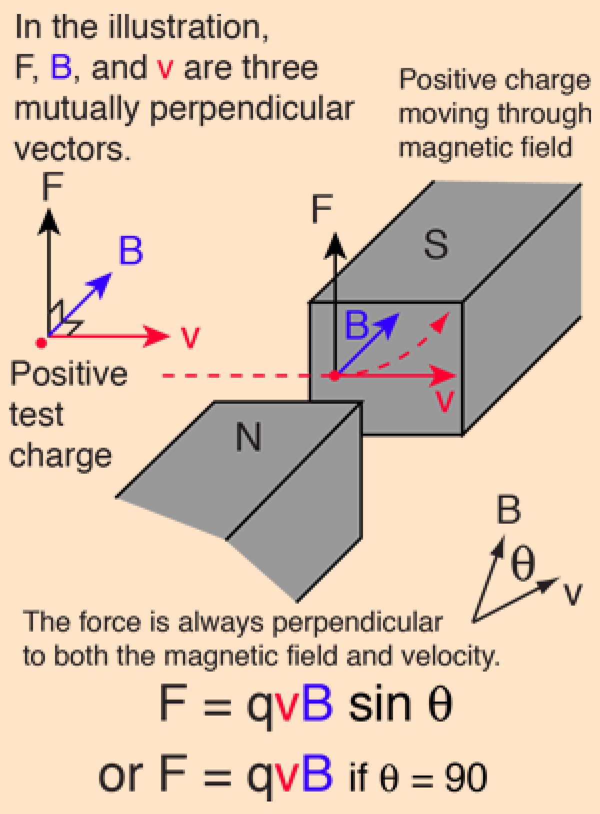
GOVERNMENT POLYTECHNIC LOHAGHAT, CHAMPAWAT
SUBJECT: PHYSICS SEMEST ER : SECOND

Magnetic Forces on Moving Charges



The magnetic force on a free moving charge is perpendicular to both the velocity of the charge and the magnetic field with direction given by the right hand rule. The force is given by the charge times the vector product of velocity and magnetic field.

Magnetic interactions with charge

Magnetic force applications

Bending a charge into a circular path

If the velocity is perpendicular to the magnetic field then the force is given by the simple product:

Force = charge x velocity x B-field

The simplest case occurs when a charged particle moves perpendicular to a uniform *B*-field (Figure 1). If the field is in a vacuum, the magnetic field is the dominant factor determining the motion. Since the magnetic force is perpendicular to the direction of travel, a charged particle follows a curved path in a magnetic field. The particle continues to follow this curved path until it forms a complete circle. Another way to look at this is that the magnetic force is always perpendicular to velocity, so that it does no work on the charged particle. The particle's kinetic energy and speed thus remain constant. The direction of motion is affected but not the speed.

