

# Magnetic fields

A-Level Physics 9702 · Topic 20 revision notes · A2

Magnetic fields and flux density, forces on currents and moving charges, the fields made by currents, and electromagnetic induction.

13 definitions to learn word for word, 10 equations in their own column, 13 diagrams and graphs. Read it, cover it, test yourself.

1. 20.1 Concept of a magnetic field
2. 20.2 Force on a current-carrying conductor
3. 20.3 Force on a moving charge
4. 20.4 Magnetic fields due to currents
5. 20.5 Electromagnetic induction

Definitions (mark-scheme wording) Equations Exam traps

## 20.1 Concept of a magnetic field

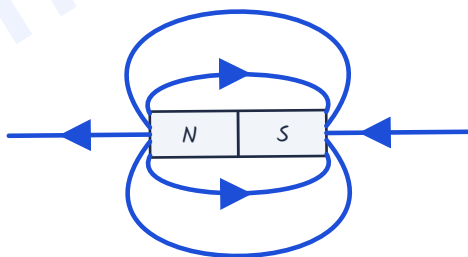
### Definitions

**Magnetic field:** a region of space in which a magnetic pole, a current-carrying conductor or a moving charge experiences a force.

**Magnetic field line:** a line showing the direction of the force on a north pole placed at that point.

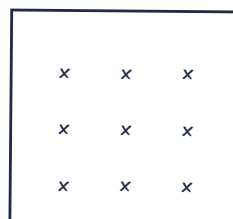
### Key points

- ✓ Magnetic fields are produced by **permanent magnets** and by **moving charges** (electric currents).
- ✓ Field lines run from **N to S** outside a magnet, never cross, and are **closest where the field is strongest**.
- ✓ Evenly spaced parallel lines = a **uniform field** (e.g. between flat poles, inside a solenoid).
- ✓ Field into the page is drawn as **crosses (x)**; out of the page as **dots (·)**.
- ✓ Like poles repel, unlike poles attract; a **stationary** charge feels no magnetic force.



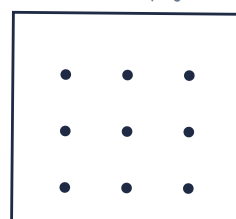
Bar magnet: lines leave N, curve round and enter S; they are most crowded at the poles.

B into page



uniform field

B out of page



Uniform field into the page (crosses) and out of the page (dots).

### Watch out!

- ! A magnetic force acts only on a **moving** charge or a current. A charge at rest in a magnetic field feels no magnetic force.
- ! Field lines never cross; if two lines appear to meet, the diagram is wrong.

## 20.2 Force on a current-carrying conductor

### Definitions

**Magnetic flux density (B):** the force per unit current per unit length on a straight conductor placed at right angles to the field.

**Tesla (T):** the flux density when a conductor of length 1 m carrying 1 A at right angles to the field experiences a force of 1 N ( $1 \text{ T} = 1 \text{ N A}^{-1} \text{ m}^{-1}$ ).

**Fleming's left-hand rule:** with thumb, first finger and second finger mutually at right angles: first finger = field, second finger = current, thumb = force (motion).

### Equations

$$F = BIL \sin \theta$$

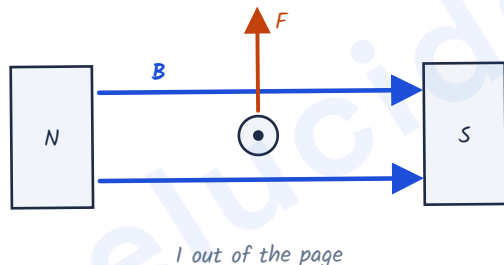
force on a conductor;  $\theta$  = angle between wire and field  
N

$$B = F / (IL)$$

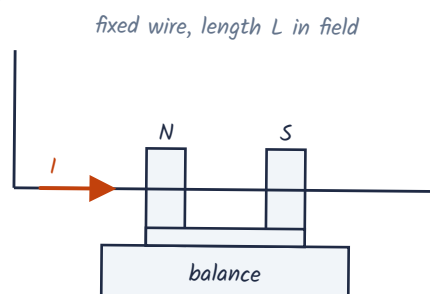
flux density (wire perpendicular to B)  
T

### Key points

- ✓ A current in a magnetic field feels a force **perpendicular to both B and I** (the motor effect).
- ✓ Force is **maximum when the wire is perpendicular to B** and **zero when parallel**.
- ✓ Reversing either the current or the field reverses the force.
- ✓ **Measuring B** with a current balance: wire fixed over magnets on a top-pan balance;  $F = \text{change in reading (kg)} \times g$ .
- ✓ Plot F against I: straight line through origin, **gradient = BL**.
- ✓ A **Hall probe** (see 20.3) also measures B directly once calibrated.



Motor effect: B from N to S, current out of the page, so by Fleming's left-hand rule F is upwards.



Current balance: the force on the fixed wire pushes the magnets down (or up), changing the reading;  $F = \Delta m g$ , then  $B = F/(IL)$ .

### Watch out!

- !  $\theta$  is the angle between the **wire and the field**. Parallel ( $\theta = 0$ ) gives zero force.
- ! Use only the length of wire actually **inside the field** for L.

