Electricity and magnetism

IGCSE Physics

Magnetism

A **magnet** 磁体 can attract some metals. Every magnet has two ends, called **poles** 磁极: a **north pole** 北极 (N pole) and a **south pole** 南极 (S pole).

Like poles repel; unlike poles attract

The rule for two poles is like the rule for charges:

- Poles that are the same (N and N, or S and S) **repel** 排斥 (push apart): this is **repulsion** 排斥力.
- Poles that are different (N and S) **attract** 吸引 (pull together): this is **attraction** 吸引力.

A magnet attracts a **magnetic material** 磁性材料, such as iron, steel, cobalt and nickel. Other materials (copper, plastic, wood) are non-magnetic and feel no force.

Induced magnetism

Put a piece of iron near or touching a magnet, and the iron becomes a magnet itself. This is **induced magnetism** 感应磁性. The end of the iron nearest the magnet gains the opposite pole, so the two then attract.

Temporary and permanent magnets

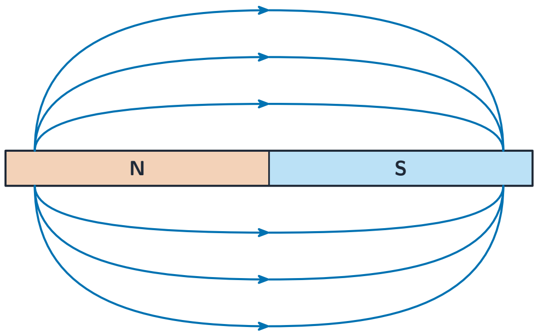
- **Soft iron** 软铁 is easy to **magnetise** 磁化 but loses its magnetism quickly. It is used for a **temporary magnet** 临时磁体.
- **Steel** 钢 is harder to magnetise but keeps its magnetism. It is used for a **permanent magnet** 永磁体.

So an **unmagnetised** 未磁化 piece of soft iron is the best core for an electromagnet, while steel is best for a bar magnet.

Magnetic fields

A **magnetic field** 磁场 is a **region** 区域 where a magnetic pole feels a force. We draw it with **magnetic field lines** 磁场线:

- The lines come *out of* the N pole and go *into* the S pole.
- The field direction at a point is the direction of the force on the N pole of a small test magnet placed there.
- Where the lines are close together the field is strong; where they are far apart the field is weak.



The field lines of a bar magnet come out of the N pole and go into the S pole

You can show the pattern by sprinkling **iron filings** 铁屑 on paper over a magnet, or by moving a small plotting **compass** 指南针 around it (the needle points along the field).

Iron filings line up along the field lines, showing the field pattern of a bar magnet

Uses of magnets

- **Permanent magnets**: fridge door catches, compass needles, loudspeakers.
- **Electromagnets** 电磁铁 (magnetic only while a current flows): cranes that lift scrap iron, electric bells, relays. An electromagnet can be switched on and off and made stronger, which a permanent magnet cannot.

Magnetic forces happen because the fields of the two magnets push and pull on each other.

Static electricity

There are two kinds of **electric charge** 电荷: **positive charge** 正电荷 and **negative charge** 负电荷. The rule is like the rule for poles — same charges repel, different charges attract.

Every hair picks up the same charge from the dome, and like charges repel — so the hairs push apart

Charging by friction

When you rub two different materials together, **electrons** 电子 (tiny negative particles) move from one to the other. This is **charging by friction** 摩擦起电.

- The material that gains electrons becomes negative.
- The material that loses electrons becomes positive.

Only the negative electrons move; the positive charge stays in place. For example, a plastic rod rubbed with a cloth becomes negative because electrons move from the cloth onto the rod, leaving the cloth positive.

Detecting a charge. A charged rod picks up small pieces of paper, and it bends a thin stream of water from a tap. Hang one charged rod from a thread and bring another charged rod near it: if the two have the same kind of charge, the hanging rod swings away. Repulsion is the only sure test for a charge, because attraction also happens with uncharged objects.

