PHYSICS 0625 · CHAPTER 4

Electricity and Magnetism

Magnets and magnetic fields, electric charge and fields, current, e.m.f., potential difference and resistance, circuits and components, series and parallel, electrical power and safety, electromagnetic induction, generators, motors, transformers and the oscilloscope.

4.1 Simple magnetism and magnetic fields

Poles and forces

A magnet has two poles, a **north pole (N)** and a **south pole (S)**.

- **Unlike** poles **attract** (N and S).
- **Like** poles **repel** (N and N, or S and S).
- A magnet also attracts **magnetic materials**: iron, steel, nickel and cobalt. Other materials, such as copper, aluminium, plastic and glass, are **non-magnetic**.

NOTE

Attraction alone does not prove that something is a magnet, because a magnet attracts an unmagnetised piece of iron too. **Repulsion** is the only sure test for a magnet.

Induced magnetism

A piece of magnetic material becomes a magnet when it is placed near or touching a magnet. This is **induced magnetism**. The end nearest the magnet becomes the opposite pole, so the two attract. A nail held to a magnet picks up pins in this way. When the magnet is taken away, soft iron loses almost all of its magnetism.

Note Academy

Temporary and permanent magnets

	Soft iron (temporary magnet)	Steel (permanent magnet)
how easily magnetised	easily	with more difficulty
keeps its magnetism?	no, it loses it quickly	yes, it keeps it
used for	cores of electromagnets, relays	compasses, fridge door catches, loudspeakers

Magnetic fields

A **magnetic field** is a region in which a magnetic pole experiences a force.

- **The direction** of the field at a point is the direction of the force on a **north pole** placed there. Field lines point away from N and towards S.
- **Plotting the field.** Place a plotting compass near a magnet, mark where the needle points, move the compass along and repeat. Joining the marks gives a field line. Iron filings sprinkled on paper over a magnet line up along the field lines. A compass needle points along the field, so it can be used to find the direction of the field.
- **Pattern around a bar magnet.** The field lines leave the N pole, curve round and enter the S pole, and never cross.
- **Strength.** The field is stronger where the lines are **closer together**, which is near the poles.

Uses of magnets

- **Permanent magnets:** compasses, fridge door catches, loudspeakers, electric motors.
- **Electromagnets** (a coil of wire with an iron core, magnetic only while a current flows): scrapyard cranes, relays, electric bells, circuit breakers.

4.2.1 Electrical charge

There are two kinds of electric charge, **positive** and **negative**. Charge is measured in **coulombs (C)**.

> **Unlike charges attract and like charges repel.**

Charging by friction. Rubbing two insulators together transfers **electrons** (negative charge) from one to the other. Protons do not move.

Note Academy

- A polythene rod rubbed with a cloth **gains** electrons and becomes **negative**. The cloth loses electrons and becomes **positive**.
- An acetate rod rubbed with a cloth **loses** electrons and becomes **positive**.
- A charged rod attracts small pieces of paper. Two negative rods repel, while a negative and a positive rod attract.

Electric fields

An **electric field** is a region in which an electric charge experiences a force. The direction of an electric field line at a point is the direction of the force on a **positive** charge there.

Situation	Field pattern
a point charge	straight lines radiating **outwards** from a positive charge, or **inwards** to a negative charge
a charged conducting sphere	the same as a point charge, outside the sphere
between two oppositely charged parallel plates	evenly spaced **parallel lines** from the positive plate to the negative plate (a uniform field; ignore the ends)

Conductors and insulators

- **Conductors** let charge flow through them. Examples are metals and graphite.
- **Insulators** do not. Examples are plastic, glass, rubber and dry air.

Experiment. Connect a cell, a lamp and two clips in a circuit. Touch the clips to the test material. If the lamp lights, the material is a conductor.

Electron model. In a metal, some electrons are **free** to move through the material, so a current can flow. In an insulator, all the electrons are held tightly by their atoms, so there are no free charges to carry a current.

4.2.2 Electrical current

$\text{current} = \dfrac{\text{charge}}{\text{time}}$, **that is** $I = \dfrac{Q}{t}$. **The unit is the ampere (A), and** $1\ \text{A} = 1\ \text{C/s}$.

TRY IT

A charge of $12\ \text{C}$ passes a point in $4.0\ \text{s}$. Find the current. How much charge flows in $30\ \text{s}$ at $2.0\ \text{A}$?

