Cambridge IGCSE · Physics 0625 · Notes

Electrical quantities

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Read first: **Energy, work and power**

What you need to know

This topic covers charge, current, voltage, resistance, and electrical energy and power. The parts marked **Extended only** are tested on Papers 2 and 4 only. By the end of it you should be able to:

Electric charge

1. **State that there are positive and negative charges**, and that like charges repel while unlike charges (positive and negative) attract.
2. **Describe simple experiments** that produce charges by rubbing (friction) and that detect charges.
3. **Explain that charging a solid by friction moves only negative charge (electrons)** from one object to the other.
4. **Describe an experiment to tell conductors from insulators**, and use a simple model of free electrons to explain the difference, with typical examples.
5. **Extended only:** state that charge is measured in **coulombs** (C).
6. **Extended only:** describe an **electric field** as a region in which an electric charge experiences a force, and state that its direction at a point is the direction of the force on a **positive** charge there.
7. **Extended only:** draw the field patterns, with directions, around a point charge, around a charged conducting sphere, and between two oppositely charged parallel plates.

Electric current

8. **Know that current is related to the flow of charge**, and that in metals it is the movement of **free electrons**.
9. **Describe how to use ammeters** (analogue and digital) with different ranges.
10. **Know the difference between direct current (d.c.) and alternating current (a.c.).**
11. **Extended only:** define current as the charge passing a point per unit time, and use $I = \dfrac{Q}{t}$.
12. **Extended only:** state that conventional current goes from positive to negative, and free electrons flow from negative to positive.

Electromotive force and potential difference

13. **Define e.m.f.** as the electrical work done by a source in moving a unit charge around a complete circuit, and **p.d.** as the work done by a unit charge passing through a component; both are measured in **volts** (V).
14. **Describe how to use voltmeters** (analogue and digital) with different ranges.
15. **Extended only:** use $E = \frac{W}{Q}$ for e.m.f. and $V = \frac{W}{Q}$ for p.d.

Resistance

16. **Use** $R = \frac{V}{I}$, and describe an experiment to find a resistance with a voltmeter and an ammeter.
17. **State, in words, how a metal wire's resistance depends on its length and its cross-sectional area.**
18. **Extended only:** sketch and explain the current–voltage graphs of a fixed resistor, a filament lamp and a diode.
19. **Extended only:** use the facts that resistance is **directly proportional to length** and **inversely proportional to cross-sectional area**.

Electrical energy and power

20. **Understand that circuits transfer energy** from a source (a cell or the mains) to the components and then to the surroundings.
21. **Use** $P = IV$ **and** $E = IVt$**.**
22. **Define the kilowatt-hour (kW h)** and work out the cost of using appliances.

Adding up e.m.f.s and resistances in series and parallel belongs to the next topic, electric circuits; this note shows only the few simple facts that questions here need.

Understand it

Charge: two kinds, and the forces between them

Everything is made of atoms, which contain positive **protons** in the nucleus and negative **electrons** around it. A neutral object has equal amounts of positive and negative charge. An object becomes **charged** when it gains or loses electrons:

- **gains electrons: negatively charged**;
- **loses electrons: positively charged**.

Protons are held in the nucleus and never move in charging. Only electrons move.

Charged objects push or pull on each other:

- **like charges repel** (positive and positive, or negative and negative);
- **unlike charges attract** (positive and negative).

Extended only: charge Q is measured in **coulombs** (C). One electron carries a tiny charge, about 1.6×10^{-19} C, so a coulomb is the charge of a huge number of electrons.

Charging by friction

Rub a plastic rod with a dry cloth, and the rubbing moves electrons from one surface to the other. Which way they go depends on the two materials: polythene gains electrons from wool and becomes negative, while acetate or glass loses electrons to the cloth and becomes positive.

- The rod and the cloth end up with **equal and opposite** charges: the electrons one loses, the other gains.
- It works with **insulators** (plastic, glass, rubber), because the charge stays where it was rubbed. A metal rod held in the hand does not stay charged: electrons flow through the metal and your body to earth.

Experiments. To **produce** charge: rub a polythene or acetate strip with a dry cloth. To **detect** it:

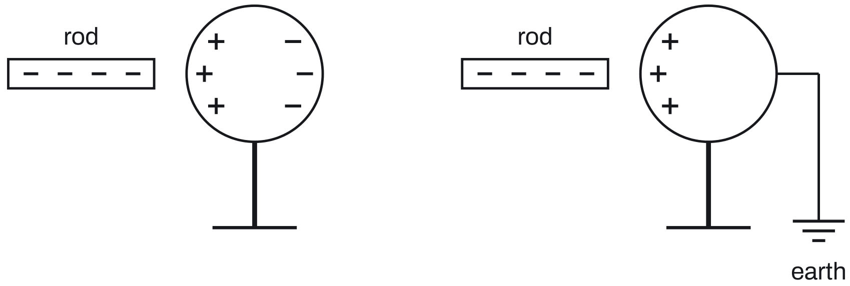
- hang the charged strip on a thread from a stand (in a paper stirrup) and bring another charged strip near: **repulsion** means both have the same kind of charge;
- bring the strip near small pieces of paper, or a thin stream of water: they are attracted to it.

Only repulsion proves that an object is charged. Attraction happens between unlike charges, and also between a charged object and an **uncharged** one, as the next section explains.

Charging by induction, and earthing

Bring a negatively charged rod near a **neutral metal sphere** on an insulating stand, without touching it. The metal's free electrons are repelled by the rod and move to the far side. The near side is left short of electrons, so it is **positive**; the far side is **negative**. The sphere is still neutral overall, but the positive side is closer to the rod, so the attraction is stronger than the repulsion: **the sphere is attracted to the rod**. That is why a charged object attracts small uncharged pieces of paper. (With a positive rod, electrons are pulled to the near side, which becomes negative.)

Now connect the far side to **earth** with a wire while the rod is still there. The electrons repelled by the rod flow **down the wire to earth**. The near side stays positive, held there by the rod's attraction, and the far side has no charge left.