Conductors and insulators

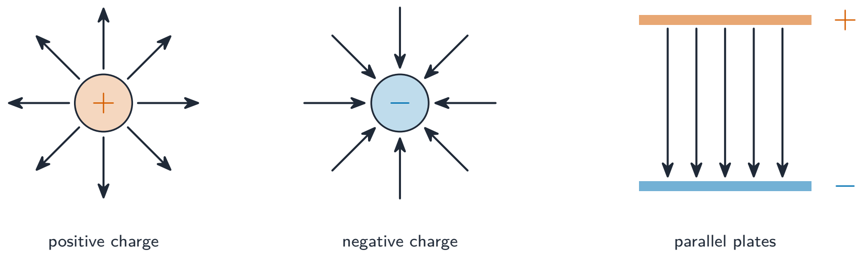
- A **conductor** 导体 (copper and other metals) lets charge flow through it easily, because it has free electrons that can move.
- An **insulator** 绝缘体 (plastic, rubber, glass) does not let charge flow, because its electrons cannot move freely.

To test a material, join it in a circuit with a lamp and a battery: the lamp lights only for a conductor.

Electric fields and ions

Charge is measured in **coulombs** 库仑 (C). An **electric field** 电场 is a region where an electric charge feels a force. Its direction at a point is the direction of the force on a positive charge. Simple field patterns (the arrows show the direction):

- around a **point charge** 点电荷: straight lines, pointing away from a positive charge and towards a negative charge;
- around a charged ball (sphere): the same, spreading out evenly all around;
- between two parallel plates with opposite charges: straight, evenly spaced lines from the positive plate to the negative plate.



Electric field lines point away from a positive charge and towards a negative one; between parallel plates the field is uniform

An atom is normally neutral. If it loses electrons it becomes a positive **ion** 离子; if it gains electrons it becomes a negative ion.

Electric current

An **electric current** 电流 is a flow of electric charge. It is measured in **amperes** 安培 (A) with an **ammeter** 电流表, joined in series in the circuit.

An **analogue** 模拟 ammeter has a needle that moves over a scale; a **digital** 数字 ammeter shows the reading as a number. Both come with different **ranges** 量程. Choose the range just above the biggest current you expect, so the reading is accurate: a 0–1 A range for a current of about 0.4 A, or a 0–100 mA range for a few milliamps.

Current is the charge that passes a point each second:

$$I = \frac{Q}{t}$$

Here I is current (A), Q is charge (C) and t is time (s). Rearranged, $Q = It$.

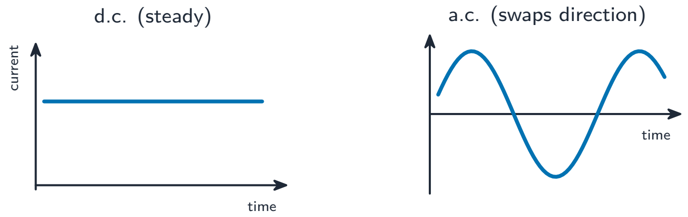
Worked example. A current of 3.0 A flows through a lamp for 20 s. How much charge passes through it?

$$Q = It = 3.0 \times 20 = 60 \text{ C}$$

In a metal the current is a flow of **free electrons** 自由电子. There are two "directions" to know:

- **Conventional current** 常规电流 is taken to flow from + to − round the outside of the cell.
- The free electrons really drift the other way, from − to +.

A **direct current** 直流电 (d.c.) always flows one way, as from a battery. An **alternating current** 交流电 (a.c.) keeps swapping direction many times each second, as from the **mains supply** 市电.



Direct current is steady in one direction; alternating current keeps swapping direction, crossing zero many times each second

E.m.f. and potential difference

A cell gives **energy** 能量 to the charges that move through it. Two quantities describe this, and both are measured in **volts** 伏特 (V).

- The **electromotive force** 电动势 (e.m.f.) of a source is the electrical work it does to drive unit charge all the way round a complete **circuit** 电路.
- The **potential difference** 电势差 (p.d.) across a component is the work done by unit charge as it passes *through that component.*

A **voltmeter** 电压表 measures e.m.f. or p.d. It is joined in parallel (across the component). Like ammeters, voltmeters are analogue or digital and have different ranges: pick the range just above the largest voltage you expect.

*A voltmeter across the **cell** reads the e.m.f. (energy each coulomb is given); a voltmeter across the **lamp** reads the p.d. (energy each coulomb spends there).*

Both are work done per unit charge:

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

where W is the energy transferred (J) and Q is the charge (C). For example, if a cell does 120 J of work moving 60 C of charge round a circuit, its e.m.f. is $120/60 = 2$ V.

