Cambridge AS & A Level · Physics 9702 · Notes

Magnetic fields A2

Read online at **pastopic.com/cambridge/physics-9702/notes/magnetic-fields**

Last checked 29 September 2026

Read first: **Electricity**, **Motion in a circle**, **Electric fields**

What you need to know

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

1. **Understand that a magnetic field is a field of force** made either by moving charges (a current) or by permanent magnets.
2. **Draw a magnetic field with field lines.**
3. **Understand that a current-carrying conductor in a magnetic field can feel a force.**
4. **Recall and use** $F = BIL \sin\theta$, finding the direction of the force with Fleming's left-hand rule.
5. **Define magnetic flux density** B as the force per unit current per unit length on a wire placed at right angles to the field.
6. **Find the direction of the force on a charge moving in a magnetic field.**
7. **Recall and use** $F = BQv \sin\theta$**.**
8. **Explain where the Hall voltage comes from**, derive $V_H = \frac{BI}{ntq}$ (t = thickness) and use it.
9. **Understand how a Hall probe measures magnetic flux density.**
10. **Describe the motion of a charged particle** moving at right angles to a uniform magnetic field: a circle at constant speed.
11. **Explain how crossed electric and magnetic fields select particles of one velocity.**
12. **Sketch the field patterns** of a long straight wire, a flat circular coil and a long solenoid, and know that an iron (ferrous) core makes a solenoid's field stronger.
13. **Explain why two current-carrying conductors exert forces on each other**, and find the directions of those forces.
14. **Define magnetic flux** as flux density times the area at right angles to the field, **recall and use** $\Phi = BA$, and use **magnetic flux linkage** $N\Phi$.
15. **Understand and explain experiments showing** that a changing flux induces an e.m.f., that the e.m.f. opposes the change that causes it, and which factors decide its size; **recall and use Faraday's and Lenz's laws.**

Current, $I = Anvq$ and potential difference come from Electricity; centripetal force from Motion in a circle; $E = \frac{V}{d}$ and $F = qE$ from Electric fields.

Understand it

A magnetic field

A **magnetic field** is a region where a force acts on a magnetic pole, on a current-carrying conductor or on a moving charge. Permanent magnets make one; so does any current, because a current is moving charge.

Field lines show the field:

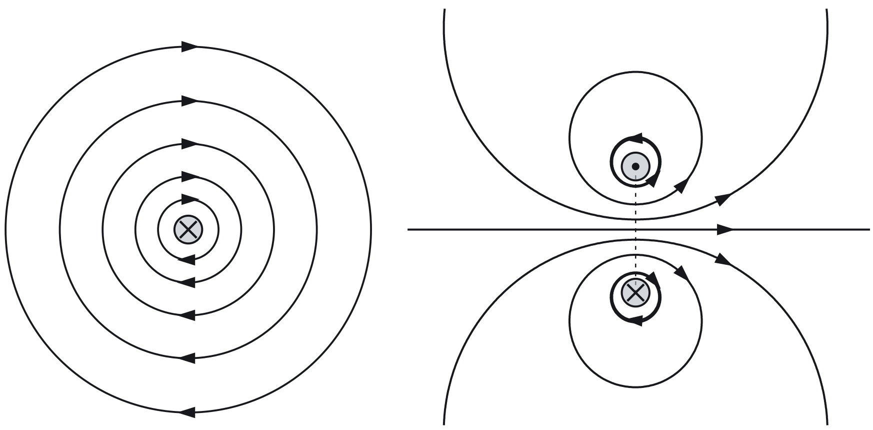
- the arrow on a line shows the direction a free north pole would be pushed (outside a magnet, from its north pole to its south pole);
- the closer the lines, the stronger the field; equally spaced parallel lines mean a **uniform** field;
- lines never cross.

On a flat page, a field pointing **out of the page** is drawn as dots (⊙, the point of an arrow coming towards you) and a field **into the page** as crosses (⊗, the tail feathers of an arrow going away). The same symbols show a current out of or into the page in a wire seen end-on.

Fields made by currents

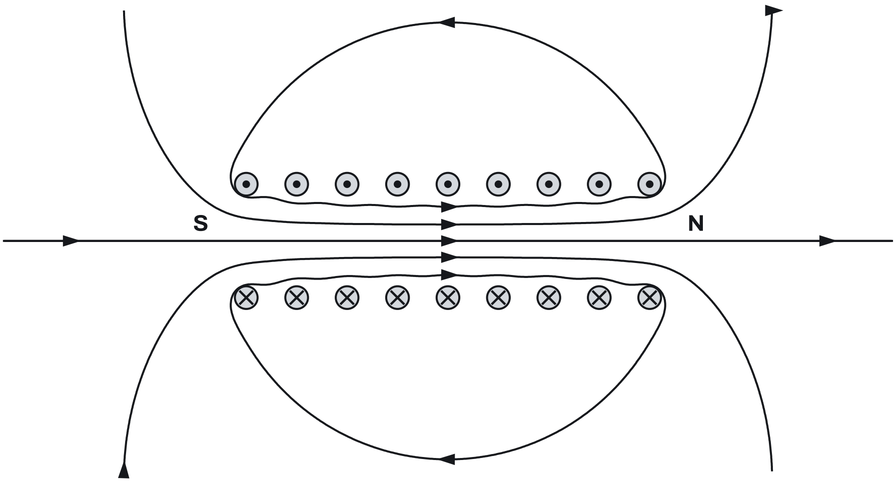
Right-hand grip rule: grip the wire with your right hand, thumb along the (conventional) current; your fingers curl the way the field lines go.