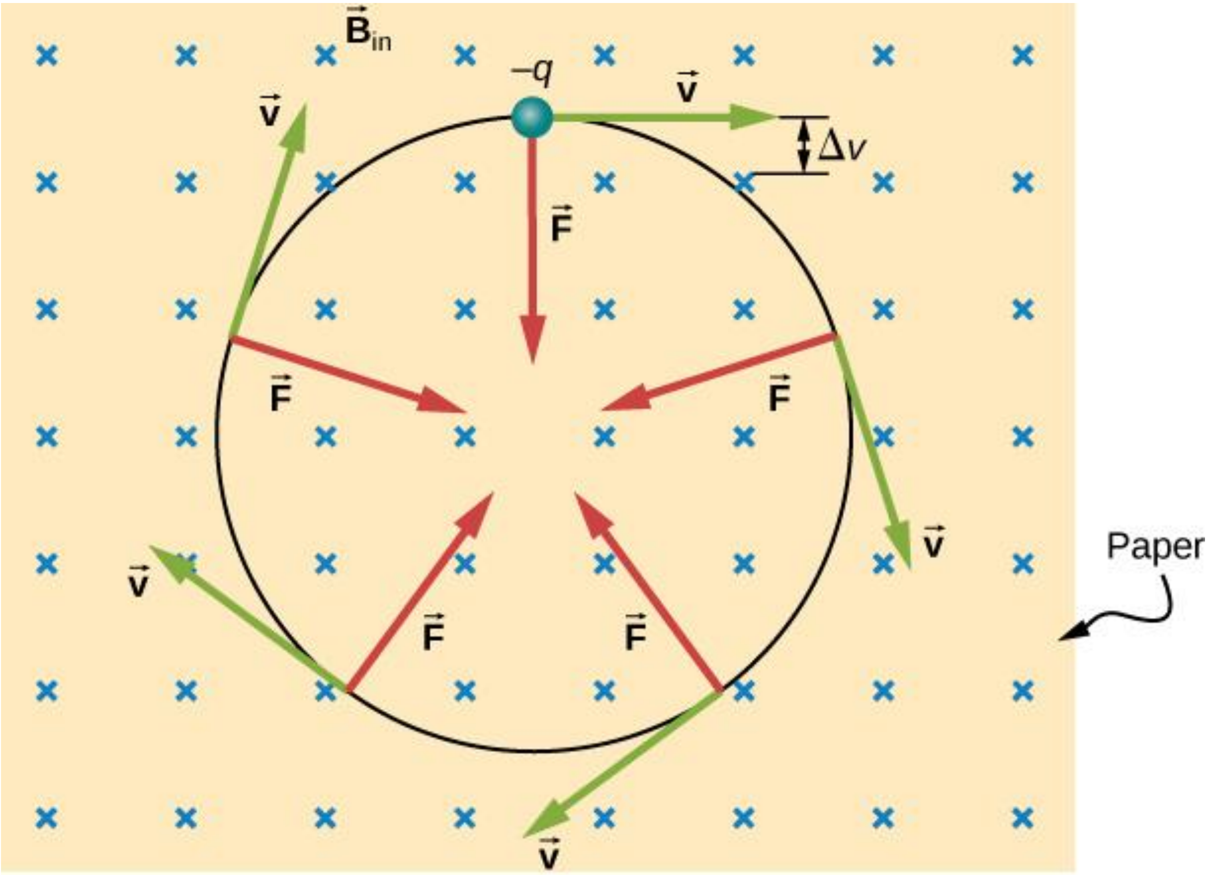
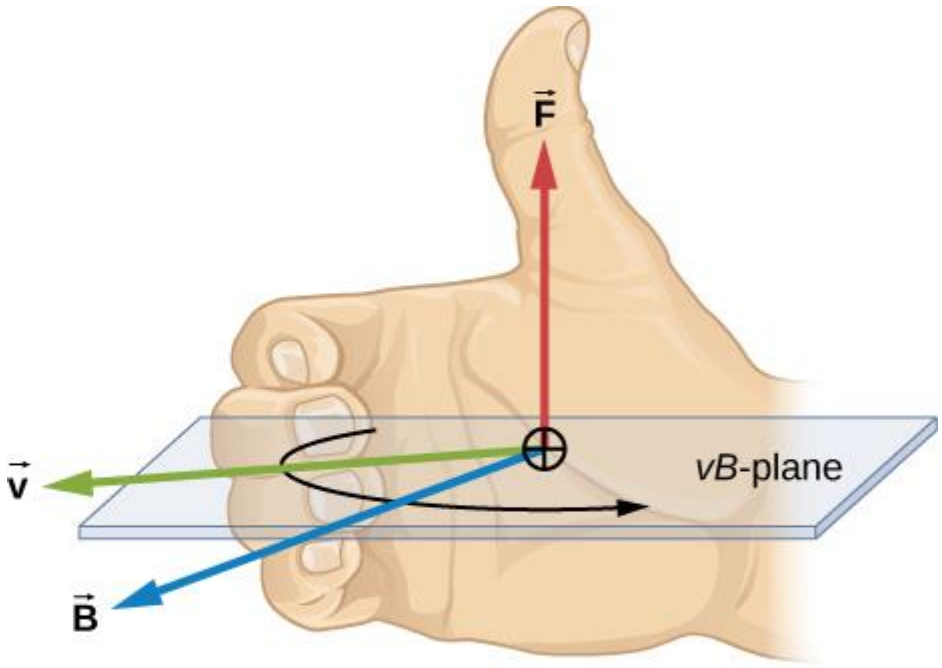


Fig. 1

The direction of the magnetic force F is perpendicular to the plane formed by v and B as determined by the right-hand thumb rule, which is illustrated in (Figure).

