Edexcel A Level Physics

Your notes

Magnetic Fields

Contents

Magnetic Flux Density, Flux & Flux Linkage

Magnetic Flux Density

- The strength of a magnetic field is defined by the density of the magnetic field lines, or **magnetic flux density**, at that point
  - Magnetic flux density is defined by the symbol *B*
  - It is measured in **Tesla** (T)
- Rearranging the equation for magnetic force on a wire, the magnetic flux density is defined by the equation:

$$B = \frac{F}{IL}$$

- Where:
  - B = magnetic flux density (T)
  - F = magnetic force on a current-carrying wire (N)
  - I = current (A)
  - L = length of the wire (m)
- For reference, the Earth's magnetic flux density is around 0.032 mT and an ordinary fridge magnet is around 5 mT
- The magnetic flux density is sometimes referred to as the **magnetic field strength**

Magnetic Flux

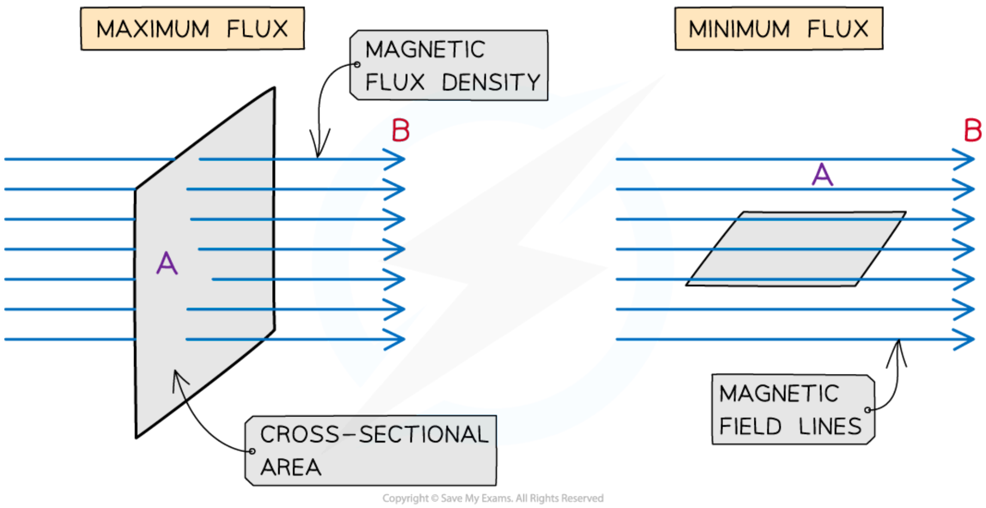
- Magnetic flux is a quantity which signifies how much of a magnetic field passes **perpendicularly** through some area
- For example, the amount of magnetic flux through a rotating coil will vary as the coil rotates in the magnetic field
  - It is a maximum when the magnetic field lines are **perpendicular** to the coil area
  - It is at a minimum when the magnetic field lines are **parallel** to the coil area
- The **magnetic flux** is defined as:

  The product of the magnetic flux density and the cross-sectional area perpendicular to the direction of the magnetic flux density

- Magnetic flux is defined by the symbol Φ (greek letter 'phi')
- It is measured in units of **Webers (Wb)**
- Magnetic flux can be calculated using the equation:

$$\Phi = BA$$

- Where:
  - Φ = magnetic flux (Wb)
  - B = magnetic flux density (T)
  - A = cross-sectional area (m^2)

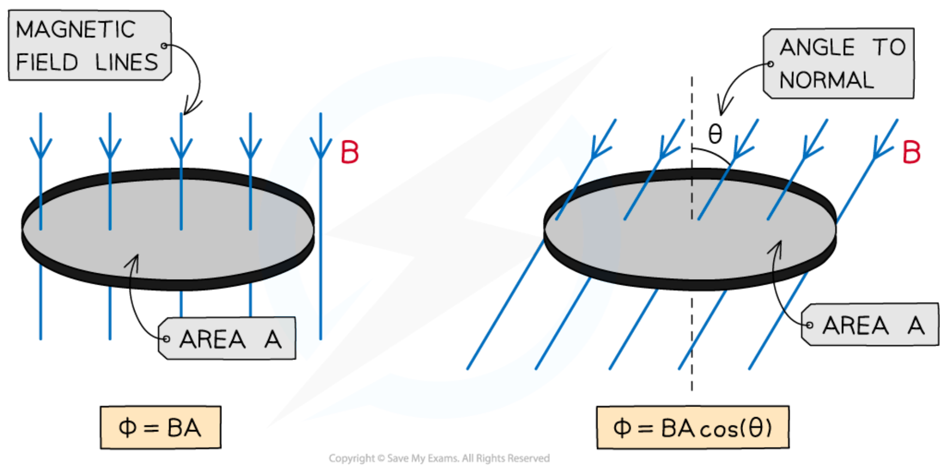


The magnetic flux is maximised when the magnetic field lines and the area through which they are passing through are perpendicular

