20 Magnetic fields

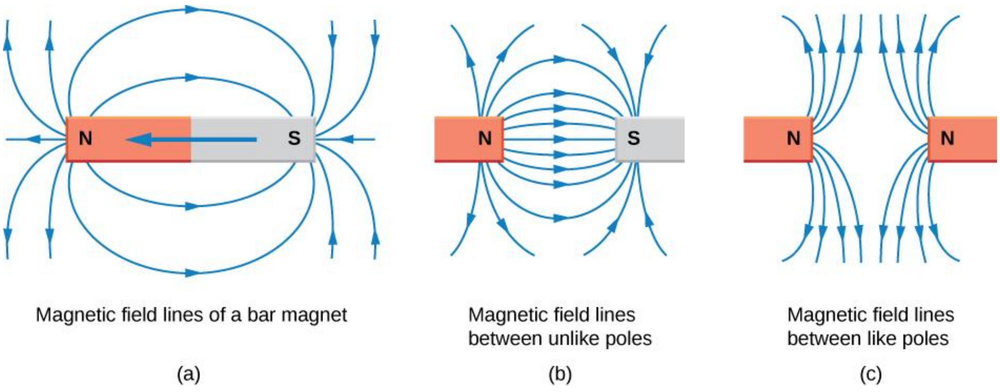
20.1 Concept of a magnetic field

Candidates should be able to:

1 understand that a magnetic field is an example of a field of force produced either by moving charges or by permanent magnets

2 represent a magnetic field by field lines

- There are two types of magnetic field that is created either by a **permanent magnet** or a **temporary magnet** created around a current carrying wire to moving charges.



20.2 Force on a current-carrying conductor

Candidates should be able to:

1 understand that a force might act on a current-carrying conductor placed in a magnetic field

2 recall and use the equation $F = BIL \sin \theta$, with directions as interpreted by Fleming's left-hand rule

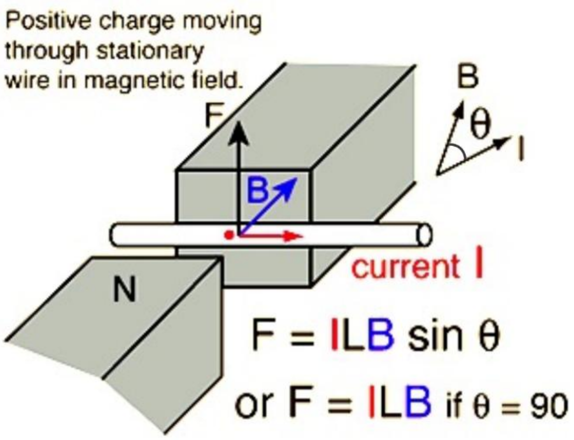
3 define magnetic flux density as the force acting per unit current per unit length on a wire placed at right-angles to the magnetic field

- A current carrying conductor produces its own magnetic field.
- When interacting with an external magnetic field, it will experience a force.
- A current-carrying conductor will only experience a force if the current through it is **perpendicular** to the direction of the magnetic field lines.
- Magnetic field strength is measured in magnetic flux density (B).
- The units for B are in **Tesla**.
- The force (F) on a conductor carrying current (I) at right angles to a magnetic field flux density (B) is given by

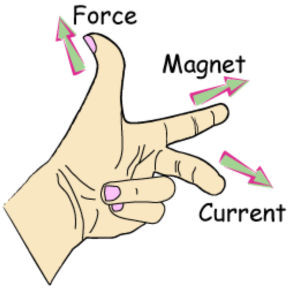
$$F = BIL \sin \theta$$

Here I is the current in the conductor (A), L is the length of the conductor (meters) and θ is the angle between the conductor and external magnetic field B (degrees).

- Based on the equation above, your maximum force occurs when the conductor is **perpendicular** to B ($\theta = 90^0$) since sin 90 = 1.
- Force will be zero when the conductor is parallel to B ($\theta = 0^0$) since sin 0 = 0.



- Fleming's left-hand rule can be used to determine the directions of the force, magnetic field and current if they are perpendicular to each other.