(a) isolated sphere
(b) far side earthed

If you then disconnect the earth wire **before** taking the rod away, the sphere keeps its missing electrons and is left **positively charged**: charged by **induction**, with the opposite sign to the rod. The same idea works in reverse: a positive rod pulls electrons **up from earth**, leaving a negative object once the earth is removed and the rod taken away.

A person charged by walking on a carpet feels a small shock when touching a metal tap: electrons flow between the person and earth through the tap.

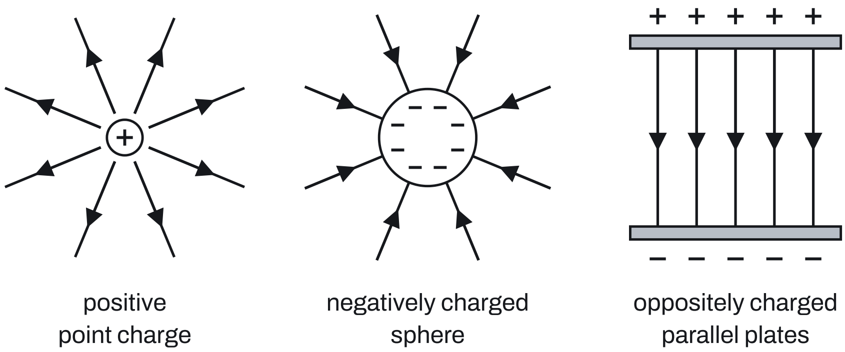
Conductors and insulators

- **Conductors** let charge flow through them easily. Metals (copper, silver, gold, aluminium, iron) are good conductors because some electrons are **free**: they are not tied to one atom and can drift through the whole metal.
- **Insulators** do not let charge flow. In plastic, rubber, glass, wood, dry air and nylon, **all electrons are held tightly** in their atoms, so there are no free electrons to carry charge.

Experiment to tell them apart: make a circuit with a cell, a lamp (or an ammeter) and two crocodile clips with a gap between them. Clip each material across the gap in turn. If the lamp lights (or the ammeter shows a current), the material is a **conductor**; if not, it is an **insulator**. Keep everything else the same.

Extended only: electric fields

A charged object has an **electric field** around it: **a region in which an electric charge experiences a force**. The **direction** of the field at a point is the direction of the force on a **small positive charge** placed there. So field lines point **away from positive** charges and **towards negative** ones. A negative charge in the field feels a force **opposite** to the field lines.



- **Point charge**: straight lines going out radially, like spokes, **outwards** for a positive charge and **inwards** for a negative one. The lines spread out, so the field is weaker further away.
- **Charged conducting sphere**: the same radial pattern, but the lines start at the sphere's **surface**, at right angles to it. Outside, it looks just like a point charge at the centre.
- **Two oppositely charged parallel plates**: straight, parallel, **evenly spaced** lines from the **positive plate to the negative plate**, at right angles to the plates. The field is the same everywhere between the plates (a uniform field). (You won't be asked about the curved lines at the ends.)

A positive charge between the plates is pushed towards the negative plate; an electron is pushed towards the positive plate, and speeds up that way.

Electric current

An **electric current** is a **flow of charge**. In a metal wire the charges that move are the **free electrons**: a cell pushes them along the wire, all drifting the same way. The metal atoms (and their protons) stay where they are.

Extended only: current is **the charge passing a point per unit time**:

$$I = \frac{Q}{t}, \qquad Q = It$$

with I in **amperes** (A), Q in coulombs (C) and t in **seconds** (s). A current of 1 A means 1 C passes each second. For example, 0.35 A for 4.0 minutes carries $Q = 0.35 \times 240 = 84$ C.

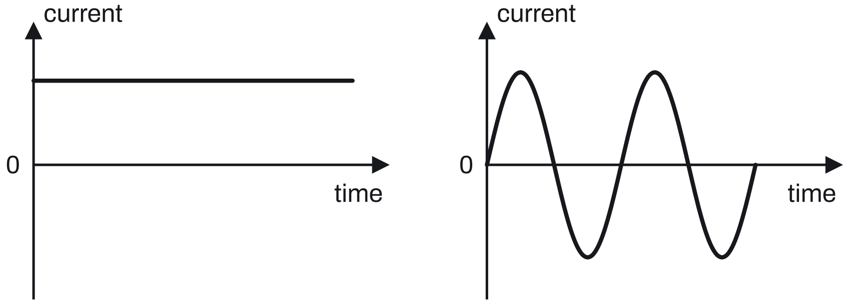
Extended only: conventional current. Before electrons were discovered, current was taken to flow from the **positive** terminal round the circuit to the **negative** terminal. We still draw it that way: this is **conventional current**. The electrons really flow the other way, from **negative to positive**. In circuit diagrams the cell's longer line is the positive terminal.

Ammeters measure current:

- connect the ammeter **in series** (in the loop), so the current you want passes **through** it;
- choose a range bigger than the largest current you expect but not much bigger, so the reading is precise (for about 0.7 A, use a 0–1 A meter, not 0–0.5 A or 0–10 A);
- **analogue** meters have a needle and a scale: read it at eye level, straight on, and check it reads zero before you start. **Digital** meters show the number; check the unit (A or mA).

Direct and alternating current

- **Direct current (d.c.)** flows in **one direction only**, like the current from a cell or battery. Its size may change, but it never reverses.
- **Alternating current (a.c.) keeps reversing direction**, many times a second. The mains supply is a.c.



d.c.: one direction only
a.c.: keeps reversing

On a graph of current (or voltage) against time, **d.c. stays on one side of the time axis**; **a.c. crosses it**, positive then negative.

Electromotive force and potential difference

A cell or battery **gives energy** to the charge it pushes round a circuit; the components **take energy** from the charge as it passes through them. Two quantities measure these, **both in volts** (V):

- **Electromotive force (e.m.f.)**: the electrical work done **by a source** in moving a unit charge (one coulomb) **around a complete circuit**. Despite its name, e.m.f. is not a force.
- **Potential difference (p.d.)**: the work done **by a unit charge passing through a component** (the energy the charge gives to the component).