- When magnetic flux is not completely perpendicular to the area *A*, then the component of magnetic flux density *B* perpendicular to the area is taken
- The equation then becomes:

$$\Phi = BA\cos(\theta)$$

- Where:
  - θ = angle between magnetic field lines and the line **perpendicular** to the plane of the area (often called the normal line) (degrees)



The magnetic flux increases as the angle between the field lines and the normal decreases

- This means the magnetic flux is:
  - **Maximum** = BA when cos(θ) =1 therefore **θ = 0°**. The magnetic field lines are perpendicular to the plane of the area
  - **Minimum** = 0 when cos(θ) = 0 therefore **θ = 90°**. The magnetic fields lines are parallel to the plane of the area
- An e.m.f is induced in a circuit when the magnetic flux linkage changes with respect to time
- This means an e.m.f is induced when there is:
  - A changing magnetic flux density *B*
  - A changing cross-sectional area *A*
  - A change in angle *θ*

Magnetic Flux Linkage

- The **magnetic flux linkage** is a quantity commonly used for solenoids which are made of *N* turns of wire
- The flux linkage is defined as:

  The product of the magnetic flux and the number of turns of the coil

- It is calculated using the equation:

$$\textbf{Flux linkage} = \Phi N = BAN$$

- Where:
  - Φ = magnetic flux (Wb)
  - *N* = number of turns of the coil
  - *B* = magnetic flux density (T)

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- A = cross-sectional area (m^2)

- The flux linkage ΦN has the units of **Weber turns (Wb turns)**

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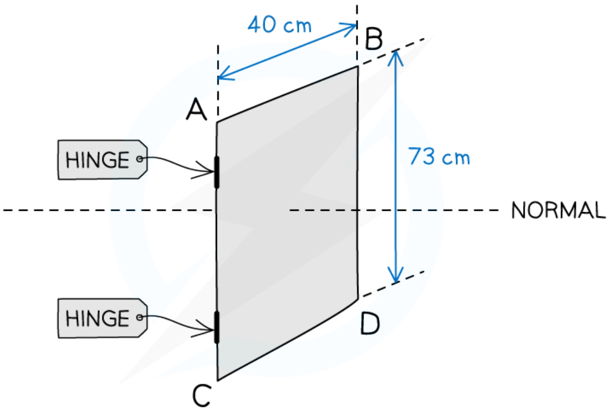
Worked Example

An aluminium window frame has a width of 40 cm and length of 73 cm as shown in the figure below



The frame is hinged along the vertical edge AC. When the window is closed, the frame is normal to the Earth's magnetic field with magnetic flux density 1.8×10^{-5} T

Calculate the magnetic flux through the window when it is closed

Answer:

Step 1: Write out the known quantities

Cross-sectional area, A = 40 cm × 73 cm = $(40 \times 10^{-2}) \times (73 \times 10^{-2}) = 0.292\ m^2$
Magnetic flux density, B = 1.8×10^{-5} T

Step 2: Write down the equation for magnetic flux

$$\Phi = BA$$

Step 3: Substitute in values

$$\Phi = (1.8 \times 10^{-5}) \times 0.292 = 5.256 \times 10^{-6} = 5.3 \times 10^{-6}\ \text{Wb}$$

Worked Example

A solenoid of circular cross-sectional radius 0.40 m and 300 turns is placed perpendicular to a magnetic field with a magnetic flux density of 5.1 mT.

Determine the magnetic flux linkage for this solenoid.

Answer:

Step 1: Write out the known quantities

- Cross-sectional area, $A = \pi r^2 = \pi(0.4)^2 = 0.503\ m^2$
- Magnetic flux density, $B = 5.1$ mT
- Number of turns of the coil, $N = 300$ turns

Step 2: Write down the equation for the magnetic flux linkage

$$\Phi N = BAN$$

Step 3: Substitute in values and calculate

$$\Phi N = (5.1 \times 10^{-3}) \times 0.503 \times 300 = 0.7691 = \mathbf{0.8\ Wb\ turns\ (2\ s.f)}$$

Examiner Tips and Tricks

Consider carefully the value of θ, it is the angle between the field lines and the line **normal** (perpendicular) to the plane of the area the field lines are passing through. If it helps, drawing the normal on the area provided will help visualise the correct angle.