- The forefinger, middle finger and thumb are perpendicular (90° degrees) to each other.
- The forefinger points along the direction to the magnetic field, middle finger points in the current direction and the thumb points along the direction of the force.
- **Magnetic flux density (B)** is defined as **the force acting per unit current per unit length on a current carrying conductor placed perpendicular to the magnetic field**.

$$B = F/IL$$

- The equation above already assumed that B is perpendicular to current $\theta = 90^0$ hence $\sin 90 = 1$

20.3 Force on a moving charge

Candidates should be able to:

1 determine the direction of the force on a charge moving in a magnetic field

2 recall and use $F = BQv \sin \theta$

3 understand the origin of the Hall voltage and derive and use the expression $V_H = BI/(ntq)$, where t = thickness

4 understand the use of a Hall probe to measure magnetic flux density

5 describe the motion of a charged particle moving in a uniform magnetic field perpendicular to the direction of motion of the particle

6 explain how electric and magnetic fields can be used in velocity selection

- The force on an isolating moving charge, i.e., electron or proton, is given by the equation

$$F = BQv \sin \theta$$

  Here Q is the charge of an electron (1.6×10^{-19}C), v is the speed of the charge (ms^{-1}) and θ the angle between the charge's trajectory and magnetic field (degrees).
- Again, Fleming's Left-Hand rule can be used to determine the directions of the force on the charge, magnetic field and motion of the charge.

- **Hall's voltage** is defined as **the generation of an electric potential perpendicular to both an electric current flowing along a conducting material and an external magnetic field applied at right angles to the current upon application of the magnetic field.**
- When an external magnetic field is applied perpendicular to the direction of current through a conductor, the electrons experience a magnetic force.
- This causes the electrons to drift to one side of the conductor.
- That side becomes negatively charged.
- The other side becomes positively charged.
- There's now a potential difference between both sides.
- This potential difference is called Hall Voltage (V_H).
- The electric field strength (E) across both sides is given by the equation

$$E = \frac{v_H}{d}$$

Recall that

$$F = Bqv$$

and $F = qE$

$$qE = Bqv$$

substituting into the electric field strength equation, we get

$$\frac{v_H}{d} = Bv$$

Current (I) is related to the drift velocity v by the equation

$$I = nAvq$$

Here A is the cross-sectional area of the conductor (m^2) and n is the number density of electrons (m^{-3}). Rearranging the equation in terms of v and substituting into the equation above

$$\frac{v_H}{d} = B\frac{I}{nAq}$$

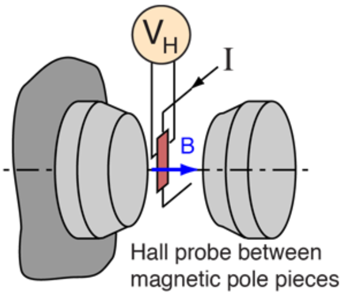
The area is the product of width d and thickness t

$$A = dt$$

Substituting into the equation above and cancelling d we get

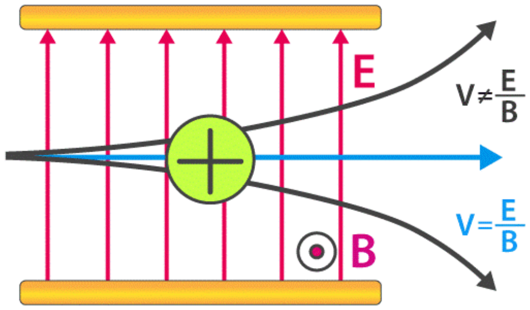
$$v_H = B\frac{I}{ntq}$$

- This equation shows that **V_H** is directly **proportional** to **B**
- A Hall probe can be used to measure magnetic flux density (B) between two magnets based on the Hall effect



The polarity of the Hall voltage for a copper probe shows that electrons are the charge carriers.

