Electromagnetism

6.1 MAGNETIC FIELD

When there is an electric current in a conductor magnetic forces are produced surrounding the conductor. We say that a *magnetic field* is set up. A magnetic field is a condition of space. It is shown by hypothetical magnetic lines called *magnetic flux*. The magnetic lines always form closed loops. Electromagnetism is the study of magnetic fields produced by conductors carrying current. Magnetic effects are due to moving charges (currents).

6.2 DIRECTION OF CURRENT IN A CONDUCTOR

It is convenient to show the cross-section of a conductor instead of showing the conductor as a whole. The current direction is represented by an arrow. Consider an arrow *BA* as shown in Fig. 6.1. An observer towards end *A* observes the *point* of the arrow. The current is coming towards him. Hence a *dot* (representing the point of the arrow) within the conductor represents the current coming towards the observer. An observer towards end *B* observes the *tail* or *crossed feathers* of the arrow. The current is going away from the observer. Hence, a *cross* within a conductor represents the current going away from the observer.

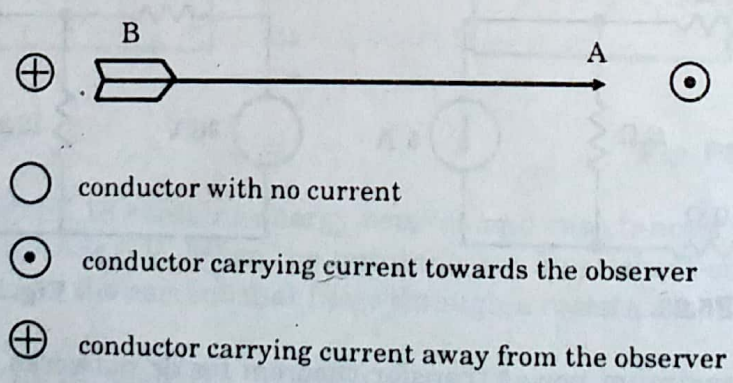

Fig. 6.1. Direction of current in a conductor.

6.3 DIRECTION OF MAGNETIC FLUX

The direction of magnetic flux can easily be found either by right-hand rule or right-hand screw rule.

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6.3.1 Right-hand Rule

Imagine the conductor to be grasped by the right hand in such a way that the thumb points in the direction of current, then the fingers give the direction of the magnetic flux around the conductor. The illustration of right-hand rule is given in Fig. 6.2.

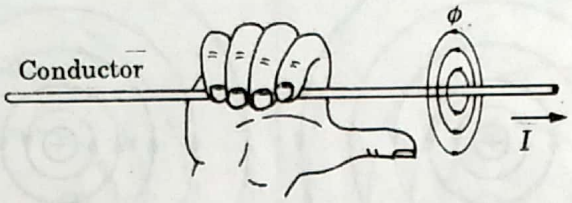

Fig. 6.2. Illustrating right-hand rule.

6.3.2 Right-hand Screw Rule

Imagine a right-handed screw to point in the direction of current, then the direction of the magnetic flux is in the direction in which the screw has to be turned to move it in the forward direction. The application of right-hand screw rule is given in Fig. 6.3.

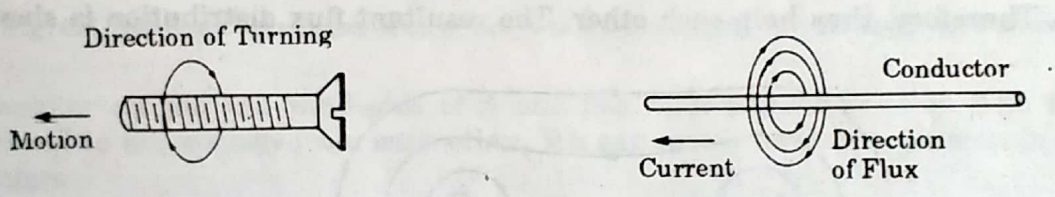

Fig. 6.3. Illustrating right-hand screw rule.

6.4 FLUX DISTRIBUTIONS OF ISOLATED CONDUCTORS

The magnetic field or distribution of isolated conductors is shown in Fig. 6.4. The flux distribution in a conductor carrying current coming towards an observer is given in Fig. 6.4 (*a*) and the flux distribution in a conductor carrying current going away from the observer is given in Fig. 6.4 (*b*). The direction of the field is determined either with the help of the right-hand rule or the right-hand screw rule.

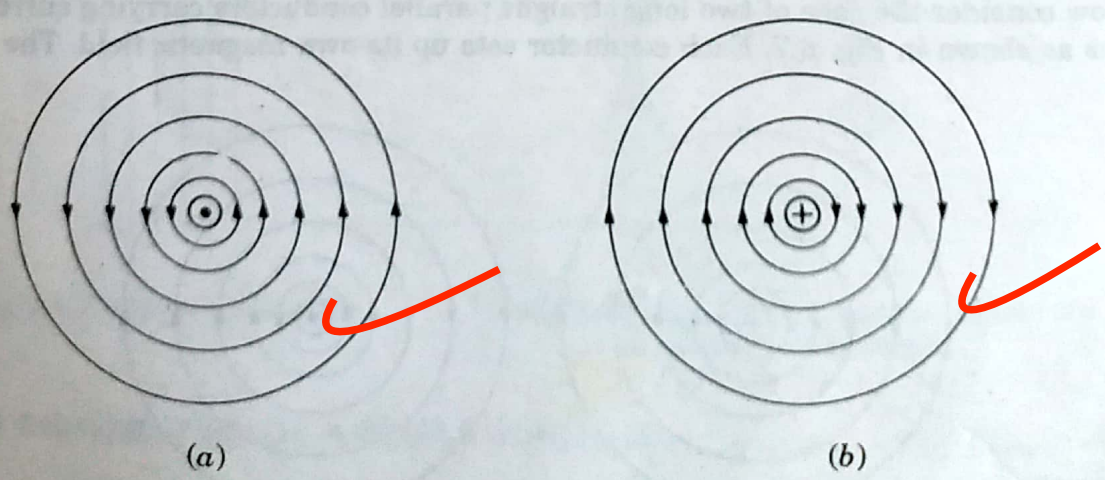

Fig. 6.4. Magnetic fields surrounding isolated long, straight, current-carrying conductors.

