is the charge that passes a point when a current of one ampere flows for one second: $1\ \mathrm{C} = 1\ \mathrm{A\ s}$.

- A torch bulb carrying 0.38 A for 85 s passes $Q = 0.38 \times 85 = 32.3$ C.
- The direction of **conventional current** is the direction positive charge would move. Electrons are negative, so in a metal they drift the **opposite** way: from the negative terminal of the cell, round the circuit, to the positive terminal.
- Charge is not used up. In a single loop the current is the same everywhere; where the path splits, the currents in the branches add up to the current before the split (the D.C. circuits topic calls this Kirchhoff's first law).

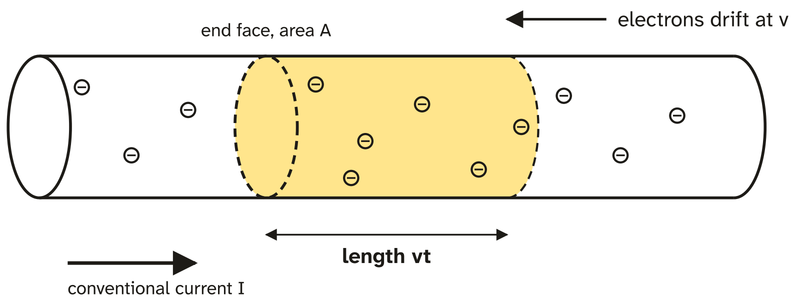
Charge is quantised

Charge comes in lumps. Every charge is a whole-number multiple of the **elementary charge** $e = 1.60 \times 10^{-19}$ C (given on the data sheet). An electron carries $-e$, a proton $+e$ and an alpha particle $+2e$.

- A charge of 2.24×10^{-18} C is possible: $\frac{2.24\times10^{-18}}{1.60\times10^{-19}} = 14$, a whole number.
- A charge of 3.0×10^{-19} C is **not** possible: it would be $1.875e$.
- The **number of carriers** that pass in time t is $N = \frac{Q}{e} = \frac{It}{e}$. The 32.3 C through the torch bulb is $\frac{32.3}{1.60\times10^{-19}} = 2.02 \times 10^{20}$ electrons.
- The charge on a carrier is fixed. It does not depend on the potential difference or the current.

Drift speed and $I = Anvq$

The free electrons in a metal move about randomly at high speed. When there is a p.d. across the wire, they also slowly **drift** along it. Their average speed along the wire is the **average drift speed** v.



in time t, every carrier in the shaded length vt passes the end face:
number = n × (A × vt), charge Q = nAvt × q
I = Q ÷ t = Anvq

Take a wire of cross-sectional area A, with n charge carriers per unit volume, each of charge q, drifting at average speed v. In time t each carrier moves a distance vt. So every carrier within a length vt of a chosen cross-section passes through it in that time:

- volume of that length $= A \times vt$;
- number of carriers in it $= nAvt$;
- charge that passes $Q = nAvtq$;
- current $I = \frac{Q}{t} = Anvq$.

n is the **number density**: the number of free charge carriers **per unit volume** (unit m^{-3}), not the total number in the wire. If you know the total number N in a wire of length L, then $n = \frac{N}{AL}$.

Drift speeds are tiny. A wire of area 1.6×10^{-6} m² with $n = 1.0 \times 10^{29}$ m^{-3} carrying 2.0 A has

$$v = \frac{I}{Anq} = \frac{2.0}{1.6 \times 10^{-6} \times 1.0 \times 10^{29} \times 1.60 \times 10^{-19}} = 7.8 \times 10^{-5}\ \mathrm{m\ s^{-1}},$$

less than a tenth of a millimetre per second.

What v depends on, from $v = \frac{I}{Anq}$:

- **Same current, thinner part:** in a series circuit every part carries the same current. If the parts are the same metal (same n), then $v \propto \frac{1}{A}$. A diameter 0.7 times as large means 0.49 of the area and $\frac{1}{0.49} = 2.04$ times the drift speed. A wire that narrows along its length has a drift speed that rises as it narrows.
- **Different metals, same current and area:** a metal with fewer free electrons per unit volume (smaller n) has a larger drift speed.
- **Length has no effect on its own.** A longer wire does not change n or q. It only changes v if it changes the current.

Potential difference and energy

As charge flows through a component, energy is transferred from the electrical energy of the charge to other forms (thermal energy in a resistor, light in a lamp). The **potential difference (p.d.)** across a component is the **energy transferred per unit charge** passing through it:

$$V = \frac{W}{Q} \qquad \text{so} \qquad W = QV = VIt$$

One **volt** is one joule per coulomb: $1\ \mathrm{V} = 1\ \mathrm{J\ C^{-1}}$. The definition needs "per unit charge". "Current × resistance" is a way to calculate a p.d., not its definition. If 32.3 C passes through the torch bulb while the p.d. across it is 2.9 V, the energy transferred is $32.3 \times 2.9 = 94$ J.

