

Magnetic Fields

A2 Physics ■ Topic 20

A-Level Physics



What we will cover

- 1 Magnetic fields and field lines
- 2 Force on a current: $F = BIL$
- 3 Force on a charge: $F = BQv$
- 4 Parallel currents
- 5 Electromagnetic induction
- 6 Recap



A field that acts on moving charge

A **magnetic field** is a region where a moving charge (or a **current**) feels a **force** .

There are two ways to make one.

moving charges

usually a current in a wire

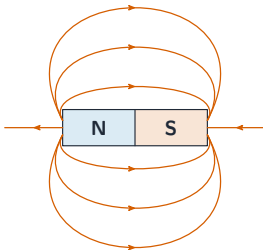
permanent magnets

tiny atomic currents
inside the material

Both are the same thing underneath: a magnetic field is made by **moving charge**, whether it flows along a wire or circulates inside an atom.

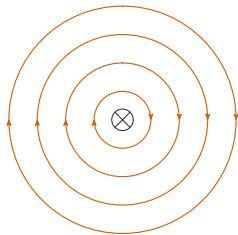
The field of a bar magnet

field lines run from **N** to **S** outside the magnet



Field lines run from **N** to **S** outside the magnet, and never cross. Where they crowd together the field is **strongest** – at the poles.

Field around a long straight wire

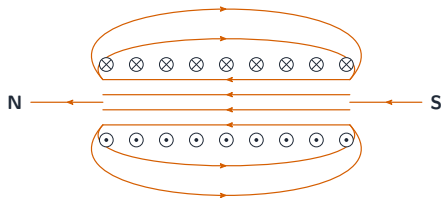


⊗ current I
into the page

circular field lines (right-hand grip rule)

*Field around a long straight wire – **right-hand grip rule***

field nearly uniform inside, spreads out like a bar magnet outside

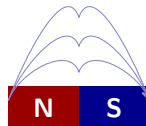


Field of a solenoid

The field is **circles** around the wire, closer together near it. Grip the wire with the right hand, thumb along the current, and the fingers curl the way the field points.

Field-line rules

- **field lines** run N to S outside a magnet (S to N inside – closed loops)
- lines never cross
- closer lines $\Rightarrow$ a stronger field – **flux density** B , in **tesla**
- a **long solenoid** has a uniform field inside and looks like a bar magnet outside



Four patterns you must recognise

bar magnet

curved $N \rightarrow S$ outside; strongest near the poles

straight wire

circles; **right-hand grip** : thumb = current, fingers = field

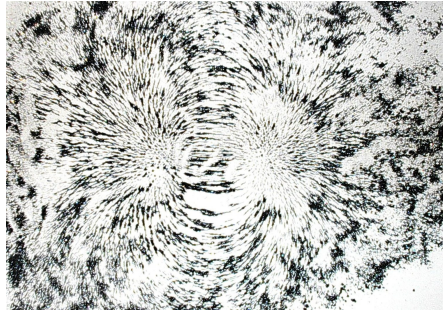
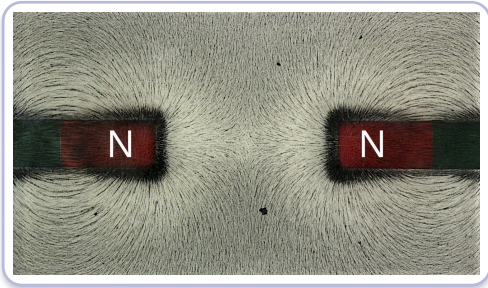
flat coil

field through the centre is at right angles; acts like a small bar magnet

solenoid

nearly **uniform** inside along the axis; outside falls off fast

The same patterns, in iron filings



Each filing turns to lie **along** the field, and they crowd where it is **strongest**. Between two like poles they part, leaving a **neutral point**.

An iron core multiplies the field

An **iron core** inside a solenoid greatly **increases** the field: the iron's atomic magnets line up and add to it. That is why **electromagnets** and **transformers** have iron cores.