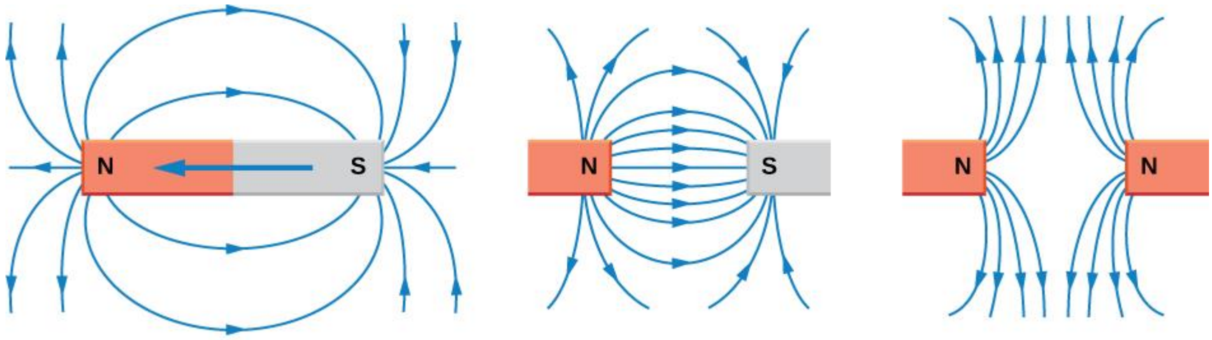
1. Orient your right hand so that your fingers curl in the plane defined by the velocity and magnetic field vectors.
2. Using your right hand, sweep from the velocity toward the magnetic field with your fingers through the smallest angle possible.
3. The magnetic force is directed where your thumb is pointing.
4. If the charge was negative, reverse the direction found by these steps.

Magnetic fields exert forces on moving charges. The direction of the magnetic force on a moving charge is perpendicular to the plane formed by v and B and follows the right-hand thumb rule as shown. The magnitude of the force is proportional to q,v,B and the sine of the angle between v and B



Magnetic field lines have following rules:

1. The direction of the magnetic field is tangent to the field line at any point in space. A small compass will point in the direction of the field line.
2. The strength of the field is proportional to the closeness of the lines. It is exactly proportional to the number of lines per unit area perpendicular to the lines (called the areal density).
3. Magnetic field lines can never cross, meaning that the field is unique at any point in space.
4. Magnetic field lines are continuous, forming closed loops without a beginning or end. They are directed from the north pole to the south pole.



Magnetic field lines of a bar magnet

(a)

Magnetic field lines between unlike poles

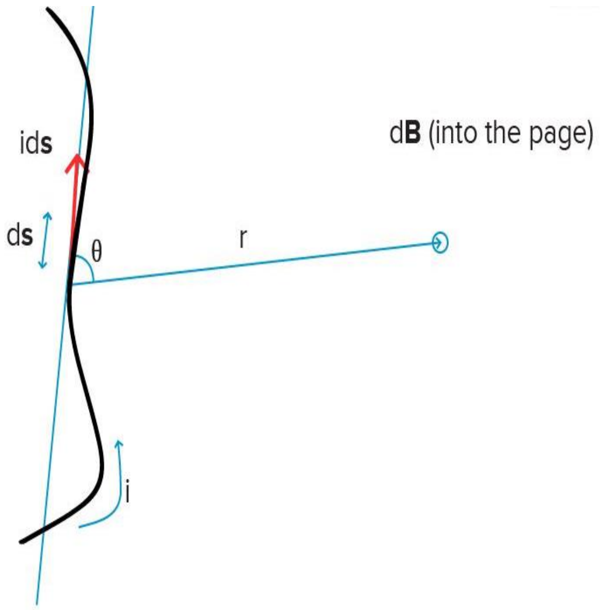
(b)

Magnetic field lines between like poles

(c)

Biot-Savart Law

Biot-Savart's law is an equation that gives the magnetic field produced due to a current carrying segment. This segment is taken as a vector quantity known as the current element.



Formula of Biot-Savart's Law

Consider a current carrying wire 'i' in a specific direction as shown in the above figure. Take a small element of the wire of length ds. The direction of this element is along that of the current so that it forms a vector i ds.

