17 ELECTROMAGNETIC FORCES

H2 Physics 9478

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Learning Outcomes

Candidates should be able to:

(a) show an understanding that a magnetic field is an example of a field of force produced either by current carrying conductors or by permanent magnets

(b) sketch magnetic field lines due to currents in a long straight wire, a flat circular coil, and a long solenoid

(c) use $B = \frac{\mu_0 I}{2\pi d}$, $B = \frac{\mu_0 N I}{2r}$ and $B = \mu_0 n I$ for the magnetic flux densities of the fields due to currents in a long straight wire, a flat circular coil, and a long solenoid respectively **[Not in H1 syllabus]**

(d) show an understanding that the magnetic field due to a solenoid may be influenced by the presence of a ferrous core **[Not in H1 syllabus]**

(e) show an understanding that a current-carrying conductor placed in a magnetic field might experience a force

(f) recall and solve problems using the equation $F = BIL\sin\theta$, with directions as interpreted by Fleming's left-hand rule

(g) define magnetic flux density as the force acting per unit current per unit length on a conductor placed perpendicular to the magnetic field

(h) show an understanding of how the force on a current-carrying conductor can be used to measure the flux density of a magnetic field using a current balance

(i) explain the forces between current-carrying conductors and predict the direction of the forces **[not in H1 syllabus]**

(j) predict the direction of the force on a charge moving in a uniform magnetic field.

(k) recall and solve problems using the equation $F = BQv\sin\theta$.

(l) describe and analyse deflections of beams of charged particles by uniform electric fields and uniform magnetic fields.

(m) explain how perpendicular electric and magnetic fields can be used in velocity selection for charged particles

17.1 Concept of a Magnetic Field

❖ Properties of Magnets

- Natural magnets were discovered from ancient archaeological sites more than two thousand years old. The term 'magnet' comes from the name of one of the locations these stones were found.
- Experiments have shown that
  - (i) magnetic poles are of two kinds, i.e. north (**N**) or south (**S**),
  - (ii) like poles repel each other, unlike poles attract,
  - (iii) poles occur only in opposite pairs (dipoles),
  - (iv) when no other magnet is near, a freely suspended magnet will rotate so that the line joining its poles is approximately parallel to the Earth's axis of rotation, and
  - (v) the pole of the magnet that points towards the Earth's Geomagnetic North is called the north pole of the magnet and the other the south pole of the magnet.

❖ Magnetic Field

- Forces between magnets can be explained using the concept of a magnetic field.
  - A magnet sets up a magnetic field in its vicinity.
  - The force exerted by one magnet on another magnet is due to the interaction between the magnetic fields set up by both magnets.

Definition 1

A magnetic field is a region of space in which a moving charge or a current-carrying conductor or a ferromagnetic object can experience a magnetic force when it is placed in the magnetic field.

Hence, it is known as a field of force.

- Quantitatively, the "strength" of a magnetic field is expressed by a quantity called the **magnetic flux density (*B*)**. Its SI unit is the **tesla (T)**. (The magnetic flux density and its unit will be defined later.)

  Magnetic flux density is a vector.

- It is important to note that a **moving charge** placed in a magnetic field can experience a magnetic force when it is not moving parallel to the magnetic field. (Static charge placed in a magnetic field will not experience a magnetic force.)

Note:
There is a subtle difference between the following two terms:
- magnetic flux density, denoted by symbol B (in syllabus).
- magnetic field strength, denoted by symbol H, where $B = \mu_0 H$ (not in syllabus).

❖ Representation of a Magnetic Field

A magnetic field can be represented by field lines drawn such that

- the tangent to a field line at a point gives the direction of *B* at that point,
- the number of lines per unit cross–sectional area is an indicaton of the magnitude of *B*, i.e. if the lines are spaced closer, the magnitude of *B* is greater. If the field is uniform, the field lines are parallel and evenly spaced, and
- the arrows point away from the north pole of a magnet to the south pole. This is because the direction of a field line is given by the direction of the force that acts on the north pole of a magnet.

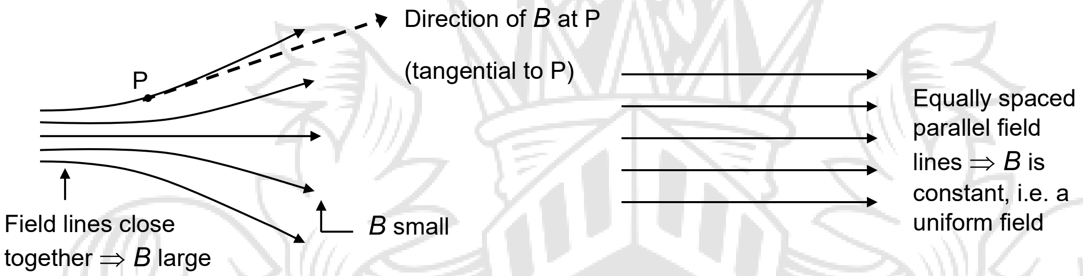


Fig. 17.1

For a two-dimensional view, magnetic fields can be represented by dots or crosses, depending on whether it is perpendicularly pointing out of or into the plane of the paper, respectively.

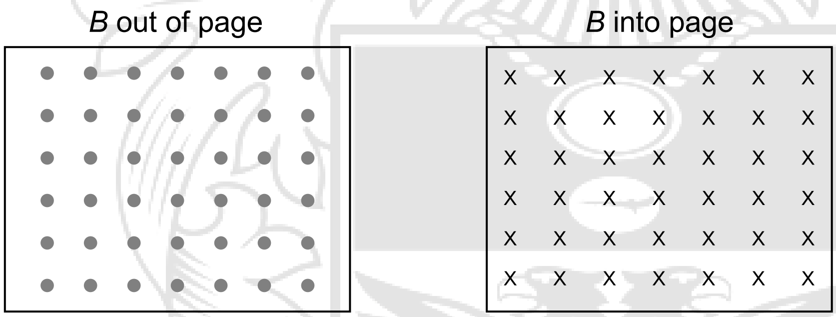
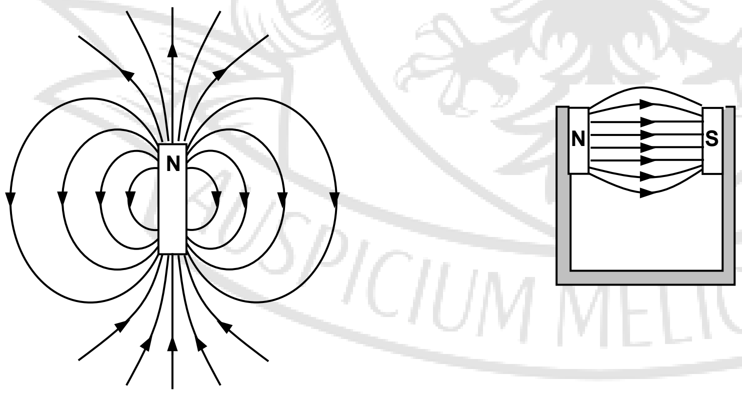


Fig. 17.2

❖ Examples of Field Patterns



(a) Bar magnet (b) U-shaped magnet

Fig. 17.3

❖ Earth's Magnetic Field

- The Earth's magnetic field is a weak magnetic field believed to be caused by electric currents circulating within the core of the Earth.
- The magnitude and direction of this field varies with position over the Earth's surface and changes gradually with time.
- The axis of the Earth's magnetic field is tilted approximately 11 ° with respect to its rotational axis. Hence, the geographical North does not coincide exactly with the geomagnetic North.
- The field pattern is similar to that of a bar magnet embedded deep inside the Earth as shown in Fig. 17.4.