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Magnetic Force on a Charged Particle

- The magnetic force on an isolated moving charged particle, such as a proton, is given by the equation:

$$F = BQv$$

- Where:
  - F = magnetic force on the particle (N)
  - B = magnetic flux density (T)
  - Q = charge of the particle (C)
  - v = speed of the particle (m s^{-1})
- This is the maximum force on the charged particle, when F, B and v are mutually perpendicular
  - Therefore if a particle travels **parallel** to a magnetic field, it will not experience a magnetic force
- Current is the rate of flow of **positive** charge
  - This means that the direction of the 'current' for a flow of negative charge (e.g. an electron beam) is in the opposite direction to its motion
- If the charged particle is moving at an angle θ to the magnetic field lines, then the size of the magnetic force F is given by the equation:

$$F = BQv \sin\theta$$

- This equation shows that:
  - The size of the magnetic force is **zero** if the angle θ is **zero** (i.e. the particle moves **parallel** to the field lines)
  - The size of the magnetic force is **maximum** if the angle θ is **90°** (i.e. the particle moves **perpendicular** to field lines)

Worked Example

A beta particle is incident at 70° to a magnetic field of flux density 0.5 mT, travelling at a speed of 1.5×10^6 m s^{-1}.

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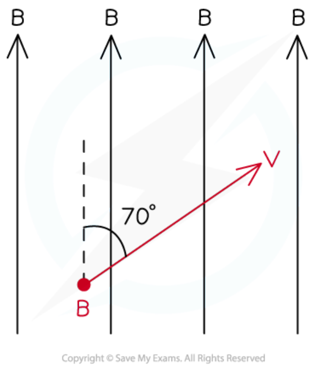

Calculate:

a) The magnitude of the magnetic force on the beta particle

b) The magnitude of the maximum possible force on a beta particle in this magnetic field, travelling with the same speed

Answer:

Part (a)

Step 1: Write out the known quantities

- Magnetic flux density $B = 0.5$ mT $= 0.5 \times 10^{-3}$ T
- Speed $v = 1.5 \times 10^{6}$ m s^{-1}
- Angle θ between the flux and the velocity = 70°

Step 2: Substitute quantities into the equation for magnetic force on a charged particle

- A beta particle is an electron
- Therefore, the **magnitude** of electron charge $Q = 1.6 \times 10^{-19}$ C
- Substituting values gives:

$$F = BQv \sin \theta$$

$$F = (0.5 \times 10^{-3}) \times (1.6 \times 10^{-19}) \times (1.5 \times 10^{6}) \times \sin (70)$$

$$F = 1.1 \times 10^{-16} \text{ N}$$

Part (b)

Step 1: Write out the known quantities

- Magnetic flux density $B = 0.5$ mT $= 0.5 \times 10^{-3}$ T
- Speed $v = 1.5 \times 10^{6}$ m s^{-1}

Step 2: Determine the angle to the flux lines

- Angle θ between the flux and the velocity = 90° if the magnetic force is a maximum

Step 3: Substitute quantities into the equation for magnetic force on a charged particle

- The **magnitude** of electron charge $Q = 1.6 \times 10^{-19}$ C

- Substituting values gives:

$$F = BQv \sin\theta = BQv \text{ when } \sin 90 = 1$$

$$F = (0.5 \times 10^{-3}) \times (1.6 \times 10^{-19}) \times (1.5 \times 10^{6})$$

$$F = 1.2 \times 10^{-16}\text{ N}$$

Examiner Tips and Tricks

Remember not to mix this up with $F = BIL \sin\theta$!

- ***F* = *BIL* sin *θ*** is the force on a current-carrying conductor
- ***F* = *BQv* sin *θ*** is the force on an isolated moving charged particle (which may be inside a conductor)

Another super important fact to remember for typical exam questions is that the magnetic force on a charged particle is **centripetal,** because it **always acts at 90°** to the particle's velocity. You should practise using Fleming's Left Hand Rule to determine the exact direction!