- **Long straight wire**: the lines are **circles centred on the wire**, getting further apart as you move out, because the field gets weaker with distance. A current into the page gives clockwise circles; out of the page, anticlockwise.
- **Flat circular coil**: loops round each side of the wire; through the middle, nearly straight lines along the axis.
- **Long solenoid**: inside, the lines are straight, parallel and evenly spaced: a strong, **uniform** field along the axis. Outside the field is weak and looks like a bar magnet's. The end the lines come out of acts as a north pole.



straight wire, current into the page
clockwise circles, further apart outwards

flat coil seen edge-on
top side: out of the page · bottom side: into the page



top row: current out of the page · bottom row: into the page

A **ferrous core** (iron) inside a solenoid makes its field much stronger: the iron is magnetised and adds its own field in the same direction.

Force on a current-carrying conductor

A wire carrying a current across a magnetic field feels a force. It is largest when the wire is at right angles to the field and zero when the wire is parallel to it:

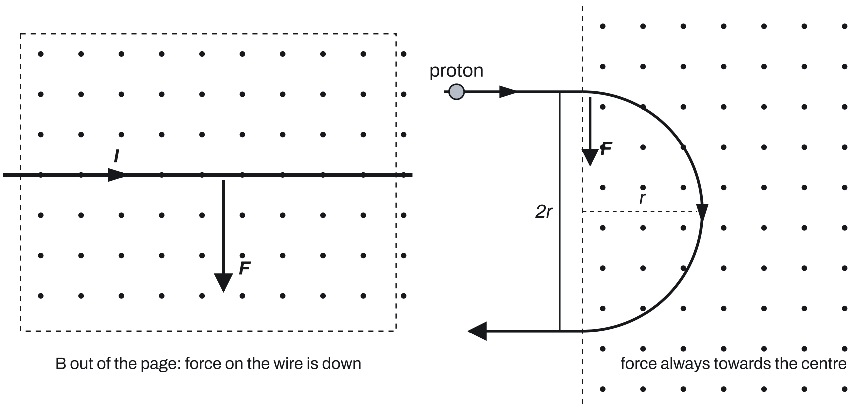
$$F = BIL\sin\theta$$

θ is the angle between the wire (the current) and the field, and L is the length of wire **inside** the field. A 0.20 m wire carrying 3.0 A at right angles to a 0.050 T field feels 0.030 N; at 30° to the field it feels half that, 0.015 N.

Fleming's left-hand rule gives the direction. Hold the thumb and first two fingers of your left hand at right angles to each other:

- **F**irst finger: **F**ield (north to south);
- se**C**ond finger: **C**urrent (conventional, $+$ to $-$);
- thu**M**b: the force, and so the **M**otion.

The force is always at right angles to **both** the current and the field; at an angle, use the rule with the component of the current across the field.



B out of the page: force on the wire is down
force always towards the centre

Magnetic flux density B is defined from this force: it is the **force per unit current per unit length** on a wire placed **at right angles** to the field,

$$B = \frac{F}{IL}.$$

Its unit is the **tesla**: 1 T is the flux density that gives a force of 1 N on each metre of wire carrying 1 A at right angles to the field ($1\ \mathrm{T} = 1\ \mathrm{N\ A^{-1}\ m^{-1}}$).

A **coil of N turns** has N wires side by side, so the force on one side is $NBIL$. On a rectangular coil, the forces on opposite sides are equal and opposite but act along different lines, so they make a **turning effect** (a couple), as in a motor.

Forces between currents

Each of two parallel wires sits in the **field made by the other**, and its current crosses that field at right angles, so each feels a force $F = BIL$.

- Currents in the **same** direction **attract**; currents in **opposite** directions **repel**.
- The two forces are **equal and opposite** (Newton's third law), even when the currents are different.
- Reverse **both** currents and the forces don't change direction: each field and each current reverses, so the two changes cancel.

From first principles: find the field of wire 1 at wire 2 with the right-hand grip rule, then use the left-hand rule on wire 2's current. The turns of a coiled spring carry current the same way, so they attract and the spring gets shorter.

Force on a moving charge

A current is moving charges, so each charge Q moving at speed v across a field feels a force

$$F = BQv\sin\theta$$

where θ is the angle between the velocity and the field. An electron at 1.0×10^{7} m s^{-1} at right angles to a 5.0 mT field feels $5.0 \times 10^{-3} \times 1.60 \times 10^{-19} \times 1.0 \times 10^{7} = 8.0 \times 10^{-15}$ N.

- **Direction**: the left-hand rule, with the second finger along the **current**. For a positive charge the current is along its velocity; for a **negative** charge (an electron) point the second finger **opposite** to its velocity.
- **No force** if the charge is **at rest**, or if it moves **parallel** (or antiparallel) to the field.
- The force is always **at right angles to the velocity**, so it does no work: it changes the direction of motion but **never the speed** or the kinetic energy.

Circular motion in a magnetic field

A charged particle moving at right angles to a uniform field has a force of constant size at right angles to its velocity: exactly what is needed for motion in a **circle at constant speed**. The magnetic force is the centripetal force:

$$BQv = \frac{mv^2}{r} \quad \Rightarrow \quad r = \frac{mv}{BQ}$$

- Faster or heavier: a **bigger** circle; stronger field or bigger charge: a **smaller** one.
- The time for one orbit, $T = \frac{2\pi r}{v} = \frac{2\pi m}{BQ}$, does **not** depend on the speed or the radius.
- Opposite charges curve opposite ways. A particle entering a field region at right angles to its straight edge goes round a **semicircle** and leaves moving back the way it came, a distance $2r$ (the diameter) from where it entered.
- With v from an accelerating voltage ($\frac{1}{2}mv^2 = QV$), $r = \frac{mv}{BQ}$ gives the **specific charge** $\frac{Q}{m} = \frac{2V}{B^2r^2}$.