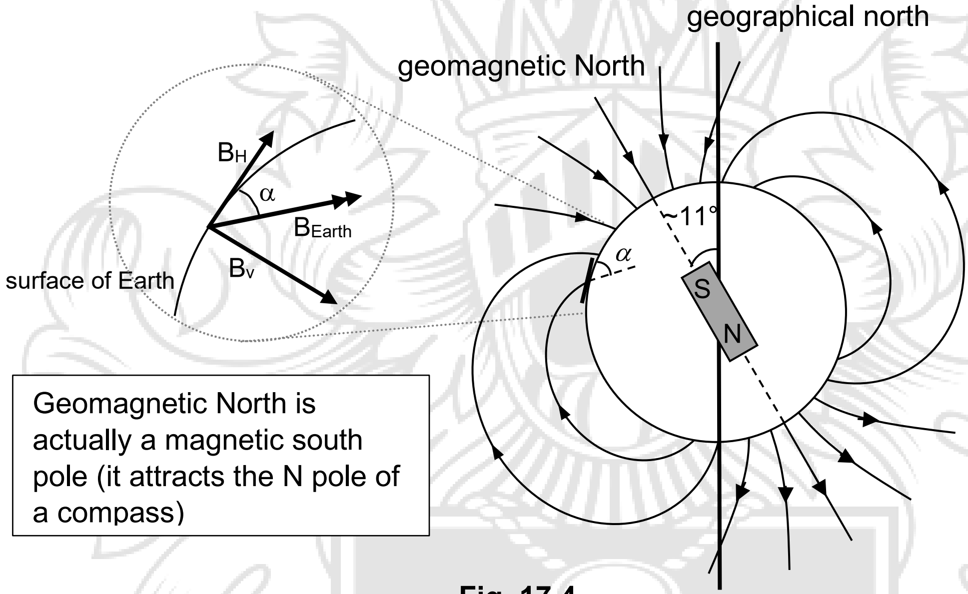


Fig. 17.4

- From the field pattern, it is seen that near the equator, the Earth's magnetic field, B_{Earth}, is almost horizontal.
- At all other positions, the B_{Earth} is inclined at various angles (called the *angle of dip,* α) from the horizontal.

It is useful to resolve B_{Earth} into horizontal and vertical components.

$$B_H = B_{\text{Earth}} \cos \alpha$$
$$B_V = B_{\text{Earth}} \sin \alpha$$

Compass needles whose motion is confined in a horizontal plane are affected only by B_H.

17.2 Magnetic Fields Due to Currents

❖ The Birth of Electromagnetism

In 1820, Hans Christian Oersted discovered the magnetic effect of an electric current. His findings saw the birth of electromagnetism.

He found that when compasses were placed on different sides of a current-carrying conductor, the needles of the compasses would be deflected in different ways as shown in Fig. 17.5.

Following Oersted's discovery, experiments showed that there is a relationship between the magnetic field due to a current carrying conductor and the current which flows through it.

The direction of magnetic field can be determined using Maxwell's *right-hand grip rule* as shown in Fig. 17.6.

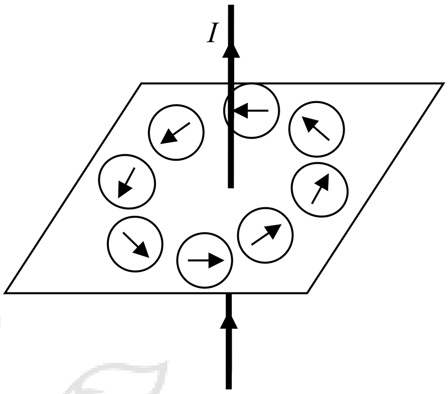
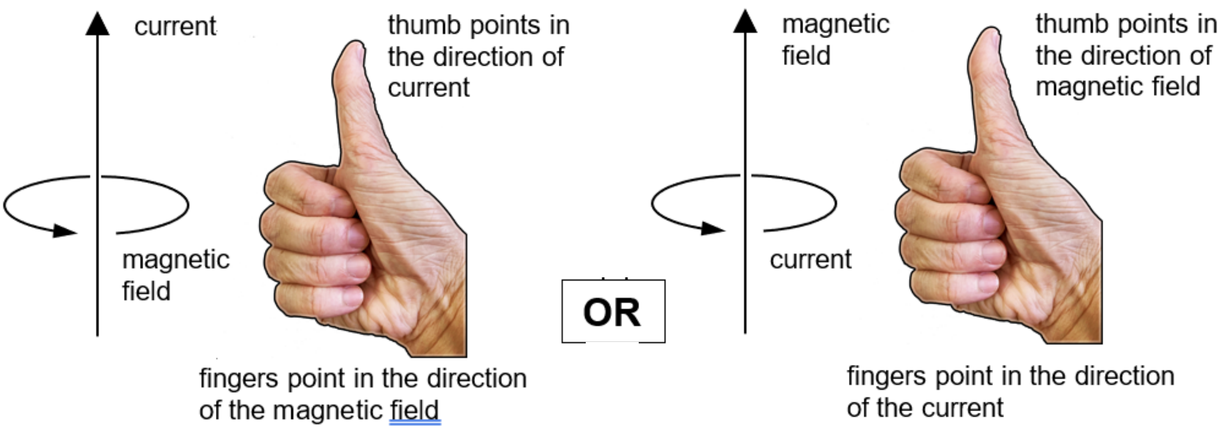


Fig. 17.5



(a) right-hand grip rule for straight wire

(b) right-hand grip rule for coil or solenoid

Fig. 17.6

❖ Magnetic Field due to an Infinitely Long Straight Current-Carrying Wire

Fig. 17.7 shows the field pattern around an infinitely long straight current-carrying wire.

- The magnetic field lines are concentric circles.
- The separation between the field lines increases with distance from the wire. This indicates that the magnetic flux density decreases in magnitude with distance from the wire.

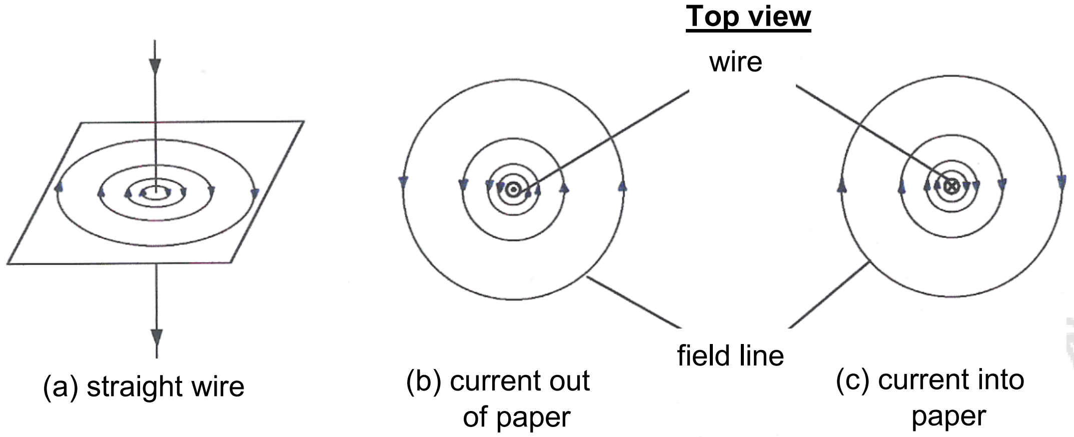


Fig. 17.7

The direction of magnetic field in Fig. 17.7(b) can be determined using Maxwell's *right-hand grip rule* as shown in Fig. 17.8.

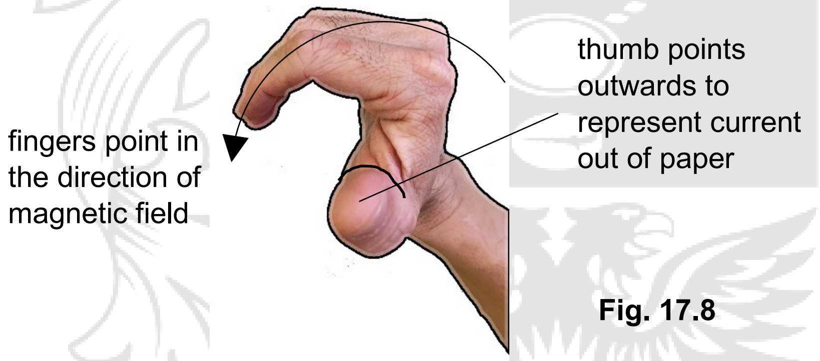


Fig. 17.8

Fig. 17.9 shows an infinitely long straight wire lying in the plane of the paper. At the point P, the magnetic flux density due to the current in the wire is directed into the paper and its magnitude is given by

$$\boxed{B = \frac{\mu_0 I}{2\pi r}}$$ (provided in the formula list)

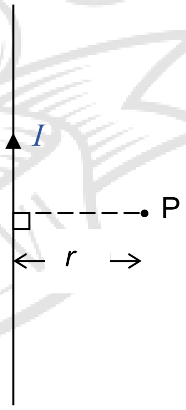


Fig. 17.9

where B = magnetic flux density

I = current in the wire

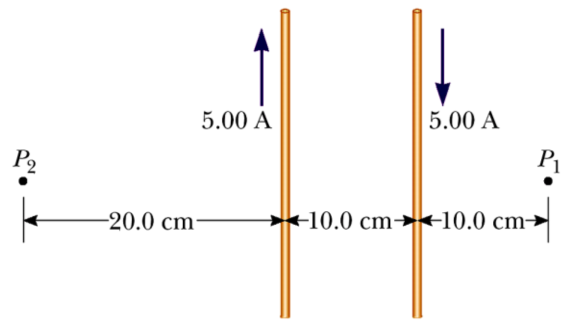
r = perpendicular distance of P from wire

μ_0 = permeability of free space(vacuum)

= $4\pi \times 10^{-7}$ H m^{-1}

Quick Check

Determine the direction of the magnetic field at point P_1 and P_2.