Fleming's Left Hand Rule for a Charged Particle

- **Fleming's left hand rule** can be used to determine the direction of the magnetic force on a moving charged particle in a magnetic field
    - The **First Finger** = direction of the magnetic field
    - The **Second Finger** = direction of conventional current (i.e. the velocity of a moving **positive charge**)
    - The **Thumb** = direction of the magnetic force
- Fleming's Left Hand Rule is illustrated in the image below:

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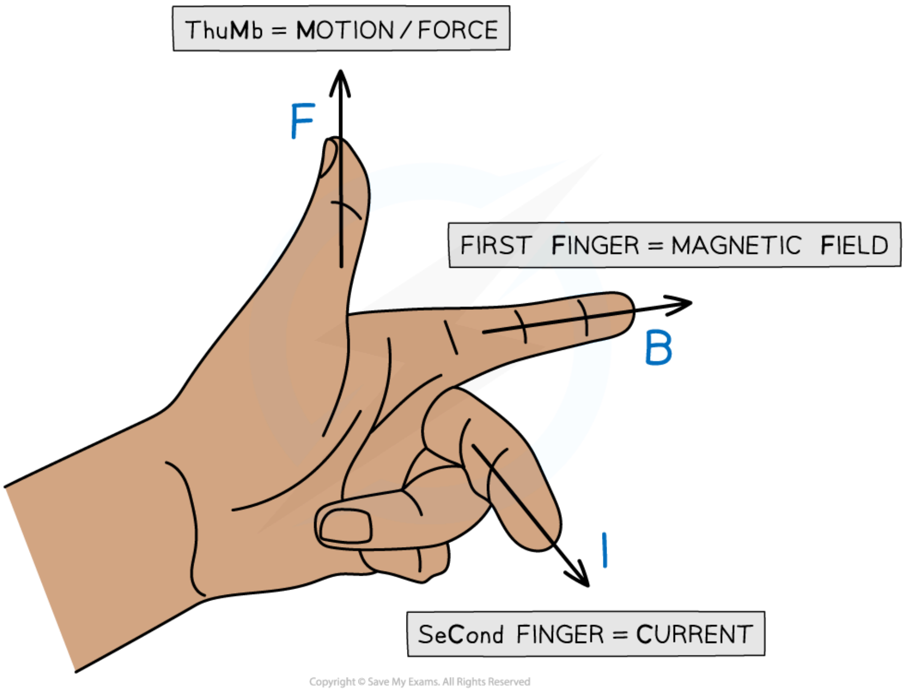
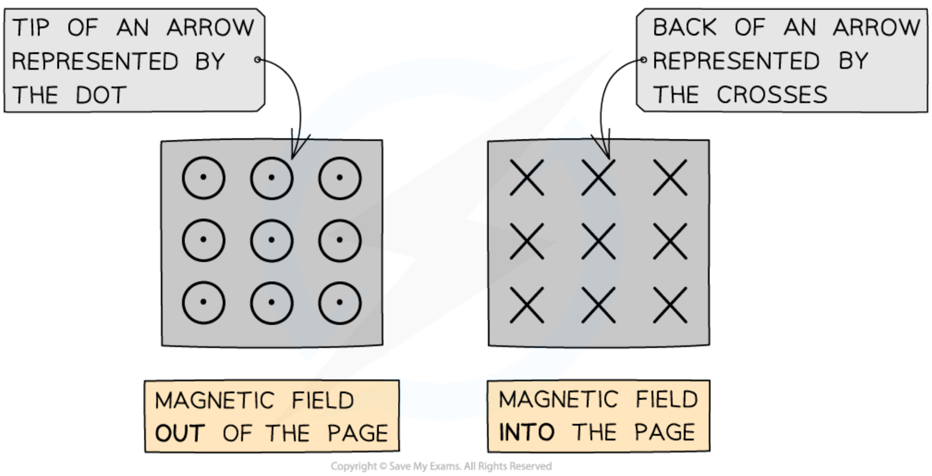


Fleming's Left Hand Rule shows the magnetic force, magnetic field and conventional current (flow of positive charge) are all perpendicular to each other

- Since this is represented in 3D space, sometimes the flow of charge, magnetic force or magnetic field could be directed into or out of the page, not just left, right, up and down
- The direction of the magnetic field **into** or **out of** the page in 3D is represented by the following symbols:
  - **Dots** (sometimes with a circle around them) represent the magnetic field directed **out** of the plane of the page
  - **Crosses** represent the magnetic field directed **into** the plane of the page



The magnetic field into or out of the page is represented by circles with dots or crosses