Resistance

Resistance 电阻 measures how hard it is for current to flow. A bigger resistance gives a smaller current. It is measured in **ohms** 欧姆 (Ω).

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

Measuring resistance. Connect the component in series with a cell, a switch, an ammeter and a **variable resistor** 可变电阻器, and connect a voltmeter across the component. Close the switch, read I and V, then change the variable resistor to get several more pairs of readings. Either calculate $R = V/I$ for each pair and take the

average, or plot V against I: for a metal wire at constant temperature the graph is a straight line through the origin, and its gradient is R.

Worked example. A 12 V battery drives a current of 0.50 A through a lamp. Find the lamp's resistance.

$$R = \frac{V}{I} = \frac{12}{0.50} = 24\ \Omega$$

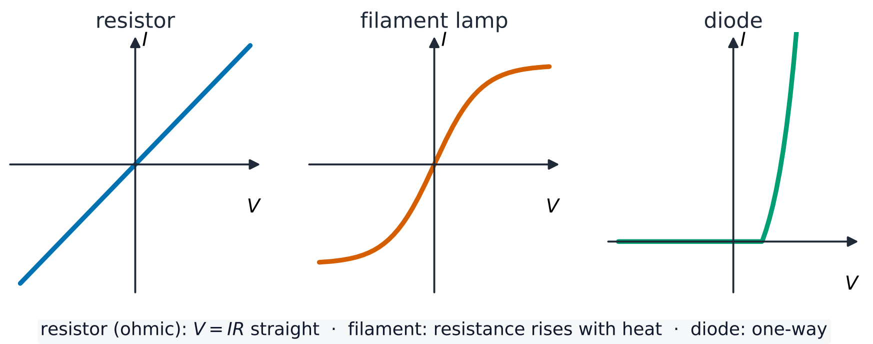
For a metal wire at constant temperature:

- a longer wire has a bigger resistance — resistance is **directly proportional** 成正比 to length, $R \propto l$;
- a thicker wire has a smaller resistance — resistance is **inversely proportional** 成反比 to **cross-sectional area** 横截面积, $R \propto \dfrac{1}{A}$.

So doubling the length doubles the resistance; doubling the area halves it. (Area depends on the diameter squared, so a small change in diameter changes the resistance a lot.)

Current–voltage graphs show how three components behave:

Component	Shape of the I–V graph	What it tells you
resistor 电阻器 (fixed)	straight line through the origin	resistance is constant, so $I \propto V$
filament lamp 灯丝灯泡	S-shaped, getting flatter as V rises	the wire heats up, so its resistance rises
diode 二极管	current one way only	very high resistance the "wrong" way



A resistor gives a straight line; a filament lamp curves as it heats up; a diode lets current pass only one way

Electrical energy and power

A circuit transfers energy from a source (a cell or the mains) to the components, and then into the surroundings (often as heat, light or sound).

Electrical power 电功率 is the energy transferred each second, measured in **watts** 瓦特 (W):

$$P = IV$$

The **electrical energy** 电能 transferred in a time t, measured in **joules** 焦耳 (J), is:

$$E = IVt$$

Worked example. A 12 V motor draws a current of 2.0 A. Find its power, and the energy it transfers in 30 s.

$$P = IV = 2.0 \times 12 = 24 \text{ W}$$

$$E = Pt = 24 \times 30 = 720 \text{ J}$$

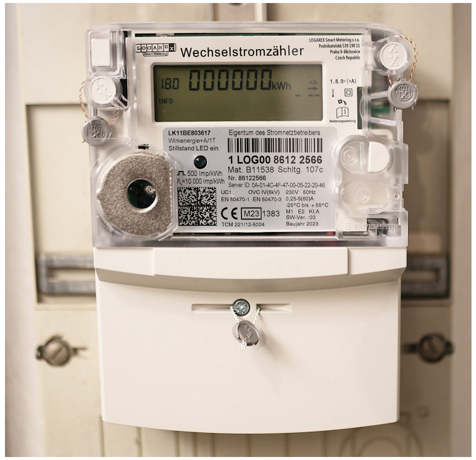
The kilowatt-hour

Home electricity bills use a bigger energy unit, the **kilowatt-hour** 千瓦时 (kWh). One kilowatt-hour is the energy used by a 1 kW **appliance** 电器 in 1 hour.

$$\text{energy (kWh)} = \text{power (kW)} \times \text{time (h)}$$

$$\text{cost} = \text{energy (kWh)} \times \text{price per kWh}$$

For example, a 2 kW **heater** 加热器 used for 3 hours uses $2 \times 3 = 6$ kWh. If one kWh costs 20 cents, the cost is $6 \times 20 = 120$ cents.