❖ **Magnetic Fields due to a flat Circular Coil and a long Solenoid**

Fig. 17.10 shows the field patterns due to a flat circular coil and a long solenoid.

- The direction of the field lines within the coil and the solenoid can be found using the *right-hand grip rule*: Grip the coil in your right hand with your fingers pointing in the direction of the current, then your thumb gives the direction of the magnetic field.
- When the turns of a solenoid are closely spaced, each can be regarded as a circular coil. Hence, the net field in a solenoid is due to the effect of many circular turns.
- The magnetic field inside a long solenoid is uniform.

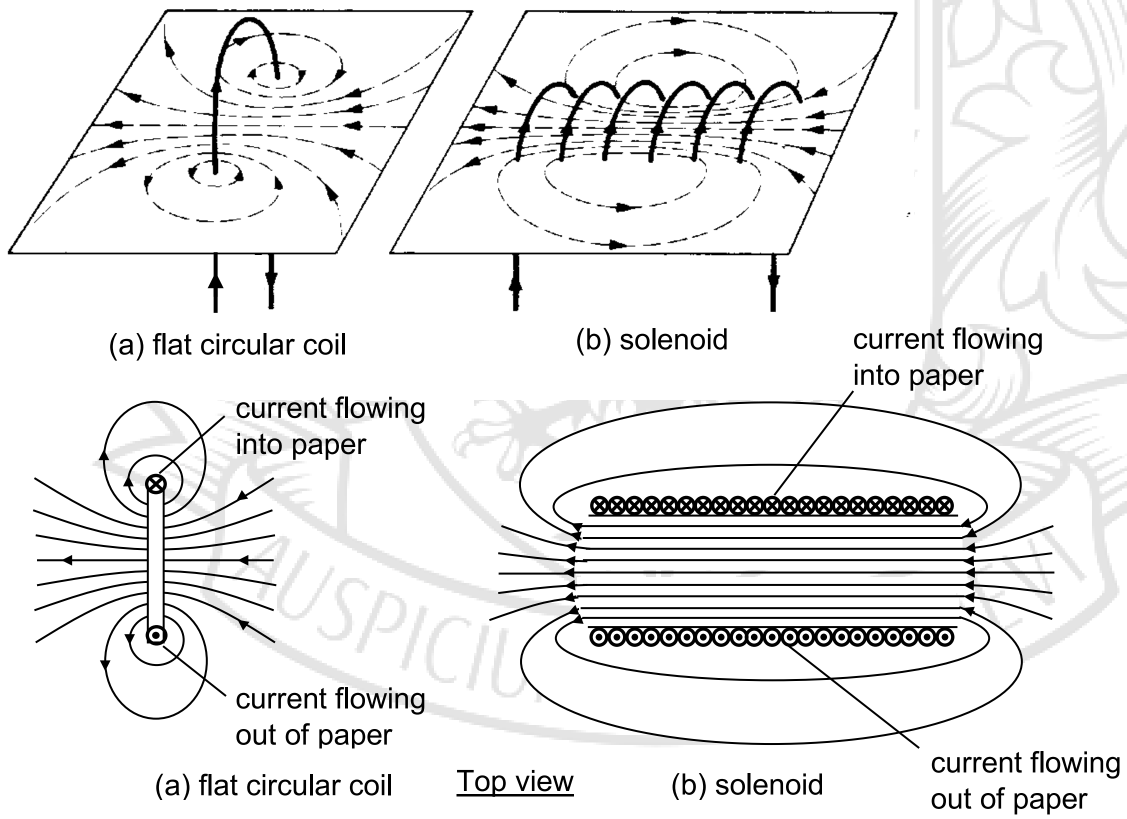


Fig 17.10

Flat Circular Coil

Fig. 17.11 shows a flat circular coil lying in the plane of the paper. At the centre of the coil, the magnetic flux density B due to the current in the coil is directed into the paper (by the right-hand grip rule) and its magnitude is given by

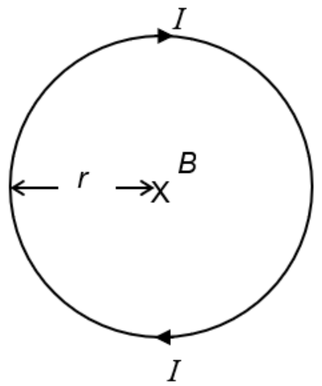


Fig. 17.11

$$\boxed{B = \frac{\mu_0 N I}{2r}}$$ (provided in formula list)

where B = magnetic flux density at the centre of coil

μ_0 = permeability of free space

N = number of turns

I = current in the coil

r = radius of the coil

Long Solenoid

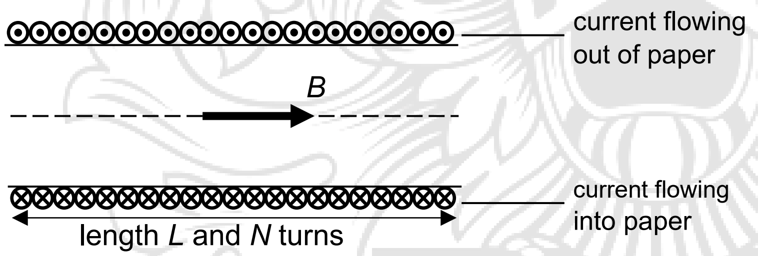


Fig. 17.12: Cross sectional view of a solenoid

The magnetic flux density inside an infinitely long solenoid is directed along the axis and its magnitude is given by

$$\boxed{B = \mu_0 n I}$$ (provided in formula list)

where B = magnetic flux density

μ_0 = permeability of free space

n = number of turns per unit length of solenoid = N/L

I = current in the solenoid

At either end of a long solenoid, the magnetic flux density is $\frac{1}{2}\mu_0 n I$.

❖ Effects of Iron Core in Solenoids and Electromagnets

A bar of soft iron can be magnetized by placing it inside a solenoid. When a current passes through the solenoid, it produces a magnetic field along its axis and the bar is magnetized accordingly. The resultant magnetic field is the sum of the field due to the current and that due to the soft iron core so that the magnitude of the resultant field can have a magnitude of hundreds to thousand times that due to the current alone.

[Making a speaker]

17.3 Force on a Current-Carrying Conductor

❖ Direction of the Magnetic Force

A current–carrying conductor in a magnetic field may experience a force.

This force is always perpendicular to the direction of the current and the direction of the magnetic field.

The relative directions of current, field and force are summarized by ***Fleming's Left–Hand Rule*** as shown in Fig. 17.13.

