

Electrical interactions II: Electromagnetism

SYMBOL AND UNIT SUMMARY

<i>Symbol</i>	<i>Quantity</i>	<i>Unit</i>
B	magnetic flux density	T or Wb m^{-2}
v	charge velocity	m s^{-1}
F	magnetic force	N
θ	angle between B and v	o
m	mass of particle	kg
r	radius of path	m
q/m	ratio of charge/mass	C kg^{-1}
n	number of turns of wire	
I	conventional current for a rectangular wire loop:	A
	—length	m
	—breadth	m
A	—area	m^2
τ	—torque	Nm

Magnetism and magnets

Background

The word magnetism is derived from the name of the place Magnesia in Asia Minor where about 600 BC the ancient Greeks noted that an iron ore called lodestone or magnetite (Fe_3O_4) would attract small pieces of iron.

Magnetism is the property of a substance which enables it to attract iron. Iron dust collects at regions on the ore called magnetic poles. In the Middle Ages the Chinese built a primitive compass by floating lodestone on wood and noting that it came to rest in a N-S direction. The word lodestone comes from an old English word meaning 'way'. Magnets when freely suspended (e.g. the needle in a magnetic compass) will oscillate, then align with the Earth's magnetic lines of force. The magnetic field represented by these lines of force is thought to be generated by moving charges in the Earth.

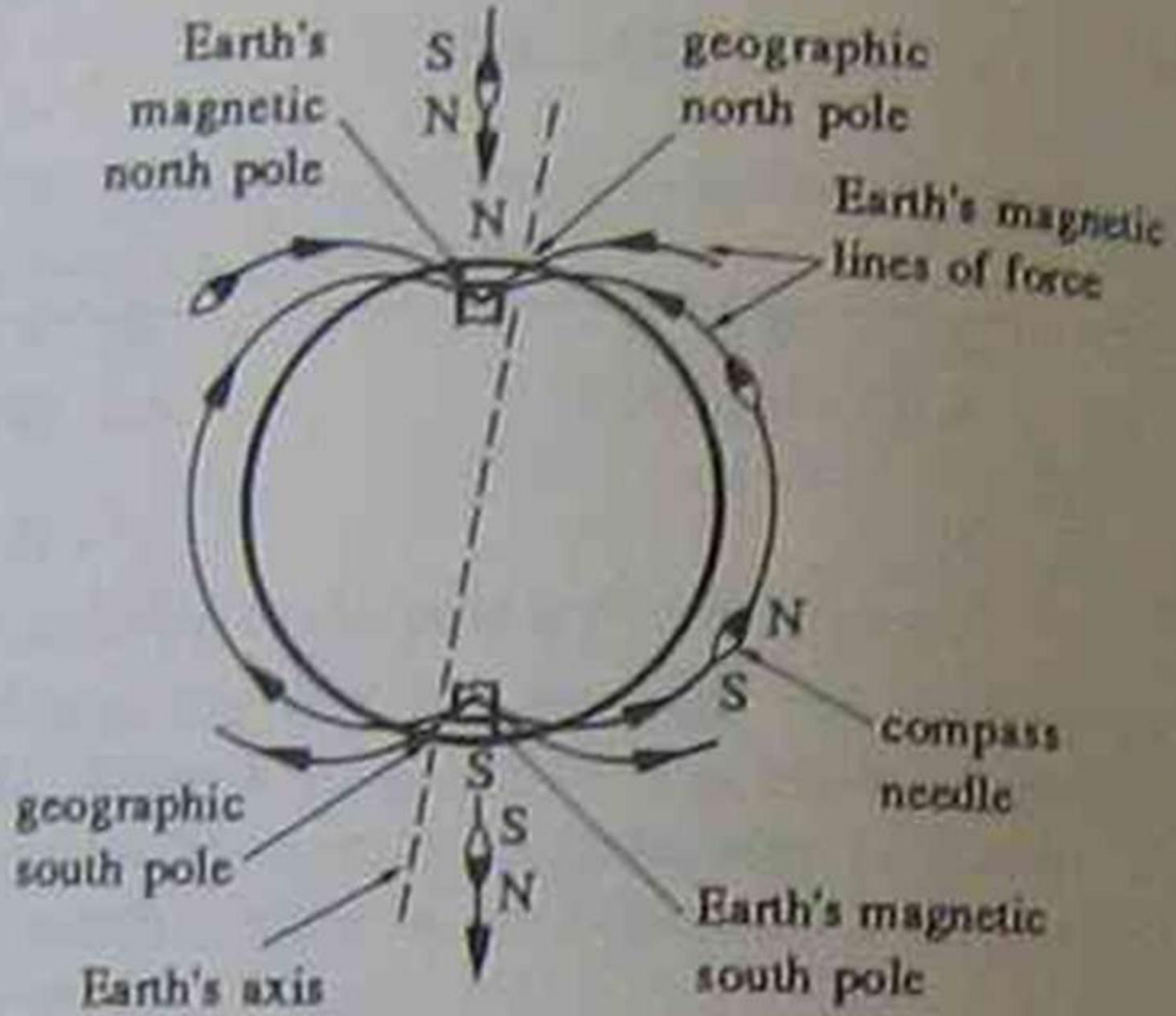


Fig. 15.1

The end of the magnet pointing north is called the north-seeking pole or N pole. The part of the magnet pointing south is the south-seeking pole or S pole. A magnet has an N pole and a S pole which are difficult to isolate.

QUESTION

Laws of magnetism

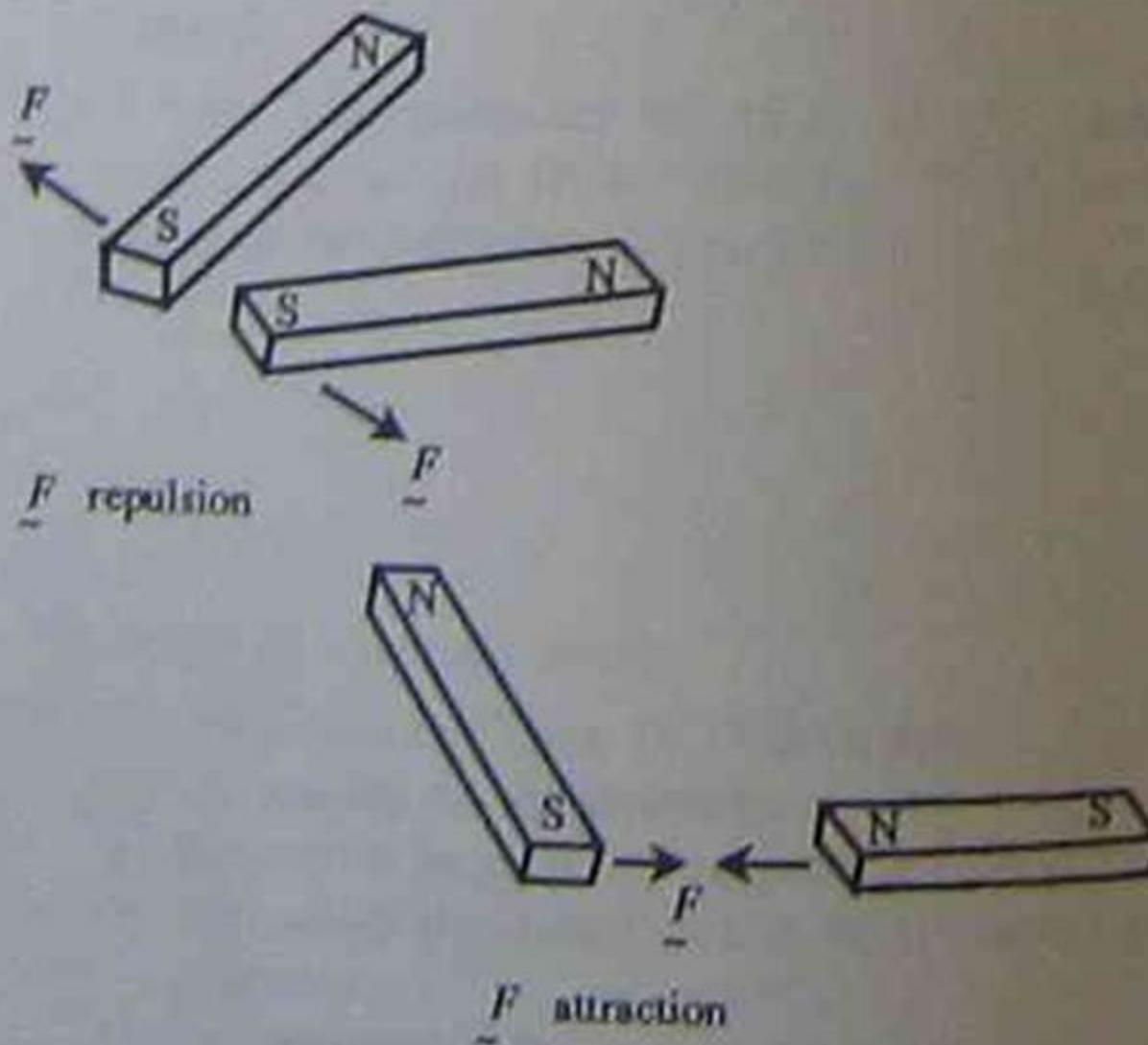


Fig. 15.2

1. Like magnetic poles repel each other.
2. Unlike magnetic poles attract one another.

Magnetic materials

Ferromagnetic materials are those that show strong magnetic effects. Ferromagnetic elements are iron, cobalt, nickel, gadolinium and dysprosium. Magnetic substances described as magnetically hard can be strongly magnetised and not easily demagnetised and therefore make good permanent magnets, e.g. hard steel and special alloys such as Alnico (Al, Ni, Co, Cu & Fe), Triconal GX (Fe, Co, Al & Cu) and Magnadur (ceramic oxides of Fe and Ba).