Velocity selection

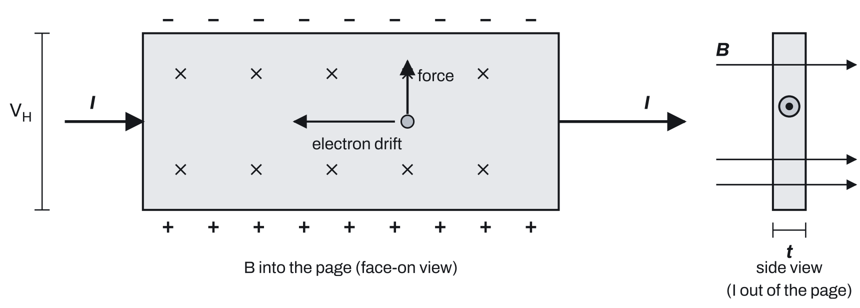
Add an electric field at right angles to both the velocity and the magnetic field, set so the electric force is **opposite** to the magnetic force. A particle goes straight through, undeflected, when the two forces are equal:

$$QE = BQv \quad \Rightarrow \quad v = \frac{E}{B}$$

Q cancels, so the selected speed doesn't depend on the charge **or** the mass. A **faster** particle has a bigger magnetic force (the electric force is unchanged) and bends the way the magnetic force points; a **slower** one bends the way the electric force points. Between plates, $E = \frac{V}{d}$, so $v = \frac{V}{Bd}$. With $E = 3.0 \times 10^4$ V m^{-1} and $B = 0.015$ T, only particles at 2.0×10^6 m s^{-1} get through a narrow exit slit.

The Hall effect

Pass a current I along a thin slice of conductor or semiconductor, with a magnetic field at right angles to its large face.



1. The moving charge carriers feel a magnetic force Bqv at right angles to the current and the field, so they are pushed to one side of the slice.
2. Charge builds up there, and the opposite side is left with the opposite charge. This sets up an **electric field** across the slice, and a voltage between the two sides: the **Hall voltage** V_H.
3. The electric force on the carriers grows until it **balances** the magnetic force. Then no more carriers are pushed aside and V_H is **steady**.

Deriving V_H. Let the slice have width d (across which V_H appears) and thickness t (measured along the field). At balance,

$$\frac{qV_H}{d} = Bqv \quad \Rightarrow \quad V_H = Bvd.$$

The current is $I = Anvq$ with cross-section $A = dt$, so $v = \frac{I}{ndtq}$. Substituting:

$$V_H = \frac{BI}{ntq}$$

n is the **number density of charge carriers** (carriers per m³) and q the charge on each.

- $V_H \propto \frac{1}{n}$: a metal has so many free electrons (around 10^{28} to 10^{29} per m³) that they drift very slowly and V_H is far too small to measure. A **semiconductor** has a much **smaller** n, so the carriers drift faster and V_H is much **larger**.
- $V_H \propto \frac{1}{t}$: a **thin** slice gives a bigger, measurable V_H.

A Hall probe is such a slice with a steady current, so $V_H \propto B$ and, once calibrated, it measures flux density, steady fields included. The reading is **largest** with the field at right angles to the slice's face and **zero** with it parallel, so rotate the probe to the maximum reading.

Magnetic flux and flux linkage

Magnetic flux Φ through an area is the flux density times the area **at right angles** to the field:

$$\Phi = BA$$

Its unit is the **weber** (Wb): $1\ \mathrm{Wb} = 1\ \mathrm{T\ m}^2$. If the field is at an angle to the area, only the area at right angles to it counts (or, equally, only the component of B at right angles to the area).

Magnetic flux linkage of a coil of N turns is $N\Phi$: each turn links the flux, so the total is N times as big. For a coil of 150 turns and radius 1.5 cm at right angles to a 0.20 T field, $\Phi = 0.20 \times \pi \times 0.015^2 = 1.41 \times 10^{-4}$ Wb and $N\Phi = 2.12 \times 10^{-2}$ Wb.

Electromagnetic induction

Push a magnet into a coil connected to a centre-zero meter: the meter flicks one way while the magnet moves, reads zero while it is still, and flicks the other way as it is pulled out. An **e.m.f. is induced whenever the flux linking a circuit changes**: by moving a magnet or a coil, by switching or changing a current in a nearby coil, or by a wire moving across a field (cutting flux). It is **bigger** with faster movement, a stronger magnet, more turns or a bigger area: anything that makes the flux linkage change **faster**. In a complete circuit it drives a current.

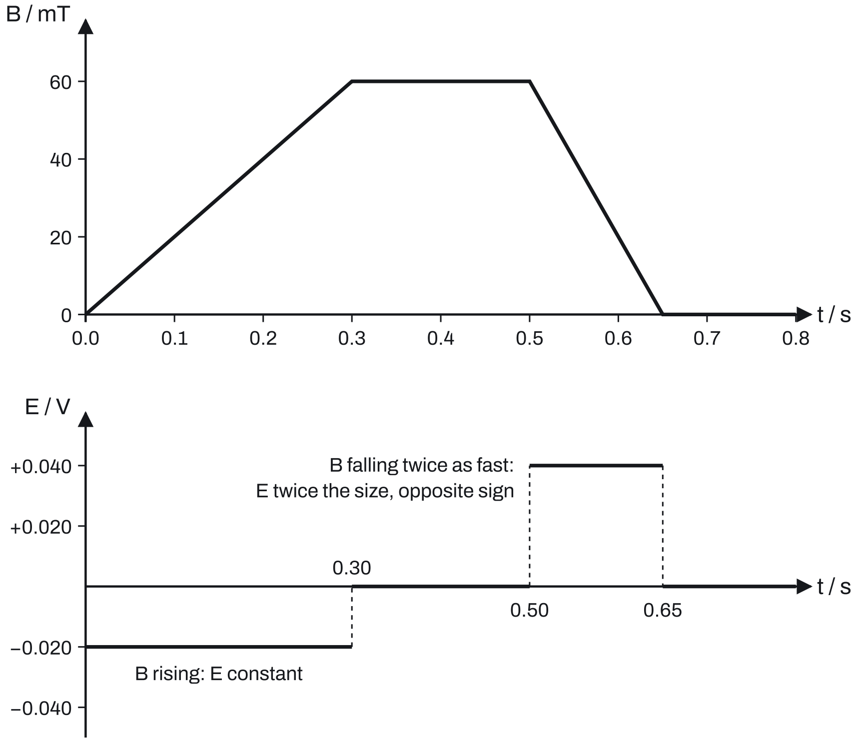
Faraday's law: the induced e.m.f. is proportional to (and in SI units equal to) the **rate of change of magnetic flux linkage**.

