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Magnetic Field & Force on Current

1. What do you understand by magnetic dipole?

An arrangement of two magnetic poles of equal and opposite strength by a finite distance is called magnetic dipole. The two poles of a magnetic dipole are called north and south poles which are at equal strength but in opposite nature. An isolated system north pole and south does not exist, two magnetic dipole always exist in pair.

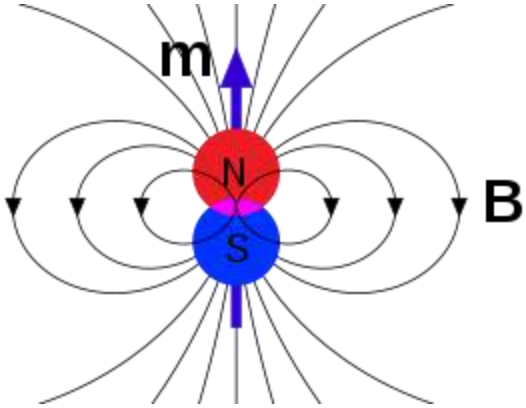


Figure 3.3 magnetic dipole

2. Define: Magnetic Field, Magnetic field strength, magnetic flux.

Magnetic Field

The space around a moving charge or a current carrying conductor through which the magnetic lines of forces exist is called magnetic field or field of magnetic induction. It is denoted by $\vec{B}$ and its unit is Tesla.

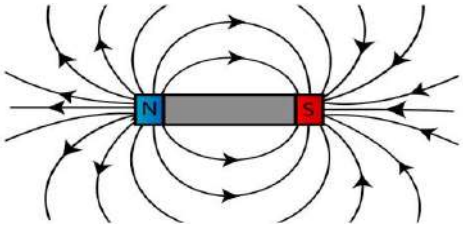


Figure 3.1 Magnetic field and magnetic field lines

Magnetic field strength

Magnetic field strength is one of two ways that the intensity of a magnetic field can be expressed. Technically, a distinction is made between magnetic field strength H, measured in amperes per meter (A/m), and magnetic flux density B, measured in Newton-meters per ampere (Nm/A), also called tesla (T).

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Magnetic flux

The total number of magnetic field lines penetrating an area is called the magnetic flux. The unit of the magnetic flux is the tesla meter squared ($T \cdot m^2$, also called the weber and symbolized Wb).

It is denoted by Φ_B .

$$\Phi_B = BA \text{ Where, B is magnetic field within area A.}$$

3. **Difference between Electric and Magnetic field.**

Difference Between Electric Field vs Magnetic Field	
Electric Field	**Magnetic Field**
It creates electric charge in surrounding	Creates electric charge around moving magnets
Measured as newton per coulomb, volt per meter	Measured as gauss or tesla
Proportional for the electric charge	Proportional to speed of electric charge
Are perpendicular to the magnetic field	Are perpendicular to the electric field