Force on a current-carrying wire

$$F = BIL \sin \theta$$

θ is the angle between the wire and the field. Largest when the wire is at right angles ($F = BIL$); zero when the wire is along the field. This also **defines** the **magnetic flux density** B :

$$B = \frac{F}{IL} \quad (\text{wire} \perp \text{field}), \quad [B] = \text{T} = \text{N A}^{-1} \text{m}^{-1}$$

Fleming's left-hand rule

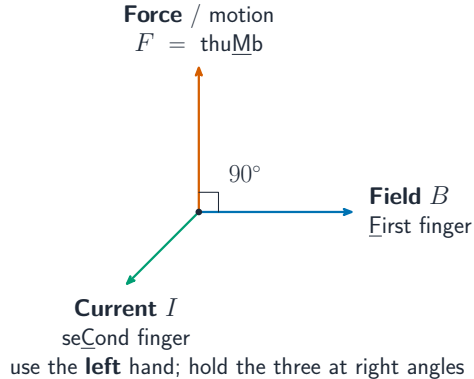
Use the **left** hand. Three fingers at right angles:

- **F**irst finger – **F**ield
- se**C**ond finger – **C**urrent
- **t**humb – **t**hrust (force)

$$L = 0.20 \text{ m}, I = 3.0 \text{ A}, B = 0.50 \text{ T}, \\ \theta = 90^\circ$$

$$F = BIL = 0.50 \times 3.0 \times 0.20 \\ = 0.30 \text{ N}$$

Fleming's left-hand rule: thumb = force



Hold the three at **right angles**: **F**orce on the thumb, **F**ield on the first finger, **C**urrent on the second. It is the **left** hand for a motor – the right hand is for a generator.



Force on a moving charge

$$F = BQv\sin\theta$$

Same left-hand rule – the second finger is the motion of a **positive** charge (reverse it for a negative one). In a wire that motion is the electrons' **drift velocity**. Largest when $v \perp B$; zero when v is along B .

The force is always perpendicular to the velocity, so it does **no work** – it changes direction, never speed.

Circular path in a uniform field

$BQv = mv^2/r$ gives

$$r = \frac{mv}{BQ}, \quad T = \frac{2\pi m}{BQ}$$

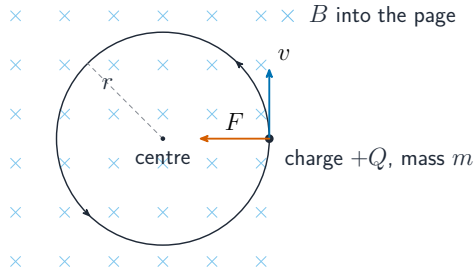
Here BQv is the **centripetal force**. T does **not** depend on speed – a faster particle goes in a bigger circle but takes the same time per turn, and its **kinetic energy** never changes because the force does no work. A

component of v along B is unchanged, so the path is a **helix**.

Proton: $m = 1.7 \times 10^{-27} \text{ kg}$, $v = 2.0 \times 10^6 \text{ m s}^{-1}$, $B = 0.50 \text{ T}$

$$r = \frac{mv}{BQ} \approx 0.043 \text{ m}$$

Circular motion in a uniform field



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

Circular path of a charged particle in a magnetic field

Hall effect – a voltage across a current

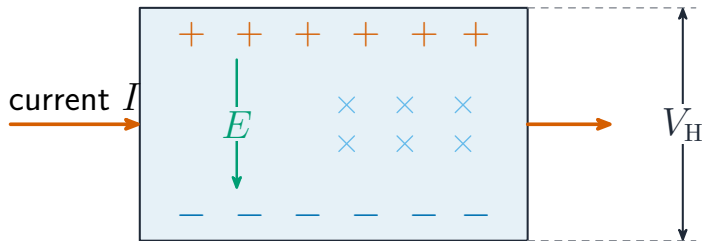
A slab carrying I , in a field B at right angles, develops a **Hall voltage**. Charges feel BQv_d , pile up, and make an electric field that opposes further build-up. At steady state $E = Bv_d$:

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

A **Hall probe** measures B : known current through a thin semiconductor, read V_H . Largest when the slab is at right angles to B .

Inside the Hall probe

Charges are pushed sideways until the electric field they build up balances the magnetic force – so V_H measures B .



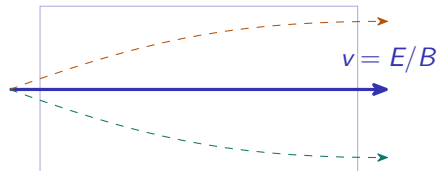
$\times$ B into the page $V_H = \frac{B I}{n t q}$

Velocity selector – only one speed gets through

Crossed E and B fields. The electric force qE and magnetic force qvB oppose. Net force is zero only when

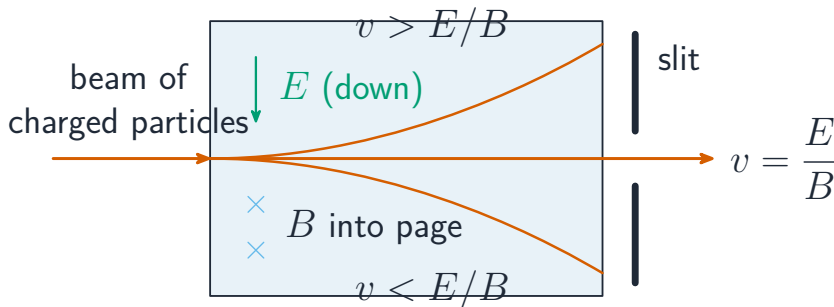
$$v = \frac{E}{B}$$

Particles at that speed go straight; faster or slower ones are deflected.



