

Barlow's wheel

Fig. 15.20

Magnetic force between parallel current-carrying conductors

Currents I_1 and I_2 are in the same direction.

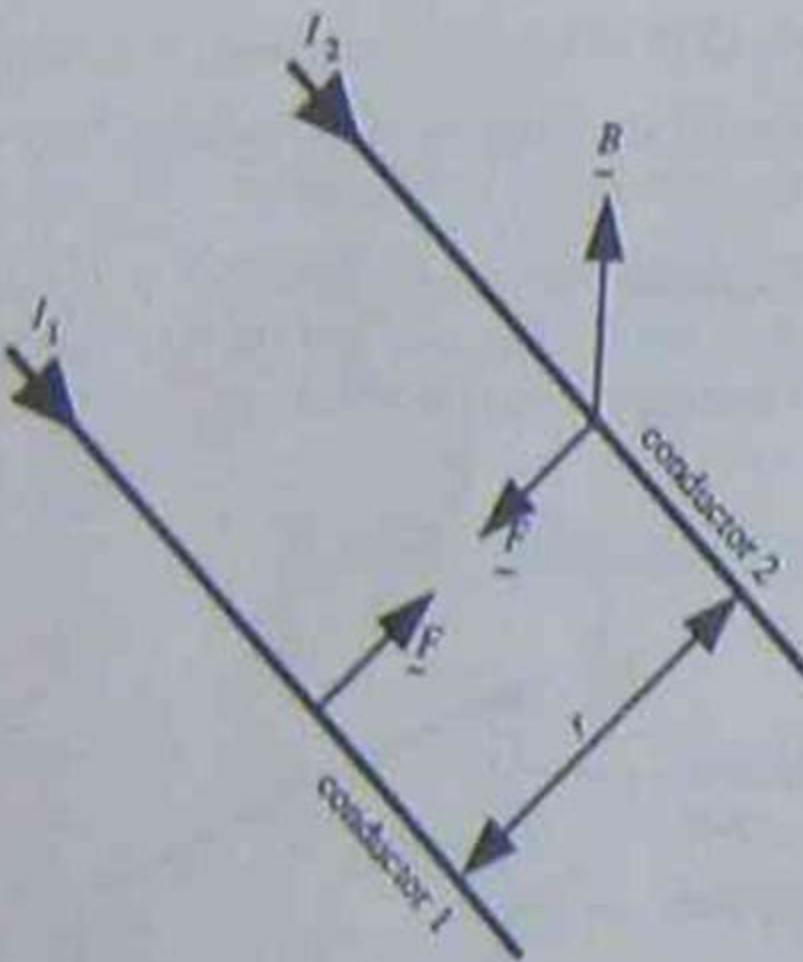


Fig. 15.21

B is the field at conductor 2 due to the current in I_1

$$B = k I_1 / r \quad k = \mu_0 / 2\pi = 2 \times 10^{-7} \text{ T m A}^{-1}$$

The direction of the magnetic force F on conductor 2 of length l by Fleming's Left Hand Rule is towards conductor 1.

$$F = BI_2 l = k I_1 I_2 l / r$$

Similarly the force on conductor 1 has magnitude of F and is directed towards conductor 2. Thus when the currents are in the same direction the force between the conductors is one of attraction. When the currents are in the opposite direction the force between the conductors is one of repulsion.

Magnetic fields between parallel current-carrying wires

Michael Faraday suggested that magnetic field lines have longitudinal tension and sideways repulsion. Thus decreasing the number of field lines in the same direction would give rise to attraction between field lines. Currents travelling in the same direction down parallel wires decrease the number of field lines between the conductors, thus currents travelling in the same direction attract one another (Fig. 15.22). Currents travelling in opposite directions down parallel wires increase the number of field lines between the wires, hence currents travelling in opposite directions repel one another (Fig. 15.23).

Definition of the SI unit of current, the ampere (A)

One ampere is that current which, if maintained in two parallel wires of infinite length and negligible cross-section placed 1 m apart in free space, will produce a magnetic force between the wires of 2×10^{-7} N for every metre of length of wire.

Definition of the SI unit of charge, the coulomb (C)

One coulomb is the charge q moving past a point in 1 second when a current of 1 ampere is flowing.

$$q = It = 1 \times 1 \text{ C} = 1 \text{ C}$$

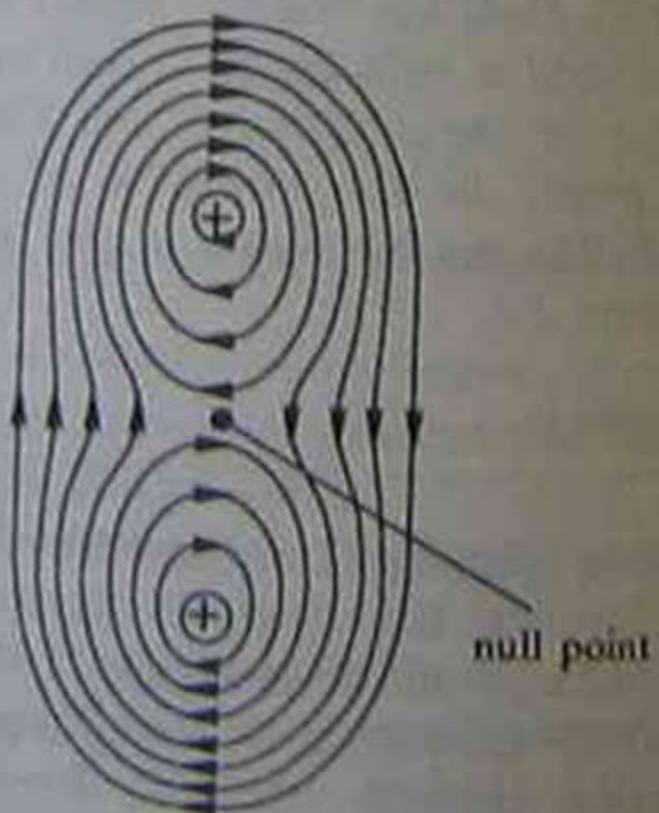
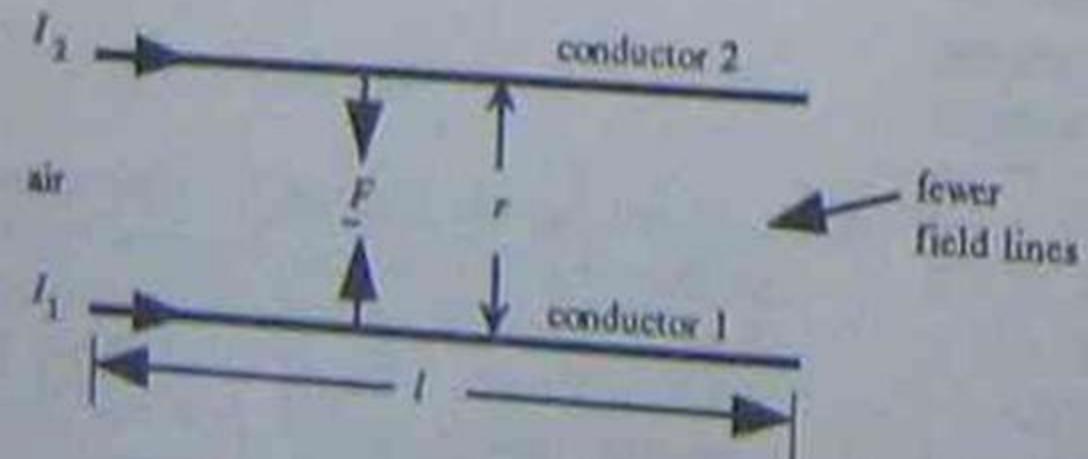