Note Academy

$I = \frac{12}{4.0} = 3.0\ \text{A} \qquad Q = It = 2.0 \times 30 = 60\ \text{C}$

- In **metals**, a current is a flow of free electrons.
- **Conventional current** is taken to flow from the **positive** terminal to the **negative** terminal. The electrons flow the other way, from negative to positive.
- **Direct current (d.c.)** flows in one direction only. **Alternating current (a.c.)** keeps reversing direction.
- An **ammeter** measures current. It is connected **in series** with the component. Choose a range that is bigger than the expected current, then move to a smaller range for a more precise reading.

4.2.3 Electromotive force and potential difference

e.m.f. is the electrical work done by a source in moving a unit charge round a complete circuit: $E = \frac{W}{Q}$. p.d. is the work done by a unit charge passing through a component: $V = \frac{W}{Q}$.

Both are measured in **volts (V)**, and $1\ \text{V} = 1\ \text{J/C}$.

> **TRY IT**
>
> A cell does $36\ \text{J}$ of work moving $12\ \text{C}$ of charge round a circuit. Find its e.m.f.

$E = \frac{36}{12} = 3.0\ \text{V}$

- A **voltmeter** measures p.d. It is connected **in parallel** across the component.
- Cells in **series** add their e.m.f.s: three $1.5\ \text{V}$ cells in series give $4.5\ \text{V}$.
- Identical cells in **parallel** give the e.m.f. of **one** cell.

4.2.4 Resistance

$\text{resistance} = \frac{\text{p.d.}}{\text{current}}$, that is $R = \frac{V}{I}$. The unit is the ohm (Ω).

> **TRY IT**
>
> A p.d. of $6.0\ \text{V}$ across a resistor gives a current of $2.0\ \text{A}$. Find its resistance.

$R = \frac{6.0}{2.0} = 3.0\ \Omega$

Experiment to find a resistance. Connect the resistor in series with an ammeter and a variable resistor, and a voltmeter in parallel across the resistor. Change the variable resistor to get several pairs of readings of V and I. Calculate $\frac{V}{I}$ each time and average them (or plot a graph of V against I; the gradient is R).

Note Academy

Resistance of a wire. For a wire of the same material:

- the resistance is **directly proportional to the length**: twice as long, twice the resistance;
- the resistance is **inversely proportional to the cross-sectional area**: twice as thick, half the resistance.

> **Ohm's law. The current in a conductor is directly proportional to the p.d. across it, provided its temperature is constant.**

Current–voltage graphs

Component	Shape of the I–V graph	Explanation
resistor of constant resistance	a straight line through the origin	$I \propto V$, so it obeys Ohm's law
filament lamp	an S-shaped curve that gets flatter as V increases	the filament heats up, its atoms vibrate more and impede the electrons, so the resistance increases with temperature
diode	no current for one direction of p.d., then a sharp rise for the other	a diode lets current pass in **one direction only**

An increase in temperature increases the resistance of a metal such as the filament of a lamp.

Note Academy

4.3.1 Circuit diagrams and circuit components

Component	What it does
cell, battery, power supply	provide the e.m.f. that pushes the current (a battery is two or more cells)
generator	transfers kinetic energy into electrical energy
switch	opens or closes a circuit
fixed resistor	limits the current by a set amount
variable resistor	resistance can be changed, so the current can be changed
heater	transfers electrical energy to thermal energy
thermistor (NTC)	its resistance **decreases** as the temperature rises
light-dependent resistor (LDR)	its resistance **decreases** as the light gets brighter
lamp	gives out light
motor	transfers electrical energy to kinetic energy
ammeter	measures the current (in series)
voltmeter	measures the p.d. (in parallel)
oscilloscope	displays voltage against time
potential divider	splits a voltage between two resistors, or a variable resistor
magnetising coil, solenoid	a coil that becomes magnetic when a current flows
transformer	changes the size of an alternating voltage
fuse	melts and breaks the circuit if the current is too high
relay	an electromagnetic switch: a small current in a coil switches a second circuit
diode	lets current pass in one direction only
light-emitting diode (LED)	a diode that gives out light when current passes through it

4.3.2 Series and parallel circuits

Series circuit (one path for the current):

- the **current is the same** at every point;

Note Academy

- the **total p.d.** across the components is the sum of the p.d.s across each.