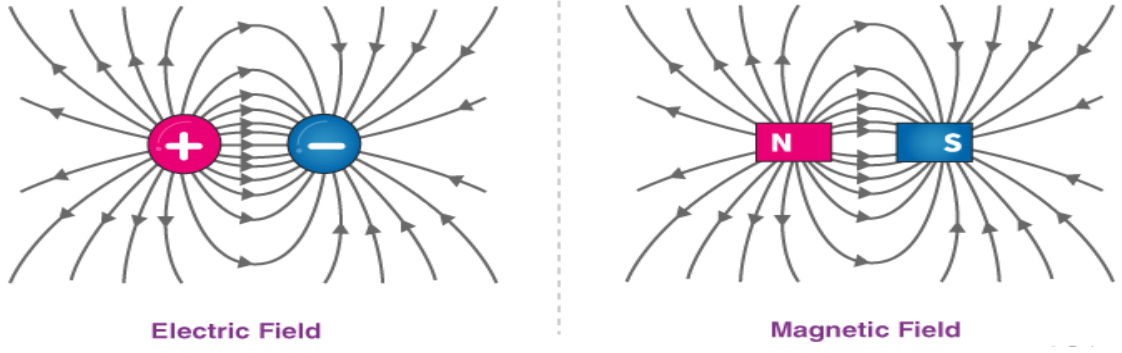


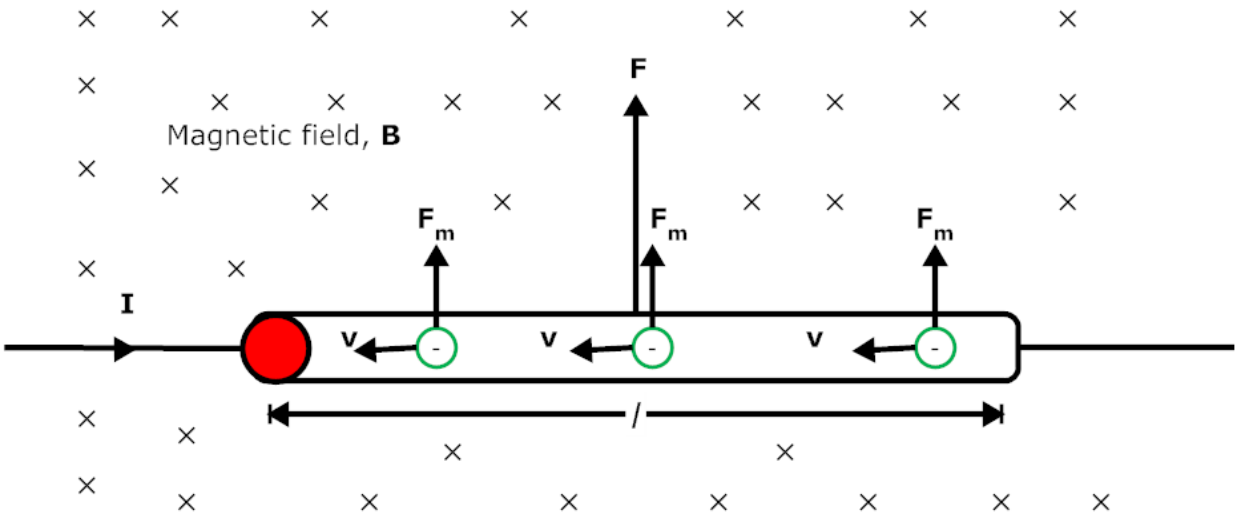
Figure: 3.2

4. **Show that magnetic force acting on a current carrying conductor of length L in $\vec{F} = I(\vec{L} \times \vec{B})$, where symbols have their usual meaning.**

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Or, Deduce the expression of force on a current carrying conductor.

Figure shows a conductor placed perpendicular to a uniform magnetic field. In the figure the × sign indicates that the direction of the uniform magnetic field $\vec{B}$ is perpendicular to the plane of the paper inwards. Current I is flowing through the conductor from left to right; so, charge carrier



electrons are moving from right to left direction.

Figure: 3.4

Let,
l = length of the conductor
A = area of cross-section of the conductor
n = number of electrons per unit volume of the conductor
q = charge of each electron
v = drift velocity of electron
B = magnitude of the magnetic field
I = current in the conductor
As the current carrying conductor is placed perpendicular to the magnetic field, force applied on each electron of the conductor is,

$F_m = qvB\ sin90°$ = qvB
Now, if the total number of electron in the conductor is N, then force applied on all electrons i.e., force applied on the conductor would be,

$$F = N\ F_m$$

But, N = n × volume of the conductor = nAl

$$\therefore F = nAlF_m$$
$$= nAlqvB$$

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But, we know, $I = naqv$

$$\therefore \mathrm{F} = BIl$$

Instead of being perpendicular if the current carrying conductor makes an angle θ with the magnetic field, then force applied on a single electron would be

$$F_m = qvB\ sin\ \theta$$

And force applied on whole conductor would be,

$$F = BIlsin\ \theta$$

If there is a coil of N turns, then force on it would be,

$$F = NBIlsin\ \theta$$

In vector form,

$$\vec{F} = N\ I\vec{l} \times \vec{B}$$

5.Find out the expression of torque and potential energy of a current loop placed in a magnetic field.

Direction of Force

The direction of the force $\vec{F}$ applied on a current carrying conductor is always perpendicular to direction of electric current and magnetic field $\vec{B}$. Its direction is found from the right hand screw rule regarding the direction of vector product. If a right handed screw is placed perpendicularly on the plane of electric current i.e., conductor and magnetic field $\vec{B}$ and rotating it from the direction of electric current to $\vec{B}$ in smaller angle, then the direction of advancement of the screw would indicate the direction of force $\vec{F}$.

Special case: If the electric current, that is the conductor is at right angles to the magnetic field, then the direction of force can be found from Fleming's left hand rule.

6.What is Lorentz force?

Lorentz Force

When a charged particle moves through a region where both an electric and a magnetic field are present, then the resultant force is given by

$$\vec{F} = q_0\vec{E} + q_0\vec{v} \times \vec{B}$$

$$= q_0(\vec{E} + \vec{v} \times \vec{B})$$

The resultant force is called Lorentz force. Where, $\vec{\mathrm{E}}$ electric field ; $\vec{\mathrm{B}}$ is magnetic field in free space and q_0 is test charge.

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7. State and explain Fleming's left hand rule and Fleming's right-hand rule.

Fleming's left hand rule:

If the first finger, middle finger and thumb of left hand are stretched mutually perpendicular to each other and the first finger points in the direction of magnetic field, the middle finger points in the direction of current; then the thumb points in the direction of force on the current carrying conductor or the direction of the motion of the current carrying conductor.

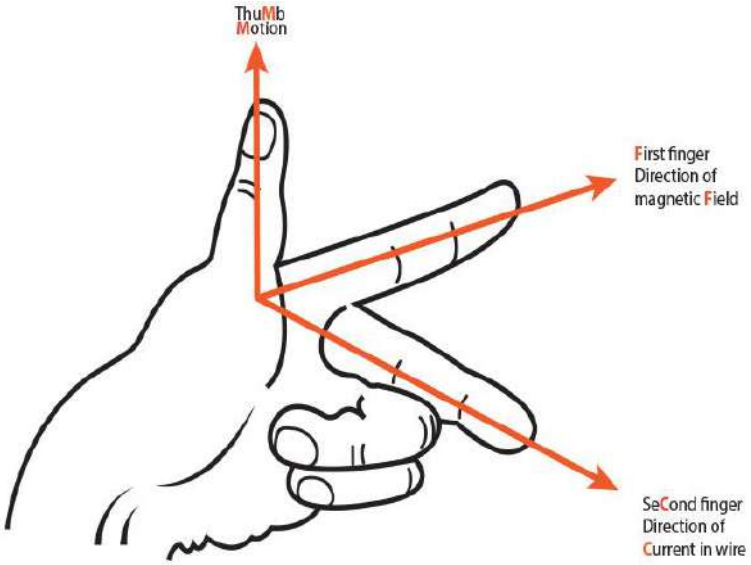


Figure: 3.5

- The Thu**m**b represents the direction of **M**otion resulting from the force on the conductor
- The **F**irst finger represents the direction of the magnetic **F**ield
- The Se**c**ond finger represents the direction of the **C**urrent

Fleming's right-hand rule

When a conductor such as a wire attached to a circuit moves through a magnetic field, an electric current is induced in the wire due to Faraday's law of induction. The current in the wire can have two possible directions. Fleming's right-hand rule gives which direction the current flows.