## 20.3 Force on a moving charge

### Definitions

**Hall voltage:** the potential difference produced across a current-carrying conductor (or semiconductor slab) in a magnetic field, perpendicular to both the current and the field.

### Key points

- ✓ Force on a moving charge is **perpendicular to its velocity**, so it does **no work**: speed and kinetic energy stay constant.
- ✓ In a uniform field perpendicular to  $v$  the charge moves in a **circle**;  $BQv$  provides the centripetal force.
- ✓ Faster or heavier particles make **bigger circles**; a stronger  $B$  makes smaller ones.
- ✓ In the left-hand rule, a moving **electron** counts as a current in the opposite direction.
- ✓ Hall effect: charges pile up on one face until the electric force balances  $BQv$ ;  $V_H$  is much larger in **semiconductors** (small  $n$ ).
- ✓ **Velocity selector**: crossed  $E$  and  $B$  fields; only particles with  $v = E/B$  pass undeflected (independent of mass and charge).
- ✓ Charge-to-mass ratio: measure  $r$  in a known  $B$  at a known speed, then  $Q/m = v/(Br)$ .

### Equations

$$F = BQv \sin \theta$$

force on a moving charge  
 $N$

$$r = mv / (BQ)$$

radius of circular path (from  $BQv = mv^2/r$ )  
 $m$

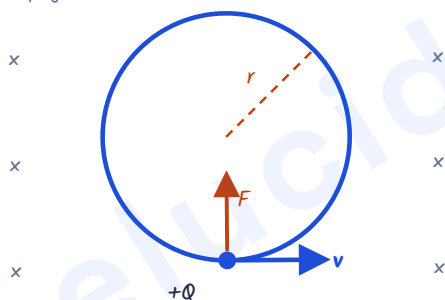
$$V_H = BI / (ntq)$$

Hall voltage;  $n$  = charge carriers per unit volume,  $t$  = slab thickness  
 $V$

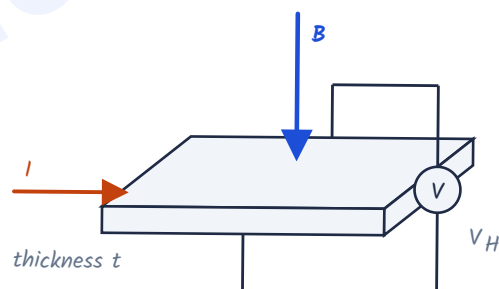
$$v = E / B$$

speed selected by crossed fields ( $EQ = BQv$ )  
 $m\ s^{-1}$

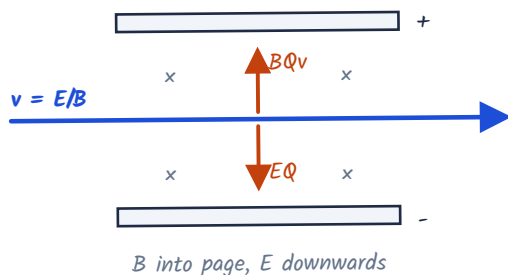
$B$  into page



Positive charge in  $B$  into the page: the force always points to the centre, giving a circle of radius  $r = mv/(BQ)$ .



Hall effect: carriers are pushed towards the front or back face, so  $V_H$  appears between them (thickness  $t$  measured along  $B$ ).



Velocity selector: electric force  $EQ$  balances magnetic force  $BQv$  only for  $v = E/B$ .

### Watch out!

- ! The magnetic force **never changes the speed**; it only changes direction. Kinetic energy is constant.
- ! For electrons, reverse the direction given by the left-hand rule (conventional current is opposite).
- ! In  $V_H = BI/(ntq)$ ,  $t$  is the slab thickness **along  $B$** , not the width across which  $V_H$  is measured.

## 20.4 Magnetic fields due to currents

### Definitions

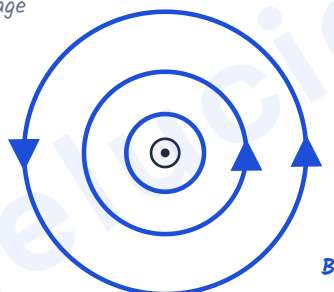
**Right-hand grip rule:** grip the wire with the thumb along the conventional current; the curled fingers give the direction of the field lines.

**Solenoid:** a long coil of wire; when it carries a current its field is uniform inside and like that of a bar magnet outside.

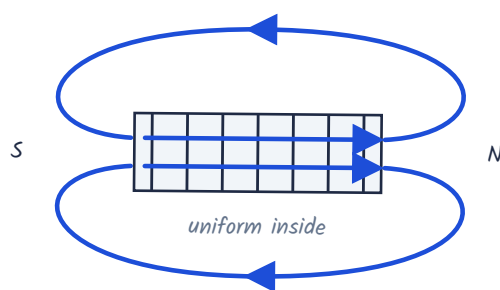
### Key points

- ✓ Long straight wire: **concentric circles**, further apart with distance (field weakens with distance).
- ✓ Flat circular coil: field lines through the centre are nearly straight, like a short bar magnet.
- ✓ Solenoid: **uniform, parallel field inside**; bar-magnet pattern outside. Grip rule on the coil: thumb points to N.
- ✓ A **ferrous (soft iron) core** greatly increases the flux density without changing the field shape.
- ✓ Field strength increases with **current** and **turns per unit length**.
- ✓ Two parallel wires: each sits in the other's field, so they exert **equal and opposite forces** (Newton's third law).
- ✓ Currents in the **same direction attract**; opposite directions repel.