Extended only: as equations, with W the work done (energy transferred) in joules:

$$E = \frac{W}{Q} \qquad V = \frac{W}{Q}$$

So 1 V $= 1$ J/C: a 1.5 V cell gives 1.5 J to every coulomb it drives round the circuit. A lamp with 6.0 V across it takes 6.0 J from each coulomb that passes through it.

The **similarity**: both are energy per unit charge, in volts. The **difference**: e.m.f. is energy **given to** the charge by the **source**, round the whole circuit; p.d. is energy **given out** by the charge **in one component**.

Voltmeters measure e.m.f. and p.d.: connect them **in parallel**, across the component (one lead on each side of it), never in the loop. As with ammeters, choose a suitable range, read an analogue scale straight on and check for a zero error.

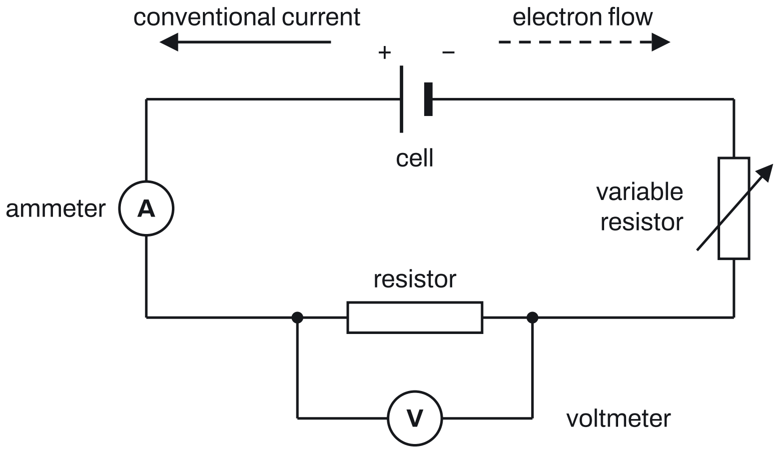
Resistance

Resistance is how hard it is for a current to pass through a component. It is defined by

$$R = \frac{V}{I}$$

with R in **ohms** (Ω). A larger resistance means a smaller current for the same p.d. For example, a lamp with 7.2 V across it and 0.45 A through it has $R = \frac{7.2}{0.45} = 16\ \Omega$. Rearranged, $V = IR$ and $I = \frac{V}{R}$. Watch the prefixes: 1 mA $= 0.001$ A and 1 k$\Omega = 1000\ \Omega$.

Experiment to find a resistance. Connect the component in series with a cell (or power supply) and an ammeter, with a voltmeter across the component. A variable resistor in series lets you change the current.



1. Read the current I on the ammeter and the p.d. V on the voltmeter.
2. Calculate $R = V \div I$.
3. Change the variable resistor to get several pairs of readings, work out R each time and take the average (or plot V against I).

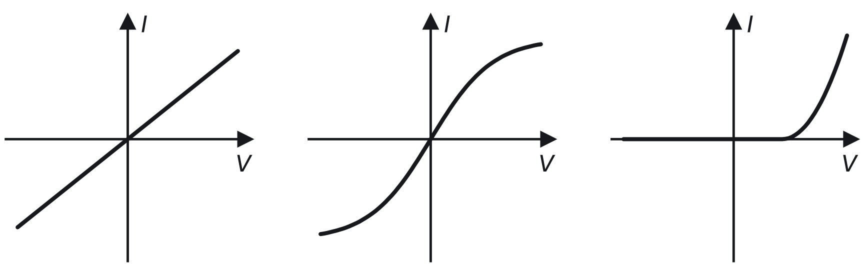
Length and thickness of a wire. A metal wire has **more resistance if it is longer** (the electrons have further to go) and **less resistance if it is thicker** (a larger cross-sectional area gives more room for the current).

Extended only: exactly,

$$R \propto L \qquad R \propto \frac{1}{A}$$

so doubling the length doubles R, and doubling the cross-sectional area halves R. For a round wire, $A = \pi r^2 = \frac{\pi d^2}{4}$, so the area goes with the **diameter squared**: **double the diameter gives four times the area, and a quarter of the resistance**.

Extended only: current–voltage graphs



fixed resistor filament lamp diode

- **Fixed resistor** (or a metal wire at constant temperature): a **straight line through the origin**. I is directly proportional to V, so $\frac{V}{I}$, the resistance, is **constant**. (This is Ohm's law, and it applies only where the line is straight.)

- **Filament lamp**: a curve that gets **less steep** as the voltage rises. As the current increases, the filament gets **hotter**; its metal atoms vibrate more, so the electrons collide with them more often, and the **resistance increases**. Each extra volt adds less current.
- **Diode**: almost **no current in one direction** (the reverse direction): its resistance is very high. In the forward direction, once the p.d. passes a small value, the current rises steeply: the resistance is low. A diode lets current through **one way only**.

To find the resistance at a point on a graph, read off V and I there and divide; don't use the gradient.

Electrical energy and power

A circuit is an energy transfer. The **source** (a cell's chemical store, or the mains supply from a power station) transfers energy **electrically** to the components; they transfer it to the **surroundings**: a heater warms the room, a lamp gives out light and heat, a motor does work, and a loudspeaker makes sound. Energy is not "used up": it ends up spread out in the surroundings, mostly as thermal energy.

Power is the rate of energy transfer, in **watts** (W), and **energy** is power × time:

$$P = IV \qquad E = IVt$$

with E in joules and t in **seconds**. A heater taking 3.5 A from a 230 V supply has power $3.5 \times 230 = 805$ W; in 20 minutes it transfers $805 \times 1200 = 966\,000$ J.

Combining with R. Substituting $V = IR$ into $P = IV$ gives $P = I^2R$, and substituting $I = \frac{V}{R}$ gives $P = \frac{V^2}{R}$. You can always do it in two steps instead: find the missing quantity with $R = \frac{V}{I}$ first.

