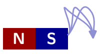
Magnetic Fields

A2 Physics ▪ Topic 20

A-Level Physics



What we will cover

1 Magnetic fields

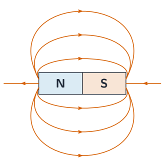
A field that acts on moving charge

A **magnetic field** 磁场 is a region where a moving charge (or a **current** 电流) feels a **force** 力. There are two ways to make one.

moving charges	**permanent magnets**
usually a current in a wire	tiny atomic currents inside the material

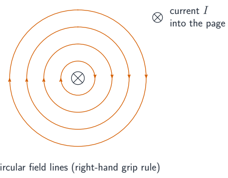
> Both are the same thing underneath: a magnetic field is made by moving charge, whether it flows along a wire or circulates inside an atom.

The field of a bar magnet

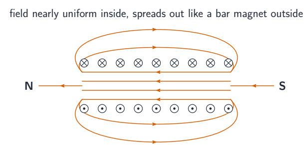


> Field lines run from N to S outside the magnet, and never cross. Where they crowd together the field is strongest – at the poles.

Field around a long straight wire



*Field around a long straight wire – **right-hand grip rule** 右手螺旋定则*

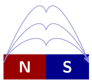


Field of a solenoid

> 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** 场线 run N to S outside a magnet (S to N inside – closed loops)
- lines never cross
- closer lines ⇒ a stronger field – **flux density** 磁通密度 B, in **tesla** 特斯拉
- a **long solenoid** 长螺线管 has a uniform field inside and looks like a bar magnet outside



Four patterns you must recognise

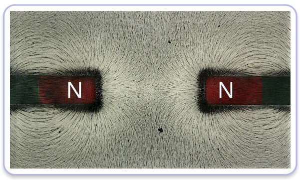
bar magnet
curved N→S outside; strongest near the poles

straight wire
circles; **right-hand grip** 右手定则: 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** 铁芯 inside a solenoid greatly increases the field: the iron's atomic magnets line up and add to it. That is why **electromagnets** 电磁铁 and **transformers** 变压器 have iron cores.

2 Force on a current

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** 磁通密度 B:

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

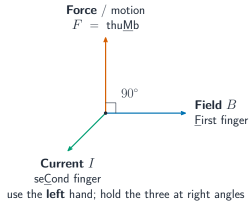
Fleming's left-hand rule

Use the left hand. Three fingers at right angles:

- **First** finger – **F**ield
- se**C**ond finger – **C**urrent
- **thumb** – **thu**rust (force)

$L = 0.20\,\mathrm{m}$, $I = 3.0\,\mathrm{A}$, $B = 0.50\,\mathrm{T}$, $\theta = 90°$
$F = BIL = 0.50 \times 3.0 \times 0.20$
$= 0.30\,\mathrm{N}$

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.

3 Force on a charge

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 is the electrons' **drift velocity** 漂移速度. 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

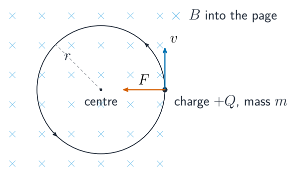
$BQv = mv^2/r$ gives

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

Here BQv is the **centripetal force** 向心力. 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** 动能 never changes because the force does no work. A component of v along B is unchanged, so the path is a **helix** 螺旋.

Proton: $m = 1.7 \times 10^{-27}\,\mathrm{kg}$, $v = 2.0 \times 10^{6}\,\mathrm{m\,s^{-1}}$, $B = 0.50\,\mathrm{T}$
$r = \dfrac{mv}{BQ} \approx 0.043\,\mathrm{m}$

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** 霍尔电压. Charges feel BQv_{d}, pile up, and make an electric field that opposes further build-up.

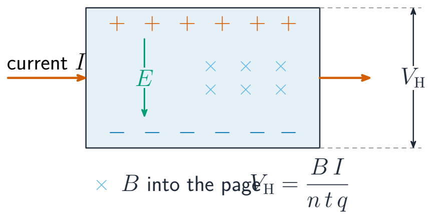
At steady state $E = Bv_{\mathrm{d}}$:

$$V_{\mathrm{H}} = \frac{BI}{ntq}$$

A **Hall probe** 霍尔探头 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.

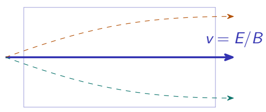


Velocity selector – only one speed gets through

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

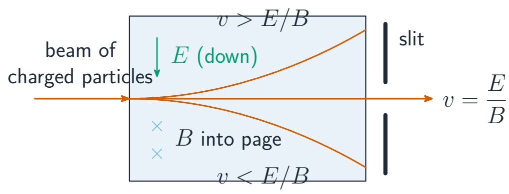
$$v = \frac{E}{B}$$

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.



4 Parallel currents

Two wires, each in the other's field

Using Fleming's left-hand rule:

same direction	opposite directions
currents attract	currents repel

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

5 Electromagnetic induction

Flux and flux linkage

Magnetic flux 磁通量 through a flat area A:

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

Unit: **weber** 韦伯, $\mathrm{Wb} = \mathrm{T\,m^2}$. For a **coil** 线圈 of N turns the **flux linkage** 磁链 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 法拉第: the induced e.m.f. equals the rate of change of flux linkage

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

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

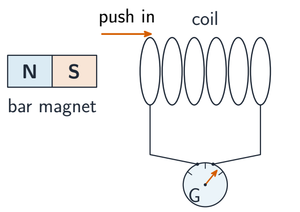
$$\varepsilon = -\frac{d(N\Phi)}{dt}$$

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

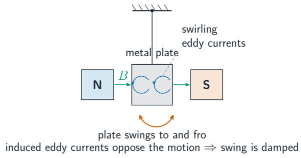
$\Delta(N\Phi) = NBA = 1.0\,\mathrm{Wb}$

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

Seeing induction happen



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



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

What makes the induced e.m.f. larger

From $\varepsilon = N\mathrm{d}\Phi/\mathrm{d}t$ 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).

6 Recap

Topic 20 – key takeaways

1 On a wire

$F = BIL\sin\theta$ – left-hand rule

2 On a charge

$r = mv/BQ$; Hall $V_{\mathrm{H}} = BI/ntq$

3 Two wires

same way attract, opposite repel

4 Induction

$\varepsilon = -d(N\Phi)/dt$ – 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)