Magnetically soft materials are those which can also be strongly magnetised by an applied magnetic field but readily lose their magnetism when the applied field no longer exists, e.g. soft iron, permalloy (Ni & Fe) and high resistivity ferromagnetic magnetic oxide materials called ferrites. Ferrites, e.g. a Ni/Zn ferrite, are used as magnetic core materials at high frequencies because their high resistivity means eddy-current losses are minimised.

Curie temperature, T_c , is the temperature at which a ferromagnetic material loses most of its magnetism.

Table 15.1 Curie temperatures

Material	iron	cobalt	nickel	gadolinium
Curie temp. ($^{\circ}\text{C}$)	770	1131	358	16

Magnetic fields

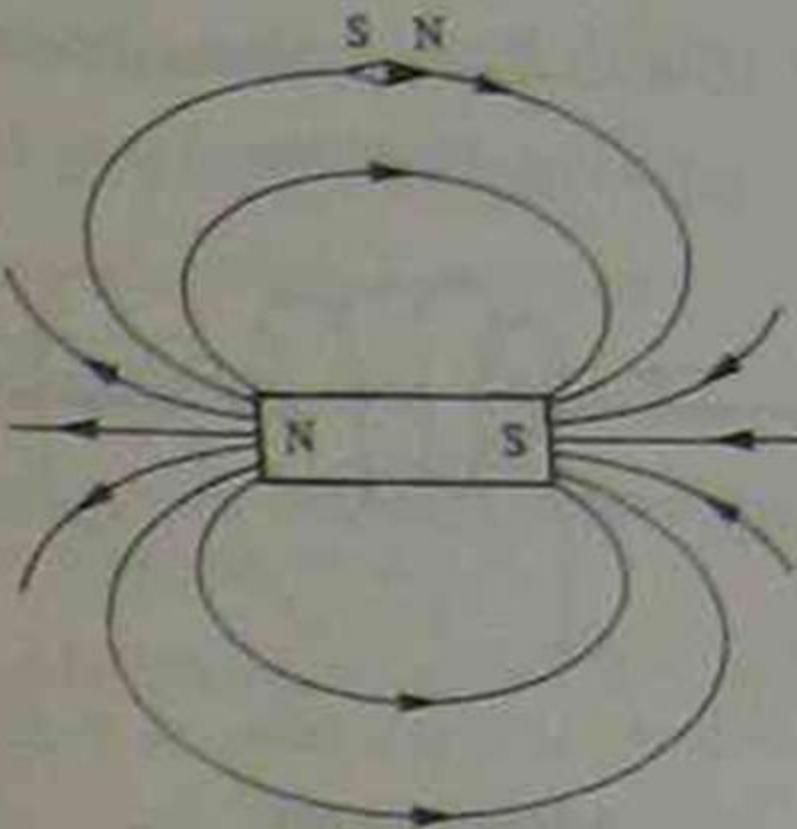
A magnetic field is a region where a magnet (such as a compass needle) and/or a moving charge experience a magnetic force. The direction of this force on the N pole of the compass is in the direction of the magnetic

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field. Magnetic fields are represented by lines of magnetic force, or magnetic flux lines, which are drawn as arrowed lines pointing away from the N pole of a magnet and towards a magnet's S pole.

Permanent magnets



Field around a bar magnet

Fig. 15.3

Current in a long straight wire

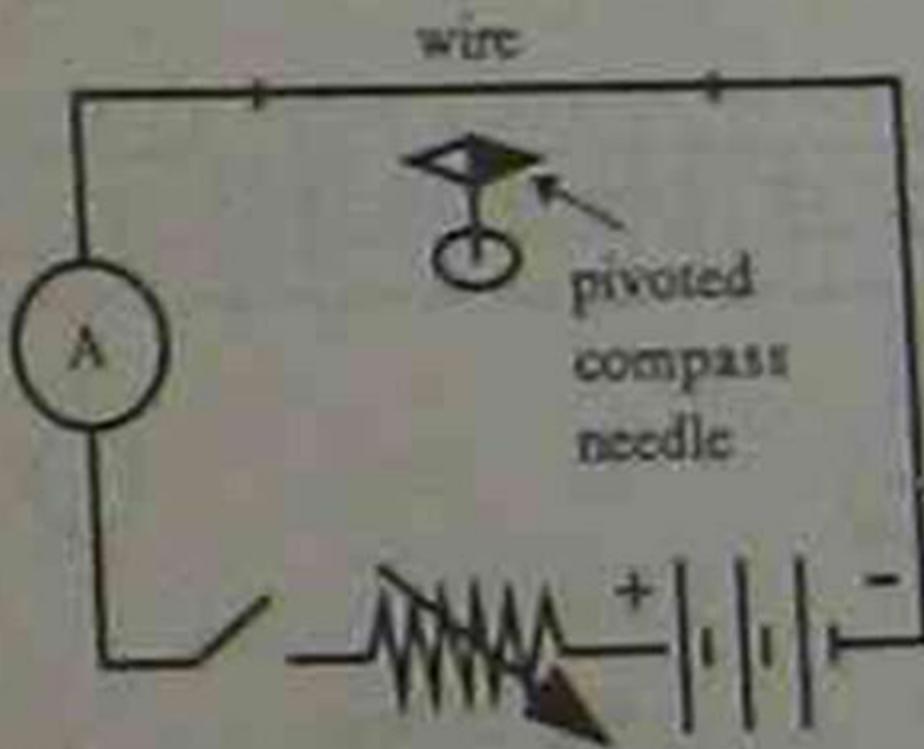
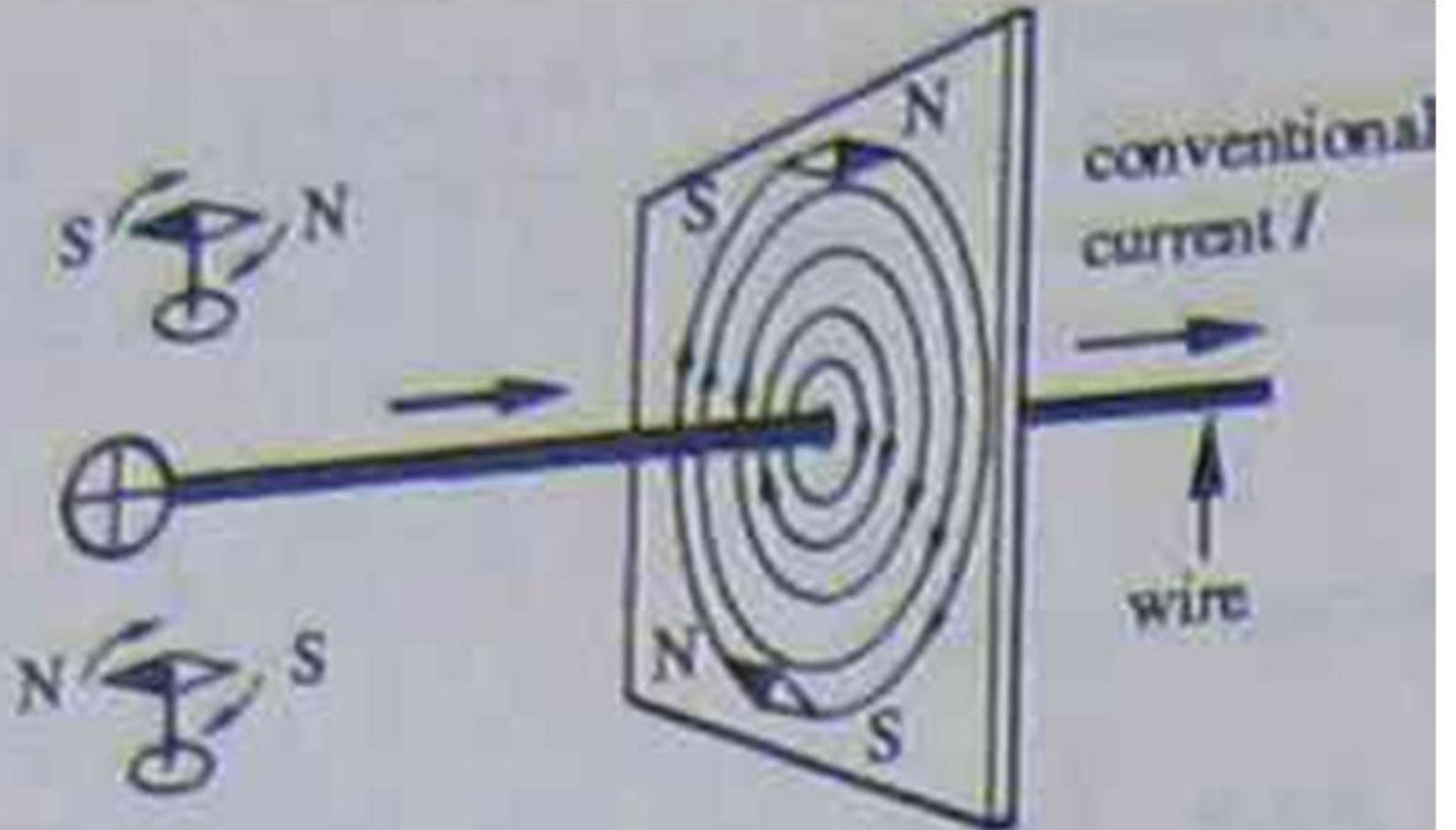