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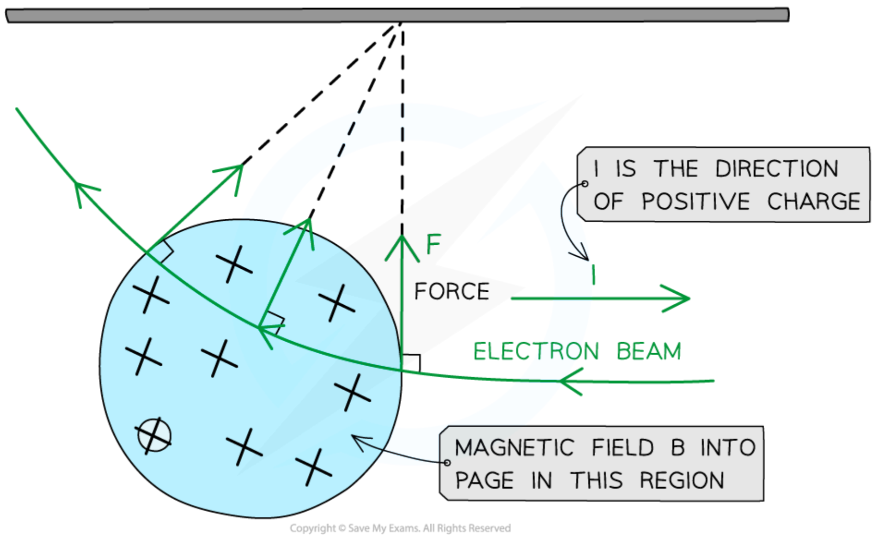
- The way to remember this is by imagining an arrow used in archery or darts:
  - If the arrow is approaching **head-on**, such as out of a page, only the very tip of the arrow can be seen (a dot)
  - When the arrow is **moving away**, such as into a page, only the cross of the feathers at the back can be seen (a cross)

An Electron Moving in a Magnetic Field

- The maximum magnetic force on a moving charged particle is always perpendicular to its velocity
  - This means magnetic forces cause charged particles to move in a **circle**
- The **direction** of magnetic force on the charged particle can be determined using Fleming's Left Hand Rule
  - The image below shows an electron incident on a uniform magnetic field *B* directed into the page:



An electron moving to the left as shown is equivalent to a conventional positive charge or current moving to the right. Using Fleming's Left Hand Rule, the direction of the force can be determined

- According to Fleming's Left Hand Rule:
  - *B* is directed into the page, therefore the first finger should point **into** the page
  - The conventional current (or velocity of a **positive charge**) is directed to the **right** (because an electron is moving to the left), therefore the second finger should point to the **right**
  - Therefore, the force on the electron as shown by the thumb is initially **upwards** as it enters the magnetic field
- The force due to the magnetic field **is always perpendicular to the velocity** of the electron

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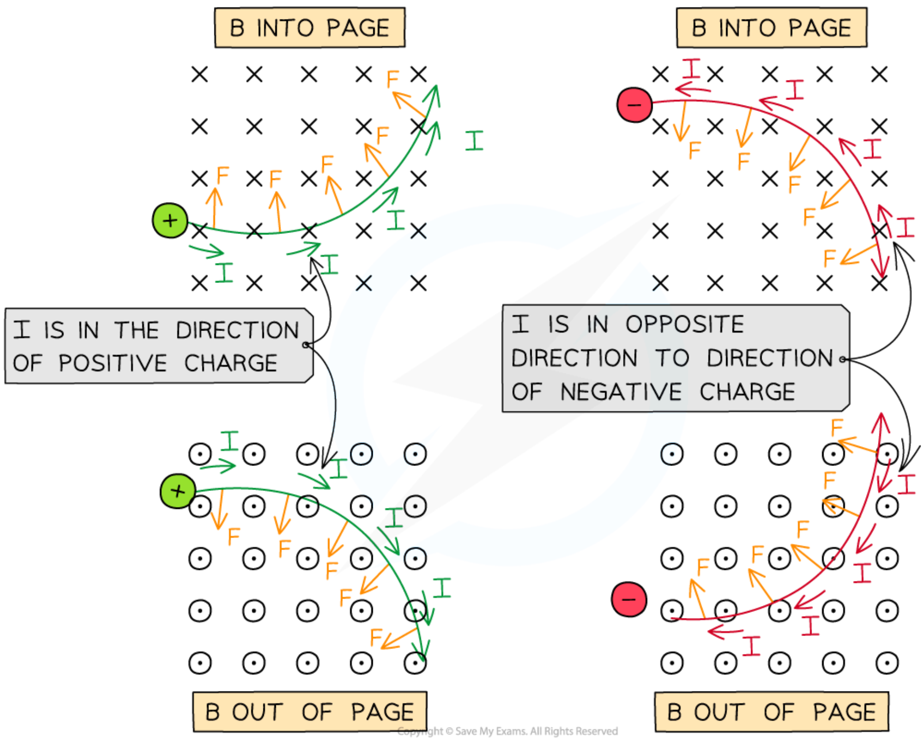
- **Note:** this is equivalent to circular motion
    - Therefore, the magnetic force on a moving charge is a **centripetal force**
- The centripetal force is what keeps moving charges following a **circular** trajectory
- Examples of the direction of the magnetic force on positive and negative particles are:



The direction of the magnetic force F on positive and negative particles in a B field in and out of the page

- Fleming's Left Hand Rule can be used again to find the direction of the force, magnetic field and velocity
    - The key difference is that the second finger, representing current *I* (direction of positive charge), can now be used as the **direction of velocity *v*** of a **positive** charge

Examiner Tips and Tricks

The most important point when using Fleming's left hand rule is the direction of the **charge** (or **current** flow). This is always the direction of **positive** charge. Therefore, for electrons, or negatively charged ions, you should point your second finger for the current in the **opposite** direction to its motion.

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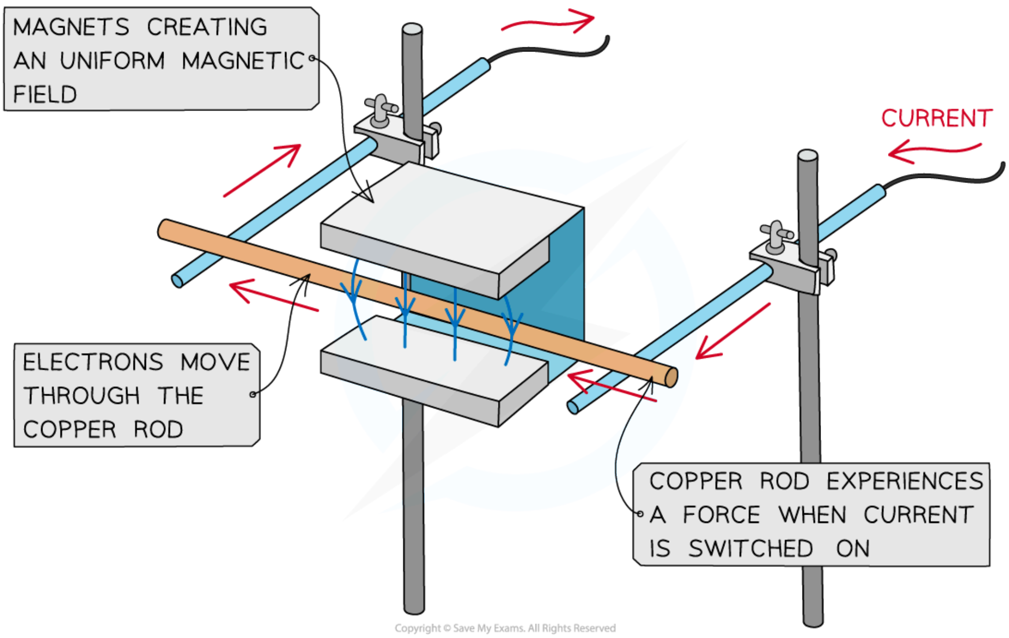
Magnetic Force on a Current-Carrying Conductor

- A current-carrying conductor produces its own **magnetic field**
  - An **external magnetic field** will therefore exert a **magnetic force** on it
- A current-carrying conductor (eg. a wire) will experience the **maximum** magnetic force if the current through it is **perpendicular** to the direction of the magnetic flux lines
  - A simple situation would be a copper rod placed within a uniform magnetic field
  - When current is passed through the copper rod, it experiences a **force** which makes it accelerate



A copper rod moves within a magnetic field when current is passed through it

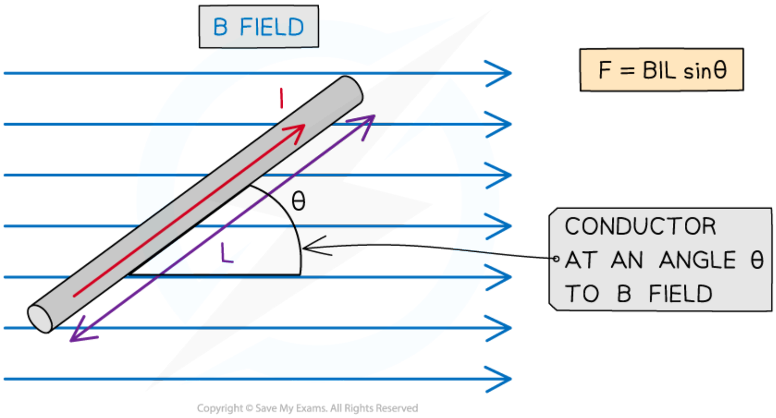
- The force F on a conductor carrying current I in a magnetic field with flux density B is defined by the equation

