THE GOVERNMENT OF THE REPUBLIC OF THE UNION OF MYANMAR

MINISTRY OF EDUCATION

PHYSICS

GRADE 10

BASIC EDUCATION CURRICULUM, SYLLABUS AND

TEXTBOOK COMMITTEE

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FOREWORD

This text book is prescribed for the eleventh grade students. It covers of the whole course for a student studying physics in the upper secondary level of basic education (i.e. for the eleventh grade).

The division and order of subject content in separate fields presented in the whole course of upper secondary level physics follow the sequence mentioned below:

(I) Mechanics

(2) Heat

(3) Waves and Sound

(4) Optics

(5) Electricity and Magnetism

(6) Modern Physics

The present text book covers the above fields with certain additional material to up date the text.

Physics is generally defined as the study of matter and motion. In fact, neither this nor any other one-sentence statement adequately covers the whole definition of physics. It is a unified structure of the following features:

(a) creativity,

(b) accumulation of knowledge,

(c) unification of concepts,

(d) mathematical equations and formulation,

(e) philosophical reasoning,

(f) practical applications.

Both text books are designed to give students not only an understanding of the important facts, laws and basic concepts of physics, but the practical application of theoretical knowledge to solving problems also.

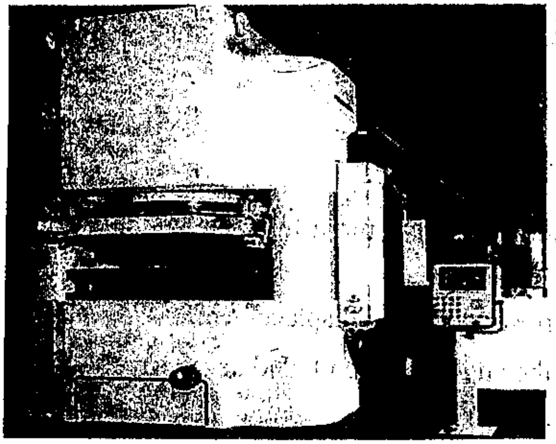
CONTENTS

MECHANICS

HEAT

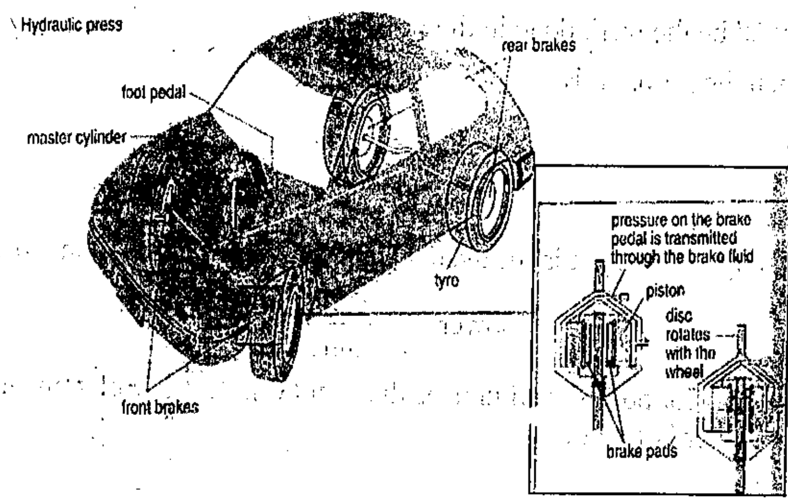
ELECTRICITY AND MAGNETISM

MODERN PHYSICS



Hydraulic press

MECHANICS



Hydraulic brake system

CHAPTER 1

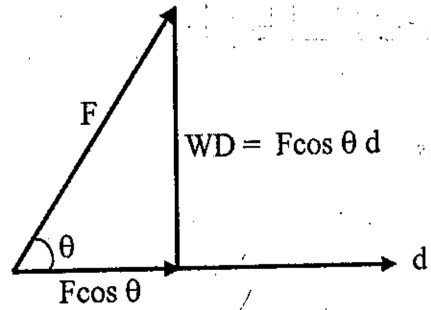
WORK DONE AND POWER

1.1 POWER AND ITS UNITS

Power is another concept in mechanics. Although it is not a fundamental concept of physics, it is very useful in practice.

Work may be defined as the product of force applied and displacement.

WD (work done) = W = $F\cos\theta\, d$, θ is the angle between F and d.



The importance of the concept of work (how it is related to energy) has also been described. There are many cases where it is necessary to know the magnitude of the work done, but for some other cases it is more important to know the rate of doing work rather than the total amount of the work done.

The rate of doing work is defined as power. Car engines, water pumps, refrigerators, air conditioners and electric bulbs, fluorescent tubes, etc., are classified according to their rated powers.

Let W be the work done in time period t.

Then the power P is

$$P = \frac{W}{t} \qquad (1.1)$$

Strictly speaking, it is the average power. When expressed in words

$$\text{power} = \frac{\text{work}}{\text{time}}$$

The unit for power in SI units is the watt (W). If the work done in 1 second is 1 joule, the power is 1 watt.

Therefore,

$$1\ W = 1\ J\ s^{-1}$$

(Care should be taken not to confuse the notation W for watt and W for work.)

The units of power which are larger than watt are kilowatt (kW) and megawatt (MW).

$$1\ kW = 1000\ W = 10^3\ W$$

$$1 MW = 1000\,000\ W = 10^6\ W$$

In the CGS system, the unit of power is erg s^{-1}. If the work done is 1 erg in 1 second the power is 1 erg s^{-1} (erg s^{-1} has no other name).

In the British system the unit of power is foot-pound per second (ft-lb s^{-1}) and another unit is the horse power (hp).

The relationships between different units of power are

$$1\ W = 1\ J\ s^{-1}$$

$$= 10^7\ erg\ s^{-1}$$

$$1\ hp = 550\ ft\text{-}lb\ s^{-1}$$

$$= 746\ W$$

$$= 746 \times 10^7\ erg\ s^{-1}$$

If s is the displacement produced by **a force F** acting for the time t, the work done is Fs. Hence, the rate of doing work or power is

$$P = \frac{Fs}{t}$$

$$= F\frac{s}{t}$$

$$P = Fv$$

and when expressed in words, we have

power = force × velocity

Example (1) A 70 kg man is running up the stairs which is 3 m high in 2 s. (a) How much work is done by the man? (b) What is the power exerted by the man?

(a) Since the work done is the change in the potential energy of the man

$$W = mgh$$

$$= 70 \times 9.8 \times 3 = 2058\ J$$

(b) The power exerted by the man is

$$P = \frac{W}{t} = \frac{2058}{2} = 1029\ W$$

(This value of power is very large. A man is able to produce such a power only for a short duration for a short duration.)

Example (2) A water-pump can raise 200 kg water to a height of 6 m in 10 s. Find the power of the water-pump.

The work done by the water-pump in 10 s is

$$W = mgh$$
$$= 200 \times 9.8 \times 6 \text{ J}$$

and the power of the water-pump is

$$P = \frac{W}{t}$$
$$= \frac{200 \times 9.8 \times 6}{10} = 1176 \text{ J s}^{-1}$$

Example (3) A crane is lifting a 500 lb piano with a velocity of 2 ft s^{-1}. Express the power of the crane in hp.

Since the force and the velocity are in the same direction

$$P = Fv = 500 \times 2 = 1000 \text{ ft-lb s}^{-1}$$

But, since

$$1 \text{ hp} = 550 \text{ft-lbs}^{-1}$$
$$P = \frac{1000}{550} = 1.82 \text{ hp}$$

1.2 EFFICIENCY

Efficiency is another technical term that is derived from everyday usage. In physics and engineering efficiency has a precise meaning. This term is used in association with machines and devices which transmit force from one point to the next.

Before we define efficiency, we will define the concepts of mechanical advantage and velocity ratio.

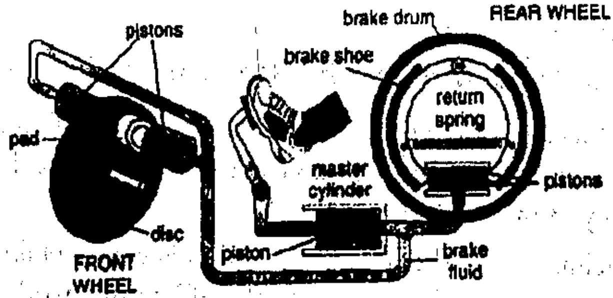
Mechanical Advantage

Machines, in general, are made up of simpler components - simple machines. These simple machines fall into any one of three types:

(1) the lever (e.g. a crowbar),

(2) the inclined plane (e.g. a screwjack) and

(3) the hydraulic press (e.g. brake system of a car).



Hydraulic brakes

If a load W is raised steadily by a machine when an effort P is applied, the mechanical advantage of the machine is defined as the ratio W/P, or

$$\text{mechanical advantage (MA)} = \frac{load(W)}{effort(P)}$$

Suppose an effort P of 25 N is applied at one end of a crowbar and just overcomes the resistance W of 100 N at the lid of a case.

Then

$$\text{mechanical advantage (MA) of crowbar} = \frac{W}{P} = \frac{100}{25} = 4$$

In practice, not all of the effort is used up in lifting the load, some of it is spent in overcoming frictional forces present. It should, therefore, be remembered that the MA of a machine depends on the friction present.

Velocity Ratio

Let us suppose that in lifting a large load, a machine is employed. In using this machine, the small effort applied will have to move through a large distance for the heavy load to move through a small distance in the same time interval.

The ratio of the distance per second moved steadily by the effort to that of the load is called the velocity ratio of the machine. Thus

$$\text{velocity ratio (VR)} = \frac{\text{distance moved by effort}}{\text{distance moved by load in the same time}}$$

Suppose that in lifting a load with a pulley, the effort moves through 250 cm while the load moves through 50 cm in the same time interval. For this case

$$\text{velocity ratio (VR)} = \frac{250}{50} = 5$$

The VR is usually much greater than 1.

Efficiency and its Relations to Mechanical Advantage and velocity Ratio

Now that we have defined mechanical advantage and velocity ratio of a machine, we will define its efficiency and express the relation between mechanical advantage, velocity ratio and efficiency of the machine.

In lifting a load with a machine, work is done on the load; this work obtained is called the output work. At the same time work is done by the effort; this work supplied is called the input work. The ratio of output work to input work is defined as the efficiency of the machine. This quantity is generally expressed in the percentage form. Thus

$$\text{efficiency} = \frac{\text{output work}}{\text{input work}} \times 100\,\%$$

Efficiency is related to MA and VR as follows:

$$\text{efficiency} = \frac{\text{MA}}{\text{VR}} \times 100\,\%$$

Example (4) A machine with a velocity ratio of 8 requires 1000 J of work to raise a load of 500 N through a vertical distance of 1 m. Find the efficiency and mechanical advantage of the machine.

$$\text{efficiency} = \frac{\text{output work}}{\text{input work}} \times 100\,\%$$

$$= \frac{500 \times 1}{1000} \times 100\,\%$$

$$= \frac{1}{2} \times 100\%$$

$$= 50\%$$

and since $\quad \text{efficiency} = \dfrac{\text{MA}}{\text{VR}} \times 100\%$

$$50 = \frac{\text{MA}}{8} \times 100$$

$$\text{MA} = \frac{50 \times 8}{100} = 4$$

It is impossible, in practice, to build a perfect machine for which output work is equal to input work; input work always exceeds output work. Therefore, the efficiency of a machine must always be less than 100 %.

1.3 THE STRETCHING OF THREADS AND STRINGS

Consider a spring suspended as shown in Fig. 1.1 (a). If a small load is attached to the free end of this spring as shown in Fig. 1.1 (b) the string will be stretched or elongated. When the load is taken off, the spring will return to its original length and form. If, now, a bigger load is hanged at the free end, the spring will again be elongated, but this time elongation will be larger than the case when the smaller load was hanged. Thus, as we attach bigger and bigger load the spring will be elongated more and more. Also, whenever the load is removed the spring returns to its original length and form. This ability to retain the original form is called elasticity. Not only springs but also other objects such as threads and rubber bands have elastic property.

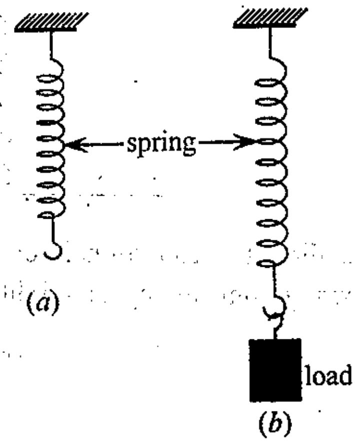


Fig. 1.1

There is a limit, however, beyond which if the spring or any other elastic object is stretched, it will not return to its original form. Such a limit is called the elastic limit. This limit, of course, is different for different elastic bodies.

Hooke's Law

Robert Hooke noted that when an elastic body such as a spring is stretched by a weight or a force, the amount of elongation of the spring is proportional to the force that produces it so long as the elastic limit is not exceeded. Hooke called the applied force the stress, and the elongation produced the strain. Hooke's law is formally stated as follows:

> As long as the elastic limit of a body is not exceeded, the strain produced is proportional to the stress causing it.
>
> In symbols $F \propto x$ or $F = kx$ (k = constant)

where F is the applied force or stress and x is the elongation or strain.

In order to illustrate Hooke's law, let us look at the stress and strain data obtained from an idealised experiment. Table 1.1 lists these data. It is found that the strain is proportional to the stress; that is, for each of a series of forces applied to the elastic body, the ratio of the force (stress) and elongation (strain) F/x, is constant.

Table 1.1

Force (lb)	Elongation(in)
0.	0.0
1	0.5
2	1.0
3	1.5
4	2.0
5	2.5

The directly proportional relationship between F, the stress, and x, the strain, is shown graphically by a straight line (Fig. 1.2).

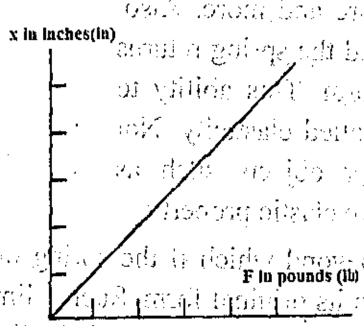


Fig (1.2)

SUMMARY

Elastic limit There is a limit beyond which if the spring or any other elastic object is stretched, it will not return to its original form. Such a limit is called the elastic limit.

Efficiency The ratio of output work to input work is defined as the efficiency of the machine.

$$\text{efficiency} = \frac{\text{output work}}{\text{input work}} \times 100\,\%$$

$$\text{efficiency} = \frac{\text{Mechanical Advantage}}{\text{Velocity Ratio}} \times 100\,\%$$

Elasticity The ability to retain the original form is called elasticity.

Hydraulic system A system that transfers force from place to place using fluids.

Hooke's Law *Relates to the elastic behaviour of materials:* As long as the elastic limit of a body is not exceeded, the strain produced is proportional to the stress causing it.

$$F \propto x \qquad \text{or } F = kx \qquad (k = \text{constant})$$

Lever An appliance which is pivoted about some point, and which generates a turning effect when a force is applied at some point other than the pivot.

Machine An appliance that enables work to be done.

Mechanical advantage (MA) The mechanical advantage of the machine is defined as the ratio of a load W to an effort P.

Power (P) The rate of doing work is defined as power. (power $= \frac{\text{work}}{\text{time}}$)

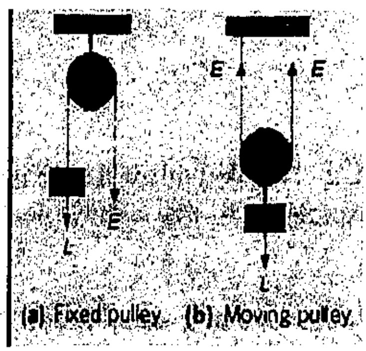
Velocity ratio (VR) The ratio of the distance per second moved steadily by the effort to that of the load is called the velocity ratio of the machine.

$$\text{velocity ratio (VR)} = \frac{\text{distance moved by effort}}{\text{distance moved by load in the same time}}$$

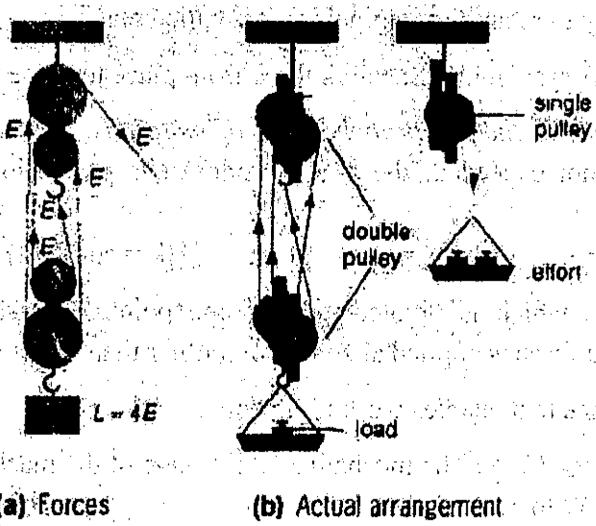
Watt The unit of power, equal to a rate of energy transfer (or work done) of 1 joule per second.

Work The energy transferred in any system where a force causes movement. The work done is the product of the force and the distance moved by its point of application along the line in which the force acts.

Pulleys



A crane using a "block and tackle" pulley system



Block and tackle pulleys

(E: effort; L: load)

EXERCISES

1. Define "power".

2. Power is not a fundamental concept like energy but it is a very important concept for engineering works. Explain why power is a useful concept in practical works.

3. Which is more advantageous: to pay wages according to the amount of work done or according to power?

4. The rate of doing work for the first worker is twice that of the second worker. But the working hours per day of the second is two and a half times that of the first. Who is a better worker?

5. Fill in the blanks.

   Since power has only (1) and no direction, it is a (2). The SI unit for power is (3). The powers of motors and engines are also expressed in (4) which is a unit in British engineering system.

6. A machine of high power should be used if a lot of work has to be done quickly. True or false?

7. Choose the correct answer from the following:

(a) When a large power machine and a small power the machine are operated for the same period of time, the large power machine consumes less fuel.

(b) A lot of work can be done only if a large power machine is used.

(c) A lot of work can be done by operating a small power machine for as long as necessary.

Give explanation to support the chosen answer.

8. What do you understand by the efficiency of a machine ?

9. Define velocity ratio and mechanical advantage.

10. State Hooke's law. What is meant by elasticity ?

11. A system of levers with a velocity ratio of 25 overcomes a resistance of 3300 N when an effort of 165 N is applied to it, calculate:

(a) the mechanical advantage of the system;

(b) its efficiency.

12. By using a block-and-tackle a man can raise a load of 720 N by an effort of 200 N. Find the mechanical advantage of the method.

13. A spring is loaded by stages and its length noted each time. The results are shown in the table.

Load (N)	0.5	1.0	1.5	2.0	2.5
Length of spring (cm)	36.0	41.5	48.5	54.0	60.0

Draw a graph of these results, plotting 'load' across the page and 'length of spring' up the page.

(i) What will be the length of the spring when a load of 1.1 N is applied to it?

(ii) What is the length of the unstretched spring?

(iii) What load will produce an extension of 20 cm?

14. In a tug-of-war A-team is leading B-team. The rope is moving towards A-team at a regular rate of 0.01 m s^{-1}. If the tension of the rope is 4000 N what is the power output of A-team ?

15. A woman of 40 kg mass climbs up by pulling a rope 8 m long with a constant velocity for 15 s. Find the power output of the woman.

16. The power output of the motor of a crane is 2000 W. With what speed can the machine lift a 1000 kg load?

17. A water pump is pumping up water from a well which is 200 m deep.

(a) How much work must be done by the pump to raise 1 kg of water?

(b) What is the power output of the pump if it pumps up water at rate of 10kg min^{-1}?

Prof Dr Mg Mg Kha (1915-2005) MSc (Lond), PhD (Lond), DIC, MInstP, FRMetS(Lond)

Prof Dr Mg Mg Kha was the very first Myanmar Professor of Physics. Wrote many high school and university physics texts. Introduced MSc research programme which eventually led to the introduction of PhD in 1994. Acted as a prominent member of PhD Steering Committee in Physics between 1994-2005. Wrote research papers on acoustics and meteorology. Served for many years as Chief Consultant to Myanmar Atomic Energy Committee. Was Professor between 1945-1964 and Rector (Vice Chancellor) from 1963 to 1978. Introduced distance learning at the degree level (correspondence courses) soon after his official retirement as Yangon University Rector in Myanmar and was head of the section till 1981.

CHAPTER 2

PRESSURE

2.1 ATMOSPHERIC PRESSURE

The earth is surrounded by the atmosphere up to a height of many many miles. The atmosphere which consists largely of masses of gases has weight. Therefore, it is obvious that the atmosphere exerts pressure. Atmospheric pressure acts on all living and non-living things on earth. The atmospheric pressure which acts on human beings and animals on the surface of the earth is actually very high. Since the surface area of the body of an average person is about $2m^2$, the magnitude of force acting on him is 200 k N or 20 tons. This is because the magnitude of the atmospheric pressure at the earth's surface is about 100 k Nm^{-2}. Although the atmospheric pressure on a person is very high the blood pressure inside the body is even a bit higher than the atmospheric pressure. This is the reason why we are able to withstand atmospheric pressure. Nose bleeding which sometimes occurs at a place of low atmospheric pressure is due to the fact that the blood pressure is higher than the atmospheric pressure.

The atmospheric pressure changes according to locality and time. The atmospheric pressure at the plains is higher than that at the hilly regions. There are occasions when the atmospheric pressure changes from day to day for the same locality. Due to the possibility of this variation it is necessary to define a standard atmospheric pressure for reference. The atmospheric pressure at sea level is measured many times for many days and the average value is taken as ordinary atmospheric pressure or normal atmospheric pressure.

Barometer

A device for measuring atmospheric pressure. We will describe simple mercury barometer. The mercury barometer is a simplest form. It consists of a glass tube about 1 metre long sealed at one end and filled with mercury. The tube is then inverted and the open end is submerged in a reservoir of mercury; the mercury column is held up by the pressure of the atmosphere acting on the surface of mercury in the reservoir (Fig.2.1).

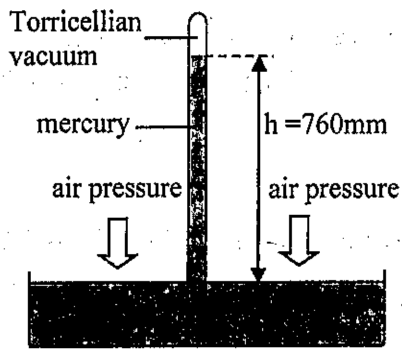


Fig. 2.1 Mercury barometer

This type of device was inverted by the Italian scientist Evangelista Torricelli (1608-47), who first noticed the variation of pressure due to height from day to day, and constructed a barometer in 1644.In such a device, the force exerted by the atmosphere balanced the weight of the mercury column.

If the height of the column is h
the cross-sectional area of the tube is A
then the volume of the mercury in the column is hA and
its weight is $hA\rho g$ (where ρ is the density of mercury)
the force is thus $hA\rho g$ (where g is the acceleration of free fall)
the pressure exerted is (force divided by the area of the tube) $h\rho g$

Standard atmospheric pressure
A pressure of 760 mmHg is known as standard atmospheric pressure, or 1 atmosphere [1 atm]. Its value in Pa can found by calculating the pressure at the bottom of a column of mercury 760 mm high, as shown in Fig 2.2.

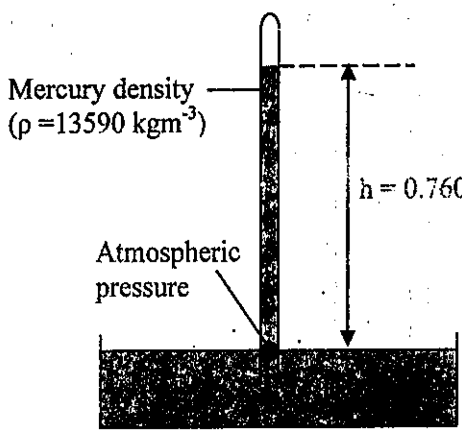


Fig. 2.2.

The density of mercury, ρ, is 13590 kg m^{-3}, g is 9.81 m s^{-2} if you use its more accurate value rather than the approximation of 10 ms^{-2} and the height of the mercury h is 0.760 m.

Therefore,

$$\text{pressure} = \rho g h$$
$$= 13590 \text{ kg m}^{-3} \times 9.81 \text{ ms}^{-2} \times 0.760 \text{ m} = 101300 \text{ Pa}$$

Standard atmospheric pressure, 760 mmHg or 1 atm is therefore a pressure of 101300 Pa.

It must be noted that the vertical height of the mercury is dependent only on the pressure outside the tube. Fig. 2.3 (a) It does not depend on the tilt of the column. (b) shows the barometer being tilted but the vertical height h of mercury column remains unaffected, and independent of the diameter(width) of the tube (c). The pressures are the same at each of the points marked **X** in figure because the pressure in a liquid doesn't depend on the container angle or width .Of course if the tube is lowered below 760 mm, the mercury would completely fill the tube as in (d).

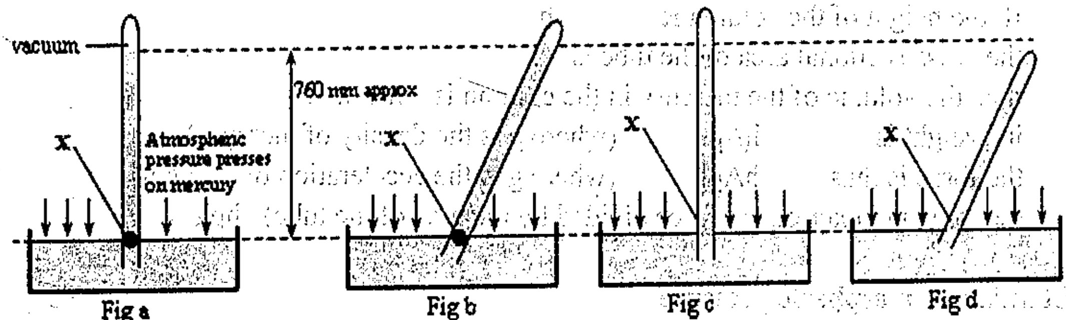
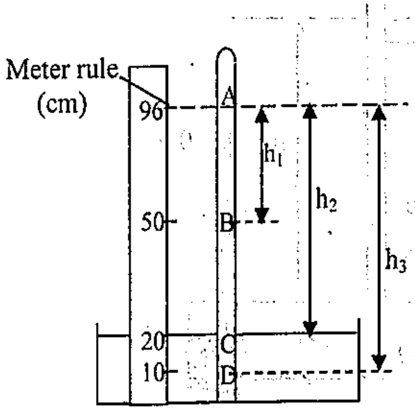


Fig. 2.3

Example(1) Find the pressure at the points A, B, C and D as shown in Figure.



To find the pressure at A, p_A notice that the space above is a vacuum.

hence, $p_A = 0$

From the ruler reading, we have

$h_1 = 46$ cm , $h_2 = 76$ cm, $h_3 = 86$ cm

Hence

Pressure at B, $p_B = 46$ cm Hg

Pressure at C, $p_C = 76$ cm Hg

Pressure at D, $p_D = 86$ cm Hg

The normal atmospheric pressure at sea level is expressed in various units as shown below.

$$1 \text{ atm} = 1.013 \times 10^5 \text{ P}_a$$
$$= 14.7 \text{ lb in}^{-2}$$
$$= 1.01 \text{ b}$$
$$= 760 \text{ torr}$$
$$= 760 \text{ mm Hg}$$

This pressure can support a column of mercury of height 760 mm or 0.76 m.

Example (2) Express 2 atm pressure in mm Hg and bars.

$$2 \text{ atm} = 2 \times (760 \text{ mm Hg})$$
$$= 1520 \text{ mm Hg}$$

and

$$2 \text{ atm} = 2 \times (1.01 \text{ b})$$
$$= 2.02 \text{ b}$$

Example (3) Find the force due to the atmosphere which is acting 3 m^2 area on the earth's surface.

The force acting is $F = pA$

$$= 100 \times 3 \qquad (\because p = 100\ kN\ m^{-2})$$

$$= 300\ kN$$

Example (4) Compare the atmospheric pressures and forces acting on a man and a child who are standing side by side.

Pressures are the same. Let it be p. Let the surface are of the man be A_1 and that of the child be A_2. Then

$$A_1 > A_2$$

$$p A_1 > p A_2$$

$$F_1 > F_2$$

The force acting on the man > the force acting on the child.

Using Atomospheric Pressure

Two simple applications of atmospheric pressure in our daily life.

Sucking

The action of sucking increases the volume of the lungs, thereby reducing the air pressure in the lungs and the mouth Fig. 2.4. The atmospheric pressure acting on the surface of the liquid will then be greater than the pressure in the mouth, thus forcing the liquid to rise up the straw into the mouth.

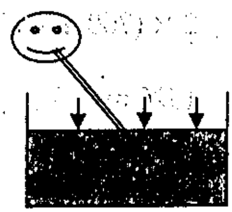


Fig. 2.4

Syringe

To draw liquid into the syringe, as shown in Fig. 2.5 , the piston of the syringe is drawn upwards. This decreases the pressure within the cylinder. Atmospheric pressure acting on the liquid drives the liquid into the cylinder through the nozzle.

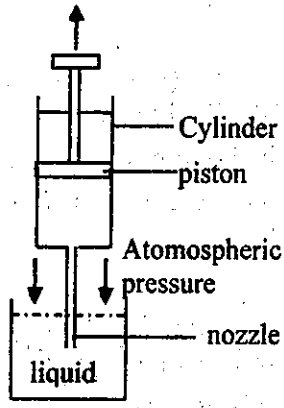


Fig. 2.5

2.2 PRESSURE IN A LIQUID

The existence of pressure in liquids has already been mentioned. The pressure depends on the depth under the surface of the liquid. The deeper the point inside the liquid the greater is the pressure at that point. Since the weight of liquid becomes greater as the depth increases, the pressure also increases with depth. Let us fill up a cylindrical tank of height h and having bottom surface area A with a liquid whose density is ρ.

Since the volume of the tank is

$$V = Ah$$

The mass of liquid which fills the tank is

$$m = \rho V = \rho Ah$$

Therefore, the weight of the liquid will be

$$w = mg = \rho g Ah$$

Thus, the pressure exerted by the liquid at the bottom surface is

$$p = \frac{F}{A}$$

$$\frac{W}{A} = \frac{\rho g A h}{A} = \rho g h$$

It is seen therefore that the pressure ($p' = \rho g h$) exerted by the liquid is directly proportional to the height h of the liquid column and the density ρ. The above result is true not only for a point at the bottom of the tank but also for any depth inside the liquid. For example, the liquid pressure at the depth h_1 ($h_1 < h$) inside the liquid is $\rho g h_1$.

The pressure p' in the above discussion is only the liquid pressure. Actually, there is atmospheric pressure at the surface of the liquid in the tank. Therefore, the true pressure at the depth h in the liquid will be

$$p = p_{atm} + \rho g h$$

where p_{atm} is the atmospheric pressure.

Pressure at any point inside a liquid is the same in all directions (Fig. 2.6).

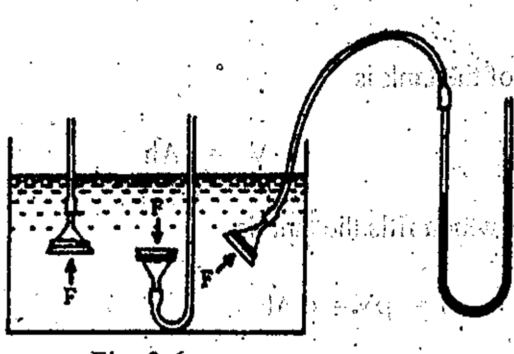


Fig. 2.6

Let a body be totally immersed in a liquid which is in a tank. There will be pressure not only at the top of the body but also upward pressure at the bottom of the body and lateral pressures at the sides of the body (Fig. 2.7).

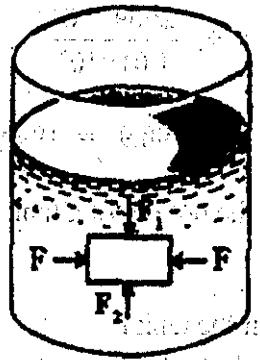


Fig. 2.7

If a body is spherical in shape, pressure will be exerted on the body from every direction (Fig. 2.8).

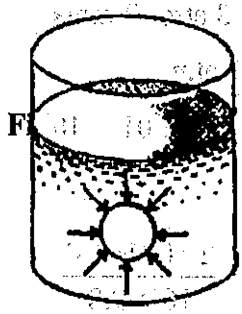


Fig. 2.8

Example (5) The density of sea water is 1025 kg m^{-3}. How many times is the pressure at the depth of 2 km under the sea surface greater than the atmospheric pressure?

$$\text{The liquid pressure} = \rho g h$$

$$= 1025 \times 9.8 \times 2 \times 10^3$$

$$= 2009 \times 10^4 \text{ Pa}$$

The pressure at the depth of 2 km is

$$p_{2\,km} = p_{atm} + \rho g h$$

$$\frac{p_{2km}}{p_{atm}} = 1 + \frac{\rho g h}{p_{atm}}$$

$$= 1 + \frac{2009 \times 10^4}{1.01 \times 10^5}$$

$$= 1 + 198.9 = 199.9$$

Example (6) The total pressure at the bottom of a tank is 3 atm. To what height has the water been filled in the tank?

The pressure at the water surface in the tank is

$$p_{atm} = 1 \text{ atm}$$

Therefore, the pressure due to water at the bottom of the tank is

$$p_{water} = 3 \text{ atm} - 1 \text{ atm}$$

$$\rho gh = 2 \text{ atm}$$

$$1000 \times 9.8 \times h = 2 \times 1.01 \times 10^5$$

and hence

$$h = \frac{2 \times 1.01 \times 10^5}{10^3 \times 9.8}$$

$$= 20.61 \text{ m}$$

Example(7) Find the pressure on a diver who is at a depth of 5 m below the surface of the water.

The pressure on the diver is

$$p_{5m} = p_{atm} + \rho g h$$

$$= 1.01 \times 10^5 + 1000 \times 9.8 \times 5$$

$$= 1.50 \times 10^5 \text{ Pa}$$

Example (8) The pressure at the height of 1 m from the floor is the normal atmospheric pressure 1.01 x 10^5 Pa. If the temperature is 0°C, what is the difference between the pressure on the floor and the pressure at 1 m height? (Density of air = 1.29 kg m^{-3}.)

The pressure on the floor is

$$p_{floor} = p_{1m} + \rho g h$$
$$= p_{atm} + \rho g h \qquad (\because p_{1m} = p_{atm})$$
$$= 1.01 \times 10^5 + 1.29 \times 9.8 \times 1$$
$$= (1.01 \times 10^5 + 12.6)\ \text{Pa}$$

Therefore, $p_{floor} - p_{1m} = 12.6\ \text{Pa}$

The pressure on the floor is greater than the pressure at the height of 1 m by 12.6 Pa. It is almost negligible. (It is only 1 in 10^4 or 0.01 per cent.)

Pressure in liquids

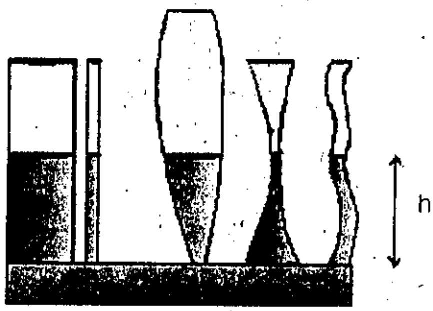


Fig. 2.9

We find that though the **weight** of the liquid column depends on its base area, the **pressure** exerted by the column is independent of area. (Fig. 2.9)

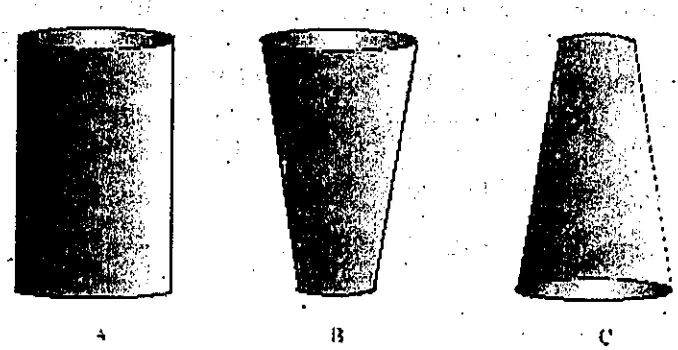


Fig. 2.10

Let A, B and C shown in the Fig. 2.10 above be liquids of the same density in containers all having the same height. The pressures exerted on their bases would be the same even though their weights differ.

2.3 MANOMETERS

A glass tube, open at both ends and bent into a U-shape, serves as a sensitive device for measuring pressure when filled with coloured water or light oil. Such a device, shown in Fig. 2.11 is called a manometer. Mercury can also be used as the filling liquid for a manometer.

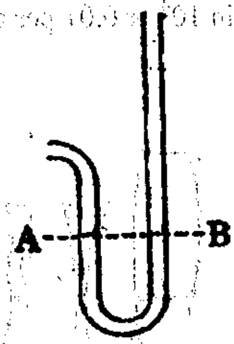


Fig. 2.11

When both sides of the U-tube are exposed to the atmosphere, the respective pressures exerted on the liquid columns in both sides are the same and the levels of the liquid in the two sides are, therefore, the same. If, however, the pressures, on the two liquid columns are different, the levels will no longer be the same.

Suppose we wish to measure the pressure of methane gas produced in a bio-gas digester. We leave one end of the tube as it is and connect the other end to the gas reservoir of the digester as shown in Fig. 2.12. The liquid column which is on the side connected to the gas reservoir will be found to dip below the level of the other liquid column. This means that the pressure inside the gas chamber of the bio-gas digester is higher than the atmospheric pressure. The liquid in each side below the line AB balanced out. Thus, the pressure acting at A is balanced at B by the atmosphere plus the pressure exerted by the column of liquid CB. The value of the pressure P at A can be given in either of the following two ways:

(a) It exceeds atmospheric pressure by the amount of pressure exerted by the column of liquid CB.

(b) It is equal to atmospheric pressure + pressure due to the liquid column BC.

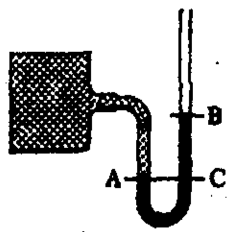


Fig. 2.12

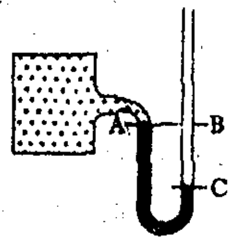


Fig. 2.13

Let us suppose that the liquid in the manometer is mercury and that CB = 40 mm. Then, the pressure p = 760 + 40 = 800 mm Hg. Or, we can say that the pressure at A exceeds that at B by 40 mm Hg. (Note: 1 mm Hg = 1.33×10^2 Pa)

Suppose the methane gas in the digester has been pumped out to such an extent that the pressure inside the reservoir dips below the atmospheric pressure. In such a situation the levels in the manometer will be as shown in Fig. 2.13. The pressure at A is less than that at C. The difference in the two pressures is equal to the pressure due to the column of liquid BC. Here, too, if BC = 40 mm Hg and if the liquid is mercury, then the pressure at A + 40 mm Hg = the pressure at C: or pressure at A = 760 - 40 = 720 mm Hg.

Manometers are very sensitive for measuring pressure differences, especially when the filling liquid is water or light oil. A manometer filled with a denser liquid such as mercury is not as sensitive.

Manometers have been used regularly until quite recently whenever pressures needed to be measured very accurately. However, over the last few years they have tended to give way to electrical pressure sensors.

2.4 ARCHIMEDES' PRINCIPLE

When bodies are immersed in a liquid there is loss in weight. This is because of a property of liquids called buoyancy.

Let us consider a block which is totally immersed in a liquid of density ρ as shown in Fig. 2.14.

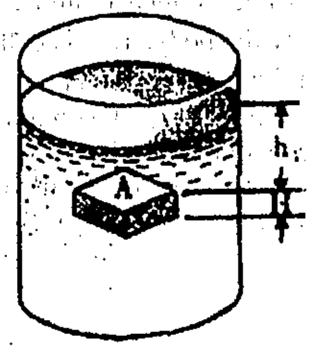


Fig. 2.14

Let the top of the block be at the depth of h_1 from the surface of the liquid, the thickness of the block be H, and its top and bottom surface area be A.

The pressure on the top surface of the block is

$$p_1 = p_{atm} + \rho g h_1$$

and the pressure on the bottom surface is

$$p_2 = p_{atm} + \rho g (h_1 + H)$$

Therefore, the downward force which is acting on the block is

$$F_1 = Ap_1$$

and the upward force is $F_2 = Ap_2$

The forces acting on the sides of the block cancel out. Then, the net force acting on the block in the upward direction is

$$F = F_2 - F_1$$

$$= A(p_2 - p_1)$$

$$= A \rho g H$$

This force is called upward thrust.

Since the volume of the block is

$$V = AH, \text{ we have}$$

$$F = V \rho g$$

Therefore, it is found that

upward thrust = the weight of liquid displaced

The upward thrust acting on a body which is immersed in a liquid is equal to the weight of the liquid displaced by the body. This is called Archimedes' principle. This principle was discovered by Archimedes more than two thousand years ago.
Only the upward thrust acting on a body can be obtained from Archimedes' principle. The resultant force, however, cannot be found from this principle. If the weight of the body is greater than the upward thrust the body will sink and if the weight is smaller the body will rise up to the surface.

The densities of various substances can also be obtained by using Archimedes' principle. A method of finding density is illustrated in example (9).

Although Archimedes' principle refers to liquids it will be more general and correct to replace the word "liquid" with "fluid". This is because Archimedes' principle is true not only for liquids but also for gases.

A body will float in a liquid (fluid) if the upward thrust, due to the liquid (fluid), acting on it is equal to its weight. If the volume of the portion of the body which is immersed in the liquid (fluid) is V_s, we have

the upward thrust $= \rho_0 g V_s$

where ρ_0 is the density of the liquid (fluid).

The weight of the body is

$$w = mg = \rho g V \qquad (\because m = \rho V)$$

where ρ is the density of the body.

Since the body is in equilibrium

$$w = \text{upward thrust}$$

$$\rho g V = \rho_0 g V_s$$

$$\frac{\rho}{\rho_0} = \frac{V_s}{V}$$

Therefore, the ratio of the densities is equal to the ratio of the volume of the immersed portion to the volume of the whole body. This is illustrated in example (10).

Hydrometer

When an object is placed in a liquid of a lower density, the object sinks. If it is placed in a liquid of a greater density, it floats.

For example, an **ice** cube of density 0.92 g cm^{-3} sinks in **turpentine** of density 0.87 g cm^{-3} but floats in **mercury** of density 13.6 g cm^{-3}, the denser the liquid, the higher an object will float in the liquid. The greater the specific gravity of a liquid, the less will be submerged portion of a body floating on it Fig. 2.15.(ice ρ=0.92 g cm^{-3})

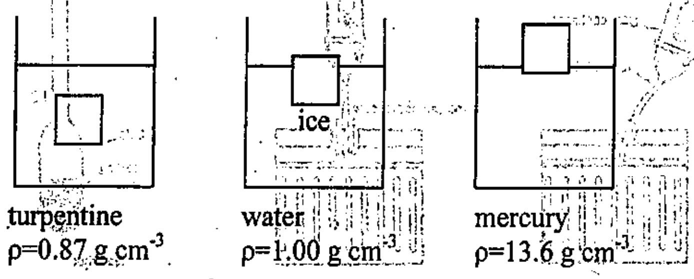


Fig. 2.15.

More exactly, the amount of a floating body that is submerged is inversely proportional to the specific gravity of the liquid the more the submerged, the less the specific gravity. The **hydrometer** is an instrument for measuring the density or relative density of liquids. It usually consists of a glass tube with a long bulb at one end. The bulb is weighted with lead shot so that the device floats vertically in the liquid, the relative density being read off its calibrated stem by the depth of immersion. If the hydrometer floats higher, it indicates that the liquid has a higher density. One form of this hydrometer is shown in Fig. 2.16

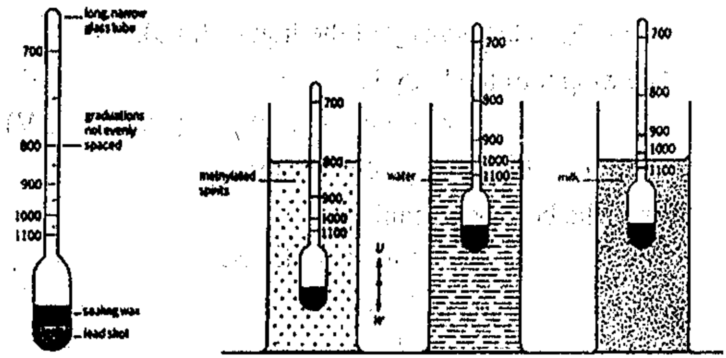


Fig. 2.16

The hydrometer sinks in the liquid until the weight of the liquid displaced is equal to the weight of the hydrometer. The hydrometer is calibrated to measure the density of the liquid of the liquid in kg m^{-3}.

Special hydrometers are used to test the specific gravity of solutions in storage batteries, in order to determine the condition of the battery (Fig. 2.17).The relative density of the acid in a fully charged car battery is 1.25. Milk and wine can be tested to make sure they have not been diluted with water.

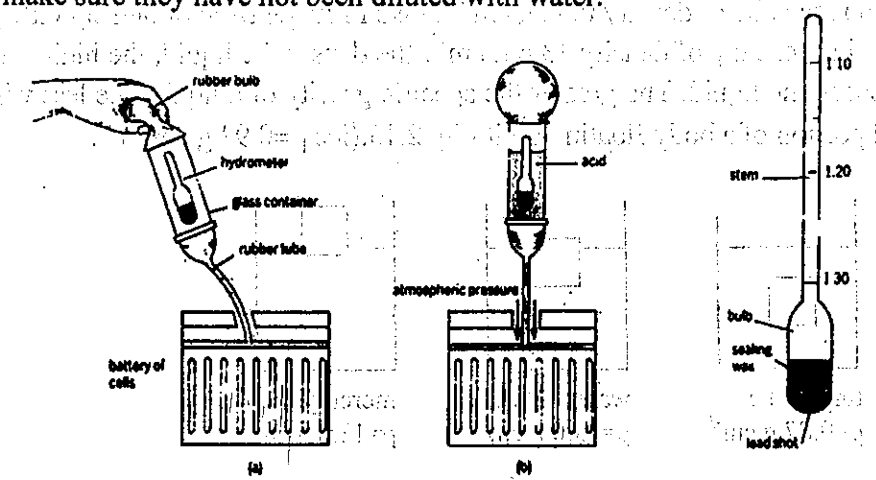


Fig. 2.17

Example (9) The weight of a metal block of unknown volume is 10 N. The apparent weight of the metal block is only 8 N when it is immersed in water. Find the density ρ of the metal.

Let the volume of the metal block be V.

The weight of the body before it is immersed in water is

$$w_i = \rho g V$$

and the apparent weight when it is immersed in water is

$$w_f = (\rho - \rho_0) g V$$

where ρ_0 is the density of water.

Therefore,
$$\frac{w_f}{w_i} = \frac{\rho - \rho_o}{\rho}$$

and ρ can be calculated

$$\rho = \frac{\rho_0 w_i}{w_i - w_f}$$

$$= \frac{1000 \times 10}{10 - 8}$$

$$= 5\,000 \text{ kg m}^{-3}$$

Example (10) Icebergs are made of fresh-water ice, which has a density of 0.92×10^3 kg/m^3 at 0°C. Ocean water, largely because of the dissolved salt, has a density of about 1.025×10^3 kg/m^3. What fraction of an iceberg lies below the surface?

Let the volume of the block of ice be V and the volume immersed in sea water be V_s.

The portion which is immersed is

$$\frac{V_s}{V} = \frac{\rho}{\rho_0}$$

$$= \frac{920}{1025}$$

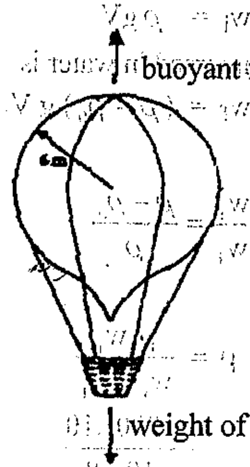
$$= 0.898$$

Nearly 90% of the ice block will be immersed in water.

Example (11) A helium balloon is designed to support a load of 1000 kg. If the balloon is filled with helium what should its volume be? (The mass of helium is not included in the net load of 1000 kg.)

$$\rho_{air} = 1.29\ kgm^{-3}$$

$$\rho_{He} = 0.18\ kg\ m^{-3}$$



The total weight to be supported is weight of 1000 kg + weight of helium.

$$w = mg$$

$$w = (1000 + V\ \rho_{He})g$$

where V = volume of helium, and ρ_{He} = density of helium.

Thus, the buoyant force acting on the balloon is

$$F = V\rho_{air}\ g$$

It is in equilibrium while supporting the load.

Therefore,
$$F = w$$

$$V\rho_{air}\ g = (1000 + V\ \rho_{He})\ g$$

$$V = \frac{1000}{\rho_{air} - \rho_{He}}$$

$$V = \frac{1000}{(1.29-0.18)} = 900\ m^3$$

In this case the balloon, whose volume is 900 m^3, has a radius of about 6 m.

2.5 PASCAL'S LAW

When a fluid completely fills a vessel, and a pressure is applied to it at any part of the surface, that pressure is transmitted equally throughout the whole of the enclosed fluid.

This is known as Pascal's law named after the French scientist Pascal who discovered it in 1650.

Pascal's law is very useful in practical applications. The constructions of hydraulic brakes and hydraulic presses are based on this law. Hydraulic brakes are used in cars and other road vehicles.