Power

Power is the rate of transfer of energy, $P = \frac{W}{t}$. With $W = VIt$ this gives $P = VI$. Using $V = IR$ to replace V or I gives two more forms:

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

A 6.5 Ω resistor carrying 1.6 A has $V = 1.6 \times 6.5 = 10.4$ V across it, and $P = I^2R = 1.6^2 \times 6.5 = 16.64$ W; $VI = 10.4 \times 1.6$ gives the same 16.64 W, about 17 W.

Choose the form that uses what stays **the same**:

- **Same current** (components in series): use $P = I^2R$. The larger resistance has the larger power. With 20 Ω and 80 Ω in series, the powers are in the ratio $1 : 4$.
- **Same p.d.** (components in parallel, or one component across a fixed supply): use $P = \frac{V^2}{R}$. The **smaller** resistance has the larger power. The same 20 Ω and 80 Ω in parallel have powers in the ratio $4 : 1$.
- $P \propto I^2$ for a fixed resistor: a current 1.3 times as large gives $1.3^2 = 1.69$ times the power.

Resistance and Ohm's law

The **resistance** of a component is the **potential difference across it divided by the current in it**:

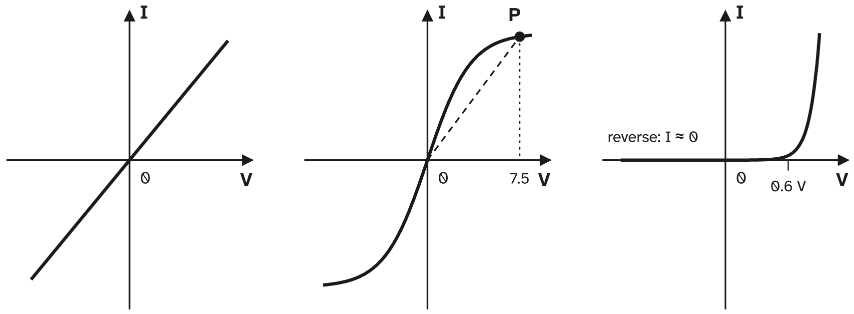
$$R = \frac{V}{I} \qquad \text{or} \qquad V = IR$$

The **ohm** is one volt per ampere: $1\ \Omega = 1\ \mathrm{V\ A^{-1}}$.

At any point on an I–V graph, the resistance is $\frac{V}{I}$ **at that point**. It is **not** the gradient of the graph, unless the graph is a straight line through the origin.

Ohm's law: for a metallic conductor at constant temperature, the current is **directly proportional** to the potential difference across it. A component that obeys it has an I–V graph that is a straight line **through the origin**, and a constant resistance. A straight line that does not pass through the origin is not direct proportion.

I-V characteristics



metallic conductor — at constant temperature; straight line: obeys Ohm's law

filament lamp — R at P = V ÷ I = 24 Ω

semiconductor diode — conducts one way only

Metallic conductor at constant temperature. A straight line through the origin, the same in both directions. Its resistance is constant: it obeys Ohm's law.

Filament lamp. The graph goes through the origin and is symmetrical (reversing the p.d. just reverses the current). Near the origin it is straight, then it **curves towards the V axis**: equal steps of p.d. give smaller and smaller increases in current. The reason: a larger current transfers more power to the filament, so its **temperature rises**, and the resistance of the metal increases with temperature. So $\frac{V}{I}$ **increases** as the current increases, and it **decreases** again when the current decreases and the filament cools.

In the diagram the lamp follows $I = 0.32\tanh\left(\frac{V}{3.5}\right)$. Near the origin its resistance is about $\frac{3.5}{0.32} = 11$ Ω. At P, 7.5 V and 0.311 A, it is $\frac{7.5}{0.311} = 24$ Ω: about twice as large, because the filament is much hotter.

When a lamp is first switched on, the filament is cold and its resistance small, so the current is briefly larger than its steady value.

Semiconductor diode. For a p.d. in the **reverse** direction the current is almost zero: the resistance is **very high**. In the **forward** direction there is almost no current until the p.d. reaches about 0.6 V (the threshold). Above that the current rises steeply, and the resistance **falls** as the p.d. increases. A diode lets current through in one direction only. Above the threshold the graph may look nearly straight, but it does not pass through the origin, so the diode still does not obey Ohm's law.

