Electromagnetism

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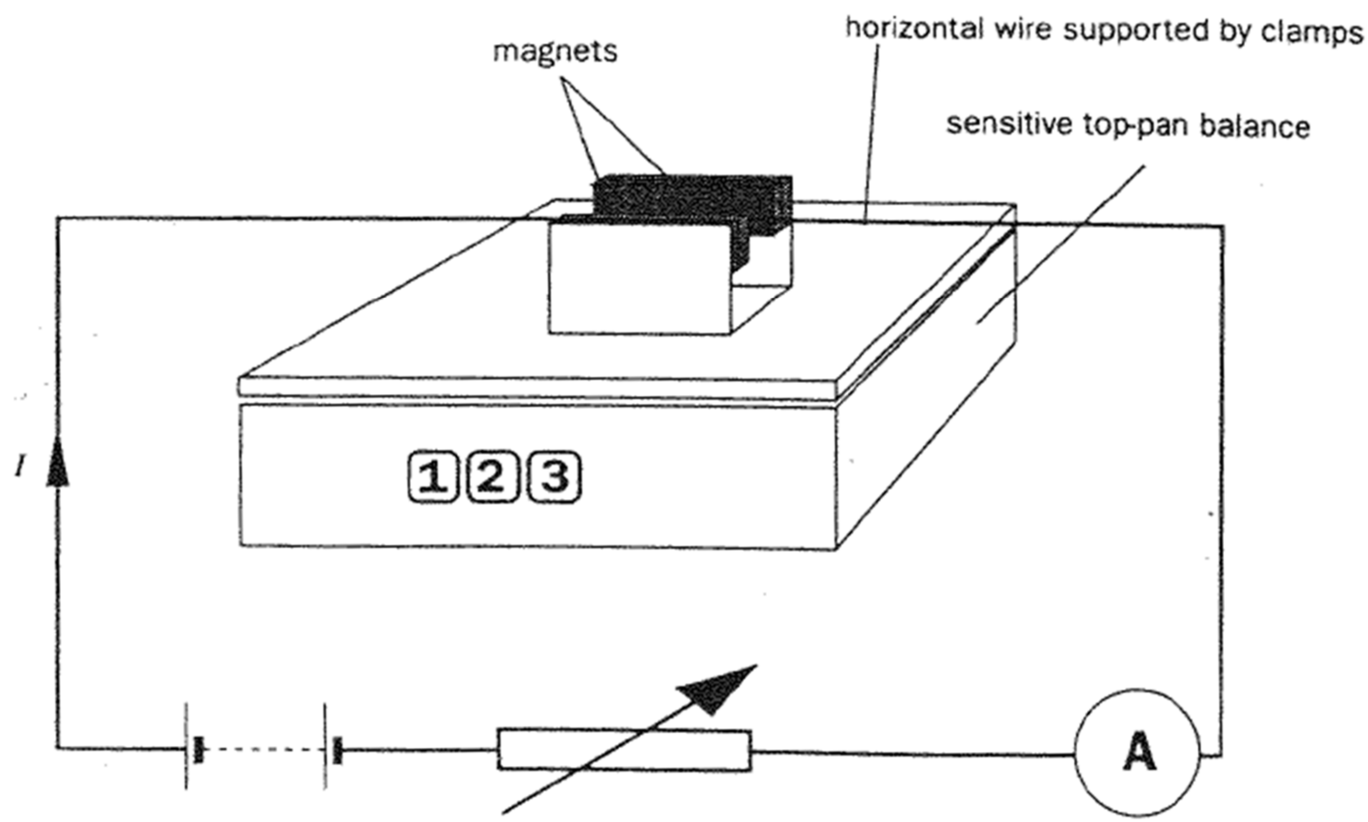


Measuring the force on a current-carrying conductor in a magnetic field

Force on a current-carrying conductor in a magnetic field

- Whenever 2 magnetic fields interact, there may be forces exerted.
- The previous slide figure shows an arrangement which can be used to demonstrate the fact that a current-carrying wire placed in a magnetic field experiences a force.
- The strong magnets are attached to the soft iron frame with opposite pole facing each other, so that a strong magnetic field is created in the space between.
- The top pan balance is set to read zero when the magnets are placed on the pan.
- When there is a current (I) through the clamped wire, a force is created which acts on the current in the wire.
- According to Newton's Third Law, there will be an equal but opposite force exerted on the magnets and this will cause a change in the reading of the balance.
- A downward force on the magnets will cause an increase in the reading, while an upward force will cause a decrease.

Force on a current-carrying conductor in a magnetic field

- The following factors have been proven to affect on the magnitude and direction of the force:

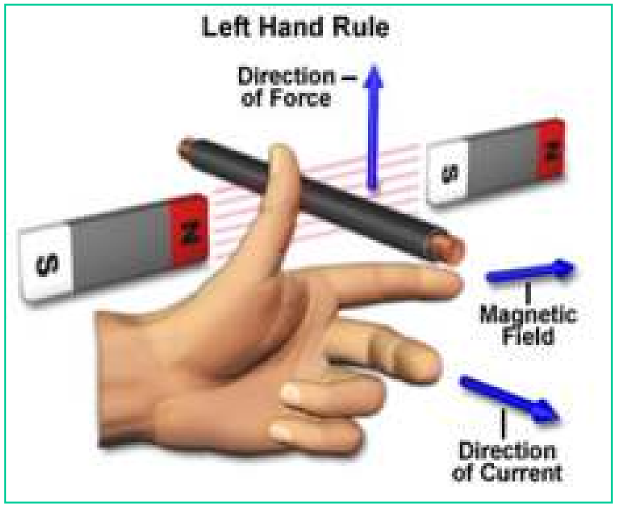
  a.) Magnitude and direction of the current.
  b.) Strength and direction of the magnetic field.
  c.) Length of conductor in the magnetic field.