A hydraulic press is a very useful machine. It is used for baling jute; and for shaping steel and metal sheets. It has numerous other uses, from the compression of soft metals into cups of varying shapes to the pressing of automobile bodies.

The following is an explanation of how a small effort applied on a hydraulic press is turned into a large force.

A schematic diagram of hydraulic press is shown in Fig. 2.18.

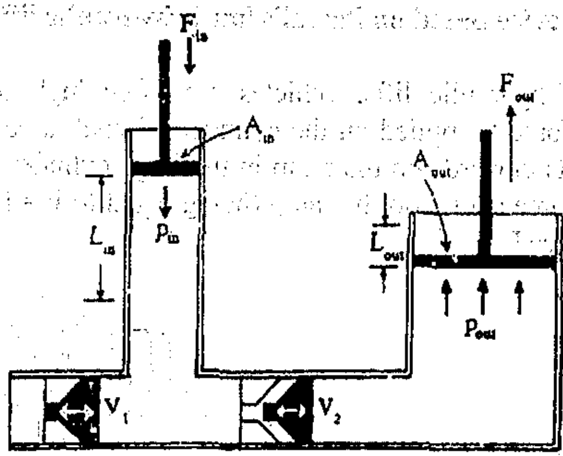


Fig. 2.18

While the intake piston is moving downward valve V_1 is closed and valve V_2 is open. While the intake piston is moving upward valve V_1 is open and valve V_2 is closed.

The pressure obtained by applying effort F_{in} on area A_{in} of the piston is

$$p = \frac{F_{in}}{A_{in}}$$

This pressure is exerted equally in the liquid in all directions. Therefore, the upward pressure acting on the piston whose area is A_{out} will be p. The upward pressure is acting normally on area A_{out}.

Therefore, the upward thrust acting on area A_{out} is

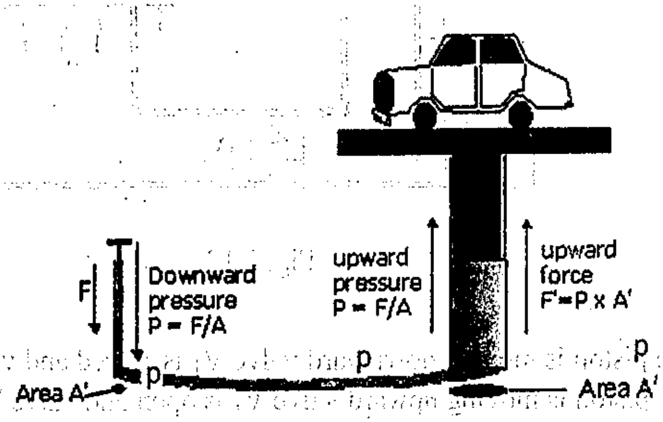
$$F_{out} = p_{out} \times A_{out}$$

$$= \frac{F_{in}}{A_{in}} \times A_{out}$$

The upward thrust is the product of the effort and the area ratio: $\frac{A_{out}}{A_{in}}$. A large upward thrust can be produced by applying only a small effort if A_{out} is large and A_{in} is small.

Very useful device based on Pascal's law is hydraulic lift shown in Fig 2.19.

By means of hydraulic lifts, vehicles are lifted high on ramps for repairs and servicing. A force F applied on the cylinder of small area A, creates a pressure p = F/A which acts upwards on the ramp in the large cylinder of cross sectional area A'. The upward force acting on the ramp (being equal to F'= FA'/A) is much larger than the applied force F.



Hydraulic lift
Fig. 2.19

Example (12) The areas of the pistons of a hydraulic press are 2 in^2, and 10 in^2. How much effort should be applied on the small piston to produce an upward thrust of 500 lb on the larger piston?

$A_{in} = 2in^2$, $A_{out} = 10\ in^2$ and $F_{out} = 500$ lb, and we get

$$F_{in} = \frac{A_{in}}{A_{out}} \times F_{out}$$

$$= \frac{2}{10} \times 500$$

$$= 100 \text{ lb}$$

Example(13) The radii of the small piston and the large piston of a hydraulic press are 1 in and 10 in respectively. Find the upward thrust on the large piston when 20 lb effort is applied to the small piston.

$$A_{in} = \pi r^2$$

$$= \pi \times (1)^2$$

$$= \pi \text{ in}^2$$

$$A_{out} = \pi r^2$$

$$A_{out} = \pi \times (10)^2$$

$$= 100\ \pi \text{ in}^2$$

$$F_{in} = 20 \text{ lb}$$

$$F_{out} = \frac{A_{out}}{A_{in}} \times F_{in}$$

$$= \frac{100\ \pi}{\pi} \times 20$$

$$= 2000 \text{ lb}$$

SUMMARY

Atmospheric pressure The pressure exerted on a body by the atmosphere, due to the weight of the atmosphere. At the surface of the earth atmospheric pressure is 100 k Nm^{-2} (100 kPa)

Archimedes' principle The upward thrust acting on a body which is immersed in a liquid is equal to the weight of the liquid displaced by the body. (The upward thrust = the weight of liquid displaced)

Hydrometer The **hydrometer** is an instrument for measuring the density or relative density of liquids. It usually consists of a glass tube with a long bulb at one end. The bulb is weighted with lead shot so that the device floats vertically in the liquid, the relative density being read off its calibrated stem by the depth of immersion.

Manometer A glass tube, open at both ends and bent into a U-shape, serves as a sensitive device for measuring pressure when filled with coloured water or light oil. Such a device, is called a manometer.

Pascal A unit of pressure equivalent to a force of 1 newton acting on 1 m^2.
Pascal's law When a fluid completely fills a vessel, and a pressure is applied to it at any part of the surface, that pressure is transmitted equally throughout the whole of the enclosed fluid. This is known as Pascal's law.

Pressure The force per unit area acting on a surface in such a way that it is tending to change the dimensions of the surface.

EXERCISES

1. Write down Pascal's law. Mention one of the uses of this law.
2. "Although Pascal's law is not a fundamental law, it is a very useful law for practical purposes." Is this statement correct? Discuss.
3. Write down Archimedes' principle.
4. Calculate the height of a column of water which could be supported by the atmosphere at sea level.(the density of water is 1000 kg m^{-3}) **(Ans: 10m)**
5. What will be the new height of the column, if water is used instead of mercury? (mercury is 13.6 times heavier than water) . **(Ans: 10.27m)**

6. What will be the effect, if any, on the mercury column if the glass tube used has

   (a) a smaller internal diameter (b) a slightly bigger internal diameter ?

   (Ans: There will be no effect for both cases. The mercury column will remain at 76cm.)

7. Will the mercury column be higher or lower than 76 cm when the whole up of the barometer is taken to a high mountain top? Explain your observation?

   (Ans: Less, because the pressure of the surrounding air is less than that at sea level. This is because, at greater heights, air is thin.)

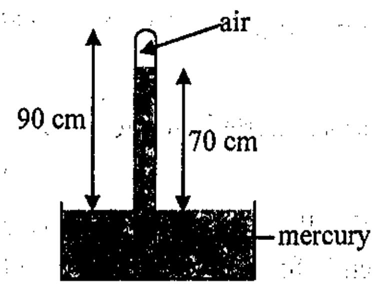
8. Why is mercury used in a barometer rather than water?

9. What is the effect on the vertical height of the mercury column in a barometer of (a)using a wider glass tube (b) pushing the tube further into the bowl (c) tilting the glass tube at an angle (d) taking the barometer to the top of the mountain?

10. At sea level, what is the approximately value of atmosphere pressure (a) in Pa (b) in mm Hg (c) in atm ?

    (Ans: (a) 10^5 Pa (b) 760 mm Hg (c) 1 atm)

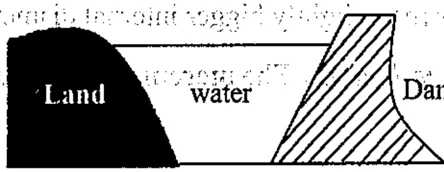
11. The mercury barometer in Fig contains some trapped air in the tube. If an barometers reads 75 cm Hg, what is the pressure exerted by the trapped air? **(Ans: 5cm Hg)**



12. At sea level the atmospheric pressure is 76 cm Hg. If pressure falls by 10mm Hg per 120m ascent, what is the height of a mountain where the barometer reads 70.5 cm Hg? **(Ans: 660 m)**

13. What is the height of a column of turpentine that would exert the same pressure as 5.0cm of the mercury? (density of turpentine = 840 kg m^{-3}density of mercury =13600 kg m^{-3}) **(Ans: 81 cm)**

14. Explain why the thickness of the dam increases downwards.



(Ans:The thickness of the wall of the dam increases downwards because the deeper it is, the greater the water pressure. A thicker wall is required to withstand a greater pressure.)

15. A beaker containing water and placed on a pan is balanced by the weight which is in the other pan of the balance. Explain what will happen if a man immerses his finger in the water without touching the beaker.

16. An ocean-liner was loaded at the port of Yangon. Would the ocean-liner sink deeper or not when it reached the ocean?

(The density of sea-water is greater than that of fresh - water.)

17. Steel will float in liquid (mercury) but sink in water. So how does a steel ship manage to float in water?

(Ans: There is far more air in a ship than steel, (because a ship is hollow and contains air),so the average density of the ship is less than that of water.)

18. At what depth will the pressure exerted on a man be twice that of the pressure at the surface of water?

19. The total mass of gas which fills a meteorological balloon is 50 kg. The balloon string is tied to a post which is fixed to the earth. Find the tension in the string if the volume of the balloon is 110 m^3 and the density of air is 1.3kg m^{-3}.

20. The weight of a body in its normal (standard) condition is 300 N and the weight is 200 N when it is immersed in water. Find the density and volume of the body.

21. The density of 1 cm^3 cubical ice block is 0.9 g cm^{-3}. What portion of the floating ice block will be above the water surface?

22. The density of the lead block is 11.5 g cm^{-3} and it is floating in mercury of density 13.6 g cm^{-3}.

(a) What portion of the lead block is immersed in mercury?

(b) What force is needed to press the block to immerse it totally if the mass of the lead block is 2 kg?

23. A hydraulic (water power) press consists of 1 cm and 5 cm diameter pistons.

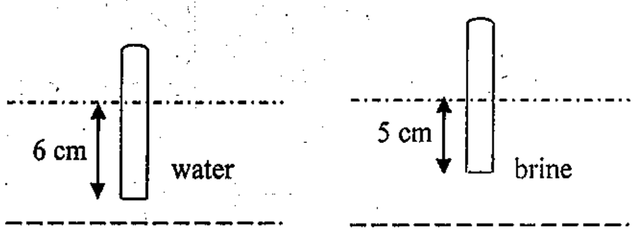
(a) What force must be applied on the small piston so that the large piston will be able to raise 10 N load?

(b) To what height would the load be raised when the small piston has moved 0.1 m?

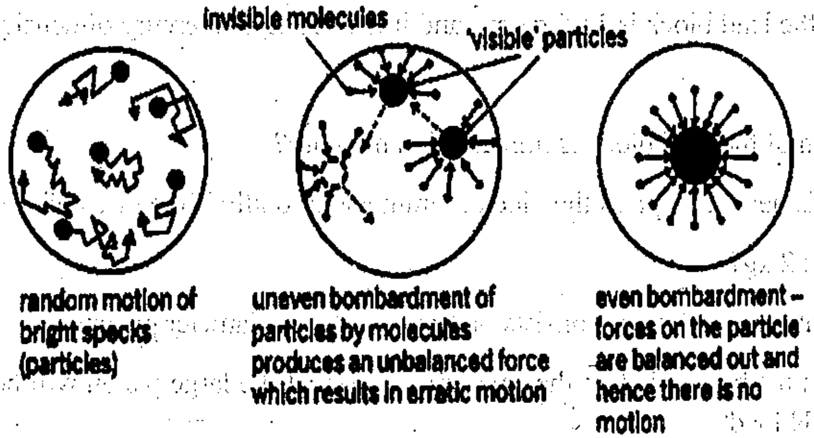
24. A 30 kg balloon is filled with 100 m^3 hydrogen. What force is needed to hold the balloon to prevent it from rising up?

(Density of hydrogen is 0.09 kg m^{-3} and that of helium is 0.18 kg m^{-3}.)

25. The weighted rod in figure floats with 6cm of its length under water (density 1000 kg m^{-3}). What length is under the surface when the rod floats in brine? (density 1200 kg m^{-3}). **(Ans: 5 cm)**

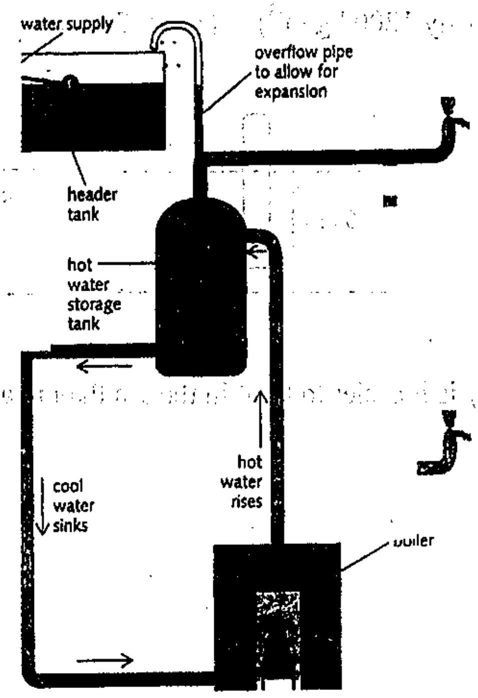


26. Why is it easier to float in the sea than in a swimming pool?



The Brownian motion

HEAT



Household hot-water system
(The use of heat convention)

CHAPTER 3

TRANSFER OF HEAT

There are three different modes by which heat may be transferred from one place to another. They are: conduction, convection and radiation. When one end of an iron rod is placed in a fire, the other end becomes warm as a result of the conduction of heat through the iron. When a kettle containing water is placed on a stove, both the kettle and water get heated slowly. The whole mass of water gets heated through convection, which is the actual movement of parts of heated water which are closest to the stove. Radiation is a mode of heat transfer whereby energy is transported by means of electromagnetic waves. No material medium is required for the passage of such waves.

3.1 HEAT CONDUCTION

Heat conduction is one mode of energy transfer. The individual parts of a medium do not move as a whole in heat conduction. For example if a tea spoon is put into a very hot cup of tea, the spoon handle becomes hot. But the spoon, which acts as a medium for heat transfer, does not move at all. At first the end of the spoon placed in the hot tea gains heat energy. Then the handle end of the spoon becomes hot by successive distribution of heat energy among the adjacent parts. Heat conduction in solids, liquids and gases takes place due to temperature difference. Heat is transmitted from the region of higher to lower temperature in heat transfer process. The two isolated objects separated by the medium will gradually reach the same temperature.

When two objects at temperatures T_1 and T_2 are connected by a rectangular rod, their temperature difference $T_2 - T_1$ will diminish steadily (Fig.3.1). The connecting rod is assumed to have a cross-sectional area A and length ℓ. The rate at which heat flows from higher to lower temperature is found to be proportional to the cross- sectional area A.

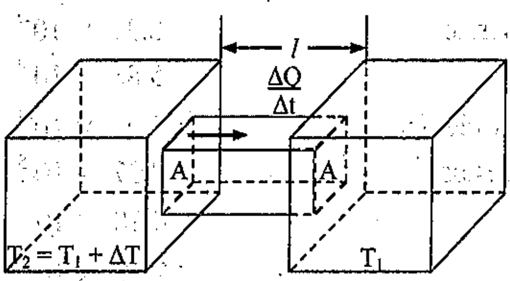


Fig. 3.1

The rate of heat flow also depends on temperature difference $T_2 - T_1$ and length ℓ. Although the temperature difference $T_2 - T_1$ and length ℓ are both doubled at the same time, the rate of heat flow remains unchanged.
Keeping the length constant and doubling the temperature difference $T_2 - T_1$, doubles the rate of heat flow. Again the rate of heat flow also doubles if the temperature difference is unchanged and the length is halved. Thus, the rate of flow must depend on the ratio $(T_2 - T_1)/\ell$, and this ratio is called temperature gradient.
Combining the facts discussed above, the rate of heat flow H, which is also called heat current, can be expressed as

$$H = \kappa A \frac{T_2 - T_1}{\ell} \qquad (3.1)$$

where κ is a proportionality constant called the thermal conductivity. Equation (3.1) becomes exact only when T_2-T_1 is very small. However, the process of heat conduction becomes more complicated if κ varies with temperature or when the geometry of the body along which heat flows is not so simple. In this chapter κ is assumed to be constant.

The values of κ for some substances are given in Table 3.1. Since the unit of H is watt (W) we can express the unit of κ in $W\ m^{-1}\ K^{-1}$ or $J\ s^{-1}\ m^{-1}\ K^{-1}$.

Table 3.1

Substance	Thermal Conductivity, κ ($k\ J\ s^{-1}\ m^{-1}\ K^{-1}$)
Silver	0.42
Copper	0.40
Aluminum	0.24
Steel	0.08
Ice	1.67×10^{-3}
Glass, concrete	8.37×10^{-4}
Water	5.86×10^{-4}
Animal muscle, fat	2.09×10^{-4}
Wood, asbestos	8.37×10^{-5}
Felt	4.18×10^{-5}
Air	2.39×10^{-5}
Down	1.93×10^{-5}

Table (3.1) shows that the values of κ can differ by quite a large amount depending on the type of material. For example, the thermal conductivities of metals, which are good conductors, are greater than those of thermal insulators such as wood and asbestos by factors of 10^3 to 10^4. Good conductors are used where heat has to be readily transmitted. Thus, saucepans, kettles and other cooking utensils which have to be heated directly are made of metals such as aluminum, copper and steel.

Poor conductors or insulators are also useful. They help keep unwanted heat away. Saucepans, kettles and electric irons usually have plastic or wooden handles. Cloth, plastic and wood are all poor conductors and good insulators.

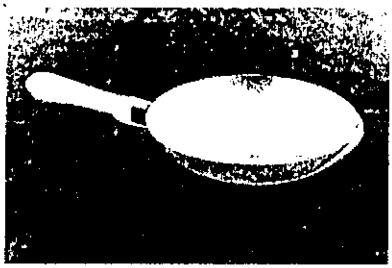


Fig. 3.2 A saucepan makes use of good conductors and insulators.

One of the most important insulators is air. For a person, who is wearing warm clothes, it is air that keeps him warm by reducing heat losses. When wearing a woollen sweater, the wool traps air in the woollen fibres and this air acts as an insulator. Thus, the person wearing a woollen sweater feels warm.

Body tissue is also a good insulator. When the environment gets warm, the body temperature remains quite uniform (Fig. 3.3 (a)). The interior of the body can be kept warm even in a cold environment because body tissues are poor conductors (Fig. 3.3 (b)).

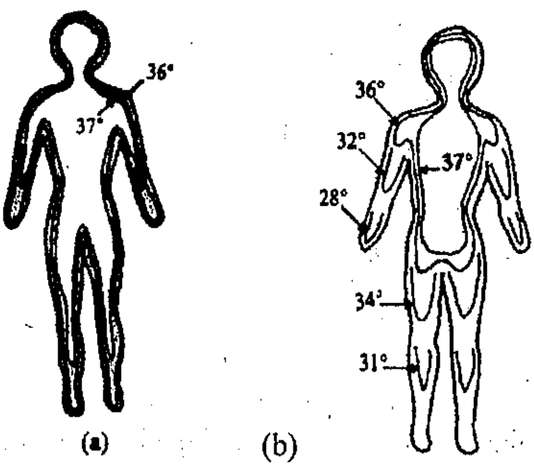


Fig. 3.3

Example (1) A person walking at a regular speed generates heat at the rate of 0.07 W. If the surface area of the body is 1.5 m^2 and heat is to be generated 0.03m below the skin, what should be the temperature difference between the skin and interior of the body if the heat is to be conducted to the surface of the skin? (Assume $\kappa = 5 \times 10^{-5}$ $Wm^{-1} K^{-1}$).

For a small section of the tissue the equation $H = \kappa A \frac{T_2 - T_1}{\ell}$ can be correctly applied.

Therefore,

$$T_2 - T_1 = \frac{\ell H}{\kappa A}$$

$$= \frac{0.03m \times 0.07W}{5 \times 10^{-5} Wm^{-1}K^{-1} \times 1.5m^2}$$

$$= 28\text{ K or } 28^{\circ}\text{C}$$

Actually, the temperature difference in a body is only a few degrees. Heat cannot be removed from the body by conduction through tissues from the interior to the exterior of the body. In fact, the flow of warm blood is the major factor in body heat transport.

3.2 HEAT CONVECTION

Although some heat is transferred by conduction in liquids and gases, a much larger quantity of heat may be carried by the motion of the fluid itself. This is called convection. In Fig. 3.4, when the liquid in the container is heated from the bottom, the lowest part of the liquid nearest to the heat source acquires heat first and expands slightly.

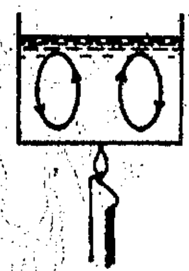


Fig. 3.4

This portion of the liquid becomes lighter than the upper portion. It then rises and is replaced by cooler and heavier liquid. When the warmer liquid arrives at the cooler region of the container, it becomes cool and heavier and begins to sink again. Had the container been heated from the top, convection would not have occurred and the bulk of the liquid would have been heated by the much slower conduction process.

In cold regions where rooms are heated by fire, heating is done by convection process. The fluid carrying the heat is the air in the room (Fig. 3.5).

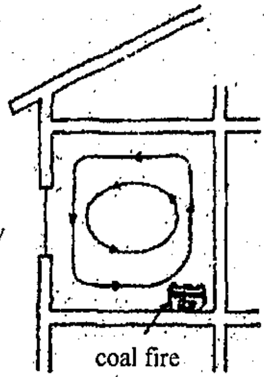


Fig. 3.5

There are many difficulties involved in developing an exact equation for heat convection. The approximate equation can be derived only on the basis of experimental results. In still air the rate of heat convection for a surface area A is given approximately by the equation

$$H = q A (T_2 - T_1) \quad (3.2)$$

Here $T_2 - T_1$ is the temperature difference between the surface and the air at some distance from the surface, q is the heat convection constant and depends to some extent on $T_2 - T_1$.

The following example illustrates that heat loss by convection is important for living beings.

Example (2) In a warm room, an animal's body has a skin temperature of 33 °C. If the room temperature is 29° C and the surface area of the body is 1.5 m², what is the rate of heat loss due to convection? (Assume $q = 1.7 \times 10^{-3}$ $Wm^{-2} K^{-1}$.)

Using $q = 1.7 \times 10^{-3}\ Wm^{-2} K^{-1}$

We have
$$H = q A \Delta T$$
$$= 1.7 \times 10^{-3} \times 1.5 \times (33 - 29)$$
$$= 0.01\ W$$

The animal at rest in this situation will generate heat at about twice this rate. Thus, 50 percent of the animal's heat loss is due to heat convection process. If there is a breeze or if the room temperature is lower than normal, heat losses by convection will increase accordingly.

Some of the weather conditions are created by heat convection. The reason why the weather is fair at the base of mountain ranges, at the sea coast, lakes and ponds is that the hot air in those regions rises and is replaced by cooler air. This process occurs due to heat convection.

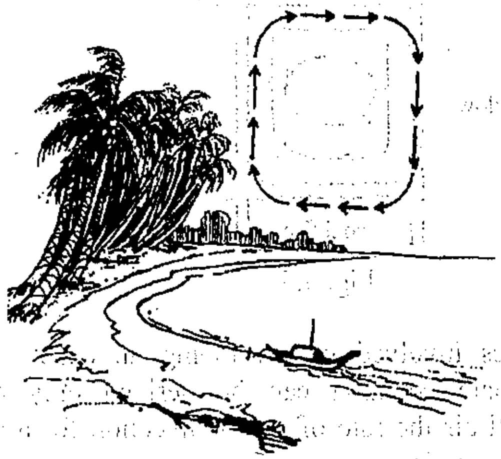


Fig. 3.6

3.3 HEAT TRANSFER BY RADIATION

The sun warms the earth and is the major source of heat for the earth. Heat transfer from the sun to the earth is neither by conduction nor convection. This is because in the space between the sun and the earth there are hardly any molecules and this space is a vacuum. If so how can heat be transmitted from the sun to the earth?

Every object including the sun emits energy in the form of electromagnetic radiation. Thermal radiation or infrared radiation, which is a form of electromagnetic radiation, has the range of wavelength from about 1 μm to about 100 μm ($1\ \mu m = 10^{-6}$ m.)

Electromagnetic waves can travel through vacuum.

Energy can be exchanged as radiant heat between the two objects A and B. If heat conduction and convection are not possible between two objects A and B, energy can be exchanged as radiant heat. Suppose A emits more radiation than B, then A must absorb more radiation than B to have the same temperature. If an object has a good rate of emission of radiation then it also has a good rate of absorption.

The best absorber *is defined as the object which can absorb all the electromagnetic radiations falling upon it.* This object is called a *black body*. The black body is not only a perfect absorber but is also the best in emitting radiation. The black body is taken as a reference body in studying the emissivity of bodies.

The total emissive power *is defined as the total radiant energy of different wavelengths emitted from unit area of a surface of a body in one second.* The total emissive power of a black body ε_0 is directly proportional to the fourth power of absolute temperature.

$$\varepsilon_0 = \sigma T^4 \qquad (3.3)$$

This equation is called ***Stephan-Boltzmann's law*** and σ is called Stephan's constant. The value of this constant is

$$\sigma = 5.685 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$$

The total emissive power ε of objects other than a black body is

$$\varepsilon = e\varepsilon_0 \qquad (3.4)$$

where e is the emissivity and its value is less than 1.
An object emits radiation, no matter whether there is temperature difference between the object and its environment or not. If there is no temperature difference the amount of heat absorbed by the object is equal to that emitted by it. If the temperature T of the object is higher than that of its environment T_o, then the magnitude of the net radiation per unit area of surface per second is

$$e\sigma T^4 - e\sigma T_0^4 = e\sigma(T^4 - T_0^4) \qquad (3.5)$$

Example (3) The animal in example (2) has a skin temperature of 33 °C = 306 K and is in a room where the walls are at temperature 29° C = 302 K. If the emissivity is 1 and the body surface area is 1.5 m^2, find the rate of heat loss due to radiation. (σ = 5.685 x 10^{-8} W m^{-2} K^{-4})

It is necessary to consider two processes simultaneously. One is the emission of radiation by the animal and the other is the emission of radiation by the walls.

The rate of heat radiated from the animal at the temperature T_2 = 33°C = 306 K is

$$H_{out} = e\sigma AT_2^4$$
$$= 1 \times 5.685 \times 10^{-8} \times 1.5 \times 306^4$$
$$= 747.665 \text{ W}$$

The animal absorbs the heat radiated from the walls. The rate of heat absorbed by the animal is

$$H_{in} = e\sigma AT_1^4$$
$$= 1 \times 5.685 \times 10^{-8} \times 1.5 \times 302^4$$
$$= 709.331 \text{ W}$$

Thus the net rate of heat loss for the animal is

$$H_{out} - H_{in} = 747.665 - 709.331$$
$$= 38.334 \text{ W}$$

If the animal does not get back some heat from the surrounding it will freeze at temperature of 33° C.

SUMMARY

Conduction is the transfer of heat through a material medium, without the medium moving. (That is, the individual parts of the medium do not move as a whole.)

Convection is the transfer of heat due to the movement of a fluid (i.e. a liquid or a gas) itself.

Radiation is the transfer of heat that does not require a material medium. Energy is transferred by electromagnetic waves(infrared radiation) that passes through a medium or even vacuum.

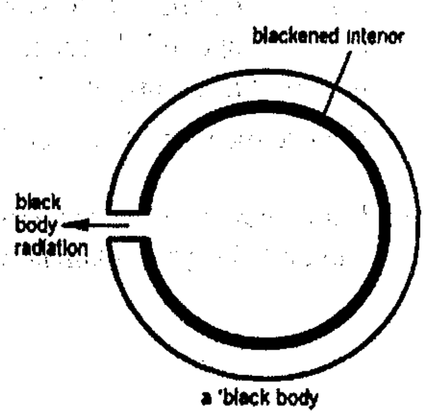
The object which can absorb all the electromagnetic radiations falling upon it is called a **black body**. The black body is not only a perfect absorber but is also a best emitter of radiation.

If an object has a good rate of emission of radiation then it also has a good rate of absorption.

The total emissive power is defined as the total radiant energy of different wavelengths emitted from unit area of a surface of a body in one second.

The total emissive power of a black body (ε_0) is directly proportional to the fourth power of absolute temperature. ($\varepsilon_0 = \sigma T^4$) **(Stephan-Boltzmann's law)**

Black body a sphere with very small hole in it and with a blackened interior surface; all radiation that falls on it will be absorbed, If the cavity is heated then radiation will be emitted from the black body which will be black body radiation.



EXERCISES

1. Define heat conduction, convection and radiation.

2. What is thermal conductivity? Express its unit in the SI system.

3. Is the following statement correct?
   "The reason why we feel warm when wearing wool and down clothes is that wool and down are very good insulators."

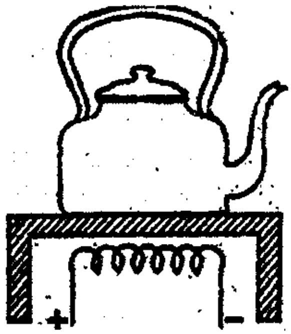
4. One end of a poker is placed in fire. After some time the other end becomes hot. Explain how heat is transferred along the poker. Name the method of heat transfer in this case.

5. A silver spoon and a wooden spoon are at room temperature. The silver spoon feels cold when it is touched. The reason is because
   (a) silver is denser,
   (b) silver is a good conductor,
   (c) silver can be polished and made to shine,
   (d) silver spoon is heavier,
   (e) wood is not bright.

   Choose the correct answer from *(a)*, *(b)*, *(c)*, *(d)* and *(e)*.

6. If a person wearing ordinary clothes travels out into space, the liquid in the body will boil. Why? Explain how a space suit can prevent this effect.

7. A kettle on an electric stove is shown in the figure. Mark a point A where the heat is conducted to water. Mark a point B where the heat convection is occurring. Mark a point C where heat is radiating. Mark a point D where an insulator ought to be used.



8. In cold regions it is seen that birds on the branches of trees often ruffle their feathers. Explain the reason why the birds feel warm by ruffling their feathers.

9. How does a blanket wrapped round your body keep you warm on a cold day?

10. Which of the heat transfer processes are involved in a vacuum flask?

11. Example with a diagram why a person sitting in the middle of the upper room feels warm when a furnace is placed at the ground floor in winter.

12. Explain with a diagram why an air conditioner should be best positioned high, near the ceiling of a room.

13. What processes of heat transfer are involved in the working of a car radiator?

14. How is heat transmitted from the sun to the earth?

15. The area and thickness of a glass plate of a window are 0.25 m^2 and 4 mm respectively. The temperature of inside surface of glass plate is 25°C and its outside surface temperature is 26°C. Find the amount of heat that passes through the glass plate in one hour. The thermal conductivity of glass is 0.6276 $W\ m^{-1}\ K^{-1}$.

16. How much heat per second is conducted through a wooden wall of area 25 m^2 and thickness 0.04 m if the temperature inside is 20 °C and the temperature outside is -10 °C?

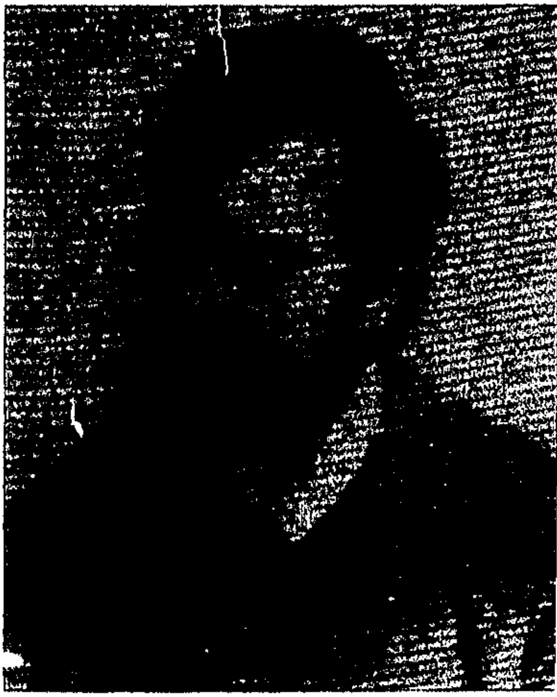
17. The filament of an 100 W electric bulb is made of tungsten. The emissivity of tungsten is 0.3 and its length is 0.2 m. Find the diameter of the filament if its temperature is 3000 K when the bulb is switched on.

18. The temperature of the filament is 2500 K when the bulb is switched on. The diameter of the filament is 0.1 mm and it is made of metal of emissivity 0.35. If the emissive power is 40 W find the length of the filament.

19. From calculations based on the radiation measurement of solar energy falling on the earth it is found that the sun is radiating energy at a rate of 62.5 MWm^{-2}. Assuming that the sun is emitting energy as a black body, find the temperature of the surface of the sun.

20. If the rate of energy radiation from a black body of area 100 cm^2 is 42 W, find the temperature of that black body.

21. Compare the rates of energy radiation of a black body at temperatures 327° C and at 27° C.



L Boltzmann (1844-1906) PhD (Vienna 1866 at the age of 22) Professor 1873(University of Vienna)
Discovered Boltzmann equation known as Maxwell-Boltzmann statistics in 1872 or Maxwell-Boltzmann velocity distribution law. A very deep thinking and anxious man he became famous for explaining the paradox between the irreversibility of the macroscopic world and the symmetry laws of physics (statistics) at the atomic level. He was much concerned with student welfare and he was always generous with awarding good marks to deserving students. In his last years of his life none of his students failed!
The constant "k" is called Boltzmann constant which often appears as
E= kT.

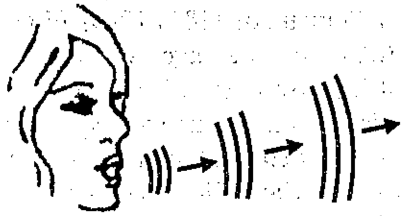
Professor Ludwig Boltzmann

Max Karl Ernst Ludwig Planck

1858–1947

Awarded (in 1919) the 1918 Nobel Prize for physics for his contributions to the development of physics by his discovery of the element of action [quantum theory].

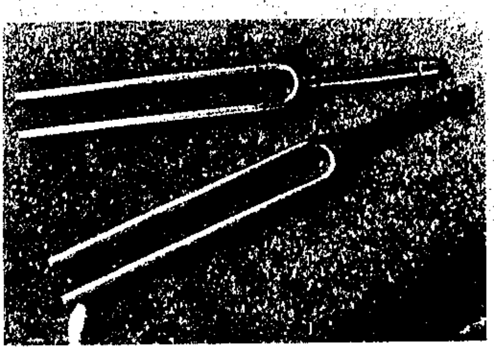
Max Planck(1858-1947)
PhD(Munich 1919)
1889-92 University of Berlin;
Prof/Emeritus Prof 1892-1947
University of Berlin
He used Boltzmann's equation to propose that the energy of a set of oscillators (particles executing a periodic to and fro motion) occured only in multiples of an energy packet E=hv the famous relation between a quantum of energy and frequency where h is now known as Planck's constant. Einstein used the concept of quanta (plural of quantum) to explain the photoelectric effect and this concept was applied in the Rutherford-Bohr model of the atom.



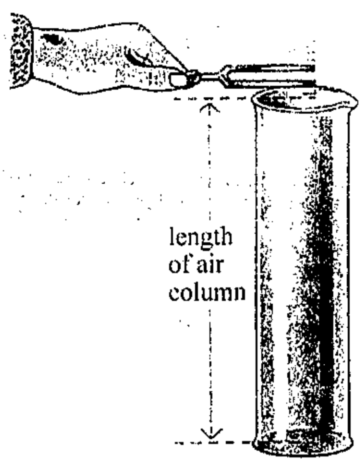
Progressive waves

Stationary waves

WAVES AND SOUND



Tuning fork



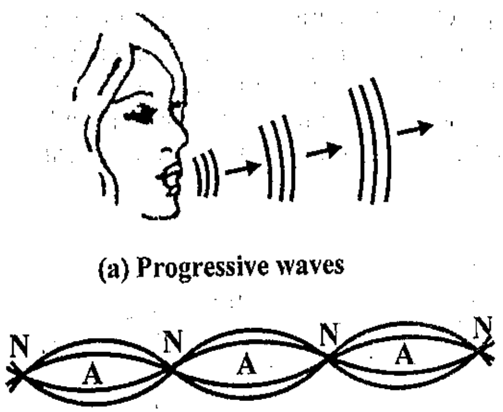
CHAPTER 4

VIBRATION OF STRINGS, RESONANCE AND VIBRATION OF AIR COLUMNS

Sound waves which travel in air when we speak and water waves which travel on the water surface when a stone is dropped are called progressive waves. The waves produced in hollow tubes such as flutes and in stringed musical instruments such as violins and mandolins are called stationary waves. Unlike progressive waves they do not spread out but remain in the region in which they are produced.

4.1 STATIONARY WAVES

Progressive waves and stationary waves are shown in Fig.4.1



(a) Progressive waves

(b) Stationary waves

Fig. 4.1

The difference between a stationary wave and a progressive wave is that in the former, certain points remain a stationary all the time. The points marked N in the stationary wave of Fig.4.1(b) are always stationary. These points are called nodes.

The points between nodes are vibrating with different amplitudes. The mid-points between successive nodes have the largest amplitudes and are called antinodes. The points A in Fig. 4.1 (b) are antinodes.

The distance between two successive nodes or antinodes is equal to $\lambda/2$ where λ is the wavelength.
The distance from a node to the nearest antinodes, NA, is equal to $\lambda/4$.

Fig. 4.2 Demonstration of production of stationary waves

The formation of a stationary wave can be demonstrated as follows. Fasten one end of a string to the hammer of an electric bell and hold the other end in the hand. When the electric bell is activated while the string is held tight, stationary waves are produced due to the vibration of the hammer of the bell. The incident wave travels from the hammer to the hand and the reflected wave travels from the hand to the hammer. The resultant wave obtained from the superposition of the incident and the reflected wave is a stationary wave. It can be said, therefore, that a stationary wave is obtained when two waves having equal amplitudes and velocities travelling in opposite directions are superposed on each other.

4.2 VIBRATING STRINGS

In most of the musical instruments (for example, violin, cello, etc.) the stretched strings act as a source of sound (source of wave). The stationary waves produced when the stretched strings are plucked can only have certain specific frequencies. To understand why only certain frequencies can occur consider a string of length ℓ rigidly fixed at both ends. When the string is plucked the stationary waves with nodes at the fixed ends are formed. Four types of waves with nodes at the fixed ends are shown in Fig. 4.3. The waves that are formed on the string are called harmonics. The longest wave vibrating in one single segment shown at the top of Fig. 4.3. is called the fundamental or the first harmonic. The first four harmonics of the vibrating string are shown in Fig. 4.3.

The wavelength in Fig. 4.3 can be labelled with a subscript n, where n is a positive integer.

For the nth harmonic $\lambda_n = \frac{2\ell}{n}$,

$n = 1, 2, 3, \ldots\ldots$

The corresponding frequencies are calculated from $f_n \lambda_n = v$, where v is the wave velocity.

Thus for a string of length ℓ, $f_n = \frac{nv}{2\ell}$,

$n = 1, 2, 3, \ldots\ldots$

Since $v = \sqrt{\frac{T}{\mu}}$ for a string

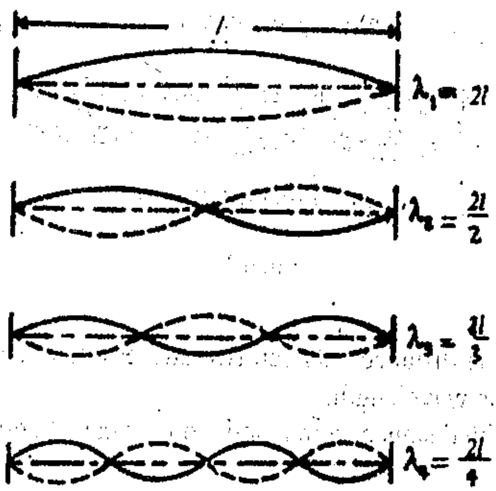


Fig .4.3

(T = tension, μ = mass per unit length of the string),

we have $$f_n = \frac{n}{2\ell}\sqrt{\frac{T}{\mu}} \qquad n = 1, 2, 3, \ldots\ldots$$

Then $$f_1 = \frac{1}{2\ell}\sqrt{\frac{T}{\mu}}$$ (first harmonic)

$$f_2 = \frac{1}{\ell}\sqrt{\frac{T}{\mu}}$$ (second harmonic)

$$f_5 = \frac{5}{2\ell}\sqrt{\frac{T}{\mu}}$$ (fifth harmonic)

Example (1) Find the frequencies of the first three harmonics of the longest string in a grand piano. The length of the string is 1.98 m and the velocity of the wave in the string is $v = 130 \text{ m s}^{-1}$.

For the first harmonic, n = 1

$$f_1 = \frac{v}{2\ell} = \frac{130 \text{ ms}^{-1}}{2 \times 1.98 \text{ m}} = 32.8 \text{ Hz}$$

For the second harmonic, n = 2

$$f_2 = \frac{2v}{2\ell} = \frac{130 \text{ ms}^{-1}}{1.98 \text{ m}} = 65.6 \text{ Hz}$$

For the third harmonic, n = 3

$$f_3 = \frac{3v}{2\ell} = \frac{3 \times 130 \text{ ms}^{-1}}{2 \times 1.98 \text{ m}} = 98.4 \text{ Hz}$$

Example (2) The wave velocity in the highest frequency violin string is 435 m s^{-1}, and its length ℓ is 0.33 m. If a violin player lightly touches the string at a point which is at a distance $\ell/3$ from one end, a node is formed at that point. What is the lowest frequency that can now be produced by the string?

According to Fig. 4.3, the harmonic produced in the string is third harmonic. Hence

$$\lambda_3 = \frac{2\ell}{3}$$

and, therefore, $$f_3 = \frac{v}{\lambda_3}$$

$$= \frac{v}{\frac{2\ell}{3}} = \frac{3v}{2\ell}$$

$$= \frac{3\times435}{2\times0.33} = 1977\text{ Hz}$$

Example (3) The highest and lowest frequency strings of a piano are tuned to fundamentals of $f_H = 4186$ Hz and $f_L = 32.8$ Hz. Their lengths are 0.051 m and 1.98 m respectively. If the tension in these two strings is the same, compare the masses per unit length of the two strings.

For $n = 1$, solving μ from equation

$$f_n = \frac{n}{2\ell}\sqrt{\frac{T}{\mu}}$$

$$\mu = \frac{T}{(2\ell f_1)^2}$$

is obtained. Thus the ratio of μ_L for the low frequency string to μ_H for the high frequency string is $\frac{\mu_L}{\mu_H} = \frac{T/(2\ell_L f_L)^2}{T/(2\ell_H f_H)^2} = \frac{(\ell_H f_H)^2}{(\ell_L f_L)^2}$

$$= \frac{(0.051\times4186)^2}{(1.98\times32.8)^2} = 10.8$$

4.3 RESONANCE COLUMN AND ORGAN PIPES

Forced vibrations and Resonance

Suppose a mass spring system having some natural frequency of vibration f_0 is pushed back and forth with a periodic force whose frequency is f. The system will vibrate at the frequency f of the driving force. This type of motion is referred to as forced motion. The amplitude of the motion reaches a maximum when the frequency of driving force equals the natural frequency of the system, f_0 called the *resonant frequency* of the system. Under this condition, the system is said to be in *resonance*.

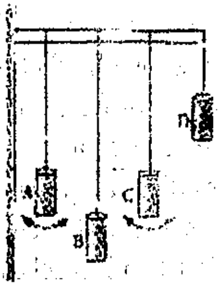
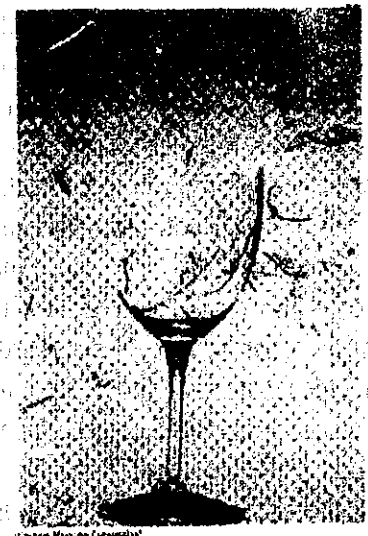


Fig. 4.4 Resonance: If pendulum A is set up into oscillation, only pendulum C, whose length is the same as that of A, will eventually oscillate with large amplitude, or resonate.



Several pendulums of different lengths are suspended from a flexible beam. If one of them such as A, is set into motion, the others will begin to oscillate because they are coupled by vibrations in flexible beam. Pendulum C, whose length is the same as that of A, will oscillate with the greatest amplitude since its natural frequency matches that of pendulum A (the driving force).

Fig. 4.5 A wine glass shattered by the amplified sound of human voice.

If a vibrating tuning fork is placed over the open end of a glass tube partly filled with water, the sound of the tuning fork can be greatly amplified under certain conditions. The water level will rise in the glass tube if the reservoir is raised while the fork is placed as shown in Fig. 4.6.

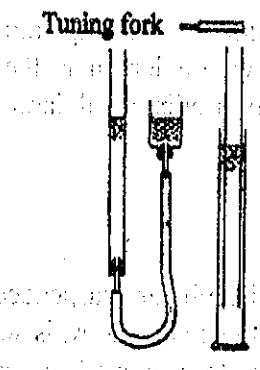


Fig. 4.6

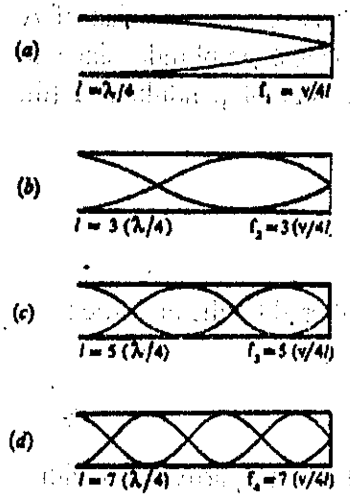


Fig.4.7

At a certain height of the water, the loud sound at resonance will be heard from the tube. In fact the resonant sound will be heard at several different heights. The situation here is similar to the case of a vibrating string. The wave is sent down the air column in the tube and it is reflected upwards when it hits the water surface. Once again it is reflec.ed downwards when it reaches the source (the tuning fork). If the air column is just the proper length, the reflected wave will be reinforced by the vibrating source as it travels down the tube a second time. In this way the wave is reinforced for a number of times and resonance is obtained from these multiple reinforcements. The tube shown in Fig. 4.6 will have an anti-node near the open end and a node at the closed end. This is because the air molecules cannot move at the closed end since the water at that end will not allow them to move downward. At the open end the air molecules can easily move out into the open air. Thus there can be maximum displacement and an antinode will be formed at the open end. Resonance can only be produced under the situation where a node is formed at one end and an antinode is formed at the other. Some of the waves conforming to such a condition are shown in Fig. 4.7.

Note that the distance between two successive nodes or two successive antinodes is $\lambda/2$. Thus the distance from a node to the nearest antinodes is $\lambda/4$. If we take the length of the pipe as ℓ, $\ell = \lambda/4$ for Fig. 4.7 (a) and $\ell = 3(\lambda/4)$ for Fig. 4.7 (b) and so on.

We can now easily find the corresponding resonant frequency. Here, $f_1 = v/4\ell$ for the first harmonic, $f_2 = 3f_1$ for the third harmonic, $f_3 = 5f_1$ for the fifth harmonic and so on. Third harmonic and fifth harmonic are also called first overtone and second overtone respectively.

The same thing happens in organ pipes as in the tubes described above. In closed organ pipes, an anti-node exists near the open end (blowing end), while a node is formed at the closed end. It is possible to obtain two tones at the same time by making the air resonate at two frequencies simultaneously. The resonant frequencies for a closed organ pipe are shown in Fig. 4.8.

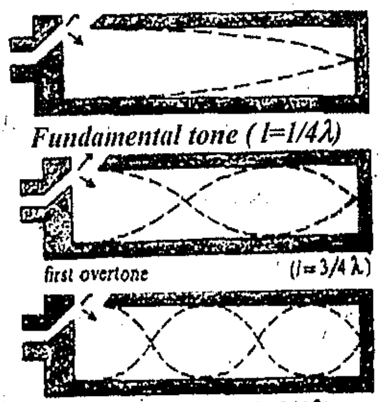


Fig. 4.8

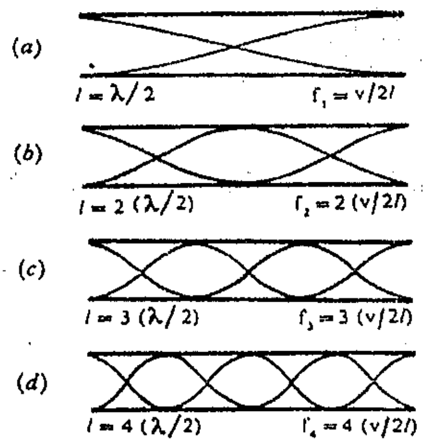


Fig. 4.9 The resonance phenomena in open organ pipes are illustrated.

Beat

When two sound waves of equal intensity (amplitude) but slightly different frequencies interfere, the resultant wave is a pulsed disturbance with a beat frequency. The number of beats per second or beat frequency, equals the difference in frequency between the two sources.