Fig. 15.4(a)

Using equipment similar to that shown in Figure 15.4(a) in 1819, Christian Oersted (1777–1851) plotted the magnetic field round a straight current-carrying wire. The lines of magnetic force can be regarded as concentric cylinders round the wire (Fig. 15.4(b)). The field pattern can be mapped with iron filings. The directions of the lines of force are given by application of the Right Hand Grip Rule: 'grip the conductor in your right hand so that your thumb points in the direction of conventional current; your fingers point in the direction of the field' (Fig. 15.4(c)).



key ————— S N ————— Direction of field line
Fig. 15.4(b)

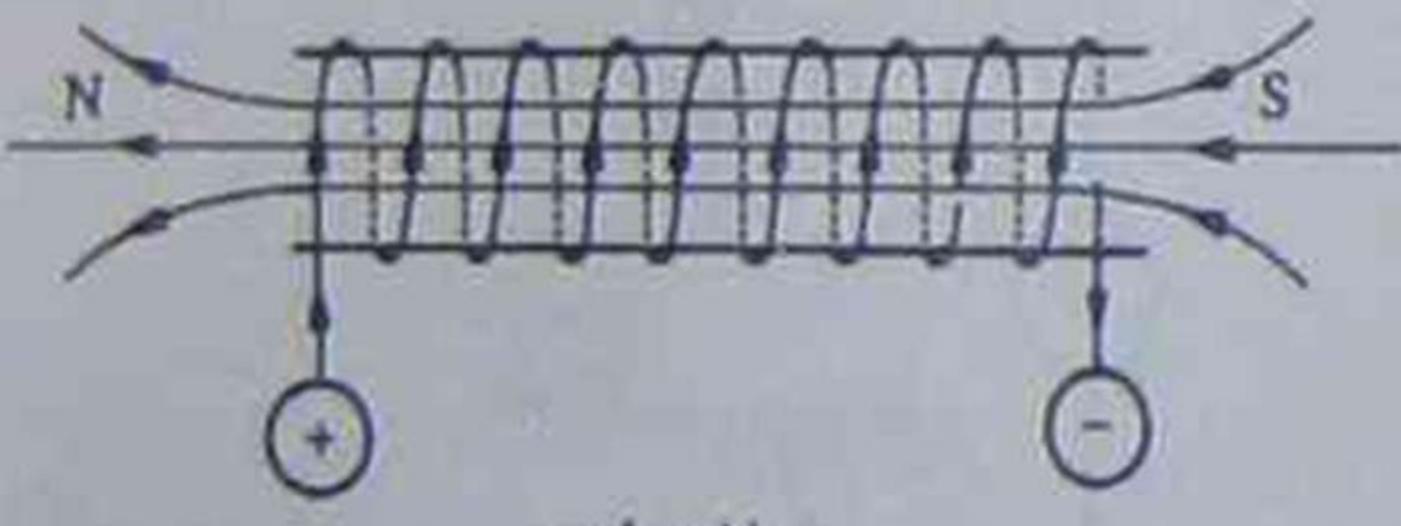


right hand grip rule

Fig. 15.4(c)

A solenoid

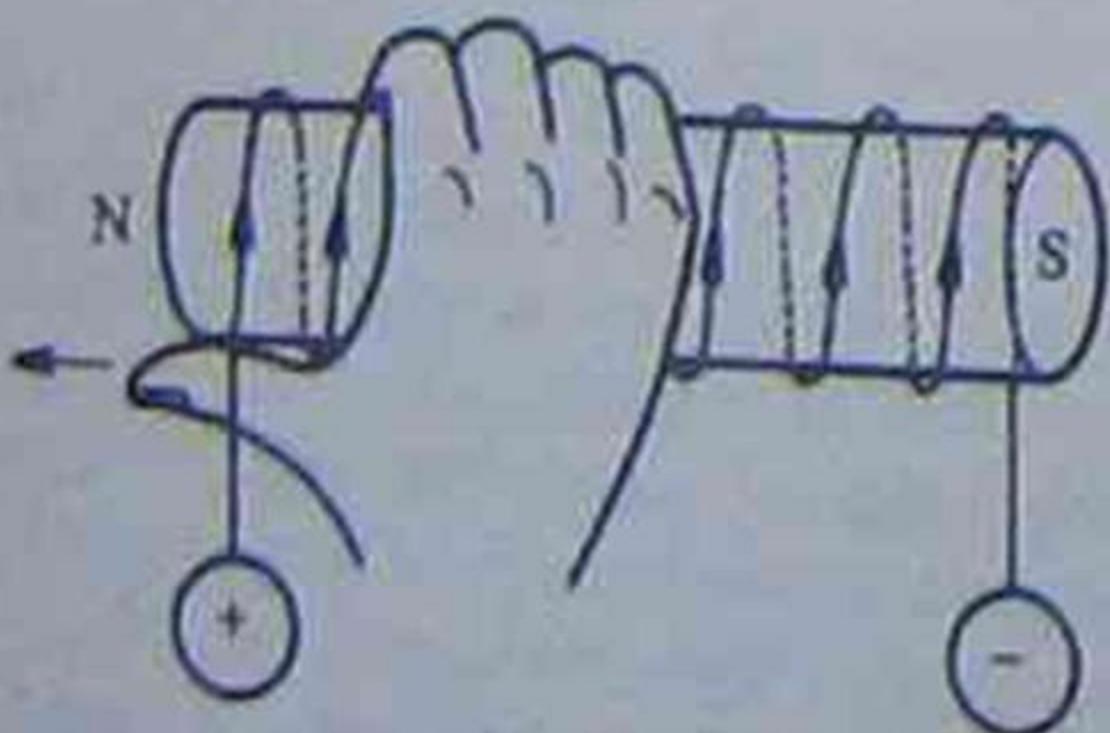
A solenoid is a cylindrical coil of insulated wire. The magnetic fluxes due to each turn add, to yield the magnetic flux of a bar magnet.



solenoid

Fig. 15.5(a)

fingers in direction of
conventional current



right hand coil rule

Fig. 15.5(b)

Magnetic polarity of the solenoid is given by the 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 north pole of the coil', (see Figure 15.5(b)). In 1825 William Sturgeon placed soft iron in the core of a solenoid and noted that the iron was strongly magnetised only when current passed through the coil. He produced an electromagnet which is a solenoid with a strong magnetic core. Electromagnets are used in magnetic cranes, electric bells, magnetic switches, telephone earpieces, motors and generators.

Magnetic permeability

The capacity of a substance to conduct magnetism is called relative permeability, μ . Air is given a relative permeability of 1; for soft iron and Mn/Zn ferrite μ may be as large as 2000.

Magnetic flux density \tilde{B}

Magnetic flux density is a vector quantity in the direction of the magnetic flux. Magnetic flux density is a measure of magnetic field strength or intensity and is the number of magnetic flux lines passing through 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). When $B = 2\text{ T}$ this means 2 flux lines threading through 1 square metre. This would be a very strong field. The Earth's magnetic field has a strength of about $1/10000\text{ T}$.