Lenz's law: the **direction** of the induced e.m.f. is such that it tends to produce effects that **oppose the change** that caused it.

Together:

$$E = -\frac{d(N\Phi)}{dt}$$

The minus sign is Lenz's law. For a steady change, $E = \frac{\Delta(N\Phi)}{\Delta t}$ in size. On a graph of B (or Φ) against time, the e.m.f. is proportional to the **gradient**: largest where the graph is steepest, zero where it is flat, and opposite in sign while the flux rises and while it falls.



Why Lenz's law must be true: energy. If the induced current helped the change, it would get energy from nothing. Instead it pushes back: a magnet pushed into a coil is repelled by the coil's induced field, so you do work pushing it, and that work becomes electrical energy (then thermal energy in the resistance).

Using Lenz's law means asking what the change is (then the right-hand grip rule turns the induced field into a current direction):

- a flux that is **increasing** through a coil: the induced current makes a field **against** it;
- a flux that is **decreasing**: the induced current makes a field **in the same direction**, to keep it up;
- a conductor **moving** through a field: the induced current makes a force (by the left-hand rule) that **opposes the motion**.

Cutting flux

A straight conductor of length l moving at speed v at right angles to a field sweeps out area lv each second, so it cuts flux Blv each second:

$$E = Blv$$

In general, e.m.f. $=$ flux cut per second $= B\times$ (area swept per second). A metal rod 1.5 m long spinning about one end at 4.0 revolutions per second in a vertical field of 50 μT sweeps $\pi \times 1.5^2$ m² each turn, so $E = 50 \times 10^{-6} \times \pi \times 1.5^2 \times 4.0 = 1.41 \times 10^{-3}$ V between its ends.

To find which end of a moving conductor is **positive**, use the left-hand rule on the **opposing force**: the force on the rod from the induced current must oppose its motion, so the rule tells you which way that current flows in the rod. Inside the rod, as inside any source of e.m.f., current flows from the negative end to the **positive** end.

Eddy currents and damping. A solid metal plate or ring moving through a field has currents induced in it; by Lenz's law they oppose the motion, and they heat the metal, so the motion is **damped**. Slots in the plate, or a break in the ring, make the currents much smaller (or zero): far less damping. A magnet oscillating in a coil joined to a resistor is damped the same way; a bigger resistance means less current and less damping.

Key facts and formulas

"Given" means it is on the data sheet printed in the paper (the Hall voltage is on the Paper 4 sheet). "Learn it" means you must remember it.

Formula	Status
Force on a current $F = BIL\sin\theta$; on a coil side of N turns $F = NBIL$	Learn it
Flux density $B = \dfrac{F}{IL}$ (wire at right angles to the field); $1\ \mathrm{T} = 1\ \mathrm{N\ A^{-1}\ m^{-1}}$	Learn it
Force on a moving charge $F = BQv\sin\theta$	Learn it
Radius in a field $r = \dfrac{mv}{BQ}$ (from $BQv = \dfrac{mv^2}{r}$); period $T = \dfrac{2\pi m}{BQ}$	Learn it
Velocity selector $v = \dfrac{E}{B}$ (from $QE = BQv$)	Learn it
Hall voltage $V_H = \dfrac{BI}{ntq}$	Given
Current $I = Anvq$	Given
Magnetic flux $\Phi = BA$ (A at right angles to B); $1\ \mathrm{Wb} = 1\ \mathrm{T\ m^2}$	Learn it
Flux linkage $N\Phi = NBA$	Learn it
Faraday and Lenz: $E = -\dfrac{d(N\Phi)}{dt}$; for a steady change $E = \dfrac{\Delta(N\Phi)}{\Delta t}$	Learn it

Formula	Status
Conductor cutting flux $E = Blv$; e.m.f. $=$ flux cut per second	Learn it
$E = \dfrac{V}{d}$, $F = QE$, $\frac{1}{2}mv^2 = QV$, $F = \dfrac{mv^2}{r}$	Learn it
$e = 1.60 \times 10^{-19}$ C, $m_e = 9.11 \times 10^{-31}$ kg, $m_p = 1.67 \times 10^{-27}$ kg, $1\ \mathrm{u} = 1.66 \times 10^{-27}$ kg, $g = 9.81$ m s^{-2}	Given

How to do it

In the Paper 4 questions we have tagged for this topic (32 different questions, 2021–2025; 11 more appear on two papers), the types came up this often. 27 of the 32 questions mix two or more types, so the counts add up to more than 32.

Question type	Questions
Definitions and laws	20
Lenz's law: directions and explanations	11
Induced e.m.f. from a changing flux linkage	10
Fields due to currents and forces between wires	8
Charged particles moving in a magnetic field	5
E.m.f. in a moving conductor (cutting flux)	4
The Hall effect and Hall probes	4
Force on a current-carrying conductor	4
Velocity selection	3

1. Definitions and laws (20 questions)

Learn these, in meaning; each phrase in bold is usually a mark.

