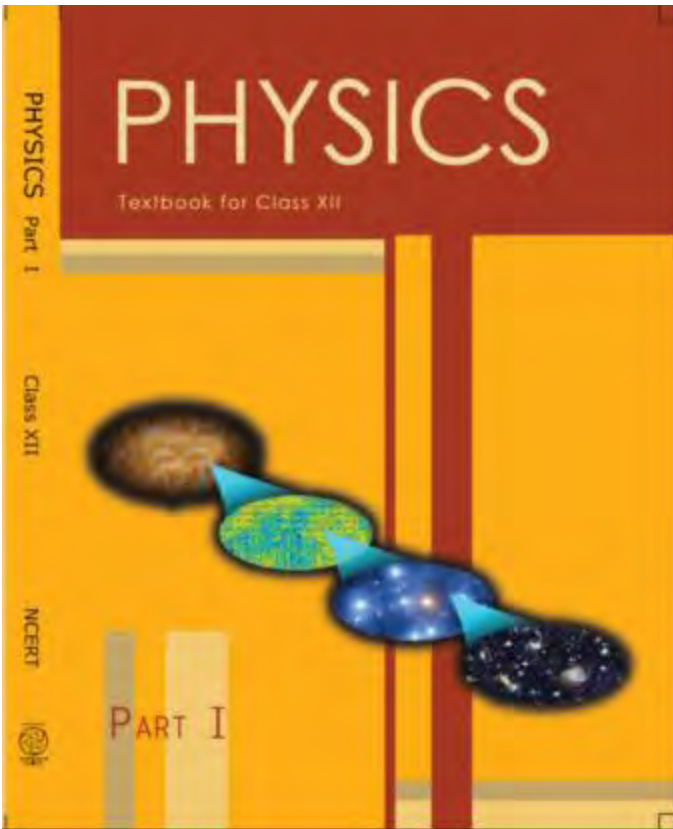


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Chapter One

ELECTRIC CHARGES

AND FIELDS

1.1 INTRODUCTION

All of us have the experience of seeing a spark or hearing a crackle when

we take off our synthetic clothes or sweater, particularly in dry weather. This is almost inevitable with ladies garments like a polyester saree. Have you ever tried to find any explanation for this phenomenon? Another common example of electric discharge is the lightning that we see in the sky during thunderstorms. We also experience a sensation of an electric shock either while opening the door of a car or holding the iron bar of a bus after sliding from our seat. The reason for these experiences is discharge of electric charges through our body, which were accumulated due to rubbing of insulating surfaces. You might have also heard that this is due to generation of static electricity. This is precisely the topic we are going to discuss in this and the next chapter. Static means anything that does not move or change with time. *Electrostatics deals with the study of forces, fields and potentials arising from static charges.*

1.2 ELECTRIC CHARGE

Historically the credit of discovery of the fact that amber rubbed with wool or silk cloth attracts light objects goes to Thales of Miletus, Greece, around 600 BC. The name electricity is coined from the Greek word *elektron* meaning *amber*. Many such pairs of materials were known which

Physics

on rubbing could attract light objects like straw, pith balls and bits of papers.

You can perform the following activity at home to experience such an effect.

Cut out long thin strips of white paper and lightly iron them. Take them near a TV screen or computer monitor. You will see that the strips get attracted to the screen. In fact they remain stuck to the screen for a while.

It was observed that if two glass rods rubbed with wool or silk cloth are brought close to each other, they repel each other [Fig. 1.1(a)]. The two strands

FIGURE 1.1 Rods and pith balls: like charges repel and unlike charges attract each other.

of wool or two pieces of silk cloth, with which the rods were rubbed, also repel each other. However, the glass rod and wool attracted each other. Similarly, two plastic rods rubbed with cat's fur repelled each other [Fig. 1.1(b)] but attracted the fur. On the other hand, the plastic rod attracts the glass rod [Fig. 1.1(c)] and repel the silk

or wool with which the glass rod is rubbed. The glass rod repels the fur. If a plastic rod rubbed with fur is made to touch two small pith balls (now-a-days we can use polystyrene balls) suspended by silk or nylon thread, then the balls repel each other [Fig. 1.1(d)] and are also repelled by the rod. A similar effect is found if the pith balls are touched with a glass rod rubbed with silk [Fig. 1.1(e)]. A dramatic observation is that a pith ball touched with glass rod attracts another pith ball touched with plastic rod [Fig. 1.1(f)].

These seemingly simple facts were established from years of efforts and careful experiments and their analyses. It was concluded, after many careful studies by different scientists, that there were only two kinds of an entity which is called the *electric charge*. We say that the bodies like glass or plastic rods, silk, fur and pith balls are electrified. They acquire an electric charge on rubbing. The experiments on pith balls suggested that there are two kinds of electrification and we find that (i) *like charges repel* and (ii) *unlike charges attract* each other. The experiments also demonstrated that the charges are transferred from the rods to the pith balls on contact. It is said that the pith balls are electrified or are charged by contact. The property which differentiates the two kinds of charges is called the *polarity* of charge.

When a glass rod is rubbed with silk, the rod acquires one kind of

Interactive animation on simple electrostatic experiments:

<http://ephysics.physics.ucla.edu/travoltage/HTML/>

charge and the silk acquires the second kind of charge. This is true for any pair of objects that are rubbed to be electrified. Now if the electrified glass rod is brought in contact with silk, with which it was rubbed, they no longer attract each other. They also do not attract or repel other light objects as they did on being electrified.

Thus, the charges acquired after rubbing are lost when the charged bodies are brought in contact. What can you conclude from these

2

observations? It just tells us that unlike charges acquired by the objects

Electric Charges

and Fields

neutralise or nullify each other's effect. Therefore the charges were named as *positive* and *negative* by the American scientist Benjamin Franklin.

We know that when we add a positive number to a negative number of the same magnitude, the sum is zero. This might have been the philosophy in naming the charges as positive and negative. By convention, the charge on glass rod or cat's fur is called positive and that on plastic rod or silk is termed negative. If an object possesses an electric charge, it is said to be electrified or charged. When it has no charge it is said to be neutral.

UNIFICATION OF ELECTRICITY AND MAGNETISM

In olden days, electricity and magnetism were treated as separate subjects. Electricity dealt with charges on glass rods, cat's fur, batteries, lightning, etc., while magnetism described interactions of magnets, iron filings, compass needles, *etc.* In 1820 Danish scientist Oersted found that a compass needle is deflected by passing an electric current through a wire placed near the needle. Ampere and Faraday supported this observation by saying that electric charges in motion produce magnetic fields and moving magnets generate electricity. The unification was achieved when the Scottish physicist Maxwell and the Dutch physicist Lorentz put forward a theory where they showed the interdependence of these two subjects. This field is called *electromagnetism*. Most of the phenomena occurring around us can be described under electromagnetism. Virtually every force that we can think of like friction, chemical force between atoms holding the matter together, and even the forces describing processes occurring in cells of living organisms, have its origin in electromagnetic force. Electromagnetic force is one of the fundamental forces of nature.

Maxwell put forth four equations that play the same role in classical electromagnetism as Newton's equations of motion and gravitation law play in mechanics. He also argued that light is electromagnetic in nature and its speed can be found by making purely electric and magnetic measurements. He claimed that the science of optics is intimately related to that of electricity and magnetism.

The science of electricity and magnetism is the foundation for the modern technological civilisation. Electric power, telecommunication, radio and television, and a wide variety of the practical appliances used in daily life are based on the principles of this science.

Although charged particles in motion exert both electric and magnetic forces, in the frame of reference where all the charges are at rest, the forces are purely electrical. You know that gravitational force is a long-range force. Its effect is felt even when the distance between the interacting particles is very large because the force decreases inversely as the square of the distance between the interacting bodies. We will learn in this chapter that electric force is also as pervasive and is in fact stronger than the

gravitational force by several orders of magnitude (refer to Chapter 1 of Class XI Physics Textbook).

A simple apparatus to detect charge on a body is the *gold-leaf*

electroscope [Fig. 1.2(a)]. It consists of a vertical metal rod housed in a box, with two thin gold leaves attached to its bottom end. When a charged object touches the metal knob at the top of the rod, charge flows on to

the leaves and they diverge. The degree of divergance is an indicator of

3

the amount of charge.

Physics

Students can make a simple electroscope as

follows [Fig. 1.2(b)]: Take a thin aluminium curtain

rod with ball ends fitted for hanging the curtain. Cut

out a piece of length about 20 cm with the ball at

one end and flatten the cut end. Take a large bottle

that can hold this rod and a cork which will fit in the

opening of the bottle. Make a hole in the cork

sufficient to hold the curtain rod snugly. Slide the

rod through the hole in the cork with the cut end on

the lower side and ball end projecting above the cork.

Fold a small, thin aluminium foil (about 6 cm in

length) in the middle and attach it to the flattened end of the rod by cellulose tape. This forms the leaves of your electroscope. Fit the cork in the bottle with about 5 cm of the ball end projecting above the cork. A paper scale may be put inside the bottle in advance to measure the separation of leaves. The separation is a rough measure of the amount of charge on the electroscope.

To understand how the electroscope works, use the white paper strips we used for seeing the attraction of charged bodies. Fold the strips into half so that you make a mark of fold. Open the strip and

FIGURE 1.2 Electroscopes: (a) The gold leaf iron it lightly with the mountain fold up, as shown electroscope, (b) Schematics of a simple in Fig. 1.3. Hold the strip by pinching it at the fold. electroscope.

You would notice that the two halves move apart.

This shows that the strip has acquired charge on ironing. When you fold it into half, both the halves have the same charge. Hence they repel each

other. The same effect is seen in the leaf electroscope. On charging the curtain rod by touching the ball end with an electrified body, charge is transferred to the curtain rod and the attached aluminium foil. Both the halves of the foil get similar charge and therefore repel each other. The divergence in the leaves depends on the amount of charge on them. Let us first try to understand why material bodies acquire charge.

You know that all matter is made up of atoms and/or molecules.

Although normally the materials are electrically neutral, they do contain charges; but their charges are exactly balanced. Forces that hold the molecules together, forces that hold atoms together in a solid, the adhesive force of glue, forces associated with surface tension, all are basically electrical in nature, arising from the forces between charged particles.

Thus the electric force is all pervasive and it encompasses almost each and every field associated with our life. It is therefore essential that we learn more about such a force.

To electrify a neutral body, we need to add or remove one kind of

FIGURE 1.3 Paper strip charge. When we say that a body is charged, we always refer to this experiment.

excess charge or deficit of charge. In solids, some of the electrons, being less tightly bound in the atom, are the charges which are transferred from one body to the other. A body can thus be charged positively by

losing some of its electrons. Similarly, a body can be charged negatively

Electric Charges

and Fields

by gaining electrons. When we rub a glass rod with silk, some of the electrons from the rod are transferred to the silk cloth. Thus the rod gets positively charged and the silk gets negatively charged. No new charge is created in the process of rubbing. Also the number of electrons, that are transferred, is a very small fraction of the total number of electrons in the material body. Also only the less tightly bound electrons in a material body can be transferred from it to another by rubbing. Therefore, when a body is rubbed with another, the bodies get charged and that is why we have to stick to certain pairs of materials to notice charging on rubbing the bodies.

1.3 CONDUCTORS AND INSULATORS

A metal rod held in hand and rubbed with wool will not show any sign of being charged. However, if a metal rod with a wooden or plastic handle is rubbed without touching its metal part, it shows signs of charging.

Suppose we connect one end of a copper wire to a neutral pith ball and the other end to a negatively charged plastic rod. We will find that the

pith ball acquires a negative charge. If a similar experiment is repeated with a nylon thread or a rubber band, no transfer of charge will take place from the plastic rod to the pith ball. Why does the transfer of charge not take place from the rod to the ball?

Some substances readily allow passage of electricity through them, others do not. Those which allow electricity to pass through them easily are called *conductors*. They have electric charges (electrons) that are comparatively free to move inside the material. Metals, human and animal bodies and earth are conductors. Most of the non-metals like glass, porcelain, plastic, nylon, wood offer high resistance to the passage of electricity through them. They are called *insulators*. Most substances fall into one of the two classes stated above*.

When some charge is transferred to a conductor, it readily gets distributed over the entire surface of the conductor. In contrast, if some charge is put on an insulator, it stays at the same place. You will learn why this happens in the next chapter.

This property of the materials tells you why a nylon or plastic comb gets electrified on combing dry hair or on rubbing, but a metal article like spoon does not. The charges on metal leak through our body to the ground as both are conductors of electricity.

When we bring a charged body in contact with the earth, all the

excess charge on the body disappears by causing a momentary current to pass to the ground through the connecting conductor (such as our body). This process of sharing the charges with the earth is called *grounding or earthing*. Earthing provides a safety measure for electrical circuits and appliances. A thick metal plate is buried deep into the earth and thick wires are drawn from this plate; these are used in buildings for the purpose of earthing near the mains supply. The electric wiring in our houses has three wires: live, neutral and earth. The first two carry

* There is a third category called *semiconductors*, which offer resistance to the movement of charges which is intermediate between the conductors and

5

insulators.

Physics

electric current from the power station and the third is earthed by connecting it to the buried metal plate. Metallic bodies of the electric appliances such as electric iron, refrigerator, TV are connected to the earth wire. When any fault occurs or live wire touches the metallic body, the charge flows to the earth without damaging the appliance and without causing any injury to the humans; this would have otherwise been unavoidable since the human body is a conductor of electricity.

1.4 CHARGING BY INDUCTION

When we touch a pith ball with an electrified plastic rod, some of the

negative charges on the rod are transferred to the pith ball and it also gets charged. Thus the pith ball is *charged by contact*. It is then repelled by the plastic rod but is attracted by a glass rod which is oppositely charged. However, why a electrified rod attracts light objects, is a question we have still left unanswered. Let us try to understand what could be happening by performing the following experiment.

(i) Bring two metal spheres, A and B, supported on insulating stands, in contact as shown in Fig. 1.4(a).

(ii) Bring a positively charged rod near one of the spheres, say A, taking care that it does not touch the sphere. The free electrons in the spheres are attracted towards the rod. This leaves an excess of positive charge on the rear surface of sphere B. Both kinds of charges are bound in the metal spheres and cannot escape. They, therefore, reside on the surfaces, as shown in Fig. 1.4(b). The left surface of sphere A, has an excess of negative charge and the right surface of sphere B, has an excess of positive charge. However, not all of the electrons in the spheres have accumulated on the left surface of A. As the negative charge starts building up at the left surface of A, other electrons are repelled by these. In a short time, equilibrium is reached under the action of force of attraction of the rod and the force of repulsion due to the accumulated charges. Fig. 1.4(b) shows the equilibrium situation.

The process is called *induction of charge* and happens almost

instantly. The accumulated charges remain on the surface, as shown, till the glass rod is held near the sphere. If the rod is removed, the charges are not acted by any outside force and they redistribute to their original neutral state.

(iii) Separate the spheres by a small distance while the glass rod is still held near sphere A, as shown in Fig. 1.4(c). The two spheres are found to be oppositely charged and attract each other.

(iv) Remove the rod. The charges on spheres rearrange themselves as shown in Fig. 1.4(d). Now, separate the spheres quite apart. The charges on them get uniformly distributed over them, as shown in Fig. 1.4(e).

In this process, the metal spheres will each be equal and oppositely charged. This is *charging by induction*. The positively charged glass rod does not lose any of its charge, contrary to the process of charging by **FIGURE 1.4** Charging

contact.

by induction.

When electrified rods are brought near light objects, a similar effect takes place. The rods induce opposite charges on the near surfaces of

6

the objects and similar charges move to the farther side of the object.

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Electric Charges and Fields

[This happens even when the light object is not a conductor. The mechanism for how this happens is explained later in Sections 1.10 and 2.10.] The centres of the two types of charges are slightly separated. We know that opposite charges attract while similar charges repel. However, the magnitude of force depends on the distance between the charges and in this case the force of attraction overweighs the force of repulsion. As a result the particles like bits of paper or pith balls, being light, are pulled towards the rods.

Example 1.1 How can you charge a metal sphere positively without touching it?

Solution Figure 1.5(a) shows an uncharged metallic sphere on an

<http://www.physicsclassroom.com/mmedia/estatics/estaticTOC.html>

Interactive animation on charging a two-sphere system by induction: insulating metal stand. Bring a negatively charged rod close to the metallic sphere, as shown in Fig. 1.5(b). As the rod is brought close to the sphere, the free electrons in the sphere move away due to repulsion and start piling up at the farther end. The near end becomes positively charged due to deficit of electrons. This process of charge distribution stops when the net force on the free electrons inside the metal is zero. Connect the sphere to the ground by a conducting wire. The electrons will flow to the ground while the positive charges at the near end will remain held there due to the attractive force of the negative charges on the rod, as shown in Fig. 1.5(c). Disconnect the sphere from the ground. The positive charge continues to be held at the near end [Fig. 1.5(d)]. Remove the electrified rod. The positive charge will spread uniformly over the sphere as shown in Fig. 1.5(e).

FIGURE 1.5

In this experiment, the metal sphere gets charged by the process

E

of induction and the rod does not lose any of its charge.

XAMPLE

Similar steps are involved in charging a metal sphere negatively by induction, by bringing a positively charged rod near it. In this

1.1

case the electrons will flow from the ground to the sphere when the sphere is connected to the ground with a wire. Can you explain why?

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Physics

1.5 BASIC PROPERTIES OF ELECTRIC CHARGE

We have seen that there are two types of charges, namely positive and negative and their effects tend to cancel each other. Here, we shall now describe some other properties of the electric charge.

If the sizes of charged bodies are very small as compared to the distances between them, we treat them as *point charges*. All the charge content of the body is assumed to be concentrated at one point in space.

1.5.1 Additivity of charges

We have not as yet given a quantitative definition of a charge; we shall follow it up in the next section. We shall tentatively assume that this can be done and proceed. If a system contains two point charges q and q_1

2

the total charge of the system is obtained simply by adding algebraically

q and q , i.e., charges add up like real numbers or they are scalars like 1

2

the mass of a body. If a system contains n charges q, q, q, \dots, q , then 1

2

3

n

the total charge of the system is $q + q + q + \dots + q$. Charge has

1

2

3

n

magnitude but no direction, similar to the mass. However, there is one

difference between mass and charge. Mass of a body is always positive

whereas a charge can be either positive or negative. Proper signs have to

be used while adding the charges in a system. For example, the

total charge of a system containing five charges +1, +2, -3, +4 and -5,

in some arbitrary unit, is $(+1) + (+2) + (-3) + (+4) + (-5) = -1$ in the

same unit.

1.5.2 Charge is conserved

We have already hinted to the fact that when bodies are charged by rubbing, there is transfer of electrons from one body to the other; no new charges are either created or destroyed. A picture of particles of electric charge enables us to understand the idea of conservation of charge. When we rub two bodies, what one body gains in charge the other body loses. Within an isolated system consisting of many charged bodies, due to interactions among the bodies, charges may get redistributed but it is found that *the total charge of the isolated system is always conserved*. Conservation of charge has been established experimentally.

It is not possible to create or destroy net charge carried by any isolated system although the charge carrying particles may be created or destroyed in a process. Sometimes nature creates charged particles: a neutron turns into a proton and an electron. The proton and electron thus created have equal and opposite charges and the total charge is zero before and after the creation.

1.5.3 Quantisation of charge

Experimentally it is established that all free charges are integral multiples of a basic unit of charge denoted by e . Thus charge q on a body is always given by

8

$$q = ne$$

Electric Charges

and Fields

where n is any integer, positive or negative. This basic unit of charge is the charge that an electron or proton carries. By convention, the charge on an electron is taken to be negative; therefore charge on an electron is

written as $-e$ and that on a proton as $+e$.

The fact that electric charge is always an integral multiple of e is termed as *quantisation of charge*. There are a large number of situations in physics where certain physical quantities are quantised. The quantisation of charge was first suggested by the experimental laws of electrolysis discovered by

English experimentalist Faraday. It was experimentally demonstrated by Millikan in 1912.

In the International System (SI) of Units, a unit of charge is called a *coulomb* and is denoted by the symbol C. A coulomb is defined in terms the unit of the electric current which you are going to learn in a subsequent chapter. In terms of this definition, one coulomb is the charge flowing through a wire in 1 s if the current is 1 A (ampere), (see Chapter 2 of Class XI, Physics Textbook , Part I). In this system, the value of the basic unit of charge is

$$e = 1.602192 \times 10^{-19} \text{ C}$$

Thus, there are about 6×10^{18} electrons in a charge of -1C . In electrostatics, charges of this large magnitude are seldom encountered

and hence we use smaller units $1 \mu\text{C}$ (micro coulomb) = 10^{-6} C or 1 mC (milli coulomb) = 10^{-3} C.

If the protons and electrons are the only basic charges in the universe, all the observable charges have to be integral multiples of e . Thus, if a body contains n electrons and n protons, the total amount of charge

2

on the body is $n \times e + n \times (-e) = (n - n) e$. Since n and n are integers, 2

1

2

1

1

2

their difference is also an integer. Thus the charge on any body is always

an integral multiple of e and can be increased or decreased also in steps of e .

The step size e is, however, very small because at the macroscopic

level, we deal with charges of a few μC . At this scale the fact that charge of a body can increase or decrease in units of e is not visible. The grainy nature of the charge is lost and it appears to be continuous.

This situation can be compared with the geometrical concepts of points

and lines. A dotted line viewed from a distance appears continuous to

us but is not continuous in reality. As many points very close to

each other normally give an impression of a continuous line, many small charges taken together appear as a continuous charge distribution.

At the macroscopic level, one deals with charges that are enormous compared to the magnitude of charge e . Since $e = 1.6 \times 10^{-19} \text{ C}$, a charge of magnitude, say $1 \mu\text{C}$, contains something like 10^{13} times the electronic charge. At this scale, the fact that charge can increase or decrease only in units of e is not very different from saying that charge can take continuous values. Thus, at the macroscopic level, the quantisation of charge has no practical consequence and can be ignored. At the microscopic level, where

9

the charges involved are of the order of a few tens or hundreds of e , i.e.,

Physics

they can be counted, they appear in discrete lumps and quantisation of charge cannot be ignored. It is the scale involved that is very important.

Example 1.2 If 10^9 electrons move out of a body to another body every second, how much time is required to get a total charge of 1 C on the other body?

Solution In one second 10^9 electrons move out of the body. Therefore the charge given out in one second is $1.6 \times 10^{-19} \times 10^9 \text{ C} = 1.6 \times 10^{-10} \text{ C}$. The time required to accumulate a charge of 1 C can then be estimated to be $1 \text{ C} \div (1.6 \times 10^{-10} \text{ C/s}) = 6.25 \times 10^9 \text{ s} = 6.25 \times 10^9 \div (365 \times 24 \times$

3600) years = 198 years. Thus to collect a charge of one coulomb, from a body from which 10^9 electrons move out every second, we will need approximately 200 years. One coulomb is, therefore, a very large

1.2

unit for many practical purposes.

It is, however, also important to know what is roughly the number of electrons contained in a piece of one cubic centimetre of a material.

XAMPLE

A cubic piece of copper of side 1 cm contains about 2.5×10^{24}

E

electrons.

Example 1.3 How much positive and negative charge is there in a cup of water?

Solution Let us assume that the mass of one cup of water is 250 g. The molecular mass of water is 18g. Thus, one mole (= 6.02×10^{23} molecules) of water is 18 g. Therefore the number of molecules in one cup of water is $(250/18) \times 6.02 \times 10^{23}$.

1.3

Each molecule of water contains two hydrogen atoms and one oxygen atom, i.e., 10 electrons and 10 protons. Hence the total positive and

total negative charge has the same magnitude. It is equal to

XAMPLE

E

$$(250/18) \times 6.02 \times 10^{23} \times 10 \times 1.6 \times 10^{-19} \text{ C} = 1.34 \times 10^7 \text{ C}.$$

1.6 COULOMB'S LAW

Coulomb's law is a quantitative statement about the force between two point charges. When the linear size of charged bodies are much smaller

than the distance separating them, the size may be ignored and the

charged bodies are treated as *point charges*. Coulomb measured the force between two point charges and found that *it varied inversely as the square of the distance between the charges and was directly*

proportional to the product of the magnitude of the two charges and

acted along the line joining the two charges. Thus, if two point charges q_1, q_2 are separated by a distance r in vacuum, the magnitude of the force

is

force (**F**) between them is given by

q_1

q_2

1

2

$$F = k$$

(1.1)

2

r

How did Coulomb arrive at this law from his experiments? Coulomb

used a torsion balance* for measuring the force between two charged metallic

* A torsion balance is a sensitive device to measure force. It was also used later by Cavendish to measure the very feeble gravitational force between two objects, 10

to verify Newton's Law of Gravitation.



Electric Charges

and Fields

spheres. When the separation between two spheres is much

larger than the radius of each sphere, the charged spheres

may be regarded as point charges. However, the charges

on the spheres were unknown, to begin with. How then

could he discover a relation like Eq. (1.1)? Coulomb

thought of the following simple way: Suppose the charge

on a metallic sphere is q . If the sphere is put in contact with an identical uncharged sphere, the charge will spread over the two spheres. By symmetry, the charge on each sphere will be $q/2$. Repeating this process, we can get charges $q/2, q/4, \text{etc.}$ Coulomb varied the distance for a fixed pair of charges and measured the force for different

CHARLES AUGUSTIN DE COULOMB

separations. He then varied the charges in pairs, keeping the distance fixed for each pair. Comparing forces for

Charles Augustin de

different pairs of charges at different distances, Coulomb

Coulomb (1736 – 1806)

arrived at the relation, Eq. (1.1).

Coulomb, a French

Coulomb's law, a simple mathematical statement,

physicist, began his career

as a military engineer in

was initially experimentally arrived at in the manner

the West Indies. In 1776, he

described above. While the original experiments

returned to Paris and

established it at a macroscopic scale, it has also been

retired to a small estate to

established down to subatomic level ($r \sim 10^{-10}$ m).

do his scientific research.

Coulomb discovered his law without knowing the

He invented a torsion

explicit magnitude of the charge. In fact, it is the other

balance to measure the

way round: Coulomb's law can *now* be employed to

quantity of a force and used

furnish a definition for a unit of charge. In the relation,

it for determination of

Eq. (1.1), k is so far arbitrary. We can choose any positive

forces of electric attraction

value of k . The choice of k determines the size of the unit

or repulsion between small

charged spheres. He thus

of charge. In SI units, the value of k is about 9×10^9 .

arrived in 1785 at the

The unit of charge that results from this choice is called
inverse square law relation,

a coulomb which we defined earlier in Section 1.4.

now known as Coulomb's

Putting this value of k in Eq. (1.1), we see that for

law. The law had been

(

$$q = q = 1 \text{ C}, r = 1 \text{ m}$$

1

1

2

anticipated by Priestley and

73

$$F = 9 \times 10^9 \text{ N}$$

also by Cavendish earlier,

though Cavendish never

6

That is, 1 C is the charge that when placed at a

published his results.

-1

distance of 1 m from another charge of the same

Coulomb also found the

8

magnitude *in vacuum* experiences an electrical force of

inverse square law of force

0

repulsion of magnitude 9×10^9 N. One coulomb is

6

between unlike and like

)

evidently too big a unit to be used. In practice, in

magnetic poles.

electrostatics, one uses smaller units like 1 mC or 1 μ C.

The constant k in Eq. (1.1) is usually put as

$k = 1/4\pi\epsilon$ for later convenience, so that Coulomb's law is written as

0

1

$q q$

1

2

$F =$

2

(1.2)

$4 \pi \epsilon$

r

0

ϵ is called the *permittivity of free space*. The value of ϵ in SI units is 0

0

$\epsilon = 8.854 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$

0

* Implicit in this is the assumption of additivity of charges and conservation: 11

two charges ($q/2$ each) add up to make a total charge q .

Physics

Since force is a vector, it is better to write

Coulomb's law in the vector notation. Let the

position vectors of charges q and q be \mathbf{r} and \mathbf{r}

1

2

1

2

respectively [see Fig.1.6(a)]. We denote force on

q_2 due to q_1 by \mathbf{F}_{21} and force on q_1 due to q_2 by \mathbf{F}_{12}

2

12

2

1

\mathbf{F} . The two point charges q_1 and q_2 have been

21

1

2

numbered 1 and 2 for convenience and the vector

leading from 1 to 2 is denoted by \mathbf{r}_{12} :

21

$$\mathbf{r}_{12} = \mathbf{r}_2 - \mathbf{r}_1$$

21

2

1

In the same way, the vector leading from 2 to

1 is denoted by \mathbf{r}_{21} :

12

$$\mathbf{r} = \mathbf{r} - \mathbf{r} = -\mathbf{r}$$

12

1

2

21

The magnitude of the vectors \mathbf{r} and \mathbf{r} is

21

12

denoted by r and r , respectively ($r = r$). The 21

12

12

21

direction of a vector is specified by a unit vector

along the vector. To denote the direction from 1

to 2 (or from 2 to 1), we define the unit vectors:

FIGURE 1.6 (a) Geometry and

\mathbf{r}

21

^

(b) Forces between charges.

= \mathbf{r}

\mathbf{r}

12

$\hat{\mathbf{r}}$

=

,

$\hat{\mathbf{r}}$

= $\hat{\mathbf{r}}$

21

,

r

12

21

12

r

21

12

Coulomb's force law between two point charges q and q located at 1

2

\mathbf{r} and \mathbf{r} is then expressed as

1

2

1

q

q

1

2

F

=

$\hat{\mathbf{r}}$

21

2

21

(1.3)

$4 \pi \epsilon$

r

o

21

Some remarks on Eq. (1.3) are relevant:

• Equation (1.3) is valid for any sign of q_1 and q_2 whether positive or

2

negative. If q_1 and q_2 are of the same sign (either both positive or both

2

negative), \mathbf{F} is along $\hat{\mathbf{r}}_{12}$

, which denotes repulsion, as it should be for

21

21

like charges. If q_1 and q_2 are of opposite signs, \mathbf{F} is along $-\hat{\mathbf{r}}_{12}$ ($=\hat{\mathbf{r}}_{21}$),

2

21

21

12

which denotes attraction, as expected for unlike charges. Thus, we do

not have to write separate equations for the cases of like and unlike

charges. Equation (1.3) takes care of both cases correctly [Fig. 1.6(b)].

• The force \mathbf{F} on charge q_1 due to charge q_2 , is obtained from Eq. (1.3),

1

2

by simply interchanging 1 and 2, i.e.,

1

q

q

1

2

\mathbf{F}

=

$\hat{\mathbf{r}}$

= $-\mathbf{F}$

12

2

12

21

$4 \pi \epsilon$

r

0

12

Thus, Coulomb's law agrees with the Newton's third law.

• Coulomb's law [Eq. (1.3)] gives the force between two charges q and

1

q in vacuum. If the charges are placed in matter or the intervening

2

space has matter, the situation gets complicated due to the presence of charged constituents of matter. We shall consider electrostatics in

12

matter in the next chapter.

Electric Charges

and Fields

Example 1.4 Coulomb's law for electrostatic force between two point charges and Newton's law for gravitational force between two stationary point masses, both have inverse-square dependence on the distance between the charges/masses. (a) Compare the strength of these forces by determining the ratio of their magnitudes (i) for an electron and a proton and (ii) for two protons. (b) Estimate the accelerations of electron and proton due to the electrical force of their mutual attraction when they are 1 \AA ($= 10^{-10} \text{ m}$) apart? ($m = 1.67 \times$

p

10^{-27} kg , $m = 9.11 \times 10^{-31} \text{ kg}$)

e

Solution

(a) (i) The electric force between an electron and a proton at a distance

http://webphysics.davidson.edu/physlet_resources/bu_semester2/co1_coulomb.html

Interactive animation on Coulomb's law:

r apart is:

2

1

e

$F = -$

e

2

$4\pi\epsilon r$

0

where the negative sign indicates that the force is attractive. The

corresponding gravitational force (always attractive) is:

m

m

p

e

$F =$

G

—

G

2

r

where m and m are the masses of a proton and an electron

p

e

respectively.

2

F

e

e

39

=

= 2.4×10

F

4 ϵ

$\pi Gm m$

G

0

p

e

(ii) On similar lines, the ratio of the magnitudes of electric force to the gravitational force between two protons at a distance r apart is :

2

F

e

e

=

=

F

4ϵ

π

1.3×10^{36}

$Gm m$

G

0

p

p

However, it may be mentioned here that the signs of the two forces are different. For two protons, the gravitational force is attractive in nature and the Coulomb force is repulsive. The actual values of these forces between two protons inside a nucleus (distance between two protons is $\sim 10^{-15}$ m inside a nucleus) are $F \sim 230$ N

e

whereas $F \sim 1.9 \times 10^{-34}$ N.

G

The (dimensionless) ratio of the two forces shows that electrical forces are enormously stronger than the gravitational forces.

(b) The electric force \mathbf{F} exerted by a proton on an electron is same in magnitude to the force exerted by an electron on a proton; however the masses of an electron and a proton are different. Thus, the magnitude of force is

2

1

e

$|\mathbf{F}| =$

$$2 = 8.987 \times 10^9 \text{ Nm}^2/\text{C}^2 \times (1.6 \times 10^{-19}\text{C})^2 / (10^{-10}\text{m})^2$$

$$4\pi\epsilon r$$

$$0$$

$$= 2.3 \times 10^{-8} \text{ N}$$

Using Newton's second law of motion, $F = ma$, the acceleration that an electron will undergo is $a = 2.3 \times 10^{-8} \text{ N} / 9.11 \times 10^{-31} \text{ kg} = 2.5 \times 10^{22} \text{ m/s}^2$

E

Comparing this with the value of acceleration due to gravity, we

XAMPLE

can conclude that the effect of gravitational field is negligible on the motion of electron and it undergoes very large accelerations under the action of Coulomb force due to a proton.

1.4

The value for acceleration of the proton is

$$2.3 \times 10^{-8} \text{ N} / 1.67 \times 10^{-27} \text{ kg} = 1.4 \times 10^{19} \text{ ms}^2$$

13

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--





Physics

Example 1.5 A charged metallic sphere A is suspended by a nylon thread. Another charged metallic sphere B held by an insulating handle is brought close to A such that the distance between their centres is 10 cm, as shown in Fig. 1.7(a). The resulting repulsion of A is noted (for example, by shining a beam of light and measuring the deflection of its shadow on a screen). Spheres A and B are touched by uncharged spheres C and D respectively, as shown in Fig. 1.7(b). C and D are then removed and B is brought closer to A to a distance of 5.0 cm between their centres, as shown in Fig. 1.7(c). What is the expected repulsion of A on the basis of Coulomb's law? Spheres A and C and spheres B and D have identical sizes. Ignore the sizes of A and B in comparison to the separation between their centres.

1.5

XAMPLE

14

E

FIGURE 1.7

Electric Charges

and Fields

Solution Let the original charge on sphere A be q and that on B be q' . At a distance r between their centres, the magnitude of the electrostatic force on each is given by

$$F = \frac{1}{4\pi\epsilon_0} \frac{qq'}{r^2}$$

neglecting the sizes of spheres A and B in comparison to r . When an identical but uncharged sphere C touches A, the charges redistribute on A and C and, by symmetry, each sphere carries a charge $q/2$.

Similarly, after D touches B, the redistributed charge on each is $q'/2$. Now, if the separation between A and B is halved, the magnitude of the electrostatic force on each is

E

XAMPLE

1

$$(q/2)(q'/2)$$

1

$$(qq')$$

$$F' =$$

=

$$= F$$

2

2

$$4\varepsilon$$

π

$$(r/2)$$

$$4\pi\varepsilon$$

r

0

0

1.5

Thus the electrostatic force on A, due to B, remains unaltered.

1.7 FORCES BETWEEN MULTIPLE CHARGES

The mutual electric force between two charges is given

by Coulomb's law. How to calculate the force on a

charge where there are not one but several charges

around? Consider a system of n stationary charges

$q_1, q_2, q_3, \dots, q_n$ in vacuum. What is the force on q_1

2

3

n

1

to q_2, q_3, \dots, q_n ? Coulomb's law is not enough to answer 2

3

n

this question. Recall that forces of mechanical origin

add according to the parallelogram law of addition. Is

the same true for forces of electrostatic origin?

Experimentally it is verified that *force on any*

charge due to a number of other charges is the vector

sum of all the forces on that charge due to the other

charges, taken one at a time. The individual forces

are unaffected due to the presence of other charges.

This is termed as the *principle of superposition*.

To better understand the concept, consider a

system of three charges q , q and q , as shown in

1,

2

3

Fig. 1.8(a). The force on one charge, say q , due to two

1

other charges q , q can therefore be obtained by

2

3

performing a vector addition of the forces due to each

one of these charges. Thus, if the force on q due to q

1

2

is denoted by \mathbf{F} , \mathbf{F} is given by Eq. (1.3) even though

12

12

other charges are present.

1

q , q

Thus, \mathbf{F}

1 2

=

$\hat{\mathbf{r}}$

12

2

12

$4\pi\epsilon$

r

0

12

In the same way, the force on q due to q , denoted

1

3

FIGURE 1.8 A system of (a) three

by \mathbf{F} , is given by

13

charges (b) multiple charges.

1

$q q$

1 3

F

=

$\hat{\mathbf{r}}$

13

2

13

4ϵ

π

r

15

0

13

Physics

which again is the Coulomb force on q due to q , even though other 1

3

charge q is present.

2

Thus the total force **F** on q due to the two charges q and q is 1

1

2

3

given as

1

$q q$

1

$q q$

1 2

1 3

F = F

+ **F =**

$\hat{\mathbf{r}} +$

$\hat{\mathbf{r}}$

1

12

13

2

12

2

13

$4\pi\epsilon$

r

4ϵ

π

r

(1.4)

0

12

0

13

The above calculation of force can be generalised to a system of charges more than three, as shown in Fig. 1.8(b).

The principle of superposition says that in a system of charges q_1, q_2, \dots, q_n , the force on q_1 due to q_2 is the same as given by Coulomb's law, 2

1

q_1, \dots, q_n , the force on q_1 due to q_2 is the same as given by Coulomb's law, 2

n

1

2

i.e., it is unaffected by the presence of the other charges q_3, q_4, \dots, q_n . The 3

4

n

total force \mathbf{F} on the charge q , due to all other charges, is then given by

1

the vector sum of the forces $\mathbf{F}_1, \mathbf{F}_2, \dots, \mathbf{F}_n$:

12

13

1 n

i.e.,

1

[$q q$

$q q$

$q q$

]

1 2

1 3

1

$$\mathbf{F} = \mathbf{F}_1 + \mathbf{F}_2 + \dots + \mathbf{F}_n$$

=

^

|

r

+

$\hat{\mathbf{r}} + \dots$

n

+

$\hat{\mathbf{r}}$

1

12

13

ln

|

2

12

2

13

2

1

4

n

ε

π

r

r

r

0]

12

13

1 n

]

n

q

q

1

i

=

^

$\sum \mathbf{r}$

2 1

(1.5)

4

i

ϵ

π

r

$0 \ i = 2 \ 1 \ i$

The vector sum is obtained as usual by the parallelogram law of addition of vectors. All of electrostatics is basically a consequence of Coulomb's law and the superposition principle.

Example 1.6 Consider three charges q, q, q each equal to q at the 1

2

3

vertices of an equilateral triangle of side l . What is the force on a charge Q (with the same sign as q) placed at the centroid of the triangle, as shown in Fig. 1.9?

FIGURE 1.9

1.6

Solution In the given equilateral triangle ABC of sides of length l , if we draw a perpendicular AD to the side BC, **XAMPLE**

$AD = AC \cos 30^\circ = (3/2) l$ and the distance AO of the centroid O

16

E

from A is $(2/3) AD = (1/3) l$. By symmetry $AO = BO = CO$.

Electric Charges

and Fields

Thus,

3

Qq

Force F on Q due to charge q at A =

along AO

1

2

4ϵ

π

l

0

3

Qq

Force F on Q due to charge q at B =

2

2

4ϵ

π

along BO

l

0

3

Qq

Force \mathbf{F} on Q due to charge q at C =

3

2

4 ϵ

π

along CO

l

0

3

Qq

The resultant of forces \mathbf{F} and \mathbf{F} is

2

3

2

4ϵ

π

along OA, by the

l

0

3

$Qq (\hat{\mathbf{r}} - \hat{\mathbf{r}})$

parallelogram law. Therefore, the total force on $Q =$

2

4ϵ

π

l

0

E

XAMPLE

$= 0$, where $\hat{\mathbf{r}}$

\mathbf{r} is the unit vector along OA.

It is clear also by symmetry that the three forces will sum to zero.

Suppose that the resultant force was nonzero but in some direction.

1.6

Consider what would happen if the system was rotated through 60° about O.

Example 1.7 Consider the charges q , q , and $-q$ placed at the vertices of an equilateral triangle, as shown in Fig. 1.10. What is the force on each charge?

FIGURE 1.10

Solution The forces acting on charge q at A due to charges q at B and $-q$ at C are \mathbf{F} along BA and \mathbf{F} along AC respectively, as shown 12

13

in Fig. 1.10. By the parallelogram law, the total force \mathbf{F} on the charge 1 q at A is given by

$\mathbf{F} = F \hat{\mathbf{r}}$ where $\hat{\mathbf{r}}$ is a unit vector along BC.

1

1

1

The force of attraction or repulsion for each pair of charges has the

E

XAMPLE

2

q

same magnitude $F =$

2

$4 \pi \epsilon l$

0

1.7

The total force \mathbf{F} on charge q at B is thus $\mathbf{F} = F \hat{\mathbf{r}}$

\mathbf{r} , where $\hat{\mathbf{r}}$ is a

2

2

2

2

unit vector along AC.

17

Physics

Similarly the total force on charge $-q$ at C is $\mathbf{F} = 3 F \hat{\mathbf{n}}$

\mathbf{n} , where $\hat{\mathbf{n}}$

\mathbf{n} is

3

the unit vector along the direction bisecting the $\angle BCA$.

It is interesting to see that the sum of the forces on the three charges is zero, i.e.,

1.7

$$\mathbf{F} + \mathbf{F} + \mathbf{F} = 0$$

1

2

3

The result is not at all surprising. It follows straight from the fact that Coulomb's law is consistent with Newton's third law. The proof

XAMPLE

E

is left to you as an exercise.

1.8 ELECTRIC FIELD

Let us consider a point charge Q placed in vacuum, at the origin O . If we place another point charge q at a point P , where $\mathbf{OP} = \mathbf{r}$, then the charge Q

will exert a force on q as per Coulomb's law. We may ask the question: If charge q is removed, then what is left in the surrounding? Is there nothing? If there is nothing at the point P , then how does a force act

when we place the charge q at P . In order to answer such questions, the early scientists introduced the concept of *field*. According to this, we say that the charge Q produces an electric field everywhere in the surrounding.

When another charge q is brought at some point P , the field there acts on it and produces a force. The electric field produced by the charge Q at a point

\mathbf{r} is given as $\mathbf{E}(\mathbf{r})$

1

Q

1

Q

=

$\hat{\mathbf{r}} =$

$\hat{\mathbf{r}}$

2

2

$4\pi\epsilon$

(1.6)

r

4ϵ

πr

0

0

where $\hat{\mathbf{r}} = \mathbf{r}/r$, is a unit vector from the origin to the point \mathbf{r} . Thus, Eq.(1.6) specifies the value of the electric field for each value of the position vector \mathbf{r} . The word “field” signifies how some distributed quantity (which could be a scalar or a vector) varies with position. The effect of the charge has been incorporated in the existence of the electric field. We obtain the

force \mathbf{F} exerted by a charge Q on a charge q , as

1

Qq

$\mathbf{F} =$

$\hat{\mathbf{r}}$

2

(1.7)

$4\pi\epsilon r$

0

Note that the charge q also exerts an equal and opposite force on the

charge Q . The electrostatic force between the charges Q and q can be looked upon as an interaction between charge q and the electric field of Q and *vice versa*. If we denote the position of charge q by the vector \mathbf{r} , it experiences a force \mathbf{F} equal to the charge q multiplied by the electric field \mathbf{E} at the location of q . Thus, $\mathbf{F}(\mathbf{r}) = q \mathbf{E}(\mathbf{r})$

(1.8)

Equation (1.8) defines the SI unit of electric field as N/C*.

Some important remarks may be made here:

(i) From Eq. (1.8), we can infer that if q is unity, the electric field due to a charge Q is numerically equal to the force exerted by it. Thus, the **FIGURE 1.11** Electric

field (a) due to a

electric field due to a charge Q at a point in space may be defined as the force that a unit positive charge would experience if placed

charge $-Q$.

18

* An alternate unit V/m will be introduced in the next chapter.

Electric Charges

and Fields

at that point. The charge Q , which is producing the electric field, is called a *source charge* and the charge q , which tests the effect of a source charge, is called a *test charge*. Note that the source charge Q

must remain at its original location. However, if a charge q is brought at any point around Q , Q itself is bound to experience an electrical force due to q and will tend to move. A way out of this difficulty is to make q negligibly small. The force \mathbf{F} is then negligibly small but the ratio \mathbf{F}/q is finite and defines the electric field: (\mathbf{E})

$$\mathbf{E} = \lim_{q \rightarrow 0} \left(\frac{\mathbf{F}}{q} \right)$$

(1.9)

$$q \rightarrow 0 \text{ (} q \text{)}$$

A practical way to get around the problem (of keeping Q undisturbed in the presence of q) is to hold Q to its location by unspecified forces!

This may look strange but actually this is what happens in practice.

When we are considering the electric force on a test charge q due to a

charged planar sheet (Section 1.15), the charges on the sheet are held to their locations by the forces due to the unspecified charged constituents inside the sheet.

(ii) Note that the electric field \mathbf{E} due to Q , though defined operationally in terms of some test charge q , is independent of q . This is because \mathbf{F} is proportional to q , so the ratio \mathbf{F}/q does not depend on q . The force \mathbf{F} on the charge q due to the charge Q depends on the particular location of charge q which may take any value in the space around the charge Q . Thus, the electric field \mathbf{E} due to Q is also dependent on the space coordinate \mathbf{r} . For different positions of the charge q all over the space, we get different values of electric field \mathbf{E} . The field exists at every point in three-dimensional space.

(iii) For a positive charge, the electric field will be directed radially outwards from the charge. On the other hand, if the source charge is negative, the electric field vector, at each point, points radially inwards.

(iv) Since the magnitude of the force \mathbf{F} on charge q due to charge Q depends only on the distance r of the charge q from charge Q , the magnitude of the electric field \mathbf{E} will also depend only on the distance r . Thus at equal distances from the charge Q , the magnitude of its electric field \mathbf{E} is same. The magnitude of electric field \mathbf{E} due to a point charge is thus same on a sphere with the point charge at its centre; in other words, it has a spherical symmetry.

1.8.1 Electric field due to a system of charges

Consider a system of charges q_1, q_2, \dots, q_n with position vectors $\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_n$

2

n

1

$\mathbf{r}_1, \dots, \mathbf{r}_n$ relative to some origin O . Like the electric field at a point in 2

n

space due to a single charge, electric field at a point in space due to the

system of charges is defined to be the force experienced by a unit

test charge placed at that point, without disturbing the original

positions of charges q_1, q_2, \dots, q_n . We can use Coulomb's law and the 1

2

n

superposition principle to determine this field at a point P denoted by

19

position vector \mathbf{r} .

Physics

Electric field \mathbf{E} at \mathbf{r} due to q at \mathbf{r}' is given by 1

1

1

1

q

$\mathbf{E} =$

$\frac{1}{4\pi\epsilon_0} \frac{q}{r^2} \hat{\mathbf{r}}$

\mathbf{r}

1

2

1P

$4\pi\epsilon r$

0

1P

where $\hat{\mathbf{r}}$ is a unit vector in the direction from q to P,

1P

1

and r is the distance between q and P.

1P

1

In the same manner, electric field \mathbf{E} at \mathbf{r} due to q at

2

2

\mathbf{r} is

2

1

q

$\mathbf{E} =$

$\frac{1}{4\pi\epsilon_0} \sum_i \frac{q_i}{r_i^2} \hat{\mathbf{r}}_i$

where

$\hat{\mathbf{r}}_i$

is a unit vector

in the direction from q_i to P.

r_i is the distance between q_i and P.

Similar

expressions hold good for fields $\mathbf{E}_1, \mathbf{E}_2, \dots, \mathbf{E}_n$ due to

charges q_1, q_2, \dots, q_n respectively.

FIGURE 1.12 Electric field at a

point due to a system of charges is

the vector sum of the fields $\mathbf{E}_1, \mathbf{E}_2, \dots, \mathbf{E}_n$ due to

charges q_1, q_2, \dots, q_n respectively.

FIGURE 1.12

Electric field at a

point due to a system of charges is

the vector sum of the fields $\mathbf{E}_1, \mathbf{E}_2, \dots, \mathbf{E}_n$ due to

charges q_1, q_2, \dots, q_n respectively.

FIGURE 1.12

n

the vector sum of the electric fields

charges q_1, q_2, \dots, q_n .

3

4

n

at the point due to individual

By the superposition principle, the electric field \mathbf{E} at \mathbf{r} charges.

due to the system of charges is (as shown in Fig. 1.12)

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}_1(\mathbf{r}) + \mathbf{E}_2(\mathbf{r}) + \dots + \mathbf{E}_n(\mathbf{r})$$

2

n

1

q_1

1

q_2

1

q_n

=

1

2

$\hat{\mathbf{r}}$

+

$\hat{\mathbf{r}}$

+ ...

n

+

$\hat{\mathbf{r}}$

2

1P

2

2P

2

n P

$4\pi\epsilon r$

$4\pi\epsilon r$

$4\pi\epsilon r$

0

1P

0

2P

0

n P

1

n

q

$\mathbf{E}(\mathbf{r}) =$

i

$\sum \hat{\mathbf{r}}$

(1.10)

2

i P

$4\pi\epsilon$

r

$0 i 1$

=

i P

\mathbf{E} is a vector quantity that varies from one point to another point in space and is determined from the positions of the source charges.

1.8.2 Physical significance of electric field

You may wonder why the notion of electric field has been introduced here at all. After all, for any system of charges, the measurable quantity is the force on a charge which can be directly determined using Coulomb's law and the superposition principle [Eq. (1.5)]. Why then introduce this intermediate quantity called the electric field?

For electrostatics, the concept of electric field is convenient, but not really necessary. Electric field is an elegant way of characterising the electrical environment of a system of charges. Electric field at a point in the space around a system of charges tells you the force a unit positive test charge would experience if placed at that point (without disturbing the system). Electric field is a characteristic of the system of charges and is independent of the test charge that you place at a point to determine the field. The term *field* in physics generally refers to a quantity that is defined at every point in space and may vary from point to point. Electric field is a vector field, since force is a vector quantity.

The true physical significance of the concept of electric field, however, emerges only when we go beyond electrostatics and deal with time-dependent electromagnetic phenomena. Suppose we consider the force between two distant charges q_1, q_2 in accelerated motion. Now the greatest 1
2
speed with which a signal or information can go from one point to another

20

is c , the speed of light. Thus, the effect of any motion of q on q cannot 1

2

Electric Charges

and Fields

arise instantaneously. There will be some time delay between the effect

(force on q) and the cause (motion of q). It is precisely here that the 2

1

notion of electric field (strictly, electromagnetic field) is natural and very

useful. *The field picture is this: the accelerated motion of charge q 1*

produces electromagnetic waves, which then propagate with the speed

c , reach q and cause a force on q . The notion of field elegantly accounts 2

2

for the time delay. Thus, even though electric and magnetic fields can be

detected only by their effects (forces) on charges, they are regarded as

physical entities, not merely mathematical constructs. They have an

independent dynamics of their own, i.e., they evolve according to laws of their *own*. They can also transport energy. Thus, a source of time-dependent electromagnetic fields, turned on briefly and switched off, leaves behind propagating electromagnetic fields transporting energy. The

concept of field was first introduced by Faraday and is now among the

central concepts in physics.

Example 1.8 An electron falls through a distance of 1.5 cm in a uniform electric field of magnitude $2.0 \times 10^4 \text{ N C}^{-1}$ [Fig. 1.13(a)]. The direction of the field is reversed keeping its magnitude unchanged and a proton falls through the same distance [Fig. 1.13(b)]. Compute the time of fall in each case. Contrast the situation with that of ‘free fall under gravity’.

FIGURE 1.13

Solution In Fig. 1.13(a) the field is upward, so the negatively charged electron experiences a downward force of magnitude eE where E is the magnitude of the electric field. The acceleration of the electron is $a = eE/m$

e

e

where m is the mass of the electron.

e

Starting from rest, the time required by the electron to fall through a

$2h$

$2hm/e$

distance h is given by $t =$

$=$

e

a

eE

e

For $e = 1.6 \times 10^{-19}\text{C}$, $m = 9.11 \times 10^{-31}\text{ kg}$,

e

$E = 2.0 \times 10^4\text{ N C}^{-1}$, $h = 1.5 \times 10^{-2}\text{ m}$,

$t = 2.9 \times 10^{-9}\text{s}$

e

In Fig. 1.13 (b), the field is downward, and the positively charged

E

proton experiences a downward force of magnitude eE . The

XAMPLE

acceleration of the proton is

$$a = eE / m$$

p

p

1.8

where m is the mass of the proton; $m = 1.67 \times 10^{-27}\text{ kg}$. The time of *p*

p

fall for the proton is

21

Physics

$2 h$

$2 h m p$

-7

t

=

=

$= 1.3 \times 10^{-7} \text{ s}$

p

a

$e E$

p

Thus, the heavier particle (proton) takes a greater time to fall through the same distance. This is in basic contrast to the situation of ‘free fall under gravity’ where the time of fall is independent of the mass of the body. Note that in this example we have ignored the acceleration due to gravity in calculating the time of fall. To see if this is justified, let us calculate the acceleration of the proton in the given electric field:

$e E$

$a =$

p

$m p$

-19

4

1

$(1.6 \times 10$

$C) \times (2.0 \times 10$

$N C-)$

$=$

27

16

$.7 \times 10^{-}$

kg

12

-2

$= 19$

$\times 10$

m s

1.8

which is enormous compared to the value of g (9.8 m s^{-2}), the acceleration due to gravity. The acceleration of the electron is even **XAMPLE**

greater. Thus, the effect of acceleration due to gravity can be ignored

E

in this example.

Example 1.9 Two point charges q and q , of magnitude $+10^{-8} \text{ C}$ and 1

2

-10^{-8} C , respectively, are placed 0.1 m apart. Calculate the electric

fields at points A, B and C shown in Fig. 1.14.

FIGURE 1.14

Solution The electric field vector **E** at A due to the positive charge $1A$

q points towards the right and has a magnitude

1

9

2

-2

8

$(9 \times 10^9 \text{ Nm}^2 \text{ C}^{-2}) (10^{-8})$

\times

\times

C)

E

$=$

$$= 3.6 \times 10^4 \text{ N C}^{-1}$$

1A

2

(0.05 m)

The electric field vector \mathbf{E} at A due to the negative charge q points 2A

2

1.9

towards the right and has the same magnitude. Hence the magnitude

of the total electric field E at A is

A

$$E = E + E = 7.2 \times 10^4 \text{ N C}^{-1}$$

A

1A

2A

XAMPLE

E is directed toward the right.

22

E

A

Electric Charges

and Fields

The electric field vector **E** at B due to the positive charge *q* points 1B

1

towards the left and has a magnitude

9

2

-2

8

(9 10 Nm C) (10-

×

×

C)

E

=

$$= 3.6 \times 10^4 \text{ N C}^{-1}$$

1B

2

(0.05 m)

The electric field vector \mathbf{E} at B due to the negative charge q points 2B

2

towards the right and has a magnitude

9

2

-2

8

(9 10 Nm C) (10-

×

×

C)

E

=

$$= 4 \times 10^3 \text{ N C}^{-1}$$

2B

2

(0.15 m)

The magnitude of the total electric field at B is

$$E = E - E = 3.2 \times 10^4 \text{ N C}^{-1}$$

B

1B

2B

E is directed towards the left.

B

The magnitude of each electric field vector at point C, due to charge

q and q is

1

2

9

2

-2

-8

$$(9 \times 10 \text{ Nm C}) \times (10 \text{ C})$$

E

$= E$

=

$$= 9 \times 10^3 \text{ N C}^{-1}$$

$$1 \text{ C}$$

$$2 \text{ C}$$

$$2$$

$$(0.10 \text{ m})$$

E

The directions in which these two vectors point are indicated in

XAMPLE

Fig. 1.14. The resultant of these two vectors is

$$\pi$$

$$\pi$$

$$E = E \cos$$

$$+ E \cos$$

$$= 9 \times 10^3 \text{ N C}^{-1}$$

1.9

C

1

2

3

3

\mathbf{E} points towards the right.

C

1.9 ELECTRIC FIELD LINES

We have studied electric field in the last section. It is a vector quantity and can be represented as we represent vectors. Let us try to represent \mathbf{E} due to a point charge pictorially. Let the point charge be placed at the origin. Draw vectors pointing along the direction of the electric field with their lengths proportional to the strength of the field at each point. Since the magnitude of electric field at a point decreases inversely as the square of the distance of that point from the charge, the vector gets shorter as one goes away from the origin, always pointing radially outward.

Figure 1.15 shows such a picture. In this figure, each arrow indicates the electric field, i.e., the force acting on a unit positive charge, placed at the tail of that arrow.

Connect the arrows pointing in one direction and the resulting figure represents a field line. We thus get many field lines, all pointing outwards from the point charge.

Have we lost the information about the strength or magnitude of the field now, because it was contained in

the length of the arrow? No. Now the magnitude of the field is represented by the density of field lines. \mathbf{E} is strong near the charge, so the density of field lines is more near the charge and the lines are closer. Away from the charge, **FIGURE 1.15** Field of a point charge.

the field gets weaker and the density of field lines is less, resulting in well-separated lines.

Another person may draw more lines. But the number of lines is not

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important. In fact, an infinite number of lines can be drawn in any region.

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It is the relative density of lines in different regions which is important.

We draw the figure on the plane of paper, *i.e.*, in two-dimensions but we live in three-dimensions. So if one wishes

to estimate the density of field lines, one has to consider the

number of lines per unit cross-sectional area, perpendicular

to the lines. Since the electric field decreases as the square of

the distance from a point charge and the area enclosing the

charge increases as the square of the distance, the number

of field lines crossing the enclosing area remains constant,

whatever may be the distance of the area from the charge.

We started by saying that the field lines carry information about the direction of electric field at different points in space.

FIGURE 1.16 Dependence of

Having drawn a certain set of field lines, the relative density electric field strength on the

(i.e., closeness) of the field lines at different points indicates distance and its relation to the

the relative strength of electric field at those points. The field number of field lines.

lines crowd where the field is strong and are spaced apart

where it is weak. Figure 1.16 shows a set of field lines. We

can imagine two equal and small elements of area placed at points R and S normal to the field lines there. The number of field lines in our picture

cutting the area elements is proportional to the magnitude of field at these points. The picture shows that the field at R is stronger than at S.

To understand the dependence of the field lines on the area, or rather

the *solid angle* subtended by an area element, let us try to relate the area with the solid angle, a generalization of angle to three dimensions.

Recall how a (plane) angle is defined in two-dimensions. Let a small

transverse line element Δl be placed at a distance r from a point O. Then the angle subtended by Δl at O can be approximated as $\Delta\theta = \Delta l / r$.

Likewise, in three-dimensions the solid angle* subtended by a small

perpendicular plane area ΔS , at a distance r , can be written as $\Delta\Omega = \Delta S / r^2$

2. We know that in a given solid angle the number of radial field lines is the same. In Fig. 1.16, for two points P and P at distances r_1

2

r_2 and r from the charge, the element of area subtending the solid angle $\Delta\Omega$

2

$\Delta\Omega$ is $\Delta S_1 / r_1^2$

$r_2 \Delta\Omega$ at P and an element of area ΔS_2

$r_1 \Delta\Omega$ at P, respectively. The

1

1

2

2

number of lines (say n) cutting these area elements are the same. The

number of field lines, cutting unit area element is therefore $n / (2$

$r \Delta\Omega)$ at

1

P and $n / (2$

$r \Delta\Omega$) at P, respectively. Since n and $\Delta\Omega$ are common, the

1

2

2

strength of the field clearly has a $1/r^2$ dependence.

The picture of field lines was invented by Faraday to develop an intuitive non-mathematical way of visualizing electric fields around charged configurations. Faraday called them *lines of force*. *This term is somewhat misleading, especially in case of magnetic fields. The more appropriate term is field lines (electric or magnetic) that we have adopted in this book.*

Electric field lines are thus a way of pictorially mapping the electric field around a configuration of charges. An electric field line is, in general,

* Solid angle is a measure of a cone. Consider the intersection of the given cone with a sphere of radius R . The solid angle $\Delta\Omega$ of the cone is defined to be equal to

$\Delta S/R^2$, where ΔS is the area on the sphere cut out by the cone.

Electric Charges

and Fields

a curve drawn in such a way that the tangent to it at each point is in the direction of the net field at that point. An

arrow on the curve is obviously necessary to specify the direction of electric field from the two possible directions indicated by a tangent to the curve. A field line is a space curve, i.e., a curve in three dimensions.

Figure 1.17 shows the field lines around some simple charge configurations. As mentioned earlier, the field lines are in 3-dimensional space, though the figure shows them only in a plane. The field lines of a single positive charge are radially outward while those of a single negative charge are radially inward. The field lines around a system of two positive charges (q, q) give a vivid pictorial description of their mutual repulsion, while those around the configuration of two equal and opposite charges ($q, -q$), a dipole, show clearly the mutual attraction between the charges. The field lines follow some important general properties:

(i) Field lines start from positive charges and end at negative charges. If there is a single charge, they may start or end at infinity.

(ii) In a charge-free region, electric field lines can be taken

to be continuous curves without any breaks.

(iii) Two field lines can never cross each other. (If they did, the field at the point of intersection will not have a unique direction, which is absurd.)

(iv) Electro *static* field lines do not form any closed loops.

This follows from the conservative nature of electric field (Chapter 2).

1.10 ELECTRIC FLUX

Consider flow of a liquid with velocity \mathbf{v} , through a small flat surface dS , in a direction normal to the surface. The rate of flow of liquid is given by the volume crossing the

area per unit time $v dS$ and represents the flux of liquid flowing across the plane. If the normal to the surface is not parallel to the direction of flow of liquid, *i.e.*, to \mathbf{v} , but makes an angle θ with it, the projected area in a plane perpendicular to \mathbf{v} is $v dS \cos \theta$. Therefore the flux going out of the surface dS is $\mathbf{v} \cdot \hat{\mathbf{n}} dS$.

$\mathbf{n} dS$.

For the case of the electric field, we define an analogous quantity and call it *electric flux*.

We should however note that there is no *flow* of a physically observable quantity unlike the case of liquid flow.

In the picture of electric field lines described above,

FIGURE 1.17 Field lines due to

we saw that the number of field lines crossing a unit area,
some simple charge configurations.

placed normal to the field at a point is a measure of the

25

strength of electric field at that point. This means that if





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we place a small planar element of area ΔS normal to \mathbf{E} at a point, the number of field lines crossing it is proportional* to $E \Delta S$. Now suppose we tilt the area element by angle θ . Clearly, the number of field lines crossing the area element will be smaller. The projection of

the area element normal to E is $\Delta S \cos\theta$. Thus, the number of field lines crossing ΔS is proportional to $E \Delta S \cos\theta$. When $\theta = 90^\circ$, field lines will be parallel to ΔS and will not cross it at all (Fig. 1.18).

The orientation of area element and not merely its magnitude is important in many contexts. For example, in a stream, the amount of water flowing through a ring will naturally depend on how you hold the ring. If you hold it normal to the flow, maximum water will flow

FIGURE 1.18 Dependence of flux on the through it than if you hold it with some other inclination θ between \mathbf{E} and $\hat{\mathbf{n}}$.

orientation. This shows that an area element should be treated as a vector. It has a magnitude and also a direction. How to specify the direction of a planar area? Clearly, the normal to the plane specifies the orientation of the plane. Thus the direction of a planar area vector is along its normal. How to associate a vector to the area of a curved surface? We imagine

dividing the surface into a large number of very small area elements.

Each small area element may be treated as planar and a vector associated with it, as explained before.

Notice one ambiguity here. The direction of an area element is along its normal. But a normal can point in two directions. Which direction do we choose as the direction of the vector associated with the area element?

This problem is resolved by some convention appropriate to the given context. For the case of a closed surface, this convention is very simple.

The vector associated with every area element of a closed surface is taken to be in the direction of the *outward* normal. This is the convention used in Fig. 1.19. Thus, the area element vector $\Delta \mathbf{S}$ at a point on a closed surface equals $\Delta S \hat{\mathbf{n}}$

where ΔS is the magnitude of the area element and

$\hat{\mathbf{n}}$

is a unit vector in the direction of outward normal at that point.

We now come to the definition of electric flux. Electric flux $\Delta \phi$ through an area element $\Delta \mathbf{S}$ is defined by

$$\Delta \phi = \mathbf{E} \cdot \Delta \mathbf{S} = E \Delta S \cos \theta$$

(1.11)

which, as seen before, is proportional to the number of field lines cutting

the area element. The angle θ here is the angle between \mathbf{E} and $\Delta\mathbf{S}$. For a closed surface, with the convention stated already, θ is the angle between \mathbf{E} and the outward normal to the area element. Notice we could look at

FIGURE 1.19

the expression $E \Delta S \cos\theta$ in two ways: $E (\Delta S \cos\theta)$ i.e., E times the
 Convention for defining normal

^

\mathbf{n} and ΔS .

* It will not be proper to say that the number of field lines is equal to $E\Delta S$. The number of field lines is after all, a matter of how many field lines we choose to draw. What is physically significant is the relative number of field lines crossing

a given area at different points.

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projection of area normal to \mathbf{E} , or $E \perp \Delta S$, i.e., component of \mathbf{E} along the normal to the area element times the magnitude of the area element. The unit of electric flux is $\text{N C}^{-1} \text{m}^2$.

The basic definition of electric flux given by Eq. (1.11) can be used, in principle, to calculate the total flux through any given surface. All we have to do is to divide the surface into small area elements, calculate the flux at each element and add them up. Thus, the total flux ϕ through a surface S is

$$\phi \sim \sum \mathbf{E} \cdot \Delta\mathbf{S}$$

(1.12)

The approximation sign is put because the electric field \mathbf{E} is taken to be constant over the small area element. This is mathematically exact only when you take the limit $\Delta S \rightarrow 0$ and the sum in Eq. (1.12) is written as an integral.

1.11 ELECTRIC DIPOLE

An electric dipole is a pair of equal and opposite point charges q and $-q$, separated by a distance $2a$. The line connecting the two charges defines a direction in space. By convention, the direction from $-q$ to q is said to be the direction of the dipole. The midpoint of locations of $-q$ and q is called the centre of the dipole.

The total charge of the electric dipole is obviously zero. This does not mean that the field of the electric dipole is zero. Since the charge q and $-q$ are separated by some distance, the electric fields due to them, when added, do not exactly cancel out. However, at distances much larger than the separation of the two charges forming a dipole ($r \gg 2a$), the fields due to q and $-q$ nearly cancel out. The electric field due to a dipole therefore falls off, at large distance, faster than like $1/r^2$ (the dependence on r of the field due to a single charge q). These qualitative ideas are borne out by the explicit calculation as follows: **1.11.1 The field of an electric dipole**

The electric field of the pair of charges ($-q$ and q) at any point in space can be found out from Coulomb's law and the superposition principle.

The results are simple for the following two cases: (i) when the point is on the dipole axis, and (ii) when it is in the *equatorial plane* of the dipole, i.e., on a plane perpendicular to the dipole axis through its centre. The electric field at any general point P is obtained by adding the electric

fields \mathbf{E} due to the charge $-q$ and \mathbf{E} due to the charge q , by the

$-q$

$+q$

parallelogram law of vectors.

(i) For points on the axis

Let the point P be at distance r from the centre of the dipole on the side of the charge q , as shown in Fig. 1.20(a). Then q

E

$= -$

\hat{p}

$-$

p

q

2

$4\pi\epsilon (r + a)$

[1.13(a)]

0

where \hat{p}

p is the unit vector along the dipole axis (from $-q$ to q). Also q

E

$=$

^

+

p

q

2

[1.13(b)]

27

$4 \pi \epsilon (r - a)$

0

Physics

The total field at P is

q

[

1

1

]

E = E

+ **E =**

|

-

^

+

p

q

- *q*

|

2

2

$4 \pi \epsilon [(r - a)$

$(r + a)$

0

]

q

$4 a r$

=

^

p

2

2 2

$4 \pi \epsilon$

(1.14)

$(r - a)$

o

For $r \gg a$

$4 q a$

$\mathbf{E} =$

\hat{r}

\mathbf{p}

3

$(r \gg a)$

(1.15)

$4\pi\epsilon r$

0

(ii) For points on the equatorial plane

The magnitudes of the electric fields due to the two charges $+q$ and $-q$ are given by

q

1

E

=

$+q$

2

2

$4\pi\epsilon r +$

[1.16(a)]

a

0

q

1

E

=

$-q$

2

2

$4\pi\epsilon r +$

[1.16(b)]

a

0

FIGURE 1.20 Electric field of a dipole and are equal.

at (a) a point on the axis, (b) a point

The directions of \mathbf{E} and \mathbf{E} are as shown in

$+q$

$-q$

on the equatorial plane of the dipole. Fig. 1.20(b). Clearly, the components normal to the dipole \mathbf{p} is the dipole moment vector of axis cancel away. The components along the dipole axis

magnitude $p = q \times 2a$ and

add up. The total electric field is opposite to $\hat{\mathbf{p}}$

\mathbf{p} . We have

directed from $-q$ to q .

$$\mathbf{E} = - (E + E) \cos\theta \hat{\mathbf{p}}$$

$+q$

$-q$

$2qa$

$= -$

$\hat{\mathbf{p}}$

\mathbf{p}

2

$23/2$

(1.17)

$$4\pi\epsilon(r+a)$$

o

At large distances ($r \gg a$), this reduces to

$$2 q a$$

$$\mathbf{E} = -$$

\hat{r}

\mathbf{p}

$$(r \gg a)$$

3

$$(1.18)$$

$$4 \pi \epsilon r$$

o

From Eqs. (1.15) and (1.18), it is clear that the dipole field at large

distances does not involve q and a separately; it depends on the product qa . This suggests the definition of dipole moment. The *dipole moment vector* \mathbf{p} of an electric dipole is defined by $\mathbf{p} = q \times 2 a \hat{r}$

\mathbf{p}

$$(1.19)$$

that is, it is a vector whose magnitude is charge q times the separation $2 a$ (between the pair of charges $q, -q$) and the direction is along the line from $-q$ to q . In terms of \mathbf{p} , the electric field of a dipole at large distances takes simple forms: *At a point on the dipole axis*

2

=

p

E

3

$(r \gg a)$

(1.20)

$4\pi\epsilon r$

o

At a point on the equatorial plane

E = -

p

28

3

$4\pi\epsilon r$

$(r \gg a)$

(1.21)

o

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and Fields

Notice the important point that the dipole field at large distances

falls off not as $1/r^2$ but as $1/r^3$. Further, the magnitude and the direction of the dipole field depends not only on the distance r but also on the *angle* between the position vector \mathbf{r} and the dipole moment \mathbf{p} .

We can think of the limit when the dipole size $2a$ approaches zero,

the charge q approaches infinity in such a way that the product

$p = q \times 2a$ is finite. Such a dipole is referred to as a *point dipole*. For a point dipole, Eqs. (1.20) and (1.21) are exact, true for any r .

1.11.2 Physical significance of dipoles

In most molecules, the centres of positive charges and of negative charges*

lie at the same place. Therefore, their dipole moment is zero. CO and

2

CH are of this type of molecules. However, they develop a dipole moment

4

when an electric field is applied. But in some molecules, the centres of negative charges and of positive charges do not coincide. Therefore they have a permanent electric dipole moment, even in the absence of an electric field. Such molecules are called polar molecules. Water molecules, H₂O,

2

is an example of this type. Various materials give rise to interesting properties and important applications in the presence or absence of

electric field.

Example 1.10 Two charges $\pm 10 \mu\text{C}$ are placed 5.0 mm apart.

Determine the electric field at (a) a point P on the axis of the dipole 15 cm away from its centre O on the side of the positive charge, as shown in Fig. 1.21(a), and (b) a point Q, 15 cm away from O on a line passing through O and normal to the axis of the dipole, as shown in Fig. 1.21(b).

E

XAMPLE

1.10

FIGURE 1.21

* Centre of a collection of positive point charges is defined much the same way

$$\sum q \mathbf{r}$$

i i

as the centre of mass:

i

r

=

.

cm

$$\sum q_i$$

29

i

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Solution (a) Field at P due to charge $+10 \mu\text{C}$

5

10^{-6} C

1

=

×

-12

2

1

—

2

—

$4 (8.854 \times 10^{-12})$

C N^{-2}

m^{-2}

π

\times

)

2

4

2

$(15 - 0.25) \times 10$

m

$= 4.13 \times 10^6 \text{ N C}^{-1}$ along BP

Field at P due to charge $-10 \mu\text{C}$

-5

10 C

=

1

\times

12

-

2

-1

-2

-

$$4\pi (8.854 \times$$

10

C N

m)

2

4

2

$$(15 + 0.25) \times 10$$

m

$$= 3.86 \times 10^6 \text{ N C}^{-1} \text{ along PA}$$

The resultant electric field at P due to the two charges at A and B is

$$= 2.7 \times 10^5 \text{ N C}^{-1} \text{ along BP.}$$

In this example, the ratio OP/OB is quite large (= 60). Thus, we can

expect to get approximately the same result as above by directly using

the formula for electric field at a far-away point on the axis of a dipole.

For a dipole consisting of charges $\pm q$, $2a$ distance apart, the electric field at a distance r from the centre on the axis of the dipole has a magnitude

$$2p$$

$$E =$$

3

$$(r/a \gg 1)$$

$$4\pi\epsilon r$$

0

where $p = 2 a q$ is the magnitude of the dipole moment.

The direction of electric field on the dipole axis is always along the

direction of the dipole moment vector (i.e., from $-q$ to q). Here, $p = 10^{-5} \text{ C} \times 5 \times 10^{-3} \text{ m} = 5 \times 10^{-8} \text{ C m}$ Therefore,

-8

$$2 \times 5 \times 10$$

C m

1

$$E =$$

×

12

—

2

1

—

2

—

$$4\pi (8.854 \times 10$$

$$\text{C N m}^{-2})$$

3

6

3

$$(15) \times$$

$$= 2.6 \times 10^5 \text{ N C}^{-1}$$

10

m

along the dipole moment direction AB, which is close to the result obtained earlier.

(b) Field at Q due to charge + 10 μC at B

5

10⁻⁶ C

1

=

×

12

—

2

1

—

−2

$$4 \pi (8.854 \times 10$$

C N

m

)

2

2

4

—

2

$$[15 + (0.25)] \times 10$$

m

$$= 3.99 \times 10^6 \text{ N C}^{-1} \text{ along BQ}$$

Field at Q due to charge $-10 \mu\text{C}$ at A

5

10- C

1

=

×

-12

2

1

-

-2

-

$4 \pi (8.854 \times 10$

C N

m)

2

2

4

2

$[15 + (0.25)] \times 10 \text{ m}$

$= 3.99 \times 10^6 \text{ N C}^{-1} \text{ along QA.}$

Clearly, the components of these two forces with equal magnitudes

cancel along the direction OQ but add up along the direction parallel to BA. Therefore, the resultant electric field at Q due to the two charges at A and B is

$$0.25$$

$$6$$

$$-1$$

$$= 2 \times$$

$$\times 3.99 \times 10 \text{ N C along BA}$$

$$2$$

$$2$$

$$15$$

$$+ (0.25)$$

$$\mathbf{1.10}$$

$$= 1.33 \times 10^5 \text{ N C}^{-1} \text{ along BA.}$$

As in (a), we can expect to get approximately the same result by

XAMPLE

directly using the formula for dipole field at a point on the normal to

$$30$$

$$\mathbf{E}$$

the axis of the dipole:

Electric Charges
and Fields

ρ

$E =$

3

$(r/a \gg 1)$

$4\pi\epsilon r$

0

8

E

5×10

C m

1

XAMPLE

12

2

-1

-2

$4\pi (8.854 \times 10$

C N

m)

3

6

3

$(15) \times 10$

m

$= 1.33 \times 10^5 \text{ N C}^{-1}$.

The direction of electric field in this case is opposite to the direction

1.10

of the dipole moment vector. Again the result agrees with that obtained before.

1.12 DIPOLE IN A UNIFORM EXTERNAL FIELD

Consider a permanent dipole of dipole moment \mathbf{p} in a uniform

external field \mathbf{E} , as shown in Fig. 1.22. (By permanent dipole, we

mean that \mathbf{p} exists irrespective of \mathbf{E} ; it has not been induced by \mathbf{E} .) There is a force $q\mathbf{E}$ on q and a force $-q\mathbf{E}$ on $-q$. The net force on the dipole is zero,

since \mathbf{E} is uniform. However, the charges are separated, so the forces act at different points, resulting in a torque

on the dipole. When the net force is zero, the torque (couple) is independent of the origin. Its magnitude equals the magnitude of

FIGURE 1.22 Dipole in a

each force multiplied by the arm of the couple (perpendicular uniform electric field.

distance between the two antiparallel forces).

Magnitude of torque = $q E \times 2 a \sin\theta$

$$= 2 q a E \sin\theta$$

Its direction is normal to the plane of the paper, coming out of it.

The magnitude of $\mathbf{p} \times \mathbf{E}$ is also $p E \sin\theta$ and its direction is normal to the paper, coming out of it. Thus, $\boldsymbol{\tau} = \mathbf{p} \times \mathbf{E}$

(1.22)

This torque will tend to align the dipole with the field

\mathbf{E} . When \mathbf{p} is aligned with \mathbf{E} , the torque is zero.

What happens if the field is not uniform? In that case, the net force will evidently be nonzero. In addition there will, in general, be a torque on the system as before. The general case is involved, so let us consider the simpler

situations when \mathbf{p} is parallel to \mathbf{E} or antiparallel to \mathbf{E} . In either case, the net torque is zero, but there is a net force on the dipole if \mathbf{E} is not uniform.

Figure 1.23 is self-explanatory. It is easily seen that

when \mathbf{p} is parallel to \mathbf{E} , the dipole has a net force in the direction of increasing field. When \mathbf{p} is antiparallel to \mathbf{E} , the net force on the dipole is in the direction of decreasing field. In general, the force depends on the orientation of \mathbf{p} with respect to \mathbf{E} .

This brings us to a common observation in frictional electricity. A comb run through dry hair attracts pieces of

FIGURE 1.23 Electric force on a

paper. The comb, as we know, acquires charge through

dipole: (a) \mathbf{E} parallel to \mathbf{p} , (b) \mathbf{E}

friction. But the paper is not charged. What then explains antiparallel to \mathbf{p} .

31

the attractive force? Taking the clue from the preceding

Physics

discussion, the charged comb ‘polarizes’ the piece of paper, i.e., induces a net dipole moment in the direction of field. Further, the electric field due to the comb is not uniform. In this situation, it is easily seen that the

paper should move in the direction of the comb!

1.13 CONTINUOUS CHARGE DISTRIBUTION

We have so far dealt with charge configurations involving discrete charges q_1, q_2, \dots, q_n . One reason why we restricted to discrete charges is that the

mathematical

treatment

is simpler and does not involve calculus. For

many purposes, however, it is impractical to work in terms of discrete

charges and we need to work with continuous charge distributions. For

example, on the surface of a charged conductor, it is impractical to specify

the charge distribution in terms of the locations of the microscopic charged

constituents. It is more feasible to consider an area element ΔS (Fig. 1.24) on the surface of the conductor (which is very small on the macroscopic scale but big enough to include a very large number of electrons) and

specify the charge ΔQ on that element. We then define a *surface charge density* σ at the area element by Q

$$\sigma$$
$$\Delta$$
$$= S$$
$$\Delta$$
$$(1.23)$$

We can do this at different points on the conductor and thus arrive at a continuous function σ , called the surface charge density. The surface charge density σ so defined ignores the quantisation of charge and the discontinuity in charge distribution at the microscopic level*. σ represents macroscopic surface charge density, which in a sense, is a smoothed out average of the microscopic charge density over an area element ΔS which, as said before, is large microscopically but small macroscopically. The units for σ are C/m².

Similar considerations apply for a line charge distribution and a volume

FIGURE 1.24

charge distribution. The *linear charge density* λ of a wire is defined by Definition of linear,

$$Q$$

surface and volume

$$\lambda$$

$$\Delta$$

$$= \Delta$$

$$(1.24)$$

$$l$$

charge densities.

In each case, the

where Δl is a small line element of wire on the macroscopic scale that, element ($\Delta l, \Delta S, \Delta V$) however, includes a large number of microscopic

charged constituents,

chosen is small on

and ΔQ is the charge contained in that line element. The units for λ are the macroscopic

C/m. The *volume charge density* (sometimes simply called charge density) scale but contains

is defined in a similar manner:

a very large number

of microscopic

Q

ρ

Δ

=

constituents.

Δ

(1.25)

V

where ΔQ is the charge included in the macroscopically small volume element ΔV that includes a large number of microscopic charged constituents. The units for ρ are C/m³.

The notion of continuous charge distribution is similar to that we

adopt for continuous mass distribution in mechanics. When we refer to

* At the microscopic level, charge distribution is discontinuous, because they are 32

discrete charges separated by intervening space where there is no charge.

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and Fields

the density of a liquid, we are referring to its macroscopic density. We regard it as a continuous fluid and ignore its discrete molecular constitution.

The field due to a continuous charge distribution can be obtained in much the same way as for a system of discrete charges, Eq. (1.10). Suppose a continuous charge distribution in space has a charge density ρ . Choose any convenient origin O and let the position vector of any point in the charge distribution be \mathbf{r} . The charge density ρ may vary from point to point, i.e., it is a function of \mathbf{r} . Divide the charge distribution into small volume elements of size ΔV . The charge in a volume element ΔV is $\rho \Delta V$.

Now, consider any general point P (inside or outside the distribution)

with position vector \mathbf{R} (Fig. 1.24). Electric field due to the charge $\rho \Delta V$ is given by Coulomb's law: 1

$$\rho \Delta V$$

$$\Delta \mathbf{E} =$$

\hat{r}'

\mathbf{r}

2

(1.26)

$4\pi\epsilon$

r'

0

where r' is the distance between the charge element and P, and \hat{r}' is a unit vector in the direction from the charge element to P. By the superposition principle, the total electric field due to the charge

distribution is obtained by summing over electric fields due to different

volume elements:

1

ρV

Δ

$\mathbf{E} \cong$

Σ

\hat{r}

\mathbf{r}

2

4

(1.27)

all

V

$\pi\epsilon$

Δ

r'

0

Note that ρ , r' , $\hat{\mathbf{r}}'$ all can vary from point to point. In a strict mathematical method, we should let $\Delta V \rightarrow 0$ and the sum then becomes an integral; but we omit that discussion here, for simplicity. In short,

using Coulomb's law and the superposition principle, electric field can be determined for any charge distribution, discrete or continuous or part discrete and part continuous.

1.14 GAUSS'S LAW

As a simple application of the notion of electric flux, let us consider the total flux through a sphere of radius r , which encloses a point charge q at its centre. Divide the sphere into small area elements, as shown in Fig. 1.25.

The flux through an area element ΔS is

$$\Delta\phi = \mathbf{E} \cdot \Delta \mathbf{S} =$$

$$E \Delta S \cos \theta$$

$$= \frac{q}{4\pi\epsilon_0 r^2} \Delta S \cos \theta$$

$$(1.28)$$

$$= \frac{q}{4\pi\epsilon_0 r^2} \Delta S \cos \theta$$

$$\pi r^2 \cos \theta$$

$$0$$

where we have used Coulomb's law for the electric field due to a single charge q . The unit vector $\hat{\mathbf{r}}$

\mathbf{r} is along the radius vector from the centre to

the area element. Now, since the normal to a sphere at every point is

along the radius vector at that point, the area element ΔS and \hat{r} have the same direction. Therefore, q

FIGURE 1.25 Flux

$$\Delta\phi =$$

$$\Delta S$$

through a sphere

$$2$$

$$4\pi\epsilon r$$

$$(1.29)$$

$$0$$

enclosing a point

since the magnitude of a unit vector is 1.

charge q at its centre.

The total flux through the sphere is obtained by adding up flux

33

through all the different area elements:



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Physics

q

$$\varphi = \Sigma$$

ΔS

2

all S

Δ

$4 \pi \epsilon r$

0

Since each area element of the sphere is at the same distance r from the charge,

FIGURE 1.26 Calculation of the

q

q

$\varphi =$

$\Sigma \Delta S =$

S

2

2

flux of uniform electric field

4

all S

$\pi \epsilon r$

Δ

$$4\pi\epsilon r$$

$$o$$

$$0$$

through the surface of a cylinder.

Now S , the total area of the sphere, equals $4\pi r^2$. Thus,

$$q$$

$$q$$

$$2$$

$$\phi =$$

$$\times 4\pi r^2 =$$

$$2$$

$$4\pi\epsilon r$$

$$\epsilon$$

$$(1.30)$$

$$0$$

$$0$$

Equation (1.30) is a simple illustration of a general result of electrostatics called Gauss's law.