Parallel circuit (more than one path):

- the **currents** entering a junction equal the currents leaving it (so the branch currents add up to the total current);
- the p.d. across each branch is **the same** as across the whole arrangement.

Resistors in series: $R = R_1 + R_2 + \ldots$ **Two resistors in parallel:** $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$, **or** $R = \frac{R_1 R_2}{R_1 + R_2}$.

The total resistance of resistors in parallel is always **less than the smallest** resistor.

TRY IT

A $4.0\ \Omega$ resistor and a $6.0\ \Omega$ resistor are in series with a $12\ \text{V}$ supply. Find the current and the p.d. across each resistor.

$R = 4.0 + 6.0 = 10\ \Omega$ $I = \frac{12}{10} = 1.2\ \text{A}$

$V_{4\Omega} = 1.2 \times 4.0 = 4.8\ \text{V}$ $V_{6\Omega} = 1.2 \times 6.0 = 7.2\ \text{V}$

The two p.d.s add up to $12\ \text{V}$.

TRY IT

A $6.0\ \Omega$ resistor and a $3.0\ \Omega$ resistor are in parallel with a $12\ \text{V}$ supply. Find the combined resistance and the current in each resistor and in total.

$R = \frac{6.0 \times 3.0}{6.0 + 3.0} = \frac{18}{9} = 2.0\ \Omega$

Each resistor has $12\ \text{V}$ across it: $I_{6\Omega} = \frac{12}{6.0} = 2.0\ \text{A}$ and $I_{3\Omega} = \frac{12}{3.0} = 4.0\ \text{A}$. The total current is $2.0 + 4.0 = 6.0\ \text{A}$, which agrees with $\frac{12}{2.0} = 6.0\ \text{A}$.

4.3.3 Action and use of circuit components

- A **thermistor** (NTC type) has a resistance that falls as its temperature rises. It is used as a temperature sensor, for example in a fire alarm or a thermostat.
- A **light-dependent resistor** has a resistance that falls as the light gets brighter. It is used as a light sensor, for example to switch on street lights when it gets dark.

Note Academy

The potential divider

Two resistors in series across a supply share the supply voltage in the ratio of their resistances.

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

TRY IT

A $12\ \text{V}$ supply is connected across a $2.0\ \text{k}\Omega$ resistor in series with a $4.0\ \text{k}\Omega$ resistor. Find the p.d. across each.

The total is $6.0\ \text{k}\Omega$, so

$V_1 = 12 \times \frac{2.0}{6.0} = 4.0\ \text{V}$ $\quad$ $V_2 = 12 \times \frac{4.0}{6.0} = 8.0\ \text{V}$

Check: $\frac{R_1}{R_2} = 0.5$ and $\frac{V_1}{V_2} = 0.5$.

A **variable potential divider** uses a variable resistor with a sliding contact. Moving the contact changes the output p.d. smoothly from $0\ \text{V}$ up to the full supply voltage (for example in a volume control). If a thermistor or LDR is one of the two resistors, the output p.d. changes with temperature or light, so the circuit can act as an **input sensor** that switches something on or off.

4.4.1 Uses of electricity

Electricity is used for heating, lighting, charging batteries, and powering motors and electronic systems.

Lamps in a lighting circuit are connected in parallel. Each lamp has the full supply voltage and can be switched on and off independently, and if one lamp fails the others stay on.

power = current × voltage**, that is** $P = IV$**.** $\quad$ energy = current × voltage × time**, that is** $E = IVt$**.**

TRY IT

A kettle element draws $10\ \text{A}$ from a $230\ \text{V}$ supply. Find its power.

$P = IV = 10 \times 230 = 2300\ \text{W} = 2.3\ \text{kW}$

TRY IT

Note Academy

A current of $2.0\ \text{A}$ flows through a heater at $12\ \text{V}$ for $5.0\ \text{s}$. How much energy is transferred?

$E = IVt = 2.0 \times 12 \times 5.0 = 120\ \text{J}$

The kilowatt-hour

The **kilowatt-hour (kW h)** is the energy used by a device of power $1\ \text{kW}$ running for $1\ \text{hour}$.

energy in kW h = power in kW × time in hours. cost = energy in kW h × cost of one kW h.