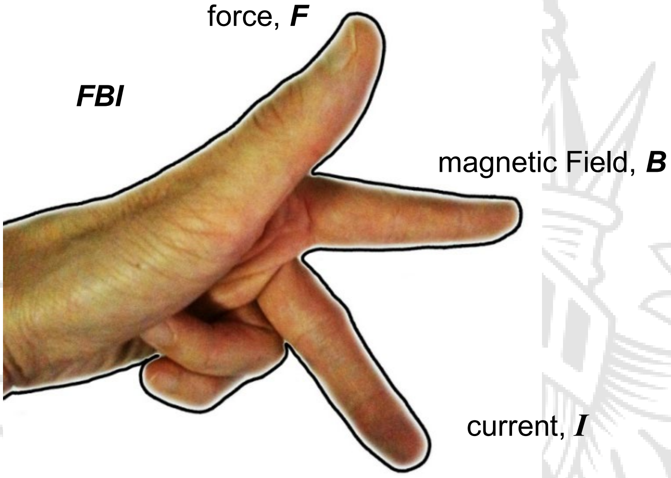


Fig. 17.13

The 'kicking wire' experiment

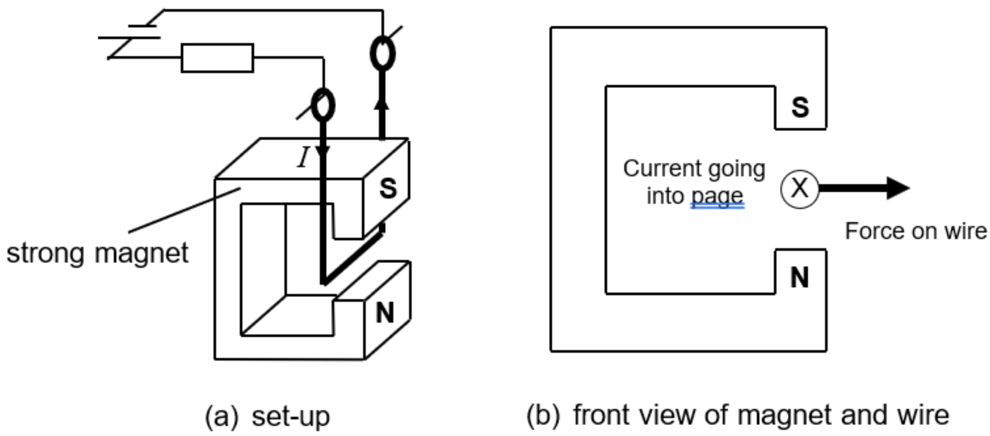


Fig. 17.14

The 'kicking wire' experiment in Fig. 17.14 shows that when a current passes through the wire, a magnetic force acts on the wire causing it to 'kick' in the direction shown.

Determining magnetic flux density from current-carrying wire

❖ Magnitude of the Magnetic Force

Experiments with a wire placed at right angles to the magnetic field show that the magnitude of the magnetic force F is directly proportional to

- the **current I** in the wire
- the **length L** of the wire in the magnetic field
- the **magnetic flux density B**

This leads to a definition of magnetic flux density:

Definition 2

The magnetic flux density of a magnetic field is numerically equal to the force per unit length per unit current acting on a long straight current-carrying conductor placed at right angles to the magnetic field.

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

where B = magnetic flux density
F = magnetic force acting on the wire
I = current flowing through the wire
L = length of wire

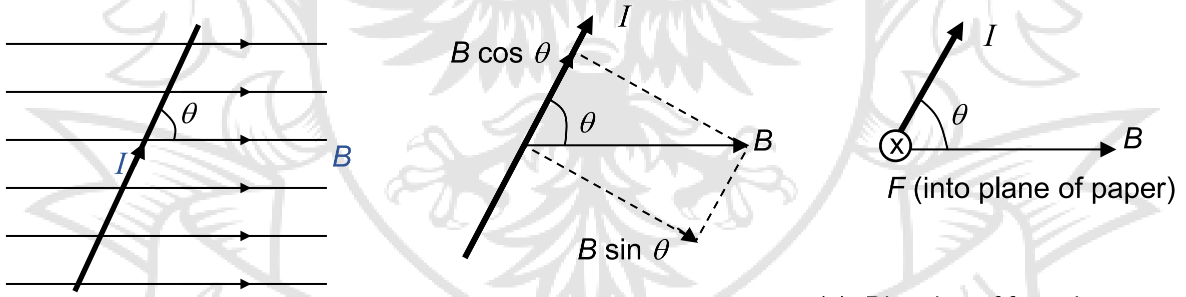
The S.I. unit for flux density is **tesla** (T).

$$1\ \mathrm{T} \equiv 1\ \mathrm{N\,A^{-1}\,m^{-1}} \equiv 1\ \mathrm{kg\,s^{-2}\,A^{-1}}$$

Re–arranging the equation for magnetic flux density, the magnetic force F acting on a wire of length L carrying a current I when placed at right angles to the field is given by

$$F = BIL$$

In the general case, if the conductor makes an angle θ with the magnetic field as shown in Fig. 17.15(a), the force can be regarded as due to the *component* of the field *perpendicular* to the current ($B \sin \theta$); the component parallel to the current produces no force.



(a) Top view of a conductor placed on a horizontal surface

(b) Components of magnetic field parallel and perpendicular to conductor

(c) Direction of force is perpendicular to plane containing B and I, found using Fleming's Left-hand Rule

Fig. 17.15

Thus, magnetic force F is given by $\boxed{F = BIL \sin\theta}$, where angle θ is between B and I.

Example 1

A wire, 2.0 m in length, carrying a current of 10 A is placed in a field of flux density 0.15 T. Determine the magnitude of the force on the wire if it is placed

(a) at right angles to the field,

(b) at 30° to the field, and

(c) along the field.

[Solution]

❖ Measuring Magnetic Flux Density using a Current Balance

A current balance is an arrangement that can be used to measure the magnetic flux density *B* of a magnetic field. It makes use of the principle of moments.

Current Balance

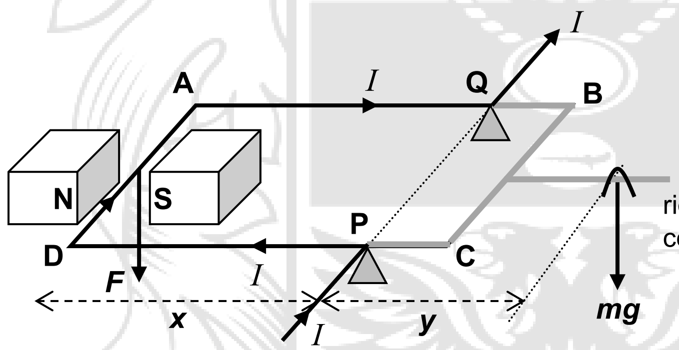


Fig. 17.16

- A wire frame ABCD is balanced on 2 pivots P and Q through which a current I from a d.c. source enters from P and leaves from Q.
- The frame is arranged such that the side AD of length L lies within a magnetic field whose flux density B is to be determined.
- When there is no current, the frame is horizontal.
- When a current flows, a magnetic force acts on AD and pushes that side of the frame downwards (by Fleming's left-hand rule).
- A mass m (known as a rider) is suspended on the right side to restore the frame to its horizontal position.

By the principle of moments,

$$\text{sum of clockwise moments} = \text{sum of anticlockwise moments}$$

$$mgy = Fx$$

$$= BILx$$

$$B = \frac{mgy}{ILx}$$

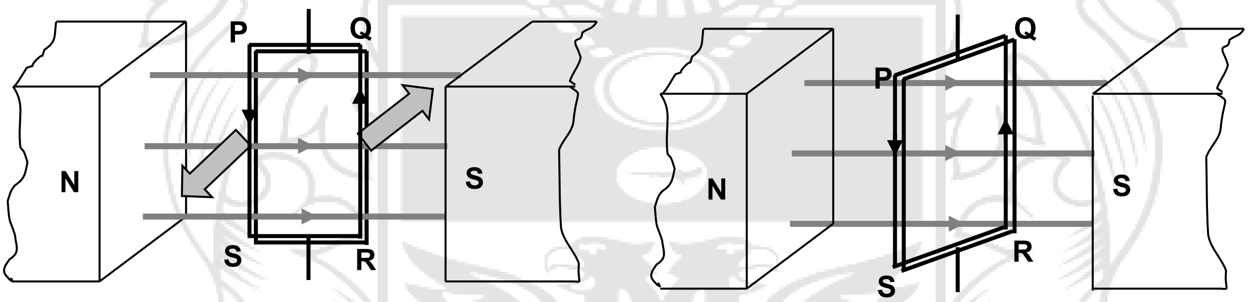
Hence, the magnetic flux density B of a magnetic field can be determined with the appropriate quantities known.

❖ Current Balance vs Hall Probe (not in syllabus)

<u>**Current Balance**</u>	<u>**Hall Probe**</u>
• Does not require calibration. Deduces B using force, current and lengths.	• Requires calibration by a magnetic field of known magnetic flux density.
• Unable to measure weak fields.	• Can measure very weak fields.
• Apparatus is bulky. Not so practical and portable.	• Practical and convenient due to the small size of the probe.

