CAIE Physics A-level

Topic 20: Magnetic Fields
Notes

20 - Magnetic Fields

20.1 - Concept of a Magnetic Field

A **magnetic field** arises due to the **relative motion of charges** or from substances referred to as **permanent magnets**. Magnetic fields can be represented with field lines similar to the electric fields discussed previously. When drawing magnetic field lines, the convention for the direction is to go from **north to south**.
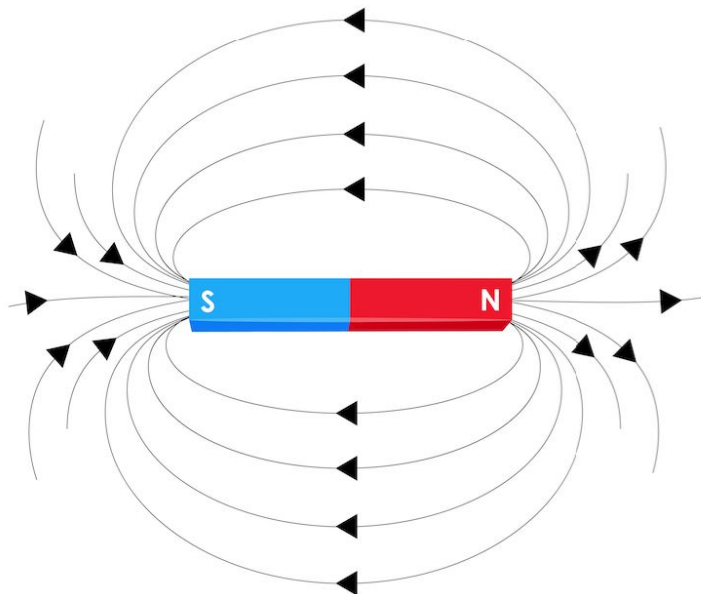

Image Source: https://www.drpawluk.com/education/magnetic-science/magnetic-field-polarity/

20.2 - Force on a Current-Carrying Conductor

If a current carrying conductor is placed in a magnetic field (e.g. between two magnetic poles), the motion of the charges in the field will cause a force to be exerted on the conductor, as long as the direction of the current (motion of the charges) is not parallel to the field lines.
The magnitude of this force F is given by

$$F = BILsin\theta$$

where B is the **magnetic flux density** (usually in teslas, T), I is the current in the conductor, L is the length of the conductor, and θ is the angle between the field lines and the direction of current. This means that the force experienced by the wire is greatest when the field and current are perpendicular to each other.

Magnetic flux density, B is the force acting per unit current per unit length on a wire placed at right angles to a magnetic field.

The direction of the force, and the subsequent motion that it causes in the conductor, can be inferred by using **Fleming's Left Hand Rule**. This is a handy mnemonic which allows you to

use your index finger, middle finger, and thumb of your left hand to find the perpendicular orientations and directions of the magnetic force, the motion it causes, and the current in the wire.
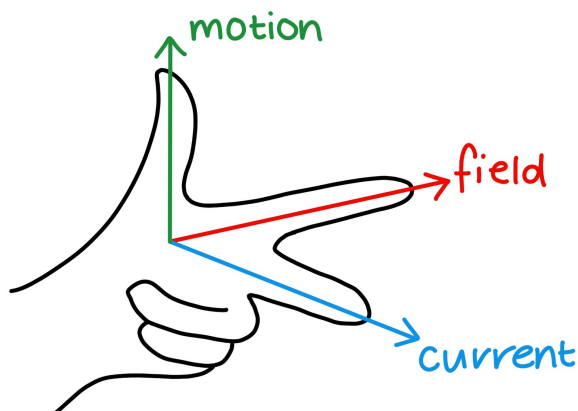
20.3 - Force on a Moving Charge

As a charged particle moves through a magnetic field, it experiences a force dependent on both the magnetic flux density, and its charge and velocity:

$$F = BQv\sin\theta$$

This equation immediately appears similar to the force on a current carrying wire equation from before. Effectively, the Qv terms equate to the previous IL terms as representing charge flow.