- **Magnetic field**: a region where a **force** acts on a **current-carrying conductor**, a **moving charge** or a magnetic pole.
- **Magnetic flux density** (and **the tesla**): the **force per unit current per unit length** on a wire **carrying a current at right angles to the field**. The tesla: 1 N per ampere per metre.
- **Magnetic flux**: the **product of flux density and the area at right angles to the field**. Not "the number of field lines".
- **Magnetic flux linkage**: the **number of turns** times the **flux through the coil**.
- **Faraday's law**: the induced e.m.f. is **proportional to the rate of change of** magnetic flux linkage.
- **Lenz's law**: the **direction of the induced e.m.f.** is such as to **oppose the change** that causes it.

Variation you will meet: the **conditions for a force on a wire**: a current in it, and not parallel to the field.

2. Lenz's law: directions and explanations (11 questions)

The rules are in "Using Lenz's law" and "Eddy currents and damping" above. Quoting the laws alone earns nothing: apply them to the parts of this apparatus.

1. **Say what changes**: which flux, linking which coil, ring or plate, and why.
2. **Say where an e.m.f. is induced** (Faraday), and that it drives a **current** only in a **complete** circuit.
3. **Say what the current does**: it feels a **force** in the field, or heats a resistance, taking **energy** from the motion.
4. **Use Lenz's law for the direction**: the force opposes the motion, or the induced field opposes the change in flux.

Variations you will meet:

- **Which end of a moving rod is positive**: as in "Cutting flux": the opposing force fixes the current in the rod, which flows **towards the positive end inside** it.
- **A coil connected to a resistor slows down** (a generator with a load): forces on the induced current oppose the rotation; kinetic energy becomes thermal energy.
- **A ring that jumps when a current is switched on** in a coil beneath it: the rising flux induces a current in the ring whose field opposes the coil's, so the ring is repelled. Reverse the supply and both fields reverse: it **still** jumps.
- **Damping of a swinging plate, ring or magnet**, and why a slotted plate or cut ring swings longer: see "Eddy currents and damping".
- **Joining a coil's terminals**, or **pulling a closed coil out of a field**: now a current flows, heating the coil, and the forces on it oppose the motion, so work must be done.

3. Induced e.m.f. from a changing flux linkage (10 questions)

1. **Flux linkage**: $N\Phi = NBA$, with A in m² (1 cm² $= 10^{-4}$ m²) and B in T. Give the unit Wb.
2. **E.m.f.**: $E = \dfrac{\Delta(N\Phi)}{\Delta t}$. For B changing, $E = NA\dfrac{\Delta B}{\Delta t}$: NA times the **gradient** of the B–t graph.
3. **Sketching E against t** from a B–t (or Φ–t, or current–t) graph:
   - straight sloping section: **constant** E, sized by the gradient (twice as steep, twice the e.m.f.);
   - flat section: $E = 0$;
   - rising and falling sections: **opposite signs**.

Variations you will meet:

- **Sinusoidal B or current**: E follows the gradient, so it is sinusoidal **a quarter-cycle out of step**: zero at the peaks of B, largest where B crosses zero. For the maximum, draw a tangent at the steepest point and multiply its gradient by NA.

- **A coil moved through a solenoid** with a steady current: inside, B is uniform, so the flux linkage is constant (a horizontal line) and $E = 0$.
- **Flux reversed**: the change is from $+N\Phi$ to $-N\Phi$, so $\Delta(N\Phi) = 2N\Phi$.
- **Two coils in one solenoid**: a coil wider than the solenoid links only the solenoid's area; flux linkage then multiplies by each coil's turns.
- **A generator rotated faster**: the peak e.m.f. rises in proportion to the speed; the period falls in the same ratio.
- **Hall probe readings as the field**: get B from V_H first, then use $E = NA\dfrac{\Delta B}{\Delta t}$.

4. Fields due to currents and forces between wires (8 questions)

- **Field lines of a straight wire**: at least four **concentric circles**, **further apart** further out, arrows by the right-hand grip rule.
- **Solenoid**: the field is **uniform** inside (the same at any two points) and weaker outside, where it points the **opposite** way to inside.
- **Why two wires exert forces, and which way**: give the explanation and rules in "Forces between currents" (each wire is in the other's field), not just the directions. The same section covers different currents, reversed currents and a coiled spring.
- **Force per unit length**: $\dfrac{F}{L} = BI$, with B the field **of the other wire**. If wire Q, with 6.0 A, is in a field of 1.8 mT from wire P, the force per metre on Q is $1.8 \times 10^{-3} \times 6.0 = 1.1 \times 10^{-2}$ N m^{-1}.
- **Different currents**: equal and opposite forces mean $B_P I_Q = B_Q I_P$, which gives an unknown current or field.
- **A ferrous core**: increases the flux density, so any force (or torque) that depends on it increases.

5. Charged particles moving in a magnetic field (5 questions)

1. **Force**: $F = BQv$; direction by the left-hand rule (second finger **against** the velocity for a negative charge).
2. **Path**: a circular arc in the field, straight lines outside. The force (and acceleration) points **towards the centre**.
3. **Radius**: $BQv = \dfrac{mv^2}{r}$, so $r = \dfrac{mv}{BQ}$. If the particle does a semicircle, the gap between its paths in and out is $2r$.

Variations you will meet:

- **Two situations with no force on a charge**: it is at rest, or it moves parallel to the field.
- **"Show that $B = \dfrac{2\pi m}{QT}$"**: write $BQv = \dfrac{mv^2}{r}$, substitute $v = \dfrac{2\pi r}{T}$ and simplify. T doesn't depend on r or v: two identical particles at different speeds in the same field take the same time per orbit.
- **A different particle**: compare $r = \dfrac{mv}{BQ}$; an opposite charge curves the **other way**.