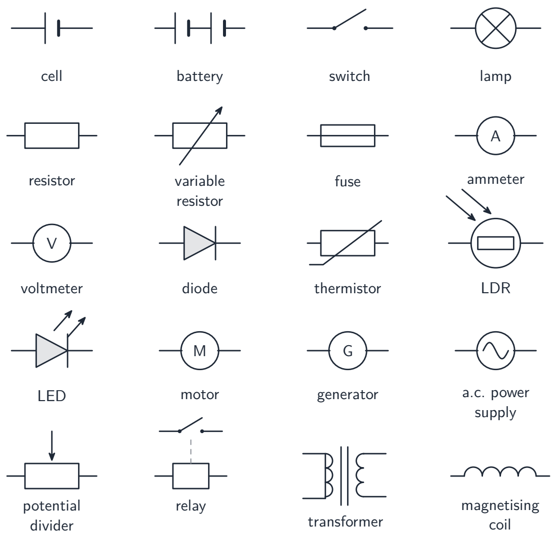
A household electricity meter counts the energy used, in kilowatt-hours (kWh) — the number it shows is what you pay for

Circuits

Circuit components

You should know these components and how they behave:

Component	What it does
cell 电池 / **battery** 电池组	drives current round the circuit (a battery is two or more cells)
power supply 电源	a source of d.c. or a.c.
switch 开关	breaks or completes the circuit
resistor (fixed)	gives a fixed resistance
variable resistor	a resistance you can change, to control the current
fuse 保险丝	melts and breaks the circuit if the current is too big
lamp / **heater**	turns electrical energy into light / into heat
thermistor 热敏电阻	its resistance falls as it gets hotter
light-dependent resistor 光敏电阻 (LDR)	its resistance falls as the light gets brighter
diode / **light-emitting diode** 发光二极管 (LED)	lets current one way only; an LED also gives out light
relay 继电器	a switch worked by an electromagnet (small current controls a big one)
motor 电动机	turns electrical energy into movement
bell 电铃	makes a sound
transformer 变压器	changes the size of an a.c. voltage



The standard symbols used to draw circuit diagrams

Real resistors: the coloured bands give each one's resistance in ohms

Series and parallel

In a **series** 串联 circuit the parts form one single loop:

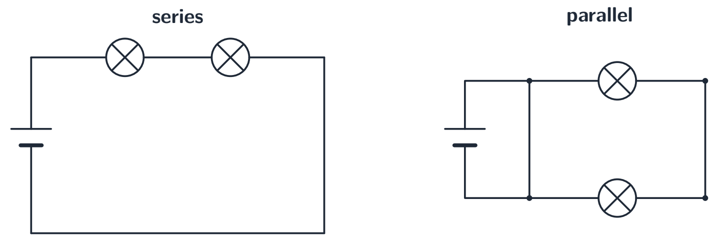
- the current is the same at every point;

- the supply p.d. is shared between the components;
- cells in series add their e.m.f.s (when they point the same way);
- resistors in series add up: $R_{\text{total}} = R_1 + R_2 + \ldots$

In a **parallel** 并联 circuit the parts are on separate branches:

- each branch gets the full supply p.d.;
- the current splits, so the current from the source is bigger than the current in any one branch;
- the **total resistance** 总电阻 is less than the smallest single resistance.

Lamps in a home are wired in parallel: each gets the full voltage, and if one fails the others stay on.