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6.5 FLUX DISTRIBUTION OF TWO CURRENT-CARRYING CONDUCTORS

Consider two long, straight, parallel conductors A and B carrying currents away from the observer as shown in Fig. 6.5. Each conductor sets up its own magnetic field. In the space between the

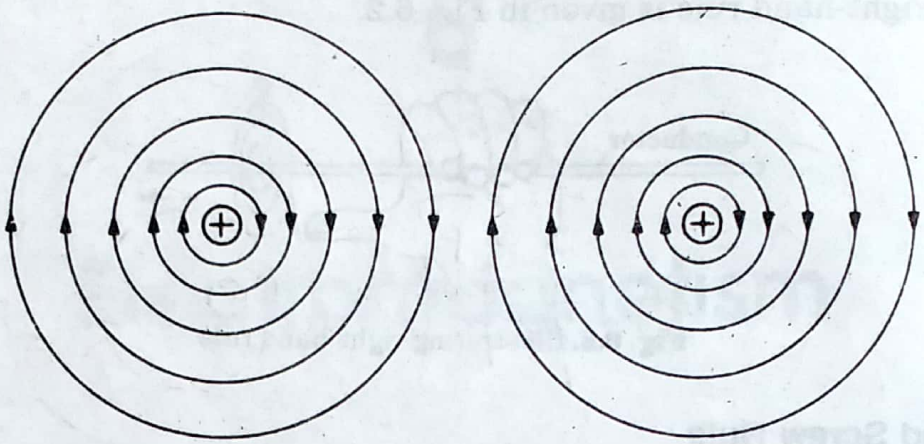

Fig. 6.5. Flux distribution of two conductors carrying current in the same direction.

conductors, the directions of the two fields are opposite to each other. Hence the resultant field is neutralized there. On the left-hand side of A and on the right-hand side of B the fields are in the same direction. Therefore, they help each other. The resultant flux distribution is shown in Fig. 6.6.

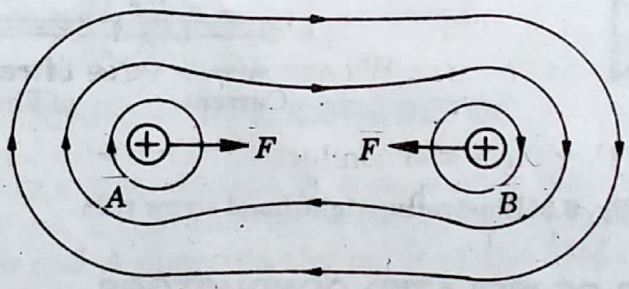

Fig. 6.6. Resultant flux distribution of two conductors carrying current in the same direction.

The flux lines are in state of tension and have a tendency to shorten themselves. The two conductors, therefore, tend to move *towards* each other. We say that a force of attraction is set up between the conductors.

Now consider the case of two long straight parallel conductors carrying current in opposite directions as shown in Fig. 6.7. Each conductor sets up its own magnetic field. The resultant flux

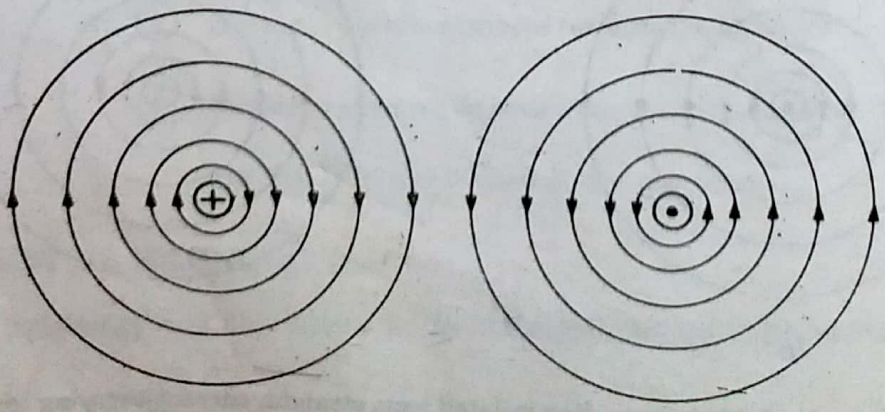

Fig. 6.7. Flux distribution of two conductors carrying current in opposite directions.

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distribution is shown in Fig. 6.8. The fields are in the same direction in the space between the conductors. Thus, the resultant field becomes stronger in the space between the conductors and

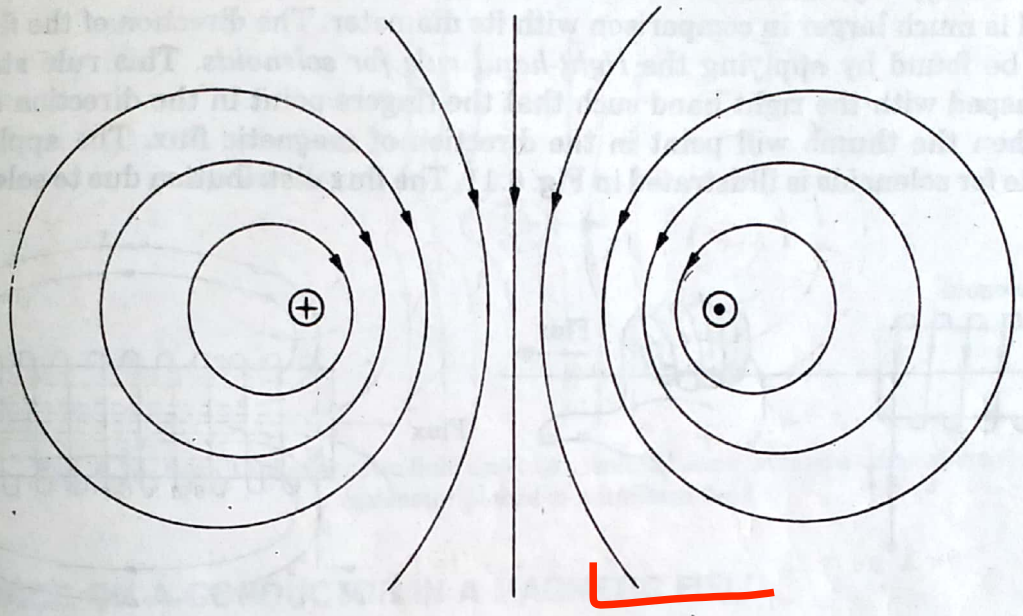

Fig. 6.8. Resultant flux distribution of two conductors carrying current in opposite directions.