- **Specific charge**: eliminate v from $QV = \frac{1}{2}mv^2$ and $r = \dfrac{mv}{BQ}$ to get $\dfrac{Q}{m} = \dfrac{2V}{B^2r^2}$. A much smaller $\frac{Q}{m}$ (an alpha particle rather than an electron) would need an impractically large circle.
- **Direction of the field** from a drawn path: the force points towards the centre of the curve; work the left-hand rule backwards.

6. E.m.f. in a moving conductor (cutting flux) (4 questions)

1. **Flux cut**: $\Phi = B\times$ area swept. A rod rotating about one end sweeps a circle of radius equal to its length; a moving wing or rod sweeps (length $\times$ distance moved).
2. **E.m.f.** $=$ flux cut per second: for a rotating rod, (flux per turn) $\times$ (turns per second); for a straight rod, $E = Blv$.
3. **Which end is positive**: see type 2. Use the component of the field that is at right angles to the motion and the rod (for an aircraft flying level, the **vertical** component of the Earth's field).

For example, a plane with wingspan 30 m flying level at 250 m s^{-1} where the vertical field is 40 μT has $E = 40 \times 10^{-6} \times 30 \times 250 = 0.30$ V between its wingtips.

Variations you will meet:

- **Given e.m.f., find the speed**: $v = \dfrac{E}{Bl}$.
- **Rod accelerating from rest**: $E = Blat$, a straight line through the origin on an E–t graph.
- **A spinning disc** between its axle and rim: the same as a rod of length equal to the radius, rotating about one end.

7. The Hall effect and Hall probes (4 questions)

1. **Explaining** V_H: give steps 1–3 of "The Hall effect" above, ending with the electric and magnetic forces in balance.
2. **Symbols**: n is the number density of charge carriers; t is the thickness measured **along the field** (the dimension between the two faces the field passes through); q is the charge on each carrier.
3. **Calculation**: $V_H = \dfrac{BI}{ntq}$ with t in m. For $B = 0.050$ T, $I = 16$ mA, $n = 5.0 \times 10^{21}$ m^{-3} and $t = 0.20$ mm:
   $$V_H = \frac{0.050 \times 0.016}{5.0 \times 10^{21} \times 0.20 \times 10^{-3} \times 1.60 \times 10^{-19}} = 5.0 \times 10^{-3} \text{ V.}$$

Variations you will meet:

- **Which face the carriers collect on**: the left-hand rule, with electrons moving opposite to the current.
- **Why a semiconductor, why thin**: a **smaller** n than a metal and a small t both give a larger V_H.
- **Reading zero, then maximum as the probe turns**: see "The Hall effect".
- **Sketching V_H against time**: $V_H \propto B$, so the V_H graph has the **same shape** as the B graph (unlike an induced e.m.f., which follows the gradient). Use one known pair of values to scale it.

8. Force on a current-carrying conductor (4 questions)

1. $F = BIL\sin\theta$, with θ between the wire and the field. With N turns, multiply by N.
2. Direction: left-hand rule. The force is **vertical** when the current and field are both horizontal (it is at right angles to both).

Variations you will meet:

- **A coil on a balance, a magnet on a top-pan balance**: the magnetic force on the coil and the force on the magnet are equal and opposite (Newton's third law). The balance reading changes by Δm, so $F = \Delta m\, g$ and $B = \frac{\Delta m\, g}{NIL}$. For 25 turns, a 4.0 cm side in the field, 2.0 A and a change of 1.50 g: $B = \frac{1.50 \times 10^{-3} \times 9.81}{25 \times 2.0 \times 0.040} = 7.36 \times 10^{-3}$ T. If the balance reading rises, a newton meter holding the coil reads **less** by the same force.
- **Torque on a rectangular coil** of width w: the sides across the field feel equal, opposite forces $F = NBIL$; with the coil's plane at θ to the field, torque $= Fw\cos\theta$. For 80 turns, sides 6.0 cm long in a 0.020 T field, 0.50 A and width 2.0 cm: $F = 0.048$ N and torque $= 9.6 \times 10^{-4}\cos\theta$ N m, largest when the coil's plane is along the field and zero when it is at right angles.

9. Velocity selection (3 questions)

1. **Directions**: the electric force must be opposite to the magnetic force. Find the magnetic force with the left-hand rule, then set the electric field so the force on the particle points the other way (for a positive particle, E points the same way as the electric force).
2. **Balance**: $QE = BQv$, so $v = \frac{E}{B}$; with plates, $E = \frac{V}{d}$, so $v = \frac{V}{Bd}$.
3. **Say why it selects**: only at this speed are the forces equal; there is no m or Q in it, so any particle at that speed passes.

Variations you will meet:

- **Find B from kinetic energy**: $v = \sqrt{\frac{2E_k}{m}}$ first, then $B = \frac{V}{vd}$.
- **Faster or slower particles**: faster, magnetic force wins; slower, electric force wins; the path curves smoothly one way from where the fields start.
- **Direction of B from the plates**: the plate signs give the electric force; the magnetic force is opposite; the left-hand rule then gives the field.
- **After a circle question**: once B is known, the electric field that makes the particle go straight is $E = Bv$ (unit V m^{-1} or N C^{-1}).

Worked examples

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

- **M1** method mark: for a correct method, even if the numbers slip.
- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

A straight horizontal wire carries a current of 2.5 A. A 4.0 cm length of the wire lies in a uniform horizontal magnetic field of flux density 0.090 T, between the poles of a magnet. The wire makes an angle of 30° with the field lines.