- To measure B between two magnets, the flat surface of the probe must be placed between both magnets so that the magnetic field lines pass completely **perpendicularly** to this surface.
- The probe is then connected to a voltmeter to measure Hall voltage (V_H). Since V_H is directly proportional to B, the flux density of the magnets can be obtained.
- A Hall probe will have zero voltage when B is **parallel** to the probe.
- A charged particle moving in a uniform magnetic field perpendicular to the direction of motion of said particle travels in a **circular** path.
- This is due to the force (F) being perpendicular to its velocity (v).
- Refer to Fleming's left-hand rule.
- The magnetic force (F) provides the **centripetal force** on the particle.
- A velocity selector is a region in which there is a uniform electric and magnetic field.
- The fields are perpendicular to each other and perpendicular to the initial velocity of the charged particles that are passing through the region.
- This allows a specific velocity to be filtered.



- A velocity selector consists of two horizontals oppositely charged plates situated in a vacuum chamber.
- There is also a uniform magnetic field with flux density (B) applied perpendicular to the E field.
- The forces exerted on a charged particle by the E field is given by

$$F_E = qE$$

- The magnitude of the force exerted by the B field is

$$F_B = qvB$$

- The idea is that, if both forces are equal and opposite ($F_E = F_B$), the net force is zero, and the particle passes through the region without changing direction.
- With the magnetic force being speed dependent, any charges travelling faster or slower than the ones that go straight though will be deflected (up or down) out of the beam.

20.4 Magnetic fields due to currents

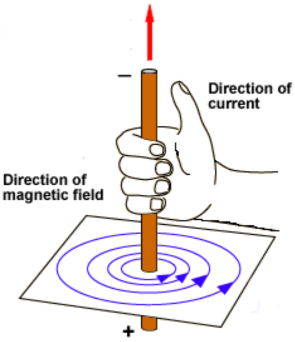
Candidates should be able to:

1 sketch magnetic field patterns due to the currents in a long straight wire, a flat circular coil and a long solenoid

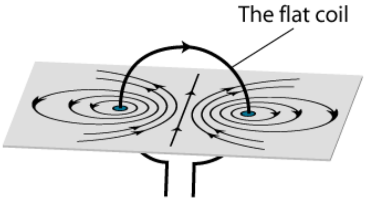
2 understand that the magnetic field due to the current in a solenoid is increased by a ferrous core

3 explain the origin of the forces between current-carrying conductors and determine the direction of the forces

- Magnetic field patterns are formed wherever a current is flowing.
- An electromagnet is a temporary magnet made by winding an insulated wire around a soft iron core, forming a coil known as a solenoid.
- When current passes through the solenoid it produces a magnetic field.
- The solenoid is said to magnetised and becomes an electromagnet.
- Magnetic field patterns:
  -Straight wire

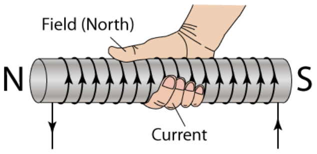


Use your Right Hand when you want to determine the magnetic field patterns! Your thumb is the direction of your current while your four fingers are the direction of the magnetic field.