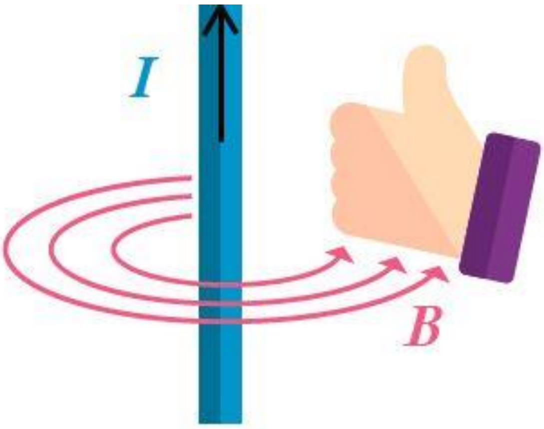
To know the magnetic field produced at a point due to this small element, one can apply Biot-Savart's Law. Let the position vector of the point in question drawn from the current element be **r** and the angle between the two be θ. Then,

$$|dB| = (\mu_0 / 4\pi)(Idl\sin\Theta / r^2)$$

Where

- μ_0 is the permeability of free space and is equal to $4\pi \times 10^{-7}$ TmA^{-1}.

The direction of the magnetic field is always in a plane perpendicular to the line of element and position vector. It is given by the right-hand thumb rule where the thumb points to the direction of conventional current and the other fingers show the magnetic field's direction.



In the figure shown above, the direction of the magnetic field is pointing into the page.

Ampere's Circuital Law

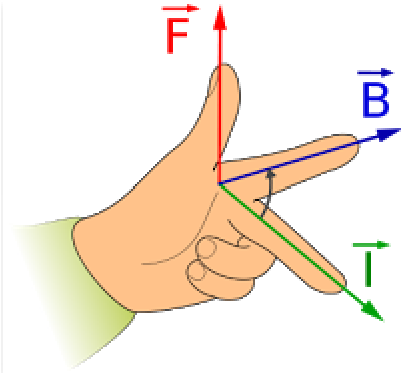
Ampere's Circuital Law **states the relationship between the current and the magnetic field created by it.**

This law states that the integral of magnetic field density (B) along an imaginary closed path is equal to the product of current enclosed by the path and permeability of the medium. $\oint \vec{B} \cdot \vec{dl} = \mu_0 I$

Force on A Current-carrying Conductor

When a conductor carrying a current is placed in a magnetic field, the conductor experiences a magnetic force.

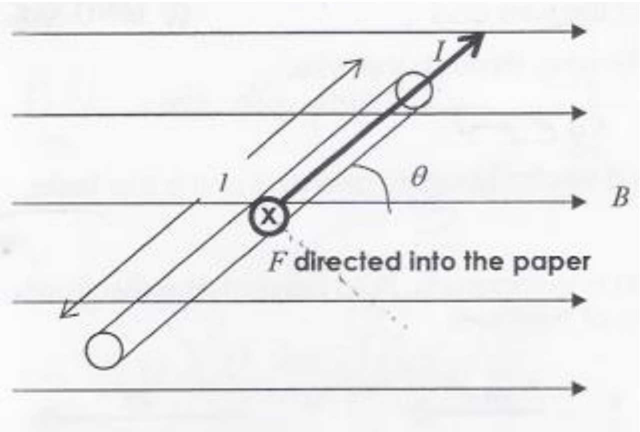
- The direction of this force is always right angles to the plane containing both the conductor and the magnetic field, and is predicted by Fleming's Left-Hand Rule.



Referring to the diagram above, F is Force, B is Magnetic field, I is current.

Factors affecting magnetic force on a current-carrying conductor in a magnetic field:

- Strength of the magnetic field
- Current flowing through the wire
- Length of the wire



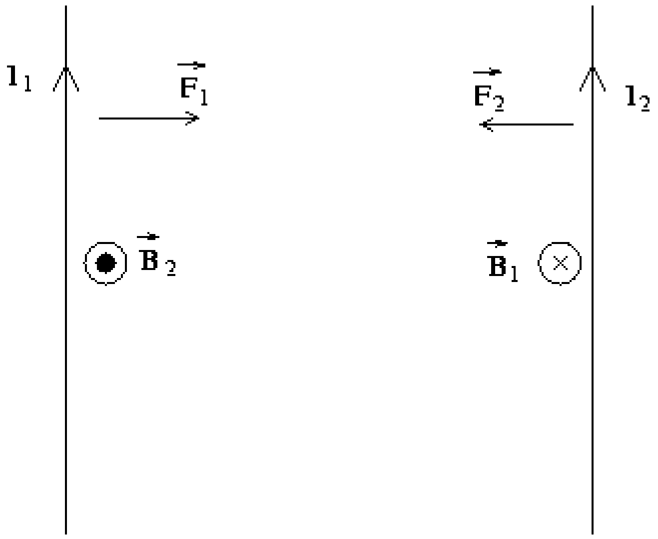
$F = BIl\sin\theta$, where

- F is force acting on a current carrying conductor,B is magnetic flux density (magnetic field strength),
- I is magnitude of current flowing through the conductor,
- ll is length of conductor,
- θθ is angle that conductor makes with the magnetic field.