The right hand is held with the thumb, index finger and middle finger mutually perpendicular to each other (at right angles), as shown in the diagram.

- The thu**m**b is pointed in the direction of the **m**otion of the conductor relative to the magnetic field.
- The **f**irst finger is pointed in the direction of the magnetic **f**ield. (north to south)

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- Then the second finger represents the direction of the induced or generated current within the conductor.

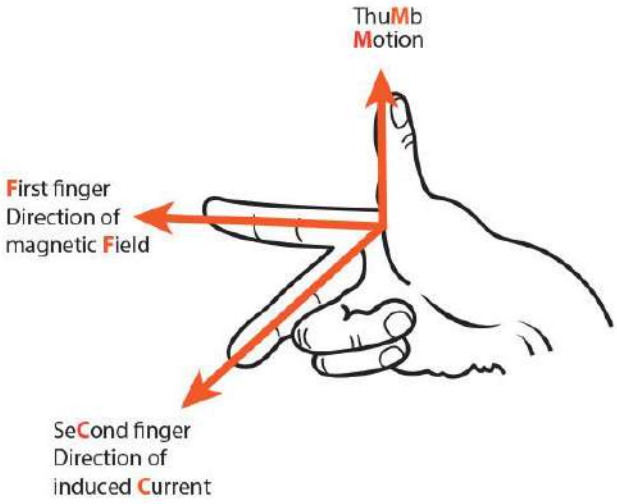
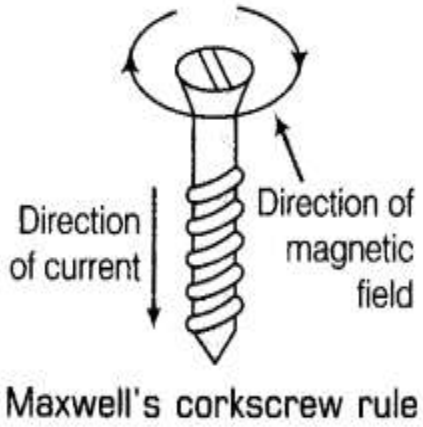


Figure: 3.6

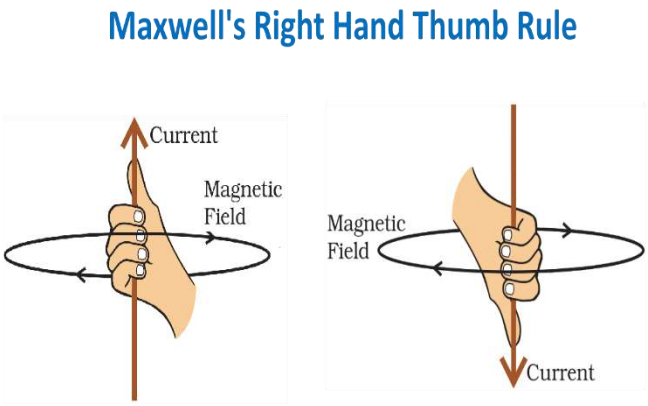
Q. Explain Maxwell's Right hand Thumb Rule.

Maxwell's Right hand Thumb Rule

This rule is also called Maxwell's corkscrew rule. If we consider ourselves driving a corkscrew in the direction of the current, then the direction of the corkscrew is the direction of the magnetic field.



Maxwell's corkscrew rule



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Figure: 3.7

Numerical Example 3.1 A wire is placed at an angle 60° with a magnetic field of 10^{-2} T, an electric current of 2A is passed through the wire. If the length of the wire is 50 cm then how much force will be felt by the wire?

Solution : We know,

$F = I l B \sin\theta$

$= 2A \times 0.5\ m \times 10^{-2}\ T \times \sin 60°$

$= 8.66 \times 10^{-3}\ N$

Ans. 8.66×10^{-3} N

Here,

Magnetic field, $B = 10^{-2}$ T

The angle between the magnetic field and the conductor, $\theta = 60°$

Electric current, $I = 2$ A

Length of the wire, $l = 50$ cm $= 0.5$ m

Force, $F = ?$

8. Difference between Fleming's Left-Hand and Right-Hand Rule.

Difference between Fleming's Left-Hand and Right-Hand Rule

Left-Hand Rule	Right-Hand Rule
It was invented by John Ambrose Fleming	It was invented by John Ambrose Fleming

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It is used for electric motors	It is used for electric generators
The purpose of the rule is to find the direction of motion in an electric motor	The purpose of the rule is to find the direction of induced current when a conductor moves in a magnetic field.
The thumb represents the direction of the thrust on the conductor	The thumb represents the direction of motion of the conductor.
The index finger represents the direction of the Magnetic Field	The index finger represents the direction of the Magnetic Field
The middle finger represents the direction of the current	The middle finger represents the direction of the induced current

9. State and explain Hall Effect and Hal voltage.

Hall Effect

When a current carrying conductor is placed in a magnetic field, then a potential difference i.e. , a voltage is developed perpendicular to both current and magnetic field. This phenomenon is known is Hall Effect.