In a series circuit the components share one loop; in a parallel circuit each lamp has its own branch

For calculations (with the rules above):

- at a **junction** 节点, the total current flowing in equals the total current flowing out;
- in series, the supply p.d. equals the sum of the p.d.s across the components;
- in parallel, the p.d. across each branch is the same;
- two resistors in parallel combine as

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2}$$

Worked example. A 6 Ω resistor and a 3 Ω resistor are connected in parallel. Find their combined resistance.

$$\frac{1}{R_{\text{total}}} = \frac{1}{6} + \frac{1}{3} = \frac{1}{6} + \frac{2}{6} = \frac{3}{6} = \frac{1}{2} \quad \Rightarrow \quad R_{\text{total}} = 2\ \Omega$$

Notice the combined resistance (2 Ω) is smaller than the smaller of the two resistors.

Potential dividers

Two resistors in series share the supply voltage. This is a **potential divider** 分压器. For the same current, a bigger resistance has a bigger p.d. across it, so the bigger resistor takes the bigger share:

$$\frac{R_1}{R_2} = \frac{V_1}{V_2}$$

A *variable* potential divider (or a variable resistor) lets you change the output voltage smoothly, for example from 0 V up to the full supply. If you use a thermistor or an LDR as one of the resistors, the output voltage changes with temperature or light — handy for switching a heater or a lamp on and off automatically.

Electrical safety

A home is fed by the mains. The mains is dangerous if it is used wrongly.

Hazards

These are **hazards** 危险 (dangers) with mains electricity:

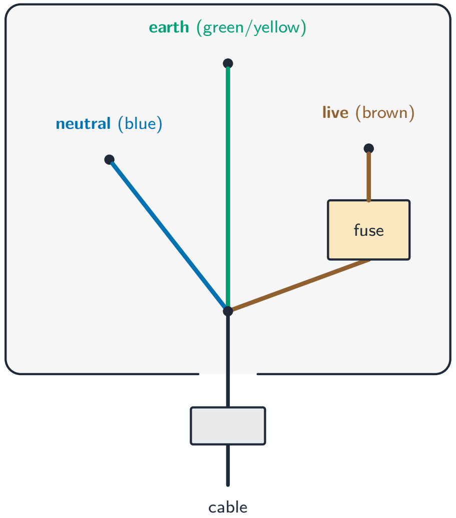
- damaged **insulation** 绝缘层 — bare wires can give a shock or start a fire;
- **overheating** 过热 cables — too much current makes a cable hot, which can start a fire;
- **damp** 潮湿 conditions — water lets current pass into a person, raising the risk of a shock;
- **overloading** 过载 — plugging too many appliances into one **socket** 插座 draws too much current.

Live, neutral and earth

A mains cable has three wires:

- the **live wire** 火线 carries the high voltage;
- the **neutral wire** 零线 completes the circuit at about zero voltage;
- the **earth wire** 地线 is a safety wire joined to the ground.

A switch (and a fuse) must be fitted in the *live* wire. Then, when the switch is off, the appliance is cut off from the high voltage and is safe to touch.



*In a three-pin plug the **live** (brown) and **neutral** (blue) carry the current, the **earth** (green/yellow) is the safety wire, and the **fuse** always sits in the live wire.*

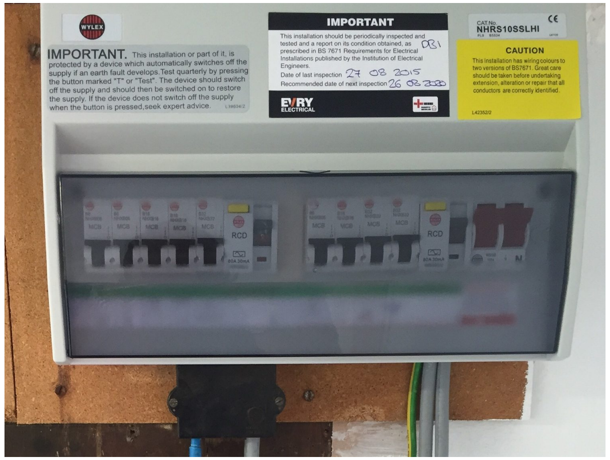
Fuses, trip switches and earthing

A fuse is a thin wire that melts if the current gets too big, breaking the circuit before the cable overheats. Choose a **fuse rating** 额定值 just above the normal working current — for example a 13 A fuse for an appliance that normally uses about 10 A.