Magnetic flux Φ

Magnetic flux is the total number of magnetic flux lines through an area A at right angles to the field. See Figure 15.7(a). For a uniform field:

$$\Phi = BA$$

where the plane of A is at right angles to B . When the plane of the coil is rotated through an angle θ the area at right angles to B is $A \cos \theta$ as shown in Figure 15.7(b). Under these conditions

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

The SI unit of Φ is T m^2 or weber (Wb).

Magnetic flux density B due to current in a long straight wire

The magnetic flux density B at a point is:

- proportional to the current in the wire;
- inversely proportional to the perpendicular distance r of the point from the wire.

$$B = k I/r \text{ where } k = \mu_0 / 2\pi = 2 \times 10^{-7} \text{ TmA}^{-1}$$

μ_0 = permeability of air or free space

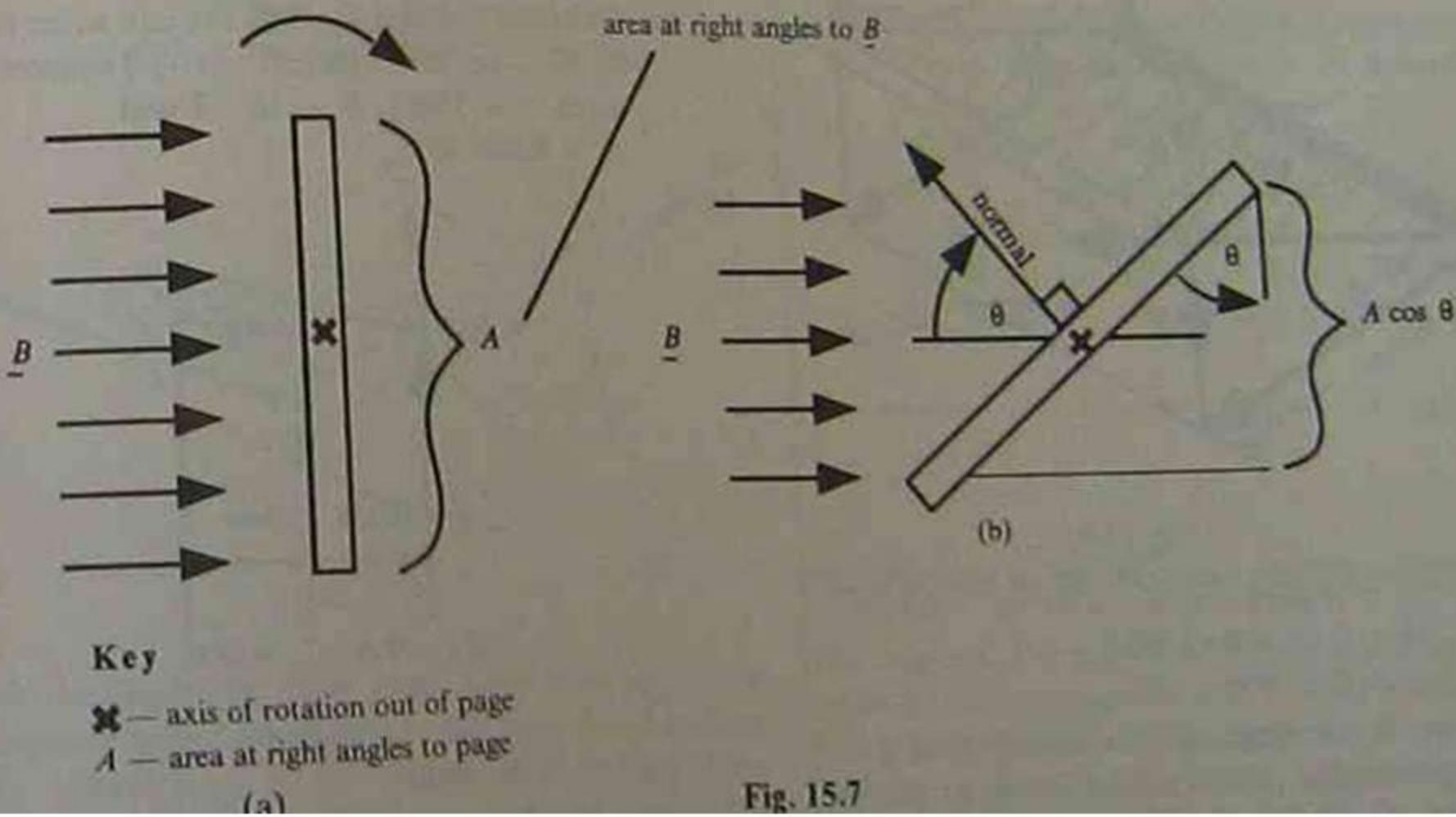


Fig. 15.7

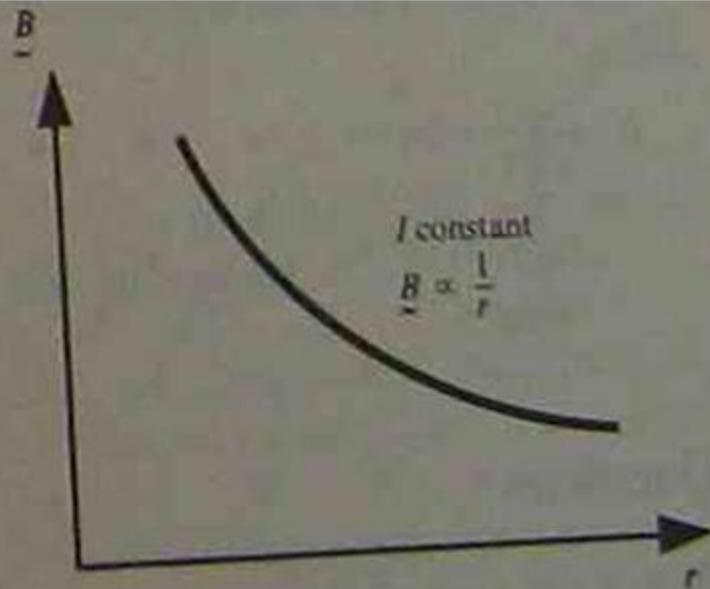
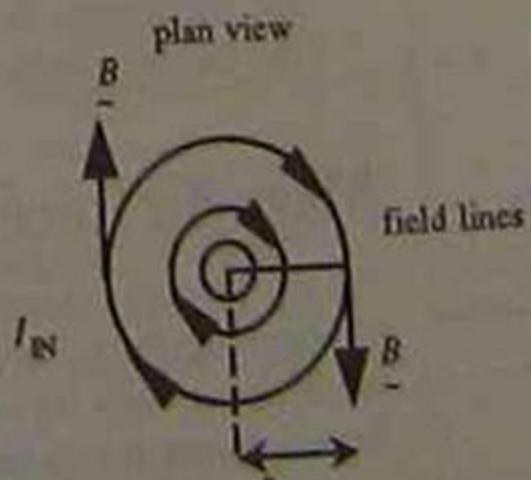
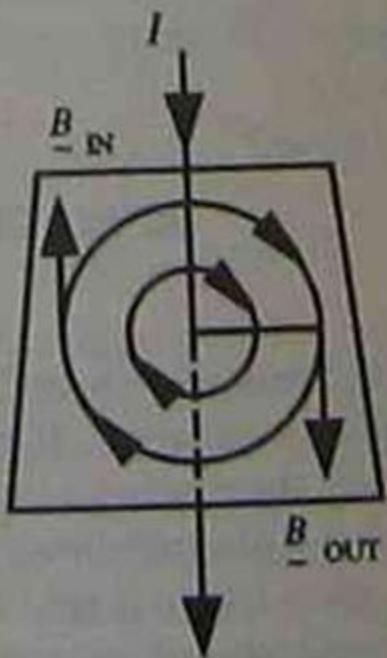


Fig. 15.8

EXAMPLES

1. A straight wire 8 cm long moves at 3.0 m s^{-1} horizontally to the right through a vertical magnetic field of 0.25 T. Calculate:
 - (a) the area A swept by the wire in 2.0 s;
 - (b) the flux Φ cut by the wire in 2.0 s;
 - (c) the flux cut by the wire when moved for 2.0 s along a direction 30° below the horizontal.

Answer

(a) $A = l \times s$, but

$$s = v \times t = 3.0 \times 2.0 \text{ m} = 6.0 \text{ m}$$

$$\begin{aligned}A &= 0.080 \times 6.0 \text{ m}^2 \\&= 0.48 \text{ m}^2\end{aligned}$$

(b) $\Phi = BA$, where A = area swept at right angles to B ,

$$\begin{aligned}&= 0.25 \times 0.48 \text{ T m}^2 \\&= 0.12 \text{ Wb}\end{aligned}$$

(c) $\Phi = BA'$, where A' = area swept at right angles to B .