Explanation

The Hall effect is the movement of charge carriers through a conductor towards a magnetic attraction. The phenomenon is named for Edwin Hall, who discovered the effect in 1879.

The Hall effect causes a measurable voltage differential across the conductor such that one side is positively charged and the other negatively. The effect is manipulated and measured in the functioning of many electronic devices including joystick-like controls, compasses in smartphones, magnetometers, sensors and current-measuring devices. On a large scale, the effect is harnessed in Hall effect thrusters (HET) that launch some crafts into space. In the natural world, the Hall effect plays a role in gravitational collapses that result in the formation of protostars.

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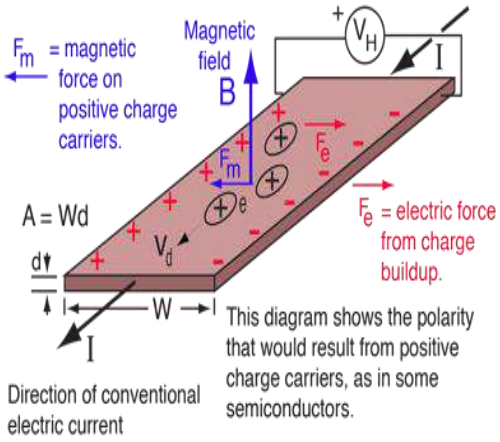


Figure: 3.8

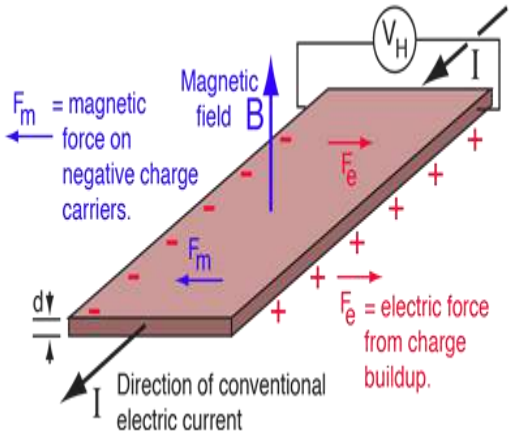


Figure: 3.9

Electrons normally travel in a straight line. The Hall effect occurs with the production of a transverse force (Lorentz force) on the charge carriers moving through a conductor, such that they actively conduct a current in the presence of a perpendicular magnetic field. The magnet's north pole pulls the negative charge carriers (typically electrons) to the side of the conductor nearest the magnet. With all the flowing electrons of the carried current on one side of the conductor, that side is negatively charged and the other side is positively charged.

In a semiconductor, the effect is even greater as they have moving positive charge carriers, which are known as Halls. Halls are atoms that are positively charged, having lost one of their electrons. The positive charge carriers flow on the side of the semiconductor nearest the magnetic south pole, influencing the negative charge carriers on the side nearest the north pole. Both carriers are repelled by their opposing magnetic force.

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Definition of Hall Voltage : When a current carrying conductor is placed in a magnetic field, then the potential difference *i.e.*, a voltage which is developed perpendicular to both current and magnetic field is called Hall potential difference or, Hall voltage.

Expression for Hall Voltage :

In fig. 3.10, a flat plate shaped conductor is shown. Current is flowing through it along positive *X*-axis. A uniform magnetic field is applied right angles to it *i.e.*, along positive *Y*-axis.

Let,

A = area of cross-section of the conductor

d = width of the conductor *i.e.*, distance between its upper and lower end

t = thickness of the conductor

B = magnetic field

q = charge of each charge carrier

v = drift velocity of charge carrier

n = number of charge carrier per unit volume of the conductor

I = electric current

V_H = Hall voltage

E = intensity of Hall electric field

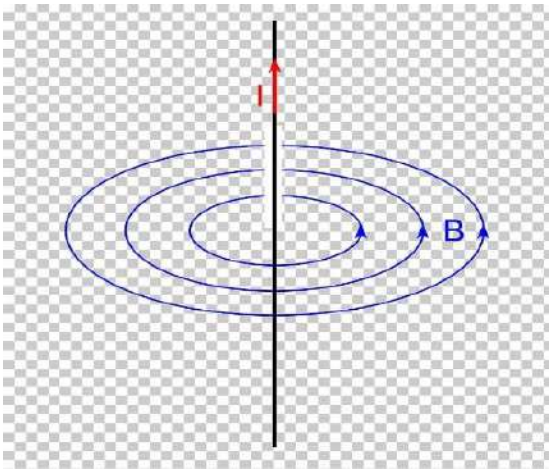


Figure 3.10

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Now, magnetic force applied on charge carrier

$F_m = qvB$ (since v and B are at right angles $\therefore \theta = 90°$)

Again, electric force on the charge carrier due to potential difference of two ends of the conductor *i.e.*, due to electric field ;

$$F_e = qE = q\frac{V_H}{d} \quad [\because V_H = Ed]$$

In equilibrium condition,

$$F_m = F_e$$

$$\text{or, } qvB = q\frac{V_H}{d}$$

$$\text{or, } V_H = Bvd \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

Thus, it is seen that, if the width d and magnetic field is known, then by measuring Hall voltage V_H, we can determine the drift velocity of the charge carrier.