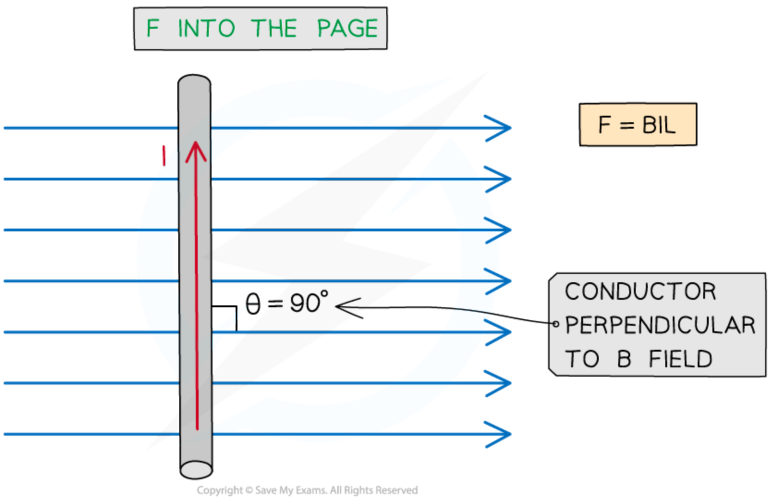
$$F = BIL \sin \theta$$

- Where:
  - F = magnetic force on the current-carrying conductor (N)
  - B = magnetic flux density of external magnetic field (T)
  - I = current in the conductor (A)

- L = length of the conductor in the field (m)
- θ = angle between the conductor and external flux lines (degrees)

- This equation shows that the magnitude of the magnetic force F is **proportional** to:
  - Current I
  - Magnetic flux density B
  - Length of conductor in the field L
  - The sine of the angle θ between the conductor and the magnetic flux lines





Magnitude of the force on a current carrying conductor depends on the angle of the conductor to the external B field

- The **maximum** force occurs when $\sin\theta = 1$
  - This means $\theta = 90°$ and the conductor is **perpendicular** to the B field
  - This equation for the magnetic force now becomes:

$$F = BIL$$

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- The **minimum** force (0) is when sin θ = 0
  - This means θ = 0° and the conductor is **parallel** to the B field
- It is important to note that a current-carrying conductor will experience **no** force if the current in the conductor is parallel to the field

Your notes

Worked Example

A current of 0.87 A flows in a wire of length 1.4 m placed at 30° to a magnetic field of flux density 80 mT.

Calculate the force on the wire.

Answer:

Step 1: Write down the known quantities

- Magnetic flux density, B = 80 mT = 80 × 10^{-3} T
- Current, I = 0.87 A
- Length of wire, L = 1.4 m
- Angle between the wire and the magnetic flux lines, θ = 30°

Step 2: Write down the equation for the magnetic force on a current-carrying conductor

$$F = BIL \sin \theta$$

Step 3: Substitute in values and calculate

$$F = (80 \times 10^{-3}) \times (0.87) \times (1.4) \times \sin(30) = 0.04872 = 0.049 \text{ N (2 s.f)}$$