We state *Gauss's law* without proof:

Electric flux through a closed surface S

$$= q/\epsilon$$

(1.31)

0

$q = \text{total charge enclosed by } S.$

The law implies that the total electric flux through a closed surface is zero if no charge is enclosed by the surface. We can see that explicitly in the simple situation of Fig. 1.26.

Here the electric field is uniform and we are considering a closed cylindrical surface, with its axis parallel to the uniform field \mathbf{E} . The total flux ϕ through the surface is $\phi = \phi_1 + \phi_2 + \phi_3$, where ϕ_1 and ϕ_2 represent

2

3

1

2

the flux through the surfaces 1 and 2 (of circular cross-section) of the cylinder and ϕ_3 is the flux through the curved cylindrical part of the

3

closed surface. Now the normal to the surface 3 at every point is perpendicular to \mathbf{E} , so by definition of flux, $\phi_3 = 0$. Further, the outward normal to 2 is along \mathbf{E} while the outward normal to 1 is opposite to \mathbf{E} .

Therefore,

$$\phi = - E S, \phi = + E S$$

1

1

2

2

$$S = S = S$$

1

2

where S is the area of circular cross-section. Thus, the total flux is zero, as expected by Gauss's law. Thus, whenever you find that the net electric flux through a closed surface is zero, we conclude that the total charge

contained in the closed surface is zero.

The great significance of Gauss's law Eq. (1.31), is that it is true in general, and not only for the simple cases we have considered above. Let us note some important points regarding this law:

(i) Gauss's law is true for any closed surface, no matter what its shape or size.

(ii) The term q on the right side of Gauss's law, Eq. (1.31), includes the sum of all charges enclosed by the surface. The charges may be located anywhere inside the surface.

(iii) In the situation when the surface is so chosen that there are some charges inside and some outside, the electric field [whose flux appears

on the left side of Eq. (1.31)] is due to all the charges, both inside and outside S . The term q on the right side of Gauss's law, however, 34 represents only the total charge inside S .

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Electric Charges

and Fields

(iv) The surface that we choose for the application of Gauss's law is called the Gaussian surface. You may choose any Gaussian surface and apply Gauss's law. However, take care not to let the Gaussian surface pass through any discrete charge. This is because electric field due to a system of discrete charges is not well defined at the location of any charge. (As you go close to the charge, the field grows without any bound.) However, the Gaussian surface can pass through a continuous charge distribution.

(v) Gauss's law is often useful towards a much easier calculation of the electrostatic field *when the system has some symmetry*. This is

facilitated by the choice of a suitable Gaussian surface.

(vi) Finally, Gauss's law is based on the inverse square dependence on distance contained in the Coulomb's law. Any violation of Gauss's law will indicate departure from the inverse square law.

Example 1.11 The electric field components in Fig. 1.27 are

$E = \alpha x^{1/2}$, $E_y = E_z = 0$, in which $\alpha = 800 \text{ N/C m}^{1/2}$. Calculate (a) the x

y

z

flux through the cube, and (b) the charge within the cube. Assume that $a = 0.1 \text{ m}$.

FIGURE 1.27

Solution

(a) Since the electric field has only an x component, for faces perpendicular to x direction, the angle between \mathbf{E} and $\Delta\mathbf{S}$ is

$\pm \pi/2$. Therefore, the flux $\phi = \mathbf{E} \cdot \Delta\mathbf{S}$ is separately zero for each face of the cube except the two shaded ones. Now the magnitude of the electric field at the left face is

$$E = \alpha x^{1/2} = \alpha a^{1/2}$$

L

($x = a$ at the left face).

The magnitude of electric field at the right face is

$$E = \alpha x^{1/2} = \alpha (2a)^{1/2}$$

R

($x = 2a$ at the right face).

E

The corresponding fluxes are

XAMPLE

$$\phi = \mathbf{E} \cdot \Delta \mathbf{S} = \Delta S \mathbf{E} \cdot \hat{\mathbf{n}} = E \Delta S \cos \theta = -E \Delta S, \text{ since } \theta = 180^\circ$$

L

L

L

L

L

L

$$= -E a^2$$

L

1.11

$$\phi = \mathbf{E} \Delta \mathbf{S} = E \Delta S \cos \theta = E \Delta S, \text{ since } \theta = 0^\circ$$

R

R

R

R

$$= E a^2$$

R

Net flux through the cube

35

Physics

$$= \phi + \phi = E a^2 - E a^2 = a^2 (E - E) = \alpha a^2 [(2a)^{1/2} - a^{1/2}]$$

R

L

R

L

R

L

$$= \alpha a^{5/2} (2 -)$$

1

$$= 800 (0.1)^{5/2} (2 -)$$

1

1.11

$$= 1.05 \text{ N m}^2 \text{ C}^{-1}$$

(b) We can use Gauss's law to find the total charge q inside the cube.

We have $\phi = q/\epsilon$ or $q = \phi\epsilon$. Therefore,

0

0

EXAMPLE

E

$$q = 1.05 \times 8.854 \times 10^{-12} \text{ C} = 9.27 \times 10^{-12} \text{ C}.$$

Example 1.12 An electric field is uniform, and in the positive x

direction for positive x , and uniform with the same magnitude but in

the negative x direction for negative x . It is given that $\mathbf{E} = 200 \hat{\mathbf{i}} \text{ N/C}$

for $x > 0$ and $\mathbf{E} = -200 \hat{\mathbf{i}} \text{ N/C}$ for $x < 0$. A right circular cylinder of length 20 cm and radius 5 cm has its centre at the origin and its axis along the x -axis so that one face is at $x = +10 \text{ cm}$ and the other is at $x = -10 \text{ cm}$ (Fig. 1.28). (a) What is the net outward flux through each flat face? (b) What is the flux through the side of the cylinder?

(c) What is the net outward flux through the cylinder? (d) What is the

net charge inside the cylinder?

Solution

(a) We can see from the figure that on the left face \mathbf{E} and $\Delta\mathbf{S}$ are parallel. Therefore, the outward flux is $\phi = \mathbf{E} \cdot \Delta\mathbf{S} = -200 \hat{\mathbf{i}} \Delta\mathbf{S}$

L

$$= +200 \Delta S, \text{ since } \hat{\mathbf{i}} \Delta\mathbf{S} = -\Delta\mathbf{S}$$

$$= + 200 \times \pi (0.05)^2 = + 1.57 \text{ N m}^2 \text{ C}^{-1}$$

On the right face, \mathbf{E} and $\Delta\mathbf{S}$ are parallel and therefore

$$\phi = \mathbf{E} \cdot \Delta\mathbf{S} = + 1.57 \text{ N m}^2 \text{ C}^{-1}.$$

R

(b) For any point on the side of the cylinder \mathbf{E} is perpendicular to

$\Delta\mathbf{S}$ and hence $\mathbf{E} \cdot \Delta\mathbf{S} = 0$. Therefore, the flux out of the side of the cylinder is zero.

(c)

Net outward flux through the cylinder

$$\phi = 1.57 + 1.57 + 0 = 3.14 \text{ N m}^2 \text{ C}^{-1}$$

FIGURE 1.28

(d) The net charge within the cylinder can be found by using Gauss's

1.12

law which gives

$$q = \epsilon \phi$$

$$0$$

$$= 3.14 \times 8.854 \times 10^{-12} \text{ C}$$

XAMPLE

$$= 2.78 \times 10^{-11} \text{ C}$$

E

Electric Charges

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1.15 APPLICATIONS OF GAUSS'S LAW

The electric field due to a general charge distribution is, as seen above, given by Eq. (1.27). In practice, except for some special cases, the summation (or integration) involved in this equation cannot be carried out to give electric field at every point in space. For some symmetric charge configurations, however, it is possible to obtain the electric field in a simple way using the Gauss's law. This is best understood by some examples.

1.15.1 Field due to an infinitely

long straight uniformly

charged wire

Consider an infinitely long thin straight wire with uniform linear charge density λ . The wire is obviously an axis of symmetry. Suppose we take the radial vector from O to P and rotate it

around the wire. The points P, P', P'' so obtained are completely equivalent with respect to the charged wire. This implies that the electric field must have the same magnitude at these points. The direction of electric field at every point must be radial (outward if $\lambda > 0$, inward if $\lambda < 0$). This is clear from Fig. 1.29.

Consider a pair of line elements P and P

1

2

of the wire, as shown. The electric fields produced by the two elements of the pair when summed give a resultant electric field which is radial (the components normal to the radial vector cancel). This is true for any such pair and hence the total field at any point P is radial. Finally, since the wire is infinite, electric field does not depend on the position of P along the length of the wire. In short, the electric field is everywhere radial in the plane

cutting the wire normally, and its magnitude depends only on the radial distance r .

To calculate the field, imagine a cylindrical Gaussian surface, as shown in the Fig. 1.29(b).

Since the field is everywhere radial, flux through the two ends of the cylindrical

Gaussian surface is zero. At the cylindrical

FIGURE 1.29 (a) Electric field due to an part of the surface, \mathbf{E} is normal to the surface

infinitely long thin straight wire is radial, at every point, and its magnitude is constant,

(b) The Gaussian surface for a long thin wire of uniform linear charge density. since it depends only on r . The surface area

of the curved part is $2\pi rl$, where l is the length

37

of the cylinder.

Physics

Flux through the Gaussian surface

=

flux through the curved cylindrical part of the surface

=

$$E \times 2\pi rl$$

The surface includes charge equal to λl . Gauss's law then gives

$$E \times 2\pi rl = \lambda l / \epsilon_0$$

$$\lambda$$

i.e.,

$$E = 2\pi\epsilon r$$

$$0$$

Vectorially, \mathbf{E} at any point is given by

$$\lambda$$

$$\mathbf{E} =$$

^

$$\mathbf{n}$$

$$(1.32)$$

$$2\pi\epsilon r$$

$$0$$

where ^

\mathbf{n} is the radial unit vector in the plane normal to the wire passing

through the point. \mathbf{E} is directed outward if λ is positive and inward if λ is negative.

Note that when we write a vector \mathbf{A} as a scalar multiplied by a unit vector, i.e., as $\mathbf{A} = A \hat{\mathbf{a}}$, the scalar A is an algebraic number. It can be negative or positive. The direction of \mathbf{A} will be the same as that of the unit vector $\hat{\mathbf{a}}$ if $A > 0$ and opposite to $\hat{\mathbf{a}}$ if $A < 0$. When we want to restrict to non-negative values, we use the symbol \mathbf{A} and call it the modulus of \mathbf{A} .

Thus, $\mathbf{A} \geq 0$.

Also note that though only the charge enclosed by the surface (λl) was included above, the electric field \mathbf{E} is due to the charge on the entire wire. Further, the assumption that the wire is infinitely long is crucial.

Without this assumption, we cannot take \mathbf{E} to be normal to the curved part of the cylindrical Gaussian surface. However, Eq. (1.32) is approximately true for electric field around the central portions of a long wire, where the end effects may be ignored.

1.15.2 Field due to a uniformly charged infinite plane sheet

Let σ be the uniform surface charge density of an infinite plane sheet

(Fig. 1.30). We take the x -axis normal to the given plane. By symmetry, the electric field will not depend on y and z coordinates and its direction at every point must be parallel to the x -direction.

We can take the Gaussian surface to be a rectangular parallelepiped of cross sectional area A , as shown. (A cylindrical surface will also do.) As seen from the figure, only the two faces 1 and 2 will contribute to the flux; electric field lines are parallel

to the other faces and they, therefore, do not contribute to the total flux.

The unit vector normal to surface 1 is in $-x$ direction while the unit vector normal to surface 2 is in the $+x$ direction. Therefore, flux $\mathbf{E} \cdot \Delta\mathbf{S}$ through both the surfaces are equal and add up. Therefore

FIGURE 1.30 Gaussian surface for a uniformly charged infinite plane sheet. the net flux through the Gaussian surface is $2 EA$.

The charge enclosed by the closed surface is σA .

38

Therefore by Gauss's law,

Electric Charges

and Fields

$$2 EA = \sigma A / \epsilon_0$$

$$\text{or, } E = \sigma / 2\epsilon_0$$

Vectorically,

σ

$\mathbf{E} =$

\hat{x}

\mathbf{n}

(1.33)

$2\epsilon_0$

where $\hat{\mathbf{n}}$

\mathbf{n} is a unit vector normal to the plane and going away from it.

\mathbf{E} is directed away from the plate if σ is positive and toward the plate if σ is negative. Note that the above application of the Gauss' law has brought out an additional fact: E is independent of x also.

For a finite large planar sheet, Eq. (1.33) is approximately true in the middle regions of the planar sheet, away from the ends.

1.15.3 Field due to a uniformly charged thin spherical shell Let σ be the uniform surface charge density of a thin spherical shell of radius R (Fig. 1.31). The situation has obvious spherical symmetry. The field at any point P , outside or inside, can depend only on r (the radial distance from the centre of the shell to the point) and must be radial (i.e., along the radius vector).

(i) Field outside the shell: Consider a point P outside the shell with radius vector \mathbf{r} . To calculate \mathbf{E} at P , we take the Gaussian surface to be a sphere of radius r and with centre O , passing through P . All points on this sphere are equivalent relative to the given charged configuration. (That is what we mean by spherical symmetry.) The electric field at each point of the Gaussian surface, therefore, has the same magnitude

E and is along the radius vector at each point. Thus, \mathbf{E} and

$\Delta \mathbf{S}$ at every point are parallel and the flux through each

element is $E \Delta S$. Summing over all ΔS , the flux through the Gaussian surface is $E \times 4 \pi r^2$. The charge enclosed is $\sigma \times 4 \pi R^2$. By Gauss's law

σ

2

$E \times 4 \pi r^2 =$

$4 \pi R^2$

ϵ_0

2

σR^2

q

Or, $E =$

$=$

2

2

ϵr

$4 \pi \epsilon r$

0

0

where $q = 4 \pi R^2 \sigma$ is the total charge on the spherical shell.

Vectorially,

q

$\mathbf{E} =$

$\hat{\mathbf{r}}$

FIGURE 1.31 Gaussian

2

(1.34)

$4\pi\epsilon r$

surfaces for a point with

0

(a) $r > R$, (b) $r < R$.

The electric field is directed outward if $q > 0$ and inward if

$q < 0$. This, however, is exactly the field produced by a charge

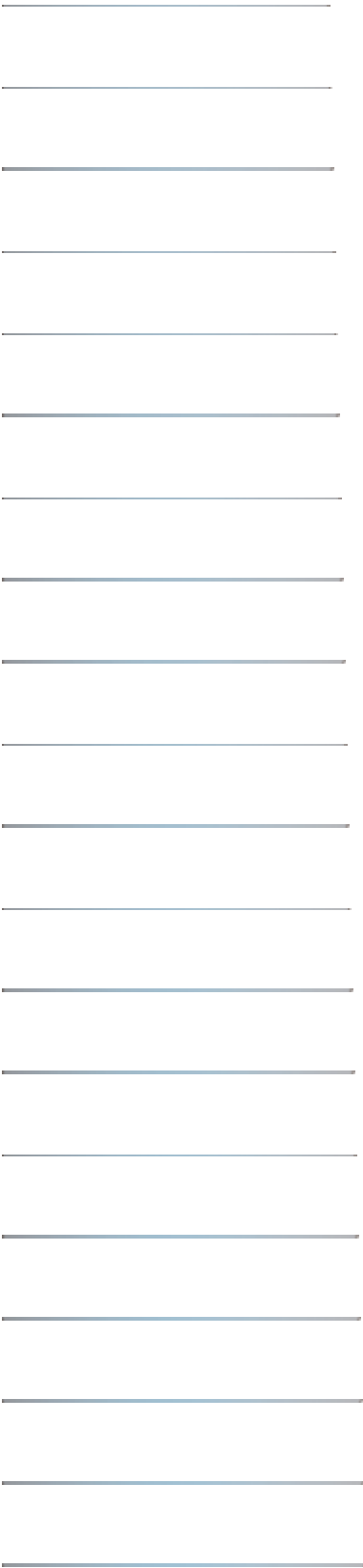
q placed at the centre O. Thus for points outside the shell, the field due to a uniformly charged shell is as if the entire charge of the shell is concentrated at its centre.

(ii) Field inside the shell: In Fig. 1.31(b), the point P is inside the shell. The Gaussian surface is again a sphere through P centred at O.

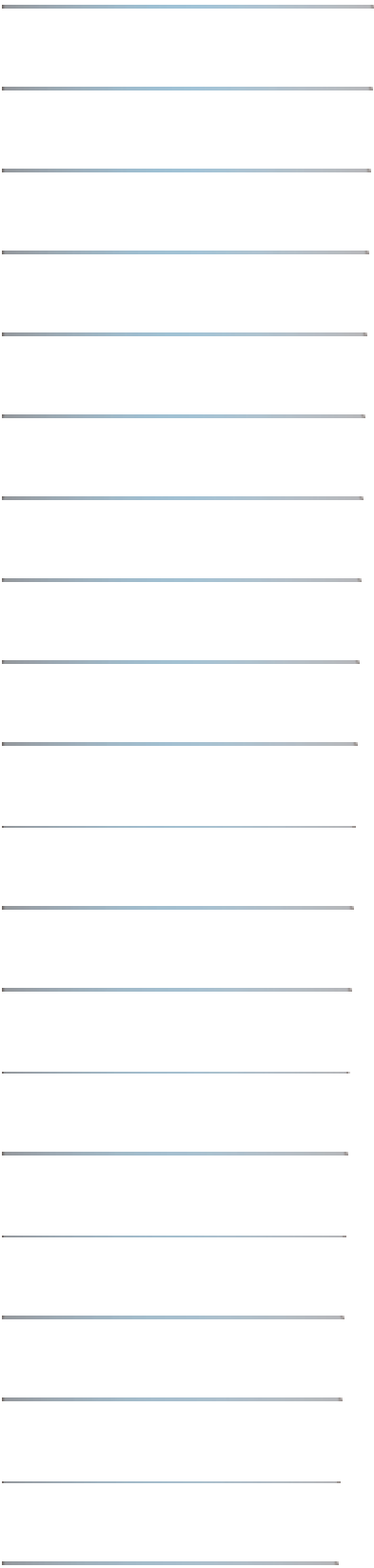
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Physics

The flux through the Gaussian surface, calculated as before, is

$E \times 4 \pi r^2$. However, in this case, the Gaussian surface encloses no charge. Gauss's law then gives $E \times 4 \pi r^2 = 0$

i.e., $E = 0 (r < R)$

(1.35)

that is, the field due to a uniformly charged thin shell is zero at all points

inside the shell*. This important result is a direct consequence of Gauss's law which follows from Coulomb's law. The experimental verification of this result confirms the $1/ r^2$ dependence in Coulomb's law.

Example 1.13 An early model for an atom considered it to have a positively charged point nucleus of charge Ze , surrounded by a uniform density of negative charge up to a radius R . The atom as a

whole is neutral. For this model, what is the electric field at a distance r from the nucleus?

FIGURE 1.32

Solution The charge distribution for this model of the atom is as shown in Fig. 1.32. The total negative charge in the uniform spherical charge distribution of radius R must be $-Ze$, since the atom (nucleus of charge $Ze +$ negative charge) is neutral. This immediately gives us the negative charge density ρ , since we must have

$$\rho = \frac{-Ze}{\frac{4}{3}\pi R^3}$$

To find the electric field $\mathbf{E}(\mathbf{r})$ at a point P which is a distance r away from the nucleus, we use Gauss's law. Because of the spherical symmetry of the charge distribution, the magnitude of the electric

field $\mathbf{E}(\mathbf{r})$ depends only on the radial distance, no matter what the direction of \mathbf{r} . Its direction is along (or opposite to) the radius vector \mathbf{r} from the origin to the point P. The obvious Gaussian surface is a spherical surface centred at the nucleus. We consider two situations,

1.13

namely, $r < R$ and $r > R$.

(i) $r < R$: The electric flux ϕ enclosed by the spherical surface is $\phi = E (r) \times 4 \pi r^2$

XAMPLE

E

where $E (r)$ is the magnitude of the electric field at r . This is because

* Compare this with a uniform mass shell discussed in Section 8.5 of Class XI 40

Textbook of Physics.

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the field at any point on the spherical Gaussian surface has the same direction as the normal to the surface there, and has the same magnitude at all points on the surface.

The charge q enclosed by the Gaussian surface is the positive nuclear charge and the negative charge within the sphere of radius r ,

3

$4 \pi r$

i.e., $q = Z e +$

ρ

3

Substituting for the charge density ρ obtained earlier, we have

3

r

$$q = Ze - Ze$$

3

R

Gauss's law then gives,

Ze

(1

r)

$$E(r) =$$

|

-

|;

$$r < R$$

2

3

$4\pi\epsilon$

(r

R

0

The electric field is directed radially outward.

E

(ii) $r > R$: In this case, the total charge enclosed by the Gaussian **XAMPLE**

spherical surface is zero since the atom is neutral. Thus, from Gauss's

law,

$$E(r) \times 4\pi r^2 = 0 \text{ or } E(r) = 0; r > R$$

1.13

At $r = R$, both cases give the same result: $E = 0$.

ON SYMMETRY OPERATIONS

In Physics, we often encounter systems with various symmetries. Consideration of these symmetries helps one arrive at results much faster than otherwise by a straightforward calculation. Consider, for example an infinite uniform sheet of charge (surface charge density σ) along the y - z plane. This system is unchanged if (a) translated parallel to the y - z plane in any direction, (b) rotated about the x -axis through any angle. As the system is unchanged under such symmetry operation, so must its properties be. In particular, in this example, the electric field **E** must be unchanged.

Translation symmetry along the y -axis shows that the electric field must be the same at a point $(0, y, 0)$ as at $(0, y, 0)$. Similarly translational symmetry along the z -axis

2

shows that the electric field at two point $(0, 0, z)$ and $(0, 0, z)$ must be the same. By 1

2

using rotation symmetry around the x -axis, we can conclude that \mathbf{E} must be perpendicular to the y - z plane, that is, it must be parallel to the x -direction.

Try to think of a symmetry now which will tell you that the magnitude of the electric field is a constant, independent of the x -coordinate. It thus turns out that the magnitude of the electric field due to a uniformly charged infinite conducting sheet is the same at all points in space. The direction, however, is opposite of each other on either side of the sheet.

Compare this with the effort needed to arrive at this result by a direct calculation using Coulomb's law.

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Physics

SUMMARY

1.

Electric and magnetic forces determine the properties of atoms, molecules and bulk matter.

2.

From simple experiments on frictional electricity, one can infer that there are two types of charges in nature; and that like charges repel and unlike charges attract. By convention, the charge on a glass rod rubbed with silk is positive; that on a plastic rod rubbed with fur is then negative.

3.

Conductors allow movement of electric charge through them, insulators do not. In metals, the mobile charges are electrons; in electrolytes both positive and negative ions are mobile.

4.

Electric charge has three basic properties: quantisation, additivity and conservation.

Quantisation of electric charge means that total charge (q) of a body is always an integral multiple of a basic quantum of charge (e) i.e., $q = n e$, where $n = 0, \pm 1, \pm 2, \pm 3, \dots$. Proton and electron have charges $+ e, - e$, respectively. For macroscopic charges for which n is a very large number, quantisation of charge can be ignored.

Additivity of electric charges means that the total charge of a system is the algebraic sum (i.e., the sum taking into account proper signs) of all individual charges in the system.

Conservation of electric charges means that the total charge of an isolated system remains unchanged with time. This means that when bodies are charged through friction, there is a transfer of electric charge from one body to another, but no creation or destruction of charge.

5.

Coulomb's Law: The mutual electrostatic force between two point charges q and q is proportional to the product $q q$ and inversely 1

2

1 2

proportional to the square of the distance r separating them.

21

Mathematically,

$k (q q)$

\mathbf{F} = force on q due to

1 2

$q =$

$\hat{\mathbf{r}}$

21

2

1

2

21

r 21

1

where $\hat{\mathbf{r}}$ is a unit vector in the direction from q to q and $k =$

21

1

2

4ϵ

$\pi 0$

is the constant of proportionality.

In SI units, the unit of charge is coulomb. The experimental value of the constant ϵ is

0

$$\epsilon = 8.854 \times 10^{-12} \text{ C}^2 \text{ N}^{-1} \text{ m}^{-2}$$

0

The approximate value of k is

$$k = 9 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$$

6.

The ratio of electric force and gravitational force between a proton and an electron is

2

$k e$

39

$$\cong 2.4 \times 10$$

$G m m$

e

p

7.

Superposition Principle: The principle is based on the property that the forces with which two charges attract or repel each other are not affected by the presence of a third (or more) additional charge(s). For

an assembly of charges q_1, q_2, q_3, \dots , the force on any charge, say q_i , is

2

3

1

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and Fields

the vector sum of the force on q_i due to q_1 , the force on q_i due to q_2 , 1

2

1

3

and so on. For each pair, the force is given by the Coulomb's law for two charges stated earlier.

8.

The electric field \mathbf{E} at a point due to a charge configuration is the force on a small positive test charge q placed at the point divided by

the magnitude of the charge. Electric field due to a point charge q has a magnitude $|q|/4\pi\epsilon r^2$; it is radially outwards from q , if q is positive, 0 and radially inwards if q is negative. Like Coulomb force, electric field also satisfies superposition principle.

9.

An electric field line is a curve drawn in such a way that the tangent at each point on the curve gives the direction of electric field at that point. The relative closeness of field lines indicates the relative strength of electric field at different points; they crowd near each other in regions of strong electric field and are far apart where the electric field is weak. In regions of constant electric field, the field lines are uniformly spaced parallel straight lines.

10. Some of the important properties of field lines are: (i) Field lines are continuous curves without any breaks. (ii) Two field lines cannot cross each other. (iii) Electrostatic field lines start at positive charges and end at negative charges—they cannot form closed loops.

11. An electric dipole is a pair of equal and opposite charges q and $-q$ separated by some distance $2a$. Its dipole moment vector \mathbf{p} has magnitude $2qa$ and is in the direction of the dipole axis from $-q$ to q .

12. Field of an electric dipole in its equatorial plane (i.e., the plane perpendicular to its axis and passing through its centre) at a distance r from the centre:

$-\mathbf{p}$

1

$\mathbf{E} =$

2

$23/2$

4ϵ

π

$(a + r)$

o

—

|||

\mathbf{p}

,

for $r \gg a$

3

4ϵ

πr

o

Dipole electric field on the axis at a distance r from the centre:

$2 \mathbf{p} r$

$\mathbf{E} =$

2

2 2

4 ϵ

$\pi (r - a)$

0

2

112

\mathbf{p}

for

$r \gg a$

3

4 ϵ

πr

0

The $1/r^3$ dependence of dipole electric fields should be noted in contrast to the $1/r^2$ dependence of electric field due to a point charge.

13. In a uniform electric field \mathbf{E} , a dipole experiences a torque τ given by $\tau = \mathbf{p} \times \mathbf{E}$

but experiences no net force.

14. The flux $\Delta\phi$ of electric field \mathbf{E} through a small area element $\Delta\mathbf{S}$ is given by

$$\Delta\phi = \mathbf{E} \cdot \Delta\mathbf{S}$$

The vector area element $\Delta\mathbf{S}$ is

$$\Delta\mathbf{S} = \Delta S \hat{\mathbf{n}}$$

where ΔS is the magnitude of the area element and $\hat{\mathbf{n}}$

\mathbf{n} is normal to the

area element, which can be considered planar for sufficiently small ΔS .

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Physics

For an area element of a closed surface, $\hat{\mathbf{n}}$

\mathbf{n} is taken to be the direction

of *outward* normal, by convention.

15. *Gauss's law*: The flux of electric field through any closed surface S is $1/\epsilon_0$ times the total charge enclosed by S . The law is especially useful

in determining electric field \mathbf{E} , when the source distribution has simple symmetry:

(i) *Thin infinitely long straight wire of uniform linear charge density λ*

λ

$\mathbf{E} =$

$\hat{\mathbf{r}}$

\mathbf{n}

2ϵ

π

r

0

where r is the perpendicular distance of the point from the wire and

^

\mathbf{n} is the radial unit vector in the plane normal to the wire passing through the point.

(ii) Infinite thin plane sheet of uniform surface charge density σ

σ

$\mathbf{E} =$

^

\mathbf{n}

$2 \epsilon_0$

where ^

\mathbf{n} is a unit vector normal to the plane, outward on either side.

(iii) Thin spherical shell of uniform surface charge density σ

q

$\mathbf{E} =$

$\hat{\mathbf{r}}$ $(r$ $\geq R)$ 2 4ϵ π r 0 $\mathbf{E} = 0$ $(r < R)$

where r is the distance of the point from the centre of the shell and R the radius of the shell. q is the total charge of the shell: $q = 4\pi R^2\sigma$.

The electric field outside the shell is as though the total charge is concentrated at the centre. The same result is true for a solid sphere of uniform volume charge density. The field is zero at all points inside the shell

Physical quantity

Symbol

Dimensions

Unit

Remarks

Vector area element

$\Delta \mathbf{S}$

[L²]

m²

$$\Delta \mathbf{S} = \Delta S \hat{\mathbf{n}}$$

Electric field

\mathbf{E}

[MLT⁻³A⁻¹]

V m⁻¹

Electric flux

ϕ

[ML³ T⁻³A⁻¹]

V m

$$\Delta \phi = \mathbf{E} \cdot \Delta \mathbf{S}$$

Dipole moment

\mathbf{p}

[LTA]

C m

Vector directed
from negative to
positive charge

Charge density
linear

λ

[L⁻¹ TA]

C m⁻¹

Charge/length
surface

σ

[L⁻² TA]

C m⁻²

Charge/area

volume

ρ

[L⁻³ TA]

C m⁻³

Charge/volume

44

Electric Charges

and Fields

POINTS TO PONDER

1.

You might wonder why the protons, all carrying positive charges, are compactly residing inside the nucleus. Why do they not fly away? You will learn that there is a third kind of a fundamental force, called the strong force which holds them together. The range of distance where this force is effective is, however, very small $\sim 10^{-14}$ m. This is precisely the size of the nucleus. Also the electrons are not allowed to sit on top of the protons, *i.e.* inside the nucleus, due to the laws of quantum mechanics. This gives the atoms their structure as they exist in nature.

2.

Coulomb force and gravitational force follow the same inverse-square law. But gravitational force has only one sign (always attractive), while Coulomb force can be of both signs (attractive and repulsive), allowing possibility of cancellation of electric forces. This is how gravity, despite being a much weaker force, can be a dominating and more pervasive force in nature.

3.

The constant of proportionality k in Coulomb's law is a matter of choice if the unit of charge is to be defined using Coulomb's law. In SI units, however, what is defined is the unit of current (A) via its magnetic effect (Ampere's law) and the unit of charge (coulomb) is simply defined by ($1\text{C} = 1\text{ A s}$). In this case, the value of k is no longer arbitrary; it is approximately $9 \times 10^9\text{ N m}^2\text{ C}^{-2}$.

4.

The rather large value of k , i.e., the large size of the unit of charge (1C) from the point of view of electric effects arises because (as mentioned in point 3 already) the unit of charge is defined in terms of magnetic forces (forces on current-carrying wires) which are generally much weaker than the electric forces. Thus while 1 ampere is a unit of reasonable size for magnetic effects, $1\text{ C} = 1\text{ A s}$, is too big a unit for electric effects.

5.

The additive property of charge is not an 'obvious' property. It is related to the fact that electric charge has no direction associated with it; charge is a scalar.

6.

Charge is not only a scalar (or invariant) under rotation; it is also invariant for frames of reference in relative motion. This is not always true for every scalar. For example, kinetic energy is a scalar under rotation, but is not invariant for frames of reference in relative motion.

7.

Conservation of total charge of an isolated system is a property independent of the scalar nature of charge noted in point 6.

Conservation refers to invariance in time in a given frame of reference.

A quantity may be scalar but not conserved (like kinetic energy in an inelastic collision). On the other hand, one can have conserved vector quantity (e.g., angular momentum of an isolated system).

8.

Quantisation of electric charge is a basic (unexplained) law of nature; interestingly, there is no analogous law on quantisation of mass.

9.

Superposition principle should not be regarded as ‘obvious’, or equated with the law of addition of vectors. It says two things: force on one charge due to another charge is unaffected by the presence of other charges, and there are no additional three-body, four-body, etc., forces which arise only when there are more than two charges.

10. The electric field due to a discrete charge configuration is not defined at the locations of the discrete charges. For continuous volume charge distribution, it is defined at any point in the distribution. For a surface charge distribution, electric field is discontinuous across the surface.

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Physics

11. The electric field due to a charge configuration with total charge zero is not zero; but for distances large compared to the size of the configuration, its field falls off faster than $1/r^2$, typical of field due to a single charge. An electric dipole is the simplest example of this fact.

EXERCISES

1.1

What is the force between two small charged spheres having charges of $2 \times 10^{-7}\text{C}$ and $3 \times 10^{-7}\text{C}$ placed 30 cm apart in air?

1.2

The electrostatic force on a small sphere of charge $0.4 \mu\text{C}$ due to another small sphere of charge $-0.8 \mu\text{C}$ in air is 0.2 N . (a) What is the distance between the two spheres? (b) What is the force on the second sphere due to the first?

1.3

Check that the ratio $ke^2 / G m m$ is dimensionless. Look up a Table *e* *p* of Physical Constants and determine the value of this ratio. What does the ratio signify?

1.4

(a) Explain the meaning of the statement ‘electric charge of a body is quantised’.

(b) Why can one ignore quantisation of electric charge when dealing with macroscopic i.e., large scale charges?

1.5

When a glass rod is rubbed with a silk cloth, charges appear on both. A similar phenomenon is observed with many other pairs of bodies. Explain how this observation is consistent with the law of conservation of charge.

1.6

Four point charges $q = 2 \mu\text{C}$, $q = -5 \mu\text{C}$, $q = 2 \mu\text{C}$, and $q = -5 \mu\text{C}$ are A

B

C

D

located at the corners of a square ABCD of side 10 cm. What is the force on a charge of $1 \mu\text{C}$ placed at the centre of the square?

1.7

(a) An electrostatic field line is a continuous curve. That is, a field line cannot have sudden breaks. Why not?

(b) Explain why two field lines never cross each other at any point?

1.8

Two point charges $q = 3 \mu\text{C}$ and $q = -3 \mu\text{C}$ are located 20 cm apart A

B

in vacuum.

(a) What is the electric field at the midpoint O of the line AB joining the two charges?

(b) If a negative test charge of magnitude $1.5 \times 10^{-9} \text{ C}$ is placed at this point, what is the force experienced by the test charge?

1.9

A system has two charges $q = 2.5 \times 10^{-7} \text{ C}$ and $q = -2.5 \times 10^{-7} \text{ C}$

A

B

located at points A: (0, 0, -15 cm) and B: (0,0, +15 cm), respectively.

What are the total charge and electric dipole moment of the system?

1.10

An electric dipole with dipole moment $4 \times 10^{-9} \text{ C m}$ is aligned at 30° with the direction of a uniform electric field of magnitude $5 \times 10^4 \text{ NC}^{-1}$.

Calculate the magnitude of the torque acting on the dipole.

1.11

A polythene piece rubbed with wool is found to have a negative charge of $3 \times 10^{-7} \text{ C}$.

(a) Estimate the number of electrons transferred (from which to which?)

(b) Is there a transfer of mass from wool to polythene?

1.12

(a) Two insulated charged copper spheres A and B have their centres

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separated by a distance of 50 cm. What is the mutual force of

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and Fields

electrostatic repulsion if the charge on each is $6.5 \times 10^{-7} \text{ C}$? The radii of A and B are negligible compared to the distance of separation.

(b) What is the force of repulsion if each sphere is charged double the above amount, and the distance between them is halved?

1.13

Suppose the spheres A and B in Exercise 1.12 have identical sizes. A third sphere of the same size but uncharged is brought in contact with the first, then brought in contact with the second, and finally removed from both. What is the new force of repulsion between A and B?

1.14

Figure 1.33 shows tracks of three charged particles in a uniform electrostatic field. Give the signs of the three charges. Which particle has the highest charge to mass ratio?

FIGURE 1.33

1.15

Consider a uniform electric field $\mathbf{E} = 3 \times 10^3 \hat{\mathbf{i}} \text{ N/C}$. (a) What is the flux of this field through a square of 10 cm on a side whose plane is parallel to the yz plane? (b) What is the flux through the same

square if the normal to its plane makes a 60° angle with the x -axis?

1.16

What is the net flux of the uniform electric field of Exercise 1.15 through a cube of side 20 cm oriented so that its faces are parallel to the coordinate planes?

1.17

Careful measurement of the electric field at the surface of a black box indicates that the net outward flux through the surface of the box is $8.0 \times 10^3 \text{ Nm}^2/\text{C}$. (a) What is the net charge inside the box? (b) If the net outward flux through the surface of the box were zero, could you conclude that there were no charges inside the box? Why or Why not?

1.18

A point charge $+10 \mu\text{C}$ is a distance 5 cm directly above the centre of a square of side 10 cm, as shown in Fig. 1.34. What is the magnitude of the electric flux through the square? (*Hint*: Think of the square as one face of a cube with edge 10 cm.)

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FIGURE 1.34

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1.19

A point charge of $2.0 \mu\text{C}$ is at the centre of a cubic Gaussian surface 9.0 cm on edge. What is the net electric flux through the surface?

1.20

A point charge causes an electric flux of $-1.0 \times 10^3 \text{ Nm}^2/\text{C}$ to pass through a spherical Gaussian surface of 10.0 cm radius centred on the charge. (a) If the radius of the Gaussian surface were doubled, how much flux would pass through the surface? (b) What is the value of the point charge?

1.21

A conducting sphere of radius 10 cm has an unknown charge. If the electric field 20 cm from the centre of the sphere is $1.5 \times 10^3 \text{ N/C}$ and points radially inward, what is the net charge on the sphere?

1.22

A uniformly charged conducting sphere of 2.4 m diameter has a surface charge density of $80.0 \mu\text{C}/\text{m}^2$. (a) Find the charge on the sphere. (b) What is the total electric flux leaving the surface of the sphere?

1.23

An infinite line charge produces a field of $9 \times 10^4 \text{ N/C}$ at a distance

of 2 cm. Calculate the linear charge density.

1.24

Two large, thin metal plates are parallel and close to each other. On their inner faces, the plates have surface charge densities of opposite signs and of magnitude $17.0 \times 10^{-22} \text{ C/m}^2$. What is \mathbf{E} : (a) in the outer region of the first plate, (b) in the outer region of the second plate, and (c) between the plates?

ADDITIONAL EXERCISES

1.25

An oil drop of 12 excess electrons is held stationary under a constant electric field of $2.55 \times 10^4 \text{ NC}^{-1}$ in Millikan's oil drop experiment. The density of the oil is 1.26 g cm^{-3} . Estimate the radius of the drop.

($g = 9.81 \text{ m s}^{-2}$; $e = 1.60 \times 10^{-19} \text{ C}$).

1.26

Which among the curves shown in Fig. 1.35 cannot possibly represent electrostatic field lines?

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Electric Charges

and Fields

FIGURE 1.35

1.27

In a certain region of space, electric field is along the z -direction throughout. The magnitude of electric field is, however, not constant but increases uniformly along the positive z -direction, at the rate of 10^5 NC^{-1} per metre. What are the force and torque experienced by a system having a total dipole moment equal to 10^{-7} Cm in the negative z -direction ?

1.28

(a) A conductor A with a cavity as shown in Fig. 1.36(a) is given a charge Q . Show that the entire charge must appear on the outer surface of the conductor. (b) Another conductor B with charge q is inserted into the cavity keeping B insulated from A. Show that the total charge on the outside surface of A is $Q + q$ [Fig. 1.36(b)]. (c) A sensitive instrument is to be shielded from the strong electrostatic fields in its environment. Suggest a possible way.

FIGURE 1.36

1.29

A hollow charged conductor has a tiny hole cut into its surface.

Show that the electric field in the hole is $(\sigma/2\epsilon_0) \hat{n}$,

where \hat{n}

is the

unit

vector in the outward normal direction, and σ is the surface charge density near the hole.

1.30

Obtain the formula for the electric field due to a long thin wire of uniform linear charge density λ without using Gauss's law. [*Hint:* Use Coulomb's law directly and evaluate the necessary integral.]

1.31

It is now believed that protons and neutrons (which constitute nuclei of ordinary matter) are themselves built out of more elementary units called quarks. A proton and a neutron consist of three quarks each.

Two types of quarks, the so called 'up' quark (denoted by u) of charge $+(2/3)e$, and the 'down' quark (denoted by d) of charge $(-1/3)e$, together with electrons build up ordinary matter. (Quarks of other types have also been found which give rise to different unusual

varieties of matter.) Suggest a possible quark composition of a

proton and neutron.

Physics

1.32

(a) Consider an arbitrary electrostatic field configuration. A small test charge is placed at a null point (i.e., where $\mathbf{E} = 0$) of the configuration. Show that the equilibrium of the test charge is necessarily unstable.

(b) Verify this result for the simple configuration of two charges of the same magnitude and sign placed a certain distance apart.

1.33

A particle of mass m and charge $(-q)$ enters the region between the two charged plates initially moving along x -axis with speed v (like x particle 1 in Fig. 1.33). The length of plate is L and an uniform

electric field E is maintained between the plates. Show that the vertical deflection of the particle at the far edge of the plate is

$$qEL^2/(2mv^2).$$

x

Compare this motion with motion of a projectile in gravitational field discussed in Section 4.10 of Class XI Textbook of Physics.

1.34

Suppose that the particle in Exercise in 1.33 is an electron projected

with velocity $v = 2.0 \times 10^6 \text{ m s}^{-1}$. If E between the plates separated x by 0.5 cm is $9.1 \times 10^2 \text{ N/C}$, where will the electron strike the upper plate? ($|e| = 1.6 \times 10^{-19} \text{ C}$, $m = 9.1 \times 10^{-31} \text{ kg}$.)

e

50

Chapter Two

ELECTROSTATIC

POTENTIAL AND

CAPACITANCE

2.1 INTRODUCTION

In Chapters 6 and 8 (Class XI), the notion of potential energy was introduced. When an external force does work in taking a body from a point to another against a force like spring force or gravitational force, that work gets stored as potential energy of the body. When the external force is removed, the body moves, gaining kinetic energy and losing an equal amount of potential energy. The sum of kinetic and potential energies is thus conserved. Forces of this kind are called conservative forces. Spring force and gravitational force are examples of conservative forces.

Coulomb force between two (stationary) charges, like the gravitational

force, is also a conservative force. This is not surprising, since both have inverse-square dependence on distance and differ mainly in the proportionality constants – the masses in the gravitational law are replaced by charges in Coulomb’s law. Thus, like the potential energy of a mass in a gravitational field, we can define electrostatic potential energy of a charge in an electrostatic field.

Consider an electrostatic field \mathbf{E} due to some charge configuration.

First, for simplicity, consider the field \mathbf{E} due to a charge Q placed at the origin. Now, imagine that we bring a test charge q from a point R to a point P against the repulsive force on it due to the charge Q . With reference

Physics

to Fig. 2.1, this will happen if Q and q are both positive or both negative. For definiteness, let us take $Q, q > 0$.

Two remarks may be made here. First, we assume that the test charge q is so small that it does not disturb the original configuration, namely the charge Q at the origin (or else, we keep Q fixed at the origin by some unspecified force). Second, in bringing the charge q from

FIGURE 2.1 A test charge $q (> 0)$ is

R to P, we apply an external force \mathbf{F} just enough to moved from the point R to the

ext

point P against the repulsive

counter the repulsive electric force \mathbf{F} (i.e, $\mathbf{F} = -\mathbf{F}$).

E

ext

E

force on it by the charge $Q (> 0)$

This means there is no net force on or acceleration of
placed at the origin.

the charge q when it is brought from R to P, i.e., it is

brought with infinitesimally slow constant speed. In

this situation, work done by the external force is the negative of the work
done by the electric force, and gets fully stored in the form of potential

energy of the charge q . If the external force is removed on reaching P, the
electric force will take the charge away from Q – the stored energy
(potential energy) at P is used to provide kinetic energy to the charge q in
such a way that the sum of the kinetic and potential energies is conserved.

Thus, work done by external forces in moving a charge q from R to P is

P

W =

d

$$\int_{P}^{R} \mathbf{F} \cdot d\mathbf{r}$$

ext

RP

R

P

= -

d

$$\int_{P}^{R} \mathbf{F} \cdot d\mathbf{r}$$

E

(2.1)

R

This work done is against electrostatic repulsive force and gets stored as potential energy.

At every point in electric field, a particle with charge q possesses a certain electrostatic potential energy, this work done increases its potential energy by an amount equal to potential energy difference between points R and P.

Thus, potential energy difference

$$\Delta U = U - U = W$$

(2.2)

P

R

RP

(Note here that this displacement is in an opposite sense to the electric force and hence work done by electric field is negative, *i.e.* , $-W$

.)

RP

Therefore, we can define electric potential energy difference between two points as the work required to be done by an external force in moving (without accelerating) charge q from one point to another for electric field of any arbitrary charge configuration.

Two important comments may be made at this stage:

(i) The right side of Eq. (2.2) depends only on the initial and final positions of the charge. It means that the work done by an electrostatic field in moving a charge from one point to another depends only on the initial and the final points and is independent of the path taken to go from one point to the other. This is the fundamental characteristic of a conservative force. The concept of the potential energy would not be meaningful if the work depended on the path. The path-independence of work done by an electrostatic field can be proved using the

Coulomb's law. We omit this proof here.



Electrostatic Potential and Capacitance

(ii) Equation (2.2) defines *potential energy difference* in terms of the physically meaningful quantity *work*. Clearly, potential energy so defined is undetermined to within an additive constant. What this means is that the actual value of potential energy is not physically significant; it is only the difference of potential energy that is significant. We can always add an arbitrary constant α to potential energy at every point, since this will not change the potential energy difference:

$$(U + \alpha) - (U + \alpha) = U - U$$

P

R

P

R

Put it differently, there is a freedom in choosing the point where potential energy is zero. A convenient choice is to have electrostatic potential energy zero at infinity. With this choice, if we take the point R at infinity, we get from Eq. (2.2)

Count Alessandro Volta

COUNT ALESSANDRO VOLTA (1745 –1827)

(1745 – 1827) Italian

W

$$= U - U = U$$

∞

(2.3)

P

P

∞

P

physicist, professor at

Since the point P is arbitrary, Eq. (2.3) provides us with a

Pavia. Volta established

definition of potential energy of a charge q at any point.

that the *animal electri-*

Potential energy of charge q at a point (in the presence of field

city observed by Luigi

due to any charge configuration) *is the work done by the*

Galvani, 1737–1798, in

experiments with frog

external force (equal and opposite to the electric force) *in*

muscle tissue placed in

bringing the charge q from infinity to that point.

contact with dissimilar

2.2 E

metals, was not due to

LECTROSTATIC POTENTIAL

any exceptional property

Consider any general static charge configuration. We define

of animal tissues but

potential energy of a test charge q in terms of the work done

was also generated

whenever any wet body

on the charge q . This work is obviously proportional to q , since was sandwiched between

the force at any point is $q\mathbf{E}$, where \mathbf{E} is the electric field at that dissimilar metals. This point due to the given charge configuration. It is, therefore,

led him to develop the

convenient to divide the work by the amount of charge q , so

first *voltaic pile*, or

that the resulting quantity is independent of q . In other words,

battery, consisting of a

work done per unit test charge is characteristic of the electric

large stack of moist disks

field associated with the charge configuration. This leads to

of cardboard (electrolyte) sandwiched

the idea of electrostatic potential V due to a given charge

between disks of metal

configuration. From Eq. (2.1), we get:

(electrodes).

Work done by external force in bringing a unit positive

charge from point R to P

$$U - U$$

$$= V - V$$

P

R

=

(2.4)

P

R

q

where V and V are the electrostatic potentials at P and R, respectively.

P

R

Note, as before, that it is not the actual value of potential but the potential difference that is physically significant. If, as before, we choose the potential to be zero at infinity, Eq. (2.4) implies:

Work done by an external force in bringing a unit positive charge

53

from infinity to a point = electrostatic potential (V) at that point.

Physics

In other words, the electrostatic potential (V)

at any point in a region with electrostatic field is the work done in bringing a unit positive charge (without acceleration) from infinity to that point.

The qualifying remarks made earlier regarding potential energy also apply to the definition of potential. To obtain the work done per unit test charge, we should take an infinitesimal test charge

FIGURE 2.2 Work done on a test charge q

δq , obtain the work done δW in bringing it from infinity to the point and determine the ratio $\delta W/\delta q$. Also, the external force at every point of the path, and depends only on the path is to be equal and opposite to the electrostatic force on the test charge at that point.

charge configuration is independent

2.3 POTENTIAL DUE TO A POINT CHARGE

Consider a point charge Q at the origin (Fig. 2.3). For definiteness, take Q

to be positive. We wish to determine the potential at any point P with position vector \mathbf{r} from the origin. For that we must calculate the work done in bringing a unit positive test charge from infinity to the point P. For $Q > 0$, the work done against the repulsive force on the test charge is positive. Since work done is independent of the path, we choose a convenient path – along the radial direction from infinity to the point P.

At some intermediate point P' on the path, the electrostatic force on a unit positive charge is

FIGURE 2.3 Work done in bringing a unit positive test charge from infinity to the

$$Q \times 1 \text{ C}$$

point P, against the repulsive force of

$$\frac{1}{4\pi\epsilon_0} \frac{Q}{r^2}$$

$$\frac{1}{4\pi\epsilon_0} \frac{Q}{r^2}$$

$$\frac{1}{4\pi\epsilon_0} \frac{Q}{r^2}$$

$$\frac{1}{4\pi\epsilon_0} \frac{Q}{r^2}$$

$$(2.5)$$

r'

0

charge Q ($Q > 0$), is the potential at P due to the charge Q .

where $\hat{\mathbf{r}}'$ is the unit vector along OP' . Work done against this force from \mathbf{r}' to $\mathbf{r}' + \Delta\mathbf{r}'$ is

Q

$\Delta W = -$

$\Delta r'$

2

(2.6)

4ϵ

$\pi r'$

0

The negative sign appears because for $\Delta r' < 0$, ΔW is positive. Total work done (W) by the external force is obtained by integrating Eq. (2.6) from $r' = \infty$ to $r' = r$,

r

r

Q

Q

Q

$W = -$

$dr' =$

$=$

\int

2

(2.7)

$4\pi\epsilon r'$

$4\pi\epsilon r' \infty$

$4\pi\epsilon r$

∞

0

0

0

This, by definition is the potential at P due to the charge Q

Q

$=$

54

$V(r)$

(2.8)

4ϵ

πr

0

Electrostatic Potential

and Capacitance

Equation (2.8) is true for any

sign of the charge Q , though we

considered $Q > 0$ in its derivation.

For $Q < 0$, $V < 0$, i.e., work done (by

the external force) per unit positive

test charge in bringing it from

infinity to the point is negative. This

is equivalent to saying that work

done by the electrostatic force in

bringing the unit positive charge

from infinity to the point P is

positive. [This is as it should be,

since for $Q < 0$, the force on a unit

positive test charge is attractive, so

that the electrostatic force and the

displacement (from infinity to P) are

FIGURE 2.4 Variation of potential V with r [in units of

in the same direction.] Finally, we

($Q/4\pi\epsilon$) m⁻¹] (blue curve) and field with r [in units

0

note that Eq. (2.8) is consistent with

of ($Q/4\pi\epsilon$) m⁻²] (black curve) for a point charge Q .

0

the choice that potential at infinity

be zero.

Figure (2.4) shows how the electrostatic potential ($\propto 1/r$) and the

electrostatic field ($\propto 1/r^2$) varies with r .

Example 2.1

(a) Calculate the potential at a point P due to a charge of 4×10^{-7} C

located 9 cm away.

(b) Hence obtain the work done in bringing a charge of 2×10^{-9} C

from infinity to the point P. Does the answer depend on the path

along which the charge is brought?

Solution

7

1

Q

—

×

9

2

−2

$4 \times 10^{-8} \text{ C}$

(a) $V =$

$= 9 \times 10^9 \text{ Nm C}^{-2} \times$

$4\pi\epsilon_0 r$

0.09 m

0

$= 4 \times 10^4 \text{ V}$

(b)

9

—

4

$W = qV = 2 \times 10^{-8} \text{ C} \times 4 \times 10^4 \text{ V}$

E

XAMPLE

$$= 8 \times 10^{-5} \text{ J}$$

No, work done will be path independent. Any arbitrary infinitesimal path can be resolved into two perpendicular displacements: One along

2.1

\mathbf{r} and another perpendicular to \mathbf{r} . The work done corresponding to the later will be zero.

2.4 POTENTIAL DUE TO AN ELECTRIC DIPOLE

As we learnt in the last chapter, an electric dipole consists of two charges

q and $-q$ separated by a (small) distance $2a$. Its total charge is zero. It is characterised by a dipole moment vector \mathbf{p} whose magnitude is $q \times 2a$ and which points in the direction from $-q$ to q (Fig. 2.5). We also saw that the electric field of a dipole at a point with position vector \mathbf{r} depends not

just on the magnitude r , but also on the angle between \mathbf{r} and \mathbf{p} . Further,

Physics

the field falls off, at large distance, not as

$1/r^2$ (typical of field due to a single charge)

but as $1/r^3$. We, now, determine the electric

potential due to a dipole and contrast it

with the potential due to a single charge.

As before, we take the origin at the

centre of the dipole. Now we know that the

electric field obeys the superposition principle. Since potential is related to the work done by the field, electrostatic potential also follows the superposition principle. Thus, the potential due to the dipole is the sum of potentials due to the charges q and $-q$

$$V = \frac{1}{4\pi\epsilon_0} \left[\frac{q}{r_1} - \frac{q}{r_2} \right]$$

FIGURE 2.5 Quantities involved in the calculation

$$V = \frac{1}{4\pi\epsilon_0} \left[\frac{q}{r_1} - \frac{q}{r_2} \right] \tag{2.9}$$

2

of potential due to a dipole.

where r_1 and r_2 are the distances of the

1

2

point P from q and $-q$, respectively.

Now, by geometry,

2

2

2

$$r_2 = r_1 + a - 2 a r_1 \cos\theta$$

1

2

2

2

$$r_1 = r_2 + a + 2 a r_2 \cos\theta$$

(2.10)

2

We take r much greater than a ($r \gg a$) and retain terms only upto the first order in a/r

a

θa

2

2

2 cos

$r = r$

1 -

+

1

2

r

r

a

θ

2

$2 \cos$

$\cong r$

1

-

r

(2.11)

Similarly,

a

θ

2

2

$2 \cos$

$r \cong r$

1

+

2

r

(2.12)

Using the Binomial theorem and retaining terms upto the first order

in a/r ; we obtain,

$- 1/2$

1

1

$2 a \cos\theta$

1

a

112

1

1

112

$$1 + \cos\theta$$

r

r

r

r

r

[2.13(a)]

1

$- 1/2$

1

1

$2 a \cos\theta$

1

a

1

+

||

1

- cosθ

r

r

r

r

r

[2.13(b)]

2

Using Eqs. (2.9) and (2.13) and $p = 2 qa$, we get

q

2 *a* cosθ

p cosθ

$$V =$$

=

2

2

(2.14)

4ϵ

π

r

4ϵ

πr

0

0

56

Now, $p \cos \theta = \mathbf{p} \cdot \hat{\mathbf{r}}$

Electrostatic Potential

and Capacitance

where $\hat{\mathbf{r}}$ is the unit vector along the position vector \mathbf{OP} .

The electric potential of a dipole is then given by

1

$\mathbf{p} \cdot \hat{\mathbf{r}}$

$$V = \frac{1}{4\pi\epsilon_0} \frac{p \cos\theta}{r^2} \quad ; (r \gg a)$$

(2.15)

$$4\pi\epsilon_0$$

$$\pi$$

$$r$$

$$0$$

Equation (2.15) is, as indicated, approximately true only for distances large compared to the size of the dipole, so that higher order terms in a/r are negligible. For a point dipole \mathbf{p} at the origin, Eq. (2.15) is, however, exact.

From Eq. (2.15), potential on the dipole axis ($\theta = 0, \pi$) is given by

$$V = \pm \frac{p}{4\pi\epsilon_0 r^2}$$

(2.16)

$$r$$

0

(Positive sign for $\theta = 0$, negative sign for $\theta = \pi$.) The potential in the equatorial plane ($\theta = \pi/2$) is zero.

The important contrasting features of electric potential of a dipole from that due to a single charge are clear from Eqs. (2.8) and (2.15):

(i) The potential due to a dipole depends not just on r but also on the angle between the position vector \mathbf{r} and the dipole moment vector \mathbf{p} .

(It is, however, axially symmetric about \mathbf{p} . That is, if you rotate the position vector \mathbf{r} about \mathbf{p} , keeping θ fixed, the points corresponding to P on the cone so generated will have the same potential as at P.) (ii) The electric dipole potential falls off, at large distance, as $1/r^2$, not as $1/r$, characteristic of the potential due to a single charge. (You can refer to the Fig. 2.5 for graphs of $1/r^2$ versus r and $1/r$ versus r , drawn there in another context.)

2.5 POTENTIAL DUE TO A SYSTEM OF CHARGES

Consider a system of charges q_1, q_2, \dots, q_n with position vectors $\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_n$

relative to some origin (Fig. 2.6). The potential V at P due to the charge q_1

is

$V_1 = \frac{1}{4\pi\epsilon_0} \frac{q_1}{r_{1P}}$

and

the potential V_2 at P due to the charge q_2 is

$V_2 = \frac{1}{4\pi\epsilon_0} \frac{q_2}{r_{2P}}$

and so on.

The total potential V at P is

1

q

$V =$

1

4ϵ

πr

0

1P

where r is the distance between q and P.

1P

1

Similarly, the potential V at P due to q and

2

2

V due to q are given by

3

3

1

q

1

q

2

$V =$

3

$V =$

2

,

4ϵ

πr

3

4ϵ

πr

0

2P

0

3P

where r and r are the distances of P from

2P

3P

charges q and q , respectively; and so on for the

2

3

potential due to other charges. By the

FIGURE 2.6 Potential at a point due to a superposition principle, the potential V at P due to the total charge configuration is the algebraic sum of the potentials due to the individual charges.

sum of the potentials due to the individual charges

$$V = V + V + \dots + V$$

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(2.17)

1

2

n

Physics

1

q

q

q

1

2

=

+

+

n

+

4ϵ

πr

r

r

(2.18)

0

1P

2P

$n P$

If we have a continuous charge distribution characterised by a charge

density $\rho(\mathbf{r})$, we divide it, as before, into small volume elements each of size Δv and carrying a charge $\rho \Delta v$. We then determine the potential due to each volume element and sum (strictly speaking, integrate) over all such contributions, and thus determine the potential due to the entire distribution.

We have seen in Chapter 1 that for a uniformly charged spherical shell, the electric field outside the shell is as if the entire charge is concentrated at the centre. Thus, the potential outside the shell is given by 1

$$V = \frac{q}{4\pi\epsilon_0 r} \geq \frac{q}{4\pi\epsilon_0 R}$$

[2.19(a)]

4ϵ

πr

$(r$

$R)$

0

where q is the total charge on the shell and R its radius. The electric field inside the shell is zero. This implies (Section 2.6) that potential is constant inside the shell (as no work is done in moving a charge inside the shell), and, therefore, equals its value at the surface, which is

1

q

$$V =$$

$$[2.19(b)]$$

$$4 \epsilon$$

$$\pi R$$

$$0$$

Example 2.2 Two charges $3 \times 10^{-8} \text{ C}$ and $-2 \times 10^{-8} \text{ C}$ are located 15 cm apart. At what point on the line joining the two charges is the electric potential zero? Take the potential at infinity to be zero.

Solution Let us take the origin O at the location of the positive charge.

The line joining the two charges is taken to be the x -axis; the negative charge is taken to be on the right side of the origin (Fig. 2.7).

FIGURE 2.7

Let P be the required point on the x -axis where the potential is zero.

If x is the x -coordinate of P, obviously x must be positive. (There is no possibility of potentials due to the two charges adding up to zero for $x < 0$.)

If x lies between O and A, we have

$$-8$$

$$-8$$

$$1$$

$$3 \times 10$$

$$2 \times 10$$

$$= 0$$

$$-2$$

$$-2$$

$$4\pi\epsilon$$

$$x \times 10$$

$$(15 - x) \times 10$$

$$0$$

where x is in cm. That is,

$$3$$

$$2$$

$$= 0$$

$$x$$

$$15 - x$$

$$2.2$$

which gives $x = 9$ cm.

If x lies on the extended line OA, the required condition is

3

2

XAMPLE

—

= 0

x

$x - 15$

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E

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E

which gives

XAMPLE

$x = 45$ cm

Thus, electric potential is zero at 9 cm and 45 cm away from the positive charge on the side of the negative charge. Note that the

2.2

formula for potential used in the calculation required choosing potential to be zero at infinity.

Example 2.3 Figures 2.8 (a) and (b) show the field lines of a positive and negative point charge respectively.

<http://sol.sci.uop.edu/~jfalward/electricpotential/electricpotential.html>

Electric potential, equipotential surfaces: FIGURE 2.8

(a) Give the signs of the potential difference $V - V$; $V - V$.

P

Q

B

A

(b) Give the sign of the potential energy difference of a small negative charge between the points Q and P; A and B.

(c) Give the sign of the work done by the field in moving a small positive charge from Q to P.

(d) Give the sign of the work done by the external agency in moving a small negative charge from B to A.

(e) Does the kinetic energy of a small negative charge increase or decrease in going from B to A?

Solution

(a) As $V \propto \frac{1}{r}$

, $V_P > V_Q$. Thus, $(V_P - V_Q)$ is positive. Also V_P is less negative than V_Q .

Q

P

Q

B

than V_Q . Thus, $V_P > V_Q$ or $(V_P - V_Q)$ is positive.

A

B

A

B

A

(b) A small negative charge will be attracted towards positive charge.

The negative charge moves from higher potential energy to lower potential energy. Therefore the sign of potential energy difference of a small negative charge between Q and P is positive.

Similarly, $(P.E.)_Q > (P.E.)_P$ and hence sign of potential energy

A

B

differences is positive.

(c) In moving a small positive charge from Q to P, work has to be done by an external agency against the electric field. Therefore,

E

work done by the field is negative.

XAMPLE

(d) In moving a small negative charge from B to A work has to be done by the external agency. It is positive.

2.3

(e) Due to force of repulsion on the negative charge, velocity decreases and hence the kinetic energy decreases in going from B to A.

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2.6 EQUIPOTENTIAL SURFACES

An equipotential surface is a surface with a constant value of potential at all points on the surface. For a single charge q , the potential is given by Eq. (2.8):

1

q

$$V = \frac{1}{4\pi\epsilon_0} \frac{q}{r}$$

πr

o

This shows that V is a constant if r is constant. Thus, equipotential surfaces of a single point charge are concentric spherical surfaces centred at the charge.

Now the electric field lines for a single charge q are radial lines starting from or ending at the charge, depending on whether q is positive or negative.

Clearly, the electric field at every point is normal to the equipotential surface passing through that point. This is true in general: *for any charge configuration, equipotential surface through a point is normal to the electric field at that point.* The proof of this statement is simple.

If the field were not normal to the equipotential surface, it would have nonzero component along the surface. To move a unit test charge against the direction of the component of the field, work would have to be done. But this is in contradiction to the definition of an equipotential

FIGURE 2.9 For a

surface: there is no potential difference between any two points on the single charge q

surface and no work is required to move a test charge on the surface.

(a) equipotential

The electric field must, therefore, be normal to the equipotential surface surfaces are

at every point. Equipotential surfaces offer an alternative visual picture

spherical surfaces

in addition to the picture of electric field lines around a charge

centred at the

configuration.

charge, and

(b) electric field

lines are radial,

starting from the

charge if $q > 0$.

FIGURE 2.10 Equipotential surfaces for a uniform electric field.

For a uniform electric field \mathbf{E} , say, along the x -axis, the equipotential surfaces are planes normal to the x -axis, i.e., planes parallel to the y - z plane (Fig. 2.10). Equipotential surfaces for (a) a dipole and (b) two identical positive charges are shown in Fig. 2.11.

FIGURE 2.11 Some equipotential surfaces for (a) a dipole,

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(b) two identical positive charges.

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2.6.1 Relation between field and potential

Consider two closely spaced equipotential surfaces A and B (Fig. 2.12)

with potential values V and $V + \delta V$, where δV is the change in V in the direction of the electric field \mathbf{E} . Let P be a point on the surface B . δl is the perpendicular distance of the

surface A from P . Imagine that a unit positive charge is moved along this perpendicular from the surface B to surface A against the electric field. The work done in this process is $|\mathbf{E}|\delta l$.

This work equals the potential difference

$$V - V_A$$

A

B

Thus,

$$|\mathbf{E}|\delta l = V - (V + \delta V) = -\delta V$$

$$\delta V$$

$$\text{i.e., } |\mathbf{E}| = -$$

$$(2.20)$$

$$\delta l$$

Since δV is negative, $\delta V = -|\delta V|$. we can rewrite

FIGURE 2.12 From the

Eq (2.20) as

potential to the field.

$$\delta V$$

$$\delta V$$

$$\mathbf{E} = -$$

$$= +$$

$$\delta$$

$$(2.21)$$

$$l$$

$$\delta l$$

We thus arrive at two important conclusions concerning the relation between electric field and potential:

(i) *Electric field is in the direction in which the potential decreases steepest.*

(ii) *Its magnitude is given by the change in the magnitude of potential per unit displacement normal to the equipotential surface at the point.*

2.7 POTENTIAL ENERGY OF A SYSTEM OF CHARGES

Consider first the simple case of two charges q_1 and q_2 with position vector \mathbf{r}_1

\mathbf{r}_2

and \mathbf{r} relative to some origin. Let us calculate the work done W

W

(externally) in building up this configuration. This means that we consider

the charges q_1 and q_2 initially at infinity and determine the work done by

2

an external agency to bring the charges to the given locations. Suppose,

first the charge q_1 is brought from infinity to the point \mathbf{r}_1 . There is no

1

external field against which work needs to be done, so work done in

bringing q_1 from infinity to \mathbf{r}_1 is zero. This charge produces a potential in

1

space given by

1

$V =$

$V =$

1

$4\pi\epsilon_0$

πr^2

0

1P

where r is the distance of a point P in space from the location of q_1 .

1P

1

From the definition of potential, work done in bringing charge q from

2

infinity to the point \mathbf{r} is q times the potential at \mathbf{r} due to q : 2

2

2

1

1

$q q$

work done on $q =$

1 2

2

4ϵ

π

r

61

0

12

Physics

where r is the distance between points 1 and 2.

12

Since electrostatic force is conservative, this work gets stored in the form of potential energy of the system. Thus, the potential energy of a system of two charges q_1 and q_2 is

$$U = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r_{12}}$$

FIGURE 2.13 Potential energy of a

$$U =$$

$$\frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r_{12}}$$

$$U =$$

$$U =$$

system of charges q_1 and q_2 is

$$(2.22)$$

$$U =$$

$$U =$$

$$U = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r_{12}}$$

$$U =$$

$$U =$$

$$U =$$

$$U =$$

directly proportional to the product

Obviously, if q was brought first to its present location and
of charges and inversely to the

2

q brought later, the potential energy U would be the same.
distance between them.

1

More generally, the potential energy expression,

Eq. (2.22), is unaltered whatever way the charges are brought to the
specified

locations, because of path-independence of work for electrostatic force.

Equation (2.22) is true for any sign of q and q . If $q q > 0$, potential 1

2

1 2

energy is positive. This is as expected, since for like charges ($q q > 0$), 1 2
electrostatic force is repulsive and a positive amount of work is needed to
be done against this force to bring the charges from infinity to a finite
distance apart. For unlike charges ($q q < 0$), the electrostatic force is 1 2
attractive. In that case, a positive amount of work is needed against this
force to take the charges from the given location to infinity. In other words,
a negative amount of work is needed for the reverse path (from infinity to
the present locations), so the potential energy is negative.

Equation (2.22) is easily generalised for a system of any number of point charges. Let us calculate the potential energy of a system of three charges q_1 , q_2 and q_3 located at \mathbf{r}_1 , \mathbf{r}_2 , \mathbf{r}_3 , respectively. To bring q_1 first

3

1 2

3

1

from infinity to \mathbf{r}_1 , no work is required. Next we bring q_2 from infinity to 1

2

\mathbf{r}_2 . As before, work done in this step is

2

1

$q_1 q_2$

1 2

$q_3 V(\mathbf{r}_3) =$

2

1

2

(2.23)

$4 \epsilon_0$

π

r

0

12

The charges q and q produce a potential, which at any point P is 1

2

given by

1

q

q

1

2

V

=

+

1, 2

4ϵ

πr

r

(2.24)

0

1P

2P

Work done next in bringing q from infinity to the point \mathbf{r} is q times 3

3

3

V

at \mathbf{r}

1, 2

3

1

$q q$

$q q$

1 3

2

3

$q V$

$(\mathbf{r}) =$

+

(2.25)

3

1,2

3

4ε

πr

r

0

13

23

The total work done in assembling the charges at the given locations is obtained by adding the work done in different steps [Eq. (2.23) and Eq. (2.25)],

1

$q q$

$q q$

$q q$

1 2

1 3

2

3

$U =$

+

+

FIGURE 2.14 Potential energy of a

4ϵ

πr

r

r

(2.26)

0

12

13

23

system of three charges is given by

Again, because of the conservative nature of the

Eq. (2.26), with the notation given

electrostatic force (or equivalently, the path

in the figure.

independence of work done), the final expression for

U , Eq. (2.26), is independent of the manner in which

62

the configuration is assembled. *The potential energy*

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and Capacitance

is characteristic of the present state of configuration, and not the way the state is achieved.

Example 2.4 Four charges are arranged at the corners of a square ABCD of side d , as shown in Fig. 2.15.(a) Find the work required to put together this arrangement. (b) A charge q is brought to the centre O E of the square, the four charges being held fixed at its corners. How much extra work is needed to do this?

FIGURE 2.15

Solution

(a) Since the work done depends on the final arrangement of the charges, and not on how they are put together, we calculate work needed for one way of putting the charges at A, B, C and D. Suppose, first the charge $+q$ is brought to A, and then the charges $-q$, $+q$, and $-q$ are brought to B, C and D, respectively. The total work needed can be calculated in steps:

(i)

Work needed to bring charge $+q$ to A when no charge is present elsewhere: this is zero.

(ii) Work needed to bring $-q$ to B when $+q$ is at A. This is given by (charge at B) \times (electrostatic potential at B due to charge $+q$ at A) ²

q

q

$$= q$$

$$- \times$$

$$= -$$

$$4\pi\epsilon d$$

$$4\pi\epsilon d$$

$$0$$

$$0$$

(iii) Work needed to bring charge $+q$ to C when $+q$ is at A and $-q$ is at B. This is given by (charge at C) \times (potential at C due to charges at A and B)

$$+ q$$

$$- q$$

$$= + q$$

$$+$$

$$4\pi\epsilon d 2 4 \epsilon$$

$$\pi d$$

$$0$$

0

2

$-q$

1

=

1 -

4ϵ

πd

0

2

(iv) Work needed to bring $-q$ to D when $+q$ at A, $-q$ at B, and $+q$ at C.

This is given by (charge at D) \times (potential at D due to charges at A,

E

B and C)

XAMPLE

$+q$

$-q$

q

$=q$

-

+

+

4ϵ

$\pi d 4\pi\epsilon d 2 4 \epsilon$

πd

0

0

0

2.4

2

q

-

1

=

2 -

$4\pi\epsilon d$

0

2

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Add the work done in steps (i), (ii), (iii) and (iv). The total work required is

2

- q

1

1

=

(0

) + (1) + 1 -

+ 2 -

4 ε

πd

0

2

2

2

- q

=

(4- 2)

4ϵ

πd

0

The work done depends only on the arrangement of the charges, and not how they are assembled. By definition, this is the total electrostatic energy of the charges.

(Students may try calculating same work/energy by taking charges in any other order they desire and convince themselves that the energy will remain the same.)

(b) The extra work necessary to bring a charge q to the point E when

0

2.4

the four charges are at A, B, C and D is $q \times$ (electrostatic potential at 0 E due to the charges at A, B, C and D). The electrostatic potential at E is clearly zero since potential due to A and C is cancelled by that

XAMPLE

due to B and D. Hence no work is required to bring any charge to

E

point E.

2.8 POTENTIAL ENERGY IN AN EXTERNAL FIELD

2.8.1 Potential energy of a single charge

In Section 2.7, the source of the electric field was specified – the charges and their locations - and the potential energy of the system of those charges was determined. In this section, we ask a related but a distinct question.

What is the potential energy of a charge q in a given field? This question was, in fact, the starting point that led us to the notion of the electrostatic potential (Sections 2.1 and 2.2). But here we address this question again to clarify in what way it is different from the discussion in Section 2.7.

The main difference is that we are now concerned with the potential energy of a charge (or charges) in an *external* field. The external field \mathbf{E} is *not* produced by the given charge(s) whose potential energy we wish to calculate. \mathbf{E} is produced by sources external to the given charge(s). The external sources may be known, but often they are unknown or unspecified; what is specified is the electric field \mathbf{E} or the electrostatic potential V due to the external sources. We assume that the charge q does not significantly affect the sources producing the external field. This is true if q is very small, or the external sources are held fixed by other unspecified forces. Even if q is finite, its influence on the external sources may still be ignored in the situation when very strong sources far away at infinity produce a finite field \mathbf{E} in the region of interest. Note again that we are interested in determining the potential energy of a given charge q (and later, a system of charges) in the external field; we are not interested

in the potential energy of the sources producing the external electric field.

The external electric field \mathbf{E} and the corresponding external potential

V may vary from point to point. By definition, V at a point P is the work done in bringing a unit positive charge from infinity to the point P.

Electrostatic Potential

and Capacitance

(We continue to take potential at infinity to be zero.) Thus, work done in bringing a charge q from infinity to the point P in the external field is qV .

This work is stored in the form of potential energy of q . If the point P has position vector \mathbf{r} relative to some origin, we can write: Potential energy of q at \mathbf{r} in an external field

$$= qV(\mathbf{r})$$

(2.27)

where $V(\mathbf{r})$ is the external potential at the point \mathbf{r} .

Thus, if an electron with charge $q = e = 1.6 \times 10^{-19}$ C is accelerated by a potential difference of $\Delta V = 1$ volt, it would gain energy of $q\Delta V = 1.6 \times$

10^{-19} J. This unit of energy is defined as 1 *electron volt* or 1eV, i.e., 1 eV = 1.6×10^{-19} J. The units based on eV are most commonly used in atomic, nuclear and particle physics, (1 keV = 10^3 eV = 1.6×10^{-16} J, 1 MeV

= 10^6 eV = 1.6×10^{-13} J, 1 GeV = 10^9 eV = 1.6×10^{-10} J and 1 TeV = 10^{12} eV

= 1.6×10^{-7} J). [This has already been defined on Page 117, XI Physics

Part I, Table 6.1.]

2.8.2 Potential energy of a system of two charges in an external field

Next, we ask: what is the potential energy of a system of two charges q_1

and q located at \mathbf{r} and \mathbf{r}' , respectively, in an external field? First, we

1

2

calculate the work done in bringing the charge q from infinity to \mathbf{r} .

1

1

Work done in this step is $q V(\mathbf{r})$, using Eq. (2.27). Next, we consider the

1

work done in bringing q to \mathbf{r} . In this step, work is done not only against

2

the external field \mathbf{E} but also against the field due to q .

1

Work done on q against the external field

2

$= q V(\mathbf{r})$

2

2

Work done on q against the field due to q

2

1

$q_1 q_2$

$1/2$

$$= \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r_{12}}$$

where r_{12}

is the distance between q_1 and q_2 . We have made use of Eqs.

(2.27)

and

(2.22).

By the superposition principle for fields, we add up

the work done on q_2 against the two fields (\mathbf{E}_1 and that due to q_1):

$W_{12} = q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r} + q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r}$

Work done in bringing q_2 to \mathbf{r}

$= q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r} + q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r}$

$= q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r} + q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r}$

$= q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r} + q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r}$

$= q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r} + q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r}$

$$= q_2 V(\mathbf{r}) + q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r}$$

$= q_2 V(\mathbf{r}) + q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r}$

$= q_2 V(\mathbf{r}) + q_2 \int_{r_2}^{\mathbf{r}} \mathbf{E}_1 \cdot d\mathbf{r}$

(2.28)

4ϵ

πr

$o 12$

Thus,

Potential energy of the system

= the total work done in assembling the configuration

$q q$

$1 2$

$= q V(\mathbf{r}) + q V(\mathbf{r}) +$

1

1

2

2

(2.29)

4ϵ

πr

$0 12$

E

Example 2.5

XAMPLE

(a) Determine the electrostatic potential energy of a system consisting of two charges $7 \mu\text{C}$ and $-2 \mu\text{C}$ (and with no external field) placed at $(-9 \text{ cm}, 0, 0)$ and $(9 \text{ cm}, 0, 0)$ respectively.

2.5

(b) How much work is required to separate the two charges infinitely away from each other?

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(c) Suppose that the same system of charges is now placed in an external electric field $E = A (1/r^2)$; $A = 9 \times 10^5 \text{ C m}^{-2}$. What would the electrostatic energy of the configuration be?

Solution

12

1

$q q$

$7 (2) 10^{-}$

$\times - \times$

(a)

1 2

9

$U =$

$$= 9 \times 10 \times$$

$$4 \varepsilon$$

$$\pi$$

$$= -0.7 \text{ J.}$$

$$r$$

$$0.18$$

$$0$$

$$(b) W = U - U = 0 - U = 0 - (-0.7) = 0.7 \text{ J.}$$

$$2$$

$$1$$

(c) The mutual interaction energy of the two charges remains unchanged. In addition, there is the energy of interaction of the two charges with the external electric field. We find,

$$7 \text{ C}$$

$$\mu$$

$$2$$

$$- \text{C}$$

$$\mu$$

$$q V_{\mathbf{r}} + q V_{\mathbf{r}}$$

$$= A$$

+ A

1

(1) 2 (2)

0.09m

0.09m

and the net electrostatic energy is

2.5

μ

- μ

$q V(\mathbf{r}) + q V(\mathbf{r})$

$q q$

7 C

2 C

1 2

+

= A

+ A

- 0.7 J

1

1

2

2

4ϵ

πr

0.09 m

0.09 m

0.12

XAMPLE

$= 70 - 20 - 0.7 = 49.3 \text{ J}$

E

2.8.3 Potential energy of a dipole in an external field

Consider a dipole with charges $q = +q$ and $q = -q$ placed in a uniform

1

electric field **E**, as shown in Fig. 2.16.

As seen in the last chapter, in a uniform electric field,

the dipole experiences no net force; but experiences a

torque

τ given by

=

$\tau =$

$$\boldsymbol{\tau} = \mathbf{p} \times \mathbf{E}$$

(2.30)

which will tend to rotate it (unless \mathbf{p} is parallel or antiparallel to \mathbf{E}). Suppose an external torque τ

is

τ_{ext}

applied in such a manner that it just neutralises this

torque and rotates it in the plane of paper from angle θ_0

to angle θ

1 at an infinitesimal angular speed and *without*

angular acceleration. The amount of work done by the

external torque will be given by

$\int_{\theta_0}^{\theta}$

$\tau(\theta) d\theta$

$W =$

$\int_{\theta_0}^{\theta} \tau(\theta) d\theta$

$=$

$pE \sin \theta d\theta$

FIGURE 2.16 Potential energy of a

$$\int$$

$$\int$$

ext

θ_0

θ_0

dipole in a uniform external field.

$$= pE (\cos\theta - \cos$$

0

$\theta_1)$

(2.31)

This work is stored as the potential energy of the system. We can then

associate potential energy $U(\theta)$ with an inclination θ of the dipole. Similar to other potential energies, there is a freedom in choosing the angle where the potential energy U is taken to be zero. A natural choice is to take $\theta = \pi / 2$. (An explanation for it is provided towards the end of discussion.) 0

We can then write,

π

$$U(\theta) = pE \cos$$

$$- \cos\theta = -pE \cos\theta = -$$

pCE

2

(2.32)

Electrostatic Potential

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This expression can alternately be understood also from Eq. (2.29).

We apply Eq. (2.29) to the present system of two charges $+q$ and $-q$. The potential energy expression then reads ' (θ)

q

U

$$= q [V(\mathbf{r}) - V(\mathbf{r})$$

2

]-

1

2

(2.33)

4ϵ

$\pi \times 2 a$

0

Here, \mathbf{r} and \mathbf{r} denote the position vectors of $+q$ and $-q$. Now, the

2

potential difference between positions \mathbf{r} and \mathbf{r} equals the work done

2

in bringing a unit positive charge against field from \mathbf{r} to \mathbf{r} . The

1

displacement parallel to the force is $2 a \cos\theta$. Thus, $[V(\mathbf{r}) - V(\mathbf{r})] =$

1

2

$-E \times 2 a \cos\theta$. We thus obtain,

' (θ)

2

2

q

q

U

$= -pE \cos\theta -$

$$= -\mathbf{p} \cdot \mathbf{E}$$

$$C -$$

$$(2.34)$$

$$4 \varepsilon$$

$$\pi \times 2 a$$

$$4\pi$$

×

$$0$$

$$\varepsilon$$

$$2 a$$

$$0$$

We note that $U'(\theta)$ differs from $U(\theta)$ by a quantity which is just a constant for a given dipole. Since a constant is insignificant for potential energy, we can drop the second term in Eq. (2.34) and it then reduces to Eq. (2.32).

We can now understand why we took $\theta = \pi/2$. In this case, the work

$$0$$

done against the *external* field \mathbf{E} in bringing $+q$ and $-q$ are equal and opposite and cancel out, i.e., $q [V(\mathbf{r}) - V(\mathbf{r})] = 0$.

$$1$$

$$2$$

Example 2.6 A molecule of a substance has a permanent electric

dipole moment of magnitude 10^{-29} C m. A mole of this substance is polarised (at low temperature) by applying a strong electrostatic field of magnitude 10^6 V m⁻¹. The direction of the field is suddenly changed by an angle of 60° . Estimate the heat released by the substance in aligning its dipoles along the new direction of the field. For simplicity, assume 100% polarisation of the sample.

Solution Here, dipole moment of each molecules = 10^{-29} C m

As 1 mole of the substance contains 6×10^{23} molecules,

total dipole moment of all the molecules, $p = 6 \times 10^{23} \times 10^{-29}$ C m

E

$$= 6 \times 10^{-6} \text{ C m}$$

XAMPLE

Initial potential energy, $U = -pE \cos \theta = -6 \times 10^{-6} \times 10^6 \cos 0^\circ = -6 \text{ J}$

i

Final potential energy (when $\theta = 60^\circ$), $U = -6 \times 10^{-6} \times 10^6 \cos 60^\circ = -3 \text{ J}$

f

Change in potential energy = $-3 \text{ J} - (-6 \text{ J}) = 3 \text{ J}$

2.6

So, there is loss in potential energy. This must be the energy released

by the substance in the form of heat in aligning its dipoles.

2.9 ELECTROSTATICS OF CONDUCTORS

Conductors and insulators were described briefly in Chapter 1.

Conductors contain mobile charge carriers. In metallic conductors, these charge carriers are electrons. In a metal, the outer (valence) electrons part away from their atoms and are free to move. These electrons are free within the metal but not free to leave the metal. The free electrons form a kind of ‘gas’; they collide with each other and with the ions, and move randomly in different directions. In an external electric field, they drift against the direction of the field. The positive ions made up of the nuclei and the bound electrons remain held in their fixed positions. In electrolytic

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conductors, the charge carriers are both positive and negative ions; but

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the situation in this case is more involved – the movement of the charge carriers is affected both by the external electric field as also by the so-called chemical forces (see Chapter 3). We shall restrict our discussion to metallic solid conductors. Let us note important results regarding electrostatics of conductors.

1. Inside a conductor, electrostatic field is zero

Consider a conductor, neutral or charged. There may also be an external electrostatic field. In the static situation, when there is no current inside or on the surface of the conductor, the electric field is zero everywhere inside the conductor. This fact can be taken as the defining property of a conductor. A conductor has free electrons. As long as electric field is not zero, the free charge carriers would experience force and drift. In the static situation, the free charges have so distributed themselves that the electric field is zero everywhere inside. *Electrostatic field is zero inside a conductor.*

2. At the surface of a charged conductor, electrostatic field must be normal to the surface at every point

If \mathbf{E} were not normal to the surface, it would have some nonzero component along the surface. Free charges on the surface of the conductor would then experience force and move. In the static situation, therefore, \mathbf{E} should have no tangential component. Thus *electrostatic field at the surface of a charged conductor must be normal to the surface at every point.* (For a conductor without any surface charge density, field is zero even at the surface.) See result 5.

3. The interior of a conductor can have no excess charge in the static situation

A neutral conductor has equal amounts of positive and negative charges in every small volume or surface element. When the conductor is charged,

the excess charge can reside only on the surface in the static situation.

This follows from the Gauss's law. Consider any arbitrary volume element v inside a conductor. On the closed surface S bounding the volume element v , electrostatic field is zero. Thus the total electric flux through S

is zero. Hence, by Gauss's law, there is no net charge enclosed by S . But the surface S can be made as small as you like, i.e., the volume v can be made vanishingly small. This means *there is no net charge at any point inside the conductor*, and *any excess charge must reside at the surface*.