Again, we know

$$I = nAvq$$

$$\text{or, } v = \frac{I}{nAq}$$

Now, from fig 4.12, $A = dt$

$$\therefore v = \frac{I}{ndtq}$$

Putting the value of v in equation (4.17), we get

$$V_H = \frac{BI}{ntq} \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

Now if B, I, t, q remain constant, then

$$V_H \propto \frac{1}{n}$$

That is Hall voltage is inversely proportional to the number of charge carrier per unit volume.

Problems. A copper strip 2.0 cm wide and 1.0 mm thick is placed in a magnetic field with B= 1.5 T. If a current of 200 A is set up in the strip, what Hall potential difference appears across the strip? [For Cu, $n = 8.4 \times 10^{28}/m^3$]

Solution:

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We know,

$$V_H = \frac{BI}{ntq}$$

$$= \frac{1.5 \times 200}{8.4 \times 10^{28} \times 1 \times 10^{-3} \times 1.6 \times 10^{-19}}$$

$$= 2.2 \times 10^{-5}\ V$$

$$= 22 \times 10^{-6}\ V$$

$$= 22\ \mu V$$

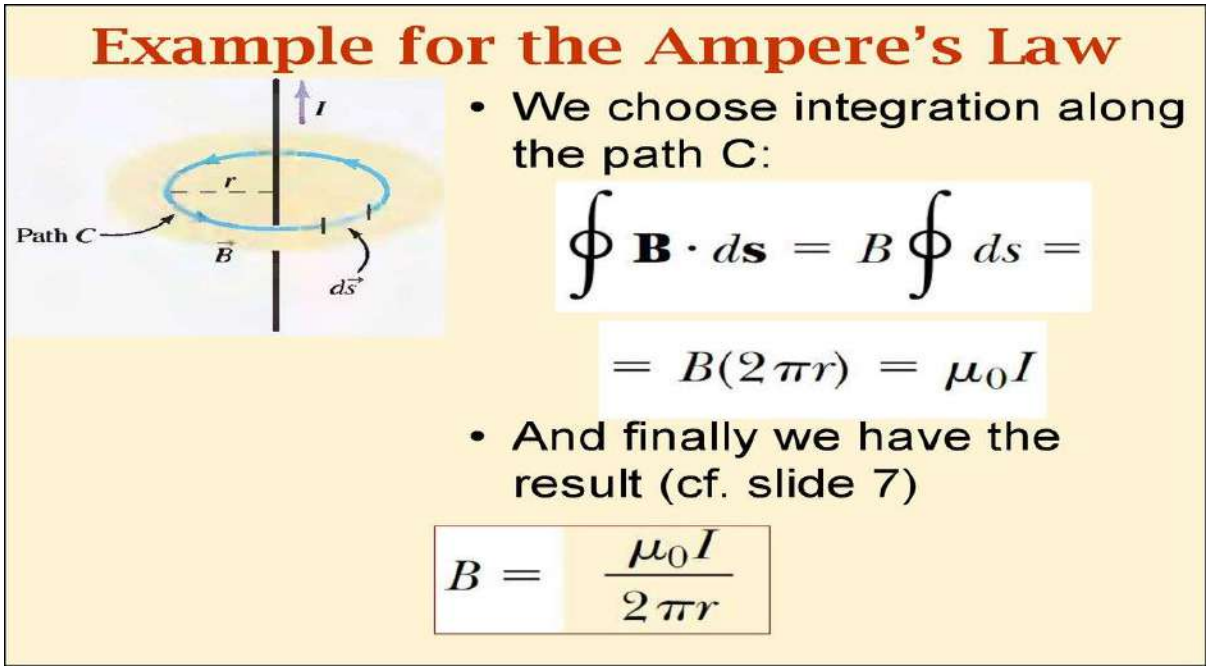
10. State and explain Amperes law.

Ampere's Law

The law states that the line integral of $\vec{B}$ around a closed path is equal to μ_0 times the current enclosed by the path. That is $\oint \vec{B}.d\vec{l} = \mu_0 i$

If the path does not enclose the current then

$$\oint \vec{B}.d\vec{l} = 0$$



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Application

3. Various applications of Ampere's law. Find the magnetic field $\vec{B}$ everywhere in space for the following steady current distributions:

a. Very long wire carrying a current "I",
b. Very long wire of radius "a", carrying a current "I_0",
c. Toroid with "N" turns,
d. Coaxial cable with current I in the "go" wire and with current I in the opposite direction in the "return" wire.
e. Very long solenoid with "n" turns per unit length and carrying current I.