When the conductor is perpendicular to the magnetic field, the force will be maximum. When it is parallel to the magnetic field, the force will be zero.

Force between two infinite parallel current carrying conductor

- We have learned about the existence of a magnetic field due to a current carrying conductor and the Biot – Savart's law.
- We have also learned that an external magnetic field exerts a force on a current-carrying conductor and the Lorentz force formula that governs this principle.
- Thus, from the two studies, we can say that any two current carrying conductors when placed near each other, will exert a magnetic force on each other.



Consider the system shown in the figure above. Here, we have two parallel Current carrying conductor, separated by a distance 'd', such that one of the conductors is carrying a current I_1 and the other is carrying I_2, as shown in the figure. From the knowledge gained before, we can say that the conductor 2 experiences the same magnetic field at every point along its length due to the conductor 1. The direction of magnetic force is indicated in the figure and is found using the right-hand thumb rule. The direction of magnetic field, as we can see, is downwards due to the first conductor.

From the Ampere's circuital law, the magnitude of the field due to the first conductor can be given by,

$B_a = \mu_0 I1/2\pi d$

The force on a segment of length L of the conductor 2 due to the conductor 1 can be given as,

$F_{21} = I_2 L B_1 = \mu_0 I_1 I_2 L / 2\pi d$

Similarly, we can calculate the force exerted by the conductor 2 on the conductor 1. We see that, the conductor 1 experiences the same force due to the conductor 2 but the direction is opposite. Thus,

$F_{12} = F_{21}$

We also observe that, the currents flowing in the same direction make the conductors attract each other and that showing in the opposite direction makes the conductors repel each other. The magnitude of force acting per unit length can be given as,

$f_{ba} = \mu_0 I_a I_b / 2\pi d$

Torque experienced by a current loop in a uniform magnetic field

Let us consider a rectangular loop PQRS of length l and breadth b (Fig 3.24). It carries a current of I along PQRS. The loop is placed in a uniform magnetic field of induction B. Let Ɵ be the angle between the normal to the plane of the loop and the direction of the magnetic field.

Torque experienced by a current loop in a uniform magnetic field

Let us consider a rectangular loop PQRS of length *l* and breadth *b* (Fig 3.24). It carries a current of I along PQRS. The loop is placed in a uniform magnetic field of induction B. Let θ be the angle between the normal to the plane of the loop and the direction of the magnetic field.