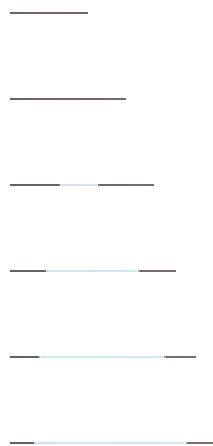
4. Electrostatic potential is constant throughout the volume of the conductor and has the same value (as inside) on its surface

This follows from results 1 and 2 above. Since $\mathbf{E} = 0$ inside the conductor and has no tangential component on the surface, no work is done in moving a small test charge within the conductor and on its surface. That

is, there is no potential difference between any two points inside or on

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the surface of the conductor. Hence, the result. If the conductor is charged,



Electrostatic Potential

and Capacitance

electric field normal to the surface exists; this means potential will be different for the surface and a point just outside the surface.

In a system of conductors of arbitrary size, shape and charge configuration, each conductor is characterised by a constant value of potential, but this constant may differ from one conductor to the other.

5. Electric field at the surface of a charged conductor

σ

$\mathbf{E} =$

\hat{n}

$\epsilon \mathbf{n}$

(2.35)

0

where σ is the surface charge density and \hat{n}

\mathbf{n} is a unit vector normal

to the surface in the outward direction.

To derive the result, choose a pill box (a short cylinder) as the Gaussian surface about any point P on the surface, as shown in Fig. 2.17. The pill box is partly inside and partly outside the surface of the conductor. It has a small area of cross section δS and negligible height.

Just inside the surface, the electrostatic field is zero; just outside, the field is normal to the surface with magnitude E . Thus, the contribution to the total flux through the pill box comes only from the outside (circular) cross-section of the pill box. This equals $\pm E\delta S$ (positive for $\sigma > 0$, negative for $\sigma < 0$), since over the small area δS , \mathbf{E} may be considered constant and \mathbf{E} and δS are parallel or antiparallel. The charge enclosed by the pill box is $\sigma\delta S$.

By Gauss's law

$$\sigma \delta S$$

$$E\delta S = \epsilon_0$$

$$\sigma$$

$$E = \epsilon$$

(2.36)

0

Including the fact that electric field is normal to the

FIGURE 2.17 The Gaussian surface

surface, we get the vector relation, Eq. (2.35), which

(a pill box) chosen to derive Eq. (2.35)

is true for both signs of σ . For $\sigma > 0$, electric field is

for electric field at the surface of a

normal to the surface outward; for $\sigma < 0$, electric field

charged conductor.

is normal to the surface inward.

6. Electrostatic shielding

Consider a conductor with a cavity, with no charges inside the cavity. A

remarkable result is that the electric field inside the cavity is zero, whatever be the size and shape of the cavity and whatever be the charge on the conductor and the external fields in which it might be placed. We have

proved a simple case of this result already: the electric field inside a charged spherical shell is zero. The proof of the result for the shell makes use of the spherical symmetry of the shell (see Chapter 1). But the vanishing of

electric field in the (charge-free) cavity of a conductor is, as mentioned

above, a very general result. A related result is that even if the conductor

Physics

is charged or charges are induced on a neutral conductor by an external field, all charges reside only on the outer surface of a conductor with cavity.

The proofs of the results noted in Fig. 2.18 are omitted here, but we note their important implication. Whatever be the charge and field configuration outside, any cavity in a conductor remains shielded from outside electric influence: *the field inside the cavity is always zero*. This is known as *electrostatic shielding*. The effect can be made use of in protecting sensitive instruments from

FIGURE 2.18 The electric field inside a

outside electrical influence. Figure 2.19 gives a cavity of any conductor is zero. All

summary of the important electrostatic properties charges reside only on the outer surface of a conductor.

of a conductor with cavity. (There are no

charges placed in the cavity.)

FIGURE 2.19 Some important electrostatic properties of a conductor.

Example 2.7

(a) A comb run through one's dry hair attracts small bits of paper.

Why?

What happens if the hair is wet or if it is a rainy day? (Remember, a paper does not conduct electricity.)

(b) Ordinary rubber is an insulator. But special rubber tyres of aircraft are made slightly conducting. Why is this necessary?

(c) Vehicles carrying inflammable materials usually have metallic ropes touching the ground during motion. Why?

(d) A bird perches on a bare high power line, and nothing happens to the bird. A man standing on the ground touches the same line and gets a fatal shock. Why?

Solution

(a) This is because the comb gets charged by friction. The molecules

2.7

in the paper gets polarised by the charged comb, resulting in a net force of attraction. If the hair is wet, or if it is rainy day, friction between hair and the comb reduces. The comb does not get

XAMPLE

charged and thus it will not attract small bits of paper.

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E

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and Capacitance

E

(b) To enable them to conduct charge (produced by friction) to the

XAMPLE

ground; as too much of static electricity accumulated may result in spark and result in fire.

2.7

(c) Reason similar to (b).

(d) Current passes only when there is difference in potential.

2.10 DIELECTRICS AND POLARISATION

Dielectrics are non-conducting substances. In contrast to conductors, they have no (or negligible number of) charge carriers. Recall from Section 2.9 what happens when a conductor is placed in an external electric field. The free charge carriers move and charge distribution in the conductor adjusts

itself in such a way that the electric field due to induced charges opposes the external field within the conductor. This happens until, in the static situation, the two fields cancel each other and the net electrostatic field in the conductor is zero. In a dielectric, this free movement of charges is not possible. It turns out that the external field induces dipole moment by stretching or reorienting molecules of the dielectric. The collective effect of all the molecular dipole moments is net charges on the surface of the dielectric which produce a field that

FIGURE 2.20 Difference in behaviour

of a conductor and a dielectric

opposes the external field. Unlike in a conductor, in an external electric field.

however, the opposing field so induced does not exactly cancel the external field. It only reduces it.

The extent of the effect depends on the nature of the dielectric. To understand the effect, we need to look at the charge

distribution of a dielectric at the molecular level.

The molecules of a substance may be polar or non-polar. In a non-polar molecule, the centres of positive and negative charges coincide. The molecule then has no permanent (or intrinsic) dipole moment. Examples of non-polar molecules are oxygen (O₂) and hydrogen (H₂)

2

2

molecules which, because of their symmetry, have no dipole moment. On the other hand, a polar molecule is one in which the centres of positive and negative charges are separated (even when there is no

FIGURE 2.21

external field). Such molecules have a permanent dipole moment. Some examples of polar and non-polar molecules.

permanent dipole moment. An ionic molecule such as HCl or a molecule of water (H₂O) are examples of polar molecules.

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2

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In an external electric field, the positive and negative charges of a non-polar molecule are displaced in opposite

directions. The displacement stops when the external force on the constituent charges of the molecule is balanced by the restoring force (due to internal fields in the molecule). The non-polar molecule thus develops an induced dipole moment.

The dielectric is said to be polarised by the external field. We consider only the simple situation when the induced dipole moment is in the direction of the field and is proportional to the field strength.

(Substances for which this assumption

is true are called *linear isotropic dielectrics*.) The induced dipole moments of different molecules add up giving a net dipole moment of the dielectric in the presence of the external field.

A dielectric with polar molecules also develops a net dipole moment in an external field, but for a different reason.

FIGURE 2.22 A dielectric develops a net dipole

In the absence of any external field, the moment in an external electric field. (a) Non-polar different permanent dipoles are oriented molecules, (b) Polar molecules.

randomly due to thermal agitation; so the total dipole moment is zero. When an external field is applied, the individual dipole moments tend to align with the field. When summed over all the molecules, there is then a net dipole moment in the direction of the external field, i.e., the dielectric is polarised. The extent of polarisation depends on the relative strength of two mutually opposite factors: the dipole potential energy in the external

field tending to align the dipoles with the field and thermal energy tending to disrupt the alignment. There may be, in addition, the 'induced dipole moment' effect as for non-polar molecules, but generally the alignment effect is more important for polar molecules.

Thus in either case, whether polar or non-polar, a dielectric develops a net dipole moment in the presence of an external field. The dipole moment per unit volume is called *polarisation* and is denoted by \mathbf{P} . For linear isotropic dielectrics, $\mathbf{P} = \chi \mathbf{E}$

(2.37)

e

where χ is a constant characteristic of the dielectric and is known as the

e

electric susceptibility of the dielectric medium.

It is possible to relate χ to the molecular properties of the substance,

e

but we shall not pursue that here.

The question is: how does the polarised dielectric modify the original external field inside it? Let us consider, for simplicity, a rectangular dielectric slab placed in a uniform external field \mathbf{E} parallel to two of its

0

faces. The field causes a uniform polarisation \mathbf{P} of the dielectric. Thus



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every volume element Δv of the slab has a dipole moment

$\mathbf{P} \Delta v$ in the direction of the field. The volume element Δv is macroscopically small but contains a very large number of molecular dipoles. Anywhere inside the dielectric, the

volume element Δv has no net charge (though it has net dipole moment). This is, because, the positive charge of one dipole sits close to the negative charge of the adjacent dipole.

However, at the surfaces of the dielectric normal to the electric field, there is evidently a net charge density. As seen in Fig 2.23, the positive ends of the dipoles remain unneutralised at the right surface and the negative ends at the left surface. The unbalanced charges are the induced charges due to the external field.

Thus the polarised dielectric is equivalent to two charged surfaces with induced surface charge densities, say σ_p and $-\sigma_p$. Clearly, the field produced by these surface charges

p

opposes the external field. The total field in the dielectric

FIGURE 2.23 A uniformly

is, thereby, reduced from the case when no dielectric is

polarised dielectric amounts

present. We should note that the surface charge density

to induced surface charge

$\pm\sigma$ arises from bound (not free charges) in the dielectric.

density, but no volume

ρ

charge density.

2.11 CAPACITORS AND CAPACITANCE

A capacitor is a system of two conductors separated by an insulator

(Fig. 2.24). The conductors have charges, say Q and Q , and potentials 1

2

V and V . Usually, in practice, the two conductors have charges Q

1

2

and $-Q$, with potential difference $V = V - V$ between them. We shall 1

2

consider only this kind of charge configuration of the capacitor. (Even a

single conductor can be used as a capacitor by assuming the other at infinity.) The conductors may be so charged by connecting them to the two terminals of a battery. Q is called the charge of the capacitor, though this, in fact, is the charge on one of the conductors – the total charge of the capacitor is zero.

The electric field in the region between the conductors is proportional to the charge Q . That is, if the charge on the capacitor is, say doubled, the electric field will also be doubled at every point.

(This follows from the direct proportionality between field and charge implied by Coulomb's law and the superposition principle.) Now, potential difference V is the work done per unit positive charge in taking a small test charge from the conductor 2 to 1 against the field.

FIGURE 2.24 A system of two conductors

Consequently, V is also proportional to Q , and separated by an insulator forms a capacitor.

the ratio Q/V is a constant:

Q

$C =$

(2.38)

V

The constant C is called the *capacitance* of the capacitor. C is independent
73

of Q or V , as stated above. The capacitance C depends only on the

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geometrical configuration (shape, size, separation) of the system of two
conductors. [As we shall see later, it also depends on the nature of the
insulator (dielectric) separating the two conductors.] The SI unit of
capacitance is 1 farad (=1 coulomb volt⁻¹) or 1 F = 1 C V⁻¹. A capacitor
with fixed capacitance is symbolically shown as ---||--, while the one with
variable capacitance is shown as

.

Equation (2.38) shows that for large C , V is small for a given Q . This means
a capacitor with large capacitance can hold large amount of charge Q at a
relatively small V . This is of practical importance. High potential difference
implies strong electric field around the conductors. A strong electric field
can ionise the surrounding air and accelerate the charges so

produced to the oppositely charged plates, thereby neutralising the charge
on the capacitor plates, at least partly. In other words, the charge of the
capacitor leaks away due to the reduction in insulating power of the
intervening medium.

The maximum electric field that a dielectric medium can withstand without breakdown (of its insulating property) is called its *dielectric strength*; for air it is about $3 \times 10^6 \text{ Vm}^{-1}$. For a separation between conductors of the order of 1 cm or so, this field corresponds to a potential difference of $3 \times 10^4 \text{ V}$ between the conductors. Thus, for a capacitor to store a large amount of charge without leaking, its capacitance should be high enough so that the potential difference and hence the electric field do not exceed the breakdown limits. Put differently, there is a limit to the amount of charge that can be stored on a given capacitor without significant leaking. In practice, a farad is a very big unit; the most common units are its sub-multiples $1 \mu\text{F} = 10^{-6} \text{ F}$, $1 \text{ nF} = 10^{-9} \text{ F}$, $1 \text{ pF} = 10^{-12} \text{ F}$, *etc.* Besides its use in storing charge, a capacitor is a key element of most ac circuits with important functions, as described in Chapter 7.

2.12 THE PARALLEL PLATE CAPACITOR

A parallel plate capacitor consists of two large plane parallel conducting plates separated by a small distance (Fig. 2.25). We first take the intervening medium between the plates to be vacuum. The effect of a dielectric medium between the plates is discussed in the next section. Let A be the area of each plate and d the separation between

them. The two plates have charges Q and $-Q$. Since d is much smaller than the linear dimension of the plates ($d \ll A$), we can use the result on electric field by an infinite plane sheet of uniform surface charge density (Section 1.15). Plate 1 has surface charge density $\sigma = Q/A$ and plate 2 has a surface charge density $-\sigma$. Using Eq. (1.33), the electric field in different regions is:

Outer region I (region above the plate 1),

FIGURE 2.25 The parallel plate capacitor.



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$$E = \frac{\sigma}{\epsilon_0} - \frac{\sigma}{\epsilon_0} = 0$$

(2.39)

$$2\epsilon$$

2ε

0

0

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and Capacitance

Outer region II (region below the plate 2),

σ

σ

$E =$

—

$= 0$

(2.40)

2ε

2ε

0

0

In the inner region between the plates 1 and 2, the electric fields due to the two charged plates add up, giving

σ

σ

σ Q $E =$

+

=

=

(2.41)

 2ε 2ε ε εA

0

0

0

0

The direction of electric field is from the positive to the negative plate.

Thus, the electric field is localised between the two plates and is

uniform throughout. For plates with finite area, this will not be true near

the outer boundaries of the plates. The field lines bend outward at the

edges – an effect called ‘fringing of the field’. By the same token, σ will not

<http://micro.magnet.fsa.edu/electromag/java/capacitance/> **Interactive Java**

tutorial Factors affecting capacitance, capacitors in action be strictly uniform on the entire plate. [E and σ are related by Eq. (2.35).]

However, for $d \ll A$, these effects can be ignored in the regions sufficiently far from the edges, and the field there is given by Eq. (2.41). Now for uniform electric field, potential difference is simply the electric field times the distance between the plates, that is, $V = E d$

$$V = E d = \frac{Q}{\epsilon A} d$$

(2.42)

0

The capacitance C of the parallel plate capacitor is then

Q

ϵA

$C =$

=

0

=

(2.43)

V

d

which, as expected, depends only on the geometry of the system. For

typical values like $A = 1 \text{ m}^2$, $d = 1 \text{ mm}$, we get

12

—

2

−1

−2

2

8.85×10

C N m

$\times 1\text{m}$

9

$C =$

$= 8.85 \times 10^{-9} \text{ F}$

(2.44)

3

10^{-9} m^2

(You can check that if $1\text{F} = 1\text{C V}^{-1} = 1\text{C} (\text{NC}^{-1}\text{m})^{-1} = 1 \text{ C}^2 \text{ N}^{-1}\text{m}^{-1}$.)

This shows that 1F is too big a unit in practice, as remarked earlier.

Another way of seeing the ‘bigness’ of 1F is to calculate the area of the plates needed to have $C = 1\text{F}$ for a separation of, say 1 cm:

Cd

-2

×

A =

=

1F 10 m

9

2

ε

= 10 m

-12

2

-1

-2

0

8.85 ×

(2.45)

10

C N m

which is a plate about 30 km in length and breadth!

2.13 EFFECT OF DIELECTRIC ON CAPACITANCE

With the understanding of the behavior of dielectrics in an external field developed in Section 2.10, let us see how the capacitance of a parallel plate capacitor is modified when a dielectric is present. As before, we have two large plates, each of area A , separated by a distance d . The charge on the plates is $\pm Q$, corresponding to the charge density $\pm\sigma$ (with $\sigma = Q/A$). When there is vacuum between the plates, σ

$$E =$$

$$0$$

$$75$$

$$\epsilon_0$$

Physics

and the potential difference V is

$$0$$

$$V = E d$$

$$0$$

$$0$$

The capacitance C in this case is

$$0$$

$$Q$$

$$A$$

$$C =$$

$$= \epsilon$$

$$0$$

$$0$$

$$V$$

$$d$$

$$(2.46)$$

$$0$$

Consider next a dielectric inserted between the plates fully occupying the intervening region. The dielectric is polarised by the field and, as explained in Section 2.10, the effect is equivalent to two charged sheets (at the surfaces of the dielectric normal to the field) with surface charge densities σ and $-\sigma$. The electric field in the dielectric then corresponds

$$p$$

$$p$$

to the case when the net surface charge density on the plates is $\pm(\sigma - \sigma)$.

$$p$$

That is,

$$\sigma - \sigma P$$

$$E =$$

$$\epsilon$$

(2.47)

0

so that the potential difference across the plates is

$$\sigma - \sigma P$$

$$V = E d =$$

d

ϵ

(2.48)

0

For linear dielectrics, we expect σ to be proportional to E , i.e., to σ .

p

0

Thus, $(\sigma - \sigma)$ is proportional to σ and we can write

p

σ

$$\sigma - \sigma =$$

P

(2.49)

K

where K is a constant characteristic of the dielectric. Clearly, $K > 1$. We then have

$$\sigma d$$

$$Qd$$

$$V =$$

=

$$\epsilon K$$

$$A \epsilon K$$

$$(2.50)$$

$$0$$

$$0$$

The capacitance C , with dielectric between the plates, is then

$$Q$$

$$\epsilon KA$$

$$0$$

$$C =$$

=

$$(2.51)$$

$$V$$

$$d$$

The product ϵK is called the *permittivity* of the medium and is 0

denoted by ϵ

$$\epsilon = \epsilon K$$

(2.52)

0

For vacuum $K = 1$ and $\epsilon = \epsilon_0$; ϵ_0 is called the *permittivity of the vacuum*.

0

0

The dimensionless ratio

ϵ

$$K = \epsilon / \epsilon_0$$

(2.53)

0

is called the *dielectric constant* of the substance. As remarked before, from Eq. (2.49), it is clear that K is greater than 1. From Eqs. (2.46) and (2.51) C

$$K = C / C_0$$

(2.54)

0

Thus, the dielectric constant of a substance is the factor (>1) by which the capacitance increases from its vacuum value, when the dielectric is

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inserted fully between the plates of a capacitor. Though we arrived at

Electrostatic Potential

and Capacitance

Eq. (2.54) for the case of a parallel plate capacitor, it holds good for any type of capacitor and can, in fact, be viewed in general as a definition of the dielectric constant of a substance.

ELECTRIC DISPLACEMENT

We have introduced the notion of dielectric constant and arrived at Eq. (2.54), without giving the explicit relation between the induced charge density σ and the polarisation \mathbf{P} .

\mathbf{P}

We take without proof the result that

$$\sigma = \mathbf{P} \cdot \hat{\mathbf{n}}$$

\mathbf{P}

where $\hat{\mathbf{n}}$

$\hat{\mathbf{n}}$ is a unit vector along the outward normal to the surface. Above equation is general, true for any shape of the dielectric. For the slab in Fig. 2.23, \mathbf{P} is along $\hat{\mathbf{n}}$

$\hat{\mathbf{n}}$ at the

right surface and opposite to $\hat{\mathbf{n}}$

$\hat{\mathbf{n}}$ at the left surface. Thus at the right surface, induced

charge density is positive and at the left surface, it is negative, as guessed already in our qualitative discussion before. Putting the equation for electric field in vector form $\sigma = \mathbf{C} \cdot \hat{\mathbf{n}}$

$\mathbf{C} \cdot \hat{\mathbf{n}} =$

$\mathbf{P} \cdot \mathbf{n}$

$\mathbf{E} \cdot \mathbf{n}$

ϵ_0

or $(\epsilon \mathbf{E} + \mathbf{P}) \cdot \mathbf{C}^{\wedge}$

$\mathbf{n} = \sigma$

0

The quantity $\epsilon \mathbf{E} + \mathbf{P}$ is called the *electric displacement* and is denoted by \mathbf{D} . It is a 0

vector quantity. Thus,

$\mathbf{D} = \epsilon \mathbf{E} + \mathbf{P}, \mathbf{D} \cdot \mathbf{C}^{\wedge}$

$\mathbf{n} = \sigma,$

0

The significance of \mathbf{D} is this : in vacuum, \mathbf{E} is related to the free charge density σ .

When a dielectric medium is present, the corresponding role is taken up by \mathbf{D} . For a dielectric medium, it is \mathbf{D} not \mathbf{E} that is directly related to free charge density σ , as seen in above equation. Since \mathbf{P} is in the same direction as \mathbf{E} , all the three vectors \mathbf{P} , \mathbf{E} and \mathbf{D} are parallel.

The ratio of the magnitudes of \mathbf{D} and \mathbf{E} is

D

$\sigma \epsilon_0$

=

$$= \epsilon K$$

0

E

$$\sigma - \sigma P$$

Thus,

$$\mathbf{D} = \epsilon K \mathbf{E}$$

0

$$\text{and } \mathbf{P} = \mathbf{D} - \epsilon \mathbf{E} = \epsilon (K - 1)\mathbf{E}$$

0

0

This gives for the electric susceptibility χ defined in Eq. (2.37)

e

$$\chi = \epsilon (K - 1)$$

e

0

Example 2.8 A slab of material of dielectric constant K has the same area as the plates of a parallel-plate capacitor but has a thickness $(3/4)d$, where d is the separation of the plates. How is the capacitance \mathbf{E}

XAMPLE

changed when the slab is inserted between the plates?

Solution Let $E = V/d$ be the electric field between the plates when 0

0

there is no dielectric and the potential difference is V . If the dielectric 0

2.8

is now inserted, the electric field in the dielectric will be $E = E / K$.

0

The potential difference will then be

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1

E

3

0

$$V = E (d) +$$

(d)

0 4

$K 4$

1

3

$K + 3$

$$= E d(+$$

$$) = V$$

$$0$$

$$0$$

$$4$$

$$4 K$$

$$4 K$$

The potential difference decreases by the factor $(K + 3)/4 K$ while the **2.8**

free charge Q on the plates remains unchanged. The capacitance

$$0$$

thus increases

XAMPLE

$$Q$$

$$4 K Q$$

$$4 K$$

$$0$$

$$0$$

$$C =$$

$$=$$

$$=$$

$$C$$

E

0

V

$K + 3 V$

$K + 3$

0

2.14 COMBINATION OF CAPACITORS

We can combine several capacitors of capacitance C_1, C_2, \dots, C_n to obtain

2

n

a system with some effective capacitance C . The effective capacitance depends on the way the individual capacitors are combined. Two simple possibilities are discussed below.

2.14.1 Capacitors in series

Figure 2.26 shows capacitors C_1 and C_2 combined in series.

1

2

The left plate of C_1 and the right plate of C_2 are connected to two

2

terminals of a battery and have charges Q and $-Q$,

respectively. It then follows that the right plate of C_1

1

has charge $-Q$ and the left plate of C_2 has charge Q .

2

If this was not so, the net charge on each capacitor would not be zero. This would result in an electric field in the conductor connecting C_1 and C_2 . Charge

1

2

would flow until the net charge on both C_1 and C_2

1

2

is zero and there is no electric field in the conductor connecting C_1 and C_2 . Thus, in the series

1

2

combination, charges on the two plates ($\pm Q$) are the same on each capacitor. The total potential drop V across the combination is the sum of the potential

drops V_1 and V_2 across C_1 and C_2 , respectively.

1

2

1

2

FIGURE 2.26 Combination of two

Q

Q

capacitors in series.

$$V = V_1 + V_2 =$$

+

(2.55)

1

2

C_1

C_2

1

2

V

1

1

i.e.,

=

+

Q

C

C_1 ,

(2.56)

1

2

Now we can regard the combination as an effective capacitor with charge Q and potential difference V . The *effective capacitance* of the combination is

Q

$C =$

(2.57)

V

We compare Eq. (2.57) with Eq. (2.56), and obtain

FIGURE 2.27 Combination of n

capacitors in series.

1

1

1

78

=

+

C

C

C

(2.58)

1

2

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The proof clearly goes through for any number of capacitors arranged in a similar way. Equation (2.55),

for n capacitors arranged in series, generalises to

Q

Q Q

$$V = V + V + \dots + V =$$

 $+$ $+ \dots +$

1

2

n

 C C C

(2.59)

1

2

n

Following the same steps as for the case of two capacitors, we get the general formula for effective capacitance of a series combination of n capacitors:

1

1

1

1

1

=

+

+

+ ... +

C

C

C

C

C

(2.60)

1

2

3

n

2.14.2 Capacitors in parallel

Figure 2.28 (a) shows two capacitors arranged in parallel. In this case, the same potential difference is

applied across both the capacitors. But the plate charges ($\pm Q$) on capacitor 1 and the plate charges ($\pm Q$) on the

1

2

capacitor 2 are not necessarily the same:

$$Q = C V, Q = C V$$

(2.61)

1

1

2

2

The equivalent capacitor is one with charge

$$Q = Q + Q$$

(2.62)

1

2

and potential difference V .

$$Q = C V = C V + C V$$

(2.63)

1

2

The effective capacitance C is, from Eq. (2.63),

$$C = C + C$$

(2.64)

1

2

The general formula for effective capacitance C for parallel combination of n capacitors [Fig. 2.28 (b)]

FIGURE 2.28 Parallel combination of

follows similarly,

(a) two capacitors, (b) n capacitors.

$$Q = Q + Q + \dots + Q$$

(2.65)

1

2

n

i.e., $CV = CV + CV + \dots CV$

(2.66)

1

2

n

which gives

$$C = C + C + \dots + C$$

(2.67)

1

2

n

Example 2.9 A network of four $10 \mu\text{F}$ capacitors is connected to a 500 V supply, as shown in Fig. 2.29. Determine (a) the equivalent capacitance of the network and (b) the charge on each capacitor. (Note, the *charge on a capacitor* is the charge on the plate with higher potential, equal and opposite to the charge on the plate with lower potential.)

E

XAMPLE

2.9

FIGURE 2.29

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Physics

Solution

(a) In the given network, C , C and C are connected in series. The 1

2

3

effective capacitance C' of these three capacitors is given by

1

1

1

1

=

+

+

C'

C

C

C

1

2

3

For $C = C = C = 10 \mu\text{F}$, $C' = (10/3) \mu\text{F}$. The network has C' and C

1

2

3

4

connected in parallel. Thus, the equivalent capacitance C of the network is

10

$$C = C' + C =$$

+10

4

3

$$\mu\text{F} = 13.3\mu\text{F}$$

(b) Clearly, from the figure, the charge on each of the capacitors, C , 1
 C and C is the same, say Q . Let the charge on C be Q' . Now, since 2

3

4

the potential difference across AB is Q/C , across BC is Q/C , across 1

2

CD is Q/C , we have

3

Q

Q

Q

+

+

= 500 V .

C

C

C

1

2

3

Also, $Q/C = 500$ V.

4

2.9

This gives for the given value of the capacitances,

10

-3

$Q = 500 V \times$

$\mu\text{F} = 1.7 \times 10^{-3} \text{ C}$ and

3

XAMPLE

3

—

' =

×

$\mu =$

×

E

Q

500 V

10 F

5.0 10

C

2.15 ENERGY STORED IN A CAPACITOR

A capacitor, as we have seen above, is a system of two conductors with charge Q and $-Q$. To determine the energy stored in this configuration, consider initially two uncharged conductors 1 and 2. Imagine next a process of transferring charge from conductor 2 to conductor 1 bit by bit, so that at the end, conductor 1 gets charge Q . By charge conservation, conductor 2 has charge $-Q$ at

the end (Fig 2.30).

In transferring positive charge from conductor 2 to conductor 1, work will be done externally, since at any stage conductor 1 is at a higher potential than conductor 2. To calculate the total work done, we first calculate the work done in a small step involving transfer of an infinitesimal (i.e., vanishingly small) amount of charge. Consider the intermediate situation when the conductors 1 and 2 have charges Q' and $-Q'$ respectively. At this stage, the potential difference

FIGURE 2.30 (a) Work done in a small

V' between conductors 1 to 2 is Q'/C , where C is the step of building charge on conductor 1

capacitance of the system. Next imagine that a small

from Q' to $Q' + \delta Q'$. (b) Total work done

charge $\delta Q'$ is transferred from conductor 2 to 1. Work

in charging the capacitor may be

done in this step ($\delta W'$), resulting in charge Q' on

viewed as stored in the energy of

conductor 1 increasing to $Q' + \delta Q'$, is given by

electric field between the plates.

Q'

80

$$\delta W = V' \delta Q' =$$

$\delta Q'$

(2.68)

C

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and Capacitance

Since $\delta Q'$ can be made as small as we like, Eq. (2.68) can be written as 1

2

2

$$\delta W =$$

$$[(Q' + \delta Q') - Q']$$

(2.69)

2 C

Equations (2.68) and (2.69) are identical because the term of second

order in $\delta Q'$, i.e., $\delta Q' / 2 C$, is negligible, since $\delta Q'$ is arbitrarily small. The total work done (W) is the sum of the small work (δW) over the very large number of steps involved in building the charge Q' from zero to Q .

$$W =$$

Σ

δW

sum over all steps

1

2

2

=

$[(Q$

\sum

$^2 + \delta Q') - Q']$

$2 C$

(2.70)

sum over all steps

1

2

2

2

=

$\{[\delta Q' - 0] + [(2\delta Q') - \delta Q']\}$

2

2

$$+ \{ (3\delta Q') - (2\delta Q') \} + \dots$$

$$2 C$$

$$2$$

$$2$$

$$+ \{ Q - (Q - \delta Q) \}$$

$$(2.71)$$

$$2$$

$$1$$

$$Q$$

$$2$$

=

$$[Q - 0] =$$

$$(2.72)$$

$$2 C$$

$$2 C$$

The same result can be obtained directly from Eq. (2.68) by integration

$$Q$$

$$2 Q$$

2

Q'

1 Q'

Q

$W =$

$\delta Q' =$

=

$\int C$

C^2

2 C

0

0

This is not surprising since integration is nothing but summation of a large number of small terms.

We can write the final result, Eq. (2.72) in different ways

2

Q

1

1

2

$$W =$$

$$= CV = QV$$

(2.73)

$$\frac{1}{2} C$$

$$V^2$$

$$= \frac{1}{2} C V^2$$

Since electrostatic force is conservative, this work is stored in the form of potential energy of the system. For the same reason, the final result for potential energy [Eq. (2.73)] is independent of the manner in which the charge configuration of the capacitor is built up. When the capacitor discharges, this stored-up energy is released. It is possible to view the potential energy of the capacitor as ‘stored’ in the electric field between the plates. To see this, consider for simplicity, a parallel plate capacitor [of area A (of each plate) and separation d between the plates].

Energy stored in the capacitor

$$\frac{1}{2} C$$

$$V^2$$

$$= \frac{1}{2} C V^2$$

$$= \frac{1}{2} (A\epsilon_0 \frac{V}{d}) V^2$$

d

=

=

×

(2.74)

$2 C$

2

ϵA

0

The surface charge density σ is related to the electric field E between the plates,

σ

$E = \epsilon$

(2.75)

0

From Eqs. (2.74) and (2.75) , we get

Energy stored in the capacitor

81

$U = (1/2)$

2

$\epsilon E \times A d$

(2.76)

0

Physics

Note that Ad is the volume of the region between the plates (where electric field alone exists). If we define *energy density as energy stored per unit volume of space*, Eq (2.76) shows that

Energy density of electric field,

$$u = (1/2)\epsilon E^2$$

(2.77)

0

Though we derived Eq. (2.77) for the case of a parallel plate capacitor, the result on energy density of an electric field is, in fact, very general and holds true for electric field due to any configuration of charges.

Example 2.10 (a) A 900 pF capacitor is charged by 100 V battery

[Fig. 2.31(a)]. How much electrostatic energy is stored by the capacitor?

(b) The capacitor is disconnected from the battery and connected to

another 900 pF capacitor [Fig. 2.31(b)]. What is the electrostatic energy stored by the system?

FIGURE 2.31

Solution

(a) The charge on the capacitor is

$$Q = CV = 900 \times 10^{-12} \text{ F} \times 100 \text{ V} = 9 \times 10^{-8} \text{ C}$$

The energy stored by the capacitor is

$$= (1/2) CV^2 = (1/2) QV$$

$$= (1/2) \times 9 \times 10^{-8} \text{ C} \times 100 \text{ V} = 4.5 \times 10^{-6} \text{ J}$$

(b) In the steady situation, the two capacitors have their positive plates at the same potential, and their negative plates at the

same potential. Let the common potential difference be V' . The

charge on each capacitor is then $Q' = CV'$. By charge conservation, $Q' = Q/2$. This implies $V' = V/2$. The total energy of the system is

1

6

2

$$Q' V'$$

$$QV$$

$$2.25 \times 10^{-6}$$

$$= \times$$

$$=$$

$$=$$

$$\times$$

J

2

4

Thus in going from (a) to (b), though no charge is lost; the final energy is only half the initial energy. *Where has the remaining*

2.10

energy gone?

There is a transient period before the system settles to the situation (b). During this period, a transient current flows from

XAMPLE

the first capacitor to the second. Energy is lost during this time

82

E

in the form of heat and electromagnetic radiation.

Electrostatic Potential

and Capacitance

2.16 VAN DE GRAAFF GENERATOR

This is a machine that can build up high voltages of the order of a few million volts. The resulting large electric fields are used to accelerate charged particles (electrons, protons, ions) to high energies needed for experiments to probe the small scale structure of matter. The principle underlying the machine is as follows.

<http://www.coe.ufrj.br/~acmg/myvdg.html>
<http://amasce.com/emotor/vdg.html> \mathbf{V}

Suppose we have a large spherical conducting shell of radius R , on

an de Graaff generator

which we place a charge Q . This charge spreads itself uniformly all over the sphere. As we have seen in Section 1.14, the field outside the sphere is just that of a point charge Q at the centre; while the field inside the sphere vanishes. So the potential outside is that of a point charge; and inside it is constant, namely the value at the radius R . We thus have:

Potential inside conducting spherical shell of radius R carrying charge Q

= constant

1

Q

, principle and demonstration:

=

(2.78)

4ϵ

πR

0

Now, as shown in Fig. 2.32, let us suppose that in some way we

introduce a small sphere of radius r , carrying some charge q , into the large one, and place it at the centre. The potential due to this new charge clearly has the following values at the radii indicated:

Potential due to small sphere of radius r carrying charge q

1

q

=

at surface of small sphere

4ϵ

πr

0

1

q

=

at large shell of radius R .

(2.79)

4ϵ

πR

0

Taking both charges q and Q into account we have for the total potential V and the potential difference the values

1

$Q q$

$$V(R) =$$

+

$$4 \epsilon$$

$$\pi R R$$

$$0$$

$$1$$

$$Q q$$

$$V(r) =$$

+

$$4\pi\epsilon R$$

$$r$$

$$0$$

$$q$$

$$1 1$$

$$V(r) - V(R) =$$

-

(2.80)

4ϵ

πr

R

0

Assume now that q is positive. We see that,

independent of the amount of charge Q that may have

accumulated on the larger sphere and even if it is

positive, the inner sphere is always at a higher

potential: the difference $V(r) - V(R)$ is positive. The potential due to Q is constant upto radius R and so **FIGURE 2.32** Illustrating the principle

of the electrostatic generator.

This means that if we now connect the smaller and

larger sphere by a wire, the charge q on the former

83

Physics

will immediately flow onto the matter, even

though the charge Q may be quite large. The

natural tendency is for positive charge to

move from higher to lower potential. Thus,

provided we are somehow able to introduce the small charged sphere into the larger one, we can in this way keep piling up larger and larger amount of charge on the latter. The potential (Eq. 2.78) at the outer sphere would also keep rising, at least until we reach the breakdown field of air.

This is the principle of the van de Graaff generator. It is a machine capable of building up potential difference of a few million volts, and fields close to the breakdown field of air which is about 3×10^6 V/m. A schematic diagram of the van de Graaff generator is given in Fig. 2.33. A large spherical conducting

FIGURE 2.33 Principle of construction shell (of few metres radius) is supported at a of Van de Graaff generator.

height several meters above the ground on an insulating column. A long narrow endless belt insulating material, like rubber or silk, is wound around two pulleys –

one at ground level, one at the centre of the shell. This belt is kept continuously moving by a motor driving the lower pulley. It continuously carries positive charge, sprayed on to it by a brush at ground level, to the top. There it transfers its positive charge to another conducting brush connected to the large shell. Thus positive charge is transferred to the shell, where it spreads out uniformly on the outer surface. In this way, voltage differences of as much as 6 or 8 million volts (with respect to ground) can be built up.

SUMMARY

1.

Electrostatic force is a conservative force. Work done by an external force (equal and opposite to the electrostatic force) in bringing a charge q from a point R to a point P is $V_P - V_R$, which is the difference in potential energy of charge q between the final and initial points.

2.

Potential at a point is the work done per unit charge (by an external agency) in bringing a charge from infinity to that point. Potential at a point is arbitrary to within an additive constant, since it is the potential difference between two points which is physically significant. If potential

at infinity is chosen to be zero; potential at a point with position vector \mathbf{r} due to a point charge Q placed at the origin is given by

$$V(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \frac{Q}{r}$$

3.

The electrostatic potential at a point with position vector \mathbf{r} due to a point dipole of dipole moment \mathbf{p} placed at the origin is

$$V(\mathbf{r}) = \frac{1}{4\pi\epsilon_0} \frac{\mathbf{p} \cdot \hat{\mathbf{r}}}{r^2}$$

84
4 ϵ
 π
 r
 o

Electrostatic Potential and Capacitance

The result is true also for a dipole (with charges $-q$ and q separated by $2a$) for $r \gg a$.

4.

For a charge configuration q_1, q_2, \dots, q_n with position vectors $\mathbf{r}_1,$

$\mathbf{r}_2,$

$\dots,$

$\mathbf{r}_n,$

the potential at a point P is given by the superposition principle

$V =$

$\frac{1}{4\pi\epsilon_0} \left(\frac{q_1}{r_{1P}} + \frac{q_2}{r_{2P}} + \dots + \frac{q_n}{r_{nP}} \right)$

$\frac{q_1}{r_{1P}}$

$+$

$\frac{q_2}{r_{2P}}$

$+$

\dots

$+$

$\frac{q_n}{r_{nP}}$

$+$

\dots

$+$

$)$

4ϵ

π

r

r

r

0

1P

2P

P

n

where r is the distance between q and P, as and so on.

1P

1

5.

An equipotential surface is a surface over which potential has a constant

value. For a point charge, concentric spheres centered at a location of

the charge are equipotential surfaces. The electric field \mathbf{E} at a point is perpendicular to the equipotential surface through the point. \mathbf{E} is in the direction of the steepest decrease of potential.

6.

Potential energy stored in a system of charges is the work done (by an

external agency) in assembling the charges at their locations. Potential energy of two charges q_1, q_2 at $\mathbf{r}_1, \mathbf{r}_2$ is given by

2

1

2

1

$q_1 q_2$

1

2

$$U = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r}$$

0

12

where r is distance between q_1 and q_2 .

12

1

2

7.

The potential energy of a charge q in an external potential $V(\mathbf{r})$ is $qV(\mathbf{r})$.

The potential energy of a dipole moment \mathbf{p} in a uniform electric field \mathbf{E} is $-\mathbf{p} \cdot \mathbf{E}$.

8. Electrostatics field \mathbf{E} is zero in the interior of a conductor; just outside the surface of a charged conductor, \mathbf{E} is normal to the surface given by σ

$\mathbf{E} =$

\hat{n}

$\epsilon \mathbf{n}$ where $\hat{\mathbf{n}}$ is the unit vector along the outward normal to the 0

surface and σ is the surface charge density. Charges in a conductor can reside only at its surface. Potential is constant within and on the surface of a conductor. In a cavity within a conductor (with no charges), the electric field is zero.

9.

A capacitor is a system of two conductors separated by an insulator. Its

capacitance is defined by $C = Q/V$, where Q and $-Q$ are the charges on the two conductors and V is the potential difference between them. C is determined purely geometrically, by the shapes, sizes and relative positions of the two conductors. The unit of capacitance is farad;

$1 \text{ F} = 1 \text{ C V}^{-1}$. For a parallel plate capacitor (with vacuum between the plates),

A

$$C = \epsilon_0 \frac{A}{d}$$

where A is the area of each plate and d the separation between them.

10. If the medium between the plates of a capacitor is filled with an insulating substance (dielectric), the electric field due to the charged plates

induces a net dipole moment in the dielectric. This effect, called polarisation,

gives rise to a field in the opposite direction. The net electric field inside the dielectric and hence the potential difference between the plates is thus reduced. Consequently, the capacitance C increases from its value C_0 when there is no medium (vacuum),

$$C = KC_0$$

where K is the dielectric constant of the insulating substance.

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Physics

11. For capacitors in the series combination, the total capacitance C is given by

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots$$

C

C

C

1

2

3

In the parallel combination, the total capacitance C is:

$$C = C + C + C + \dots$$

1

2

3

where C , C , $C \dots$ are individual capacitances.

1

2

3

12. The energy U stored in a capacitor of capacitance C , with charge Q and voltage V is 2

1

1

Q

2

1

$U =$

$QV =$

CV

=

2

2

2 C

The electric energy density (energy per unit volume) in a region with electric field is $(1/2)\epsilon E^2$.

0

13. A Van de Graaff generator consists of a large spherical conducting shell (a few metre in diameter). By means of a moving belt and suitable brushes, charge is continuously transferred to the shell and potential difference of the order of several million volts is built up, which can be used for accelerating charged particles.

Physical quantity

Symbol

Dimensions

Unit

Remark

Potential

ϕ or V

[M¹ L² T⁻³ A⁻¹]

V

Potential difference is

physically significant

Capacitance

C

[M⁻¹ L⁻² T⁻⁴ A²]

F

Polarisation

P

[L⁻² AT]

C m⁻²

Dipole moment per unit

volume

Dielectric constant

K

[Dimensionless]

POINTS TO PONDER

1.

Electrostatics deals with forces between charges at rest. But if there is a force on a charge, how can it be at rest? Thus, when we are talking of electrostatic force between charges, it should be understood that each charge is being kept at rest by some unspecified force that opposes the net Coulomb force on the charge.

2.

A capacitor is so configured that it confines the electric field lines within a small region of space. Thus, even though field may have considerable strength, the potential difference between the two conductors of a capacitor is small.

3.

Electric field is discontinuous across the surface of a spherical charged

σ

shell. It is zero inside and

^

$\epsilon \mathbf{n}$ outside. Electric potential is, however

0

continuous across the surface, equal to $q/4\pi\epsilon R$ at the surface.

0

4.

The torque $\mathbf{p} \times \mathbf{E}$ on a dipole causes it to oscillate about \mathbf{E} . Only if there is a dissipative mechanism, the oscillations are damped and the dipole 86

eventually aligns with \mathbf{E} .

Electrostatic Potential

and Capacitance

5.

Potential due to a charge q at its own location is not defined – it is infinite.

6.

In the expression $qV(\mathbf{r})$ for potential energy of a charge q , $V(\mathbf{r})$ is the potential due to external charges and not the potential due to q . As seen in point 5, this expression will be ill-defined if $V(\mathbf{r})$ includes potential due to a charge q itself.

7.

A cavity inside a conductor is shielded from outside electrical influences.

It is worth noting that electrostatic shielding does not work the other way round; that is, if you put charges inside the cavity, the exterior of the conductor is not shielded from the fields by the inside charges.

EXERCISES

2.1

Two charges $5 \times 10^{-8} \text{ C}$ and $-3 \times 10^{-8} \text{ C}$ are located 16 cm apart. At what point(s) on the line joining the two charges is the electric potential zero? Take the potential at infinity to be zero.

2.2

A regular hexagon of side 10 cm has a charge $5 \mu\text{C}$ at each of its vertices. Calculate the potential at the centre of the hexagon.

2.3

Two charges $2 \mu\text{C}$ and $-2 \mu\text{C}$ are placed at points A and B 6 cm apart.

(a)

Identify an equipotential surface of the system.

(b)

What is the direction of the electric field at every point on this surface?

2.4

A spherical conductor of radius 12 cm has a charge of $1.6 \times 10^{-7} \text{C}$ distributed uniformly on its surface. What is the electric field

(a)

inside the sphere

(b)

just outside the sphere

(c)

at a point 18 cm from the centre of the sphere?

2.5

A parallel plate capacitor with air between the plates has a capacitance of 8 pF ($1 \text{pF} = 10^{-12} \text{F}$). What will be the capacitance if the distance between the plates is reduced by half, and the space between them is filled with a substance of dielectric constant 6?

2.6

Three capacitors each of capacitance 9 pF are connected in series.

(a)

What is the total capacitance of the combination?

(b)

What is the potential difference across each capacitor if the combination is connected to a 120 V supply?

2.7

Three capacitors of capacitances 2 pF, 3 pF and 4 pF are connected in parallel.

(a)

What is the total capacitance of the combination?

(b)

Determine the charge on each capacitor if the combination is connected to a 100 V supply.

2.8

In a parallel plate capacitor with air between the plates, each plate has an area of $6 \times 10^{-3} \text{ m}^2$ and the distance between the plates is 3 mm.

Calculate the capacitance of the capacitor. If this capacitor is connected to a 100 V supply, what is the charge on each plate of

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the capacitor?

Physics

2.9

Explain what would happen if in the capacitor given in Exercise 2.8, a 3 mm thick mica sheet (of dielectric constant = 6) were inserted between the plates,

(a)

while the voltage supply remained connected.

(b)

after the supply was disconnected.

2.10

A 12pF capacitor is connected to a 50V battery. How much electrostatic energy is stored in the capacitor?

2.11

A 600pF capacitor is charged by a 200V supply. It is then disconnected from the supply and is connected to another uncharged 600 pF capacitor. How much electrostatic energy is lost in the process?

ADDITIONAL EXERCISES

2.12

A charge of 8 mC is located at the origin. Calculate the work done in taking a small charge of -2×10^{-9} C from a point P (0, 0, 3 cm) to a point Q (0, 4 cm, 0), via a point R (0, 6 cm, 9 cm).

2.13

A cube of side b has a charge q at each of its vertices. Determine the potential and electric field due to this charge array at the centre of the cube.

2.14

Two tiny spheres carrying charges $1.5 \mu\text{C}$ and $2.5 \mu\text{C}$ are located 30 cm apart. Find the potential and electric field:

(a)

at the midpoint of the line joining the two charges, and

(b)

at a point 10 cm from this midpoint in a plane normal to the line and passing through the midpoint.

2.15

A spherical conducting shell of inner radius r_1 and outer radius r_2

1

2

has a charge Q .

(a)

A charge q is placed at the centre of the shell. What is the surface charge density on the inner and outer surfaces of the shell?

(b)

Is the electric field inside a cavity (with no charge) zero, even if the shell is not spherical, but has any irregular shape? Explain.

2.16

(a)

Show that the normal component of electrostatic field has a discontinuity from one side of a charged surface to another given by

σ

$$(\mathbf{E}_2 - \mathbf{E}_1) \cdot \hat{\mathbf{n}} = \frac{\sigma}{\epsilon_0}$$

$\hat{\mathbf{n}} =$

2

1

ϵ_0

where $\hat{\mathbf{n}}$

$\hat{\mathbf{n}}$ is a unit vector normal to the surface at a point and

σ is the surface charge density at that point. (The direction of

$\hat{\mathbf{n}}$

$\hat{\mathbf{n}}$ is from side 1 to side 2.) Hence show that just outside a

conductor, the electric field is $\frac{\sigma}{\epsilon_0} \hat{\mathbf{n}}$.

$\frac{\sigma}{\epsilon_0} \hat{\mathbf{n}}$.

0

(b)

Show that the tangential component of electrostatic field is

continuous from one side of a charged surface to another. [Hint: For (a), use Gauss's law. For, (b) use the fact that work done by electrostatic field on a closed loop is zero.]

2.17

A long charged cylinder of linear charged density λ is surrounded by a hollow co-axial conducting cylinder. What is the electric field in the space between the two cylinders?

2.18

In a hydrogen atom, the electron and proton are bound at a distance

88

of about 0.53 \AA :

Electrostatic Potential

and Capacitance

(a)

Estimate the potential energy of the system in eV, taking the zero of the potential energy at infinite separation of the electron from proton.

(b)

What is the minimum work required to free the electron, given that its kinetic energy in the orbit is half the magnitude of

potential energy obtained in (a)?

(c)

What are the answers to (a) and (b) above if the zero of potential energy is taken at 1.06 \AA separation?

2.19

If one of the two electrons of a H molecule is removed, we get a

2

hydrogen molecular ion H^+ . In the ground state of an H^+ , the two

2

2

protons are separated by roughly 1.5 \AA , and the electron is roughly 1 \AA from each proton. Determine the potential energy of the system.

Specify your choice of the zero of potential energy.

2.20

Two charged conducting spheres of radii a and b are connected to each other by a wire. What is the ratio of electric fields at the surfaces of the two spheres? Use the result obtained to explain why charge

density on the sharp and pointed ends of a conductor is higher than on its flatter portions.

2.21

Two charges $-q$ and $+q$ are located at points $(0, 0, -a)$ and $(0, 0, a)$, respectively.

(a)

What is the electrostatic potential at the points $(0, 0, z)$ and $(x, y, 0)$?

(b)

Obtain the dependence of potential on the distance r of a point from the origin when $r/a \gg 1$.

(c)

How much work is done in moving a small test charge from the point $(5,0,0)$ to $(-7,0,0)$ along the x -axis? Does the answer change if the path of the test charge between the same points is not along the x -axis?

2.22

Figure 2.34 shows a charge array known as an *electric quadrupole*.

For a point on the axis of the quadrupole, obtain the dependence of potential on r for $r/a \gg 1$, and contrast your results with that due to an electric dipole, and an electric monopole (i.e., a single charge).

FIGURE 2.34

2.23

An electrical technician requires a capacitance of $2 \mu\text{F}$ in a circuit

across a potential difference of 1 kV. A large number of $1 \mu\text{F}$ capacitors are available to him each of which can withstand a potential difference of not more than 400 V. Suggest a possible arrangement that requires the minimum number of capacitors.

2.24

What is the area of the plates of a 2 F parallel plate capacitor, given that the separation between the plates is 0.5 cm? [You will realise from your answer why ordinary capacitors are in the range of μF or less. However, electrolytic capacitors do have a much larger capacitance (0.1 F) because of very minute separation between the
89
conductors.]

Physics

2.25

Obtain the equivalent capacitance of the network in Fig. 2.35. For a 300 V supply, determine the charge and voltage across each capacitor.

FIGURE 2.35

2.26

The plates of a parallel plate capacitor have an area of 90 cm^2 each and are separated by 2.5 mm. The capacitor is charged by connecting

it to a 400 V supply.

(a)

How much electrostatic energy is stored by the capacitor?

(b)

View this energy as stored in the electrostatic field between the plates, and obtain the energy per unit volume u . Hence arrive at a relation between u and the magnitude of electric field E between the plates.

2.27

A 4 μF capacitor is charged by a 200 V supply. It is then disconnected from the supply, and is connected to another uncharged 2 μF capacitor. How much electrostatic energy of the first capacitor is lost in the form of heat and electromagnetic radiation?

2.28

Show that the force on each plate of a parallel plate capacitor has a magnitude equal to $(\frac{1}{2}) QE$, where Q is the charge on the capacitor, and E is the magnitude of electric field between the plates. Explain the origin of the factor $\frac{1}{2}$.

2.29

A spherical capacitor consists of two concentric spherical conductors, held in position by suitable insulating supports (Fig. 2.36). Show

FIGURE 2.36

Electrostatic Potential
and Capacitance

that the capacitance of a spherical capacitor is given by

$$4 \epsilon$$

$$\pi r r$$

$$0 1 2$$

$$C = r - r$$

$$1$$

$$2$$

where r

and r are the radii of outer and inner spheres,

$$1$$

$$2$$

respectively.

2.30

A spherical capacitor has an inner sphere of radius 12 cm and an outer sphere of radius 13 cm. The outer sphere is earthed and the inner sphere is given a charge of $2.5 \mu\text{C}$. The space between the

concentric spheres is filled with a liquid of dielectric constant 32.

(a)

Determine the capacitance of the capacitor.

(b)

What is the potential of the inner sphere?

(c)

Compare the capacitance of this capacitor with that of an isolated sphere of radius 12 cm. Explain why the latter is much smaller.

2.31

Answer carefully:

(a)

Two large conducting spheres carrying charges Q and Q are

1

2

brought close to each other. Is the magnitude of electrostatic

force between them exactly given by $Q Q / 4\pi\epsilon r^2$, where r is 1

2

0

the distance between their centres?

(b)

If Coulomb's law involved $1/r^3$ dependence (instead of $1/r^2$), would Gauss's law be still true ?

(c)

A small test charge is released at rest at a point in an electrostatic field configuration. Will it travel along the field line passing through that point?

(d)

What is the work done by the field of a nucleus in a complete circular orbit of the electron? What if the orbit is elliptical?

(e)

We know that electric field is discontinuous across the surface of a charged conductor. Is electric potential also discontinuous there?

(f)

What meaning would you give to the capacitance of a single conductor?

(g)

Guess a possible reason why water has a much greater dielectric constant (= 80) than say, mica (= 6).

2.32

A cylindrical capacitor has two co-axial cylinders of length 15 cm and radii 1.5 cm and 1.4 cm. The outer cylinder is earthed and the inner cylinder is given a charge of $3.5 \mu\text{C}$. Determine the capacitance of the system and the potential of the inner cylinder. Neglect end effects (i.e., bending of field lines at the ends).

2.33

A parallel plate capacitor is to be designed with a voltage rating 1 kV, using a material of dielectric constant 3 and dielectric strength about 10^7 Vm^{-1} . (Dielectric strength is the maximum electric field a material can tolerate without breakdown, i.e., without starting to conduct electricity through partial ionisation.) For safety, we should like the field never to exceed, say 10% of the dielectric strength. What minimum area of the plates is required to have a capacitance of 50 pF?

2.34

Describe schematically the equipotential surfaces corresponding to

(a)

a constant electric field in the z -direction,

(b)

a field that uniformly increases in magnitude but remains in a

91

constant (say, z) direction,

Physics

(c)

a single positive charge at the origin, and

(d)

a uniform grid consisting of long equally spaced parallel charged wires in a plane.

2.35

In a Van de Graaff type generator a spherical metal shell is to be a 15×10^6 V electrode. The dielectric strength of the gas surrounding the electrode is 5×10^7 Vm⁻¹. What is the minimum radius of the spherical shell required? (You will learn from this exercise why one cannot build an electrostatic generator using a very small shell which requires a small charge to acquire a high potential.)

2.36

A small sphere of radius r and charge q is enclosed by a spherical 1

1

shell of radius r and charge q . Show that if q is positive, charge 2

2

1

will necessarily flow from the sphere to the shell (when the two are connected by a wire) no matter what the charge q on the shell is.

2

2.37

Answer the following:

(a)

The top of the atmosphere is at about 400 kV with respect to the surface of the earth, corresponding to an electric field that decreases with altitude. Near the surface of the earth, the field is about 100 Vm^{-1} . Why then do we not get an electric shock as we step out of our house into the open? (Assume the house to be a steel cage so there is no field inside!)

(b)

A man fixes outside his house one evening a two metre high insulating slab carrying on its top a large aluminium sheet of area 1 m^2 . Will he get an electric shock if he touches the metal sheet next morning?

(c)

The discharging current in the atmosphere due to the small conductivity of air is known to be 1800 A on an average over the globe. Why then does the atmosphere not discharge itself completely in due course and become electrically neutral? In other words, what keeps the atmosphere charged?

(d)

What are the forms of energy into which the electrical energy of the atmosphere is dissipated during a lightning?

(Hint: The earth has an electric field of about 100 Vm^{-1} at its surface in the downward direction, corresponding to a surface charge density = $-10^{-9} \text{ C m}^{-2}$. Due to the slight conductivity of the atmosphere up to about 50 km (beyond which it is good conductor), about + 1800 C is pumped every second into the earth as a whole. The earth, however, does not get discharged since thunderstorms and lightning occurring continually all over the globe pump an equal amount of negative charge on the earth.)

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Chapter Three

CURRENT

ELECTRICITY

3.1 INTRODUCTION

In Chapter 1, all charges whether free or bound, were considered to be at rest. Charges in motion constitute an electric current. Such currents occur naturally in many situations. Lightning is one such phenomenon in which charges flow from the clouds to the earth through the atmosphere, sometimes with disastrous results. The flow of charges in lightning is not steady, but in our everyday life we see many devices where charges flow in a steady manner, like water flowing smoothly in a river. A torch and a cell-driven clock are examples of such devices. In the present chapter, we shall study some of the basic laws concerning steady electric currents.

3.2 ELECTRIC CURRENT

Imagine a small area held normal to the direction of flow of charges. Both the positive and the negative charges may flow forward and backward across the area. In a given time interval t , let q be the net amount (*i.e.*,

+

forward *minus* backward) of positive charge that flows in the forward direction across the area. Similarly, let q be the net amount of negative – charge flowing across the area in the forward direction. The net amount of charge flowing across the area in the forward direction in the time

interval t , then, is $q = q - q$. This is proportional to t for steady current +

–

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and the quotient

q

$I =$

(3.1)

t

is defined to be the *current* across the area in the forward direction. (If it turn out to be a negative number, it implies a current in the backward direction.)

Currents are not always steady and hence more generally, we define

the current as follows. Let ΔQ be the net charge flowing across a cross-section of a conductor during the time interval Δt [i.e., between times t and $(t + \Delta t)$]. Then, the current at time t across the cross-section of the conductor is defined as the value of the ratio of ΔQ to Δt in the limit of Δt tending to zero, ()

ΔQ

$I t \equiv \lim$

t

$\Delta \rightarrow 0 \Delta$

(3.2)

t

In SI units, the unit of current is ampere. An ampere is defined through magnetic effects of currents that we will study in the following chapter. An ampere is typically the order of magnitude of currents in domestic appliances. An average lightning carries currents of the order of tens of thousands of amperes and at the other extreme, currents in our nerves are in microamperes.

3.3 ELECTRIC CURRENTS IN CONDUCTORS

An electric charge will experience a force if an electric field is applied. If it is free to move, it will thus move contributing to a current. In nature, free charged particles do exist like in upper strata of atmosphere called the *ionosphere*. However, in atoms and molecules, the negatively charged electrons and the positively charged nuclei are bound to each other and are thus not free to move. Bulk matter is made up of many molecules, a gram of water, for example, contains approximately 10^{22} molecules. These molecules are so closely packed that the electrons are no longer attached to individual nuclei. In some materials, the electrons will still be bound, i.e., they will not accelerate even if an electric field is applied. In other materials, notably metals, some of the electrons are practically free to move within the bulk material. These materials, generally called conductors, develop electric currents in them when an electric field is applied.

If we consider solid conductors, then of course the atoms are tightly

bound to each other so that the current is carried by the negatively charged electrons. There are, however, other types of conductors like electrolytic solutions where positive and negative charges both can move. In our discussions, we will focus only on solid conductors so that the current is carried by the negatively charged electrons in the background of fixed positive ions.

Consider first the case when no electric field is present. The electrons will be moving due to thermal motion during which they collide with the fixed ions. An electron colliding with an ion emerges with the same speed as before the collision. However, the direction of its velocity after the collision is completely random. At a given time, there is no preferential

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direction for the velocities of the electrons. Thus on the average, the

Current

Electricity

number of electrons travelling in any direction will be equal to the number of electrons travelling in the opposite direction. So, there will be no net electric current.

Let us now see what happens to such a piece of conductor if an electric field is applied.

To focus our thoughts, imagine the conductor in the shape of a cylinder of radius R (Fig. 3.1).

Suppose we now take two thin circular discs

FIGURE 3.1 Charges $+Q$ and $-Q$ put at the ends

of a dielectric of the same radius and put

of a metallic cylinder. The electrons will drift

positive charge $+Q$ distributed over one disc

because of the electric field created to

and similarly $-Q$ at the other disc. We attach

neutralise the charges. The current thus

the two discs on the two flat surfaces of the

will stop after a while unless the charges $+Q$

cylinder. An electric field will be created and

and $-Q$ are continuously replenished.

is directed from the positive towards the

negative charge. The electrons will be accelerated due to this field towards

$+Q$. They will thus move to neutralise the charges. The electrons, as long as they are moving, will constitute an electric current. Hence in the situation considered, there will be a current for a very short while and no

current thereafter.

We can also imagine a mechanism where the ends of the cylinder are

supplied with fresh charges to make up for any charges neutralised by electrons moving inside the conductor. In that case, there will be a steady electric field in the body of the conductor. This will result in a continuous current rather than a current for a short period of time. Mechanisms, which maintain a steady electric field are cells or batteries that we shall study later in this chapter. In the next sections, we shall study the steady current that results from a steady electric field in conductors.

3.4 OHM'S LAW

A basic law regarding flow of currents was discovered by G.S. Ohm in 1828, long before the physical mechanism responsible for flow of currents was discovered. Imagine a conductor through which a current I is flowing and let V be the potential difference between the ends of the conductor.

Then Ohm's law states that

$$V \propto I$$

or, $V = R I$

(3.3)

where the constant of proportionality R is called the *resistance* of the conductor. The SI units of resistance is *ohm*, and is denoted by the symbol Ω . The resistance R not only depends on the material of the conductor but also on the dimensions of the conductor. The dependence of R on the dimensions of the conductor can easily be determined as follows.

FIGURE 3.2

Consider a conductor satisfying Eq. (3.3) to be in the form of a slab of

Illustrating the

length l and cross sectional area A [Fig. 3.2(a)]. Imagine placing two such relation $R = \rho l / A$ for identical slabs side by side [Fig. 3.2(b)], so that the length of the

a rectangular slab

combination is $2l$. The current flowing through the combination is the

of length l and area

of cross-section A .

same as that flowing through either of the slabs. If V is the potential difference across the ends of the first slab, then V is also the potential 95

difference across the ends of the second slab since the second slab is



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identical to the first and the same current I flows through

both. The potential difference across the ends of the

combination is clearly sum of the potential difference

across the two individual slabs and hence equals $2V$. The

current through the combination is I and the resistance

)4

of the combination R is [from Eq. (3.3)],

C

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2 V

1

$R =$

$= 2 R$

C

(3.4)

I

since $V/I = R$, the resistance of either of the slabs. Thus,

doubling the length of a conductor doubles the

(1787–

resistance. In general, then resistance is proportional to

length,

$R \propto l$

(3.5)

Georg Simon Ohm (1787–

Next, imagine dividing the slab into two by cutting it

1854) German physicist,

lengthwise so that the slab can be considered as a

professor at Munich. Ohm

combination of two identical slabs of length l , but each

was led to his law by an

having a cross sectional area of $A/2$ [Fig. 3.2(c)].

analogy between the

For a given voltage V across the slab, if I is the current

conduction of heat: the

through the entire slab, then clearly the current flowing

electric field is analogous to

through each of the two half-slabs is $I/2$. Since the

the temperature gradient,

potential difference across the ends of the half-slabs is V ,

GEORG SIMON OHM

and the electric current is

analogous to the heat flow.

i.e., the same as across the full slab, the resistance of each

of the half-slabs R is

1

V

V

$R =$

$= 2 = 2 .$

R

1

(3.6)

$(I/2)$

I

Thus, halving the area of the cross-section of a conductor doubles

the resistance. In general, then the resistance R is inversely proportional to the cross-sectional area, 1

$R \propto$

(3.7)

A

Combining Eqs. (3.5) and (3.7), we have

l

$R \propto$

(3.8)

A

and hence for a given conductor

l

$$R = \rho$$

(3.9)

A

where the constant of proportionality ρ depends on the material of the conductor but not on its dimensions. ρ is called *resistivity*.

Using the last equation, Ohm's law reads

Il

ρ

$$V = I \times R =$$

(3.10)

A

Current per unit area (taken normal to the current), I/A , is called *current density* and is denoted by j . The SI units of the current density are A/m². Further, if E is the magnitude of uniform electric field in the conductor whose length is l , then the potential difference V across its

ends is El . Using these, the last equation reads

Current

Electricity

$$E l = j \rho l$$

$$\text{or, } E = j \rho$$

(3.11)

The above relation for *magnitudes* E and j can indeed be cast in a *vector* form. The current density, (which we have defined as the current through unit area *normal* to the current) is also directed along \mathbf{E} , and is also a vector \mathbf{j} ($\equiv j \mathbf{E}/E$). Thus, the last equation can be written as, $\mathbf{E} = \mathbf{j}\rho$

(3.12)

$$\text{or, } \mathbf{j} = \sigma \mathbf{E}$$

(3.13)

where $\sigma \equiv 1/\rho$ is called the *conductivity*. Ohm's law is often stated in an equivalent form, Eq. (3.13) in addition to Eq.(3.3). In the next section, we will try to understand the origin of the Ohm's law as arising from the characteristics of the drift of electrons.

3.5 DRIFT OF ELECTRONS AND THE ORIGIN OF RESISTIVITY

As remarked before, an electron will suffer collisions with the heavy fixed ions, but after collision, it will emerge with the same speed but in random directions. If we consider all the electrons, their average velocity will be zero since their directions are random. Thus, if there are N electrons and the velocity of the i th electron ($i = 1, 2, 3, \dots N$) at a given time is \mathbf{v}_i , then

$$\sum_{i=1}^N \mathbf{v}_i = 0$$

i

N

(3.14)

$i = 1$

Consider now the situation when an electric field is present. Electrons will be accelerated due to this field by

$-e$

=

E

a

(3.15)

m

where $-e$ is the charge and m is the mass of an electron.

Consider again the i th electron at a given time t . This electron would have had its last collision some time before t , and let t be the time elapsed after its last

i

collision. If \mathbf{v} was its velocity immediately after the last

i

collision, then its velocity \mathbf{V} at time t is

i

e

=

E

V

$v -$

t

i

i

i

(3.16)

m

FIGURE 3.3 A schematic picture of

since starting with its last collision it was accelerated

an electron moving from a point A to

(Fig. 3.3) with an acceleration given by Eq. (3.15) for a

another point B through repeated

time interval t . The average velocity of the electrons at

i

collisions, and straight line travel

time t is the average of all the V 's. The average of v 's is i

i

between collisions (full lines). If an

zero [Eq. (3.14)] since immediately after any collision,

electric field is applied as shown, the

the direction of the velocity of an electron is completely

electron ends up at point B' (dotted

random. The collisions of the electrons do not occur at

lines). A slight drift in a direction

regular intervals but at random times. Let us denote by

opposite the electric field is visible.

τ , the average time between successive collisions. Then

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at a given time, some of the electrons would have spent

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time more than τ and some less than τ . In other words, the time t in

i

Eq. (3.16) will be less than τ for some and more than τ for others as we go

through the values of $i = 1, 2, \dots, N$. The average value of t then is τ

i

(known as *relaxation time*). Thus, averaging Eq. (3.16) over the

N -electrons at any given time t gives us for the average velocity \mathbf{v}

\equiv

$=$

$-\mathbf{E}$

\mathbf{v}

\mathbf{V}

\mathbf{v}

t

d

(i)

(i)

(i)

average

average

) *average*

m

$e\mathbf{E}$

e

$=$

E

0 –

$\tau = -$

τ

(3.17)

m

m

This last result is surprising. It tells us that the electrons move with an average velocity which is independent of time, although electrons are accelerated. This is the phenomenon of drift and the velocity \mathbf{v} in Eq. (3.17) is called the *drift velocity*.

d

Because of the drift, there will be net transport of charges across any area perpendicular to \mathbf{E} . Consider a planar area A , located inside the conductor such that

FIGURE 3.4 Current in a metallic

the normal to the area is parallel to \mathbf{E}

conductor. The magnitude of current

(Fig. 3.4). Then because of the drift, in an infinitesimal

density in a metal is the magnitude of
amount of time Δt , all electrons to the left of the area at
charge contained in a cylinder of unit
distances upto $|\mathbf{v}| \Delta t$ would have crossed the area. If

d

area and length v .

d

n is the number of free electrons per unit volume in
the metal, then there are $n \Delta t |\mathbf{v}| A$ such electrons.

d

Since each electron carries a charge $-e$, the total charge transported across
this area A to the right in time Δt is $-ne A |\mathbf{v}| \Delta t$. \mathbf{E} is directed towards the d
left and hence the total charge transported along \mathbf{E} across the area is

negative of this. The amount of charge crossing the area A in time Δt is by
definition [Eq. (3.2)] $I \Delta t$, where I is the magnitude of the current. Hence, I
 $\Delta t = + n e A v t$

Δ

(3.18)

d

Substituting the value of $|\mathbf{v}|$ from Eq. (3.17)

d

2

$e A$

$I \Delta t =$

$\tau n \Delta t \mathbf{E}$

(3.19)

m

By definition I is related to the magnitude $|\mathbf{j}|$ of the current density by $I = |\mathbf{j}| A$ (3.20)

Hence, from Eqs.(3.19) and (3.20),

2

ne

$\mathbf{j} =$

$\tau \mathbf{E}$

(3.21)

m

The vector \mathbf{j} is parallel to \mathbf{E} and hence we can write Eq. (3.21) in the vector form

2

ne

$\mathbf{j} =$

$\tau \mathbf{E}$

(3.22)

m

Comparison with Eq. (3.13) shows that Eq. (3.22) is exactly the Ohm's

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law, if we identify the conductivity σ as

Current

Electricity

2

ne

$\sigma =$

τ

(3.23)

m

We thus see that a very simple picture of electrical conduction

reproduces Ohm's law. We have, of course, made assumptions that τ

and n are constants, independent of E . We shall, in the next section, discuss the limitations of Ohm's law.

Example 3.1 (a) Estimate the average drift speed of conduction

electrons in a copper wire of cross-sectional area $1.0 \times 10^{-7} \text{ m}^2$ carrying

a current of 1.5 A. Assume that each copper atom contributes roughly

one conduction electron. The density of copper is $9.0 \times 10^3 \text{ kg/m}^3$,

and its atomic mass is 63.5 u. (b) Compare the drift speed obtained

above with, (i) thermal speeds of copper atoms at ordinary temperatures, (ii) speed of propagation of electric field along the conductor which causes the drift motion.

Solution

(a) The direction of drift velocity of conduction electrons is opposite to the electric field direction, i.e., electrons drift in the direction of increasing potential. The drift speed v is given by Eq. (3.18)

d

$$v = (I / neA)$$

d

Now, $e = 1.6 \times 10^{-19}$ C, $A = 1.0 \times 10^{-7}$ m², $I = 1.5$ A. The density of conduction electrons, n is equal to the number of atoms per cubic metre (assuming one conduction electron per Cu atom as is

reasonable from its valence electron count of one). A cubic metre of copper has a mass of 9.0×10^3 kg. Since 6.0×10^{23} copper atoms have a mass of 63.5 g,

23

$$6.0 \times 10$$

6

$$n =$$

$$\times 9.0 \times 10$$

63.5

$$= 8.5 \times 10^{28} \text{ m}^{-3}$$

which gives,

1.5

$$vd =$$

28

-19

-7

$$8.5 \times 10$$

$$\times 1.6 \times 10$$

$$\times 1.0 \times 10$$

$$= 1.1 \times 10^{-3} \text{ m s}^{-1} = 1.1 \text{ mm s}^{-1}$$

(b) (i) At a temperature T , the thermal speed* of a copper atom of mass M is obtained from $[\langle (1/2) Mv^2 \rangle = (3/2) k T]$ and is thus B

typically of the order of k

/

TM

B

, where k is the Boltzmann

B

constant. For copper at 300 K, this is about 2×10^2 m/s. This

figure indicates the random vibrational speeds of copper atoms in a conductor. Note that the drift speed of electrons is much smaller, about 10^{-5} times the typical thermal speed at ordinary temperatures.

XAMPLE

(ii) An electric field travelling along the conductor has a speed of an electromagnetic wave, namely equal to $3.0 \times 10^8 \text{ m s}^{-1}$

3.1

(You will learn about this in Chapter 8). The drift speed is, in comparison, extremely small; smaller by a factor of 10^{11} .

* See Eq. (13.23) of Chapter 13 from Class XI book.

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Example 3.2

(a) In Example 3.1, the electron drift speed is estimated to be only a few mm s^{-1} for currents in the range of a few amperes? How then is current established almost the instant a circuit is closed?

(b) The electron drift arises due to the force experienced by electrons in the electric field inside the conductor. But force should cause

acceleration. Why then do the electrons acquire a steady average drift speed?

(c) If the electron drift speed is so small, and the electron's charge is small, how can we still obtain large amounts of current in a conductor?

(d) When electrons drift in a metal from lower to higher potential, does it mean that all the 'free' electrons of the metal are moving in the same direction?

(e) Are the paths of electrons straight lines between successive collisions (with the positive ions of the metal) in the (i) absence of electric field, (ii) presence of electric field?

Solution

(a) Electric field is established throughout the circuit, almost instantly (with the speed of light) causing at every point a *local electron drift*. Establishment of a current does not have to wait for electrons from one end of the conductor travelling to the other end. However, it does take a little while for the current to reach its steady value.

(b) Each 'free' electron does accelerate, increasing its drift speed until it collides with a positive ion of the metal. It loses its drift speed after collision but starts to accelerate and increases its drift speed

again only to suffer a collision again and so on. On the average, therefore, electrons acquire only a drift speed.

(c) Simple, because the electron number density is enormous,

3.2

$\sim 10^{29} \text{ m}^{-3}$.

(d) By no means. The drift velocity is superposed over the large random velocities of electrons.

XAMPLE

(e) In the absence of electric field, the paths are straight lines; in the

E

presence of electric field, the paths are, in general, curved.

3.5.1 Mobility

As we have seen, conductivity arises from mobile charge carriers. In metals, these mobile charge carriers are electrons; in an ionised gas, they are electrons and positive charged ions; in an electrolyte, these can be both positive and negative ions.

An important quantity is the *mobility* μ defined as the magnitude of the drift velocity per unit electric field:

$$|\mathbf{v}_d|$$

$$\mu =$$

(3.24)

E

The SI unit of mobility is m^2/Vs and is 10^4 of the mobility in practical units (cm^2/Vs). Mobility is positive. From Eq. (3.17), we have

$e \tau E$

100

$v =$

d

m

Current

Electricity

Hence,

v

$e \tau$

d

$\mu =$

=

(3.25)

E

m

where τ is the average collision time for electrons.

3.6 LIMITATIONS OF OHM'S LAW

Although Ohm's law has been found valid over a large class of materials, there do exist materials and devices used in

electric circuits where the proportionality of V and I does not hold. The deviations broadly are one or more of the following **FIGURE 3.5** The dashed line

types:

represents the linear Ohm's

(a) V ceases to be proportional to I (Fig. 3.5).

law. The solid line is the voltage

(b) The relation between V and I depends on the sign of V . In V versus current I for a good other words, if I is the current for a certain V , then reversing conductor.

the direction of V keeping its magnitude fixed, does not

produce a current of the same magnitude as I in the opposite direction

(Fig. 3.6). This happens, for example, in a diode which we will study

in Chapter 14.

FIGURE 3.6 Characteristic curve

FIGURE 3.7 Variation of current

of a diode. Note the different

versus voltage for GaAs.

scales for negative and positive values of the voltage and current.

(c) The relation between V and I is not unique, i.e., there is more than one value of V for the same current I (Fig. 3.7). A material exhibiting such behaviour is GaAs.

Materials and devices not obeying Ohm's law in the form of Eq. (3.3) are actually widely used in electronic circuits. In this and a few subsequent chapters, however, we will study the electrical currents in materials that obey Ohm's law.

3.7 RESISTIVITY OF VARIOUS MATERIALS

The resistivities of various common materials are listed in Table 3.1. The

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materials are classified as conductors, semiconductors and insulators

Physics

depending on their resistivities, in an increasing order of their values.

Metals have low resistivities in the range of $10^{-8} \Omega\text{m}$ to $10^{-6} \Omega\text{m}$. At the other end are insulators like ceramic, rubber and plastics having

resistivities 10^{18} times greater than metals or more. In between the two are the semiconductors. These, however, have resistivities

characteristically decreasing with a rise in temperature. The resistivities of semiconductors are also affected by presence of small amount of

impurities. This last feature is exploited in use of semiconductors for electronic devices.

TABLE 3.1 RESISTIVITIES OF SOME MATERIALS

Material

Resistivity, ρ

Temperature coefficient

(Ω m) at 0°C

of resistivity, α (°C) ⁻¹

$\frac{1}{\rho} \frac{d\rho}{dT}$ at 0

°C

$\frac{d\rho}{dT}$

Conductors

Silver

1.6×10^{-8}

0.0041

Copper

1.7×10^{-8}

0.0068

Aluminium

2.7×10^{-8}

0.0043

Tungsten

5.6×10^{-8}

0.0045

Iron

10×10^{-8}

0.0065

Platinum

11×10^{-8}

0.0039

Mercury

98×10^{-8}

0.0009

Nichrome

$\sim 100 \times 10^{-8}$

0.0004

(alloy of Ni, Fe, Cr)

Manganin (alloy)

48×10^{-8}

0.002×10^{-3}

Semiconductors

Carbon (graphite)

3.5×10^{-5}

– 0.0005

Germanium

0.46

– 0.05

Silicon

2300

– 0.07

Insulators

Pure Water

2.5×10^5

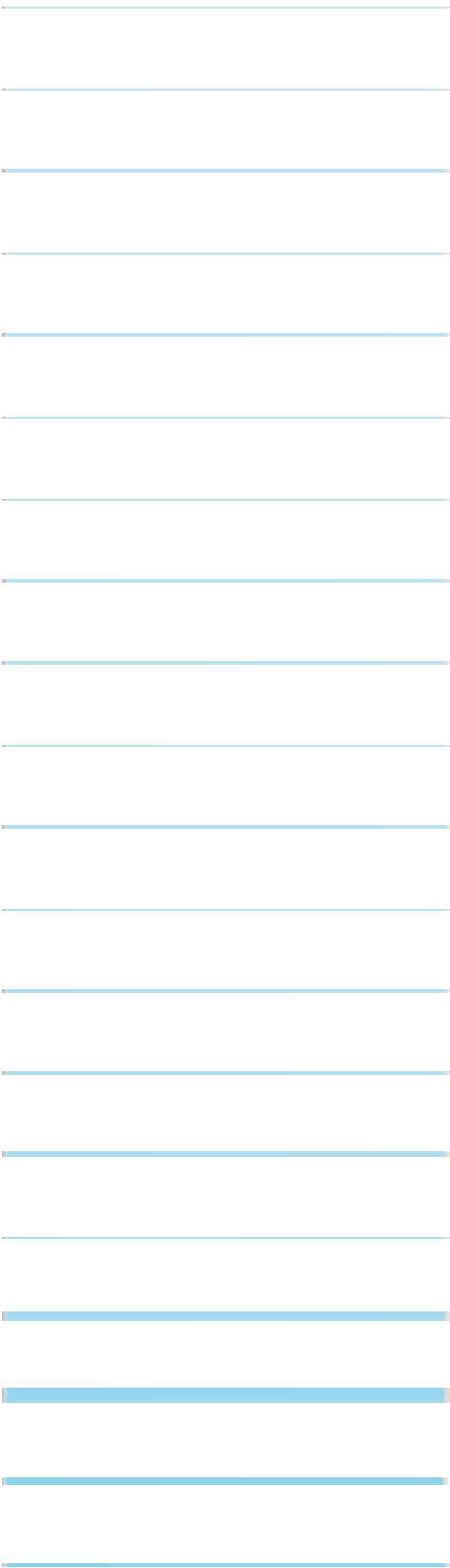
Glass

1010 – 1014

Hard Rubber

1013 – 1016

NaCl





Current

Electricity

Resistors in the higher range are made mostly from carbon. Carbon resistors are compact, inexpensive and thus find extensive use in electronic circuits. Carbon resistors are small in size and hence their values are given using a colour code.

TABLE 3.2 RESISTOR COLOUR CODES

Colour

Number

Multiplier

Tolerance (%)

Black

0

1

Brown

1

101

Red

2

102

Orange

3

103

Yellow

4

104

Green

5

105

Blue

6

106

Violet

7

107

Gray

8

108

White

9

109

Gold

10-1

5

Silver

10-2

10

No colour

20

The resistors have a set of co-axial coloured rings on them whose significance are listed in Table 3.2. The first two *bands* from the end indicate the first two significant figures of the resistance in ohms. The third band indicates the decimal multiplier (as listed in Table 3.2). The last band stands for tolerance or possible

variation in percentage about the indicated values.

Sometimes, this last band is absent and that indicates a tolerance of 20% (Fig. 3.8). For example, if the four colours are orange, blue, yellow and gold, the resistance value is $36 \times 10^4 \Omega$, with a tolerance value of 5%.

3.8

TEMPERATURE DEPENDENCE OF RESISTIVITY

The resistivity of a material is found to be dependent on the temperature. Different materials do not exhibit the same dependence on temperatures. Over a limited range

FIGURE 3.8 Colour coded resistors

(a) $(22 \times 10^2 \Omega) \pm 10\%$,

of temperatures, that is not too large, the resistivity of a

(b) $(47 \times 10 \Omega) \pm 5\%$.

metallic conductor is approximately given by,

$$\rho = \rho [1 + \alpha (T - T_0)]$$

(3.26)

T

0

0

where ρ is the resistivity at a temperature T and ρ_0 is the same at a

T_0

0

reference temperature T_0 . α is called the *temperature coefficient of*

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resistivity, and from Eq. (3.26), the dimension of α is (Temperature)⁻¹.

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For metals, α is positive and values of α for some metals at $T = 0^\circ\text{C}$ are 0

listed in Table 3.1.

The relation of Eq. (3.26) implies that a graph of ρ plotted against T

T

would be a straight line. At temperatures much lower than 0°C , the graph,

however, deviates considerably from a straight line (Fig. 3.9).

Equation (3.26) thus, can be used approximately over a limited range

of T around any reference temperature T_0 , where the graph can be 0

approximated as a straight line.

FIGURE 3.9

FIGURE 3.10 Resistivity

FIGURE 3.11

Resistivity ρ of

ρ of nichrome as a

Temperature dependence

T

T

copper as a function

function of absolute

of resistivity for a typical

of temperature T .

temperature T .

semiconductor.

Some materials like Nichrome (which is an alloy of nickel, iron and chromium) exhibit a very weak dependence of resistivity with temperature (Fig. 3.10). Manganin and constantan have similar properties. These materials are thus widely used in wire bound standard resistors since their resistance values would change very little with temperatures.

Unlike metals, the resistivities of semiconductors decrease with increasing temperatures. A typical dependence is shown in Fig. 3.11.

We can qualitatively understand the temperature dependence of resistivity, in the light of our derivation of Eq. (3.23). From this equation,

resistivity of a material is given by

1

m

$\rho = =$

2

$\sigma n e \tau$

(3.27)

ρ thus depends inversely both on the number n of free electrons per unit volume and on the average time τ between collisions. As we increase temperature, average speed of the electrons, which act as the carriers of current, increases resulting in more frequent collisions. The average time of collisions τ , thus decreases with temperature.

In a metal, n is not dependent on temperature to any appreciable extent and thus the decrease in the value of τ with rise in temperature causes ρ to increase as we have observed.

For insulators and semiconductors, however, n increases with temperature. This increase more than compensates any decrease in τ in

104

Eq.(3.23) so that for such materials, ρ decreases with temperature.

Current

Electricity

Example 3.3 An electric toaster uses nichrome for its heating element. When a negligibly small current passes through it, its resistance at room temperature ($27.0\text{ }^{\circ}\text{C}$) is found to be $75.3\ \Omega$. When the toaster is connected to a $230\ \text{V}$ supply, the current settles, after a few seconds, to a steady value of $2.68\ \text{A}$. What is the steady temperature of the nichrome element? The temperature coefficient of resistance of nichrome averaged over the temperature range involved, is $1.70 \times 10^{-4}\text{ }^{\circ}\text{C}^{-1}$.

Solution When the current through the element is very small, heating effects can be ignored and the temperature T of the element is the

1

same as room temperature. When the toaster is connected to the supply, its initial current will be slightly higher than its steady value of $2.68\ \text{A}$. But due to heating effect of the current, the temperature will rise. This will cause an increase in resistance and a slight decrease in current. In a few seconds, a steady state will be reached when temperature will rise no further, and both the resistance of the element and the current drawn will achieve steady values. The resistance R at the steady temperature T is

2

2

230 V

$R =$

$= 85.8 \Omega$

2

2.68 A

Using the relation

$$R = R [1 + \alpha (T - T)]$$

2

1

2

1

with $\alpha = 1.70 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$, we get

$(85.8 - 75.3)$

E

$T - T =$

$= 820 \text{ }^\circ\text{C}$

2

1

-4

$$(75.3) \times 1.70 \times 10$$

XAMPLE

that is, $T = (820 + 27.0) \text{ }^\circ\text{C} = 847 \text{ }^\circ\text{C}$

2

Thus, the steady temperature of the heating element (when heating

3.3

effect due to the current equals heat loss to the surroundings) is

847 °C.

Example 3.4 The resistance of the platinum wire of a platinum resistance thermometer at the ice point is 5 Ω and at steam point is 5.23 Ω. When the thermometer is inserted in a hot bath, the resistance of the platinum wire is 5.795 Ω. Calculate the temperature of the bath.