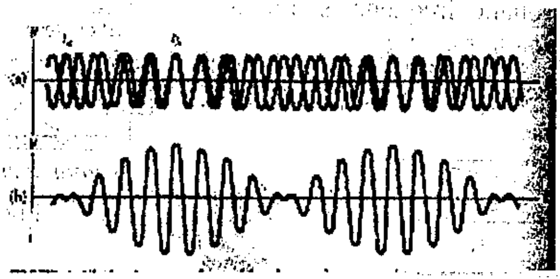


Fig. 4.10

Example (4) If two tuning forks with frequencies of 512 Hz and 516 Hz vibrate simultaneously, find the beat frequency.

$$f_b = f_2 - f_1$$
$$= 516 - 512 = 4\text{ Hz}$$

That is there would be four pulsating sounds will be heard.

Noise Exposure limits

Sound with very high intensities can be dangerous. Above the threshold of pain (about 120 dB), sound is painfully loud to ear. Brief exposure to levels of 140 to 150 dB can rupture eardrums and cause permanent hearing loss. Consequently, ear protectors or ear valves must be worn in some occupations and noise intensity levels must be monitored.

Longer exposure to lower sound (noise) levels can also damage hearing. For example, there may be a hearing loss for a certain frequency range.

Table 4.1 Permissible Noise Exposure Limits

Sr.No.	Maximum Duration per Day (Hours)	Sound level (dB)		Sr.No.	Maximum Duration per Day (Hours)	Sound level (dB)
1	8	90		6	11/2	102
2	6	92		7	1	105
3	4	95		8	½	110
4	3	97		9	1/4/or less	115
5	2	100				

4.4 ENERGY AND MOMENTUM IN WAVES

Although it is not always apparent, waves of every kind in fact carry energy and momentum. The waves acquire energy and momentum from their sources. This may be illustrated by some examples. The energy provided by the light from the sun makes life possible on our planet. Ocean waves can transform the shape of coast lines. They can also exert large forces on a person standing in shallow water near the seashore. Intense sound waves can crack window glasses.

Waves which can be represented by a sine function have energy and momentum stored in them which are directly proportional to the square of the amplitude.

If the intensity and amplitude of the wave are represented by I and A respectively,

$$I \propto A^2$$

Here the intensity I is the power transported across a unit cross-sectional area.

SUMMARY

Amplitude The maximum displacement of an oscillation from its mean position.

Diffraction The spreading of waves as they pass by the edge of an obstacle or through a narrow slit.

Frequency The rate at which some regular disturbance takes place. For a wave this represents the number of complete oscillations per second.

Hertz A unit of frequency of vibrations. 1 hertz is equivalent to one oscillation per second.

Longitudinal wave An energy-carrying wave in which the movement of the particles is in line with the direction in which the energy is being transferred.

Oscillation One complete to-and-fro motion of a vibrating object.

Transverse wave A wave in which the oscillations are at right angles to the direction in which the wave transfers energy.

Wave equation The relation ***speed = frequency × wavelength*** which applies to all forms of wave motion.

Wavelength The distance between two successive points on a wave that are at the same stage of oscillation, i.e. in terms of their direction and displacement from their mean position.

Progressive waves Sound waves which travel in air when we speak and water waves which travel on the water surface when a stone is dropped are called progressiv waves.

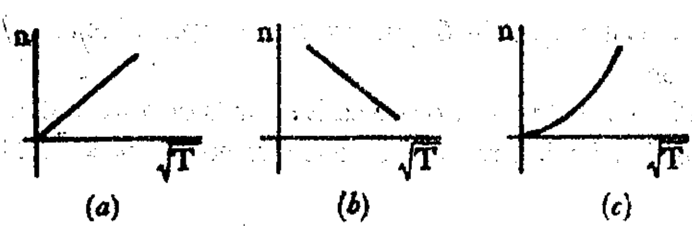
Stationary waves The waves produced in hollow tubes such as flutes and in stringed musical instruments such as violins and mandolins are called stationary waves.

Nodes The points marked N in the stationary wave are always stationary. These points are called nodes.

Antinodes The mid-points between successive nodes have the largest amplitudes and are called antinodes.

EXERCISES

1. What is a stationary wave?
   Describe how stationary waves can be produced.
2. There are always points that do not move in stationary waves.
   (a) What are those points called? (b) How is the distance between two such successive points related to the wavelength?
3. The distance between two successive nodes of stationary waves produced in a stretched string is 0.4 m. Find the wavelength of that stationary wave. If the frequency is 105 Hz, what is the velocity of the wave in the string?
4. If the distance between two consecutive nodes of a stationary wave in a stretched string is 0.5 m, (a) find the distance between two successive antinodes, (b) find the distance between a node and the nearest antinode.
5. How does the velocity of a stationary wave formed in a string, with both ends firmly fixed, depend on the tension and mass per unit length of the string?
6. Which of the following graphs correctly describes the relation n - $\sqrt{T}$ for the stretched string? (n = frequency of the string, T = tension in the string.)



7. If the mass of a string of 1 m length is 0.3 g and its tension is 48 N, find the fundamental (the lowest) frequency of the string.

8. What is the tension required for a violin string to vibrate at fundamental frequency of 440 Hz? The length of the violin siring is 0.33 m, its diameter is 0.05cm and the density of the material of which the string is made is 3.5×10^3 kg m^{-3}.

9. Find the fundamental frequency of a tube of length 4.5 m and diameter 2.5cm.

10. Find the harmonics which will be formed in a closed organ pipe of length 0.4m. Velocity of sound in air is 340 ms^{-1}.

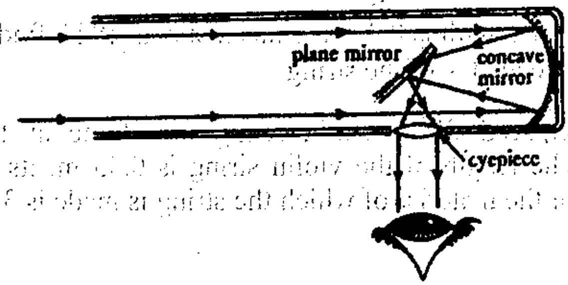
11. A tuning fork is struck and placed over the open end of a resonance tube with adjustable air column. If resonances occur when the air column is 17.9 cm and 56.7 cm long, find the velocity of sound from these values. Frequency of tuning fork is 440 Hz.

12. A vibrating tuning fork is placed over the top end of a glass tube, almost full of water, as shown in the figure. Explain what will happen if the water surface in the glass tube is lowered when the water tap is opened.

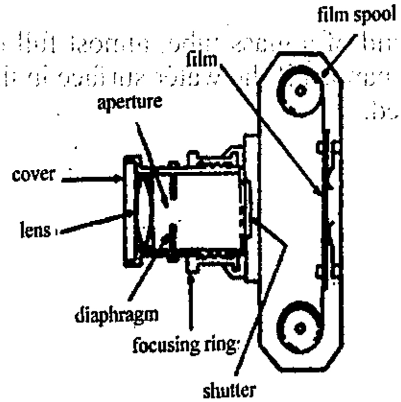
13. At room temperature (20°C), a closed organ pipe has a fundamental frequency of 256 Hz. What is the length of the pipe?

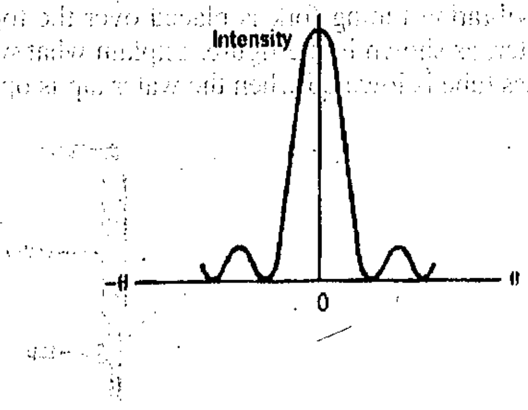
14. What is the beat frequency of two tones with the frequencies 256 Hz and 260 Hz?

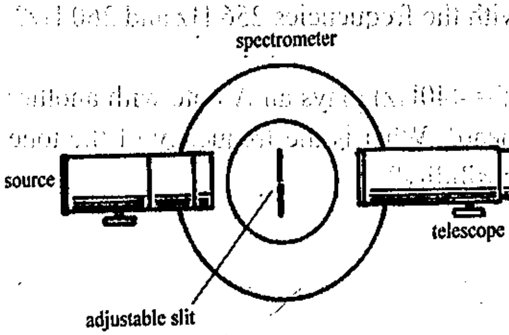
15. A violist with a perfectly tuned a string (f = 440Hz) plays an A note with another violist, and a beat frequency of 2 Hz is heard. What is the frequency of the tone from the other violin? Is there only one possibility?

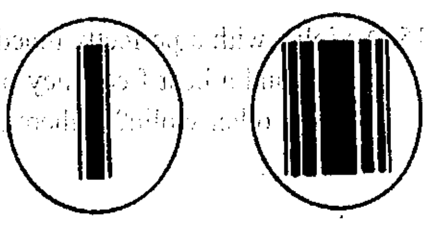

plane mirror
concave mirror
eyepiece

OPTICS


film spool
film
aperture
cover
lens
diaphragm
focusing ring
shutter


Intensity
0


spectrometer
source
telescope
adjustable slit



CHAPTER 5

INTRODUCTION TO LIGHT

Light is a form of energy which stimulates our sense of vision. It is essential for life on earth. Almost all of the natural light comes to us from the sun. In this chapter we shall study the nature of light, sources of light and methods for determining the speed of light.

5.1 THE NATURE OF LIGHT

By the middle of the seventeenth century, two theories about the nature of light were introduced.

Newton suggested that light was made up of a stream of tiny particles known as corpuscles. These corpuscles are given off or emitted by light sources such as the sun and the candle flame. They travel outward from light sources in straight lines. Thus, a thin pencil or ray of light is in fact a stream of corpuscles. They can pass through transparent materials and are bounced back or reflected from surfaces of opaque materials through which they cannot pass. When they enter the eye, the sense of sight is stimulated. By using this corpuscular theory, Newton could explain the phenomena of reflection and refraction of light.

Huygens, contemporary of Newton, suggested that like water waves and sound waves, light also has wave nature. However, the majority of scientists did not accept the wave theory of light immediately. Water waves and sound waves can bend around obstacles in their path. Therefore, light, if it is to be considered as a wave motion, must also be able to bend around obstacles and it should be possible to see objects hidden by an obstacle. However, since such objects cannot be observed, the majority did not accept the wave theory of light. Light in fact can bend round an obstacle. But the wavelengths of light are so short compared to those of water waves and sound waves that the bending of light cannot be ordinarily observed.

The phenomena of interference, diffraction and polarization could be well explained only, if light was considered as a wave motion. In addition, it was discovered by the end of the nineteenth century that light consists of electromagnetic waves. However, it could not be said that Newton's corpuscular theory of light was completely wrong, because it was found at the beginning of the twentieth century that in addition to the wave nature, light has corpuscular or particle nature as well.

Hence, light can exhibit both wave and particle character. Light behaves like particles in some phenomena and acts as waves in others. Today, it is generally accepted that light has wave-particle duality. Therefore, the corpuscular theory and wave theory of light are not contradictory but are complementary to each other.

5.2 VELOCITY OF LIGHT

The velocity of light is usually denoted by the symbol c and it appears in many fundamental formulae in advanced physics. For example, Einstein has shown that the energy E released from an atom is given by $E = mc^2$. Here m is the decrease in mass of the atom or the mass defect. Thus, c is an important physical constant. Some methods of measuring the velocity of light are described below.

Galileo's Method

By the middle of seventeenth century Galileo had tried to measure the velocity of light by measuring the distance between the two hilltops and the time taken by light to travel between them. One night, Galileo stationed himself on one hilltop with one lamp and his assistant on another hilltop with a similar lamp. The lamps were covered at first. Then, Galileo uncovered the first lamp and his assistant uncovered the lamp he was holding as soon as be saw the light from Galileo's lamp. Galileo noted the time as soon as he saw the light from his assistant's lamp. In this way, Galileo tried to measure the time interval taken by light. He was unable to measure it as light travelled with very high speed. Galileo's method of measuring the velocity of light was entirely correct in principle. But his experiment failed since the method of measuring the extremely short time interval was not accurate enough.

Roemer's Method

Roemer was the first to successfully measure the velocity of light. Four of twelve small satellites or moons moving around Jupiter could be observed with a moderately good telescope. Roemer chose one moon and measured the time of revolution of that moon about Jupiter. It was found that the period of time was longer than 42 hours while the earth was receding from Jupiter and shorter than 42 hours while it was approaching Jupiter. Roemer concluded correctly that the differences in times were due to varying distances between Jupiter and the earth (Fig. 5.1). According to his calculations the time of 22 minutes was required for light to travel the distance equal to the diameter of the earth orbit. The best value for the diameter of the earth orbit at that time (in Roemer's time), was about 172 000 000 miles. If that value was used, the velocity of light was found to be 130 000 miles per second or 2.1×10^8 metres per second.

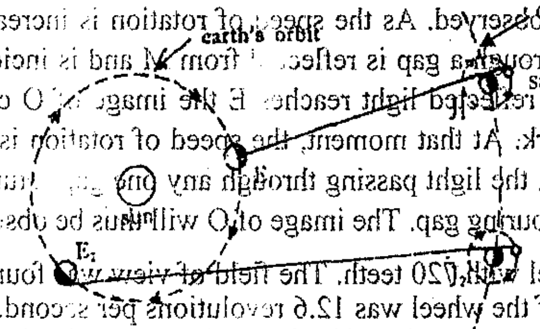


Fig. 5.1 Roemer's method for measuring the velocity of light

Fizeau's Method

Fizeau was the first to successfully determine the velocity of light from purely terrestrial measurements. A schematic diagram of his apparatus is shown in Fig. 5.2.

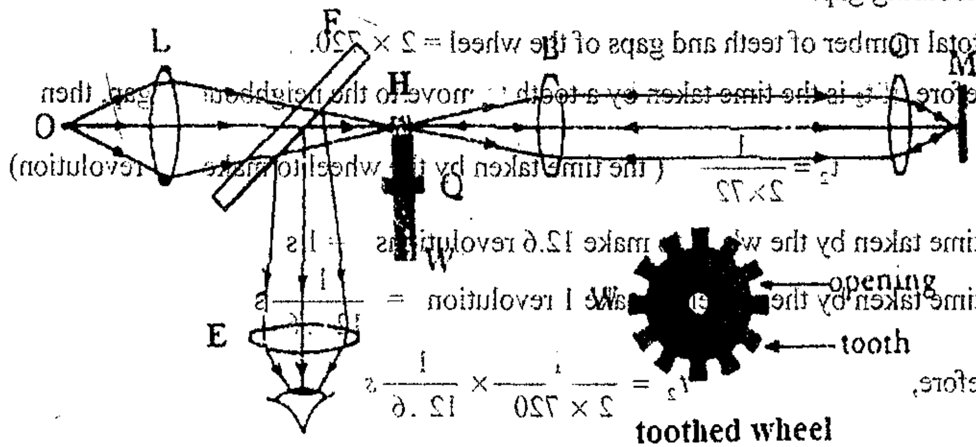


Fig. 5.2 Fizeau's method for determining the velocity of light

The light from a bright source O after refraction through the lens L converges to a point H and is then incident on a lens B. H is the focus of lens B and the parallel rays coming out of B reach a lens C which is several miles away from B. Since a plane mirror M is at the focus of C the reflected rays from M retrace their paths and is then reflected from the glass plate F. The rays then pass through a lens E into the eye of an observer. The image of O is thus observed.

A toothed wheel W can rotate about a horizontal axis Q. The rim of W is placed at H.

A tooth and a gap or an opening between two teeth have the same width. The image of O is observed when the reflected light passes through a gap of the wheel in rotation. Before the speed of rotation exceeds 10 revolutions per second the image of

O is continuously observed. As the speed of rotation is increased, at one instant the light that passes through a gap is reflected from M and is incident on a tooth next to that gap. Since no reflected light reaches E the image of O cannot be seen and the field of view is dark. At that moment, the speed of rotation is noted. If the speed of rotation is doubled, the light passing through any one gap returns from M and passes through the neighbouring gap. The image of O will thus be observed.

Fizeau used a wheel with 720 teeth. The field of view was found to be dark when the speed of rotation of the wheel was 12.6 revolutions per second. The distance between H and M was 8633 metres. Thus, if t_1 is the time taken for the light to travel from H to M and back, then

$$t_1 = \frac{2 \times 8633}{c} s$$

But this is the time taken by a tooth to move to a position corresponding to a neighbouring gap.

The total number of teeth and gaps of the wheel = 2 × 720.

Therefore, if t_2 is the time taken by a tooth to move to the neighbouring gap, then

$$t_2 = \frac{1}{2 \times 720} \times \text{(the time taken by the wheel to make one revolution)}$$

The time taken by the wheel to make 12.6 revolutions = 1 s

The time taken by the wheel to make 1 revolution $= \frac{1}{12.6} s$

Therefore, $$t_2 = \frac{1}{2 \times 720} \times \frac{1}{12.6} s$$

Since $t_1 = t_2$

$$\frac{2 \times 8633}{c} = \frac{1}{2 \times 720 \times 12.6}$$

$$c = 3.1 \times 10^8 \, ms^{-1}$$

The most precise measurement of velocity of light was made by Michelson. His method will not be presented here. We shall just quote the value of the velocity of light obtained by him. It is

$$c = 186\,000 \, mi \, s^{-1}$$

$$= 3 \times 10^8 \, ms^{-1}$$

The velocity of light has also been measured by other methods. Of the values of the velocity of light reported to date, the one regarded as the best value is

$$c = 2.997\,93 \times 10^{8}\ ms^{-1}$$

This value is estimated to have an error of $\pm 300\ ms^{-1}$. Today, the velocity of light can be measured with the use of electronic devices in the laboratory.

In Fizeau's method the lenses were kept several miles apart but electronic devices need to be placed only a few metres apart.

The velocity of light in free space c is one of the fundamental constants of nature. The value of this constant is taken as $3 \times 10^{8}\ ms^{-1}$.

5.3 REFRACTION OF LIGHT

Now that we have studied the reflection at mirrors, we shall go on to study how light passes through transparent materials or transparent media. A thick slab of glass appears to have only two-thirds of its real thickness when viewed from a vertical position; water in a pond appears to have only three-quarters of its true depth. These, and many similar effects are caused by refraction, or change in direction of light when it passes from one medium to another.

Refraction at Plane Surfaces

Transparent media such as air, water, oil and glass have different optical densities. However, light travels in straight lines in each of these media. In practice, a medium cannot exist alone but is always in contact with other media. Suppose that there is some water in a glass cup. Water is in contact with glass and both water and glass are in contact with air. When light passes through two media of different optical densities, the direction of light changes in passing from the first to the second medium. This phenomenon is called refraction of light. The change in direction of light occurs because the velocity of light changes when it passes from one medium to another. In refraction, both magnitude and direction of velocity of light change.

The velocity of light in a medium depends upon the optical density of that medium. The more optically dense a medium is, the smaller is the velocity of light in that medium. Now, consider water in a glass container and air above the surface of water. It is found that when a ray of light passes from air to water, the velocity of light in water decreases. On the other hand, when the ray of light passes from water to air, the velocity of light increases.

An example of refraction of light is shown in Fig. 5.3. When a ruler is partly immersed in water, the part under the water appears to be bent. This is due to the refraction of light coming from the immersed part of the ruler.

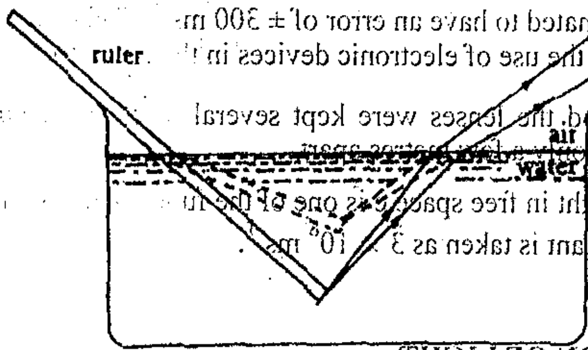


Fig. 5.3 A ruler appears bent in water

After studying the laws of refraction, the bending of a ruler partly immersed in water can be explained by drawing a ray diagram.

5.4 LAWS OF REFRACTION

In studying refraction through media, we shall assume that the boundary between two media is a plane surface. In Fig. 5.4, x and y are media of different optical densities and PQ is the boundary between them. Suppose that light travels from a less dense medium x to a more dense medium y. For example, suppose that x is air and y is water. A ray AO is incident on PQ at a point O and NON' is the normal.

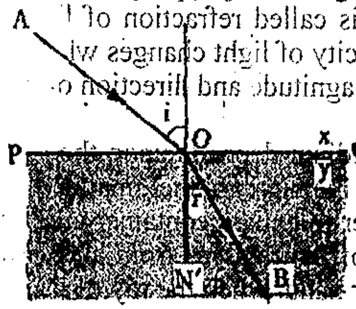


Fig. 5.4 Refraction of light at a plane surface

The incident ray AO changes its direction when it passes from x to y. This phenomenon is called refraction in medium y. AO travels along a new direction OB. In other words, AO is refracted along OB and OB is called the refracted ray. Since y is a denser medium the refracted ray OB is bent towards the normal. The angle between AO and the normal ON is called the angle of incidence and is represented by i. The angle between OB and the normal ON is called the angle of refraction and is represented by r. In this case r is smaller than i.

In refraction of light the light rays also obey the principle of reversibility of light. Thus, in Fig. 6.2 if BO is the incident ray in medium y, it will be refracted along OA. In the less dense medium x, OA will be refracted away from the normal. In this case r is the angle of incidence, i is the angle of refraction and the angle of refraction will be greater than the angle of incidence.

The laws governing the refraction of light which are obtained from experiments are stated below.

The Laws of Refraction

(1) The incident ray, the refracted ray and the normal all lie in the same plane.

(2) For a particular wavelength of light and for a given pair of media, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant.

(The second law is called Snell's law since it was so named in honour of its discoverer-Snell.)

5.5 REFRACTIVE INDEX

The ratio of the velocity of light in air, c, to the velocity of light in a particular medium, v, is called the refractive index n, of the medium. The refractive index, is given by

$$n = \frac{c}{v} \qquad (5.1)$$

The more optically dense a medium is, the smaller is the velocity of light in that medium and the greater is its refractive index.

If v_x and v_y are the velocities of light in media x and y respectively, and n_x and n_y are the refractive indices of media x and y respectively, then

$$n_x = \frac{c}{v_x} \text{ and } n_y = \frac{c}{v_y}$$

Therefore, $$\frac{n_x}{n_y} = \frac{c/v_x}{c/v_y}$$

$$= \frac{v_y}{v_x}$$

or $$n_x v_x = n_y v_y$$

If v is the velocity of light, f is the frequency of light and λ is the wavelength of light, then

$$v = f\lambda \qquad (5.2)$$

When light passes from one medium to another the frequency remains the same but the wavelength alters. Hence, if λ_x and λ_y are the wavelengths of light in media x and y respectively, we get

$$v_x = f\lambda_x \text{ and } v_y = f\lambda_y$$

Since

$$n_x v_x = n_y v_y$$

$$n_x f\lambda_x = n_y f\lambda_y$$

$$n_x \lambda_x = n_y \lambda_y$$

If the velocity of light v in a medium is known, its refractive index can be calculated from n = c/v. Otherwise, it can be calculated from Snell's law.

The refracted ray may be bent away from or towards the normal depending upon the optical density of the medium concerned. However, Snell's law states that ratio of the sine of the angle of incidence to the sine of the angle of refraction is always a constant. That constant is the refractive index of the medium through which the refracted ray passes.

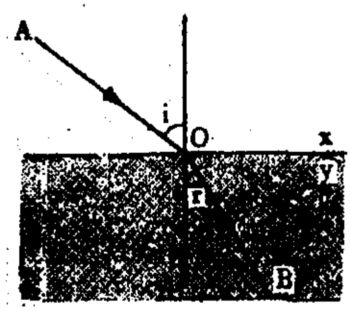


Fig. 5.5 Refraction of light

In Fig. 5.5 the incident ray AO in medium x is refracted along OB in the more optically dense medium y. Here, i is the angle of incidence and r is the angle of refraction.

By Snell's law $$\frac{\sin i}{\sin r} = n \qquad (5.3)$$

where n is the refractive index of medium y which contains the refracted ray OB. In order to express the refractive index more fully, the medium containing the incident ray must also be stated. Medium x, containing the incident ray, is shown at the left-subscript of n and the medium y containing the refracted ray is shown at the right-subscript of n. Therefore, for the refraction from medium x to medium y, the refractive index is expressed as

$$_x n_y = \frac{\sin i}{\sin r} \qquad (1)$$

In accordance with the principle of reversibility of light. If BO is an incident ray in medium y, it will be refracted away from the normal along OA in medium x. In this case, r is the angle of incidence, i is the angle of refraction and the refractive index is

$$_y n_x = \frac{\sin r}{\sin i} \qquad (2)$$

Multiplying equation (1) by (2), we obtain

$$_x n_y \times {_y n_x} = \frac{\sin i}{\sin r} \times \frac{\sin r}{\sin i}$$
$$= 1$$
$$_x n_y = \frac{1}{_y n_x}$$

Therefore, the refractive index of the medium y with respect to x is equal to the reciprocal of the refractive index of medium x with respect to y.

Absolute Refractive Index

The above stated media x and y may be any two media. Specifically, if x is a vacuum (v) the refractive index of the medium y for light travelling from vacuum into y is $_v n_y$. For this case $_v n_y$ is called the absolute refractive index of medium y.

The refractive index of any medium for the refraction of light from vacuum to that medium is, therefore, called the absolute refractive index of that medium. It is, however, seldom used in practice.

Refractive Index from Air to a Medium

The refractive index of a medium with respect to air is easier to determine than the refractive index of the medium with respect to vacuum. The refractive index from air to a medium is normally used to compare the refractive indices of different media.

The refractive index of a medium with respect to air is represented by n alone. However, in order to distinguish between the refractive-indices of different media, the medium concerned is used as a right-subscript for n. Thus, the refractive index of water with respect to air is written as n_w and that for glass with respect to air is written as n_g. Refractive indices of some media are given in Table 5.1.

Table 5.1

Substance	Refractive Index
Ice	1.31
Water	1.33
Ethyl Alcohol	1.36
Oleic Acid	1.46
Glycerine	1.47
Quartz	1.54
Glass	1.5-1.9
Diamond	2.42

Relation between Angle of Incidence and Angle of Emergence for a Ray passing through a Glass Slab with Parallel Sides

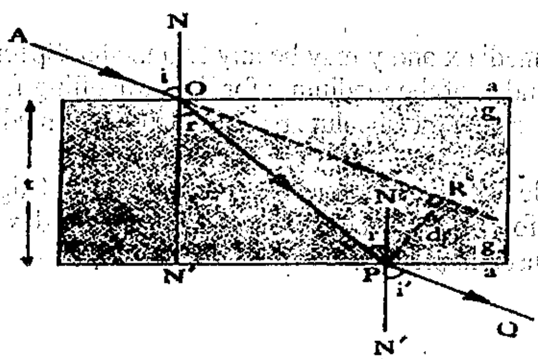


Fig. 5.6 Refraction through a glass slab

In Fig. 5.6, **a** is an air medium and **g** is a glass slab. An incident ray AO in air is refracted along OP in the glass slab and it emerges along PQ into the air, **i** is the angle of incidence and **i'** is the angle of emergence.
Since glass is a more optically dense medium, the refracted ray OP is bent towards the normal in the glass. Again, OP is refracted along PQ away from the normal into the air. Thus, refraction occurs twice.

For the first refraction $$ {}_{a}n_{g} = \frac{\sin i}{\sin r} $$

For the second refraction $$ {}_{g}n_{a} = \frac{\sin r}{\sin i'} $$

Since $$ {}_{a}n_{g} \times {}_{g}n_{a} = 1 $$

$$ \frac{\sin i}{\sin r} \times \frac{\sin r}{\sin i'} = 1 $$

$$ \sin i = \sin i' $$

$$ i = i' $$

Therefore, the angle of incidence is equal to the angle of emergence for a ray passing through a glass slab with parallel sides. This holds true not only for glass and air but also for any two media having parallel boundary surfaces between them. In other words, the incident ray and the emergent ray are parallel for such a pair of media.

Lateral Displacement of a Ray passing through a Glass Slab with Parallel Sides

In Fig. 5.6 the perpendicular distance PR between AO produced beyond O and the emergent ray PQ is a lateral displacement of AO, denoted by d. The thickness of the glass slab, that is, the distance between its parallel sides is denoted by t.
In the triangle OPR of Fig. 5.6 $\angle POR = i - r$

$$ \text{Sin } (i - r) = \frac{PR}{OP} $$

In the triangle OPN', $$ \cos r = \frac{ON'}{OP} = \frac{t}{OP} $$

$$ OP = \frac{t}{\cos r} $$

Therefore, $$ \sin (i - r) = \frac{PR}{t/\cos r} = \frac{PR \cos r}{t} $$

Since PR = d, then $$ \sin(i - r) = \frac{d \cos r}{t} $$

Therefore, the lateral displacement $$ d = \frac{t \sin(i - r)}{\cos r} \qquad (5.4) $$

Refraction through three Parallel Media

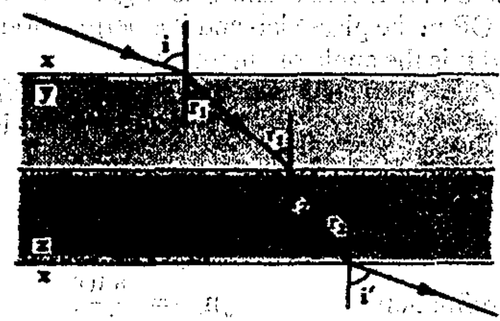


Fig. 5.7 Refraction through three parallel media

In Fig. 5.7 media x, y and z have different refractive indices. A ray in medium x is refracted through media y and z and emerges into medium x. The refraction occurs three times and the angle of incidence i is equal to the angle of emergence i'.

For the first refraction $\quad {}_x n_y = \dfrac{\sin i}{\sin r_1}$

For the second refraction $\quad {}_y n_z = \dfrac{\sin r_1}{\sin r_2}$

For the third refraction $\quad {}_z n_x = \dfrac{\sin r_2}{\sin i'}$

$$ {}_x n_y \times {}_y n_z \times {}_z n_x = \frac{\sin i}{\sin r_1} \times \frac{\sin r_1}{\sin r_2} \times \frac{\sin r_2}{\sin i'} $$

$$ = 1 $$

Therefore, $\quad {}_y n_z = \dfrac{1}{{}_x n_y \times {}_z n_x}$

Since $\quad {}_x n_z = \dfrac{1}{{}_z n_x}$

$$ {}_y n_z = \frac{{}_x n_z}{{}_x n_y} $$

If medium x is air, we have $\quad {}_y n_z = \dfrac{n_z}{n_y} \qquad (5.5)$

Therefore, the refractive index of medium z with respect to y is the ratio of the refractive index of z with respect to air to the refractive index of y with respect to air.

For example, consider two media, water (w) and glass (g).

Since $_{y}n_{z}=\frac{n_z}{n_y}$, we have $_{g}n_{w}=\frac{n_w}{n_g}$ and $_{w}n_{g}=\frac{n_g}{n_w}$

In Fig. 5.7, since $_{y}n_{z}=\frac{n_z}{n_y}=\frac{\sin r_1}{\sin r_2}$

$$n_y \sin r_1 = n_z \sin r_2 \qquad (5.6)$$

Therefore, the product of the sine of angle of incidence and the refractive index of the medium containing the incident ray is equal to the product of the sine of angle of refraction and the refractive index of the medium containing the refracted ray.

Refractive Index Related to Real and Apparent Depths

Figs. 5.8 and 5.9 show the positions of objects in one medium and their respective images when viewed from the neighbouring medium. Medium y has greater refractive index than medium x.

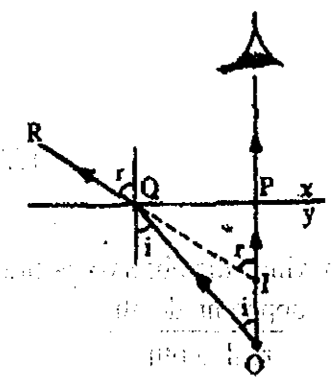


Fig. 5.8 Apparent depth when viewed from a less dense medium

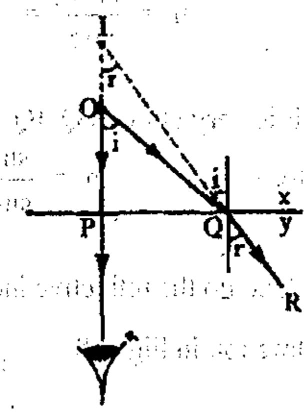


Fig. 5.9 Apparent depth when viewed from a denser medium

In Fig. 5.8 an object O is in medium y and the observer in medium x, looks at it directly from above. A ray OP from O perpendicular to the x-y boundary passes straight into medium x. A ray OQ from O is refracted along QR away from the normal, i is the angle of incidence and r is the angle of refraction. The point I, which is the point of intersection of OP and the refracted ray QR produced backwards, is the position of the image of O, Therefore, the observer in medium x, viewing O directly from above, sees it in the position I. In other words, the object appears nearer to the observer.

In Fig. 5.9 an object O is in medium x and the observer is in medium y. A ray OQ from O is refracted along QR which is bent towards the normal. The point which is the point of intersection of OP produced backwards and QR produced backwards, is the image of O. Therefore, the observer in the medium y viewing O sees it in the position I. In other words, the object appears farther away from the observer.

Since the refracted ray QR enters the observer's eyes, Q is actually very close to P in practice. (For the sake of clarity Figs. 5.8 and 5.9 are shown exaggerated.)

The perpendicular distance from the object O to the x-y boundary surface is called the real depth and is represented by u. The perpendicular distance from the image I to the x-y boundary surface is called the apparent depth and is represented by v.
In Figs. 5.8 and 5.9 PO = u, PI = v and we have

$$\sin i = \frac{PQ}{OQ}, \qquad \sin r = \frac{PQ}{IQ}$$

Then $$n = \frac{\sin i}{\sin r} = \frac{PQ/OQ}{PQ/IQ} = \frac{IQ}{OQ}$$

Since P is very close to Q, IQ = PI and OQ = PO.

Therefore $$n = \frac{\sin i}{\sin r} = \frac{PI}{PO} = \frac{v}{u} \qquad (5.7)$$

Let us take up the refractive index of the medium in which the observer is situated.

For refraction in Fig. 5.8 $${}_{y}n_{x} = \frac{\sin i}{\sin r} = \frac{v}{u} = \frac{\text{apparent depth}}{\text{real depth}}$$

For refraction in Fig. 5.9 $${}_{x}n_{y} = \frac{\sin i}{\sin r} = \frac{v}{u} = \frac{\text{apparent depth}}{\text{real depth}}$$

The refractive index of the medium in which an observer is situated is the ratio of the apparent depth to the real depth.

Next, we shall take up the refractive index of the medium in which the object is situated.

For refraction in Fig. 5.8 $\quad {}_x n_y = \dfrac{1}{{}_y n_x} = \dfrac{\text{real depth}}{\text{apparent depth}}$

For refraction in Fig. 5.9 $\quad {}_y n_x = \dfrac{1}{{}_x n_y} = \dfrac{\text{real depth}}{\text{apparent depth}}$

Therefore the refractive index of the medium in which an object is situated is the ratio of the real depth to the apparent depth.

Critical Angle and Total Internal Reflection

When light passes from a medium to a more optically dense medium both reflection and refraction will occur for all angles of incidence. But when light passes from a medium to a less optically dense medium both reflection and refraction will occur only for some angles of incidence.

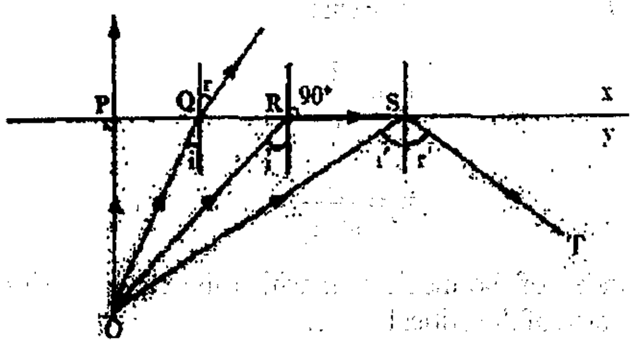


Fig. 5.10 Illustration of total internal reflection

In Fig. 5.10 an object O is in medium y which has greater refractive index than medium x. A ray OP from O is coincident with the normal so that it is not refracted but travels straight into medium x. A ray OQ which is not coincident with the normal is refracted away from the normal. Thus, the angle of refraction r is greater than the angle of incidence i. As the angle of incidence increases, the angle of refraction also increases. At a certain angle of incidence the angle of refraction becomes 90°. This means that the refracted ray lies in the boundary plane between the two media. The angle of incidence corresponding to the angle of refraction 90° is called the critical angle and is denoted by i_c. In Fig. 5.10 the incident ray OR from O is refracted along the x-y boundary and the angle of incidence i_c is the critical angle.

When the angle of incidence is greater than i_c light does not enter medium x at all, but is reflected back into medium y. Since the angle of incidence of the ray OS is greater than i_c, that ray is reflected along ST in medium y. Thus, the light in one medium does not enter the optically less dense medium and is reflected back into the first medium for all angles of incidence greater than i_c. This phenomenon is called total internal reflection.

Relation between Critical Angle and Refractive Index

In the case of refraction in Fig. 5.10 using Snell's law

$$ {}_y n_x = \frac{\sin i}{\sin r} $$

When $i = i_c$ $\quad r = 90°$

Therefore $\quad {}_y n_x = \frac{\sin i_c}{\sin 90}$

Since $\sin 90° = 1$, $\quad {}_y n_x = \sin i_c$

Since $\quad {}_x n_y = \frac{1}{{}_y n_x}$

$$ {}_x n_y = \frac{1}{\sin i_c} $$

The refractive index of the medium in which the object is situated is equal to the reciprocal of the sine of the critical angle.

If medium x is air $\quad n_y = \frac{1}{\sin i_c} \qquad (5.8)$

If the refractive index of glass is 1.5, the critical angle of glass is, using the above equation, calculated to be 42°.

Refraction through a Prism

A prism is a transparent object usually made of glass (Fig. 5.11). It has two plane surfaces, ABED and ACFD, inclined to each other.

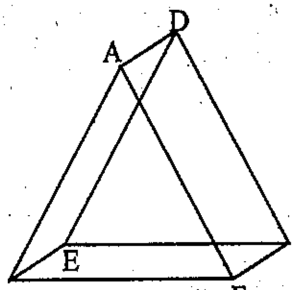


Fig. 5.11 A glass prism

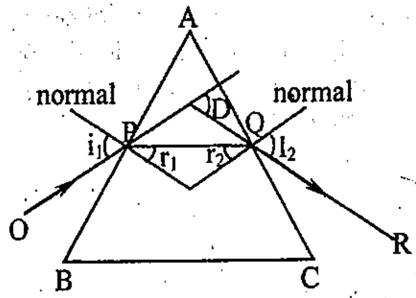


Fig. 5.12 Refraction by a prism

Fig. 5.12 shows a cross-section of the prism. The angle A is known as the angle of prism and BC is its base. A ray OP in air incident at the surface AB is refracted along PQ in the prism and emerges from the surface AC into the air along QR. The emergent ray QR is directed towards the base. AB is called the incident surface and AC the emergent surface. The refractive index of glass is greater than that of air. Thus PQ is refracted towards the normal and QR that emerges into the air is bent away from the normal. OPQR is the path of light travelling through the prism. If a ray is incident at the surface AC along RQ it will travel along RQPO.

The incident ray OP after refraction through the prism emerges along QR and the direction of OP is changed or deviated by it. This is called the deviation of light by the prism. The angle D, between the direction of incident ray OP and that of emergent ray QR is known as the angle of deviation. When the angle of incidence i is varied the angle of deviation D also varies. When i is increased gradually, D decreases gradually to a minimum value and then increases. Fig. 5.13 shows the appearance of an i-D graph obtained if the experimental values of i are plotted against those of D.

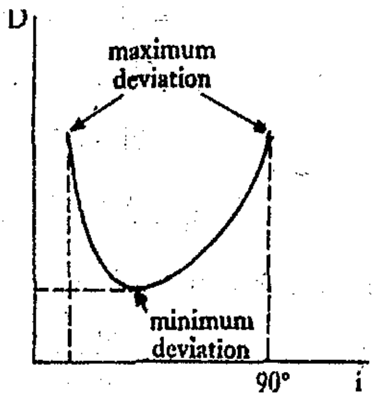


Fig. 5.13 The minimum deviation

The angle of minimum deviation is denoted by D_m. It is found that the angle of incidence is equal to the angle of emergence when the angle of deviation is minimum. In the minimum deviation case the formula for the refractive index of a prism can be obtained as follows.

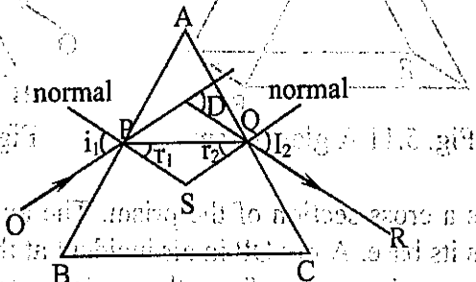


Fig. 5.14 Deviation in a prism

From Fig. 5.14 $A + \angle PSQ = 180°$ $(A = \angle BAC)$

From the triangle PQS, $r_1 + r_2 + \angle PSQ = 180°$

From these equations $A = r_1 + r_2$

When $D = D_m$, $i_1 = i_2$ and $r_1 = r_2$

Therefore $A = 2r_1$ (1)

From the triangle PQD $D = \angle PQD + \angle QPD$

$= (i_1 - r_1) + (i_2 - r_2)$

$= (i_1 + i_2) - (r_1 + r_2)$

When $D = D_m$, $D_m = 2i_1 - 2r_1$

$= 2i_1 - A$

$$i_1 = \frac{(A + D_m)}{2} \quad (2)$$

By Snell's law the refractive index of the prism is

$$n = \frac{\sin i_1}{\sin r_1} \quad (3)$$

Substituting the values of i_1 and r_1 from equations (1) and (2) into (3), we get

$$n = \frac{\sin\frac{(A + D_m)}{2}}{\sin(\frac{A}{2})} \tag{5.9}$$

This is the formula for the refractive index of the prism. The refractive index of the prism can be calculated from this formula provided that the angle of prism. A and D_m are known.

The Angle of Deviation of Thin Prism or Small-angled Prism

A prism whose angle is very small is called a thin prism. In Fig. 5.14 the refractive index of the prism is

$$n = \frac{\sin i_1}{\sin r_1} \quad \text{or} \quad n = \frac{\sin i_2}{\sin r_2}$$

When i_1 is very small, so are r_1, r_2 and i_2

Then $n = \frac{i_1}{r_1}$ or $i_1 = n\,r_1$

$$n = \frac{i_2}{r_2} \quad \text{or} \quad i_2 = n\,r_2$$

It has been shown that $D = (i_1 + i_2) - (r_1 + r_2)$

Substituting for i_1 and i_2 in the above equation,

$$D = n(r_1 + r_2) - (r_1 + r_2)$$

$$= (n - 1)(r_1 + r_2)$$

Since $A = r_1 + r_2$

$$D = (n - 1)A \tag{5.10}$$

Therefore, the angle of deviation D of a thin prism is constant for very small angles of incidence.

Some Applications of Total Internal Reflection

We have found that the critical angle of glass of refractive index 1.5 is 42°. Thus, the total internal reflection can occur in a prism of angles 90°-45°- 45°. A prism having such angles can be used as a total reflecting prism. In the total reflecting prism 100 percent of the light is reflected while other reflecting surfaces reflect only some of the light incident on them.

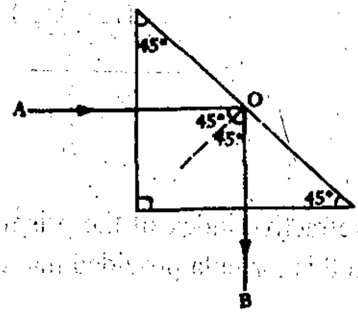


Fig. 5.15 Totally reflecting prism (hypotenuse-surface)

A ray AO in the air is incident normally on one surface of the prism (Fig.5.15). The ray passes normally through this surface and is incident on the hypotenuse-surface at O. The angle of incidence of that ray is 45°. Since the angle of incidence is greater than the critical angle of glass, which is 42°, the total internal reflection occurs in the prism. The reflected ray OB is incident normally on the other surface of the prism and emerges into the air. The deviation in this case is 90°. Total reflecting prisms are used in periscopes and binoculars.

In Fig. 5.16 a ray is incident normally on the hypotenuse-surface of the 90°-45°-45° prism. Total internal reflection occurs at each of the other surfaces and the ray emerges normally from the hypotenuse-surface. The deviation in this case is 180°.

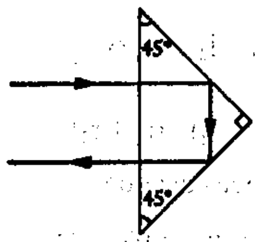


Fig. 5.16 Totally reflecting prism (side surfaces)

The images seen in the 90°-45° -45° prisms are shown in Fig. 5.17.

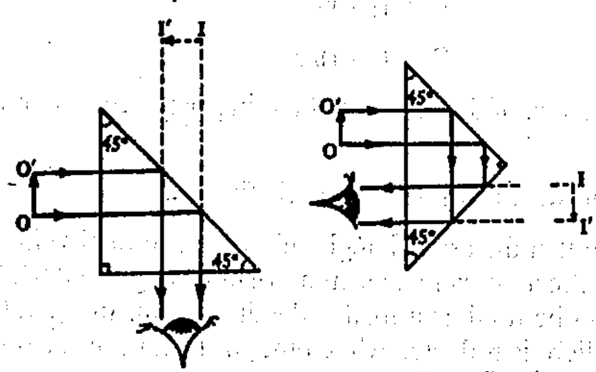


Fig. 5.17 Formation of image by a totally reflecting prism

The concept of total internal reflection is used in cutting the facets of diamond for its brightness. If the rays entering the diamond are totally reflected from its base and emerge from the surfaces, the diamond becomes brighter. In order to obtain the brilliance, the facets of diamonds must be cut systematically.

Suppose that a ray enters one end of a glass rod or a transparent plastic rod. If the successive total internal reflections occur in the rod the ray will emerge from the other end (Fig.5.18). Such a transparent rod is called a light pipe.

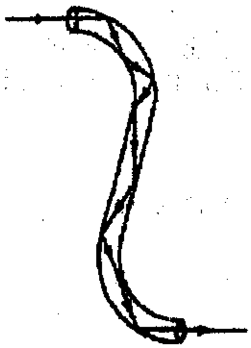


Fig. 5.18 Total internal reflection in a light pipe

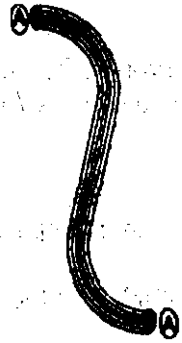


Fig. 5.19 Total internal reflection in a cluster of glass fibres

If a cluster of narrow glass fibres is used instead of a glass rod, an image can be transferred from one end to the other since each fibre carries intact a part of the image (Fig. 5.19).

Light pipes are used to examine, objects which are normally difficult to see. For example, the light pipe or the fibre gastroscope is inserted through the throat to the stomach. Light reflected from the stomach wall is reflected back up through the fibres of the bundle and forms an image on the film of the camera. Visual observation is also possible with the help of a special attachment.

Example (1) The angle of incidence of a ray of light passing from air to a transparent medium x is 30° and the angle of refraction is 19° 28'. If another ray is incident at 35° on that medium find the angle of refraction.

$$i = 30°, \quad r = 19°\ 28'$$

$$\therefore n_x = \frac{\sin i}{\sin r}$$

$$n_x = \frac{\sin 30°}{\sin 19° 28'}$$

$$= 1.5$$

For another ray $i_1 = 35°$, r_1 = angle of refraction, and

$$n_x = \frac{\sin i_1}{\sin r_1}$$

$$\sin r_1 = \frac{\sin i_1}{n_x} = \frac{\sin 35°}{1.5} = 0.38$$

Therefore $r_1 = 22° \; 18'$

Example (2) When a drop of ink at the bottom of a glass slab 6 cm thick is viewed from above, it is seen at a spot 1.67 cm above the bottom. Find the refractive index of glass.

Real depth = 6 cm ; Apparent depth = 6 - 1.67 = 4.33 cm

Since the drop of ink is at the bottom of the glass slab,

$$\text{the refractive index of glass} = \frac{\text{real depth}}{\text{apparent depth}} = \frac{6}{4.33} = 1.38$$

Example (3) (a) Find the critical angle of a liquid of refractive index 1.32. (b) Find the refractive index of diamond of critical angle 24° 27'.

(a) $n_l = 1.32$; $\sin i_c = \frac{1}{n_l} = \frac{1}{1.32}$

Therefore $i_c = 49°$

(b) $i_c = 24° \; 27'$, n_d = refractive index of diamond

$$n_d = \frac{1}{\sin i_c} = \frac{1}{\sin 24° 27'} = 2.42$$

Example (4) The refractive index of a liquid is 1.32 and that of glass is 1.5. If a ray of angle of incidence 30° enters from liquid to glass find the angle of refraction.

$n_\ell = 1.32$, $n_g = 1.5$

$${}_\ell n_g = \frac{n_g}{n_\ell} = \frac{1.5}{1.32} = 1.14$$

$i = 30°$, r = angle of refraction in glass

$$ {}_{\ell}n_g = \frac{\sin i}{\text{sim } r} $$

$$ \sin r = \frac{\text{Sin } i}{{}_{\ell}n_g} = \frac{\sin 30^\circ}{1.14} = 0.44 $$

That is $r = 26^\circ 6'$

Dispersion by a Prism

When a narrow pencil of white light passes through a prism as shown in Fig.5.20, it is split into bands of different colours. Such a band of different colours is called a spectrum.