becomes weaker on the left-hand side of *A* and the right-hand side of *B*. The two conductors, therefore, tend to move *away* from each other. We say that a force of repulsion is set up between the conductors.

Thus, we conclude that if there are two conductors carrying current in the *same* direction there is a force of *attraction* between them. If the two conductors carry current in *opposite* directions there is a force of *repulsion* between them.

6.6 REPRESENTATION OF UNIFORM MAGNETIC FIELD

A uniform magnetic field is represented by equally spaced lines as given in Fig. 6.9.

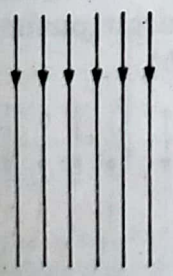

Fig. 6.9. Uniform magnetic field.

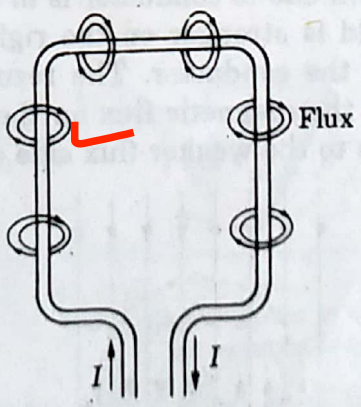

Fig. 6.10. Magnetic field due to single turn of a conductor carrying current.

6.7 FLUX DISTRIBUTION OF A SINGLE-TURN COIL

If a conductor is made into a loop and current is passed through it, the magnetic flux lines are concentric circles all along its length as shown in Fig. 6.10. The direction of the field is either determined by the right-hand rule or right-hand screw rule.

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6.8 FLUX DISTRIBUTION OF A SOLENOID

A solenoid is (usually) a cylindrical coil wound with one or more layers of insulated wire. The length of the solenoid is much larger in comparison with its diameter. The direction of the field inside the solenoid may be found by applying the *right-hand rule for solenoids*. This rule states that if a solenoid is grasped with the right hand such that the fingers point in the direction of the current in the wire, then the thumb will point in the direction of magnetic flux. The application of the right-hand rule for solenoids is illustrated in Fig. 6.11. The flux distribution due to solenoid carrying

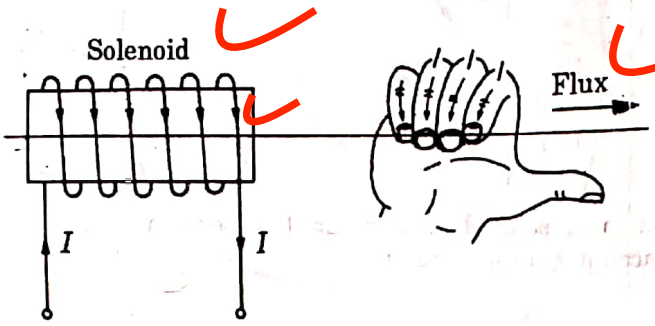

Fig. 6.11. Right-hand rule for solenoids.

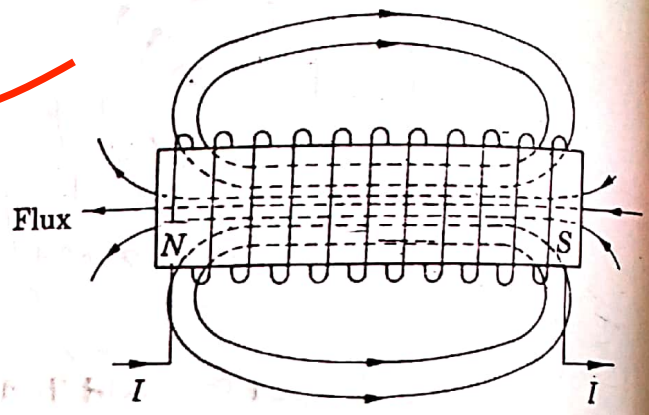

Fig. 6.12. Magnetic field due to a solenoid carrying current.

current is given in Fig. 6.12. The magnetic field produced by a solenoid is similar to that of a bar magnet. One end of the solenoid becomes a north pole (N) where the flux leaves the solenoid. The other end becomes the south pole (S) where the flux enters it.

6.9 ISOLATED CONDUCTOR IN A UNIFORM MAGNETIC FIELD

Consider an isolated, long, straight conductor, carrying current away from the observer, placed in a uniform magnetic field acting vertically downwards [Fig. 6.13 (*a*)]. The field due to conductor on its right-hand side is in the direction of the main magnetic field. On the left-hand side of the conductor, the field due to conductor is in a direction opposite to that of the main field. Therefore the resultant field is stronger on the right-hand side of the conductor and it is weaker on the left-hand side of the conductor. The resultant flux distribution is shown in Fig. 6.13 (*b*). The nonuniformity of the magnetic flux on the two sides of the conductor pushes the conductor from stronger flux side to the weaker flux side as shown in Fig. 6.13 (*b*).