- This force is produced as a result of the interaction between the magnetic field surrounding the current-carrying wire, and the magnetic field of the permanent magnets.

- Remember, as the current-carrying conductor experiences a force in one direction, the permanent magnet will also experience a same magnitude of force but in the opposite direction. (Newton's 3rd Law)

- Next we will see how to determine the **DIRECTION** and **MAGNITUDE** of the force acting on the current-carrying conductor.

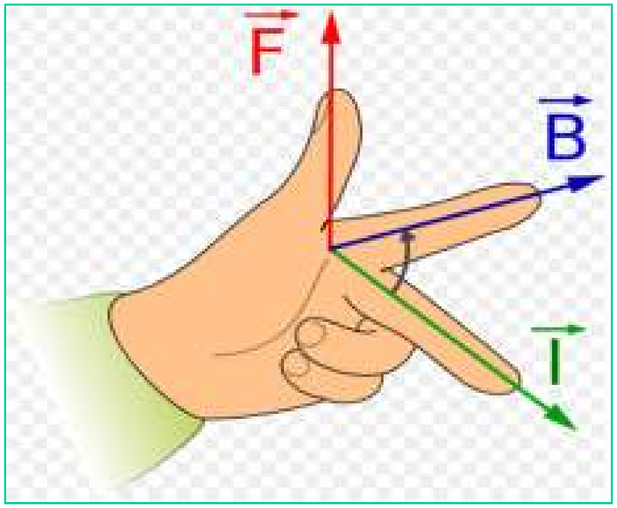
Determining the **DIRECTION** of the Force on the current-carrying conductor



- The direction of the force on the wire/conductor depends on the:

  a.) Direction of the magnetic field of the other party (i.e: the permanent magnet)
  b.) Direction of the current flowing in the wire.

- This can be determined using Fleming's left-hand rule as shown in figure on the left.



- F = force (thumb)
- B = magnetic field (index finger)
- I = current (middle finger)

- Just remember FBI.

Determining the **MAGNITUDE** of the Force on the current-carrying conductor

- Experiment shows that the size of the force, F acting on the wire is directly proportional to:

  a.) strength of the magnetic field
  b.) magnitude of the current
  c.) length of the wire in the field

- Thus a wire of length (L) carrying a steady current (I) situated in a magnetic field of strength (B) which is at **right angle** to the wire, the force (F) acting on the wire is given by:

$$(F = BIL)$$

$$(B = F / IL)$$

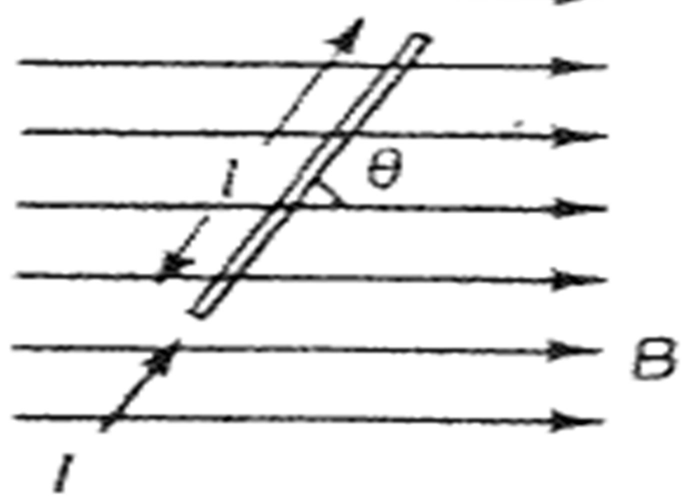
- **Magnetic flux density (B)** is defined as the *force acting per unit current in a wire of unit length which is perpendicular to the field.*

- **One Tesla** is the *magnetic flux density if a wire of length one metre carrying a current of one ampere has a force exerted on it of one Newton in a direction at right angles to both the flux and the current.*

Determining the **MAGNITUDE** of the Force on the current-carrying conductor

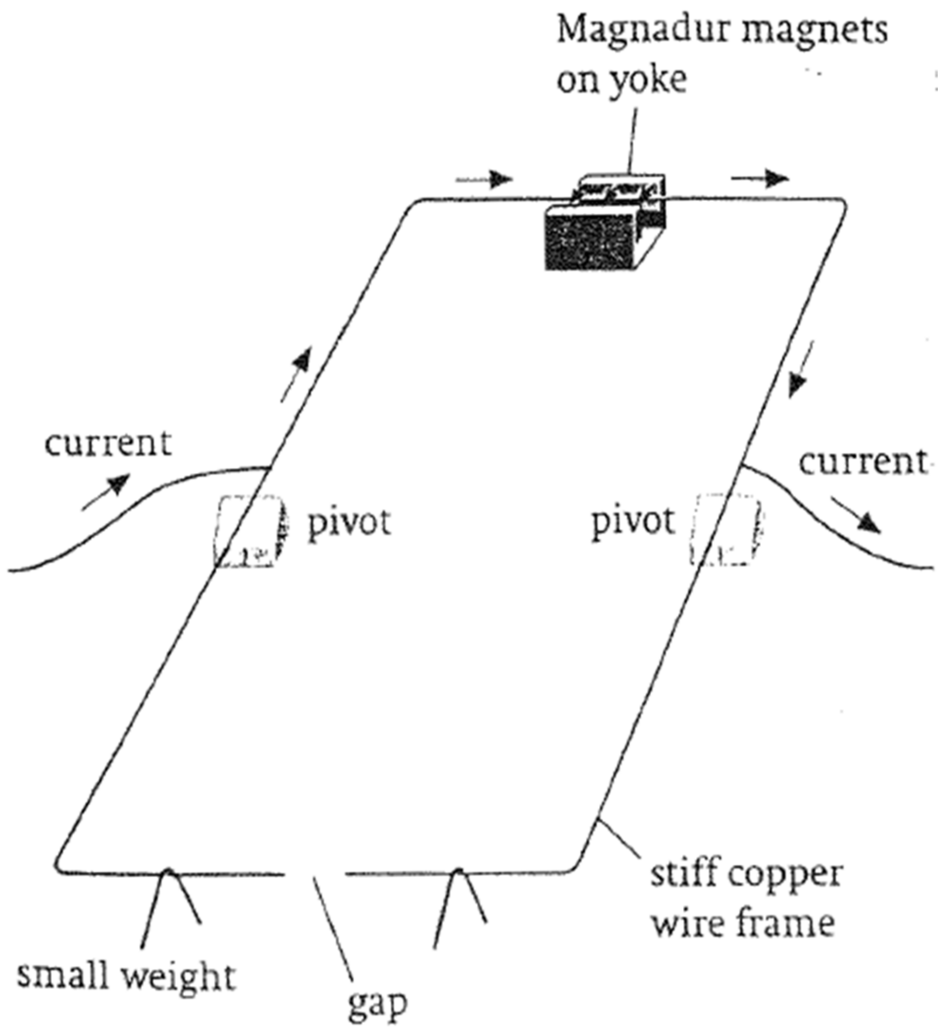
- If the wire is some angle, θ to the magnetic field, the force is then given by:

$$\mathbf{F = BIL\sin\theta}$$



- **Wire perpendicular to field, θ = 90°, sin 90° = 1, thus F = BIL**
- **Wire parallel to field, θ = 0°, sin 0° = 0, thus F = 0**
- **http://www.youtube.com/watch?v=14SmN_7EcGY**

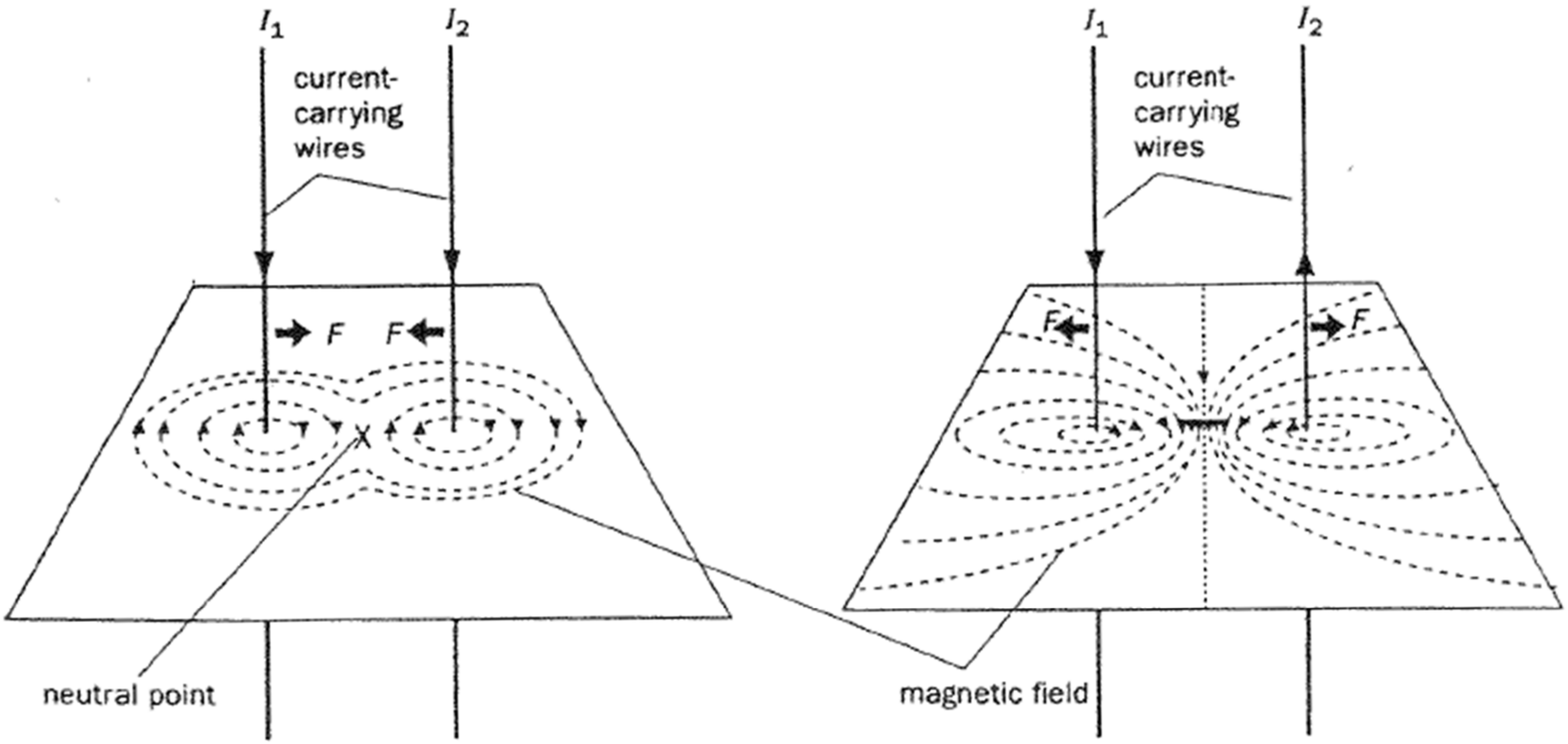
Current Balance Experiment



A laboratory current balance.

- A current balance can be used in experiments to investigate the force on a current-carrying conductor in a magnetic field. The wire frame is placed mid-point on the pivot.
- Current flows through the wire frame, the magnetic field pushes the frame downwards.
- By adding small weights to the other side of the frame, the wire frame can be restored to a balanced position.
- By using the principle of moments, since the distance is the same, thus the magnetic force (F) must be equal to the restoring weight (W).