A **trip switch** 跳闸开关 (circuit breaker) does the same job but acts faster and can be reset instead of replaced.

The metal **casing** 外壳 of an appliance must be made safe in one of two ways:

- **earthed** 接地: the casing is joined to the earth wire. If a live wire touches the casing, a large current flows to earth and blows the fuse.
- **double-insulated** 双重绝缘: the casing is plastic, so it can never become live. Such an appliance needs no earth wire; its fuse still protects the cable.



A home consumer unit: each MCB is a trip switch that cuts off its circuit when the current gets too big; the RCD (80 A, 30 mA) cuts off even faster if it detects a fault to earth

Electromagnetic effects

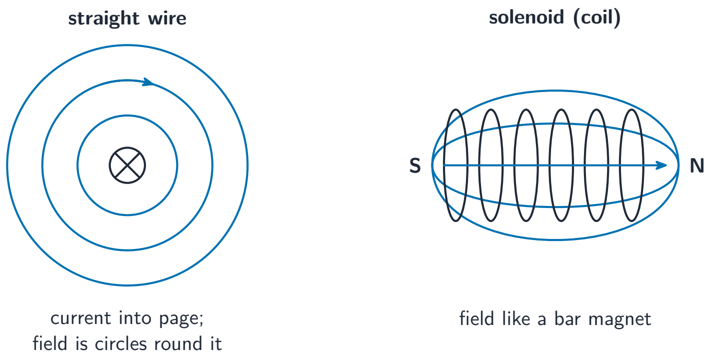
The magnetic effect of a current

A current in a wire makes a magnetic field around it.

- Around a straight wire the field lines are circles around the wire; the field is stronger close to the wire. Reverse the current and the field reverses.

- A **solenoid** 螺线管 (a long **coil** 线圈 of wire) makes a field just like a bar magnet, with a N pole at one end and a S pole at the other. The field inside is strong and even.

You can show both patterns with iron filings or a plotting compass. The field gets stronger if you increase the current, add more turns, or place a soft-iron core inside.



A current makes circular field lines around a straight wire, and a bar-magnet-like field for a solenoid

The magnetic effect is used in a relay and in a loudspeaker. In a relay, a small current in a coil magnetises a soft-iron core, which pulls a switch closed in a second circuit. The second circuit can carry a large current, so a small switch or a sensor can safely control a motor or a heater (for example, the ignition switch of a car starts its motor through a relay). In a **loudspeaker** 扬声器 a changing current in a coil makes the coil push and pull a paper cone, which moves the air and makes sound.

Electromagnetic induction

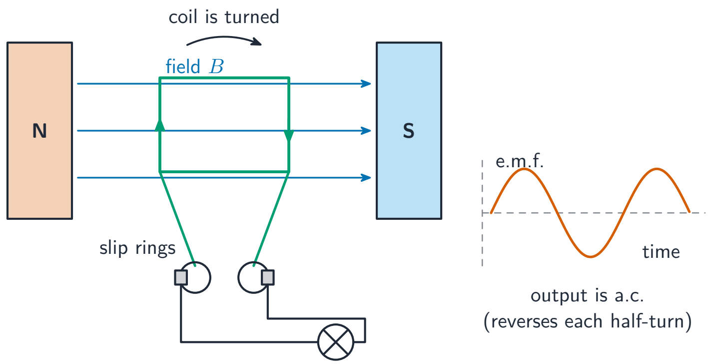
When a wire moves across a magnetic field, or the field through a coil changes, an e.m.f. is **induced** in the wire. If the wire is part of a complete circuit, this e.m.f. drives a current. This is **electromagnetic induction** 电磁感应.

To show it: move a magnet in and out of a coil joined to a sensitive meter, and watch the needle flick. The induced e.m.f. is bigger when you use a stronger magnet, move faster, or use more turns on the coil. The induced e.m.f. always acts to *oppose* the change that causes it. The direction of the induced current is given by **Fleming's right-hand rule** 弗莱明右手定则: hold the thumb, first finger and second finger of the right hand at right angles to one another; the thumb points along the motion of the wire, the first finger along the field (N to S), and the second finger then gives the induced current.

The a.c. generator

An **a.c. generator** 交流发电机 turns movement into electricity. A coil is spun in a magnetic field (or a magnet is spun near a coil). As it turns, the field through the coil keeps changing, so an alternating e.m.f. is induced.