TRY IT

A $3.0\ \text{kW}$ heater runs for $4.0\ \text{hours}$. Electricity costs 15 cents per kW h. Find the energy used and the cost.

energy $= 3.0 \times 4.0 = 12\ \text{kW h}$ cost $= 12 \times 15 = 180$ cents

4.4.2 Electrical safety

Hazards

- **Damaged insulation** can expose live wires, so a person can get an electric shock.
- **Overheating cables** can start a fire. A cable heats up if the current is too large for it.
- **Damp conditions** are dangerous because water conducts electricity, so the resistance of the body falls and a larger, more dangerous current can flow.
- **Overloading** a plug, extension lead or socket by plugging in too many appliances draws a very large current, which overheats the wires.

The mains wiring

Wire	Colour	Job
live (line)	brown	carries the current to the appliance, at high voltage
neutral	blue	completes the circuit, at about $0\ \text{V}$
earth	green and yellow	a safety wire that connects the metal case to the ground

Note Academy

The switch, the fuse and the circuit breaker are always in the live wire. If they were in the neutral wire, the appliance would still be connected to the live wire when it is "off", so touching its inside could give a shock.

Fuses and trip switches

- A **fuse** is a thin wire that melts if the current gets too high, breaking the circuit. Choose a fuse with a rating just **above** the normal current of the appliance. A $2.3\ \text{kW}$ appliance on $230\ \text{V}$ draws $\frac{2300}{230} = 10\ \text{A}$, so a $13\ \text{A}$ fuse is suitable and a $3\ \text{A}$ fuse is not.
- A **trip switch (circuit breaker)** uses an electromagnet to open a switch when the current is too high. It does the same job as a fuse, but can be reset instead of being replaced.

Earthing and double insulation

If a loose live wire touches a metal case, an **earthed** case carries a large current to the ground. This blows the fuse (or trips the breaker), cutting off the supply before anyone gets a shock. If the case were not earthed, it would become live and could give a fatal shock.

An appliance with a plastic casing (**double insulated**) has no metal that can become live, so it does not need an earth wire. The outer casing of an appliance must therefore be either non-conducting (double insulated) or earthed.

4.5.1 Electromagnetic induction

When a conductor **cuts magnetic field lines**, an **e.m.f. is induced** in it. If there is a complete circuit, a current flows.

Experiment. Connect a coil to a sensitive meter. Push a bar magnet into the coil, and the meter flickers. Hold the magnet still inside the coil, and the reading falls to zero. Pull the magnet out, and the meter flickers the opposite way. An e.m.f. is induced only while the magnetic field in the coil is changing.

The induced e.m.f. is **bigger** when:

- the magnet is moved **faster** (the rate of change of the field, or the rate of cutting field lines, is greater);
- the magnet is **stronger**;
- the coil has **more turns**.

> **Lenz's law. The current produced by an induced e.m.f. flows in the direction that opposes the change that produced it.**

Note Academy

For example, when the N pole of a magnet is pushed into a coil, the end of the coil nearest it becomes a north pole, which repels the magnet. The person pushing has to do work, and this work is the source of the electrical energy. A magnet dropped down a copper tube falls slowly for the same reason.

4.5.2 The a.c. generator

> NOTE
>
> **Supplement only.** This topic is in the Extended (Supplement) syllabus, so it is asked in Papers 2, 4 and 6. If you sit the Core papers you do not need it.

A simple **a.c. generator** has a coil that is rotated between the poles of a permanent magnet (or a magnet that rotates inside a coil).

- The ends of the coil connect to **slip rings**. **Brushes** (carbon contacts) press against the slip rings and connect the coil to the external circuit.
- As the coil turns, its sides cut the field lines and an e.m.f. is induced.

The graph of e.m.f. against time is a repeating wave (a sine wave).

- The e.m.f. is **zero** when the plane of the coil is **perpendicular** to the field, because the sides of the coil are moving along the field lines and not cutting them.
- The e.m.f. is at a **maximum (a peak or a trough)** when the plane of the coil is **parallel** to the field, because the sides cut the field lines at the greatest rate. The sign changes each half turn, so the current alternates.

Turning the coil **faster** increases both the size of the e.m.f. and the frequency. More turns on the coil, or a stronger magnet, also increase the e.m.f.