Parallel current-carrying wires

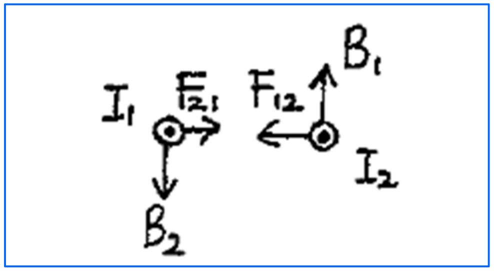


(a) Currents in same direction – attractive forces **(b) Currents in opposite directions – repulsive forces**

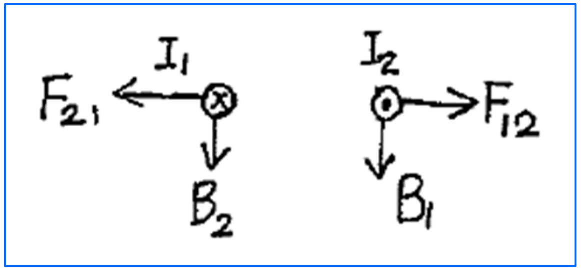
Fields around parallel current-carrying wires

Parallel current-carrying wires

- Figure shows the shape of the resultant magnetic field for 2 straight, parallel wires which are placed side by side and carry currents in a.) same direction b.) opposite direction.
- Each wire is in the magnetic field of the other and so they experience a force which is at right angles to both the current and the field.



Current same direction



Current opposite direction

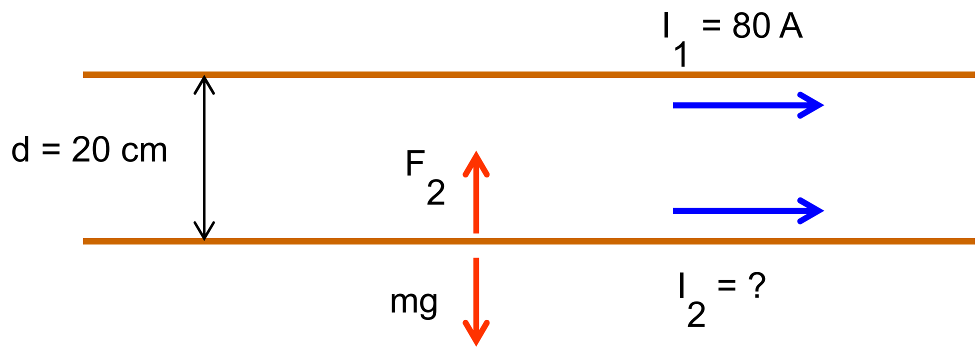
- For current in the same directions, the force is attractive and opposite directions, the force is repulsive.
- Note that there is a neutral point in the case of currents in same direction. This happens because at the position, the magnetic field are equal in magnitude and opposite in direction.
- If two currents are not equal in magnitude, the neutral point would be closer to the wire with the smaller current.

Example 1

- Two wires of a 2.0 m long each, are 3.0 mm apart and carry a current of 8.0 A in opposite directions. Calculate the force between these wires. Are the wires attracted to each other or repel from one another?

Example 2

- A horizontal wire carries a current I_1 = 80 A. A second parallel wire 20 cm below it must carry how much current I_2 so that it does not fall due to gravity? The lower wire has a mass of 0.12 g per meter of length.



Example 3

- The magnetic flux density B at a distance x from a long straight wire due to a current I in the wire is given by the expression

$$B = \frac{\mu_0 I}{2\pi x},$$

where μ_0 is the permeability of free space.

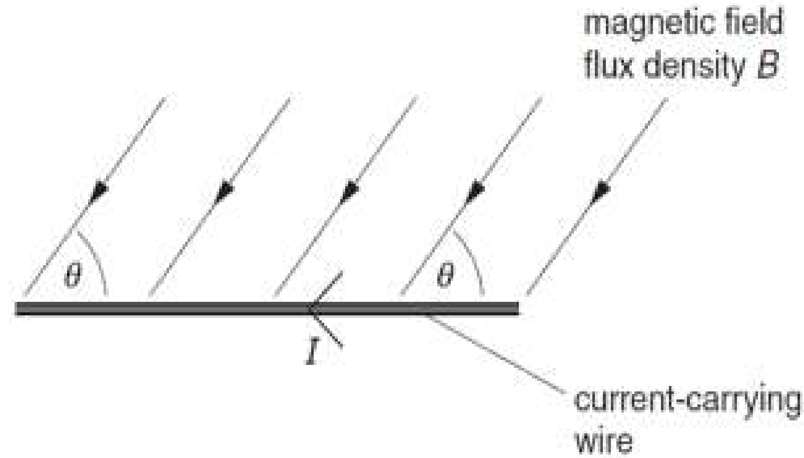
The current in wire X is 5.0 A and that in wire Y is 7.0 A. The separation of the wires is 2.5 cm.

(i) Calculate the force per unit length on wire Y due to the current in wire X.

(ii) The currents in the wires are not equal. State and explain whether the forces on the two wires are equal in magnitude.