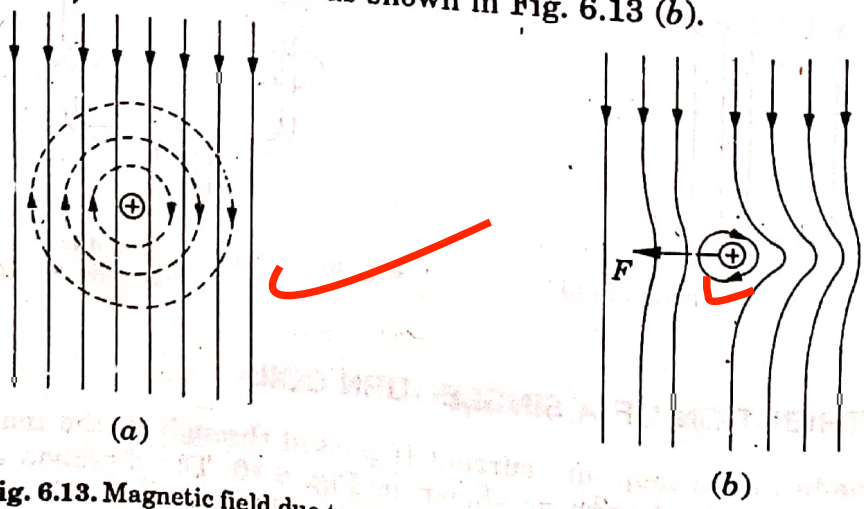

Fig. 6.13. Magnetic field due to an isolated, long, straight current-carrying conductor placed in a uniform field.

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If the direction of current is reversed in the conductor, the force produced on the conductor is also reversed. This is shown in Fig. 6.14.

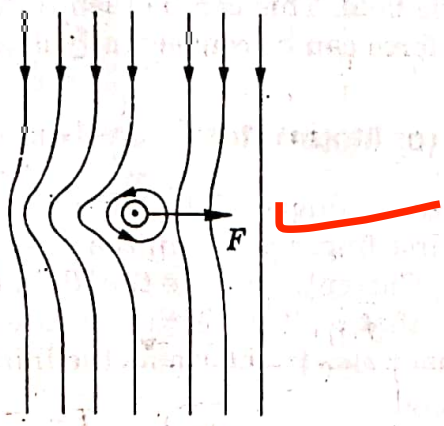

Fig. 6.14. Resultant magnetic field due to an isolated, long, straight current-carrying conductor placed in a uniform field.

6.10 FORCE ON A CONDUCTOR IN A MAGNETIC FIELD

Experimentally it has been shown that the force experienced by a current-carrying conductor placed in a magnetic field is given by

$$F = BIl \tag{6.10.1}$$

where F = force on the conductor in newtons (N)

B = flux density in teslas (T)

I = current in the conductor in amperes (A)

l = effective length of the conductor perpendicular to the field in metres (m)

The effective length is the length of the conductor lying within the field.

The relationship given in Eq. (6.10.1) is used to define the flux density as follows : If $l = 1$ m, $I = 1$ A, $F = 1$ N, then $B = 1$ tesla (T). Thus, if a force of 1 N is exerted on a conductor of length 1 m carrying a current of 1 A, it is said to be situated at right angles (Fig. 6.15) to a uniform magnetic field of flux density 1 tesla.

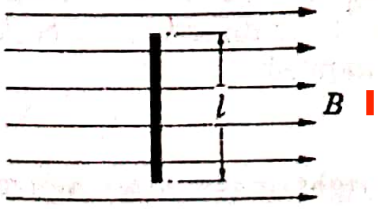

Fig. 6.15. Conductor in a magnetic field placed perpendicular to it.

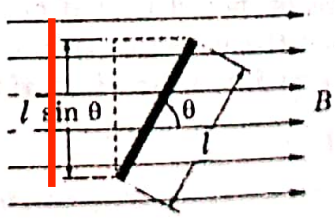

Fig. 6.16. Conductor in a magnetic field at an angle to the field.

If the angle between the conductor and the field is θ (Fig. 6.16), then the effective length of the conductor perpendicular to the field is $l \sin \theta$ and the force on the conductor is given by

$$F = BIl \sin \theta \tag{6.10.2}$$

If $\theta = 0$, that is, the conductor is placed *parallel* to the field, there is no force exerted on the conductor.

The principle of force production on a current-carrying conductor placed in a magnetic field forms the basis of the operation of the electric motor. That is why it is known as the *motor principle*.

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6.11 RELATIVE DIRECTIONS OF CURRENT, FLUX AND FORCE

The mechanical force F produced in a magnetic field is always perpendicular to the plane containing the conductor and the magnetic field. This can be seen from Fig. 6.13 and Fig. 6.14. The relative directions of current, flux and force can be conveniently determined by Fleming's left-hand rule.

6.11.1 Fleming's Left-hand (or Motor) Rule

The thumb, first finger and second finger of the left hand are held mutually at right angles as indicated in Fig. 6.17. If the *F*irst finger points in the direction of the magnetic *F*lux, the seCond finger points in the direction of *C*urrent, then the thu*M*b indicates the direction of the *M*echanical force acting on the conductor ; that is, it gives the direction of the *M*otion of the conductor as a result of the force. This rule enables us to determine the third if the directions of the other two are given.