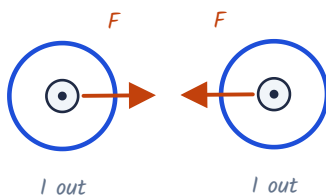
$I$  out of page



Long straight wire, current out of the page: anticlockwise concentric circles, spacing grows with distance.



Solenoid: parallel, uniform field inside; N at the end the lines leave.



**same direction: attract**

Parallel currents in the same direction: the field between them partly cancels, so the wires attract.

### Watch out!

- ! Parallel currents in the **same** direction **attract**: the opposite of like charges repelling.
- ! The forces on the two wires are equal and opposite even if the currents are different.

## 20.5 Electromagnetic induction

### Definitions

**Magnetic flux ( $\Phi$ )**: the product of the magnetic flux density and the area normal to the field:  $\Phi = BA$ .

**Weber (Wb)**: the flux when a flux density of 1 T passes normally through an area of 1 m<sup>2</sup> (1 Wb = 1 T m<sup>2</sup>).

**Magnetic flux linkage**: the product of the magnetic flux and the number of turns:  $N\Phi$ .

**Faraday's law**: the magnitude of the induced e.m.f. is proportional to (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 causing it.

### Equations

$$\Phi = BA$$

flux,  $B$  normal to area  $A$  ( $BA \cos \theta$  if tilted)

Wb

$$\text{flux linkage} = N\Phi$$

flux times number of turns

Wb

$$E = -\Delta(N\Phi) / \Delta t$$

Faraday's law with Lenz's minus sign

V

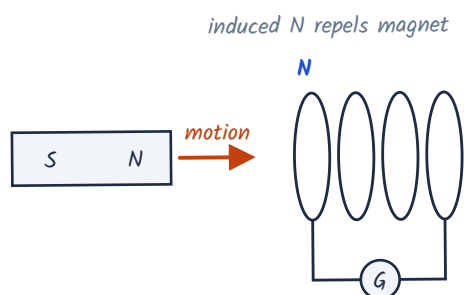
$$E = BLv$$

rod of length  $L$  moving at  $v$  perpendicular to  $B$

V

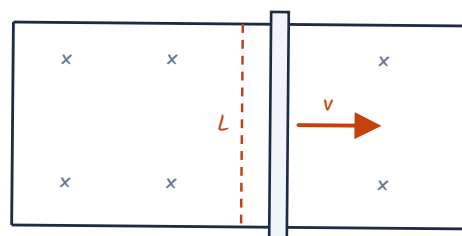
### Key points

- ✓ An e.m.f. is induced whenever the **flux linkage changes**: moving a magnet or coil, rotating a coil, or changing a current.
- ✓ Bigger e.m.f.: faster movement, stronger magnet, more turns, larger area.
- ✓ Straight rod moving at speed  $v$  across  $B$ : rate of cutting flux =  $BLv$ , so  $E = BLv$ .
- ✓ Lenz's law is **conservation of energy**: work must be done against the opposing force to generate electrical energy.
- ✓ Demonstrations: magnet into coil with a galvanometer; reverse direction reverses deflection; no motion, no reading.
- ✓ The minus sign in Faraday's law expresses Lenz's law.
- ✓ An e.m.f. is induced even in an open circuit; a current flows only if the circuit is complete.



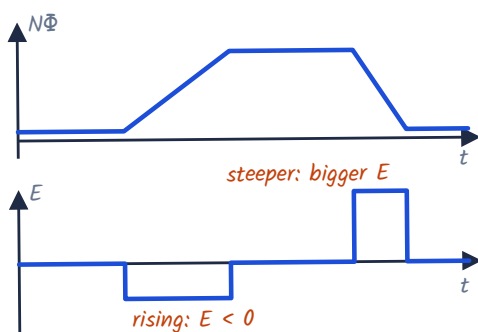
Lenz's law: as N approaches, the coil's near face becomes N to repel it, so work is done against the motion.

$B$  into page



$$E = BLv$$

Rod moving along rails across  $B$ : it sweeps area  $Lv$  per second, so  $E = BLv$ ; the induced current feels a force opposing the motion.



Flux linkage against time and the induced e.m.f.:  $E$  is minus the gradient of the  $N\Phi$ - $t$  graph.

### Watch out!

- ! It is the **rate of change** of flux linkage that induces an e.m.f. A steady large flux induces nothing.
- ! Flux uses the area **normal to  $B$** : a coil turned edge-on to the field has zero flux through it.
- ! Do not forget  $N$ : flux linkage  $N\Phi$ , not  $\Phi$ , goes into Faraday's law for a coil.