If a conducting material is moving through a magnetic field, the charge carriers within it (such as the electrons within a metal) experience the magnetic force, shifting their position within the material. The resultant asymmetric buildup of charge carriers induces a potential difference called the **Hall Voltage**- this is the **Hall Effect**. The magnitude of this voltage is given by
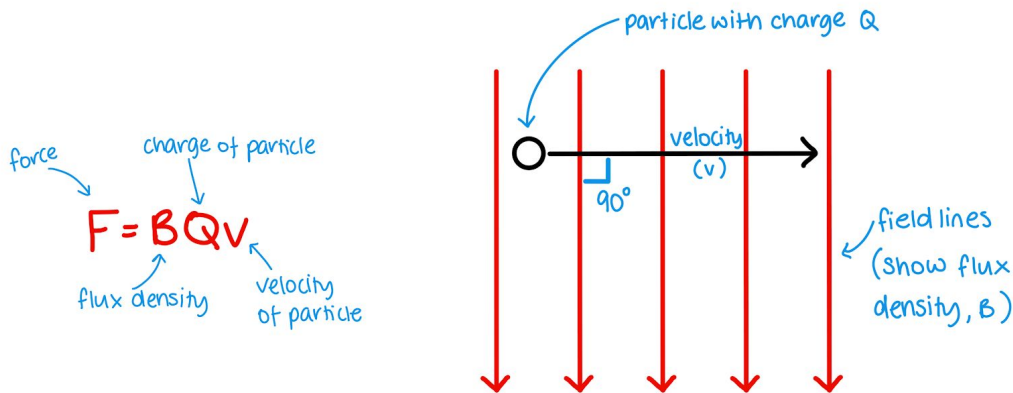
$$V_H = \frac{BI}{nQt}$$

where t is the thickness of the material, Q is the charge of one of the charge carriers (usually electrons and elementary charge), and n is the charge carrier number density.

A **Hall Probe** can be used to measure magnetic flux density. This probe is usually a thin sheet of metal with a known charge carrier density. Placing it within the magnetic field allows for the field strength to be measured.

Hall probe between magnetic pole pieces
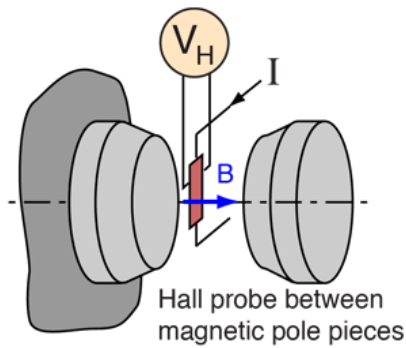
A charged particle moving through a perpendicular magnetic field will experience force and motion in the directions given by Fleming's Left Hand Rule. In the case of the field below, the particle will accelerate into the page and move in a curved path

$$F = BQv$$

force — charge of particle — velocity of particle — flux density

particle with charge Q
velocity (v)
90°
field lines (show flux density, B)

A **velocity selector** can be made using perpendicular magnetic and electric fields to filter out particles from a beam with a desired velocity.
By equating the definitions of the magnetic and electric forces on a charged particle, an expression for the velocity can be obtained:

$$F = BQv = EQ$$

$$v = E/B$$

If the particle is going at this speed v then it will pass through the selector without deflection. If it is moving faster or slower than v. its path will change. The electric and magnetic field strengths can be adjusted to select particles of a particular velocity.
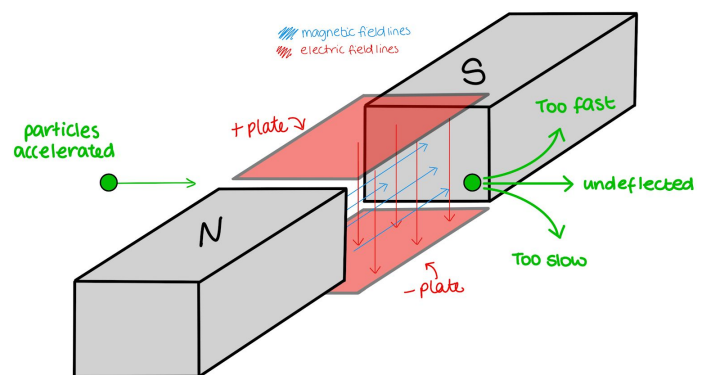
### 20.4 - Magnetic Fields due to Currents

The magnetic field created by the movement of charge through current in a straight wire can be pictured using **Fleming's Right Hand Rule**. This is a way of remembering that the magnetic field lines go around the wire current in an anti-clockwise direction, like the direction your fingers curl around the line of your thumb, as shown on the right.

The magnetic field strength of such a current carrying wire is given by **Ampere's Law**:

$$\sum B\Delta l \;=\; B2\pi r \;=\; \mu_0 I$$

$$B = \frac{\mu_0 I}{2\pi r}$$

If two such current carrying wires are placed so that they are adjacent, they will exert a force on each other. This force will instead be dependent on the product of the two currents. The direction of the forces can be inferred by using the hand rules.