Solution $R = 5 \text{ } \Omega$, R

$= 5.23 \text{ } \Omega$ and $R = 5.795 \text{ } \Omega$

0

100

t

$R - R$

t

0

Now,

$t =$

$\times 100,$

$$R = R (1 + \alpha t)$$

t

0

R

$- R$

100

0

E

XAMPLE

5.795 - 5

=

$\times 100$

5.23 - 5

3.4

0.795

=

$$\times 100 = 345.65 \text{ }^\circ\text{C}$$

0.23

3.9 ELECTRICAL ENERGY, POWER

Consider a conductor with end points A and B, in which a current I is

105

flowing from A to B. The electric potential at A and B are denoted by $V(A)$

Physics

and $V(B)$ respectively. Since current is flowing from A to B, $V(A) > V(B)$ and the potential difference across AB is $V = V(A) - V(B) > 0$.

In a time interval Δt , an amount of charge $\Delta Q = I \Delta t$ travels from A to B. The potential energy of the charge at A, by definition, was $Q V(A)$ and similarly at B, it is $Q V(B)$. Thus, change in its potential energy ΔU is pot $\Delta U = \text{Final potential energy} - \text{Initial potential energy}$

pot

$$= \Delta Q [V(B) - V(A)] = -\Delta Q V$$

$$= -I V \Delta t < 0$$

(3.28)

If charges moved without collisions through the conductor, their kinetic energy would also change so that the total energy is unchanged.

Conservation of total energy would then imply that,

$$\Delta K = -\Delta U$$

(3.29)

pot

that is,

$$\Delta K = I V \Delta t > 0$$

(3.30)

Thus, in case charges were moving freely through the conductor under the action of electric field, their kinetic energy would increase as they move. We have, however, seen earlier that on the average, charge carriers do not move with acceleration but with a steady drift velocity. This is because of the collisions with ions and atoms during transit. During collisions, the energy gained by the charges thus is shared with the atoms. The atoms vibrate more vigorously, i.e., the conductor heats up. Thus, in an actual conductor, an amount of energy dissipated as heat in the conductor during the time interval Δt is,

$$\Delta W = I V \Delta t$$

(3.31)

The energy dissipated per unit time is the power dissipated

$P = \Delta W / \Delta t$ and we have,

$$P = I V$$

(3.32)

Using Ohm's law $V = IR$, we get

$$P = I^2 R = V^2 / R$$

(3.33)

as the power loss (“ohmic loss”) in a conductor of resistance R carrying a current I . It is this power which heats up, for example, the coil of an electric bulb to incandescence, radiating out heat and light.

Where does the power come from? As we have reasoned before, we need an external source to keep a steady current through the conductor. It is clearly this source which must supply this power. In the simple circuit shown with a cell (Fig.3.12), it is the chemical energy of the cell which supplies this power for as long as it can.

The expressions for power, Eqs. (3.32) and (3.33),

FIGURE 3.12 Heat is produced in the

resistor R which is connected across

show the dependence of the power dissipated in a

the terminals of a cell. The energy

resistor R on the current through it and the voltage

dissipated in the resistor R comes from

across it.

the chemical energy of the electrolyte.

Equation (3.33) has an important application to power transmission. Electrical power is transmitted

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from power stations to homes and factories, which

Current

Electricity

may be hundreds of miles away, via transmission cables. One obviously wants to minimise the power loss in the transmission cables connecting the power stations to homes and factories. We shall see now how this

can be achieved. Consider a device R , to which a power P is to be delivered via transmission cables having a resistance R to be dissipated by it finally.

c

If V is the voltage across R and I the current through it, then $P = VI$

(3.34)

The connecting wires from the power station to the device has a finite resistance R . The power dissipated in the connecting wires, which is

c

wasted is P with

c

$$P = I^2 R$$

c

c

2

$P R$

c

$=$

(3.35)

2

V

from Eq. (3.32). Thus, to drive a device of power P , the power wasted in the connecting wires is inversely proportional to V^2 . The transmission cables from power stations are hundreds of miles long and their resistance R is c considerable. To reduce P , these wires carry current at enormous values c

of V and this is the reason for the high voltage danger signs on transmission lines — a common sight as we move away from populated areas. Using electricity at such voltages is not safe and hence at the other end, a device

called a transformer lowers the voltage to a value suitable for use.

3.10 COMBINATION OF RESISTORS – SERIES AND

PARALLEL

The current through a single resistor R across which there is a potential difference V is given by Ohm's law $I = V/R$. Resistors are sometimes joined together and there are simple rules for calculation of equivalent resistance of such combination.

FIGURE 3.13 A series combination of two resistor R and R .

1

2

Two resistors are said to be in *series* if only one of their end points is joined (Fig. 3.13). If a third resistor is joined with the series combination of the two (Fig. 3.14), then all three are said to be in series. Clearly, we

can extend this definition to series combination of any number of resistors.

FIGURE 3.14 A series combination of three resistors R_1, R_2, R_3 .

1

2

3

Two or more resistors are said to be in *parallel* if one end of all the resistors is joined together and similarly the other ends joined together (Fig. 3.15).

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FIGURE 3.15 Two resistors R_1 and R_2 connected in parallel.

1

2

Physics

Consider two resistors R_1 and R_2 in series. The charge which leaves R_1

1

2

I

must be entering R . Since current measures the rate of flow of charge, 2

this means that the same current I flows through R and R . By Ohm's law: I

2

Potential difference across $R = V = IR$, and

1

1

1

Potential difference across $R = V = IR$.

2

2

2

The potential difference V across the combination is $V + V$. Hence, 1

2

$$V = V + V = I(R + R)$$

(3.36)

1

2

1

2

This is as if the combination had an equivalent resistance R , which

eq

by Ohm's law is

V

$R \equiv$

$= (R + R)$

(3.37)

eq

I

1

2

If we had three resistors connected in series, then similarly

$V = IR + IR + IR = I(R + R + R).$

(3.38)

1

2

3

1

2

3

This obviously can be extended to a series combination of any number n of resistors R_1, R_2, \dots, R_n . The equivalent resistance R_{eq} is

2

n

eq

$$R_{eq} = R_1 + R_2 + \dots + R_n$$

(3.39)

eq

1

2

n

Consider now the parallel combination of two resistors (Fig. 3.15).

The charge that flows in at A from the left flows out partly through R_1 and partly through R_2 . The currents I, I_1, I_2 shown in the figure are the

1

2

rates of flow of charge at the points indicated. Hence,

$$I = I_1 + I_2$$

(3.40)

1

2

The potential difference between A and B is given by the Ohm's law applied to R_1

$$V = I R_1$$

(3.41)

1

1

Also, Ohm's law applied to R_2 gives

2

$$V = I R_2$$

(3.42)

2

2

V

V

1

1

$$\therefore I = I_1 + I_2 =$$

+

$$= V$$

+

1

2

R

R

R

R

(3.43)

1

2

1

2

If the combination was replaced by an equivalent resistance R , we

eq

would have, by Ohm's law

V

$$I = R$$

(3.44)

eq

Hence,

1

1

1

=

+

R

R

R

(3.45)

eq

1

2

We can easily see how this extends to three resistors in parallel

(Fig. 3.16).

108

FIGURE 3.16 Parallel combination of three resistors *R* , *R* and *R* .

1

2

3

Current

Electricity

Exactly as before

$$I = I + I + I$$

(3.46)

1

2

3

and applying Ohm's law to R , R and R we get,

1

2

3

$$V = IR, V = IR, V = IR$$

(3.47)

1

1

2

2

3

3

So that

1

1

1

$$I = I + I + I = V$$

+

+

(3.48)

1

2

3

R

R

R

1

2

3

An equivalent resistance R that replaces the combination, would be

$e q$

such that

V

$I = R$

(3.49)

$e q$

and hence

1

1

1

1

=

+

+

R

R

R

R

(3.50)

eq

1

2

3

We can reason similarly for any number of resistors in parallel. The equivalent resistance of n resistors R_1, R_2, \dots, R_n is

2

n

1

1

1

1

=

+

+ ... +

R_1

R_2

R_3

R_n

(3.51)

eq

1

2

n

These formulae for equivalent resistances can be used to find out currents and voltages in more complicated circuits. Consider for example, the circuit in Fig. (3.17), where there are three resistors R_1 , R_2 and R_3 .

1

2

3

R_2 and R_3 are in parallel and hence we can

2

3

replace them by an equivalent R_{23}

R_{eq} between

point B and C with

1

1

1

=

+

23

R

R

R

eq

2

3

R R

23

2

3

or, *R*

=

eq

R + R

(3.52)

2

3

The circuit now has R and 23

R

in series

1

eq

and hence their combination can be

replaced by an equivalent resistance 123

R_{eq}

FIGURE 3.17 A combination of three resistors R ,

with

1

R and R . R , R are in parallel with an

2

3

2

3

123

23

R

$$= R + R$$

(3.53)

equivalent resistance 23

R

. R and 23

R

are in

eq

eq

1

eq

1

eq

If the voltage between A and C is V , the

series with an equivalent resistance 123

R_{eq} .

current I is given by

V

V

$I =$

$=$

123

R

$R + R R$

$R + R$

eq

/

1

2

3

(2

3)

$V(R + R$

2

3)

$= R R + R R +$

(3.54)

$R R$

1

2

1

3

2

3

Physics

3.11 CELLS, EMF, INTERNAL RESISTANCE

We have already mentioned that a simple device to maintain a steady current in an electric circuit is the electrolytic cell. Basically a cell has two electrodes, called the positive (P) and the negative (N), as shown in Fig. 3.18. They are immersed in an electrolytic solution. Dipped in the solution, the electrodes exchange charges with the electrolyte. The positive electrode has a potential difference V ($V > 0$) between

+

+

itself and the electrolyte solution immediately adjacent to it marked

A in the figure. Similarly, the negative electrode develops a negative

potential $-V$ ($V \geq 0$) relative to the electrolyte adjacent to it,



marked as B in the figure. When there is no current, the electrolyte has the same potential throughout, so that the potential difference between P and N is $V - (-V) = V + V$. This difference is called the



electromotive force (emf) of the cell and is denoted by ϵ . Thus

$$\epsilon = V + V > 0$$

(3.55)



Note that ϵ is, actually, a potential difference and *not a force*. The name emf, however, is used because of historical reasons, and was given at a time when the phenomenon was not understood properly.

To understand the significance of ϵ , consider a resistor R connected across the cell (Fig. 3.18). A current I flows across R

from C to D. As explained before, a steady current is maintained because current flows from N to P through the electrolyte. Clearly, across the electrolyte the same current flows through the electrolyte

FIGURE 3.18 (a) Sketch of

but from N to P, whereas through R , it flows from P to N.

an electrolyte cell with

The electrolyte through which a current flows has a finite

positive terminal P and

resistance r , called the *internal resistance*. Consider first the negative terminal N. The

gap between the electrodes

situation when R is infinite so that $I = V/R = 0$, where V is the is exaggerated for clarity. A potential difference between P and N. Now,

and B are points in the

$V =$ Potential difference between P and A

electrolyte typically close to

+ Potential difference between A and B

P and N. (b) the symbol for

+ Potential difference between B and N

a cell, + referring to P and

$= \epsilon$

(3.56)

– referring to the N

Thus, emf ε is the potential difference between the positive and

electrode. Electrical

negative electrodes in an open circuit, i.e., when no current is

connections to the cell are

flowing through the cell.

made at P and N.

If however R is finite, I is not zero. In that case the potential difference between P and N is $V = V + V - I r$

+

-

$$= \varepsilon - I r$$

(3.57)

Note the negative sign in the expression ($I r$) for the potential difference between A and B. This is because the current I flows from B to A in the electrolyte.

In practical calculations, internal resistances of cells in the circuit

may be neglected when the current I is such that $\varepsilon \gg I r$. The actual values of the internal resistances of cells vary from cell to cell. The internal resistance of dry cells, however, is much higher than the common 110

electrolytic cells.

Current

Electricity

We also observe that since V is the potential difference across R , we have from Ohm's law

$$V = IR$$

(3.58)

Combining Eqs. (3.57) and (3.58), we get

$$IR = \varepsilon - Ir$$

ε

Or, $I =$

(3.59)

$R + r$

The maximum current that can be drawn from a cell is for $R = 0$ and

it is I

$= \varepsilon / r$. However, in most cells the maximum allowed current is

max

much lower than this to prevent permanent damage to the cell.

CHARGES IN CLOUDS

In olden days lightning was considered as an atmospheric flash of supernatural origin.

It was believed to be the great weapon of Gods. But today the phenomenon of lightning can be explained scientifically by elementary principles of physics.

Atmospheric electricity arises due to the separation of electric charges. In the ionosphere and magnetosphere strong electric current is generated from the solar-terrestrial interaction. In the lower atmosphere the current is weaker and is maintained by thunderstorm.

There are ice particles in the clouds, which grow, collide, fracture and break apart.

The smaller particles acquire positive charge and the larger ones negative charge. These charged particles get separated by updrafts in the clouds and gravity. The upper portion of the cloud becomes positively charged and the middle negatively charged, leading to dipole structure. Sometimes a very weak positive charge is found near the base of the cloud. The ground is positively charged at the time of thunderstorm development. Also cosmic and radioactive radiations ionise air into positive and negative ions and air becomes (weakly) electrically conductive. The separation of charges produce tremendous amount of electrical potential within the cloud as well as between the cloud and ground. This can amount to millions of volts and eventually the electrical resistance in the air breaks down and lightning flash begins and thousands of amperes of current flows. The electric field is of the order of 10^5 V/m. A lightning flash is composed of a series of strokes with an average of about four and the duration of each flash is about 30 seconds. The average peak power per stroke is about 10¹² watts.

During fair weather also there is charge in the atmosphere. The fair weather electric field arises due to the existence of a surface charge density at ground and an atmospheric conductivity as well as due to the flow of current from the ionosphere to the earth's surface, which is of the order of picoampere *square metre*. *The surface charge density at ground is negative; the electric field is directed downward. Over land the average electric field is about 120 V/m, which corresponds to a surface charge density of -1.2×10^{-9} C/m². Over the entire earth's surface, the total negative charge amount to about 600 kC. An equal positive charge exists in the atmosphere. This electric field is not noticeable in daily life. The reason why it is not*

noticed is that virtually everything, including our bodies, is conductor compared to air.

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Physics

Example 3.5 A network of resistors is connected to a 16 V battery with internal resistance of 1Ω , as shown in Fig. 3.19: (a) Compute the equivalent resistance of the network. (b) Obtain the current in each resistor. (c) Obtain the voltage drops V_1 , V_2 and V_3 .

AB

BC

CD

FIGURE 3.19

Solution

(a) The network is a simple series and parallel combination of resistors. First the two 4Ω resistors in parallel are equivalent to a resistor = $[(4 \times 4)/(4 + 4)] \Omega = 2 \Omega$.

In the same way, the 12Ω and 6Ω resistors in parallel are equivalent to a resistor of

$$[(12 \times 6)/(12 + 6)] \Omega = 4 \Omega.$$

The equivalent resistance R of the network is obtained by combining these resistors (2Ω and 4Ω) with 1Ω in series,

that is,

$$R = 2 \Omega + 4 \Omega + 1 \Omega = 7 \Omega.$$

(b) The total current I in the circuit is

ε

$$16 \text{ V}$$

$$I =$$

=

$$= 2 \text{ A}$$

$$R + r$$

$$(7 + 1) \Omega$$

Consider the resistors between A and B. If I is the current in one

1

of the 4Ω resistors and I the current in the other,

2

$$I \times 4 = I \times 4$$

1

2

that is, $I = I$, which is otherwise obvious from the symmetry of 1

2

the two arms. But $I + I = I = 2 \text{ A}$. Thus,

1

2

$$I = I = 1 \text{ A}$$

1

2

that is, current in each 4Ω resistor is 1 A. Current in 1Ω resistor between B and C would be 2 A.

Now, consider the resistances between C and D. If I is the current

3

in the 12Ω resistor, and I in the 6Ω resistor,

4

$$I \times 12 = I \times 6, \text{ i.e., } I = 2 I$$

3

4

4

3

But, $I + I = I = 2 \text{ A}$

3

4

2

4

Thus, $I =$

=

3

$$3 \text{ A}, I 4$$

$$3 \text{ A}$$

that is, the current in the 12Ω resistor is $(2/3) \text{ A}$, while the current in the 6Ω resistor is $(4/3) \text{ A}$.

3.5

(c) The voltage drop across AB is

$$V = I \times 4 = 1 \text{ A} \times 4 \Omega = 4 \text{ V},$$

AB

1

XAMPLE

This can also be obtained by multiplying the total current between

112

E

A and B by the equivalent resistance between A and B, that is,

Current

Electricity

$$V = 2 \text{ A} \times 2 \Omega = 4 \text{ V}$$

AB

The voltage drop across BC is

$$V = 2 \text{ A} \times 1 \ \Omega = 2 \text{ V}$$

BC

Finally, the voltage drop across CD is

2

$$V = 12 \ \Omega \times I = 12 \ \Omega \times$$

CD

3

$$3 \text{ A} = 8 \text{ V.}$$

This can alternately be obtained by multiplying total current between C and D by the equivalent resistance between C and D, that is,

E

$$V = 2 \text{ A} \times 4 \ \Omega = 8 \text{ V}$$

XAMPLE

CD

Note that the total voltage drop across AD is $4 \text{ V} + 2 \text{ V} + 8 \text{ V} = 14 \text{ V}$.

Thus, the terminal voltage of the battery is 14 V, while its emf is 16 V.

3.5

The loss of the voltage ($= 2 \text{ V}$) is accounted for by the internal resistance

1 Ω of the battery [$2 \text{ A} \times 1 \Omega = 2 \text{ V}$].

3.12 CELLS IN SERIES AND IN PARALLEL

Like resistors, cells can be combined together in an electric circuit. And like resistors, one can, for calculating currents and voltages in a circuit, replace a combination of cells by an equivalent cell.

FIGURE 3.20 Two cells of emf's ϵ_1 and ϵ_2 in the series. r_1, r_2 are their

2

1

2

internal resistances. For connections across A and C, the combination can be considered as one cell of emf ϵ and an internal resistance r .

eq

eq

Consider first two cells in series (Fig. 3.20), where one terminal of the two cells is joined together leaving the other terminal in either cell free.

ϵ_1, ϵ_2 are the emf's of the two cells and r_1, r_2 their internal resistances, 1

2

1

2

respectively.

Let $V(A)$, $V(B)$, $V(C)$ be the potentials at points A, B and C shown in Fig. 3.20. Then $V(A) - V(B)$ is the potential difference between the positive and negative terminals of the first cell. We have already calculated it in Eq. (3.57) and hence,

V

$$\equiv V(A) - V(B) = \varepsilon - I r$$

(3.60)

AB

1

1

Similarly,

V

$$\equiv V(B) - V(C) = \varepsilon - I r$$

(3.61)

BC

2

2

Hence, the potential difference between the terminals A and C of the combination is

V

$$\equiv V(A) - V(C) = V$$

$$V_A - V_B + V_B - V_C$$

AC

()

() ()

()

113

$$= (\varepsilon + \varepsilon - I r + r$$

(3.62)

1

2)

(1 2)

Physics

If we wish to replace the combination by a single cell between A and

C of emf ε and internal resistance r , we would have

eq

eq

$$V = \varepsilon - I r$$

(3.63)

AC

eq

eq

Comparing the last two equations, we get

$$\varepsilon = \varepsilon + \varepsilon$$

(3.64)

eq

1

2

and $r = r + r$

(3.65)

eq

1

2

In Fig.3.20, we had connected the negative electrode of the first to the positive electrode of the second. If instead we connect the two negatives,

Eq. (3.61) would change to $V = -\varepsilon - Ir$ and we will get

BC

2

2

$$\varepsilon = \varepsilon - \varepsilon$$

$$> \varepsilon)$$

$$(3.66)$$

eq

1

2 (ε_1

2

The rule for series combination clearly can be extended to any number of cells:

(i) The equivalent emf of a series combination of n cells is just the sum of their individual emf's, and

(ii) The equivalent internal resistance of a series combination of n cells is just the sum of their internal resistances.

This is so, when the current leaves each cell from the positive electrode. If in the combination, the current leaves any cell from the *negative* electrode, the emf of the cell enters the expression for ε with a *negative* sign, as in Eq. (3.66).

eq

Next, consider a parallel combination of the cells (Fig. 3.21).

I_1 and I_2 are the currents leaving the positive electrodes of the 1

2

cells. At the point B , I and I flow in whereas the current I flows 1

1

2

out. Since as much charge flows in as out, we have

$$I = I + I$$

(3.67)

FIGURE 3.21 Two cells in

1

2

parallel. For connections

Let $V(B)$ and $V(B)$ be the potentials at B and B , respectively.

1

2

1

2

across A and C, the

Then, considering the first cell, the potential difference across its

combination can be

terminals is $V(B) - V(B)$. Hence, from Eq. (3.57) 1

2

replaced by one cell of emf

ε

V

and internal resistances

$$\equiv V (B - V B = \varepsilon - I r$$

(3.68)

1)

(2) 1 1 1

eq

r whose values are given in

eq

Points *B* and *B* are connected exactly similarly to the second

1

2

Eqs. (3.64) and (3.65).

cell. Hence considering the second cell, we also have

$$V \equiv V (B - V B = \varepsilon - I r$$

(3.69)

1)

(2) 2 2 2

Combining the last three equations

$$I = I + I$$

1

2

$$\varepsilon - V \varepsilon - V \quad \varepsilon$$

ε

1

1

1

2

1

2

=

+

=

+

$-V$

+

r

r

r

r

r

r

(3.70)

1

2

1

2

1

2

Hence, V is given by,

$$\varepsilon r + \varepsilon r$$

$$r r$$

$$1 2$$

$$2 1$$

$$1 2$$

$$V =$$

$$-I$$

$$r + r$$

$$r + r$$

$$(3.71)$$

$$1$$

$$2$$

$$1$$

$$2$$

If we want to replace the combination by a single cell, between B and

$$1$$

B , of emf ε and internal resistance r , we would have

$$2$$

$$eq$$

$$eq$$

114

$$V = \varepsilon - I r$$

(3.72)

eq

eq



Current

Electricity

The last two equations should be the same and hence

εr

εr

1 2

2 1

ε

+

=

eq

$r + r$

(3.73)

GUST

1

2

$r r$

1 2

$r =$

eq

$r + r$

(3.74)

A

1

2

V

We can put these equations in a simpler way,

ROBER

1

1

1

= +

r

r

r

(3.75)

eq

1

2

T

ϵ

ϵ

ϵ

KIRCHHOFF (1824 – 1887)

eq

1

2

=

+

r

r

r

(3.76)

eq

1

2

In Fig. (3.21), we had joined the positive terminals

Gustav Robert Kirchhoff

together and similarly the two negative ones, so that the

(1824 – 1887) German

currents I , I flow out of positive terminals. If the negative 1

2

physicist, professor at

terminal of the second is connected to positive terminal

Heidelberg and at

of the first, Eqs. (3.75) and (3.76) would still be valid with

Berlin. Mainly known for

$\varepsilon \rightarrow -\varepsilon$

2

2

his development of

Equations (3.75) and (3.76) can be extended easily.

spectroscopy, he also

If there are n cells of emf $\epsilon_1, \dots, \epsilon_n$ and of internal resistances

made many important

1

n

r_1, \dots, r_n respectively, connected in parallel, the

contributions to mathe—

1

n

combination is equivalent to a single cell of emf ϵ and

mathematical physics, among

eq

internal resistance r , such that

them, his first and

eq

second rules for circuits.

1

1

1

=

+ L +

r

r

r

(3.77)

eq

1

n

ε

ε

ε

eq

1

n

=

+ L +

r

r

r

(3.78)

eq

1

n

3.13 KIRCHHOFF'S RULES

Electric circuits generally consist of a number of resistors and cells interconnected sometimes in a complicated way. The formulae we have derived earlier for series and parallel combinations of resistors are not always sufficient to determine all the currents and potential differences in the circuit. Two rules, called *Kirchhoff's rules*, are very useful for analysis of electric circuits.

Given a circuit, we start by labelling currents in each resistor by a symbol, say I , and a directed arrow to indicate that a current I flows along the resistor in the direction indicated. If ultimately I is determined to be positive, the actual current in the resistor is in the direction of the arrow. If I turns out to be negative, the current actually flows in a direction opposite to the arrow. Similarly, for each source (i.e., cell or some other source of electrical power) the positive and negative electrodes are labelled

as well as a directed arrow with a symbol for the current flowing through

115

the cell. This will tell us the potential difference, $V = V(\text{P}) - V(\text{N}) = \varepsilon - I r$

Physics

[Eq. (3.57) between the positive terminal P and the negative terminal N; I here is the current flowing from N to P through the cell]. If, while labelling the current I through the cell one goes from P to N, then of course

$$V = \varepsilon + I r$$

(3.79)

Having clarified labelling, we now state the rules and the proof:

(a) Junction rule: At any junction, the sum of the currents entering the junction is equal to the sum of currents leaving the junction (Fig. 3.22).

This applies equally well if instead of a junction of several lines, we consider a point in a line.

The proof of this rule follows from the fact that when currents are steady, there is no accumulation

FIGURE 3.22 At junction a the current

of charges at any junction or at any point in a line.

leaving is $I + I$ and current entering is I .

1

2

3

Thus, the total current flowing in, (which is the rate

The junction rule says $I = I + I$. At point

3

1

2

at which charge flows into the junction), must equal

h current entering is I . There is only one

1

the total current flowing out.

current leaving h and by junction rule

(b) Loop rule: The algebraic sum of changes in

that will also be I . For the loops ‘ahdcba’

1

and ‘ahdefga’, the loop rules give $-30 I -$

potential around any closed loop involving

1

$41 I + 45 = 0$ and $-30 I + 21 I - 80 = 0$.

resistors and cells in the loop is zero (Fig. 3.22).

3

1

2

This rule is also obvious, since electric potential is dependent on the location of the point. Thus starting with any point if we come back to the same point, the total change must be zero. In a closed loop, we do come back to the starting point and hence the rule.

Example 3.6 A battery of 10 V and negligible internal resistance is connected across the diagonally opposite corners of a cubical network consisting of 12 resistors each of resistance 1Ω (Fig. 3.23). Determine the equivalent resistance of the network and the current along each edge of the cube.

3.6

XAMPLE

116

E

FIGURE 3.23

Current

Electricity

Solution The network is not reducible to a simple series and parallel combinations of resistors. There is, however, a clear symmetry in the problem which we can exploit to obtain the equivalent resistance of

the network.

The paths AA', AD and AB are obviously symmetrically placed in the network. Thus, the current in each must be the same, say, I . Further, at the corners A', B and D, the incoming current I must split equally into the two outgoing branches. In this manner, the current in all the 12 edges of the cube are easily written down in terms of I , using Kirchhoff's first rule and the symmetry in the problem.

Next take a closed loop, say, ABCC'EA, and apply Kirchhoff's second rule:

$$-IR - (1/2)IR - IR + \varepsilon = 0$$

where R is the resistance of each edge and ε the emf of battery. Thus,

$$\varepsilon = 5IR$$

<http://www.phys.hawaii.edu/~teb/optics/java/kirch3/> **Simulation for application of Kirchhoff 2**

The equivalent resistance R of the network is

ε

5

R

=

= R

eq

E

$3 I$

6

XAMPLE

For $R = 1 \Omega$, $R = (5/6) \Omega$ and for $\varepsilon = 10 \text{ V}$, the total current ($= 3 I$) in *eq* the network is

$$3 I = 10 \text{ V} / (5/6) \Omega = 12 \text{ A, i.e., } I = 4 \text{ A}$$

3.6

The current flowing in each edge can now be read off from the Fig. 3.23.

It should be noted that because of the symmetry of the network, the great power of Kirchhoff's rules has not been very apparent in Example 3.6.

In a general network, there will be no such simplification due to symmetry, and only by application of Kirchhoff's rules to junctions and closed loops (as many as necessary to solve the unknowns in the network)

is r

can we handle the problem. This will be illustrated in Example 3.7.

ules:

Example 3.7 Determine the current in each branch of the network

shown in Fig. 3.24.

E

XAMPLE

3.7

FIGURE 3.24

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Physics

Solution Each branch of the network is assigned an unknown current to be determined by the application of Kirchhoff's rules. To reduce the number of unknowns at the outset, the first rule of Kirchhoff is used at every junction to assign the unknown current in each branch.

We then have three unknowns I , I and I which can be found by 1

2

3

applying the second rule of Kirchhoff to three different closed loops.

Kirchhoff's second rule for the closed loop ADCA gives,

$$10 - 4(I - I) + 2(I + I - I) - I = 0$$

[3.80(a)]

1

2

2

3

1

1

that is, $7 I - 6 I - 2 I = 10$

1

2

3

For the closed loop ABCA, we get

$$10 - 4 I - 2 (I + I) - I = 0$$

2

2

3

1

that is, $I + 6 I + 2 I = 10$

[3.80(b)]

1

2

3

For the closed loop BCDEB, we get

$$5 - 2(I + I) - 2(I + I - I) = 0$$

2

3

2

3

1

that is, $2I - 4I - 4I = -5$

[3.80(c)]

1

2

3

Equations (3.80 a, b, c) are three simultaneous equations in three unknowns. These can be solved by the usual method to give

5

7

$$I = 2.5A, I =$$

$$A, I = 1$$

A

1

2

8

3

8

The currents in the various branches of the network are

5

1

7

AB :

A, CA : 2

A, DEB : 1

A

8

2

8

7

1

AD : 1

A, CD : 0 A, BC : 2

A

8

2

It is easily verified that Kirchhoff's second rule applied to the remaining closed loops does not provide any additional independent equation, that is, the above values of currents satisfy the second rule for every closed loop of the network. For example, the total voltage

3.7

drop over the closed loop BADEB

5

15

$5\text{ V} + \quad \times 4\text{ V}$

—

$\times 4\text{ V}$

8

8

XAMPLE

E

equal to zero, as required by Kirchhoff's second rule.

3.14 WHEATSTONE BRIDGE

As an application of Kirchhoff's rules consider the circuit shown in Fig. 3.25, which is called the *Wheatstone bridge*. The bridge has four resistors R_1 , R_2 , R_3 and R_4 . Across one pair of diagonally opposite

2

3

4

points (A and C in the figure) a source is connected. This (*i.e.* , AC) is called the battery arm. Between the other two vertices, B and D, a galvanometer G (which is a device to detect currents) is connected. This line, shown as BD in the figure, is called the galvanometer arm.

For simplicity, we assume that the cell has no internal resistance. In general there will be currents flowing across all the resistors as well as a current I through G. Of special interest, is the case of a *balanced* bridge g where the resistors are such that $I = 0$. We can easily get the balance g condition, such that there is no current through G. In this case, the

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Kirchhoff's junction rule applied to junctions D and B (see the figure)

Current

Electricity

immediately gives us the relations $I = I$ and $I = I$. Next, we apply 1

3

2

4

Kirchhoff's loop rule to closed loops ADBA and CBDC. The first

loop gives

$$-IR + 0 + IR = 0 \quad (I = 0)$$

(3.81)

1

1

2

2

g

and the second loop gives, upon using $I = I$, $I = I$ 3

1

4

2

$$IR + 0 - IR = 0$$

(3.82)

2

4

1

3

From Eq. (3.81), we obtain,

I

R

1

2

=

I

R

2

1

whereas from Eq. (3.82), we obtain,

I

R

1

4

=

I

R

2

3

Hence, we obtain the condition

R

R

FIGURE 3.25

2

4

=

[3.83(a)]

R

R

1

3

This last equation relating the four resistors is called the *balance condition* for the galvanometer to give zero or null deflection.

The Wheatstone bridge and its balance condition provide a practical method for determination of an unknown resistance. Let us suppose we

have an unknown resistance, which we insert in the fourth arm; R is

4

thus not known. Keeping known resistances R and R in the first and 1

2

second arm of the bridge, we go on varying R till the galvanometer shows 3

a null deflection. The bridge then is balanced, and from the balance

condition the value of the unknown resistance R is given by,

4

R_2

$R = R$

4

3 R

[3.83(b)]

1

A practical device using this principle is called the *meter bridge*. It

will be discussed in the next section.

Example 3.8 The four arms of a Wheatstone bridge (Fig. 3.26) have the following resistances:

$AB = 100\Omega$, $BC = 10\Omega$, $CD = 5\Omega$, and $DA = 60\Omega$.

E

XAMPLE

3.8

FIGURE 3.26

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Physics

A galvanometer of 15Ω resistance is connected across BD. Calculate the current through the galvanometer when a potential difference of 10 V is maintained across AC.

Solution Considering the mesh BADB, we have

$$100 I + 15 I - 60 I = 0$$

1

g

2

$$\text{or } 20 I + 3 I - 12 I = 0$$

[3.84(a)]

1

g

2

Considering the mesh BCDB, we have

$$10 (I - I) - 15 I - 5 (I + I) = 0$$

1

g

g

2

g

$$10 I - 30 I - 5 I = 0$$

1

g

2

$$2 I - 6 I - I = 0$$

[3.84(b)]

1

g

2

Considering the mesh ADCEA,

$$60 I + 5 (I + I) = 10$$

2

2

g

$$65 I + 5 I = 10$$

2

g

$$13 I + I = 2$$

[3.84(c)]

2

g

Multiplying Eq. (3.84b) by 10

$$20 I - 60 I - 10 I = 0$$

[3.84(d)]

1

g

2

From Eqs. (3.84d) and (3.84a) we have

$$63 I - 2 I = 0$$

g

2

$$I = 31.5 I$$

[3.84(e)]

2

g

Substituting the value of I into Eq. [3.84(c)], we get

2

3.8

$$13 (31.5 I) + I = 2$$

g

g

$$410.5 I = 2$$

g

XAMPLE

E

$$I = 4.87 \text{ mA.}$$

g

3.15 METER BRIDGE

The meter bridge is shown in Fig. 3.27. It consists of a wire of length 1 m and of uniform cross sectional area stretched taut and clamped between two thick metallic strips bent at right angles, as shown. The metallic strip has two gaps across which resistors can be connected. The end points where the wire is clamped are connected to a cell through a key. One

end of a galvanometer is connected to the metallic

FIGURE 3.27 A meter bridge. Wire AC

strip midway between the two gaps. The other end of

is 1 m long. R is a resistance to be

the galvanometer is connected to a 'jockey'. The jockey

measured and S is a standard

is essentially a metallic rod whose one end has a

resistance.

knife-edge which can slide over the wire to make

electrical connection.

R is an unknown resistance whose value we want to determine. It is

120

connected across one of the gaps. Across the other gap, we connect a

Current

Electricity

standard known resistance S . The jockey is connected to some point D

on the wire, a distance l cm from the end A. The jockey can be moved

along the wire. The portion AD of the wire has a resistance $R l$, where cm

R is the resistance of the wire per unit centimetre. The portion DC of cm

the wire similarly has a resistance $R (100 - l)$.

cm

The four arms AB, BC, DA and CD [with resistances R , S , $R l$ and cm
 $R (100- l)$] obviously form a Wheatstone bridge with AC as the battery cm
arm and BD the galvanometer arm. If the jockey is moved along the wire,
then there will be one position where the galvanometer will show no
current. Let the distance of the jockey from the end A at the balance
point be $l= l$. The four resistances of the bridge at the balance point then 1
are R , S , $R l$ and $R (100- l)$. The balance condition, Eq. [3.83(a)]

cm

1

cm

1

gives

R

R

l

l

cm 1

=

=

S

R

l

l

(3.85)

$cm (100 -$

)

l

$100 -$

l

l

Thus, once we have found out l , the unknown resistance R is known

in terms of the standard known resistance S by

l

$R = S$

(3.86)

$100 - l$

By choosing various values of S , we would get various values of l ,

and calculate R each time. An error in measurement of l would naturally

result in an error in R . It can be shown that the percentage error in R can be minimised by adjusting the balance point near the middle of the bridge, i.e.,

when l is close to 50 cm. (This requires a suitable choice l of S .)

Example 3.9 In a metre bridge (Fig. 3.27), the null point is found at a distance of 33.7 cm from A. If now a resistance of 12Ω is connected in parallel with S , the null point occurs at 51.9 cm. Determine the values of R and S .

Solution From the first balance point, we get

$$\frac{R}{33.7} = \frac{S}{66.3}$$

(3.87)

S

66.3

After S is connected in parallel with a resistance of 12Ω , the resistance across the gap changes from S to S' , where eq

$12 S$

S

=

eq

$S + 12$

and hence the new balance condition now gives

51.9

R

$R (S + 12)$

=

=

48.1

S

$12 S$

(3.88)

eq

E

Substituting the value of R/ S from Eq. (3.87), we get

XAMPLE

51.9

$S + 12$

33.7

=

g

48.1

12

66.3

3.9

which gives $S = 13.5\Omega$. Using the value of R/S above, we get $R = 6.86\Omega$.

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Physics

3.16 POTENTIOMETER

This is a versatile instrument. It is basically a long piece of uniform wire, sometimes a few meters in length across which a standard cell is connected. In actual design, the wire is sometimes cut in several pieces placed side by side and connected at the ends by thick metal strip.

(Fig. 3.28). In the figure, the wires run from A to C. The small vertical portions are the thick metal strips connecting the various sections of the wire.

A current I flows through the wire which can be varied by a variable resistance (rheostat, R) in the circuit. Since the wire is uniform, the potential difference between A and any point at a distance l from A is $\varepsilon(l) = \phi l$

(3.89)

where ϕ is the potential drop per unit length.

Figure 3.28 (a) shows an application of the potentiometer to compare the emf of two cells of emf ε and ε' . The points marked 1, 2, 3 form a two

2

way key. Consider first a position of the key where 1 and 3 are connected so that the galvanometer is connected to ε . The jockey

1

is moved along the wire till at a point N, at a distance l

1

1

from A, there is no deflection in the galvanometer. We can apply Kirchhoff's loop rule to the closed loop

AN G31A and get,

1

$$\phi l + 0 - \varepsilon = 0$$

(3.90)

1

1

Similarly, if another emf ε is balanced against l (AN)

2

2

2

$$\phi l + 0 - \varepsilon = 0$$

(3.91)

2

2

From the last two equations

ε

l

1

1

=

ε

l

(3.92)

2

2

This simple mechanism thus allows one to compare the emf's of any two sources. In practice one of the cells is chosen as a standard cell whose emf is known to a high degree of accuracy. The emf of the other cell is then easily calculated from Eq. (3.92).

We can also use a potentiometer to measure internal

resistance of a cell [Fig. 3.28 (b)]. For this the cell (emf ϵ) whose internal resistance (r) is to be determined is connected across a resistance box through a key K, as

2

FIGURE 3.28 A potentiometer. G is

shown in the figure. With key K open, balance is

2

a galvanometer and R a variable

obtained at length l (AN). Then,

1

1

resistance (rheostat). 1, 2, 3 are

$$\epsilon = \phi l$$

[3.93(a)]

terminals of a two way key

1

(a) circuit for comparing emfs of two

When key K is closed, the cell sends a current (I)

2

cells; (b) circuit for determining

through the resistance box (R). If V is the terminal internal resistance of a cell.

potential difference of the cell and balance is obtained at length l (AN),

2

2

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$$V = \phi l$$

[3.93(b)]

2

Current

Electricity

So, we have $\epsilon / V = l / l$

[3.94(a)]

1

2

But, $\epsilon = I (r + R)$ and $V = IR$. This gives

$$\epsilon / V = (r + R) / R$$

[3.94(b)]

From Eq. [3.94(a)] and [3.94(b)] we have

$$(R+r)/R = l/l$$

1

2

l

1

$$r = R$$

- 1

l

(3.95)

2

Using Eq. (3.95) we can find the internal resistance of a given cell.

The potentiometer has the advantage that it draws *no current* from the voltage source being measured. As such it is unaffected by the internal resistance of the source.

Example 3.10 A resistance of $R \Omega$ draws current from a potentiometer. The potentiometer has a total resistance $R \Omega$

0

(Fig. 3.29). A voltage V is supplied to the potentiometer. Derive an expression for the voltage across R when the sliding contact is in the middle of the potentiometer.

FIGURE 3.29

Solution While the slide is in the middle of the potentiometer only half of its resistance ($R/2$) will be between the points A and B. Hence, 0 the total resistance between A and B, say, R , will be given by the

1

following expression:

1

1

1

$$= +$$

R

R

$(R/2)$

1

0

$R R$

0

$$R =$$

1

$$R + 2R$$

0

The total resistance between A and C will be sum of resistance between

A and B and B and C, i.e., $R + R/2$

1

0

∴ The current flowing through the potentiometer will be

$$V$$

$$2V$$

$$I =$$

=

E

$$R + R/2$$

$$2R + R$$

1

0

1

0

XAMPLE

The voltage V taken from the potentiometer will be the product of

1

current I and resistance R ,

1

3.10

2 V

$$V = IR =$$

$$\times R$$

1

1

1

$$2R + R$$

1

0

123

Physics

Substituting for R , we have a

1

2 V

$R \times R$

0

$V =$

\times

1

$R \times R$

$R + 2 R$

0

0

2

$+ R 0$

$R + 2 R$

0

$2 VR$

=

3.10

$V \frac{1}{2R} + R + 2R$

0

or V

$2 VR$

XAMPLE

1 =

+

.

E

R

$4 R$

0

SUMMARY

1.

Current through a given area of a conductor is the net charge passing per unit time through the area.

2.

To maintain a steady current, we must have a closed circuit in which an external agency moves electric charge from lower to higher potential energy. The work done per unit charge by the source in taking the charge from lower to higher potential energy (i.e., from one terminal of the source to the other) is called the electromotive force, or *emf*, of the source. Note that the emf is not a force; it is the voltage difference between the two terminals of a source in open circuit.

3.

Ohm's law: The electric current I flowing through a substance is proportional to the voltage V across its ends, i.e., $V \propto I$ or $V = RI$, where R is called the *resistance* of the substance. The unit of resistance is ohm: $1\Omega = 1 \text{ V A}^{-1}$.

4.

The *resistance* R of a conductor depends on its length l and constant cross-sectional area A through the relation, ρl

$$R = \frac{\rho l}{A}$$

where ρ , called *resistivity* is a property of the material and depends on temperature and pressure.

5.

Electrical resistivity of substances varies over a very wide range. Metals have low resistivity, in the range of $10^{-8} \Omega \text{ m}$ to $10^{-6} \Omega \text{ m}$. Insulators like glass and rubber have 10^{22} to 10^{24} times greater resistivity.

Semiconductors like Si and Ge lie roughly in the middle range of resistivity on a logarithmic scale.

6.

In most substances, the carriers of current are electrons; in some cases, for example, ionic crystals and electrolytic liquids, positive and negative ions carry the electric current.

7.

Current density \mathbf{j} gives the amount of charge flowing per second per unit area normal to the flow, $\mathbf{j} = nq \mathbf{v}$

where n is the number density (number per unit volume) of charge carriers each of charge q , and \mathbf{v} is the *drift velocity* of the charge

carriers. For electrons $q = -e$. If \mathbf{j} is normal to a cross-sectional area \mathbf{A} and is constant over the area, the magnitude of the current I through the area is $nevA$.

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d

Current

Electricity

8.

Using $E = V/l$, $I = nevA$, and Ohm's law, one obtains

d

2

eE

ne

$= \rho$

vd

m

m

The proportionality between the *force* eE on the electrons in a metal due to the external field E and the drift velocity v (not acceleration) d can be understood, if we assume that the electrons suffer collisions with ions in the metal, which deflect them randomly. If such collisions occur on an average at a time interval τ ,

$$v = a\tau = eE\tau / m$$

d

where a is the acceleration of the electron. This gives

m

$\rho =$

2

$ne \tau$

9.

In the temperature range in which resistivity increases linearly with

temperature, the *temperature coefficient of resistivity* α is defined as the fractional increase in resistivity per unit increase in temperature.

10. Ohm's law is obeyed by many substances, but it is not a fundamental law of nature. It fails if

(a) V depends on I non-linearly.

(b) the relation between V and I depends on the sign of V for the same absolute value of V .

(c) The relation between V and I is non-unique.

An example of (a) is when ρ increases with I (even if temperature is kept fixed). A rectifier combines features (a) and (b). GaAs shows the feature (c).

11. When a source of emf ε is connected to an external resistance R , the voltage V across R is given by *ext*

ε

$V = IR =$

R

ext

$R + r$

where r is the *internal resistance* of the source.

12. (a) Total resistance R of n resistors connected in *series* is given by $R = R + R + \dots + R$

1

2

n

(b) Total resistance R of n resistors connected in *parallel* is given by

$\frac{1}{R}$

$= \frac{1}{R_1}$

$+$

$=$

$+$

$+ \dots +$

$\frac{1}{R_n}$

$\frac{1}{R}$

$\frac{1}{R}$

$\frac{1}{R}$

$\frac{1}{R}$

$\frac{1}{R}$

$\frac{1}{R}$

13. Kirchhoff's Rules –

(a) *Junction Rule*: At any junction of circuit elements, the sum of currents entering the junction must equal the sum of currents leaving it.

(b) *Loop Rule*: The algebraic sum of changes in potential around any

closed loop must be zero.

14. The *Wheatstone bridge* is an arrangement of four resistances – R_1, R_2, R_3, R_4 as shown in the text. The null-point condition is given by

R_1

R_2 as shown in the text. The null-point condition is given by

R_3

R_4

R_1

R_2

R_3

R_4

=

R_1

R_2

R_3

R_4

using which the value of one resistance can be determined, knowing

the other three resistances.

15. The *potentiometer* is a device to compare potential differences. Since the method involves a condition of *no* current flow, the device can be used to measure potential difference; internal resistance of a cell and

compare emf's of two sources.

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Physics

Physical Quantity

Symbol

Dimensions

Unit

Remark

Electric current

I

[A]

A

SI base unit

Charge

Q, q

[T A]

C

Voltage, Electric

V

[M L² T⁻³ A⁻¹]

V

Work/charge

potential difference

Electromotive force

ε

$[M L^2 T^{-3} A^{-1}]$

V

Work/charge

Resistance

R

$[M L^2 T^{-3} A^{-2}]$

Ω

$$R = V / I$$

Resistivity

ρ

$[M L^3 T^{-3} A^{-2}]$

$\Omega \text{ m}$

$$R = \rho l / A$$

Electrical

σ

$[M^{-1} L^{-3} T^3 A^2]$

S

$$\sigma = 1/\rho$$

conductivity

Electric field

E

$$[M L T^{-3} A^{-1}]$$

$$V m^{-1}$$

Electric force

charge

$$e E$$

Drift speed

v

$$[L T^{-1}]$$

$$m s^{-1}$$

$$v =$$

τ

d

d

m

Relaxation time

τ

[T]

s

Current density

\mathbf{j}

[L⁻² A]

A m⁻²

current/area

Mobility

μ

[M L³ T⁻⁴ A⁻¹]

m² V⁻¹ s⁻¹

v / E

d

POINTS TO PONDER

1.

Current is a scalar although we represent current with an arrow.

Currents do not obey the law of vector addition. That current is a

scalar also follows from its definition. The current I through an area of cross-section is given by the scalar product of two vectors: $I = \mathbf{j} \cdot \Delta\mathbf{S}$

where \mathbf{j} and $\Delta\mathbf{S}$ are vectors.

2.

Refer to V - I curves of a resistor and a diode as drawn in the text. A

resistor obeys Ohm's law while a diode does not. The assertion that

$V = IR$ is a statement of Ohm's law is not true. This equation defines resistance and it may be applied to all conducting devices whether they obey Ohm's law or not. The Ohm's law asserts that the plot of I

versus V is linear i.e., R is independent of V .

Equation $\mathbf{E} = \rho \mathbf{j}$ leads to another statement of *Ohm's* law, i.e., a conducting material obeys Ohm's law when the resistivity of the material does not depend on the magnitude and direction of applied

electric field.

3.

Homogeneous conductors like silver or semiconductors like pure

germanium or germanium containing impurities obey Ohm's law

within some range of electric field values. If the field becomes too

strong, there are departures from Ohm's law in all cases.

4.

Motion of conduction electrons in electric field \mathbf{E} is the sum of (i)

motion due to random collisions and (ii) that due to \mathbf{E} . The motion

Current

Electricity

due to random collisions averages to zero and does not contribute to

v (Chapter 11, Textbook of Class XI). v , thus is only due to applied d

d

electric field on the electron.

5.

The relation $\mathbf{j} = \rho \mathbf{v}$ should be applied to each type of charge carriers separately. In a conducting wire, the total current and charge density arises from both positive and negative charges:

$$\mathbf{j} = \rho \mathbf{v} + \rho \mathbf{v}$$

+

+

-

-

$$\rho = \rho + \rho$$

+

-

Now in a neutral wire carrying electric current,

$$\rho = -\rho$$

+

-

Further, $v \sim 0$ which gives

+

$$\rho = 0$$

$$\mathbf{j} = \rho \mathbf{v}$$

-

Thus, the relation $\mathbf{j} = \rho \mathbf{v}$ does not apply to the total current charge density.

6.

Kirchhoff's junction rule is based on conservation of charge and the outgoing currents add up and are equal to incoming current at a junction. Bending or reorienting the wire does not change the validity of Kirchhoff's junction rule.

EXERCISES

3.1

The storage battery of a car has an emf of 12 V. If the internal resistance of the battery is 0.4Ω , what is the maximum current that can be drawn from the battery?

3.2

A battery of emf 10 V and internal resistance $3\ \Omega$ is connected to a resistor. If the current in the circuit is 0.5 A, what is the resistance of the resistor? What is the terminal voltage of the battery when the circuit is closed?

3.3

(a) Three resistors $1\ \Omega$, $2\ \Omega$, and $3\ \Omega$ are combined in series. What is the total resistance of the combination?

(b) If the combination is connected to a battery of emf 12 V and negligible internal resistance, obtain the potential drop across each resistor.

3.4

(a) Three resistors $2\ \Omega$, $4\ \Omega$ and $5\ \Omega$ are combined in parallel. What is the total resistance of the combination?

(b) If the combination is connected to a battery of emf 20 V and negligible internal resistance, determine the current through each resistor, and the total current drawn from the battery.

3.5

At room temperature ($27.0\ ^\circ\text{C}$) the resistance of a heating element is $100\ \Omega$. What is the temperature of the element if the resistance is found to be $117\ \Omega$, given that the temperature coefficient of the

material of the resistor is $1.70 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$.

3.6

A negligibly small current is passed through a wire of length 15 m and uniform cross-section $6.0 \times 10^{-7} \text{ m}^2$, and its resistance is measured to be $5.0 \text{ } \Omega$. What is the resistivity of the material at the temperature of the experiment?

3.7

A silver wire has a resistance of $2.1 \text{ } \Omega$ at $27.5 \text{ }^\circ\text{C}$, and a resistance of $2.7 \text{ } \Omega$ at $100 \text{ }^\circ\text{C}$. Determine the temperature coefficient of resistivity of silver.

3.8

A heating element using nichrome connected to a 230 V supply

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draws an initial current of 3.2 A which settles after a few seconds to

Physics

a steady value of 2.8 A. What is the steady temperature of the heating element if the room temperature is $27.0 \text{ }^\circ\text{C}$? Temperature coefficient of resistance of nichrome averaged over the temperature range involved is $1.70 \times 10^{-4} \text{ }^\circ\text{C}^{-1}$.

3.9

Determine the current in each branch of the network shown in

Fig. 3.30:

FIGURE 3.30

3.10

(a) In a metre bridge [Fig. 3.27], the balance point is found to be at 39.5 cm from the end A , when the resistor Y is of 12.5Ω .

Determine the resistance of X . Why are the connections between resistors in a Wheatstone or meter bridge made of thick copper strips?

(b) Determine the balance point of the bridge above if X and Y are interchanged.

(c) What happens if the galvanometer and cell are interchanged at the balance point of the bridge? Would the galvanometer show any current?

3.11

A storage battery of emf 8.0 V and internal resistance 0.5Ω is being charged by a 120 V dc supply using a series resistor of 15.5Ω . What is the terminal voltage of the battery during charging? What is the purpose of having a series resistor in the charging circuit?

3.12

In a potentiometer arrangement, a cell of emf 1.25 V gives a balance

point at 35.0 cm length of the wire. If the cell is replaced by another cell and the balance point shifts to 63.0 cm, what is the emf of the second cell?

3. 13

The number density of free electrons in a copper conductor estimated in Example 3.1 is $8.5 \times 10^{28} \text{ m}^{-3}$. How long does an electron take to drift from one end of a wire 3.0 m long to its other end? The area of cross-section of the wire is $2.0 \times 10^{-6} \text{ m}^2$ and it is carrying a current of 3.0 A.

ADDITIONAL EXERCISES

3. 14

The earth's surface has a negative surface charge density of 10^{-9} C m^{-2} . The potential difference of 400 kV between the top of the atmosphere and the surface results (due to the low conductivity of the lower atmosphere) in a current of only 1800 A over the entire

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globe. If there were no mechanism of sustaining atmospheric electric

Current

Electricity

field, how much time (roughly) would be required to neutralise the

earth's surface? (This never happens in practice because there is a mechanism to replenish electric charges, namely the continual thunderstorms and lightning in different parts of the globe). (Radius of earth = 6.37×10^6 m.)

3.15

(a) Six lead-acid type of secondary cells each of emf 2.0 V and internal resistance 0.015Ω are joined in series to provide a supply to a resistance of 8.5Ω . What are the current drawn from the supply and its terminal voltage?

(b) A secondary cell after long use has an emf of 1.9 V and a large internal resistance of 380Ω . What maximum current can be drawn from the cell? Could the cell drive the starting motor of a car?

3.16

Two wires of equal length, one of aluminium and the other of copper have the same resistance. Which of the two wires is lighter? Hence explain why aluminium wires are preferred for overhead power cables.

($\rho = 2.63 \times 10^{-8} \Omega \text{ m}$, $\rho = 1.72 \times 10^{-8} \Omega \text{ m}$, Relative density of

Al

Cu

Al = 2.7, of Cu = 8.9.)

3.17

What conclusion can you draw from the following observations on a resistor made of alloy manganin?

Current

Voltage

Current

Voltage

A

V

A

V

0.2

3.94

3.0

59.2

0.4

7.87

4.0

78.8

0.6

11.8

5.0

98.6

0.8

15.7

6.0

118.5

1.0

19.7

7.0

138.2

2.0

39.4

8.0

158.0

3.18

Answer the following questions:

(a) A steady current flows in a metallic conductor of nonuniform cross-section. Which of these quantities is constant along the conductor: current, current density, electric field, drift speed?

(b) Is Ohm's law universally applicable for all conducting elements?

If not, give examples of elements which do not obey Ohm's law.

(c) A low voltage supply from which one needs high currents must have very low internal resistance. Why?

(d) A high tension (HT) supply of, say, 6 kV must have a very large internal resistance. Why?

3.19

Choose the correct alternative:

(a) Alloys of metals usually have (greater/less) resistivity than that of their constituent metals.

(b) Alloys usually have much (lower/higher) temperature coefficients of resistance than pure metals.

(c) The resistivity of the alloy manganin is nearly independent of/ increases rapidly with increase of temperature.

(d) The resistivity of a typical insulator (e.g., amber) is greater than that of a metal by a factor of the order of ($10^{22}/10^3$).

3.20

(a) Given n resistors each of resistance R , how will you combine them to get the (i) maximum (ii) minimum effective resistance?

What is the ratio of the maximum to minimum resistance?

(b) Given the resistances of 1Ω , 2Ω , 3Ω , how will be combine them

to get an equivalent resistance of (i) $(11/3) \Omega$ (ii) $(11/5) \Omega$, (iii) 6Ω , (iv) $(6/11) \Omega$?

(c) Determine the equivalent resistance of networks shown in

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Fig. 3.31.

Physics

FIGURE 3.31

3.21

Determine the current drawn from a 12V supply with internal resistance 0.5Ω by the infinite network shown in Fig. 3.32. Each resistor has 1Ω resistance.

FIGURE 3.32

3.22

Figure 3.33 shows a potentiometer with a cell of 2.0 V and internal resistance 0.40Ω maintaining a potential drop across the resistor wire AB. A standard cell which maintains a constant emf of 1.02 V (for very moderate currents upto a few mA) gives a balance point at 67.3 cm length of the wire. To ensure very low currents drawn from the standard cell, a very high resistance of $600 \text{ k}\Omega$ is put in series with it, which is shorted close to the balance point. The standard

cell is then replaced by a cell of unknown emf ε and the balance point found similarly, turns out to be at 82.3 cm length of the wire.

FIGURE 3.33

(a) What is the value ε ?

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(b) What purpose does the high resistance of $600 \text{ k}\Omega$ have?

Current

Electricity

(c) Is the balance point affected by this high resistance?

(d) Is the balance point affected by the internal resistance of the driver cell?

(e) Would the method work in the above situation if the driver cell of the potentiometer had an emf of 1.0V instead of 2.0V?

(f) Would the circuit work well for determining an extremely small emf, say of the order of a few mV (such as the typical emf of a thermo-couple)? If not, how will you modify the circuit?

3.23

Figure 3.34 shows a potentiometer circuit for comparison of two resistances. The balance point with a standard resistor $R = 10.0 \Omega$ is found to be 58.3 cm, while that with the unknown resistance X is

68.5 cm. Determine the value of X . What might you do if you failed to find a balance point with the given cell of emf ϵ ?

FIGURE 3.34

3.24

Figure 3.35 shows a 2.0 V potentiometer used for the determination of internal resistance of a 1.5 V cell. The balance point of the cell in open circuit is 76.3 cm. When a resistor of 9.5Ω is used in the external circuit of the cell, the balance point shifts to 64.8 cm length of the potentiometer wire. Determine the internal resistance of the cell.

FIGURE 3.35

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Chapter Four

MOVING CHARGES

AND MAGNETISM

4.1 INTRODUCTION

Both Electricity and Magnetism have been known for more than 2000 years. However, it was only about 200 years ago, in 1820, that it was realised that they were intimately related*. During a lecture demonstration in the summer of 1820, the Danish physicist Hans Christian Oersted noticed that a current in a straight wire caused a noticeable deflection in a nearby magnetic compass needle. He investigated this phenomenon.

He found that the alignment of the needle is tangential to an imaginary circle which has the straight wire as its centre and has its plane perpendicular to the wire. This situation is depicted in Fig.4.1(a). It is noticeable when the current is large and the needle sufficiently close to the wire so that the earth's magnetic field may be ignored. Reversing the direction of the current reverses the orientation of the needle [Fig. 4.1(b)]. The deflection increases on increasing the current or bringing the needle closer to the wire. Iron filings sprinkled around the wire arrange themselves in concentric circles with the wire as the centre [Fig. 4.1(c)]. Oersted concluded that *moving charges or currents produced a magnetic field in the surrounding space.*

Following this there was intense experimentation. In 1864, the laws obeyed by electricity and magnetism were unified and formulated by

* See the box in Chapter 1, Page 3.



Moving Charges and
Magnetism

James Maxwell who then realised that light was electromagnetic waves. Radio waves were discovered by Hertz, and produced by J.C. Bose and G. Marconi by the end of the 19th century. A remarkable scientific and technological progress has taken place in the 20th century. This is due to our increased understanding of electromagnetism and the invention of devices for production, amplification, transmission and detection of electromagnetic waves.

FIGURE 4.1 The magnetic field due to a straight long current-carrying wire. The wire is perpendicular to the plane of the paper. A ring of compass needles surrounds the wire. The orientation of the needles is shown when (a) the current emerges out of the plane of the paper, (b) the current moves into the plane of the paper. (c) The arrangement of iron filings around the wire. The darkened ends of the needle represent north poles. The effect of the earth's magnetic field is neglected.

In this chapter, we will see how magnetic field exerts forces on moving charged particles, like electrons,

HANS CHRISTIAN OERSTED

protons, and current-carrying wires. We shall also learn how currents produce magnetic fields. We shall see how particles can be accelerated to very high energies in a

cyclotron. We shall study how currents and voltages are detected by a galvanometer.

In this and subsequent Chapter on magnetism, we adopt the following convention: A current or a field (electric or magnetic) emerging out of the plane of the paper is depicted by a dot (\odot). A current or a field going into the plane of the paper is depicted by a cross (\otimes)*.

Figures. 4.1(a) and 4.1(b) correspond to these two

Hans Christian Oersted

situations, respectively.

(1777–1851) Danish

physicist and chemist,

4.2 MAGNETIC FORCE

professor at Copenhagen.

He observed that a

4.2.1 Sources and fields

(

compass needle suffers a

1777–

Before we introduce the concept of a magnetic field \mathbf{B} , we shall recapitulate what we have learnt in Chapter 1 about electric current. This

1

the electric field \mathbf{E} . We have seen that the interaction discovery gave the first

851

between two charges can be considered in two stages. empirical evidence of a

The charge Q , the source of the field, produces an electric connection between electric

)

field \mathbf{E} , where

and magnetic phenomena.

* A dot appears like the tip of an arrow pointed at you, a cross is like the feathered 133

tail of an arrow moving away from you.



Physics

$$\mathbf{E} = Q \hat{\mathbf{r}} / (4\pi\epsilon) r^2$$

(4.1)

0

where $\hat{\mathbf{r}}$ is unit vector along \mathbf{r} , and the field \mathbf{E} is a vector field. A charge q interacts with this field and experiences a force \mathbf{F} given by

$$\mathbf{F} = q \mathbf{E} = q Q \hat{\mathbf{r}} / (4\pi\epsilon) r^2$$

(4.2)

0

As pointed out in the Chapter 1, the field \mathbf{E} is not just an artefact but has a physical role. It can convey energy and momentum and is not established instantaneously but takes finite time to propagate. The concept of a field was specially stressed by Faraday and was incorporated by Maxwell in his unification of electricity and magnetism. In addition to depending on

)

each point in space, it can also vary with time, i.e., be a

82

Hendrik Antoon Lorentz

function of time. In our discussions in this chapter, we

9

(1853 – 1928) Dutch

will assume that the fields do not change with time.

1

theoretical physicist,

The field at a particular point can be due to one or

professor at Leiden. He

more charges. If there are more charges the fields add

53 –

investigated the

vectorially. You have already learnt in Chapter 1 that this

8

relationship between

is called the principle of superposition. Once the field is

(1

electricity, magnetism, and mechanics. In order to know, the force on a test charge is given by Eq. (4.2). explain the observed effect

Just as static charges produce an electric field, the existence of magnetic fields on currents or moving charges produce (in addition) a magnetic field, denoted by $\mathbf{B}(\mathbf{r})$, again a vector field. It has several basic properties identical to the electric field. It is defined at each point in space (and can in addition depend on time). Experimentally, it is found to obey the principle of superposition: *the magnetic field of several sources is the vector addition of magnetic field of each*

(known after him, as

individual source.

Lorentz transformation

equations) by some tangled

4.2.2 Magnetic Field, Lorentz Force

mathematical arguments,

Let us suppose that there is a point charge q (moving

but he was not aware that

with a velocity \mathbf{v} and, located at \mathbf{r} at a given time t) in these equations hinge on a

HENDRIK ANTOON LORENTZ

presence of both the electric field $\mathbf{E}(\mathbf{r})$ and the magnetic

new concept of space and

field $\mathbf{B}(\mathbf{r})$. The force on an electric charge q due to both of

time.

them can be written as

$$\mathbf{F} = q [\mathbf{E}(\mathbf{r}) + \mathbf{v} \times \mathbf{B}(\mathbf{r})] \equiv \mathbf{F}$$

+ \mathbf{F}

(4.3)

electric

magnetic

This force was given first by H.A. Lorentz based on the extensive experiments of Ampere and others. It is called the *Lorentz force*. You have already studied in detail the force due to the electric field. If we look at the interaction with the magnetic field, we find the following features.

(i) It depends on q , \mathbf{v} and \mathbf{B} (charge of the particle, the velocity and the magnetic field). *Force on a negative charge is opposite to that on a positive charge.*

(ii) The magnetic force $q [\mathbf{v} \times \mathbf{B}]$ includes a vector product of velocity 134 and magnetic field. The vector product makes the force due to magnetic

Moving Charges and

Magnetism

field vanish (become zero) if velocity and magnetic field are parallel or antiparallel. The force acts in a (sideways) direction perpendicular to both the velocity and the magnetic field.

Its direction is given by the screw rule or right hand rule for vector (or cross) product as illustrated in Fig. 4.2.

(iii) The magnetic force is zero if charge is not moving (as then $|\mathbf{v}|=0$). Only a moving charge feels the magnetic force.

The expression for the magnetic force helps us to define the unit of the magnetic field, if one takes q , \mathbf{F} and \mathbf{v} , all to be unity in the force equation $\mathbf{F} = q [\mathbf{v} \times \mathbf{B}] = q v B \sin \theta \hat{\mathbf{n}}$

\mathbf{n}

FIGURE 4.2 The direction of the magnetic

, where θ

force acting on a charged particle. (a) The is the angle between \mathbf{v} and \mathbf{B} [see Fig. 4.2 (a)].

force on a positively charged particle with

The magnitude of magnetic field B is 1 SI unit,

velocity \mathbf{v} and making an angle θ with the

when the force acting on a unit charge (1 C),

magnetic field \mathbf{B} is given by the right-hand

moving perpendicular to \mathbf{B} with a speed 1m/s,

rule. (b) A moving charged particle q is

is one newton.

deflected in an opposite sense to $-q$ in the

Dimensionally, we have $[B] = [F/qv]$ and the unit

presence of magnetic field.

of **B** are Newton second / (coulomb metre). This unit is called *tesla* (T) named after Nikola Tesla (1856 – 1943). Tesla is a rather large unit. A smaller unit (non-SI) called *gauss* (=10⁻⁴ tesla) is also often used. The earth's magnetic field is about 3.6×10^{-5} T. Table 4.1 lists magnetic fields over a wide range in the universe.

TABLE 4.1 ORDER OF MAGNITUDES OF MAGNETIC FIELDS IN A VARIETY OF PHYSICAL SITUATIONS

Physical situation

Magnitude of B (in tesla)

Surface of a neutron star

10⁸

Typical large field in a laboratory

1

Near a small bar magnet

10⁻²

On the earth's surface

10⁻⁵

Human nerve fibre

10⁻¹⁰

Interstellar space

4.2.3 Magnetic force on a current-carrying conductor

We can extend the analysis for force due to magnetic field on a single moving charge to a straight rod carrying current. Consider a rod of a

uniform cross-sectional area A and length l . We shall assume one kind of mobile carriers as in a conductor (here electrons). Let the number density of these mobile charge carriers in it be n . Then the total number of mobile charge carriers in it is nAl . For a steady current I in this

conducting rod, we may assume that each mobile carrier has an average

Physics

drift velocity \mathbf{v} (see Chapter 3). In the presence of an external magnetic field \mathbf{B} , the force on these carriers is:

$$\mathbf{F} = (nAl) q \mathbf{v} \times \mathbf{B}$$

d

where q is the value of the charge on a carrier. Now $nq\mathbf{v}$ is the current density \mathbf{j} and $|(nq\mathbf{v})| A$ is the current I (see Chapter 3 for the discussion of current and current density). Thus,

density \mathbf{j} and $|(nq\mathbf{v})| A$ is the current I (see Chapter 3 for the discussion of current and current density). Thus,

$$\mathbf{F} = [(nq\mathbf{v}) Al] \times \mathbf{B} = [\mathbf{j} Al] \times \mathbf{B}$$

d

$$= I \mathbf{l} \times \mathbf{B}$$

(4.4)

where \mathbf{l} is a vector of magnitude l , the length of the rod, and with a direction identical to the current I . Note that the current I is not a vector. In the last step leading to Eq. (4.4), we have transferred the vector sign from \mathbf{j} to \mathbf{l} .

Equation (4.4) holds for a straight rod. In this equation, \mathbf{B} is the external magnetic field. It is not the field produced by the current-carrying rod. If the wire has an arbitrary shape we can calculate the Lorentz force on it

by considering it as a collection of linear strips $d\mathbf{l}$ and summing

\mathbf{j}

$\mathbf{F} =$

d

I

$\sum \mathbf{l} \times \mathbf{B}$

\mathbf{j}

\mathbf{j}

This summation can be converted to an integral in most cases.

ON PERMITTIVITY AND PERMEABILITY

In the universal law of gravitation, we say that any two point masses exert a force on each other which is proportional to the product of the masses m_1, m_2 and inversely

2

proportional to the square of the distance r between them. We write it as $F = Gm_1 m_2 / r^2$

1

2

where G is the universal constant of gravitation. Similarly in Coulomb's law of electrostatics we write the force between two point charges q_1, q_2 , separated by a distance r as

2

$F = k q_1 q_2 / r^2$ where k is a constant of proportionality. In SI units, k is taken as

$1/4\pi\epsilon_0$ where ϵ_0 is the permittivity of the medium. Also in magnetism, we get another constant, which in SI units, is taken as $\mu_0/4\pi$ where μ_0 is the permeability of the medium.

Although G , ϵ_0 and μ_0 arise as proportionality constants, there is a difference between gravitational force and electromagnetic force. While the gravitational force does not depend on the intervening medium, the electromagnetic force depends on the medium between the two charges or magnets. Hence while G is a universal constant, ϵ_0 and μ_0 depend on the medium. They have different values for different media. The product $\epsilon_0\mu_0$ turns out to be related to the speed v of electromagnetic radiation in the medium through $\epsilon_0\mu_0 = 1/v^2$.

Electric permittivity ϵ_0 is a physical quantity that describes how an electric field affects and is affected by a medium. It is determined by the ability of a material to polarise in response to an applied field, and thereby to cancel, partially, the field inside the material.

Similarly, magnetic permeability μ_0 is the ability of a substance to acquire magnetisation in magnetic fields. It is a measure of the extent to which magnetic field can penetrate matter.

4.1

Example 4.1 A straight wire of mass 200 g and length 1.5 m carries a current of 2 A. It is suspended in mid-air by a uniform horizontal

magnetic field **B** (Fig. 4.3). What is the magnitude of the magnetic

XAMPLE

field?

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E

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FIGURE 4.3

Solution From Eq. (4.4), we find that there is an upward force **F**, of magnitude IlB , . For mid-air suspension, this must be balanced by the force due to gravity:

$$m g = I l B$$

$$m g$$

$$B = I l$$

E

<http://www.phys.hawaii.edu/~teb/optics/java/partmagn/index.html>

Interactive demonstration: Charged particles moving in a magnetic field.

XAMPLE

$$0.2 \times 9.8$$

=

$$= 0.65 \text{ T}$$

$$2 \times 1.5$$

Note that it would have been sufficient to specify m/l , the mass per

4.1

unit length of the wire. The earth's magnetic field is approximately

4×10^{-5} T and we have ignored it.

Example 4.2 If the magnetic field is parallel to the positive y -axis and the charged particle is moving along the positive x -axis (Fig. 4.4), which way would the Lorentz force be for (a) an electron (negative charge), (b) a proton (positive charge).

E

FIGURE 4.4

XAMPLE

Solution The velocity \mathbf{v} of particle is along the x -axis, while \mathbf{B} , the magnetic field is along the y -axis, so $\mathbf{v} \times \mathbf{B}$ is along the z -axis (screw rule or right-hand thumb rule). So, (a) for electron it will be along $-z$ axis. (b) for a positive charge (proton) the force is along $+z$ axis.

4.3 MOTION IN A MAGNETIC FIELD

We will now consider, in greater detail, the motion of a charge moving in a magnetic field. We have learnt in Mechanics (see Class XI book, Chapter 6) that a force on a particle does work if the force has a component along (or opposed to) the direction of motion of the particle. In the case of motion

Physics

of a charge in a magnetic field, the magnetic force is perpendicular to the velocity of the particle. So no work is done and no change in the magnitude of the velocity is produced (though the direction of momentum may be changed). [Notice that this is unlike the force due to an electric field, $q \mathbf{E}$, which *can* have a component parallel (or antiparallel) to motion and thus can transfer energy in addition to momentum.]

We shall consider motion of a charged particle in a *uniform* magnetic field. First consider the case of \mathbf{v} perpendicular to \mathbf{B} .

The perpendicular force, $q \mathbf{v} \times \mathbf{B}$, acts as a centripetal force and produces a circular motion perpendicular to the magnetic field.

The particle will describe a circle if \mathbf{v} and \mathbf{B} are perpendicular to each other (Fig. 4.5).

If velocity has a component along \mathbf{B} , this component

FIGURE 4.5 Circular motion

remains unchanged as the motion along the magnetic field will not be affected by the magnetic field. The motion in a plane perpendicular to \mathbf{B} is as before a circular one, thereby producing a *helical motion* (Fig. 4.6).

You have already learnt in earlier classes

(See Class XI, Chapter 4) that if r is the radius of the circular path of a particle, then a force of $m v^2 / r$, acts perpendicular to the path towards the centre of the circle, and is called the centripetal force. If the velocity \mathbf{v} is perpendicular to the magnetic field \mathbf{B} , the magnetic force is perpendicular to both \mathbf{v} and \mathbf{B} and acts like a centripetal force. It has a magnitude $q v B$. Equating the two expressions for centripetal force,

$$m v^2 / r = q v B, \text{ which gives}$$

$$r = m v / qB$$

(4.5)

FIGURE 4.6 Helical motion

for the radius of the circle described by the charged particle. The larger the momentum, the larger is the radius and bigger the circle described. If ω is the angular frequency, then $v = \omega r$. So,

$$\omega = 2\pi v = q B / m$$

[4.6(a)]

which is independent of the velocity or energy. Here ν is the frequency of rotation. The independence of ν from energy has important application in the design of a cyclotron (see Section 4.4.2).

The time taken for one revolution is $T = 2\pi/\omega \equiv 1/\nu$. If there is a component of the velocity parallel to the magnetic field (denoted by v_{\parallel}), it

||

will make the particle move along the field and the path of the particle would be a helical one (Fig. 4.6). The distance moved along the magnetic field in one rotation is called pitch p . Using Eq. [4.6 (a)], we have $p = v_{\parallel} T = 2\pi m v_{\parallel} / q B$

[4.6(b)]

||

||

The radius of the circular component of motion is called the *radius* of

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the *helix*.

Moving Charges and

Magnetism

Example 4.3 What is the radius of the path of an electron (mass 9×10^{-31} kg and charge 1.6×10^{-19} C) moving at a speed of 3×10^7 m/s in a magnetic field of 6×10^{-4} T perpendicular to it? What is its

frequency? Calculate its energy in keV. ($1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$).

E

Solution Using Eq. (4.5) we find

XAMPLE

$$r = m v / (qB) = 9 \times 10^{-31} \text{ kg} \times 3 \times 10^7 \text{ m s}^{-1} / (1.6 \times 10^{-19} \text{ C} \times 6 \times 10^{-4} \text{ T})$$

$$= 26 \times 10^{-2} \text{ m} = 26 \text{ cm}$$

$$\nu = v / (2 \pi r) = 2 \times 10^6 \text{ s}^{-1} = 2 \times 10^6 \text{ Hz} = 2 \text{ MHz.}$$

4.3

$$E = (\frac{1}{2}) m v^2 = (\frac{1}{2}) 9 \times 10^{-31} \text{ kg} \times 9 \times 10^{14} \text{ m}^2/\text{s}^2 = 40.5 \times 10^{-17} \text{ J}$$

$$\approx 4 \times 10^{-16} \text{ J} = 2.5 \text{ keV.}$$

HELICAL MOTION OF CHARGED PARTICLES AND AURORA BORIOLIS

In polar regions like Alaska and Northern Canada, a splendid display of colours is seen in the sky. The appearance of dancing green pink lights is fascinating, and equally puzzling. An explanation of this natural phenomenon is now found in physics, in terms of what we have studied here.

Consider a charged particle of mass m and charge q , entering a region of magnetic field \mathbf{B} with an initial velocity \mathbf{v} . Let this velocity have a component \mathbf{v} parallel to the magnetic field and a component \mathbf{v} normal to it. There is no force on a charged particle in the

direction of the field. Hence the particle continues to travel with the velocity \mathbf{v} parallel to the

to the field. The normal component v of the particle results in a Lorentz force $(\mathbf{v} \times \mathbf{B}) \cdot \mathbf{n}$

which is perpendicular to both \mathbf{v} and \mathbf{B} . As seen in Section 4.3.1 the particle thus has a

tendency to perform a circular motion in a plane perpendicular to the magnetic field.

When this is coupled with the velocity parallel to the field, the resulting trajectory will be a helix along the magnetic field line, as shown in Figure (a) here. Even if the field line bends, the helically moving particle is trapped and guided to move around the field line.

Since the Lorentz force is normal to the velocity of each point, the field does no work on the particle and the magnitude of velocity remains the same.

During a solar flare, a large number of electrons and protons are ejected from the sun.

Some of them get trapped in the earth's magnetic field and move in helical paths along the field lines. The field lines come closer to each other near the magnetic poles; see figure (b).

Hence the density of charges increases near the poles. These particles collide with atoms and molecules of the atmosphere. Excited oxygen atoms emit green light and excited nitrogen atoms emits pink light. This phenomenon is called *Aurora Boriolis* in physics.

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4.4

MOTION IN COMBINED ELECTRIC AND MAGNETIC FIELDS

4.4.1 Velocity selector

You know that a charge q moving with velocity \mathbf{v} in presence of both electric and magnetic fields experiences a force given by Eq. (4.3), that is, $\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = \mathbf{F}_E + \mathbf{F}_B$

\mathbf{E}

\mathbf{B}

We shall consider the simple case in which electric and magnetic fields are perpendicular to each other and also perpendicular to the velocity of the particle, as shown in Fig. 4.7. We have,

\hat{i}

\hat{j}

\hat{k}

$$\mathbf{E} = E \hat{j}$$

$$\mathbf{B} = B \hat{k} \quad \mathbf{v} = v \hat{i}$$

\hat{i}

$$\mathbf{F}_E = q\mathbf{E} = qE \hat{j} \quad \mathbf{F}_B = q\mathbf{v} \times \mathbf{B} = q(v \hat{i} \times B \hat{k})$$

\hat{i}

$$= qvB \hat{j}$$

\hat{j}

\hat{k}

\hat{k}

$$= -qB \mathbf{j}$$

E

B

Therefore, $\mathbf{F} = q (E - vB) \hat{\mathbf{j}}$

—

\mathbf{j} .

Thus, electric and magnetic forces are in opposite directions as

shown in the figure. Suppose, we adjust the value of \mathbf{E} and \mathbf{B} such that magnitude of the two forces are equal. Then, total force on the charge is zero and the charge will move in the fields undeflected.

FIGURE 4.7

This happens when,

E

$$qE = qvB \text{ or } v =$$

(4.7)

B

This condition can be used to select charged particles of a particular velocity out of a beam containing charges moving with different speeds (irrespective of their charge and mass). The crossed E and B fields, therefore, serve as a *velocity selector*. Only particles with speed E/B pass undeflected through the region of crossed fields. This method was employed by J. J. Thomson in 1897 to measure the charge to mass ratio

(e/m) of an electron. The principle is also employed in Mass Spectrometer

–

a device that separates charged particles, usually ions, according to their charge to mass ratio.

4.4.2 Cyclotron

The cyclotron is a machine to accelerate charged particles or ions to high energies. It was invented by E.O. Lawrence and M.S. Livingston in 1934 to investigate nuclear structure. The cyclotron uses both electric and magnetic fields in combination to increase the energy of charged particles.

As the fields are perpendicular to each other they are called *crossed*

fields. Cyclotron uses the fact that the frequency of revolution of the charged particle in a magnetic field is independent of its energy. The particles move most of the time inside two semicircular disc-like metal

containers, D and D , which are called *dees* as they look like the letter 1

2

Cyclotron

Interactive demonstration:

<http://www.phy.ntnu.edu.tw/ntnujava/viewtopic.php?t=50>

D. Figure 4.8 shows a schematic view of the cyclotron. Inside the metal boxes the particle is shielded and is not acted on by the electric field. The magnetic field, however, acts on the particle and makes it go round in a circular path inside a dee. Every time the particle moves from one dee to another it is acted upon by the electric field. The sign of the electric field is changed alternately in tune with the circular motion of the particle. This ensures that the particle is always accelerated by the electric field.

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Each time the acceleration increases the energy of the particle. As energy

Moving Charges and

Magnetism

increases, the radius of the circular path increases. So the path is a spiral one.

The whole assembly is evacuated to minimise collisions between the ions and the air molecules. A high frequency alternating voltage is applied to the dees. In the sketch shown in Fig. 4.8, positive ions or positively charged particles (e.g., protons) are released at the centre P. They move in a semicircular path in one of the dees and arrive in the gap between

the dees in a time interval $T/2$; where T , the period of revolution, is given by Eq. (4.6),

$$2m$$

$$\pi$$

$$T =$$

$$=$$

$$v$$

$$qB$$

$$c$$

$$qB$$

$$\text{or } v =$$

$$c$$

$$2\pi$$

$$(4.8)$$

$$m$$

This frequency is called the *cyclotron frequency* for obvious reasons and is denoted by ν .

$$c$$

The frequency ν of the applied voltage is adjusted so that the polarity

$$a$$

of the dees is reversed in the same time that it takes the ions to complete

one half of the revolution. The requirement $v = v$ is called the *resonance a*
c

condition. The phase of the supply is adjusted so that when the positive ions arrive at the edge of D , D is at a lower l

2

potential and the ions are accelerated across the gap. Inside the dees the particles travel in a region free of the electric field. The increase in their kinetic energy is qV each time they cross from one dee to another (V refers to the voltage across the dees at that time). From Eq. (4.5), it is clear that the radius of their path goes on increasing each time their kinetic energy increases. The ions are repeatedly accelerated across the dees until they have the required energy to have a radius approximately that of the dees. They are then deflected by a magnetic field and leave the system via an exit slit. From Eq. (4.5) we have,

$$qBR$$

$$v =$$

$$(4.9)$$

m

where R is the radius of the trajectory at exit, and equals the radius of a dee.

Hence, the kinetic energy of the ions is,

FIGURE 4.8 A schematic sketch of the cyclotron. There is a source of charged

2

2

2

1

$q B R$

2

$mv =$

(4.10)

particles or ions at P which move in a

2

2 m

circular fashion in the dees, D_1 and D_2 , on

1

2

account of a uniform perpendicular

The operation of the cyclotron is based on the magnetic field B . An alternating voltage source accelerates these ions to high speeds. The ions are eventually 'extracted'

The cyclotron is used to bombard nuclei with at the exit port.

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energetic particles, so accelerated by it, and study

Physics

the resulting nuclear reactions. It is also used to implant ions into solids and modify their properties or even synthesise new materials. It is used in hospitals to produce radioactive substances which can be used in diagnosis and treatment.

Example 4.4 A cyclotron's oscillator frequency is 10 MHz. What should be the operating magnetic field for accelerating protons? If the radius of its 'dees' is 60 cm, what is the kinetic energy (in MeV) of the proton beam produced by the accelerator.

($e = 1.60 \times 10^{-19}$ C, $m = 1.67 \times 10^{-27}$ kg, $1 \text{ MeV} = 1.6 \times 10^{-13}$ J).

p

Solution The oscillator frequency should be same as proton's cyclotron frequency.

Using Eqs. (4.5) and [4.6(a)] we have

$$B = 2\pi m v / q = 6.3 \times 1.67 \times 10^{-27} \times 10^7 / (1.6 \times 10^{-19}) = 0.66 \text{ T}$$

4.4

Final velocity of protons is

$$v = r \times 2\pi \nu = 0.6 \text{ m} \times 6.3 \times 10^7 = 3.78 \times 10^7 \text{ m/s.}$$

XAMPLE

$$E = \frac{1}{2} m v^2 = 1.67 \times 10^{-27} \times 14.3 \times 10^{14} / (2 \times 1.6 \times 10^{-13}) = 7 \text{ MeV.}$$

E

ACCELERATORS IN INDIA

India has been an early entrant in the area of accelerator-based research. The vision of Dr. Meghnath Saha created a 37" Cyclotron in the Saha Institute of Nuclear Physics in Kolkata in 1953. This was soon followed by a series of Cockroft-Walton type of accelerators established in Tata Institute of Fundamental Research (TIFR), Mumbai, Aligarh Muslim University (AMU), Aligarh, Bose Institute, Kolkata and Andhra University, Waltair.

The sixties saw the commissioning of a number of Van de Graaff accelerators: a 5.5 MV

terminal machine in Bhabha Atomic Research Centre (BARC), Mumbai (1963); a 2 MV terminal machine in Indian Institute of Technology (IIT), Kanpur; a 400 kV terminal machine in Banaras Hindu University (BHU),

Varanasi; and Punjabi University, Patiala. One 66 cm Cyclotron donated by the Rochester University of USA was commissioned in Panjab University, Chandigarh. A small electron accelerator was also established in University of Pune, Pune.

In a major initiative taken in the seventies and eighties, a Variable Energy Cyclotron was built indigenously in Variable Energy Cyclotron Centre (VECC), Kolkata; 2 MV Tandem Van de Graaff accelerator was developed and built in BARC and a 14 MV Tandem Pelletron accelerator was installed in TIFR.

This was soon followed by a 15 MV Tandem Pelletron established by University Grants Commission (UGC), as an inter-university facility in Inter-University Accelerator Centre (IUAC), New Delhi; a 3 MV Tandem Pelletron in Institute of Physics, Bhubaneswar; and two 1.7 MV Tandetrans in Atomic Minerals Directorate for Exploration and Research, Hyderabad and Indira Gandhi Centre for Atomic Research, Kalpakkam. Both TIFR and IUAC are augmenting their facilities with the addition of superconducting LINAC modules to accelerate the ions to higher energies.