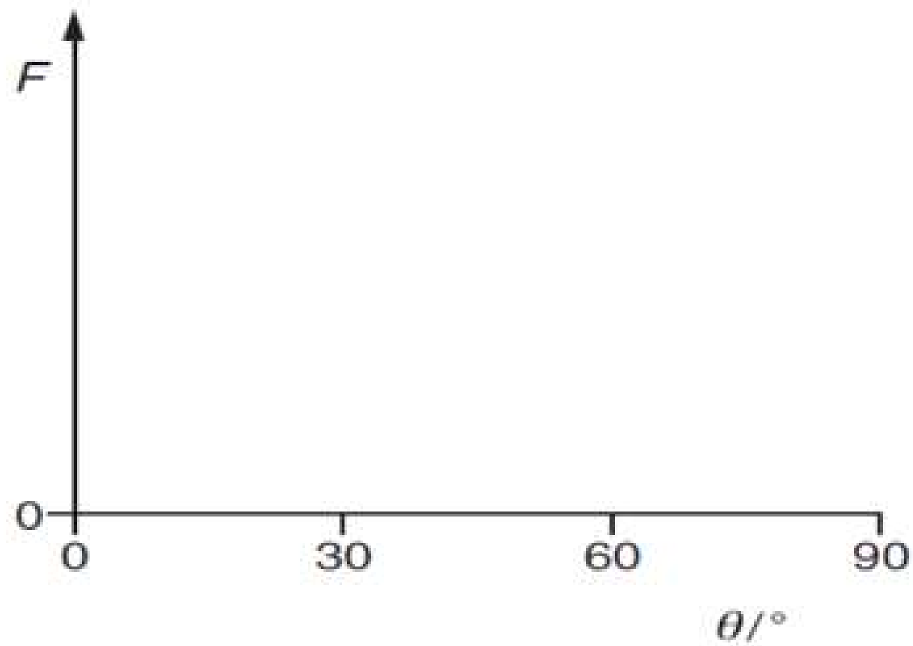
Example 4

- A uniform magnetic field has constant flux density B. A straight wire of fixed length carries a current I at an angle θ to the magnetic field, as shown on the right.



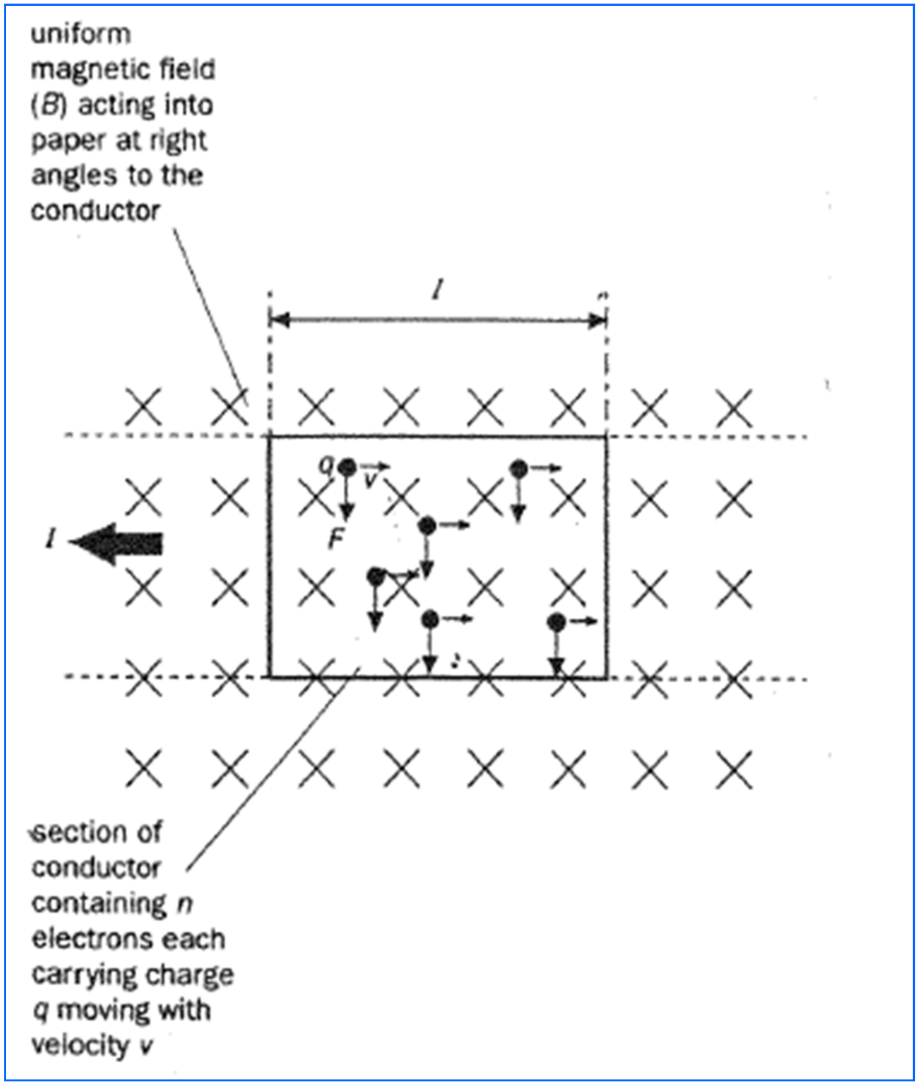
- The current I in the wire is changed, keeping the angle θ constant. On figure below, sketch a graph to show the variation with current I of the force F on the wire.

- The angle θ between the wire and the magnetic field is now varied. The current I is kept constant. On figure below, sketch a graph to show the variation with angle θ of the force F on the wire.



Force on Individual moving charges in magnetic field

- We have seen how a wire placed in a magnetic field experiences a force when there is current through it.
- Since we regard the current in the wire as a flow of electrons, it seems reasonable to conclude that the force exerted on the wire in the field is the resultant of the forces acting on each of the moving electrons.
- Figure shows a length (L) of wire containing (n) electrons of charge (q) and average drift velocity (v) which is situated in a magnetic field of flux density (B) directed at right angles to the wire.