Resistivity

The resistance of a wire depends on its **material**, its **length** L and its **cross-sectional area** A:

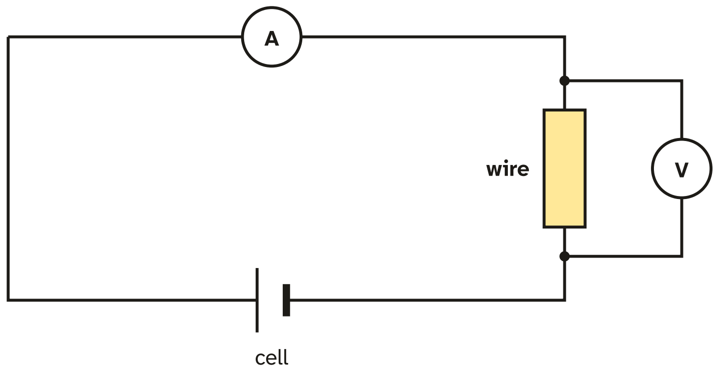
$$R = \frac{\rho L}{A}$$

ρ (rho) is the **resistivity** of the material, in **Ω m** (from $\rho = \frac{RA}{L}$: Ω × m² ÷ m). It is a property of the material at a given temperature, not of a particular wire: cutting, stretching or reshaping the wire does not change ρ.

- **Longer wire, more resistance:** $R \propto L$. 1.5 times the length, 1.5 times the resistance.

- **Thicker wire, less resistance:** $R \propto \frac{1}{A}$, and for a round wire $A = \frac{\pi d^2}{4}$, so $R \propto \frac{1}{d^2}$. Three times the diameter means a **ninth** of the resistance.
- For an aluminium cable ($\rho = 2.7 \times 10^{-8}$ Ω m) 25 m long with a diameter of 1.2 mm: $A = \pi(0.60 \times 10^{-3})^2 = 1.131 \times 10^{-6}$ m² and $R = \frac{2.7 \times 10^{-8} \times 25}{1.131 \times 10^{-6}} = 0.60$ Ω.

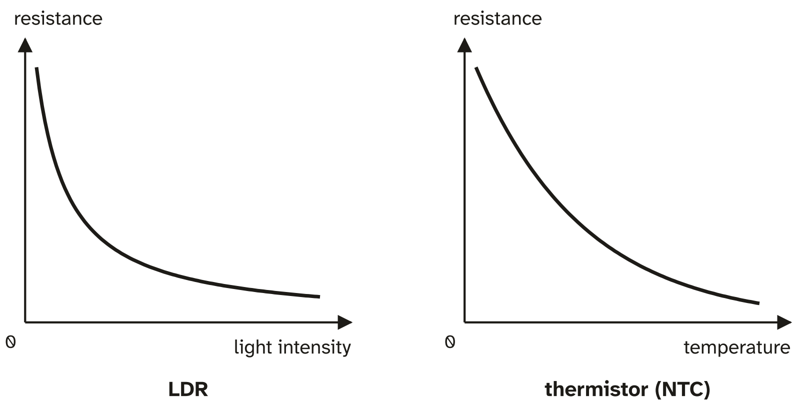
Stretching or reshaping at constant volume. The volume $V_0 = AL$ stays the same, so the area falls as the length grows: $A = \frac{V_0}{L}$. Then $R = \frac{\rho L}{A} = \frac{\rho L^2}{V_0}$, so $R \propto L^2$. Stretching a wire to 1.2 times its length multiplies its resistance by $1.2^2 = 1.44$: once for the extra length and once for the smaller area.



ammeter in series: same current as the wire
voltmeter in parallel: across the wire only
R = V ÷ I, then ρ = RA ÷ L with A = πd²/4

Measuring resistivity. Connect the wire in series with an ammeter and a cell, with a voltmeter across the wire only. Then $R = \frac{V}{I}$. Measure the length with a metre rule and the diameter with a micrometer at several places (take the mean), find $A = \frac{\pi d^2}{4}$ and calculate $\rho = \frac{RA}{L}$. The percentage uncertainty in ρ is the sum of those in R (from V and I), in L, and **twice** that in d, because d is squared.

LDRs and thermistors



more light, or hotter → lower resistance

- A **light-dependent resistor (LDR)**: its resistance **decreases** as the **light intensity increases**. It is very high in the dark.
- A **thermistor** (negative temperature coefficient, the only kind in this course): its resistance **decreases** as the **temperature increases**.

They are used as sensors. With one of them connected across a supply of fixed p.d., more light (or a higher temperature) means lower resistance, so a **larger current** and more power ($P = \frac{V^2}{R}$). In series with a fixed resistor, the current in both rises as the sensor's resistance falls, so the p.d. across the fixed resistor rises too.