Fig. 15.22

ELECTROMAGNETIS

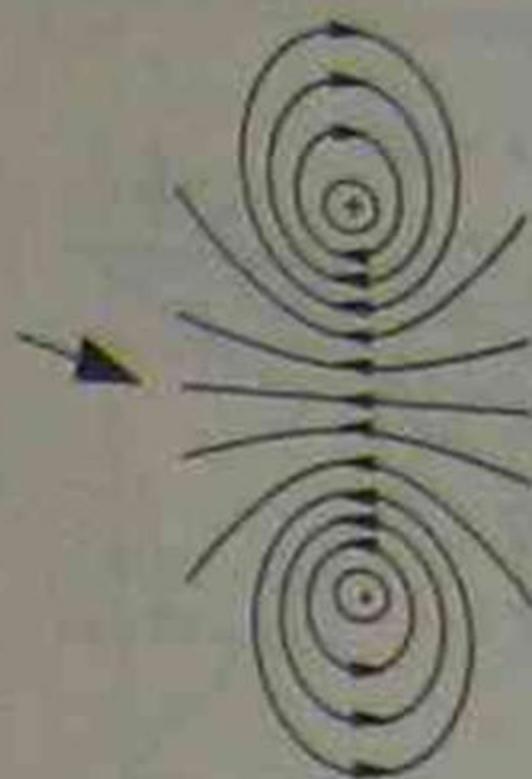
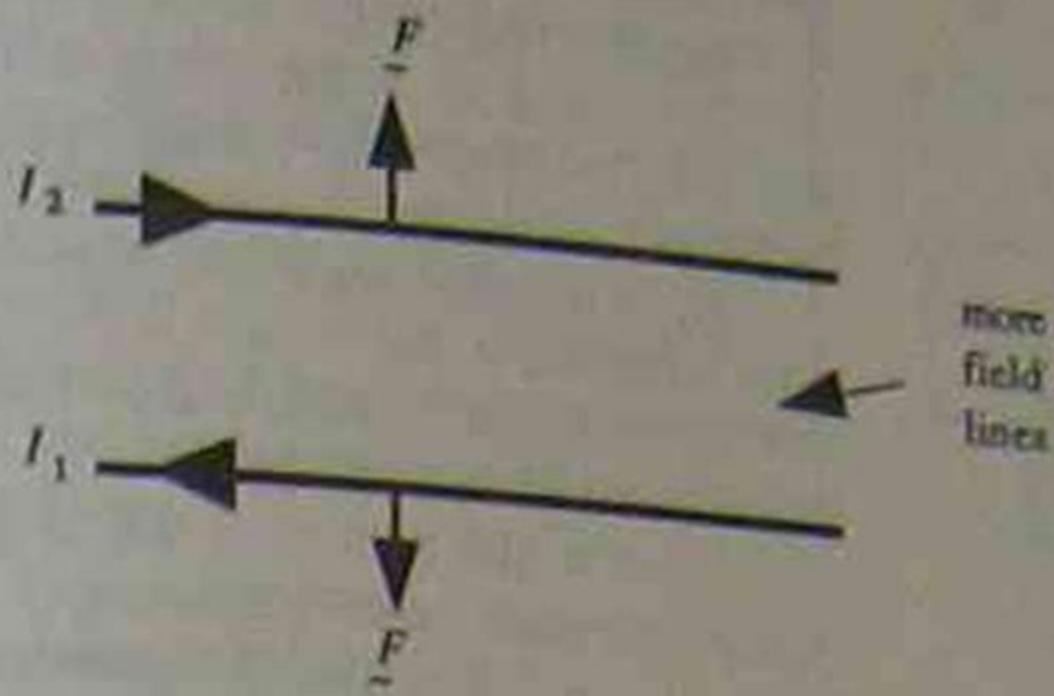


Fig. 15.23

EXAMPLE

- (a) Calculate the magnetic force F between the two parallel conductors shown in Figure 15.22 when (i) currents are in the same direction; (ii) currents are in opposite directions.

Take $I_1 = I_2 = 7.0 \text{ A}$, $r = 10 \text{ cm}$,
 $l = 2.0 \text{ m}$, and $k = \mu_0/2\pi = 2 \times 10^{-7}$
SI units.

- (b) What is the force between the conductors when r is (i) halved; (ii) doubled?

Answer

Answer

(a) $F = (\mu_0/2\pi)I_1 I_2 l/r$

(i) $F = 2 \times 10^{-7} \times 7.0 \times 7.0 \times 2.0 /$
 $10 \times 10^{-2} \text{ N}$

$= 1.96 \times 10^{-4} \text{ N}$, attractive

(ii) $F = 1.96 \times 10^{-4} \text{ N}$, repulsive

(b) Since $F \propto 1/r$,

(i) when r is halved, F is doubled to
 $3.92 \times 10^{-4} \text{ N}$,

and

(ii) if r is doubled, F is halved to $9.8 \times 10^{-5} \text{ N}$.