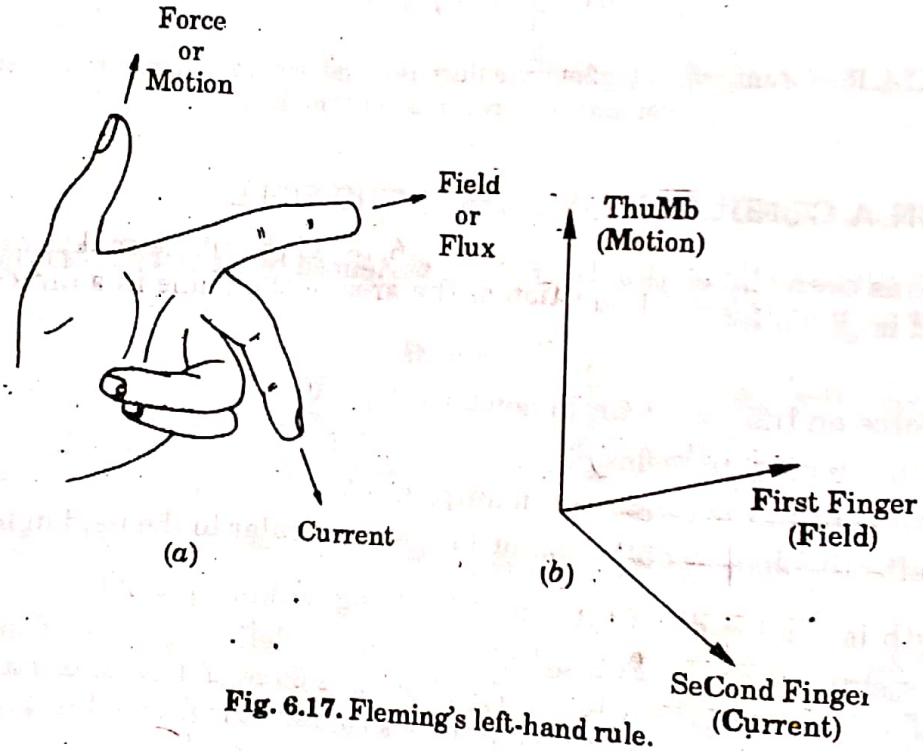

Fig. 6.17. Fleming's left-hand rule.

It is to be noted that if either the direction of the current or the direction of the field is reversed, then the direction of the force is also reversed. If the directions of *both* the current and field are reversed, the direction of the force remains unchanged.

EXAMPLE 6.1

A conductor 1.5 m long carries a current of 50 A at right angles to a magnetic field of density 1.2 T. Calculate the force on the conductor.

SOLUTION

$$B = 1.2\ \text{T},\ I = 50\ \text{A},\ l = 1.5\ \text{m}$$
$$F = BIl = 1.2 \times 50 \times 1.5 = 90\ \text{N}$$

EXAMPLE 6.2

In a loudspeaker, the moving coil consists of 200 turns of fine wire wound on a circular former so that the coil has an effective diameter of 30 mm. The coil is situated in a radial field of the speaker magnet so that the whole of its length is perpendicular to the field which has a flux density of 1.5 T. Calculate the force on the coil when it is carrying a current of 125 mA.

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SOLUTION

The coil may be considered as one conductor of length = number of turns × circumference of the former *i.e.*,

$$l = 200 \times \pi \times 30 \times 10^{-3}\ \text{m} = 6\pi\ \text{m}$$

$$I = 125\ \text{mA} = 125 \times 10^{-3}\ \text{A},\ B = 1.5\ \text{T}$$

$$F = BIl = 1.5 \times 125 \times 10^{-3} \times 6\pi = 3.53\ \text{N}$$

6.12 MAGNETIC FLUX

For a uniform magnetic field of density B teslas, the flux ϕ passing normally (*i.e.*, at right angles) through a plane of surface area a m^2 is measured in webers (Wb). It was given by

$$\phi = Ba \text{ webers (Wb)} \tag{6.12.1}$$

$$B = \frac{\phi}{a} \text{ teslas} \tag{6.12.2}$$

where 1 tesla = 1 weber/m^2

$$1\ \text{T} = 1\ \text{Wb/m}^2 \tag{6.12.3}$$

A plane cutting the flux normally is shown in Fig. 6.18. If the plane makes as angle θ with the direction of the flux (Fig. 6.19), the projection of the area of the plane in a direction normal to the flux is ($a \sin \theta$).

$$\therefore \qquad \phi = Ba \sin \theta \tag{6.12.4}$$

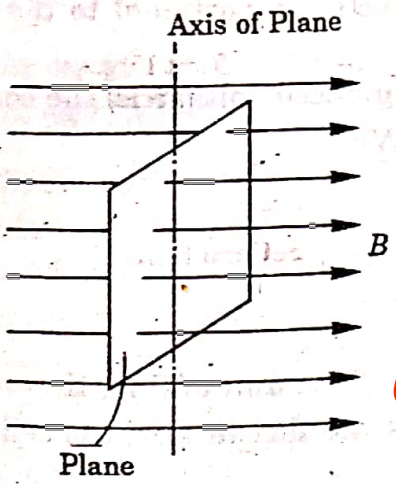

Fig. 6.18. Plane normal to the flux.

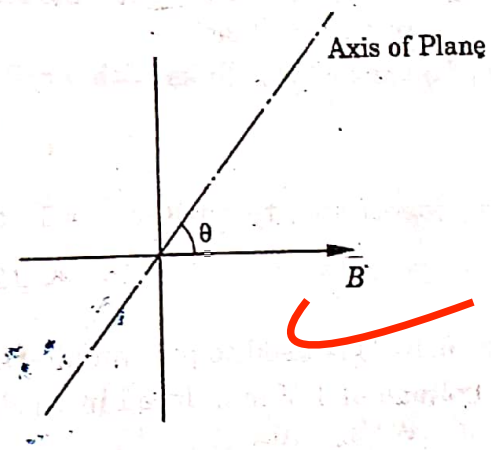

Fig. 6.19. Plane at an angle θ with the flux.

Equation (6.12.4) shows that when the plane is parallel to the direction of flux (*i.e.*, $\theta = 0$), no flux will cut the plane.

6.13 ELECTROMAGNETIC INDUCTION

A magnetic field is set up around a conductor carrying current. As the current increases the magnetic field becomes stronger. If the conductor is made into a coil, as shown in Fig. 6.20 (*a*), the magnetic flux at each section of the conductor is added together. Thus, the resultant field becomes stronger as shown in Fig. 6.20 (*b*). If the number of turns in the coil increases, the number of fields of individual sections also increases. This results in a stronger field. Thus, the strength of the field depends upon the flux and the number of turns of the coil. The product (ϕ N) is called the *flux linkage*, where ϕ is the flux linking N turns of the coil.