Key facts and formulas

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

Formula	Status
$Q = It$	Learn it
Elementary charge $e = 1.60 \times 10^{-19}$ C; any charge = whole number $\times\, e$	Given (the value)
Number of carriers $N = \dfrac{Q}{e}$	Learn it
$I = Anvq$	Given
Number density $n = \dfrac{\text{number of carriers}}{\text{volume}}$	Learn it
$V = \dfrac{W}{Q}$, so $W = QV = VIt$	Learn it
$P = VI = I^2R = \dfrac{V^2}{R}$	Learn it
$P = \dfrac{W}{t}$	Learn it
$R = \dfrac{V}{I}$, $V = IR$	Learn it
$R = \dfrac{\rho L}{A}$	Learn it
Area of a round wire $A = \dfrac{\pi d^2}{4} = \pi r^2$	Learn it
Units: $1\ \mathrm{C} = 1\ \mathrm{A\ s}$, $1\ \mathrm{V} = 1\ \mathrm{J\ C^{-1}}$, $1\ \Omega = 1\ \mathrm{V\ A^{-1}}$, ρ in Ω m	Learn it

Prefixes that appear here: mA $= 10^{-3}$ A, μA $= 10^{-6}$ A, kΩ $= 10^3$ Ω, mΩ $= 10^{-3}$ Ω, and mm² $= 10^{-6}$ m² (not 10^{-3}).

How to do it

In the Paper 1 and Paper 2 questions we have tagged for this topic (149 different questions, 2021–2025; 5 more appear on two papers), the types came up this often. 26 of the 149 questions mix two or more types, so the counts add up to more than 149. Many Paper 2 questions also have parts on D.C. circuits.

Question type	Questions
Resistance and resistivity	46
Potential difference, energy and power	46

Question type	Questions
I–V characteristics, Ohm's law, LDRs and thermistors	38
Charge, current and charge carriers	31
Drift speed and $I = Anvq$	26

1. Resistance and resistivity (46 questions)

1. **Write** $R = \dfrac{\rho L}{A}$ (or $R = \dfrac{V}{I}$ to get R from meter readings first).
2. **Convert to metres**: cm → m, mm → m, and mm² → m² (multiply by 10^{-6}). Area from a diameter: $A = \frac{\pi d^2}{4}$; do not forget to halve the diameter if you use πr^2.
3. **Rearrange** for the unknown: $\rho = \frac{RA}{L}$, $L = \frac{RA}{\rho}$, $A = \frac{\rho L}{R}$, then $d = \sqrt{\frac{4A}{\pi}}$.

Variations you will meet:

- **"Define resistance"**: potential difference across the component divided by the current in it. **"Define the ohm"**: one volt per ampere (a unit is defined from other units).
- **Ratio questions** (two wires, same or different metal): write $R = \frac{\rho L}{A}$ for each and divide. With diameters, square the ratio: wire Y three times as long with half the diameter has $3 \times 2^2 = 12$ times the resistance.
- **Same resistance, different metal**: a metal with larger ρ needs a larger area (or shorter length) to have the same R: $\frac{L}{A} \propto \frac{1}{\rho}$.
- **Stretched or reshaped at constant volume**: $R \propto L^2$, or in terms of the diameter, $R \propto \frac{1}{d^4}$ (since $L \propto \frac{1}{d^2}$). A wire whose diameter falls to 0.9 of its value has $\frac{1}{0.9^4} = 1.52$ times the resistance.
- **Same mass of the same metal** means the same volume, so again $R \propto L^2$.
- **Strands in parallel**: identical parallel strands of the same length act like one wire whose area is the total area.
- **Wire resistance from an I–V graph**: read one point, $R = \frac{V}{I}$, then $\rho = \frac{RA}{L}$.
- **Resistance per unit length** (Ω m^{-1}) is $\frac{R}{L} = \frac{\rho}{A}$, so $\rho = \frac{R}{L} \times A$.
- **A thicker wire across the same supply**: smaller R, so a **larger** current and **more** power ($P = \frac{V^2}{R}$).
- **Draw the circuit to measure R**: cell, ammeter and wire in one loop, voltmeter across the wire only.
- **Uncertainty in ρ**: add the percentage uncertainties of V, I and L, and **twice** that of d. Absolute uncertainty $=$ percentage $\div 100 \times \rho$.
- **Unit of resistivity**: Ω m.

2. Potential difference, energy and power (46 questions)

1. **Pick the equation** that links what you know: $V = \frac{W}{Q}$, $W = VIt$, $P = VI$, $P = I^2R$, $P = \frac{V^2}{R}$.
2. **Convert** minutes and hours to seconds, kW to W, mA to A.
3. **Energy or power?** Energy in joules is Pt; power in watts is a rate.