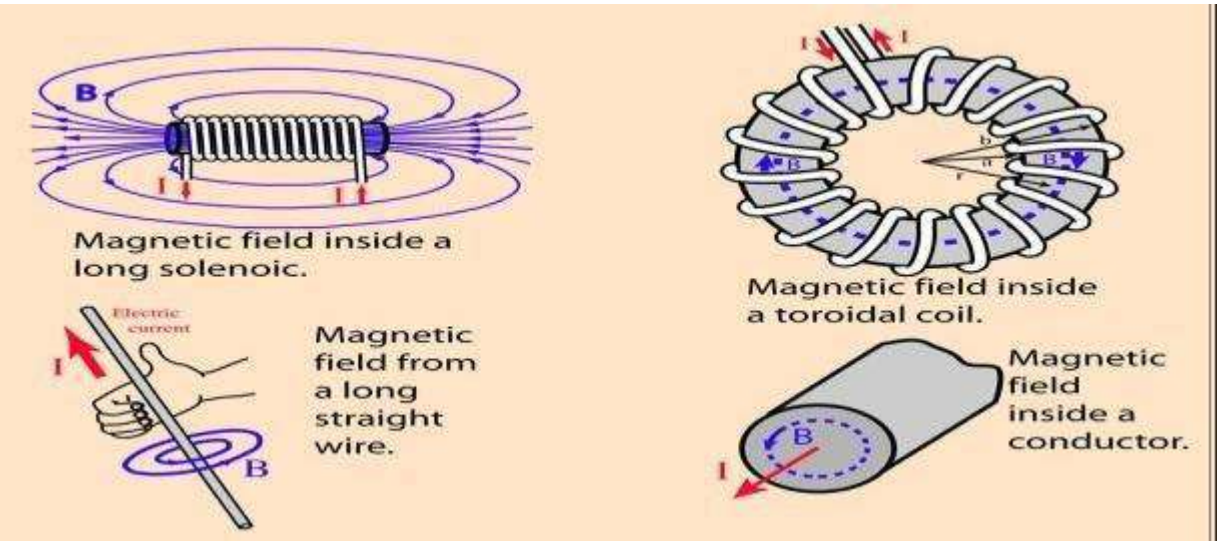


Figure: 3.11 Application of Ampere's Law

Problems. If the wire is carrying a current of 0.1 amps, what is the magnitude and direction of the magnetic field at a distance of 0.01 meters above the wire?

Solution:

We know,

$$B = \frac{\mu_0 i}{2\pi r}$$

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$$= \frac{4\pi \times 10^{-7} \times 0.1}{2\pi \times 0.01} = 2 \times 10^{-6}\, T = 2\mu T$$

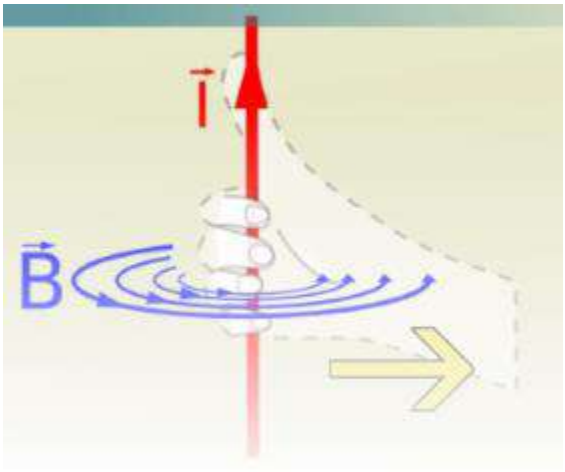


Figure 3.10 direction of $\vec{B}$

Q.11. Calculate the magnetic field ′B′ for a solenoid or a pack coil or a packed current loop.

Answer:

The magnetic field ′B′ for a solenoid:

To understand the solenoid field, we will first start with a straight wire, then a single coil, then multiple coils. Magnetic field lines always form loops around the current. The direction of the field can be found by the right-hand grip rule. For a single long straight wire the field direction is given by placing the thumb of the right hand in the direction of the current, then the fingers will curve in the direction of the field as shown in Figure 1.



.**Figure: 1**

Now if you imagine bending the wire into a circle and apply the right-hand grip rule to a single coil of the solenoid, the field lines still wrap around the current in the wire. Figure 2 shows an edge on view of a single coil where the current is going into the page on the top and coming out of the page on the bottom. In this you will notice that inside the coil the field lines point predominantly to the left along what would be the solenoid axis, and outside the coil they point to the predominantly right.

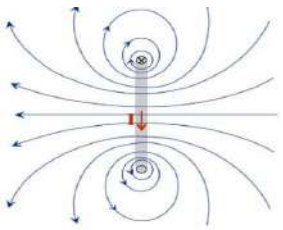


Figure: 2

When you superimpose the fields for several adjacent coils of an ideal solenoid the components of the field inside the solenoid that are not exactly to the left cancel out leaving a purely leftward

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pointing field as shown in Figure 3. On the outside a similar cancellation occurs and the field points to the right. The field is concentrated in the interior of the coil and is considerably weaker outside the coil.

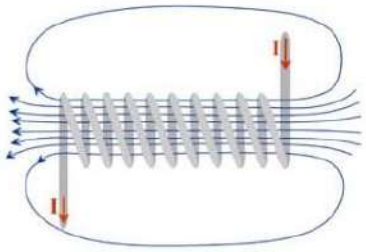


Figure: 3

The longer the coil the weaker the field outside the coil will be. An infinitely long coil will have zero field outside.

Now, we apply Ampere's Law to determine the value of the magnitude of the field. Ampere's Law states that the line integral of the magnetic field around a closed path P is proportional to the amount of current that is enclosed by the path.

$$\oint B.dl = \mu_0 i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The constant of proportionality is called the permeability of free space and has a value of

$$\mu_0 = 4\pi \times 10^{-7} \ {}^{T.m}/_{A} \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where, T is the SI unit of magnetic field strength. The fields that you will measure in this experiment are much smaller than a Tesla so we will use units of Gauss when measuring field strength. The conversion between Tesla and Gauss is given by

$$1G = 10^{-4}T \ \ldots\ldots\ldots\ldots\ldots\ldots \ (3)$$

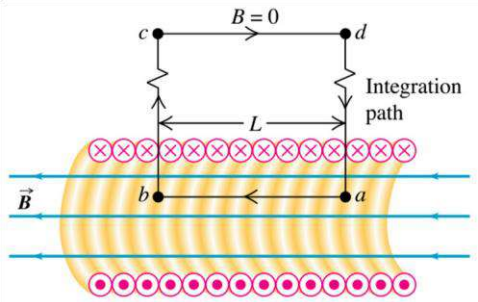


Figure: 4

To apply Ampere's Law consider an imaginary Amperian loop in the shape of a rectangle abcd as shown in Figure 4. On path ab the field is in the same direction as $d\vec{l}$ so the integrand will just have the value BL. On paths bc and da the field will be perpendicular to the path and $\vec{B} \, . \, d\vec{l}$ will