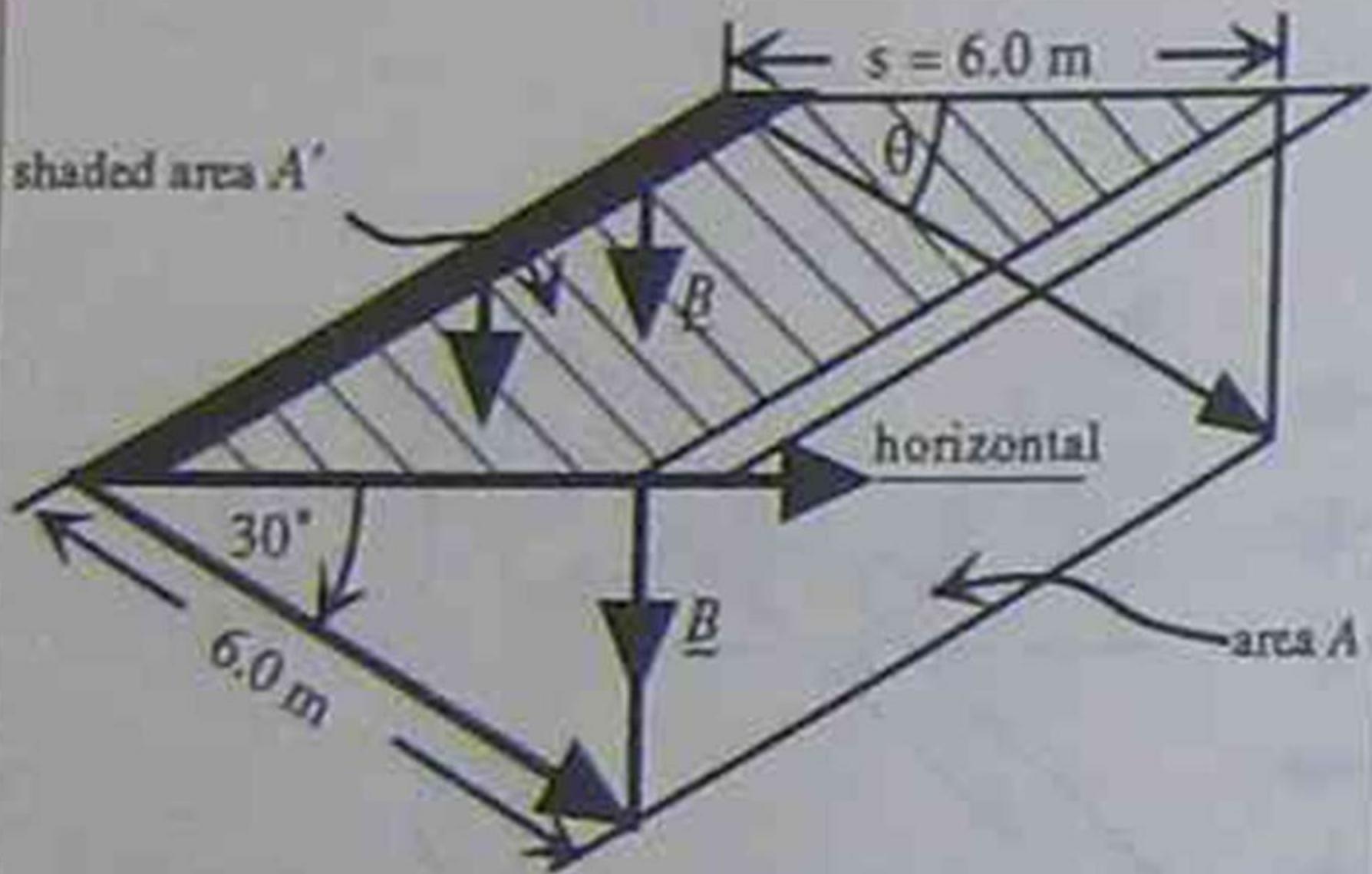


Fig. 15.9

$$A' = A \cos \theta = 0.48 \cos 30^\circ \text{ m}^2 = 0.42 \text{ m}^2$$
$$\therefore \Phi = 0.25 \times 0.42 \text{ Wb}$$
$$= 0.10 \text{ Wb}$$

2. What is the magnetic flux density B at a perpendicular distance of 5.0 cm to the right of a vertical wire? The current of 10 A flows up the wire which is in air.

Answer

$$B = \frac{\mu_0 I}{2\pi r}$$
$$= 2 \times 10^{-7} \times 10/0.050 \text{ T}$$
$$= 4.0 \times 10^{-5} \text{ T horizontally into the page.}$$

Magnetic force

As we saw in Chapter 5, 'Electrostatics', there is an electrostatic force between stationary charges. If there is relative motion between charges there exists a second force between the charges which is a magnetic force.

A single moving charge q_1 , gives rise to a field B as shown in Figure 15.11. A second charge q_2 moving with velocity v in B will experience a magnetic force F at right angles to the plane of B and v .

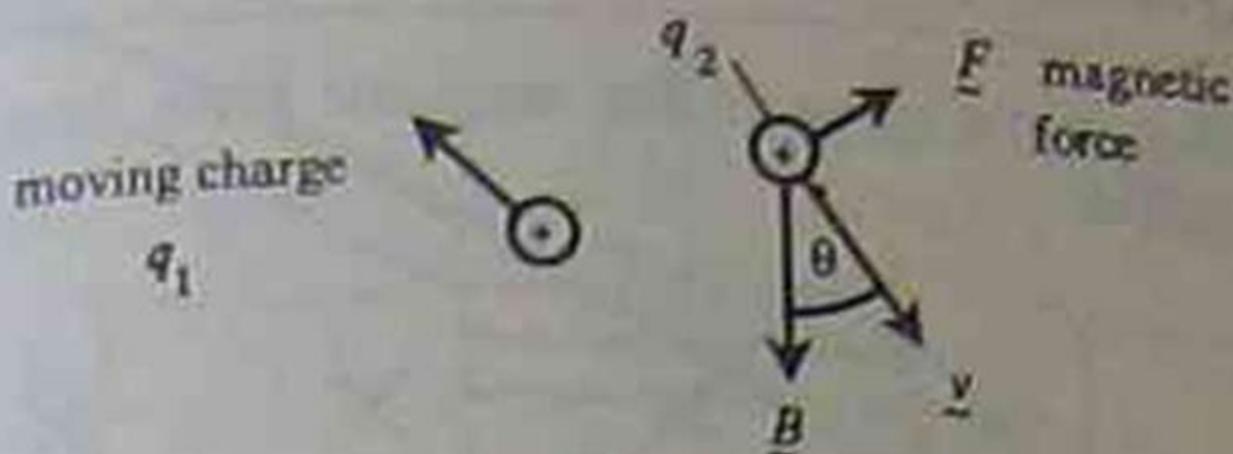


Fig. 15.11

F is proportional to B , q , v , and $\sin \theta$, where θ is the angle between the direction of B and v . In SI units:

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

The direction of F on a positive charge is given by the *Right Hand Palm Rule*:

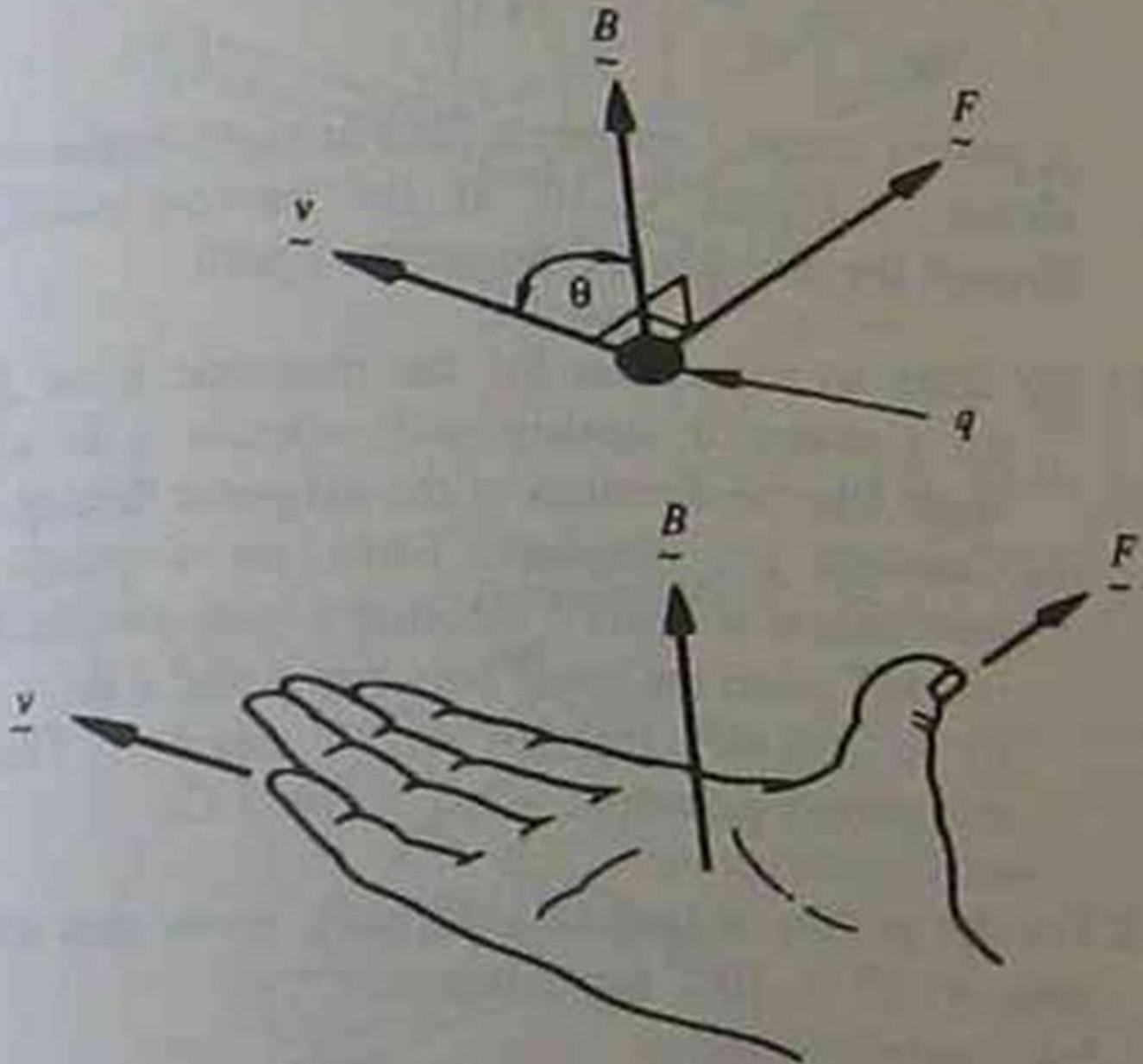


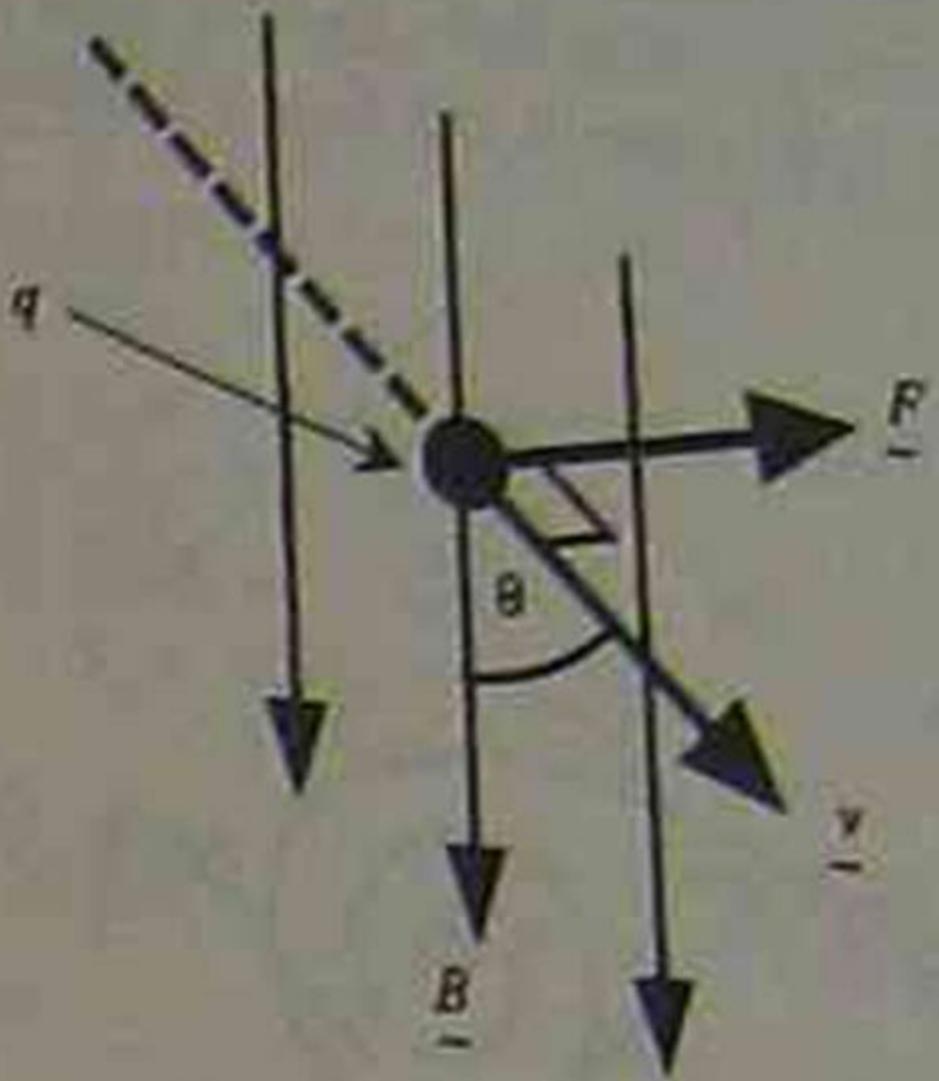
Fig. 15.12

'With the fingers of your right hand pointing in the direction of \mathbf{v} and the palm of your right hand pushing in the direction of \mathbf{B} , the thumb of your right hand points in the direction of \mathbf{F} on a positive charge'. The magnetic force on a negative charge is in the opposite direction to that on a positive charge.

EXAMPLE

A charge q of 10^{-10} C travelling with a velocity v of 10^5 m s $^{-1}$ enters a magnetic field at an angle θ to the direction of a magnetic field, $B = 0.6$ T as shown in Figure 15.13.

- Write an expression for the magnetic force F in terms of B , q , v and θ .
- How can you determine the direction of F ?
- Calculate F when θ is (i) 90° (ii) 30° (iii) 0° .



Answer

- (a) $F = Bqv \sin \theta$.
- (b) Apply the Right Hand Palm Rule (see text).
- (c) F is at right angles to both B and v as shown in Figure 15.13.

(i) When $\theta = 90^\circ$,

$$\begin{aligned}F &= 0.6 \times 10^{-19} \times 10^5 \sin 90^\circ \text{ N} \\&= 6.0 \times 10^{-15} \text{ N}\end{aligned}$$

(ii) When $\theta = 30^\circ$, $F = 3.0 \times 10^{-15} \text{ N}$.

(iii) When $\theta = 0^\circ$, B and v are parallel.
 $F = 0 \text{ N}$.

Magnetic force on moving charge entering a magnetic field

The magnetic force F on a positive charge q when it enters a uniform magnetic field at right angles is Bqv . While the particle is in the field this force is at right angles to v so the particle follows a circular path. This magnetic force provides the centripetal force mv^2/r for circular motion of the charged particle.