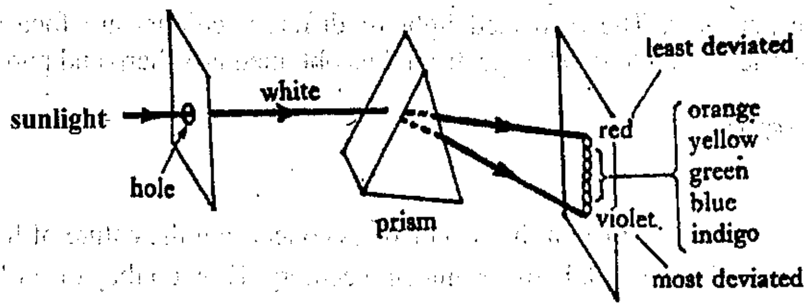


Fig. 5.20 Dispersion by prism

The violet colour-band is deviated the most from the original path of white light. And the red colour-band is deviated the least. Splitting of white light into different colour-bands is called dispersion of light.

Since violet light is deviated the most, the refractive index of the prism material for this colour has the largest value. The refractive index for the red light is the smallest.

We have learnt that the velocity of light is directly proportional to the wave-length. Thus, violet light, having a shorter wavelength than the red light, must have a velocity less than that of the red light.

The spectrum as obtained by the arrangement shown in the above figure is not sharp. The formation of a sharp and pure spectrum can be obtained with the experimental arrangement shown in Fig. 5.21.

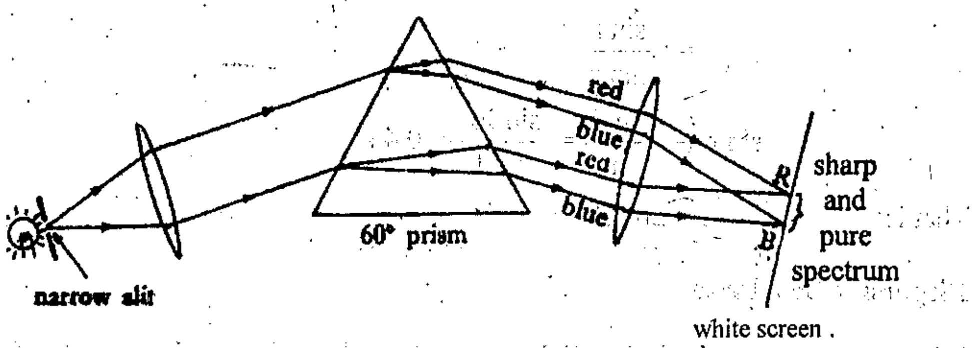


Fig. 5.21 Formation of pure spectrum

In Fig. 5.21 the first lens, the one between the light source and the prism, turned the rays from the source into a parallel beam. This beam is then incident onto the prism which disperses it. The dispersed light of different colours are focussed onto the screen by the second lens. The spectrum thus obtained is a sharp and pure one.

EXERCISES

1. Write down the names of the two theories concerning the nature of light that were introduced by the middle of seventeenth century. How do they differ?

2. What are the optical phenomena that cannot be explained by Newton's corpuscular theory?

3. Why did the majority of scientists hesitate to accept Huygens' wave theory of light when it was first introduced?

4. Why can the bending of light not be seen although the bending of water waves can be seen?

5. Choose the correct answer from the following.

(a) Light has only particle nature. (b) Light has only wave nature. (c) Light has both particle and wave nature.

6. Choose the correct answer from the following.

(a) All optical phenomena can be explained by Huygens' wave theory. (b) All optical phenomena can be explained by Newton's corpuscular theory. (c) The statements given in (a) and (b) are both wrong.

7. Why did Galileo not succeed in measuring the velocity of light?

8. Can an object move with a velocity greater than the velocity of light?

9. Choose the correct answer from the following.

If c_1 is the velocity of light coming from the sun and c_2 is that coming from the candle flame, then

(a) $c_1 > c_2$ (b) $c_1 < c_2$ (C) $c_1 = c_2$

10. Write down the values of the velocity of light obtained by Fizeau and Michelson. The rest mass of electron is 9.1×10^{-31} kg. If the value of the velocity of light obtained by Fizeau is used, what is the error percent in evaluating the rest energy of electron? $E = mc^2$?

11. The velocity of sound in air is 330 m s^{-1}. A man hears a thunderclap 5 s after seeing a lightning flash. How far away is the source of thunder from that man?

12. (a) What is meant by refraction ? (b) State the laws of refraction, (c) Explain the statement: "the refractive index of glass is 1.5".

13. (a) If the velocity of light in a medium is 2.3×10^8 m s^{-1}, find the refractive index of the medium.
(b) The wavelength of a ray of light in air is 5×10^{-7} m. With what velocity will that ray pass through diamond whose refractive index is 2.42? Find the wavelength of that ray in diamond.

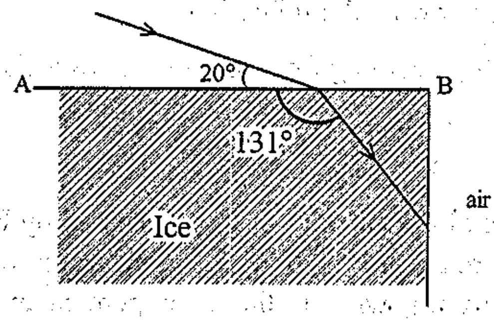
14. In the formation of the spectrum of white light by a prism (i) which colour is deviated least ? (ii) which colour is deviated most ?

15. A narrow beam of white light is incident upon a triangular glass prism. Draw a clear diagram to illustrate what is meant by (a) deviation (b) dispersion.

16. A ray of light in water has a wavelength of 4.42×10^{-7} m. What is the wavelength of that ray while passing through ice? ($n_w = 1.33$; $n_{ice} = 1.31$)

17. When a ray of light is incident on the surface of a glass slab, both reflection and refraction of light take place. If the angle of incidence of the ray is 30° and the refractive index of glass is 1.5, find the angle between the reflected ray and the refracted ray.

18. The path of a ray of light through one corner of a block of ice is shown below,



Find (a) the angle of incidence on the face AB, (b) the angle of refraction at this face, (c) the refractive index of ice, (d) the critical angle for ice and (e) determine whether the ray will emerge from the block of ice.

19. A ray of light in air is incident on the surface of a glass slab 4 cm thick at an angle of 60°. It emerges from the slab and travels into the air from the other side of the glass slab. If the refractive index of glass is 1.5, find the lateral displacement between the incident ray and the emergent ray.

20. A ray of light in air enters a prism (having an angle 60°) from one surface and emerges into the air from the other surface. If the emergent ray lies in the surface of the prism find the angle of incidence. The refractive index of glass is 1.5.

21. A cube of ice of refractive index 1.31 is placed on a glass slab of refractive index 1.6. If a ray of light passing from the glass slab to the ice has an angle of incidence of 35°, will the ray enter the ice?

22. (a) The angle of a glass prism is 60° and the angle of minimum deviation is 39°. Find the refractive index of glass (b) If the refractive index of glass is 1.66 and the angle of prism is 60°, find the angle of minimum deviation.

23. Where is the image of P after reflection and refraction?

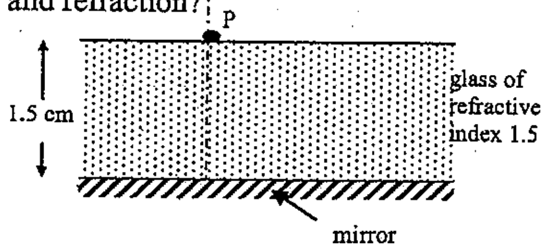
A 2 cm below P

B 2 cm above P

C 3 cm below P

D 3 cm above P

E 4.5 cm below P



24. In the following experiment, what is the refractive index of water?

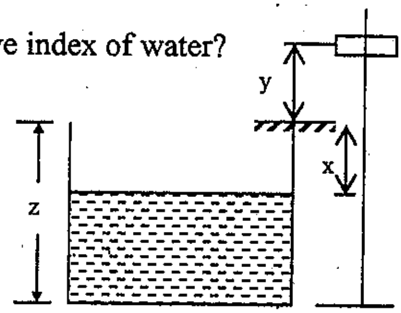
A $\frac{z}{y-x}$

B $\frac{y-x}{z}$

C $\frac{z-x}{y-x}$

D $\frac{z}{y}$

E $\frac{z-x}{y}$



25. In an experiment to find the refractive index of glass (see diagram), the eye sees that the emergent beam suddenly becomes bright when the beam is along PQ. If $\angle OAP = 84°$, the refractive index of glass is

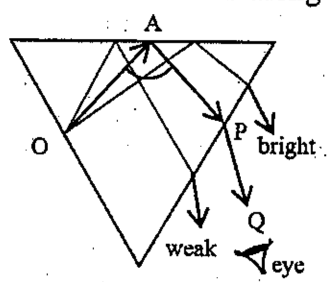
A 1.33

B 1.45

C 1.50

D 1.67

E 1.80



26. In a periscope, 2 glass prisms are used as shown. The image seen is

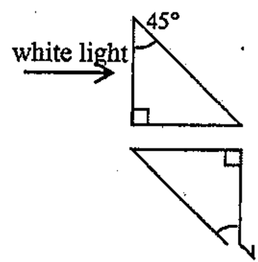
A erect

B coloured due to dispersion

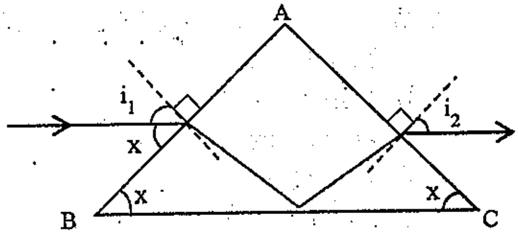
C accompanied by multiple images

D brighter than the object

E magnified



27. ABC is an isosceles triangle with base angle 'x' suitably chosen so that the ray can emerge from AC. Then



A $i_2 = i_1$

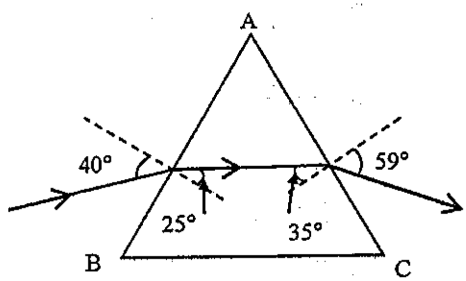
B $i_2 = i_1$

C $i_2 = i_1$

D cannot be determined because the refractive index is not given

E cannot be determined because the value of 'x' is not given

28. The angle of deviation is



A 60°

B 39°

C 19°

D 9°

E cannot be determine because the values of A, B C are not known

29. Mirages are formed because

A the ground acts as a reflecting surface

B the air has uniform refractive index

C the refractive index of air increases with height

D the refractive index of air decreases with height

E the sky acts as a reflecting surface

30. Given $n_w = 4/3$, $n_g = 3/2$

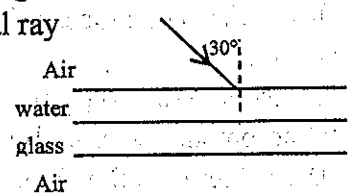
A the ray undergoes total internal reflection at the air-water interface

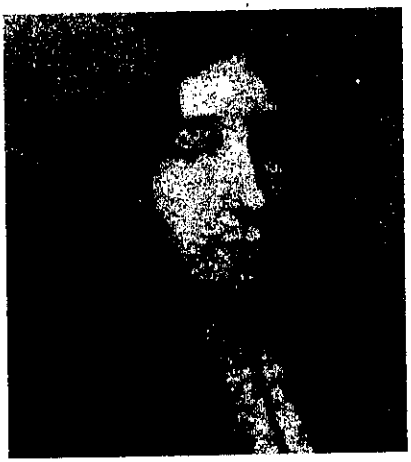
B the ray undergoes total internal reflection at the water-glass interface

C the ray undergoes total internal reflection at the glass-air interface

D the emergent ray in air is parallel to the original ray

E the emergent ray in air is deviated





Christiaan Huygen (1629-95)

Dutch physicist who was the leading proponent of the wave theory of light. In *Traité de la Luminère* (1690), he developed the concept of the wavefront, but could not explain colour. In contradiction to Newton, Huygens correctly believed that light must travel more slowly when it is refracted towards the normal, although this was not proven until experiments by Foucault in the nineteenth century. Huygens also made important contributions to mechanics, stating that in a collision between bodies, neither loses nor gains "motion" (his term for momentum). He stated that the center of gravity moves uniformly in a straight line, and gave the expression for centrifugal force as

$$F = mv^2/r$$

Sir Isaac Newton MA DLit FRS (1642-1727)

Fellow of Trinity College, Cambridge (1667) wrote "Principia" in 1687 and "Opticks" in

held by Sir Joseph Larmor , PAM Dirac and Sir James Lighthill .

He discovered the three laws of motion , the science of spectroscopy using the prism , the Universal law of Gravitation

$$F = GmM/r^2$$

and calculus (independently of Leibniz). He proposed a corpuscular and undulatory nature of light a concept akin to wave-particle duality of modern physics. The laws presented in Principia are the basis of nearly all practical calculations in science and engineering even today. He was not only an excellent mathematical physicist but also a very accomplished experimental physicist. He invented the reflecting telescope, built a mathematical bridge without the use of nuts and bolts across the river (Beck) at Cambridge. Although he is known for his corpuscular theory of light he used corpuscular and undulatory concepts to explain optical phenomena such as Newton's rings and polarization of light etc. It would be fair to say that he rejected

1704. Lucasian Professor at Cambridge (1669 -1699),Warden of the Mint(1696), Master of the Mint (1699-1727),President of the Royal Society(1703-1727) The incumbent (Lucasian Prof) is SW Hawking and was previously	only the purely wave theory of light. An extraordinary man but not an ivory tower type of scientist ,Newton took his job as Master of Mint and the President of the Royal Society very seriously although he was not too keen a Member of the British Parliament.

CHAPTER 6

REFRACTION, DIFFRACTION AND INTERFERENCE OF LIGHT

Generally diffraction is the deviation of waves (electromagnetic waves, x rays, water waves, sound waves) in a single medium by a narrow aperture or obstacle and there is no change in wavelength or speed. Refraction is the deviation of waves when they cross the boundary between two different media and there is a change in both the wavelength and speed. You will learn more about diffraction in the section dealing with x ray diffraction [x rays (x-rays) are electromagnetic waves of short wavelengths ~1angstrom (1 Å) or 0.10 nm] which has brought about an interdisciplinary nature to physics teaching and research (See Section 6.5). A very practical example of interference is the production of beats which may be described as the interaction or superposition of two waves of nearly equal frequency that produces a periodic rise and fall in intensity.

6.1 REFRACTION AT A CURVED SURFACE

In preparation for the study of thin lenses, we first look at refraction at a single spherical surface.

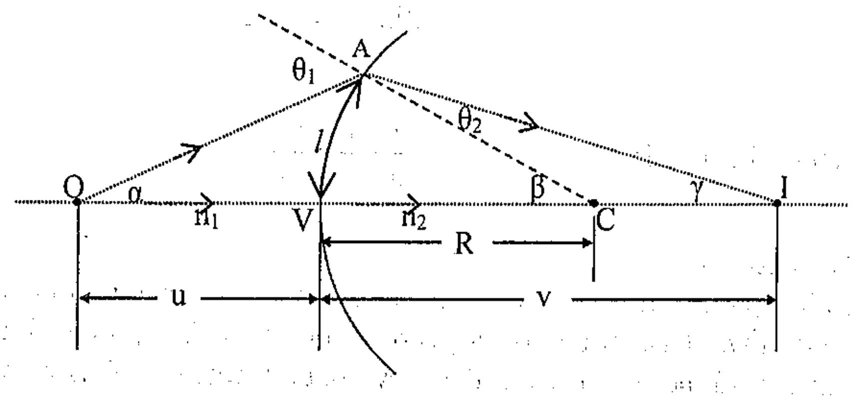


Fig. 6.1 Refraction at a spherical surface

Consider the two rays shown leaving point object O in the above figure. The ray incident at A will be refracted at the surface and meet the ray propagating along the axis at point I. The light ray along the axis is incident on the surface normally and hence is not bent. An object at point object O thus has its image at I. If the rays are paraxial, then the angles α, β, γ, θ_1 and θ_2 are all small. From Snell's law,

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

Since the angles are small, $\sin\theta_1 \approx \theta_1$ and $\sin\theta_2 \approx \theta_2$

$$n_1\,\theta_1 = n_2\,\theta_2 \qquad (6.1)$$

In triangle OAC, $\theta_1 = \alpha + \beta$ and in triangle IAC, $\beta = \theta_2 + \gamma$

The angles θ_1 and θ_2 can now be eliminated between these equations. Substituting for θ_2 from Eq. 6.1 we have,

$$\beta = \frac{n_1}{n_2}\,\theta_1 + \gamma$$

or

$$\beta = \frac{n_1}{n_2}\,(\alpha + \beta) + \gamma$$

Simplifying, we get

$$n_1\,\alpha + n_2\,\gamma = \beta\,(n_2 - n_1)$$

But $\beta = l/R$, $\alpha = l/u$ and $\gamma = l/v$. Thus

$$\frac{n_1}{u} + \frac{n_2}{v} = \frac{n_2 - n_1}{R} \qquad (6.2)$$

If the first medium is air,

$$\frac{1}{u} + \frac{n}{v} = \frac{n-1}{R} \qquad (6.3)$$

Sign Convention for R

A radius R is positive if the centre of curvature C is on the same side of the surface as the refracted ray. Thus, for a refracting surface, the radius R is positive if the surface is convex toward the object (as in the above figure), where as R is negative if the surface is concave toward the object.

6.2 THE LENS EQUATION

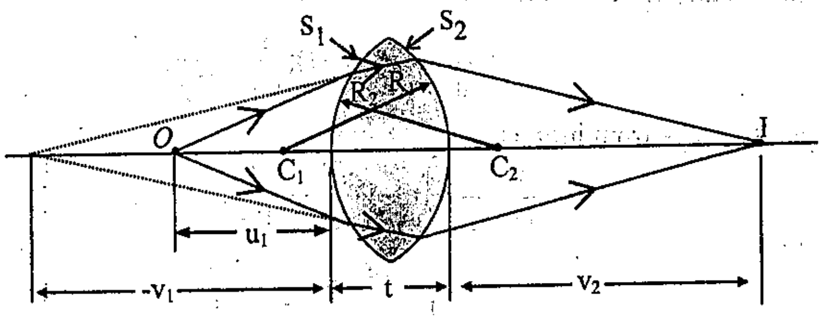


Fig. 6.2 Path of light rays from an object at O through a lens to the image at I

The above figure shows the path of rays from object O, through a lens, to image I. For the refraction at the first surface S_1,

$$\frac{n_1}{u_1}+\frac{n_2}{v_1}=\frac{n_2-n_1}{R_1}$$

The image formed by the first surface acts as the object for the second surface of the lens:

$u_2 = - v_1 + t$; where t is the lens thickness. The negative sign comes from the convention we have adopted in which the virtual objects have negative object distances. In the thin lens approximation, the thickness 't' of the lens is small compared with the object and image distances. In this approximation, $u_2 = - v_1$.

For the refraction at the second surface S_2

$$\frac{n_2}{u_2}+\frac{n_1}{v_2}=\frac{n_2}{-v_1}+\frac{n_1}{v_2}=\frac{n_1-n_2}{R_2}=\frac{n_2-n_1}{-R_2}$$

Rearranging, we get

$$\frac{n_1}{u_1}+\frac{n_1}{v_2}=(n_2-n_1)\left(\frac{1}{R_1}-\frac{1}{R_2}\right)$$

Considering the lens as a single entity, (i) let the object distance for the lens as a whole be $u = u_1$, (ii) let the image distance for the lens as a whole be $v = v_2$, and (iii) let the focal length of the lens as a whole be 'f'. The focal length 'f' of the lens is defined to be equal to v as $u \rightarrow \infty$.

If medium 1 is air, $n_1=1$ and the equation becomes

$$\frac{1}{u}+\frac{1}{v}=(n-1)(\frac{1}{R_1}-\frac{1}{R_2}) \quad (6.4)$$

For the parallel rays from infinity,

$$\frac{1}{\infty}+\frac{1}{f}=(n-1)(\frac{1}{R_1}-\frac{1}{R_2})$$

or

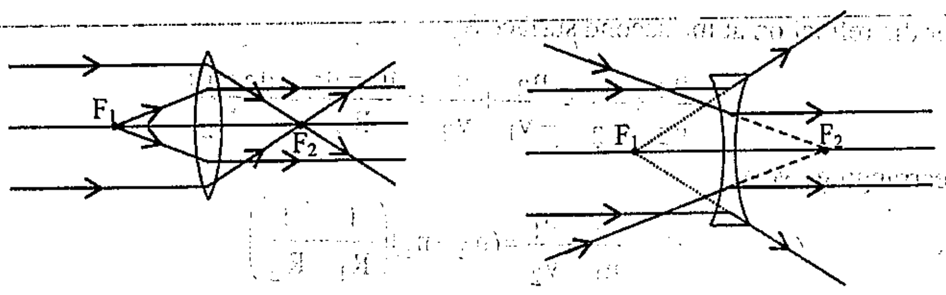
$$\frac{1}{f}=(n-1)(\frac{1}{R_1}-\frac{1}{R_2}) \quad (6.5)$$

Equation (6.5) is known as the lens-makers' equation.

It gives a prescription for making a lens with a given focal length. With these notation changes, Eq. 6.4 becomes the lens equation,

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f} \quad (6.6)$$

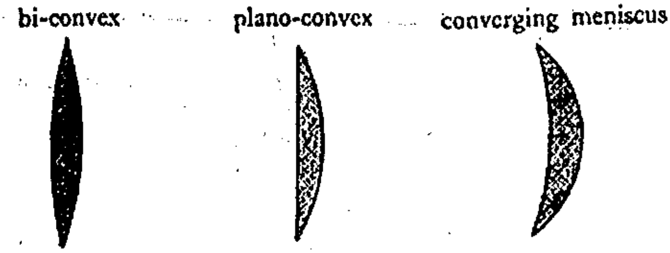
A mirror has one focal point, whereas a lens has two, as shown in the following figure. The second focal point F_2 is the position where parallel light incident on the lens is focused. The first focal point F_1 is the position where and object produces an image at infinity.



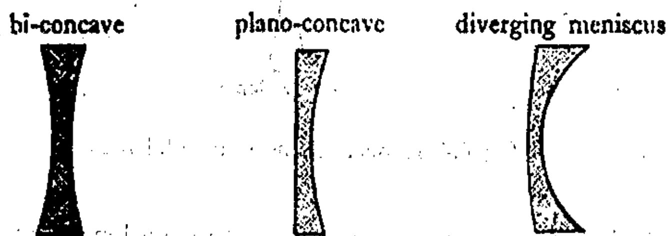
6.3 REFRACTION THROUGH LENSES

A transparent material which can diverge or converge rays of light is called a lens. A lens has at least one curved surface. Generally, a lens has a spherical face.
Lenses have different shapes and are very useful objects. They are used in spectacles, cameras, projectors, telescopes and microscopes. The converging lens or convex lens is used as a magnifying glass. The lenses in spectacles used by a short-sighted person are diverging lenses or concave lenses.

A convex lens is thicker in the middle than at the edges. Three types of convex lens are bi-convex, plano-convex and converging meniscus (Fig. 6.3).



Converging (convex) lenses



Diverging (concave) lenses

Fig 6.3

A concave lens is thinner in the middle than at the edges. Three types of concave lens are bi-concave lens, plano-concave lens and diverging meniscus (Fig. 6.3). Bi-convex and bi-concave lens are widely used. Refraction through such lenses will now be studied. For simplicity, a bi-convex lens will be called a convex lens and a bi-concave will be called a concave lens from now on.

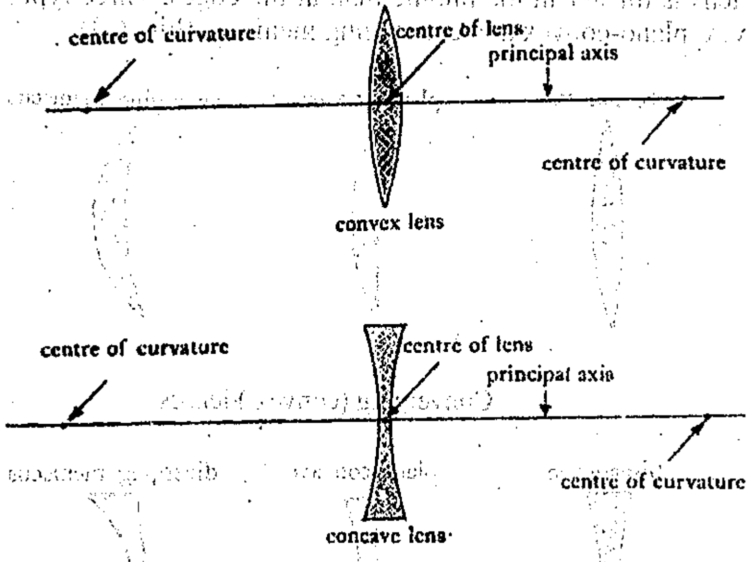


Fig 6.4 Terms in connection with lenses

Each surface of a lens has a centre of curvature. Since a lens has two surfaces it has two centres of curvature. The line joining the centres of curvature of two surfaces is the principal axis of a lens. It passes through the middle of the lens. Radii of curvature of the two surfaces of a lens may not be equal. If they are equal a lens is said to be symmetric. A point in the middle of such a lens on the principal axis is the centre of a lens or the optical centre of a lens (Fig. 6.4)

As in the case of reflection at concave and convex mirrors, only rays close to the principal axis will be used in studying the refraction through lenses.

Principal Focus and Focal Length

Concave and convex lenses may be regarded as made up of a very large number of thin prisms. The portions of a convex lens are shown in Fig. 6.5(a). Each portion represents one prism. Consider the rays of light parallel to the principal axis which pass through the lens. The bases of the prisms are facing the center of the lens. It has been found that a ray entering a prism is deviated towards its base. The angles of prisms increase from the middle of the lens to its edges. It has been shown that the angle of deviation of a ray of light in a thin prism is given by $D = (n - 1) A$. Thus, the prisms nearer the centre of a lens deviates an incident ray less than those prisms farther away from the centre of the lens.

The central portion of a lens may be regarded as a small part of a parallel-side slab. Rays passing through are not deviated but only slightly displaced parallel to their original direction. For a thin lens this displacement is sufficiently small and it can be ignored. Hence we can say that rays passing through the centre of the lens remain undeviated. Rays parallel to the principal axis converge at a point on the principal axis after passing through a convex lens. This point is called the principal focus, and is denoted by F. Since these rays actually pass through the focus, the focus of the convex lens is real.

In Fig. 6.5(a) the rays parallel to the principal axis enter the lens from the left and pass through the focus on the right. If the rays parallel to the principal axis enter the lens from the right, they will pass through the focus on the left. Thus, a lens has two focii. The distance between the centre of lens and the focus is the focal length of the lens.

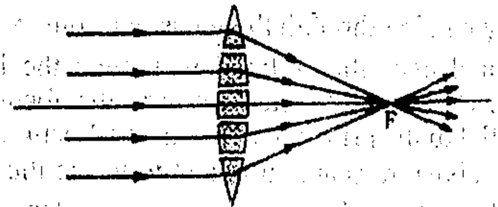


Fig 6.5(a) Construction of bi-convex lens

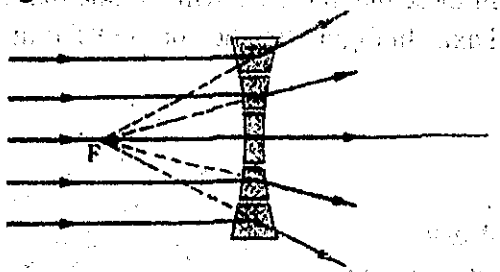


Fig. 6.5(b) Construction of bi-concave lens

In Fig. 6.5(b) the bases of prisms in the concave lens are facing the edges of the lens. Refraction through a concave lens is opposite to that through a convex lens. The rays parallel to the principal axis are divergent after passing through the concave lens. Those divergent rays appear to come from a point on the principal axis. This point is called the focus of the concave lens. Since the divergent rays do not actually pass through that point the focus of the concave lens is virtual.

Like a convex lens, a concave lens has two focii. In Fig. 6.5(b) the focus, corresponding to the rays parallel to the principal axis which enter the concave lens from the left, is also on the left of the lens. The focus on the right of the concave lens corresponds to the rays parallel to the principal axis which enter the lens from the right.

The points at a distance of twice the focal length from the centre of lens are represented by 2F. These points are very important for the lens.

Formation of Images by Lenses

The images formed by lenses can be studied by means of ray diagrams which can be drawn using the principal rays stated below.

(1) A ray parallel to the principal axis passes through the focus after refraction through a convex lens.

(2) A ray parallel to the principal axis is refracted through a concave lens and the refracted ray produced backward passes through the focus F.

(3) A ray passing through the centre of the lens emerges in the same direction.

(4) A ray passing through the focus of a convex lens emerges parallel to the principal axis after refraction through the lens. A ray on one side of a concave lens directed towards the focus on the other side, emerges parallel to the principal axis after refraction through the lens.

Only two of the above rays are sufficient to locate the image of an object in various positions. The formation of images in a convex lens by drawing ray diagrams are shown below. In these diagrams we will assume that an object OO' is placed upright on the principal axis. In Figure 6.6 the object OO' is at infinity. Its image is

(1) at F,

(2) real,

(3) inverted, and

(4) smaller than the object.

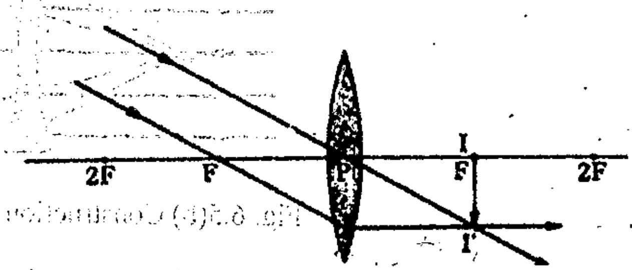


Fig. 6.6 Object at infinity

In Fig. 6.7 the Object OO' is beyond 2F. Its image II' is

(1) between F and 2F,

(2) real,

(3) inverted, and

(4) smaller than the object.

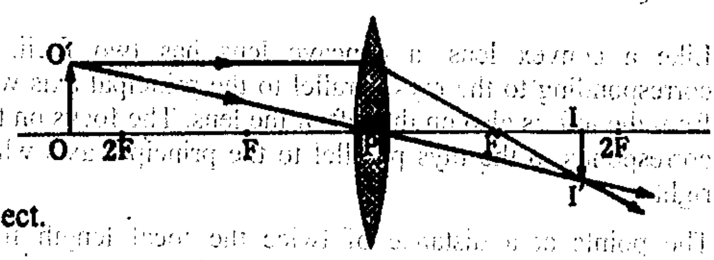


Fig 6.7 Object beyond 2F

In Fig 6.8 the Object OO' is at 2F. Its image II' is

(1) at 2F,

(2) real,

(3) inverted, and

(4) same size as the object.

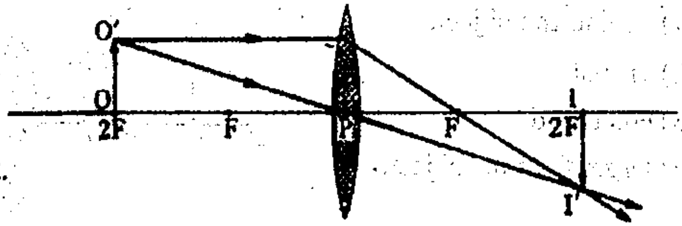


Fig. 6.8 Object at 2F

In Fig. 6.9 the object OO' is between F and 2F. Its image II' is

(1) beyond 2 F,

(2) real,

(3) inverted, and

(4) larger than the object.

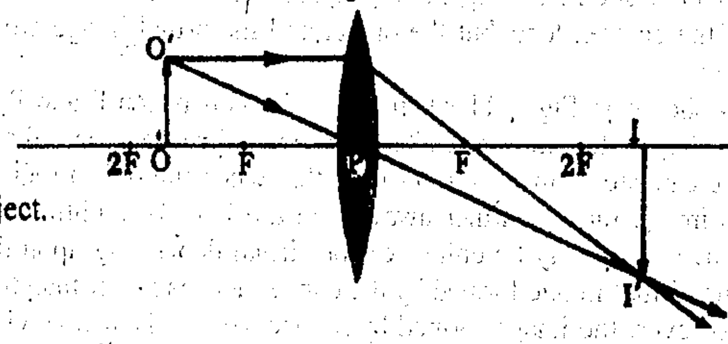


Fig. 6.9 Object between F and 2F

In Fig. 6.10 the object OO' is at F. Its image is at infinity.

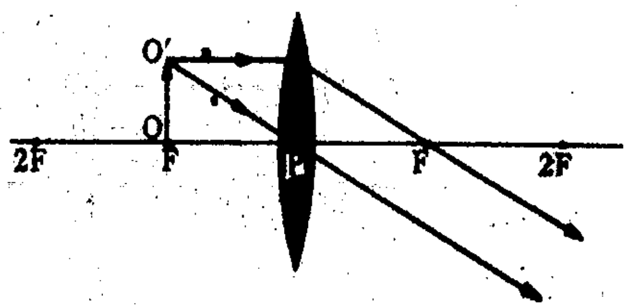


Fig. 6.10 Object is at F

In Fig. 6.11 the object OO' is between F and P. Its image II' is

(1) behind the object,

(2) virtual,

(3) erect, and

(4) larger than the object.

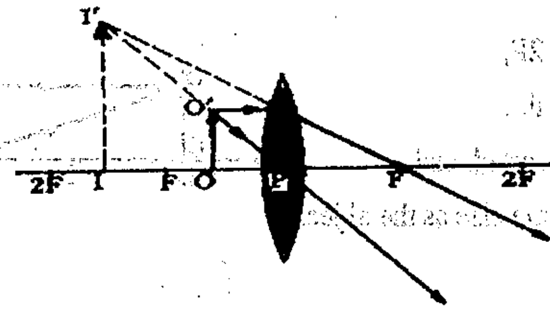


Fig. 6.11 Object between F and P

It can be seen from Figs. 6.6 - 6.9 that the object and its real images are on either side of the convex lens, but the object and its virtual image are on the same side in Fig. 6.11.

As shown in Fig. 6.11 when the object is between F and P its image is erect, virtual and larger than the object. Thus, a convex lens can be used as a magnifying glass.

We can see from Figs. 6.6 - 6.11 that when the object OO' moves closer to the lens, its image moves farther away from the lens. In addition, the image formed by the convex lens may be either real or virtual depending upon the position of the object. The virtual image formed by the convex lens is larger than the object.

However, the image formed by a concave lens is always virtual and smaller than the object. The virtual image formed by the convex or concave lens is the same side as the object only when the object is in contact with the lens. Fig.6.12 shows the image formed by the concave lens.

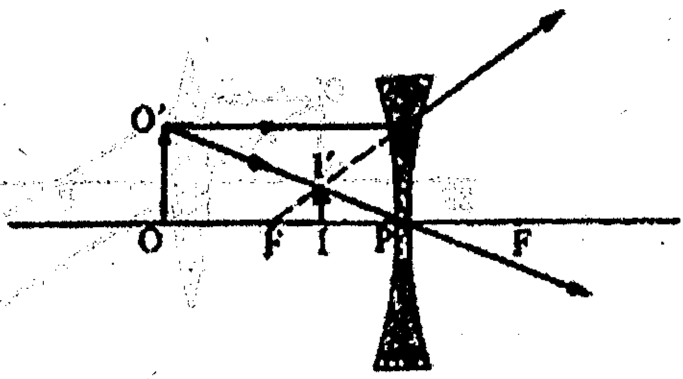


Fig. 6.12 Image formed by a concave lens

Lens Formula

The object distance, u, the image distance, v, and the focal length, f, are related by the formula

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f} \qquad (6.6)$$

This is the general lens formula. The object distance, u, and the image distance, v, are measured from the centre of the lens (P). The position, and nature of the image formed by the lens can be calculated by using the lens formula. The sign conventions for the lenses which are the same as those for the mirrors must be used in calculations. The lens formula can be derived as follows:

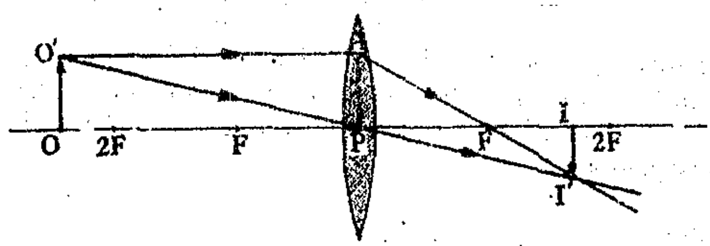


Fig. 6.13 Relation between u, v and f in a convex lens

In Fig. 6.13 II'F and APF are similar triangles.

Therefore $$\frac{II'}{PA}=\frac{FI}{PF} \qquad (1)$$

II'P and OO'P are also similar triangles

Therefore $$\frac{II'}{OO'}=\frac{PI}{PO} \qquad (2)$$

Since $$PA = OO', \quad \frac{II'}{PA}=\frac{PI}{PO} \qquad (3)$$

From equations (1) and (3)

$$\frac{FI}{PF}=\frac{PI}{PO}$$

$$\frac{PI-PF}{PF}=\frac{PI}{PO} \qquad (4)$$

In Fig. 6.15 PI = v = image distance

PF = f = focal length

PO = u = object distance

By sign conventions, the focal length f of the convex lens is positive and the real image distance v is also positive. Thus, equation (4) can be written as

$$\frac{(+v)-(+f)}{+f} = \frac{(+v)}{u}$$

$$uv - uf = fv \qquad (5)$$

Dividing by uvf,

$$\frac{1}{f} - \frac{1}{v} = \frac{1}{u} \quad \text{or} \quad \frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

In deriving this equation, OO' is situated beyond 2F. This equation can also be derived when OO' is in any other position. In addition, this equation can be derived for a concave lens as well. However, the appropriate sign conventions must be used in deriving the equation.

Magnification

The linear magnification is the ratio of the height of the image to the height of the object. It is usually denoted by m.

If OO' is the height or the size of the object and II' is the height or the size of the image, then

$$m = \frac{II'}{OO'}$$

In Fig. 6.15 the triangles OO'P and II'P are similar.

Therefore, $$\frac{II'}{OO'} = \frac{PI}{PO}$$

PI = v = image distance

PO = u = object distance

When the corresponding sign conventions are used, II'

$$-\frac{II'}{OO'} = \frac{v}{u} \quad \text{or} \quad \frac{II'}{OO'} = -\frac{v}{u}$$

Therefore, $m = \frac{II'}{OO'} = -\frac{v}{u}$ (6.7)

or $m = \frac{\text{size of image}}{\text{size of object}}$

$= -\frac{\text{image distance}}{\text{object distance}}$

The minus sign in the above equation indicates the nature and configuration of the image.

6.4 POWER OF A LENS

The power of a lens is inversely proportional to the focal length of the lens. It is denoted by the letter P. If the focal length f is measured in metres,

$$P = \frac{1}{f} \qquad (6.8)$$

The shorter the focal length the greater is the power of the lens. The lens having greater power can make the rays parallel to the principal axis more convergent or divergent. Since the focal length of a convex lens is positive in sign it has a positive power. The focal length of a concave lens is negative so that it has a negative power. The signs of the powers of the lenses used here are the same as those used by the lens-makers.

Unit Power or Dioptre

If a lens has a focal length of 1 metre, it has one unit power or one dioptre. Dioptre is denoted by D.

Therefore $P = \frac{1}{f(m)} D$

For example, if the power of a lens is + 2D, it is a convex lens and its focal length is 0.5 m or 50 cm.

If the power of a lens is - 4D, it is a concave lens and its focal length is 0.25m or 25cm.

Example (1) (a) An object is placed 30 cm from a convex lens of focal length 10cm. Find the position of its image and the magnification. (b) An object is placed 30 cm from a concave lens of focal length 10 cm. Find the position of its image and the magnification.

(a) $f = +10$ cm, $u = +30$ cm

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\frac{1}{+30} + \frac{1}{v} = \frac{1}{+10}; \quad \frac{1}{v} = \frac{1}{10} - \frac{1}{30}$$

$$v = 15 \text{ cm}$$

Hence the image is real and 15 cm from the lens.

$$m = -\frac{v}{u} = -\frac{15}{30} = -\frac{1}{2}$$

Since m has a minus sign the image is inverted.

(b) $f = -10$ cm, $u = +30$ cm

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\frac{1}{+30} + \frac{1}{v} = \frac{1}{-10}; \quad \frac{1}{v} = -\frac{1}{10} - \frac{1}{30}$$

$$v = -7.5 \text{ cm}$$

The image, therefore, is virtual and 7.5 cm from the lens.

$$m = -\frac{v}{u} = -\frac{(-7.5)}{30} = 0.25$$

Since m has a plus sign the image is erect.

Example (2) An object is 30 cm from a lens and its image is formed 10 cm on the same side as the object from the lens. (a) Find the type of the lens and its focal length. (b) Find the power of the lens.

(a) Since the image is formed on the same side as the object, it is a virtual image.

In addition, $u = 30$ cm and $v = 10$ cm so that the image is between the object and the lens. Thus the lens is a concave lens.

$u = +30$ cm, $v = -10$ cm

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\frac{1}{+30} + \frac{1}{-10} = \frac{1}{f}; \quad \frac{1-3}{30} = \frac{1}{f}$$

$$f = -15 \text{cm}$$

The focal length of the concave lens is 15 cm.

(b) $P = \frac{1}{f}$

$F = -15 \text{ cm} = -\frac{15}{100}\text{m}; \quad P = \frac{1}{-\frac{15}{100}}; = -6.67 \text{ D}$

Example (3) An image, which is five times the size of an object, is to be produce by a convex lens of power + 2D on the same side as the object. How far should the object be placed from the lens?

The power $P = \frac{1}{f}$

$$+2 = \frac{1}{f}$$

Therefore, $f = \frac{1}{2}\text{ m} = \frac{1}{2}\times 100 \text{ cm} = 50 \text{ cm}$

$$II' = 5 \times OO'$$

$$\frac{II'}{OO'} = 5$$

$$m = +5 = -\frac{v}{u}$$

$$+5 = -\frac{v}{u}$$

Therefore, $v = -5u$

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\frac{1}{u} + \frac{1}{-5u} = \frac{1}{50}$$

$$u = 40\text{cm}$$

Example (4) An image which is ten times the size of the object is formed on the wall by a convex lens of focal length 10 cm. (a) How far is the object from the lens? (b) How far is the wall from the lens?

(a) magnification $m = -\frac{v}{u}$

Since the image is real and inverted $v = 10\,u$;

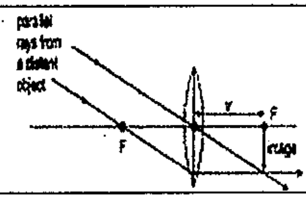
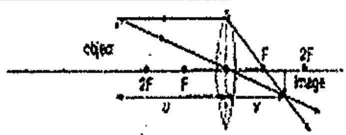
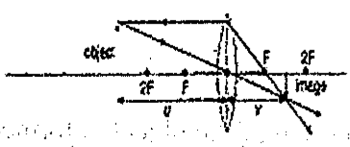
$$-10 = -\frac{v}{u}$$

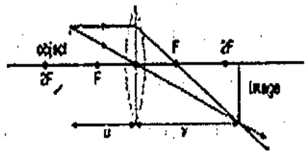
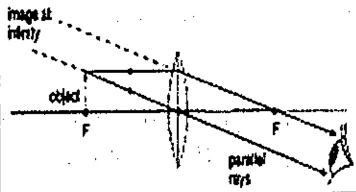
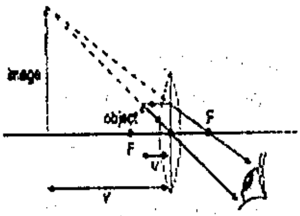
$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}; \quad \frac{1}{u} + \frac{1}{10u} = \frac{1}{+10}$$

$\frac{10 + 1}{10\,u} = \frac{1}{10}$; $u = 11$ cm. The object is 11 cm from the lens.

(b) $v = 10\,u = 10 \times 11 = 110$ cm. The wall is 110 cm from the lens.

Table 6.1 Images formed by a thin converging lens

Object distance (u)	Ray diagram	Type of Image	Image distance (v)	Uses
u=∞		Inverted real diminished	v = f opposite side of the lens	object lens of a telescope
u>2f		inverted real diminished	f < v < 2f opposite side of the lens	camera; eye
u=2f		inverted real same size	v = 2f opposite side of the lens	photocopier making equal-sized copy

f< u<2f		inverted real magnified	v > 2f opposite side of the lens	projector; photograph enlarger
u=f		upright magnified virtual	image at infinity; same side of the lens	to produce a parallel beam of light, as in a spotlight
u<f		upright magnified virtual	image is behind the object; same side of the lens	magnifying glass

EXERCISES

1. (a) What is a lens ?
   (b) What do you understand by focus of a convex lens and focus of a concave lens?

2. Choose the correct answer from the following.
   When a pencil 10 cm long is placed vertically 100 cm from a lens of focal length + 50 cm, the image is (a) erect and 5 cm tall. (b) inverted and 5 cm tall. (c) erect and 10 cm tall. (d) inverted and 10cm tall.

3. Choose the correct answer from the following.
   The image of an object which is 10 cm from a lens is formed on the same side as the object. If the image is 10 cm from the object, the focal length of the lens is
   (a) +6.7 cm. (c) +20cm.
   (b) -6.7 cm. (d) -20cm.

4. Choose the correct answer from the following.
   The human eye has a lens of focal length + 5 cm. The power of the eye is
   (a) 0.05 D. (c) 5 D.
   (b) 0.02 D. (d) 20 D.

5. State the sign conventions for lenses. Explain why sign conventions are used.

6. What is the major difference between real and virtual images? Draw ray diagrams to show how the real and virtual images can be formed by a convex lens.

7. The virtual image of an object is formed 24 cm from a lens of focal length 8cm. (a) Find the distance between the object and the lens. (b) How far must the object be placed from the lens to obtain a real image of the same size as the virtual image obtained previously?

8. An object 3 cm tall is 30 cm from a convex lens of focal length 20 cm. (a) Find the size of the image and the image distance. (b) If the object is moved 5 cm closer to the lens how far does the image move?

9. (a) State the properties of an image formed by a concave lens.
   (b) How far must the object be placed from a concave lens of focal length 10cm to obtain an image 4 cm from the lens? Draw a ray diagram to show the formation of the image.

10. A magnifying glass of focal length 9 cm is used to produce an image which is three times the size of an object. How far must the magnifying glass be placed from the object?

11. An object is placed 60 cm in front of a screen. Is it possible to obtain a sharp image larger than the size of an object on the screen by placing a convex lens of focal length 15 cm somewhere between the screen and the object? Answer this by doing the necessary calculations. What changes can occur when the object and the screen are interchanged?

12. An object is placed 18 cm from a screen. Where must a lens of focal length 4 cm be placed between the screen and the object to produce an image on the screen?

13. When an object is placed 12 cm from a convex lens a real image formed is three times the size of the object. If a real image which is four times the size of the object is required, how far must the object be moved?

14. An object 1.05 cm tall is 80 cm away from the screen and the size of its image on the screen is 0.35 cm. Find the position and focal length of the lens.

15. Determine the nature of the images formed in the mirrors and the lens for the magnifications given below
    (a) magnification is between -1 and 0 (b) magnification is between 0 and +1
    (c) magnification is greater than 1.

ADDITIONAL EXERCISES

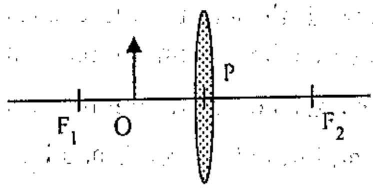
1 In the diagram, F_1 and F_2 are the principal foci and P is the optical centre.