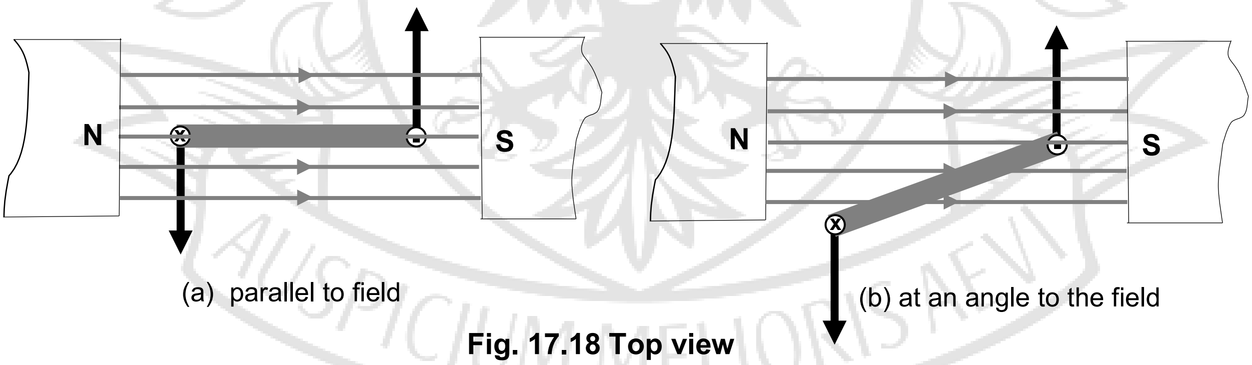
❖ Torque on a Current-Carrying Coil in a Magnetic Field

Consider a rectangular coil placed in a uniform magnetic field as shown in Fig. 17.17 (a). The plane of the coil is initially parallel to the field lines.



(a) parallel to field (b) at an angle to the field

Fig. 17.17 Front view



(a) parallel to field (b) at an angle to the field

Fig. 17.18 Top view

When a steady current passes through the coil, a magnetic force acts on sides PS and QR, which are at right angles to the field lines.

Using Fleming's Left Hand Rule, the force on PS is opposite to the force on QR. These two forces form a couple and provide a torque (turning effect) on the coil. Hence, the coil will rotate in the direction as shown in Fig. 17.18. This is the principle behind moving-coil meters and motors.

Let us take a closer look to determine an expression for the torque on a coil. Fig. 17.19 shows the same coil PQRS placed in a uniform magnetic field *B* such that the vertical sides PS and QR are always 90° to the field while the horizontal sides PQ and SR make an angle θ to the field. Assume that the coil has *N* turns and its horizontal and vertical sides are of length *x* and *y* respectively.

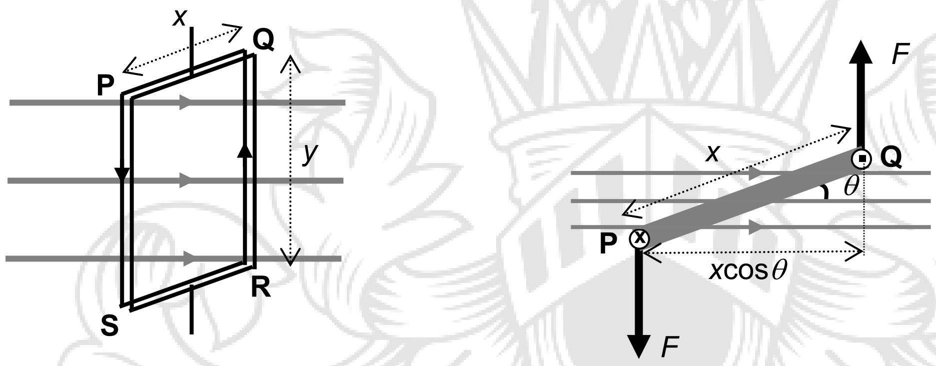


Fig. 17.19

- When current flows in the coil, each side of the coil experiences a force.

- The forces on the horizontal sides of the coil (PQ and SR) do not give rise to a turning effect as they act in the vertical direction and may distort the coil (if it is not rigid enough).

- The forces on the vertical sides (PS and QR), each of length *y*, are opposite in direction and equal in magnitude, given by $F = NBIy$.

- Whatever the position of the coil, its vertical sides are at right angles to the magnetic field and so the force *F* remains constant in magnitude.

- The forces *F* constitute a couple whose torque τ is given by

$$\begin{aligned}\tau &= (\text{force}) \times (\text{perpendicular distance b/w lines of action of the forces}) \\ &= F\left(x\cos\theta\right) \\ &= \left(NBIL\right)\left(x\cos\theta\right) \\ &= NBIyx\cos\theta\end{aligned}$$

$$\boxed{\tau = NBIA\cos\theta}$$

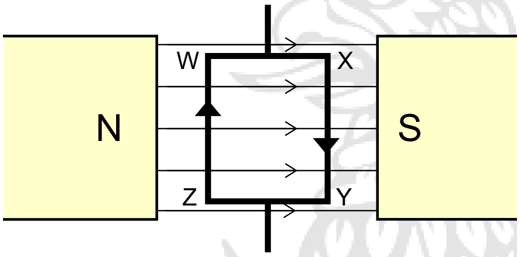
where *A* = area of the coil = *xy*.

Note:
- τ is maximum when θ = 0°, i.e. the plane of the coil is parallel to *B*.

- τ is zero when θ = 90°, i.e. the plane of the coil is perpendicular to *B*.

Example 2

In an electric motor, a rectangular coil WXYZ has 20 turns and is in a uniform magnetic field of flux density 0.83 T. The lengths of sides XY and ZW are 0.17 m and of sides WX and YZ are 0.11 m. The current in the coil is 4.5 A.



(a) Calculate maximum torque τ on the coil

(b) Calculate the torque on the coil when its plane makes an angle of 30° with the magnetic flux density.

(c) At what angle does the plane of the coil make with the magnetic field when the torque is zero?

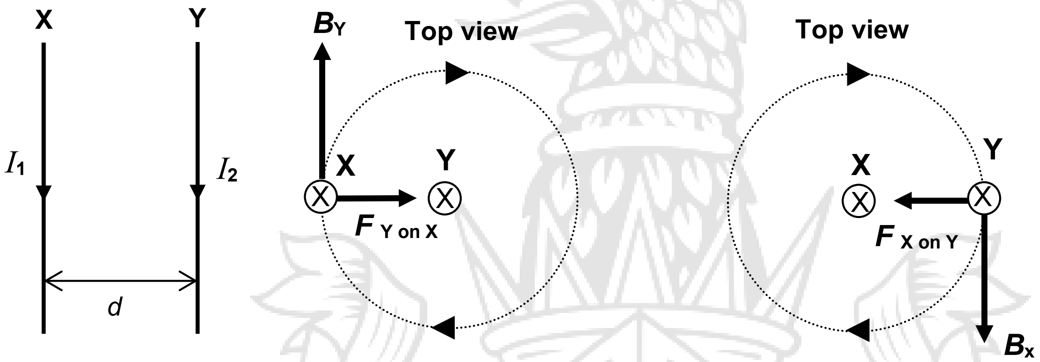
[adapted from N2010/P1/31]

[Solution]

17.4 Forces Between Current-Carrying Conductors

❖ Currents Flowing in the Same Direction (Attraction)

Consider two infinitely long parallel vertical wires X and Y carrying currents I_1 and I_2 flowing in the same direction, separated by a distance *d*, as shown in Fig. 17.20(a).



(a) Front view of wire X and Y (b) Force acting on X (c) Force acting on Y

Fig. 17.20

Referring to Fig. 17.20(a), the current in X produces a magnetic field directed out of the page (using right-hand grip) at wire Y (refer to Fig. 17.20(c)) given by

$$B_X = \frac{\mu_o I_1}{2\pi d}\ .$$

At Y, the direction of the field B_x due to X is perpendicular to Y as shown in Fig. 17.20(c). Using Fleming's Left-Hand Rule, the magnetic force F_{XonY} on a length *L* of Y would be **towards** X and has a magnitude of

$$F_{X \text{ on } Y} = B_X I_2 L = \left(\frac{\mu_o I_1}{2\pi d}\right) I_2 L\ .$$

Similarly, the magnetic force F_{YonX} on a length *L* of X is **towards** Y as shown in Fig. 17.20(b) and has a magnitude of

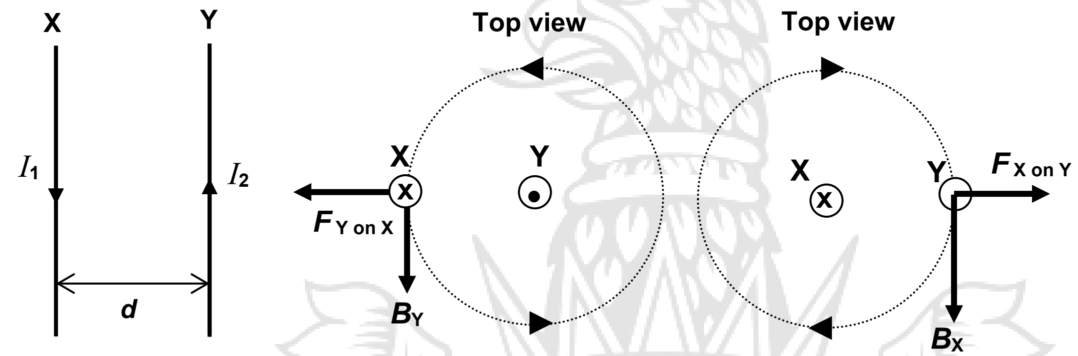
$$F_{Y \text{ on } X} = B_Y I_1 L = \left(\frac{\mu_o I_2}{2\pi d}\right) I_1 L\ .$$

By Newton's Third Law, $F_{X \text{ on } Y}$ and $F_{Y \text{ on } X}$ are equal and opposite forces. The two wires **attract** one another.