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be zero. Path cd can be chosen to be a very large distance from the solenoid where the field will be zero. When these observations are inserted into Ampere's Law we will obtain

$$\oint \vec{B} \cdot d\vec{l} = \int_a^b \vec{B} \cdot d\vec{l} + \int_b^c \vec{B} \cdot d\vec{l} + \int_c^d \vec{B} \cdot d\vec{l} + \int_d^a \vec{B} \cdot d\vec{l} = \mu_0 i \quad \ldots\ldots\ldots\ldots\ldots (4)$$

$$\oint \vec{B} \cdot d\vec{l} = BL + 0 + 0 + 0 = \mu_0 i \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The current enclosed in the loop will be the number of turns N in the length L that go thru the loop

Multiplied by the current i in each coil $i_{encl} = Ni$. So, equation (5) simplifies to

$$BL = \mu_0 Ni \ldots\ldots\ldots\ldots\ldots (6)$$

If we define the number of turns per unit length as n = N/L , then we have the result for the field magnitude inside the soldenoid

$$B = \mu_0 ni \ldots\ldots\ldots\ldots\ldots (7)$$

This equation gives the field inside an infinitely long solenoid whose coils are very closely spaced. You will have the opportunity in this experiment to see how well this equation holds for a solenoid that is not ideal. In particular you will measure the field at the end and outside on the solenoid axis.

History of Biot Savart Law

The **Biot Savart Law** is an equation describing the magnetic field generated by a constant electric current. It relates the magnetic field to the magnitude, direction, length, and proximity of the electric current. Biot–Savart law is consistent with both Ampere's circuital law and Gauss's theorem. The Biot Savart law is fundamental to magnetostatics, playing a role similar to that of Coulomb's law in electrostatics.

Biot Savart law was created by two French physicists, Jean Baptiste Biot and Felix Savart derived the mathematical expression for magnetic flux density at a point due a nearby current carrying conductor, in 1820. Viewing the deflection of a magantic compass needle, these two scientists concluded that any current element projects a magnetic field into the space around it.

Through observations and calculations they had derived a mathematical expression, which shows, the magnetic flux density of which dB, is directly proportional to the length of the element dl, the current I, the sine of the angle and θ between direction of the current and the vector joining a given point of the field and the current element and is inversely proportional to the square of the distance of the given point from the current element, r.

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Q.12. Explain Biot- Savart Law express it in vector form.

Biot- Savart Law:

Consider a wire carrying a current I in a specific direction as shown in the figure 1. Take a small element of the wire of length dl. The direction of this element is along that of the current so that it forms a vector Idl. If we want to know the magnetic field produced at a point due to this small element, then we can use the Biot-Savart's Law.

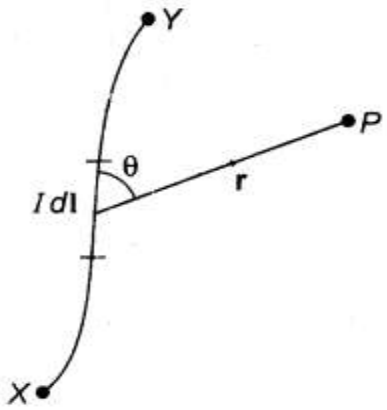


Figure: 1

The magnitude of the magnetic field dB at a distance r from a current carrying element dl is found to be proportional to I, $sin\theta$ and to the length dl. And is inversely proportional to the square of the distance |r|. The direction of the Magnetic Field is perpendicular to the line element dl as well as radius r. So,

$$dB \propto I$$

$$dB \propto \frac{1}{r^2}$$

$$Hence,\ dB \propto dl sin\theta$$

Now, combining these three, we can write,

$$dB \propto \frac{I \cdot dl \cdot sin\theta}{r^2}$$

$$dB = k\frac{I\ dl\ sin\theta}{r^2}$$

Where, k is a constant, depending upon the magnetic properties of the medium and system of the units employed and $k = \frac{\mu_0}{4\pi}$.

So,

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$$dB = \frac{\mu_0 I}{4\pi} \frac{dl\ sin\theta}{r^2}$$

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

In vector Form,

$$d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{dl\ sin\theta}{r^2}\ \hat{r}$$

$$d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{dl\ sin\theta}{r^3}$$

Where, $\hat{r} = \frac{\vec{r}}{r}$

Q. 13. Find the expression B by using Biot Savart law for a long straight wire.

B for a long straight wire:

Let us consider a long straight wire shown in figure 1. Current I is flowing through it and P is point at a distance R from the wire small element dx. The magnetic field B is given by using Biot Savart law,

$$dB = \frac{\mu_0 I}{4\pi} \frac{dx\ sin\theta}{r^2}$$

At point P, therefore, the magnetic fields due to all current elements i. e. for whole length, we get

$$B = \frac{\mu_0 I}{4\pi} \int_{-\infty}^{+\infty} \frac{dx\ sin\theta}{r^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