The image of the object at O is:

(i) on the left of O

(ii) larger than the object

(iii) virtual



A (i) only

B (ii) only

C (iii) only

D (ii) and (iii) only

E (i)(ii)(iii)

2 IF the image of an object in a converging lens has the same size as the object then the object distance is: (f = focal length of lens)

A ½ f

B f

C 1½ f

D 2f

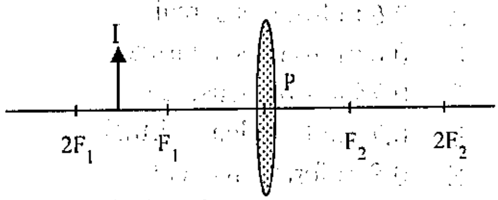
E infinity

3 I is the image formed in a converging lens. The object is:

(i) situated between F_2 and $2F_2$

(ii) smaller than the image

(iii) inverted with respect to the image



A (i) only

B (ii) only

C (iii) only

D (ii) and (iii) only

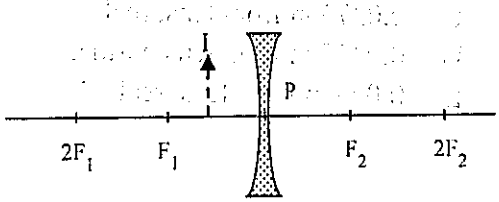
E (i) (ii) (iii)

4 The object whose image is I is:

(i) larger than the image

(ii) erect with respect to the image

(iii) situated on the left of I



A (i) only

B (ii) only

C (i) and (ii) only

D (ii) and (iii) only

E all of them

5 An object situated at focus F_1 is moved away from the lens as shown. The image will move

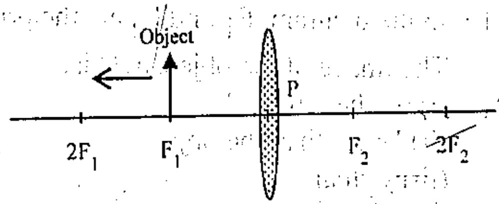
A away from the lens

B towards the lens until it reaches P

C towards the lens until it reaches $2F_2$

D towards the lens until it reaches F_2

E to and from between C and F_2



6 If the object is moved away from the lens as shown, then its image will:

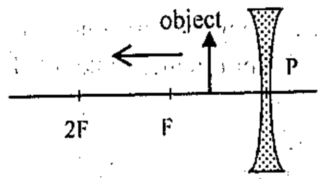
(i) move towards the lens

(ii) move away from the lens but cannot go beyond 2F

(iii) move away from the lens but cannot go beyond F

(iv) becomes larger and larger

(v) becomes smaller and smaller



A (i) (iv) only

B (i) (v) only

C (iii) (iv) only

D (ii) (v) only

E (iii) (v) only

7 An object is placed 0.2 m from a converging lens of focal length 0.15 m. The image formed is:

A 0.6 m from lens, real

B 0.6 m from lens, virtual

C 0.75 m from lens, real

D 0.75 m from lens, virtual

E 0.8 m form lens, real

8 In the previous question, if the object distance is 0.05 m the image is:

A 0.075 m from lens, real

B 0.075 m from lens, virtual

C 0.0375 m from lens, real

D 0.0375 m from lens, virtual

E 0.025 m form lens, real

9 A four time magnified erect image is formed if an object place at 0.1 m from a converging lens. The image distance is

A 0.4 m on same side as object

B 0.4 m on opposite side to object

C 0.025 m on same side as object

D 0.025 m on opposite side to object

E cannot be determined because it is not given whether the image is real or virtual

10 The focal length of the lens is:

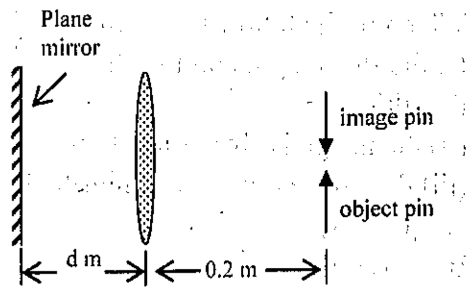
A 0.1 m

B 0.2 m

C (0.2−2d) m

D (0.2+2d) m

E (0.2−d) m



11 When the eye looks into the mirror, the beam seems to diverge from I. Find the focal length of the lens.

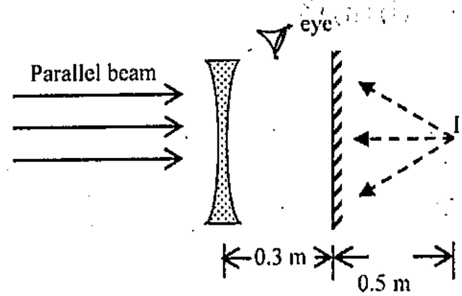
A 0.8 m

B 0.5 m

C 0.3 m

D 0.2 m

E 0.1 m



12 The value of x is:

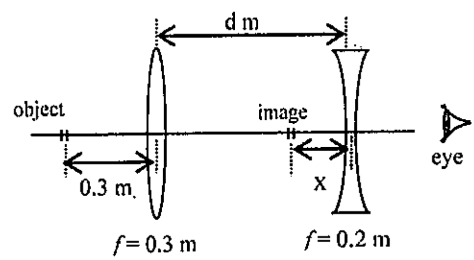
A 0.1 m

B 0.2 m

C 0.3 m

D 0.5 m

E cannot be determined because d is not given



13 In the previous question, if the object is now placed at 0.4 m from the converging lens, what is the value of x?

A 0.1 m

B 0.2 m

C 0.3 m

D 0.5 m

E cannot be determined because of d is not given

14 Which of the following statements about a camera is/are true?

(i) the diaphragm and the shutter regulates the amount of light energy falling on the film

(ii) the image is always inverted

(iii) the image is always diminished

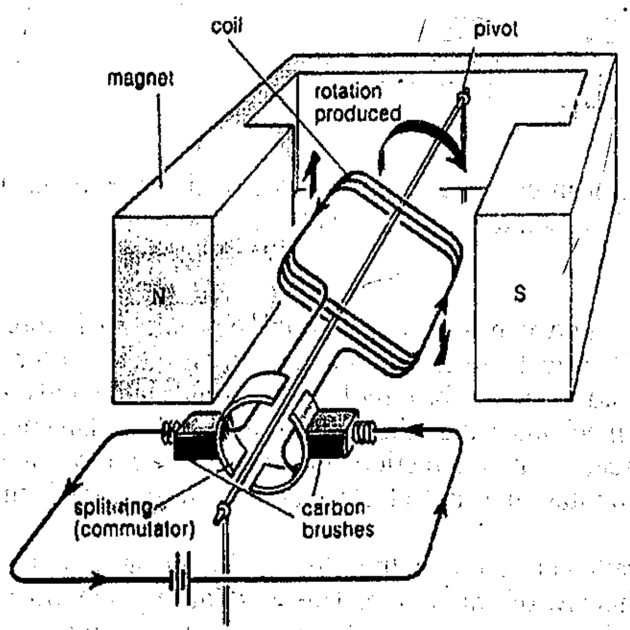
A (i) only

B (ii) only

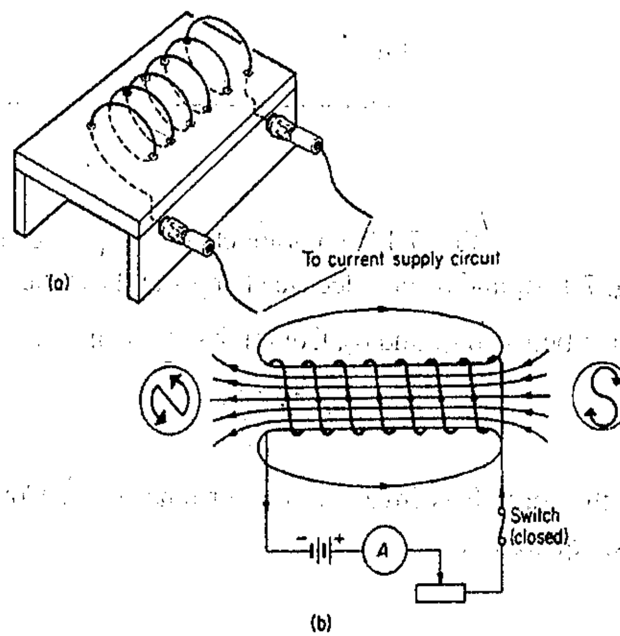
C (iii) only

D (i) and (ii) only

E (i) (ii) (iii)



ELECTRICITY AND MAGNETISM



Magnetic flux pattern due to current in a solenoid

CHAPTER 7

THE ELECTRIC FIELD

Two electric charges, which are not in contact, can exert electrical forces on each other. The concept of electric field is used to explain this phenomenon.

7.1 COULOME'S LAW

Just as there is a gravitational force between two masses so there is an electric force between two charged particles. Electrical forces bind electrons and nuclei to form atoms. In addition, these forces hold atoms to form molecules, liquids and solids. It has already been mentioned in mechanics that there are only four fundamental forces, namely, gravitational force, weak interaction, electromagnetic force and nuclear force. Of these forces gravitational and electromagnetic forces are long-range forces.

Based on the values of measurements taken in the study of planetary motion, Newton was able to put forward his law of gravitation. This is because gravitational forces are appreciable only when the masses of the bodies are very large. However, the law that electrical forces obey can be readily determined in the laboratory because these forces are so much greater in magnitude than gravitational forces.

The French scientist, Coulomb, studied systematically the attractive and repulsive forces acting between pairs of charges and discovered a certain law. This law is called **Coulomb's law** and it states that:

The electric force between two charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them.

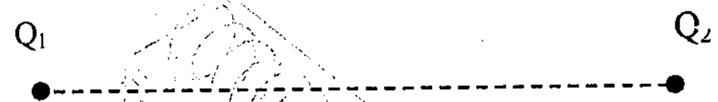


Fig. 7.1 Two point charges separated by a distance

In Fig. 7.1, q_1 and q_2 are electric charges and r is the distance between them. If F is the force between q_1 and q_2, Coulomb's law can be expressed as

$$F = K\frac{Q_1Q_2}{r^2} \tag{7.1}$$

Since the force F is inversely proportional to r^2, Coulomb's law is also called an inverse square law.

In equation 7.1, K is a constant. The value of K depends upon the units of F, Q_1, Q_2 and r and upon the medium in which the charges Q_1 and Q_2 are located.

Electrical force is, of course, a vector quantity. Equation (7.1) only gives the magnitude of the force between two electric charges. The direction of electrical force is always along the line joining the two charges. If the charges are like charges the force between them is repulsive and is directed outward. If the charges are unlike charges the force between them is attractive and directed inwards. Fig. (7.2)

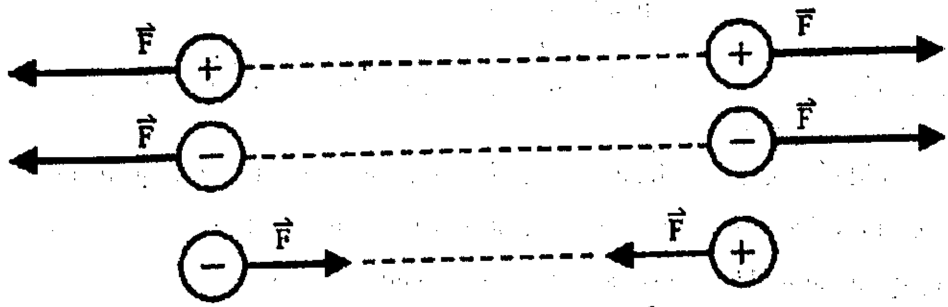


Fig. 7.2 Direction of force between two charges

In the SI system, charge q is measured in coulomb, the distance r in metre and the force F in newton. In the SI system,

$$K = \frac{1}{4\pi\varepsilon_0}$$

where ε is a constant called the permittivity of the medium in which the charges are located. Then, equation (7.1) can be rewritten as

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1 Q_2}{r^2}$$

When charges are located in vacuum, and the value of K in air is approximately equal to that of K in vacuum, $K = \frac{1}{4\pi\varepsilon_0}$ where ε_0 is the permittivity of vacuum and

$\varepsilon_0 = 8.85 \times 10^{-12} C^2 N^{-1} m^{-2}$, and the value of K in vacuum is

$$K = \frac{1}{4\pi\varepsilon_0} = \frac{1}{4\pi \times 8.85 \times 10^{-12}} = 8.98742 \times 10^9 Nm^2C^{-2}$$

However, for convenience in calculation, the value of K in vacuum will be taken as

$$K = 9 \times 10^9 \, N\, m^2 C^{-2}$$

Therefore,

$$F = \frac{1}{4\pi\varepsilon_0} \frac{Q_1 Q_2}{r^2}$$

Coulomb's law equation in vector form is

$$\bar{F} = K \frac{Q_1 Q_2}{r^2} \hat{r}$$

$\hat{r}$ is the unit vector, its direction is always along the line joining between two charges and outward.

It should be noted that the above reminds one of the expression for the gravitational force introduced by Sir Isaac Newton but gravitational force between two masses m_1, m_2 separated by a distance r which is an attractive interaction

$$\bar{F} = -G \frac{m_1 m_2}{r^2} \hat{r}$$

whereas the Coulomb force may be attractive or repulsive depending on sign the charges carry. $G = 6.67 \times 10^{-11}$ J m^2 kg^{-2} here represents gravitational constant

Example (1) Find the force between two charges of 1 C each that are 1 m apart.

$Q_1 = 1$ C, $Q_2 = 1$ C, r = 1 m

$$F = \frac{1}{4\pi\varepsilon_0} \frac{Q_1 Q_2}{r^2}$$

$$= 9 \times 10^9 \, N\, m^2 C^{-2} \times \frac{1C \times 1C}{1m^2}$$

$$= 9 \times 10^9 \, N$$

Example (2) (a) Calculate the values of two equal charges if they repel one another with a force of 0.1 N when situated 50 cm apart in vacuum. (b) Calculate the values of two equal charges if they repel one another with a force of Q 1 N when situated 50 cm apart in a liquid whose permittivity is 10 times that of vacuum.

(a) r = 50 cm = 0.5 m, F = 0.1 N

$$F = \frac{1}{4\pi\varepsilon_0} \frac{Q_1 Q_2}{r^2}$$

Since they are equal charges, $Q_1 = Q_2 = Q$

Therefore, $$F = \frac{1}{4\pi\varepsilon_0}\frac{Q^2}{(0.5)^2}; \quad 0.1 = 9\times10^9 \times \frac{Q^2}{(0.5)^2}$$

$$Q^2 = \frac{0.1\times(0.5)^2}{9\times10^9}; \quad Q = 1.67\times10^{-6}\ C = 1.67\ \mu C$$

(b) The permittivity of the liquid medium $\varepsilon = 10\,\varepsilon_0$

$$F = \frac{1}{4\pi\varepsilon}\frac{Q_1Q_2}{r^2} = \frac{1}{10(4\pi\varepsilon_0)}\frac{Q^2}{r^2}$$

$$0.1 = \frac{9\times10^9}{10}\frac{Q^2}{(0.5)^2}$$

$$Q^2 = \frac{0.1\times(0.5)^2\times10}{9\times10^2}$$

$$Q = 5.27\times10^{-6}\ C = 5.27\ \mu C$$

Example (3) If the force acting on a charge Q, 6 cm from a charge of $+50\times10^{-8}$ C is 0.24 N, find the magnitude of Q.

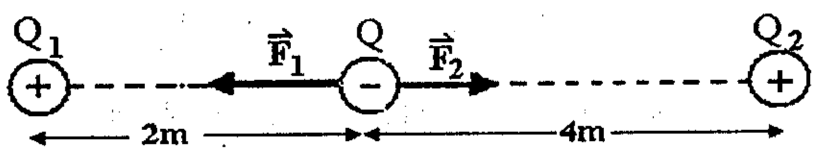
$Q_1 = 50\times10^{-8}$ C, $Q_2 = Q$, r = 6 cm = 0.06 m, F = 0.24 N

$$F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{r^2}$$

$$0.24 = 9\times10^9\times\frac{50\times10^{-8}Q_2}{(0.06)^2}$$

$$Q = \frac{0.24\times(0.06)^2}{9\times10^9\times50\times10^{-8}} = 1.92\times10^{-7}\ C$$

Example (4) Find the force on the centre charge q in the figure shown below. ($Q_1 = +4\times10^{-6}$ C, $Q = -5\times10^{-6}$ C and $Q_2 = +6\times10^{-6}$ C)



$$F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{r^2}$$

The attractive force on Q exerted by Q_1,

$$F_1 = \frac{9\times10^9\times(4\times10^{-6})\times(5\times10^{-6})}{2^2}$$

$$= 0.05\ N$$

$\vec{F}$ is directed toward Q_1.

The attractive force on Q exerted by Q_2,

$$F_2 = \frac{9\times10^9\times(5\times10^{-6})\times(6\times10^{-6})}{4^2}$$

$$= 0.02\ N$$

$\vec{F}$ is directed toward Q_2, the resultant force acting on Q is

$$\vec{F} = \vec{F_1} + \vec{F_2}$$

Since $\vec{F_1}$ and $\vec{F_2}$ are opposite forces

$$F = F_1 - F_2$$

$$= 0.05 - 0.02$$

$$= 0.03\ N$$

$\vec{F}$ is directed toward Q_1.

7.2 ELECTRIC FIELD AND ELECTRIC FIELD INTENSITY

When a positive charge q is brought close to another positive charge Q, which is placed at a point, the charge q is found to be acted upon by a repulsive force. The repulsive force becomes greater as q gets nearer to Q. That is, Q has a field surrounding it where electric forces due to it may act. In other words, Q produces or sets up an electric field around it.

Fig. 7.3 Electric Field around charged bodies

In Fig.7.3 the force is exerted on q directly by the electric field produced by Q. Even though q is removed, the electric field of Q still exists. In addition, if q is placed at any other point in the vicinity of Q, it will be found that a repulsive force due to electric field of Q still acts on q. Since Q also experiences a repulsive force, q is said to produce an electric field in its vicinity. *An electric field, therefore, can be defined as a region where electrical forces act.*

Not just the positive charges but the negative charges as well are surrounded by electric fields.

We may say, then, that *any electric charge gives rise to an electric field in its vicinity.*

In order to test whether an electric field exists at a certain point, a test charge must be placed at that point. If an electric force is exerted on the test charge, then we can say that an electric field exists at the point under consideration. Generally, a *unit positive charge is considered as a test charge.*

The Electric Field Intensity

We have seen that when an electric charge is placed in an electric field a force is exerted on it. If the charge is moved from a point to another point in the field, the magnitude and direction of the force acting upon it will change. This means that the magnitude and direction of the force acting upon the charge will change in accordance with the change in position of the charge. It is necessary to know the electric field intensity in order to specify an electric field. The electric field intensity is defined as follows.

The electric field intensity at a point in an electric field is the electric force acting upon a unit positive charge placed at that point. The electric field intensity is a vector quantity. The electric field intensity is represented by $\vec{E}$.

In Fig. 7.3 the force on q exerted by Q is $\vec{F}$.

The force exerted by Q on a unit positive charge is $\frac{\vec{F}}{q}$.

Since the force acting upon a unit positive charge is the electric field intensity, the electric field intensity $\vec{E}$ can be expressed as

$$\vec{E} = \frac{\vec{F}}{q} \qquad (7.2)$$

From equation (7.2) we see that the direction of $\vec{E}$ is the same as that of $\vec{F}$. In the SI system the unit of electric force $\vec{F}$ is newton (N) and the unit of electric charge q is coulomb (C). Thus, the unit of electric field intensity $\vec{E}$ is newton per coulomb ($N\,C^{-1}$)

Equation (7.2) can be rewritten as

$$\vec{F} = q\vec{E}$$

If the values of q and $\vec{E}$ are known the force $\vec{F}$ acting upon q can be calculated from the above equation.

Calculation of the Electric Field Intensity from Coulomb's Law

The electric field intensity at a point, a certain distance from the charge, can be calculated by using Coulomb's law.

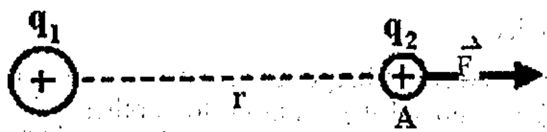


Fig. 7.4 Force on a charge in an electric field

We shall consider the electric field surrounding the charge Q, shown in Fig. 7.4 and then find the electric field intensity at a point A in the field, at a distance r from Q. Suppose that a small positive charge q is placed at A.

By Coulomb's law the force F on q due to Q is

$$F = \frac{1}{4\pi\varepsilon}\frac{Qq}{r^2}$$

The force on a unit positive charge due to Q is by definition the electric field intensity; thus

$$\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}\hat{r} \qquad (7.3)$$

Equation (7.3) gives the magnitude of the electric field intensity at the point A.

In the SI system the unit of the charge Q is coulomb (C) and the unit of distance r is metre (m). When these units and the SI unit of $\frac{1}{4\pi\varepsilon_0}$ are used in equation (7.3), the unit of E is newton per coulomb (NC^{-1}).

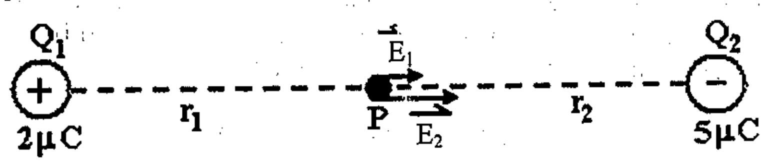
The direction of the electric field intensity at the point A is *along the line joining q and Q and away from Q.*
If a negative charge Q is put in place of the positive charge Q, the magnitude of the electric field intensity at the point A will not change. But its direction will be along the line joining q and Q and towards Q.
If the resultant electric field intensity at a point due to two or more charges is to be found, the vector sum of the electric field intensities at that point must be taken. This means that if the electric field intensities at a point due to the charges are $\vec{E}_1, \vec{E}_2, \vec{E}_3, \ldots\ldots\ldots\ldots$, then the resultant electric field intensity E at that point is

$$\vec{E} = \vec{E}_1 + \vec{E}_2 + \vec{E}_3 + \ldots\ldots\ldots\ldots \qquad (7.4)$$

Example (5) The magnitude of electric field intensity at a point in an electric field is $2\times10^5\,\text{NC}^{-1}$. If a charge of magnitudes $5\times10^{-6}\,\text{C}$ is placed at that point, find the magnitude of the force on that charge.

$$E = 2\times10^5\,\text{NC}^{-1}, \quad q = 5\times10^{-6}\,\text{C}$$
$$F = qE$$
$$= 5\times10^{-6}\,\text{C} \times 2\times10^5\,\text{NC}^{-1}$$
$$= 1\text{ N}$$

Example (6) Two charges of $+2\,\mu\text{C}$ and $-5\,\mu\text{C}$ are 6 m apart. Find the electric field intensity at the point P midway between them.



$Q_1 = 2\,\mu\text{C} = 2\times10^{-6}\,\text{C}, \quad Q_2 = 5\,\mu\text{C} = 5\times10^{-6}\,\text{C}$

$r_1 = 3\text{ m} \qquad r_2 = 3\text{ m}$

If E_1 = the magnitude of the electric field intensity of P due to Q_1

$$E_1 = \frac{1}{4\pi\varepsilon_0}\frac{Q_1}{r^2}$$

$$= 9\times10^9 \times \frac{2\times10^{-6}}{3^2}$$

$$= 2\times10^3\,\text{NC}^{-1}$$

The direction of $\vec{E}$ is to the right (toward - 5 μC)

If E_2 is the magnitude of the electric field intensity at P due to Q_2

$$E_2 = \frac{1}{4\pi\varepsilon_0}\frac{Q_2}{r^2}$$

$$= 9 \times 10^9 \times \frac{5\times10^{-6}}{3^2}$$

$$= 5 \times 10^3\ NC^{-1}$$

The direction of $\vec{E}$ is to the right (toward – 5 μC)
$\vec{E}$ and $\vec{E}$ are in the same direction.

Therefore $\vec{E} = \vec{E}_1 + \vec{E}_2$

The magnitude of the resultant electric intensity at P is

$$E = E_1 + E_2 = 2 \times 10^3 + 5 \times 10^3 = 7 \times 10^3\ NC^{-1}$$

The direction of $\vec{E}$ is to the right (toward -5 μ C).

Example (7) If the magnitude of the electric field intensity at a point 9 m from a charge + Q is 2×10^3 N C^{-1} (a) find the magnitude of + Q ; (b) find the magnitude of the electric field intensity at a point 18 m from + Q.

(a) $E = 2 \times 10^3\ N C^{-1}$, $r = 9$ m

$$E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$$

$$2 \times 10^3 = 9\times 10^9 \times \frac{Q}{9^2}$$

$$Q = 2 \times 10^3 \times 9\times 10^{-9}$$

$$= 18 \times 10^{-6} C$$

$$= 18\ \mu C$$

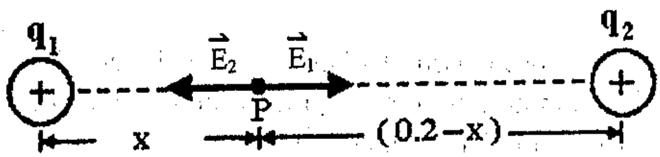
(b) $r = 18$ m

$$E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$$

$$= 9\times 10^9 \times \frac{18\times10^{-6}}{(18)^2}$$

$$= 500\ NC^{-1}$$

Example (8) A charge $+1.5\times10^{-6}$ C is 0.2 m away from another charge $+3\times10^{-6}$C. Where is the electric field in their vicinity equal to zero?



$q_1 = 1.5\times10^{-6}$ C, $q_2 = 3\times10^{-6}$ C, $r = 0.2$ m

The electric field intensity is the force acting upon a unit positive charge. Thus forces acting on a unit positive charge will be in opposite directions only when the unit charge is at any point between q_1 and q_2. In addition, the resultant electric field intensity at that point will be zero only when the point is further away from q_2 (which has greater magnitude) than from q_1. It will be assumed that the resultant electric field intensity at the point P, x m from q_1 is zero.

The electric field intensity at P due to q_1 is $E_1 = \frac{1}{4\pi\varepsilon_0}\frac{q_1}{x^2}$

The electric field intensity at P due to q_2 is $E_2 = \frac{1}{4\pi\varepsilon_0}\frac{q_2}{(0.2-x)^2}$

Since the electric field intensity at P is zero,

$$E_1 = E_2$$

$$\frac{1}{4\pi\varepsilon_0}\frac{q_1}{x^2} = \frac{1}{4\pi\varepsilon_0}\frac{q_2}{(0.2-x)^2}$$

$$\frac{q_1}{x^2} = \frac{q_2}{(0.2-x)^2}$$

$$\frac{1.5\times10^{-6}}{x^2} = \frac{3\times10^{-6}}{(0.2-x)^2}$$

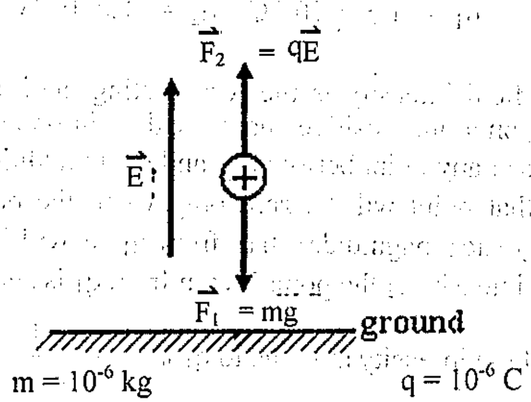
$$\frac{1}{x^2} = \frac{2}{(0.2-x)^2}$$

$$(0.2-x)^2 = 2x^2$$

$$0.2 - x = 1.414\,x$$

$$x = 0.08\text{ m}$$

Example (9) A body whose mass is 10^{-6} kg carries a charge $+10^{-6}$ C. If the body is suspended in equilibrium at a point above the ground by an electric field, find the magnitude of the electric field. ($g = 9.8\text{ ms}^{-2}$)



The gravitational force on the body $F_1 = mg$

If the magnitude of the electric field which lifts the body is E, the electric force acting on the body is $F_2 = qE$. Since the body is in equilibrium

$$F_1 = F_2$$

$$mg = qE$$

$$E = \frac{mg}{q}$$

$$= \frac{10^{-6}\times9.8}{10^{-6}} = 9.8\text{ NC}^{-1}$$

7.3 ELECTRIC LINES OF FORCE

Although there exists an electric field in the vicinity of an electric charge, the electric field, however, cannot be seen at all. The concept of lines of force was introduced by Faraday as an aid in visualizing an electric field. Electric lines of force do not really exist. They are only imaginary lines.

An electric line of force is a path such that the tangent, drawn at any point on it, indicates the direction of the electric field at that point.

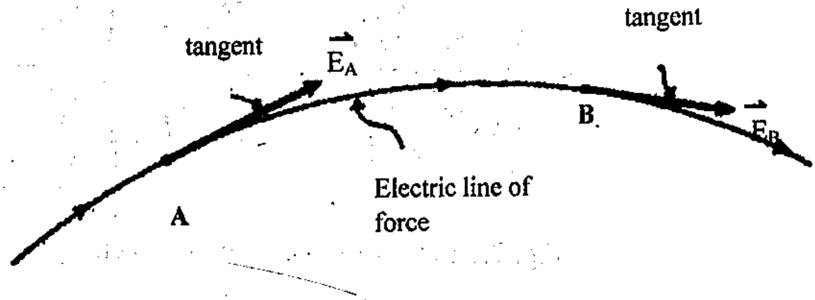


Fig. 7.5 Finding the direction of electric field intensity

The directions of the electric field intensities E_A and E_B at the points A and B on an electric line of force can be drawn tangent to the line of these points shown in Fig.7.5.

The electric lines of force around a positive charge Q can be drawn as follows. A small positive charge is placed at a point near Q. An arrow which points in the direction of the force acting on that charge is drawn. The length of the arrow is drawn so that it is directly proportional to the magnitude of the force. The above procedure is repeated by placing that positive charge at other points around Q [Fig.7.6 (a)]. By Coulomb's law the magnitude of the force on q gets smaller as q gets further away from Q. Accordingly, the length of arrow gets shorter as q gets further away from Q. When the arrows having the same direction are joined, the electric lines of force as shown in Fig. 7.6(b) are obtained.

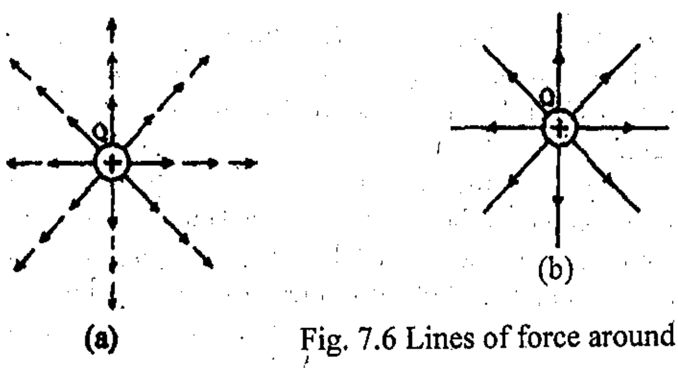


Fig. 7.6 Lines of force around a positive charge

The electric lines of force around two equal charges, one positive and one negative, are shown in Fig. 7.7(a), Fig. 7.7(b) shows the electric lines of force around two equal positive charges. In drawing these electric lines of force the arrows are drawn by using a small positive charge at various positions. When the arrows are joined to obtain smooth curves, the electric lines of force shown in Fig. 7.7 are obtained.

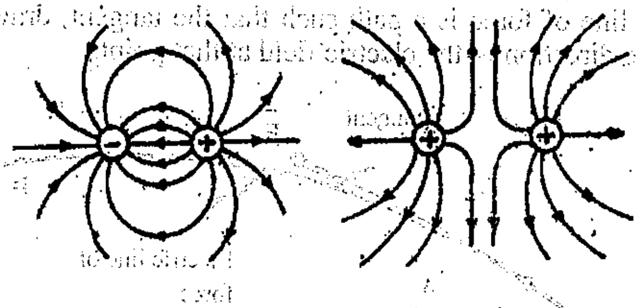


Fig. 7.7 Lines of force around two charges

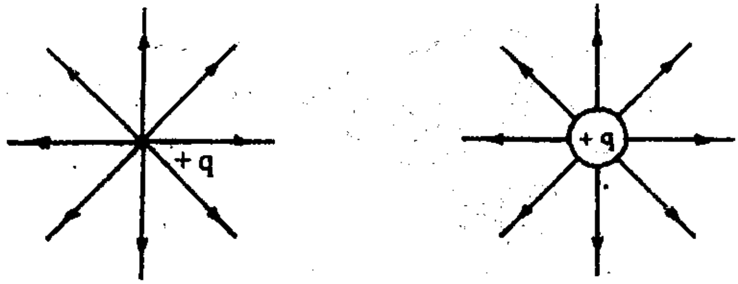
Since, in general, the direction of the electric field varies from point to point, the electric lines of force are usually curves. In order to know the direction of the electric field at a point on the electric line of force a tangent must be drawn at that point. An arrowhead on the electric line of force indicates the direction in which the tangent is to be drawn. The electric lines of forces in an electrostatic field are continuous lines which start from a positive charge and end on a negative charge. If a small positive charge is placed in the electric field it will move along a particular electric line of force.

In Fig.7.6 (a) the electric lines of force around a single positive charge are directed radially outward. They will terminate on negative charges situated at infinity. It can be seen from Figs. 7.6 and 7.7 that the electric lines of force are close together when the electric field intensity is large and far apart when the electric field intensity is small. In addition, the electric lines of force never intersect. Because the electric field intensity at any point can have only one direction, only one electric line of force can pass through that point.

The Electric Field around a Charged Metal Sphere

Suppose that a positive charge q is given to a metal sphere. Since the individual electric charges which form the charge q repel each other, they will move on the surface of the sphere.

They will stop moving when they are as far apart as possible and the charge q spreads out uniformly on the surface of the sphere. Thus, the electric field around a point charge q and that around a metal sphere carrying a charge q can be represented by the same number of electric lines of force. In addition, the pattern of electric lines of force around a point charge q is identical with that around a metal sphere carrying a charge q (Fig. 7.8)



Point charge metal sphere

Fig. 7.8 Similarity of lines of force around a charge q

It is known from experiments that when a positive charge q is given to a hollow metal sphere, *the charges are uniformly distributed only on the outer surface of the sphere.* Also, when a charge is given to a conducting object of any shape the charge is found to be spread out over the outer surface of the object. But the charge is not uniformly distributed. The more highly curved parts of the objects have greater concentration of charge than the less curved parts.

Therefore, we can say that charges are highly concentrated at the pointed portion of the object (Fig. 7.9). For a charged pointed rod shown in Fig. 7.9(d) the charge concentration at the pointed end is so large that some of the charges leak off into the air. This makes a pointed rod very useful as a lightning conductor.

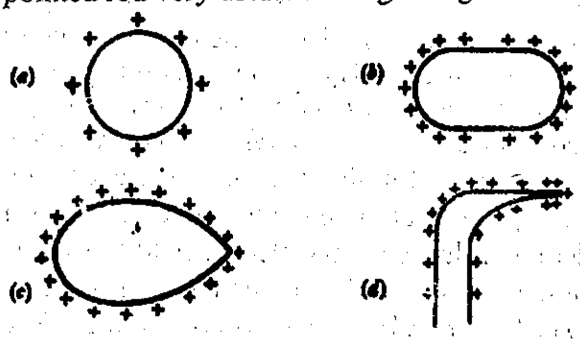


Fig. 7.9 Charge distribution on a conductor

Lightning Conductor

Copper rods are used as lightning conductors because of higher conductivity (Fig. 8.10). The copper rod is fixed to an outside wall of the building so that its pointed end reaches above the highest part of the building. The other end is connected to a copper plate buried in the earth. When a thundercloud containing charged particles of water passes over the building it induces an opposite charge in the lightning conductor. When the charge is concentrated at the pointed end it leaks off gradually and neutralizes the charge of the cloud. In this way lightning discharge is prevented. Even if lightning occurs the electric discharge passes harmlessly to the earth through the lightning conductor. The lightning, therefore, does not strike the building.

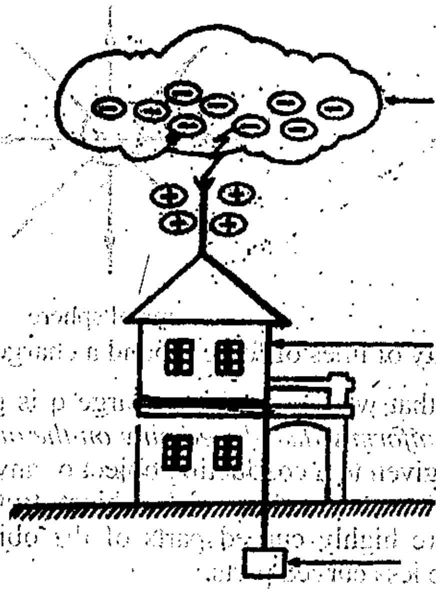


Fig. 7.10 Use of a lightning conductor

The Electric Field in a Charged Conducting Object

It has been stated that there is an electric field surrounding a charged conducting object. However, the electric fields due to the individual charges on the surface of the charged conducting object *all cancel out inside the object. Therefore, the electric field is zero everywhere inside a charged conducting object of any shape.*

If there were an electric field in the interior of the charged conducting object, the charges inside the object that are free to move (free electrons in the case of a metal) would move under the influence of the electric field E. But the motion of charges or the current is not observed in a charged conducting object. *Therefore the electric field is zero everywhere inside a charged conducting object of any shape* (Fig. 7.11).

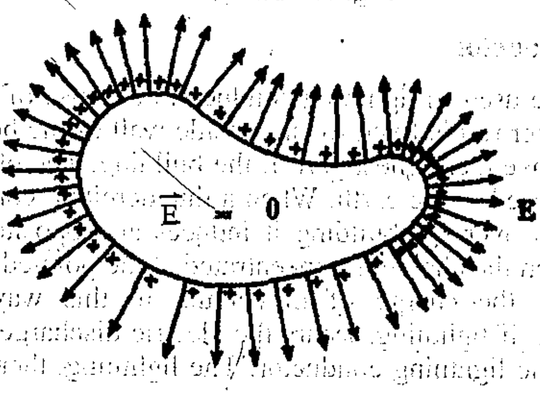


Fig. 7.11 Field inside a charged object

Non-uniform Electric Field and Uniform Electric Field

We see from equation 7.3 that the magnitude of the electric field intensity E at a point, situated at a distance r from the charge Q, is inversely proportional to r^2. This means that the magnitude of the electric field intensity around Q depends on the distance from Q. Thus, the electric field intensity around Q varies from point to point. Such an electric field is called a non-uniform electric field.

In Fig.7.6 (b) the electric field around Q is represented by the electric lines of force. The electric lines of force near Q are close together while those away from Q are far apart. The electric field around Q is a non-uniform electric field. We can therefore say, that the electric lines of force, which represent a non-uniform electric field, are not parallel.

If, in a certain region of space, the electric field intensity at every point is the same in magnitude and direction, the electric field in that region of space is called a uniform electric field.

As shown in Fig. 7.12 a uniform electric field is represented by uniformly spaced parallel lines of the same length. The arrows indicate the direction of the electric field.

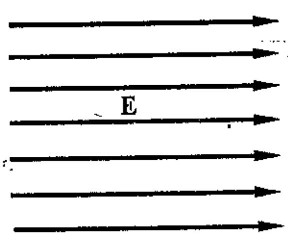


Fig. 7.12. Uniform field

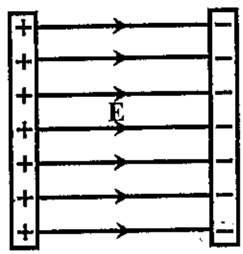


Fig. 7.13 Field between two parallel plates

Two parallel metal plates in (Fig. 7.13) have charges of equal magnitude but opposite sign. The majority of charges are distributed on the inner surfaces of the plates. Except for the field near the ends of the plates, the electric field between the plates is uniform and the electric lines of force between the plates are *equally spaced and parallel.*

Example (10) An electron of charge 1.6×10^{-19} C is situated in a uniform electric field of intensity 1.2×10^{5} NC^{-1}. (a) Find the force on the electron. (b) Find the acceleration of the electron. (c) How long does the electron take to travel a distance 20 mm from rest? (Mass of electron = 9.1×10^{-31} kg)

$q = 1.6 \times 10^{-19}$ C, $E = 1.2 \times 10^{5}$ NC^{-1}

(a) The force on the electron $F = qE$

$$= 1.6 \times 10^{-19} \text{ C} \times 1.2 \times 10^{5}$$

$$= 1.92 \times 10^{-14} \text{ N}$$

(b) If a is the acceleration of the electron, $F = ma$.

$$a = \frac{F}{m} = \frac{1.92\times10^{-14}}{9.1\times10^{-31}} = 2.11\times 10^{16} \text{ ms}^{-2}$$

(c) $s = 20$ mm $= 0.02$ m

Since the electron starts from rest, $v_0 = 0$. Therefore, $s = \frac{1}{2}at^2$

$$t = \sqrt{\frac{2s}{a}}$$

$$= \sqrt{\frac{2 \times 0.02}{2.11 \times 10^{16}}}$$

$$= 1.37 \times 10^{-9} \text{ s}$$

EXERCISES

1. (a) State Coulomb's law in words as well as in symbols.
   (b) State the similarity and the difference between Newton's gravitational law and Coulomb's law.
2. When a plastic comb is run through dry hair for a long time the comb becomes a charged body and attracts small pieces of paper, although the plastic comb is negatively charged, the pieces of paper are initially uncharged. Explain why the comb can attract the pieces of paper.
3. A positive charge of 4.0×10^{-6} C exerts a force of repulsion of 7.2 N on a second charge 0.25 m away. What is the sign and magnitude of the second charge?
4. Find the force between two charges of $+1\ \mu$C and $+2\ \mu$C when they are 0.03 m in apart.

5. A hydrogen atom is composed of a proton and an electron at a distance of 5.3×10^{-11} m from each other. The magnitude of the charge on each particle is 1.6×10^{-19} C. Compute the attractive farce between them.
6. Two charges of unknown magnitude and sign are observed to repel one another with a force of 0.1 N when they are 5 cm apart. Find the repulsive force between them when they are (a) 10 cm apart (b) 50 cm apart (c) 1 cm apart.
7. Two charges, $+1 \times 10^{-4}$ C and -1×10^{-4} C, are 40 cm apart. A particle carrying a charge of $+ 6 \times 10^{-5}$ C is located halfway between them. If all charges lie on the same straight line, find the force acting on the charge located halfway between them.
8. A small sphere carrying a charge of $+ 2 \times 10^{-4}$C is 0.1 m from another small sphere carrying a charge of -5×10^{-4} C. Find the magnitude and the direction of the force exerted by the -5×10^{-4} C charge on the $+ 2 \times 10^{-4}$ C charge.
9. How far apart are two electrons if the force each exerts on the other is equal to the weight of an electron? ($g = 10 \text{ m s}^{-2}$)
10. A test charge of -5×10^{-5} C is placed between two other charges so that it is 5cm from a charge of -3×10^{-5} C and 10 cm from a charge of $- 6 \times 10^{-5}$ C. If the three charges lie on a straight line find the magnitude and, the direction of the force on the test charge.
11. Two metal spheres of the same size, one with a charge of $+ 2 \times 10^{-5}$ C and the other with a charge of -1×10^{-5} C are 10 cm apart. (a) What is the force between them? (b) The two spheres are brought into contact, and then separated again to 10 cm. What is the force between them now?
12. An electron has a mass of 9.1×10^{-31} kg and an electric charge of -1.6×10^{-19} C. The gravitational force between two bodies of mass m and M a distance d apart is

$$F = G\frac{Mm}{d^2}$$

where $G = 6.6 \times 10^{-11} \text{N m}^2 \text{kg}^{-2}$. Compare the gravitational and electrical forces acting between two electrons.
13. To perform a process of charging by induction, a charged rod is placed near two uncharged metal spheres of the same size which are initially in contact, then the spheres are separated while the rod is still in position. They are found to attract each other with a force of 9×10^{-5} N when 10 cm apart. How many electrons

moved from one sphere to the other during the process of charging by induction?

14. Choose the correct answer from the following.

Electric lines of force

(a) exist everywhere.

(b) exist only in the immediate vicinity of electric charges.

(c) exist only when both positive and negative charges are near one another.

(d) are imaginary.

15. Choose the correct answer from the following.

The electric field intensity at a point in space is equal in magnitude to

(a) the electric charge there.

(b) the force a charge of + 1 C would experience there.

(c) the force an electron would experience there.

16. Choose the correct answer from the following.

When one million electrons are placed on a solid copper sphere they become

(a) uniformly distributed in the sphere's interior.

(b) concentrated at the centre of the sphere.

(c) uniformly distributed on the sphere's surface.

(d) concentrated at the bottom of the sphere.

17. Choose the correct answer from the following.

The electric field intensity 2 cm from a certain charge has a magnitude of 10^5 NC^{-1}. The value of the electric field intensity 1 cm from the charge is

(a) 2.5×10^4 NC^{-1} (b) 5×10^4 NC^{-1}

(c) 2.5×10^5 NC^{-1} (d) 4×10^5 NC^{-1}

18. (a) Define an electric field. (b) What is an electric line of force?

(c) Why don't the electric lines of force intersect one another?

(d) Draw the electric lines of force around a single negative charge.

19. (a) Define electric field intensity. (b) Is it correct to say that an electric field intensity is a vector quantity? (c) What is the unit of electric field intensity?

20. The electric field intensities $\vec{E_1}$, $\vec{E_2}$ and $\vec{E_3}$ at a point P correspond to the charges q_1, q_2 and q_3 respectively. If $\vec{E_1} = -5\vec{E_2}$ and $\vec{E_2} = \vec{E_3}/4$, find the resultant electric field intensity at P.

21. An insulating rod has a positive charge at one end and a negative charge of the same magnitude at the other. This rod is placed in a uniform electric field.

    (a) How would the rod behave when the direction of the electric field is parallel to the rod?

    (b) How would the rod behave when the direction of the electric field is perpendicular to the rod?

22. What is the electric field intensity at a point 0.4 m from a charge of $+7 \times 10^{-5}$ C?

23. Two charges of $+4 \times 10^{-6}$ C and $+8 \times 10^{-6}$ C are 2m.apart. What is the electric field intensity midway between them?

24. Find the magnitude of the force exerted on an electron in a uniform electric field whose intensity is 1000 N C^{-1}. Find the direction of motion of the electron.

25. An electron is accelerated to 10^8 m s^{-2} by an electric field. What is the direction and magnitude of the field?

26. A particle carrying a charge of 10^{-5} C starts moving from rest in a uniform electric field whose intensity is 50 N C^{-1}.
    (a) What is the force on the particle?
    (b) How much kinetic energy will the particle have after it has moved 1 m?

27. Two charges, -20×10^{-6} C and $+.5 \times 10^{-6}$ C, are 2 m apart. Where is the electric field intensity in their vicinity equal to zero?

28. Two charges, -2×10^{-6} C and -8×10^{-6} C, are 2 m apart. Where is the electric field intensity in their vicinity equal to zero?

29. A uranium nucleus has a charge of 92e. (a) Find the direction and the magnitude of the electric field intensity due to the nucleus at a point 10^{-10} m from the nucleus. (b) Find the direction and magnitude of the force on an electron placed at that point.

30. (a) What is meant by a uniform electric field?

    (b) What is the difference between the electric lines of force which represent a non-uniform electric field and those which represent a uniform electric field?

31. Explain why the electric field intensity is zero everywhere inside a charged conductor.

32. Give two reasons why a lightning conductor is made of copper rather than iron.

33. Four charges of $+1\times10^{-8}$ C each are located at the four corners of a square of side 1 m. Find the electric field intensity at the centre of the square.

CHAPTER 8

ELECTRIC POTENTIAL

Work and potential energy have already been studied in mechanics. The concepts of work and potential energy are also very useful in the study of electrical phenomena. Let us review what we have learned thus far about these concepts.

In Fig. 8.1 (a), a body of mass m is situated on the ground. When the body is lifted to a certain height, work is done against the gravitational force mg. If the body is lifted to a height h, the work done is mgh [Fig. 8.1 (b)]. This work does not disappear but resides in the body as potential energy. This means that the body has potential energy with respect to the ground. So, external work must be done to separate two bodies which attract each other. The work done is then transformed into the potential energy of the body.

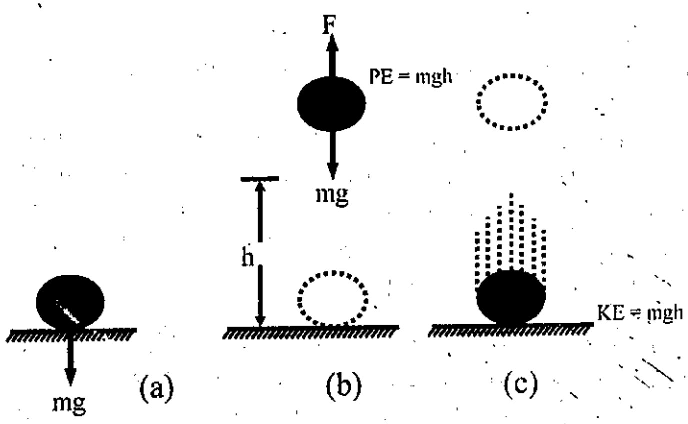


Fig. 8.1 Mechanical analogy of electric potential energy

If the body is released it will fall to the ground [Fig. 8.1 (c)]. While falling to the ground its potential energy gets less and less. But as it falls, the speed increases and therefore its kinetic energy also increase. The potential energy of the body is changing gradually into kinetic energy. As soon as the body strikes the ground the potential energy is totally transformed into kinetic energy. It has been described in mechanics that the kinetic energy of the body when it strikes the ground is equal to the work done in lifting the body to the height h. Thus, as soon as the body strikes the ground the potential energy stored while it is at the height h is completely converted into kinetic energy. In other words, work is done on the body falling from a height by the gravitational field.

Although the above facts concern the gravitational force, they are also true for electric forces. This means that work must be done to separate two bodies having opposite charges since they attract each other. Likewise, work must be done to bring closer two bodies having the same kind of charge since they repel each other. In both cases the work done is stored up as electric potential energy in the charged bodies.

8.1 ELECTRIC POTENTIAL AND POTENTIAL DIFFERENCE

The electric field around the charge +Q, shown in Fig. 8.2, will now be considered. It has been found that the direction of the electric field around +Q is radially outward. The points A and B are in the electric field around +Q.

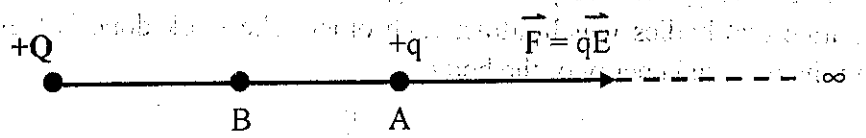


Fig. 8.2 Electric potential at a point in an electric field

When a small positive charge q is placed at A the charges Q and q repel each other. The repulsive force acting on q is F = qE. When q is brought to B, a point which is closer to Q, work must be done against the electric force. This work has been transformed into electric potential energy of q at B. This means that the small positive charge q has gained potential energy.

Let us suppose that q is initially not at A but at infinity. If q is now brought to B work must again be done and hence q gains electric potential energy. If instead of q a unit positive charge is brought from infinity to B, then the unit positive charge will gain electric potential energy. The electric potential energy of the unit positive charge at B is defined as the electric potential at B. The electric potential may therefore be defined as follows.

The electric potential at a point in an electric field is the work done in bringing a unit positive charge against the electric force from infinity to that point.

Let W be the work done in bringing the small positive charge q from infinity to a point in the electric field around Q. If V is the electric potential at that point, then it may be expressed as

$$V = \frac{W}{q} \qquad (8.1)$$

Since the electric potential is actually the amount of work done, it is a *scalar* quantity. The electric potential at infinity is taken as zero by convention. The electric potential at a point in the electric field around Q is expressed relative to the electric potential at infinity.