The force per unit length on each wire is given by $\boxed{\dfrac{F}{L} = \dfrac{\mu_o I_1 I_2}{2\pi d}}$.

❖ Currents Flowing in Opposite Directions (Repulsion)

Consider two infinitely long parallel vertical wires X and Y carrying currents I_1 and I_2 flowing in opposite directions, separated by a distance *d*, as shown in Fig. 17.21(a).



(a) Front view of wire X and Y
(b) Force acting on X
(c) Force acting on Y

Fig. 17.21

Referring to Fig. 17.21(a), the current in X produces a magnetic field directed out of the page (using right-hand grip) at wire Y (refer to Fig. 17.21(c)) given by

$$B_X = \frac{\mu_o I_1}{2\pi d}.$$

At Y, the direction of the field B_x due to X is perpendicular to Y as shown in Fig. 17.21(c). Using Fleming's Left-Hand Rule, the magnetic force F_{XonY} on a length *L* of Y would be **away from** X and has a magnitude of

$$F_{\text{X on Y}} = B_X I_2 L = \left(\frac{\mu_o I_1}{2\pi d}\right) I_2 L.$$

Similarly, the magnetic force on a length *L* of X is **away from** Y as shown in Fig. 17.21(b) and has a magnitude of

$$F_{\text{Y on X}} = B_Y I_1 L = \left(\frac{\mu_o I_2}{2\pi d}\right) I_1 L.$$

By Newton's Third Law, $F_{\text{X on Y}}$ and $F_{\text{Y on X}}$ are equal and opposite forces. The two wires **repel** one another.

The force per unit length on each wire is given by $\boxed{\frac{F}{L} = \frac{\mu_o I_1 I_2}{2\pi d}}$.

Note:

For two parallel current-carrying conductors,

i) the **force per unit length** on each wire is given by the equation

$$\frac{F}{L} = \frac{\mu_o I_1 I_2}{2\pi d}$$

ii) **"Like currents attract**, **unlike currents repel"** as shown in Fig. 17.22.

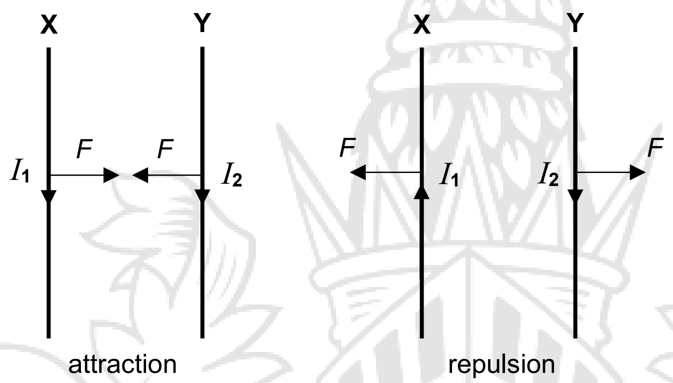


Fig. 17.22

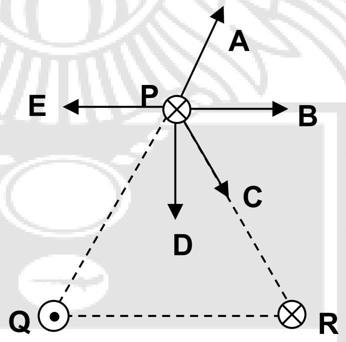
Example 3

Three long vertical wires pass through the corners of an equilateral triangle PQR.

P and R carry currents directed into the plane of the paper and wire Q carries a current directed out of the paper .

All three currents have the same magnitude.

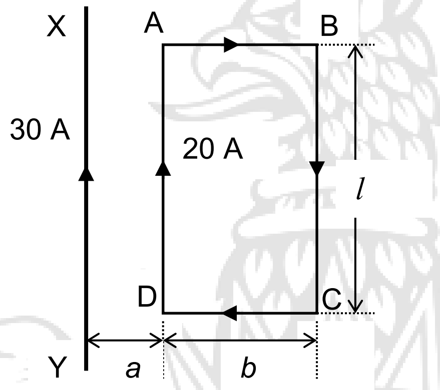
Which arrow shows the direction of the resultant force acting on P?



[Solution]

Example 4

The figure shows a long wire XY carrying a current of 30 A. The rectangular loop ABCD carries a current of 20 A. The lengths *a*, *b* and l are 1.0 cm, 8.0 cm and 30 cm respectively.



(a) Calculate the magnetic flux density due to the current in XY along

(i) AD

(ii) BC

(b) Calculate the resultant force acting on the loop.

[Solution]

17.5 Force on a Moving Charge

❖ Force on a Charged Particle Moving in a Magnetic Field

Since a current-carrying conductor can experience a force in a magnetic field, **a moving charge should also experience a force in a magnetic field.**

What causes the aurora?

Consider a section of a conducting wire of uniform cross-sectional area A in a uniform magnetic field of magnetic flux density B which is directed perpendicularly to the wire.

Let the total number of positive charge carriers, each of charge q, within the cylindrical volume between faces 1 and 2 be N. If each charge carrier has drift velocity v, after duration t, the distance L the charge carrier moves is vt. If n is the number density, then $N = nAL = nAvt$.

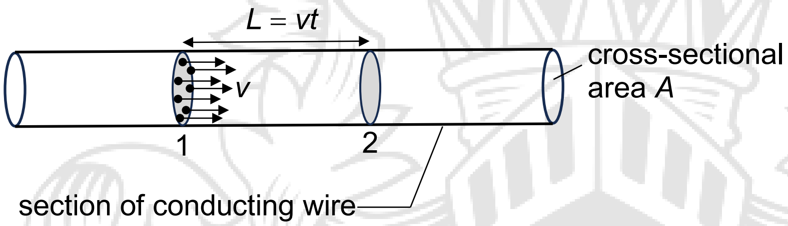


Fig. 17.23(a)

The total charge Q within the cylindrical volume between faces 1 and 2,

$$Q = Nq = (nAvt)q\,.$$

.

Since current $I = \dfrac{\mathrm{d}Q}{\mathrm{d}t} \Rightarrow I = nAvq$.

The magnetic force F_{wire} on the section of wire between faces 1 and 2 is

$$F_{\text{wire}} = BIL = B(nAvq)L$$

Since volume V of the section is $V = AL \Rightarrow F_{\text{wire}} = BNqv$.

Hence the force on one charge carrier is $F = \dfrac{F_{\text{wire}}}{N} = Bqv$.

(a) Charge moving perpendicularly to the magnetic field

(b) Charge moving at an angle to the magnetic field

Fig. 17.23(b)

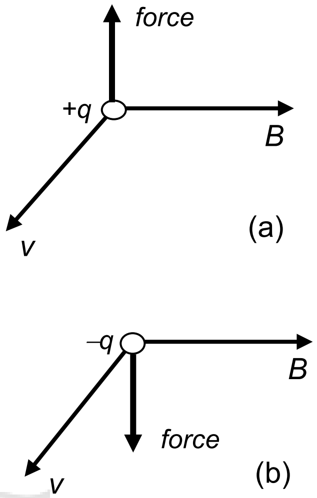


Fig. 17.24

If the velocity and field are inclined to each other by an angle θ as shown in Fig. 17. 23(b), then

$$\boxed{F = Bqv\sin\theta}$$

where F = magnitude of magnetic force acting on the charge
B = magnitude of magnetic flux density
q = magnitude of charge
v = speed of charge
θ = angle the velocity makes with the field

Remember that Fleming's left-hand rule considers the direction of conventional current. Hence, for a

a) positive charge, the direction of the current is the same as the motion of the charge,

b) negative charge, the direction of the current is in the opposite direction to the direction of motion of the charge. See Fig. 17.24.