- **Slip rings** 滑环 and carbon **brushes** 电刷 carry the current out to the circuit while the coil keeps turning.
- The e.m.f. is largest when the coil is flat (moving fastest across the field) and zero when the coil is upright (moving along the field). So the e.m.f.–time graph is a wave: peak, zero, opposite peak, zero, for each turn.



Turning the coil induces an alternating e.m.f.; the slip rings carry the a.c. out to the circuit

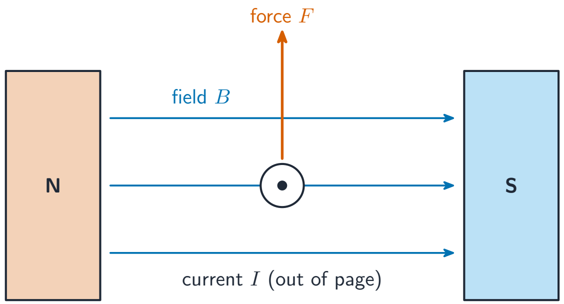
Force on a current-carrying conductor

When a current-carrying wire lies in a magnetic field, the field of the wire and the field of the magnet push on each other, so the wire feels a force. This is the **motor effect**.

- Reverse the current, *or* reverse the field, and the force reverses.
- Make the current bigger or the field stronger, and the force is bigger.

The force, the field and the current are at right angles to one another. You can find the force direction with **Fleming's left-hand rule** 弗莱明左手定则: thumb = force (motion), first finger = field (N to S), second finger = current.

Showing the force. Lay a stiff copper wire (or a strip of aluminium foil) between the poles of a U-shaped magnet and connect it to a cell through a switch. When the current flows, the wire jumps up or down. Reverse the cell and the wire jumps the other way; turn the magnet over and it reverses again. A bigger current or a stronger magnet gives a bigger jump.



F, B and I are all at 90° (Fleming's left-hand rule)

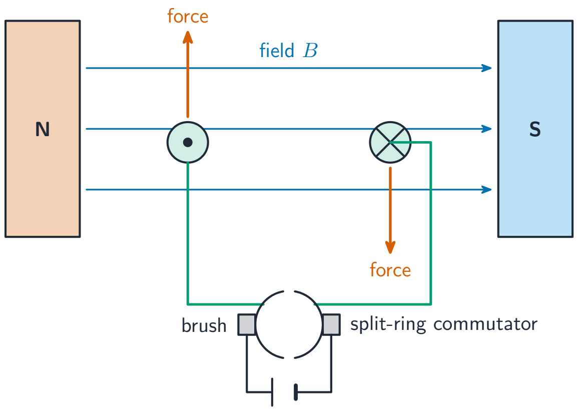
A current-carrying wire in a magnetic field feels a force at right angles to both the field and the current

A moving stream of charged particles is a current, so a magnetic field pushes it sideways too — it **deflects** 偏转 the beam. (Remember electrons flow opposite to the conventional current.)

The d.c. motor

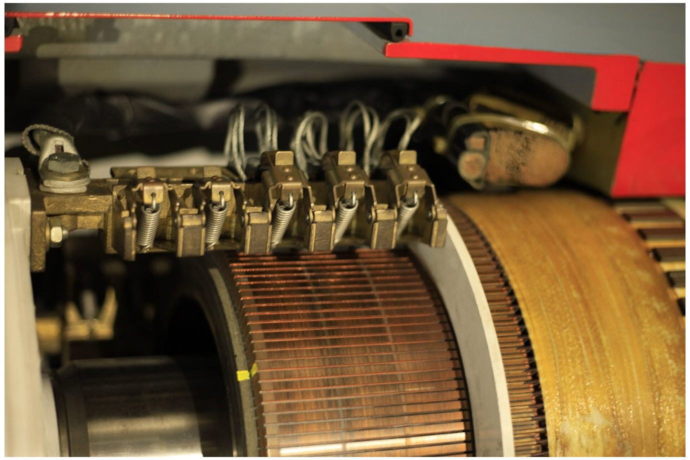
A coil carrying a current in a magnetic field feels a **turning effect** 转动效应, because the forces on its two sides act in opposite directions. This is a **d.c. motor** 直流电动机. The turning effect is bigger with more turns on the coil, a bigger current, or a stronger field.