In Fig. 8.2 if the unit positive charge brought to B is set free it will move away from Q to infinity. While moving away from Q its electric potential decreases gradually and becomes zero when it is back at infinity. The electric force does work on the unit positive charge while it is moving away from Q.

The Unit of Electric Potential

The practical unit of electric potential is *the volt (V)*. If the work done in bringing +1 coulomb from infinity to a point in an electric field is 1 joule, the electric potential at that point is 1 joule per coulomb ($1\ J\ C^{-1}$) or 1 V.

The Electric Potential Difference

In Fig. 8.3 the points A and B are in the electric field of a point charge + Q. A is at a distance of "a" from + Q and B is at a distance of "b" from + Q. Then, the distance between A and B is (a – b).

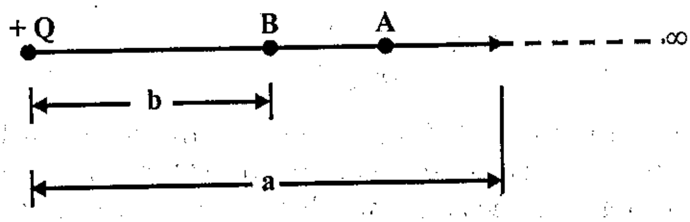


Fig. 8.3 The electric potential difference between two points in an electric field

Let V_A be the electric potential at A and V_B be the electric potential at B. By definition, V_A and V_B can be expressed as follows.

V_A = the work done in bringing a unit positive charge from infinity to A

V_B = the work done in bringing a unit positive charge from infinity to B

= the work done in bringing a unit positive charge from infinity to A + the work done in bringing a unit positive charge from A to B

= V_A + the work done in bringing a unit positive charge from A to B

Therefore, $V_B - V_A$ = the work done in bringing a unit positive charge from A to B. But $V_B - V_A$ is the electric potential difference between A and B. The electric potential difference between two points in an electric field can be defined as follows.

The electric potential difference between two points in an electric field is the work done in bringing a unit positive charge from one point to another against electric forces.

The Unit of Electric Potential Difference

If the work done in bringing a charge of + 1 C from one point to another in an electric field is 1 J, the electric potential difference between those points is 1 V.

In Fig. 8.3 the electric potential at B is higher than that at A. If a small positive charge is placed at B it will move toward A since it is repelled by + Q. A small positive charge will move from a point of higher electric potential to a point of lower electric potential. If a small negative charge is placed at A it will move toward B since it is attracted by + Q. A small negative charge will move from a point of lower electric potential to a point of higher electric potential.

The Electric Potential due to a Point Charge

The electric potential at a distance r from a point charge + Q can be expressed as

$$V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r} \qquad (8.2)$$

Therefore, the electric potential V at a point is directly proportional to the charge Q and inversely proportional to the distance r between Q and that point.

Suppose that the total electric potential at a point due to several point charges is to be determined. First, the electric potentials at that point due to the individual charges must be calculated. In doing so the signs of the individual charges must be taken into account. That is to say the individual electric potentials must be added algebraically. If the electric potentials due to the charges $+Q_1$, $+Q_2$, $+Q_3$, ..., are V_1, V_2, V_3, ...,

respectively, the total electric potential V is

$$V = V_1 + V_2 + V_3 + \ldots\ldots\ldots\ldots \qquad \mathbf{(8.3)}$$

Example(1) Find the electric potential at a point 3 m from a point charge of + 6.0 × 10^{-9} C.

$Q = +6.0 \times 10^{-9}$ C, r = 3 m

$$V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}$$

$$= 9 \times 10^{-9}\ \text{N m}^2\text{C}^{-2} \times \frac{(+6.0\times10^{-9}\ \text{C})}{3\text{m}}$$

$$= 18\ \text{V}$$

Example (2) Find the electric potential at a point 6 m from a point charge -3.0 × 10^{-9} C.

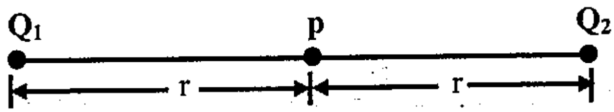
$$Q = -3.0 \times 10^{-9}\ \text{C}, \quad r = 6\text{m}$$

$$V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}$$

$$= 9 \times 10^{9} \times \frac{(-3.0\times10^{-9})}{6}$$

$$= -4.5\ \text{V}$$

Example (3) Two point charges of +4.0 × 10^{-8} C and - 3.0 × 10^{-8} C are l m apart. (a) Find the electric potential at P midway between the two charges. (b) Find the work done in bringing a charge + 3.0 × 10^{-9} C from infinity to P.



$Q_1 = +4.0 \times 10^{-8}$ C $\qquad Q_2 = -3.0 \times 10^{-8}$ C $\qquad r = 0.5$ m

$$V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}$$

The electric potential at P due to Q_1

$$V_1 = \frac{1}{4\pi\varepsilon_0}\frac{Q_1}{r}$$

$$= 9 \times 10^{9} \times \frac{(+4.0\times10^{-8})}{0.5} = 720\ \text{V}$$

The electric potential at P due to Q_2,

$$V = \frac{1}{4\pi\varepsilon_0}\frac{Q_2}{r}$$

$$= 9\times10^9 \times \frac{(-3.0\times10^{-8})}{0.5}$$

$$= -540 \text{ V}$$

Total electric potential at P,

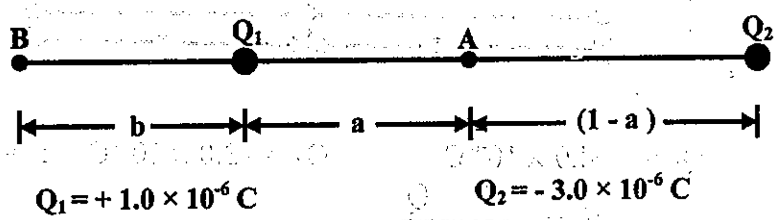
$$V = V_1 + V_2$$
$$= 720 + (-540)$$
$$= 180 \text{ V}$$

(b) $q = +3.0 \times 10^{-9}$ C

If W is the work done in bringing the charge q from infinity to P

$$W = V \text{ (the electric potential at P)} \times q \text{ (the charge)}$$
$$= 180 \times 3.0 \times 10^{-9}$$
$$= 0.54 \times 10^{-6} \text{ J}$$

Example (4) Two charges of $+1.0 \times 10^{-6}$ C and -3.0×10^{-6} C are 1 m apart. Find the points on the line joining the two charges where the electric potentials are equal to zero.



Since the magnitude of Q_1 is less than that of Q_2 the points of equal electric potentials are nearer to Q_1.

Let us suppose that electric potential at the point A (between Q_1 and Q_2) which is at a distance "a" from Q_1 is zero.

The electric potential at A due to Q_1,

$$V_1 = \frac{1}{4\pi\varepsilon_0}\frac{Q_1}{a}$$

$$= 9 \times 10^9 \times \frac{(+1.0\times10^{-6})}{a}$$

$$= \frac{9\,000}{a} V$$

The electric potential at A due to Q_2,

$$V_2 = \frac{1}{4\pi\varepsilon_0}\frac{Q_2}{(1-a)}$$

$$= 9\times10^9\times\frac{(-3.0\times10^{-6})}{(1-a)}$$

$$= \frac{-27\,000}{(1-a)} V$$

Since the electric potential at A is zero

$$V_1 + V_2 = 0$$

$$\frac{9\,000}{a} - \frac{27\,000}{1-a} = 0$$

$$a = 0.25 \text{ m}$$

We will now find the point on the other side of Q_1 and away from Q_2, where the electric potential is zero. Let that point be B at a distance "b" from Q_1.
The electric potential at B due to Q_1.

$$V_1 = \frac{1}{4\pi\varepsilon_0}\frac{Q_1}{b}$$

$$= 9\times10^9\times\frac{(+1.0\times10^{-6})}{b}$$

$$= \frac{9\,000}{b} v$$

the electric potential at B due to Q_2,

$$V_2 = \frac{1}{4\pi\varepsilon_0}\frac{Q_2}{(1+b)}$$

$$V_2 = 9\times10^9 \times \frac{(-3.0\times10^{-6})}{(1+b)}$$

$$= \frac{-27\,000}{(1+b)}\ \text{V}$$

Since the electric potential at B is zero,

$$V_1 + V_2 = 0$$

$$\frac{9\,000}{b} - \frac{27\,000}{(1+b)} = 0$$

$$b = 0.5\ \text{m}$$

The Path of the Charge and the Work Done

In Fig. 8.4 the points A and B are situated in an electric field due to the charge +Q. A and B are at distances of r_a and r_b from + Q respectively. A unit positive charge may be taken from A to B along the path 1 or 2 or any other path.

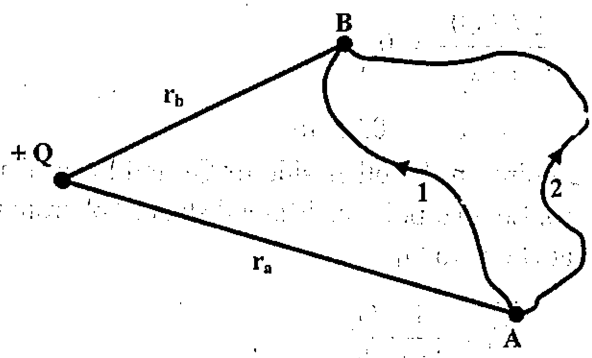


Fig. 8.4 Work done is independent of the path taken

From equation (8.1)

electric potential at A, $V_A = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r_a}$

electric potential at B, $V_B = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r_b}$

If $r_a > r_b$, $V_A < V_B$. This means that the electric potential at B is higher than that at A. The electric potential difference between A and B is

$$V_B - V_A = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r_b} - \frac{1}{4\pi\varepsilon_0}\frac{Q}{r_a}$$

From this equation it can be seen that the electric potential difference between A and B is just the difference in the electric potentials of the two end points of the path. The electric potential difference is independent of the path taken by the charge. This means that the electric potential difference between A and B is the same, along whichever path the unit positive charge is taken. In other words, the same amount of work must be done whenever the unit positive charge is taken along any path from A to B.

The external force does work when a unit positive charge is taken from A, a point of lower electric potential, to B, a point of higher electric potential. The force due to the electric field does work when a unit positive charge is taken from B, a point of higher electric potential, to A, a point of lower electric potential.

Example (5) If the points A and B are at distances of 0.5 m and 1 m respectively from the charge + 5.0 $\times 10^{-6}$ C, find the electric potential difference between them.

$Q = +5.0 \times 10^{-6}$ C, $r_a = 0.5$ m, $r_b = 1$ m

$$V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}$$

The electric potential at A,

$$V_A = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r_a}$$

$$= 9\times10^9 \times \frac{(+5.0\times10^{-6})}{0.5}$$

$$= 90\,000 \text{ V}$$

The electric potential at B,

$$V_B = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r_b}$$

$$= 9\times10^9 \times \frac{(+5.0\times10^{-6})}{1}$$

$$= 45\,000 \text{ V}$$

The electric potential difference between A and B,

$$V_{AB} = V_A - V_B$$
$$= 90\,000 - 45\,000$$
$$= 45\,000 \text{ V}$$

Example (6) How much work is done when the charge $+2.0 \times 10^{-6}$ C is brought from B to A in example (5)?

$$q = +2.0 \times 10^{-6} \text{ C}$$

$V_A - V_B$ = the work done in bringing a unit positive charge from B to A

If W is the work done in bringing the charge q from B to A,

$$W = (V_A - V_B)\, q$$
$$= 45\,000 \times 2.0 \times 10^{-6} = 0.09 \text{ J}$$

Equipotential Surfaces

In an eclectic field the points at the same potential are usually represented by a surface. Such *a surface drawn through the points at the same potential is called an equipotential surface.*

The surface of a charged conducting sphere is an equipotential surface. This is because the charges, distributed uniformly on its surface, are stationary. If its surface were not an equipotential surface the charges would move from point to point,

The charged conductors may have any shape but their surfaces are all equipotential surfaces (Fig. 8.5).

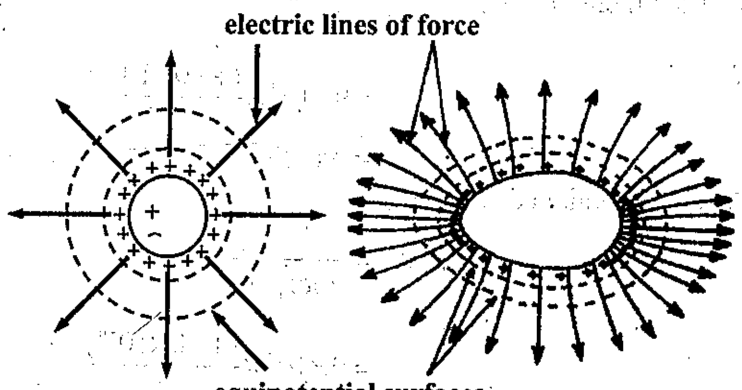


Fig. 8.5 Equipotential surfaces

We have seen that the electric potential difference between two points in an electric field is the work done in bringing a unit positive charge from one point to another point. If the electric potentials at two points are the same, the work done is zero since the electric potential difference between those two points is zero. Thus the work done is zero in bringing a unit positive charge from one point to another point on the equipotential surface.

The equipotential surfaces around a charge + Q are shown in Fig. 8.5. They are the spherical surfaces centred about the charge + Q. This is because equation (8.2) shows that electric potentials at points equidistant from + Q are equal. In Fig.8.6 the radial lines are electric lines of force around + Q. The electric lines of force are perpendicular to the equipotential surfaces. In addition, the electric lines of force are perpendicular to the surface of the charged conductor.

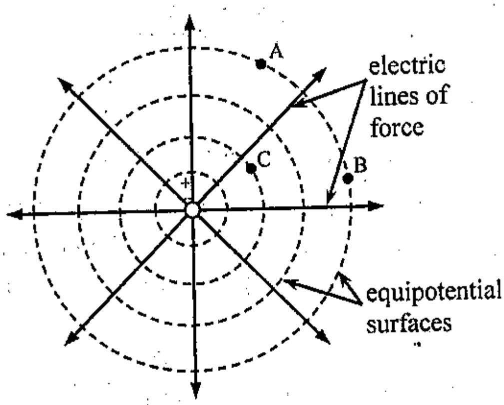


Fig. 8.6 Electric lines of force are perpendicular to equipotential surfaces

In Fig. 8.6 the points A and B are situated on an equipotential surface. No work is done in bringing a charge from A to B or from B to A. The work done in bringing a charge from A to C via any path is equal to the work done in bringing that charge from B to C via any path.

8.2 ELECTRIC POTENTIAL OF THE EARTH

It has been mentioned that the electric potential at an infinite distance from a charge + Q is taken conventionally as zero. The electric potentials of charged conductors are expressed relative to the electric potential of the surface of the earth. That is the electric potential of the earth is taken as zero.

The earth is a good conductor. Moreover, since it is very large compared to other conductors it can receive as well as give out quite a number of electrons. When compared to the size of the earth the number of electrons gained or lost by it is very small so that the net charge of the earth does not change. It is, therefore, quite correct to take the electric potential of the earth as zero. This makes it very convenient in the study of electric potentials of conductors. The *electric potential of a conductor becomes zero when it is connected to the earth.*

Suppose a negatively charged body is connected to the earth as shown in Fig. 8.7 (a). Due to repulsion between electrons, the electrons flow into the earth until the body has no net charge. When a positively charged body is connected to the earth as shown in Fig. 8.7 (b) it attracts electrons from the earth until it has no net charge.

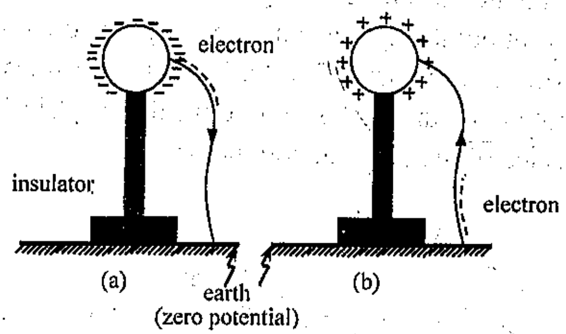


Fig. 8.7 The electric potential of the earth

8.3 POTENTIAL BETWEEN TWO PARALLEL CHARGED PLATES

In Fig. 8.8, A and B are two parallel charged plates. The distance between A and B is d. The charge on A is +Q and that on B is - Q. The electric field between the plates is uniform.

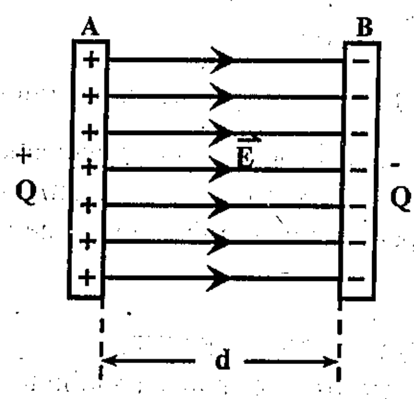


Fig. 8.8 The electric potential difference between two parallel charged plates

Suppose that the electric field intensity between the parallel plates is $\vec{E}$. By the definition of the electric field intensity the force acting upon a unit positive charge is $\vec{E}$. If W is the work done in bringing a unit positive charge from B to A against that force,

$$W = Ed \qquad (8.4)$$

By the definition of the electric potential difference, the work done in bringing a uint positive charge from B to A is, in fact, the electric potential difference between those two plates. If V is the electric potential difference between those two plates,

$$V = W$$

From the above two equations,

$$V = Ed \qquad (8.5)$$

In SI units the electric potential difference is measured in volts (V) and the distance is measured in metres (m). And the unit of electric field intensity is volt per metre ($V\ m^{-1}$). The electric field intensity has been defined so that its unit is newton per coulomb($N\ C^{-1}$). The unit of the electric field intensity is expressed either in NC^{-1} or $V\ m^{-1}$.

Example (7) A 6 V battery is connected to two parallel metal plates. If the distance between the two plates is 0.5 cm, find the electric field intensity between them.

$$V = 6\ V,\quad d = 0.5\ cm = 0.005\ m$$

$$V = Ed$$

$$E = \frac{V}{d}$$

$$= \frac{6}{0.005}$$

$$= 1\,200\ NC^{-1} \text{ or } Vm^{-1}$$

Example (8) A 6 V battery is connected to two parallel metal plates. The electric field intensity between the plates is 300 $V\ m^{-1}$. (a) How far are the plates apart? (b) Find the work done in carrying an electron from one plate to the other.

(a) $V = 6\ V,\quad E = 300\ V\ m^{-1}$

$$V = Ed$$

$$d = \frac{V}{E}$$

$$= \frac{6}{300} = 0.02 \text{ m}$$

(b) $q = e = 1.6 \times 10^{-19}$ C

$$W = Vq$$
$$= 6 \times 1.6 \times 10^{-19}$$
$$= 9.6 \times 10^{-19} \text{ J}$$

Example (9) If an electron is placed on the negatively charged plate in example (8) what is the velocity of the electron when it strikes the positively charged plate?

Suppose that v is the velocity of electron when it strikes the plate.

KE of the electron $= \frac{1}{2} mv^2$

KE of the electron = the work done in carrying an electron from one plate to another

Therefore $\frac{1}{2} mv^2 = W$

$$\frac{1}{2} \times (9.1 \times 10^{-31}) v^2 = 9.6 \times 10^{-19}$$

$$v^2 = \frac{2 \times 9.6 \times 10^{-19}}{9.1 \times 10^{-31}}$$

$$v = 1.45 \times 10^{6} \text{ ms}^{-1}$$

EXERCISES

1. (a) What do you understand by electric potential energy ? (b) Define electric potential. (c) Write down the units of electric potential energy and electric potential.
2. (a) Why is electric potential a scalar quantity? (b) Can electrons by themselves move from a point of lower electric potential to a point of higher electric potential?
3. Explain how work is done in carrying a unit positive charge from a point of higher electric potential to a point of lower electric potential and how work is done in carrying a unit positive charge from a point of lower electric potential to a point of higher electric potential.

4. If the electric field intensity at a point in an electric field is zero, is the electric potential at that point necessarily zero?

5. State the definition of electric potential difference and write down its unit.

6. (a) What is an equipotential surface? (b) How much work is done in moving a charge of $+1.6 \times 10^{-19}$ C from one point to another on an equipotential surface of 200 V?

7. Draw the equipotential surfaces between two parallel plates having charges of equal magnitude and opposite sign.

8. Why can the earth be regarded as a body having zero electric potential?

9. Choose the correct answer from the following.
By definition, the unit of electric field intensity E is N C^{-1}. An equivalent unit of E is (a) V m (b) Vm^2 (c) V m^{-1} (d) V m^{-2}.

10. Choose the correct answer from the following.
An electric field intensity of magnitude 200 N C^{-1} is produced by applying a potential difference of 10 V to two parallel metal plates. The distance between them is
(a) 2 cm (b) 5 cm (c) 20 m (d) 2000 m.

11. Choose the correct answer from the following.
A charge $+1.0 \times 10^{-9}$ C lying between two parallel metal plates which are 1 cm apart experiences a force of 10^{-4} N. The potential difference between the plates is (a) 10^{-5} V (b) 10 V (c) 10^3 V (d) 10^5 V

12. What is the radius of an equipotential surface of 30 V surrounding a point charge of $+1.5 \times 10^{-6}$ C ?

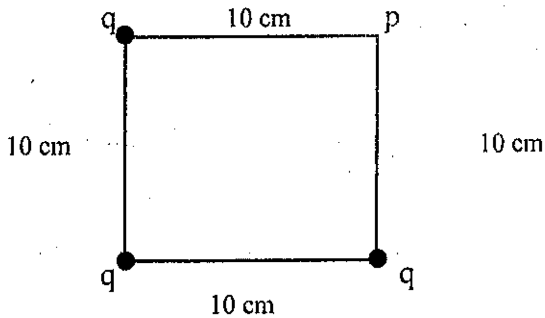
13. The electric potential and the magnitude of the electric field intensity at a point at some distance from a point charge are 300 V and 100 N C^{-1} respectively. (a) How far is the point from the charge? (b) What is the magnitude of the charge?

14. A carbon nucleus has a charge of $+6e$. Find the electric potential and electric field intensity at a point 10^{-10} m from the nucleus. ($e = 1.6 \times 10^{-19}$C).

15. Two charges of $+1.0 \times 10^{-12}$ C and -4.0×10^{-12} C are 5.0 m apart in air. Determine the electric field intensity and the electric potential midway between them.

16. Two point charges, $+4\times10^{-9}$ C and -9.0×10^{-9} C, are 50 cm apart. (a) Find the point where the electric field intensity is zero. (b) Find the points of equal electric potential which are on the line joining the two charges.

17. Find the total electric potential at the point P in the diagram given below. The value of q is $+5.0\times10^{-9}$ C.



18. The electric potential difference between two parallel metal plates which are 0.5cm apart is 0.5×10^{3} V. Find the force on an electron located between the plates.
19. Two parallel metal plates are 4 cm apart. If the force on an electron between the plates is 1.0×10^{-14} N, what is the potential difference between them?
20. An electron is accelerated by a uniform electric field from rest to a velocity of 10^{6} ms^{-1}. If the accelerating region is 0.2 m long, find the magnitude of the electric field.

CHAPTER 9

CAPACITANCE

Capacitors are widely used in electrical circuits. They are used in radio, television and other electrical appliances. They are of different types and shapes. However, in this chapter we shall study only one type: the parallel plate capacitor.

9.1 CAPACITORS

A capacitor is an electrical device that stores electrical energy in the form of an electric field. A capacitor consists of two conductors separated by a small distance. An insulator is inserted between its conductors. Its conductors have charges of equal magnitude and opposite signs; if one conductor of a capacitor has a charge + Q the other has a charge −Q. The magnitude of the charge on each conductor, Q, is called the charge of the capacitor. The potential difference between two conductors of the capacitor, V, is called the potential difference of the capacitor. The capacitance of a capacitor is defined as follows.

The capacitance of a capacitor is the ratio of the charge to the potential difference between two conductors of that capacitor.

Since the capacitance is represented by C,

$$C = \frac{Q}{V} \qquad (9.1)$$

In the SI system, the unit of the capacitance C is coulomb per volt ($C\ V^{-1}$). If the potential difference of the capacitor is 1 V when it is given a charge 1 C its capacitance is $1C\ V^{-1}$. But $1\ C\ V^{-1}$ is expressed as 1 F (farad). The unit farad is named in honour of Michael Faraday. The sub-multiple units of farad are used for practical purposes,

1 microfarad (μF) = 10^{-6} F

1 nanofarad (nF) = 10^{-9} F

1 picofarad (pF) = 10^{-12} F

The charge of a capacitor Q is found to be directly proportional to its potential difference V. When Q on the capacitor is increased, V also increases proportionally. By equation (9.1) the capacitance of a capacitor C is constant.

Although the capacitance of a capacitor does not depend On Q and V, it depends on the size and the shape of the capacitor and on the nature of the insulator between the two conductors.

The symbol for a capacitor is shown in [Fig. 9.1 (a)]. It consists of two parallel lines of the same length. The symbol for a battery is shown in [Fig. 9.1 (b)]. The short line and the long line represent the negative terminal and the positive terminal of a battery respectively.

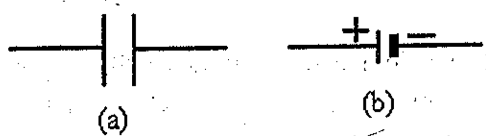


Fig. 9.1 Symbols for a capacitor and a battery

A parallel-plate capacitor is the simplest capacitor. It consists of two parallel metal plates separated by air or other insulating material [Fig. 9.2 (a)]. The plates are connected to a battery. The capacitor connected to a battery can be represented by an electric circuit diagram shown in Fig. 9.2 (b).This diagram shows the charging a capacitor.

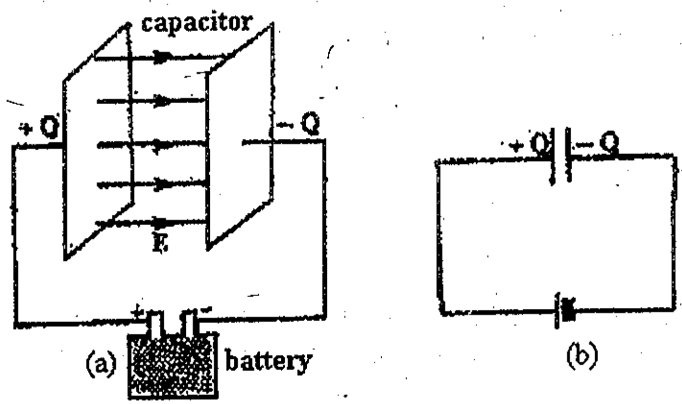


Fig. 9.2 Charging a capacitor

It has already been mentioned above how the capacitance of a capacitor consisting of two conductors is defined. If a conductor is given some charge its potential will also change. The amount of charge given to a conductor to change its potential by one unit is called the electric capacity of that conductor. The electric capacity of a conductor, C, can be calculated from equation (9.1).

9.2 PARALLEL-PLATE CAPACITOR

A parallel-plate capacitor is shown in Fig. 9.3. One plate of it has a charge + Q and the other plate has a charge-Q. The potential difference between the plates is V. The area of each plate is A and the distance between the plates is d. Suppose that an insulating medium of permittivity ε is placed between the plates.

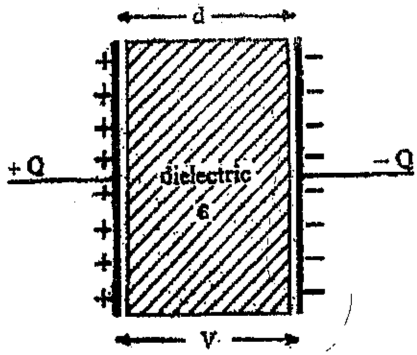


Fig. 9.3 Effect of a dielectric between the plates of a capacitor

The electric field between the plates is a uniform electric field and the electric field intensity, E, is, by equation (8.5).

$$E = \frac{V}{d}$$

The magnitude of the charge per unit area of the plate is called the surface charge density which is represented by σ.

Therefore,

$$\sigma = \frac{Q}{A} \qquad (9.2)$$

The electric field intensity E between the two plates is related to σ as

$$E = \frac{\sigma}{\varepsilon} \qquad (9.3)$$

From the above equations,

$$\frac{V}{d} = \frac{\sigma}{\varepsilon}$$

$$= \frac{1}{\varepsilon}\frac{Q}{A}$$

Therefore, $$\frac{Q}{V} = \varepsilon \frac{A}{d}$$

Since $$C = \frac{Q}{V}$$

$$C = \varepsilon \frac{A}{d} \tag{9.4}$$

The permittivity of a medium, ε, is related to that of a vacuum, ε_0, as

$$\varepsilon = \kappa \varepsilon_0 \tag{9.5}$$

Here κ is the dielectric constant or the relative permittivity of the medium.
From equations (9.4) and (9.5) the capacitance of a parallel-plate capacitor is

$$C = \frac{\kappa \varepsilon_0 A}{d} \tag{9.6}$$

Since $$\varepsilon_0 = 8.85 \times 10^{-12} C^2 N^{-1} m^{-2}$$

$$C = 8.85 \times 10^{-12} \frac{\kappa A}{d} \tag{9.7}$$

We find that for a given medium the capacitance of a parallel-plate capacitor is directly proportional to the area of the plate and inversely proportional to the distance between the plates.

For a vacuum $\kappa = 1$ and for other media $\kappa > 1$.

The values of κ for some insulating materials commonly used in capacitors are listed in Table (9.1). These insulating materials are also called dielectrics.

Table 9.1

Material	Dielectric Constant κ
Vacuum	1
Air (l atm)	1.0006
Waxed paper	2
Plywood	2.1
Rubber (hard)	3
Amber	3
Nylon (solid)	3.8
Mica	3-6
Glass	5-8
Marble	6
Ammonia (liquid)	25
Ethyl alcohol (0°C)	28.4
Water (18°C)	81

Dielectric Constant

In Fig. 9.3 a parallel-plate capacitor has an insulating material between its plates and its capacitance C is as expressed by equation (9.6). If there is a vacuum between its plates, its capacitance C_0 is

$$C_0 = \frac{\varepsilon_0 A}{d}$$

When the above equation is substituted in equation (9.6),

$$C = \kappa C_0$$

or $$\kappa = \frac{C}{C_0} \qquad (9.8)$$

Therefore, the ratio of the capacitance of a capacitor with an insulating material between its two conductors to the capacitance of that capacitor with a vacuum between its two conductors is called the dielectric constant of that insulating material.

The potential difference of the capacitor is found to decrease when an air medium between its plates is replaced by an insulating material. By V = Ed, V decreases as E decreases. Since the charge of the capacitor does not change at all, the capacitance of a capacitor increases. Various types of capacitors commonly used are shown in Fig. 9.4.

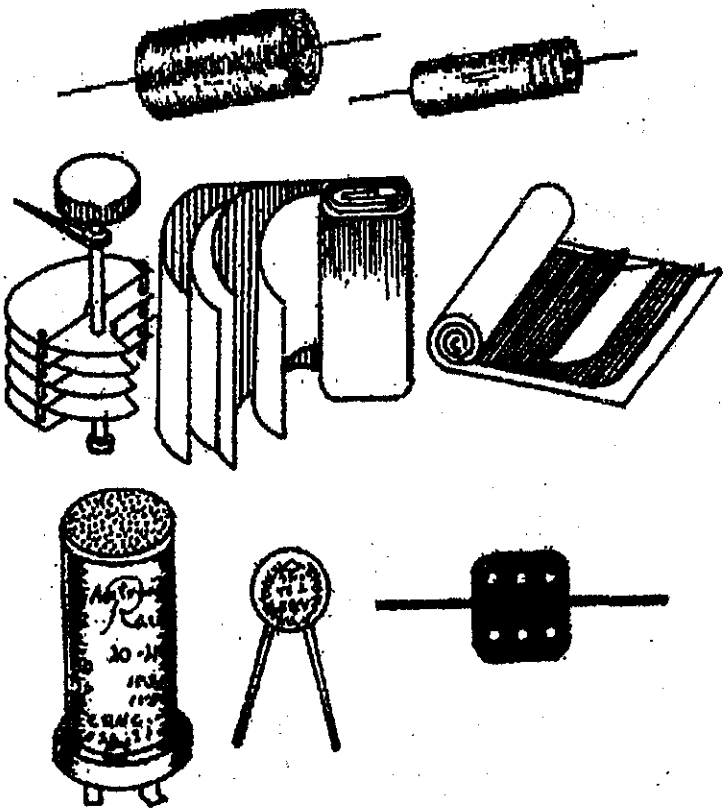


Fig. 9.4 Different kinds of capacitors

Example (1) When a parallel-plate capacitor is connected to a 50 V battery each plate receives a charge of magnitude 0.002 C. Find its capacitance.

$$Q = 0.002\ \text{C}, \qquad V = 50\ \text{V}$$

$$C = \frac{Q}{V}$$

$$= \frac{0.002\ \text{C}}{50\ \text{V}}$$

$$= 40\ \mu\text{F}$$

9.3 ENERGY OF A CAPACITOR

A capacitor stores electrical energy in the form of an electric field. We shall now calculate the energy stored by a capacitor.

Before a capacitor is charged each of its conductors has no charge, and the potential difference between two conductors is zero.

When a capacitor is charged the charge has been transferred from a conductor at lower potential to a conductor at higher potential. Work has been done for such a transfer of charge. The magnitude of the charge on the two conductors increases gradually and the potential difference between them also increases gradually.

Suppose that after the capacitor is charged each conductor receives a charge of magnitude Q and the potential difference between the conductors is V.

If the average potential difference of the capacitor before and after it is charged is $\overline{V}$, then

$$\overline{V} = \frac{0 + V}{2} = \frac{V}{2}$$

If the work done for transferring charge of Q between the two conductors is W,

$$W = \overline{V}Q$$

$$= \tfrac{1}{2} VQ$$

This amount of work is, in fact, the electrical energy stored by the capacitor in the form of an electric field.

Therefore the energy of the capacitor $= \tfrac{1}{2}$ QV

Since C = Q/V, the energy, W, of the capacitor can be expressed as

$$\left.\begin{aligned} W &= \tfrac{1}{2} QV \\ &= \tfrac{1}{2} CV^2 \\ &= \tfrac{1}{2}\frac{Q^2}{C} \end{aligned}\right\} \qquad (9.9)$$

Example (2) The area of each plate of a parallel-plate capacitor is 2 m^2 and the distance between two plates is 4 mm. If the potential difference between the plates is 12 000 V and the dielectric constant of the material inserted between them is 3, find (a) the capacitance of the parallel-plate capacitor, (b) the magnitude of the charge on each plate, (c) the electric field intensity between the plates and(d) the energy stored by the capacitor.

(a) $A = 2m^2$, $d = 4\ mm = 4.0 \times 10^{-3}\ m$, $V = 12\ 000\ V$, $\kappa = 3$

$$C = 8.85 \times 10^{-12} \times \frac{\kappa A}{d}$$

$$= 8.85 \times 10^{-12} \times \frac{3 \times 2}{4.0 \times 10^{-3}}$$

$$= 13.275 \times 10^{-9}\ F$$

$$= 13.275\ nF$$

(b) If Q is the charge on each plate,

$$Q = CV$$

$$= 13.275 \times 10^{-9} \times 12\ 000$$

$$= 1.59 \times 10^{-4}\ C$$

(c) If E is the electric field between the plates

$$E = \frac{V}{d}$$

$$= \frac{12\ 000}{4.0 \times 10^{-3}}$$

$$= 3.0 \times 10^{6}\ Vm^{-1}$$

(d) If W is the energy stored by the capacitor

$$W = \frac{1}{2} QV$$

$$= \frac{1}{2} \times 1.59 \times 10^{-4} \times 12\ 000$$

$$= 0.95\ J$$

9.4 CAPACITANCE OF PARALLEL-PLATE CAPACITORS

(a) Capacitors in Parallel

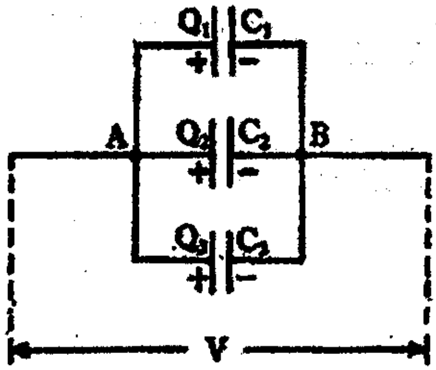


Fig. 9.5 Capacitors in parallel

In Fig. 9.5 three capacitors are connected in parallel. The plates of the capacitors connected together at the point A have positive charges and the plates connected together at the point B have negative charges; all the capacitors have the same potential difference. But they carry different amounts of charges.

The respective capacitors have capacitances C_1, C_2 and C_3 and charges Q_1, Q_2 and Q_3 respectively. If the potential difference of each capacitor is V,

$$\left.\begin{aligned} C_1 &= \frac{Q_1}{V} \\ C_2 &= \frac{Q_2}{V} \\ C_3 &= \frac{Q_3}{V} \end{aligned}\right\} \qquad (1)$$

If Q is the total charge on the three capacitors, then

$$Q = Q_1 + Q_2 + Q_3 \qquad (2)$$

From equations (1) and (2), we get

$$Q = V(C_1 + C_2 + C_3)$$

$$\frac{Q}{V} = C_1 + C_2 + C_3 \qquad (3)$$

Suppose that the same effect is obtained when the capacitors in Fig. 9.5 are replaced by a single capacitor. That single capacitor is called an equivalent capacitor.

The charge of the equivalent capacitor is the sum of the charges of the individual capacitors and the potential difference of it is the same as that of the individual capacitors.

If the capacitance of the equivalent capacitor or the resultant capacitance of the capacitors connected in parallel is C, then

$$C = \frac{Q}{V} \qquad (4)$$

From equation (3) and (4)

$$C = C_1 + C_2 + C_3$$

If n capacitors having capacitances C_1, C_2, C_3, ..., C_n and charges Q_1, Q_2, Q_3, ..., Q_n respectively, are connected in parallel, the equivalent capacitance C is

$$C = C_1 + C_2 + C_3 \text{ ....} + C_n \qquad (9.10)$$

The equivalent capacitance of the capacitors connected in parallel is the sum of the capacitances of the individual capacitors.

(b) Capacitors in Series

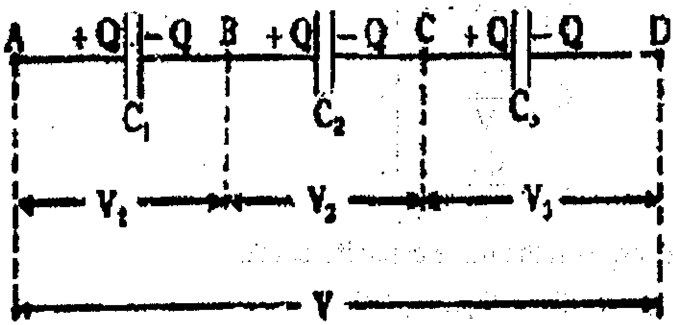


Fig. 9.6 Capacitors in series

In Fig. 9.6 three capacitors having the capacitances C_1, C_2 and C_3 respectively, are connected in series. The negatively charged plate of one capacitor is connected to the positively charged plate of the other.

Since the capacitors are connected in series each capacitor has the same charge. But they have different potential differences.

If the charge on the individual capacitors is Q and their potential differences are V_1, V_2 and V_3 their capacitances are

$$\left.\begin{aligned} C_1 &= \frac{Q}{V_1} \\ C_2 &= \frac{Q}{V_2} \\ C_3 &= \frac{Q}{V_3} \end{aligned}\right\} \qquad (1)$$

Suppose that V is the potential difference between A and D which are the end points of the combination of capacitors shown in Fig 9.6. If an equivalent capacitor is used between A and D it has the charge Q and the potential difference V. If the capacitance of the equivalent capacitor or the equivalent capacitance of three capacitors connected in series is C, then

$$C = \frac{Q}{V} \qquad (2)$$

But the potential difference between A and D is

$$V = V_1 + V_2 + V_3 \qquad (3)$$

Substituting equations (1) and (2) into (3), we obtain

$$\frac{Q}{C} = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3}$$

or

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

If n capacitors having capacitances C_1, C_2, C_3, ... , C_n , respectively, are connected in series, the capacitance of the equivalent capacitor or the equivalent capacitance of those capacitors C is

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots\ldots\ldots\ldots + \frac{1}{C_n} \qquad (9.11)$$

When the capacitors are connected in series the reciprocal of the equivalent capacitance is the sum of the reciprocals of their individual capacitances.

Example (3) If two capacitors having the capacitances of 4 μF and 12 μF are connected in series, find the equivalent capacitance of the combination of the two capacitors. If the potential difference of the combination is 200 V, find the potential difference of the 12uF capacitor.

$$C_1 = 4\ \mu F,\ C_2 = 12\ \mu F$$

If the equivalent capacitance of the combination of the capacitors in series is C, we get

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

Therefore

$$\frac{1}{C} = \frac{1}{4} + \frac{1}{12}$$

$$= \frac{4}{12}$$

$$C = 3\ \mu F$$

Suppose that the magnitude of the charge on the combination is Q.

Then

$$Q = CV$$

$$= 3 \times 10^{-6} \times 200$$

$$= 600 \times 10^{-6} C = 600\ \mu C$$

This magnitude of charge is received by the individual capacitors. Therefore, if the potential difference of the 12 μF capacitor is V_2,

$$V_2 = \frac{Q}{C_2}$$

$$= \frac{600}{12}$$

$$= 50\ V$$

Example (4) A capacitor having a capacitance of 2 μF and a charge of 2000 μC is connected in series with another capacitor having a capacitance of 8 μF and a charge of 1600 μC. (a) Find the potential difference of the individual capacitors prior to the connection. (b) ~~Find the~~ potential difference of the individual capacitors after the connection.

(a) For the first capacitor $C_1 = 2\ \mu F, Q_1 = 2\,000\ \mu C$

If its potential difference is V_1, then

$$V_1 = \frac{Q_1}{C_1}$$

$$= \frac{2000 \times 10^{-6}}{2 \times 10^{-6}}$$

$$= 1\,000\ V$$

For the second capacitor $C_2 = 8\ \mu F,\ \ Q_2 = 1\,600\ \mu C,$

If its potential difference is V_2, we get

$$V_2 = \frac{Q_2}{C_2}$$

$$= \frac{1600 \times 10^{-6}}{8 \times 10^{-6}}$$

$$= 200\ V$$

(b)If the potential difference of the equivalent capacitor is V after the capacitors are connected in series, then

$$V = V_1 + V_2$$

$$= 1000 + 200$$

$$= 1200V$$

If the equivalent capacitance of the capacitors is C, we get

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

$$= \frac{1}{2} + \frac{1}{8}$$

$$= \frac{5}{8}$$

$$C = 1.6\ \mu\ F$$

After the connection of the capacitors in series, each capacitor has a charge Q.

Then $$Q = CV$$

$$= 1.6 \times 1200$$

$$= 1920\ \mu C$$

If V_a is the potential difference of the first capacitor after connection, we get

$$V_a = \frac{Q}{C_1}$$

$$= \frac{1920 \times 10^{-6}}{2 \times 10^{-6}}$$

$$= 960\ V$$

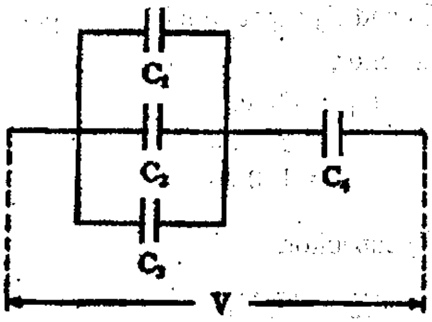
If V_b is the potential difference of the second capacitor after connection, we get

$$V_b = \frac{Q}{C_2}$$

$$= \frac{1920 \times 10^{-6}}{8 \times 10^{-6}}$$

$$= 240\ V$$

Example (5) In the arrangement of the capacitors shown below, $C_1 = 2\ \mu F$, $C_2 = 3\ \mu F$, $C_3 = 7\ \mu F$, $C_4 = 4\ \mu F$ and $V = 240$ V. Find the potential difference and the charge on each capacitor.



If the equivalent capacitance of the combination of the C_1, C_2 and C_3 capacitors in parallel is C_a, we get

$$C_a = C_1 + C_2 + C_3$$

$$= 2 + 3 + 7$$

$$= 12\ \mu F$$

If the equivalent capacitance of the C_a and C_4 capacitors connected in series is C, we get

$$\frac{1}{C} = \frac{1}{C_a} + \frac{1}{C_4}$$

$$= \frac{1}{12} + \frac{1}{4}$$

$$= \frac{4}{12}$$

$$C = 3\ \mu F$$

The C_a and C_4 capacitors connected in series have the same magnitude of charge Q. Then

$$Q = CV$$

$$= 3 \times 240$$

$$= 720\ \mu C$$

If the potential difference of the equivalent capacitor C_a is V_a, we get

$$V_a = \frac{Q}{C}$$

$$= \frac{720 \times 10^{-6}}{12 \times 10^{-6}} = 60\ V$$

Therefore the C_1, C_2 and C_3 capacitors have the potential difference of 60 V. The charge on the C_1 capacitor,

$$\begin{aligned} Q_1 &= C_1 V_a \\ &= 2 \times 60 \\ &= 120\ \mu C \end{aligned}$$

The charge on the C_2 capacitor,

$$\begin{aligned} Q_2 &= C_2 V_a \\ &= 3 \times 60 \\ &= 180\ \mu C \end{aligned}$$

The charge on the C_3 capacitor,

$$\begin{aligned} Q_3 &= C_3 V_a \\ &= 7 \times 60 \\ &= 420\ \mu C \end{aligned}$$

If the potential difference of the C_4 capacitor is V_b, then

$$\begin{aligned} V_b &= \frac{Q}{C_4} \\ &= \frac{720 \times 10^{-6}}{4 \times 10^{-6}} \\ &= 180\ V \end{aligned}$$

EXERCISES

1. (a) What electrical device is a capacitor? (b) When an insulating material is inserted between the conductors of a capacitor in a vacuum, does its capacitance increase or decrease? Explain.
2 State whether the following are True (T) or False (F),
   (i) If one conductor of a capacitor has a charge +Q the other has a charge −2Q.
   (ii) The charge of the capacitor is the magnitude of the charge on each conductor.
   (iii) The potential difference of the capacitor is the potential difference between two conductors of the capacitor
3. Define (a) capacitance (b) 1 farad and (c) dielectric constant.
4. (a) When the charge on a capacitor is increased, does its capacitance increase ? Explain. (b) What must be done to increase the capacitance of a capacitor?

5. (a) When the distance between the two parallel plates of a capacitor is doubled, by what percent does its capacitance change?

(b) When the distance between two parallel plates having the charges of equal magnitude and opposite signs is reduced, what will happen to the potential difference between the plates?

6. Capacitors can be connected either in parallel or in series.

(a) In which connection of the capacitors has each capacitor the same charge? (b) In which connection of the capacitors is the potential difference of each capacitor the same?

7. A capacitor has a capacitance of 5.0 μF. How much of the charge should be removed in order that the potential difference between its plates decreases by 40V?

8. Choose the correct answer from the following.

The plates of a parallel-plate capacitor of capacitance C are brought together to a third of their original separation. The capacitance is now

(a) $\frac{1}{9}$ C (b) $\frac{1}{3}$ C (c) 3 C (d) 9 C

9. (a) Is there any kind of material that, when inserted between the plates of a capacitor, reduces its capacitance ?

(b) The plates of a parallel-plate capacitor of capacitance C are moved apart to double their original separation. What is the new capacitance?

10. (a) How much work must be done to charge a 12 μF capacitor until the potential difference between its plates is 250 V?

(b) A parallel-plate capacitor of capacitance C is given the charge Q and then disconnected from the circuit. How much work is required to pull apart the plates of this capacitor to twice their original separation?

11. The plates of a parallel-plate capacitor are 50 cm^2 in area and 1 mm apart. (a) What is its capacitance? (b) When the capacitor is connected to a 45 V battery, what is the charge on either plate? (c) What is the energy of the capacitor?

12. The capacitance of a parallel-plate capacitor is increased from 8 μF to 50 μF when a sheet of glass is inserted between its plates. What is the dielectric constant of the glass?

13. (a) What potential difference must be applied across a 10 μF capacitor if it is to have an energy content of 1 J ?

(b) A parallel-plate capacitor has a capacitance of 5 μF when air is between its plates and 30 μF when this space is filled with a sheet of glass. Find the dielectric constant of glass.

14. (a) Draw a labelled diagram of a parallel plate capacitor.

(b) What is the relationship between capacitance, voltage and charge?

A 2μF capacitor is charged to a potential of 200V and then disconnected from the power supply.

(c) What is 2μF expressed in farads?

(d) What is the size of the charge on each plate of the capacitor?

(e) One plate of the capacitor carries a positive charge; the other plate is earthed. Explain why the earthed plate carries a negative charge.

15. In an experiment with a capacitor, the charge which was stored was measured for different values of charging potential difference. The results are tabulated below.

Charge stored (μC)	7.5	30	60	75	90
Potential difference (V)	1.0	4.0	8.0	10.0	12.0

(i) Plot a graph of charge stored on the y-axis against potential difference on x-axis.

(ii) Use the graph to calculate the capacitance of the capacitor used in the experiment.

16. Three capacitors have capacitances of 5 μF, 10 μF and 15 μF.

(a) Find the equivalent capacitance when they are connected in parallel.

(b) Find the equivalent capacitance when they are connected in series.