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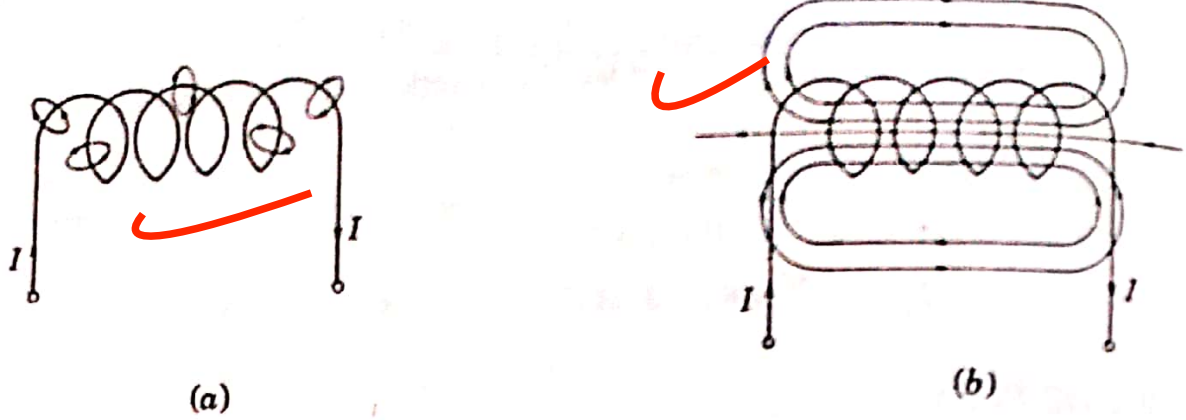

Fig. 6.20. Magnetic field of a coil.

Whenever the magnetic flux linking a coil *changes*, a voltage is induced in the coil. The greater the rate of change of flux linkage, the greater is the induced voltage in the coil. The production of induced voltage in a circuit by the change of magnetic flux linkage is called the *electromagnetic induction*.

6.14 FARADAY'S LAWS OF ELECTROMAGNETIC INDUCTION

There are two principal laws of electromagnetic induction, known as Faraday's laws. These two laws may be stated as follows :

(1) Whenever there is a *change* in the magnetic flux linkage in a circuit a voltage is induced in it.

(2) The *magnitude* of the induced voltage is directly proportional to the rate of change of flux linkage.

If a flux of ϕ weber (Wb) links with a coil of N turns, the induced voltage in the coil is given by

$$e \propto \frac{d(\phi N)}{dt} = k\frac{d(\phi N)}{dt}$$

In SI the proportionality constant $k = 1$ and

$$e = \frac{d(\phi N)}{dt} \tag{6.14.1}$$

Equation (6.14.1) is used to give an alternative definition of the unit of flux, the weber.

A voltage of 1 V is induced in a coil of 1 turn when the flux linking the coil is changing at the rate of 1 Wb/s.

6.15 LENZ'S LAW

Faraday's law gives the *magnitude* of an induced voltage. The polarity of the induced voltage is determined by Lenz's law. It states that *the polarity of the induced voltage is such as to oppose the change which produces it*. The direction of an induced emf is always such that it tends to cause a current flow which opposes the change inducing the emf. Lenz's law is actually the application of the principle that if there is any action to change the state of a system, the system reacts in such a way to oppose this action.

Consider two coils 1 and 2 placed close to each other as shown in Fig. 6.21. The current i in coil 1 produces a flux ϕ which also links the turns of coil 2. If the current i increases, the flux also increases. The increase in flux linkage in coil 2 induces a voltage in it. Suppose that the circuit of coil 2 is closed through a resistor R. There will be a current in coil 2 due to the induced voltage.

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By Lenz's law this current will produce a flux which will oppose the *increase* of initial flux. This requires that terminal P should be of positive polarity.

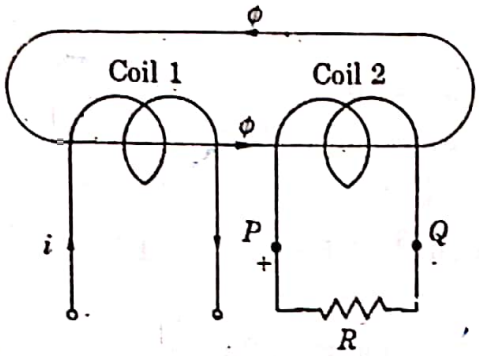

Fig. 6.21. Illustrating Lenz's law.

Faraday's law and Lenz's law may be combined into a single equation for the induced voltage

$$e = -\frac{d(\phi N)}{dt} \qquad (6.15.1)$$

The minus sign indicates that the induced voltage opposes the applied voltage which is responsible for the increase in flux.

It should be noted that the voltage is induced only when the magnetic flux linking the coil is *changing*. The change of flux linkage may take place by the following methods :

1. *Changing the current in the coil*

The voltage induced in a coil by changing the current in it is called *self-induced voltage*.

2. *Changing the current in another coil placed close to it*

The voltage induced in a coil by the change of current in another coil placed close to it is called the *mutually-induced voltage*. The operation of a transformer is based upon this principle.

The voltages induced by the first and second methods are called *statically-induced voltages*. Self- and mutually-induced voltages are discussed in Chapter 8.

3. *Relative motion of the coil and a magnetic field*

Whenever there is a relative motion of a coil and a magnetic field, a voltage is induced in the coil. Such a voltage is called the *dynamically induced voltage* or the *generated voltage*. The operation of generators is based upon this principle.

6.16 AVERAGE INDUCED VOLTAGE

If the flux changes from ϕ_1 to ϕ_2 in t seconds at a uniform rate, then the rate of change of flux is

$$\frac{\phi_2 - \phi_1}{t}$$

and induced voltage

$$e = -N \times \text{rate of change of flux} \qquad (6.16.1)$$

$$e = -N \times \frac{\phi_2 - \phi_1}{t}$$

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EXAMPLE 6.3

A flux of 0.5 m Wb links a coil of 400 turns. If the flux is reversed in 0.2 s determine the average value of the induced voltage in the coil.