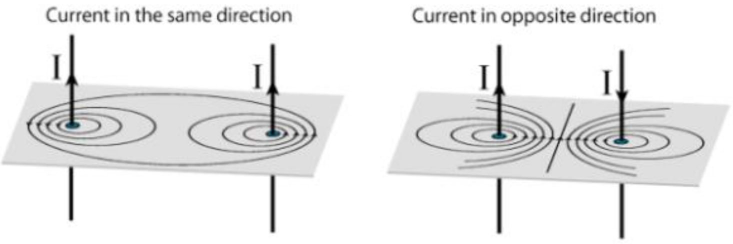


Magnetic field pattern generated by a flat coil

-Magnetic field in solenoid



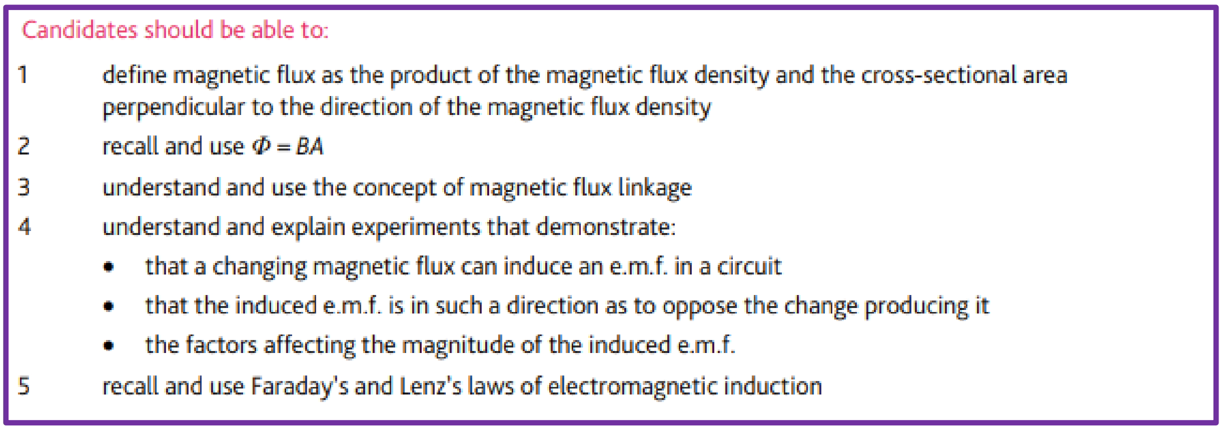
- The strength of the magnetic field of a solenoid can be increased by
  -adding a core made from a ferrous material
  -adding more turns in a core
- The reason adding an iron core strengthens the B field is because the iron core prevents flux leakage and concentrates the B field lines.
- Parallel carrying conductors will repel or attract each other as shown in the diagram below.



Catapult field produced by 2 straight curretn carrying conductors

- When the conductors attract, the magnetic force (F_B) will be towards each other.
- When the conductors repel, F_B will be away from each other.
- You can use Fleming's left-hand rule to confirm this!

20.5 Electromagnetic induction



Candidates should be able to:

1 define magnetic flux as the product of the magnetic flux density and the cross-sectional area perpendicular to the direction of the magnetic flux density

2 recall and use $\Phi = BA$

3 understand and use the concept of magnetic flux linkage

4 understand and explain experiments that demonstrate:

- that a changing magnetic flux can induce an e.m.f. in a circuit
- that the induced e.m.f. is in such a direction as to oppose the change producing it
- the factors affecting the magnitude of the induced e.m.f.

5 recall and use Faraday's and Lenz's laws of electromagnetic induction

- Electromagnetic induction is when an emf is induced in a closed-circuit conductor due to it cutting through a magnetic field.
- **Magnetic flux (Φ)** is defined as **the product of the magnetic flux density (B) and the cross-sectional area (A) perpendicular to the direction of the magnetic flux density**.
- In simpler terms, magnetic flux is the number of magnetic field lines through a given area.

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

- The units for Φ are in Webers (Wb).
- Magnetic flux is maximum when θ = 0 i.e., the B field are perpendicular to the **area *A***.
- Magnetic flux is maximum when θ = 0 i.e., the B field are perpendicular to the **area *A***.
- The magnetic flux linkage is a quantity commonly used for solenoids which are made of N turns of wire
- **Magnetic flux linkage (ΦN)** is defined as **the product of the magnetic flux and the number of turns**

$$\Phi N = BAN \cos \theta$$

- ΦN has the units of Weber turns (Wb turns)
- The candidate will need to be familiar with three experiments in this chapter
  -Moving a magnet through a coil
  -Moving a wire through a magnetic field
  -Evidence for Lenz's Law
- **Faraday's Law** states that **the magnitude of the induced emf is directly proportional to the rate of change of magnetic flux linkage (ε) through a solenoid or the rate of the magnetic flux linkage (ε) being cut**.
- In a nutshell what he was trying to say was move the magnet faster or use a stronger magnet or increase the number of coils in the solenoid.

$$\varepsilon = N\frac{\Delta\phi}{\Delta t}$$

- **Lenz Law** states that **the induced current always flows in the direction that opposes the change in magnetic flux linkage.**
- This law obeys the conservation of energy principle. Work is done to move the magnet against the repulsive force.
- This work done is converted to electric energy (current).