17. Find the capacitance that can be obtained by combining three 10 μF capacitors in all possible ways.

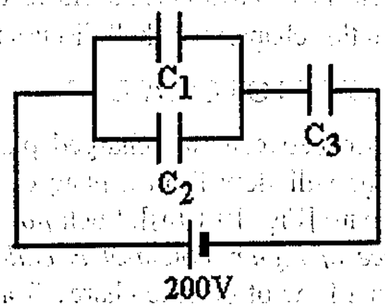
18. The equivalent capacitance is 10 μF when n identical capacitors are connected in parallel and 0.4 μF when they are connected in series. Determine n.

19. A 35 μF capacitor is needed, but only 10 μF capacitors are available. How should a minimum number of 10 μF capacitors be connected so that the combination has a capacitance of 35 μF?

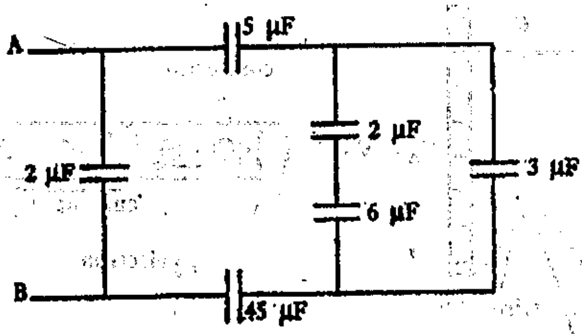
20. Three capacitors have capacitances of 3 μF, 10 μF, and 15 μF. How should they be connected to obtain the equivalent capacitances of (a) 2 μF (b) 9 μF (c) 12.5 μF?

21. Three capacitors of capacitances 3 μF, 10 μF and 15 μF are connected in series with 100 V battery. What is the charge and the potential difference on each capacitor?

22. In the electric circuit diagram $C_1 = 4\ \mu F$, $C_2 = 12\ \mu F$ and $C_3 = 8\ \mu F$. (a) Find the capacitance of the electric circuit, (b) Find the charge on each capacitor, (c) Find the potential difference of the C_3 capacitor, (d) Find the potential difference across the parallel combination.



23. Find the equivalent capacitance between A and B of the arrangement of capacitors shown below.



CHAPTER 10

CURRENT AND ELECTRIC CIRCUITS

Most applications of electricity and magnetism involve moving charges or electric currents in conductors. When an electric current flows through substances, it can produce three main effects. In this chapter we shall discuss these effects.

10.1 CURRENT AND EFFECTS OF CURRENT

There is a potential difference between two charged plates. If the two plates are joined by a wire the electrons will flow from a plate of lower potential to that of higher potential through the wire [Fig. 10.1 (a)]. Such *flow of electrons from a place of lower potential to a place of higher potential is called an electric current.* In general, an electric current is a flow of electric charge from one place to another. In Fig. 10.1 (a) the electrons will flow until the potential difference between the plates become zero.

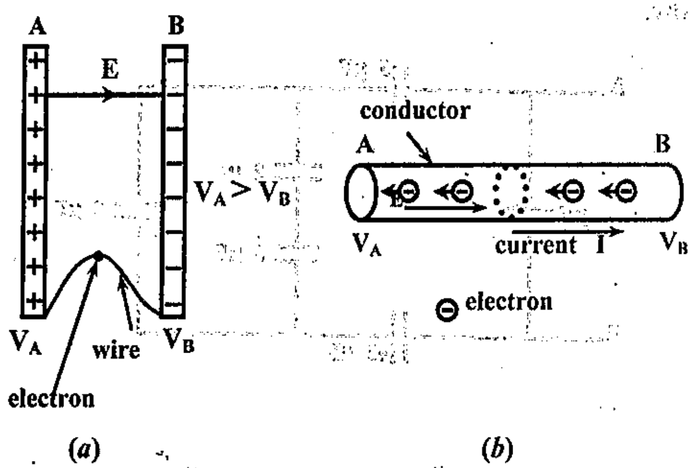


Fig. 10.1 Moving charges constitute the electric current

Conductors contain a large number of free electrons. If the potential difference is established between the two ends of a conductor, electrons will flow from the end of lower potential to that of higher potential. In Fig 10.1 (b) the potential of the end A is assumed to be higher than that of the end B. Thus the electrons will flow from B to A. The electrons flow as the electric field in the conductor exerts a force (F = qE) upon them. The electrons keep flowing as long as there is a potential difference between A and B. This means that an electric current flows through that conductor. An electric current flowing through a conductor is defined as follows.

The amount of charge passing through a cross-sectional area of a conductor in one second is called an electric current.

Current is a scalar quantity by the above definition. Suppose that the amount of charge Q passes through a cross-sectional area of a conductor in time t. If the current flowing through the conductor is I then by definition,

$$I = \frac{Q}{t} \qquad (10.1)$$

Unit of Current

In the SI system, the unit of Q is coulomb (C) and the unit of t is second (s). Therefore the unit of I is coulomb per second (Cs^{-1}). 1 Cs^{-1} is called 1 ampere (A) in honour of the French physicist, Andre Ampere.

If the amount of charge 1 C passes through a cross-sectional area of a conductor in 1 s the current is 1 A.

Thus, 2 Cs^{-1} is 2 A and 0.5 Cs^{-1} is 0.5 A. In measuring the current the following sub-multiple units are also used.

$$1 \text{ milliampere (mA)} = 10^{-3} \text{ A}$$

$$1 \text{ microampere } (\mu \text{A}) = 10^{-6} \text{ A}$$

Direction of Current

The direction of current is conventionally defined as the direction of the flow of positive charges. In Fig. 10.1 (b) the electrons flow from the point B of lower potential to the point A of higher potential. This is equivalent to saying that the positive charges flow from A to B. The current, then, will flow from A to B and the direction of current is opposite to that of the flow of electrons. The direction of current is just a generally accepted convention. Even though we speak of the direction of current it is, nevertheless, a scalar quantity.

Example (1) A charge of 6 C passes through a cross-sectional area of a conductor in 2 s. (a) Find the current flowing through the conductor. (b) How many electrons pass through that area in 1 s?

(a) $Q = 6\text{ C}, \quad t = 2\text{ s}$

$$I = \frac{Q}{t} = \frac{6\text{C}}{2\text{s}} = 3\text{ A}$$

(b) The magnitude of the charge of an electron, $e = 1.6 \times 10^{-19}$ C. If n is the number of electrons passing through the cross-sectional area in 1 s,

$$I = \frac{Q}{t} = \frac{ne}{t}$$

Therefore $$n = \frac{It}{e}$$

$$= \frac{3A \times 1\,s}{1.6 \times 10^{-19}\,C}$$

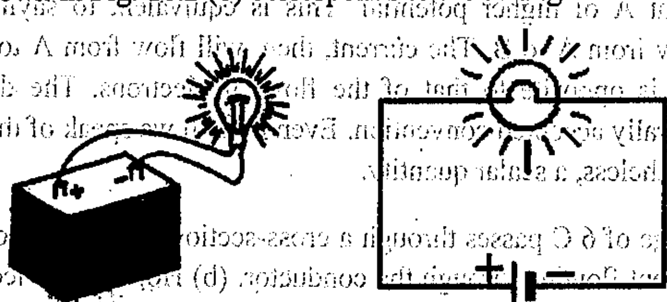
$$n = 1.875 \times 10^{19}$$

Effects of Current

When an electric current is passed through substances it can produce three main effects. They are (1) heating effect (2) chemical effect and (3) magnetic effect.

(1) Heating Effect

As shown in Fig. 10.2 (a) a small bulb glows when a battery is connected to it. As an electric current flows through a tungsten wire in the bulb the wire becomes hot and emits light. Thus *a metal conductor produces heat energy when a current passes through it.* Practical application of the heating effect of current is utilized in electrical application such as electric stove, electric iron and immersion heater. The circuit diagram shown in Fig. 10.2 (b) corresponds to the arrangement in Fig. 10.2 (a).

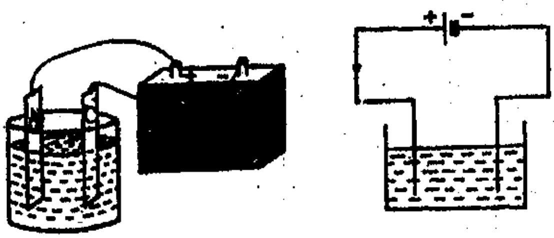


(a) (b)

Fig. 10.2 Heating effect of current

(2) The Chemical Effect

When a current is passed through copper sulphate solution with copper plates A and C dipping into it, some copper is seen deposited on the plate C after some time [Fig. 10.3 (a)]; electric current produces chemical effect. The chemical effect of current is used in charging batteries, purifying metals, electro-plating and in the manufacture of aluminum by chemical methods. The circuit diagram shown in Fig. 10.3(b) corresponds to the arrangement in Fig. 10.3(a).



(a) (b)

Fig. 10.3 Chemical effect of current

(3) The Magnetic Effect

When a current flows through a coil of insulated wire which is wound round a bar of soft iron, the bar becomes a magnet and attracts steel pins [Fig. 10.4(a)]; the electric current produces magnetic effect. The magnetic effect of current is used in electromagnets. Electromagnets are used in electrical devices such as electric bell, telephone and electric motor. The circuit diagram shown in Fig. 10.4 (b) corresponds to the arrangement in Fig. 10.4(a).

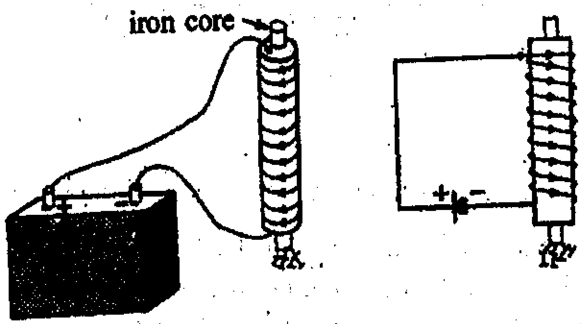


Fig.10.4 Magnetic effect of current

10.2 OHM'S LAW AND ELECTRICAL RESISTANCE

When there is a potential difference between the two ends of a conductor, a current flows through it. In 1826 the German physicist George Simon Ohm carried out experiments with different resistant wires to discover how the current through each depended on the potential difference applied across its ends. He discovered a law. That law is called Ohm's law and is stated as follows.

If a conductor is kept at a constant temperature, the current flowing through it is directly proportional to the potential difference between its ends.

p.d(V)	current(A)
0	0
1	0.2
2	0.4
3	0.6
4	0.8
5	1

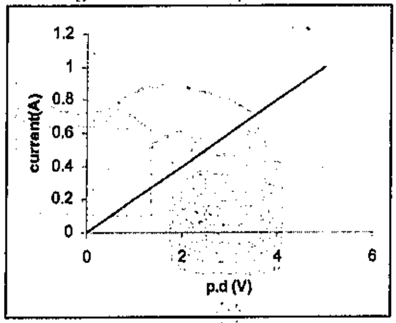


Fig. 10.5a Relation between the potential difference and the current.

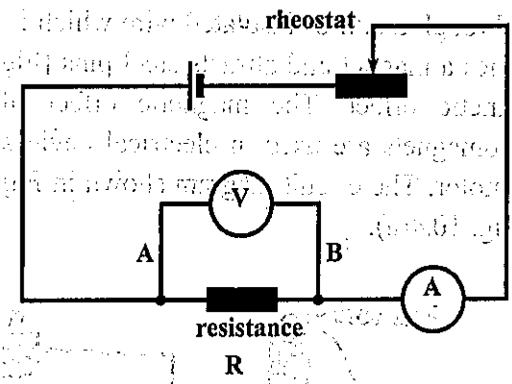


Fig. 10.5b Electric circuit for measurement of current and voltage.

In Fig.10.5b the potential at A is assumed to be higher than the potential at B; a current will flow from A to B. If the potential difference between A and B is V and the current flowing through the conductor is I, by Ohm's law

$$I \propto V$$

$$I = \frac{1}{R} V$$

or $$V = IR \qquad (10.2)$$

Here R is a constant which is called the resistance of the conductor. The SI unit of the resistance R is ohm (Ω).

Resistivity of a Conductor

At a given temperature the resistance of a conductor is directly proportional to its length and inversely proportional to its cross-sectional area.

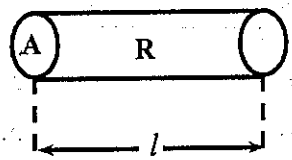


Fig. 10.6 Dependence of resistance on length and area

In Fig. 10.6 the conductor shown has a cross-sectional area of A and length of ℓ. If its resistance is R,

$$R \propto \frac{\ell}{A}$$

$$R = \rho \frac{\ell}{A} \qquad (10.3)$$

Here ρ is a constant called the resistivity of the conductor and is defined as the resistance of a conductor having one unit cross-sectional area and one unit length. The unit of resistivity is ohm metre (Ω m).

Temperature Coefficient of Resistance

The resistance of a conductor increases with increasing temperature. The resistances of carbon (a non-metal), semiconductors such as silicon and germanium and electrolytes, decrease with increasing temperature. Resistances of most conductors are found to increase with increasing temperature.

Suppose that R_0 is the resistance of a conductor at the temperature of 0°C and R_t is its resistance at t° C. R_t is related to R_0 as follows.

$$R_t = R_0(1 + \alpha t) \qquad (10.4)$$

Here α is a constant called the temperature coefficient of resistance. The unit of α is per °C (°C^{-1}). By equation (10.3), if the length or the cross-sectional area of a substance changes, its resistance will also change. But its resistivity remains the same. This means that a particular substance has only a single value of resistivity. As the resistivity varies slightly with temperature it can be taken as a constant. The resistivities and the values of the temperature coefficients of some conductors are given in Table 10.1.

Table 10.1

Substance	Resistivity ρ (Ω m) (at 20° C)	Temperature Coefficient of resistance α (°C^{-1})
Aluminum	2.82×10^{-8}	3.9×10^{-3}
Copper	1.72×10^{-8}	4.3×10^{-3}
Iron	9.80×10^{-8}	5.6×10^{-3}
Silver	1.62×10^{-8}	3.9×10^{-3}
Tungsten	5.50×10^{-8}	5.8×10^{-3}
Mercury	95.77×10^{-8}	0.9×10^{-3}
Carbon (graphite)	33 to 185×10^{-8}	-0.6 to -0.1×10^{-3}

Example(2) A current of 2 A flows through a conductor when the potential difference between its ends is 12 V. If the potential difference is reduced to 3 V how much does the value of current drop?

$$V\,(PD) = 12\text{ V}, \quad I = 2\text{ A}$$

By Ohm's law $V = IR$

$$R = \frac{V}{I} = \frac{12}{2} = 6\ \Omega$$

Now, $V(PD) = 3V, \quad R = 6\ \Omega$

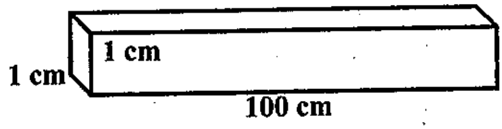
$$I = \frac{V}{R} = \frac{3}{6} = 0.5\text{ A}$$

The current drop $= 2 - 0.5 = 1.5$ A

Example (3) A rectangular silver slab has dimensions 1 cm x 1 cm x 100 cm. What is the resistance between its two square surfaces? The resistivity of silver is $1.62 \times 10^{-8}\ \Omega$ m.

$$A = 1\text{ cm} \times 1\text{ cm} = 10^{-2}\text{ m} \times 10^{-2}\text{ m} = 10^{-4}\text{ m}^2; \quad \ell = 100\text{ cm} = 1\text{m}$$

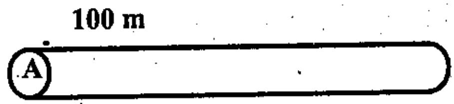
$$\rho = 1.62 \times 10^{-8}\ \Omega\text{ m}$$



$$R = \rho \frac{\ell}{A}$$

$$= 1.62 \times 10^{-8} \times \frac{1}{10^{-4}} = 1.62 \times 10^{-4}\ \Omega$$

Example (4) A tungsten wire has a length of 100 m, a diameter of 2 mm and a resistivity of $4.8 \times 10^{-8}\ \Omega$ m. Find its resistance.



$$\ell = 100\text{m}, \quad r = \frac{2\text{mm}}{2} = 1\text{ mm} = 10^{-3}\text{ m}$$

$$A = \pi r^2 = 3.142 \times (10^{-3})^2\ \text{m}^2$$

$$\rho = 4.8 \times 10^{-8}\ \Omega\ \text{m}$$

$$R = \rho \frac{\ell}{A}$$

$$R = 4.8 \times 10^{-8} \times \frac{100}{3.142 \times (10^{-3})^2} = 1.53\ \Omega$$

Example (5) When a platinum resistance thermometer is placed in a mixture of ice and water at 0°C its resistance is $10\,\Omega$. When it is placed in a furnace of unknown temperature its resistance is $100\,\Omega$. If the temperature coefficient of platinum is $0.0036°C^{-1}$, find the temperature of the furnace.

$R_0 = 10\ \Omega$

$R_t = 100\ \Omega$

$\alpha = 0.0036°C^{-1}$

t = temperature of the furnace

$R_t = R_0(1 + \alpha t)$

$100 = 10(1 + 0.0036\, t)$

$t = 2500°C$

10.3 RESISTORS IN SERIES

A resistor is a circuit component which is made from a substance having resistance. Radio and television receivers contain a large number of resistors. Resistors have resistances of anything from a few ohms to millions of ohms. They are supplied with leads (wire ends) for convenience in connection. There are two types of resistors: fixed resistors and variable resistors. Fig 10.7 (a) shows the symbol for a fixed resistor. A rheostat (A variable resistor) and its symbol are shown in Fig. 10.7 (b) and (c) respectively.

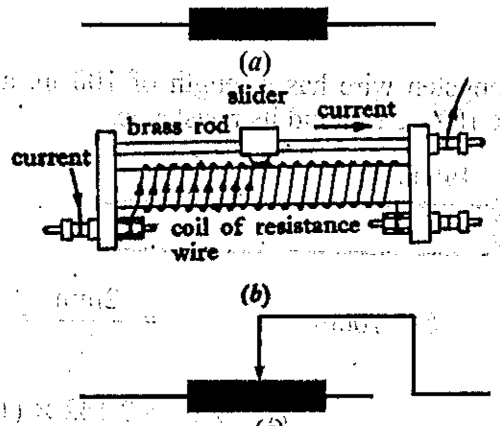


Fig. 10.7 Fixed and variable resistors

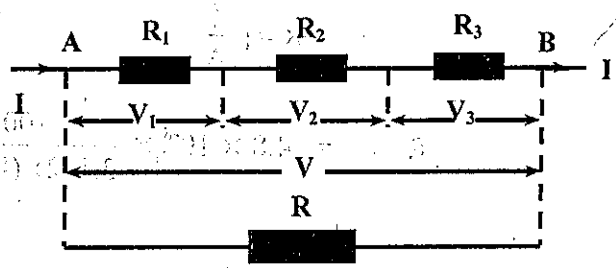


Fig. 10.8 Resistors in series

The resistors are said to be connected in series if they are connected in such a way that the same current flows through each resistor (Fig. 10.8). The resistors R_1, R_2 and R_3 are connected in series. The point A is assumed to have a higher potential than the point B. Then a current will flow from A to B through the resistors. Since the resistors are connected in series the same current I flows through each resistor.

If the individual potential differences across the resistors are V_1, V_2 and V_3 respectively, and the total potential difference across the combination is V, then

$$V = V_1 + V_2 + V_3 \quad \text{(i)}$$

By Ohm's law $V_1 = IR_1$

$$V_2 = IR_2$$
$$V_3 = IR_3$$

When the above equations are substituted in equation (i),

$$V = I(R_1 + R_2 + R_3) \qquad \text{(ii)}$$

If the equivalent resistance of the combination of the resistors is R the potential difference across the combination is

$$V = IR \qquad \text{(iii)}$$

From equation (ii) and (iii),

$$R = R_1 + R_2 + R_3$$

If n resistors of resistances R_1, R_2, R_3, ..., R_n are connected in series and the equivalent resistance is R, then

$$R = R_1 + R_2 + R_3 + \ldots\ldots\ldots\ldots + R_n \qquad (10.5)$$

That is, the equivalent resistance of the resistors in series is equal to the sum of the resistances of the individual resistor.

10.4 RESISTORS IN PARALLEL

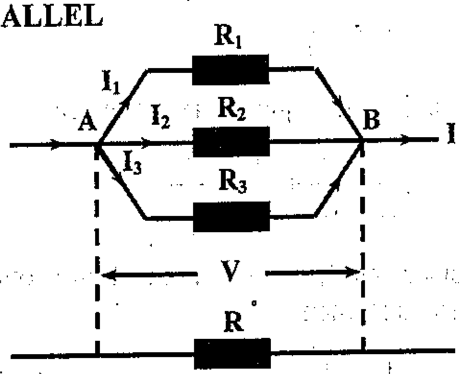


Fig. 10.9 Resistors in parallel

Resistors are said to be connected in parallel if they are connected in such a way that the same potential appears across each and every resistor (Fig 10.9). The resistors R_1, R_2 and R_3 are connected in parallel. One end of each resistor is joined at the point A and the remaining ends are joined at the point B. The point A is assumed to have a higher potential than the point B. The current I divides into three currents at the point A and flow through the resistors. These three currents recombine at the point B. The current leaving the point B is also I.

Let I_1 = current flowing through the resistor R_1

I_2 = current flowing through the resistor R_2

I_3 = current flowing through the resistor R_3

$$I = I_1 + I_2 + I_3 \qquad \text{(iv)}$$

Since the two ends of each resistor are joined at the points A and B, respectively, the potential difference across each resistor is the potential difference V between A and B.

By Ohm's law,

The potential difference across the resistor R_1, $V = I_1 R_1$

The potential difference across the resistor R_2, $V = I_2 R_2$

and the potential difference across the resistor R_3, $V = I_3 R_3$

Substituting the above equations in equation (iv), one obtains

$$I = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \qquad \text{(v)}$$

If the equivalent resistance of the combination of the resistors R_1, R_2 and R_3 is R and the potential difference between A and B is V, then

$$V = IR$$

or

$$I = \frac{V}{R}$$

From the above equation and equation (v), one gets

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

If n resistors of resistances R_1, R_2, R_3, ..., R_n are connected in parallel and the equivalent resistance is R, then

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots\ldots\ldots\ldots + \frac{1}{R_n} \qquad (10.6)$$

That is, the reciprocal of the equivalent resistance of resistors connected in parallel is equal to the sum of the reciprocal of the individual resistances.

Example (6) Find the equivalent resistance when three 6 Ω resistors are connected (a) in series and (b) in parallel. (c) Find the equivalent resistance when two resistors in parallel are connected to the remaining resistor in series.

(a) If the equivalent resistance of three 6 Ω resistors connected in series is R, then

$$R = R_1 + R_2 + R_3$$

$$= 6 + 6 + 6$$

$$= 18\ \Omega$$

(b) If the equivalent resistance of three 6 Ω resistors connected in parallel is R, then

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$= \frac{1}{6} + \frac{1}{6} + \frac{1}{6}$$

$$= \frac{3}{6}$$

$$R = 2\ \Omega$$

(c) If the equivalent resistance of two 6 Ω resistors connected in parallel is R_2, then

$$\frac{1}{R_a} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$= \frac{1}{6} + \frac{1}{6}$$

$$= \frac{2}{6}$$

$$R_a = 3\ \Omega$$

If the equivalent resistance of R_a and the 6 Ω resistor connected in series is R, then

$$R = R_a + 6$$

$$= 3 + 6$$

$$= 9\ \Omega$$

10.5 ELECTROMOTIVE FORCE AND ELECTRIC CIRCUITS

When a potential difference is set up between the two ends of a conductor, a current flows through it. A steady current will flow through the conductor if a steady potential difference is maintained between its ends. The steady potential difference can always be maintained between the ends of the conductor by using batteries and generators. Batteries and generators are called the sources of electromotive force.

The sources of electromotive force convert energy from some other form into electrical form. Chemical energy is converted into electrical energy in a battery. In generators, mechanical energy is converted into electrical energy.

Electromotive Force

A source of electromotive force has a positive terminal and a negative terminal. The main function of the source is to send the positive charges from the negative terminal to the positive terminal within the source. Alternately, it can be said that the main function of the source is to send negative charges from the positive terminal to the negative terminal within the source. In doing so work has to be done by the source.

The electromotive force (EMF, emf) of a source before its terminals are connected to an external circuit is defined as follows.
The electromotive force of a source is the work done in moving a unit positive charge from its negative terminal to the positive one. The electromotive force is abbreviated as e.m.f. (EMF, emf).

Unit of Electromotive Force
If 1 J of work is done in moving a unit positive charge from the negative terminal to the positive terminal of a source, then the electromotive force of that source is 1 V.

Electromotive Force of a Source used in an Electric Circuit

Generally, a source of electromotive force has an internal resistance. A battery which has an internal resistance of r must be viewed as shown in Fig 10.10 (a). This means that a resistor of resistance r must be regarded as being connected in series to the battery. Or, it must be understood that the symbol shown in Fig. 10.10 (b) represents a battery which has an internal resistance of r.

Fig. 10.10 Symbols for a battery

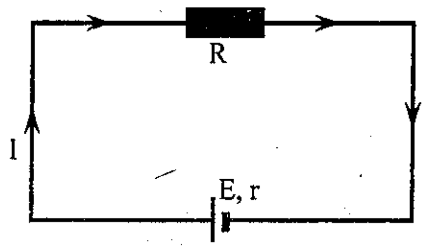


Fig 10.11 A battery connected to an external circuit

In Fig. 10.11 the positive and negative terminals of a battery of internal resistance r are connected to a resistor R. As a result, a current flows through the resistor since the resistor has a potential difference between its ends. In the external circuit the current flows from the positive terminal to the negative terminal through the resistor R. It, however, flows from the negative terminal to the positive terminal in the battery. Thus the current in the external circuit and the current in the battery are the same. The e.m.f. of a source when it is connected to an external circuit is defined as follows.

The e.m.f.(emf EMF) of a source connected to an external circuit is the work done in moving a unit positive charge round the complete circuit.

In Fig. 10.11 the wires connecting the battery to the resistor are assumed to have zero resistance and hence they are represented by lines. There are only two resistances, the resistance R of the resistor and the internal resistance r of the battery, in the circuit. R and r are connected in series.

Suppose that the current in that circuit is I. If the potential difference across the resistor R is V, we have, by Ohm's law, V = IR. By the definition of the potential difference, the work done in moving a unit positive charge from one end to another of the resistor R is IR.

Similarly, the work done in moving a unit positive charge from one end to another of the internal resistance r of the battery (from the negative terminal to the positive terminal of the battery) is Ir.

The work done in moving a unit positive charge round the complete circuit is IR + Ir. By definition, that work is the e.m.f. of the battery connected in the circuit. If its e.m.f. is E,

$$E = IR + Ir$$

or

$$I = \frac{E}{R+r} \qquad (10.7)$$

This equation is called ***the circuit equation.***

Equation 10.7 can be rewritten as

$$IR = E - Ir.$$

Since the two ends of the resistor R are, of course, the positive and negative terminals of the battery shown in Fig. 10.11, the potential difference between its terminals, V (= IR), is given by

$$V = E - Ir.$$

This equation gives the potential difference between the positive and negative terminals of a battery when it is connected to an external circuit. When a battery having an internal resistance is part of a complete circuit the potential difference between the terminals of the battery is always less than its emf (EMF).

Accordingly, when a 12 V battery having an internal resistance is connected to an external circuit the potential difference across its terminals is less than 12 V. This means that the potential difference available from that battery is not 12 V but less than 12V. Therefore, the potential difference across the terminals of a battery connected to an external circuit is called the available voltage of that battery.

Charging a battery means supplying it with electrical energy from some exte... source. This means the chemical energy of the battery which has been used up is now supplied back by external electrical energy. The external electrical energy required for unit positive charge is equal to the e.m.f. E of the battery plus the energy per unit positive charge dissipated in the battery as heat, which is Ir. Therefore, in charging a battery, the potential difference between the terminals must be equal to E + Ir.

Use of Ammeter and Voltmeter in Electric Circuits

An ammeter is a device which is used to measure the current. Milliammeters and microammeters are used to measure very small currents. Fig. 10.12(a) shows the symbol for an ammeter. *An ammeter must be placed in a circuit in such a way that the current to be measured flows through it.* In doing so *the current must enter the ammeter from its positive terminal.*

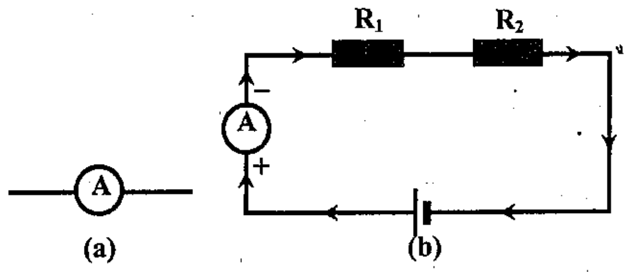


Fig. 10.12 Connection of ammeter in a circuit

Fig. 10.12(b) shows how to use an ammeter in a circuit consisting of the resistors R_1 and R_2 connected in series. The ammeter can be placed not only between the battery and R_1 but also between R_1 and R_2 or between the battery and R_2 in the circuit. Wherever the ammeter is in that circuit it reads the same current.

A voltmeter is a device which is used to measure the potential difference. Millivoltmeters and microvoltmeters are used to measure very small potential differences. Fig. 10.13 (a) shows the symbol for a voltmeter. The terminals of *a voltmeter must be connected to two points between which the potential difference is to be measured.* For such a connection the positive terminal of the voltmeter must be connected to the higher potential point of the two.

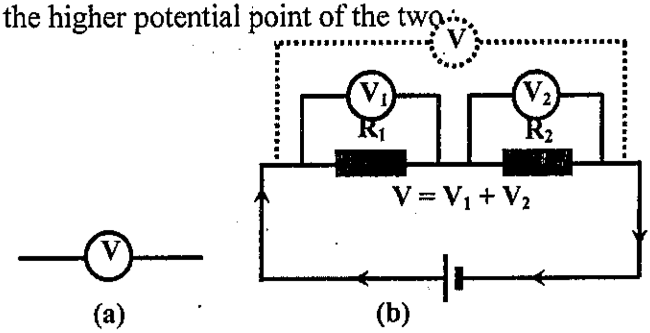


Fig. 10.13 Connection of ammeter in a circuit

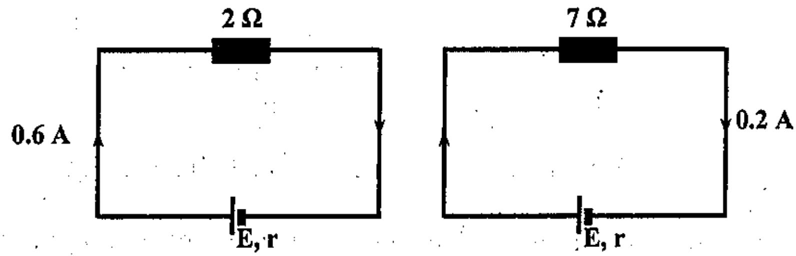
Fig. 10.13 (b) shows how to use the voltmeters to measure the potential differences between the ends of the resistor R_1 and that between the ends of the resistor R_2. When the potential difference across the ends of the combination of R_1 and R_2 is to be measured the voltmeter must be connected as shown by the dotted line.

Example (7) When a battery is connected to a 2 Ω resistor it drives a current of 0.6 A through the resistor. When it is connected to a 7 Ω resistor it drives a current of 0.2 A through the resistor. Find the e.m.f. and the internal resistance of the battery.

$R_1 = 2\ \Omega ; I_1 = 0.6\ A, \qquad R_2 = 7\ \Omega , I_2 = 0.2\ A$

Let E = emf of the battery

r = internal resistance of the battery



Then the current in the first circuit, $I_1 = \dfrac{E}{R_1 + r}$

$$E = I_1 (R_1 + r)$$

$$= 0.6\ (2 + r) \qquad (1)$$

The current in the second circuit, $I_2 = \dfrac{E}{R_2 + r}$

$$E = I_2 (R_2 + r)$$

$$= 0.2\ (7 + r) \qquad (2)$$

From equations (1) and (2),

$$0.6\ (2+r) = 0.2\ (7+r)$$

$$0.4r = 0.2$$

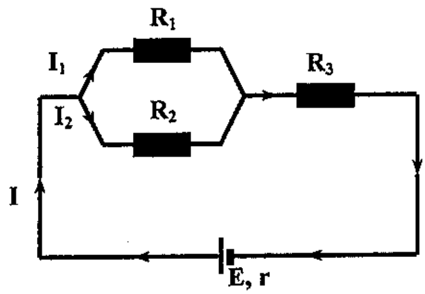
$$r = 0.5\ \Omega$$

Substituting the value of r into equation (1),

$$E = 0.6\ (2 + 0.5)$$

$$= 1.5\ V$$

Example(8). Find the current flowing through each resistor and the potential difference across the 1 Ω resistor in the circuit diagram given below.



$R_1 = 4\ \Omega$
$R_2 = 6\ \Omega$
$R_3 = 1\ \Omega$
$E = 12\ V$
$r = 0.6\ \Omega$

If the equivalent resistance of R_1 and R_2 is R_a,

$$\frac{1}{R_a} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{4} + \frac{1}{6} = \frac{5}{12}$$

$$R_a = 2.4\ \Omega$$

If the equivalent resistance of R_a and R_3 is R_b,

$$R_b = R_a + R_3 = 2.4 + 1 = 3.4\ \Omega$$

If the total resistance in the circuit is R,

$$R = R_b + r = 3.4 + 0.6 = 4\ \Omega$$

If the current in the circuit is I,

$$I = \frac{E}{R} = \frac{12}{4} = 3\ A$$

If the potential difference across R_3 is V_3,

$$V_3 = IR_3 = 3 \times 1 = 3\ V$$

If the potential difference between the ends of the combination of R_1 and R_2 resistors is V_{12},

$$V_{12} = IR_a = 3 \times 2.4 = 7.2\ V$$

If the current flowing through R_2 is I_1,

$$I_1 = \frac{V_{12}}{R_1} = \frac{7.2}{4} = 1.8\ A$$

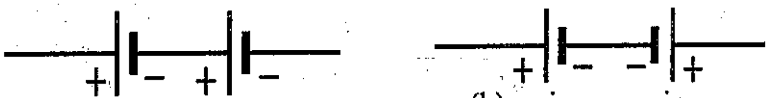
If the current flowing through R_3 is I_2,

$$I_2 = \frac{V_{12}}{R_2} = \frac{7.2}{6} = 1.2\ A$$

10.6 BATTERIES IN SERIES AND IN PARALLEL

(a) Batteries in Series

When two or more sources of e.m.f. are connected in series, the resultant e.m.f. is the algebraic sum of the individual e.m.f.s.

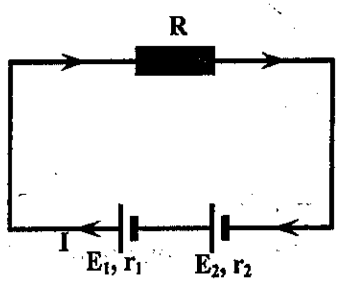


(a) series aiding (b) series opposing

Fig.10.14 Batteries in series

In Fig 10.14(a) two batteries are connected in series. In this arrangement the currents leaving the batteries are in the same direction so that the resultant e.m.f. is $E_1 + E_2$. Such a connection of batteries is called "series aiding". The total internal resistance of those two batteries is $r_1 + r_2$. They can be regarded as a single battery having an emf (EMF) $E_1 + E_2$ and internal resistance $r_1 + r_2$.

In Fig 10.14 (b) also two batteries are connected in series. But the e.m.f.s. of the batteries are in opposition. The resultant e.m.f. is the difference between the individual e.m.f.s. Such a connection of batteries is called "series opposing". If E_1 is greater than E_2 the resultant e.m.f. of those two batteries is $E_1 - E_2$. But their total internal resistance is still $r_1 + r_2$. Thus they can be regarded as a single battery having an e.m.f. $E_1 - E_2$ and an internal resistance $r_1 + r_2$.



Resultant e.m.f. = $E_1 + E_2$

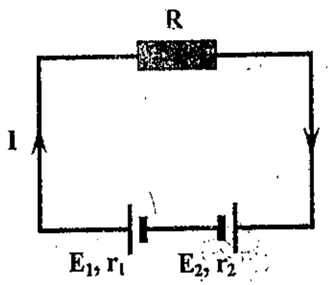
Total $r = r_1 + r_2$

Fig. 10.15 Batteries in series aiding

In Fig. 10.15 two batteries, connected in series aiding arrangement, are connected to a resistor R. In the circuit the total e.m.f. is $E_1 + E_2$, and the total resistance is $R + r_1 + r_2$.

If the current in the circuit is I the circuit equation is

$$I = \frac{E_1 + E_2}{R + r_1 + r_2} \qquad (10.8)$$



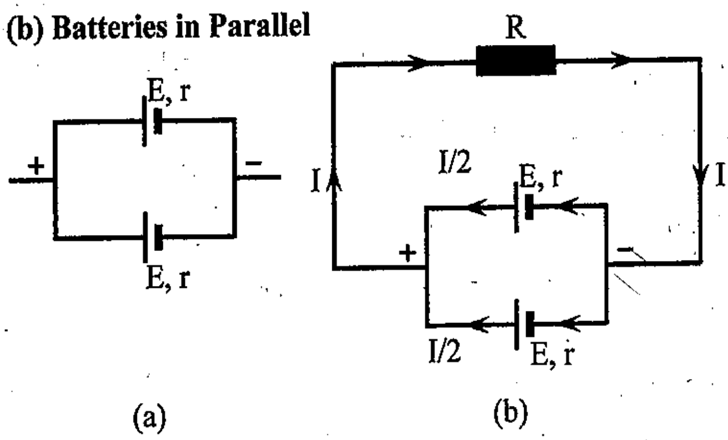
Resultant e.m.f. = $E_1 - E_2$ (if $E_1 > E_2$)
Total $r = r_1 + r_2$

Fig. 10.16 Batteries in series opposing

In Fig. 10.16 two batteries, connected in series opposing arrangement, are connected to a resistor R. Suppose that E_1 is greater than E_2. In the circuit the total e.m.f. is $E_1 - E_2$ and the total resistance is $R + r_1 + r_2$. If the current in the circuit is I the circuit equation is

$$I = \frac{E_1 - E_2}{R + r_1 + r_2} \qquad (10.9)$$

(b) Batteries in Parallel



Resultant e.m.f. = E
Total r = $\frac{r}{2}$

Fig. 10.17 Batteries in parallel

In Fig. 10.17 (a) two batteries having equal e.m.f.s and equal internal resistances are connected in parallel. It should be noticed that the positive terminals are connected together and that the same is true of the negative terminals. The resultant e.m.f. of that parallel-combination is just the e.m.f. E of a single battery in that combination. Since the internal resistances of the batteries are in parallel-combination, the resultant resistance is r/2. The combination of batteries can be regarded as a single battery having an e.m.f. E and an internal resistance r/2.

In Fig. 10.17 (b) the two batteries in parallel-combination are connected to a resistor R. In the circuit the resultant e.m.f. is E and the total resistance is $R + \frac{r}{2}$. If the current in the circuit is I the circuit equation is

$$I = \frac{E}{R + \frac{r}{2}} \qquad \textbf{(10.10)}$$

Since the two batteries have equal e.m.f.s and equal internal resistances the current flowing through each battery is 1/2.

Example (9) Two batteries each having an e.m.f. of 6 V and an internal resistance of 2 Ω are connected: (a) in series and (b) in parallel. Find the current in each case when the batteries are connected to a 1 Ω resistor.

(a) **(i) in series aiding**

If the resultant e.m.f. of two batteries in series aiding is E, $E = 6 + 6 = 12V$

If the total resistance in the circuit is R, $R = 1 + 2 + 2 = 5\ \Omega$

If the current in the circuit is I, $I = \frac{E}{R} = \frac{12}{5} = 2.4\ A$

(ii) in series opposing

If the resultant e.m.f. of two batteries in series opposing is E, $E = 6 - 6 = 0\ V$

If the total resistance in the circuit is R, $R = 1 + 2 + 2 = 5\ \Omega$

If the current in the circuit is I, $I = \frac{E}{R} = 0$

(b) If the resultant e.m.f. of the batteries in parallel is E, E= 6V

The internal resistances of the batteries are in parallel. If the resultant resistance is r,

$$\frac{1}{r} = \frac{1}{2} + \frac{1}{2} = \frac{2}{2}$$

$$r = 1\,\Omega$$

If the total resistance in the circuit is R,

$$R = r + 1$$

$$= 1 + 1$$

$$= 2\,\Omega$$

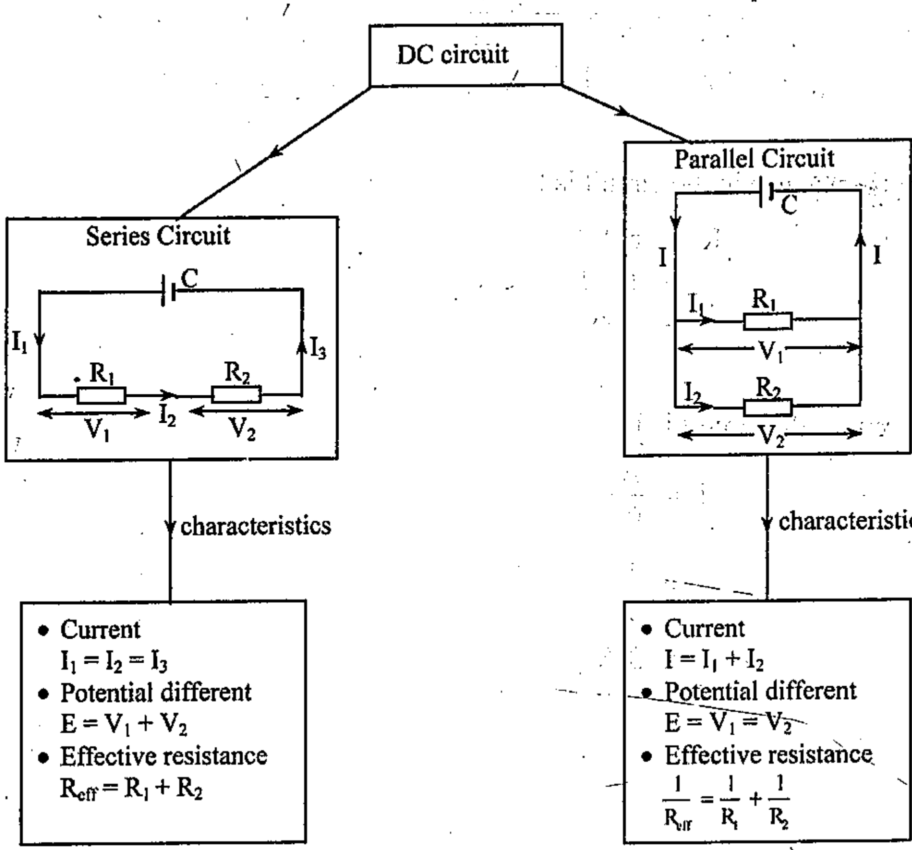
If the current in the circuit is I,

$$I = \frac{E}{R}$$

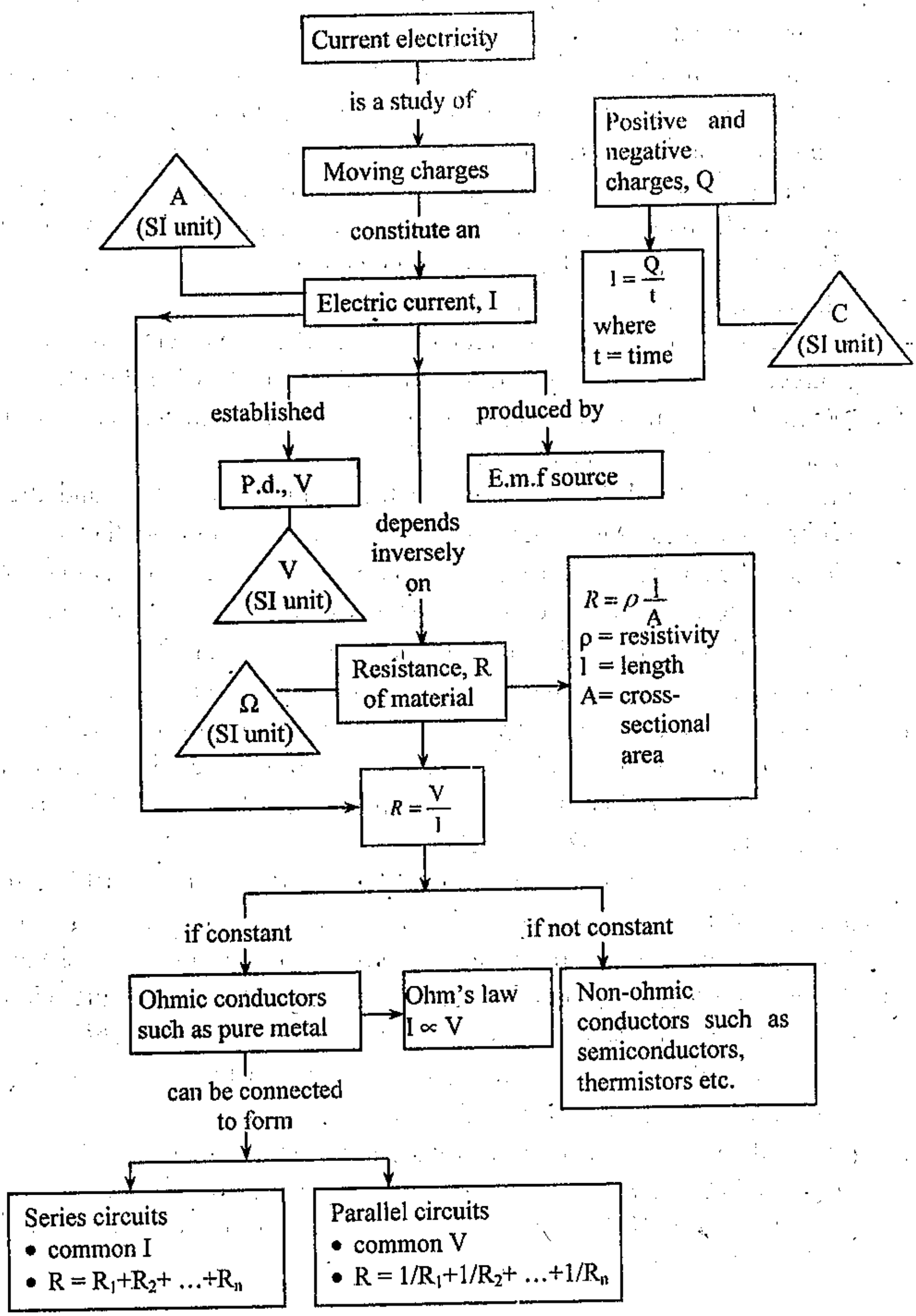
$$= \frac{6}{2}$$

$$= 3\,A$$

Concept Map (DC circuit)



Concept Map (Current electricity)



EXERCISES

1. (a) What is an electric current ? (b) How is an electric current defined? (c) Is an electric current a scalar quantity or a vector quantity? (d) Write down the unit of electric current.
2. (a) State Ohm's law. (b) Using Ohm's law define the resistance of a conductor. (c) What is "resistivity" of a conductor? Write down the unit of resistivity, (d) Which is more fundamental, the resistance or the resistivity? Explain.
3. A current of 4 A flows through a conductor of resistance 20 Ω for 5 min (a) How much charge will pass through a cross-sectional area of the conductor? (b) How many electrons will pass through that area?
4. Choose the correct answer from the following.
   An electric iron draws a current of 15 A when connected to a 120 V power source. Its resistance is (a) 0.125 Ω (b) 8 Ω (c) 16 Ω (d) 1800 Ω.
5. When the length of a wire is doubled and its diameter is halved will the resistance of the wire be the same as before?
6. (a) What is the difference between the e.m.f. of a battery and the potential difference across its terminals ? (b) Under what condition are they the same?
7. Choose the correct answer from the following. A certain piece of copper is to be shaped into a conductor of minimum resistance. Its length and cross-sectional area should be (a) ℓ and A. (b) 2ℓ and A/2. (c) $\ell/2$ and 2A. (d) can assume any value so long as the volume of copper remains the same.
8. A copper wire and a silver wire have the same length and the same potential difference across their ends. If the currents through the wires are the same, find the ratio of the radii of the wires. The resistivity of copper is 1.72×10^{-8} Ω m and that of silver is 1.62×10^{-8} Ω m.
9. A wire of length 100 m is made of silver of resistivity 1.62×10^{-8} Ω m, and has a radius of 1 mm. (a) Find the resistance of the wire. (b) A second wire is made from the same mass of silver but has double the radius. Find its resistance.
10. A wire of 10 Ω is stretched to double its original length. If the resistivity and density of the wire do not change, find its resistance after stretching.
11. If the ratio of the resistances of a tungsten wire at 100 °C and 150 °C is 6/7 what is the temperature coefficient of the wire?
12. (a) A silver wire 2 m long is to have a resistance of 0.5 Ω. What should its diameter be? (b) A 2 Ω resistor is to be made from 100 cm^3 of copper, of resistivity 1.7×10^{-8} Ω m. If the copper is drawn into a wire of circular cross-section, what is its diameter?

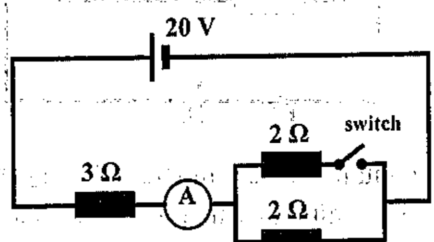
13. (a) Draw diagrams to show that resistances of 20 Ω and 12.5 Ω can be obtained by using one 10 Ω resistor and two 5 Ω resistors. (b) What resistances can be obtained by using three 1 Ω resistors? (c) When the parallel combination of two resistors having different resistances is connected to a battery, which resistor will draw a greater current?