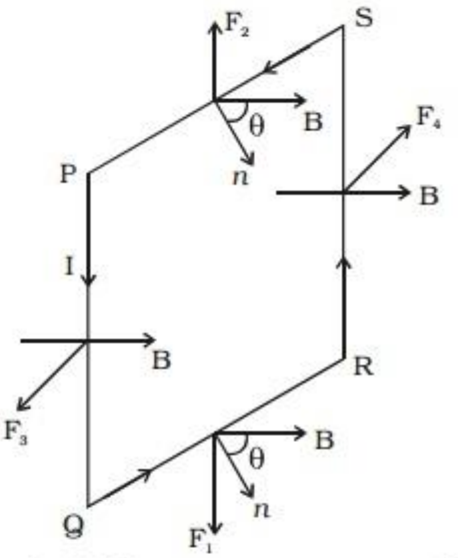


Fig 3.24 Torque on a current loop placed in a magnetic field

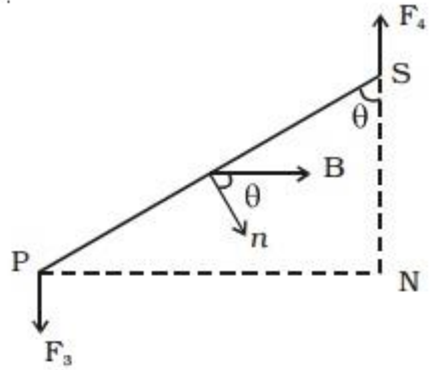


Fig 3.25 Torque

Force on the arm QR, $\vec{F}_1 = \overline{I(QR)} \times \vec{B}$

Since the angle between $\overline{I(QR)}$ and $\vec{B}$ is $(90^o - \theta)$,

Magnitude of the force $F_1 = BIb \sin (90^o - \theta)$

ie. $F_1 = BIb \cos \theta$

Force on the arm SP, $\vec{F}_2 = \overline{I(SP)} \times \vec{B}$

Since the angle between $\overline{I(SP)}$ and $\vec{B}$ is $(90^o + \theta)$,

Magnitude of the force $F_2 = BIb \cos \theta$

The forces F_1 and F_2 are equal in magnitude, opposite in direction and have the same line of action. Hence their resultant effect on the loop is zero.

Force on the arm PQ, $\vec{F}_3 = \overline{I(PQ)} \times \vec{B}$

Since the angle between $\overline{I(PQ)}$ and $\vec{B}$ is 90^o, Magnitude of the force $F_3 = BIl \sin 90^\circ = BIl$

F_3 acts perpendicular to the plane of the paper and outwards.

Force on the arm RS, $\vec{F_4} = \overline{I(RS)} \times \vec{B}$

Since the angle between $\overline{I(RS)}$ and $\vec{B}$ is 90°,

Magnitude of the force $F_4 = BIl \sin 90^\circ = BIl$

Magnitude of the force $F_4 = BIl \sin 90_o = BIl$

F_4 acts perpendicular to the plane of the paper and inwards.

The forces F_3 and F_4 are equal in magnitude, opposite in direction and have different lines of action. So, they constitute a couple.

Hence, Torque = $BIl \times PN = BIl \times PS \times \sin\theta$ (Fig 3.25)

$= BIl \times b \sin\theta = BIA \sin\theta$

If the coil contains n turns, $\tau = nBIA \sin\theta$

So, the torque is maximum when the coil is parallel to the magnetic field and zero when the coil is perpendicular to the magnetic field.

Moving coil galvanometer

Moving coil galvanometer is a device used for measuring the current in a circuit.

Principle

Moving coil galvanometer works on the principle that a current carrying coil placed in a magnetic field experiences a torque.

Construction

It consists of a rectangular coil of a large number of turns of thin insulated copper wire wound over a light metallic frame *(Fig 3.26)*. The coil is suspended between the pole pieces of a horse-shoe magnet by a fine phosphor – bronze strip from a movable torsion head. The lower end of the coil is connected to a hair spring (HS) of phosphor bronze having only a few turns. The other end of the spring is connected to a binding screw. A soft iron cylinder is placed symmetrically inside the coil. The hemispherical magnetic poles produce a radial magnetic field in which the plane of the coil is parallel to the magnetic field in all its positions *(Fig 3.27).*

A small plane mirror (m) attached to the suspension wire is used along with a lamp and scale arrangement to measure the deflection of the coil.