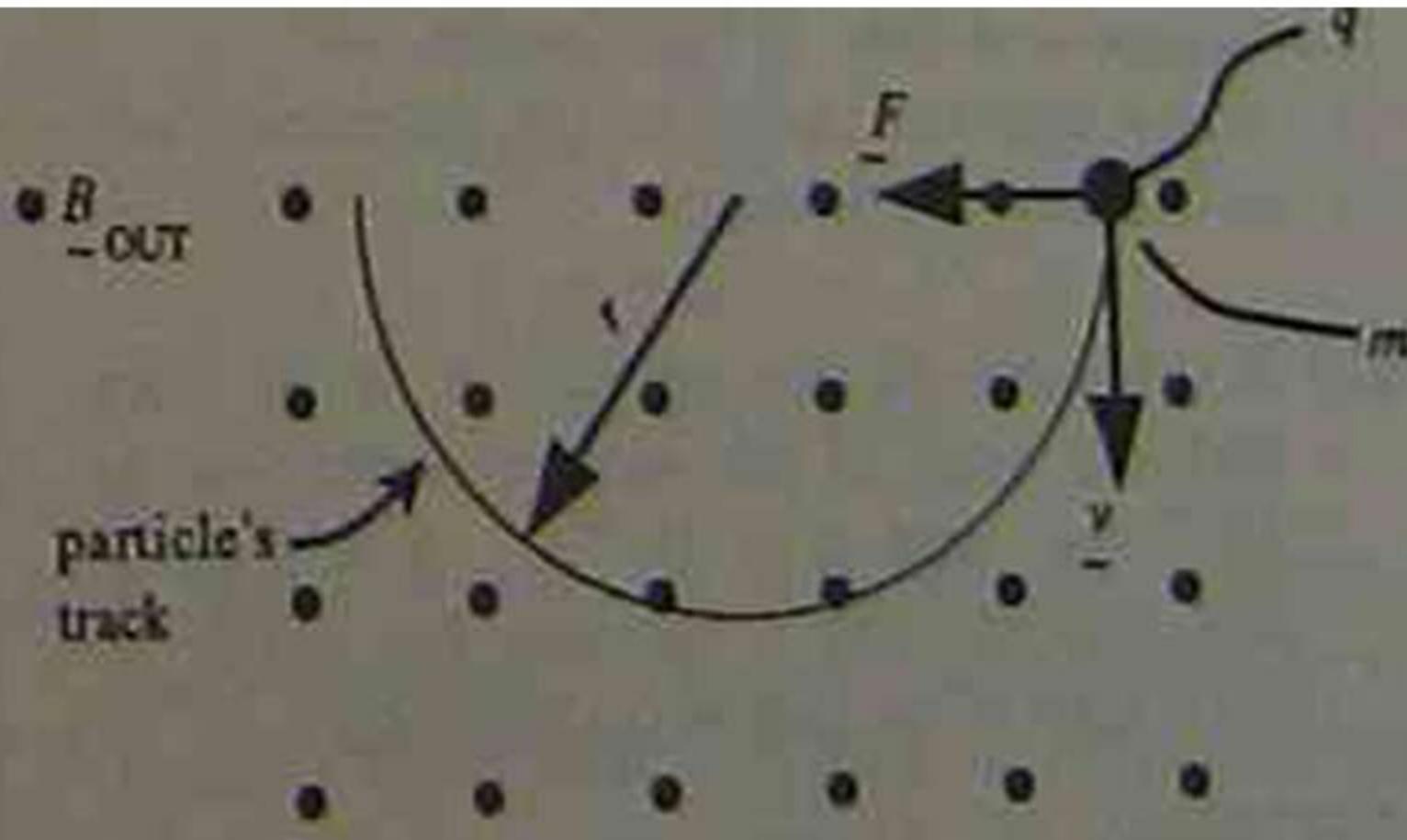


Fig. 15.14

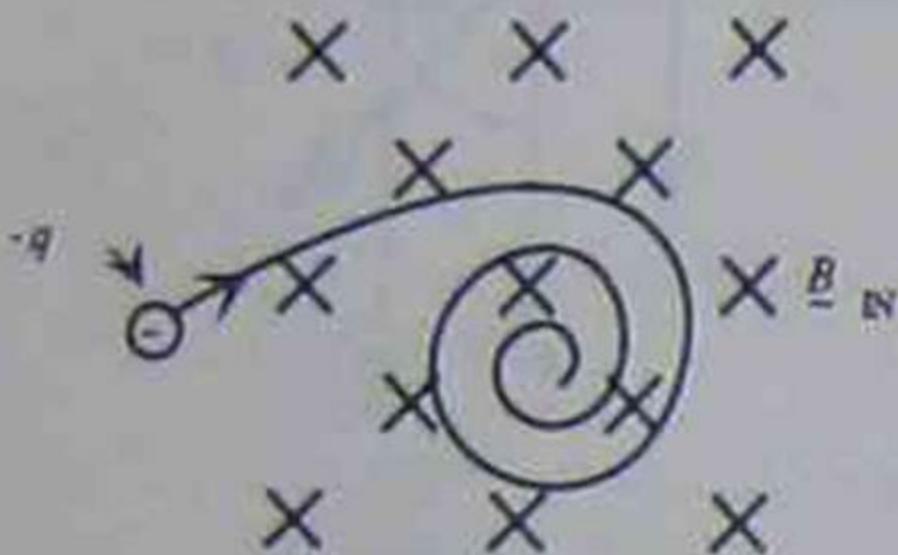
Thus
therefore

$$mv^2/r = Bqv,$$

$$r = mv/Bq$$

NB If the particle loses energy, say, due to collisions, γ decreases, and if m , B and q are constant, so does r and the particle follows a spiral path.

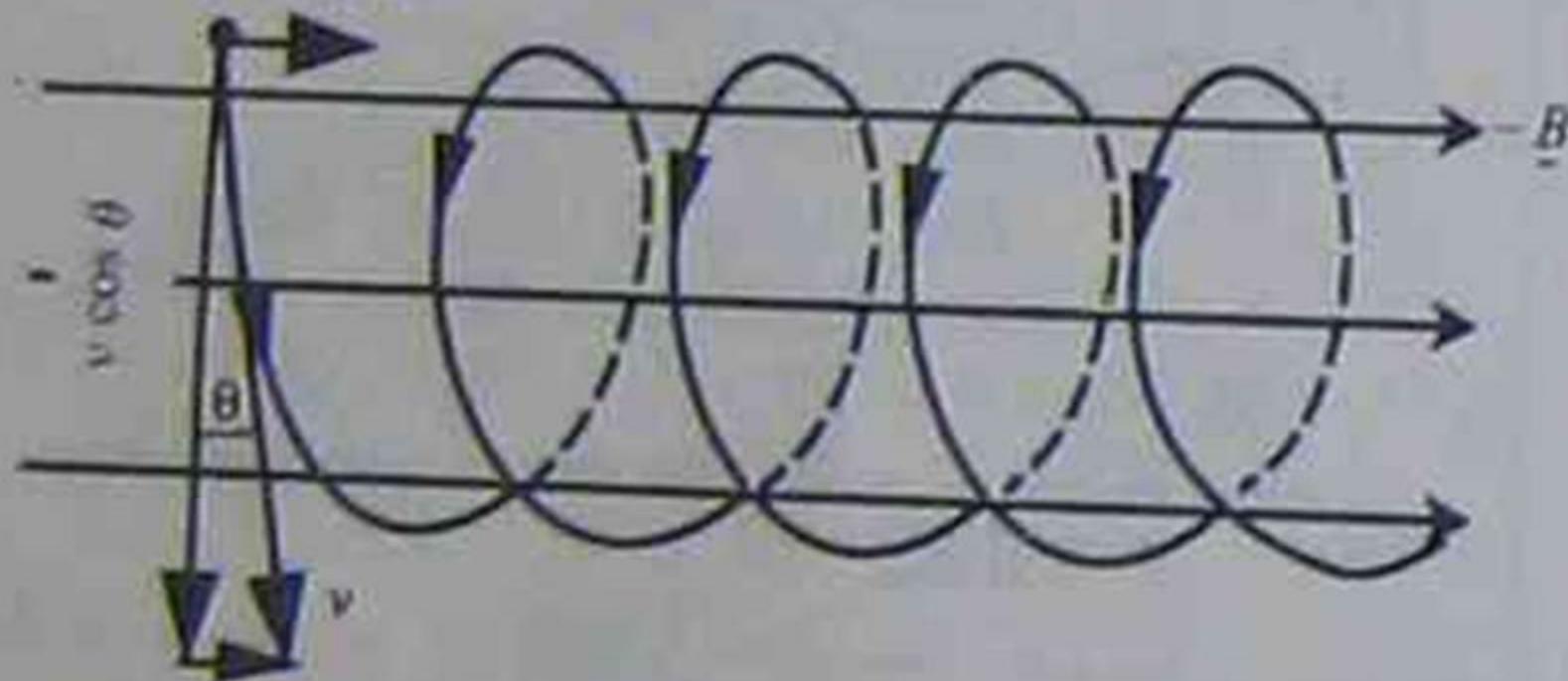
If the particle enters the magnetic field at an angle other than a right angle, it will follow a helical path.



(a) spiral path

a negatively charged particle

$$\sim q v \sin \theta$$



(b) helical path

Fig. 15.15

EXAMPLE

Two particles with the same charge and velocity enter a uniform field at right angles.

(a) Show that the radius of the particles' track in the field is given by:

$$r = mv/Bq$$

(b) If the mass of one particle m_1 is 10^{-25} kg and the mass of the second particle m_2 is 10^{-24} kg, and $q = 10^{-18}$ C, $B = 0.10$ T and v is 10^5 ms $^{-1}$, calculate the radius of the tracks of m_1 and m_2 in the field.

Answer

(a) See text.

(b) $r_1 = 10^{-25} \times 10^5 / 10^{-1} \times 10^{-18} \text{ m} = 10^{-1} \text{ m}$
 $r_1 = 10 \text{ cm}$, similarly $r_2 = 1.0 \text{ m}$.

Magnetic force on a current-carrying conductor in a magnetic field

Force F on a current-carrying conductor at an angle θ to a magnetic field B is given by:

$$F = BIL \sin \theta$$

where F is at right angles to B and I ,

I is conventional current,

L is the length of conductor in B .