Magnetic torque on a current balance

A current balance is a device used to determine magnetic field strength B . This device is a see-saw arrangement in which a current-carrying U-shaped

loop of wire usually attached to a uniformly thick rectangular insulator is held in a horizontal position. When horizontal the torque from a gravitational force F_{grav} is balanced by a torque due to a magnetic force F_{mag} on the loop as shown in Figure 15.24.

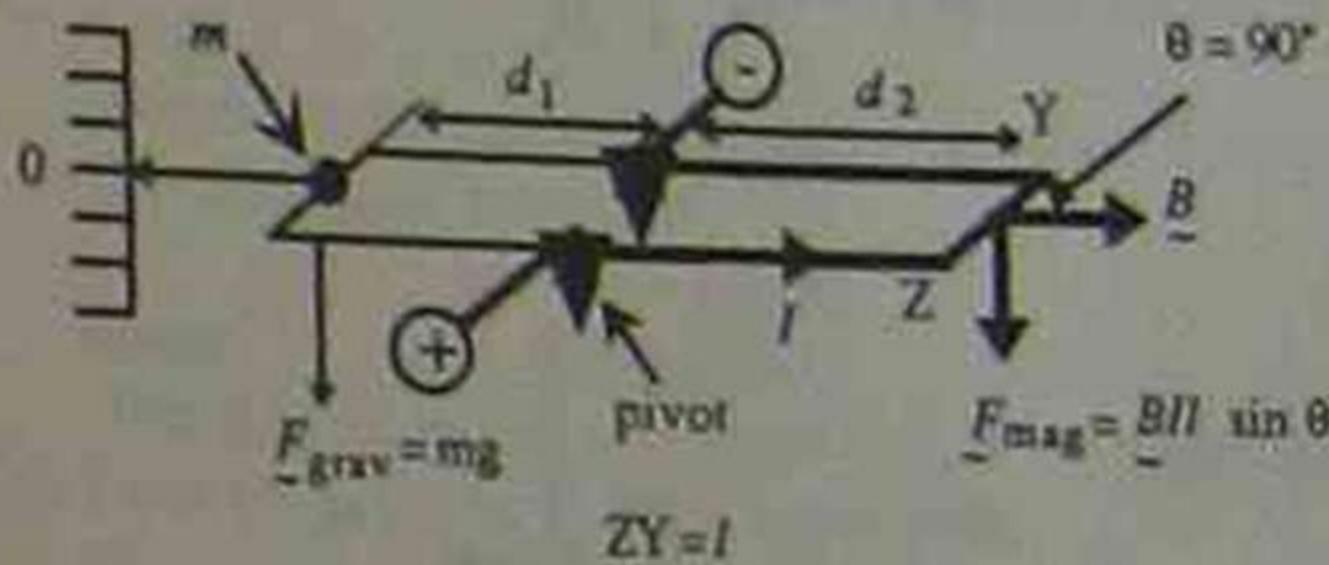


Fig. 15.24

When current I flows through the loop, m is the mass added to establish horizontal balance.

At balance, clockwise torque = anticlockwise torque

$$mgd_1 = BId_2,$$

where d_1 and d_2 are perpendicular distances from the lines of force to the pivot.

Magnetic torque on a coil in a uniform field

When B is parallel to the plane of the coil the torque on a single turn is (see Fig. 15.25):

$\tau = Fb + Fb$, where $F = BIl$ and b is the "arm" of the torque.

$$\begin{aligned}\tau &= BIl \times 2b \\ &= BIA \quad (I \times 2b = A = \text{area of 1 turn.})\end{aligned}$$

Thus the torque on a coil of n turns is:

$$\tau = nBIA$$

When the plane of the coil is at an angle θ to the field as shown in Figure 15.26:

$$\begin{aligned}\tau &= 2Fb' = 2Fb \cos \theta \\ &= nBIA \cos \theta\end{aligned}$$