The kilowatt-hour

The joule is too small for household bills, so electricity companies use the **kilowatt-hour** (kW h): **the energy transferred by a 1 kW appliance in 1 hour**.

$$\text{energy (kW h)} = \text{power (kW)} \times \text{time (h)} \qquad \text{cost} = \text{energy (kW h)} \times \text{price per kW h}$$

1 kW h $= 1000\text{ W} \times 3600\text{ s} = 3\,600\,000$ J $= 3.6$ MJ. A 1.8 kW heater on for 5 hours uses 9.0 kW h; at 22 cents per kW h that costs 198 cents. You can also read the energy from the difference between two electricity meter readings.

Key facts and formulas

The 0625 papers have no formula sheet, so every equation here must be learned.

Formula	Status
Like charges repel; unlike charges attract	Learn it

Formula	Status
Charging by friction: only electrons move; gaining electrons makes an object negative, losing them makes it positive	Learn it
Conductors have free electrons; insulators do not	Learn it
Extended only: electric field: a region in which an electric charge experiences a force; direction = direction of the force on a positive charge	Learn it
Extended only: $I = \frac{Q}{t}$ (charge Q in coulombs)	Learn it
Extended only: conventional current: $+$ to $-$; electrons: $-$ to $+$	Learn it
e.m.f.: electrical work done by a source in moving unit charge around a complete circuit	Learn it
p.d.: work done by unit charge passing through a component	Learn it
Extended only: $E = \frac{W}{Q}$ and $V = \frac{W}{Q}$ (1 V $= 1$ J/C)	Learn it
$R = \frac{V}{I}$	Learn it
Longer wire: more resistance; thicker wire: less resistance	Learn it
Extended only: $R \propto L$ and $R \propto \frac{1}{A}$; $A \propto d^2$ for a round wire	Learn it
$P = IV$	Learn it
$E = IVt$	Learn it
$P = I^2R$ and $P = \frac{V^2}{R}$ (from $P = IV$ and $V = IR$)	Learn it
Energy (kW h) $=$ power (kW) $\times$ time (h); 1 kW h $= 3.6 \times 10^6$ J	Learn it
Ammeter in series; voltmeter in parallel	Learn it

Units: current in A, charge in C, e.m.f. and p.d. in V, resistance in Ω, power in W, energy in J (or kW h), time in s (or h for kW h).

How to do it

We have tagged 288 questions for this topic across Papers 1–4, 2021–2025 (251 different ones: some multiple-choice questions appear on more than one paper). 53 of the 288 mix two or more types, so the counts add up to more than 288.

Question type	Questions
Calculate resistance, p.d. or current with $R = V/I$	41
Calculate energy, e.m.f. or p.d. with $E = IVt$ or $W = QV$	36
Explain charging by friction	35
Compare wire resistance from length and cross-sectional area	35
Define or recognise e.m.f., p.d. and electrical units	30
Place meters and choose the circuit to measure resistance	26
Current as a flow of charge; conventional current and electron flow	25
Calculate power or current with $P = IV$	22
Induced charge and earthing	20
Predict attraction or repulsion, or deduce the sign of a charge	18
Extended: electric fields, definition and patterns	17
Extended: charge, current and time with $Q = It$	15
Distinguish a.c. from d.c.	13
Extended: current–voltage graphs	12
Identify conductors and insulators	11
Energy in kW h and its cost	8
Cells and resistors in series and parallel	7

1. Calculate resistance, p.d. or current with R = V/I (41 questions)

1. **Write the equation**: $R = \dfrac{V}{I}$ (or $V = IR$, $I = \dfrac{V}{R}$).
2. **Convert units**: mA to A (divide by 1000), kΩ to Ω (multiply by 1000).
3. **Substitute and calculate**, then give the answer with its unit (Ω, V or A), to 2 or 3 significant figures.

For example, 36 V across a resistor with 1.5 mA in it: $R = \frac{36}{0.0015} = 24\,000\ \Omega$ (24 kΩ).

Variations you will meet:

- **Meter readings on a diagram**: the voltmeter gives V (across the component), the ammeter gives I. Core Paper 3 almost always has this: "calculate the resistance of the lamp".

- **"Which equation?"** in multiple choice: $R = \frac{V}{I}$, not $V \times I$ or $\frac{I}{V}$.
- **Qualitative**: for the same p.d., more resistance means less current; when a variable resistor's resistance goes up, the current goes down.
- **Extended only: find the p.d. across one part first.** In a series circuit, the p.d.s across the parts add up to the supply's e.m.f.; subtract the p.d. across the other parts, then use $R = \frac{V}{I}$.
- **Extended only: from a graph.** Read one pair of V and I from the line and divide.
- **Choosing an ammeter range**: work out $I = \frac{V}{R}$ first, then pick the smallest range that is bigger than it.

2. Calculate energy, e.m.f. or p.d. with E = IVt or W = QV (36 questions)

1. **Write the equation**: $E = IVt$, or $E = Pt$ if you know the power.
2. **Convert the time to seconds** (minutes × 60; hours × 3600) and mA to A.
3. **Substitute, calculate, and give the unit J.**

For example, an indicator light on a 9.0 V supply with 15 mA for 10 minutes: $E = 0.015 \times 9.0 \times 600 = 81$ J.

Variations you will meet:

- **"Which quantity does IVt (or IV) give?"** IVt is the energy transferred; IV is the power.
- **Rearranging**: $t = \frac{E}{IV}$, or $t = \frac{E}{P}$.
- **Extended only: e.m.f. or p.d. from energy and charge.** $E = \frac{W}{Q}$ for a source, $V = \frac{W}{Q}$ for a component; the reverse, $W = QV$. For example, a battery moving 8.0 C round a circuit and transferring 36 J has e.m.f. $\frac{36}{8.0} = 4.5$ V.
- **Extended only: charge first.** If you're given I and t but need Q, use $Q = It$, then $E = \frac{W}{Q}$. For example, a battery transferring 60 J while it drives 0.80 A for 25 s moves $Q = 20$ C, so its e.m.f. is $\frac{60}{20} = 3.0$ V.
- **Extended only: parallel branches.** Only part of the total charge passes through each branch. If 48 C leaves the battery and splits equally between four identical lamps in parallel, 12 C goes through each lamp; 30 J of work in one lamp means its p.d. is $\frac{30}{12} = 2.5$ V.
- **Extended only: with efficiency.** Useful energy $=$ efficiency × electrical energy input.