(a) Define magnetic flux density. **[2]**

(b) Calculate the magnetic force on the wire. **[2]**

(c) The magnet rests on a top-pan balance. The force on the wire is upwards. State and explain how the balance reading changes when the current is switched on, and calculate the change in grams. **[3]**

(d) State the angle between the wire and the field that would give the largest force, and calculate this force. **[2]**

Solution

(a) The force per unit current per unit length **B1** on a wire carrying a current at right angles to the field. **B1**

(b) $F = BIL\sin\theta = 0.090 \times 2.5 \times 0.040 \times \sin 30^\circ$ **C1** $= 4.5 \times 10^{-3}$ N. **A1**

(c) By Newton's third law the wire pushes the magnet **down** with an equal force, **M1** so the reading **increases**. **A1** Change $= \dfrac{F}{g} = \dfrac{4.5 \times 10^{-3}}{9.81} = 4.59 \times 10^{-4}$ kg $= 0.459$ g. **A1**

(d) 90° (wire at right angles to the field). **B1** $F = 0.090 \times 2.5 \times 0.040 = 9.0 \times 10^{-3}$ N. **B1**

Example 2

A proton moving at 2.4×10^6 m s^{-1} enters a region of uniform magnetic field of flux density 0.12 T, at right angles to the field. The field points out of the page and the proton moves to the right as it enters, as in the third diagram in "Understand it".

(a) Calculate the magnetic force on the proton and state its direction as it enters. **[3]**

(b) Calculate the radius of its path and the time it spends in the field before leaving. **[4]**

(c) Two horizontal parallel plates, 1.5 cm apart, are now placed so that their electric field acts in the same region as the magnetic field. Determine the p.d. needed between the plates for the proton to pass straight through, and state which plate must be positive. **[3]**

(d) A slower proton enters the fields in (c). State and explain which way it is deflected. **[2]**

Solution

(a) $F = BQv = 0.12 \times 1.60 \times 10^{-19} \times 2.4 \times 10^{6}$ **C1** $= 4.6 \times 10^{-14}$ N **A1**, down the page (left-hand rule: field out of the page, current to the right). **B1**

(b) $BQv = \frac{mv^2}{r}$, so $r = \frac{mv}{BQ} = \frac{1.67 \times 10^{-27} \times 2.4 \times 10^{6}}{0.12 \times 1.60 \times 10^{-19}}$ **C1** $= 0.209$ m. **A1** It goes round a semicircle, so the time is $\frac{\pi r}{v} = \frac{\pi \times 0.209}{2.4 \times 10^{6}}$ **C1** $= 2.73 \times 10^{-7}$ s. **A1**

(c) For no deflection, $QE = BQv$, so $E = Bv = 0.12 \times 2.4 \times 10^{6} = 2.88 \times 10^{5}$ V m^{-1}. **C1** $V = Ed = 2.88 \times 10^{5} \times 0.015 = 4.32 \times 10^{3}$ V. **A1** The magnetic force is down, so the electric force must be up: the **lower** plate is positive. **B1**

(d) The electric force QE is unchanged but the magnetic force BQv is smaller, **M1** so the resultant force is upwards and the proton curves **up**, towards the upper (negative) plate. **A1**

Example 3

A flat coil of 250 turns, each of area 4.0 cm², is held with its plane at right angles to a uniform magnetic field. The flux density B rises steadily from zero to 60 mT between $t = 0$ and $t = 0.30$ s, stays constant until $t = 0.50$ s, then falls steadily to zero at $t = 0.65$ s.

(a) State Faraday's law of electromagnetic induction. **[2]**

(b) Calculate the maximum magnetic flux linkage of the coil. Give a unit. **[2]**

(c) Calculate the size of the e.m.f. induced in the coil in each of the three time intervals. **[3]**

(d) Sketch the variation with t of the induced e.m.f. from $t = 0$ to $t = 0.80$ s. **[3]**

Solution

(a) The induced e.m.f. is proportional **M1** to the rate of change of magnetic flux linkage. **A1**

(b) $N\Phi = NBA = 250 \times 0.060 \times 4.0 \times 10^{-4}$ **C1** $= 6.0 \times 10^{-3}$ Wb. **A1**

(c) 0 to 0.30 s: $E = \frac{6.0 \times 10^{-3}}{0.30} = 0.020$ V. **B1** 0.30 to 0.50 s: the flux linkage is constant, so $E = 0$. **B1** 0.50 to 0.65 s: $E = \frac{6.0 \times 10^{-3}}{0.15} = 0.040$ V. **B1**

(d) See the fifth diagram in "Understand it": a constant e.m.f. of 0.020 V from 0 to 0.30 s **B1**; zero from 0.30 s to 0.50 s and after 0.65 s **B1**; a constant 0.040 V from 0.50 s to 0.65 s, of the **opposite sign** to the first section. **B1**

Example 4

A metal rod of length 0.25 m rests across two horizontal parallel rails. The rails are joined at one end by a $1.5\ \Omega$ resistor, and there is a uniform vertical magnetic field of flux density 0.40 T. The rod is pulled along the rails at a constant speed of 3.0 m s^{-1}. The resistance of the rod and rails is negligible.