Besides these ion accelerators, the Department of Atomic Energy (DAE) has developed many electron accelerators. A 2 GeV Synchrotron Radiation Source is being built in Raja Ramanna Centre for Advanced Technologies, Indore.

The Department of Atomic Energy is considering Accelerator Driven Systems (ADS) for power production and fissile material breeding as future options.

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Magnetism

4.5

MAGNETIC FIELD DUE TO A CURRENT ELEMENT,

BIOT-SAVART LAW

All magnetic fields that we know are due to currents (or moving charges) and due to intrinsic magnetic moments of particles. Here, we shall study the relation between current and the magnetic field it produces.

It is given by the Biot-Savart's law. Figure 4.9 shows a finite conductor XY carrying current I . Consider an infinitesimal

element $d l$ of the conductor. The magnetic field $d\mathbf{B}$ due to this element is to be determined at a point P which is at a distance r from it. Let θ be the angle between $d\mathbf{l}$ and the displacement vector

\mathbf{r} . According to Biot-Savart's law, the magnitude of the magnetic

field $d\mathbf{B}$ is proportional to the current I , the element length $|d\mathbf{l}|$, and inversely proportional to the square of the distance r . Its direction* is perpendicular to the plane containing $d\mathbf{l}$ and \mathbf{r} .

Thus, in vector notation,

$$I d \times$$

$$d$$

$$\propto$$

$$l$$

$$r$$

$$\mathbf{B}$$

$$3$$

$$r$$

FIGURE 4.9 Illustration of

μ

the Biot-Savart law. The

$I d\mathbf{l} \times \mathbf{r}$

0

=

current element $I d\mathbf{l}$

3

[4.11(a)]

4π

r

produces a field $d\mathbf{B}$ at a

where $\mu / 4\pi$ is a constant of proportionality. The above

distance r . The \otimes sign

0

expression holds when the medium is vacuum.

indicates that the

The magnitude of this field is,

field is perpendicular

to the plane of this

$$\mu I d l \sin\theta$$

0

page and directed

$$d\mathbf{B} =$$

2

$$[4.11(b)]$$

$$4\pi$$

r

into it.

where we have used the property of cross-product. Equation [4.11 (a)]

constitutes our basic equation for the magnetic field. The proportionality

constant in SI units has the exact value,

$$\mu_0$$

7

10-

=

$$\text{Tm/A}$$

$$4\pi$$

$$[4.11(c)]$$

We call μ the *permeability* of free space (or vacuum).

0

The Biot-Savart law for the magnetic field has certain similarities as well as differences with the Coulomb's law for the electrostatic field. Some of these are:

(i) Both are long range, since both depend inversely on the square of distance from the source to the point of interest. The principle of superposition applies to both fields. [In this connection, note that the magnetic field is *linear* in the *source* $I d\mathbf{l}$ just as the electrostatic field is linear in its source: the electric charge.]

(ii) The electrostatic field is produced by a scalar source, namely, the electric charge. The magnetic field is produced by a vector source $I d\mathbf{l}$.

* The sense of $d\mathbf{l} \times \mathbf{r}$ is also given by the *Right Hand Screw rule* : Look at the plane containing vectors $d\mathbf{l}$ and \mathbf{r} . Imagine moving from the first vector towards second vector. If the movement is anticlockwise, the resultant is towards you. If it is

clockwise, the resultant is away from you.

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(iii) The electrostatic field is along the displacement vector joining the source and the field point. The magnetic field is perpendicular to the plane containing the displacement vector \mathbf{r} and the current element

$I d\mathbf{l}$.

(iv) There is an angle dependence in the Biot-Savart law which is not present in the electrostatic case. In Fig. 4.9, the magnetic field at any point in the direction of $d\mathbf{l}$ (the dashed line) is zero. Along this line, $\theta = 0$, $\sin \theta = 0$ and from Eq. [4.11(a)], $|d\mathbf{B}| = 0$.

There is an interesting relation between ϵ_0 , the permittivity of free space;

μ_0 , the permeability of free space; and c , the speed of light in vacuum:

$$\frac{1}{\epsilon_0 \mu_0} = c^2$$

7

=

10-

=

=

0

0

0

9

()

4π

9×10

8 2

2

(3×10)

c

We will discuss this connection further in Chapter 8 on the electromagnetic waves. Since the speed of light in vacuum is constant, the product $\mu \epsilon$ is fixed in magnitude. Choosing the value of either ϵ or

ϵ_0

ϵ_0

μ_0 , fixes the value of the other. In SI units, μ_0 is fixed to

ϵ_0

ϵ_0

be equal to

$4\pi \times 10^{-7}$ in magnitude.

Example 4.5 An element

^

$\Delta l = x$

Δl is placed at the origin and carries

a large current $I = 10$ A (Fig. 4.10). What is the magnetic field on the y -axis at a distance of 0.5 m. $\Delta x = 1$ cm.

FIGURE 4.10

Solution

$\mu I d l \sin \theta$

0

$|\mathbf{dB}| =$

2

[using Eq. (4.11)]

4π

r

-2

T m

$d l = x$

$\Delta = 10 \text{ m}, I = 10 \text{ A}, r = 0.5 \text{ m} = y,$

7

$\mu / 4$

10-

$\pi =$

0

A

$\theta = 90^\circ ; \sin \theta = 1$

7

-

2

10

$\times 10 \times 10^{-}$

$d\mathbf{B} =$

—

$= 4 \times 10^{-8} \text{ T}$

2

25×10

The direction of the field is in the + z-direction. This is so since,

^

^

$d\mathbf{l} \times$

^

^

$\mathbf{r} = x$

$\Delta \mathbf{i} \times y \mathbf{j} = y x$

$\Delta (\mathbf{i} \times \mathbf{j})$

^

$= y x$

$\Delta \mathbf{k}$

4.5

We remind you of the following cyclic property of cross-products,

^

^

^^

^

^^

^

^

$$\mathbf{i} \times \mathbf{j} = \mathbf{k} ; \mathbf{j} \times \mathbf{k} = \mathbf{i}; \mathbf{k} \times \mathbf{i} = \mathbf{j} \text{ XAMPLE}$$

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E

Note that the field is small in magnitude.

Moving Charges and

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In the next section, we shall use the Biot-Savart law to calculate the magnetic field due to a circular loop.

4.6 MAGNETIC FIELD ON THE AXIS OF A CIRCULAR CURRENT LOOP

In this section, we shall evaluate the magnetic field due to a circular coil along its axis. The evaluation entails summing up the effect of infinitesimal

current elements ($I d\mathbf{l}$) mentioned in the previous section.

We assume that the current I is steady and that the evaluation is carried out in free space (i.e., vacuum).

Figure 4.11 depicts a circular loop carrying a steady current I . The loop is placed in the y - z plane with its centre at the origin O and has a radius R . The x -axis is the axis of the loop. We wish to calculate the magnetic field at the point P on this axis. Let x be the distance of P from the centre O of the loop.

Consider a conducting element $d\mathbf{l}$ of the loop. This is shown in Fig. 4.11. The magnitude $d B$ of the magnetic field due to $d \mathbf{l}$ is given by the Biot-Savart law [Eq. 4.11(a)],

$$\mu I d$$

$$0$$

$$dB =$$

$$\mathbf{l} \times \mathbf{r}$$

$$(4.12)$$

$$3$$

$$4\pi$$

$$r$$

FIGURE 4.11 Magnetic field on the

Now $r^2 = x^2 + R^2$. Further, any element of the loop

axis of a current carrying circular

will be perpendicular to the displacement vector from

loop of radius R . Shown are the

the element to the axial point. For example, the element

magnetic field $d\mathbf{B}$ (due to a line

$d\mathbf{l}$ in Fig. 4.11 is in the y - z plane whereas the

element $d\mathbf{l}$) and its

displacement vector \mathbf{r} from $d\mathbf{l}$ to the axial point P is in

components along and

the x - y plane. Hence $|d\mathbf{l} \times \mathbf{r}| = r dl$. Thus, perpendicular to the axis.

μ

d

$I l$

0

$d B =$

$4\pi (2$

2

$x + R)$

(4.13)

The direction of $d\mathbf{B}$ is shown in Fig. 4.11. It is perpendicular to the plane formed by $d\mathbf{l}$ and \mathbf{r} . It has an x -component $d\mathbf{B}$ and a component x perpendicular to x -axis, $d\mathbf{B}_\perp$. When the components perpendicular to the x -axis are summed over, they cancel out and we obtain a null result.

For example, the $d\mathbf{B}_\perp$ component due to $d\mathbf{l}$ is cancelled by the contribution due to the diametrically opposite $d\mathbf{l}$ element, shown in Fig. 4.11. Thus, only the x -component survives. The net contribution along x -direction can be obtained by integrating $d B = d B \cos \theta$ over the x loop. For Fig. 4.11,

R

$\cos\theta =$

2

$2 \ 1/ 2$

$(x +$

(4.14)

$R)$

From Eqs. (4.13) and (4.14),

μd

dl

R

0

$dB =$

x

4π

$3/2$

2

2

145

$(x + R)$

Physics

The summation of elements dl over the loop yields $2\pi R$, the circumference of the loop. Thus, the magnetic field at P due to entire circular loop is

2

μIR

0

\hat{z}

\hat{z}

$$\mathbf{B} = B \mathbf{i} =$$

$$\mathbf{i}$$

$$x$$

$$(4.15)$$

$$2 (x + R)^{3/2}$$

$$2$$

$$2$$

As a special case of the above result, we may obtain the field at the centre of the loop. Here $x = 0$, and we obtain,

$$\mu I$$

$$0$$

$$\hat{\mathbf{i}}$$

$$\mathbf{B} =$$

$$\mathbf{i}$$

$$0$$

$$(4.16)$$

$$2 R$$

The magnetic field lines due to a circular wire form closed loops and are shown in Fig. 4.12. The direction of the magnetic field is given by (another) *right-hand thumb rule* stated below:

Curl the palm of your right hand around the circular wire with the fingers pointing in the direction of the current. The right-hand thumb gives the direction of the magnetic field.

FIGURE 4.12 The magnetic field lines for a current loop. The direction of the field is given by the right-hand thumb rule described in the text. The upper side of the loop may be thought of as the north pole and the lower side as the south pole of a magnet.

Example 4.6 A straight wire carrying a current of 12 A is bent into a semicircular arc of radius 2.0 cm as shown in Fig. 4.13(a). Consider the magnetic field \mathbf{B} at the centre of the arc. (a) What is the magnetic field due to the straight segments? (b) In what way the contribution to \mathbf{B} from the semicircle differs from that of a circular loop and in what way does it resemble? (c) Would your answer be different if the wire were bent into a semicircular arc of the same radius but in the opposite way as shown in Fig. 4.13(b)?

4.6

XAMPLE

146

E

FIGURE 4.13

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Magnetism

Solution

(a) $d\mathbf{l}$ and \mathbf{r} for each element of the straight segments are parallel.

Therefore, $d\mathbf{l} \times \mathbf{r} = 0$. Straight segments do not contribute to $|\mathbf{B}|$.

(b) For all segments of the semicircular arc, $d\mathbf{l} \times \mathbf{r}$ are all parallel to \mathbf{E} each other (into the plane of the paper). All such contributions

XAMPLE

add up in magnitude. Hence direction of \mathbf{B} for a semicircular arc is given by the right-hand rule and magnitude is half that of a circular loop. Thus \mathbf{B} is 1.9×10^{-4} T normal to the plane of the

4.6

paper going into it.

(c) Same magnitude of \mathbf{B} but opposite in direction to that in (b).

Example 4.7 Consider a tightly wound 100 turn coil of radius 10 cm, carrying a current of 1 A. What is the magnitude of the magnetic field at the centre of the coil?

E

Solution Since the coil is tightly wound, we may take each circular element to have the same radius $R = 10 \text{ cm} = 0.1 \text{ m}$. The number of

XAMPLE

turns $N = 100$. The magnitude of the magnetic field is,

-7

2

μNI

$4\pi \times 10$

$\times 10 \times 1$

4.7

0

$B =$

$=$

4

$-$

$=$

\times

-1

2

$10-$

$= \pi \times$

4

62

.810

T

2R

2×10

4.7 AMPERE'S CIRCUITAL LAW

There is an alternative and appealing way in which the Biot-Savart law may be expressed. Ampere's circuital law considers an open surface with a boundary (Fig. 4.14). The surface has current passing through it. We consider the boundary to be made up of a number of small line elements. Consider one such element of length dl . We take the value of the tangential component of the magnetic field, B_t , at this element and multiply it by the length of that element dl [Note: $\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I$]. All such products are added together. We consider the limit as the lengths of elements get smaller and their number gets larger. The sum then tends to an integral. Ampere's law states that this integral is equal to μ_0 times the total current

0

FIGURE 4.14

passing through the surface, i.e.,

d

$$g = \mu I$$

$$\oint \mathbf{B} \cdot d\mathbf{l} = \mu I$$

\tilde{N}

[4.17(a)]

where I is the total current through the surface. The integral is taken over the closed loop coinciding with the boundary C of the surface. The relation above involves a sign-convention, given by the right-hand rule.

Let the fingers of the right-hand be curled in the sense the boundary is

traversed in the loop integral " $\mathbf{B} \cdot d\mathbf{l}$ ". Then the direction of the thumb gives the sense in which the current I is regarded as positive.

For several applications, a much simplified version of Eq. [4.17(a)]

proves sufficient. We shall assume that, in such cases, it is possible to

choose the loop (called an *amperian loop*) such that at each point of the 147

loop, *either*



Physics

(i)

\mathbf{B} is tangential to the loop and is a nonzero *constant*

\mathbf{B} , *or*

(ii) \mathbf{B} is normal to the loop, *or*

(iii) \mathbf{B} vanishes.

Now, let L be the length (part) of the loop for which \mathbf{B} is tangential. Let I be the current enclosed by the loop.

e

Then, Eq. (4.17) reduces to,

$$BL = \mu I$$

[4.17(b)]

$0 e$

When there is a system with a symmetry such as for a *straight infinite current-carrying wire* in Fig. 4.15, the Ampere's law enables an easy evaluation of the magnetic field, much the same way Gauss' law helps in determination of the electric field. This is exhibited in the Example 4.8 below. The boundary of the loop chosen is

Andre Ampere (1775 –

1836) Andre Marie Ampere

a circle and magnetic field is tangential to the
was a French physicist,
circumference of the circle. The law gives, for the left hand
mathematician and
side of Eq. [4.17 (b)], $B \cdot 2\pi r$. We find that the magnetic
chemist who founded the
field at a distance r outside the wire is *tangential* and
science of electrodynamics.

given by

Ampere was a child prodigy

who mastered advanced

$$B \times 2\pi r = \mu I,$$

0

mathematics by the age of

$$B = \mu I / (2\pi r)$$

(4.18)

0

12. Ampere grasped the

significance of Oersted's

The above result for the infinite wire is interesting

discovery. He carried out a
from several points of view.

large series of experiments

(i) It implies that the field at every point on a circle of

to explore the relationship

radius r , (with the wire along the axis), is same in

between current electricity

magnitude. In other words, the magnetic field

and magnetism. These

possesses what is called a *cylindrical symmetry*. The

investigations culminated

field that normally can depend on three coordinates

)

in 1827 with the

depends only on one: r . Whenever there is symmetry,

publication of the

the solutions simplify.

‘Mathematical Theory of

(ii) The field direction at any point on this circle is

Electrodynamic Phenomena Deduced Solely from

tangential to it. Thus, the lines of constant magnitude

Experiments'. He hypo—

of magnetic field form concentric circles. Notice now,

thesised that *all* magnetic

in Fig. 4.1(c), the iron filings form concentric circles.

(1775 –1836

phenomena are due to

These lines called *magnetic field lines* form closed

circulating electric

loops. This is unlike the electrostatic field lines which

currents. Ampere was

originate from positive charges and end at negative

charges. The expression for the magnetic field of a

straight wire provides a theoretical justification to

invitations to dine with the

Oersted's experiments.

Emperor Napoleon. He died

of pneumonia at the age of

(iii) Another interesting point to note is that even though

61. His gravestone bears

the wire is infinite, the field due to it at a nonzero

ANDRE AMPERE

the epitaph: *Tandem Felix*

distance is *not* infinite. It tends to blow up only when

(Happy at last).

we come very close to the wire. The field is directly

proportional to the current and inversely proportional

to the distance from the (infinitely long) current

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source.

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Magnetism

(iv) There exists a simple rule to determine the direction of the magnetic

field due to a long wire. This rule, called the *right-hand rule**, is: *Grasp the wire in your right hand with your extended thumb pointing in the direction of the current. Your fingers will curl around in the*

direction of the magnetic field.

Ampere's circuital law is not new in content from Biot-Savart law.

Both relate the magnetic field and the current, and both express the same

physical consequences of a steady electrical current. Ampere's law is to Biot-Savart law, what Gauss's law is to Coulomb's law. Both, Ampere's and Gauss's law relate a physical quantity on the periphery or boundary (magnetic or electric field) to another physical quantity, namely, the source, in the interior (current or charge). We also note that Ampere's circuital law holds for steady currents which do not fluctuate with time. The following example will help us understand what is meant by the term *enclosed* current.

Example 4.8 Figure 4.15 shows a long straight wire of a circular cross-section (radius a) carrying steady current I . The current I is uniformly distributed across this cross-section. Calculate the magnetic field in the region $r < a$ and $r > a$.

FIGURE 4.15

Solution (a) Consider the case $r > a$. The Amperian loop, labelled 2, is a circle concentric with the cross-section. For this loop, $L = 2 \pi r$

$$I = \text{Current enclosed by the loop} = I$$

e

The result is the familiar expression for a long straight wire

$$B (2\pi r) = \mu I$$

0

$$\mu I$$

0

$B =$

[4.19(a)]

$2 \delta r$

E

1

XAMPLE

$B \propto$

$(r > a)$

r

(b) Consider the case $r < a$. The Amperian loop is a circle labelled 1.

4.8

For this loop, taking the radius of the circle to be r ,

$L = 2 \pi r$

* Note that there are *two distinct* right-hand rules: One which gives the direction of **B** on the axis of current-loop and the other which gives direction of **B**

for a straight conducting wire. Fingers and thumb play different roles in

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the two.

Physics

Now the current enclosed I is not I , but is less than this value.

e

Since the current distribution is uniform, the current enclosed is,

2

πr

2

$I r$

$I = I$

=

e

2

πa

2

a

2

$I r$

Using Ampere's law, $B (2 \delta r) = \mu_0$

2

a

$$B = \frac{\mu_0 I}{2\pi a^2} r^2 \quad (r < a)$$

[4.19(b)]

$$B \propto r \quad (r < a)$$

FIGURE 4.16

Figure (4.16) shows a plot of the magnitude of **B** with distance *r* from the centre of the wire. The direction of the field is tangential to

4.8

the respective circular loop (1 or 2) and given by the right-hand rule described earlier in this section.

This example possesses the required symmetry so that Ampere's

EXAMPLE

E

law can be applied readily.

It should be noted that while Ampere's circuital law holds for any loop, it may not always facilitate an evaluation of the magnetic field in

every case. For example, for the case of the circular loop discussed in Section 4.6, it cannot be applied to extract the simple expression $B = \mu I/2R$ [Eq. (4.16)] for the field at the centre of the loop. However, there exists a large number of situations of high symmetry where the law can be conveniently applied. We shall use it in the next section to calculate the magnetic field produced by two commonly used and very useful magnetic systems: the *solenoid* and the *toroid*.

4.8 THE SOLENOID AND THE TOROID

The solenoid and the toroid are two pieces of equipment which generate magnetic fields. The television uses the solenoid to generate magnetic fields needed. The synchrotron uses a combination of both to generate the high magnetic fields required. In both, solenoid and toroid, we come across a situation of high symmetry where Ampere's law can be

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conveniently applied.

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4.8.1 The solenoid

We shall discuss a long solenoid. By long solenoid we mean that the solenoid's length is large compared to its radius. It consists of a long

wire wound in the form of a helix where the neighbouring turns are closely spaced. So each turn can be regarded as a circular loop. The net magnetic field is the vector sum of the fields due to all the turns. Enamelled wires are used for winding so that turns are insulated from each other.

FIGURE 4.17 (a) The magnetic field due to a section of the solenoid which has been stretched out for clarity. Only the exterior semicircular part is shown. Notice how the circular loops between neighbouring turns tend to cancel.

(b) The magnetic field of a finite solenoid.

Figure 4.17 displays the magnetic field lines for a finite solenoid. We show a section of this solenoid in an enlarged manner in Fig. 4.17(a).

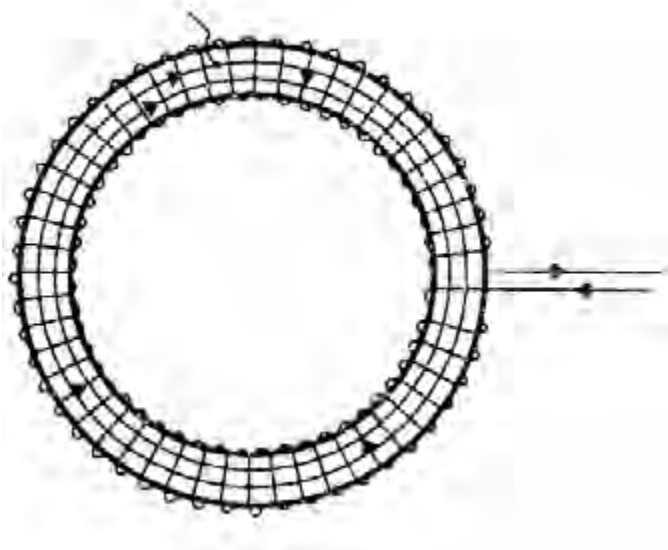
Figure 4.17(b) shows the entire finite solenoid with its magnetic field. In Fig. 4.17(a), it is clear from the circular loops that the field between two neighbouring turns vanishes. In Fig. 4.17(b), we see that the field at the interior midpoint P is uniform, strong and along the axis of the solenoid. The field at the exterior midpoint Q is weak and moreover is along the axis of the solenoid with no perpendicular or normal component. As the solenoid is made longer it appears like a long cylindrical metal sheet.

Figure 4.18 represents this idealised picture. The field outside the solenoid approaches zero. We shall assume that the field outside is zero. The field inside becomes everywhere parallel to the axis.

FIGURE 4.18 The magnetic field of a very long solenoid. We consider a

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rectangular Amperian loop abcd to determine the field.



Physics

Consider a rectangular Amperian loop abcd. Along cd the field is zero as argued above. Along transverse sections bc and ad, the field component is zero. Thus, these two sections make no contribution. Let the field along ab be B . Thus, the relevant length of the Amperian loop is, $L = h$.

Let n be the number of turns per unit length, then the total number

of turns is nh . The enclosed current is, $I_e = I (n h)$, where I is the current in the solenoid. From Ampere's circuital law [Eq. 4.17 (b)]

$$BL = \mu I, B h = \mu I (n h)$$

0 e

0

$$B = \mu n I$$

(4.20)

0

The direction of the field is given by the right-hand rule. The solenoid is commonly used to obtain a uniform magnetic field. We shall see in the next chapter that a large field is possible by inserting a soft iron core inside the solenoid.

4.8.2 The toroid

The toroid is a hollow circular ring on which a large number of turns of a wire are closely wound. It can be viewed as a solenoid which has been bent into a circular shape to close on itself. It is shown in Fig. 4.19(a) carrying a current I . We shall see that the magnetic field in the open space inside (point P) and exterior to the toroid (point Q) is zero. The field \mathbf{B} inside the toroid is constant in magnitude for the *ideal* toroid of closely wound turns.

Figure 4.19(b) shows a sectional view of the toroid. The direction of the magnetic field inside is clockwise as per the right-hand thumb rule for circular loops. Three circular

Amperian loops 1, 2 and 3 are shown by dashed lines. By symmetry, the magnetic field should be tangential to each of them and constant in magnitude for a given loop. The circular areas bounded by loops 2 and 3 both cut the toroid: so that each turn of current carrying wire is cut once by the loop 2 and twice by the loop 3.

Let the magnetic field along loop 1 be B in magnitude.

1

Then in Ampere's circuital law [Eq. 4.17(a)], $L = 2\pi r$.

1

However, the loop encloses no current, so $I = 0$. Thus,

e

$$B (2 \pi r) = \mu (0), B = 0$$

1

1

0

1

FIGURE 4.19 (a) A toroid carrying

Thus, the magnetic field at any point P in the open space a current I . (b) A sectional view of

inside the toroid is zero.

the toroid. The magnetic field can

We shall now show that magnetic field at Q is likewise

be obtained at an arbitrary

zero. Let the magnetic field along loop 3 be B . Once again

distance r from the centre O of

3

from Ampere's law $L = 2$

the toroid by Ampere's circuital

πr . However, from the sectional

3

law. The dashed lines labelled

cut, we see that the current coming out of the plane of the

1, 2 and 3 are three circular

paper is cancelled exactly by the current going into it. Thus,

Amperian loops.

$I = 0$, and $B = 0$. Let the magnetic field inside the solenoid

e

3

be B . We shall now consider the magnetic field at S. Once again we employ Ampere's law in the form of Eq. [4.17 (a)]. We find, $L = 2\pi r$.

The current enclosed I is (for N turns of toroidal coil) NI .

e

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$$B(2\pi r) = \mu NI$$

0

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Magnetism

$$\mu NI$$

0

$$B = \frac{\mu NI}{2\pi r}$$

π

(4.21)

We shall now compare the two results: for a toroid and solenoid. We

re-express Eq. (4.21) to make the comparison easier with the solenoid

result given in Eq. (4.20). Let r be the average radius of the toroid and n be the number of turns per unit length. Then $N = 2\pi r n =$ *(average) perimeter of the toroid*

\times *number of turns per unit length*

and thus,

$$B = \mu$$

$$2\pi r n I,$$

(4.22)

i.e., the result for the solenoid!

In an ideal toroid the coils are circular. In reality the turns of the toroidal coil form a helix and there is always a small magnetic field external to the toroid.

MAGNETIC CONFINEMENT

We have seen in Section 4.3 (see also the box on helical motion of charged particles earlier in this chapter) that orbits of charged particles are helical. If the magnetic field is nonuniform, but does not change much during one circular orbit, then the radius of the helix will decrease as it enters stronger magnetic field and the radius will increase when it enters weaker magnetic fields. We consider two solenoids at a distance from each other, enclosed in an evacuated container (see figure below where we have not shown the container).

Charged particles moving in the region between the two solenoids will start with a small radius. The radius will increase as field decreases and the radius will decrease again as field due to the second solenoid takes over. The solenoids act as a mirror or reflector. [See the direction of \mathbf{F} as the particle approaches coil 2 in the figure. It has a horizontal component against the forward motion.] This makes the particles turn back when they approach the solenoid. Such an arrangement will act like *magnetic bottle* or magnetic container. The particles will never touch the sides of the container. Such magnetic bottles are of great use in confining the high energy plasma in fusion experiments. The plasma will destroy any other form of material container because of its high temperature. Another useful container is a toroid. Toroids are expected to play a key role in the *tokamak*, an equipment for plasma confinement in fusion power reactors. There is an international collaboration called the *International Thermonuclear Experimental Reactor* (ITER), being set up in France, for achieving controlled fusion, of which India is a collaborating nation. For details of ITER

collaboration and the project, you may visit <http://www.iter.org>.

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Example 4.9 A solenoid of length 0.5 m has a radius of 1 cm and is made up of 500 turns. It carries a current of 5 A. What is the magnitude of the magnetic field inside the solenoid?

Solution The number of turns per unit length is,

500

$n =$

$= 1000 \text{ turns/m}$

0.5

4.9

The length $l = 0.5 \text{ m}$ and radius $r = 0.01 \text{ m}$. Thus, $l/a = 50$ i.e., $l \gg a$.

Hence, we can use the *long* solenoid formula, namely, Eq. (4.20)

$$B = \mu n I$$

0

XAMPLE

$$= 4\pi \times 10^{-7} \times 103 \times 5$$

E

$$= 6.28 \times 10^{-3} \text{ T}$$

4.9 FORCE BETWEEN TWO PARALLEL CURRENTS, THE AMPERE

We have learnt that there exists a magnetic field due to a conductor carrying a current which obeys the Biot-Savart law. Further, we have learnt that an external magnetic field will exert a force on a current-carrying conductor. This follows from the Lorentz force formula. Thus, it is logical to expect that two current-carrying conductors placed near each other will exert (magnetic) forces on each other. In the period 1820-25, Ampere studied the nature of this magnetic force and its dependence on the magnitude of the current, on the shape and size of the conductors as well as the distances between the conductors. In this section, we shall take the simple example of two parallel current-carrying conductors, which will perhaps help us to appreciate Ampere's painstaking work.

Figure 4.20 shows two long parallel conductors a

FIGURE 4.20 Two long straight

and b separated by a distance d and carrying (parallel)

parallel conductors carrying steady

currents I and I , respectively. The conductor 'a'

currents I and I and separated by a

a

b

a

b

distance d . \mathbf{B} is the magnetic field set

produces, the same magnetic field \mathbf{B} at all points along

a

a

up by conductor 'a' at conductor 'b'.

the conductor 'b'. The right-hand rule tells us that the

direction of this field is downwards (when the conductors

are placed horizontally). Its magnitude is given by Eq. [4.19(a)] or from

Ampere's circuital law,

μI

$0 a$

$B =$

a

$2 \pi d$

The conductor 'b' carrying a current I will experience a sideways

b

force due to the field \mathbf{B} . The direction of this force is towards the

a

conductor 'a' (Verify this). We label this force as \mathbf{F} , the force on a

ba

segment L of 'b' due to 'a'. The magnitude of this force is given by

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Eq. (4.4),

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Magnetism

$$F = I L B$$

ba

b

a

$$\mu I I$$

0

a

b

=

L

2π

(4.23)

d

It is of course possible to compute the force on 'a' due to 'b'. From considerations similar to above we can find the force \mathbf{F} , on a segment of length L of 'a' due to the current in 'b'. It is equal in magnitude to F , ba and directed towards 'b'. Thus,

$$\mathbf{F} = -\mathbf{F}$$

(4.24)

ba

ab

Note that this is consistent with Newton's third Law. Thus, at least for parallel conductors and steady currents, we have shown that the Biot-Savart law and the Lorentz force yield results in accordance with Newton's third Law*.

We have seen from above that currents flowing in the same direction attract each other. One can show that oppositely directed currents repel each other. Thus,

Parallel currents attract, and antiparallel currents repel.

This rule is the opposite of what we find in electrostatics. Like (same

sign) charges repel each other, but like (parallel) currents attract each other.

Let f represent the magnitude of the force \mathbf{F} per unit length. Then, f

from Eq. (4.23),

$$\mu I I$$

$$0 a b$$

$$f$$

$$=$$

$$ba$$

$$(4.25)$$

$$2 \delta d$$

The above expression is used to define the ampere (A), which is one of the seven SI base units.

The *ampere* is the value of that steady current which, when maintained in each of the two very long, straight, parallel conductors of negligible cross-section, and placed one metre apart in vacuum, would produce on each of these conductors a force equal to 2×10^{-7} newtons per metre of length.

This definition of the ampere was adopted in 1946. It is a theoretical

definition. In practice one must eliminate the effect of the earth's magnetic field and substitute very long wires by multiturn coils of appropriate geometries. An instrument called the current balance is used to measure this mechanical force.

The SI unit of charge, namely, the coulomb, can now be defined in terms of the ampere.

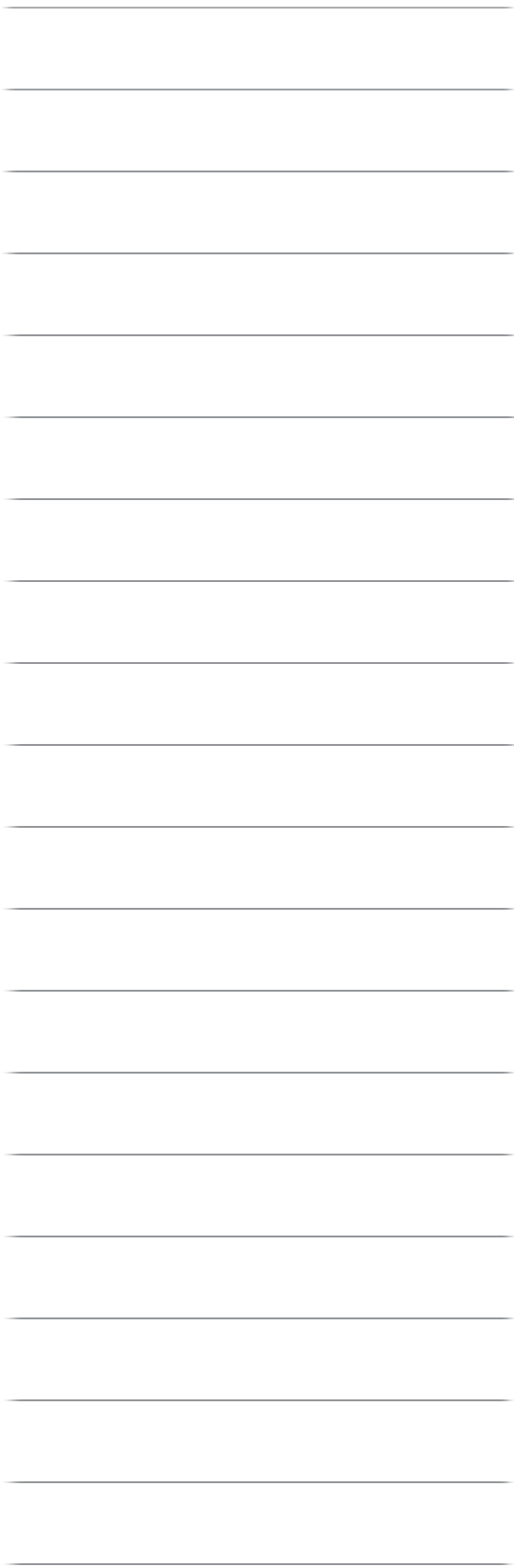
When a steady current of 1A is set up in a conductor, the quantity of charge that flows through its cross-section in 1s is one coulomb (1C).

* It turns out that when we have time-dependent currents and/or charges in motion, Newton's third law may not hold for forces between charges and/or conductors. An essential consequence of the Newton's third law in mechanics

is conservation of momentum of an isolated system. This, however, holds even

for the case of time-dependent situations with electromagnetic fields, provided 155

the momentum carried by fields is also taken into account.



Take a soft spring whose natural period of oscillations is about 0.5 – 1s. Hang it vertically and attach a pointed tip to its lower end, as shown in the figure here. Take some mercury in a dish and adjust the spring such that the tip is just above the mercury surface. Take the DC current source, connect one of its terminals to the upper end of the spring, and dip the other terminal in mercury. If the tip of the spring touches mercury, the circuit is completed through mercury.

Let the DC source be put off to begin with. Let the tip be adjusted so that it just touches the mercury surface. Switch on the constant current supply, and watch the fascinating outcome. The spring shrinks with a jerk, the tip comes out of mercury (just by a mm or so), the circuit is broken, the current stops, the spring relaxes and tries to come back to its original position, the tip again touches mercury establishing a current in the circuit, and the cycle continues with tick, tick, tick, In the beginning, you may require some small adjustments to get a good effect.

Keep your face away from mercury vapours as they are poisonous. Do not inhale

mercury vapours for long.

Example 4.10 The horizontal component of the earth's magnetic field at a certain place is 3.0×10^{-5} T and the direction of the field is from the geographic south to the geographic north. A very long straight conductor is carrying a steady current of 1A. What is the force per

unit length on it when it is placed on a horizontal table and the direction of the current is (a) east to west; (b) south to north?

Solution $\mathbf{F} = I \mathbf{l} \times \mathbf{B}$

$$F = IlB \sin\theta$$

The force per unit length is

$$f = F/l = IB \sin\theta$$

4.10

(a) When the current is flowing from east to west,

$$\theta = 90^\circ$$

Hence,

XAMPLE

$$f = IB$$

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E

$$= 1 \times 3 \times 10^{-5} = 3 \times 10^{-5} \text{ N m}^{-1}$$

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This is larger than the value $2 \times 10^{-7} \text{ Nm}^{-1}$ quoted in the definition of the ampere. Hence it is important to eliminate the effect of the earth's magnetic field and other stray fields while standardising

the ampere.

E

The direction of the force is downwards. This direction may be

XAMPLE

obtained by the directional property of cross product of vectors.

(b) When the current is flowing from south to north,

4.10

$$\theta = 0^\circ$$

$$f = 0$$

Hence there is no force on the conductor.

4.10 TORQUE ON CURRENT LOOP, MAGNETIC DIPOLE

4.10.1 Torque on a rectangular current loop in a uniform

magnetic field

We now show that a rectangular loop carrying a steady current I and

placed in a uniform magnetic field experiences a torque. It does not

experience a net force. This behaviour is analogous to

that of electric dipole in a uniform electric field

(Section 1.10).

We first consider the simple case when the

rectangular loop is placed such that the uniform

magnetic field \mathbf{B} is in the plane of the loop. This is illustrated in Fig. 4.21(a).

The field exerts no force on the two arms AD and BC of the loop. It is perpendicular to the arm AB of the loop and exerts a force \mathbf{F} on it which is directed into the

1

plane of the loop. Its magnitude is,

$$F = I b B$$

1

Similarly it exerts a force \mathbf{F} on the arm CD and \mathbf{F}

2

2

is directed out of the plane of the paper.

$$F = I b B = F$$

2

1

Thus, the *net force* on the loop *is zero*. There is a torque on the loop due to the pair of forces \mathbf{F} and \mathbf{F} .

1

2

Figure 4.21(b) shows a view of the loop from the AD end. It shows that the torque on the loop tends to rotate it anticlockwise. This torque is (in magnitude),

a

a

$$\tau = F$$

$+ F$

1

2

2

2

a

a

FIGURE 4.21 (a) A rectangular

$$= IbB + IbB$$

$$= I (ab) B$$

current-carrying coil in uniform

2

2

magnetic field. The magnetic moment

$$= I A B$$

(4.26)

\mathbf{m} points downwards. The torque τ is where $A = ab$ is the area of the rectangle.

along the axis and tends to rotate the coil anticlockwise. (b) The couple

We next consider the case when the plane of the loop, acting on the coil.

is not along the magnetic field, but makes an angle with

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it. We take the angle between the field and the normal to

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the coil to be angle θ (The previous case corresponds to $\theta = \pi/2$). Figure 4.22 illustrates this general case.

The forces on the arms BC and DA are equal, opposite, and act along the axis of the coil, which connects the centres of mass of BC and DA. Being collinear along the axis they cancel each other, resulting in no net force or torque. The forces on

arms AB and CD are F and F . They too are equal

1

2

and opposite, with magnitude,

$$F = F = I b B$$

1

2

But they are not collinear! This results in a couple as before. The torque is, however, less than the earlier case when plane of loop was along the magnetic field. This is because the perpendicular distance between the forces of the couple has decreased. Figure 4.22(b) is a view of the arrangement from the AD end and it illustrates these two forces constituting a couple. The magnitude of the torque on the loop is,

a

a

$$\tau = F$$

$$\sin \theta + F$$

$\sin \theta$

1

2

2

2

FIGURE 4.22 (a) The area vector of the loop

ABCD makes an arbitrary angle θ with

$$= I a b B \sin \theta$$

the magnetic field. (b) Top view of

$$= I A B \sin \theta$$

(4.27)

the loop. The forces \mathbf{F} and \mathbf{F} acting

1

2

As θ

on the arms AB and CD

à 0, the perpendicular distance between

are indicated.

the forces of the couple also approaches zero. This

makes the forces collinear and the net force and

torque zero. The torques in Eqs. (4.26) and (4.27) can be expressed as vector product of the magnetic moment of the coil and the magnetic field. We define the *magnetic moment* of the current loop as,

$$\mathbf{m} = I \mathbf{A}$$

(4.28)

where the direction of the area vector \mathbf{A} is given by the right-hand thumb rule and is directed into the plane of the paper in Fig. 4.21. Then as the angle between \mathbf{m} and \mathbf{B} is θ , Eqs. (4.26) and (4.27) can be expressed by one expression

$$\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B}$$

(4.29)

This is analogous to the electrostatic case (Electric dipole of dipole moment \mathbf{p} in an electric field \mathbf{E}).

e

$$\boldsymbol{\tau} = \mathbf{p} \times \mathbf{E}$$

e

As is clear from Eq. (4.28), the dimensions of the magnetic moment are $[A][L^2]$ and its unit is Am^2 .

From Eq. (4.29), we see that the torque τ vanishes when \mathbf{m} is either parallel or antiparallel to the magnetic field \mathbf{B} . This indicates a state of equilibrium as there is no torque on the coil (this also applies to any 158

object with a magnetic moment \mathbf{m}). When \mathbf{m} and \mathbf{B} are parallel the

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equilibrium is a stable one. Any small rotation of the coil produces a torque which brings it back to its original position. When they are antiparallel, the equilibrium is unstable as any rotation produces a torque which increases with the amount of rotation. The presence of this torque is also the reason why a small magnet or any magnetic dipole aligns itself with the external magnetic field.

If the loop has N closely wound turns, the expression for torque, Eq.

(4.29), still holds, with

$$\mathbf{m} = N I \mathbf{A}$$

(4.30)

Example 4.11 A 100 turn closely wound circular coil of radius 10 cm carries a current of 3.2 A. (a) What is the field at the centre of the coil? (b) What is the magnetic moment of this coil?

The coil is placed in a vertical plane and is free to rotate about a horizontal axis which coincides with its diameter. A uniform magnetic field of 2T in the horizontal direction exists such that initially the axis of the coil is in the direction of the field. The coil rotates through

an angle of 90° under the influence of the magnetic field.

(c) What are the magnitudes of the torques on the coil in the initial and final position? (d) What is the angular speed acquired by the coil when it has rotated by 90° ? The moment of inertia of the coil is 0.1 kg m^2 .

Solution

(a) From Eq. (4.16)

$$\mu NI$$

$$0$$

$$B = 2 R$$

Here, $N = 100$; $I = 3.2 \text{ A}$, and $R = 0.1 \text{ m}$. Hence,

$$7$$

—

$$2$$

$$4\pi \times 10$$

$$\times 10 \times 3.2$$

$$5$$

$$4 \times 10^{-5} \times 10$$

$$B =$$

=

1

$2 \times$

10^{-}

-1

$2 \times$

(using $\pi \times 3.2 = 10$)

10

$= 2 \times 10^{-3} \text{ T}$

The direction is given by the right-hand thumb rule.

(b) The magnetic moment is given by Eq. (4.30),

$$m = N I A = N I \pi r^2 = 100 \times 3.2 \times 3.14 \times 10^{-2} = 10 \text{ A m}^2$$

The direction is once again given by the right hand thumb rule.

(c) $\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B}$ [from Eq. (4.29)]

$$= m B \sin \theta$$

Initially, $\theta = 0$. Thus, initial torque $\tau = 0$. Finally, $\theta = \pi/2$ (or 90°).

i

Thus, final torque $\tau = m B = 10 \times 2 = 20 \text{ N m}$.

f

(d) From Newton's second law,

$d\omega$ I

$$= m B \sin\theta$$

 $d t$ **E**

where I is the moment of inertia of the coil. From chain rule,

XAMPLE $d\omega$ $d\omega d\theta$ $d\omega$ $=$ $=$ ω $d t$ $d\theta d t$ $d\theta$ **4.11**

Using this,

$$I \omega d\omega = m B \sin\theta d\theta$$

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Integrating from $\theta = 0$ to $\theta = \pi/2$,

$$\omega f$$

$$\delta / 2$$

$$1$$

$$\omega d\omega = m B$$

$$\sin \theta d\theta$$

$$\int$$
$$\int$$

$$0$$

$$0$$

$$2$$

$$\omega$$

4.11

$$f$$

$$/ 2$$

$$1$$

$$m B \cos \theta \pi$$

$$= -$$

$$= m B$$

0

2

1/2

2 *m B*

1/2

2 × 20

XAMPLE

ω

=

=

f

1

E

1

10–

= 20 s⁻¹.

Example 4.12

(a) A current-carrying circular loop lies on a smooth horizontal plane.

Can a uniform magnetic field be set up in such a manner that the loop turns around itself (i.e., turns about the vertical axis).

(b) A current-carrying circular loop is located in a uniform external magnetic field. If the loop is free to turn, what is its orientation of stable equilibrium? Show that in this orientation, the flux of the total field (external field + field produced by the loop) is maximum.

(c) A loop of irregular shape carrying current is located in an external magnetic field. If the wire is flexible, why does it change to a circular shape?

Solution

(a) No, because that would require τ to be in the vertical direction.

But $\tau = I \mathbf{A} \times \mathbf{B}$, and since \mathbf{A} of the horizontal loop is in the vertical direction, τ would be in the plane of the loop for any \mathbf{B} .

(b) Orientation of stable equilibrium is one where the area vector \mathbf{A} of the loop is in the direction of external magnetic field. In this orientation, the magnetic field produced by the loop is in the same

4.12

direction as external field, both normal to the plane of the loop, thus giving rise to maximum flux of the total field.

(c) It assumes circular shape with its plane normal to the field to

XAMPLE

maximize flux, since for a given perimeter, a circle encloses greater

E

area than any other shape.

4.10.2 Circular current loop as a magnetic dipole

In this section, we shall consider the elementary magnetic element: the current loop. We shall show that the magnetic field (at large distances) due to current in a circular current loop is very similar in behavior to the electric field of an electric dipole. In Section 4.6, we have evaluated the magnetic field on the axis of a circular loop, of a radius R , carrying a steady current I . The magnitude of this field is [(Eq. (4.15)], 2

$$\mu I R$$

$$0$$

$$B =$$

$$(x + R)^{3/2}$$

$$2$$

$$2$$

2

and its direction is along the axis and given by the right-hand thumb rule (Fig. 4.12). Here, x is the distance along the axis from the centre of the loop. For $x \gg R$, we may drop the R^2 term in the denominator. Thus,

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Magnetism

2

μR

0

$B =$

3

$2x$

Note that the area of the loop $A = \pi R^2$. Thus,

μIA

0

$B =$

3

$2\pi x$

As earlier, we define the magnetic moment \mathbf{m} to have a magnitude IA ,

$\mathbf{m} = I \mathbf{A}$. Hence,

$\mu \mathbf{m}$

0

\mathbf{B} ;

δ^3

$2x$

μ^2

0

=

\mathbf{m}

[4.31(a)]

4δ

3

x

The expression of Eq. [4.31(a)] is very similar to an expression obtained earlier for the electric field of a dipole. The similarity may be seen if we substitute,

$\mu \rightarrow 1/\epsilon$

0

0

$\mathbf{m} \rightarrow \mathbf{p}$ (electrostatic dipole)

e

$\mathbf{B} \rightarrow \mathbf{E}$ (electrostatic field)

We then obtain,

$2\mathbf{p} e$

$\mathbf{E} =$

3

$4 \pi \epsilon x$

0

which is precisely the field for an electric dipole at a point on its axis.

considered in Chapter 1, Section 1.10 [Eq. (1.20)].

It can be shown that the above analogy can be carried further. We

had found in Chapter 1 that the electric field on the perpendicular bisector

of the dipole is given by [See Eq.(1.21)],

$\mathbf{p} e$

$\mathbf{E} ;$

3

4ϵ

πx

0

where x is the distance from the dipole. If we replace \mathbf{p} à \mathbf{m} and $\mu \rightarrow 1/\epsilon$

0

0

in the above expression, we obtain the result for \mathbf{B} for a point *in the plane of the loop* at a distance x from the centre. For $x \gg R$, $\mu \mathbf{m} 0$

\mathbf{B} ;

;

$x \gg R$

3

[4.31(b)]

$4\pi x$

The results given by Eqs. [4.31(a)] and [4.31(b)] become exact for a *point* magnetic dipole.

The results obtained above can be shown to apply to any planar loop:

a planar current loop is equivalent to a magnetic dipole of dipole moment

$\mathbf{m} = I \mathbf{A}$, which is the analogue of electric dipole moment \mathbf{p} . Note, however, a fundamental difference: an electric dipole is built up of two elementary units — the charges (or electric monopoles). In magnetism, a magnetic

dipole (or a current loop) is the most elementary element. The equivalent

of electric charges, i.e., magnetic monopoles, are not known to exist.

We have shown that a current loop (i) produces a magnetic field (see

Fig. 4.12) and behaves like a magnetic dipole at large distances, and

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(ii) is subject to torque like a magnetic needle. This led Ampere to suggest that all magnetism is due to circulating currents. This seems to be partly true and no magnetic monopoles have been seen so far. However, elementary particles such as an electron or a proton also carry an *intrinsic* magnetic moment, not accounted by circulating currents.

4.10.3 The magnetic dipole moment of a revolving electron

In Chapter 12 we shall read about the Bohr model of the hydrogen atom.

You may perhaps have heard of this model which was proposed by the Danish physicist Niels Bohr in 1911 and was a stepping stone to a new kind of mechanics, namely, quantum mechanics.

In the Bohr model, the electron (a negatively charged particle) revolves around a positively charged nucleus much as a planet revolves around the sun. The force in the former case is electrostatic (Coulomb force) while it is gravitational for the planet-Sun case. We show this Bohr picture of the electron in Fig. 4.23.

The electron of charge $(-e)$ ($e = + 1.6 \times 10^{-19}$ C) performs uniform circular motion around a stationary heavy nucleus

of charge $+Ze$. This constitutes a current I , where,

e

$I =$

(4.32)

FIGURE 4.23 In the Bohr model

T

of hydrogen-like atoms, the

and T is the time period of revolution. Let r be the orbital

negatively charged electron is

radius of the electron, and v the orbital speed. Then,

revolving with uniform speed

around a centrally placed

$2\pi r$

$T =$

(4.33)

positively charged ($+Ze$)

v

nucleus. The uniform circular

Substituting in Eq. (4.32), we have $I = ev/2\pi r$.

motion of the electron

There will be a magnetic moment, usually denoted by μ ,
 constitutes a current. The

l

associated with this circulating current. From Eq. (4.28) its

direction of the magnetic

moment is into the plane of the

magnitude is, $\mu = I\pi r^2 = evr/2$.

l

paper and is indicated

The direction of this magnetic moment is into the plane

separately by \otimes .

of the paper in Fig. 4.23. [This follows from the right-hand

rule discussed earlier and the fact that the negatively charged

electron is moving anticlockwise, leading to a clockwise current.]

Multiplying and dividing the right-hand side of the above expression by

the electron mass m , we have,

e

e

$\mu =$

$(m v r)$

l 2 e me e $=$ l $[4.34(a)]$ $2 me$

Here, l is the magnitude of the angular momentum of the electron about the central nucleus (“orbital” angular momentum). Vectorially,

 e $\mu = -$ l l $[4.34(b)]$ $2 me$

The negative sign indicates that the angular momentum of the electron

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is opposite in direction to the magnetic moment. Instead of electron with

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charge ($-e$), if we had taken a particle with charge ($+q$), the angular momentum and magnetic moment would be in the same direction. The ratio

$$\mu$$
$$e$$
$$l =$$
$$(4.35)$$
$$l$$
$$2me$$

is called the *gyromagnetic ratio* and is a constant. Its value is 8.8×10^{10} C/kg for an electron, which has been verified by experiments.

The fact that even at an atomic level there is a magnetic moment, confirms Ampere's bold hypothesis of atomic magnetic moments. This according to Ampere, would help one to explain the magnetic properties

<http://patsy.hunter.cuny.edu/CORE/CORE4/LectureNotes/Electricity/electric6.htm> **Conversion of galvanometer into ammeter and voltmeter:** of materials. Can one assign a value to this atomic dipole moment? The answer is Yes. One can do so within the Bohr model. Bohr hypothesised

that the angular momentum assumes a discrete set of values, namely,

$$n h$$
$$l = 2\pi$$

(4.36)

where n is a natural number, $n = 1, 2, 3, \dots$ and h is a constant named after Max Planck (Planck's constant) with a value $h = 6.626 \times 10^{-34}$ J s.

This condition of discreteness is called the *Bohr quantisation condition*.

We shall discuss it in detail in Chapter 12. Our aim here is merely to use

it to calculate the elementary dipole moment. Take the value $n = 1$, we

have from Eq. (4.34) that,

e

(μ)

=

h

$l \text{ min}$

$4 \pi m e$

19

—

34

1.60×10

$\times 6.63 \times 10^{-}$

=

31

$4 \times 3.14 \times 9.11 \times 10^{-}$

$$= 9.27 \times 10^{-24} \text{ Am}^2$$

(4.37)

where the subscript 'min' stands for minimum. This value is called the *Bohr magneton*.

Any charge in uniform circular motion would have an associated magnetic moment given by an expression similar to Eq. (4.34). This dipole moment is labelled as the *orbital magnetic moment*. Hence the subscript 'l' in μ_l . Besides the orbital moment, the electron has an *intrinsic* magnetic

moment, which has the same numerical value as given in Eq. (4.37). It is called the *spin magnetic moment*. But we hasten to add that it is not as though the electron is spinning. The electron is an elementary particle and it does not have an axis to spin around like a top or our earth.

Nevertheless it does possess this *intrinsic* magnetic moment. The microscopic roots of magnetism in iron and other materials can be traced back to this intrinsic spin magnetic moment.

4.11 THE MOVING COIL GALVANOMETER

Currents and voltages in circuits have been discussed extensively in Chapters 3. But how do we measure them? How do we claim that current in a circuit is 1.5 A or the voltage drop across a resistor is 1.2 V?

Figure 4.24 exhibits a very useful instrument for this purpose: the *moving*

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coil galvanometer (MCG). It is a device whose principle can be understood on the basis of our discussion in Section 4.10.

The galvanometer consists of a coil, with many turns, free to rotate about a fixed axis (Fig. 4.24), in a uniform radial magnetic field. There is a cylindrical soft iron core which not only makes the field radial but also increases the strength of the magnetic field. When a current flows through the coil, a torque acts on it. This torque is given by Eq. (4.26) to be

$$\tau = NIAB$$

where the symbols have their usual meaning. Since the field is radial by design, we have taken $\sin \theta = 1$ in the above expression for the torque.

The magnetic torque $NIAB$ tends to rotate the coil. A spring S provides a p counter torque $k\phi$ that balances the magnetic torque $NIAB$; resulting in a steady angular deflection ϕ . In equilibrium $k\phi = NIAB$

where k is the torsional constant of the spring; *i.e.* the restoring torque per unit twist. The deflection ϕ is indicated on the scale by a pointer attached to the spring. We have

$$NIAB$$

$$\phi$$

=

I

k

(4.38)

The quantity in brackets is a constant for a given galvanometer.

The galvanometer can be used in a number of ways.

It can be used as a detector to check if a current is flowing in the circuit. We have come across this usage in the Wheatstone's bridge arrangement. In this usage the neutral position of the pointer (when no current is flowing through the galvanometer) is in the middle of the scale and not at the left end as shown in Fig.4.24.

Depending on the direction of the current, the pointer deflection is either to the right or the left.

The galvanometer cannot as such be used as an ammeter to measure the value of the current in a given circuit. This is for two reasons: (i) Galvanometer is a very sensitive device, it gives a full-scale deflection for

a current of the order of μA . (ii) For measuring currents, the galvanometer has to be connected in series, and as it has a large resistance, this will change the value of the current in the circuit. To overcome these difficulties, one attaches a small resistance r , s

FIGURE 4.24 The moving coil

called *shunt resistance*, in parallel with galvanometer. Its elements are

the galvanometer coil; so that most of the current described in the text. Depending on

passes through the shunt. The resistance of this the requirement, this device can be

arrangement is,

used as a current detector or for

$$R r / (R + r)$$

measuring the value of the current

$$; r \text{ if } R \gg r$$

G

s

G

s

s

G

s

(ammeter) or voltage (voltmeter).

If r has small value, in relation to the resistance of

s

the rest of the circuit R , the effect of introducing the

c

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measuring instrument is also small and negligible. This

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arrangement is schematically shown in Fig. 4.25. The scale of this

ammeter is calibrated and then graduated to read off the current value

with ease. We define the *current sensitivity of the galvanometer as the*

deflection per unit current. From Eq. (4.38) this current sensitivity is, ϕ

NAB

=

(4.39)

I

k

A convenient way for the manufacturer to increase the sensitivity is to increase the number of turns N . We choose galvanometers having sensitivities of value, required by our experiment.

The galvanometer can also be used as a voltmeter to measure the

FIGURE 4.25

voltage across a given section of the circuit. For this it must be connected

Conversion of a

in parallel with that section of the circuit. Further, it must draw a very galvanometer (G) to

small current, otherwise the voltage measurement will disturb the original

an ammeter by the

set up by an amount which is very large. Usually we like to keep the

introduction of a

disturbance due to the measuring device below one per cent. To ensure shunt resistance r of s

this, a large resistance R is connected *in series* with the galvanometer.

very small value in

This arrangement is schematically depicted in Fig.4.26. Note that the

parallel.

resistance of the voltmeter is now,

$$R + R ; R : \text{large}$$

G

The scale of the voltmeter is calibrated to read off the voltage value with ease. We define the *voltage sensitivity as the deflection per unit voltage*. From Eq. (4.38),

ϕ

$$NAB \ I$$

$$NAB \ 1$$

=

=

V

$$k \ V$$

$$k$$

(4.40)

R

An interesting point to note is that increasing the current sensitivity

may not necessarily increase the voltage sensitivity. Let us take Eq. (4.39)

which provides a measure of current sensitivity. If $N \rightarrow 2N$, i.e., we double

FIGURE 4.26

the number of turns, then

Conversion of a

ϕ

ϕ

galvanometer (G) to a

$\rightarrow 2$

voltmeter by the

I

I

introduction of a

Thus, the current sensitivity doubles. However, the resistance of the

resistance R of large

galvanometer is also likely to double, since it is proportional to the length

value in series.

of the wire. In Eq. (4.40), $N \rightarrow 2N$, and $R \rightarrow 2R$, thus the voltage sensitivity, ϕ

ϕ

\rightarrow

V

V

remains unchanged. So in general, the modification needed for conversion of a galvanometer to an ammeter will be different from what is needed for converting it into a voltmeter.

Example 4.13 In the circuit (Fig. 4.27) the current is to be

EXAMPLE

measured. What is the value of the current if the ammeter shown

(a) is a galvanometer with a resistance $R = 60.00 \Omega$; (b) is a

G

galvanometer described in (a) but converted to an ammeter by a

4.13

shunt resistance $r = 0.02 \Omega$; (c) is an ideal ammeter with zero

s

resistance?

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FIGURE 4.27

Solution

(a) Total resistance in the circuit is,

$R + 3 = 63 \Omega$. Hence, $I = 3/63 = 0.048 \text{ A}$.

G

(b) Resistance of the galvanometer converted to an ammeter is,

$R r$

$60 \Omega \times 0.02\Omega$

G

s

=

- 0.02Ω

E

$R + r$

$(60 + 0.02)\Omega$ %

XAMPLE

G

s

Total resistance in the circuit is,

$0.02 \Omega + 3 \Omega = 3.02 \Omega$. Hence, $I = 3/3.02 = 0.99 \text{ A}$.

4.13

(c) For the ideal ammeter with zero resistance,

$I = 3/3 = 1.00 \text{ A}$

SUMMARY

1.

The total force on a charge q moving with velocity \mathbf{v} in the presence of magnetic and electric fields \mathbf{B} and \mathbf{E} , respectively is called the *Lorentz force*. It is given by the expression: $\mathbf{F} = q (\mathbf{v} \times \mathbf{B} + \mathbf{E})$

The magnetic force $q (\mathbf{v} \times \mathbf{B})$ is normal to \mathbf{v} and work done by it is zero.

2.

A straight conductor of length l and carrying a steady current I experiences a force \mathbf{F} in a uniform external magnetic field \mathbf{B} ,

$$\mathbf{F} = I \mathbf{l} \times \mathbf{B}$$

where $|\mathbf{l}| = l$ and the direction of \mathbf{l} is given by the direction of the current.

3.

In a uniform magnetic field \mathbf{B} , a charge q executes a circular orbit in a plane normal to \mathbf{B} . Its frequency of uniform circular motion is called the *cyclotron frequency* and is given by:

$$q B$$

$$v =$$

$$c$$

$$2 \pi m$$

This frequency is independent of the particle's speed and radius. This fact is exploited in a machine, the cyclotron, which is used to accelerate charged particles.

4.

The *Biot-Savart* law asserts that the magnetic field $d\mathbf{B}$ due to an element $d\mathbf{l}$ carrying a steady current I at a point P at a distance r from the current element is: μ

$$d\mathbf{l} \times \mathbf{r}$$

0

$$d\mathbf{B} =$$

I

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3

4π

r

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Magnetism

To obtain the total field at P, we must integrate this vector expression over the entire length of the conductor.

5.

The magnitude of the magnetic field due to a circular coil of radius R carrying a current I at an axial distance x from the centre is

2

$$\mu IR$$

0

$$B =$$

2

$$2 \cdot 3 / 2$$

$$2(x + R)$$

At the center this reduces to

$$\mu I$$

0

$$B = 2 R$$

6.

Ampere's Circuital Law: Let an open surface S be bounded by a loop

C. Then the Ampere's law states that

d

$$g = \mu I$$

$$\int \mathbf{B} \cdot d\mathbf{l}$$

\tilde{N}

where I refers to

C

the current passing through S. The sign of I is determined from the

right-hand rule. We have discussed a simplified form of this law. If \mathbf{B}

is directed along the tangent to every point on the perimeter L of a closed curve and is constant in magnitude along perimeter then,

$$BL = \mu I$$

0

e

where I is the net current enclosed by the closed circuit.

e

7.

The magnitude of the magnetic field at a distance R from a long, straight wire carrying a current I is given by:

$$\mu I$$

0

$$B = \frac{\mu I}{2\pi R}$$

The field lines are circles concentric with the wire.

8.

The magnitude of the field B inside a *long solenoid* carrying a current I is

$$B = \mu nI$$

0

where n is the number of turns per unit length. For a *toroid* one obtains,

$$\mu NI$$

0

$$B = 2\pi r$$

where N is the total number of turns and r is the average radius.

9.

Parallel currents attract and antiparallel currents repel.

10. A planar loop carrying a current I , having N closely wound turns, and an area A possesses a magnetic moment \mathbf{m} where, $\mathbf{m} = N I \mathbf{A}$

and the direction of \mathbf{m} is given by the right-hand thumb rule : curl

the palm of your right hand along the loop with the fingers pointing

in the direction of the current. The thumb sticking out gives the

direction of \mathbf{m} (and \mathbf{A})

When this loop is placed in a uniform magnetic field \mathbf{B} , the force \mathbf{F} on it is:

$$F = 0$$

And the torque on it is,

$$\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B}$$

In a moving coil galvanometer, this torque is balanced by a counter—

torque due to a spring, yielding

$$k\phi = NIAB$$

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where ϕ is the equilibrium deflection and k the torsion constant of

the spring.

11. An electron moving around the central nucleus has a magnetic moment

μ given by:

l

e

$\mu =$

l

l

$2 m$

where l is the magnitude of the angular momentum of the circulating electron about the central nucleus. The smallest value of μ is called

l

the Bohr magneton μ and it is $\mu = 9.27 \times 10^{-24} \text{ J/T}$

B

B

12. A moving coil galvanometer can be converted into a ammeter by introducing a shunt resistance r , of small value in parallel. It can be converted into a voltmeter by introducing a resistance of a large value in series.

Physical Quantity

Symbol

Nature

Dimensions

Units

Remarks

Permeability of free

μ

Scalar

$[MLT^{-2}A^{-2}]$

$T\ m\ A^{-1}$

$4\pi \times 10^{-7}\ T\ m\ A^{-1}$

0

space

Magnetic Field

B

Vector

$[M\ T^{-2}A^{-1}]$

T (telsa)

Magnetic Moment

m

Vector

[L²A]

A m² or J/T

Torsion Constant

k

Scalar

[M L²T⁻²]

N m rad⁻¹

Appears in MCG

POINTS TO PONDER

1.

Electrostatic field lines originate at a positive charge and terminate at a negative charge or fade at infinity. Magnetic field lines always form closed loops.

2.

The discussion in this Chapter holds only for steady currents which do not vary with time.

When currents vary with time Newton's third law is valid only if momentum

carried by the electromagnetic field is taken into account.

3.

Recall the expression for the Lorentz force,

$$\mathbf{F} = q (\mathbf{v} \times \mathbf{B} + \mathbf{E})$$

This velocity dependent force has occupied the attention of some of the greatest scientific thinkers. If one switches to a frame with instantaneous velocity \mathbf{v} , the magnetic part of the force vanishes. The motion of the

charged particle is then explained by arguing that there exists an

appropriate electric field in the new frame. We shall not discuss the

details of this mechanism. However, we stress that the resolution of this

paradox implies that electricity and magnetism are linked phenomena

(*electromagnetism*) and that the Lorentz force expression *does not* imply a universal preferred frame of reference in nature.

4.

Ampere's Circuital law is not independent of the Biot-Savart law. It

can be derived from the Biot-Savart law. Its relationship to the

Biot-Savart law is similar to the relationship between Gauss's law and

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Coulomb's law.

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EXERCISES

4.1

A circular coil of wire consisting of 100 turns, each of radius 8.0 cm carries a current of 0.40 A. What is the magnitude of the magnetic field **B** at the centre of the coil?

4.2

A long straight wire carries a current of 35 A. What is the magnitude of the field **B** at a point 20 cm from the wire?

4.3

A long straight wire in the horizontal plane carries a current of 50 A in north to south direction. Give the magnitude and direction of **B** at a point 2.5 m east of the wire.

4.4

A horizontal overhead power line carries a current of 90 A in east to west direction. What is the magnitude and direction of the magnetic field due to the current 1.5 m below the line?

4.5

What is the magnitude of magnetic force per unit length on a wire

carrying a current of 8 A and making an angle of 30° with the direction of a uniform magnetic field of 0.15 T ?

4.6

A 3.0 cm wire carrying a current of 10 A is placed inside a solenoid perpendicular to its axis. The magnetic field inside the solenoid is given to be 0.27 T. What is the magnetic force on the wire?

4.7

Two long and parallel straight wires A and B carrying currents of 8.0 A and 5.0 A in the same direction are separated by a distance of 4.0 cm. Estimate the force on a 10 cm section of wire A.

4.8

A closely wound solenoid 80 cm long has 5 layers of windings of 400 turns each. The diameter of the solenoid is 1.8 cm. If the current carried is 8.0 A, estimate the magnitude of **B** inside the solenoid near its centre.

4.9

A square coil of side 10 cm consists of 20 turns and carries a current of 12 A. The coil is suspended vertically and the normal to the plane of the coil makes an angle of 30° with the direction of a uniform horizontal magnetic field of magnitude 0.80 T. What is the magnitude of torque experienced by the coil?

4.10

Two moving coil meters, M and M have the following particulars:

1

2

$$R = 10 \, \Omega, N = 30,$$

1

1

$$A = 3.6 \times 10^{-3} \, \text{m}^2, B = 0.25 \, \text{T}$$

1

1

$$R = 14 \, \Omega, N = 42,$$

2

2

$$A = 1.8 \times 10^{-3} \, \text{m}^2, B = 0.50 \, \text{T}$$

2

2

(The spring constants are identical for the two meters).

Determine the ratio of (a) current sensitivity and (b) voltage sensitivity of M and M' .

2

1

4.11

In a chamber, a uniform magnetic field of 6.5 G ($1 \text{ G} = 10^{-4} \text{ T}$) is maintained. An electron is shot into the field with a speed of $4.8 \times 10^6 \text{ m s}^{-1}$ normal to the field. Explain why the path of the electron is a circle. Determine the radius of the circular orbit.

($e = 1.6 \times 10^{-19} \text{ C}$, $m = 9.1 \times 10^{-31} \text{ kg}$)

e

4.12

In Exercise 4.11 obtain the frequency of revolution of the electron in its circular orbit. Does the answer depend on the speed of the electron? Explain.

4.13

(a) A circular coil of 30 turns and radius 8.0 cm carrying a current of 6.0 A is suspended vertically in a uniform horizontal magnetic

field of magnitude 1.0 T. The field lines make an angle of 60°

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with the normal of the coil. Calculate the magnitude of the counter torque that must be applied to prevent the coil from turning.

(b) Would your answer change, if the circular coil in (a) were replaced by a planar coil of some irregular shape that encloses the same area? (All other particulars are also unaltered.)

ADDITIONAL EXERCISES

4.14

Two concentric circular coils X and Y of radii 16 cm and 10 cm, respectively, lie in the same vertical plane containing the north to south direction. Coil X has 20 turns and carries a current of 16 A; coil Y has 25 turns and carries a current of 18 A. The sense of the current in X is anticlockwise, and clockwise in Y, for an observer looking at the coils facing west. Give the magnitude and direction of the net magnetic field due to the coils at their centre.

4.15

A magnetic field of 100 G ($1 \text{ G} = 10^{-4} \text{ T}$) is required which is uniform

in a region of linear dimension about 10 cm and area of cross-section about 10^{-3} m^2 . The maximum current-carrying capacity of a given coil of wire is 15 A and the number of turns per unit length that can be wound round a core is at most 1000 turns m^{-1} . Suggest some appropriate design particulars of a solenoid for the required purpose.

Assume the core is not ferromagnetic.

4.16

For a circular coil of radius R and N turns carrying current I , the magnitude of the magnetic field at a point on its axis at a distance x from its centre is given by,

2

$\mu I R N$

0

$B =$

$(x + R)^{3/2}$

2

2

2

(a) Show that this reduces to the familiar result for field at the centre of the coil.

(b) Consider two parallel co-axial circular coils of equal radius R ,

and number of turns N , carrying equal currents in the same direction, and separated by a distance R . Show that the field on the axis around the midpoint between the coils is uniform over a distance that is small as compared to R , and is given by,

$$\mu NI$$

$$0$$

$$B = 0.72$$

, approximately.

$$R$$

[Such an arrangement to produce a nearly uniform magnetic field over a small region is known as *Helmholtz coils*.]

4.17

A toroid has a core (non-ferromagnetic) of inner radius 25 cm and outer radius 26 cm, around which 3500 turns of a wire are wound.

If the current in the wire is 11 A, what is the magnetic field

(a) outside the toroid, (b) inside the core of the toroid, and (c) in the empty space surrounded by the toroid.

4.18

Answer the following questions:

(a) A magnetic field that varies in magnitude from point to point

but has a constant direction (east to west) is set up in a chamber.

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A charged particle enters the chamber and travels undeflected

Moving Charges and

Magnetism

along a straight path with constant speed. What can you say about the initial velocity of the particle?

(b) A charged particle enters an environment of a strong and nonuniform magnetic field varying from point to point both in magnitude and direction, and comes out of it following a complicated trajectory. Would its final speed equal the initial speed if it suffered no collisions with the environment?

(c) An electron travelling west to east enters a chamber having a uniform electrostatic field in north to south direction. Specify the direction in which a uniform magnetic field should be set up to prevent the electron from deflecting from its straight line path.

4.19

An electron emitted by a heated cathode and accelerated through a potential difference of 2.0 kV, enters a region with uniform magnetic

field of 0.15 T. Determine the trajectory of the electron if the field (a) is transverse to its initial velocity, (b) makes an angle of 30° with the initial velocity.

4.20

A magnetic field set up using Helmholtz coils (described in Exercise 4.16) is uniform in a small region and has a magnitude of 0.75 T. In the same region, a uniform electrostatic field is maintained in a direction normal to the common axis of the coils. A narrow beam of (single species) charged particles all accelerated through 15 kV enters this region in a direction perpendicular to both the axis of the coils and the electrostatic field. If the beam remains undeflected when the electrostatic field is $9.0 \times 10^{-5} \text{ V m}^{-1}$, make a simple guess as to what the beam contains. Why is the answer not unique?

4.21

A straight horizontal conducting rod of length 0.45 m and mass 60 g is suspended by two vertical wires at its ends. A current of 5.0 A is set up in the rod through the wires.

(a) What magnetic field should be set up normal to the conductor in order that the tension in the wires is zero?

(b) What will be the total tension in the wires if the direction of

current is reversed keeping the magnetic field same as before?

(Ignore the mass of the wires.) $g = 9.8 \text{ m s}^{-2}$.

4.22

The wires which connect the battery of an automobile to its starting motor carry a current of 300 A (for a short time). What is the force per unit length between the wires if they are 70 cm long and 1.5 cm apart? Is the force attractive or repulsive?

4.23

A uniform magnetic field of 1.5 T exists in a cylindrical region of radius 10.0 cm, its direction parallel to the axis along east to west. A wire carrying current of 7.0 A in the north to south direction passes through this region. What is the magnitude and direction of the force on the wire if,

- (a) the wire intersects the axis,
- (b) the wire is turned from N-S to northeast-northwest direction,
- (c) the wire in the N-S direction is lowered from the axis by a distance of 6.0 cm?

4.24

A uniform magnetic field of 3000 G is established along the positive z -direction. A rectangular loop of sides 10 cm and 5 cm carries a

current of 12 A. What is the torque on the loop in the different cases shown in Fig. 4.28? What is the force on each case? Which case

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corresponds to stable equilibrium?

Physics

FIGURE 4.28

4.25

A circular coil of 20 turns and radius 10 cm is placed in a uniform magnetic field of 0.10 T normal to the plane of the coil. If the current in the coil is 5.0 A, what is the

(a) total torque on the coil,

(b) total force on the coil,

(c) average force on each electron in the coil due to the magnetic field?

(The coil is made of copper wire of cross-sectional area 10^{-5} m^2 , and the free electron density in copper is given to be about 10^{29} m^{-3} .)

4.26

A solenoid 60 cm long and of radius 4.0 cm has 3 layers of windings of 300 turns each. A 2.0 cm long wire of mass 2.5 g lies inside the

solenoid (near its centre) normal to its axis; both the wire and the axis of the solenoid are in the horizontal plane. The wire is connected through two leads parallel to the axis of the solenoid to an external battery which supplies a current of 6.0 A in the wire. What value of current (with appropriate sense of circulation) in the windings of the solenoid can support the weight of the wire? $g = 9.8 \text{ m s}^{-2}$.

4.27

A galvanometer coil has a resistance of 12Ω and the metre shows full scale deflection for a current of 3 mA. How will you convert the metre into a voltmeter of range 0 to 18 V?

4.28

A galvanometer coil has a resistance of 15Ω and the metre shows full scale deflection for a current of 4 mA. How will you convert the metre into an ammeter of range 0 to 6 A?

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Chapter Five

MAGNETISM AND

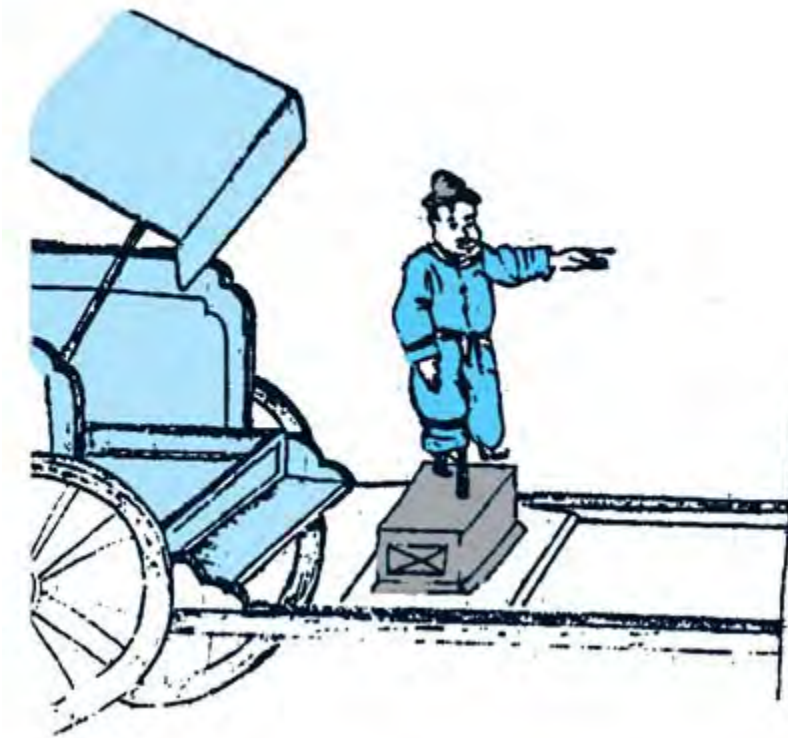
MATTER

5.1 INTRODUCTION

Magnetic phenomena are universal in nature. Vast, distant galaxies, the

tiny invisible atoms, men and beasts all are permeated through and through with a host of magnetic fields from a variety of sources. The earth's magnetism predates human evolution. The word magnet is derived from the name of an island in Greece called *magnesia* where magnetic ore deposits were found, as early as 600 BC. Shepherds on this island complained that their wooden shoes (which had nails) at times stayed struck to the ground. Their iron-tipped rods were similarly affected. This attractive property of magnets made it difficult for them to move around. The directional property of magnets was also known since ancient times. A thin long piece of a magnet, when suspended freely, pointed in the north-south direction. A similar effect was observed when it was placed on a piece of cork which was then allowed to float in still water. The name *lodestone* (or *loadstone*) given to a naturally occurring ore of iron-magnetite means leading stone. The technological exploitation of this property is generally credited to the Chinese. Chinese texts dating 400 BC mention the use of magnetic needles for navigation on ships. Caravans crossing the Gobi desert also employed magnetic needles.

A Chinese legend narrates the tale of the victory of the emperor Huang-ti about four thousand years ago, which he owed to his craftsmen (whom



Physics

nowadays you would call engineers). These ‘engineers’ built a chariot on which they placed a magnetic figure with arms outstretched. Figure 5.1 is an artist’s description of this chariot. The figure swiveled around so that the finger of the statuette on it always pointed south. With this chariot, Huang-ti’s troops were able to attack the enemy from the rear in thick fog, and to defeat them.

In the previous chapter we have learned that moving

charges or electric currents produce magnetic fields.

This discovery, which was made in the early part of the nineteenth century is credited to Oersted, Ampere, Biot and Savart, among others.

In the present chapter, we take a look at magnetism

FIGURE 5.1 The arm of the statuette

as a subject in its own right.

mounted on the chariot always points

Some of the commonly known ideas regarding

south. This is an artist's sketch of one

of the earliest known compasses,

magnetism are:

thousands of years old.

(i) The earth behaves as a magnet with the magnetic field pointing approximately from the geographic south to the north.

(ii) When a bar magnet is freely suspended, it points in the north-south direction. The tip which points to the geographic north is called the *north pole* and the tip which points to the geographic south is called the *south pole* of the magnet.

(iii) There is a repulsive force when north poles (or south poles) of two magnets are brought close together. Conversely, there is an attractive force between the north pole of one magnet and the south pole of the other.

(iv) We cannot isolate the north, or south pole of a magnet. If a bar magnet is broken into two halves, we get two similar bar magnets with somewhat weaker properties. Unlike electric charges, isolated magnetic north and south poles known as *magnetic monopoles* do not exist.

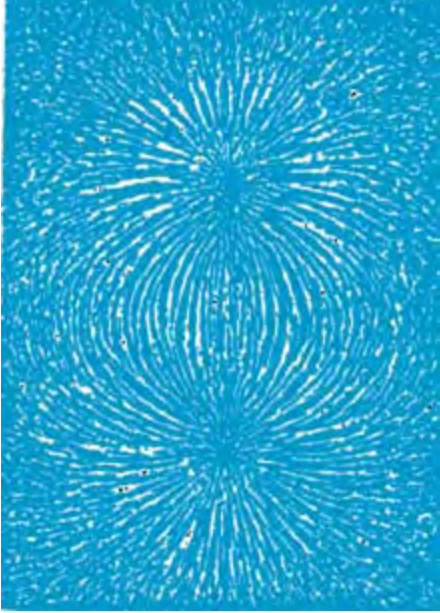
(v) It is possible to make magnets out of iron and its alloys.

We begin with a description of a bar magnet and its behaviour in an external magnetic field. We describe Gauss's law of magnetism. We then follow it up with an account of the earth's magnetic field. We next describe how materials can be classified on the basis of their magnetic properties. We describe para-, dia-, and ferromagnetism. We conclude with a section on electromagnets and permanent magnets.

5.2 THE BAR MAGNET

One of the earliest childhood memories of the famous physicist Albert Einstein was that of a magnet gifted to him by a relative. Einstein was fascinated, and played endlessly with it. He wondered how the magnet could affect objects such as nails or pins placed away from it and not in

any way *connected* to it by a spring or string.



Magnetism and

Matter

We begin our study by examining iron filings sprinkled on a sheet of glass placed over a short bar magnet. The arrangement of iron filings is shown in Fig. 5.2.

The pattern of iron filings suggests that the magnet has two poles similar to the positive and negative charge of an electric dipole. As mentioned in the introductory section, one pole is designated the *North*

pole and the other, the *South pole*. When suspended freely, these poles point approximately towards the geographic north and south poles, respectively. A similar pattern of iron filings is observed around a current

carrying solenoid.

5.2.1 The magnetic field lines

The pattern of iron filings permits us to plot the magnetic field lines*. This is **FIGURE 5.2** The shown both for the bar-magnet and the current-carrying solenoid in

arrangement of iron

Fig. 5.3. For comparison refer to the Chapter 1, Figure 1.17(d). Electric field filings surrounding a lines of an electric dipole are also displayed in Fig. 5.3(c). The magnetic field bar magnet. The lines are a visual and intuitive realisation of the magnetic field. Their

pattern mimics

properties are:

magnetic field lines.

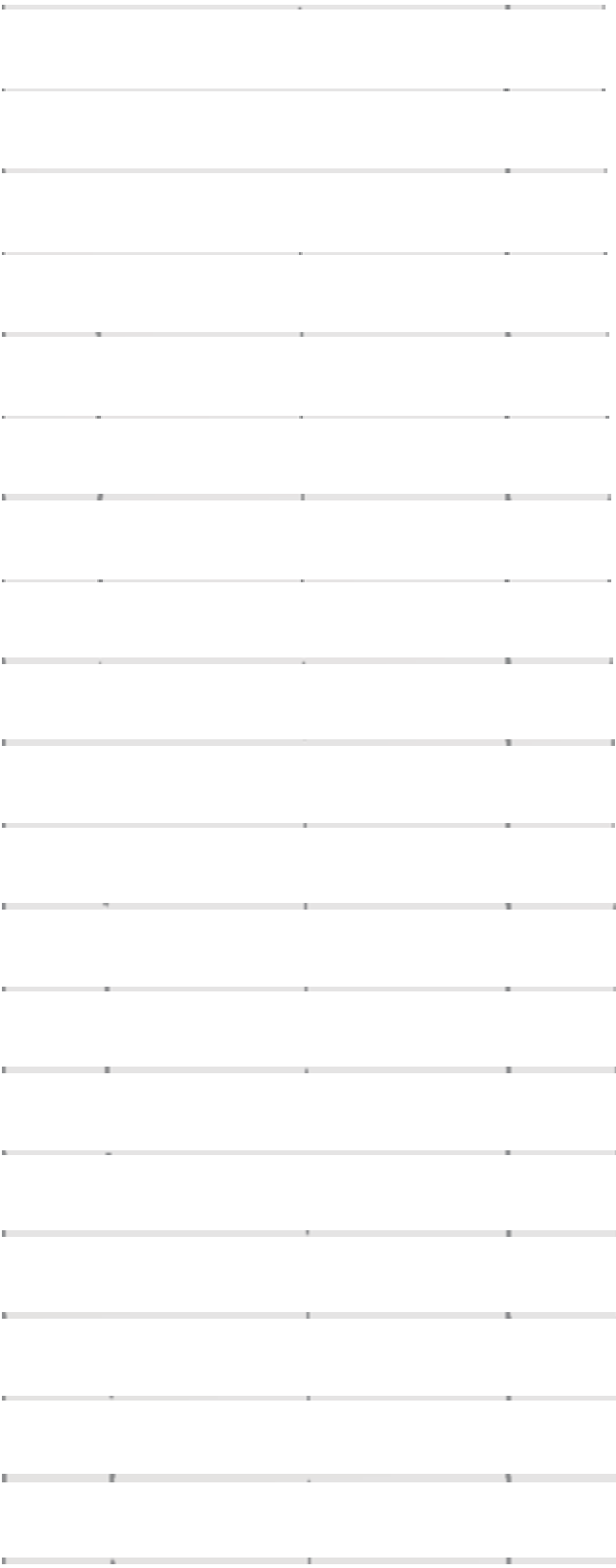
(i) The magnetic field lines of a magnet (or a solenoid) form continuous closed loops. The pattern suggests that the bar magnet is a magnetic dipole. This is unlike the electric dipole where these field lines

begin from a positive charge and end on the negative charge or escape to infinity.

(ii) The tangent to the field line at a given point represents the direction of the net magnetic field \mathbf{B} at that point.

FIGURE 5.3 The field lines of (a) a bar magnet, (b) a current-carrying finite solenoid and (c) electric dipole. At large distances, the field lines are very similar. The curves labelled i and ii are closed Gaussian surfaces.

* In some textbooks the magnetic field lines are called *magnetic lines of force*.





Physics

(iii) The larger the number of field lines crossing per unit area, the stronger is the magnitude of the magnetic field \mathbf{B} . In Fig. 5.3(a), \mathbf{B} is larger around region ii than in region i .

(iv) The magnetic field lines do not intersect, for if they did, the direction of the magnetic field would not be unique at the point of intersection.