Variations you will meet:

- **"Define potential difference"**: energy transferred **per unit charge**. **"What is one volt?"**: one joule per coulomb.
- **Which quantity is charge × p.d.?** Energy transferred.
- **Rating** such as "110 V, 1.5 kW": current $I = \frac{P}{V}$, resistance $R = \frac{V^2}{P}$. Assume the resistance stays the same unless told otherwise.
- **Proportion**: for a fixed resistor $P \propto I^2$ and $P \propto V^2$. Tripling V gives nine times the power; cutting R to a third at fixed V triples the power.
- **Which resistor dissipates more power?** Series (same I): the larger R, from I^2R. Parallel (same V): the smaller R, from $\frac{V^2}{R}$.
- **Thermistor or LDR across a fixed p.d.**: hotter or brighter → smaller R → larger $P = \frac{V^2}{R}$.
- **Power ratio** for two resistors in series: $\frac{P_1}{P_2} = \frac{R_1}{R_2}$ (same current); for two in parallel, $\frac{P_1}{P_2} = \frac{R_2}{R_1}$.
- **Energy transferred as charge passes**: $W = QV$. A battery's stored energy falls by QV when charge Q passes through it; subtract from the starting energy.
- **Power lost in connecting wires**: find the current from the supply's output ($I = \frac{P}{V}$), then $P_{\text{lost}} = I^2 R_{\text{wires}}$ and $W = Pt$.
- **Efficiency** (with the Work, energy and power topic): useful power out ÷ total power in; an electric motor takes $P = VI$ from the supply.
- **Energy from a current–time graph** at constant p.d.: area under the graph gives the charge, then $W = QV$.
- **Brightness of lamps**: brightness follows the power in the lamp. If one lamp in a network breaks, find the new currents first, then compare I^2R.

3. I–V characteristics, Ohm's law, LDRs and thermistors (38 questions)

1. **Recognise the shape**: straight through the origin → metallic conductor at constant temperature (or fixed resistor); curving towards the V axis, symmetrical → filament lamp; zero in reverse, then steep above about 0.6 V → diode.
2. **Resistance at a point** $= \frac{V}{I}$ read at that point, never the gradient.
3. **Explain with temperature** for a lamp, **light intensity** for an LDR, **temperature** for a thermistor.

Variations you will meet:

- **"State Ohm's law"**: the current in a metallic conductor is **directly proportional** to the potential difference across it, **provided the temperature (physical conditions) stays constant**.
- **Which components obey Ohm's law?** Only straight lines through the origin.
- **"Explain the shape" of a lamp's curve**: as the current increases, the filament's temperature rises, so its resistance increases; so the ratio $\frac{V}{I}$ increases and the curve bends towards the V axis.
- **Current decreasing in a lamp**: the temperature falls, so the resistance **decreases**.
- **Sketch a lamp's characteristic**: through the origin, straight near the origin, gradient decreasing; draw it in the first quadrant and, if asked, the third quadrant with the same shape.

- **Diode resistance**: very high (infinite) in reverse and below the threshold; above it the resistance decreases as V increases. "Linear" above the threshold is not "proportional".
- **Components in series read from graphs**: the same current in both, so read each p.d. at that current and add (for example a fixed resistor and a lamp, or a resistor and a diode: $R = \frac{V_{\text{supply}} - V_{\text{diode}}}{I}$).
- **Resistance against V for a lamp**: starts at a non-zero value and increases.
- **LDR and thermistor directions**: brighter → LDR resistance down; hotter → thermistor resistance down. With a constant current, the p.d. across either one falls ($V = IR$).
- **Sensor in series with a fixed resistor**: sensor's resistance falls → total resistance falls → current rises → p.d. across the fixed resistor rises. Always name **which** resistance changes and say what happens to the current.

4. Charge, current and charge carriers (31 questions)

1. **Find the charge**: $Q = It$ with t in seconds (or from $I = \frac{V}{R}$ first if you are given the p.d. and resistance).
2. **Number of carriers** $N = \frac{Q}{e}$ (for alpha particles, divide by $2e$).
3. **Give the answer** to 2 or 3 significant figures; numbers of electrons are huge, like 10^{20}.

Variations you will meet:

- **"What is an electric current?"**: a flow of charge carriers. **What can't make a current?** Neutral particles, such as neutrons.
- **Is this charge possible?** Divide by 1.60×10^{-19}: a whole number means yes. Zero is possible (a neutral droplet).
- **The coulomb**: one ampere for one second; its base units are A s.
- **Average current** from a number of electrons: $I = \frac{Ne}{t}$.
- **Direction**: electrons move from the negative terminal to the positive terminal through the external circuit; conventional current goes the other way.
- **Charge through a narrowing wire**: with a steady current, the same charge passes every cross-section in the same time, whatever the area.
- **The charge on a free electron** never changes with the p.d. or the current.

5. Drift speed and $I = Anvq$ (26 questions)

1. **Get n right**: it is carriers per unit **volume**. From a total number N in a wire: $n = \frac{N}{AL}$.
2. **Use $q = e = 1.60 \times 10^{-19}$ C** for electrons (not the total charge that flowed).
3. **Rearrange**: $v = \frac{I}{Anq}$, and convert mm² to m².