Determining the **MAGNITUDE** of the Force on the individual moving charge

- The average time (t) taken by each electron to travel distance (L) is given by:

$$t = L / v$$

- Current (I) in the wire is equal to the total charge (nq) passing a section per unit time (t):

$$I = nq / t = nqv / L$$

- The total force acting on the wire is given by:

$$F_{total} = BIL = B\,(nqv / L)\,L = Bnqv$$

- Force acting on EACH individual electron is then given by:

$F = Bqv$ (charge particle moving at right angle to field)

$F = Bqv\sin\theta$ (charge particle moving at an angle, θ to field)

- Remember that there is **NO FORCE** on the charged particle when:

i.) The charged particle is stationary. (velocity = 0, F = 0)

ii.) The charged particle moves parallel to the field. ($\theta = 0°$, $F = 0$)

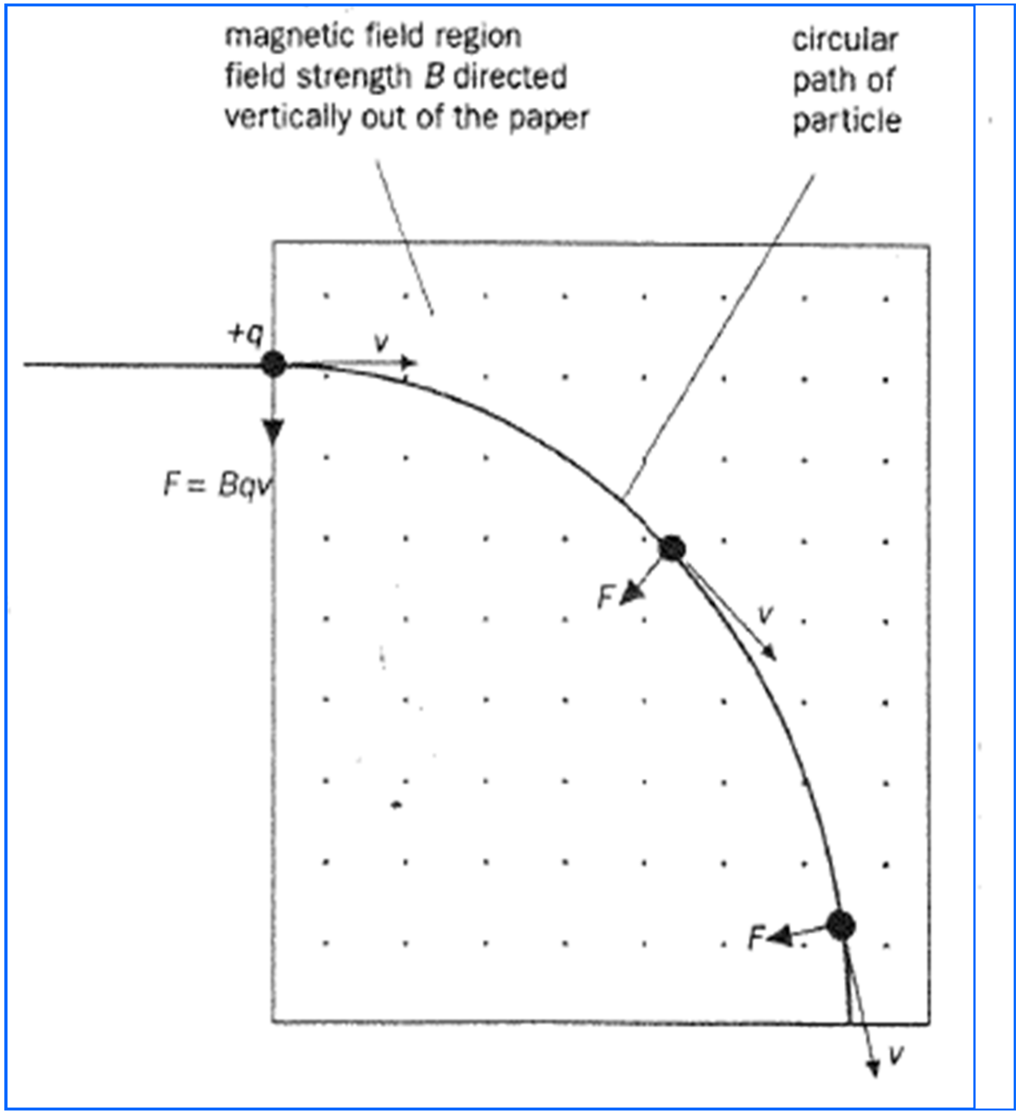
Determining the **DIRECTION** of the Force on the individual moving charge

- The direction of the force can also be determined by using the Fleming's left hand rule BUT bear in mind that the current direction is opposite to the direction of the flow of electron or any negatively charged particle.

- The force causes the moving charged particles to be deflected towards one side of the conductor. This is called Hall Effect, and is used to measure the strength of the magnetic fields using a device called the Hall Probe.

The path of charged particle in magnetic field

- When a charged particle moves at right angles to a magnetic field the constant force (F = Bqv) exerted on it is perpendicular to both the particle velocity and the field direction.
- Even tough the force continually changes the particles direction of motion, it has no effect on its speed (hence its kinetic energy)
- The result is that the charged particle moves in a circular path when it is in the field.
- A body can only move in circular path if there is centripetal force acts on it. In this case, the force due to the field (F = Bqv) is providing the necessary centripetal force.