One can plot the magnetic field lines in a variety of ways. One way is to place a small magnetic compass needle at various positions and note its orientation. This gives us an idea of the magnetic field direction at various points in space.

5.2.2 Bar magnet as an equivalent solenoid

In the previous chapter, we have explained how a current loop acts as a

magnetic dipole (Section 4.10). We mentioned Ampere's hypothesis that all magnetic phenomena can be explained in terms of circulating currents.

Recall that the magnetic dipole moment \mathbf{m} associated with a current loop was defined to be $\mathbf{m} = NI \mathbf{A}$ where N is the number of turns in the loop, I the current and \mathbf{A} the area vector (Eq. 4.30).

The resemblance of magnetic field lines for a bar magnet and a solenoid suggest that a bar magnet may be thought of as a large number of circulating currents in analogy with a solenoid. Cutting a bar magnet in half is like cutting a solenoid. We get two smaller solenoids with weaker magnetic properties.

The field lines remain continuous, emerging from one face of the solenoid and entering into the other face. One can test this analogy by moving a small compass needle in the neighbourhood of a bar magnet and a current-carrying finite solenoid and noting

that the deflections of the needle are similar in both cases.

To make this analogy more firm we calculate the axial field of a finite solenoid

FIGURE 5.4 (a) Calculation of the axial field of a depicted in Fig. 5.4 (a). We shall demonstrate finite solenoid in order to demonstrate its similarity that at large distances this axial field to that of a bar magnet. (b) A magnetic needle resembles that of a bar magnet.

in a uniform magnetic field \mathbf{B} . The arrangement may be used to

Let the solenoid of Fig. 5.4(a) consists of determine either \mathbf{B} or the magnetic

n turns per unit length. Let its length be $2l$ moment \mathbf{m} of the needle.

and radius a . We can evaluate the axial field at a point P, at a distance r from the centre O

of the solenoid. To do this, consider a circular element of thickness dx of the solenoid at a distance x from its centre. It consists of $n dx$ turns. Let I be the

current in the solenoid. In Section 4.6 of the previous chapter we have calculated the magnetic field on the axis of a circular current loop.

From Eq. (4.13), the magnitude of the field at point P due to the circular

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element is

Magnetism and

Matter

2

$$\mu n dx I a$$

0

$$dB =$$

3

2

2

2

$$2[(r - x)^2 + a^2]^{-3/2}$$

The magnitude of the total field is obtained by summing over all the

elements — in other words by integrating from $x = -l$ to $x = +l$. Thus, 2

$$\mu n I a$$

\int_{-l}^{+l}

$$dx$$

0

$B =$

\int

2

2

$2 \sqrt{3} / 2$

l

$- [(r - x) + a]$

This integration can be done by trigonometric substitutions. This

exercise, however, is not necessary for our purpose. Note that the range

of x is from $-l$ to $+l$. Consider the far axial field of the solenoid, i.e., $r \gg a$ and $r \gg l$. Then the denominator is approximated by 3

2

2

3

2

$[(r - x) + a]$

$\approx r$

$2l$

$\mu n I a$

and

0

$B =$

dx

∫

3

$2 r$

$- l$

2

$\mu n I 2 l a$

$= 0$

(5.1)

3

2

r

Note that the magnitude of the magnetic moment of the solenoid is,

$m = n (2 l) I (\pi a^2)$ — (total number of turns \times current \times cross-sectional area). Thus, $\mu 2 m$

0

$B =$

3

(5.2)

$4\pi r$

This is also the far axial magnetic field of a bar magnet which one may obtain experimentally. Thus, a bar magnet and a solenoid produce similar magnetic fields. The magnetic moment of a bar magnet is thus equal to the magnetic moment of an equivalent solenoid that produces the same magnetic field.

Some textbooks assign a *magnetic charge* (also called *pole strength*) $+q$ to the north pole and $-q$ to the south pole of a bar magnet of length m

$2l$, and magnetic moment $q(2l)$. The field strength due to q at a distance m

r from it is given by $\mu q / 4\pi r^2$. The magnetic field due to the bar magnet 0

is then obtained, both for the axial and the equatorial case, in a manner analogous to that of an electric dipole (Chapter 1). The method is simple and appealing. However, *magnetic monopoles do not exist*, and *we have avoided this approach for that reason*.

5.2.3 The dipole in a uniform magnetic field

The pattern of iron filings, i.e., the magnetic field lines gives us an approximate idea of the magnetic field \mathbf{B} . We may at times be required to determine the magnitude of \mathbf{B} accurately. This is done by placing a small compass needle of known magnetic moment \mathbf{m} and moment of inertia I

and allowing it to oscillate in the magnetic field. This arrangement is shown in Fig. 5.4(b).

The torque on the needle is [see Eq. (4.29)],

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$$\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B}$$

(5.3)

Physics

In magnitude $\tau = mB \sin\theta$

Here τ is restoring torque and θ is the angle between \mathbf{m} and \mathbf{B} .

2

$d\theta$

Therefore, in equilibrium 1

$$= -mB \sin\theta$$

2

dt

Negative sign with $mB \sin\theta$ implies that restoring torque is in opposition to deflecting torque. For small values of θ in radians, we approximate $\sin \theta \approx \theta$ and get

2

$d\theta$

1

$$\approx -mB \theta$$

$$2$$

$$dt$$

$$2$$

$$d\theta$$

$$mB$$

or,

$$= -$$

$$\theta$$

$$2$$

$$dt$$

$$1$$

This represents a simple harmonic motion. The square of the angular frequency is $\omega^2 = mB/1$ and the time period is,

$$T =$$

$$1$$

$$2\pi$$

$$(5.4)$$

$$mB$$

$$4 2$$

π

or $B =$

1

2

(5.5)

$m T$

An expression for magnetic potential energy can also be obtained on lines similar to electrostatic potential energy.

The magnetic potential energy U is given by

m

U

$= \tau(\theta) d\theta$

\int

m

$= mB \sin \theta$

\int

$= mB$

—

$\cos \theta$

$= -\mathbf{mgB}$

(5.6)

We have emphasised in Chapter 2 that the zero of potential energy can be fixed at one's convenience. Taking the constant of integration to be zero means fixing the zero of potential energy at $\theta = 90^\circ$, i.e., when the needle is perpendicular to the field. Equation (5.6) shows that potential energy is minimum ($= -m B$) at $\theta = 0^\circ$ (most stable position) and maximum ($= +m B$) at $\theta = 180^\circ$ (most unstable position).

Example 5.1 In Fig. 5.4(b), the magnetic needle has magnetic moment $6.7 \times 10^{-2} \text{ Am}^2$ and moment of inertia $I = 7.5 \times 10^{-6} \text{ kg m}^2$. It performs 10 complete oscillations in 6.70 s. What is the magnitude of the magnetic field?

Solution The time period of oscillation is,

$$6.70$$

$$T =$$

$$= 0.67 \text{ s}$$

$$10$$

From Eq. (5.5)

$$2$$

$$4\pi$$

$$B =$$

$$1$$

2

5.1

mT

2

-6

$$4 \times (3.14) \times 7.5 \times 10$$

=

-2

2

XAMPLE

$$6.7 \times 10$$

$$\times (0.67)$$

178

E

$$= 0.01 \text{ T}$$

Magnetism and

Matter

Example 5.2 A short bar magnet placed with its axis at 30° with an external field of 800 G experiences a torque of 0.016 Nm. (a) What is the magnetic moment of the magnet? (b) What is the work done in

moving it from its most stable to most unstable position? (c) The bar magnet is replaced by a solenoid of cross-sectional area $2 \times 10^{-4} \text{ m}^2$ and 1000 turns, but of the same magnetic moment. Determine the current flowing through the solenoid.

Solution

(a) From Eq. (5.3), $\tau = m B \sin \theta$, $\theta = 30^\circ$, hence $\sin \theta = 1/2$.

Thus, $0.016 = m \times (800 \times 10^{-4} \text{ T}) \times (1/2)$

$$m = 160 \times 2/800 = 0.40 \text{ A m}^2$$

(b) From Eq. (5.6), the most stable position is $\theta = 0^\circ$ and the most unstable position is $\theta = 180^\circ$. Work done is given by

$$W = U(\theta = 180^\circ)$$

$$- U(\theta = 0^\circ)$$

E

m

m

XAMPLE

$$= 2 m B = 2 \times 0.40 \times 800 \times 10^{-4} = 0.064 \text{ J}$$

(c) From Eq. (4.30), $m = NIA$. From part (a), $m = 0.40 \text{ A m}^2$

s

s

5.2

$$0.40 = 1000 \times I \times 2 \times 10^{-4}$$

$$I = 0.40 \times 10^4 / (1000 \times 2) = 2\text{A}$$

Example 5.3

- (a) What happens if a bar magnet is cut into two pieces: (i) transverse to its length, (ii) along its length?
- (b) A magnetised needle in a uniform magnetic field experiences a torque but no net force. An iron nail near a bar magnet, however, experiences a force of attraction in addition to a torque. Why?
- (c) Must every magnetic configuration have a north pole and a south pole? What about the field due to a toroid?
- (d) Two identical looking iron bars A and B are given, one of which is definitely known to be magnetised. (We do not know which one.) How would one ascertain whether or not both are magnetised? If only one is magnetised, how does one ascertain which one? [Use nothing else but the bars A and B.]

Solution

- (a) In either case, one gets two magnets, each with a north and south pole.
- (b) No force if the field is uniform. The iron nail experiences a nonuniform field due to the bar magnet. There is induced magnetic

moment in the nail, therefore, it experiences both force and torque.

The net force is attractive because the induced south pole (say) in the nail is closer to the north pole of magnet than induced north pole.

(c) Not necessarily. True only if the source of the field has a net nonzero magnetic moment. This is not so for a toroid or even for a straight infinite conductor.

E

(d) Try to bring different ends of the bars closer. A repulsive force in

XAMPLE

some situation establishes that both are magnetised. If it is always attractive, then one of them is not magnetised. In a bar magnet the intensity of the magnetic field is the strongest at the two ends

5.3

(poles) and weakest at the central region. This fact may be used to determine whether A or B is the magnet. In this case, to see which

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Physics

one of the two bars is a magnet, pick up one, (say, A) and lower one of

5.3

its ends; first on one of the ends of the other (say, B), and then on the

middle of B. If you notice that in the middle of B, A experiences no force, then B is magnetised. If you do not notice any change from the

XAMPLE

end to the middle of B, then A is magnetised.

E

5.2.4 The electrostatic analog

Comparison of Eqs. (5.2), (5.3) and (5.6) with the corresponding equations for electric dipole (Chapter 1), suggests that magnetic field at large distances due to a bar magnet of magnetic moment **m** can be obtained from the equation for electric field due to an electric dipole of dipole moment **p**, by making the following replacements: 1

μ_0

$\mathbf{E} \rightarrow \mathbf{B}, \mathbf{p} \rightarrow \mathbf{m},$

\rightarrow

4ϵ

π

4π

0

In particular, we can write down the equatorial field (**B**) of a bar magnet E at a distance *r*, for $r \gg l$, where *l* is the size of the magnet: $\mu \mathbf{m} 0$

$\mathbf{B} = -$

E

3

(5.7)

$4 \pi r$

Likewise, the axial field (\mathbf{B}) of a bar magnet for $r \gg l$ is: A

$\mu 2m$

0

$\mathbf{B} =$

A

3

(5.8)

$4 \pi r$

Equation (5.8) is just Eq. (5.2) in the vector form. Table 5.1 summarises the analogy between electric and magnetic dipoles.

TABLE 5.1 THE DIPOLE ANALOGY

Electrostatics

Magnetism

$1/\epsilon$

μ

0

0

Dipole moment

p

m

Equatorial Field for a short dipole

$$-\mathbf{p}/4\pi\epsilon r^3$$

$$-\mu \mathbf{m} / 4\pi r^3$$

0

0

Axial Field for a short dipole

$$2\mathbf{p}/4\pi\epsilon r^3$$

$$\mu 2\mathbf{m} / 4\pi r^3$$

0

0

External Field: torque

$$\mathbf{p} \times \mathbf{E}$$

$$\mathbf{m} \times \mathbf{B}$$

External Field: Energy

$$-\mathbf{p} \cdot \mathbf{E}$$

$$-\mathbf{m} \cdot \mathbf{B}$$

Example 5.4 What is the magnitude of the equatorial and axial fields due to a bar magnet of length 5.0 cm at a distance of 50 cm from its midpoint? The magnetic moment of the bar magnet is 0.40 A m², the same as in Example 5.2.

Solution From Eq. (5.7)

—
—

5.4

μm

7

7

10

$\times 0.4 \ 10 \times 0.4$

0

$B =$

=
=

7

—

E

3

=

×

$4 \pi r$

(

3.2×10

T

$0.5)^3$

0.125

$\mu 2 m$

XAMPLE

0

From Eq. (5.8), $B =$

7

—

A

3

$= 6.4 \times 10 \text{ T}$

180

E

$$4\pi r$$

Magnetism and

Matter

Example 5.5 Figure 5.5 shows a small magnetised needle P placed at a point O. The arrow shows the direction of its magnetic moment. The other arrows show different positions (and orientations of the magnetic moment) of another identical magnetised needle Q.

- (a) In which configuration the system is not in equilibrium?
- (b) In which configuration is the system in (i) stable, and (ii) unstable equilibrium?
- (c) Which configuration corresponds to the lowest potential energy among all the configurations shown?

FIGURE 5.5

Solution

Potential energy of the configuration arises due to the potential energy of one dipole (say, Q) in the magnetic field due to other (P). Use the result that the field due to P is given by the expression [Eqs. (5.7) and (5.8)]:

$$\mu_0$$

P

m

B

(on the normal bisector)

3

$4\pi r$

μ^2

0

P

=

m

B

(on the axis)

3

$4\pi r$

where **m** is the magnetic moment of the dipole P.

P

Equilibrium is stable when **m** is parallel to **B**, and unstable when it Q

P

is antiparallel to **B**.

P

For instance for the configuration Q for which Q is along the

3

perpendicular bisector of the dipole P, the magnetic moment of Q is

E

parallel to the magnetic field at the position 3. Hence Q is stable.

3

XAMPLE

Thus,

(a) PQ and PQ

1

2

5.5

(b) (i) PQ , PQ (stable); (ii) PQ , PQ (unstable)

3

6

5

4

(c) PQ6

5.3 MAGNETISM AND GAUSS'S LAW

In Chapter 1, we studied Gauss's law for electrostatics. In Fig 5.3(c), we

see that for a closed surface represented by i , the number of lines leaving the surface is equal to the number of lines entering it. This is consistent with the fact that no net charge is enclosed by the surface. However, in the same figure, for the closed surface ii , there is a net outward flux, since it does include a net (positive) charge.

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The situation is radically different for magnetic fields which are continuous and form closed loops. Examine the Gaussian surfaces represented by i or ii in Fig 5.3(a) or Fig. 5.3(b). Both cases visually demonstrate that the number of magnetic field lines leaving the surface is balanced by the number of lines entering it. The *net magnetic flux is zero for both the surfaces*. This is true

)

for any closed surface.

5581

Karl Friedrich Gauss

(1777 –

(1777 – 1855) He was a child prodigy and was gifted in mathematics, physics, engineering, astronomy and even land surveying.

The properties of numbers

FIGURE 5.6

fascinated him, and in his work he anticipated major

Consider a small vector area element $\Delta\mathbf{S}$ of a closed mathematical development surface S as in Fig. 5.6. The magnetic flux through

$\Delta\mathbf{S}$ is

of later times. Along with

defined as $\Delta\phi = \mathbf{B} \cdot \Delta\mathbf{S}$, where \mathbf{B} is the field at $\Delta\mathbf{S}$. We divide Wilhelm Welsch, he built the B

S into many small area elements and calculate the

first electric telegraph in

1833. His mathematical

individual flux through each. Then, the net flux ϕ is,

B

theory of curved surface

laid the foundation for the

$\phi =$

KARL FRIEDRICH GAUSS

$$\sum \Delta\phi = \sum \mathbf{B}g\Delta\mathbf{S} = 0$$

B

B

(5.9)

'all'

'all'

later work of Riemann.

where 'all' stands for 'all area elements $\Delta\mathbf{S}$ '. Compare this

with the Gauss's law of electrostatics. The flux through a closed surface

in that case is given by

q

$$\sum \mathbf{E}g\Delta\mathbf{S} = \epsilon_0 q$$

where *q* is the electric charge enclosed by the surface.

The difference between the Gauss's law of magnetism and that for electrostatics is a reflection of the fact that isolated magnetic poles (also called monopoles) are not known to exist. There are no sources or sinks of \mathbf{B} ; the simplest magnetic element is a dipole or a current loop. All magnetic phenomena can be explained in terms of an arrangement of dipoles and/or current loops.

Thus, Gauss's law for magnetism is:

The net magnetic flux through any closed surface is zero.

5.6

Example 5.6 Many of the diagrams given in Fig. 5.7 show magnetic field lines (thick lines in the figure) *wrongly*. Point out what is wrong with them. Some of them may describe electrostatic field lines correctly.

XAMPLE

Point out which ones.

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Matter

FIGURE 5.7

Solution

(a) *Wrong*. Magnetic field lines can never emanate from a point, as

E

shown in figure. Over any closed surface, the net flux of \mathbf{B} must

XAMPLE

always be zero, i.e., pictorially as many field lines should seem to enter the surface as the number of lines leaving it. The field lines shown, in fact, represent electric field of a long positively charged

5.6

wire. The correct magnetic field lines are circling the straight conductor, as described in Chapter 4.

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(b) *Wrong*. Magnetic field lines (like electric field lines) can never cross each other, because otherwise the direction of field at the point of intersection is ambiguous. There is further error in the figure.

Magnetostatic field lines can never form closed loops around empty space. A closed loop of static magnetic field line must enclose a region across which a current is passing. By contrast, electrostatic field lines can never form closed loops, neither in empty space, nor when the loop encloses charges.

(c) *Right*. Magnetic lines are completely confined within a toroid.

Nothing wrong here in field lines forming closed loops, since each

loop encloses a region across which a current passes. Note, for clarity of figure, only a few field lines within the toroid have been shown. Actually, the entire region enclosed by the windings contains magnetic field.

(d) *Wrong*. Field lines due to a solenoid at its ends and outside cannot be so completely straight and confined; such a thing violates Ampere's law. The lines should curve out at both ends, and meet

eventually to form closed loops.

(e) *Right*. These are field lines outside and inside a bar magnet. Note carefully the direction of field lines inside. Not all field lines emanate out of a north pole (or converge into a south pole). Around both the N-pole, and the S-pole, the net flux of the field is zero.

(f) *Wrong*. These field lines cannot possibly represent a magnetic field.

Look at the upper region. All the field lines seem to emanate out of the shaded plate. The net flux through a surface surrounding the shaded plate is not zero. This is impossible for a magnetic field.

The given field lines, in fact, show the electrostatic field lines around a positively charged upper plate and a negatively charged lower plate. The difference between Fig. [5.7(e) and (f)] should be

5.6

carefully grasped.

(g) *Wrong*. Magnetic field lines between two pole pieces cannot be precisely straight at the ends. Some fringing of lines is inevitable. Otherwise, Ampere's law is violated. This is also true for electric

XAMPLE

E

field lines.

Example 5.7

(a) Magnetic field lines show the direction (at every point) along which a small magnetised needle aligns (at the point). Do the magnetic field lines also represent the *lines of force* on a moving charged particle at every point?

(b) Magnetic field lines can be entirely confined within the core of a toroid, but not within a straight solenoid. Why?

(c) If magnetic monopoles existed, how would the Gauss's law of magnetism be modified?

(d) Does a bar magnet exert a torque on itself due to its own field?

Does one element of a current-carrying wire exert a force on another element of the *same wire*?

(e) Magnetic field arises due to charges in motion. Can a system have magnetic moments even though its net charge is zero?

5.7

Solution

(a) *No*. The magnetic force is always normal to \mathbf{B} (remember magnetic **XAMPLE**

force = $q\mathbf{v} \times \mathbf{B}$). It is misleading to call *magnetic field lines* as *lines* 184

E

of force.

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Matter

(b) If field lines were entirely confined between two ends of a straight solenoid, the flux through the cross-section at each end would be nonzero. But the flux of field \mathbf{B} through any closed surface must always be zero. For a toroid, this difficulty is absent because it has no 'ends'.

(c) Gauss's law of magnetism states that the flux of \mathbf{B} through any closed surface is always zero

d

g

$= 0$

$\int \mathbf{B} \cdot \mathbf{s}$

\tilde{N}

.

S

If monopoles existed, the right hand side would be equal to the monopole (magnetic charge) q enclosed by S . [Analogous to

m

Gauss's law of electrostatics,

d

g

$= \mu q$

$\int \mathbf{B} \cdot \mathbf{s}$

where q is the

$0 m$

S

m

(monopole) magnetic charge enclosed by S .]

(d) *No*. There is no force or torque on an element due to the field produced by that element itself. But there is a force (or torque) on an element of the same wire. (For the special case of a straight

E

wire, this force is zero.)

XAMPLE

(e) *Yes*. The average of the charge in the system may be zero. Yet, the mean of the magnetic moments due to various current loops may not be zero. We will come across such examples in connection

5.7

with paramagnetic material where atoms have net dipole moment through their net charge is zero.

5.4 THE EARTH'S MAGNETISM

Earlier we have referred to the magnetic field of the earth. The strength of the earth's magnetic field varies from place to place on the earth's surface; its value being of the order of 10^{-5} T.

<http://www.ngdc.noaa.gov/seg/geomag/> **Geomagnetic field frequently asked questions o**

What causes the earth to have a magnetic field is not clear. Originally the magnetic field was thought of as arising from a giant bar magnet placed approximately along the axis of rotation of the earth and deep in

e

the interior. However, this simplistic picture is certainly not correct. The

magnetic field is now thought to arise due to electrical currents produced

ld

by convective motion of metallic fluids (consisting mostly of molten iron and nickel) in the outer core of the earth. This is known as the *dynamo effect*.

n

The magnetic field lines of the earth resemble that of a (hypothetical) magnetic dipole located at the centre of the earth. The axis of the dipole does not coincide with the axis of rotation of the earth but is presently

titled by approximately 11.3° with respect to the later. In this way of looking at it, the magnetic poles are located where the magnetic field lines due to the dipole enter or leave the earth. The location of the north magnetic pole

io

is at a latitude of 79.74° N and a longitude of 71.8° W, a place somewhere in north Canada. The magnetic south pole is at 79.74° S, 108.22° E in the Antarctica.

The pole near the geographic north pole of the earth is called the *north*

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magnetic pole. Likewise, the pole near the geographic south pole is called

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the *south magnetic pole*. There is some confusion in the nomenclature of the poles. If one looks at the magnetic field lines of the earth (Fig. 5.8), one sees that unlike in the case of a bar magnet, the field lines go into the earth at the north magnetic pole (N) and come out from the south

m

magnetic pole (S). The convention arose because the

m

magnetic north was the direction to which the north pole of a magnetic needle pointed; the north pole of a magnet was so named as it was the *north seeking pole*. Thus, in reality, the north magnetic pole behaves

FIGURE 5.8 The earth as a giant

like the south pole of a bar magnet inside the earth and magnetic dipole.

vice versa.

Example 5.8 The earth's magnetic field at the equator is approximately 0.4 G. Estimate the earth's dipole moment.

Solution From Eq. (5.7), the equatorial magnetic field is,

μm

0

$B =$

E

3

$4 \pi r$

We are given that $B \sim 0.4 \text{ G} = 4 \times 10^{-5} \text{ T}$. For r , we take the radius of E the earth $6.4 \times 10^6 \text{ m}$. Hence,

5.8

5

—

6 3

4×10

$\times (6.4 \times 10)$

$m =$

μ

$/4\pi = 10^{-7}$)

$/ 4\pi$

$= 4 \times 10^2 \times (6.4 \times 10^6)^3 (\mu_0$

0

$= 1.05 \times 10^{23} \text{ A m}^2$

XAMPLE

E

This is close to the value $8 \times 10^{22} \text{ A m}^2$ quoted in geomagnetic texts.

5.4.1 Magnetic declination and dip

Consider a point on the earth's surface. At such a point, the direction of the longitude circle determines the geographic north-south direction, the line of longitude towards the north pole being the direction of true north. The vertical plane containing the longitude circle and the axis of rotation of the earth is called the *geographic meridian*. In a similar way, one can define *magnetic meridian* of a place as the vertical plane which passes through the imaginary line joining the magnetic north and the south poles. This plane would intersect the surface of the earth in a longitude like circle. A magnetic needle, which is free to swing horizontally, would then lie in the magnetic meridian and the north pole of the needle would point towards the magnetic north pole. Since the line joining the magnetic poles is tilted with respect to the geographic axis of the earth, the magnetic meridian at a point makes angle with the geographic meridian. This, then, is the angle between the true geographic north and

FIGURE 5.9 A magnetic needle

free to move in horizontal plane,

the north shown by a compass needle. This angle is called the

points toward the magnetic

magnetic declination or simply *declination* (Fig. 5.9).

north-south

The declination is greater at higher latitudes and smaller

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direction.

near the equator. The declination in India is small, it being

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$0^{\circ}41'$ E at Delhi and $0^{\circ}58'$ W at Mumbai. Thus, at both these places a

magnetic needle shows the true north quite accurately.

There is one more quantity of interest. If a magnetic needle is perfectly

balanced about a horizontal axis so that it can swing in a plane of the

magnetic meridian, the needle would make an angle with the horizontal

(Fig. 5.10). This is known as the *angle of dip* (also known as *inclination*).

Thus, dip is the angle that the total magnetic field **B** of the earth makes E

with the surface of the earth. Figure 5.11 shows the magnetic meridian

plane at a point P on the surface of the earth. The plane is a section through the earth. The total magnetic field at P can be resolved into a horizontal component **H** and a vertical component **Z**. The angle that **B** makes with **H** is the angle of dip, *I*.

FIGURE 5.10 The circle is a

FIGURE 5.11 The earth's section through the earth magnetic field, **B**, its horizontal component **H** and vertical component **Z**. Also shown are the

E

E

and the horizontal component

declination, D and the

\mathbf{H} is the angle of dip.

inclination or angle of dip, I .

E

In most of the northern hemisphere, the north pole of the dip needle tilts downwards. Likewise in most of the southern hemisphere, the south pole of the dip needle tilts downwards.

To describe the magnetic field of the earth at a point on its surface, we need to specify three quantities, viz., the declination D , the angle of dip or the inclination I and the horizontal component of the earth's field H . These

are known as the *element of the earth's magnetic field*.

Representing the vertical component by Z , we have

E

$$Z = B \sin I$$

[5.10(a)]

E

E

$$H = B \cos I$$

[5.10(b)]

E

E

which gives,

Z

\tan

E

$$I = H$$

[5.10(c)]

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E

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WHAT HAPPENS TO MY COMPASS NEEDLES AT THE POLES?

A compass needle consists of a magnetic needle which floats on a pivotal point. When the compass is held level, it points along the direction of the horizontal component of the earth's magnetic field at the location. Thus, the compass needle would stay along the magnetic meridian of the place. In some places on the earth there are deposits of magnetic minerals which cause the compass needle to deviate from the magnetic meridian. Knowing the magnetic declination at a place allows us to correct the compass to determine the direction of true north.

So what happens if we take our compass to the magnetic pole? At the poles, the magnetic field lines are converging or diverging vertically so that the

horizontal component is negligible.

If the needle is only capable of moving in a horizontal plane, it can point along any direction, rendering it useless as a direction finder. What one needs in such a case is a *dip needle* which is a compass pivoted to move in a vertical plane containing the magnetic field of the earth. The needle of the compass then shows the angle which the magnetic field makes with the vertical. At the magnetic poles such a needle will point straight down.

Example 5.9 In the magnetic meridian of a certain place, the horizontal component of the earth's magnetic field is 0.26G and the dip angle is 60° . What is the magnetic field of the earth at this location?

Solution

It is given that $H = 0.26$ G. From Fig. 5.11, we have

$$E$$

$$H$$

$$0$$

$$\cos 60$$

$$E$$

$$= BE$$

$$5.9$$

$$H E$$

$$B$$

$$=$$

E

0

$\cos 60$

0.26

XAMPLE

=

= 0.52 G

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E

(1/ 2)

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EARTH'S MAGNETIC FIELD

It must not be assumed that there is a giant bar magnet deep inside the earth which is causing the earth's magnetic field. Although there are large deposits of iron inside the earth, it is highly unlikely that a large solid block of iron stretches from the magnetic north pole to the magnetic south pole. The earth's core is very hot and molten, and the ions of iron and nickel are responsible for earth's magnetism. This hypothesis seems very probable. Moon, which has no molten core, has no magnetic field, Venus has a slower rate of rotation, and a weaker magnetic field, while Jupiter, which has the fastest rotation rate among planets, has a fairly strong magnetic field. However, the precise mode of these circulating currents and the energy needed to sustain them are not very well understood. These are several open questions which form an important area of continuing research.

The variation of the earth's magnetic field with position is also an interesting area of study. Charged particles emitted by the sun flow towards the earth and beyond, in a stream called the solar wind. Their motion is affected by the earth's magnetic field, and in turn, they affect the pattern of the earth's magnetic field. The pattern of magnetic field near the poles is quite different from that in other regions of the earth.

The variation of earth's magnetic field with time is no less fascinating. There are short term variations taking place over centuries and long term variations taking place over a period of a million years. In a span of 240 years from 1580 to 1820 AD, over which records are available, the magnetic declination at London has been found to change by 3.5° , suggesting that the magnetic poles inside the earth change position with time. On the scale of a million years, the earth's magnetic fields has been found to reverse its direction. Basalt contains iron, and basalt is emitted during volcanic activity. The little iron magnets inside it align themselves parallel to the magnetic field at that place as the basalt cools and solidifies.

Geological studies of basalt containing such pieces of magnetised region have provided evidence for the change of direction of earth's magnetic field, several times in the past.

5.5 MAGNETISATION AND MAGNETIC INTENSITY

The earth abounds with a bewildering variety of elements and compounds.

In addition, we have been synthesising new alloys, compounds and even elements. One would like to classify the magnetic properties of these substances. In the present section, we define and explain certain terms which will help us to carry out this exercise.

We have seen that a circulating electron in an atom has a magnetic moment. In a bulk material, these moments add up vectorially and they can give a net magnetic moment which is nonzero. We define

magnetisation \mathbf{M} of a sample to be equal to its net magnetic moment per unit volume:

net

$$= \mathbf{m}$$

\mathbf{M}

$$(5.11)$$

V

\mathbf{M} is a vector with dimensions $L^{-1} A$ and is measured in a units of $A m^{-1}$.

Consider a long solenoid of n turns per unit length and carrying a

current I . The magnetic field in the interior of the solenoid was shown to

be given by

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$$\mathbf{B} = \mu nI$$

$$(5.12)$$

0

0

If the interior of the solenoid is filled with a material with nonzero

magnetisation, the field inside the solenoid will be greater than \mathbf{B} . The 0

net \mathbf{B} field in the interior of the solenoid may be expressed as

$$\mathbf{B} = \mathbf{B} + \mathbf{B}$$

(5.13)

0

m

where **B** is the field contributed by the material core. It turns out that m this additional field **B** is proportional to the magnetisation **M** of the m material and is expressed as

$$\mathbf{B} = \mu \mathbf{M}$$

(5.14)

m

0

where μ is the same constant (permeability of vacuum) that appears in

0

Biot-Savart's law.

It is convenient to introduce another vector field **H**, called the *magnetic intensity*, which is defined by $\mathbf{H} = \mathbf{B}$

H

—

μ

M

(5.15)

0

where \mathbf{H} has the same dimensions as \mathbf{M} and is measured in units of A m^{-1} .

Thus, the total magnetic field \mathbf{B} is written as

$$\mathbf{B} = \mu (\mathbf{H} + \mathbf{M})$$

(5.16)

0

We repeat our defining procedure. We have partitioned the contribution

to the total magnetic field inside the sample into two parts: *one*, due to external factors such as the current in the solenoid. This is represented by \mathbf{H} . The *other* is due to the specific nature of the magnetic material, namely \mathbf{M} . The latter quantity can be influenced by external factors. This influence is mathematically expressed as $\mathbf{M} = \chi \mathbf{H}$

(5.17)

where χ , a dimensionless quantity, is appropriately called the *magnetic*

susceptibility. It is a measure of how a magnetic material responds to an external field. Table 5.2 lists χ for some elements. It is small and positive for materials, which are called *paramagnetic*. It is small and negative for materials, which are termed *diamagnetic*. In the latter case \mathbf{M} and \mathbf{H} are opposite in direction. From Eqs. (5.16) and (5.17) we obtain, $\mathbf{B} = \mu (1 + \chi)\mathbf{H}$

(5.18)

0

$$= \mu \mu \mathbf{H}$$

0 r

$$= \mu \mathbf{H}$$

(5.19)

where $\mu = 1 + \chi$, is a dimensionless quantity called the *relative magnetic*

r

permeability of the substance. It is the analog of the dielectric constant in electrostatics. The *magnetic permeability* of the substance is μ and it has the same dimensions and units as μ_0 ; 0

$$\mu = \mu_0 \mu_r = \mu_0 (1 + \chi).$$

$0 r$

0

The three quantities χ , μ and μ_r are interrelated and only one of

r

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them is independent. Given one, the other two may be easily determined.

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TABLE 5.2 MAGNETIC SUSCEPTIBILITY OF SOME ELEMENTS AT 300 K

Diamagnetic substance

χ

Paramagnetic substance

χ

Bismuth

$$-1.66 \times 10^{-5}$$

Aluminium

$$2.3 \times 10^{-5}$$

Copper

$$-9.8 \times 10^{-6}$$

Calcium

$$1.9 \times 10^{-5}$$

Diamond

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

Chromium

$$2.7 \times 10^{-4}$$

Gold

$$-3.6 \times 10^{-5}$$

Lithium

$$2.1 \times 10^{-5}$$

Lead

$$-1.7 \times 10^{-5}$$

Magnesium

$$1.2 \times 10^{-5}$$

Mercury

$$-2.9 \times 10^{-5}$$

Niobium

$$2.6 \times 10^{-5}$$

Nitrogen (STP)

$$-5.0 \times 10^{-9}$$

Oxygen (STP)

$$2.1 \times 10^{-6}$$

Silver

$$-2.6 \times 10^{-5}$$

Platinum

$$2.9 \times 10^{-4}$$

Silicon

$$-4.2 \times 10^{-6}$$

Tungsten

$$6.8 \times 10^{-5}$$

Example 5.10 A solenoid has a core of a material with relative permeability 400. The windings of the solenoid are insulated from the core and carry a current of 2A. If the number of turns is 1000 per metre, calculate (a) H , (b) M , (c) B and (d) the magnetising current I .

m

Solution

(a) The field H is dependent of the material of the core, and is

$$H = nI = 1000 \times 2.0 = 2 \times 10^3 \text{ A/m.}$$

(b) The magnetic field B is given by

$$B = \mu \mu_0 H$$

r

0

$$= 400 \times 4\pi \times 10^{-7} \text{ (N/A}^2\text{)} \times 2 \times 10^3 \text{ (A/m)}$$

$$= 1.0 \text{ T}$$

(c) Magnetisation is given by

$$M = (B - \mu_0 H) / \mu_0$$

0

0

E

$$= (\mu \mu_0 H - \mu_0 H) / \mu_0 = (\mu - 1) H = 399 \times H$$

r

0

0

0

r

XAMPLE

$$\cong 8 \times 10^5 \text{ A/m}$$

(d) The magnetising current I is the additional current that needs

M

to be passed through the windings of the solenoid in the absence

5.10

of the core which would give a B value as in the presence of the

core. Thus $B = \mu n (I + I)$. Using $I = 2\text{A}$, $B = 1\text{ T}$, we get $I = 794\text{ A}$.

r

0

M

M

5.6 MAGNETIC PROPERTIES OF MATERIALS

The discussion in the previous section helps us to classify materials as diamagnetic, paramagnetic or ferromagnetic. In terms of the susceptibility

χ , a material is diamagnetic if χ is negative, para-if χ is positive and small, and ferro-if χ is large and positive.

A glance at Table 5.3 gives one a better feeling for these

materials. Here ϵ is a small positive number introduced to quantify

paramagnetic materials. Next, we describe these materials in some

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detail.

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TABLE 5.3

Diamagnetic

Paramagnetic

Ferromagnetic

$$-1 \leq \chi < 0$$

$$0 < \chi < \epsilon$$

$$\chi \gg 1$$

$$0 \leq \mu < 1$$

$$1 < \mu < 1 + \epsilon$$

$$\mu \gg 1$$

r

r

r

$$\mu < \mu$$

$$\mu > \mu$$

$$\mu \gg \mu$$

0

0

0

5.6.1 Diamagnetism

Diamagnetic substances are those which have tendency to move from stronger to the weaker part of the external magnetic field. In other words, unlike the way a magnet attracts metals like iron, it would repel a diamagnetic substance.

Figure 5.12(a) shows a bar of diamagnetic material placed in an external magnetic field. The field lines are repelled or expelled and the field inside the material is reduced. In most cases, as is evident from

Table 5.2, this reduction is slight, being one part in 105. When placed in a nonuniform magnetic field, the bar will tend to move from high to low field.

The simplest explanation for diamagnetism is as follows. Electrons in an atom orbiting around nucleus possess orbital angular momentum.

These orbiting electrons are equivalent to current-carrying loop and thus possess orbital magnetic moment. Diamagnetic substances are the ones in which resultant magnetic moment in an atom is zero. When magnetic field is applied, those electrons having orbital magnetic moment in the same direction slow down and those in the opposite direction speed up.

This happens due to induced current in accordance with Lenz's law which you will study in Chapter 6. Thus, the substance develops a net magnetic moment in direction opposite to that of the applied field and hence

FIGURE 5.12

repulsion.

Behaviour of

Some diamagnetic materials are bismuth, copper, lead, silicon,

magnetic field lines

near a

nitrogen (at STP), water and sodium chloride. Diamagnetism is present

(a) diamagnetic,

in all the substances. However, the effect is so weak in most cases that it

(b) paramagnetic

gets shifted by other effects like paramagnetism, ferromagnetism, *etc.*

substance.

The most exotic diamagnetic materials are *superconductors*. These

are metals, cooled to very low temperatures which exhibits both *perfect*

conductivity and *perfect diamagnetism*. Here the field lines are completely expelled! $\chi = -1$ and $\mu = 0$. A superconductor repels a magnet and (by *r*

Newton's third law) is repelled by the magnet. The phenomenon of perfect

diamagnetism in superconductors is called the *Meissner effect*, after the name of its discoverer. Superconducting magnets can be gainfully exploited in variety of situations, for example, for running magnetically

levitated superfast trains.

5.6.2 Paramagnetism

Paramagnetic substances are those which get weakly magnetised when placed in an external magnetic field. They have tendency to move from a region of weak magnetic field to strong magnetic field, i.e., they get weakly

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attracted to a magnet.



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The individual atoms (or ions or molecules) of a paramagnetic material possess a permanent magnetic dipole moment of their own. On account of the ceaseless random thermal motion of the atoms, no net magnetisation is seen. In the presence of an external field \mathbf{B} , which is strong enough, 0 and at low temperatures, the individual atomic dipole moment can be

made to align and point in the same direction as \mathbf{B} . Figure 5.12(b) shows a bar of paramagnetic material placed in an external field. The field lines

http://www.aacg.bham.ac.uk/magnetic_materials/ **Magnetic materials, domain, etc.:** gets concentrated inside the material, and the field inside is enhanced. In most cases, as is evident from Table 5.2, this enhancement is slight, being

one part in 105. When placed in a nonuniform magnetic field, the bar will tend to move from weak field to strong.

Some paramagnetic materials are aluminium, sodium, calcium, oxygen (at STP) and copper chloride. Experimentally, one finds that the magnetisation of a paramagnetic material is inversely proportional to the absolute temperature T ,

$$B_0$$

$$M = C$$

$$[5.20(a)]$$

$$T$$

or equivalently, using Eqs. (5.12) and (5.17)

$$\mu_0$$

$$\chi = C$$

$$[5.20(b)]$$

$$T$$

This is known as *Curie's law*, after its discoverer Pierree Curie (1859—1906). The constant C is called *Curie's constant*. Thus, for a paramagnetic material both χ and μ depend not only on the material, but also r (in a simple fashion) on the sample temperature. As the field is increased or the temperature is lowered, the magnetisation increases until it reaches the saturation value M_s , at which point all the dipoles are perfectly aligned with the field. Beyond this, Curie's law [Eq. (5.20)] is no longer valid.

5.6.3 Ferromagnetism

Ferromagnetic substances are those which gets strongly magnetised when placed in an external magnetic field. They have strong tendency to move from a region of weak magnetic field to strong magnetic field, i.e., they get strongly attracted to a magnet.

The individual atoms (or ions or molecules) in a ferromagnetic material possess a dipole moment as in a paramagnetic material. However, they interact with one another in such a way that they spontaneously align themselves in a common direction over a macroscopic volume called *domain*. The explanation of this cooperative effect requires quantum mechanics and is beyond the scope of this textbook. Each domain has a net magnetisation. Typical domain size is 1mm and the domain contains

about 10¹¹ atoms. In the first instant, the magnetisation varies randomly from domain to domain and there is no bulk magnetisation. This is shown

FIGURE 5.13

in Fig. 5.13(a). When we apply an external magnetic field \mathbf{B} , the domains

(a) Randomly

orient themselves in the direction of \mathbf{B} and simultaneously the domain oriented domains,

0

oriented in the direction of \mathbf{B} grow in size. This existence of domains and

(b) Aligned domains.

0

their motion in \mathbf{B} are not speculations. One may observe this under a

0

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microscope after sprinkling a liquid suspension of powdered

Physics

ferromagnetic substance of samples. This motion of suspension can be

observed. Figure 5.12(b) shows the situation when the domains have

aligned and amalgamated to form a single 'giant' domain.

Thus, in a ferromagnetic material the field lines are highly

concentrated. In nonuniform magnetic field, the sample tends to move

towards the region of high field. We may wonder as to what happens when the external field is removed. In some ferromagnetic materials the magnetisation persists. Such materials are called *hard* magnetic materials or *hard ferromagnets*. Alnico, an alloy of iron, aluminium, nickel, cobalt and copper, is one such material. The naturally occurring lodestone is another. Such materials form permanent magnets to be used among other things as a compass needle. On the other hand, there is a class of ferromagnetic materials in which the magnetisation disappears on removal of the external field. Soft iron is one such material. Appropriately enough, such materials are called *soft ferromagnetic materials*. There are a number of elements, which are ferromagnetic: iron, cobalt, nickel, gadolinium, *etc.* The relative magnetic permeability is $>1000!$

The ferromagnetic property depends on temperature. At high enough temperature, a ferromagnet becomes a paramagnet. The domain structure disintegrates with temperature. This disappearance of magnetisation with temperature is gradual. It is a phase transition reminding us of the melting of a solid crystal. The temperature of transition from ferromagnetic to paramagnetism is called the *Curie temperature* T_c . Table 5.4 lists

c

the Curie temperature of certain ferromagnets. The susceptibility above the Curie temperature, i.e., in the paramagnetic phase is described by,

C

$\chi =$

$(T > T_c)$

c

$T - T_c$

(5.21)

c

TABLE 5.4 CURIE TEMPERATURE T_c OF SOME

C

Hysteresis in magnetic materials:

<http://hyperphysics.phy-astr.gsu.edu/hbase/solids/hyst.html>

FERROMAGNETIC MATERIALS

Material

T_c (K)

c

Cobalt

1394

Iron

1043

FeO

893

2

3

Nickel

631

Gadolinium

317

Example 5.11 A domain in ferromagnetic iron is in the form of a cube of side length $1\mu\text{m}$. Estimate the number of iron atoms in the domain

5.11

and the maximum possible dipole moment and magnetisation of the domain. The molecular mass of iron is 55 g/mole and its density is 7.9 g/cm^3 . Assume that each iron atom has a dipole moment

XAMPLE

of $9.27 \times 10^{-24}\text{ A m}^2$.

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Solution The volume of the cubic domain is

$$V = (10^{-6} \text{ m})^3 = 10^{-18} \text{ m}^3 = 10^{-12} \text{ cm}^3$$

Its mass is volume \times density = $7.9 \text{ g cm}^{-3} \times 10^{-12} \text{ cm}^3 = 7.9 \times 10^{-12} \text{ g}$

It is given that Avagadro number (6.023×10^{23}) of iron atoms have a mass of 55 g. Hence, the number of atoms in the domain is

12

—

23

$$7.9 \times 10$$

$$\times 6.023 \times 10$$

$$N =$$

55

$$= 8.65 \times 10^{10} \text{ atoms}$$

The maximum possible dipole moment m

is achieved for the

max

(unrealistic) case when all the atomic moments are perfectly aligned.

Thus,

m

$$= (8.65 \times 10^{10}) \times (9.27 \times 10^{-24})$$

max

E

$$= 8.0 \times 10^{-13} \text{ A m}^2$$

XAMPLE

The consequent magnetisation is

M

$$= m$$

/ Domain volume

max

max

5.11

$$= 8.0 \times 10^{-13} \text{ Am}^2 / 10^{-18} \text{ m}^3$$

$$= 8.0 \times 10^5 \text{ Am}^{-1}$$

The relation between **B** and **H** in ferromagnetic materials is complex.

It is often not linear and it depends on the magnetic history of the sample.

Figure 5.14 depicts the behaviour of the material as we take it through one cycle of magnetisation. Let the material be unmagnetised initially. We place it in a solenoid and increase the current through the solenoid. The magnetic field *B* in the material rises and saturates as depicted in the curve Oa. This behaviour represents the alignment and merger of domains until no

further enhancement is possible. It is pointless to increase the current (and hence the magnetic intensity H) beyond this. Next, we decrease H and reduce it to zero. At $H = 0$, $B \neq 0$. This is represented by the curve ab . The value of B at $H = 0$ is called *retentivity* or *remanence*. In Fig. 5.14, $B \sim R$

1.2 T, where the subscript R denotes retentivity. The domains are not completely randomised even though the external driving field has been removed. Next, the current in the solenoid is reversed and slowly increased. Certain domains are flipped until the net field inside stands nullified. This is represented by the curve bc . The value of H at c is called *coercivity*. In Fig. 5.14 $H \sim -90 \text{ A m}^{-1}$. As

FIGURE 5.14 The magnetic

c

the reversed current is increased in magnitude, we once again obtain saturation. The curve cd depicts this. The ferromagnetic materials.

saturated magnetic field $B \sim 1.5 \text{ T}$. Next, the current is

s

reduced (curve *de*) and reversed (curve *ea*). The cycle repeats

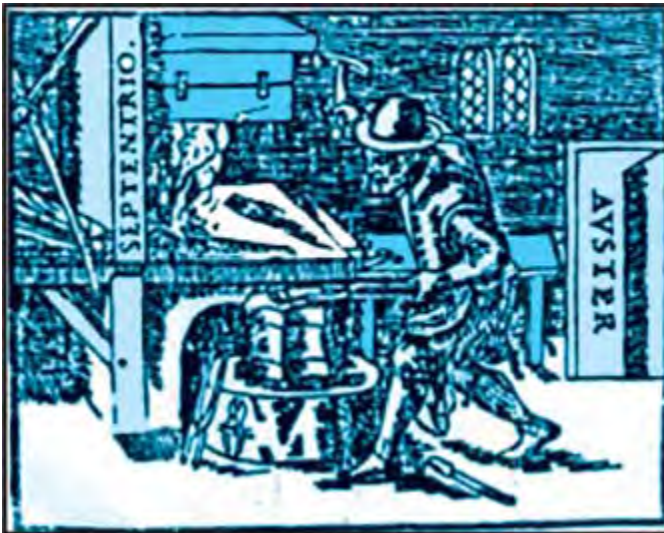
itself. Note that the curve *Oa* does not retrace itself as *H* is reduced. For a given value of *H*, *B* is not unique but depends on previous history of the sample. This phenomenon is called *hysteresis*. The word *hysteresis* means *lagging behind* (and not ‘history’).

5.7 PERMANENT MAGNETS AND ELECTROMAGNETS

Substances which at room temperature retain their ferromagnetic property

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for a long period of time are called *permanent magnets*. Permanent



Physics

magnets can be made in a variety of ways. One can hold an iron rod in the north-south direction and hammer it repeatedly. The method is illustrated in Fig. 5.15. The illustration is from a 400 year old book to emphasise that the making of permanent magnets is an old *art*. One can also hold a steel rod and stroke it with one end of a bar magnet a large number of times, always in the same sense to make a permanent magnet.

An efficient way to make a permanent magnet is to place a ferromagnetic rod in a solenoid and pass a current. The magnetic field of the solenoid magnetises the rod.

FIGURE 5.15 A blacksmith

The hysteresis curve (Fig. 5.14) allows us to select suitable materials for permanent magnets. The material should have striking a red-hot rod of iron high retentivity so that the magnet is strong and high coercivity kept in the north-south direction with a hammer. The

so that the magnetisation is not erased by stray magnetic fields, sketch is recreated from an temperature fluctuations or minor mechanical damage.

illustration in De Magnete, a

Further, the material should have a high permeability. Steel is work published in 1600 and

one-favoured choice. It has a slightly smaller retentivity than authored by William Gilbert,

soft iron but this is outweighed by the much smaller coercivity the court physician to Queen

of soft iron. Other suitable materials for permanent magnets Elizabeth of England.

are alnico, cobalt steel and ticonal.

Core of electromagnets are made of ferromagnetic materials

which have high permeability and low retentivity. Soft iron is a suitable material for electromagnets. On placing a soft iron rod in a solenoid and passing a current, we increase the magnetism of the solenoid by a

thousand fold. When we switch off the solenoid current, the magnetism is effectively switched off since the soft iron core has a low retentivity. The arrangement is shown in Fig. 5.16.

India's Magnetic Field:

<http://iigs.iigm.res.in>

FIGURE 5.16 A soft iron core in solenoid acts as an electromagnet.

In certain applications, the material goes through an ac cycle of magnetisation for a long period. This is the case in transformer cores and telephone diaphragms. The hysteresis curve of such materials must be narrow. The energy dissipated and the heating will consequently be small. The material must have a high resistivity to lower eddy current losses. You will study about eddy currents in Chapter 6.

Electromagnets are used in electric bells, loudspeakers and telephone diaphragms. Giant electromagnets are used in cranes to lift machinery,

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and bulk quantities of iron and steel.

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MAPPING INDIA'S MAGNETIC FIELD

Because of its practical application in prospecting, communication, and navigation, the magnetic field of the earth is mapped by most nations with an accuracy comparable to geographical mapping. In India over a dozen observatories exist, extending from Trivandrum (now Thiruvananthapuram) in the south to Gulmarg in the north. These observatories work under the aegis of the Indian Institute of Geomagnetism (IIG), in Colaba, Mumbai. The IIG grew out of the Colaba and Alibag

observatories and was formally established in 1971. The IIG monitors (via its nation-wide observatories), the geomagnetic fields and fluctuations on land, and under the ocean and in space. Its services are used by the Oil and Natural Gas Corporation Ltd. (ONGC), the National Institute of Oceanography (NIO) and the Indian Space Research Organisation (ISRO). It is a part of the world-wide network which ceaselessly updates the geomagnetic data. Now India has a permanent station called Gangotri.

SUMMARY

1.

The science of magnetism is old. It has been known since ancient times that magnetic materials tend to point in the north-south direction; like magnetic poles repel and unlike ones attract; and cutting a bar magnet in two leads to two smaller magnets. Magnetic poles cannot be isolated.

2.

When a bar magnet of dipole moment \mathbf{m} is placed in a uniform magnetic field \mathbf{B} ,

(a)

the force on it is zero,

(b)

the torque on it is $\mathbf{m} \times \mathbf{B}$,

(c)

its potential energy is $-\mathbf{m} \cdot \mathbf{B}$, where we choose the zero of energy at the orientation when \mathbf{m} is perpendicular to \mathbf{B} .

3.

Consider a bar magnet of size l and magnetic moment \mathbf{m} , at a distance r from its midpoint, where $r \gg l$, the magnetic field \mathbf{B} due to this bar is, $\mu \mathbf{m}$

0

$\mathbf{B} =$

3 (along axis)

$2 \pi r$

$\mu \mathbf{m}$

=

0

—

(along equator)

3

$4 \pi r$

4.

Gauss's law for magnetism states that the net magnetic flux through any closed surface is zero

$\varphi =$

$\sum \mathbf{B} \cdot \Delta \mathbf{S} = 0$

B

all area

elements ΔS

5.

The earth's magnetic field resembles that of a (hypothetical) magnetic dipole located at the centre of the earth. The pole near the geographic north pole of the earth is called the north magnetic pole. Similarly, the pole near the geographic south pole is called the south magnetic pole.

This dipole is aligned making a small angle with the rotation axis of the earth. The magnitude of the field on the earth's surface $\approx 4 \times 10^{-5}$ T.

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Physics

6.

Three quantities are needed to specify the magnetic field of the earth on its surface – the horizontal component, the magnetic declination, and the magnetic dip. These are known as the elements of the earth's magnetic field.

7.

Consider a material placed in an external magnetic field \mathbf{B} . The

0

magnetic intensity is defined as,

0

= \mathbf{B}

\mathbf{H}

μ_0

The magnetisation \mathbf{M} of the material is its dipole moment per unit volume.

The magnetic field \mathbf{B} in the material is,

$$\mathbf{B} = \mu (\mathbf{H} + \mathbf{M})$$

0

8.

For a linear material $\mathbf{M} = \chi \mathbf{H}$. So that $\mathbf{B} = \mu \mathbf{H}$ and χ is called the magnetic susceptibility of the material. The three quantities, χ , the relative magnetic permeability μ_r , and the magnetic permeability μ are

r

related as follows:

$$\mu = \mu_r \mu_0$$

0

r

$$\mu_r = 1 + \chi$$

r

9.

Magnetic materials are broadly classified as: diamagnetic, paramagnetic, and ferromagnetic. For diamagnetic materials χ is negative and small

and for paramagnetic materials it is positive and small. Ferromagnetic materials have large χ and are characterised by non-linear relation between **B** and **H**. They show the property of hysteresis.

10. Substances, which at room temperature, retain their ferromagnetic property for a long period of time are called permanent magnets.

Physical quantity

Symbol

Nature

Dimensions

Units

Remarks

Permeability of

μ

Scalar

[MLT⁻² A⁻²]

T m A⁻¹

$\mu / 4\pi = 10^{-7}$

0

0

free space

Magnetic field,

B

Vector

$[MT^{-2} A^{-1}]$

T (tesla)

104 G (gauss) = 1 T

Magnetic induction,

Magnetic flux density

Magnetic moment

m

Vector

$[L^{-2} A]$

A m²

Magnetic flux

ϕ

Scalar

$[ML^2T^{-2} A^{-1}]$

W (weber)

$W = T m^2$

B

Magnetic moment

Magnetisation

M

Vector

[L⁻¹ A]

A m⁻¹

Volume

Magnetic intensity

H

Vector

[L⁻¹ A]

A m⁻¹

$$\mathbf{B} = \mu (\mathbf{H} + \mathbf{M})$$

0

Magnetic field

strength

Magnetic

χ

Scalar

-

-

$$\mathbf{M} = \chi \mathbf{H}$$

susceptibility

Relative magnetic

μ

Scalar

-

-

$$\mathbf{B} = \mu \mu \mathbf{H}$$

r

0

r

permeability

Magnetic permeability

μ

Scalar

[MLT⁻² A⁻²]

T m A⁻¹

$\mu = \mu \mu$

0 r

N A⁻²

$$\mathbf{B} = \mu \mathbf{H}$$

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Matter

POINTS TO PONDER

1.

A satisfactory understanding of magnetic phenomenon in terms of moving charges/currents was arrived at after 1800 AD. But technological exploitation of the directional properties of magnets predates this scientific understanding by two thousand years. Thus, scientific understanding is not a necessary condition for engineering applications. Ideally, science and engineering go hand-in-hand, one leading and assisting the other in tandem.

2.

Magnetic monopoles do not exist. If you slice a magnet in half, you get two smaller magnets. On the other hand, isolated positive and negative charges exist. There exists a smallest unit of charge, for example, the electronic charge with value $|e| = 1.6 \times 10^{-19}$ C. All other charges are integral multiples of this smallest unit charge. In other words, charge is quantised. We do not know why magnetic monopoles do not exist or why electric charge is quantised.

3.

A consequence of the fact that magnetic monopoles do not exist is that

the magnetic field lines are continuous and form closed loops. In contrast, the electrostatic lines of force begin on a positive charge and terminate on the negative charge (or fade out at infinity).

4.

The earth's magnetic field is not due to a huge bar magnet inside it. The earth's core is hot and molten. Perhaps convective currents in this core are responsible for the earth's magnetic field. As to what 'dynamo' effect sustains this current, and why the earth's field reverses polarity every million years or so, we do not know.

5.

A miniscule difference in the value of χ , the magnetic susceptibility, yields radically different behaviour: diamagnetic versus paramagnetic. For diamagnetic materials $\chi = -10^{-5}$ whereas $\chi = +10^{-5}$ for paramagnetic materials.

6.

There exists *a perfect diamagnet*, namely, a superconductor. This is a metal at very low temperatures. In this case $\chi = -1$, $\mu = 0$, $\mu = 0$. The

r

external magnetic field is totally expelled. Interestingly, this material is also a perfect conductor. However, there exists no classical theory which

ties these two properties together. A quantum-mechanical theory by Bardeen, Cooper, and Schrieffer (BCS theory) explains these effects. The BCS theory was proposed in 1957 and was eventually recognised by a Nobel

Prize in physics in 1970.

7.

The phenomenon of magnetic hysteresis is reminiscent of similar behaviour concerning the elastic properties of materials. Strain may not be proportional to stress; here H and B (or M) are not linearly related. The stress-strain curve exhibits hysteresis and area enclosed by it represents the energy dissipated per unit volume.

A similar interpretation can be given to the B - H magnetic hysteresis curve.

8.

Diamagnetism is universal. It is present in all materials. But it is weak and hard to detect if the substance is para-or ferromagnetic.

9.

We have classified materials as diamagnetic, paramagnetic, and ferromagnetic. However, there exist additional types of magnetic material such as ferrimagnetic, anti-ferromagnetic, spin glass, *etc.* with properties which are exotic and mysterious.

Physics

EXERCISES

5.1

Answer the following questions regarding earth's magnetism:

(a) A vector needs three quantities for its specification. Name the three independent quantities conventionally used to specify the earth's magnetic field.

(b) The angle of dip at a location in southern India is about 18° .

Would you expect a greater or smaller dip angle in Britain?

(c) If you made a map of magnetic field lines at Melbourne in Australia, would the lines seem to go into the ground or come out of the ground?

(d) In which direction would a compass free to move in the vertical plane point to, if located right on the geomagnetic north or south pole?

(e) The earth's field, it is claimed, roughly approximates the field due to a dipole of magnetic moment $8 \times 10^{22} \text{ J T}^{-1}$ located at its centre. Check the order of magnitude of this number in some way.

(f) Geologists claim that besides the main magnetic N-S poles, there

are several local poles on the earth's surface oriented in different directions. How is such a thing possible at all?

5.2

Answer the following questions:

(a) The earth's magnetic field varies from point to point in space.

Does it also change with time? If so, on what time scale does it change appreciably?

(b) The earth's core is known to contain iron. Yet geologists do not regard this as a source of the earth's magnetism. Why?

(c) The charged currents in the outer conducting regions of the earth's core are thought to be responsible for earth's magnetism. What might be the 'battery' (i.e., the source of energy) to sustain these currents?

(d) The earth may have even reversed the direction of its field several times during its history of 4 to 5 billion years. How can geologists know about the earth's field in such distant past?

(e) The earth's field departs from its dipole shape substantially at large distances (greater than about 30,000 km). What agencies may be responsible for this distortion?

(f) Interstellar space has an extremely weak magnetic field of the

order of 10–12 T. Can such a weak field be of any significant consequence? Explain.

[**Note:** Exercise 5.2 is meant mainly to arouse your curiosity. Answers to some questions above are tentative or unknown. Brief answers wherever possible are given at the end. For details, you should consult a good text on geomagnetism.]

5.3

A short bar magnet placed with its axis at 30° with a uniform external magnetic field of 0.25 T experiences a torque of magnitude equal to 4.5×10^{-2} J. What is the magnitude of magnetic moment of the magnet?

5.4

A short bar magnet of magnetic moment $m = 0.32 \text{ JT}^{-1}$ is placed in a uniform magnetic field of 0.15 T. If the bar is free to rotate in the plane of the field, which orientation would correspond to its (a) stable, and (b) unstable equilibrium? What is the potential energy of the

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magnet in each case?

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5.5

A closely wound solenoid of 800 turns and area of cross section $2.5 \times 10^{-4} \text{ m}^2$ carries a current of 3.0 A. Explain the sense in which the solenoid acts like a bar magnet. What is its associated magnetic moment?

5.6

If the solenoid in Exercise 5.5 is free to turn about the vertical direction and a uniform horizontal magnetic field of 0.25 T is applied, what is the magnitude of torque on the solenoid when its axis makes an angle of 30° with the direction of applied field?

5.7

A bar magnet of magnetic moment 1.5 J T^{-1} lies aligned with the direction of a uniform magnetic field of 0.22 T.

(a) What is the amount of work required by an external torque to turn the magnet so as to align its magnetic moment: (i) normal to the field direction, (ii) opposite to the field direction?

(b) What is the torque on the magnet in cases (i) and (ii)?

5.8

A closely wound solenoid of 2000 turns and area of cross-section $1.6 \times 10^{-4} \text{ m}^2$, carrying a current of 4.0 A, is suspended through its centre allowing it to turn in a horizontal plane.

(a) What is the magnetic moment associated with the solenoid?

(b) What is the force and torque on the solenoid if a uniform horizontal magnetic field of 7.5×10^{-2} T is set up at an angle of 30° with the axis of the solenoid?

5.9

A circular coil of 16 turns and radius 10 cm carrying a current of 0.75 A rests with its plane normal to an external field of magnitude 5.0×10^{-2} T. The coil is free to turn about an axis in its plane perpendicular to the field direction. When the coil is turned slightly and released, it oscillates about its stable equilibrium with a frequency of 2.0 s^{-1} . What is the moment of inertia of the coil about its axis of rotation?

5.10

A magnetic needle free to rotate in a vertical plane parallel to the magnetic meridian has its north tip pointing down at 22° with the horizontal. The horizontal component of the earth's magnetic field at the place is known to be 0.35 G. Determine the magnitude of the earth's magnetic field at the place.

5.11

At a certain location in Africa, a compass points 12° west of the

geographic north. The north tip of the magnetic needle of a dip circle placed in the plane of magnetic meridian points 60° above the horizontal. The horizontal component of the earth's field is measured to be 0.16 G. Specify the direction and magnitude of the earth's field at the location.

5.12

A short bar magnet has a magnetic moment of 0.48 J T^{-1} . Give the direction and magnitude of the magnetic field produced by the magnet at a distance of 10 cm from the centre of the magnet on (a) the axis, (b) the equatorial lines (normal bisector) of the magnet.

5.13

A short bar magnet placed in a horizontal plane has its axis aligned along the magnetic north-south direction. Null points are found on the axis of the magnet at 14 cm from the centre of the magnet. The earth's magnetic field at the place is 0.36 G and the angle of dip is zero. What is the total magnetic field on the normal bisector of the magnet at the same distance as the null-point (i.e., 14 cm) from the centre of the magnet? (At *null points*, field due to a magnet is equal and opposite to the horizontal component of earth's magnetic field.)

5.14

If the bar magnet in exercise 5.13 is turned around by 180° , where

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will the new null points be located?

Physics

5.15

A short bar magnet of magnetic moment $5.25 \times 10^{-2} \text{ J T}^{-1}$ is placed with its axis perpendicular to the earth's field direction. At what distance from the centre of the magnet, the resultant field is inclined at 45° with earth's field on (a) its normal bisector and (b) its axis.

Magnitude of the earth's field at the place is given to be 0.42 G.

Ignore the length of the magnet in comparison to the distances involved.

ADDITIONAL EXERCISES

5.16

Answer the following questions:

(a) Why does a paramagnetic sample display greater magnetisation (for the same magnetising field) when cooled?

(b) Why is diamagnetism, in contrast, almost independent of temperature?

(c) If a toroid uses bismuth for its core, will the field in the core be

(slightly) greater or (slightly) less than when the core is empty?

(d) Is the permeability of a ferromagnetic material independent of the magnetic field? If not, is it more for lower or higher fields?

(e) Magnetic field lines are always nearly normal to the surface of a ferromagnet at every point. (This fact is analogous to the static electric field lines being normal to the surface of a conductor at every point.) Why?

(f) Would the maximum possible magnetisation of a paramagnetic sample be of the same order of magnitude as the magnetisation of a ferromagnet?

5.17

Answer the following questions:

(a) Explain qualitatively on the basis of domain picture the irreversibility in the magnetisation curve of a ferromagnet.

(b) The hysteresis loop of a soft iron piece has a much smaller area than that of a carbon steel piece. If the material is to go through repeated cycles of magnetisation, which piece will dissipate greater heat energy?

(c) 'A system displaying a hysteresis loop such as a ferromagnet, is a device for storing memory?' Explain the meaning of this

statement.

(d) What kind of ferromagnetic material is used for coating magnetic tapes in a cassette player, or for building 'memory stores' in a modern computer?

(e) A certain region of space is to be shielded from magnetic fields. Suggest a method.

5.18

A long straight horizontal cable carries a current of 2.5 A in the direction 10° south of west to 10° north of east. The magnetic meridian of the place happens to be 10° west of the geographic meridian. The earth's magnetic field at the location is 0.33 G, and the angle of dip is zero. Locate the line of neutral points (ignore the thickness of the cable). (At *neutral points*, magnetic field due to a current-carrying cable is equal and opposite to the horizontal component of earth's magnetic field.)

5.19

A telephone cable at a place has four long straight horizontal wires

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carrying a current of 1.0 A in the same direction east to west. The

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earth's magnetic field at the place is 0.39 G, and the angle of dip is 35° . The magnetic declination is nearly zero. What are the resultant magnetic fields at points 4.0 cm below the cable?

5.20

A compass needle free to turn in a horizontal plane is placed at the centre of circular coil of 30 turns and radius 12 cm. The coil is in a vertical plane making an angle of 45° with the magnetic meridian. When the current in the coil is 0.35 A, the needle points west to east.

(a) Determine the horizontal component of the earth's magnetic field at the location.

(b) The current in the coil is reversed, and the coil is rotated about its vertical axis by an angle of 90° in the anticlockwise sense looking from above. Predict the direction of the needle. Take the magnetic declination at the places to be zero.

5.21

A magnetic dipole is under the influence of two magnetic fields. The angle between the field directions is 60° , and one of the fields has a magnitude of 1.2×10^{-2} T. If the dipole comes to stable equilibrium at

an angle of 15° with this field, what is the magnitude of the other field?

5.22

A monoenergetic (18 keV) electron beam initially in the horizontal direction is subjected to a horizontal magnetic field of 0.04 G normal to the initial direction. Estimate the up or down deflection of the beam over a distance of 30 cm ($m = 9.11 \times 10^{-31}$ C). [Note: Data in *e* this exercise are so chosen that the answer will give you an idea of the effect of earth's magnetic field on the motion of the electron beam from the electron gun to the screen in a TV set.]

5.23

A sample of paramagnetic salt contains 2.0×10^{24} atomic dipoles each of dipole moment 1.5×10^{-23} J T⁻¹. The sample is placed under a homogeneous magnetic field of 0.64 T, and cooled to a temperature of 4.2 K. The degree of magnetic saturation achieved is equal to 15%. What is the total dipole moment of the sample for a magnetic field of 0.98 T and a temperature of 2.8 K? (Assume Curie's law)

5.24

A Rowland ring of mean radius 15 cm has 3500 turns of wire wound on a ferromagnetic core of relative permeability 800. What is the

magnetic field \mathbf{B} in the core for a magnetising current of 1.2 A?

5.25

The magnetic moment vectors μ_s and μ_l associated with the intrinsic

s

l

spin angular momentum \mathbf{S} and orbital angular momentum \mathbf{L} ,

respectively, of an electron are predicted by quantum theory (and

verified experimentally to a high accuracy) to be given by:

$$\mu_s = -\left(\frac{e\hbar}{2m}\right) \mathbf{S},$$

s

$$\mu_l = -\left(\frac{e\hbar}{2m}\right) \mathbf{L}$$

l

Which of these relations is in accordance with the result expected

classically ? Outline the derivation of the classical result.

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Chapter Six

ELECTROMAGNETIC

INDUCTION

6.1 INTRODUCTION

Electricity and magnetism were considered separate and unrelated

phenomena for a long time. In the early decades of the nineteenth century, experiments on electric current by Oersted, Ampere and a few others established the fact that electricity and magnetism are interrelated. They found that moving electric charges produce magnetic fields. For example, an electric current deflects a magnetic compass needle placed in its vicinity. This naturally raises the questions like: Is the converse effect possible? Can moving magnets produce electric currents? Does the nature permit such a relation between electricity and magnetism? The answer is resounding yes! The experiments of Michael Faraday in England and Joseph Henry in USA, conducted around 1830, demonstrated conclusively that electric currents were induced in closed coils when subjected to changing magnetic fields. In this chapter, we will study the phenomena associated with changing magnetic fields and understand the underlying principles. The phenomenon in which electric current is generated by varying magnetic fields is appropriately called *electromagnetic induction*.

When Faraday first made public his discovery that relative motion between a bar magnet and a wire loop produced a small current in the latter, he was asked, “What is the use of it?” His reply was: “What is the use of a new born baby?” The phenomenon of electromagnetic induction



Electromagnetic

Induction

is not merely of theoretical or academic interest but also of practical utility. Imagine a world where there is no electricity – no electric lights, no trains, no telephones and no personal computers. The pioneering experiments of Faraday and Henry have led directly to the development of modern day generators and transformers. Today's civilisation owes its progress to a great extent to the discovery of electromagnetic induction.

6.2 THE EXPERIMENTS OF FARADAY AND

H

JOSEPH HENRY (1797 – 1878)

ENRY

The discovery and understanding of electromagnetic induction are based on a long series of experiments carried

Joseph Henry [1797 –

out by Faraday and Henry. We shall now describe some

1878] American experimental

of these experiments.

physicist professor at

Princeton University and first

Experiment 6.1

director of the Smithsonian

Institution. He made important

Figure 6.1 shows a coil C * connected to a galvanometer

improvements in electro—

1

G. When the North-pole of a bar magnet is pushed

magnets by winding coils of

towards the coil, the pointer in the galvanometer deflects,

insulated wire around iron

pole pieces and invented an

indicating the presence of electric current in the coil. The

electromagnetic motor and a

deflection lasts as long as the bar magnet is in motion.

new, efficient telegraph. He

The galvanometer does not show any deflection when the magnet is held stationary. When the magnet is pulled away from the coil, the galvanometer shows deflection in one direction. When the magnet is pushed towards the coil, the galvanometer shows deflection in the opposite direction, which indicates reversal of the current's direction. Moreover, when the South-pole of the bar magnet is moved towards or away from the coil, the deflections in the galvanometer are opposite to that observed with the North-pole for similar movements. Further, the deflection (and hence current) is found to be larger when the magnet is pushed towards or pulled away from the coil faster. Instead, when the bar magnet is held fixed and the coil C is

1

moved towards or away from the magnet, the same effects are observed. It shows that *it is the relative*

motion between the magnet and the coil that is responsible for generation (induction) of electric current in the coil.

Experiment 6.2

FIGURE 6.1 When the bar magnet is

In Fig. 6.2 the bar magnet is replaced by a second coil pushed towards the coil, the pointer in C connected to a battery. The steady current in the the galvanometer G deflects.

2

coil C produces a steady magnetic field. As coil C is

2

2

* Wherever the term ‘coil or ‘loop’ is used, it is assumed that they are made up of conducting material and are prepared using wires which are coated with insulating 205

material.

Physics

moved towards the coil C , the galvanometer shows a

1

deflection. This indicates that electric current is induced in

coil C . When C is moved away, the galvanometer shows a

1

2

deflection again, but this time in the opposite direction. The

deflection lasts as long as coil C is in motion. When the coil

2

C is held fixed and C is moved, the same effects are observed.

2

1

Again, it is the relative motion between the coils that induces the electric current.

Experiment 6.3

The above two experiments involved relative motion between a magnet and a coil and between two coils, respectively.

Through another experiment, Faraday showed that this

relative motion is not an absolute requirement. Figure 6.3

FIGURE 6.2 Current is

shows two coils C and C held stationary. Coil C is connected

induced in coil C due to motion

1

2

1

1

to galvanometer G while the second coil C is connected to a
of the current carrying coil C .

2

2

battery through a tapping key K.

enz's law:

's experiments and L

araday

FIGURE 6.3 Experimental set-up for Experiment 6.3.

It is observed that the galvanometer shows a momentary deflection
when the tapping key K is pressed. The pointer in the galvanometer returns
to zero immediately. If the key is held pressed continuously, there is no
deflection in the galvanometer. When the key is released, a momentary
deflection is observed again, but in the opposite direction. It is also
observed that the deflection increases dramatically when an iron rod is
inserted Interactive animation on F

<http://micro.magnet.fsu.edu/electromagnet/java/faraday/index.html>

into the coils along their axis.

6.3 MAGNETIC FLUX

Faraday's great insight lay in discovering a simple mathematical relation to explain the series of experiments he carried out on electromagnetic induction. However, before we state and appreciate his laws, we must get familiar with the notion of magnetic flux, Φ . Magnetic flux is defined in

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B

the same way as electric flux is defined in Chapter 1. Magnetic flux through
Electromagnetic

Induction

a plane of area A placed in a uniform magnetic field \mathbf{B} (Fig. 6.4) can be written as

$$\Phi = \mathbf{B} \cdot \mathbf{A} = BA \cos \theta$$

(6.1)

B

where θ is angle between \mathbf{B} and \mathbf{A} . The notion of the area as a vector has been discussed earlier in Chapter 1. Equation (6.1) can be extended to curved surfaces and nonuniform fields.

If the magnetic field has different magnitudes and directions at various parts of a surface as shown in Fig. 6.5, then the magnetic flux through the surface is given by

$$\Phi = \mathbf{B}_1 \cdot d\mathbf{A}_1 + \mathbf{B}_2 \cdot d\mathbf{A}_2 + \dots = \sum \mathbf{B}_i \cdot d\mathbf{A}_i$$

(6.2)

B

1

1

2

2

i

i

all

FIGURE 6.4 A plane of

where ‘all’ stands for summation over all the area elements $d\mathbf{A}_i$ surface area \mathbf{A} placed in a comprising the surface and \mathbf{B} is the magnetic field at the area element i

uniform magnetic field \mathbf{B} .

$d\mathbf{A}_i$. The SI unit of magnetic flux is weber (Wb) or tesla meter

i

squared (T m^2). Magnetic flux is a scalar quantity.

6.4 FARADAY’S LAW OF INDUCTION

From the experimental observations, Faraday arrived at a

conclusion that an emf is induced in a coil when magnetic flux

through the coil changes with time. Experimental observations discussed in Section 6.2 can be explained using this concept.

The motion of a magnet towards or away from coil C in

1

Experiment 6.1 and moving a current-carrying coil C towards

2

or away from coil C in Experiment 6.2, change the magnetic

1

flux associated with coil C . The change in magnetic flux induces

1

emf in coil C . It was this induced emf which caused electric

1

current to flow in coil C and through the galvanometer. A

FIGURE 6.5 Magnetic field **B**

1

i

plausible explanation for the observations of Experiment 6.3 is

at the *i* th area element. $d\mathbf{A}_i$

as follows: When the tapping key K is pressed, the current in

represents area vector of the

i th area element.

coil C (and the resulting magnetic field) rises from zero to a

2

maximum value in a short time. Consequently, the magnetic

flux through the neighbouring coil C also increases. It is the change in

1

magnetic flux through coil C that produces an induced emf in coil C .

1

1

When the key is held pressed, current in coil C is constant. Therefore,

2

there is no change in the magnetic flux through coil C and the current in

1

coil C drops to zero. When the key is released, the current in C and the

1

2

resulting magnetic field decreases from the maximum value to zero in a

short time. This results in a decrease in magnetic flux through coil C1

and hence again induces an electric current in coil C *. The common

1

point in all these observations is that the time rate of change of magnetic flux through a circuit induces emf in it. Faraday stated experimental observations in the form of a law called *Faraday's law of electromagnetic induction*. The law is stated below.

* Note that sensitive electrical instruments in the vicinity of an electromagnet can be damaged due to the induced emfs (and the resulting currents) when the electromagnet is turned on or off.

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The magnitude of the induced emf in a circuit is equal to the time rate of change of magnetic flux through the circuit.

Mathematically, the induced emf is given by

$$d\Phi$$

$$\varepsilon = -$$

$$B$$

$$(6.3)$$

$d t$

The negative sign indicates the direction of ε and hence the direction of current in a closed loop. This will be discussed in detail in the next section.

In the case of a closely wound coil of N turns, change of flux associated with each turn, is the same. Therefore,

Michael Faraday [1791–

the expression for the total induced emf is given by

1867]

Faraday made

numerous contributions to

$d\Phi$

science, viz., the discovery

$\varepsilon = -$

B

N

(6.4)

$d t$

of electromagnetic

Y (1791–1867)

induction, the laws of

The induced emf can be increased by increasing the
electrolysis, benzene, and
number of turns N of a closed coil.

the fact that the plane of

From Eqs. (6.1) and (6.2), we see that the flux can be
polarisation is rotated in an

varied by changing any one or more of the terms \mathbf{B} , \mathbf{A} and
electric field. He is also

credited with the invention

θ . In Experiments 6.1 and 6.2 in Section 6.2, the flux is
of the electric motor, the

changed by varying \mathbf{B} . The flux can also be altered by
electric generator and the

changing the shape of a coil (that is, by shrinking it or
transformer. He is widely

stretching it) in a magnetic field, or rotating a coil in a
regarded as the greatest

magnetic field such that the angle θ between \mathbf{B} and \mathbf{A}

MICHAEL FARADA

experimental scientist of

changes. In these cases too, an emf is induced in the

the nineteenth century.

respective coils.

Example 6.1 Consider Experiment 6.2. (a) What would you do to obtain a large deflection of the galvanometer? (b) How would you demonstrate the presence of an induced current in the absence of a galvanometer?

Solution

(a) To obtain a large deflection, one or more of the following steps can be taken: (i) Use a rod made of soft iron inside the coil C , (ii) Connect 2 the coil to a powerful battery, and (iii) Move the arrangement rapidly towards the test coil C .

1

(b) Replace the galvanometer by a small bulb, the kind one finds in a small torch light. The relative motion between the two coils will cause

6.1

the bulb to glow and thus demonstrate the presence of an induced current.

In experimental physics one must learn to innovate. Michael Faraday

XAMPLE

who is ranked as one of the best experimentalists ever, was legendary

E

for his innovative skills.

Example 6.2 A square loop of side 10 cm and resistance 0.5Ω is

6.2

placed vertically in the east-west plane. A uniform magnetic field of 0.10 T is set up across the plane in the northeast direction. The magnetic field is decreased to zero in 0.70 s at a steady rate. Determine

XAMPLE

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the magnitudes of induced emf and current during this time-interval.

E

Electromagnetic

Induction

Solution The angle θ made by the area vector of the coil with the magnetic field is 45° . From Eq. (6.1), the initial magnetic flux is

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

$$0.1 \times 10$$

=

Wb

2

Final flux, Φ

$$= 0$$

min

The change in flux is brought about in 0.70 s. From Eq. (6.3), the magnitude of the induced emf is given by

$$\Delta\Phi$$

$$(\Phi - 0$$

$$-3$$

B

)

$$\varepsilon =$$

=

$$10$$

=

Δ

=

1.0 mV

t

Δ

t

2×0.7

And the magnitude of the current is

E

-3

ε

XAMPLE

10 V

$I =$

=

= 2 mA

R

0.5 Ω

Note that the earth's magnetic field also produces a flux through the

6.2

loop. But it is a steady field (which does not change within the time

span of the experiment) and hence does not induce any emf.

Example 6.3

A circular coil of radius 10 cm, 500 turns and resistance 2Ω is placed with its plane perpendicular to the horizontal component of the earth's magnetic field. It is rotated about its vertical diameter through 180° in 0.25 s. Estimate the magnitudes of the emf and current induced in the coil. Horizontal component of the earth's magnetic field at the place is 3.0×10^{-5} T.

Solution

Initial flux through the coil,

$$\Phi$$

$$= BA \cos \theta$$

B (initial)

$$= 3.0 \times 10^{-5} \times (\pi \times 10^{-2}) \times \cos 0^\circ$$

$$= 3\pi \times 10^{-7} \text{ Wb}$$

Final flux after the rotation,

$$\Phi$$

$$= 3.0 \times 10^{-5} \times (\pi \times 10^{-2}) \times \cos 180^\circ$$

B (final)

$$= -3\pi \times 10^{-7} \text{ Wb}$$

Therefore, estimated value of the induced emf is,

$$\Phi$$

$$\varepsilon$$

$$\Delta$$

$$= N t \Delta$$

$$= 500 \times (6\pi \times 10^{-7})/0.25$$

$$= 3.8 \times 10^{-3} \text{ V}$$

E

XAMPLE

$$I = \varepsilon / R = 1.9 \times 10^{-3} \text{ A}$$

Note that the magnitudes of ε and I are the estimated values. Their instantaneous values are different and depend upon the speed of

6.3

rotation at the particular instant.

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6.5 LENZ'S LAW AND CONSERVATION OF ENERGY

In 1834, German physicist Heinrich Friedrich Lenz (1804-1865) deduced

a rule, known as *Lenz's law* which gives the polarity of the induced emf in a clear and concise fashion. The statement of the law is: *The polarity of induced emf is such that it tends to produce a current*

which opposes the change in magnetic flux that produced it.

The negative sign shown in Eq. (6.3) represents this effect. We can understand Lenz's law by examining Experiment 6.1 in Section 6.2.1. In Fig. 6.1, we see that the North-pole of a bar magnet is being pushed towards the closed coil. As the North-pole of the bar magnet moves towards the coil, the magnetic flux through the coil increases. Hence current is induced in the coil in such a direction that it opposes the increase in flux. This is possible only if the current in the coil is in a counterclockwise direction with respect to an observer situated on the side of the magnet.

Note that magnetic moment associated with this current has North polarity towards the North-pole of the approaching magnet. Similarly, if the North-pole of the magnet is being withdrawn from the coil, the magnetic flux through the coil will decrease. To counter this decrease in magnetic flux, the induced current in the coil flows in clockwise direction and its South-pole faces the receding North-pole of the bar magnet. This would result in an attractive force which opposes the motion of the magnet and the corresponding decrease in flux.

What will happen if an open circuit is used in place of the closed loop in the above example? In this case too, an emf is induced across the open ends of the circuit. The direction of the induced emf can be found using Lenz's law. Consider Figs. 6.6 (a) and (b). They provide an easier

way to understand the direction of induced currents. Note that the direction shown by and indicate the directions of the induced currents.

A little reflection on this matter should convince us on the correctness of Lenz's law. Suppose that the induced current was in the direction opposite to the one depicted in Fig. 6.6(a). In that case, the South-pole due to the induced current will face the approaching North-pole of the magnet. The bar magnet will then be attracted towards the coil at an ever increasing acceleration. A gentle push on the magnet will initiate the process and its velocity and kinetic energy will continuously increase without expending any energy. If this can happen, one could construct a perpetual-motion machine by a suitable arrangement. This violates the law of conservation of energy and hence can not happen.

FIGURE 6.6

Now consider the correct case shown in Fig. 6.6(a). In this situation, Illustration of the bar magnet experiences a repulsive force due to the induced

Lenz's law.

current. Therefore, a person has to do work in moving the magnet.

Where does the energy spent by the person go? This energy is

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dissipated by Joule heating produced by the induced current.

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Induction

Example 6.4

Figure 6.7 shows planar loops of different shapes moving out of or into a region of a magnetic field which is directed normal to the plane of the loop away from the reader. Determine the direction of induced current in each loop using Lenz's law.

FIGURE 6.7

Solution

(i) The magnetic flux through the rectangular loop $abcd$ increases, due to the motion of the loop into the region of magnetic field, The induced current must flow along the path $bc dab$ so that it opposes the increasing flux.

(ii) Due to the outward motion, magnetic flux through the triangular loop abc decreases due to which the induced current flows along

E

back, so as to oppose the change in flux.

XAMPLE

(iii) As the magnetic flux decreases due to motion of the irregular shaped loop abcd out of the region of magnetic field, the induced current flows along cdabc, so as to oppose change in flux.

6.4

Note that there are no induced current as long as the loops are completely inside or outside the region of the magnetic field.

Example 6.5

(a) A closed loop is held stationary in the magnetic field between the north and south poles of two permanent magnets held fixed. Can we hope to generate current in the loop by using very strong magnets?

(b) A closed loop moves normal to the constant electric field between the plates of a large capacitor. Is a current induced in the loop

(i) when it is wholly inside the region between the capacitor plates

(ii) when it is partially outside the plates of the capacitor? The

E

electric field is normal to the plane of the loop.

XAMPLE

(c) A rectangular loop and a circular loop are moving out of a uniform magnetic field region (Fig. 6.8) to a field-free region with a *constant velocity* v . In which loop do you expect the induced emf to be

6.5

constant *during* the passage out of the field region? The field is normal to the loops.