17.6 Motion of a Charged Particle in a Magnetic Field

❖ Uniform Circular Motion

When a charged particle is projected at a right angle into a magnetic field, the magnetic force F is always perpendicular to the direction of travel (or velocity) and the distance travelled in the direction of the force is zero, as shown in Fig. 17.25.

Therefore, the work done on the charged particle is always zero.

This implies that no energy is gained or lost by the particle moving in the magnetic field and the particle's speed is always constant.

Since the force is of constant magnitude and is always at right angles to the velocity, the conditions for **uniform circular motion** are met.

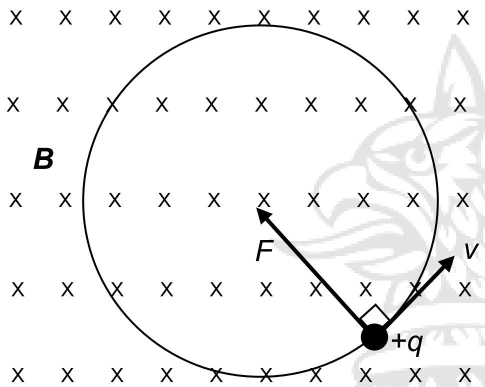


Fig. 17.25

The magnetic force on the moving charge provides for the centripetal force.

$$F_B = F_c$$
$$Bqv = \frac{mv^2}{r}$$

where m is the mass of the moving charge and r is the radius of circular path.

❖ **Helical Path**

For a charged particle entering a magnetic field at an angle θ such that $0° < \theta < 90°$, the particle will describe a **helix** as shown in Fig. 17.26.

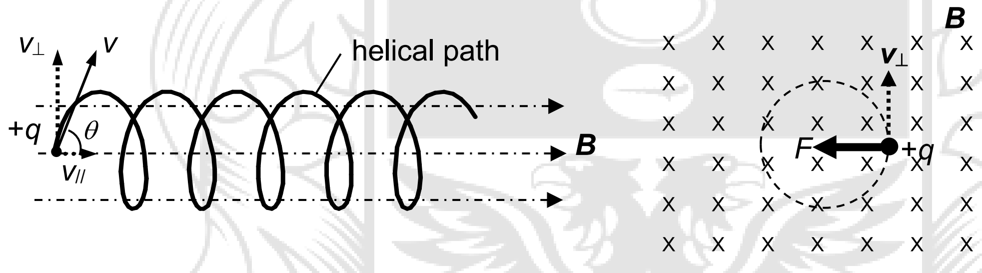


Fig. 17.26

Resolving v into 2 components:

$$v_{//} = v \cos \theta$$
$$v_{\perp} = v \sin \theta$$

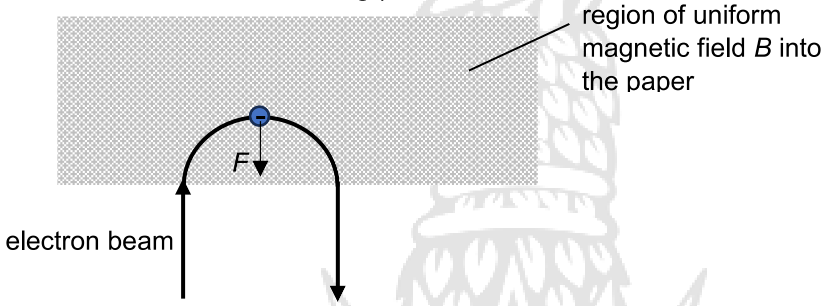
Motion of the charged particle is the result of superimposing

(i) a uniform circular motion in which the particle has speed $v_{\perp}$ in a plane perpendicular to the direction of B.

(ii) a straight-line motion with a steady speed $v_{//}$ along the direction of B.

Example 5

A beam of electrons travelling with a velocity of 3.2×10^{7} m s^{-1} enters a magnetic field of flux density 0.47 mT, as shown below. The electrons are travelling at right angles to the field.
($e = 1.60 \times 10^{-19}$ C; $m_e = 9.11 \times 10^{-31}$ kg.)



(i) Calculate the force on each electron within the field.

(ii) Calculate the radius of curvature of each electron's path while in the field.

(iii) Sketch the path travelled by an electron within and beyond the field. Indicate clearly, the direction of the electron's path, the field and the force.

[Solution]

Example 6

An α–particle of mass 6.6×10^{-27} kg and charge $+2e$ was injected at right angles into a uniform magnetic field of flux density 1.2 T. It travels in a circular path of radius 0.45 m. Calculate,

(i) its speed,

(ii) its period of revolution,

(iii) its kinetic energy, and

(iv) the potential difference of an electric field through which it would have to be accelerated from rest to achieve this energy.

[Solution]

❖ Applications of Particles Moving in Crossed Uniform Electric and Magnetic Fields – Velocity Selector

A velocity selector consists of a magnetic field and an electric field applied over the same region to allow only charged particles of a particular velocity that is perpendicular to both fields to pass through undeflected.

The two fields are applied perpendicular to each other in an orientation such that the electric force and the magnetic force on the particle act in opposite directions.

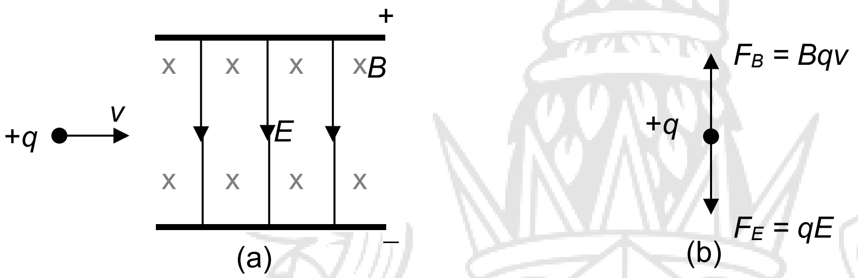


Fig. 17.27

Suppose a positive charge $+q$ enters the region where the two crossed fields are applied, with its velocity v perpendicular to both fields as shown in Fig. 17.27(a).

It experiences an upward magnetic force $F_B = Bqv$ and a downward electric force $F_E = qE$ as shown in Fig. 17.27(b).

[*The gravitational force acting on such charged particles is very small compared to F_B and F_E and hence can be ignored.*]

If $F_B > F_E$, the particle will deflect upward.
If $F_B < F_E$, the particle will deflect downward.

Particles whose velocities are such that $F_B = F_E$ will pass through undeflected.

$$Bqv = qE$$

$$v = \frac{E}{B}$$

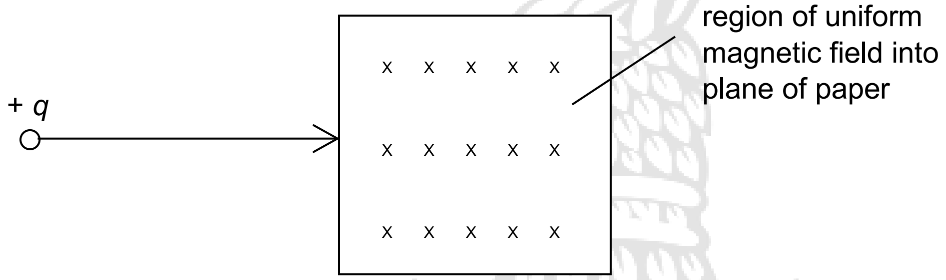
Hence, only particles having this speed v will pass through undeflected.

The concept of charged particles moving through combined electric and magnetic fields has many real-life applications.

The physics of cyclotron

Example 7

A particle of charge $+q$ enters a uniform magnetic field of flux density B that is directed into the plane of the paper. The particle is travelling with velocity v at right angles to the magnetic field.



A uniform electric field is applied in the same region as the magnetic field so that the particle passes through undeflected.

(a) On the figure above, mark, with an arrow labelled E, the direction of the electric field.

(b) State and explain the effect, if any, on a particle entering the region of the fields if the particle has
(i) charge $-q$ and speed v,
(ii) charge $+q$ and speed $2v$.

[Solution]

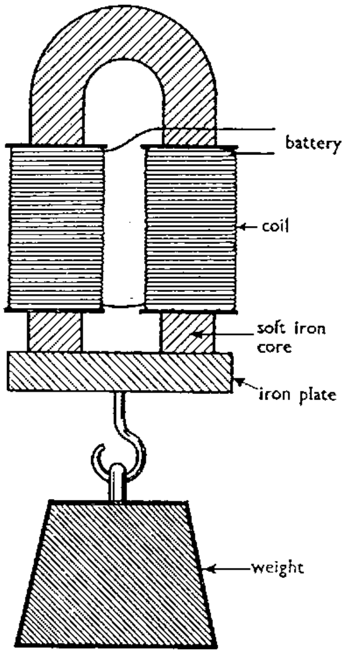
Comparison between deflections of beams of charged particles by uniform electric and uniform magnetic fields.