Circular path of a charged particle in a perpendicular magnetic field

The path of charged particle in magnetic field

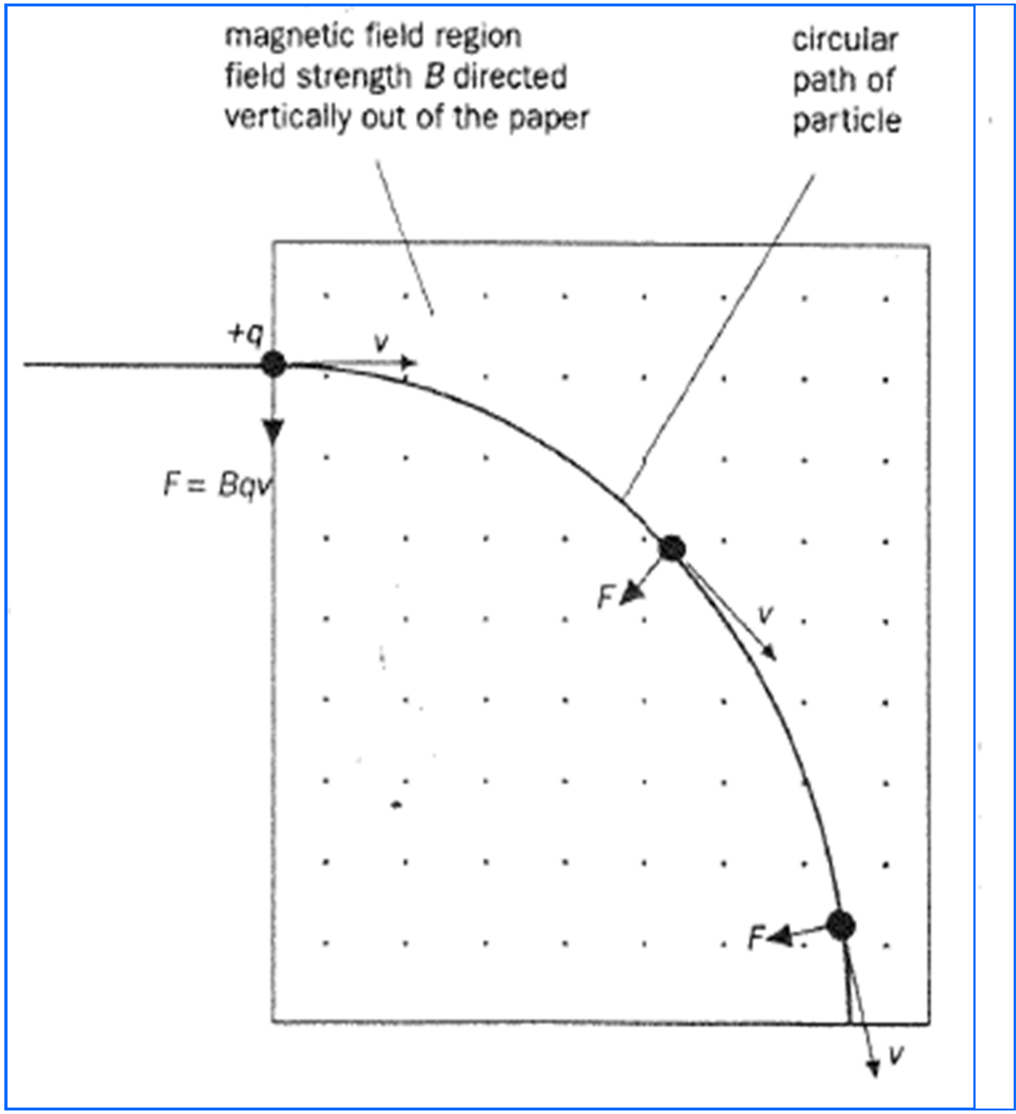
- $F = Bqv = mv^2 / r$
- **$r = mv / Bq$**
- Radius, r is the radius of the circular path which the charged particle follows.
- From the equation, we see that a smaller radius can be produced by:

a.) a smaller mass

b.) lower velocity particle

c.) a stronger magnetic field

d.) a greater charge on the particle.



Circular path of a charged particle in a perpendicular magnetic field

Example 5

- A proton travelling in a vacuum at a speed of 4.5×10^6 ms^{-1} enters a region of uniform magnetic field of flux density 0.12 T. The path of the proton in the field is a circular arc. Calculate the radius of the path of the proton in the magnetic field.

- An α-particle and a β-particle are both travelling along the same path at a speed of 1.5×10^6 ms^{-1}. They then enter a region of uniform magnetic field. Calculate the ratio of $\frac{radius\ of\ path\ of\ the\ \alpha{-}particle}{radius\ of\ path\ of\ the\ \beta{-}particle}$

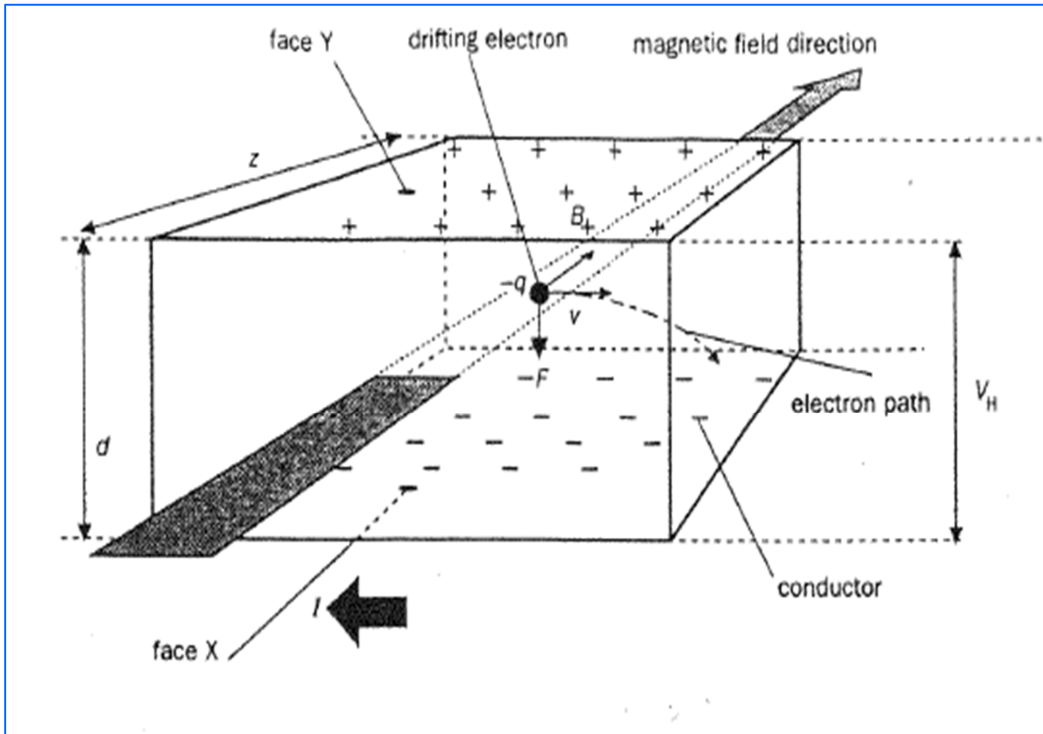
($m_p = m_n = 1.67 \times 10^{-27}$ kg, $m_e = 9.11 \times 10^{-31}$ kg)

The Hall Effect

- When a section of conducting material carries current in magnetic field, each of the charged particles carrying current experiences a force at right angles to their direction of motion and the direction of the magnetic field.
- This causes charged particles to accumulate on one side of the conductor, which produces a small potential difference across the sides of the conductor.
- This phenomenon is known as the Hall effect.