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FIGURE 6.8

(d) Predict the polarity of the capacitor in the situation described by Fig. 6.9.

FIGURE 6.9

Solution

(a) No. However strong the magnet may be, current can be induced only by changing the magnetic flux through the loop.

(b) No current is induced in *either* case. Current can not be induced by changing the electric flux.

(c) The induced emf is expected to be constant only in the case of the

6.5

rectangular loop. In the case of circular loop, the rate of change of area of the loop during its passage out of the field region is not constant, hence induced *emf* will vary accordingly.

XAMPLE

(d) The polarity of plate 'A' will be positive with respect to plate 'B' in

E

the capacitor.

6.6 MOTIONAL ELECTROMOTIVE FORCE

Let us consider a straight conductor moving in a uniform and time-independent magnetic field. Figure 6.10 shows a rectangular conductor PQRS in which the conductor PQ is free to move. The rod PQ is moved towards the left with a constant velocity \mathbf{v} as shown in the figure. Assume that there is no loss of energy due to friction. PQRS forms a closed circuit enclosing an area that changes as PQ moves. It is placed in a uniform magnetic field \mathbf{B} which is perpendicular to the plane of this system. If the length $RQ = x$ and $RS = l$, the magnetic flux Φ enclosed by the loop PQRS

B

will be

$$\Phi = Blx$$

B

Since x is changing with time, the rate of change

FIGURE 6.10

of flux

The arm PQ is moved to the left

Φ will induce an emf given by:

B

side, thus decreasing the area of the

$$- d\Phi$$

d

B

rectangular loop. This movement

$$\varepsilon =$$

$$= -$$

$$(Blx)$$

$$d t$$

$$d t$$

induces a current I as shown.

$$d x$$

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$$= -Bl$$

$$= Blv$$

(6.5)

$\frac{d}{dt}$

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where we have used $\frac{d}{dt} \Phi = -v$ which is the speed of the conductor PQ.

The induced emf Blv is called *motional emf*. Thus, we are able to produce induced emf by moving a conductor instead of varying the magnetic field, that is, by changing the magnetic flux enclosed by the circuit.

It is also possible to explain the motional emf expression in Eq. (6.5)

by invoking the Lorentz force acting on the free charge carriers of conductor

PQ. Consider any arbitrary charge q in the conductor PQ. When the rod moves with speed v , the charge will also be moving with speed v in the magnetic field \mathbf{B} . The Lorentz force on this charge is qvB in magnitude, and its direction is towards Q. All charges experience the same force, in magnitude and direction, irrespective of their position in the rod PQ.

<http://www.ngsir.netfirms.com/englishhtm/Induction.htm>

Interactive animation on motional emf:

The work done in moving the charge from P to Q is,

$$W = qv B l$$

Since emf is the work done per unit charge,

$$W$$

$$\varepsilon = q$$

$$= Blv$$

This equation gives emf induced across the rod PQ and is identical to Eq. (6.5). We stress that our presentation is not wholly rigorous. But it does help us to understand the basis of Faraday's law when the conductor is moving in a uniform and time-independent magnetic field.

On the other hand, it is not obvious how an emf is induced when a conductor is stationary and the magnetic field is changing – a fact which Faraday verified by numerous experiments. In the case of a stationary conductor, the force on its charges is given by

$$\mathbf{F} = q (\mathbf{E} + \mathbf{v} \times \mathbf{B}) = q\mathbf{E}$$

(6.6)

since $\mathbf{v} = 0$. Thus, any force on the charge must arise from the electric field term \mathbf{E} alone. Therefore, to explain the existence of induced emf or induced current, we must assume that a time-varying magnetic field generates an electric field. However, we hasten to add that electric fields produced by static electric charges have properties different from those produced by time-varying magnetic fields. In Chapter 4, we learnt that

charges in motion (current) can exert force/torque on a stationary magnet. Conversely, a bar magnet in motion (or more generally, a changing magnetic field) can exert a force on the stationary charge. This is the fundamental significance of the Faraday's discovery. Electricity and magnetism are related.

Example 6.6 A metallic rod of 1 m length is rotated with a frequency

E

of 50 rev/s, with one end hinged at the centre and the other end at the

XAMPLE

circumference of a circular metallic ring of radius 1 m, about an axis passing through the centre and perpendicular to the plane of the ring (Fig. 6.11). A constant and uniform magnetic field of 1 T parallel to the

6.6

axis is present everywhere. What is the emf between the centre and the metallic ring?

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FIGURE 6.11

Solution

Method I

As the rod is rotated, free electrons in the rod move towards the outer end due to Lorentz force and get distributed over the ring. Thus, the resulting separation of charges produces an emf across the ends of the rod. At a certain value of emf, there is no more flow of electrons and a steady state is reached. Using Eq. (6.5), the magnitude of the emf generated across a length dr of the rod as it moves at right angles to the magnetic field is given by $d\varepsilon = Bv dr$. Hence,

$$R$$

$$R$$

$$2$$

$$\omega$$

$$\varepsilon =$$

$$B R$$

$$d\varepsilon =$$

$$Bv dr$$

$$\int$$

$$\int$$

$$=$$

$$B \omega r dr =$$

$$\int$$

$$2$$

0

0

Note that we have used $v = \omega r$. This gives

1

ϵ

2

=

$$\times 1.0 \times 2\pi \times 50 \times (1)$$

2

$$= 157 \text{ V}$$

Method II

To calculate the emf, we can imagine a closed loop OPQ in which

point O and P are connected with a resistor R and OQ is the rotating

rod. The potential difference across the resistor is then equal to the

induced emf and equals $B \times$ (rate of change of area of loop). If θ is the angle between the rod and the radius of the circle at P at time t , the area of the sector OPQ is given by

θ

1

2

2

$$\pi R^2 \times$$

=

$$R \theta$$

$$2\pi$$

$$2$$

where R is the radius of the circle. Hence, the induced emf is

$$d \int 1$$

]

$$2$$

$$1$$

$$d\theta$$

$$B \omega R$$

$$\varepsilon$$

$$2$$

$$= B \times$$

$$R \theta$$

|

|

$$2$$

BR

=

$d t [2$

$] = 2$

$d t$

2

6.6

$d\theta$

[Note:

$= \omega = 2 \pi \nu]$

$d t$

This expression is identical to the expression obtained by Method I

XAMPLE

and we get the same value of ϵ .

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E

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Example 6.7

A wheel with 10 metallic spokes each 0.5 m long is rotated with a

speed of 120 rev/min in a plane normal to the horizontal component of earth's magnetic field H at a place. If $H = 0.4$ G at the place, what E

is the induced emf between the axle and the rim of the wheel? Note that $1 \text{ G} = 10^{-4} \text{ T}$.

Solution

$$\text{Induced emf} = (1/2) \omega B R^2$$

E

XAMPLE

$$= (1/2) \times 4\pi \times 0.4 \times 10^{-4} \times (0.5)^2$$

$$= 6.28 \times 10^{-5} \text{ V}$$

6.7

The number of spokes is immaterial because the emf's across the spokes are *in parallel*.

6.7 ENERGY CONSIDERATION: A QUANTITATIVE STUDY

In Section 6.5, we discussed qualitatively that Lenz's law is consistent with the law of conservation of energy. Now we shall explore this aspect further with a concrete example.

Let r be the resistance of movable arm PQ of the rectangular conductor shown in Fig. 6.10. We assume that the remaining arms QR, RS and SP

have negligible resistances compared to r . Thus, the overall resistance of the rectangular loop is r and this does not change as PQ is moved. The current I in the loop is,

$$\varepsilon$$

$$I = \frac{\varepsilon}{r}$$

$$B l v$$

=

$$(6.7)$$

$$r$$

On account of the presence of the magnetic field, there will be a force

on the arm PQ. This force $I (\mathbf{l} \times \mathbf{B})$, is directed outwards in the direction opposite to the velocity of the rod. The magnitude of this force is, 2 2

$$B l v$$

$$F = I l B =$$

$$r$$

where we have used Eq. (6.7). Note that this force arises due to drift velocity of charges (responsible for current) along the rod and the consequent Lorentz force acting on them.

Alternatively, the arm PQ is being pushed with a constant speed v ,

the power required to do this is,

$$P = F v$$

$$2 2$$

2

Blv

=

(6.8)

r

The agent that does this work is mechanical. Where does this mechanical energy go? The answer is: it is dissipated as Joule heat, and is given by

2

(Blv)

2 2

2

Blv

2

$P = I r = |$

$| r =$

J

(r)

r

which is identical to Eq. (6.8).

Physics

Thus, mechanical energy which was needed to move the arm PQ is converted into electrical energy (the induced emf) and then to thermal energy.

There is an interesting relationship between the charge flow through the circuit and the change in the magnetic flux. From Faraday's law, we have learnt that the magnitude of the induced emf is,

$$\Phi_B$$

$$\varepsilon$$

$$\Delta$$

$$= \Delta t$$

However,

$$Q$$

$$\varepsilon$$

$$\Delta$$

$$= I r =$$

$$r$$

$$t$$

$$\Delta$$

Thus,

$$\Delta \Phi B$$

$$\Delta Q = r$$

Example 6.8 Refer to Fig. 6.12(a). The arm PQ of the rectangular conductor is moved from $x = 0$, outwards. The uniform magnetic field is perpendicular to the plane and extends from $x = 0$ to $x = b$ and is zero for $x > b$. Only the arm PQ possesses substantial resistance r . Consider the situation when the arm PQ is pulled outwards from $x = 0$ to $x = 2b$, and is then moved back to $x = 0$ with constant speed v . Obtain expressions for the flux, the induced emf, the force necessary to pull the arm and the power dissipated as Joule heat. Sketch the variation of these quantities with distance.

(a)

FIGURE 6.12

Solution Let us first consider the forward motion from $x = 0$ to $x = 2b$. The flux Φ linked with the circuit SPQR is

$$\Phi = B l x$$

$$0 \leq x < b$$

B

$$= B l b$$

$$b \leq x < 2b$$

The induced emf is,

6.8

$d\Phi_B$

$$\varepsilon = - \frac{d\Phi_B}{dt}$$

$= -$

\leq

$<$

XAMPLE

Blv

0

x

b

$2b$

E

$= 0$

$$b \leq x < 2b$$

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When the induced emf is nonzero, the current I is (in magnitude)

Blv

$I =$

r

(b)

FIGURE 6.12

The force required to keep the arm PQ in constant motion is $I l B$. Its direction is to the left. In magnitude

$2 2$

$B l v$

$F =$

$0 \leq x < b$

r

$= 0$

$b \leq x < 2 b$

The Joule heating loss is

2

$P = I r$

J

$2 2$

2

$B l v$

E

=

$$0 \leq x < b$$

XAMPLE

r

$$= 0$$

$$b \leq x < 2b$$

One obtains similar expressions for the inward motion from $x = 2b$ to **6.8**
 $x = 0$. One can appreciate the whole process by examining the sketch
of various quantities displayed in Fig. 6.12(b).

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6.8 EDDY CURRENTS

So far we have studied the electric currents induced in well defined paths
in conductors like circular loops. Even when bulk pieces of conductors
are subjected to changing magnetic flux, induced currents
are produced in them. However, their flow patterns resemble
swirling eddies in water. This effect was discovered by physicist
Foucault (1819-1868) and these currents are called *eddy*

currents.

Consider the apparatus shown in Fig. 6.13. A copper plate is allowed to swing like a simple pendulum between the pole pieces of a strong magnet. It is found that the motion is damped and in a little while the plate comes to a halt in the magnetic field. We can explain this phenomenon on the basis of electromagnetic induction. Magnetic flux associated with the plate keeps on changing as the plate moves in and out of the region between magnetic poles. The flux change induces eddy currents in the plate. Directions of eddy currents are opposite when the plate swings into the region between the poles and when it swings out of the region.

If rectangular slots are made in the copper plate as shown

FIGURE 6.13 Eddy currents are

in Fig. 6.14, area available to the flow of eddy currents is less.

generated in the copper plate,

Thus, the pendulum plate with holes or slots reduces

while entering

electromagnetic damping and the plate swings more freely.

and leaving the region of

Note that magnetic moments of the induced currents (which oppose the motion) depend upon the area enclosed by the currents (recall equation $\mathbf{m} = I \mathbf{A}$ in Chapter 4).

This fact is helpful in reducing eddy currents in the metallic cores of transformers, electric motors and other such devices in which a coil is to be wound over metallic core. Eddy currents are undesirable since they heat up the core and dissipate electrical energy in the form of heat. Eddy currents are minimised by using laminations of metal to make a metal core. The laminations are separated by an insulating material like lacquer. The plane of the laminations must be arranged parallel to the magnetic field, so that they cut across the eddy current paths. This arrangement reduces the strength of the eddy currents. Since the dissipation of electrical energy into heat depends on the square of the strength of electric current, heat loss is substantially reduced.

Eddy currents are used to advantage in certain applications like:

(i) *Magnetic braking in trains*: Strong electromagnets are situated above the rails in some electrically powered trains. When the electromagnets are activated, the eddy currents induced in the

FIGURE 6.14 Cutting slots

rails oppose the motion of the train. As there are no mechanical linkages, the braking effect is smooth. The effect of eddy currents in the copper plate reduces

(ii) *Electromagnetic damping*: Certain galvanometers have a fixed core made of nonmagnetic metallic material. When the coil oscillates, the eddy currents generated in the core oppose the motion and bring the coil to rest quickly.

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(iii) *Induction furnace*: Induction furnace can be used to produce high temperatures and can be utilised to prepare alloys, by melting the constituent metals. A high frequency alternating current is passed through a coil which surrounds the metals to be melted. The eddy currents generated in the metals produce high temperatures sufficient to melt it.

(iv) *Electric power meters*: The shiny metal disc in the electric power meter (analogue type) rotates due to the eddy currents. Electric currents are induced in the disc by magnetic fields produced by sinusoidally

varying currents in a coil.

You can observe the rotating shiny disc in the power meter of your house.

ELECTROMAGNETIC DAMPING

Take two hollow thin cylindrical pipes of equal internal diameters made of aluminium and PVC, respectively. Fix them vertically with clamps on retort stands. Take a small cylindrical magnet having diameter slightly smaller than the inner diameter of the pipes and drop it through each pipe in such a way that the magnet does not touch the sides of the pipes during its fall. You will observe that the magnet dropped through the PVC pipe takes the same time to come out of the pipe as it would take when dropped through the same height without the pipe. Note the time it takes to come out of the pipe in each case. You will see that the magnet takes much longer time in the case of aluminium pipe. Why is it so? It is due to the eddy currents that are generated in the aluminium pipe which oppose the change in magnetic flux, i.e., the motion of the magnet. The retarding force due to the eddy currents inhibits the motion of the magnet. Such phenomena are referred to as *electromagnetic damping*.

Note that eddy currents are not generated in PVC pipe as its material is an insulator whereas aluminium is a conductor.

6.9 INDUCTANCE

An electric current can be induced in a coil by flux change produced by another coil in its vicinity or flux change produced by the same coil. These two situations are described separately in the next two sub-sections.

However, in both the cases, the flux through a coil is proportional to the current. That is, $\Phi \propto I$.

B

Further, if the geometry of the coil does not vary with time then,

$$d\Phi$$

$$dI$$

$$B$$

$$\propto$$

$$dt$$

$$dt$$

For a closely wound coil of N turns, the same magnetic flux is linked with all the turns. When the flux Φ through the coil changes, each turn

$$B$$

contributes to the induced emf. Therefore, a term called *flux linkage* is used which is equal to $N\Phi$ for a closely wound coil and in such a case B

$$N\Phi \propto I$$

$$B$$

The constant of proportionality, in this relation, is called *inductance*.

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We shall see that inductance depends only on the geometry of the coil

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and intrinsic material properties. This aspect is akin to capacitance which for a parallel plate capacitor depends on the plate area and plate separation

(geometry) and the dielectric constant K of the intervening medium (intrinsic material property).

Inductance is a scalar quantity. It has the dimensions of $[M L^2 T^{-2} A^{-2}]$ given by the dimensions of flux divided by the dimensions of current. The

SI unit of inductance is *henry* and is denoted by H. It is named in honour of Joseph Henry who discovered electromagnetic induction in USA, independently of Faraday in England.

6.9.1 Mutual inductance

Consider Fig. 6.15 which shows two long co-axial solenoids each of length

l . We denote the radius of the inner solenoid S by r and the number of 1

1

turns per unit length by n . The corresponding quantities for the outer 1

solenoid S are r and n , respectively. Let N and N be the total number 2

2

2

1

2

of turns of coils S and S , respectively.

1

2

When a current I is set up through S , it in turn sets up a magnetic 2

2

flux through S . Let us denote it by Φ . The corresponding flux linkage 1

1

with solenoid S is

1

$$N \Phi = M I$$

(6.9)

1

1

12 2

M is called the *mutual inductance* of solenoid S with respect to 12

1

solenoid S . It is also referred to as the *coefficient of mutual induction*.

2

For these simple co-axial solenoids it is possible to calculate M . The 12

magnetic field due to the current I in S is $\mu n I$. The resulting flux linkage 2

2

0 2 2

with coil S is,

1

$$N \Phi = (n l) (2$$

r

π

$\mu n I$

1 1

1

1) (0 2 2)

2

$= \mu n n r$

$\pi l I$

(6.10)

0

1

2

1

2

where $n l$ is the total number of turns in solenoid S . Thus, from Eq. (6.9) 1

1

and Eq. (6.10),

$$M = \mu_0 n^2 \pi r^2 l$$

(6.11)

12

0 1 2

1

Note that we neglected the edge effects and considered the magnetic field $\mu_0 n I$ to be uniform throughout the

0

2 2

length and width of the solenoid S . This is a good

2

approximation keeping in mind that the solenoid is long, implying $l \gg r$.

2

We now consider the reverse case. A current I is

1

passed through the solenoid S and the flux linkage with

1

coil S is,

2

$$N \Phi = M I$$

(6.12)

2

2

21

1

M is called the *mutual inductance* of solenoid S with

21

2

respect to solenoid S .

1

The flux due to the current I in S can be assumed to

1

1

be confined solely inside S since the solenoids are very

1

FIGURE 6.15 Two long co-axial

long. Thus, flux linkage with solenoid S is

solenoids of same

2

220

length l .

$$N \Phi = (n l) (2$$

r

π

$$\mu n I$$

2

2

2

$$1) (0 1 1)$$

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Induction

where $n l$ is the total number of turns of S . From Eq. (6.12),

2

2

$$M = \mu n n \pi r 2 l$$

$$(6.13)$$

21

0 1 2

1

Using Eq. (6.11) and Eq. (6.12), we get

M

$$= M = M \text{ (say)}$$

(6.14)

12

21

We have demonstrated this equality for long co-axial solenoids.

However, the relation is far more general. Note that if the inner solenoid was much shorter than (and placed well inside) the outer solenoid, then we could still have calculated the flux linkage $N \Phi$ because the inner

1

1

solenoid is effectively immersed in a uniform magnetic field due to the outer solenoid. In this case, the calculation of M would be easy. However, 12

it would be extremely difficult to calculate the flux linkage with the outer solenoid as the magnetic field due to the inner solenoid would vary across the length as well as cross section of the outer solenoid. Therefore, the calculation of M would also be extremely difficult in this case. The

21

equality $M = M$ is very useful in such situations.

12

21

We explained the above example with air as the medium within the solenoids. Instead, if a medium of relative permeability μ had been present,

r

the mutual inductance would be

$$M = \mu \mu_0 n_1 n_2 \pi r^2 l$$

r 0

1 2

1

It is also important to know that the mutual inductance of a pair of coils, solenoids, etc., depends on their separation as well as their relative orientation.

Example 6.9 Two concentric circular coils, one of small radius r and 1 the other of large radius r_2 , such that $r \ll r_2$, are placed co-axially 2

1

2

with centres coinciding. Obtain the mutual inductance of the arrangement.

Solution Let a current I flow through the outer circular coil. The 2

field at the centre of the coil is $B = \mu I / 2 r$. Since the other 2

0 2

2

co-axially placed coil has a very small radius, B may be considered

2

constant over its cross-sectional area. Hence,

$$\Phi = \pi r^2 B$$

1

1

2

2

μr

π

0

1

=

I^2

$2 r^2$

= M

I

12 2

Thus,

2

μr

π

0

1

M

=

12

$2 r 2$

From Eq. (6.14)

2

E

$\mu \pi r$

0

1

M

$= M =$

XAMPLE

12

21

2 r^2

Note that we calculated M from an approximate value of Φ , assuming

12

1

the magnetic field B to be uniform over the area πr^2 . However, we **6.9**

2

1

can accept this value because $r \ll r$.

1

2

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Now, let us recollect Experiment 6.3 in Section 6.2. In that experiment,

emf is induced in coil C wherever there was any change in current through

1

coil C . Let Φ be the flux through coil C (say of N turns) when current in 2

1

1

1

coil C is I_1 .

2

2

Then, from Eq. (6.9), we have

$$N_2 \Phi_{21} = M I_1$$

1

1

2

For currents varying with time,

$$d(N_2 \Phi_{21})$$

$$= d(M I_1)$$

$$= I_1 dM + M dI_1$$

$$(2)$$

=

$$= \frac{dM}{dt} I_1 + M \frac{dI_1}{dt}$$

$$= \frac{dM}{dt} I_1 + M \frac{dI_1}{dt}$$

Since induced emf in coil C is given by

1

$$= - \frac{d(N_2 \Phi_{21})}{dt}$$

$$= - \left(\frac{dM}{dt} I_1 + M \frac{dI_1}{dt} \right)$$

$$\varepsilon = -$$

$$1$$

$$d t$$

We get,

$$d I 2$$

$$\varepsilon = - M$$

$$1$$

$$d t$$

It shows that varying current in a coil can induce emf in a neighbouring coil. The magnitude of the induced emf depends upon the rate of change of current and mutual inductance of the two coils.

6.9.2 Self-inductance

In the previous sub-section, we considered the flux in one solenoid due to the current in the other. It is also possible that emf is induced in a single isolated coil due to change of flux through the coil by means of varying the current through the same coil. This phenomenon is called

self-induction. In this case, flux linkage through a coil of N turns is proportional to the current through the coil and is expressed as $N\Phi \propto I$

$$B$$

$$N\Phi = L I$$

$$(6.15)$$

B

where constant of proportionality L is called *self-inductance* of the coil. It is also called the *coefficient of self-induction* of the coil. When the current is varied, the flux linked with the coil also changes and an emf is induced in the coil. Using Eq. (6.15), the induced emf is given by

$$d(N\Phi)$$

$$\varepsilon = -$$

$$d t$$

$$d I$$

$$\varepsilon = -L$$

$$(6.16)$$

$$d t$$

Thus, the self-induced emf always opposes any change (increase or decrease) of current in the coil.

It is possible to calculate the self-inductance for circuits with simple geometries. Let us calculate the self-inductance of a long solenoid of cross-sectional area A and length l , having n turns per unit length. The magnetic field due to a current I flowing in the solenoid is $B = \mu_0 n I$ (neglecting edge effects, as before). The total flux linked with the solenoid is

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$$N\Phi = n l \mu_0 n I$$

A

B

(0)

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$$= \mu n^2 A l I$$

0

where nl is the total number of turns. Thus, the self-inductance is,

$N\Phi$

L

B

$$= I$$

2

$$= \mu n A l$$

(6.17)

0

If we fill the inside of the solenoid with a material of relative permeability

μ (for example soft iron, which has a high value of relative permeability),

r

then,

2

$$L = \mu \mu_0 n^2 A l$$

(6.18)

r

0

The self-inductance of the coil depends on its geometry and on the permeability of the medium.

The self-induced emf is also called the *back emf* as it opposes any change in the current in a circuit. Physically, the *self-inductance plays the role of inertia*. It is the electromagnetic analogue of mass in mechanics.

So, work needs to be done against the back emf (ε) in establishing the current. This work done is stored as magnetic potential energy. For the current I at an instant in a circuit, the rate of work done is

$$dW = \varepsilon I$$

$d t$

If we ignore the resistive losses and consider only inductive effect, then using Eq. (6.16),

$$dW$$

$d I$

$$= L I$$

$d t$

$d t$

Total amount of work done in establishing the current I is

I

$W = \int d W =$

$\int L I d I$

\int

\int_0^I

Thus, the energy required to build up the current I is,

$\frac{1}{2}$

2

$W =$

$\frac{1}{2} L I^2$

(6.19)

2

This expression reminds us of $\frac{1}{2} m v^2$ for the (mechanical) kinetic energy of a particle of mass m , and shows that L is analogous to m (i.e., L is electrical inertia and opposes growth and decay of current in the circuit).

Consider the general case of currents flowing simultaneously in two nearby coils. The flux linked with one coil will be the sum of two fluxes which exist independently. Equation (6.9) would be modified into

$$N\Phi = M$$

$$I + M$$

$$I$$

$$1$$

$$1$$

$$11\ 1$$

$$12$$

$$2$$

where M represents inductance due to the same coil.

$$11$$

Therefore, using Faraday's law,

$$dI$$

$$dI$$

$$1$$

$$2$$

$$\varepsilon = -M$$

$$-M$$

$$1$$

$$11$$

$$12$$

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$d t$

$d t$

Physics

M

is the *self-inductance* and is written as L . Therefore,

11

1

$d I$

$d I$

1

2

$\varepsilon = - L$

$- M$

1

1

12

$d t$

$d t$

Example 6.10 (a) Obtain the expression for the magnetic energy stored

in a solenoid in terms of magnetic field B , area A and length l of the solenoid. (b) How does this magnetic energy compare with the electrostatic energy stored in a capacitor?

Solution

(a) From Eq. (6.19), the magnetic energy is

$$U = \frac{1}{2} LI^2 = \frac{1}{2} \left(\frac{\mu_0 n^2 A l}{2} \right) I^2 = \frac{\mu_0 n^2 A l I^2}{4}$$

(since $B = \mu_0 nI$ for a solenoid)

0

(μn)

0

2

1

(B)

2

= ($\mu n Al$)

[from Eq. (6.17)]

0

|

|

2

(μn)

0

1

2

=

$B Al$

$2\mu_0$

(b) The magnetic energy per unit volume is,

$$UB$$

$$u$$

=

$$B$$

(where V is volume that contains flux)

$$V$$

$$U$$

$$B$$

$$= \frac{1}{2} \mu_0 I^2$$

$$2$$

$$B$$

=

(6.20)

$$2\mu_0$$

We have already obtained the relation for the electrostatic energy stored per unit volume in a parallel plate capacitor (refer to Chapter 2, Eq. 2.77),

Interactive animation on ac generator:

<http://micro.magnet.fsu.edu/electromagnet~java/generator/ac.html>

1

2

$u =$

ϵE

E

0

(2.77)

2

6.10

In both the cases energy is proportional to the square of the field strength. Equations (6.20) and (2.77) have been derived for special cases: a solenoid and a parallel plate capacitor, respectively. But they

XAMPLE

are general and valid for any region of space in which a magnetic field

E

or/and an electric field exist.

6.10 AC GENERATOR

The phenomenon of electromagnetic induction has been technologically exploited in many ways. An exceptionally important application is the

generation of alternating currents (ac). The modern ac generator with a typical output capacity of 100 MW is a highly evolved machine. In this section, we shall describe the basic principles behind this machine. The Yugoslav inventor Nicola Tesla is credited with the development of the

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machine. As was pointed out in Section 6.3, one method to induce an emf

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or current in a loop is through a change in the loop's orientation or a change in its effective area.

As the coil rotates in a magnetic field \mathbf{B} , the effective area of the loop (the face perpendicular to the field) is $A \cos \theta$, where θ is the angle between \mathbf{A} and \mathbf{B} . This method of producing a flux change is the principle of operation of a simple ac generator. An ac generator converts mechanical energy into electrical energy.

The basic elements of an ac generator are shown in Fig. 6.16. It consists of a coil mounted on a rotor shaft. The axis of rotation of the coil

is perpendicular to the direction of the magnetic field. The coil (called armature) is mechanically rotated in the uniform magnetic field by some external means. The rotation of the coil causes the magnetic flux through it to change, so an emf is induced in the coil. The ends of the coil are connected to an external circuit by means

FIGURE 6.16 AC Generator

of slip rings and brushes.

When the coil is rotated with a constant

angular speed ω , the angle θ between the magnetic field vector \mathbf{B} and the area vector \mathbf{A} of the coil at any instant t is $\theta = \omega t$ (assuming $\theta = 0^\circ$ at $t = 0$).

As a result, the effective area of the coil exposed to the magnetic field lines changes with time, and from Eq. (6.1), the flux at any time t is $\Phi = BA \cos \theta = BA \cos \omega t$

B

From Faraday's law, the induced emf for the rotating coil of N turns is then,

$$d\Phi$$

$$d$$

$$\varepsilon = -$$

$$B$$

$$\begin{aligned}
 &N \\
 &= - NBA \\
 &(\cos \omega t) \\
 &dt \\
 &d t
 \end{aligned}$$

Thus, the instantaneous value of the emf is

$$\begin{aligned}
 \varepsilon &= NBA \omega \sin \omega t \\
 (6.21)
 \end{aligned}$$

where $NBA\omega$ is the maximum value of the emf, which occurs when

$\sin \omega t = \pm 1$. If we denote $NBA\omega$ as ε , then

$$\begin{aligned}
 0 \\
 \varepsilon &= \varepsilon \sin \omega t \\
 (6.22)
 \end{aligned}$$

0

Since the value of the sine function varies between +1 and -1, the sign, or polarity of the emf changes with time. Note from Fig. 6.17 that the emf has its extremum value when $\theta = 90^\circ$ or $\theta = 270^\circ$, as the change of flux is greatest at these points.

The direction of the current changes periodically and therefore the current

is called *alternating current* (ac). Since $\omega = 2\pi\nu$, Eq (6.22) can be written as $\varepsilon = \varepsilon \sin 2\pi \nu t$ (6.23)

0

where ν is the frequency of revolution of the generator's coil.

Note that Eq. (6.22) and (6.23) give the instantaneous value of the emf and ϵ varies between $+\epsilon$ and $-\epsilon$ periodically. We shall learn how to

0

0

determine the time-averaged value for the alternating voltage and current

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in the next chapter.

Physics

FIGURE 6.17 An alternating emf is generated by a loop of wire rotating in a magnetic field.

In commercial generators, the mechanical energy required for rotation

of the armature is provided by water falling from a height, for example,

from dams. These are called *hydroelectric generators*. Alternatively, water is heated to produce steam using coal or other sources. The steam at high pressure produces the rotation of the armature. These are called

thermal generators. Instead of coal, if a nuclear fuel is used, we get *nuclear power generators*. Modern day generators produce electric power as high as 500 MW, i.e., one can light up 5 million 100 W bulbs! In most

generators, the coils are held stationary and it is the electromagnets which

are rotated. The frequency of rotation is 50 Hz in India. In certain countries

such as USA, it is 60 Hz.

Example 6.11 Kamla peddles a stationary bicycle the pedals of the bicycle are attached to a 100 turn coil of area 0.10 m². The coil rotates at half a revolution per second and it is placed in a uniform magnetic field of 0.01 T perpendicular to the axis of rotation of the coil. What is the maximum voltage generated in the coil?

Solution Here $f = 0.5$ Hz; $N = 100$, $A = 0.1$ m² and $B = 0.01$ T. Employing Eq. (6.21) $\epsilon_0 = NBA (2 \pi v)$

$$= 100 \times 0.01 \times 0.1 \times 2 \times 3.14 \times 0.5$$

$$= 0.314 \text{ V}$$

6.11

The maximum voltage is 0.314 V.

We urge you to explore such alternative possibilities for power

XAMPLE

generation.

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E

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Induction

MIGRATION OF BIRDS

The migratory pattern of birds is one of the mysteries in the field of biology, and indeed all of science. For example, every winter birds from Siberia fly unerringly to water spots in the Indian subcontinent. There has been a suggestion that electromagnetic induction may provide a clue to these migratory patterns. The earth's magnetic field has existed throughout evolutionary history. It would be of great benefit to migratory birds to use this field to determine the direction. As far as we know birds contain no ferromagnetic material. So electromagnetic induction seems to be the only reasonable mechanism to determine direction. Consider the optimal case where the magnetic field \mathbf{B} , the velocity of the bird \mathbf{v} , and two relevant points of its anatomy separated by a distance l , all three are mutually perpendicular. From the formula for motional emf, Eq. (6.5), $\varepsilon = Blv$

Taking $B = 4 \times 10^{-5} \text{ T}$, $l = 2 \text{ cm}$ wide, and $v = 10 \text{ m/s}$, we obtain $\varepsilon = 4 \times 10^{-5} \times 2 \times 10^{-2} \times 10 \text{ V} = 8 \times 10^{-6} \text{ V}$

$$= 8 \mu\text{V}$$

This extremely small potential difference suggests that our hypothesis is of doubtful validity. Certain kinds of fish are able to detect small potential differences. However, in these fish, special cells have been identified which detect small voltage differences. In birds no such cells have been identified. Thus, the migration patterns of birds continues to remain a mystery.

SUMMARY

1.

The magnetic flux through a surface of area \mathbf{A} placed in a uniform magnetic field \mathbf{B} is defined as, $\Phi = \mathbf{B} \cdot \mathbf{A} = BA \cos \theta$

\mathbf{B}

where θ is the angle between \mathbf{B} and \mathbf{A} .

2.

Faraday's laws of induction imply that the emf induced in a coil of N

turns is directly related to the rate of change of flux through it,

$$d\Phi_B$$

$$\varepsilon = -N \frac{d\Phi}{dt}$$

Here Φ

B is the flux linked with one turn of the coil. If the circuit is

closed, a current $I = \varepsilon / R$ is set up in it, where R is the resistance of the circuit.

3.

Lenz's law states that the polarity of the induced emf is such that it tends to produce a current which opposes the change in magnetic flux that produces it. The negative sign in the expression for Faraday's law indicates this fact.

4.

When a metal rod of length l is placed normal to a uniform magnetic field B and moved with a velocity v perpendicular to the field, the induced emf (called motional emf) across its ends is $\varepsilon = Blv$

5.

Changing magnetic fields can set up current loops in nearby metal (any conductor) bodies. They dissipate electrical energy as heat. Such currents are called eddy currents.

6.

Inductance is the ratio of the flux-linkage to current. It is equal to $N\Phi / I$.

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7.

A changing current in a coil (coil 2) can induce an emf in a nearby coil (coil 1). This relation is given by,

$d I_2$

$$\varepsilon = - M$$

1

$12 \frac{d}{dt}$

The quantity M

is called mutual inductance of coil 1 with respect to

12

coil 2. One can similarly define M_{21} . There exists a general equality,

21

$$M_{12} = M_{21}$$

12

21

8.

When a current in a coil changes, it induces a back emf in the same

coil. The self-induced emf is given by,

$$d I$$

$$\varepsilon = - L \frac{d I}{d t}$$

L is the self-inductance of the coil. It is a measure of the inertia of the coil against the change of current through it.

9.

The self-inductance of a long solenoid, the core of which consists of a magnetic material of permeability μ , is given by

r

$$L = \mu \mu_0 n^2 A l$$

$r 0$

where A is the area of cross-section of the solenoid, l its length and n the number of turns per unit length.

10. In an ac generator, mechanical energy is converted to electrical energy

by virtue of electromagnetic induction. If coil of N turn and area A is rotated at ν revolutions per second in a uniform magnetic field B , then the motional emf produced is $\varepsilon = NBA (2\pi\nu) \sin (2\pi\nu t)$

where we have assumed that at time $t = 0$ s, the coil is perpendicular to the field.

Quantity

Symbol

Units

Dimensions

Equations

Magnetic Flux

Φ

Wb (weber)

$[M L^2 T^{-2} A^{-1}]$

$$\Phi = \mathbf{B} \cdot \mathbf{i} \cdot \mathbf{A}$$

B

B

EMF

ε

V (volt)

$[M L^2 T^{-3} A^{-1}]$

$$\varepsilon = -d(N\Phi)/d t$$

B

Mutual Inductance

M

H (henry)

$[M L^2 T^{-2} A^{-2}]$

$$\varepsilon = -M d I / d t$$

12 (

2

)

1

Self Inductance

L

H (henry)

$[M L^2 T^{-2} A^{-2}]$

$$\varepsilon = -L (dI/dt)$$

POINTS TO PONDER

1.

Electricity and magnetism are intimately related. In the early part of the nineteenth century, the experiments of Oersted, Ampere and others established that moving charges (currents) produce a magnetic field. Somewhat later, around 1830, the experiments of Faraday and Henry demonstrated that a moving magnet can induce electric current.

2.

In a closed circuit, electric currents are induced so as to oppose the changing magnetic flux. It is as per the law of conservation of energy. However, in case of an open circuit, an emf is induced across its ends.



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even if the charges are stationary [and the $q(\mathbf{v} \times \mathbf{B})$ term of the Lorentz force is not operative], an emf is nevertheless induced in the presence of a time-varying magnetic field. Thus, moving charges in static field and static charges in a time-varying field seem to be symmetric situation for Faraday's law. This gives a tantalising hint on the relevance of the principle of relativity for Faraday's law.

4.

The motion of a copper plate is damped when it is allowed to oscillate between the magnetic pole-pieces. How is the damping force, produced by the eddy currents?

EXERCISES

6.1

Predict the direction of induced current in the situations described by the following Figs. 6.18(a) to (f).

FIGURE 6.18

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6.2

Use Lenz's law to determine the direction of induced current in the situations described by Fig. 6.19:

- (a) A wire of irregular shape turning into a circular shape;
- (b) A circular loop being deformed into a narrow straight wire.

FIGURE 6.19

6.3

A long solenoid with 15 turns per cm has a small loop of area 2.0 cm^2 placed inside the solenoid normal to its axis. If the current carried by the solenoid changes steadily from 2.0 A to 4.0 A in 0.1 s , what is the induced emf in the loop while the current is changing?

6.4

A rectangular wire loop of sides 8 cm and 2 cm with a small cut is moving out of a region of uniform magnetic field of magnitude 0.3 T directed normal to the loop. What is the emf developed across the cut if the velocity of the loop is 1 cm s^{-1} in a direction normal to the (a) longer side, (b) shorter side of the loop? For how long does the induced voltage last in each case?

6.5

A 1.0 m long metallic rod is rotated with an angular frequency of 400 rad s^{-1} about an axis normal to the rod passing through its one end. The other end of the rod is in contact with a circular metallic

ring. A constant and uniform magnetic field of 0.5 T parallel to the axis exists everywhere. Calculate the emf developed between the centre and the ring.

6.6

A circular coil of radius 8.0 cm and 20 turns is rotated about its vertical diameter with an angular speed of 50 rad s^{-1} in a uniform horizontal magnetic field of magnitude $3.0 \times 10^{-2} \text{ T}$. Obtain the maximum and average emf induced in the coil. If the coil forms a closed loop of resistance 10Ω , calculate the maximum value of current in the coil. Calculate the average power loss due to Joule heating.

Where does this power come from?

6.7

A horizontal straight wire 10 m long extending from east to west is falling with a speed of 5.0 m s^{-1} , at right angles to the horizontal component of the earth's magnetic field, $0.30 \times 10^{-4} \text{ Wb m}^{-2}$.

(a) What is the instantaneous value of the emf induced in the wire?

(b) What is the direction of the emf?

(c) Which end of the wire is at the higher electrical potential?

6.8

Current in a circuit falls from 5.0 A to 0.0 A in 0.1 s. If an average emf

of 200 V induced, give an estimate of the self-inductance of the circuit.

6.9

A pair of adjacent coils has a mutual inductance of 1.5 H. If the current in one coil changes from 0 to 20 A in 0.5 s, what is the change of flux linkage with the other coil?

6.10

A jet plane is travelling towards west at a speed of 1800 km/h. What

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is the voltage difference developed between the ends of the wing

Electromagnetic

Induction

having a span of 25 m, if the Earth's magnetic field at the location

has a magnitude of 5×10^{-4} T and the dip angle is 30° .

ADDITIONAL EXERCISES

6.11

Suppose the loop in Exercise 6.4 is stationary but the current feeding the electromagnet that produces the magnetic field is gradually reduced so that the field decreases from its initial value of 0.3 T at the rate of 0.02 T s^{-1} . If the cut is joined and the loop has a resistance of 1.6Ω , how much power is dissipated by the

loop as heat? What is the source of this power?

6.12

A square loop of side 12 cm with its sides parallel to X and Y axes is moved with a velocity of 8 cm s^{-1} in the positive x - direction in an

environment containing a magnetic field in the positive z -direction.

The field is neither uniform in space nor constant in time. It has a

gradient of $10^{-3} \text{ T cm}^{-1}$ along the negative x - direction (that is it increases by $10^{-3} \text{ T cm}^{-1}$ as one moves in the negative x -direction), and it is decreasing in time at the rate of 10^{-3} T s^{-1} . Determine the direction and magnitude of the induced current in the loop if its resistance is $4.50 \text{ m}\Omega$.

6.13

It is desired to measure the magnitude of field between the poles of a powerful loud speaker magnet. A small flat search coil of area 2 cm^2 with 25 closely wound turns, is positioned normal to the field direction, and then quickly snatched out of the field region.

Equivalently, one can give it a quick 90° turn to bring its plane parallel to the field direction). The total charge flown in the coil (measured by a ballistic galvanometer connected to coil) is

7.5 mC . The combined resistance of the coil and the galvanometer is 0.50Ω . Estimate the field strength of magnet.

6.14

Figure 6.20 shows a metal rod PQ resting on the smooth rails AB and positioned between the poles of a permanent magnet. The rails, the rod, and the magnetic field are in three mutual perpendicular directions. A galvanometer G connects the rails through a switch K. Length of the rod = 15 cm, $B = 0.50$ T, resistance of the closed loop containing the rod = 9.0 m Ω . Assume the field to be uniform.

(a) Suppose K is open and the rod is moved with a speed of 12 cm s $^{-1}$ in the direction shown. Give the polarity and magnitude of the induced emf.

FIGURE 6.20

(b) Is there an excess charge built up at the ends of the rods when K is open? What if K is closed?

(c) With K open and the rod moving uniformly, there is *no net force* on the electrons in the rod PQ even though they do

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experience magnetic force due to the motion of the rod. Explain.

(d) What is the retarding force on the rod when K is closed?

(e) How much power is required (by an external agent) to keep

the rod moving at the same speed ($=12 \text{ cm s}^{-1}$) when K is closed?

How much power is required when K is open?

(f) How much power is dissipated as heat in the closed circuit?

What is the source of this power?

(g) What is the induced emf in the moving rod if the magnetic field is parallel to the rails instead of being perpendicular?

6.15

An air-cored solenoid with length 30 cm, area of cross-section 25 cm^2 and number of turns 500, carries a current of 2.5 A. The current is suddenly switched off in a brief time of 10^{-3} s . How much is the average back emf induced across the ends of the open switch in the circuit? Ignore the variation in magnetic field near the ends of the solenoid.

6.16

(a) Obtain an expression for the mutual inductance between a long straight wire and a square loop of side a as shown in Fig. 6.21.

(b) Now assume that the straight wire carries a current of 50 A and the loop is moved to the right with a constant velocity, $v = 10 \text{ m/s}$.

Calculate the induced emf in the loop at the instant when $x = 0.2 \text{ m}$.

Take $a = 0.1 \text{ m}$ and assume that the loop has a large resistance.

FIGURE 6.21

6.17

A line charge λ per unit length is lodged uniformly onto the rim of a wheel of mass M and radius R . The wheel has light non-conducting spokes and is free to rotate without friction about its axis (Fig. 6.22).

A uniform magnetic field extends over a circular region within the rim. It is given by,

$$\mathbf{B} = -B \mathbf{k}$$

$$(r \leq a; a < R)$$

$$0$$

$$= 0$$

(otherwise)

What is the angular velocity of the wheel after the field is suddenly switched off ?

232

FIGURE 6.22

Chapter Seven

ALTERNATING

CURRENT

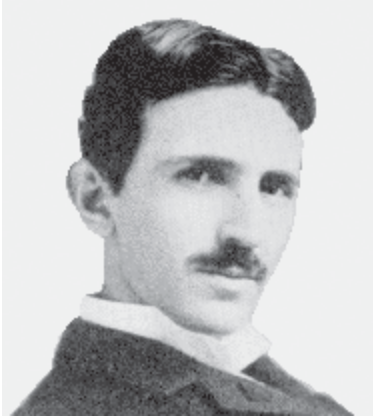
7.1 INTRODUCTION

We have so far considered direct current (dc) sources and circuits with dc sources. These currents do not change direction with time. But voltages

and currents that vary with time are very common. The electric mains supply in our homes and offices is a voltage that varies like a sine function with time. Such a voltage is called *alternating voltage* (ac voltage) and the current driven by it in a circuit is called the *alternating current* (ac current)*. Today, most of the electrical devices we use require ac voltage.

This is mainly because most of the electrical energy sold by power companies is transmitted and distributed as alternating current. The main reason for preferring use of ac voltage over dc voltage is that ac voltages can be easily and efficiently converted from one voltage to the other by means of transformers. Further, electrical energy can also be transmitted economically over long distances. AC circuits exhibit characteristics which are exploited in many devices of daily use. For example, whenever we tune our radio to a favourite station, we are taking advantage of a special property of ac circuits – one of many that you will study in this chapter.

* The phrases *ac voltage* and *ac current* are contradictory and redundant, respectively, since they mean, literally, *alternating current voltage* and *alternating current current*. Still, the abbreviation *ac* to designate an electrical quantity displaying simple harmonic time dependence has become so universally accepted that we follow others in its use. Further, *voltage* – another phrase commonly used means potential difference between two points.



Physics

7.2 AC VOLTAGE APPLIED TO A RESISTOR

Figure 7.1 shows a resistor connected to a source ε of ac voltage. The symbol for an ac source in a circuit diagram is \sim . We consider a source which produces sinusoidally varying potential difference across its terminals. Let this potential difference, also called ac voltage, be given by

$$v = v \sin \omega t$$

(7.1)

m

where v is the amplitude of the oscillating potential

m

difference and ω is its angular frequency.

Nicola Tesla (1836 –

1943) Yugoslov scientist,
inventor and genius. He
conceived the idea of the
rotating magnetic field,
1943)

which is the basis of

practically all alternating
current machinery, and
which helped usher in the
age of electric power. He

FIGURE 7.1 AC voltage applied to a resistor.

also invented among other
things the induction motor,

To find the value of current through the resistor, we
the polyphase system of ac

$$\sum \epsilon t =$$

power, and the high

apply Kirchhoff's loop rule

()

0 , to the circuit

frequency induction coil

shown in Fig. 7.1 to get

(the Tesla coil) used in radio

$$v \sin \omega t = i R$$

and television sets and

m

other electronic equipment.

vm

=

ω

NICOLA TESLA (1836

The SI unit of magnetic field

or *i*

sin

t

R

is named in his honour.

Since *R* is a constant, we can write this equation as

$$i = i \sin \omega t$$

(7.2)

m

where the current amplitude i is given by

m

v_m

$i =$

m

(7.3)

R

Equation (7.3) is just Ohm's law which for resistors works equally well for both ac and dc voltages. The voltage across a pure resistor and the current through it, given by Eqs. (7.1) and (7.2) are plotted as a function of time in Fig. 7.2. Note, in particular that both v and i reach zero, minimum and maximum values at the same time. Clearly, *the voltage and current are in*

FIGURE 7.2 In a pure

resistor, the voltage and

phase with each other.

current are in phase. The

We see that, like the applied voltage, the current varies

minima, zero and maxima

sinusoidally and has corresponding positive and negative values

occur at the same

during each cycle. Thus, the sum of the instantaneous current

respective times.

values over one complete cycle is zero, and the average current

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is zero. The fact that the average current is zero, however, does



Alternating Current

not mean that the average power consumed is zero and

that there is no dissipation of electrical energy. As you

know, Joule heating is given by $i^2 R$ and depends on i^2

(which is always positive whether i is positive or negative)

and not on i . Thus, there is Joule heating and

dissipation of electrical energy when an

ac current passes through a resistor.

The instantaneous power dissipated in the resistor is

2

2

2

$$p = i R = i R \sin \omega t$$

(7.4)

m

The average value of p over a cycle is*

2

2

2

$$p = \langle i R \rangle = \langle i R \sin \omega t \rangle$$

[7.5(a)]

m

where the bar over a letter (here, p) denotes its average

GEORGE WESTINGHOUSE (1846 – 1914)

George Westinghouse

value and $\langle \dots \rangle$ denotes taking average of the quantity

(1846 – 1914) A leading

inside the bracket. Since, i^2 and R are constants,

m

proponent of the use of

2

2

$$p = i R <$$

t

$\omega >$

[7.5(b)]

alternating current over

sin

m

direct current. Thus,

Using the trigonometric identity, $\sin^2 \omega t =$

he came into conflict

$\frac{1}{2} (1 - \cos 2\omega t)$, we have $\langle \sin^2 \omega t \rangle = \frac{1}{2} (1 - \langle \cos 2\omega t \rangle)$ with Thomas Alva Edison, and since $\langle \cos 2\omega t \rangle = 0^{**}$, we have,

an advocate of direct

curr ent. Westinghouse

1

2

$$\langle \sin \omega t \rangle =$$

was convinced that the

2

technology of alternating

Thus,

current was the key to

the electrical future.

1 2

$p =$

$i R$

[7.5(c)]

He founded the famous

2 m

Company named after him

To express ac power in the same form as dc power

and enlisted the services

($P = I^2 R$), a special value of current is defined and used.

of Nicola Tesla and

It is called, *root mean square* (rms) or *effective current*

other inventors in the

(Fig. 7.3) and is denoted by I

or I .

development of alternating

rms

current motors and

apparatus for the

transmission of high

tension current, pioneering

in large scale lighting.

FIGURE 7.3 The rms current I is related to the

peak current i by $I = i / \sqrt{2} = 0.707 i$.

m

m

m

$1/T$

* The average value of a function $F(t)$ over a period T is given by $F(t) =$

$F(t) dt$

∫

$T/0$

1

1 [sin 2

T

T

$\omega t]$

1

** $\langle \cos 2\omega t \rangle =$

$\int \cos 2\omega t dt =$

=

|

|

$[\sin 2\omega T - 0] = 0$

T

$T [$

2ω

]

$2\omega T$

0

235

0

Physics

It is defined by

i

2

1 2

m

$I = i$

=

i

=

2 m

2

= 0.707 i

(7.6)

m

In terms of I , the average power, denoted by P is

1 2

2

$P = p =$

$i R = I R$

(7.7)

2 m

Similarly, we define the *rms voltage* or *effective voltage* by

$$v_m$$

$$V =$$

$$= 0.707 v$$

$$(7.8)$$

$$2$$

$$m$$

From Eq. (7.3), we have

$$v = i R$$

$$m$$

$$m$$

$$v$$

$$i$$

$$m$$

$$m$$

or,

$$=$$

$$R$$

$$2$$

$$2$$

or, $V = IR$

(7.9)

Equation (7.9) gives the relation between ac current and ac voltage and is similar to that in the dc case. This shows the advantage of introducing the concept of rms values. In terms of rms values, the equation for power [Eq. (7.7)] and relation between current and voltage in ac circuits are essentially the same as those for the dc case.

It is customary to measure and specify rms values for ac quantities. For example, the household line voltage of 220 V is an rms value with a peak voltage of

$v =$

m

$$2 V = (1.414)(220 \text{ V}) = 311 \text{ V}$$

In fact, the I or rms current is the equivalent dc current that would produce the same average power loss as the alternating current. Equation (7.7) can also be written as

$P = V^2 / R = I V$ (since $V = I R$) **Example 7.1** A light bulb is rated at 100W for a 220 V supply. Find (a) the resistance of the bulb; (b) the peak voltage of the source; and

(c) the rms current through the bulb.

Solution

(a) We are given $P = 100 \text{ W}$ and $V = 220 \text{ V}$. The resistance of the bulb is

V

(

)²

2

220 V

$R =$

=

$= 484 \Omega$

P

100 W

(b) The peak voltage of the source is

$v =$

$2 V = 311 \text{ V}$

m

7.1

(c) Since, $P = I V$

P

100 W

XAMPLE

$I =$

$=$

$= 0.450\text{A}$

V

220 V

236

E

Alternating Current

7.3 REPRESENTATION OF AC CURRENT AND VOLTAGE BY ROTATING VECTORS — PHASORS

In the previous section, we learnt that the current through a resistor is in phase with the ac voltage. But this is not so in the case of an inductor, a capacitor or a combination of these circuit elements. In order to show phase relationship between voltage and current in an ac circuit, we use the notion of *phasors*.

The analysis of an ac circuit is facilitated by the use of a phasor diagram. A phasor* is a vector which rotates about the origin with angular speed ω , as shown in Fig. 7.4. The vertical components of phasors **V** and **I** represent the

sinusoidally varying quantities v and i . The magnitudes of phasors \mathbf{V} and \mathbf{I} represent the amplitudes or the peak values v and i of these

m

m

oscillating quantities. Figure 7.4(a) shows the

FIGURE 7.4 (a) A phasor diagram for the

voltage and current phasors and their

circuit in Fig 7.1. (b) Graph of v and

relationship at time t for the case of an ac source

i versus ωt .

1

connected to a resistor i.e., corresponding to the

circuit shown in Fig. 7.1. The projection of

voltage and current phasors on vertical axis, i.e., $v \sin \omega t$ and $i \sin \omega t$, m m

respectively represent the value of voltage and current at that instant. As

they rotate with frequency ω , curves in Fig. 7.4(b) are generated.

From Fig. 7.4(a) we see that phasors \mathbf{V} and \mathbf{I} for the case of a resistor are in the same direction. This is so for all times. This means that the phase angle between the voltage and the current is zero.

7.4 AC VOLTAGE APPLIED TO AN INDUCTOR

Figure 7.5 shows an ac source connected to an inductor. Usually, inductors have appreciable resistance in their windings, but we shall assume that this inductor has negligible resistance.

Thus, the circuit is a purely inductive ac circuit. Let the voltage across the source be $v = v_m \sin \omega t$. Using

m

the Kirchhoff's loop rule, $\sum \varepsilon (t) = 0$, and since there is no resistor in the circuit,

$d i$

$v - L$

$= 0$

(7.10)

$d t$

where the second term is the self-induced Faraday

FIGURE 7.5 An ac source

emf in the inductor; and L is the self-inductance of connected to an inductor.

* Though voltage and current in ac circuit are represented by phasors – rotating vectors, they are not vectors themselves. They are scalar quantities. It so happens that the amplitudes and phases of harmonically varying scalars combine mathematically in the same way as do the projections of rotating vectors of

corresponding magnitudes and directions. The *rotating vectors* that *represent* harmonically varying scalar quantities are introduced only to provide us with a simple way of adding these quantities using a rule that we already know.

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the inductor. The negative sign follows from Lenz's law (Chapter 6).

Combining Eqs. (7.1) and (7.10), we have

$$\begin{aligned}
 \frac{d i}{d t} &= \\
 &= \\
 &=
 \end{aligned}$$

$$\sin \omega t$$

$$(7.11)$$

$$\frac{d i}{d t}$$

$$L$$

$$L$$

Equation (7.11) implies that the equation for $i(t)$, the current as a function of time, must be such that its slope $d i/d t$ is a sinusoidally varying quantity, with the same phase as the source voltage and an amplitude given by v/L . To obtain the current, we integrate $d i/d t$ with respect to m

time:

$d i$

v

d

m

$t =$

$\sin(t$

$\omega)d t$

\int

\int

$d t$

L

and get,

$v m$

$i = -$

$\cos(\omega t) + \text{constant}$

ωL

The integration constant has the dimension of current and is time-independent. Since the source has an emf which oscillates symmetrically about zero, the current it sustains also oscillates symmetrically about zero, so that no constant or time-independent component of the current exists. Therefore, the integration constant is zero.

Using

(
)

$$-\cos(\omega t) = \sin \left| \omega \right.$$

π

$t -$

|
(

2) , we have

(
)

$$i = i \sin \left| t \right.$$

ω

π

-

m

|
(

2)

(7.12)

v

where

m

i

=

m

ω is the amplitude of the current. The quantity ωL is

L

analogous to the resistance and is called *inductive reactance*, denoted

by X :

L

$$X = \omega L$$

(7.13)

L

The amplitude of the current is, then

v_m

i

=

m

X

(7.14)

L

The dimension of inductive reactance is the same as that of resistance and its SI unit is ohm (Ω). The inductive reactance limits the current in a

Interactive animation on Phasor diagrams of ac circuits containing, R, L, C and RLC series circuits: <http://www.phys.unsw.edu.au/~jw/AC.html> purely inductive circuit in the same way as the resistance limits the

current in a purely resistive circuit. The inductive reactance is directly proportional to the inductance and to the frequency of the current.

A comparison of Eqs. (7.1) and (7.12) for the source voltage and the current in an inductor shows that the current lags the voltage by $\pi/2$ or one-quarter ($1/4$) cycle. Figure 7.6 (a) shows the voltage and the current phasors in the present case at instant t . The current phasor \mathbf{I} is $\pi/2$

1

behind the voltage phasor \mathbf{V} . When rotated with frequency ω counterclockwise, they generate the voltage and current given by Eqs. (7.1) and

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(7.12), respectively and as shown in Fig. 7.6(b).

Alternating Current

FIGURE 7.6 (a) A Phasor diagram for the circuit in Fig. 7.5.

(b) Graph of v and i versus ωt .

We see that the current reaches its maximum value later than the

$[T$

$\pi/2]$

voltage by one-fourth of a period

=

|

|

$[4$

$\omega]$. You have seen that an

inductor has reactance that limits current similar to resistance in a

dc circuit. Does it also consume power like a resistance? Let us try to

find out.

The instantaneous power supplied to the inductor is

(

$\pi)$

$$p = i v = i \sin(\omega t - \frac{\pi}{2}) \times v \sin \omega t$$

L

m

m

()

(

2)

= i

- $v \cos(t$

$\omega) \sin t$

ω

m

m

()

$i v$

m

m

= -

$\sin(2 t$

$\omega)$

2

So, the average power over a complete cycle is

$i v$

m

m

$$P = -$$

$$\sin 2\omega t$$

L

(

)

2

$i v$

m

m

= -

$$\sin (2\omega t) = 0,$$

2

since the average of $\sin (2\omega t)$ over a complete cycle is zero.

Thus, the *average power supplied to an inductor over one complete cycle is zero.*

Figure 7.7 explains it in detail.

Example 7.2 A pure inductor of 25.0 mH is connected to a source of 220 V. Find the inductive reactance and rms current in the circuit if the frequency of the source is 50 Hz.

Solution The inductive reactance,

E

—

X

=

$$\pi v L = \times .$$

3

2

2

$$3 \ 14 \times 50 \times 25 \times 10$$

W

L

XAMPLE

$$= 7.85\Omega$$

The rms current in the circuit is

7.2

V

220 V

I =

=

= 28A

X

7.85 Ω

L

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Physics

0-1 Current i through the coil entering at A

1-2 Current in the coil is still positive but is
increase from zero to a maximum value. Flux
decreasing. The core gets demagnetised and
lines are set up i.e., the core gets magnetised.
the net flux becomes zero at the end of a half

With the polarity shown voltage and current
cycle. The voltage v is negative (since $d i/d t$ is
are both positive. So their product p is positive.
negative). The product of voltage and current

ENERGY IS ABSORBED FROM THE

is negative, and ENERGY IS BEING

SOURCE.

RETURNED TO SOURCE.

One complete cycle of voltage/current. Note that the current lags the voltage.

2-3 Current i becomes negative i.e., it enters

3-4 Current i decreases and reaches its zero

at B and comes out of A. Since the direction

value at 4 when core is demagnetised and flux

of current has changed, the polarity of the

is zero. The voltage is positive but the current

magnet changes. The current and voltage are

is negative. The power is, therefore, negative.

both negative. So their product p is positive.

ENERGY ABSORBED DURING THE 1/4

ENERGY IS ABSORBED.

CYCLE 2-3 IS RETURNED TO THE SOURCE.

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FIGURE 7.7 Magnetisation and demagnetisation of an inductor.

Alternating Current

7.5 AC VOLTAGE APPLIED TO A CAPACITOR

Figure 7.8 shows an ac source ε generating ac voltage $v = v \sin \omega t$

connected to a capacitor only, a purely capacitive ac circuit.

When a capacitor is connected to a voltage source

in a dc circuit, current will flow for the short time required to charge the capacitor. As charge accumulates on the capacitor plates, the voltage across them increases, opposing the current. That is, a capacitor in a dc circuit will limit or oppose the current as it charges. When the capacitor is fully charged, the current in the circuit falls to zero.

When the capacitor is connected to an ac source, as in Fig. 7.8, it limits or regulates the current, but does not completely prevent the flow of charge. The

FIGURE 7.8 An ac source

capacitor is alternately charged and discharged as connected to a capacitor.

the current reverses each half cycle. Let q be the charge on the capacitor at any time t . The instantaneous voltage v across the capacitor is

$$q$$

$$v =$$

$$(7.15)$$

$$C$$

From the Kirchhoff's loop rule, the voltage across the source and the

capacitor are equal,

q

$v \sin \omega t =$

m

C

$d q$

To find the current, we use the relation $i = d t$

d

$i =$

$(v C \sin \omega t = \omega C v$

ωt

m

)

$\cos($

)

d

m

t

(

)

Using the relation, $\cos(\omega t) = \sin(\omega t + \frac{\pi}{2})$,

π

$t +$

|

(

2), we have

(

)

$i = i_m \sin(\omega t + \frac{\pi}{2})$

π

$t +$

m

|

(

2)

(7.16)

where the amplitude of the oscillating current is $i_m = \omega C v_m$. We can rewrite m

m

it as

v_m

i

=

m

$(1/\omega C)$

Comparing it to $i = v / R$ for a purely resistive circuit, we find that m

m

$(1/\omega C)$ plays the role of resistance. It is called *capacitive reactance* and is denoted by X_c ,

$$X_c = 1/\omega C$$

(7.17)

c

so that the amplitude of the current is

v_m

i

=

m

(7.18)

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XC

Physics

The dimension of capacitive reactance is the

same as that of resistance and its SI unit is ohm (Ω). The capacitive reactance limits the amplitude of the current in a purely capacitive circuit in the same way as the resistance limits the current in a purely resistive circuit. But it is inversely proportional to the frequency and the capacitance.

A comparison of Eq. (7.16) with the

FIGURE 7.9 (a) A Phasor diagram for the circuit in Fig. 7.8. (b) Graph of v and i versus ωt .

equation of source voltage, Eq. (7.1) shows that the current is $\pi/2$ ahead of voltage.

Figure 7.9(a) shows the phasor diagram at an instant t . Here the current phasor \mathbf{I} is $\pi/2$ ahead of the voltage phasor \mathbf{V} as they rotate counterclockwise. Figure 7.9(b) shows the variation of voltage and current with time. We see that the current reaches its maximum value earlier than the voltage by one-fourth of a period.

The instantaneous power supplied to the capacitor is

$$p = i v = i \cos(\omega t) v \sin(\omega t) c$$

m

m

$$= i v \cos(\omega t) \sin(\omega t)$$

$m m$

$i v$

m

m

=

$\sin(2 t$

$\omega)$

(7.19)

2

So, as in the case of an inductor, the average power

$i v$

$i v$

m

m

$P =$

$\sin(2 t$

$\omega)$

m

m

=

$\sin(2\omega t$

$\omega) = 0$

C

2

2

since $\langle \sin(2\omega t) \rangle = 0$ over a complete cycle. Figure 7.10 explains it in detail.

Thus, we see that in the case of an inductor, the current lags the voltage by $\pi/2$ and in the case of a capacitor, the current leads the voltage by $\pi/2$.

Example 7.3 A lamp is connected in series with a capacitor. Predict your observations for dc and ac connections. What happens in each case if the capacitance of the capacitor is reduced?

Solution When a dc source is connected to a capacitor, the capacitor gets charged and after charging no current flows in the circuit and the lamp will not glow. There will be no change even if C is reduced.

7.3

With ac source, the capacitor offers capacitive reactance $(1/\omega C)$ and the current flows in the circuit. Consequently, the lamp will shine.

Reducing C will increase reactance and the lamp will shine less brightly
XAMPLE

than before.

E

Example 7.4 A $15.0 \mu\text{F}$ capacitor is connected to a 220 V , 50 Hz source.

Find the capacitive reactance and the current (rms and peak) in the circuit. If the frequency is doubled, what happens to the capacitive reactance and the current?

Solution The capacitive reactance is

7.4

1

1

X

=

=

= 212Ω

C

-6

$2 \pi v C$

$2\pi (50\text{Hz})(15.0 \times 10^{-6} \text{ F})$

XAMPLE

The rms current is

E

Alternating Current

0-1 The current i flows as shown and from the

1-2 The current i reverses its direction. The

maximum at 0, reaches a zero value at 1. The plate

accumulated charge is depleted i.e., the capacitor is

A is charged to positive polarity while negative charge

discharged during this quarter cycle. The voltage gets

q builds up in B reaching a maximum at 1 until the

reduced but is still positive. The current is negative.

current becomes zero. The voltage $v = q/C$ is in phase

Their product, the power is negative.

c

with q and reaches maximum value at l . Current

THE ENERGY ABSORBED DURING THE 1/4

and voltage are both positive. So $p = v i$ is positive.

CYCLE **0-1** IS RETURNED DURING THIS QUARTER.

c

ENERGY IS ABSORBED FROM THE SOURCE
DURING THIS QUARTER CYCLE AS THE
CAPACITOR IS CHARGED.

One complete cycle of voltage/current. Note that the current leads the voltage.

2-3 As i continues to flow from A to B, the capacitor

3-4 The current i reverses its direction at **3** and flows

is charged to reversed polarity i.e., the plate B

from B to A. The accumulated charge is depleted

acquires positive and A acquires negative charge.

and the magnitude of the voltage v is reduced. v

c

c

Both the current and the voltage are negative. Their

becomes zero at **4** when the capacitor is fully

product p is positive. The capacitor ABSORBS

discharged. The power is negative. ENERGY

ENERGY during this 1/4 cycle.

ABSORBED DURING **2-3** IS RETURNED TO THE

SOURCE. NET ENERGY ABSORBED IS ZERO.

FIGURE 7.10 Charging and discharging of a capacitor.

Physics

V

220 V

$I =$

$=$

$= 1.04 \text{ A}$

X

212 Ω

C

The peak current is

i

$$= 2 I = (1.41)(1.04 \text{ A}) = 1.47 \text{ A}$$

m

7.4

This current oscillates between +1.47A and -1.47 A, and is ahead of the voltage by $\pi/2$.

If the frequency is doubled, the capacitive reactance is halved and

XAMPLE

E

consequently, the current is doubled.

Example 7.5 A light bulb and an open coil inductor are connected to an ac source through a key as shown in Fig. 7.11.

FIGURE 7.11

The switch is closed and after sometime, an iron rod is inserted into the interior of the inductor. The glow of the light bulb (a) increases; (b) decreases; (c) is unchanged, as the iron rod is inserted. Give your answer with reasons.

Solution As the iron rod is inserted, the magnetic field inside the coil magnetizes the iron increasing the magnetic field inside it. Hence, the inductance of the coil increases. Consequently, the inductive reactance of the coil increases. As a result, a larger fraction of the

XAMPLE

applied ac voltage appears across the inductor, leaving less voltage

E

across the bulb. Therefore, the glow of the light bulb decreases.

7.6 AC VOLTAGE APPLIED TO A SERIES LCR CIRCUIT

Figure 7.12 shows a series LCR circuit connected to an ac source ϵ . As usual, we take the voltage of the source to be $v = v \sin \omega t$.

m

If q is the charge on the capacitor and i the current, at time t , we have, from Kirchhoff's loop rule:

$$\frac{d}{dt} \left(\frac{q}{C} + Li + iR \right) = v$$

(7.20)

$$\frac{d}{dt} \left(\frac{q}{C} + Li + iR \right) = v$$

We want to determine the instantaneous current i and its phase relationship to the applied alternating voltage v . We shall solve this problem by two methods. First, we use the technique of

FIGURE 7.12 A series LCR circuit

phasors and in the second method, we solve connected to an ac source.

Eq. (7.20) analytically to obtain the time–

dependence of i .

Alternating Current

7.6.1 Phasor-diagram solution

From the circuit shown in Fig. 7.12, we see that the resistor, inductor and capacitor are in series. Therefore, the ac current in each element is the same at any time, having the same amplitude and phase. Let it be

$$i = i_m \sin(\omega t + \phi)$$

(7.21)

m

where ϕ is the phase difference between the voltage across the source and the current in the circuit. On the basis of what we have learnt in the previous sections, we shall construct a phasor diagram for the present case.

Let \mathbf{I} be the phasor representing the current in the circuit as given by

Eq. (7.21). Further, let \mathbf{V}_L , \mathbf{V}_R , \mathbf{V}_C , and \mathbf{V} represent the voltage across the **L**

R

C

inductor, resistor, capacitor and the source, respectively. From previous section, we know that \mathbf{V}_R is parallel to \mathbf{I} , \mathbf{V}_L is $\pi/2$

R

C

behind \mathbf{I} and \mathbf{V}_C is $\pi/2$ ahead of \mathbf{I} . \mathbf{V}_L , \mathbf{V}_R , \mathbf{V}_C and \mathbf{V}

L

R

C

are shown in Fig. 7.13(a) with appropriate phase—
relations.

The length of these phasors or the amplitude

of V_R , V_C and V_L are:

R

C

L

v

$$= i R, v$$

$$= i X_C, v$$

$$= i X_L$$

(7.22)

R_m

m

C_m

m

$C L m m$

L

The voltage Equation (7.20) for the circuit can be written as

$$v + v + v = v$$

(7.23)

L

R

C

The phasor relation whose vertical component gives the above equation is

FIGURE 7.13 (a) Relation between the phasors \mathbf{V} , \mathbf{V} , \mathbf{V} , and I , (b) Relation

$$\mathbf{V} + \mathbf{V} + \mathbf{V} = \mathbf{V}$$

(7.24)

L

R

C

L

R

C

between the phasors \mathbf{V} , \mathbf{V} , and $(\mathbf{V} + \mathbf{V})$

L

R

L

C

This relation is represented in Fig. 7.13(b). Since
for the circuit in Fig. 7.11.

\mathbf{V} and \mathbf{V} are always along the same line and in

C

L

opposite directions, they can be combined into a single phasor $(\mathbf{V} + \mathbf{V})$ C

L

which has a magnitude $|v - v|$. Since \mathbf{V} is represented as the Cm

Lm

hypotenuse of a right-triangle whose sides are \mathbf{V} and $(\mathbf{V} + \mathbf{V})$, the R

C

L

pythagorean theorem gives:

v

$= v$

$$+ (v - v)^2$$

$$2$$

$$2$$

$$m$$

$$Rm$$

$$Cm$$

$$Lm$$

Substituting the values of v

$$, v$$

, and v from Eq. (7.22) into the above

$$Rm$$

$$Cm$$

$$Lm$$

equation, we have

$$2$$

$$2$$

$$2$$

$$v$$

$$= (iR) + (iX - iX)$$

m

m

m

C

m

L

2

2

2

$$= i [R + (X - X)]$$

m [

C

L

]

vm

or, *i*

=

m

2

2

$R + (X -$

[7.25(a)]

$X)$

C

L

By analogy to the resistance in a circuit, we introduce the *impedance* Z in an ac circuit:

v_m

i

=

m

[7.25(b)]

Z

where

2

2

=

+

-

(7.26)

245

Z

R

$(X$

$X)$

C

L

Physics

Since phasor \mathbf{I} is always parallel to phasor \mathbf{V} , the phase angle ϕ

R

is the angle between \mathbf{V} and \mathbf{V} and can be determined from

R

Fig. 7.14:

v

$-v$

\tan

Cm

Lm

$\phi =$

vRm

Using Eq. (7.22), we have

X

X

\tan

C

L

ϕ

—

=

(7.27)

R

Equations (7.26) and (7.27) are graphically shown in Fig. (7.14).

FIGURE 7.14 Impedance

This is called *Impedance diagram* which is a right-triangle with diagram.

Z as its hypotenuse.

Equation 7.25(a) gives the amplitude of the current and Eq. (7.27)

gives the phase angle. With these, Eq. (7.21) is completely specified.

If $X > X$, ϕ is positive and the circuit is predominantly capacitive.

C

L

Consequently, the current in the circuit leads the source voltage. If

$X < X$, ϕ is negative and the circuit is predominantly inductive.

C

L

Consequently, the current in the circuit lags the source voltage.

Figure 7.15 shows the phasor diagram and variation of v and i with ωt for the case $X > X$.

C

L

Thus, we have obtained the amplitude and phase of current for an LCR series circuit using the technique of phasors. But this method of analysing ac circuits suffers from certain disadvantages. First, the phasor diagram says nothing about the initial condition. One can take any arbitrary value of t (say, t , as done throughout this chapter)

1

and draw different phasors which show the

relative angle between different phasors.

The solution so obtained is called the *steady-state solution*. This is not a general

FIGURE 7.15 (a) Phasor diagram of **V** and **I**.

solution. Additionally, we do have a

(b) Graphs of v and i versus ωt for a series *LCR*

transient solution which exists even for

circuit where $X > X$.

C

L

$v = 0$. The general solution is the sum of the

transient solution and the steady-state

solution. After a sufficiently long time, the effects of the transient solution die out and the behaviour of the circuit is described by the steady-state solution.

7.6.2 Analytical solution

The voltage equation for the circuit is

$$L \frac{di}{dt} + Ri + \frac{q}{C} = v \sin \omega t$$

We know that $i = dq/dt$. Therefore, $d^2q/dt^2 = di/dt$. Thus, in terms of q ,

the voltage equation becomes

Alternating Current

2

$$L \frac{d^2q}{dt^2} + R \frac{dq}{dt} + \frac{q}{C} = v \sin \omega t$$

$d q$ q L $+ R$ $+$ $= v \sin \omega t$ (7.28) 2 $d t$ d m t C

This is like the equation for a forced, damped oscillator, [see Eq. {14.37(b)} in Class XI Physics Textbook]. Let us assume a solution

$$q = q \sin (\omega t + \theta)$$

 $[7.29(a)]$ m $d q$

so that

$$= q \omega \cos(\omega t + \theta)$$

[7.29(b)]

d

m

t

2

$d q$

and

2

$$= -q \omega \sin(\omega t + \theta)$$

[7.29(c)]

2

d

m

t

Substituting these values in Eq. (7.28), we get

$$q \omega [R \cos(\omega t + \theta) + (X - X) \sin(\omega t + \theta)] = v \sin t \omega$$

(7.30)

m

C

L

m

where we have used the relation $X = 1/\omega C$, $X = \omega L$. Multiplying and c

L

dividing Eq. (7.30) by $Z = R + (X - X)^2$

2

, we have

c

L

$[R$

$(X - X)$

$] \int$

$q \omega Z$

$\cos(\omega t + \theta)$

C

L

$+$

$\sin(\omega t + \theta)$

m

|

| =

ω

|

v

t

(7.31)

Z

Z

|

sin

m

R

Now, let

$= \cos\varphi$

Z

$(X - X)$

and

C

L

$$= \sin \phi$$

Z

$$- X$$

$$- X$$

1

so that $\phi = \tan$

C

L

(7.32)

R

Substituting this in Eq. (7.31) and simplifying, we get:

$$q \omega Z \cos(\omega t + \theta - \phi) = v \sin \omega t$$

(7.33)

m

m

Comparing the two sides of this equation, we see that

v

$$= q \omega Z = i Z$$

m

m

m

where

i

$$= q \omega$$

m

m

[7.33(a)]

π

and θ

φ

π

$$- = - \text{ or } \theta = - + \varphi$$

[7.33(b)]

2

2

Therefore, the current in the circuit is

$d q$

$i =$

$$= q \omega \cos(\omega t + \theta)$$

d

m

t

$$= i \cos(\omega t + \theta)$$

m

$$\text{or } i = i \sin(\omega t + \varphi)$$

(7.34)

m

v

v

where

m

m

i

=

=

m

[7.34(a)]

2

2

Z

$R + (X - X)$

C

L

$-X$

$-X$

1

and $\phi = \tan$

C

L

247

R

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Thus, the analytical solution for the amplitude and phase of the current in the circuit agrees with that obtained by the technique of phasors.

7.6.3 Resonance

An interesting characteristic of the series RLC circuit is the phenomenon of resonance. The phenomenon of resonance is common among systems that have a tendency to oscillate at a particular frequency. This frequency

is called the system's *natural frequency*. If such a system is driven by an energy source at a frequency that is near the natural frequency, the amplitude of oscillation is found to be large. A familiar example of this

phenomenon is a child on a swing. The the swing has a natural frequency for swinging back and forth like a pendulum. If the child pulls on the rope at regular intervals and the frequency of the pulls is almost the same as the frequency of swinging, the amplitude of the swinging will be large (Chapter 14, Class XI).

For an *RLC* circuit driven with voltage of amplitude v and frequency m ω , we found that the current amplitude is given by

$$i = \frac{v}{\sqrt{R^2 + (X_L - X_C)^2}}$$

L

with $X = 1/\omega C$ and $X = \omega L$. So if ω is varied, then at a particular frequency

ω

(

2

2

$Z =$

$R + 0 = R$)

, $X = X$, and the impedance is minimum

. This

0

c

L

frequency is called the *resonant frequency*:

1

$X = X$ or

$= \omega L$

c

L

0

ωC

0

1

or $\omega =$

0

(7.35)

LC

At resonant frequency, the current amplitude is maximum; $i = v/R$.

m

m

Figure 7.16 shows the variation of i with ω in

m

a RLC series circuit with $L = 1.00$ mH, $C =$

1.00 nF for two values of R : (i) $R = 100 \Omega$

and (ii) $R = 200 \Omega$. For the source applied $v =$

m

(1)

100 V. ω for this case is |

|

0

$$\omega = 1.00 \times 10^6$$

rad/s.

We see that the current amplitude is maximum at the resonant frequency. Since $i = v / R$ at

m

m

resonance, the current amplitude for case (i) is twice to that for case (ii).

Resonant circuits have a variety of

FIGURE 7.16 Variation of i with ω for two

m

applications, for example, in the tuning

cases: (i) $R = 100 \Omega$, (ii) $R = 200 \Omega$,

$L = 1.00 \text{ mH}$.

mechanism of a radio or a TV set. The antenna of

a radio accepts signals from many broadcasting

stations. The signals picked up in the antenna acts as a source in the

248

tuning circuit of the radio, so the circuit can be driven at many frequencies.

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But to hear one particular radio station, we tune the radio. In tuning, we vary the capacitance of a capacitor in the tuning circuit such that the resonant frequency of the circuit becomes nearly equal to the frequency of the radio signal received. When this happens, the amplitude of the current with the frequency of the signal of the particular radio station in the circuit is maximum.

It is important to note that resonance phenomenon is exhibited by a circuit only if both L and C are present in the circuit. Only then do the voltages across L and C cancel each other (both being out of phase) and the current amplitude is v/R , the total source voltage appearing across R. This means that we cannot have resonance in a RL or RC circuit.

Sharpness of resonance

The amplitude of the current in the series LCR circuit is given by

v_m

i_m

=

v_m

2

(

)

2

1

$R + \omega L -$

|

$\omega |$

(

$C)$

and is maximum when $\omega = \omega = 1/ LC$. The maximum value is

0

max

i

$= v / R .$

m

m

For values of ω other than ω , the amplitude of the current is less

0

than the maximum value. Suppose we choose a value of ω for which the

current amplitude is $1/2$ times its maximum value. At this value, the power dissipated by the circuit becomes half. From the curve in Fig. (7.16), we see that there are two such values of ω , say, ω_1 and ω_2 , one

1

2

greater and the other smaller than ω_0 and symmetrical about ω_0 . We may

0

0

write

$$\omega_1 = \omega_0 + \Delta\omega$$

1

0

$$\omega_2 = \omega_0 - \Delta\omega$$

2

0

The difference $\omega_1 - \omega_2 = 2\Delta\omega$ is often called the *bandwidth* of the circuit.

1

2

The quantity $(\omega_0 / 2\Delta\omega)$ is regarded as a measure of the sharpness of

0

resonance. The smaller the $\Delta\omega$, the sharper or narrower is the resonance.

To get an expression for $\Delta\omega$, we note that the current amplitude i is

m

(

) max

$1/2 i$

for $\omega = \omega + \Delta\omega$. Therefore,

m

1

0

v

at ω ,

m

i

=

1

m

2

(

)

2

1

$R + \omega L -$

| 1

ω

|
(

$C)$

1

max

i

v

m

m

=

=

249

2

R^2

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2

(

1)

2

or

$$R + \omega L -$$

$$= R^2$$

| 1

ω

|

(

C)

1

2

(

)

2

1

2

or

$$R + \omega L -$$

$$= 2R$$

$$\left| \frac{1}{\omega} \right.$$

$$\omega$$

|
(

$$C)$$

$$1$$

$$1$$

$$\omega L -$$

$$= R$$

$$1$$

$$\omega C$$

$$1$$

which may be written as,

$$1$$

$$(\omega + \omega$$

$$\Delta) L -$$

$$= R$$

0

$(\omega + \omega$

$\Delta) C$

0

(

$\Delta \omega)$

1

$\omega L 1 +$

-

$= R$

0

||

$\omega |)$

(

ω

$\Delta)$

0

$\omega C 1 +$

0

|

$\omega |$

(

)

0

1

Using 2

$\omega =$

in the second term on the left hand side, we get

0

$L C$

(

ω

$\Delta \setminus$

ωL

0

$\omega L 1 +$

-

$= R$

0

||

$\omega \ll 1$

$\Delta \omega \ll 1$

0

1 +

|

$\omega \ll 1$

(

)

0

1

$\omega \ll 1$

(

$\Delta \omega \ll 1$

(

$\omega \ll 1$

$\Delta \omega \ll 1$

$\Delta \omega$

We can approximate 1 +

|

1 -

$\omega |$

(

) as |

$\omega |$

(

) since $\omega \ll 1$. Therefore,

0

0

0

(

ω

$\Delta \setminus$

(

$\Delta \omega \setminus$

$\omega L 1 +$

$-\omega L 1 -$

$= R$

0

|

|

0

ω

|

ω |

(

)

(

)

0

0

2 ω

Δ

or

ωL

= R

0

$\omega 0$

R

ω

$\Delta =$

[7.36(a)]

$$2L$$

The sharpness of resonance is given by,

$$\omega$$

$$\omega L$$

$$0$$

$$0$$

=

[7.36(b)]

$$2\Delta\omega$$

$$R$$

$$\omega L$$

The ratio 0

is also called the *quality factor*, Q of the circuit.

$$R$$

$$\omega L$$

$$0$$

$$Q =$$

[7.36(c)]

$$R$$

ω

250

From Eqs. [7.36 (b)] and [7.36 (c)], we see that

0

2ω

$\Delta =$

. So, larger the

Q

Alternating Current

value of Q , the smaller is the value of $2\Delta\omega$ or the bandwidth and sharper is the resonance. Using 2

$\omega = 1/LC$, Eq. [7.36(c)] can be equivalently

0

expressed as $Q = 1/\omega CR$.

0

We see from Fig. 7.15, that if the resonance is less sharp, not only is the maximum current less, the circuit is close to resonance for a larger range $\Delta\omega$ of frequencies and the tuning of the circuit will not be good. So, less sharp the resonance, less is the selectivity of the circuit or vice versa.

From Eq. (7.36), we see that if quality factor is large, i.e., R is low or L is large, the circuit is more selective.

Example 7.6 A resistor of 200Ω and a capacitor of $15.0 \mu\text{F}$ are connected in series to a 220 V , 50 Hz ac source. (a) Calculate the current in the circuit; (b) Calculate the voltage (rms) across the resistor and the capacitor. Is the algebraic sum of these voltages more than the source voltage? If yes, resolve the paradox.

Solution

Given

R

C

—

=

Ω

=

F

6

$200 ,$

$15.0 \mu = 15.0 \times 10^{-6} \text{ F}$

$V = 220 \text{ V}, \nu = 50 \text{ Hz}$

(a)

In order to calculate the current, we need the impedance of the

circuit. It is

2

2

2

2

Z

R

X

R

$(2\pi v C)^{-}$

=

+

=

+

C

2

6

- F 2

(200)

(2

3.14

50 10

)-

=

$\Omega +$

\times

\times

\times

2

2

$= (200 \Omega) + (212 \Omega)$

$= 291.5 \Omega$

Therefore, the current in the circuit is

V

220 V

$I =$

$=$

$= 0.755 \text{ A}$

Z

291.5 Ω

(b)

Since the current is the same throughout the circuit, we have

$$V = IR = (0.755 \text{ A})(200 \Omega) = 151 \text{ V}$$

R

$$V = IX$$

$$= (0.755 \text{ A})(212.3 \Omega) = 160.3 \text{ V}$$

C

C

The algebraic sum of the two voltages, V and V is 311.3 V which is R

C

more than the source voltage of 220 V. How to resolve this paradox?

As you have learnt in the text, the two voltages are not in the same

phase. Therefore, *they cannot be added like ordinary numbers*. The two voltages are out of phase by ninety degrees. Therefore, the total of these voltages must be obtained using the Pythagorean theorem:

E

2

2

XAMPLE

V

$$= V + V$$

$$R + C$$

$$R$$

$$C$$

$$= 220 \text{ V}$$

Thus, if the phase difference between two voltages is properly taken

7.6

into account, the total voltage across the resistor and the capacitor is equal to the voltage of the source.