	Deflection in a magnetic field	Deflection in an electric field
1.	The magnetic field can exert a magnetic force only on a moving charged particle.	The electric field exerts an electric force on a stationary or moving charged particle.
2.	The magnetic force is perpendicular to the magnetic field and the direction of the motion of the charged particle.	The electric force acts in a direction parallel to the electric field.
3.	Magnetic force is dependent on the magnetic flux density, speed, charge, and the direction of motion of the particle.	Electric force is dependent on the charge of the particle and the electric field strength.
4.	When a charged particle enters a magnetic field perpendicularly, it moves in a circular path.	When a charged particle enters an electric field perpendicularly, it moves in a parabolic path.

17.7 Appendix

❖ Uses of Electromagnets

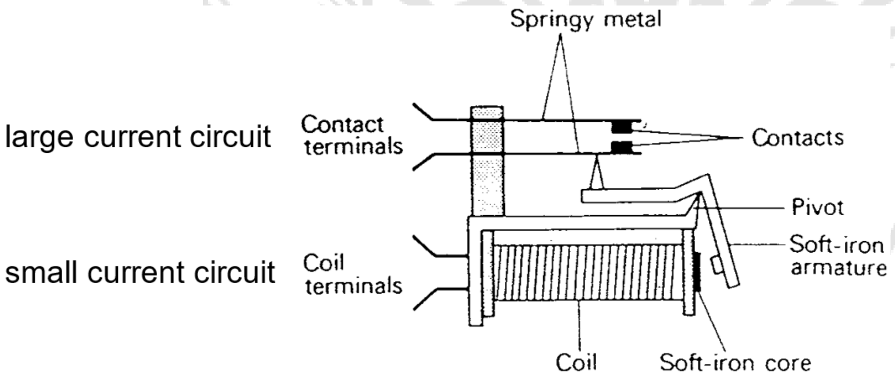
A soft iron core with a magnetizing coil wound around it is called an electromagnet. Its strength can be adjusted to exert large mechanical forces to lift heavy loads.



❖ Relay

A relay is a switch that uses an electromagnet. It is useful if we want a small current in one circuit to control another circuit containing a device such as a lamp, electric bell or motor which requires a large current.

The structure of a relay is shown below. When the controlling current flows through the coil, the soft iron core is magnetized and attracts the L–shaped soft iron armature. This rocks on its pivot and closes the electrical contacts in the circuit being controlled.



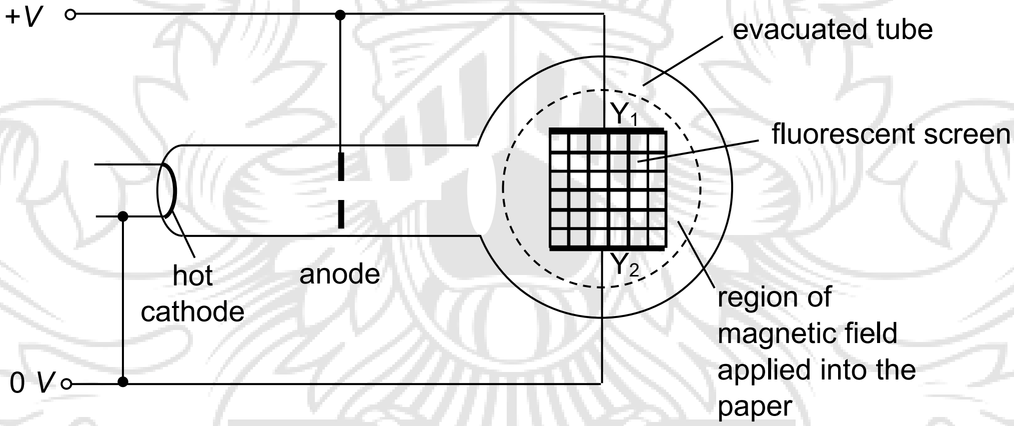
❖ Specific Charge of Electron and its Determination

The specific charge of a particle is the ratio of its charge to its mass:

$$\text{specific charge} = \frac{q}{m}$$

The charge-to-mass ratio provides a quick way to determine the mass of a particle by knowing its charge through theoretical derivations. In some experiments, it is easier to measure directly the charge-to-mass ratio of a particle.

An experiment significant to the discovery of the electron is the measurement of the specific charge of cathode rays by J.J. Thomson in 1897. The figure below shows the set-up to determine the specific charge of an electron.



Electrons produced by the hot cathode are accelerated in a vacuum towards an anode held at a potential $+V$ with respect to the cathode.

Assuming that the electrons are emitted with negligible speed from the cathode, they will leave the anode with a speed v which can be found:

Gain in K.E. of each electron = Loss in P.E. of the electron

$$\frac{1}{2}m_e v^2 - 0 = eV - 0$$

$$v = \sqrt{\frac{2eV}{m_e}} \quad \text{.......... (1)}$$

where e and m_e are the charge and the mass of an electron respectively.

The beam of electrons emerging from the anode produces a narrow luminous trace when it hits a vertical fluorescent screen supported between two parallel plates Y_1 and Y_2. Y_1 is held at a potential $+V$ with respect to Y_2, thus creating an electric field E between the plates.

A uniform magnetic field B is applied perpendicular to the electric field and the magnitudes of the two fields are adjusted so that the beam passes through undeflected. Hence,

$$Bev = eE$$

$$v = \frac{E}{B} \quad \text{........ (2)}$$

Equating equations (1) and (2),

$$\frac{E}{B} = \sqrt{\frac{2eV}{m_e}}$$

$$\frac{e}{m_e} = \frac{E^2}{2B^2V}$$

If the separation between plates Y_1 and Y_2 is *d,* then $E = \frac{V}{d}$ and the specific charge of an electron will be given by

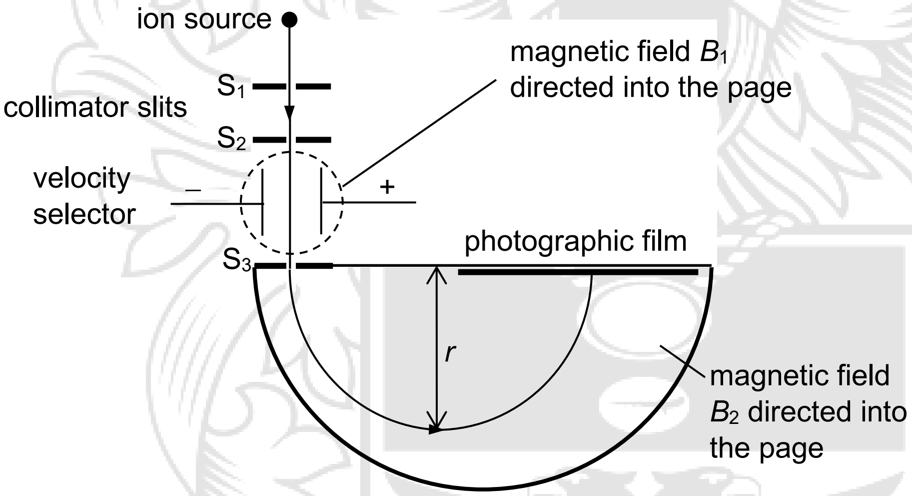
$$\frac{e}{m_e} = \frac{V}{2B^2d^2}$$

Hence, the specific charge of an electron can be found if *V, B* and *d* are known.

❖ Mass Spectrometer

A mass spectrometer separates ions according to their mass-to-charge ratio. The figure belows shows a Bainbridge Mass Spectrometer.

Mass spectrometer



Ions of charge *q* and mass *m* with velocity $v = \frac{E}{B_1}$ pass undeflected through the velocity selector and are then deflected into a semi-circular path with radius *r* in the magnetic field B_2.

The magnetic force acting on the ions in B_2 provides for the centripetal force

$$F_B = F_C$$

$$B_2qv = \frac{mv^2}{r}$$

$$r = \frac{mv}{B_2q} = \frac{mE}{B_1B_2q}$$

Since B_1 ,B_2 and E are constant, $r \propto \frac{m}{q}$.

NOTETAKING

"Natural science does not simply describe and explain nature; it is part of the interplay between nature and ourselves; it describes nature as exposed to our nature of questioning."