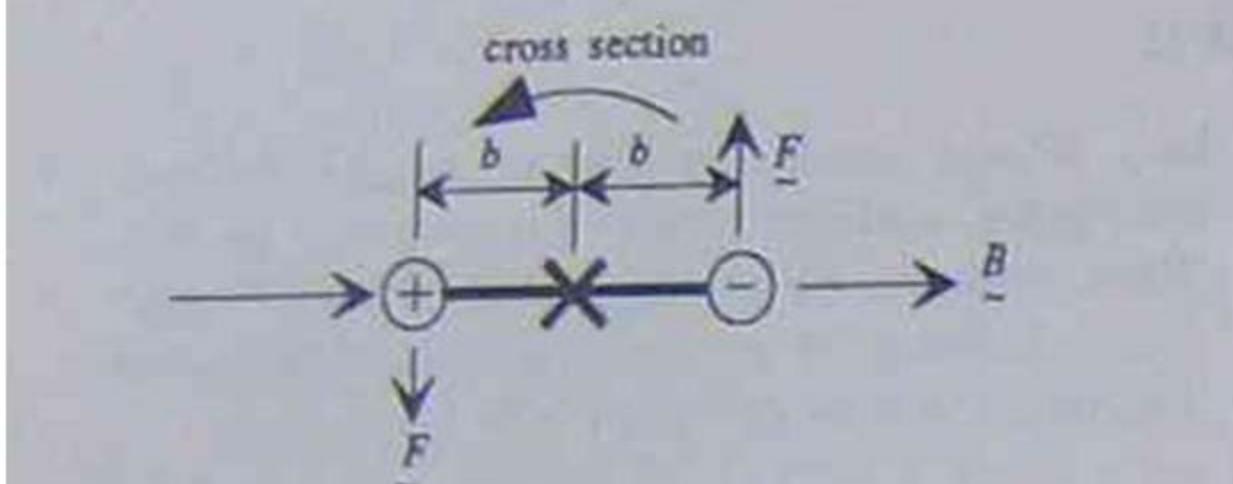
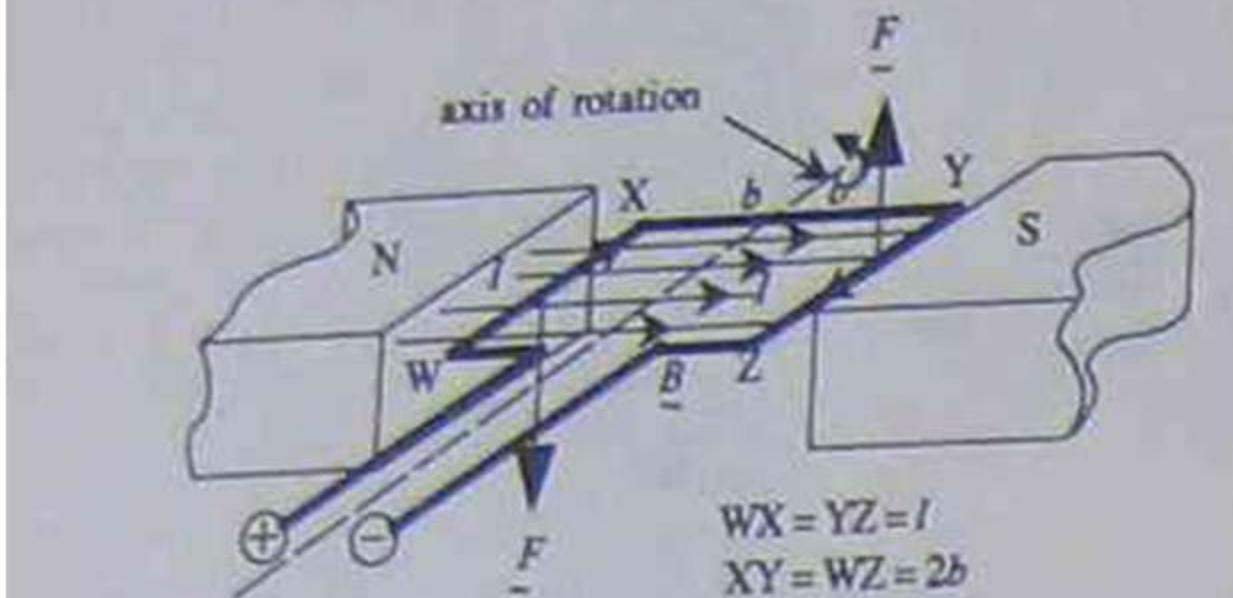
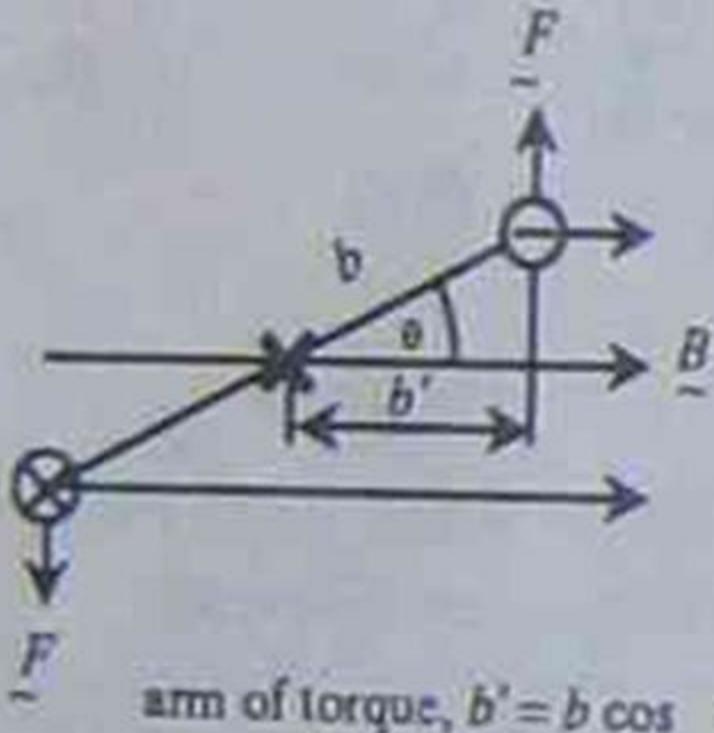


Fig. 15.25



$$\text{arm of torque, } b' = b \cos \theta$$

Fig. 15.26

EXAMPLE

A coil of n turns is placed in a uniform magnetic field as shown in Figure 15.25.

- Calculate the force on limb ZY = l .
- Calculate the torque on a coil of 100 turns when the plane of the coil is parallel to the field.
- What is the torque on the coil when the plane of the coil makes an angle with the field of:
(i) 30° (ii) 90° .

Take $B = 0.30 \text{ T}$, $I = 2.0 \text{ A}$, $l = 6.0 \text{ cm}$,

Answer

(a) $F = BIl \cos \theta$
= $0.30 \times 2.0 \times 6.0 \times 10^{-2} \cos 0^\circ \text{ N}$
= $3.6 \times 10^{-2} \text{ N up, at right angles to } B$
and I

(b) $\tau = nBIA \cos \theta$
 $A = l \times 2b$
= $6.0 \times 10^{-2} \times 2 \times 1.0 \times 10^{-2} \text{ m}^2$
= $1.2 \times 10^{-3} \text{ m}^2$
 $\tau = 100 \times 0.30 \times 2.0 \times 1.2 \times$
 $10^{-3} \cos 0^\circ \text{ Nm}$
= $7.2 \times 10^{-2} \text{ N m anticlockwise}$

(c) (i) When $\theta = 30^\circ$,
 $\tau = 7.2 \times 10^{-2} \cos 30^\circ \text{ N m}$
= $6.2 \times 10^{-2} \text{ N m anticlockwise}$

(ii) When $\theta = 90^\circ$,
 $\tau = 7.2 \times 10^{-2} \cos 90^\circ$
= 0.00 N m

Moving coil meter

The idea of a moving coil meter to measure current was suggested by Sturgeon in 1836. In this instrument a coil carrying a current is supported, usually by phosphor bronze spiral springs, so that it can rotate in a uniform magnetic field.

Spring torque τ versus its angle of twist θ is shown in Figure 15.28.