B is 1 tesla when the force on 1 metre of wire carrying 1 ampere of current at right angles to the field is 1 newton.

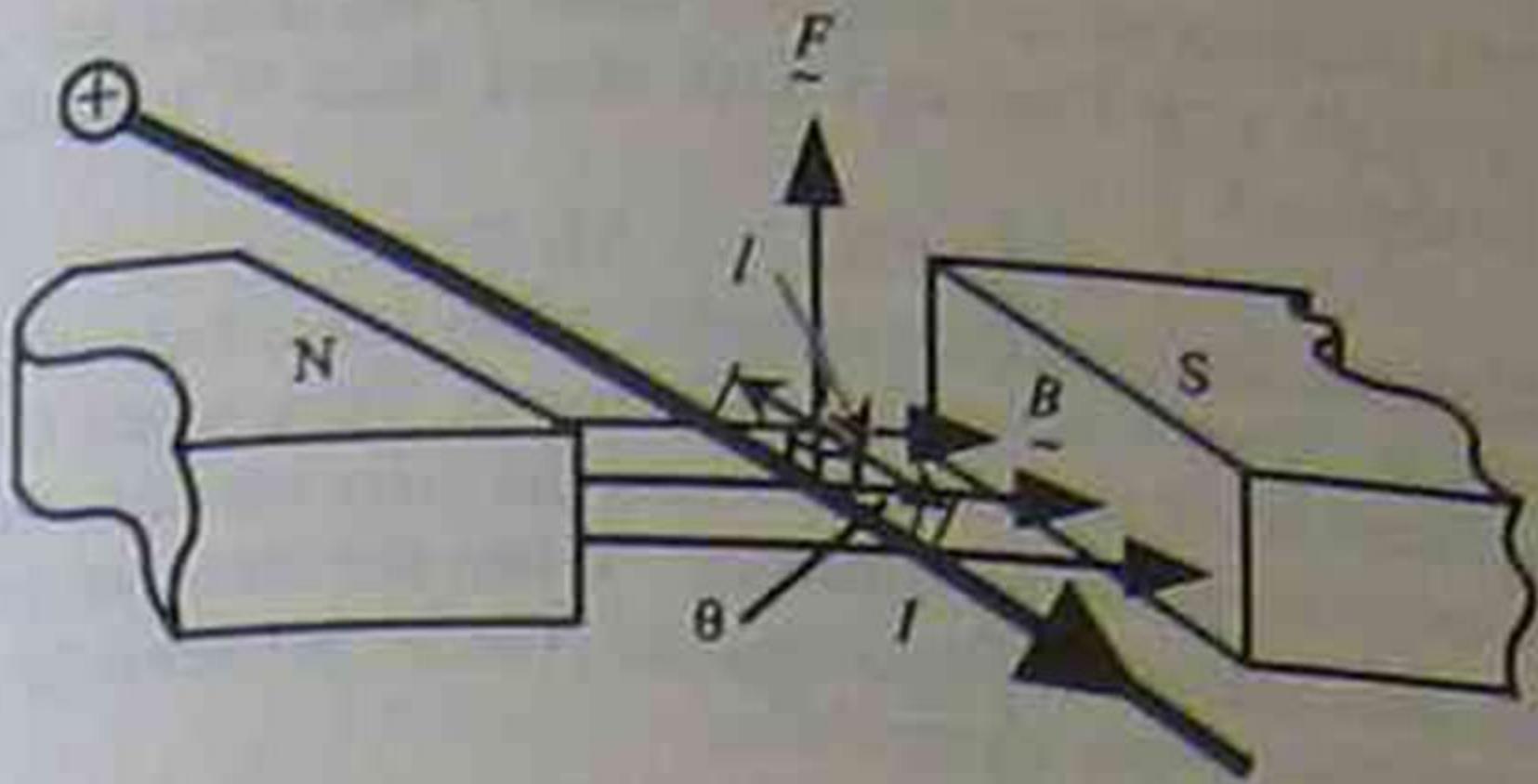
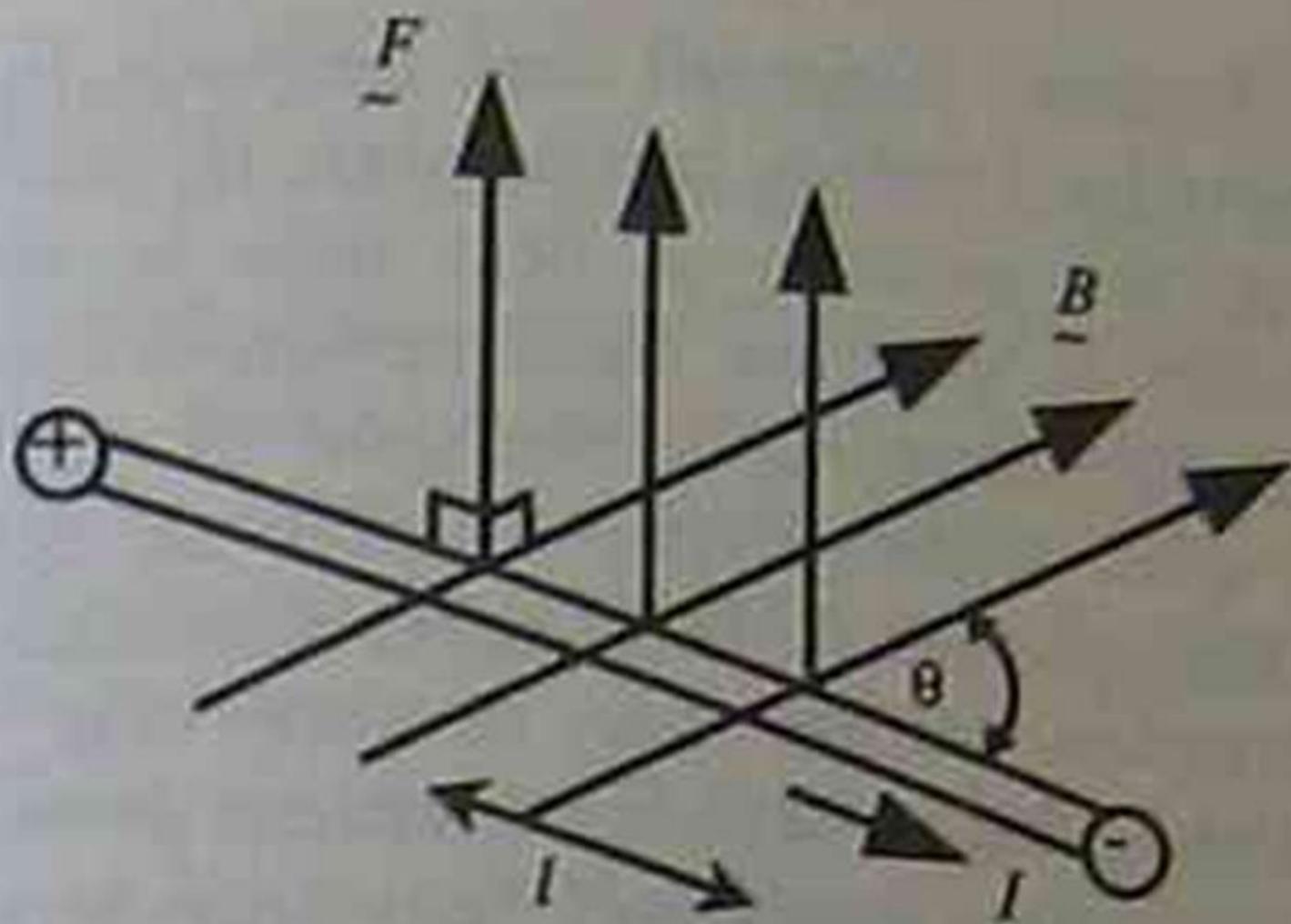


Fig. 15.17



thumb
Motion
force F

first finger
magnetic Field B



second finger
Conventional Current I

left hand

Fleming's Left Hand Rule

Fig. 15.18

The directions of F , B and I are given by the famous Fleming's Left Hand Rule, sometimes called the Motor or FBI rule: '*Hold the first two fingers and the thumb of the left hand at right angles to each other. Point the First finger in the direction of the Field B and the second finger in the direction of Conventional Current I . The thumb points in the direction of the Motion force F .*'

EXAMPLE

- (a) State Fleming's Left Hand Rule.
- (b) Calculate the magnetic force F on the conductor shown in Figure 15.18 when θ is
(i) 90° (ii) 60° (iii) 0° , i.e. B is parallel to I ,
given that $B = 0.70\text{ T}$, $I = 4.0\text{ A}$ and
 $l = 8.0\text{ cm}$.