Electric current I_1 I_2 r I B F F B Magnetic field
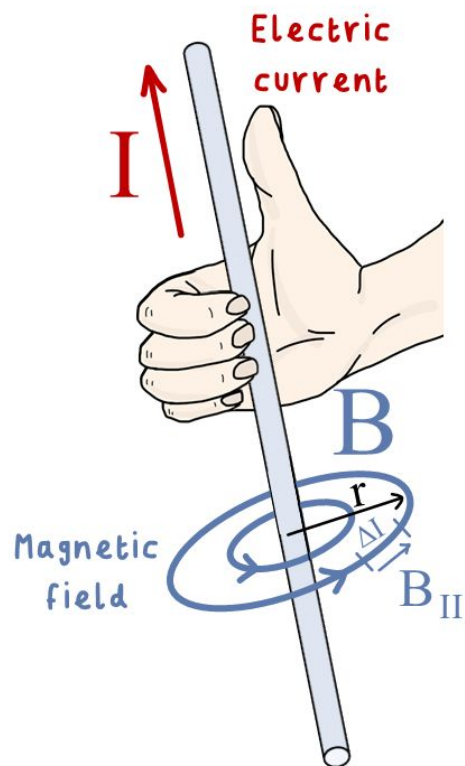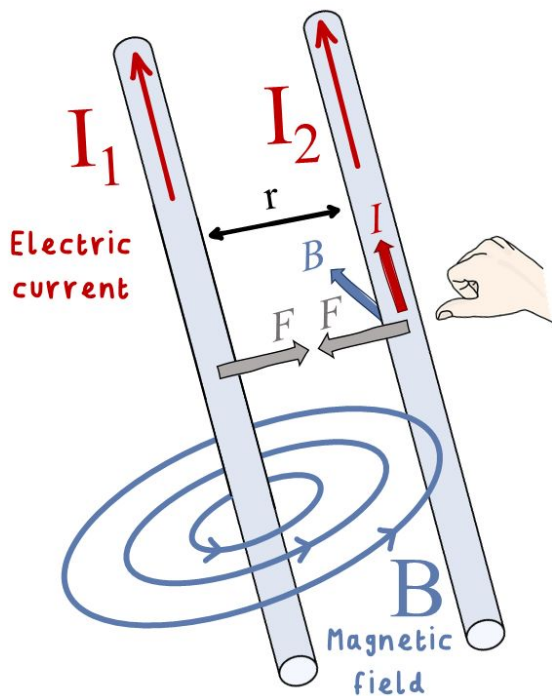
Magnetic field at wire 2 from current in wire 1:
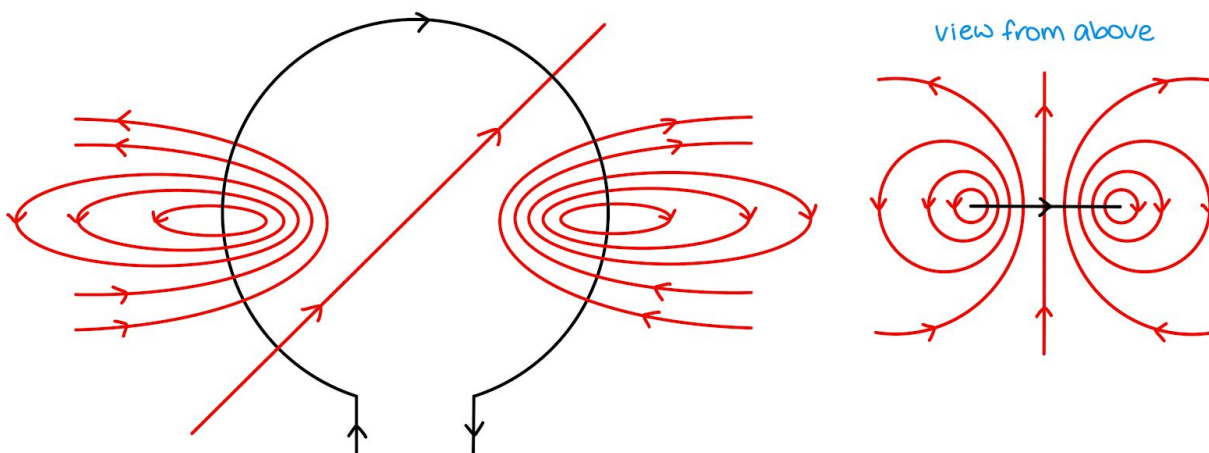
$$B = \frac{\mu_0 I_1}{2\pi r}$$

Force on a length ΔL of wire 2:

$$F = I_2 \Delta L B$$

Force per unit length in terms of the currents:

$$\frac{F}{\Delta L} = \frac{\mu_0 I_1 I_2}{2\pi r}$$

By considering the field shape of one wire, one can infer the field from different wire shapes. The field in a conducting wire loop is shown below. This kind of field could be used to accelerate charged particles through the middle of the loop.
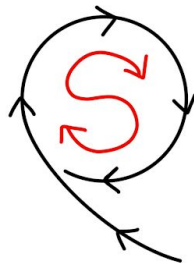

view from above

Similarly the magnetic field created by a solenoid can be pictured as below on the left, a similar acceleration effect could be achieved through this.