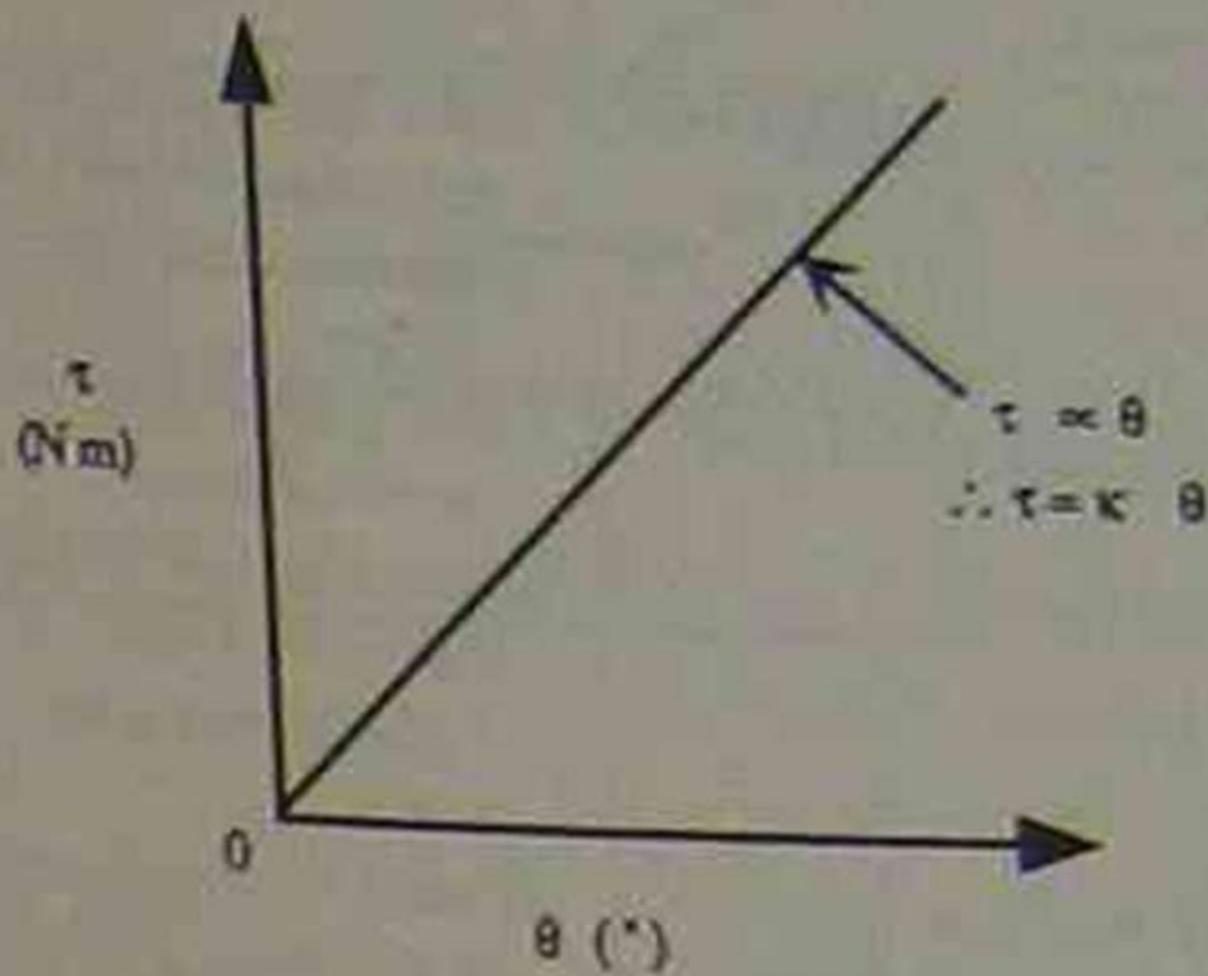


Fig. 15.28

Thus $\tau = \kappa\theta$ where κ is the torsion constant for the spring (Fig. 15.29). The magnetic field is arranged like radii so B is always parallel to the plane of the coil. Then whatever the position of the coil there is uniform torque on the coil due to current passing through it, $\tau = nBIA$.

When the pointer is stationary, the sum of torques on the coil equals zero, thus:

$$\kappa\theta = nBIA,$$

therefore

$$\theta = nBIA / \kappa.$$

When n , B , A and κ are constant, θ is proportional to I and the instrument has a linear scale.