4.5.3 Magnetic effect of a current

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

- **Straight wire.** The field lines are **concentric circles** around the wire. The field is stronger near the wire and when the current is bigger. Reversing the current reverses the direction of the field. The direction can be found with the right-hand grip rule: point the thumb along the conventional current and the fingers curl in the direction of the field.
- **Solenoid (a long coil).** The field inside is strong and uniform, and the field outside is the same as that of a bar magnet. The field is stronger with a **bigger current**, **more turns** and an **iron core**. Reversing the current swaps the poles.

Note Academy

Uses

- **A relay.** A small current through a coil magnetises an iron core, which pulls a lever (the armature) and closes the contacts of a second circuit that carries a large current. A relay lets a small, safe circuit switch a large current in another circuit.
- **A loudspeaker.** A coil is fixed to a paper cone and sits in the field of a permanent magnet. An alternating current from the amplifier makes the coil move in and out (see 4.5.4), which moves the cone and produces sound waves of the same frequency.

4.5.4 Forces on a current-carrying conductor

A wire carrying a current in a magnetic field experiences a **force**, at right angles to both the field and the current.

Experiment. Place a copper rod across two rails between the poles of a strong magnet and pass a current through it. The rod rolls along the rails. **Reversing the current** or **reversing the field** reverses the direction of the force. Reversing both brings the force back to its original direction.

> **Fleming's left-hand rule. Hold the thumb, first finger and second finger of the left hand at right angles. The First finger points in the direction of the Field (N to S), the seCond finger in the direction of the Current, and the thuMb gives the direction of the force or Motion.**

Parallel conductors. Two parallel wires with currents in the **same direction** attract each other. Two with currents in **opposite directions** repel each other. This is because the field of one wire acts on the current in the other.

4.5.5 The d.c. motor

A coil carrying a current in a magnetic field has forces on its two sides that act in **opposite directions**, so the coil experiences a **turning effect**.

The turning effect is increased by increasing:

- the number of turns on the coil,
- the current,
- the strength of the magnetic field.

How a d.c. motor works.

1. The coil is between the poles of a permanent magnet and connected to a d.c. supply through brushes.
2. The forces on the sides of the coil make it turn.
3. Each half turn, the **split-ring commutator** swaps the connections to the coil, so the current in each side reverses and the forces keep turning the coil in the same direction.

Note Academy

4. The **brushes** press against the commutator and keep contact with it as it turns.

Without the commutator, the coil would swing up to the vertical position and then be pulled back.

4.5.6 The transformer

A **transformer** changes the size of an alternating voltage. It has two coils, the **primary** and the **secondary**, wound on a soft iron core.

1. An alternating current in the primary coil produces a **changing magnetic field** in the core.
2. The iron core carries this changing field through the secondary coil.
3. The changing field induces an alternating e.m.f. in the secondary coil.

A transformer works only with a.c., because a d.c. supply gives a steady field that does not change, so nothing is induced.

- A **step-up** transformer has more turns on the secondary than on the primary, and increases the voltage.
- A **step-down** transformer has fewer turns on the secondary, and decreases the voltage.

$\frac{V_p}{V_s} = \frac{N_p}{N_s}$**, where P and S refer to the primary and secondary coils and** N **is the number of turns.**

TRY IT

A transformer has 1000 turns on its primary coil and 50 turns on its secondary coil. The primary voltage is $230\ \text{V}$. Find the secondary voltage. Is it step-up or step-down?

$V_s = V_p \times \frac{N_s}{N_p} = 230 \times \frac{50}{1000} = 11.5\ \text{V}$

It is a step-down transformer.

TRY IT

A $12\ \text{V}$ supply is connected to a 100-turn primary coil. The secondary coil has 2400 turns. Find the secondary voltage.

$V_s = 12 \times \frac{2400}{100} = 288\ \text{V}$

Note Academy

High-voltage transmission

Power stations send electricity along cables at a very high voltage (tens or hundreds of thousands of volts), and step-down transformers reduce it for homes.

The reason is that $P = IV$. For the same power, a higher voltage means a **smaller current**. Power is wasted in the cables as heat, and this loss depends on the current (it is larger when the current is larger). A smaller current means much less power is wasted.

> **TRY IT**
>
> A power station transmits $100\ \text{kW}$. Compare the current at $230\ \text{V}$ and at $23\,000\ \text{V}$.

$I = \frac{P}{V}$: $\quad \frac{100\,000}{230} = 435\ \text{A} \quad \frac{100\,000}{23\,000} = 4.35\ \text{A}$

The current is a hundred times smaller at the higher voltage.

Note Academy