Variations you will meet:

- **"What does n represent?"**: the number of (free) charge carriers per unit volume.
- **Series wires of different area, same metal**: same I, same n and q, so $v \propto \frac{1}{A} \propto \frac{1}{d^2}$. Explain by saying that I, n and q are the same.

- **Different metals or different n**: $v \propto \frac{I}{An}$; for example a filament and its copper lead in series have $\frac{v_1}{v_2} = \frac{A_2 n_2}{A_1 n_1}$.
- **Changing several things at once**: $I \propto Anv$ for the same carriers. Twice the area, three times n and half v gives $2 \times 3 \times 0.5 = 3$ times the current.
- **A wire that narrows or widens along its length**: v is largest where the area is smallest. For a wire whose radius falls steadily along it, $v \propto \frac{1}{r^2}$, so the graph of v against distance rises **more and more steeply**, not in a straight line.
- **Time for a carrier to travel a length L**: $t = \frac{L}{v}$ (long: minutes or hours). Distance moved in a given time: vt, or $\frac{Q}{nAe}$ when you are given the charge that flowed.
- **Algebra**: with N free electrons in a wire of length L carrying current I: $n = \frac{N}{AL}$, so $v = \frac{I}{Anq} = \frac{IL}{Ne}$, and the time to cross the wire is $\frac{L}{v} = \frac{Ne}{I}$.
- **A second identical wire added in parallel across a supply of negligible internal resistance**: the p.d. across the first wire is still the supply's p.d., so its current and drift speed are unchanged; the total resistance falls, so the total current (ammeter reading) increases.
- **Checking data**: if $q = \frac{I}{Anv}$ comes out as a value that is not a whole number of e (for example less than e), the data cannot be right.
- **A longer wire in place of a shorter one** across the same p.d.: larger R, smaller I, so smaller v. The length does not change n or ρ.

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 phone is charged with a steady current of 0.65 A for 42 minutes. The potential difference across the charging lead is 4.6 V.

(a) Calculate the charge that flows. **[2]**

(b) Calculate the number of electrons that pass a point in the lead in this time. **[2]**

(c) Calculate the energy transferred by this charge. **[2]**

(d) Calculate the power. **[1]**

Solution

(a) $Q = It = 0.65 \times 42 \times 60$ **C1** $= 1638$ C $= 1.6 \times 10^3$ C. **A1**

(b) $N = \dfrac{Q}{e} = \dfrac{1638}{1.60 \times 10^{-19}}$ **C1** $= 1.0 \times 10^{22}$. **A1**

(c) $W = QV = 1638 \times 4.6$ **C1** $= 7.5 \times 10^3$ J. **A1**

(d) $P = VI = 4.6 \times 0.65 = 3.0$ W. **A1** (Check: $\frac{7535}{2520} = 3.0$ W.)

Example 2

A manganin wire of length 1.85 m and diameter 0.32 mm is used as a resistor. Manganin has resistivity 4.4×10^{-7} Ω m.

(a) Show that the resistance of the wire is about 10 Ω. **[3]**

(b) The wire is connected across a supply of p.d. 5.7 V. Calculate the current in the wire and the power dissipated in it. **[3]**

(c) The same wire is now drawn out so that its length becomes 1.5 times as long. Its volume does not change. Calculate its new resistance, and the power dissipated in it when it is connected across the same 5.7 V supply. **[3]**

Solution

(a) $A = \dfrac{\pi d^2}{4} = \dfrac{\pi (0.32 \times 10^{-3})^2}{4} = 8.04 \times 10^{-8}$ m² **C1** $R = \dfrac{\rho L}{A} = \dfrac{4.4 \times 10^{-7} \times 1.85}{8.04 \times 10^{-8}}$ **C1** $= 10.1$ Ω. **A1**

(b) $I = \dfrac{V}{R} = \dfrac{5.7}{10.1} = 0.56$ A. **A1** $P = \dfrac{V^2}{R}$ **C1** $= \dfrac{5.7^2}{10.1} = 3.2$ W. **A1**

(c) Volume constant, so the area becomes $\frac{1}{1.5}$ of its value while the length becomes 1.5 times: $R \propto L^2$. **C1** $R' = 1.5^2 \times 10.1 = 22.8$ Ω. **A1** $P' = \dfrac{5.7^2}{22.8} = 1.4$ W. **A1**

Example 3

A silver wire has cross-sectional area 0.70 mm² and carries a current of 2.9 A. The number density of free electrons in silver is 5.9×10^{28} m⁻³.