3. Explain charging by friction (35 questions)

1. **Only electrons move.** Never protons, neutrons or "positive charges".
2. **Say which way**: the object that becomes **negative gained** electrons; the one that becomes **positive lost** electrons.
3. **The other object** gets the equal and **opposite** charge.

Variations you will meet:

- **"Explain, in terms of particles, how the rod becomes positive"**: "electrons move **from the rod to the cloth**, so the rod has fewer electrons than protons."
- **Multiple choice**: "the rod gains electrons" (negative) and "the rod loses electrons" (positive) are the only possible right answers. "Gains protons" and "loses protons" are always wrong.

- **Which rods can be charged by rubbing?** Insulators (plastic, glass). A metal rod held in the hand loses its charge to earth.
- **Describe an experiment to show a charge is produced**: rub a strip with a dry cloth, then show it repels another strip charged the same way, or attracts small bits of paper.

4. Compare wire resistance from length and cross-sectional area (35 questions)

1. **Core**: longer, more resistance; thicker (larger area or diameter), less resistance.
2. **Extended**: write $R \propto \dfrac{L}{A}$ and work out the **factor** each change gives.
3. **Area from diameter**: area $\propto d^2$, so a diameter $2\times$ gives area $4\times$ and resistance $\frac{1}{4}$.

For example, a wire of resistance $12\ \Omega$ is replaced by one of the same metal with three times the length and twice the diameter: $R = 12 \times 3 \div 4 = 9.0\ \Omega$.

Variations you will meet:

- **Which wire has the smallest resistance?** For each, work out $\frac{L}{d^2}$ (or $\frac{L}{A}$); the smallest value wins.
- **Which two wires have the same resistance?** The same $\frac{L}{d^2}$ (or $\frac{L}{A}$): a longer wire must have its area bigger by the same factor, so its diameter is bigger by the square root of that factor.
- **Same volume, reshaped** (putty or a stretched wire): if the wire is stretched to three times its length, then, since volume $= A \times L$, its area is $\frac{1}{3}$; so R becomes $3 \times 3 = 9$ times the original. Thicker and shorter works the other way: the resistance falls by both factors.
- **A sliding contact on a resistance wire**: moving the contact to use a longer piece of wire increases the resistance, so the current falls and a lamp in the circuit gets dimmer.
- **"Which statement is correct?"**: resistance is directly proportional to length and **inversely** proportional to cross-sectional area.

5. Define or recognise e.m.f., p.d. and electrical units (30 questions)

1. **e.m.f.**: the **electrical work done by a source** in moving **unit charge around a complete circuit**.
2. **p.d.**: the **work done by unit charge passing through a component**.
3. **Units**: both in **volts** (V $=$ J/C); current in amperes, charge in coulombs, resistance in ohms, power in watts, energy in joules.

Variations you will meet:

- **"What does e.m.f. stand for?"** Electromotive force.
- **Multiple-choice definitions**: e.m.f. is **electrical** work, not mechanical work, and round the **complete circuit**, not through one component.
- **Extended only: similarity and difference.** Both are work done (energy) per unit charge. e.m.f. is for a source, round the whole circuit; p.d. is for one component.
- **Extended only: "State the equation which defines e.m.f."**: $E = \frac{W}{Q}$.

- **Extended only: why one resistor heats more**: for the same charge, the larger p.d. means more work done per coulomb passing through it.
- **Which label on a battery is its e.m.f.?** The value in volts.

6. Place meters and choose the circuit to measure resistance (26 questions)

1. **Ammeter in series** with the component; **voltmeter in parallel** across it.
2. **Measure V and I**, then $R = \frac{V}{I}$.
3. **Draw the right symbols**: a circle with A or V inside.

Variations you will meet:

- **Pick the correct circuit from four**: look for the voltmeter across the component only, and the ammeter in the main loop.
- **A wrongly wired circuit**: if the ammeter and voltmeter have been swapped, the fix is to swap them back.
- **"Name the instrument"**: ammeter for current (the flow of charge), voltmeter for p.d.
- **Add a voltmeter to the diagram**: draw it on its own two wires joining the two ends of the component, not in the loop.
- **Checking an appliance's rating** (such as "230 V, 5 A"): ammeter in series with it, voltmeter across it.

7. Current as a flow of charge; conventional current and electron flow (25 questions)

1. **Current is a flow of charge.** In metals, **free electrons** move along the wire.
2. **Extended only:** conventional current goes from the **positive** terminal round the circuit to the **negative** terminal; electrons go from **negative to positive**.

Variations you will meet:

- **"Which particles move in a copper wire?"** Electrons. Not atoms, ions, protons or nuclei.
- **Draw arrows on a circuit** (Extended): conventional current leaving the long (positive) plate of the cell, electron flow leaving the short (negative) plate, as in the resistance circuit diagram above. Label each arrow.
- **Reversing the battery** reverses the direction of both, but a lamp is equally bright.
- **Current is the same all round a series loop.** It is not used up: the charge flows back into the cell.
- **Extended only: "Define current"**: the charge passing a point per unit time; $I = \frac{Q}{t}$.

8. Calculate power or current with P = IV (22 questions)

1. **Write $P = IV$**, rearranged if needed: $I = \frac{P}{V}$.
2. **Convert**: kW to W (× 1000), mA to A (÷ 1000).
3. **Substitute and give the unit**: W for power, A for current.

For example, a microwave oven labelled 120 V, 960 W takes $I = \frac{960}{120} = 8.0$ A.

Variations you will meet:

- **Which device has the greatest power?** Work out $I \times V$ for each row.
- **"Show that the current is about …"**: write the equation, the substitution, and the answer to one more significant figure than the value given.
- **Extended only: with resistance.** $P = I^2R$ gives $I = \sqrt{\frac{P}{R}}$; $P = \frac{V^2}{R}$ gives V or R. Or find the missing V or I with $R = \frac{V}{I}$ first.
- **Units**: "state the unit of power": watt (W).