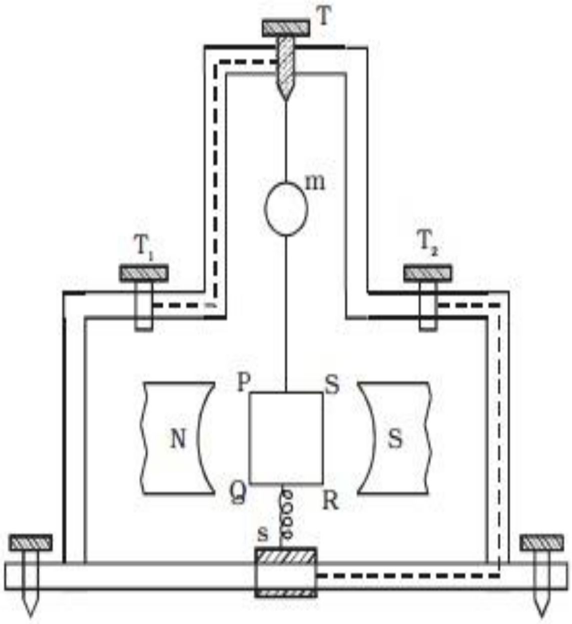


Fig 3.26 Moving coil galvanometer

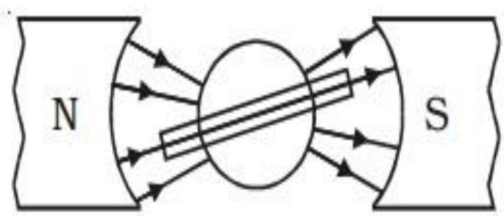
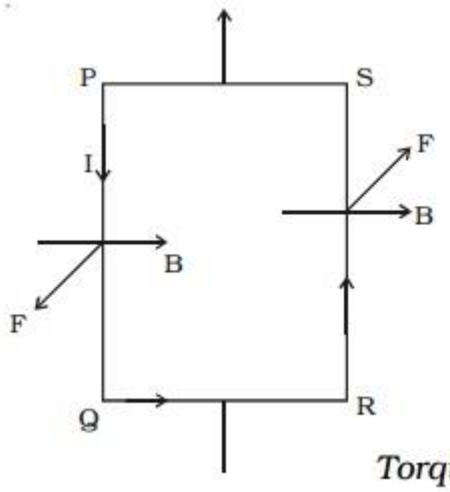


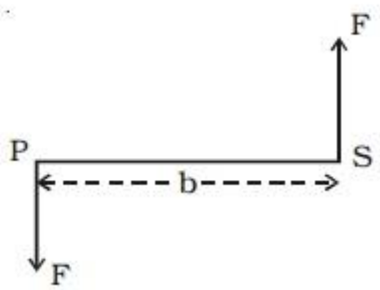
Fig 3.27 Radial magnetic field

Let PQRS be a single turn of the coil (Fig 3.28). A current I flows through the coil. In a radial magnetic field, the plane of the coil is always parallel to the magnetic field. Hence the sides QR and SP are always parallel to the field. So, they do not experience any force. The sides PQ and RS are always perpendicular to the field.

PQ = RS = l, length of the coil and PS = QR = b, breadth of the coil

Force on PQ, F = BI (PQ) = BIl. According to Fleming's left hand rule, this force is normal to the plane of the coil and acts outwards.





Torque on the coil

Fig 3.28

Fig 3.29

Force on RS, F = BI (RS) = BIl.

This force is normal to the plane of the coil and acts inwards. These two equal, oppositely directed parallel forces having different lines of action constitute a couple and deflect the coil. If there are n turns in the coil,

moment of the deflecting couple = n BIl × b (Fig 3.29)

moment of the deflecting couple = nBIA

When the coil deflects, the suspension wire is twisted. On account of elasticity, a restoring couple is set up in the wire. This couple is proportional to the twist. If θ is the angular twist, then,

moment of the restoring couple = Cθ

where C is the restoring couple per unit twist

At equilibrium, deflecting couple = restoring couple nBIA = Cθ

$$nBIA = C\theta$$

$$\therefore \quad I = \frac{C}{nBA}\theta$$

$$I = K\,\theta \text{ where } K = \frac{C}{nBA} \text{ is the galvanometer constant.}$$

i.e I α θ. Since the deflection is directly proportional to the current flowing through the coil, the scale is linear and is calibrated to give directly the value of the current.

Current sensitivity of a galvanometer

The current sensitivity of a galvanometer is defined as the deflection produced when unit current passes through the galvanometer. A galvanometer is said to be sensitive if it produces large deflection for a small current.

$$\text{In a galvanometer, } I = \frac{C}{nBA}\theta$$

$$\therefore \quad \text{Current sensitivity } \frac{\theta}{I} = \frac{nBA}{C} \qquad \ldots(1)$$

The current sensitivity of a galvanometer can be increased by

1. increasing the number of turns

2. increasing the magnetic induction

3. increasing the area of the coil

4. decreasing the couple per unit twist of the suspension wire. This explains why phosphor-bronze wire is used as the suspension wire which has small couple per unit twist.

Voltage sensitivity of a galvanometer

The voltage sensitivity of a galvanometer is defined as the deflection per unit voltage.

$$\therefore \quad \text{Voltage sensitivity } \frac{\theta}{V} = \frac{\theta}{IG} = \frac{nBA}{CG} \qquad \ldots(2)$$

where G is the galvanometer resistance.

An interesting point to note is that, increasing the current sensitivity does not necessarily, increase the voltage sensitivity. When the number of turns (n) is doubled, current sensitivity is also doubled (equation 1). But increasing the number of turns correspondingly increases the resistance (G). Hence voltage sensitivity remains unchanged.