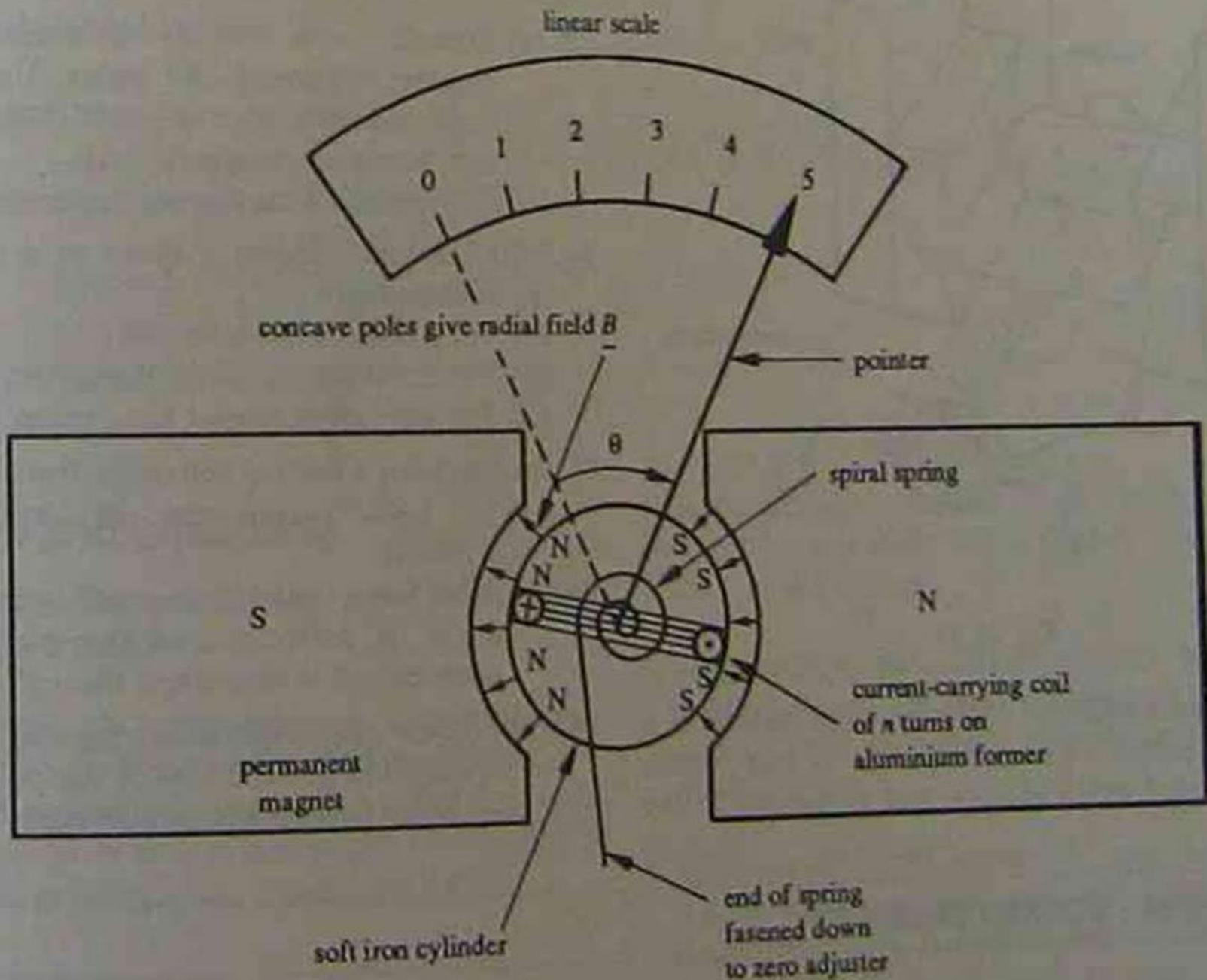


Table 15.2 Essential features of a moving coil meter

Features	Benefits or function
Circular pole pieces	Radial B always in plane of coil which thus experiences uniform torque
Coil's core of soft iron	Large B and a more sensitive meter
Spiral springs	Support coil, act as coil terminals, apply uniform torque to coil
Coil wound on light aluminium former	Induced 'eddy' currents in aluminium give rise to magnetic damping of coil

Simple direct current (dc) motor

The magnetic force on a current-carrying conductor can be arranged to spin the conductor and is part of a device that converts electrical energy into rotational kinetic energy. Such a device is the electric motor. A very simple electric motor is due to Barlow and is known as Barlow's Wheel and is shown in Figure 15.20.

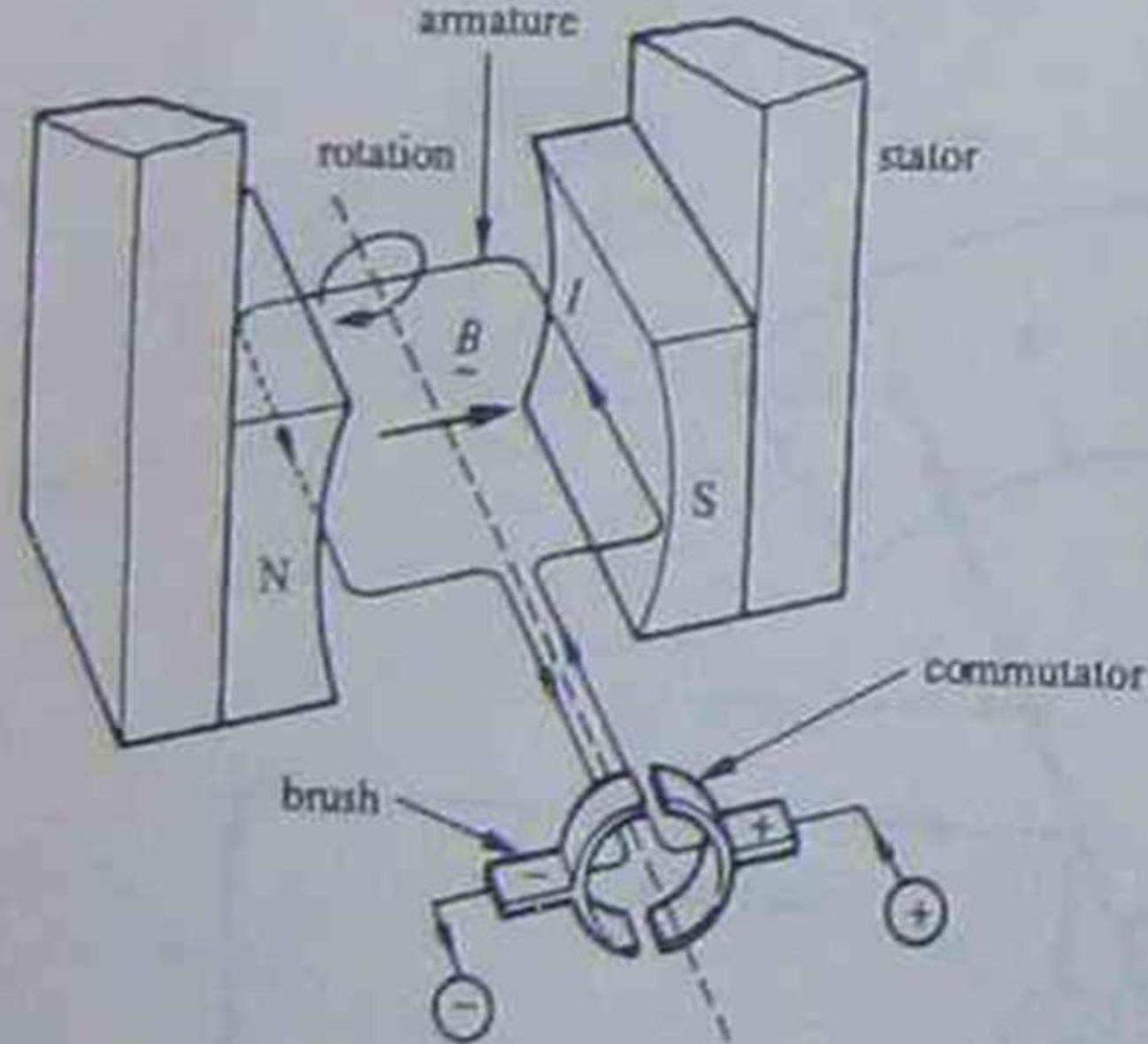


Fig. 15.30

A simple motor as shown in Figure 15.30 consists of a rotor (or armature), i.e. rotating coils of wire wound on a laminated soft-iron core and connected to the

outside circuit through a brass or copper commutator. The stationary part of the motor which surrounds the rotor is called the stator.