9. Induced charge and earthing (20 questions)

1. **Only electrons move**, in the metal object.
2. A **negative rod** repels electrons to the **far side**: near side **positive**, far side **negative**. A **positive rod** attracts electrons to the **near side**: near side **negative**, far side **positive**.
3. The object is still **neutral overall**, and it is **attracted** to the rod.
4. **Earthing**: electrons flow **to earth** (with a negative rod) or **from earth** (with a positive rod). The near side stays charged while the rod is there.

Variations you will meet:

- **Draw the charge distribution**: equal numbers of $+$ and $-$ signs on opposite sides of the isolated sphere; with the far side earthed, only the near side's charges.
- **Charge a plate by induction** (Extended): bring the charged rod near, connect the earth, **remove the earth first**, then remove the rod. The plate is left with the **opposite** charge to the rod.
- **Two touching spheres** separated while a rod is near: the one nearer the rod gets the opposite charge to the rod, the other the same charge.
- **A charged person touching an earthed metal object**: electrons flow between the person and earth until the person is neutral.
- **A charged sphere near a neutral one**: the neutral sphere's near side gets the opposite charge.

10. Predict attraction or repulsion, or deduce the sign of a charge (18 questions)

1. **Like charges repel, unlike charges attract.**
2. **Repulsion proves both objects are charged, with the same sign.**
3. **Attraction** means **either** opposite charges **or** one of the objects is uncharged (by induction).

Variations you will meet:

- **Two rods near a negative rod**: the one repelled is negative; the one attracted is positive or uncharged.
- **Balance readings**: a charged rod held above a charged rod on a balance. If the reading **goes up**, the lower rod is pushed down: **repulsion**, like charges. If it **goes down**: **attraction**.
- **Suspended spheres or balloons with the same charge** hang apart, pushed away from each other; draw the threads angled outwards.

- **Extended only: electrostatic paint spraying**: the paint drops are given the same charge, so they repel each other and spread out; the object is given (or earthed to get) the opposite charge, so they are attracted to it and cover it evenly, even round the back.
- **A small uncharged ball touches a charged rod, then flies away**: it is first attracted by induction; when it touches, it gains some of the rod's charge, so now they have the same charge and it is repelled.

11. Extended only: electric fields, definition and patterns (17 questions)

1. **Definition**: a region in which an electric **charge** experiences a **force**.
2. **Direction**: the direction of the force on a **positive** charge.
3. **Draw the patterns** as in the diagram: at least four lines, evenly spaced, with arrows.

Variations you will meet:

- **Negative point charge or sphere**: radial lines with arrows **pointing inwards**, touching the sphere at right angles.
- **Parallel plates**: straight, parallel, evenly spaced lines from $+$ to $-$, at right angles to the plates.
- **Force on a negative charge or an electron**: opposite to the field arrows. It **accelerates** in that direction (towards the positive plate).
- **Which field exerts a force on a stationary charge because of its charge?** Only an electric field. A magnetic field does not act on a charge that isn't moving, and gravity acts on its mass, not its charge.

12. Extended only: charge, current and time with Q = It (15 questions)

1. **Write** $Q = It$ (or $I = \frac{Q}{t}, t = \frac{Q}{I}$).
2. **Convert** minutes to seconds and mA to A.
3. **Give the unit**: C for charge.

For example, 0.15 A for 6.0 minutes: $Q = 0.15 \times 360 = 54$ C.

Variations you will meet:

- **Charging time**: a phone battery storing 9000 C charged at 1.2 A takes $t = \frac{9000}{1.2} = 7500$ s, about 2.1 hours.
- **Current from power first**: $I = \frac{P}{V}$, then $Q = It$.
- **Number of electrons**: divide the charge by the charge on one electron (given, 1.6×10^{-19} C). For 0.40 A, 0.40 C passes each second, so $\frac{0.40}{1.6 \times 10^{-19}} = 2.5 \times 10^{18}$ electrons pass each second.
- **Charge then energy**: $W = QV$.

13. Distinguish a.c. from d.c. (13 questions)

1. **d.c.**: one direction only (it may change in size).
2. **a.c.**: keeps reversing direction.

3. **On a graph against time**: d.c. never crosses the time axis; a.c. goes above and below it.

Variations you will meet:

- **"Describe what is meant by alternating current"**: a current that keeps changing direction (backwards and forwards).
- **A current that is steady, or that varies but never reverses**: both d.c.
- **Extended only: the time of one cycle** of a 50 Hz supply is $\frac{1}{50} = 0.02$ s (period $= \frac{1}{\text{frequency}}$).

14. Extended only: current–voltage graphs (12 questions)

1. **Know the three shapes**: straight line through the origin (resistor); curve getting less steep (filament lamp); zero one way, steep rise the other (diode).
2. **Explain the lamp**: more current, hotter filament, higher resistance, so the graph flattens.

Variations you will meet:

- **Identify a component from its graph**.
- **"How does the lamp's resistance change as the voltage increases?"** It increases (and the filament's temperature increases).
- **Where does Ohm's law apply?** Only on the straight section through the origin.
- **Components in series, from their graphs**: the current is the same in each, so read each component's p.d. at that current from its graph, then add them to get the supply voltage.
- **A metal wire's graph bending** at high voltages: the wire is heating up.

15. Identify conductors and insulators (11 questions)

1. **Conductors**: metals (copper, silver, gold, aluminium, iron, steel) and graphite.
2. **Insulators**: plastic, rubber, glass, wood, nylon, cotton, dry air.
3. **Why**: conductors have **free electrons** that can move through the material; in insulators the electrons are held in their atoms.

Variations you will meet:

- **"Why is copper used for cables?"** It contains free electrons, so it is a good conductor.
- **Describe an experiment** to test a material: the circuit with a gap, as in "Understand it".
- **Tables of materials**: electrical conductor and magnetic material are different properties: copper conducts but is not magnetic; iron is both.