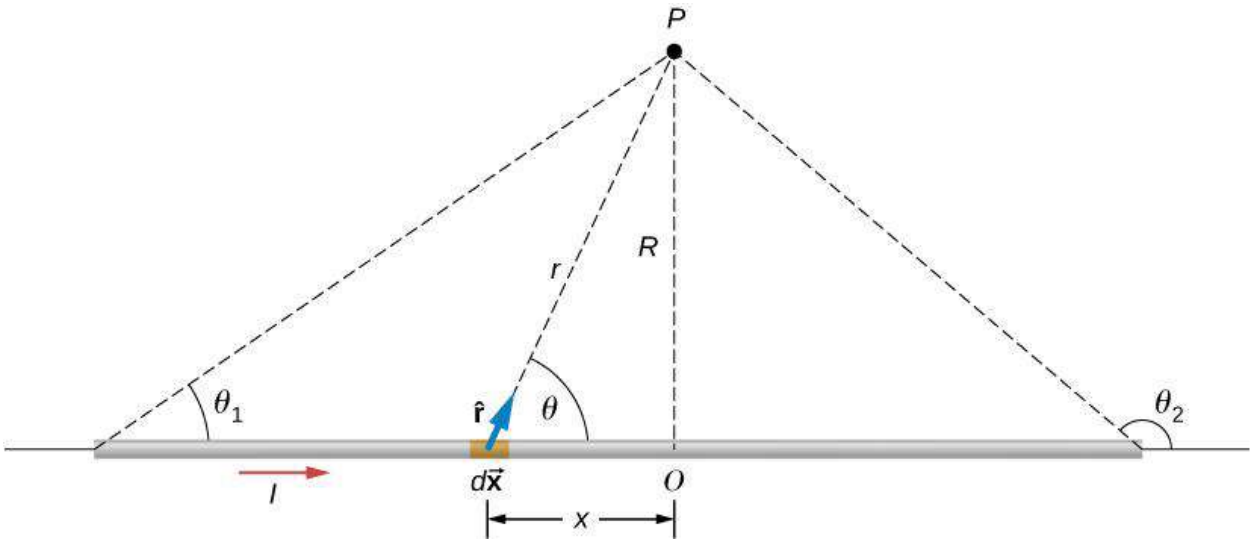


Figure:1 A section of a thin, straight current-carrying wire

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The wire is symmetrical about point O, so we can set the limits of the integration from zero to infinity and double the answer, rather than integrate from negative infinity to positive infinity. Based on the picture and trigonometry, we can write expressions for r and sinθ in terms of *x* and *R*, namely

$$r = \sqrt{x^2 + R^2}$$

$$\sin\theta = \frac{R}{\sqrt{x^2 + R^2}}$$

Substituting these expressions into Equation 1 the magnetic field integration becomes

$$B = \frac{\mu_0 I}{2\pi} \int_0^\infty \frac{R\,dx}{(x^2 + R^2)^{3/2}}.$$

From integration part, we get

$$\text{Let,} \quad x = R\tan\theta$$

$$\therefore dx = R\sec^2\theta d\theta$$

When, $x = 0, then\ \theta = 0$ and $x = \infty,\ \theta = \frac{\pi}{2}$

$$\therefore \int_0^\infty \frac{Rdx}{(x^2 + R^2)^{3/2}} = \int_0^{\frac{\pi}{2}} \frac{R\,R\sec^2\theta d\theta}{(R^2\tan^2\theta + R^2)^{3/2}} = \frac{R^2}{R^3}\int_0^{\frac{\pi}{2}} \frac{\sec^2\theta d\theta}{\sec^3\theta} = \frac{1}{R}\int_0^{\frac{\pi}{2}} \cos\theta\, d\theta = \frac{1}{R}$$

Substituting these value in the above equation, we get

$$\boxed{B = \frac{\mu_0 I}{2\pi R}.}$$

This is the required equation of B for a long straight wire.

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The magnetic field lines of the infinite wire are circular and centered at the wire (Figure 2), and they are identical in every plane perpendicular to the wire. Since the field decreases with distance from the wire, the spacing of the field lines must increase correspondingly with distance. The direction of this magnetic field may be found with a second form of the **right-hand rule** (Figure2). If you hold the wire with your right hand so that your thumb points along the current, then your fingers wrap around the wire in the same sense as $\vec{B}$.

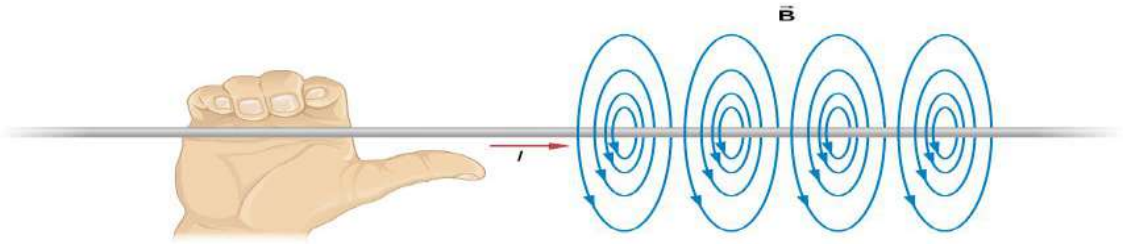


Figure: 2

14. Find the expression B by using Biot Savart law for a circular wire.