(a) Calculate the e.m.f. induced in the rod and the current in the resistor. **[3]**

(b) Use Lenz's law to explain why a force is needed to keep the rod moving at constant speed, and calculate this force. **[3]**

(c) Show that the rate at which work is done pulling the rod equals the power dissipated in the resistor. **[2]**

Solution

(a) The rod cuts flux at a rate Blv: $E = 0.40 \times 0.25 \times 3.0$ **C1** $= 0.30$ V. **A1** $I = \dfrac{E}{R} = \dfrac{0.30}{1.5} = 0.20$ A. **A1**

(b) The induced current in the rod is at right angles to the field, so the rod feels a magnetic force; by Lenz's law this force **opposes the motion**. **B1** To keep the speed constant, an equal pulling force is needed. **B1** $F = BIL = 0.40 \times 0.20 \times 0.25 = 0.020$ N. **A1**

(c) Rate of doing work $= Fv = 0.020 \times 3.0 = 0.060$ W. **B1** Power in the resistor $= I^2R = 0.20^2 \times 1.5 = 0.060$ W: the same, as energy is conserved. **B1**

Common mistakes

- **Mixing up B, Φ and $N\Phi$.** Reports in March 2021 and June 2023 found flux defined as flux density (or the other way round), flux defined as "a number of field lines", and flux linkage given as one or the other alone. Learn the three definitions and units separately.
- **Vague definitions of B.** In November 2021 and 2022 and June 2021, candidates missed "per unit current" or "per unit length", defined the tesla with units instead of quantities, or left it unclear **what** is at right angles to the field (the current or wire, not "it").
- **Lenz's law wrong way round.** June 2021, March 2022 and June 2022: Lenz's law gives the **direction** of the induced **e.m.f.**, not its size, and an e.m.f. does not "flow". The changing flux linkage induces the e.m.f.; only then, in a complete circuit, is there a current.
- **Quoting laws instead of applying them.** June 2021, June 2022 and November 2022: say **where** the flux changes and **where** the e.m.f. and current are, for this apparatus. In a spring carrying a current, the forces come from the currents in neighbouring turns, not from induction (June 2021).
- **Using the area under a graph.** The induced e.m.f. depends on the **gradient** of the B–t graph, not the area under it (March 2021); use the steepest part for the maximum (March 2023).
- **Hall voltage explained by induction.** In March 2023 many thought V_H comes from cutting flux; it comes from the magnetic force on the moving carriers. And semiconductors are used because they have a **smaller n than metals**, not just "small n" (June 2021, March 2023).

- **Slips in $F = BIL\sin\theta$.** November 2021: $\cos\theta$ used, or the angle ignored. November 2022: the number of turns left out, and the force equated to the newton meter reading rather than the change on the balance.
- **Forces between wires.** June 2022: asked **why** two wires exert forces, many gave only directions. June 2023: many forgot that opposite currents repel, or could not show it with the left-hand rule.
- **Particle paths and specific charge.** March 2025: paths drawn with a kink where the particle enters the field, with changing curvature, or bent the wrong way; the path should curve smoothly one way from where the field starts. June 2021: B or r not squared in $\frac{2V}{B^2r^2}$.

How to get the marks

- **Definitions**: every bold phrase in type 1 is a mark.
- **Calculations**: the **C1** is for the right equation with numbers in; the **A1** is the answer. Convert cm², mm and mT first. Give 2 or 3 significant figures.
- **"Give a unit"**: T for flux density, Wb for flux and flux linkage, V for e.m.f., N m^{-1} for force per unit length, V m^{-1} (or N C^{-1}) for an electric field.
- **"Show that"**: write the starting equation (for example $BQv = \frac{mv^2}{r}$), show each substitution, and give the answer to one more significant figure than printed.
- **Directions**: name the rule you used and state the result plainly ("into the page", "end X is positive").
- **"Explain" questions on induction**: separate points in the order of type 2's steps, naming the parts of the apparatus.
- **"Suggest, with a reason"**: give the effect **and** a physics reason ("the torque increases because the ferrous core increases B").
- **Field-line sketches**: shape, spacing and arrows are marked separately.
- **Graph sketches**: mark key times and values; keep signs, relative sizes and (for sinusoids) the phase right.

Quick check

1. A 0.15 m length of wire carrying 4.0 A lies at right angles to a uniform field of 0.25 T. Calculate the force on it.
2. An electron moves at 5.0×10^6 m s^{-1} at right angles to a field of 2.0 mT. Calculate the radius of its path.
3. A Hall probe reads 12 mV in a field of 40 mT with its face at right angles to the field. What does it read, in the same position, in a field of 25 mT? What would it read with its face parallel to the field?
4. A coil of 120 turns and radius 2.0 cm is at right angles to a field of 0.15 T. Calculate its flux linkage. The field is reversed steadily in 0.050 s. Calculate the average e.m.f. induced.
5. Two long parallel wires carry currents in opposite directions. Do they attract or repel? Explain why there is a force at all.

Answers

1. $F = BIL = 0.25 \times 4.0 \times 0.15 = 0.15$ N.
2. $r = \dfrac{mv}{BQ} = \dfrac{9.11 \times 10^{-31} \times 5.0 \times 10^{6}}{2.0 \times 10^{-3} \times 1.60 \times 10^{-19}} = 1.42 \times 10^{-2}$ m (1.42 cm).
3. $V_H \propto B$ for a fixed current and orientation: $12 \times \dfrac{25}{40} = 7.5$ mV. With the face parallel to the field the reading is 0.
4. $N\Phi = NBA = 120 \times 0.15 \times \pi \times 0.020^2 = 2.26 \times 10^{-2}$ Wb. Reversing changes the linkage by twice this, so $E = \dfrac{2 \times 2.26 \times 10^{-2}}{0.050} = 0.905$ V.
5. They repel. Each wire is in the magnetic field made by the other, and its current is at right angles to that field, so it feels a force BIL; the two forces are equal and opposite.

Past questions to try

- **9702/42/O/N/22 Q7**: a coil in a magnet on a top-pan balance, and the newton meter reading.
- **9702/42/F/M/24 Q5**: the period of a charged particle's circle, then an electric field to make it go straight.
- **9702/42/M/J/24 Q7**: flux linkage and the e.m.f. from a sinusoidally varying field.
- **9702/42/M/J/23 Q6**: flux through a spinning disc, the e.m.f., and Lenz's law for the current's direction.