The selector, drawn

Only a charge with $v = E/B$ passes straight through: for it the electric and magnetic forces cancel exactly, whatever its charge or mass.





Two wires, each in the other's field

Using Fleming's left-hand rule:

same direction

currents **attract**

opposite directions

currents **repel**

This is the physics behind the SI definition of the **ampere** .



Flux and flux linkage

Magnetic flux through a flat area A :

$$\Phi = BA \cos \theta$$

Unit: **weber** , $\text{Wb} = \text{T m}^2$. For a **coil** of N turns the **flux linkage** is $N\Phi$. Flux changes if you change B , change A (a rod sliding on rails), or change orientation (a coil turning – the a.c. generator).

Faraday and Lenz

Faraday : the induced e.m.f. equals the rate of change of flux linkage

$$|\varepsilon| = N \frac{d\Phi}{dt}$$

Lenz : the induced e.m.f. **opposes the change** that makes it – conservation of energy. Combined:

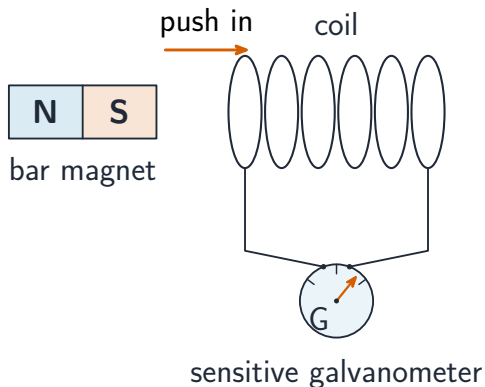
$$\varepsilon = - \frac{d(N\Phi)}{dt}$$

$N = 200$, $A = 0.010 \text{ m}^2$, B falls from 0.50 T to 0 in 0.20 s

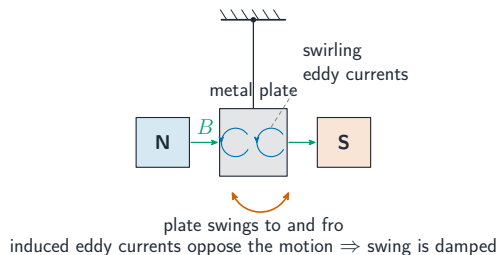
$$\Delta(N\Phi) = NBA = 1.0 \text{ Wb}$$

$$|\varepsilon| = \frac{1.0}{0.20} = 5.0 \text{ V}$$

Seeing induction happen



Faster motion, bigger deflection; reverse the motion, reverse the needle.



Eddy currents in the plate oppose its motion, so it stops quickly.

What makes the induced e.m.f. larger

From $\varepsilon = N d\Phi/dt$ with $\Phi = BA$, four things raise it:

more turns N

stronger B

larger area A

faster change

It is the **rate of change** of flux linkage that matters, not the flux itself.

Exam tips

- Force on a current $F = BIL \sin \theta$; on a moving charge $F = BQv$; find the direction with **Fleming's left-hand rule**.
- A charge moving perpendicular to B moves in a **circle** ($BQv = mv^2/r$).
- **Electromagnetic induction**: e.m.f. = rate of change of flux linkage (Faraday); its direction opposes the change (Lenz's law).



Topic 20 – key takeaways

1 On a wire

$$F = BIL \sin \theta - \text{left-hand rule}$$

2 On a charge

$$r = mv/BQ; \text{ Hall } V_H = Bl/ntq$$

3 Two wires

same way attract, opposite repel

4 Induction

$$\varepsilon = -d(N\Phi)/dt - \text{Faraday and Lenz}$$

Check yourself

- 1 When is $F = BIL$ a maximum?
- 2 Why does $T = 2\pi m/BQ$ not depend on speed?
- 3 In a velocity selector, $v = ?$
- 4 What does the minus sign in Faraday's law mean?

Answers 1. wire $\perp B$ 2. faster $\Rightarrow$ bigger r , same time per turn 3. E/B 4. the induced e.m.f. opposes the change (Lenz)