16. Energy in kW h and its cost (8 questions)

1. **Power in kW** (W ÷ 1000) and **time in hours** (minutes ÷ 60).
2. **Energy** $=$ kW × h.
3. **Cost** $=$ kW h × price per kW h.

For example, a 600 W dehumidifier on for 90 minutes at 24 cents per kW h: $0.60 \times \frac{90}{60} = 0.90$ kW h, costing $0.90 \times 24 = 21.6$ cents.

Variations you will meet:

- **Meter readings**: energy used $=$ later reading $-$ earlier reading.
- **Energy per hour already given in kW h**: multiply by the number of hours, then the price.
- **Define the kW h**: the energy transferred by a 1 kW appliance in one hour (it is a unit of **energy**, not power).

17. Cells and resistors in series and parallel (7 questions)

These overlap with the next topic, electric circuits.

- **Cells in series** (all the same way round): their e.m.f.s **add**. Three 1.5 V cells make 4.5 V; a 9.0 V battery needs six of them.
- **Resistors in series**: resistances **add**.
- **Resistors in parallel**: the combined resistance is **less than the smallest** one. So adding a second lamp **in parallel** makes the current from the cell **bigger**, and adding it in series makes it smaller.

Worked examples

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

- **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.
- **C1** compensatory mark: earned for working even though the final answer is wrong.

Example 1

A student uses the circuit in the resistance diagram above to test a small heater in place of the fixed resistor. The ammeter reads 1.6 A and the voltmeter reads 20 V.

(a) Calculate the resistance of the heater. **[3]**

(b) Calculate the power of the heater. **[3]**

(c) Calculate the energy transferred by the heater in 7.5 minutes. **[3]**

(d) The student changes the variable resistor so that its resistance is larger. State what happens to the reading on the ammeter. **[1]**

(a) $R = \dfrac{V}{I}$ **C1**. $R = \dfrac{20}{1.6}$ **C1**. $R = 12.5\ \Omega$ (or $13\ \Omega$) **A1**.

(b) $P = IV$ **C1**. $P = 1.6 \times 20$ **C1**. $P = 32$ W **A1**.

(c) $E = IVt$ (or Pt) **C1**, with $t = 7.5 \times 60 = 450$ s. $E = 1.6 \times 20 \times 450$ **C1**. $E = 14\,400$ J **A1**.

(d) It decreases: the total resistance is larger, so the current is smaller **B1**.

Example 2

A dishwasher is labelled "230 V, 1.38 kW". One wash takes 90 minutes, with the dishwasher working at full power, and it is used for 20 washes in a month.

(a) Calculate the current in the dishwasher when it is working. **[3]**

(b) Calculate the energy used in the month, in kW h. **[2]**

(c) Electricity costs 15 cents per kW h. Calculate the cost of the 20 washes. **[2]**

(d) **Extended only.** Calculate the charge that passes through the dishwasher in one wash, and use it to show that each coulomb transfers 230 J. **[3]**

(a) $I = \dfrac{P}{V}$ **C1**. $I = \dfrac{1380}{230}$ (kW changed to W) **C1**. $I = 6.0$ A **A1**.

(b) Time $= 20 \times 1.5$ h $= 30$ h. Energy $= 1.38 \times 30$ **C1** $= 41.4$ kW h **A1**.

(c) Cost $= 41.4 \times 15$ **C1** $= 621$ cents **A1**.

(d) $t = 90 \times 60 = 5400$ s, so $Q = It = 6.0 \times 5400 = 32\,400$ C **B1**. Energy in one wash $= Pt = 1380 \times 5400 = 7\,452\,000$ J **C1**. Energy per coulomb $= \dfrac{7\,452\,000}{32\,400} = 230$ J, the same as the p.d. in volts **A1**.

Example 3 (Extended)

A resistance wire of length 0.90 m and diameter 0.60 mm has a resistance of $3.0\ \Omega$.

(a) A second wire is made of the same metal. It is 1.5 m long and has a diameter of 0.30 mm. Calculate its resistance. **[3]**

(b) The second wire is connected to a 5.0 V supply. Calculate the charge that passes through it in 3.0 minutes. **[3]**

(c) The charge on an electron is 1.6×10^{-19} C. Calculate the number of electrons that pass through the wire in this time. **[1]**

(d) Calculate the energy transferred in the wire in this time. **[2]**

(a) The length is $\frac{1.5}{0.90} = \frac{5}{3}$ times as long, so R is $\frac{5}{3}$ times larger **C1**. The diameter is halved, so the area is $\frac{1}{4}$ and R is 4 times larger **C1**. $R = 3.0 \times \frac{5}{3} \times 4 = 20\ \Omega$ **A1**.

(b) $I = \dfrac{V}{R} = \dfrac{5.0}{20} = 0.25$ A **C1**. $Q = It = 0.25 \times 180$ **C1** $= 45$ C **A1**.

(c) Number $= \dfrac{45}{1.6 \times 10^{-19}} = 2.8 \times 10^{20}$ **B1**.

(d) $W = QV$ **C1** $= 45 \times 5.0 = 225$ J **A1**. (Check: $E = IVt = 0.25 \times 5.0 \times 180 = 225$ J.)

Example 4 (Extended)

An empty metal can stands on an insulating mat. A polythene strip, charged negatively by rubbing, is held close to the left side of the can, without touching it.

(a) Describe and explain the charges on the can now. **[3]**

(b) With the strip still in place, a student touches the right side of the can with a finger, which earths it. She takes her finger away, and then the strip is taken away. State the final charge on the can and explain how it was produced. **[3]**

(c) Describe the electric field pattern around the can at the end, treating it as a charged sphere, including its direction. **[2]**

(a) Free electrons in the metal are repelled by the negative strip **B1**, so they move to the right (far) side, which becomes negative, and the left (near) side, left short of electrons, becomes positive **B1**; the can is still neutral overall **B1**.

(b) Positive **B1**. While the strip is there, electrons repelled by it flow **from the can through the student to earth B1**. Her finger is removed first, so electrons cannot flow back; the can is left short of electrons when the strip is taken away **B1**.

(c) Straight lines spreading out radially from the can, at right angles to its surface **B1**, with arrows pointing **outwards**, away from the can, because it is positive **B1**.