Conversion of galvanometer into an ammeter

A galvanometer is a device used to detect the flow of current in an electrical circuit. Eventhough the deflection is directly proportional to the current, the galvanometer scale is not marked in ampere. Being a very sensitive instrument, a large current cannot be passed through the galvanometer, as it may damage the coil. However, a galvanometer is converted into an ammeter by connecting a low resistance in parallel with it. As a result, when large current flows in a circuit, only a small fraction of the current passes through the galvanometer and the remaining larger portion of the current passes through the low resistance. The low resistance connected in parallel with the galvanometer is called shunt resistance. The scale is marked in ampere.

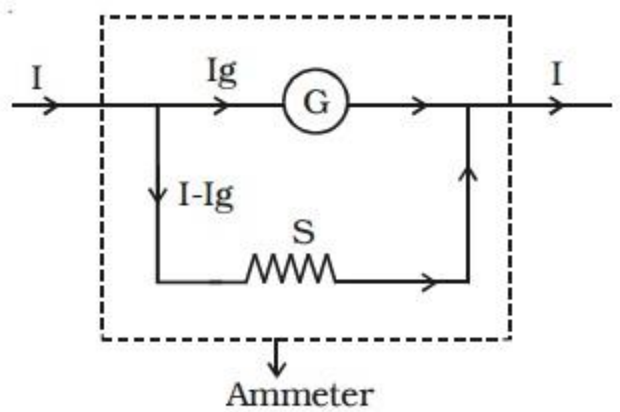


Fig 3.30 Conversion of galvanometer into an ammeter

The value of shunt resistance depends on the fraction of the total current required to be passed through the galvanometer. Let I_g be the maximum current that can be passed through the galvanometer. The current I_g will give full scale deflection in the galvanometer.

Galvanometer resistance = G

Shunt resistance = S

Current in the circuit = I

∴ Current through the shunt resistance = $I_s = (I - I_g)$

Since the galvanometer and shunt resistance are parallel, potential is common.

$$\therefore \quad I_g \cdot G = (I - I_g)S$$

$$S = G\,\frac{I_g}{I - I_g} \qquad \ldots(1)$$

The shunt resistance is very small because I_g is only a fraction of I.

The effective resistance of the ammeter R_a is (G in parallel with S)

$$\frac{1}{R_a} = \frac{1}{G} + \frac{1}{S}$$

$$\therefore \quad R_a = \frac{GS}{G + S}$$

R_a is very low and this explains why an ammeter should be connected in series. When connected in series, the ammeter does not appreciably change the resistance and current in the circuit. Hence an ideal ammeter is one which has zero resistance.

Conversion of galvanometer into a voltmeter

Voltmeter is an instrument used to measure potential difference between the two ends of a current carrying conductor.

A galvanometer can be converted into a voltmeter by connecting a high resistance in series with it. The scale is calibrated in volt. The value of the resistance

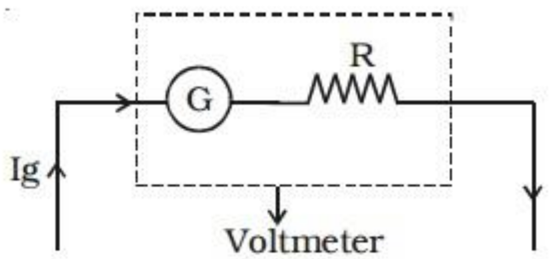


Fig 3.31 Conversion of galvanometer into voltmeter

connected in series decides the range of the voltmeter. Galvanometer resistance = G

The current required to produce full scale deflection in the galvanometer = I_g

Range of voltmeter = V

Resistance to be connected in series = R

Since R is connected in series with the galvanometer, the current through the galvanometer,

$$I_g = \frac{V}{R+G}$$

$$\therefore \quad R = \frac{V}{I_g} - G$$

From the equation the resistance to be connected in series with the galvanometer is calculated.

The effective resistance of the voltmeter is

$$R_v = G + R$$

R_v is very large, and hence a voltmeter is connected in parallel in a circuit as it draws the least current from the circuit. In other words, the resistance of the voltmeter should be very large compared to the resistance across which the voltmeter is connected to measure the potential difference. Otherwise, the voltmeter will draw a large current from the circuit and hence the current through the remaining part of the circuit decreases. In such a case the potential difference measured by the voltmeter is very much less than the actual potential difference. The error is eliminated only when the voltmeter has a high resistance. An ideal voltmeter is one which has infinite resistance.

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