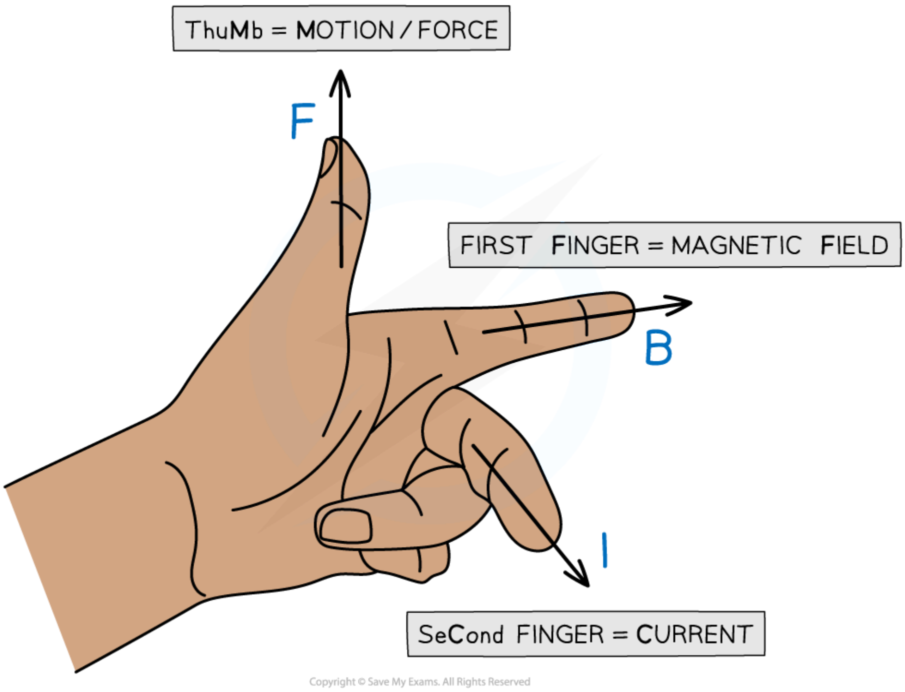
Examiner Tips and Tricks

Remember that the direction of current is the flow of **positive** charge (i.e. conventional current) and this is in the **opposite direction** to the flow of electrons (i.e. electron flow)!

Fleming's Left Hand Rule for a Current-Carrying Conductor

- Fleming's Left Hand Rule was previously used to determine the direction of the magnetic force on a moving **charged particle** in a magnetic field
- It can also be used to determine the direction of the magnetic force on a **current-carrying conductor** in a magnetic field
  - This is because inside a conductor (e.g. a wire) there are **many** charged particles flowing as a current

- As a reminder, the image representing Fleming's Left Hand Rule is shown below:

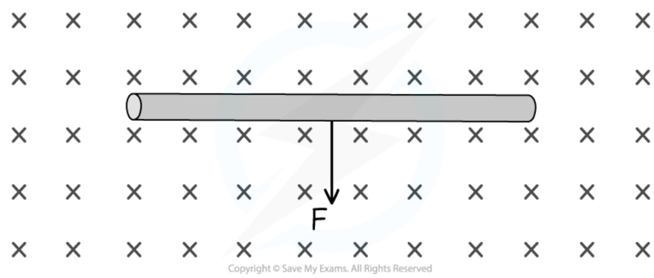


Fleming's Left Hand Rule. Remember, current is the flow of conventional current (i.e. positive to negative)

- Using the conventional symbols representing vectors like magnetic flux density ***B*** and force ***F*** that go into the page (arrows) or out of the page (dots) we can apply Fleming's Left Hand Rule to problems in 3D

Worked Example

A current flows perpendicularly to a uniform magnetic field as shown in the diagram below.



As a result, the conductor carrying the current experiences a magnetic force, *F*.

Determine the direction of the current flowing in the conductor.

Your notes

Answer:

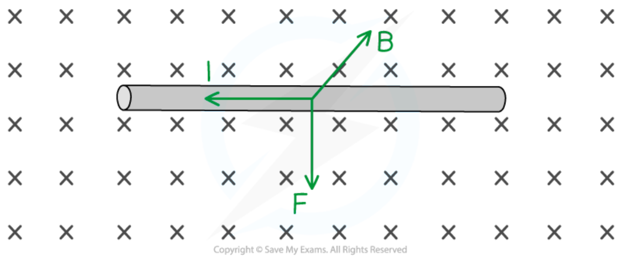
Step 1: Apply the instructions for Fleming's Left Hand Rule

- Using Fleming's Left Hand Rule for the quantities given:
  First finger is the magnetic field, *B* = into the page (or screen!)

  Thumb is the direction of the magnetic force *F* = vertically downwards

Step 2: Determine the direction of the conventional current

- The first finger should be pointing into the page (or screen!) along the direction of the field
- Rotating the entire hand allows the thumb to point downwards, along the direction of force
- The second finger should be pointing towards the left of the page (or screen!)



Examiner Tips and Tricks

You will certainly need to apply Fleming's Left Hand Rule in your examination, at some point, whenever there is a current or charge flowing in a magnetic field. Remember, it is used to give the **direction** of either the magnetic force *F*, the magnetic field *B*, or the conventional current (or flow of positive charge) *I*.

As ever, you will gain more confidence twisting your arm in funny positions with three fingers at right-angles the more questions you practise: the more, the better!

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