The diagrams on the right show a way of using the shapes 'S' and 'N' to remember the direction of the current for each pole, not the field lines.
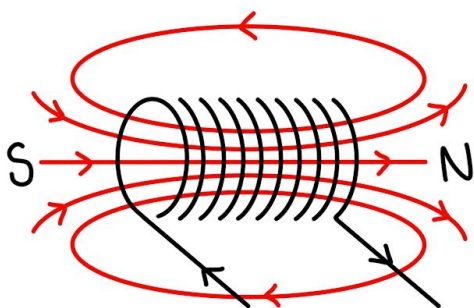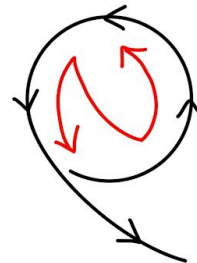
South pole:
current is clockwise

north pole:
current is anticlockwise

Placing an **iron core** through the centre of the solenoid can drastically increase the strength of the magnetic field because the iron core itself effectively becomes magnetised.
The magnetic force between two conductors can be derived from their respective magnetic fields.

20.5 - Electromagnetic Induction
Magnetic Flux Φ is the product of the magnetic flux density and the cross-sectional area perpendicular to the direction of the magnetic flux density.

$$\Phi = BA$$

In a coil of N turns of conducting wire, each turn will 'link' the flux together giving rise to the **magnetic flux linkage** $\lambda = N\Phi$.

A change in magnetic flux can **induce an emf** in a circuit. This can be demonstrated by passing a bar magnet through the loops of a solenoid: an emf will be induced and a current measured when the magnet is **moving**, because the motion causes a change in the magnetic flux through the wire.
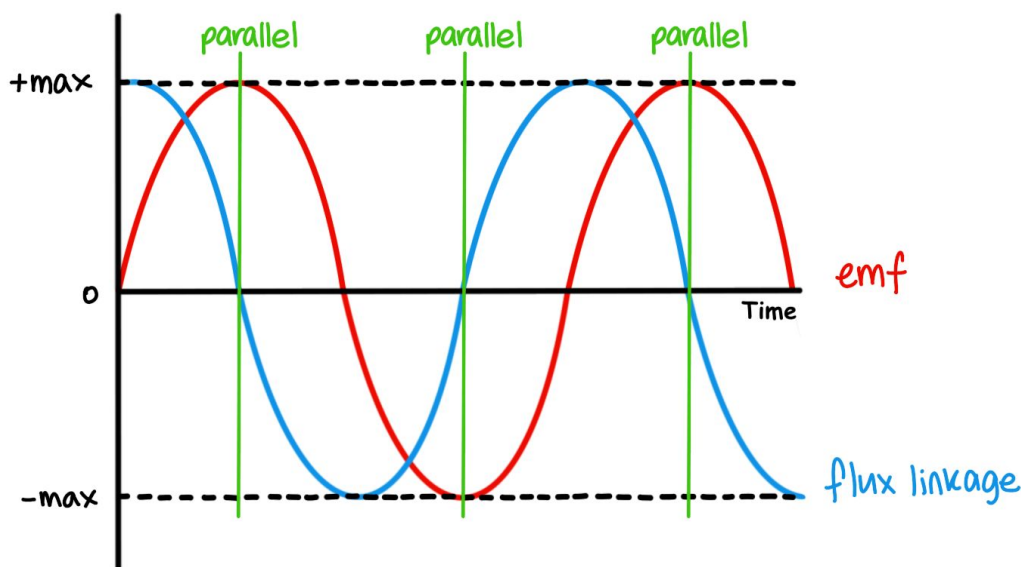
The induced emf is given by the equation below - **Faraday's Law**. This states that the induced emf is proportional to the **rate of change of magnetic flux linkage**.

This emf is induced in a direction which **opposes** the motion of the magnet inducing it. This is **Lenz's Law**, and manifests as a minus sign in the equation. The magnitude of the emf induced depends on the number of coil turns, the magnetic flux, and the time over which the change in flux linkage occurs.

$$\varepsilon = -\frac{(\Delta N\phi)}{\Delta t}$$

change of flux linkage (Wb)

induced emf (V)

change in time (s)

negative because emf acts in the opposite direction to the charge that caused it → Lenz's Law