Common mistakes

- **Protons moving.** Examiners report every year that some candidates say an object became positive by "gaining protons" or that protons flow in a wire. Only electrons move, in charging and in metal wires.
- **Getting the direction of electron transfer backwards.** A positive rod **lost** electrons; a negative rod **gained** them. Say where the electrons went ("from the rod to the cloth").
- **Using attraction to prove a charge.** A charged rod also attracts neutral objects by induction. Only repulsion proves a charge.
- **Forgetting to convert minutes to seconds.** In $E = IVt$ and $Q = It$ the time must be in seconds; this is the most common reason for losing the final mark. For kW h, the time must be in **hours**.
- **Forgetting to convert mA, kW or kΩ.** 3.5 mA is 0.0035 A; 2.8 kW is 2800 W.
- **Mixing up the equations.** Using $P = \frac{V}{I}$ (confusing it with $R = \frac{V}{I}$), or $R = V \times I$. Write the equation in symbols first.
- **Area and diameter.** Doubling the diameter does **not** halve the resistance: the area goes up four times, so the resistance is a quarter.

- **Vague definitions.** "e.m.f. is the voltage" or "e.m.f. is a force" earns nothing. Say **electrical work done by a source** per **unit charge** round a **complete circuit**. For p.d., say **work done by unit charge passing through a component**.
- **Electric field definitions that are really about magnets**, or "the field of electricity". An electric field is a region where a **charge** feels a force. The direction uses a **positive** charge.
- **Field line drawings**: too few lines, lines that don't touch the sphere, lines that cross, or missing arrows. Draw at least four evenly spaced radial lines with arrows.
- **Meters in the wrong place.** A voltmeter drawn in series, or an ammeter across a component. Ammeter in series, voltmeter in parallel.
- **The filament lamp graph.** Many candidates draw it curving upwards (getting steeper). It gets **less steep**, because the resistance rises as the filament heats up.
- **The kW h as a unit of power.** It is a unit of **energy**: the energy a 1 kW appliance transfers in 1 hour.
- **No unit, or the wrong unit.** Give Ω, V, A, C, W or J with every answer, and don't write W for joules.

How to get the marks

- **Calculations (usually 3 marks)**: one for the equation (in symbols or words), one for the correct substitution, one for the answer. Write all three lines: a wrong final answer can still earn the first two.
- **Units**: convert before substituting, and write the unit with the answer. Some questions give a separate mark for the unit.
- **Significant figures**: give 2 or 3 significant figures (as in the data), not a long calculator display, and don't round a value you will use again until the end.
- **"Show that"**: write the equation and the substitution, and give the answer to more figures than the value shown.
- **"Explain, in terms of particles"** (charging): name **electrons**, say which way they moved, and what that does to each object.
- **"Define"**: learn the definitions word for word in meaning: e.m.f., p.d., electric field (with its direction), current ($I = Q/t$), the kilowatt-hour.
- **"Draw"**: use a ruler for field lines and circuit wires; add arrows to every field line; use the standard symbols (circle with A or V).
- **"Sketch" a graph**: label the axes, start at the origin, and get the shape right (straight, flattening, or zero then steep).
- **"State the difference"** (e.m.f. and p.d., a.c. and d.c., conductor and insulator): describe **both** sides.
- **Multiple choice with two columns** (for example conventional current and electron flow): check both parts of the row you choose.

Quick check

1. A plastic comb becomes negatively charged when it is pulled through dry hair. Explain, in terms of particles, how this happens, and state the charge on the hair.

2. A 6.0 V battery drives a current of 0.30 A through a lamp for 4.0 minutes. Calculate (a) the energy transferred by the lamp; (b) **Extended only:** the charge that passes through the lamp.
3. A dashboard lamp in a lorry is rated 24 V, 36 W. Calculate the current in the lamp and its resistance when it is working normally.
4. **Extended only.** Wire X has a resistance of $18\ \Omega$. Wire Y is made of the same metal, is 1.5 times as long as X and has three times its diameter. Calculate the resistance of Y.
5. **Extended only.** A battery drives 24 C of charge round a circuit containing a lamp and a resistor in series, and transfers 108 J of energy. The lamp takes 72 J of this energy. Calculate the e.m.f. of the battery and the p.d. across the lamp and across the resistor.

Answers

1. Electrons move **from the hair to the comb**. The comb has gained electrons, so it has more electrons than protons and is negative. The hair has lost the same number of electrons, so it is **positively** charged, by an equal amount.
2. (a) $E = IVt = 0.30 \times 6.0 \times 240 = 432$ J (about 430 J), with $t = 4.0 \times 60 = 240$ s. (b) $Q = It = 0.30 \times 240 = 72$ C.
3. $I = \frac{P}{V} = \frac{36}{24} = 1.5$ A. $R = \frac{V}{I} = \frac{24}{1.5} = 16\ \Omega$ (or $\frac{V^2}{P} = \frac{24^2}{36} = 16\ \Omega$).
4. 1.5 times the length makes R 1.5 times bigger; three times the diameter makes the area 9 times as big, so R is divided by 9. $R_Y = 18 \times 1.5 \div 9 = 3.0\ \Omega$.
5. e.m.f. $= \frac{W}{Q} = \frac{108}{24} = 4.5$ V. Lamp: $V = \frac{72}{24} = 3.0$ V. Resistor: the other $108 - 72 = 36$ J, so $V = \frac{36}{24} = 1.5$ V. (The p.d.s add up to the e.m.f.: $3.0 + 1.5 = 4.5$ V.)

Past questions to try

- **0625/31/O/N/25 Q8**: resistance, power with milliamperes, and the cost of energy in kW h (Core).
- **0625/43/M/J/25 Q8**: defining an electric field, drawing the field of a point charge, and charge and energy calculations (Extended).
- **0625/41/O/N/23 Q7**: charging a rod by friction, explained in terms of particles, and the forces that follow (Extended).
- **0625/43/M/J/23 Q6**: an electric heater: current from power and resistance, the effect of the wire's length, and the cost (Extended).