Table 15.3 Essential features of a simple dc motor

Features	Benefits or function
Split-ring commutator (on armature)	Torque on coil is in one direction
Spring-loaded brushes	Connect outside circuit to rotating coil
A stator or stationary part	Contains source of magnetic field in form of permanent magnets or electromagnets containing field coils wound on laminated soft iron

Rotor (armature) or rotating part composed of wire coils on a soft-iron core

Circular magnetic pole pieces

Soft-iron laminates in armature core and field coils

soft iron

Increase B and torque on rotor

B always in plane of coil, hence uniform torque
To minimise the heating effects of induced 'eddy' current

ADDITIONAL WORKED EXAMPLES

A current is passed through the solenoid of a current balance as shown in Figure 15.31 so as to make the beam of the balance horizontal. Distances d_1 and d_2 are equal.

ELECTROMAGNETISM

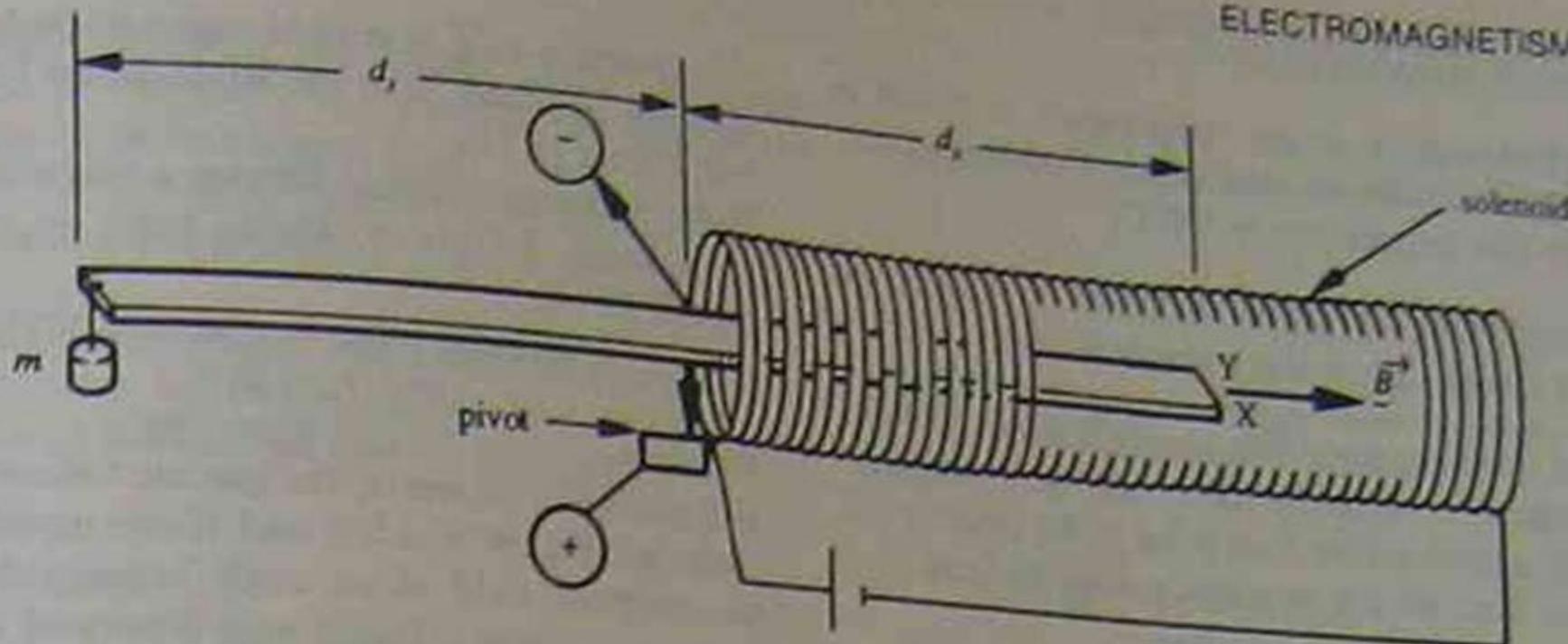


Fig. 15.31

- At which end of the solenoid is there a magnetic north pole?
- Which way does conventional current pass through the limb XY of the balance?
- At balance, mass $m = 2.0 \text{ g}$. $XY = 3.0 \text{ cm}$, and $I = 10 \text{ A}$. Determine the magnitude and direction of the magnetic flux density in the coil. Take $g = 9.8 \text{ ms}^{-2}$.

Answer

Answer

- (a) From the Right Hand Coil Rule, the right end of the coil is N.
(b) From Fleming's Rule, from X to Y.
(c) At balance:

Anticlockwise torque = clockwise torque. Let $YX = l$.

$$mgd_1 = BIl^2 d_2$$

$$2.0 \times 10^{-3} \times 9.8 = B \times 10 \times 3.0 \times 10^{-2}$$

therefore $B = 0.065$ T to the right along the axis of the solenoid.

2. An electron travelling at 2.1×10^7 m s⁻¹ enters at right angles a uniform magnetic field of 2.5×10^{-3} T. Given that the mass of an electron is 9.1×10^{-31} kg and the charge carried by an electron is -1.6×10^{-19} C, calculate for the electron in the field:
(a) the radius of its path, and (b) the period of its motion.