SOLUTION

$$\phi_1 = 0.5 \text{ m Wb} = 0.5 \times 10^{-3} \text{ Wb}$$

$$\phi_2 = -0.5 \text{ m Wb} = -0.5 \times 10^{-3} \text{ Wb}$$

Change in flux in time 0.2 s is

$$\phi_2 - \phi_1 = -0.5 \times 10^{-3} - 0.5 \times 10^{-3} = -1.0 \times 10^{-3} \text{ Wb}$$

Average induced voltage

$$= N \times \text{rate of change of flux}$$

$$= -400 \times \frac{-1.0 \times 10^{-3}}{0.2} = 2 \text{ V}$$

6.17 GENERATED VOLTAGE

If there is a relative motion between a conductor and a magnetic field and there is cutting of flux, a voltage is induced in the conductor. Consider a conductor P moving in a uniform magnetic field as shown in Fig. 6.22.

Let l = active length of the conductor in the field (m)
B = flux density of the field (T)
u = linear velocity of the conductor (m/s)

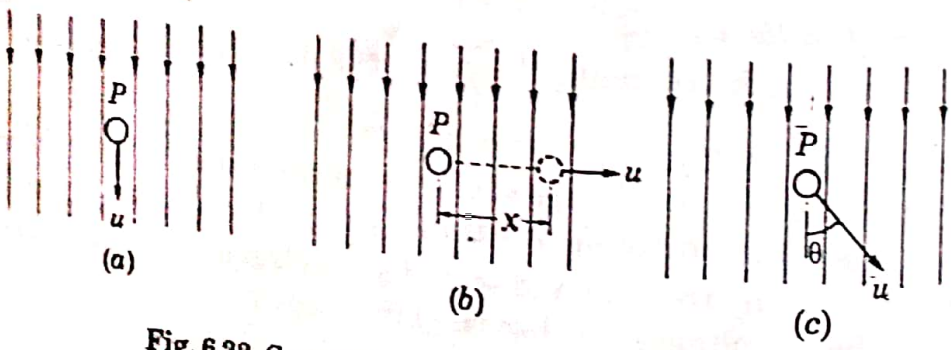

Fig. 6.22. Generation of voltage in a conductor.

Suppose that the conductor moves *parallel* to the direction of the field as shown in Fig. 6.22 (a). Since the conductor is not cutting the flux, no voltage is induced in it. Let the conductor move through a distance x metres in t seconds in a direction *perpendicular* to the direction of the field as shown in Fig. 6.22 (b). Thus, the conductor cuts the flux.

Flux cut by the conductor in time t

$$= \text{flux density} \times \text{area swept in time}$$

$$= Blx$$

Rate of change of flux

$$= Bl\frac{x}{t} = Blu$$

Since the conductor is a part of a coil of one turn, $N = 1$. Induced voltage

$$e = N \times \text{rate of change of flux}$$

$$= 1 \times Blu$$

$$e = Blu \qquad (6.17.1)$$

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Suppose that the conductor moves at an angle θ to the direction of field as shown in Fig. 6.22 (c). The component of velocity which is perpendicular to the direction of field will be responsible for inducing voltage in the conductor. The component of velocity perpendicular to the field is ($u \sin \theta$). Therefore the induced voltage when the conductor moves in a direction making an angle θ with the direction of the field is

$$e = Blu \sin \theta \tag{6.17.2}$$

If the conductor forms part of a closed circuit, there will be a current in the conductor. By Lenz's law, the current will be in such a direction as to produce a force which tends to oppose the motion of the conductor.

6.18 FLEMING'S RIGHT-HAND RULE OR GENERATOR RULE

The direction of the generated current may be determined by Fleming's right-hand rule. The thumb, first finger and second finger of the right hand are held mutually at right angles as shown in Fig. 6.23. The thuMb is pointed in the direction of Motion of the conductor relative to the field, and the First finger in the direction of the magnetic Field. The seCond finger then points in the direction of the induced Current. Fleming's right-hand rule is also known as *generator rule*. This rule gives the relative directions of field, motion and induced current. Thus, if the directions of any two are given, the direction of the third may be determined.

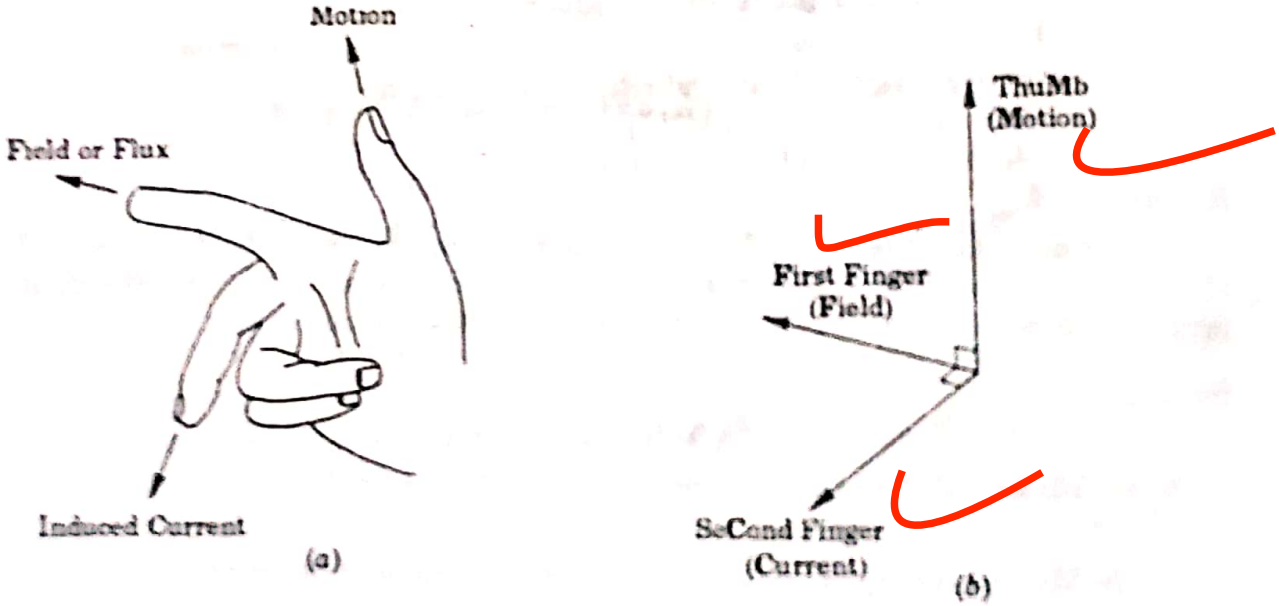

Fig. 6.23. Fleming's right-hand rule.