(a) State what is meant by the number density of free electrons. **[1]**

(b) Calculate the average drift speed of the free electrons. **[3]**

(c) The wire is joined in series with a second silver wire of cross-sectional area 0.18 mm². State and explain how the average drift speed in the second wire compares, and calculate it. **[3]**

(d) Calculate the time taken for a free electron to drift 0.58 m along the first wire. **[1]**

Solution

(a) The number of free electrons per unit volume of the metal. **B1**

(b) $I = Anvq$, so $v = \dfrac{I}{Anq}$ **C1** $= \dfrac{2.9}{0.70 \times 10^{-6} \times 5.9 \times 10^{28} \times 1.60 \times 10^{-19}}$ **C1** $= 4.4 \times 10^{-4}$ m s⁻¹. **A1**

(c) The wires are in series, so the current is the same; n and q are the same (same metal, electrons), so $v \propto \dfrac{1}{A}$. The drift speed is greater in the thinner wire. **B1** $v_2 = 4.39 \times 10^{-4} \times \dfrac{0.70}{0.18}$ **C1** $= 1.7 \times 10^{-3}$ m s⁻¹. **A1**

(d) $t = \dfrac{0.58}{4.39 \times 10^{-4}} = 1.3 \times 10^{3}$ s (about 22 minutes). **A1**

Example 4

A filament lamp is rated 24 V, 40 W.

(a) Calculate the current in the lamp and its resistance when it is working normally. **[3]**

(b) The filament is a tungsten wire of length 0.48 m. At its working temperature, tungsten has resistivity 6.6×10^{-7} Ω m. Calculate the diameter of the filament. **[3]**

(c) When the p.d. across the lamp is 2.2 V, the current is 0.52 A. Calculate the resistance of the lamp at this p.d. and explain why it is different from your answer in (a). **[3]**

(d) Sketch the I–V characteristic of the lamp for positive and negative p.d.s. **[2]**

Solution

(a) $I = \dfrac{P}{V} = \dfrac{40}{24} = 1.67$ A. **C1 A1** $R = \dfrac{V}{I} = \dfrac{24}{1.667} = 14.4$ Ω. **A1**

(b) $A = \dfrac{\rho L}{R} = \dfrac{6.6 \times 10^{-7} \times 0.48}{14.4} = 2.2 \times 10^{-8}$ m² **C1** $d = \sqrt{\dfrac{4A}{\pi}}$ **C1** $= 1.7 \times 10^{-4}$ m. **A1**

(c) $R = \dfrac{2.2}{0.52} = 4.2$ Ω. **A1** At the lower p.d. the current is smaller, so less power is dissipated and the filament is much cooler. **B1** The resistance of the metal is lower at a lower temperature, so the resistance is less than 14.4 Ω. **B1**

(d) A curve through the origin, straight near the origin with its gradient decreasing as V increases (bending towards the V axis), **M1** with the same shape in the third quadrant for negative p.d.s. **A1**

Common mistakes

- **Defining p.d. loosely.** The March 2023 report says "energy transferred **by** unit charge" is not enough (it isn't a ratio), and "current × resistance" is a formula, not a definition. Write "energy transferred **per** unit charge".
- **Defining resistance when asked for the ohm.** The June 2021 report notes this. The ohm is one volt **per ampere**.
- **Taking resistance from the gradient.** The March 2023 report describes candidates who thought a diode's resistance was constant where the graph was straight. Resistance is $\frac{V}{I}$ at the point.

- **"Linear" means "obeys Ohm's law".** The June 2022 report warns that a straight line is proportional only if it goes through the origin; a diode above its threshold is not ohmic.
- **Lamp explanations without temperature.** The June 2022, November 2022 and June 2023 reports all describe answers that did not link the change in resistance to the change in the filament's **temperature**; the June 2023 report adds that some thought resistance was inversely proportional to current. Current up → temperature up → resistance up.
- **Total number instead of number density.** The November 2021, June 2023 and March 2025 reports all describe candidates putting the total number of free electrons in the wire into $I = Anvq$. n is per unit volume: divide by AL first.
- **Wrong q in $I = Anvq$.** The November 2021 and March 2025 reports mention candidates substituting the total charge that had flowed. q is the charge of **one** carrier, 1.60×10^{-19} C.
- **mm² and mm.** The March 2022 report mentions errors converting an area from mm² to m². 0.36 mm² is 0.36×10^{-6} m², not 0.36×10^{-3} m². A diameter of 0.46 mm is a radius of 0.23×10^{-3} m.
- **Stretching a wire and changing only the length.** The June 2022 report describes, for two questions, candidates who spotted the change in length but not the fall in area. At constant volume $R \propto L^2$: twice the length, four times the resistance.
- **"Lower resistance means less power."** The March 2022 report calls this a common misconception for a thicker wire across the same supply: the current rises, and $P = \frac{V^2}{R}$ increases. The November 2022 report describes the opposite slip for two resistors carrying the **same** current, where $P = I^2R$ puts more power in the **larger** resistance.
- **Power and energy mixed up.** The November 2022 report notes candidates giving energy in joules when power was asked for. Power is energy per second.
- **Drift speed in a changing cross-section.** The June 2021 and March 2025 reports describe candidates who expected the drift speed to fall as the wire gets thinner. Same current, smaller area: **larger** drift speed.
- **Length changes ρ or n.** The November 2021 report calls this a common misconception. They are properties of the metal; a longer wire changes R and so the current.
- **LDR and thermistor the wrong way round.** The June 2023 report describes this. Both **fall** in resistance: the LDR with more light, the thermistor with higher temperature.
- **Rounding too early.** The November 2021 report describes an efficiency spoilt by rounding two powers before dividing. Keep full values until the last line.