A **split-ring commutator** 换向器 swaps the current direction in the coil every half-turn. This keeps the coil turning the same way instead of stopping after half a turn.



the two forces form a couple that turns the coil

The forces on the two sides of the coil form a couple; the split-ring commutator keeps it turning one way



In a real d.c. machine, carbon brushes press on the copper commutator bars to feed current to the spinning coil

The transformer

A **transformer** changes the size of an a.c. voltage. It has two coils wound on a **soft-iron core** 软铁芯:

- the **primary coil** 原线圈 takes in the a.c. voltage;
- the **secondary coil** 副线圈 gives out the changed voltage.

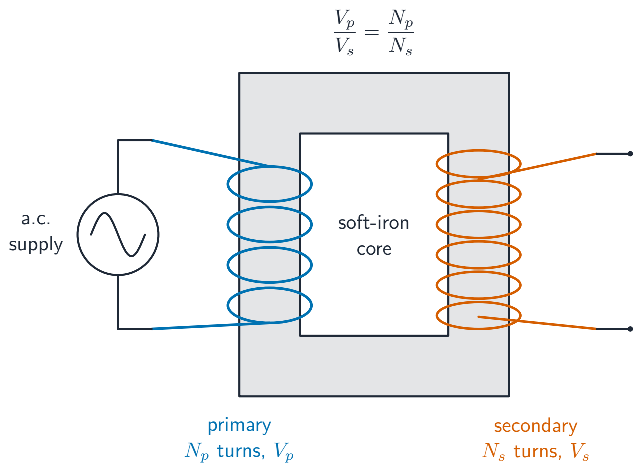
The a.c. in the primary makes a changing magnetic field in the core. The core carries this field to the secondary, where it induces an a.c. e.m.f. The voltages and the numbers of turns are linked by:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Worked example. A transformer has 1200 turns on the primary coil and 100 turns on the secondary coil. The primary is connected to a 240 V a.c. supply. Find the secondary voltage.

$$\frac{240}{V_s} = \frac{1200}{100} = 12 \quad \Rightarrow \quad V_s = \frac{240}{12} = 20 \text{ V}$$

Fewer turns on the secondary, so this is a step-down transformer.



The changing field in the core links the two coils; the voltage ratio equals the turns ratio

A real transformer on a power pole steps the high voltage in the cables down to a safer voltage for homes

If the secondary has more turns it is a **step-up** 升压 transformer (voltage rises); fewer turns make a **step-down** 降压 transformer (voltage falls). For example, a transformer changing 240 V to 12 V is a step-down type, and the primary has 20 times as many turns as the secondary.

If a transformer is 100% efficient, the power in equals the power out:

$$I_p V_p = I_s V_s$$

So a step-up transformer raises the voltage but lowers the current.

Why we use high voltage to send power

Electricity is sent across the country by **high-voltage transmission** 高压输电. The power lost as heat in the cables is

$$P = I^2 R$$

where R is the resistance of the cables. A step-up transformer raises the voltage and so lowers the current for the same power ($P = IV$). A smaller current means much less power wasted in the cables. A step-down transformer then lowers the voltage again to a safe value before it reaches homes.

Pylons hold the cables that carry electricity at very high voltage, which keeps the current — and the wasted power — low

Exam tips

- **Current** is the same everywhere in a **series** circuit; in a **parallel** circuit it splits between the branches. Voltage (p.d.) is shared out in series, but is the same across every parallel branch.
- Adding resistors in **series** increases the total resistance ($R_1 + R_2$); adding them in **parallel** makes the total *less* than the smallest single resistor.

- An **ammeter** goes in *series* and has very low resistance; a **voltmeter** goes in *parallel* across a component and has very high resistance.
- In a **transformer** $\frac{V_p}{V_s} = \frac{N_p}{N_s}$: more turns on the secondary steps the voltage *up*, fewer steps it *down*. Transformers only work on a.c.
- Power is sent across country at **high voltage** so the current — and the heat wasted in the cables, $P = I^2 R$ — is small.
- Fit the **switch and the fuse in the live wire**, and choose a fuse rating just above the appliance's normal working current.