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7.7 POWER IN AC CIRCUIT: THE POWER FACTOR

We have seen that a voltage $v = v \sin \omega t$ applied to a series RLC circuit m drives a current in the circuit given by $i = i \sin(\omega t + \phi)$ where m

v

$- (X$

$- X)$

m

i

=

and

1

$$\phi = \tan^{-1} \frac{C}{L - m}$$

C

L

m

|

|

Z

(

R

)

Therefore, the instantaneous power p supplied by the source is

$$p = v i = (v \sin \omega t) \times [i \sin(\omega t + \phi)]$$

m

$v i$

$m m$

=

$$[\cos \phi - \cos(2\omega t + \phi)]$$

(7.37)

2

The average power over a cycle is given by the average of the two terms in R.H.S. of Eq. (7.37). It is only the second term which is time-dependent. Its average is zero (the positive half of the cosine cancels the negative half). Therefore,

$v i$

v

i

$m m$

$P =$

$\cos \phi$

m

m

=

$\cos \phi$

2

2

2

$= VI \cos \phi$

[7.38(a)]

This can also be written as,

2

$$P = I Z \cos \phi$$

[7.38(b)]

So, the average power dissipated depends not only on the voltage and current but also on the cosine of the phase angle ϕ between them. The quantity $\cos\phi$ is called the *power factor*. Let us discuss the following cases:

Case (i) Resistive circuit: If the circuit contains only pure R , it is called *resistive*. In that case $\phi = 0$, $\cos \phi = 1$. There is maximum power dissipation.

Case (ii) Purely inductive or capacitive circuit: If the circuit contains only an inductor or capacitor, we know that the phase difference between voltage and current is $\pi/2$. Therefore, $\cos \phi = 0$, and no power is dissipated even though a current is flowing in the circuit. This current is sometimes referred to as *wattless current*.

Case (iii) LCR series circuit: In an LCR series circuit, power dissipated is given by Eq. (7.38) where $\phi = \tan^{-1} (X_L - X_C) / R$. So, ϕ may be nonzero in a

RL or RC or RCL circuit. Even in such cases, power is dissipated only in the resistor.

Case (iv) Power dissipated at resonance in LCR circuit: At resonance $X_L - X_C = 0$, and $\phi = 0$. Therefore, $\cos\phi = 1$ and $P = I^2 Z = I^2 R$. That is, $c L$ maximum power is dissipated in a circuit (through R) at resonance.

7.7

Example 7.7 (a) For circuits used for transporting electric power, a low power factor implies large power loss in transmission. Explain.

(b) Power factor can often be improved by the use of a capacitor of

XAMPLE

appropriate capacitance in the circuit. Explain.

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E

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Solution (a) We know that $P = I V \cos\phi$ where $\cos\phi$ is the power factor.

To supply a given power at a given voltage, if $\cos\phi$ is small, we have to increase current accordingly. But this will lead to large power loss

($I^2 R$) in transmission.

(b) Suppose in a circuit, current I lags the voltage by an angle ϕ . Then power factor $\cos\phi = R/Z$.

We can improve the power factor (tending to 1) by making Z tend to R .

Let us understand, with the help of a phasor diagram (Fig. 7.17) how this can be achieved. Let us resolve \mathbf{I} into two components. \mathbf{I} along p

FIGURE 7.17

the applied voltage \mathbf{V} and \mathbf{I} perpendicular to the applied voltage. \mathbf{I} q

q

as you have learnt in Section 7.7, is called the wattless component since corresponding to this component of current, there is no power loss. I is known as the power component because it is in phase with P the voltage and corresponds to power loss in the circuit.

E

It's clear from this analysis that if we want to improve power factor,

XAMPLE

we must completely neutralize the lagging wattless current I by an

q

equal leading wattless current I' . This can be done by connecting a

q

7.7

capacitor of appropriate value in parallel so that I and I' cancel q

q

each other and P is effectively $I V$.

p

Example 7.8 A sinusoidal voltage of peak value 283 V and frequency 50 Hz is applied to a series LCR circuit in which

$R = 3 \Omega$, $L = 25.48 \text{ mH}$, and $C = 796 \mu\text{F}$. Find (a) the impedance of the

circuit; (b) the phase difference between the voltage across the source and the current; (c) the power dissipated in the circuit; and (d) the power factor.

Solution

E

(a) To find the impedance of the circuit, we first calculate X and X .

XAMPLE

L

C

$$X = 2 \pi v L$$

L

$$= 2 \times 3.14 \times 50 \times 25.48 \times 10^{-3} \Omega = 8 \Omega$$

7.8

1

X

=

C

$$2 \pi v C$$

253

Physics

1

=

$$= 4\Omega$$

6

$$2 \times 3.14 \times 50 \times 796 \times 10^{-}$$

Therefore,

2

2

2

2

$$Z =$$

$$R + (X - X) =$$

$$3 + (8 - 4)$$

L

C

$$= 5 \Omega$$

X

$-X$

(b) Phase difference, $\phi = \tan^{-1} \frac{C}{L}$

L

R

$$- (4 - 8)$$

1

$$= \tan |$$

$$| = 5$$

$$- 3.1^\circ$$

(3)

Since ϕ is negative, the current in the circuit lags the voltage across the source.

(c) The power dissipated in the circuit is

2

$$P = I R$$

i

$$1 (283)$$

m

7.8

Now, $I =$

=

|

$$| = 40A$$

2

2 (5)

Therefore, $P =$

A 2

$$(40) \times 3 \Omega = 4800 \text{ W}$$

XAMPLE

(d) Power factor = $\cos \phi = \cos 53.1^\circ = 0.6$

E

Example 7.9 Suppose the frequency of the source in the previous example can be varied. (a) What is the frequency of the source at which resonance occurs? (b) Calculate the impedance, the current, and the power dissipated at the resonant condition.

Solution

(a) The frequency at which the resonance occurs is

1

1

$\omega =$

=

0

-3

6

LC

$$25.48 \times 10$$

$$\times 796 \times 10^{-}$$

$$= 222.1 \text{ rad/s}$$

ω

$$221.1$$

0

$$v =$$

=

$$\text{Hz} = 35.4 \text{ Hz}$$

r

$$2\pi$$

$$2 \times 3.14$$

(b) The impedance Z at resonant condition is equal to the resistance:

$$Z = R = 3 \Omega$$

The rms current at resonance is

V

V

(283) 1

=

=

=

= 66.7A

|

|

Z

R

(2) 3

The power dissipated at resonance is

7.9

2

2

$$P = I \times R = (66.7) \times 3 = 13.35 \text{ kW}$$

You can see that in the present case, power dissipated

XAMPLE

at resonance is more than the power dissipated in Example 7.8.

254

E

Alternating Current

Example 7.10 At an airport, a person is made to walk through the doorway of a metal detector, for security reasons. If she/he is carrying anything made of metal, the metal detector emits a sound. On what principle does this detector work?

Solution The metal detector works on the principle of resonance in ac circuits. When you walk through a metal detector, you are,

E

in fact, walking through a coil of many turns. The coil is connected to

XAMPLE

a capacitor tuned so that the circuit is in resonance. When you walk through with metal in your pocket, the impedance of the

7.10

circuit changes – resulting in significant change in current in the circuit. This change in current is detected and the electronic circuitry causes a sound to be emitted as an alarm.

7.8 LC OSCILLATIONS

We know that a capacitor and an inductor can store electrical and magnetic energy, respectively. When a capacitor (initially charged) is connected to an inductor, the charge on the capacitor and

the current in the circuit exhibit the phenomenon of electrical oscillations similar to oscillations in mechanical systems (Chapter 14, Class XI).

Let a capacitor be charged q (at $t = 0$) and connected

m

to an inductor as shown in Fig. 7.18.

The moment the circuit is completed, the charge on the capacitor starts decreasing, giving rise to current in the circuit. Let q and i be the charge and current in the

circuit at time t . Since $d i/d t$ is positive, the induced emf in L will have polarity as shown, i.e., $v < v$. According to $b a$

Kirchhoff's loop rule,

q

$d i$

—

FIGURE 7.18 At the

L

$= 0$

(7.39)

C

$d t$

instant shown, the current

is increasing so the

$i = - (d q/d t)$ in the present case (as q decreases, i increases).

polarity of induced emf in

Therefore, Eq. (7.39) becomes:

the inductor is as shown.

2

$d q$

1

+

$q = 0$

(7.40)

2

$d t$

LC

2

$d x$

This equation has the form

2

$+ \omega x = 0$ for a simple harmonic

2

0

$d t$

oscillator. The charge, therefore, oscillates with a natural frequency

1

$\omega =$

0

(7.41)

LC

and varies sinusoidally with time as

$$q = q \cos \omega t + \phi$$

(7.42)

m

(0

)

where q is the maximum value of q and ϕ is a phase constant. Since m

$q = q$ at $t = 0$, we have $\cos \phi = 1$ or $\phi = 0$. Therefore, in the present case, 255

m

Physics

$$q = q \cos(\omega t)$$

(7.43)

m

0

(

$d q)$

The current $i = -$

|

(

$d t)$ is given by

$$i = i \sin(\omega t)$$

(7.44)

m

0

where i

$$= \omega q$$

m

0 m

Let us now try to visualise how this oscillation takes place in the circuit.

Figure 7.19(a) shows a capacitor with initial charge q connected to

m

an ideal inductor. The electrical energy stored in the charged capacitor is

$\frac{1}{2}$

q^2/m

U

=

E

. Since, there is no current in the circuit, energy in the inductor

$\frac{1}{2} C$

is zero. Thus, the total energy of LC circuit is,

$\frac{1}{2}$

q^2/m

$U = U$

=

E

$\frac{1}{2} C$

FIGURE 7.19 The oscillations in an LC circuit are analogous to the oscillation of a block at the end of a spring. The figure depicts one-half of a cycle.

At $t = 0$, the switch is closed and the capacitor starts to discharge

[Fig. 7.19(b)]. As the current increases, it sets up a magnetic field in the

inductor and thereby, some energy gets stored in the inductor in the form of magnetic energy: $U = (1/2) Li^2$. As the current reaches its maximum value i , (at $t = T/4$) as in Fig. 7.19(c), all the energy is stored in the magnetic field: $U = (1/2) Li^2$. You can easily check that the maximum electrical energy equals the maximum magnetic energy. The capacitor now has no charge and hence no energy. The current now starts charging the capacitor, as in Fig. 7.19(d). This process continues till the capacitor is fully charged (at $t = T/2$) [Fig. 7.19(e)]. But it is charged with a polarity opposite to its initial state in Fig. 7.19(a). The whole process just described will now repeat itself till the system reverts to its original state. Thus, the energy in the system oscillates between the capacitor

256

and the inductor.

Alternating Current

The LC oscillation is similar to the mechanical oscillation of a block attached to a spring. The lower part of each figure in Fig. 7.19 depicts the corresponding stage of a mechanical system (a block attached to a

spring). As noted earlier, for a block of a mass m oscillating with frequency ω , the equation is

0

2

d^2x

2

$$+ \omega x = 0$$

2

0

d t

Here, $\omega = k / m$, and k is the spring constant. So, x corresponds to q .

0

In case of a mechanical system $F = ma = m (d v/d t) = m (d^2 x/d t^2)$. For an electrical system, $\varepsilon = -L (d i/d t) = -L (d^2 q/d t^2)$. Comparing these two equations, we see that L is analogous to mass m : L is a measure of resistance to change in current. In case of LC circuit, $\omega = 1/ LC$

0

and

for mass on a spring, $\omega = k / m$. So, $1/ C$ is analogous to k . The constant 0

$k (= F/x)$ tells us the (external) force required to produce a unit displacement whereas $1/ C (= V/q)$ tells us the potential difference required to store a unit charge. Table 7.1 gives the analogy between mechanical and electrical quantities.

TABLE 7.1 ANALOGIES BETWEEN MECHANICAL AND ELECTRICAL QUANTITIES

Mechanical system

Electrical system

Mass m

Inductance L

Force constant k

Reciprocal capacitance

$1/C$

Displacement x

Charge q

Velocity $v = dx/dt$

Current $i = dq/dt$

Mechanical energy

Electromagnetic energy

1

2

2

1

2

$1 q$

1

$E =$

$kx +$

mv

2

$U =$

$+ L i$

2

2

$2 C$

2

Note that the above discussion of LC oscillations is not realistic for two reasons:

(i) Every inductor has some resistance. The effect of this resistance is to introduce a damping effect on the charge and current in the circuit and the oscillations finally die away.

(ii) Even if the resistance were zero, the total energy of the system would not remain constant. It is radiated away from the system in the form of electromagnetic waves (discussed in the next chapter). In fact, radio

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and TV transmitters depend on this radiation.

Physics

TWO DIFFERENT PHENOMENA, SAME MATHEMATICAL TREATMENT

You may like to compare the treatment of a forced damped oscillator discussed in Section 14.10 of Class XI physics textbook, with that of an LCR circuit when an ac voltage is applied in it. We have already remarked that Eq. [14.37(b)] of Class XI Textbook is exactly similar to Eq. (7.28) here, although they use different symbols and parameters. Let us therefore list the equivalence between different quantities in the two situations:

Forced oscillations Driven LCR circuit

2

2

dx

dx

dq

dq

q

m

$+ b$

+

$kx = F \cos \omega t$

+

+

=

ω

d

L

R

$v \sin$

t

2

dt

2

m

dt

$d t$

$d t$

C

Displacement, x

Charge on capacitor, q

Time, t

Time, t

Mass, m

Self inductance, L

Damping constant, b

Resistance, R

Spring constant, k

Inverse capacitance, $1/C$

Driving frequency, ω

Driving frequency, ω

d

Natural frequency of oscillations, ω

Natural frequency of LCR circuit, ω_0

Amplitude of forced oscillations, A

Maximum charge stored, qm

Amplitude of driving force, F

Amplitude of applied voltage, v

0

m

You must note that since x corresponds to q , the amplitude A (maximum displacement) will correspond to the maximum charge stored, q . Equation [14.39 (a)] of Class XI gives m the amplitude of oscillations in terms of other parameters, which we reproduce here for convenience:

F_0

$$A = \{ m \omega^2 - \omega^2 + \omega b \}^{1/2}$$

2

2

2 2

2

2

(

)

d

d

Replace each parameter in the above equation by the corresponding electrical

quantity, and see what happens. Eliminate L , C , ω , and ω , using $X = \omega L$, $X = 1/\omega C$, and 0

L

C

$\omega^2 = 1/LC$. When you use Eqs. (7.33) and (7.34), you will see that there is a 0

perfect match.

You will come across numerous such situations in physics where diverse physical phenomena are represented by the same mathematical equation. If you have dealt with one of them, and you come across another situation, you may simply replace the corresponding quantities and interpret the result in the new context. We suggest that you may try to find more such parallel situations from different areas of physics. One must, of course, be aware of the differences too.

Alternating Current

Example 7.11 Show that in the free oscillations of an LC circuit, the sum of energies stored in the capacitor and the inductor is constant in time.

Solution Let q be the initial charge on a capacitor. Let the charged capacitor be connected to an inductor of inductance L . As you have studied in Section 7.8, this LC circuit will sustain an oscillation with frequency

$$\omega = \frac{1}{\sqrt{LC}}$$

ω

1

$$= 2\pi \nu =$$

LC)

At an instant t , charge q on the capacitor and the current i are given by:

$$q(t) = q \cos \omega t$$

0

$$i(t) = -q \omega \sin \omega t$$

0

Energy stored in the capacitor at time t is

2

2

1

$1 q$

q

2

0

2

U

=

$C V$

=

=

$\cos (t$

$\omega)$

E

2

$2 C$

$2 C$

Energy stored in the inductor at time t is

1

2

U

=

$L i$

M

2

1

2

2

2

=

$L q \omega \sin (t$

$\omega)$

0

2

2

$q 0$

2

=

$\sin(\omega t)$

(2

ω

\therefore

$= 1/LC)$

2 C

Sum of energies

2

q^2

2

2

$U + U$

=

$[\cos \omega t + \sin$

t

$\omega]$

E

M

|

]

$2 C$

E

XAMPLE

2

q_0

$= 2 C$

7.11

This sum is constant in time as q and C , both are time-independent.

o

Note that it is equal to the initial energy of the capacitor. Why it is so? Think!

7.9 TRANSFORMERS

For many purposes, it is necessary to change (or transform) an alternating voltage from one to another of greater or smaller value. This is done with a device called *transformer* using the principle of mutual induction.

A transformer consists of two sets of coils, insulated from each other.

They are wound on a soft-iron core, either one on top of the other as in

Fig. 7.20(a) or on separate limbs of the core as in Fig. 7.20(b). One of the coils called the *primary coil* has N turns. The other coil is called the *secondary coil*; it has N turns. Often the primary coil is the input coil s and the secondary coil is the output coil of the transformer.

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Physics

FIGURE 7.20 Two arrangements for winding of primary and secondary coil in a transformer: (a) two coils on top of each other, (b) two coils on separate limbs of the core.

When an alternating voltage is applied to the primary, the resulting current produces an alternating magnetic flux which links the secondary and induces an emf in it. The value of this emf depends on the number of turns in the secondary. We consider an ideal transformer in which the primary has negligible resistance and all the flux in the core links both primary and secondary windings. Let ϕ be the flux in each turn in the core at time t due to current in the primary when a voltage v is applied p to it.

Then the induced emf or voltage ε_s , in the secondary with N turns is

s

s

$d\phi$

$$\varepsilon = - N$$

s

s

$$(7.45)$$

$d t$

The alternating flux ϕ also induces an emf, called back emf in the primary. This is

$d\phi$

$$\varepsilon = - N$$

p

p

$$(7.46)$$

$d t$

But $\varepsilon = v$. If this were not so, the primary current would be infinite p

p

since the primary has zero resistance(as assumed). If the secondary is an open circuit or the current taken from it is small, then to a good approximation

$$\varepsilon = v$$

s

s

where v is the voltage across the secondary. Therefore, Eqs. (7.45) and s

(7.46) can be written as

$d\phi$

$$v = -N$$

s

s

$d t$

[7.45(a)]

$d\phi$

$$v = -N$$

p

p

[7.46(a)]

$d t$

From Eqs. [7.45 (a)] and [7.45 (a)], we have

v

N

s

s

=

260

v

N

(7.47)

p

p

Alternating Current

Note that the above relation has been obtained using three assumptions: (i) the primary resistance and current are small; (ii) the same flux links both the primary and the secondary as very little flux escapes from the core, and (iii) the secondary current is small.

If the transformer is assumed to be 100% efficient (no energy losses), the power input is equal to the power output, and since $p = i v$, $i v = i v$

(7.48)

$p p$

$s s$

Although some energy is always lost, this is a good approximation, since a well designed transformer may have an efficiency of more than

95%. Combining Eqs. (7.47) and (7.48), we have

$$\frac{v_p}{N_s} = \frac{v_s}{N_p}$$

$$\frac{v_p}{v_s} = \frac{N_s}{N_p}$$

$$\frac{i_p}{i_s} = \frac{N_s}{N_p}$$

(7.49)

$$\frac{v_p}{v_s} = \frac{N_s}{N_p}$$

$$\frac{i_p}{i_s} = \frac{N_s}{N_p}$$

Since i and v both oscillate with the same frequency as the ac source, Eq. (7.49) also gives the ratio of the amplitudes or rms values of corresponding quantities.

Now, we can see how a transformer affects the voltage and current.

We have:

$$(N)$$

(N)

s

$V =$

V

p

$I =$

I

s

|

| p

(

|

|

$N)$

and s

p

(N)

(7.50)

p

s

That is, if the secondary coil has a greater number of turns than the primary ($N_s > N_p$), the voltage is stepped up ($V_s > V_p$). This type of

s

p

arrangement is called a *step-up transformer*. However, in this arrangement, there is less current in the secondary than in the primary ($N_s / N_p > 1$ and I_s

s

$< I_p$). For example, if the primary coil of a transformer has 100 turns and p

the secondary has 200 turns, $N_s / N_p = 2$ and $N_p / N_s = 1/2$. Thus, a 220V

s

p

p

s

input at 10A will step-up to 440 V output at 5.0 A.

If the secondary coil has less turns than the primary ($N_s < N_p$), we have s

p

a *step-down transformer*. In this case, $V_s < V_p$ and $I_s > I_p$. That is, the s p

s

p

voltage is stepped down, or reduced, and the current is increased.

The equations obtained above apply to ideal transformers (without any energy losses). But in actual transformers, small energy losses do occur due to the following reasons:

(i) *Flux Leakage*: There is always some flux leakage; that is, not all of the flux due to primary passes through the secondary due to poor design of the core or the air gaps in the core. It can be reduced by

winding the primary and secondary coils one over the other.

(ii) *Resistance of the windings*: The wire used for the windings has some resistance and so, energy is lost due to heat produced in the wire ($I^2 R$). In high current, low voltage windings, these are minimised by using thick wire.

(iii) *Eddy currents*: The alternating magnetic flux induces eddy currents in the iron core and causes heating. The effect is reduced by having a laminated core.

(iv) *Hysteresis*: The magnetisation of the core is repeatedly reversed by the alternating magnetic field. The resulting expenditure of energy in the core appears as heat and is kept to a minimum by using a magnetic

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material which has a low hysteresis loss.

Physics

The large scale transmission and distribution of electrical energy over long distances is done with the use of transformers. The voltage output of the generator is stepped-up (so that current is reduced and consequently, the $I^2 R$ loss is cut down). It is then transmitted over long distances to an area substation near the consumers. There the voltage is

stepped down. It is further stepped down at distributing substations and utility poles before a power supply of 240 V reaches our homes.

SUMMARY

1.

An alternating voltage $v = v_m \sin \omega t$ applied to a resistor R drives a maximum current $i = i_m \sin \omega t$ in the resistor, i

=

. The current is in phase with

v_m

i_m

R

the applied voltage.

2.

For an alternating current $i = i_m \sin \omega t$ passing through a resistor R , the maximum average power loss P (averaged over a cycle) due to joule heating is

$(1/2) i_m^2 R$. To express it in the same form as the dc power ($P = I^2 R$), a maximum special value of current is used. It is called *root mean square* (rms)

current and is denoted by I :

i_m

$I =$

$= 0.707 i_m$

2

Similarly, the *rms voltage* is defined by

v_m

$V =$

$= 0.707 v_m$

2

We have $P = IV = I^2 R$

3.

An ac voltage $v = v \sin \omega t$ applied to a pure inductor L , drives a current m in the inductor $i = i \sin (\omega t - \pi/2)$, where $i = v / X$. $X = \omega L$ is called $m m$

m

L

L

inductive reactance. The current in the inductor lags the voltage by

$\pi/2$. The average power supplied to an inductor over one complete cycle

is zero.

4.

An ac voltage $v = v \sin \omega t$ applied to a capacitor drives a current in the m

capacitor: $i = i \sin (\omega t + \pi/2)$. Here,

m

v

1

m

i

=

, X

=

m

C

X

C

ω is called *capacitive reactance*.

C

The current through the capacitor is $\pi/2$ ahead of the applied voltage.

As in the case of inductor, the average power supplied to a capacitor over one complete cycle is zero.

5.

For a series *RLC* circuit driven by voltage $v = v \sin \omega t$, the current is m

given by $i = i \sin (\omega t + \phi)$

m

v

where

m

i

=

m

$R + (X - X$

C

$L)^2$

2

$- X$

$- X$

and

1

$\varphi = \tan$

C

L

R

$Z =$

$R + (X - X)^2$

2

is called the *impedance* of the circuit.

C

L

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Alternating Current

The average power loss over a complete cycle is given by

$$P = VI \cos\phi$$

The term $\cos\phi$ is called the *power factor*.

6.

In a purely inductive or capacitive circuit, $\cos\phi = 0$ and no power is dissipated even though a current is flowing in the circuit. In such cases, current is referred to as a *wattless current*.

7.

The phase relationship between current and voltage in an ac circuit can be shown conveniently by representing voltage and current by rotating vectors called *phasors*. A phasor is a vector which rotates about the origin with angular speed ω . The magnitude of a phasor represents the amplitude or peak value of the quantity (voltage or current) represented by the phasor.

The analysis of an ac circuit is facilitated by the use of a phasor

diagram.

8.

An interesting characteristic of a series RLC circuit is the phenomenon of *resonance*. The circuit exhibits resonance, i.e., the amplitude of the current is maximum at the resonant

1

frequency, $\omega =$

. The *quality factor* Q defined by

0

LC

ωL

1

0

$Q =$

=

is an indicator of the sharpness of the resonance,

R

ωCR

0

the higher value of Q indicating sharper peak in the current.

9.

A circuit containing an inductor L and a capacitor C (initially charged) with no ac source and no resistors exhibits *free oscillations*. The charge q of the capacitor satisfies the equation of simple harmonic motion: 2

$d^2 q$

1

+

$q = 0$

2

dt

LC

1

and therefore, the frequency ω of free oscillation is $\omega =$

0

. The

LC

energy in the system oscillates between the capacitor and the inductor but their sum or the total energy is constant in time.

10. A transformer consists of an iron core on which are bound a primary coil of N turns and a secondary coil of N turns. If the p

s

primary coil is connected to an ac source, the primary and secondary voltages are related by

$$\left(\frac{N_s}{N_p} \right)$$

s

$$V =$$

V

s

|

| p

$$\left(\frac{N_s}{N_p} \right)$$

p

and the currents are related by

$$\left(\frac{N_s}{N_p} \right)$$

p

$$I =$$

I

s

p

|

|

(N)

s

If the secondary coil has a greater number of turns than the primary, the voltage is stepped-up ($V > V$). This type of arrangement is called a *steps*

p

up transformer. If the secondary coil has turns less than the primary, we have a *step-down transformer*.

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Physics

Physical quantity

Symbol

Dimensions

Unit

Remarks

v

rms voltage

V

[M L² T⁻³ A⁻¹]

V

$V =$

m

,

v is the

2

m

amplitude of the ac voltage.

i

rms current

I

[A]

A

$I = \frac{m}{\sqrt{2}}$, i is the amplitude of

2

m

the ac current.

Reactance:

Inductive

X

[M L² T⁻³ A⁻²]

Ω

$X = \omega L$

L

L

Capacitive

X

$[M L^2 T^{-3} A^{-2}]$

Ω

$X = 1/\omega C$

C

C

Impedance

Z

$[M L^2 T^{-3} A^{-2}]$

Ω

Depends on elements

present in the circuit.

1

Resonant

ω or ω

$[T^{-1}]$

Hz

$\omega =$

for a

r

0

0

LC

frequency

series RLC circuit

ωL

1

Quality factor

Q

Dimensionless

0

$Q =$

$=$

for a series

R

$\omega C R$

0

RLC circuit.

Power factor

Dimensionless

= $\cos\phi$, ϕ is the phase

difference between voltage

applied and current in

the circuit.

POINTS TO PONDER

1.

When a value is given for ac voltage or current, it is ordinarily the rms

value. The voltage across the terminals of an outlet in your room is

normally 240 V. This refers to the *rms* value of the voltage. The amplitude of this voltage is

v

$$= 2 V = 2(240) = 340 \text{ V}$$

m

2.

The power rating of an element used in ac circuits refers to its average

power rating.

3.

The power consumed in an circuit is never negative.

4.

Both alternating current and direct current are measured in amperes.

But how is the ampere defined for an alternating current? It cannot be derived from the mutual attraction of two parallel wires carrying ac

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currents, as the dc ampere is derived. An ac current changes direction

Alternating Current

with the source frequency and the attractive force would average to

zero. Thus, the ac ampere must be defined in terms of some property

that is independent of the direction of the current. Joule heating

is such a property, and there is one ampere of *rms* value of

alternating current in a circuit if the current produces the same

average heating effect as one ampere of dc current would produce

under the same conditions.

5.

In an ac circuit, while adding voltages across different elements, one

should take care of their phases properly. For example, if V and V

R

C

are voltages across R and C , respectively in an RC circuit, then the total voltage across RC combination is 2

2

V

= $V + V$ and not

RC

R

C

$V + V$ since V is $\pi/2$ out of phase of V .

R

C

C

R

6.

Though in a phasor diagram, voltage and current are represented by vectors, these quantities are not really vectors themselves. They are scalar quantities. It so happens that the amplitudes and phases of harmonically varying scalars combine mathematically in the same way as do the projections of rotating vectors of corresponding magnitudes and directions. The 'rotating vectors' that represent harmonically varying scalar quantities are introduced only to provide us with a simple way of adding these quantities using a rule that

we already know as the law of vector addition.

7.

There are no power losses associated with pure capacitances and pure inductances in an ac circuit. The only element that dissipates energy in an ac circuit is the resistive element.

8.

In a *RLC* circuit, resonance phenomenon occur when $X_L = X_C$ or

L

C

1

$\omega =$

. For resonance to occur, the presence of both L and C

0

LC

elements in the circuit is a must. With only one of these (L or C) elements, there is no possibility of voltage cancellation and hence, no resonance is possible.

9.

The power factor in a *RLC* circuit is a measure of how close the circuit is to expending the maximum power.

10. In generators and motors, the roles of input and output are

reversed. In a motor, electric energy is the input and mechanical energy is the output. In a generator, mechanical energy is the input and electric energy is the output. Both devices simply transform energy from one form to another.

11. A transformer (step-up) changes a low-voltage into a high-voltage.

This does not violate the law of conservation of energy. The current is reduced by the same proportion.

12. The choice of whether the description of an oscillatory motion is by means of sines or cosines or by their linear combinations is unimportant, since changing the zero-time position transforms the one to the other.

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EXERCISES

7.1

A $100\ \Omega$ resistor is connected to a 220 V, 50 Hz ac supply.

(a) What is the rms value of current in the circuit?

(b) What is the net power consumed over a full cycle?

7.2

(a) The peak voltage of an ac supply is 300 V. What is the rms voltage?

(b) The rms value of current in an ac circuit is 10 A. What is the peak current?

7.3

A 44 mH inductor is connected to 220 V, 50 Hz ac supply. Determine the rms value of the current in the circuit.

7.4

A 60 μF capacitor is connected to a 110 V, 60 Hz ac supply. Determine the rms value of the current in the circuit.

7.5

In Exercises 7.3 and 7.4, what is the net power absorbed by each circuit over a complete cycle. Explain your answer.

7.6

Obtain the resonant frequency ω of a series LCR circuit with r
 $L = 2.0\text{H}$, $C = 32 \mu\text{F}$ and $R = 10 \Omega$. What is the Q -value of this circuit?

7.7

A charged 30 μF capacitor is connected to a 27 mH inductor. What is the angular frequency of free oscillations of the circuit?

7.8

Suppose the initial charge on the capacitor in Exercise 7.7 is 6 mC. What is the total energy stored in the circuit initially ? What is the

total energy at later time?

7.9

A series LCR circuit with $R = 20 \Omega$, $L = 1.5 \text{ H}$ and $C = 35 \mu\text{F}$ is connected to a variable-frequency 200 V ac supply. When the frequency of the supply equals the natural frequency of the circuit, what is the average

power transferred to the circuit in one complete cycle?

7.10

A radio can tune over the frequency range of a portion of MW

broadcast band: (800 kHz to 1200 kHz). If its LC circuit has an effective inductance of $200 \mu\text{H}$, what must be the range of its variable capacitor ?

[*Hint*: For tuning, the natural frequency i.e., the frequency of free

oscillations of the LC circuit should be equal to the frequency of the radiowave.]

7.11

Figure 7.21 shows a series LCR circuit connected to a variable frequency 230 V source. $L = 5.0 \text{ H}$, $C = 80 \mu\text{F}$, $R = 40 \Omega$.

FIGURE 7.21

(a) Determine the source frequency which drives the circuit in resonance.

(b) Obtain the impedance of the circuit and the amplitude of current at the resonating frequency.

(c) Determine the rms potential drops across the three elements of

the circuit. Show that the potential drop across the LC

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combination is zero at the resonating frequency.

Alternating Current

ADDITIONAL EXERCISES

7.12

An LC circuit contains a 20 mH inductor and a 50 μF capacitor with an initial charge of 10 mC. The resistance of the circuit is negligible.

Let the instant the circuit is closed be $t = 0$.

- (a) What is the total energy stored initially? Is it conserved during LC oscillations?
- (b) What is the natural frequency of the circuit?
- (c) At what time is the energy stored
 - (i) completely electrical (i.e., stored in the capacitor)?
 - (ii) completely magnetic (i.e., stored in the inductor)?
- (d) At what times is the total energy shared equally between the inductor and the capacitor?
- (e) If a resistor is inserted in the circuit, how much energy is eventually dissipated as heat?

7.13

A coil of inductance 0.50 H and resistance $100\ \Omega$ is connected to a 240 V , 50 Hz ac supply.

(a) What is the maximum current in the coil?

(b) What is the time lag between the voltage maximum and the current maximum?

7.14

Obtain the answers (a) to (b) in Exercise 7.13 if the circuit is connected to a high frequency supply (240 V , 10 kHz). Hence, explain the statement that at very high frequency, an inductor in a circuit nearly amounts to an open circuit. How does an inductor behave in a dc circuit after the steady state?

7.15

A $100\ \mu\text{F}$ capacitor in series with a $40\ \Omega$ resistance is connected to a 110 V , 60 Hz supply.

(a) What is the maximum current in the circuit?

(b) What is the time lag between the current maximum and the voltage maximum?

7.16

Obtain the answers to (a) and (b) in Exercise 7.15 if the circuit is connected to a 110 V , 12 kHz supply? Hence, explain the statement

that a capacitor is a conductor at very high frequencies. Compare this behaviour with that of a capacitor in a dc circuit after the steady state.

7.17

Keeping the source frequency equal to the resonating frequency of the series LCR circuit, if the three elements, L , C and R are arranged in parallel, show that the total current in the parallel LCR circuit is minimum at this frequency. Obtain the current rms value in each branch of the circuit for the elements and source specified in

Exercise 7.11 for this frequency.

7.18

A circuit containing a 80 mH inductor and a 60 μ F capacitor in series is connected to a 230 V, 50 Hz supply. The resistance of the circuit is negligible.

- (a) Obtain the current amplitude and rms values.
- (b) Obtain the rms values of potential drops across each element.
- (c) What is the average power transferred to the inductor?
- (d) What is the average power transferred to the capacitor?
- (e) What is the total average power absorbed by the circuit? [‘Average’ implies ‘averaged over one cycle’.]

7.19

Suppose the circuit in Exercise 7.18 has a resistance of 15 Ω . Obtain

the average power transferred to each element of the circuit, and

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the total power absorbed.

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7.20

A series LCR circuit with $L = 0.12$ H, $C = 480$ nF, $R = 23$ Ω is connected to a 230 V variable frequency supply.

(a) What is the source frequency for which current amplitude is maximum. Obtain this maximum value.

(b) What is the source frequency for which average power absorbed by the circuit is maximum. Obtain the value of this maximum power.

(c) For which frequencies of the source is the power transferred to the circuit half the power at resonant frequency? What is the current amplitude at these frequencies?

(d) What is the Q -factor of the given circuit?

7.21

Obtain the resonant frequency and Q -factor of a series LCR circuit with $L = 3.0$ H, $C = 27$ μ F, and $R = 7.4$ Ω . It is desired to improve the sharpness of the resonance of the circuit by reducing its 'full width at half maximum' by a factor of 2. Suggest a suitable way.

7.22

Answer the following questions:

- (a) In any ac circuit, is the applied instantaneous voltage equal to the algebraic sum of the instantaneous voltages across the series elements of the circuit? Is the same true for rms voltage?
- (b) A capacitor is used in the primary circuit of an induction coil.
- (c) An applied voltage signal consists of a superposition of a dc voltage and an ac voltage of high frequency. The circuit consists of an inductor and a capacitor in series. Show that the dc signal will appear across C and the ac signal across L .
- (d) A choke coil in series with a lamp is connected to a dc line. The lamp is seen to shine brightly. Insertion of an iron core in the choke causes no change in the lamp's brightness. Predict the corresponding observations if the connection is to an ac line.
- (e) Why is choke coil needed in the use of fluorescent tubes with ac mains? Why can we not use an ordinary resistor instead of the choke coil?

7.23

A power transmission line feeds input power at 2300 V to a step-down transformer with its primary windings having 4000 turns. What should be the number of turns in the secondary in order to get output power at 230 V?

7.24

At a hydroelectric power plant, the water pressure head is at a height of 300 m and the water flow available is $100 \text{ m}^3 \text{ s}^{-1}$. If the turbine generator efficiency is 60%, estimate the electric power available from the plant ($g = 9.8 \text{ ms}^{-2}$).

7.25

A small town with a demand of 800 kW of electric power at 220 V is situated 15 km away from an electric plant generating power at 440 V. The resistance of the two wire line carrying power is 0.5Ω per km. The town gets power from the line through a 4000-220 V step-down transformer at a substation in the town.

- (a) Estimate the line power loss in the form of heat.
- (b) How much power must the plant supply, assuming there is negligible power loss due to leakage?
- (c) Characterise the step up transformer at the plant.

7.26

Do the same exercise as above with the replacement of the earlier transformer by a 40,000-220 V step-down transformer (Neglect, as before, leakage losses though this may not be a good assumption any longer because of the very high voltage transmission involved).

Hence, explain why high voltage transmission is preferred?

Chapter Eight

ELECTROMAGNETIC

WAVES

8.1 INTRODUCTION

In Chapter 4, we learnt that an electric current produces magnetic field and that two current-carrying wires exert a magnetic force on each other. Further, in Chapter 6, we have seen that a magnetic field changing with time gives rise to an electric field. Is the converse also true? Does an electric field changing with time give rise to a magnetic field? James Clerk Maxwell (1831-1879), argued that this was indeed the case – not only an electric current but also a time-varying electric field generates magnetic field. While applying the Ampere's circuital law to find magnetic field at a point outside a capacitor connected to a time-varying current, Maxwell noticed an inconsistency in the Ampere's circuital law. He suggested the existence of an additional current, called by him, the displacement current to remove this inconsistency.

Maxwell formulated a set of equations involving electric and magnetic fields, and their sources, the charge and current densities. These

equations are known as Maxwell's equations. Together with the Lorentz force formula (Chapter 4), they mathematically express all the basic laws of electromagnetism.

The most important prediction to emerge from Maxwell's equations is the existence of electromagnetic waves, which are (coupled) time-varying electric and magnetic fields that propagate in space. The speed of the waves, according to these equations, turned out to be very close to



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the speed of light (3×10^8 m/s), obtained from optical measurements. This led to the remarkable conclusion that light is an electromagnetic wave. Maxwell's work thus unified the domain of electricity, magnetism and light. Hertz, in 1885, experimentally demonstrated the existence of electromagnetic waves. Its technological use by Marconi and others led in due course to the revolution in communication that we are witnessing

today.

In this chapter, we first discuss the need for displacement current and its consequences. Then we present a descriptive account of electromagnetic waves.

The broad spectrum of electromagnetic waves,

James Clerk Maxwell

stretching from γ rays (wavelength $\sim 10^{-12}$ m) to long

(1831 – 1879) Born in

radio waves (wavelength $\sim 10^6$ m) is described. How the

Edinburgh, Scotland,

electromagnetic waves are sent and received for

was among the greatest

communication is discussed in Chapter 15.

physicists of the

nineteenth century. He

8.2 DISPLACEMENT CURRENT

derived the thermal

velocity distribution of

We have seen in Chapter 4 that an electrical current

molecules in a gas and

produces a magnetic field around it. Maxwell showed
was among the first to
that for logical consistency, a changing electric field *must*
obtain reliable
also produce a magnetic field. This effect is of great
estimates of molecular
parameters from
importance because it explains the existence of radio
measurable quantities
waves, gamma rays and visible light, as well as all other
like viscosity, *etc.*
forms of electromagnetic waves.

Maxwell's greatest

To see how a changing electric field gives rise to
achievement was the
a magnetic field, let us consider the process of
unification of the laws of
charging of a capacitor and apply Ampere's circuital
electricity and
magnetism (discovered

law given by (Chapter 4)

by Coulomb, Oersted,

“ $\mathbf{B} \cdot d\mathbf{l} =$

Ampere and Faraday)

$\mu i (t)$

(8.1)

0

into a consistent set of

to find magnetic field at a point outside the capacitor.

equations now called

Figure 8.1(a) shows a parallel plate capacitor C which

Maxwell’s equations.

is a part of circuit through which a time-dependent

From these he arrived at

the most important

current $i (t)$ flows . Let us find the magnetic field at a

conclusion that light is

point such as P, in a region outside the parallel plate

an electromagnetic

capacitor. For this, we consider a plane circular loop of

wave. Interestingly,
 radius r whose plane is perpendicular to the direction
 Maxwell did not agree
 of the current-carrying wire, and which is centred
 with the idea (strongly
 symmetrically with respect to the wire [Fig. 8.1(a)]. From
 suggested by the
 symmetry, the magnetic field is directed along the
 Faraday's laws of
 electrolysis) that
 circumference of the circular loop and is the same in
 electricity was
 magnitude at all points on the loop so that if B is the
 JAMES CLERK MAXWELL (1831–1879)
 particulate in nature.

magnitude of the field, the left side of Eq. (8.1) is $B (2\pi r)$.

So we have

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$$B (2\pi r) = \mu i (t)$$

(8 .2)

0

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Now, consider a different surface, which has the same boundary. This is a pot like surface [Fig. 8.1(b)] which nowhere touches the current, but has its bottom between the capacitor plates; its mouth is the circular loop mentioned above. Another such surface is shaped like a tiffin box (without the lid) [Fig. 8.1(c)]. On applying Ampere's circuital law to such surfaces with the *same* perimeter, we find that the left hand side of

Eq. (8.1) has not changed but the right hand side is *zero* and *not* μi , 0

since *no* current passes through the surface of Fig. 8.1(b) and (c). So we have a *contradiction*; calculated one way, there is a magnetic field at a point P; calculated another way, the magnetic field at P is zero.

Since the contradiction arises from our use of Ampere's circuital law, this law must be missing something. The missing term must be such that one gets the same magnetic field at point P, no matter what surface is used.

We can actually guess the missing term by looking carefully at

Fig. 8.1(c). Is there anything passing through the surface S *between* the plates of the capacitor? Yes, of course, the electric field! If the plates of the capacitor have an area A , and a total charge Q , the magnitude of the electric field \mathbf{E} between the plates is $(Q/A)/\epsilon$ (see Eq. 2.41). The field is 0

perpendicular to the surface S of Fig. 8.1(c). It has the same magnitude over the area A of the capacitor plates, and vanishes outside it. So what is the *electric flux* Φ through the surface S ? Using Gauss's law, it is E

$$\frac{1}{\epsilon_0} Q$$

$$Q$$

$$\Phi = \mathbf{E} \cdot \mathbf{A} =$$

$$EA =$$

$$E$$

$$\epsilon_0 A$$

$$\epsilon_0$$

$$(8.3)$$

$$0$$

$$0$$

Now if the charge Q on the capacitor plates changes with time, there is a current $i = (dQ/dt)$, so that using Eq. (8.3), we have $d\Phi$

$$d\left(\frac{Q}{\epsilon_0 A}\right)$$

$$\frac{1}{\epsilon_0 A} dQ$$

$$E =$$

=

|

|

FIGURE 8.1 A

$d t$

$d t (\varepsilon)$

$\varepsilon d t$

parallel plate

0

0

capacitor C , as part of

This implies that for consistency,

a circuit through

which a time

$d\Phi E$

$\varepsilon ($

)

dependent current

0 |

|

$(d t) = i$

(8.4) $i (t)$ flows, (a) a loop of

radius r , to determine

This is the missing term in Ampere's circuital law. If we generalise magnetic field at a point P on the loop; this law by adding to the total current carried by conductors through the surface, another term which is ϵ times the rate of change of electric

(b) a pot-shaped

0

flux through the same surface, the *total* has the same value of current i surface passing

through the interior

for all surfaces. If this is done, there is no contradiction in the value of B between the capacitor obtained anywhere using the generalised Ampere's law. B at the point P

plates with the loop

is nonzero no matter which surface is used for calculating it. B at a

shown in (a) as its

rim; (c) a tiffin—

point P outside the plates [Fig. 8.1(a)] is the same as at a point M just

shaped surface with

inside, as it should be. The current carried by conductors due to flow of

the circular loop as

charges is called *conduction current*. The current, given by Eq. (8.4), is a its rim and a flat

circular bottom S

new term, and is due to changing electric field (or electric *displacement*, between the capacitor an old term still used sometimes). It is, therefore, called *displacement* plates. The arrows

current or Maxwell's displacement current. Figure 8.2 shows the electric show uniform electric field between the and magnetic fields inside the parallel plate capacitor discussed above.

capacitor plates.

The generalisation made by Maxwell then is the following. The source

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of a magnetic field is not *just* the conduction electric current due to flowing

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charges, but also the time rate of change of electric field. More

precisely, the total current i is the sum of the conduction current

denoted by i , and the displacement current denoted by i ($= \epsilon (d\Phi /$

c

d

0

E

$d t$). So we have

$d\Phi E$

$$i = i + i = i + \epsilon$$

e

d

c

0

(8.5)

$d t$

In explicit terms, this means that outside the capacitor plates,

we have only conduction current $i = i$, and no displacement

c

current, i.e., $i = 0$. On the other hand, inside the capacitor, there is d

no conduction current, i.e., $i = 0$, and there is only displacement

c

current, so that $i = i$.

d

The generalised (and correct) Ampere's circuital law has the same

form as Eq. (8.1), with one difference: "the *total current* passing

through any surface of which the closed loop is the perimeter" is

the sum of the conduction current and the displacement current.

The generalised law is

$$\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 \left(i_{\text{conduction}} + i_{\text{displacement}} \right)$$

$$= \mu_0 \left(\int \mathbf{J} \cdot d\mathbf{a} + \epsilon_0 \frac{d}{dt} \int \mathbf{E} \cdot d\mathbf{a} \right)$$

$$\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 \int \mathbf{J} \cdot d\mathbf{a} + \mu_0 \epsilon_0 \frac{d}{dt} \int \mathbf{E} \cdot d\mathbf{a}$$

$$=$$

$$\int \mathbf{B} \cdot d\mathbf{l} = \mu_0 \int \mathbf{J} \cdot d\mathbf{a} + \mu_0 \epsilon_0 \frac{d}{dt} \int \mathbf{E} \cdot d\mathbf{a}$$

$$\int \mathbf{B} \cdot d\mathbf{l} = \mu_0 \int \mathbf{J} \cdot d\mathbf{a} + \mu_0 \epsilon_0 \frac{d}{dt} \int \mathbf{E} \cdot d\mathbf{a}$$

$$\int \mathbf{B} \cdot d\mathbf{l} = \mu_0 \int \mathbf{J} \cdot d\mathbf{a} + \mu_0 \epsilon_0 \frac{d}{dt} \int \mathbf{E} \cdot d\mathbf{a}$$

(8.6)

$$\frac{d}{dt} \int \mathbf{E} \cdot d\mathbf{a}$$

and is known as Ampere-Maxwell law.

In all respects, the displacement current has the same physical

effects as the conduction current. In some cases, for example, steady

electric fields in a conducting wire, the displacement current may

be zero since the electric field \mathbf{E} does not change with time. In other

FIGURE 8.2 (a) The

cases, for example, the charging capacitor above, both conduction

electric and magnetic

and displacement currents may be present in different regions of

fields \mathbf{E} and \mathbf{B} between

space. In most of the cases, they both may be present in the same region of space, as there exist no perfectly conducting or perfectly insulating medium. Most interestingly, there may be large regions of space where there is *no* conduction current, but there is only a displacement current due to time-varying electric fields. In such a region, we expect a magnetic field, though there is no (conduction) current source nearby! The prediction of such a displacement current can be verified experimentally. For example, a *magnetic* field (say at point M) between the plates of the capacitor in Fig. 8.2(a) can be measured and is seen to be the same as that just outside (at P).

(a) A cross-sectional view of Fig. (a).

(b) A cross-sectional view of Fig. (a).

The displacement current has (literally) far reaching consequences. One thing we immediately notice is that the laws of electricity and magnetism are now more symmetrical*. Faraday's law of induction states that there is an induced emf *equal to the rate of change* of magnetic flux. Now, since the emf between two points 1 and 2 is the work done per unit charge in taking it from 1 to 2, the existence of an emf implies the existence of an electric field. So, we can rephrase Faraday's law of electromagnetic

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Now, since the emf between two points 1 and 2 is the work done per unit charge in taking it from 1 to 2, the existence of an emf implies the existence of an electric field. So, we can rephrase Faraday's law of electromagnetic

induction by saying that a *magnetic field*, changing with time, gives rise to an *electric field*. Then, the fact that an *electric field* changing with time gives rise to a *magnetic field*, is the symmetrical counterpart, and is * They are still not perfectly symmetrical; there are no known sources of magnetic field (magnetic monopoles) analogous to electric charges which are sources of 272

electric field.

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a consequence of the displacement current being a source of a magnetic field. Thus, time-dependent electric and magnetic fields give rise to each other! Faraday's law of electromagnetic induction and Ampere-Maxwell law give a quantitative expression of this statement, with the current being the total current, as in Eq. (8.5). One very important consequence of this symmetry is the existence of electromagnetic waves, which we discuss qualitatively in the next section.

MAXWELL'S EQUATIONS

1.

d

i

$$= Q / \epsilon$$

$$\int \mathbf{E} \cdot \mathbf{A}$$

0

(Gauss's Law for electricity)

2.

d

i

= 0

$\int \mathbf{B} \cdot \mathbf{A}$

(Gauss's Law for magnetism)

$-d\Phi$

3.

B

d

i

=

$\int \mathbf{E} \cdot \mathbf{l}$

(Faraday's Law)

d t

dΦ

4.

d

i

=

E

$\mu i + \mu \epsilon$

$\int \mathbf{B} \cdot d\mathbf{l} = \mu_0 \int \mathbf{j} \cdot d\mathbf{a} + \mu_0 \epsilon_0 \frac{d}{dt} \int \mathbf{E} \cdot d\mathbf{a}$

(Ampere – Maxwell Law)

$d t$

Example 8.1 A parallel plate capacitor with circular plates of radius

1 m has a capacitance of 1 nF. At $t = 0$, it is connected for charging in series with a resistor $R = 1 \text{ M } \Omega$ across a 2V battery (Fig. 8.3). Calculate the magnetic field at a point P, halfway between the centre and the periphery of the plates, after $t = 10^{-3}$ s. (The charge on the capacitor at time t is $q(t) = CV [1 - \exp(-t/\tau)]$, where the time constant τ is equal to CR .) **FIGURE 8.3**

Solution The time constant of the CR circuit is $\tau = CR = 10^{-3}$ s. Then, we have

$$q(t) = CV [1 - \exp(-t/\tau)]$$
$$= 2 \times 10^{-9} [1 - \exp(-t/10^{-3})]$$

E

The electric field in between the plates at time t is

XAMPLE

$q(t)$

q

$$E =$$

=

ϵ

; $A = \pi (1)^2 \text{ m}^2 = \text{area of the plates.}$

A

$\pi\epsilon$

0

0

8.1

Consider now a circular loop of radius (1/2) m parallel to the plates passing through P. The magnetic field \mathbf{B} at all points on the loop is

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along the loop and of the same value.

The flux Φ through this loop is

E

$\Phi = E \times \text{area of the loop}$

E

2

(1)

E

π

q

$$= E \times \pi \times | | =$$

=

(2)

4

$4\epsilon_0$

The displacement current

$d\Phi$

$1 d q$

E

i

$$= \epsilon$$

-6

=

$$= 0.5 \times 10 \text{ exp } -1$$

d

0

()

$d t$

$4 d t$

at $t = 10^{-3}$ s. Now, applying Ampere-Maxwell law to the loop, we get

8.1

(1)

$$B \times 2\pi \times | | = \mu i + i$$

$$= \mu 0 + i$$

0 (

)

0 (

)

(

$$\exp(-1)$$

2

c

d

d

)

$$= 0.5 \times 10^{-6} \mu_0$$

XAMPLE

or, $B = 0.74 \times 10^{-13} \text{ T}$

E

8.3 ELECTROMAGNETIC WAVES

8.3.1 Sources of electromagnetic waves

How are electromagnetic waves produced? Neither stationary charges nor charges in uniform motion (steady currents) can be sources of electromagnetic waves. The former produces only electrostatic fields, while the latter produces magnetic fields that, however, do not vary with time.

It is an important result of Maxwell's theory that accelerated charges radiate electromagnetic waves. The proof of this basic result is beyond the scope of this book, but we can accept it on the basis of rough, qualitative reasoning. Consider a charge oscillating with some frequency. (An oscillating charge is an example of accelerating charge.) This produces an oscillating electric field in space, which produces an oscillating magnetic field, which in turn, is a source of oscillating electric field, and so on. The oscillating electric and magnetic fields thus regenerate each other, so to speak, as the wave propagates through the space.

The frequency of the electromagnetic wave naturally equals the frequency of oscillation of the charge. The energy associated with the

propagating wave comes at the expense of the energy of the source – the accelerated charge.

From the preceding discussion, it might appear easy to test the prediction that light is an electromagnetic wave. We might think that all we needed to do was to set up an ac circuit in which the current oscillate at the frequency of visible light, say, yellow light. But, alas, that is not possible. The frequency of yellow light is about 6×10^{14} Hz, while the frequency that we get even with modern electronic circuits is hardly about 10^{11} Hz. This is why the experimental demonstration of electromagnetic wave had to come in the low frequency region (the radio wave region), as in the Hertz's experiment (1887).

Hertz's successful experimental test of Maxwell's theory created a sensation and sparked off other important works in this field. Two important achievements in this connection deserve mention. Seven years

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after Hertz, Jagdish Chandra Bose, working at Calcutta (now Kolkata),



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succeeded in producing and observing electromagnetic waves of much shorter wavelength (25 mm to 5 mm).

His experiment, like that of Hertz's, was confined to the laboratory.

At around the same time, Guglielmo Marconi in Italy followed Hertz's work and succeeded in transmitting electromagnetic waves over distances of many kilometres.

Marconi's experiment marks the beginning of the field of communication using electromagnetic waves.

8.3.2 Nature of electromagnetic waves

It can be shown from Maxwell's equations that electric and magnetic fields in an electromagnetic wave are

HEINRICH RUDOLF HER

perpendicular to each other, *and* to the direction of propagation. It appears reasonable, say from our

Heinrich Rudolf Hertz

discussion of the displacement current. Consider

(1857 – 1894) German

Fig. 8.2. The electric field inside the plates of the capacitor

physicist who was the

is directed perpendicular to the plates. The magnetic

first to broadcast and

receive radio waves. He

field this gives rise to via the displacement current is

produced electro—

along the perimeter of a circle parallel to the capacitor

magnetic waves, sent

plates. So \mathbf{B} and \mathbf{E} are perpendicular in this case. This

them through space, and

is a general feature.

measured their wave—

In Fig. 8.4, we show a typical example of a plane

length and speed. He

electromagnetic wave propagating along the z direction

showed that the nature

(the fields are shown as a function of the z coordinate,

of their vibration,

reflection and refraction

at a given time t). The electric field E is along the x -axis, TZ (1857–1894)

x

was the same as that of

and varies sinusoidally with z , at a given time. The

light and heat waves,

magnetic field B is along the y -axis, and again varies

y

establishing their

sinusoidally with z . The electric and magnetic fields E and

identity for the first time.

and B are perpendicular to each other, and to the

He also pioneered

y

direction z of propagation. We can write E and B as

research on discharge of

x

y

follows:

electricity through gases,

and discovered the

$$E = E \sin (kz - \omega t)$$

[8.7(a)]

x

0

photoelectric effect.

$$B = B \sin (kz - \omega t)$$

[8.7(b)]

y

0

Here k is related to the wave length λ of the wave by the usual equation

$$2\pi$$

$$k = \lambda$$

(8.8)

and ω is the angular frequency. k

is the magnitude of the wave

vector (or propagation vector) \mathbf{k}

and its direction describes the

direction of propagation of the

FIGURE 8.4 A linearly polarised electromagnetic wave,

wave. The speed of propagation

propagating in the z -direction with the oscillating electric field \mathbf{E}

of the wave is (ω/k) . Using

along the x -direction and the oscillating magnetic field \mathbf{B} along Eqs. [8.7(a) and (b)] for E and B

the y -direction.

x

y

and Maxwell's equations, one

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finds that

Physics

$\omega = ck$, where, $c = 1/\mu\epsilon$

[8.9(a)]

0 0

The relation $\omega = ck$ is the standard one for waves (see for example,

Section 15.4 of class XI Physics textbook). This relation is often written

in terms of frequency, $\nu (= \omega/2\pi)$ and wavelength, $\lambda (= 2\pi/k)$ as

(2π)

2ν

$$\pi = c | \lambda |$$

(

) or

$$v\lambda = c$$

[8.9(b)]

It is also seen from Maxwell's equations that the magnitude of the electric and the magnetic fields in an electromagnetic wave are related as

$$B = (E / c)$$

(8.10)

0

0

We here make remarks on some features of electromagnetic waves.

They are self-sustaining oscillations of electric and magnetic fields in free space, or vacuum. They differ from all the other waves we have studied

so far, in respect that *no material medium* is involved in the vibrations of the electric and magnetic fields. Sound waves in air are longitudinal waves of compression and rarefaction. Transverse waves on the surface of water

consist of water moving up and down as the wave spreads horizontally

and radially onwards. Transverse elastic (sound) waves can also propagate

in a solid, which is rigid and that resists shear. Scientists in the nineteenth century were so much used to this mechanical picture that they thought that there must be some medium pervading all space and all matter,

which responds to electric and magnetic fields just as any elastic medium

does. They called this medium *ether*. They were so convinced of the reality of this medium, that there is even a novel called *The Poison Belt* by Sir Arthur Conan Doyle (the creator of the famous detective *Sherlock Holmes*) where the solar system is supposed to pass through a poisonous region of ether! We now accept that no such physical medium is needed. The

famous experiment of Michelson and Morley in 1887 demolished

conclusively the hypothesis of ether. Electric and magnetic fields,

oscillating in space and time, can sustain each other in vacuum.

But what if a material medium is actually there? We know that light,

an electromagnetic wave, does propagate through glass, for example. We

<http://www.amanogawa.com/waves.html>

<http://www.phys.hawaii.edu/~teb/java/ntnujava/emWave/emWave.html>

have seen earlier that the total electric and magnetic fields inside a

Simulate propagation of electromagnetic waves

(i)

(ii)

medium are described in terms of a permittivity ϵ and a magnetic

permeability μ (these describe the factors by which the total fields differ

from the external fields). These replace ϵ and μ in the description to

0

0

electric and magnetic fields in Maxwell's equations with the result that in a material medium of permittivity ϵ and magnetic permeability μ , the velocity of light becomes,

1

$v =$

$\frac{1}{\mu\epsilon}$

(8.11)

Thus, the velocity of light depends on electric and magnetic properties of the medium. We shall see in the next chapter that the *refractive index* of one medium with respect to the other is equal to the ratio of velocities of light in the two media.

The velocity of electromagnetic waves in free space or vacuum is an important fundamental constant. It has been shown by experiments on

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electromagnetic waves of different wavelengths that this velocity is the

Electromagnetic

Waves

same (independent of wavelength) to within a few metres per second, out of a value of 3×10^8 m/s. The constancy of the velocity of em waves in vacuum is so strongly supported by experiments and the actual value is so well known now that this is used to define a standard of *length*.

Namely, the metre is now *defined* as the distance travelled by light in vacuum in a time $(1/c)$ seconds = $(2.99792458 \times 10^8)^{-1}$ seconds. This has come about for the following reason. The basic unit of time can be defined very accurately in terms of some atomic frequency, i.e., frequency of light emitted by an atom in a particular process. The basic unit of length is harder to define as accurately in a direct way. Earlier measurement of c using earlier units of length (metre rods, etc.) converged to a value of about 2.9979246×10^8 m/s. Since c is such a strongly fixed number, unit of length can be defined in terms of c and the unit of time!

Hertz not only showed the existence of electromagnetic waves, but also demonstrated that the waves, which had wavelength ten million times that of the light waves, could be diffracted, refracted and polarised. Thus, he conclusively established the wave nature of the radiation. Further, he produced stationary electromagnetic waves and determined their wavelength by measuring the distance between two successive nodes. Since the frequency of the wave was known (being equal to the frequency of the oscillator), he obtained the speed of the wave using the formula $v = \nu\lambda$ and found that the waves travelled with the same speed as the speed of light.

The fact that electromagnetic waves are polarised can be easily seen in the response of a portable AM radio to a broadcasting station. If an

AM radio has a telescopic antenna, it responds to the electric part of the signal. When the antenna is turned horizontal, the signal will be greatly diminished. Some portable radios have horizontal antenna (usually inside the case of radio), which are sensitive to the magnetic component of the electromagnetic wave. Such a radio must remain horizontal in order to receive the signal. In such cases, response also depends on the orientation of the radio with respect to the station.

Do electromagnetic waves carry energy and momentum like other waves? Yes, they do. We have seen in chapter 2 that in a region of free space with electric field E , there is an energy density ($\epsilon E^2/2$). Similarly, 0 as seen in Chapter 6, associated with a magnetic field B is a magnetic energy density ($B^2/2\mu$). As electromagnetic wave contains both electric 0 and magnetic fields, there is a nonzero energy density associated with it. Now consider a plane perpendicular to the direction of propagation of the electromagnetic wave (Fig. 8.4). If there are, on this plane, electric charges, they will be set and sustained in motion by the electric and magnetic fields of the electromagnetic wave. The charges thus acquire energy and momentum from the waves. This just illustrates the fact that an electromagnetic wave (like other waves) carries energy and momentum. Since it carries momentum, an electromagnetic wave also exerts pressure,

called *radiation pressure*.

If the total energy transferred to a surface in time t is U , it can be shown that the magnitude of the total momentum delivered to this surface (*for complete absorption*) is,

$$U$$
$$p =$$
$$(8.12)$$
$$277$$
$$c$$

Physics

When the sun shines on your hand, you feel the energy being absorbed from the electromagnetic waves (your hands get warm).

Electromagnetic waves also transfer momentum to your hand but

because c is very large, the amount of momentum transferred is extremely small and you do not feel the pressure. In 1903, the American scientists Nicols and Hull succeeded in measuring radiation pressure of

visible light and verified Eq. (8.12). It was found to be of the order of

7×10^{-6} N/m². Thus, on a surface of area 10 cm², the force due to radiation

is only about 7×10^{-9} N.

The great technological importance of electromagnetic waves stems from their capability to carry energy from one place to another. The

radio and TV signals from broadcasting stations carry energy. Light carries energy from the sun to the earth, thus making life possible on the earth.

Example 8.2 A plane electromagnetic wave of frequency 25 MHz travels in free space along the x -direction. At a particular point in space and time, $\mathbf{E} = 6.3 \hat{\mathbf{j}}$ V/m. What is \mathbf{B} at this point?

Solution Using Eq. (8.10), the magnitude of \mathbf{B} is

$$E$$

$$B = c$$

$$6.3 \text{ V/m}$$

$$-8$$

$$=$$

$$= 2.1 \times 10^{-8} \text{ T}$$

$$8$$

$$3 \times 10^8 \text{ m/s}$$

8.2

To find the direction, we note that \mathbf{E} is along y -direction and the wave propagates along x -axis. Therefore, \mathbf{B} should be in a direction perpendicular to both x - and y - axes. Using vector algebra, $\mathbf{E} \times \mathbf{B}$ should

be along x -direction. Since, $(+\hat{\mathbf{j}}) \times (+\hat{\mathbf{k}})$

$= +\hat{\mathbf{i}}$, \mathbf{B} is along the z -direction.

E

Thus,

$$\mathbf{B} = 2.1 \times 10^{-8} \hat{k} \text{ T}$$

k T

Example 8.3 The magnetic field in a plane electromagnetic wave is given by $B = 2 \times 10^{-7} \sin (0.5 \times 10^3 x + 1.5 \times 10^{11} t)$ T.

y

(a) What is the wavelength and frequency of the wave?

(b) Write an expression for the electric field.

Solution

(a) Comparing the given equation with

$$B = B \sin 2\pi \left[\frac{x}{\lambda} + \frac{t}{T} \right]$$

$$B = B \sin 2\pi$$

$$\left[\frac{x}{\lambda} + \frac{t}{T} \right]$$

y

0

(λT)

|

|

2π

We get, $\lambda =$

3

$0.5 \times$

$m = 1.26 \text{ cm},$

10

1

and

$= v = ($

11

$1.5 \times 10^8) / 2\pi = 23.9 \text{ GHz}$

3

T

(b) $E = B c = 2 \times 10^{-7} \text{ T} \times 3 \times 10^8 \text{ m/s} = 6 \times 10^1 \text{ V/m}$

8.

0

0

The electric field component is perpendicular to the direction of propagation and the direction of magnetic field. Therefore, the electric field component along the z -axis is obtained as

XAMPLE

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E

$$E = 60 \sin (0.5 \times 10^3 x + 1.5 \times 10^{11} t) \text{ V/m}$$

z

Electromagnetic

Waves

Example 8.4 Light with an energy flux of 18 W/cm^2 falls on a non—reflecting surface at normal incidence. If the surface has an area of 20 cm^2 , find the average force exerted on the surface during a 30 minute time span.

Solution

The total energy falling on the surface is

$$\begin{aligned} U &= (18 \text{ W/cm}^2) \times (20 \text{ cm}^2) \times (30 \times 60) \\ &= 6.48 \times 10^5 \text{ J} \end{aligned}$$

Therefore, the total momentum delivered (for complete absorption) is

5

U

$6.48 \times 10 \text{ J}$

$p =$

$=$

8

E

c

$3 \times$

$= 2.16 \times 10^{-3} \text{ kg m/s}$

10 m/s

XAMPLE

The average force exerted on the surface is

-3

p

2.16×10

$F =$

-6

$=$

$= 1.2 \times 10 \text{ N}$

8.4

4

t

0.18×10

How will your result be modified if the surface is a perfect reflector?

Example 8.5 Calculate the electric and magnetic fields produced by the radiation coming from a 100 W bulb at a distance of 3 m. Assume that the efficiency of the bulb is 2.5% and it is a point source.

Solution The bulb, as a point source, radiates light in all directions uniformly. At a distance of 3 m, the surface area of the surrounding sphere is

2

2

2

$$A = 4 \pi r^2 = 4\pi (3)^2 = 113 \text{ m}^2$$

The intensity at this distance is

Power

$$100 \text{ W} \times 2.5 \%$$

$I =$

=

2

Area

113 m

= 0.022 W/m²

Half of this intensity is provided by the electric field and half by the magnetic field.

1

1

$I =$

(2

$\epsilon E c$

0

rms

)

2

2

1

= (

2

0.022 W/m)

2

0.022

E

=

rms

(

V/m

-12

8.85×10

)

8

3×10)

= 2.9 V/m

The value of E found above is the root mean square value of the electric field. Since the electric field in a light beam is sinusoidal, the peak electric field, E is

0

E

$E = 2 E$

= 2×2.9 V/m

XAMPLE

0

rms

= 4.07 V/m

Thus, you see that the electric field strength of the light that you use

8.5

for reading is fairly large. Compare it with electric field strength of TV or FM waves, which is of the order of a few microvolts per metre.

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Physics

Now, let us calculate the strength of the magnetic field. It is

-1

E

2.9 V m

rms

B

=

=

rms

8

1

c

$3 \times$

$= 9.6 \times 10^{-9} \text{ T}$

10 m s^{-1}

8.5

Again, since the field in the light beam is sinusoidal, the peak

magnetic field is $B =$

$= 1.4 \times 10^{-8} \text{ T}$. Note that although the

0

$2 B_{\text{rms}}$

energy in the magnetic field is equal to the energy in the electric

XAMPLE

field, the magnetic field strength is evidently very weak.

E

8.4 ELECTROMAGNETIC SPECTRUM

At the time Maxwell predicted the existence of electromagnetic waves, the

only familiar electromagnetic waves were the visible light waves. The existence of ultraviolet and infrared waves was barely established. By the end of the nineteenth century, X-rays and gamma rays had also been discovered. We

now know that, electromagnetic waves include visible light waves, X-rays, gamma rays, radio waves, microwaves, ultraviolet and infrared waves. The classification of em waves according to frequency is the electromagnetic spectrum (Fig. 8.5). *There is no sharp division between one kind of wave and the next.* The classification is based roughly on how the waves are produced and/or detected.

Electromagnetic spectrum

<http://www.fnal.gov/pub/inquiring/more/light>

<http://imagine.gsfc.nasa.gov/docs/science/>

FIGURE 8.5 The electromagnetic spectrum, with common names for various

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part of it. The various regions do not have sharply defined boundaries.



Electromagnetic

Waves

We briefly describe these different types of electromagnetic waves, in order of decreasing wavelengths.

8.4.1 Radio waves

Radio waves are produced by the accelerated motion of charges in conducting

wires. They are used in radio and television communication systems. They are generally in the frequency range from 500 kHz to about 1000 MHz.

The AM (amplitude modulated) band is from 530 kHz to 1710 kHz. Higher frequencies upto 54 MHz are used for *short wave* bands. TV waves range from 54 MHz to 890 MHz. The FM (frequency modulated) radio band extends from 88 MHz to 108 MHz. Cellular phones use radio waves to transmit voice communication in the ultrahigh frequency (UHF) band. How these waves are transmitted and received is described in Chapter 15.

8.4.2 Microwaves

Microwaves (short-wavelength radio waves), with frequencies in the gigahertz (GHz) range, are produced by special vacuum tubes (called klystrons, magnetrons and Gunn diodes). Due to their short wavelengths, they are suitable for the radar systems used in aircraft navigation. Radar also provides the basis for the speed guns used to time fast balls, tennis—serves, and automobiles. Microwave ovens are an interesting domestic application of these waves. In such ovens, the frequency of the microwaves is selected to match the resonant frequency of water molecules so that energy from the waves is transferred efficiently to the kinetic energy of

the molecules. This raises the temperature of any food containing water.

MICROWAVE OVEN

The spectrum of *electromagnetic radiation* contains a part known as *microwaves*. These waves have frequency and energy smaller than visible light and wavelength larger than it.

What is the principle of a microwave oven and how does it work?

Our objective is to cook food or warm it up. All food items such as fruit, vegetables, meat, cereals, etc., contain water as a constituent. Now, what does it mean when we say that a certain object has become warmer? When the temperature of a body rises, the energy of the random motion of atoms and molecules increases and the molecules travel or vibrate or rotate with higher energies. The frequency of rotation of water molecules is about 300 crore hertz, which is 3 gigahertz (GHz). If water receives microwaves of this frequency, its molecules absorb this radiation, which is equivalent to heating up water. These molecules share this energy with neighbouring food molecules, heating up the food.

One should use porcelain vessels and not metal containers in a microwave oven because of the danger of getting a shock from accumulated electric charges. Metals may also melt from heating. The porcelain container remains unaffected and cool, because its large molecules vibrate and rotate with much smaller frequencies, and thus cannot absorb microwaves. Hence, they do not get heated up.

Thus, the basic principle of a microwave oven is to generate microwave radiation of appropriate frequency in the working space of the oven where we keep food. This way energy is not wasted in heating up the vessel. In the conventional heating method, the vessel on the burner gets heated first, and then the food inside gets heated because of transfer of energy from the vessel. In the microwave oven, on the other hand, energy is directly delivered to water molecules which is shared by the entire food.

Physics

8.4.3 Infrared waves

Infrared waves are produced by hot bodies and molecules. This band lies adjacent to the low-frequency or long-wave length end of the visible spectrum. Infrared waves are sometimes referred to as *heat waves*. This is because water molecules present in most materials readily absorb infrared waves (many other molecules, for example, CO₂, NH₃, also absorb

2

3

infrared waves). After absorption, their thermal motion increases, that is, they heat up and heat their surroundings. Infrared lamps are used in physical therapy. Infrared radiation also plays an important role in maintaining the earth's warmth or average temperature through the greenhouse effect. Incoming visible light (which passes relatively easily through the atmosphere) is absorbed by the earth's surface and re—radiated as infrared (longer wavelength) radiations. This radiation is trapped by greenhouse gases such as carbon dioxide and water vapour. Infrared detectors are used in Earth satellites, both for military purposes and to observe growth of crops. Electronic devices (for example semiconductor light emitting diodes) also emit infrared and are widely

used in the remote switches of household electronic systems such as TV sets, video recorders and hi-fi systems.

8.4.4 Visible rays

It is the most familiar form of electromagnetic waves. It is the part of the spectrum that is detected by the human eye. It runs from about 4×10^{14} Hz to about 7×10^{14} Hz or a wavelength range of about 700 – 400 nm. Visible light emitted or reflected from objects around us provides us information about the world. Our eyes are sensitive to this range of wavelengths. Different animals are sensitive to different range of wavelengths. For example, snakes can detect infrared waves, and the ‘visible’ range of many insects extends well into the ultraviolet.

8.4.5 Ultraviolet rays

It covers wavelengths ranging from about 4×10^{-7} m (400 nm) down to 6×10^{-10} m (0.6 nm). Ultraviolet (UV) radiation is produced by special lamps and very hot bodies. The sun is an important source of ultraviolet light. But fortunately, most of it is absorbed in the ozone layer in the atmosphere at an altitude of about 40 – 50 km. UV light in large quantities has harmful effects on humans. Exposure to UV radiation induces the production of more melanin, causing tanning of the skin. UV radiation is absorbed by ordinary glass. Hence, one cannot get tanned or sunburn

through glass windows.

Welders wear special glass goggles or face masks with glass windows to protect their eyes from large amount of UV produced by welding arcs.

Due to its shorter wavelengths, UV radiations can be focussed into very narrow beams for high precision applications such as LASIK (*Laser-assisted in situ keratomileusis*) eye surgery. UV lamps are used to kill germs in water purifiers.

Ozone layer in the atmosphere plays a protective role, and hence its depletion by chlorofluorocarbons (CFCs) gas (such as freon) is a matter

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of international concern.

Electromagnetic

Waves

8.4.6 X-rays

Beyond the UV region of the electromagnetic spectrum lies the X-ray region. We are familiar with X-rays because of its medical applications. It covers wavelengths from about 10^{-8} m (10 nm) down to 10^{-13} m (10^{-4} nm). One common way to generate X-rays is to bombard a metal target by high energy electrons. X-rays are used as a diagnostic tool in medicine and as a treatment for certain forms of cancer. Because X-rays damage or destroy living tissues and organisms, care must be taken to

avoid unnecessary or over exposure.

8.4.7 Gamma rays

They lie in the upper frequency range of the electromagnetic spectrum and have wavelengths of from about 10^{-10} m to less than 10^{-14} m. This high frequency radiation is produced in nuclear reactions and also emitted by radioactive nuclei. They are used in medicine to destroy cancer cells.

Table 8.1 summarises different types of electromagnetic waves, their production and detections. As mentioned earlier, the demarcation between different region is not sharp and there are over laps.

TABLE 8.1 DIFFERENT TYPES OF ELECTROMAGNETIC WAVES

Type

Wavelength range

Production

Detection

Radio

> 0.1 m

Rapid acceleration and

Receiver's aerials

decelerations of electrons

in aerials

Microwave

0.1m to 1 mm

Klystron valve or

Point contact diodes

magnetron valve

Infrared

1mm to 700 nm

Vibration of atoms

Thermopiles

and molecules

Bolometer, Infrared

photographic film

Light

700 nm to 400 nm

Electrons in atoms emit

The eye

light when they move from

Photocells

one energy level to a

Photographic film

lower energy level

Ultraviolet

400 nm to 1 nm

Inner shell electrons in

Photocells

atoms moving from one

Photographic film

energy level to a lower level

X-rays

1 nm to 10^{-3} nm

X-ray tubes or inner shell

Photographic film

electrons

Geiger tubes

Ionisation chamber

Gamma rays

$<10^{-3}$ nm

Radioactive decay of the

-do—

nucleus

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Physics

SUMMARY

1.

Maxwell found an inconsistency in the Ampere's law and suggested the existence of an additional current, called displacement current, to remove this inconsistency. This displacement current is due to time-varying electric field and is given by

$$d\Phi$$
$$i$$
$$\varepsilon$$
$$E$$
$$=$$
$$d$$
$$0$$
$$d t$$

and acts as a source of magnetic field in exactly the same way as conduction

current.

2.

An accelerating charge produces electromagnetic waves. An electric charge oscillating harmonically with frequency ν , produces electromagnetic waves of the same frequency ν . An electric dipole is a basic source of electromagnetic waves.

3.

Electromagnetic waves with wavelength of the order of a few metres were first produced and detected in the laboratory by Hertz in 1887. He thus verified a basic prediction of Maxwell's equations.

4.

Electric and magnetic fields oscillate sinusoidally in space and time in an electromagnetic wave. The oscillating electric and magnetic fields, \mathbf{E} and \mathbf{B} are perpendicular to each other, and to the direction of propagation of the electromagnetic wave. For a wave of frequency ν , wavelength λ , propagating along z -direction, we have

$$E = E_0 \sin(kz - \omega t)$$

$$B = B_0 \sin(kz - \omega t)$$

$$x(t) = E_0 \sin(\omega t)$$

┌

(z

)]

[

(z

t)]

$$= E \sin 2\pi$$

|

| - t

$$v | = E \sin 2\pi$$

|

|

| - ||

0

0

(\lambda

)

(λT)

L

J

L

J

$$B = B(t) = B \sin(kz - \omega t)$$

y

0

Γ

(z

)]

Γ

(z

t)]

$$= B \sin 2\pi$$

|

| - t

$$v = B \sin 2\pi$$

|
|
| -

0

0

λ

λ

||
(
)
(

T)

┌
└
┌
└

They are related by $E/B = c$.

0

0

5.

The speed c of electromagnetic wave in vacuum is related to μ and ϵ (the

0

free space permeability and permittivity constants) as follows:

$c = 1/\mu\epsilon$. The value of c equals the speed of light obtained from 0

0

optical measurements.

Light is an electromagnetic wave; c is, therefore, also the speed of light.

Electromagnetic waves other than light also have the same velocity c in

free space.

The speed of light, or of electromagnetic waves in a material medium is

given by $v = 1/\mu\epsilon$

where μ is the permeability of the medium and ϵ its permittivity.

6.

Electromagnetic waves carry energy as they travel through space and this energy is shared equally by the electric and magnetic fields.

Electromagnetic waves transport momentum as well. When these waves strike a surface, a pressure is exerted on the surface. If total energy

transferred to a surface in time t is U , total momentum delivered to this surface is $p = U/c$.

7.

The spectrum of electromagnetic waves stretches, in principle, over an

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infinite range of wavelengths. Different regions are known by different

Electromagnetic

Waves

names; γ -rays, X-rays, ultraviolet rays, visible rays, infrared rays,

microwaves and radio waves in order of increasing wavelength from 10^{-2} Å

or 10^{-12} m to 106 m.

They interact with matter via their electric and magnetic fields which set in oscillation charges present in all matter. The detailed interaction and so the mechanism of absorption, scattering, etc., depend on the wavelength of the electromagnetic wave, and the nature of the atoms and molecules in the medium.

POINTS TO PONDER

1.

The basic difference between various types of electromagnetic waves lies in their wavelengths or frequencies since all of them travel through vacuum with the same speed. Consequently, the waves differ considerably in their mode of interaction with matter.

2.

Accelerated charged particles radiate electromagnetic waves. The wavelength of the electromagnetic wave is often correlated with the characteristic size of the system that radiates. Thus, gamma radiation, having wavelength of 10^{-14} m to 10^{-15} m, typically originate from an atomic nucleus. X-rays are emitted from heavy atoms. Radio waves are produced by accelerating electrons in a circuit. A transmitting antenna can most efficiently radiate waves having a wavelength of about the same size as the antenna. Visible radiation emitted by atoms is, however, much longer in wavelength than atomic size.

3.

The oscillating fields of an electromagnetic wave can accelerate charges and can produce oscillating currents. Therefore, an apparatus designed to detect electromagnetic waves is based on this fact. Hertz original 'receiver' worked in exactly this way. The same basic principle is utilised in practically all modern receiving devices. High frequency electromagnetic waves are detected by other means based on the physical effects they produce on interacting with matter.

4.

Infrared waves, with frequencies lower than those of visible light, vibrate not only the electrons, but entire atoms or molecules of a

substance. This vibration increases the internal energy and consequently, the temperature of the substance. This is why infrared waves are often called *heat waves*.

5.

The centre of sensitivity of our eyes coincides with the centre of the wavelength distribution of the sun. It is because humans have evolved with visions most sensitive to the strongest wavelengths from the sun.

EXERCISES

8.1

Figure 8.6 shows a capacitor made of two circular plates each of radius 12 cm, and separated by 5.0 cm. The capacitor is being charged by an external source (not shown in the figure). The charging current is constant and equal to 0.15A.

(a) Calculate the capacitance and the rate of change of potential

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difference between the plates.

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(b) Obtain the displacement current across the plates.

(c)

Is Kirchhoff's first rule (junction rule) valid at each plate of the capacitor? Explain.

FIGURE 8.6

8.2

A parallel plate capacitor (Fig. 8.7) made of circular plates each of radius $R = 6.0$ cm has a capacitance $C = 100$ pF. The capacitor is connected to a 230 V ac supply with a (angular) frequency of 300 rad s⁻¹.

- (a) What is the rms value of the conduction current?
- (b) Is the conduction current equal to the displacement current?
- (c)

Determine the amplitude of \mathbf{B} at a point 3.0 cm from the axis between the plates.

FIGURE 8.7

8.3

What physical quantity is the same for X-rays of wavelength 10^{-10} m, red light of wavelength 6800 Å and radiowaves of wavelength 500m?

8.4

A plane electromagnetic wave travels in vacuum along z-direction. What can you say about the directions of its electric and magnetic field vectors? If the frequency of the wave is 30 MHz, what is its

wavelength?

8.5

A radio can tune in to any station in the 7.5 MHz to 12 MHz band.

What is the corresponding wavelength band?

8.6

A charged particle oscillates about its mean equilibrium position

with a frequency of 109 Hz. What is the frequency of the

electromagnetic waves produced by the oscillator?

8.7

The amplitude of the magnetic field part of a harmonic

electromagnetic wave in vacuum is $B = 510$ nT. What is the

0

amplitude of the electric field part of the wave?

8.8

Suppose that the electric field amplitude of an electromagnetic wave

is $E = 120$ N/C and that its frequency is $\nu = 50.0$ MHz. (a) Determine,

0

B , ω , k , and λ . (b) Find expressions for \mathbf{E} and \mathbf{B} .

0

8.9

The terminology of different parts of the electromagnetic spectrum is given in the text. Use the formula $E = h\nu$ (for energy of a quantum of radiation: photon) and obtain the photon energy in units of eV for different parts of the electromagnetic spectrum. In what way are the different scales of photon energies that you obtain related to the sources of electromagnetic radiation?

8.10

In a plane electromagnetic wave, the electric field oscillates

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sinusoidally at a frequency of 2.0×10^{10} Hz and amplitude 48 V m^{-1} .

Electromagnetic

Waves

- (a) What is the wavelength of the wave?
- (b) What is the amplitude of the oscillating magnetic field?
- (c)

Show that the average energy density of the **E** field equals the average energy density of the **B** field. [$c = 3 \times 10^8 \text{ m s}^{-1}$.]

ADDITIONAL EXERCISES

8.11

Suppose that the electric field part of an electromagnetic wave in vacuum is $\mathbf{E} = \{(3.1 \text{ N/C}) \cos [(1.8 \text{ rad/m}) y + (5.4 \times 10^6 \text{ rad/s}) t]\} \hat{\mathbf{i}}$.

(a) What is the direction of propagation?

(b) What is the wavelength λ ?

(c)

What is the frequency ν ?

(d) What is the amplitude of the magnetic field part of the wave?

(e)

Write an expression for the magnetic field part of the wave.

8.12

About 5% of the power of a 100 W light bulb is converted to visible radiation. What is the average intensity of visible radiation

(a) at a distance of 1m from the bulb?

(b) at a distance of 10 m?

Assume that the radiation is emitted isotropically and neglect reflection.

8.13

Use the formula $\lambda_m T = 0.29 \text{ cm K}$ to obtain the characteristic temperature ranges for different parts of the electromagnetic spectrum. What do the numbers that you obtain tell you?

8.14

Given below are some famous numbers associated with

electromagnetic radiations in different contexts in physics. State the part of the electromagnetic spectrum to which each belongs.

(a) 21 cm (wavelength emitted by atomic hydrogen in interstellar space).

(b) 1057 MHz (frequency of radiation arising from two close energy levels in hydrogen; known as Lamb shift).

(c)

2.7 K [temperature associated with the isotropic radiation filling all space-thought to be a relic of the ‘big-bang’ origin of the universe].

(d) 5890 Å - 5896 Å [double lines of sodium]

(e)

14.4 keV [energy of a particular transition in ^{57}Fe nucleus associated with a famous high resolution spectroscopic method (Mössbauer spectroscopy)].

8.15

Answer the following questions:

(a) Long distance radio broadcasts use short-wave bands. Why?

(b) It is necessary to use satellites for long distance TV transmission.

Why?

(c)

Optical and radiotelescopes are built on the ground but X-ray astronomy is possible only from satellites orbiting the earth.

Why?

(d) The small ozone layer on top of the stratosphere is crucial for human survival. Why?

(e)

If the earth did not have an atmosphere, would its average surface temperature be higher or lower than what it is now?

(f)

Some scientists have predicted that a global nuclear war on the earth would be followed by a severe 'nuclear winter' with a devastating effect on life on earth. What might be the basis of

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this prediction?