How to get the marks

- **Definitions** (key words):
  - Potential difference: energy transferred **per unit charge**.
  - Resistance: **potential difference ÷ current**.
  - The ohm: **volt per ampere**. The coulomb: **ampere second**. The volt: **joule per coulomb**.
  - Ohm's law: current **directly proportional** to p.d. **at constant temperature**.
  - Number density: number of (free) charge carriers **per unit volume**.

- **Calculations (C1 then A1)**: write the symbol equation ($R = \frac{\rho L}{A}$, $I = Anvq$, $P = VI$), substitute in SI units, then give the answer with a unit. The substitution often earns a mark even if the arithmetic slips.
- **"Show that"**: show every substitution and give the answer to one more significant figure than the value printed. Don't use the printed value to work backwards.
- **"State and explain"**: the effect **and** a reason that names the quantity. "Resistance of the LDR decreases, so the current increases, so the p.d. across the fixed resistor increases." If the question says "by reference to the current", the current must appear in your answer.
- **Name the resistance** you mean: the LDR's, the thermistor's, the wire's or the whole circuit's.
- **Ratios**: write both expressions and divide; say which quantities are the same ("same current, same n and q, so $v \propto \frac{1}{A}$").
- **Sketches**: lamp through the origin with decreasing gradient, the same shape in the third quadrant if the axes allow; diode flat along the V axis in reverse, rising steeply after about 0.6 V; straight lines with a ruler.
- **Circuit diagrams**: correct symbols, a closed loop, ammeter in series and voltmeter in parallel with the component.
- **Multiple choice**: work it out first. Wrong options often square the diameter ratio the wrong way, use the total number of electrons for n, forget the time in seconds, or treat the gradient as the resistance.

Quick check

1. Which of these could be the charge on an oil drop: 2.08×10^{-18} C or 4.4×10^{-19} C? Explain.
2. A heater is rated 110 V, 1.5 kW. Calculate the current in it and its resistance when working normally, and the charge that passes through it in 15 minutes.
3. Wire Y is made of the same metal as wire X. It is three times as long and has three times the diameter. Wire X has resistance R. Find the resistance of wire Y in terms of R.
4. Two wires of the same metal, of diameters 0.55 mm and 0.77 mm, are connected in series. Calculate the ratio $\dfrac{\text{drift speed in the thinner wire}}{\text{drift speed in the thicker wire}}$.
5. A thermistor is connected across a battery of constant p.d. and negligible internal resistance. The thermistor is warmed. State and explain what happens to the power dissipated in it.

Answers

1. $\dfrac{2.08 \times 10^{-18}}{1.60 \times 10^{-19}} = 13$, a whole number, so 2.08×10^{-18} C is possible. $\dfrac{4.4 \times 10^{-19}}{1.60 \times 10^{-19}} = 2.75$, not a whole number, so 4.4×10^{-19} C is not possible.
2. $I = \dfrac{P}{V} = \dfrac{1500}{110} = 13.6$ A. $R = \dfrac{V^2}{P} = \dfrac{110^2}{1500} = 8.07\ \Omega$. $Q = It = 13.64 \times 15 \times 60 = 1.2 \times 10^4$ C.
3. $R_Y = \dfrac{\rho(3L)}{9A} = \dfrac{1}{3}R$ (three times the diameter is nine times the area).
4. Same current, same metal, so $v \propto \dfrac{1}{d^2}$: $\left(\dfrac{0.77}{0.55}\right)^2 = 1.96$.
5. Its temperature rises, so its resistance decreases. The p.d. across it stays the same, so $P = \dfrac{V^2}{R}$ **increases** (the current $\frac{V}{R}$ increases too).

Past questions to try

- **9702/22/M/J/23 Q6**: why a lamp's resistance changes, then algebra for current, drift speed and the time for an electron to cross a wire.
- **9702/22/O/N/23 Q6**: resistivity from resistance per unit length, electrons through an LDR, and a power ratio.
- **9702/12/M/J/22 Q34**: the resistance of a shorter, thicker wire of the same metal.
- **9702/22/F/M/22 Q6**: current, electrons and resistance from power, a wire's length from its resistivity, and a thicker wire across the same supply.