- In the figure beside, a metallic conductor of rectangular cross section carries current from right to left and at right angles to the magnetic field.

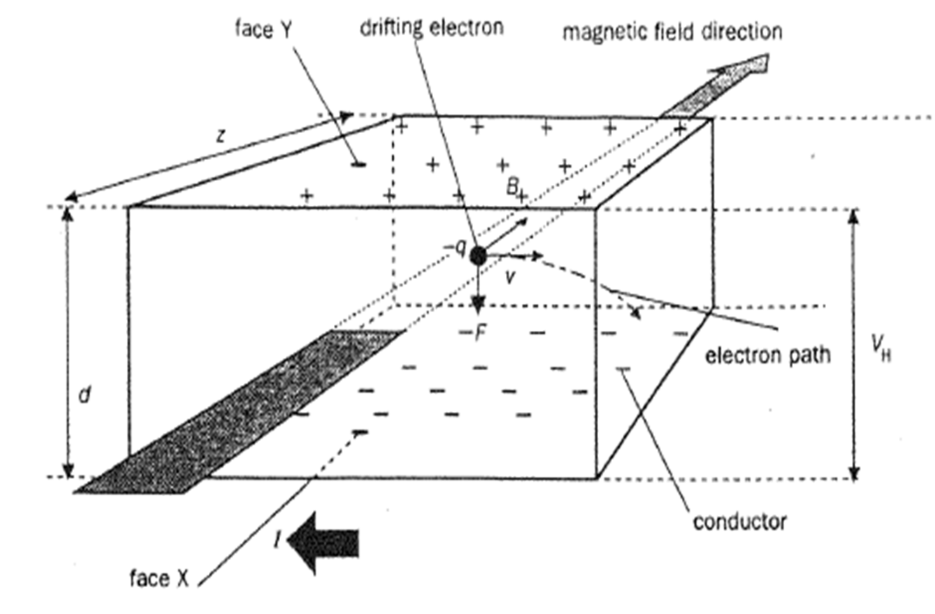
- Using left hand rule, the force will act downwards on the electrons. Electrons will move to face X causing a build-up of negative charge on X, and a consequent build-up of positive charge on Y.



Origin of the Hall effect in a metal conductor

The Hall Effect

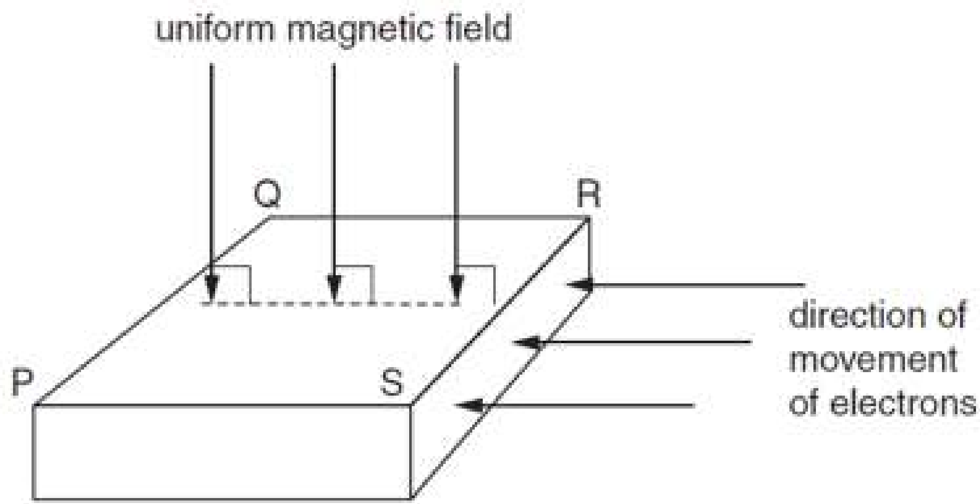
- This continues until the potential difference between X and Y becomes large enough to prevent any further movement of charge. (whereby the force can no longer push the electron to the highly negative charge face X.)
- This maximum potential difference between X and Y is called the Hall voltage (V_H).
- It is established when the force on each electron (due to magnetic field) is balanced by the oppositely directed force (due to electric field between X and Y).
- Hall voltage (V_H) is directly proportional to magnetic flux density (B).



Origin of the Hall effect in a metal conductor

Example 6

- A uniform magnetic field is directed at right-angles to the rectangular surface PQRS of a slice of a conducting material, as shown.



- Electrons, moving towards the side SR, enter the slice of conducting material. The electrons enter the slice at right-angles to side SR.

  (i) Explain why, initially, the electrons do not travel in straight lines across the slice from side SR to side PQ.

  (ii) Explain to which side, PS or QR, the electrons tend to move.

Comparison of Forces in a Gravitational field, Electric field and Magnetic field.

	Gravitational	Electric	Magnetic
1) Direction of force	Parallel to the direction of the field (same direction)	Parallel to the direction of the field (either same or opposite)	Normal to direction of the field
2) Magnitude of force	independent of speed	independent of speed	force α speed force = 0 , when charge is stationary

Example 7

- A small mass is placed in a field of force that is either magnetic, electric or gravitational. State the nature of the field of force when the mass is:

i.) charged and the force is opposite to the direction of the field.

ii.) uncharged and the force is in the direction of the field.

iii.) charged and there is force only when the mass is moving.

iv.) charged and there is no force on the mass when it is stationary or moving in a particular direction