6.19 SIMPLIFIED RIGHT-HAND RULE

Fleming's right-hand rule is applied to generators and Fleming's left-hand rule to motors. Sometimes the following difficulties are felt by the students in the application of these rules :

(1) Which rule is applicable to generators and which rule is applicable to motors ?

(2) Holding the thumb, first finger and second finger mutually at right angles.

(3) Assigning the correct quantity to the thumb, first finger and second finger.

(4) Actual application of the rules in practical cases.

To overcome these difficulties the author suggests a single rule applicable to both the motor and generator. This rule may be called as the *simplified right-hand rule*. It is stated as follows :

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Extend the four fingers of the right hand and hold the thumb at right angles to the fingers as shown in Fig. 6.24. If the *F*ingers point in the direction of *F*lux and the thu*M*b in the direction of *M*otion, then for a *motor* the *current enters* the palm normally. For a *generator* the *current leaves* the palm normally. This rule can easily be remembered by the following points :

(*a*) the four fingers are in the direction of flux lines ;

(*b*) the generator supplies the current, that is, the current leaves the generator ;

(*c*) the motor takes the current, that is, the current enters the motor.

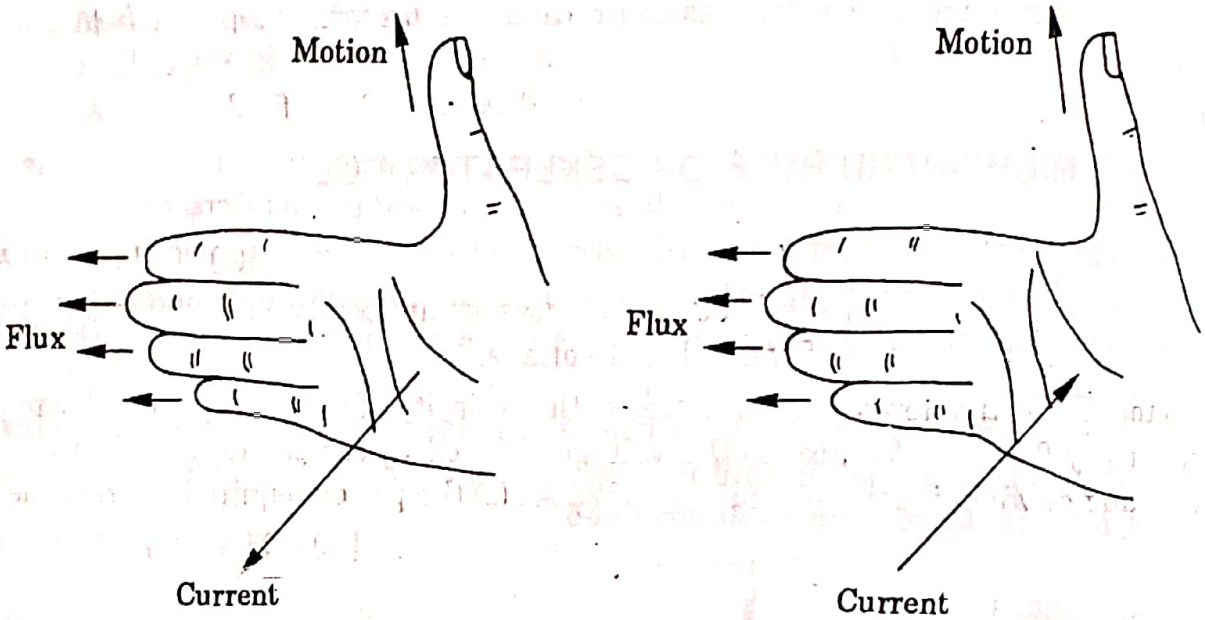

Fig. 6.24. Simplified right-hand rule.

EXAMPLE 6.4

A conductor of length 0.5 m moves in a uniform magnetic field of density 1.1 T at a velocity of 30 m/s. Calculate the induced voltage in the conductor when the direction of motion is (*a*) perpendicular to the field ; (*b*) inclined at 60° to the direction of the field.

SOLUTION

$$B = 1.1 \text{ T}, \; l = 0.5 \text{ m}, \; u = 30 \text{ m/s}$$

(*a*) Motion of the conductor perpendicular to the field

$$e = Blu = 1.1 \times 0.5 \times 30 = 16.5 \text{ V}$$

(*b*) Motion of the conductor at 60° to the direction of the field

$$e = Blu \sin \theta$$

$$= 1.1 \times 0.5 \times 30 \times \sin 60° = 1.1 \times 0.5 \times 30 \times 0.866 = 14.29 \text{ V}$$

EXAMPLE 6.5

A conductor 0.3 m long carries a current of 100 A and lies at right angles to a magnetic field of density 0.4 T. Calculate the force acting on the conductor. If the force causes the conductor to move at a velocity of 10 m/s, calculate the voltage generated in it and the power developed by it.

SOLUTION

$$l = 0.3 \text{ m}, \; I = 100 \text{ A}, \; B = 0.4 \text{ T}$$

$$F = BIl = 0.4 \times 100 \times 0.3 = 12 \text{ N}$$

$$e = Blu = 0.4 \times 0.3 \times 10 = 1.2 \text{ V}$$

Power developed = force × velocity

$$= 12 \times 10 \text{ Nm/s} = 120 \text{ W}$$

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