Answer

(a) For circular motion

$$mv^2/r = Bqv$$

therefore

$$r = mv/Bq$$

$$\begin{aligned} &= 9.1 \times 10^{-31} \times 2.1 \times 10^7 / 2.5 \times 10^{-3} \times 1.6 \times 10^{-19} \text{ m} \\ &= 0.047775 \text{ m} \\ &= 4.8 \times 10^{-2} \text{ m} \end{aligned}$$

(b) $v = s/t$, so $T = 2\pi r/v = 2 \times \pi \times 4.8 \times 10^{-2} / 2.1 \times 10^7 \text{ s}$
 $= 1.4 \times 10^{-9} \text{ s}$.

Key facts and equations

- Magnetism is the property of a substance which enables it to attract iron.
- Magnet Poles. A freely-suspended magnet will line up parallel to the Earth's magnetic lines of force. The end of the magnet pointing north is called the north-seeking pole or N pole of the magnet and the end of the magnet pointing south is called the S pole.
- Laws of Magnetism
 - Like poles repel.
 - Unlike poles attract.

- Ferromagnetic materials show strong magnetic properties, e.g. iron, cobalt, nickel, Alnico (Al, Ni and Co) and ferrites.
- Magnetically hard materials can be strongly magnetised and not easily demagnetised. They are used to make permanent magnets, e.g. hard steel, Alnico.
- Magnetically soft materials can be strongly magnetised by applied magnetic fields but they readily lose their magnetism when these fields no longer exist. They are used to make temporary magnets, e.g. soft iron, Permalloy, ferrites.

- Curie temperature is the temperature at which a ferromagnetic material loses most of its magnetism. For iron this temperature is 770°C .
- Magnetic Field. A region in which a magnet or moving charge experiences a magnetic force.
- Lines of magnetic force or magnetic flux are arrowed lines drawn to represent the region of a magnetic field; the arrows on the lines point in the direction of magnetic force on a N magnetic pole in the field.

- Magnetic Fields:

- (a) Due to permanent bar magnet, (see Figure 15.3).
- (b) Due to current in a straight conductor (Oersted's experiment of 1819), (see Figure 15.4(b)). The direction of the lines of force is given by the **Right Hand Grip Rule** ... 'grip the conductor in your right hand so that your thumb points in the direction of the conventional current; your fingers point in the direction of the field' (see Figure 15.4(c)).

Figure 15.4(c)).

- (c) Due to a solenoid, i.e. a long cylindrical coil of wire (see Figure 15.5(a)). Magnetic polarity of the solenoid is given by a Right Hand Coil Rule ... 'grip the solenoid in the right hand, with your fingers in the direction of conventional current; your thumb is in the region of the N pole (see Figure 15.5(b)). Relative magnetic permeability μ is the capacity of a substance to conduct magnetism and thereby concentrate magnetic fields.

(d) Due to an electromagnet, i.e. a solenoid (see Figure 15.5) with a core made of a high permeability and magnetically soft material such as soft iron. Electromagnets are used in magnetic cranes, magnetic switches and electric bells.

- Magnetic flux density B , (T), or magnetic field intensity, is the number of magnetic flux lines per unit area at right angles to these lines. One line of magnetic flux per square metre represents a magnetic flux density of 1 tesla (T).

- Magnetic flux Φ , (Wb), is the total number of flux lines through an area A at right angles to a field.

$$\phi = BA \quad \text{SI unit of } \Phi \text{ is T m}^2 \text{ or weber (Wb).}$$

- Magnetic flux density B , (T), due to current in a long straight wire is calculated from $B = kI/r$, where $k = \mu_0/2\pi = 2 \times 10^{-7} \text{ T m A}^{-1}$ represented as shown in Figure 15.8.
- Magnetic force depends on the relative motion between charges.
- Magnetic force F on charge q moving with velocity v at angle θ to a magnetic field B is given by:

$$F = Bqv \sin \theta.$$

The direction of F is at right angles to both B and v and can be found from the Right Hand Palm Rule (see Figure 15.12).

Note: A charged particle entering a magnetic field at right angles follows a circular track as shown in Figure 15.14.

$$\text{centripetal force} = \text{magnetic force}$$
$$mv^2/r = Bqv,$$

therefore $r = mv/Bq$

If v gradually decreases, the particle follows a spiral path, see Figure 15.15(a) and if the particle enters the magnetic field at an angle between 0 and 90 degrees it follows a helical path illustrated in Figure 15.15(b).

- Force on a Current-carrying Conductor

$F = BIl \sin \theta$, where θ is the angle between B and I . The direction of F is at right angles to both B and I and Fleming's Left Hand Rule can be used to work out the direction of F (see Figure 15.18).

- Force Between Two Long Parallel Current-carrying Conductors (see Figure 15.21).

$$F/l = (\mu_0/2\pi)I_1 I_2 / r,$$

where $\mu_0/2\pi = 2 \times 10^{-7} \text{ T m A}^{-1}$.

For I_1 and I_2 going in the same direction, the force is one of attraction. For I_1 and I_2 going in opposite directions the force is one of repulsion.

- Fields Between Two Parallel Current-carrying Wires
 - (a) For currents in the same direction see Figure 15.22.
 - (b) For currents in opposite directions see Figure 15.23.

- Definitions

The ampere, the SI unit of current: One ampere is that current which, if maintained in two parallel conductors of infinite length and negligible cross-section placed 1 m apart in free space, will produce a force between the wires of 2×10^{-7} N for every metre of length of the wires.

The coulomb, the SI unit of charge: Note: $q = It$. One coulomb is the charge moving past a given point in one second when a current of one ampere is flowing.

- Magnetic Torque on:
 - (a) A horizontal current balance, Refer to Figure 15.24.

At balance, the sum of the torques is zero, therefore:

$$(b) \text{ A coil of } n \text{ turns (see Figure 15.25),} \quad mgd_1 = BII \sin \theta d_1.$$

$$\tau = nBIA \cos \theta.$$

By arranging for B to be parallel to the plane of the coil, θ is zero and the coil experiences a uniform torque, provided n , B and A are constant.

- Moving Coil Meter (see Figure 15.29). When the pointer of the meter is stationary the sum of the torques on the coil is zero, thus:

$$\kappa\theta = nBIA, \text{ therefore } \theta = nBIA/\kappa$$

For features and benefits or function see Table 15.2.

- Direct Current Motor. For a diagram of a simple dc motor refer to Figure 15.30. The features and benefits or function are listed in Table 15.3.