14. A cell has an e.m.f. of 1.5 V and an internal resistance of 1 Ω and is connected to 2 Ω and 3 Ω resistors in series. Find the current in the electric circuit and the potential difference across the ends of each resistor.

15. A battery has an e.m.f. of 6 V and an internal resistance of 0.5 Ω. How many batteries are necessary to pass a current of 1 A through a 22 Ω resistor in an electric circuit?

16. A resistor is in series with an ammeter in an electric circuit. The reading on the ammeter is 0.1 A when the potential difference across the resistor is 3.5 V. A second resistor is joined in parallel with the first, the current rising to 0.2 A and the potential difference dropping to 3.15 V. What are the resistances of the resistors?

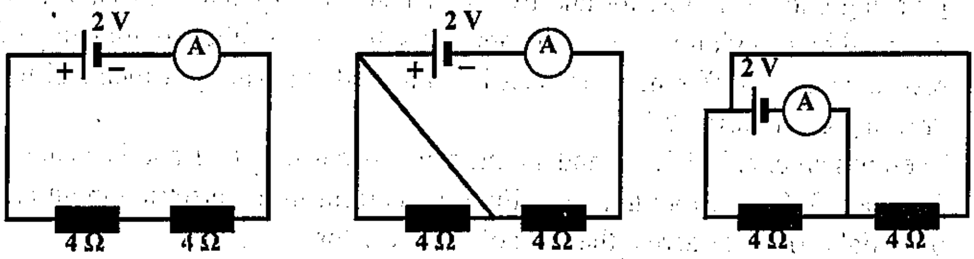
17. In the electric circuit shown below, find the reading of the ammeter A when the switch is: (a) open (b) closed. (Neglect the internal resistance of the battery.)



18. When a 12 V battery of negligible internal resistance is connected to a resistor, a current of 3 A flows through it. When another battery of e.m.f. 6V is in the circuit in series with the first one, the current flowing through the resistor remains at 3 A. Find the internal resistance of the second battery.

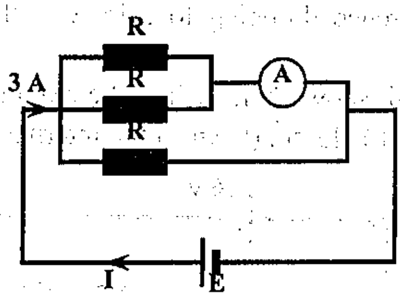
19. When two 6 V batteries, having the same internal resistance and connected in series, are connected to a 5 Ω resistor, the current in the circuit is 2 A. When these batteries are in parallel, a current of 1.5 A flows through when connected to another resistor. Find the resistance of the resistor.

20. Find the readings of the ammeter A in the electric circuits shown below.

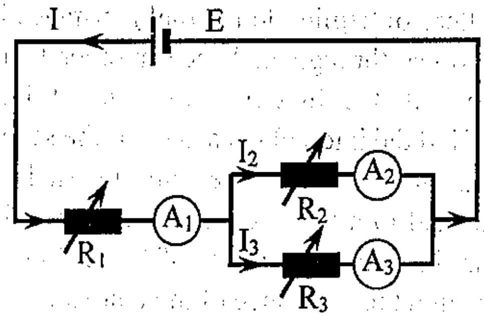


21. Which of the following resistances can be obtained by connecting a 6 Ω resistor with a 12 Ω resistor? Explain. (a) 0.25 Ω (b) 0.50 Ω (c) 2.0 Ω (d) 4.0 Ω (e) 9.0 Ω.

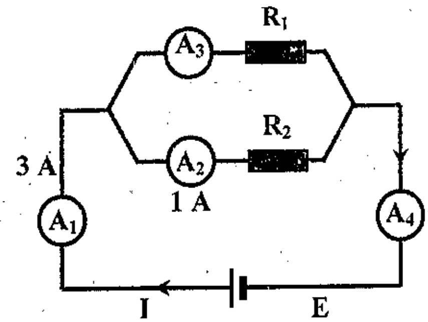
22. In the circuit shown below, find the reading of the ammeter A, when all the resistors have the same resistance R.



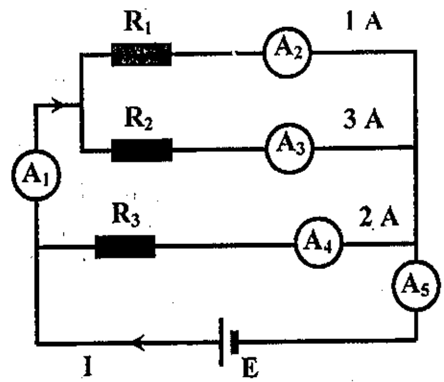
23. The circuit given below contains three ammeters A_1, A_2 and A_3 and three variable resistors R_1, R_2 and R_3. The value of which resistor must be increased in order to increase the reading of the ammeter A_2? Explain.



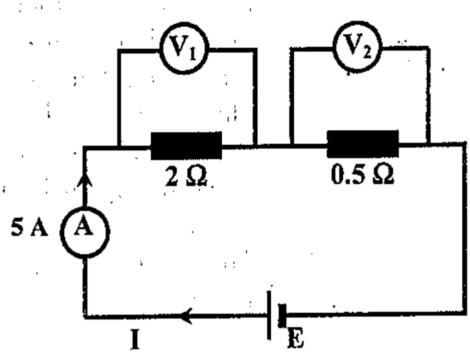
24. In the circuit shown below, find the readings of the ammeters A and A_4. Which resistor has greater resistance?



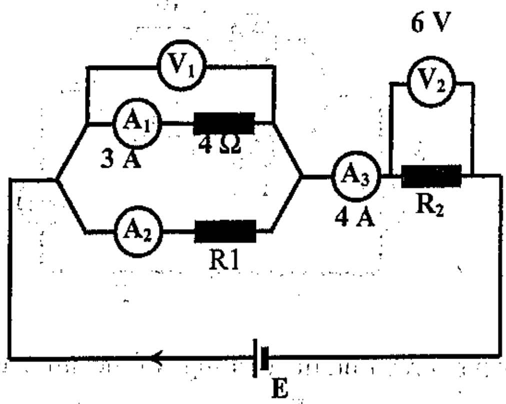
25. In the circuit shown below, find the readings of the ammeters A_1 and A_5.



26. In the circuit shown below, find the readings of the voltmeters V_1 and V_2.



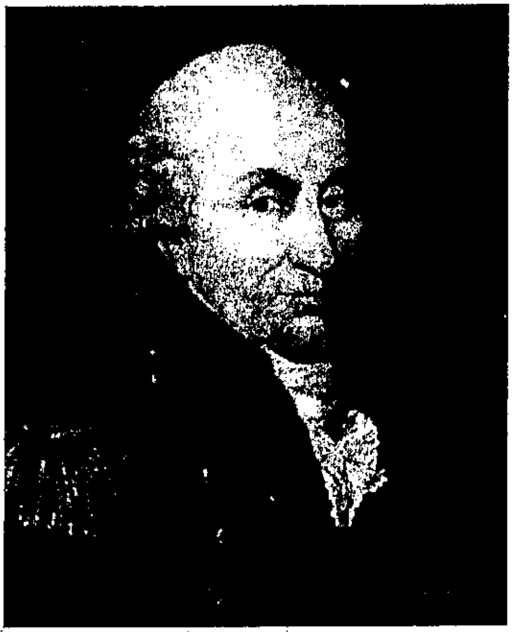
27. In the circuit given below, find the readings of the voltmeter V_1 and the ammeter A_2 and the values of the resistors R_1 and R_2.




Andre Ampere

Andre Ampere(1775-1836)

French mathematical physicist who extended **Oersted's** results by showing that the deflection of a compass relative to an electrical current obeyed the right hand rule. Ampère argued that magnetism could be explained by electric currents in molecules, and invented the solenoid, which behaved as a bar magnet. Ampère also showed that parallel wires with current in the same direction attract, those with current in opposite directions repel. He dubbed the study of currents electrodynamics, and also developed a wave theory of heat. Ampère maintained that magnetic forces were linear, but this proposition was questioned and disproved by Faraday.



Charles Augustin de Coulomb

Charles Augustin de Coulomb (1736–1806) was a French physicist.

Coulomb was born in Angoulême, France. He chose the profession of military engineer, and spent three years, to the decided injury of his health, at Fort Bourbon, Martinique. Upon his return, he was employed at La Rochelle, the Isle of Aix and Cherbourg. He discovered an inverse relationship on the force between charges and the square of its distance, later named after him as Coulomb's law. Coulomb is distinguished in the history of mechanics and of electricity and magnetism. In 1779 he published an important investigation of the laws of friction which was followed twenty years later by a memoir on viscosity. The SI unit of charge, the coulomb, and Coulomb's law are named after him

CHAPTER 11

ELECTRICAL ENERGY AND POWER

Electrical energy can be transformed into a wide variety of other useful forms of energy. One transformation that of electrical energy into heat energy, is very useful and important. Many home appliances use the heat generated from such transformation. In this chapter we shall discuss the use of electrical power and some applications of heating effects of current.

11.1 ELECTRICAL ENERGY AND POWER

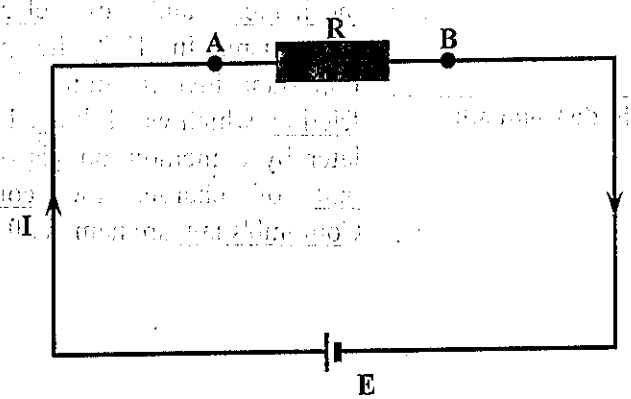


Fig. 11.1 Conversion of electrical to heat energy in the resistor

In Fig. 11.1 a resistor R is connected to a battery, which is a source of e.m.f. As the current I flows through the resistor R the potential at the point A is higher than that at the point B. Suppose that the potential difference between A and B is V. By the definition of potential difference, the work done in bringing a unit positive charge from A to B is V. If the work done in bringing the amount of charge Q from A to B is W, then

$$W = Q V \qquad (1)$$

Suppose the amount of charge Q passes through a cross-sectional area of the resistor R in the time t. By the definition of current,

$$I = \frac{Q}{t}$$

or $$Q = It \qquad (2)$$

From equations (1) and (2), the work done W is obtained as follows,

$$W = V I t \qquad (11.1)$$

The work W is done by the battery in bringing the change Q from A to B. This work is transformed into heat in the resistor R. This is because the electrons collide with the atoms in the resistor R when they pass through it. Hence the atoms acquire additional energy and therefore heat energy is produced.

The work done, by the battery in taking the charge Q from A to B is, in fact, the electrical energy supplied by the battery. Thus the electrical energy supplied by the battery is transformed into heat energy in the resistor R.

The potential difference between A and B is V = IR. And from equation (11.1), the work done or the electrical energy W produced by the battery is

$$W = V I t$$

$$= I^2Rt$$

$$= \frac{V^2}{R}t$$

If an electric motor is connected between A and B in Fig. 11.1 the electrical energy will be transformed into mechanical energy.

Unit of Electrical Energy

The practical unit of electrical energy is kilowatt hour (kWh). The relation between the unit of electrical energy kWh and the unit of work J is

$$1\ \text{kWh} = 1000\ \text{W} \times 1\ \text{h}$$

$$= 1000 \times 60 \times 60$$

$$= 3.60 \times 10^6\ \text{Ws}$$

$$= 3.6 \times 10^6\ \text{J}$$

In using electricity 1 kWh is taken as one unit of electricity or one unit of electrical energy. Electricity meters installed in homes and buildings read kWh directly. For example, if one 1 kW electric lamp is used for 1 h the meter shows an increase of one unit. If one 2 kW electric lamp is used for 1 h the meter shows an increase of 2 units. The electrical units recorded by the electricity meter show how much electrical energy is used. The payment for using electricity is made according to the cost of electricity per unit and the total number of units utilized. The horse power (hp) unit is used in expressing the power of machines.

$$1\ hp = 746\ W$$

Example (1) If a current of 2 A flows through a 50 Ω resistor for 30 min find the amount of electrical energy dissipated in the resistor.

$$R = 50\ \Omega, \quad I = 2A, \quad t = 30\ min = \frac{1}{2}\ h$$

Let W be the electrical energy dissipated in the resistor.

$$W = I^2 R t$$

$$= 2^2 A^2 \times 50\ \Omega \times \frac{1}{2} h$$

$$= 100\ Wh$$

$$= 0.1\ kWh$$

Example (2) An electric lamp of 60 Ω connected to a 240 V mains line is used for 45 min. (a) Find the amount of electrical energy dissipated in the lamp. (b) Find the cost of using it if electricity costs 25 kyats per unit.

$$R = 60\ \Omega, \quad V = 240\ V, \quad t = 45\ min = \frac{3}{4}\ h$$

(a) Let W be the electrical energy dissipated in the lamp.

$$W = \frac{V^2}{R} t$$

$$= \frac{(240)^2}{60} \times \frac{3}{4}$$

$$= 720\ Wh$$

$$= 0.72\ kWh$$

(b) One unit of electricity $= 1\ kWh$

The cost of using 0.72 kWh $= 25 \times 0.72$

$= 18$ kyats

Electrical Power

Electrical power is the rate of work done or the rate of transfer of electrical energy. If the work W is done in the time t, then the electrical power P is,

$$P = \frac{W}{t} \qquad (11.2)$$

Since $W = V\,It = I^2Rt = \frac{V^2}{R}t$

$$P = VI$$

$$= I^2R$$

$$P = \frac{V^2}{R}$$

Unit of Electrical Power

The unit of electrical power P is the watt (W). If 1 J of work is done in 1 s the electrical power is 1 J s^{-1}. 1 J s^{-1} is 1 W, as we have already seen in the ninth standard text. "Watt" is a very small unit and is, therefore, not convenient for use. The more appropriate unit is the kilowatt (kW).

11.2 JOULE'S LAW OF ELECTRICITY AND HEAT

We have already learnt that heat energy is produced by the resistor R shown in Fig.11.1. The work done or the electrical energy W supplied by the battery is transformed into heat in the resistor R, Suppose that the amount of heat produced by the resistor R is H. The work done W is related to the amount of heat H as follows.

$$W = JH \qquad (11.3)$$

J is a constant called Joule's mechanical equivalent of heat,

where $J = 4.2$ J cal

When $W = I^2Rt$ is substituted in equation (11.3) the following equation is obtained.

$$H = \frac{I^2Rt}{J} \qquad (11.3a)$$

This equation represents Joule's law of electricity and heat which can be stated as follows.

The amount of heat produced in a resistor due to a current flowing through it is directly proportional to the square of the current, the value of resistance and the time taken by the current to pass through the resistor.

H can also be written as follows:

$$H = \frac{VIt}{J} = \frac{V^2t}{RJ}$$

Example (3) If a 60 W electric lamp is connected to a 240 V mains line find (a) the current in the lamp (b) the resistance of tungsten wire of the lamp (c) the amount of charge passing through the filament in 1 min and (d) the amount of heat produced by the filament in 1 min.

(a) $P = 60W, \quad V = 240\ V$

Let I be the current in the filament.

$$P = VI$$

$$I = \frac{P}{V}$$

$$= \frac{60}{240}$$

$$= 0.25\ A$$

(b) Let R be the resistance of the filament.

$$P = I^2 R$$

$$R = \frac{P}{I^2}$$

$$= \frac{60}{(0.25)^2}$$

$$= 960\ \Omega$$

(c) Let Q be the amount of charge passing through the filament in 1 min.

$$I = \frac{Q}{t}$$

$$Q = It$$

$$= 0.25 \times 60$$

$$= 15\ C$$

(d) Let H be the amount of heat generated in 1 min.

$$H = \frac{I^2Rt}{J}$$

$$= \frac{(0.25)^2 \times 960 \times 60}{4.2}$$

$$= 857.14\ cal$$

Example (4) If a 1200 W electric iron is used for 50 min, by how many units does the meter reading increase? Calculate the payment if one unit of electricity costs 10 kyats.

$$P = 1200\ W,\ t = 50\ min = \frac{5}{6}\ h$$

Let W be the electrical energy used by the electric iron.

$$P = \frac{W}{t} \quad \text{or} \quad W = Pt$$

$$= 1200 \times \frac{5}{6}$$

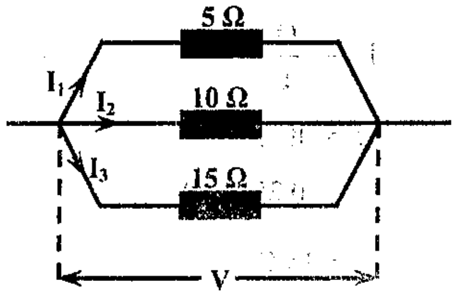
$$= 1000\ Wh$$

$$= 1\ kWh$$

One unit of electricity = 1 kWh

Therefore, the payment = 1 × 10 = 10 kyats

Example (5) One 5 Ω, one 10 Ω, and one 15 Ω resistors are connected in parallel. If each resistor has an electrical power of 0.5 W, find the maximum potential difference which may be supplied to the parallel combination and the current in each resistor.



Since the resistors are connected in parallel the potential difference across each resistor is the same.

Since the electrical power $P = \frac{V^2}{R}$, the electrical power dissipated in the 5 Ω resistor having minimum resistance would be maximum. Therefore, the 5 Ω resistor must be used to find the maximum potential difference.

$$0.5 = \frac{V^2}{5}$$

$$V = 1.58\ V$$

The current in the 5 Ω resistor, $I_1 = \frac{V}{R_1}$

$$= \frac{1.58}{5} = 0.32\ A$$

The current in the 10 Ω resistor, $I_2 = \frac{V}{R_2}$

$$= \frac{1.58}{10}$$

$$= 0.16\ A$$

The current in the 15 Ω resistor, $I_3 = \frac{V}{R_3}$

$$= \frac{1.58}{15}$$

$$= 0.11\ A$$

11.3 SOME APPLICATIONS OF THE HEATING EFFECT OF CURRENT

Electrical energy can be transformed into a wide variety of other useful forms of energy. We know that a resistor converts most of the electrical energy supplied to it into heat. The heating effect of electric current has special application in homes. For example, electric stoves, electric cookers, electric irons and immersion heaters all change electrical energy into heat energy. Some electrical appliances which use the heating effect of current are described below.

Fuse

If a current which flows through an electrical appliance is greater than the maximum it can carry, the appliance can be seriously damaged. To prevent this electrical fuses are used in electric circuits. For example suppose that a 3 A fuse is used in the electric circuit. If a current greater than 3A flows in the circuit, the fuse becomes so hot that it will melt and break the circuit. Thus the current stops flowing and the electrical appliance in the circuit is not damaged.

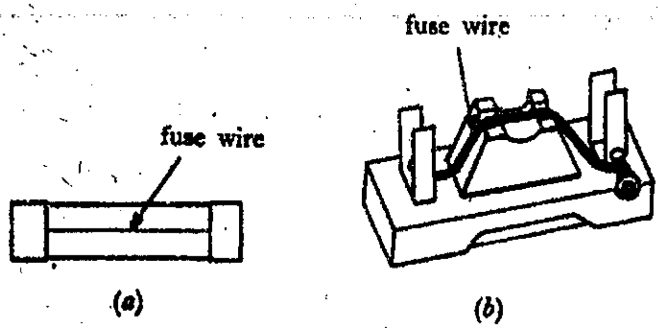


Fig. 11.2 Fuses

A fuse wire is usually made of tin-lead alloy. A cartridge fuse used in a 13A plug is shown in Fig. 11.2 (a). The fuse wire is connected to metal caps at the end of a short glass tube. Generally, 3 A fuses are used in record players and 13 A fuses are used in electric cookers.

Fig. 11.2 (b) shows a conventional fuse used in fuse boxes. Fuses from 3 A to 15 A are widely used.

Example (6) A 3A fuse is used in a circuit which contains a source of 240 V. Find the maximum power which can be consumed.

$V = 240V, \ 1 = 3A$

Let P be the maximum power which can be consumed.

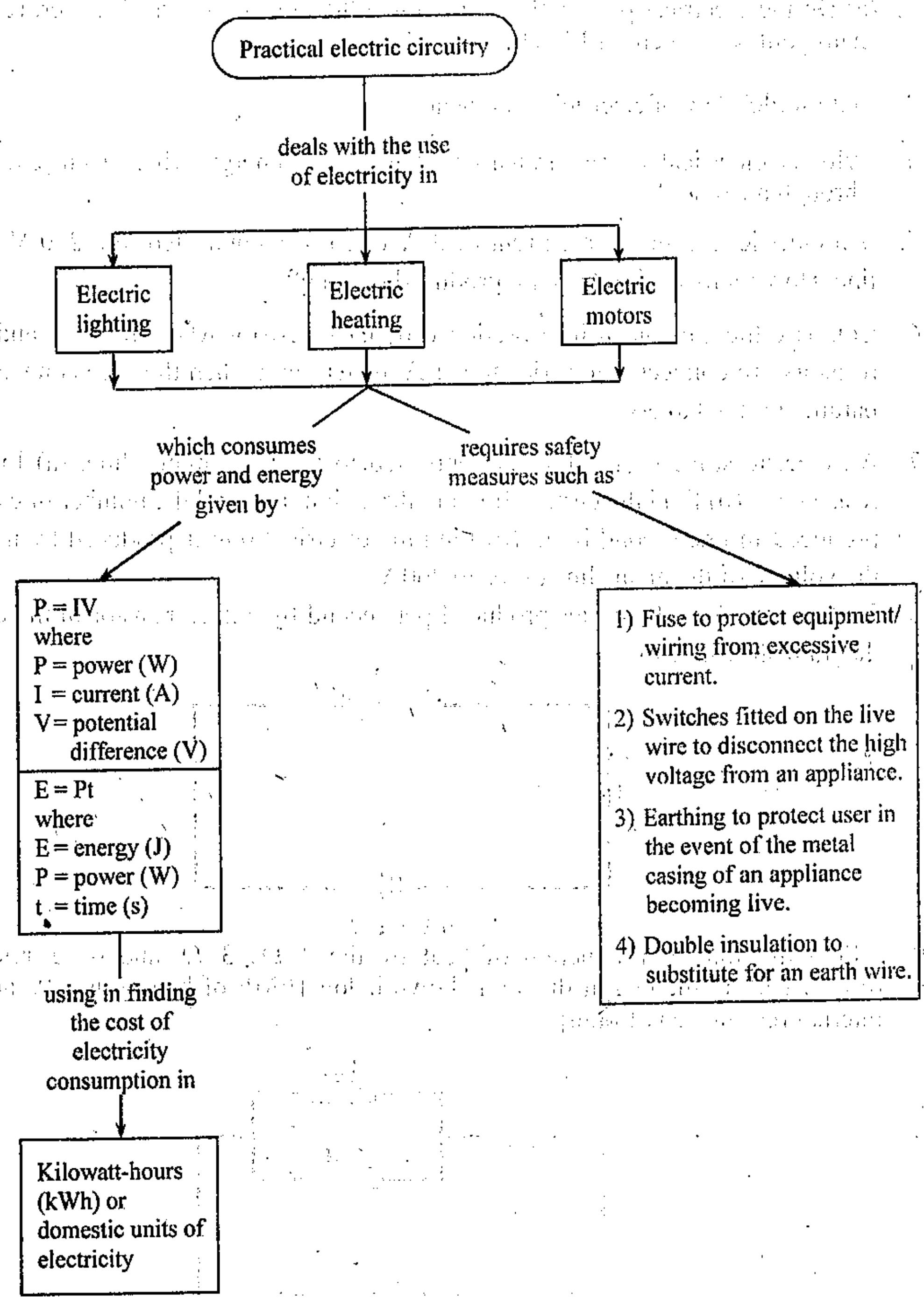
$$P = IV$$
$$= 240 \times 3$$
$$= 720\ W$$

The electrical powers of some electrical appliances used in homes are given in Table 11.1.

Table 11.1

Electrical Appliance	Electrical Power
Tape recorder	50 W
Reading lamp	40-100 W
Refrigerator	100 W
Radio and television receivers	150 W
Electric iron	750-1000 W
Electric stove	1200 W

Concept Map (Practical electric circuit)



EXERCISES

1. What is electrical energy? Express its unit.

2. (a) Define electrical power. (b) Write down the unit of electrical power. (c) How many joules are there in 1 kWh?

3. State Joule's law of electricity and heat.

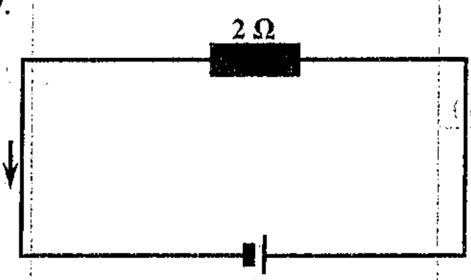
4. Why is electrical energy transformed into heat energy when a current flows through a resistor?

5. An electric iron draws a current of 3 A when it is connected to a 240 V mains line. How many kcal of heat are produced per min?

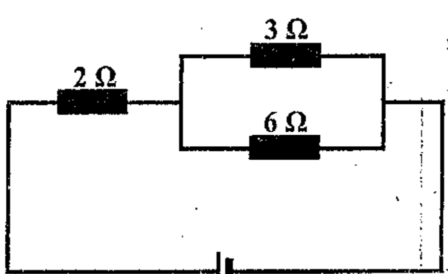
6. Compare the amount of heat produced by each resistor when the 2 Ω and 3 Ω resistors are connected in series to a 12V battery and when they are connected in parallel to that battery.

7. An electric stove of 1200 W is connected to a 240 V mains line. (a) Find its resistance. (b) Find the current flowing through it. (c) Find the number of calories produced in one second by it. (d) Find the electrical power produced by it when the voltage of the mains line drops to 200 V.

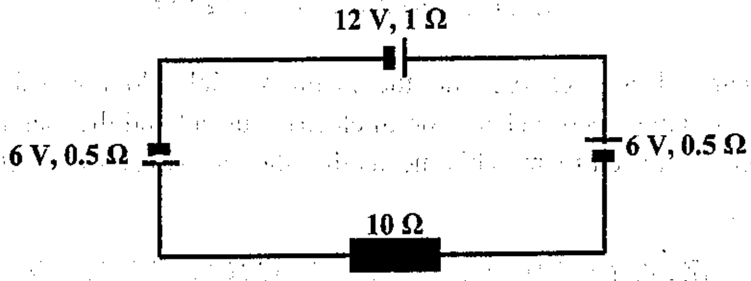
8. Find the number of calories produced per second by a 2 Ω resistor in the circuit diagram shown below.



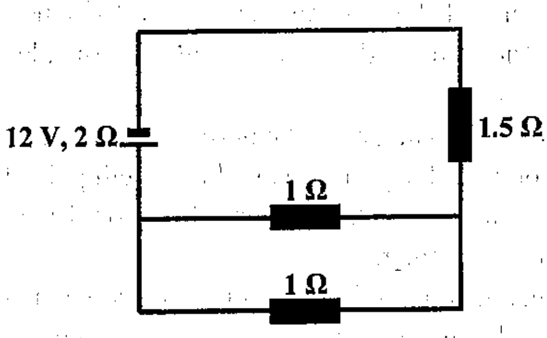
9. Find the rate of production of heat by the 2 Ω, 3 Ω and 6 Ω resistors respectively in the circuit diagram shown below.[EMF of battery is 12V and its internal resistance is 1 ohm]



10. Find the amount of heat produced in 10 min by a 10 Ω resistor in the circuit diagram shown below.



11. Find the rate of production of heat in the battery in the circuit diagram shown below.



12. When an electric stove is connected to a 240 V mains line it draws a current of 6 A. The electric stove is used for 15 min. (a) Find the amount of heat produced by it. (b) Calculate the cost of using it if the electric energy costs 10 kyats per unit.

13. An electric circuit installed in a house contains a 5A fuse and the voltage is 230 V. Find the maximum electrical power which can safely be used.

14. An electric circuit installed in a house contains a 5A fuse and the voltage is 230 V. Can twenty 60 W electric lamps be used at the same time in that circuit ?

15. An electric circuit installed in an office contains a 10 A fuse and the voltage is 230 V. Ten 100 W electric lamps and two 150 W refrigerators are being used there. Find the maximum number of 60 W electric lamps which can be safely used in addition.

16. Find the cost of using all the lamps and two refrigerators in problem (15) for 10 h. (Assume that electricity costs 10 kyats per unit.)

CHAPTER 12

ELECTROMAGNETISM

The stationary electric charge and the magnetic field do not affect each other. However, a moving electric charge or an electric current and the magnetic field have mutual effects between them. This means that the electric and magnetic phenomena are related.

12.1 MAGNETIC FIELD DUE TO AN ELECTRIC CURRENT

A substance which has the property of attracting small pieces of iron in its vicinity is called a magnet. Naturally occurring magnets were found some 2500 years ago. The magnetic iron oxide, one of the minerals, is a natural magnet. The magnet used in devices such as electric bells and telephones are man-made magnets or artificial magnets.

A bar magnet has two poles. The one at the north-seeking end is called the north pole, and the other at the south-seeking end is called the south pole. The poles of a magnet have a greater power of attraction than its central portion. Like poles repel each other and unlike poles attract each other.

The region where a magnetic force is exerted is called a magnetic field. The magnetic field is represented by the magnetic lines of force. If a tangent is drawn at any point on a magnetic line of force its direction is the same as the direction of the magnetic field intensity at that point. The magnetic lines of force leave the north pole and enter the south pole. Fig. 12.1 shows the magnetic lines of force around a bar magnet.

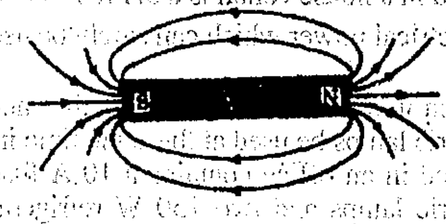


Fig. 12.1 Magnetic lines of force

The magnetic effect of an electric current will be studied now. That effect was discovered by Oersted in 1820. When a straight wire carrying a current was placed above a compass needle as shown in Fig. 12.2 (a) the needle was deflected. When the wire was placed below the needle as shown in Fig.12.2 (b) it was deflected in the opposite direction. This experiment was first done by Oersted.

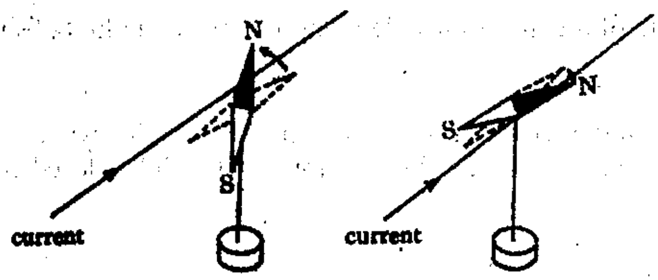


Fig.12.2 Magnetic field due to a wire carrying current

From Oersted's findings it is obvious that the current flowing through the wire produces an effect on the needle. The deflection of the needle is due to a magnetic force acting on it. In other words, there is a magnetic field in the neighbourhood of the wire. This magnetic field is the one produced by the current flowing in the wire. Therefore, there is a magnetic field around every wire carrying an electric current.

The direction of the magnetic field due to the current flowing through the wire can be found by using the right-hand rule [Fig.12.3 (a)]. Imagine the wire to be grasped in the right hand with the thumb pointing along the wire in the direction of the current. The direction of the fingers will give the direction of the magnetic field. The north pole of a compass needle indicates the direction of the magnetic field [Fig.12.3 (c)].

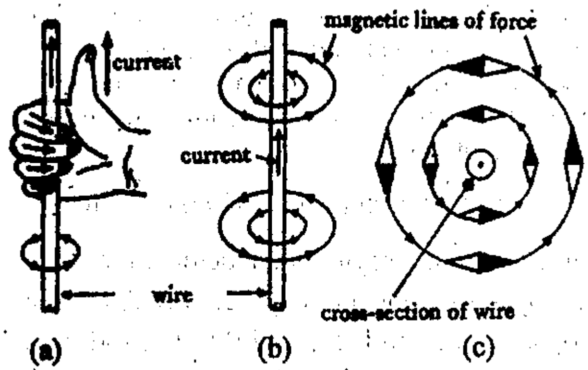


Fig. 12.3 Application of the right-hand rule

As an electric field is represented by drawing electric lines of force a magnetic field can also be represented by magnetic lines of force. The magnetic lines of force around the wire carrying a current I are shown in Fig.12.3 (b). Fig.12.3 (c) shows the cross-section of the wire as seen from the top. The dot in the cross-section indicates that the current is flowing out of the page. The magnetic lines of force are closed circular loops around the wire and they are in the plane perpendicular to the wire. The orientation of the north pole of a compass needle along the magnetic line of force is shown in Fig. 12.3 (c).

If the current flowing through the wire is reversed, the direction of the magnetic field will also be reversed. However, the magnetic lines of force will still be closed circular loops.

Magnetic Field of a Solenoid

A solenoid is a cylindrical coil of wire. A solenoid has a magnetic field in its vicinity when a current flows through it. The magnetic field of a solenoid is identical with that of a bar magnet (Fig. 12.4). Thus a solenoid can be considered as a bar magnet. One end of a solenoid acts like a north pole and the other like a south pole.

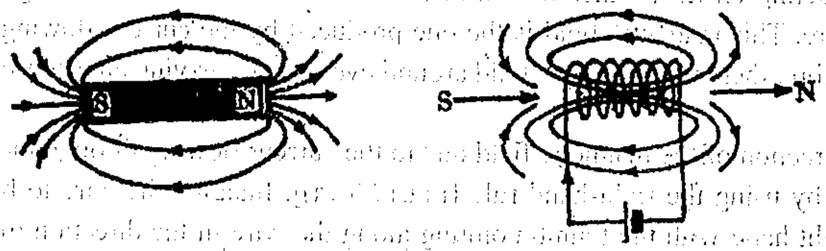


Fig. 12.4 Magnetic field of a solenoid

The magnetic poles of a solenoid carrying a current can be found as follows. When viewing one end of the solenoid, that end will be a south pole if the current is seen flowing in a clockwise direction and a north pole if the current is seen flowing in an anticlockwise direction. The right end of the solenoid shown in Fig. 12.4 is the north pole and the left end is the south pole.

Force on a Current-carrying Conductor in a Magnetic Field

The force acting on a current-carrying conductor in a magnetic field can be demonstrated with the apparatus shown in Fig. 12.5 (a). A brass cylindrical rod AL is placed across two horizontal brass rails PQ and RT. The rod AL is between the poles of a horseshoe magnet and perpendicular to the direction of the magnetic field. When PQ and RT are connected to the positive and negative terminals of a battery respectively as shown in Fig. 12.5(a), a current I flows along QALT in the circuit.

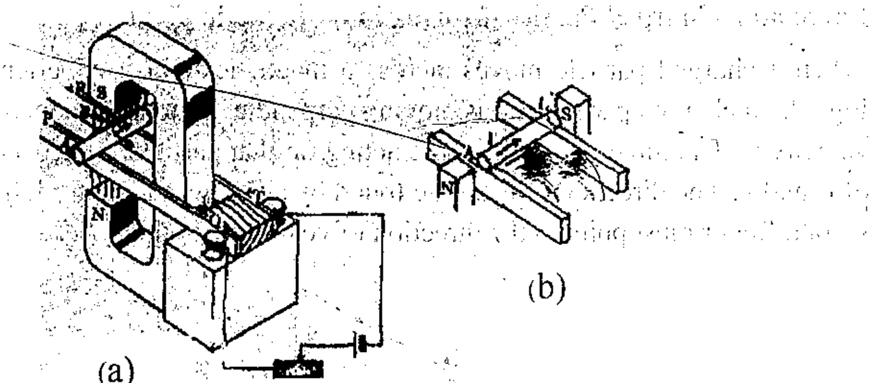


Fig. 12.5 Current-carrying conductor in a magnetic field

When the current I flows from A to L the rod is observed to roll along the rails towards, the magnet. It can be seen that a force which is perpendicular to both AL and the magnetic field B acts on the rod AL.

When PQ and RT are connected to the negative and positive terminals of the battery respectively, the current flows through the rod in the opposite direction (from L to A). In this case, the rod is observed to roll along the rails away from the magnet. It is obvious that the force F acting on the rod is in the opposite direction.

When the magnet is turned round so that the magnetic field B is parallel to the length AL of the rod, and the circuit is switched on, the rod remains still [Fig. 12.5 (b)]. There is no force acting on the rod. In Fig. 12.5 (a) B, I and F are at right angles to one another. They can be seen clearly in Fig 12.6 (a). The direction of the force F can be found by the use of Fleming's left-hand rule [Fig. 13.6 (b)].

Fleming's Left-hand Rule

Place the forefinger, second finger, and the thumb of the left hand mutually at right angles to one another. If the fore **F**inger points in the direction of the **F**ield and the se**C**ond finger in the direction of the **C**urrent, then the thu**M**b will point in the direction of the **M**otion along which the force acts.

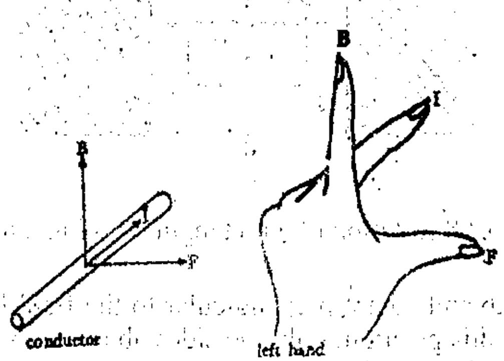


Fig. 12.6 Fleming's left-hand rule

Force on a Charged Particle Moving in a Magnetic Field

When a charged particle moves across a magnetic field it experiences a force. In Fig.12.7 a charged particle + q is moving perpendicular to the magnetic field B with a velocity v. The direction of the force acting on that particle is perpendicular to those of B and v. The direction of F can be found by applying Fleming's left-hand rule. The second finger must point in the direction of velocity v in this case.

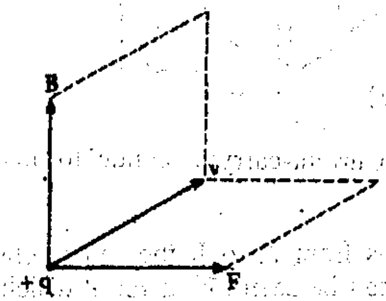


Fig. 12.7 Force on a moving charge

If the particle in Fig. 12.7 is a negatively charged one the force acting on that particle will be in the opposite direction.

Torque on a Coil in Magnetic Field

A rectangular coil of wire abcd carrying a current I is placed in a uniform magnetic field B between the poles of a magnet.

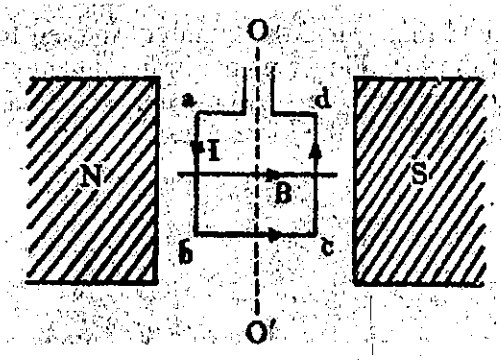


Fig. 12.8 Rotation of a rectangular coil in a magnetic field

Suppose that the side ab and cd are perpendicular to the field B and the sides ad and bc are parallel to B. In this position, only the sides ab and cd will experience a force. As the current flowing along ab is opposite to that flowing along cd with respect to the field B, the forces acting on these sides will be equal and opposite. The directions of these forces can be found by applying Fleming's left-hand rule. These two forces are called a couple. The moment of a couple is the product of one of these forces and the perpendicular distance between them. The moment of a couple is also called a torque. These forces exert a torque on the coil so that it rotates about an axis OO'.

12.2 ELECTROMAGNETS

The best method of making a magnet is to use the magnetic effect of an electric current. When a current flows through a solenoid of insulated wire a magnetic field is set up everywhere inside. If the solenoid consists of many turns and a very large current flows through it a powerful magnetic field is obtained. In Fig. 12.9, a steel bar is placed inside a solenoid of insulated wire. When a large current flows through the solenoid the steel bar becomes magnetized permanently. Such a magnet is called a permanent magnet.

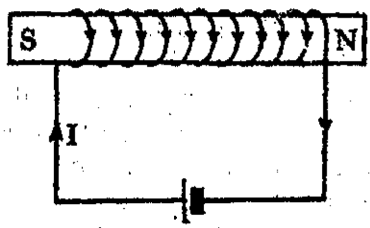


Fig. 12.9 Magnetization by electric current

Similarly, if a soft iron bar is placed inside the solenoid of insulated wire and a current flows through it, the bar becomes magnetized. It is demagnetized when the current stops. As the soft iron bar is magnetized only when the current is flowing such a magnet is called a temporary magnet or an electromagnet.

In Fig. 12.10 two solenoids are wound in opposite directions on two soft iron bars. The ends of the bars are joined by a soft iron bar. The two bars become magnetized when a current flows through the solenoids. The end of the bar on the left becomes a south pole and the end of the bar on the right becomes a north pole.

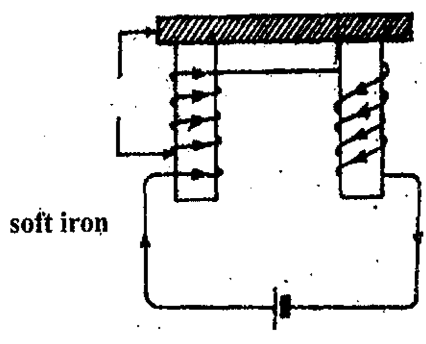


Fig. 12.10 Simple electromagnet

The Electric Bell

An electric bell is an example of the use of the magnetic effect of current. The construction of an electric bell is shown in Fig. 12.11

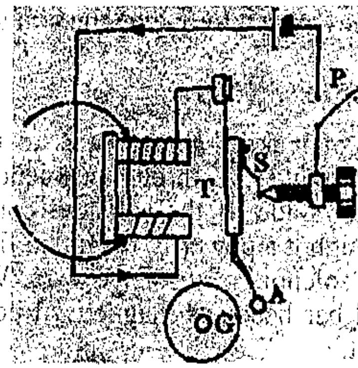


Fig. 12.11 Electric bell

The soft iron armature T is mounted on a spring S. A small metal plate which is attached to the armature acts as a contact. When the switch is pressed the current flows through the circuit and the soft iron bars become magnetized. As they attract the armature T, the hammer A attached to it strikes the gong G. At that moment the metal plate and the end of the screw are separated so that the current stops. When this happens, the magnetism in the bars disappears and the armature is returned by the spring to its original position. Contact is now remade and the action repeated. Consequently, the armature vibrates and the hammer attached to it strikes the gong G.

Electromagnetic devices used in construction work and industry consist of electromagnets. Fig. 12.12 shows an electromagnet used in research.

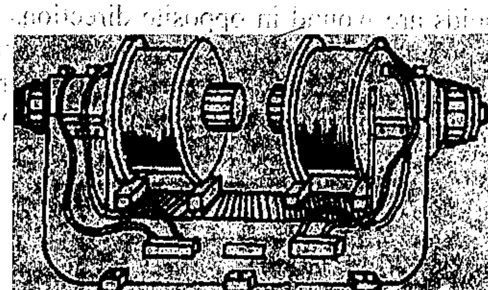


Fig. 12.12 An electromagnet

12.3 AMMETER AND VOLTMETER

Ammeters and voltmeters are electrical instruments whose constructions are based upon the principle of a moving-coil galvanometer. We know that a coil in a magnetic field rotates when a current flows through it. The effect of such rotation of a coil is used in the construction of a moving-coil galvanometer.

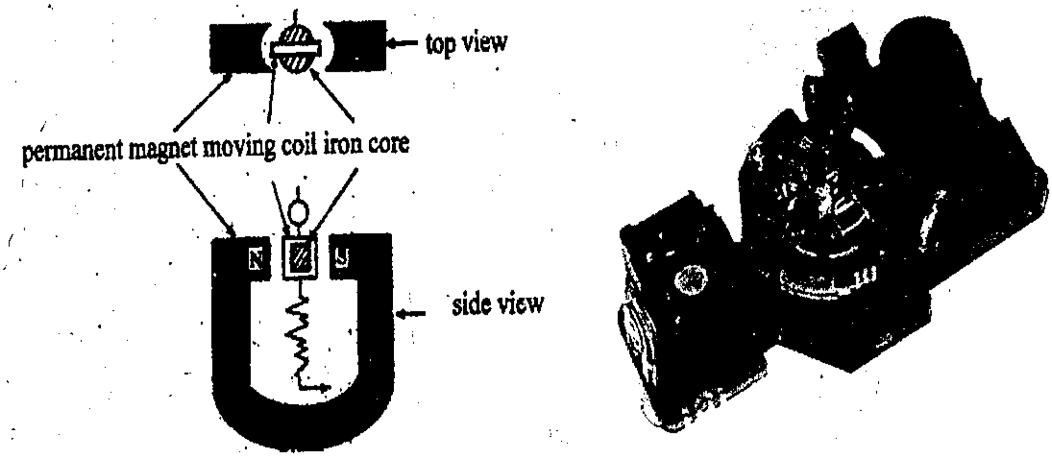
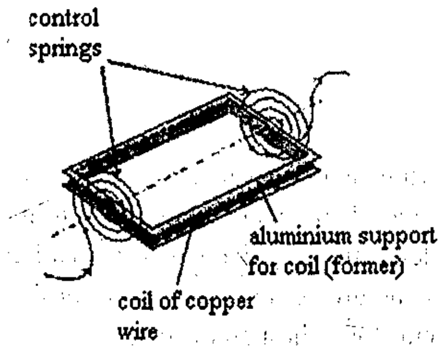
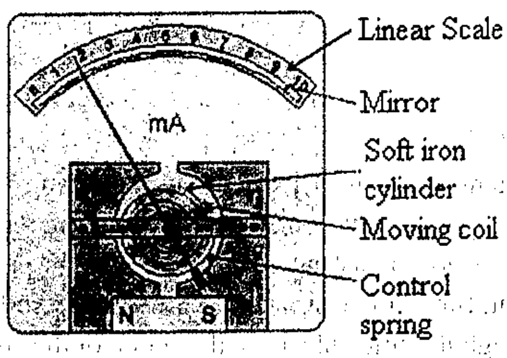


Fig. 12.13 Moving coil galvanometer





The construction of a moving-coil galvanometer is shown schematically in Fig.12.13. The coil suspended by a wire rotates when a small current flows through it. The magnetic forces acting on the coil constitute a torque and it leads to a twist in the wire which sets up a restoring torque. The electromagnetic torque and the restoring torque are opposite in direction. The coil will stop rotating when they are equal in magnitude. If the current is stopped the coil will rotate back due to the restoring torque.

The more the current flowing through the coil, the stronger the torque, and hence the farther the coil rotates. The angle of rotation can be measured by a pointer fastened to the coil as well as by a small mirror attached to a wire. As the angle of rotation is directly proportional to the current, the value of current can be measured from the angle of rotation.

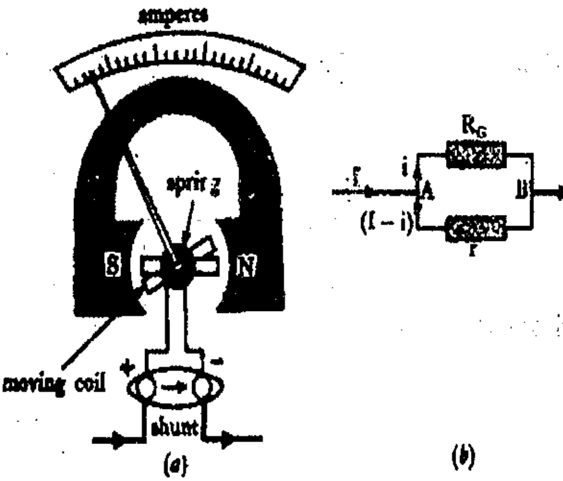


Fig. 12.14 Moving coil ammeter

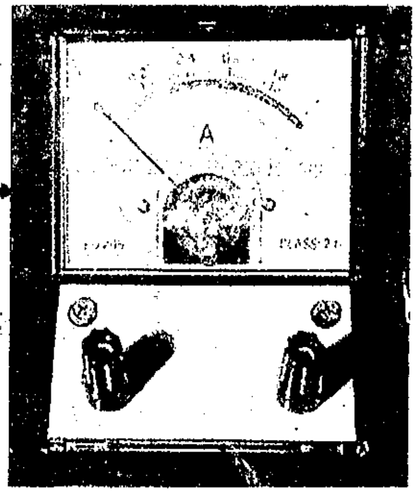


Fig. 12.14 (c) An ammeter measure currtnt

Ammeter

An ammeter which is a current-measuring instrument is shown in Fig. 12.14 a. A moving-coil galvanometer functions as an ammeter when a shunt is provided to it. A wire of low resistance which is placed in parallel with the galvanometer is called a shunt. Since the resistance of the shunt is so low the greater part of the current flows through it while only a small fraction of the current flows through the coil.

Suppose that a galvanometer gives a full-scale deflection when a current i flows through its coil. This means that the maximum value of the current which can be measured by the galvanometer is i. If a current I which is greater than i is to be measured, a shunt must be placed in parallel with the galvanometer. However, the resistance of the shunt must be chosen to ensure that the current through the coil does not exceed i. In Fig 12.14 (b), R_G is the resistance of the galvanometer and r is that of the shunt.

Suppose that current I is flowing through the instrument and the current i is flowing through the coil. Then the current flowing through the shunt is I - i. The potential difference between A and B, the two ends of the coil and the shunt, is the same.

Therefore $(I - i)\, r = i\, R_G$

$$r = R_G \frac{i}{(I-i)} \qquad (12.1)$$

The resistance of the shunt to be used can be calculated from the above equation.

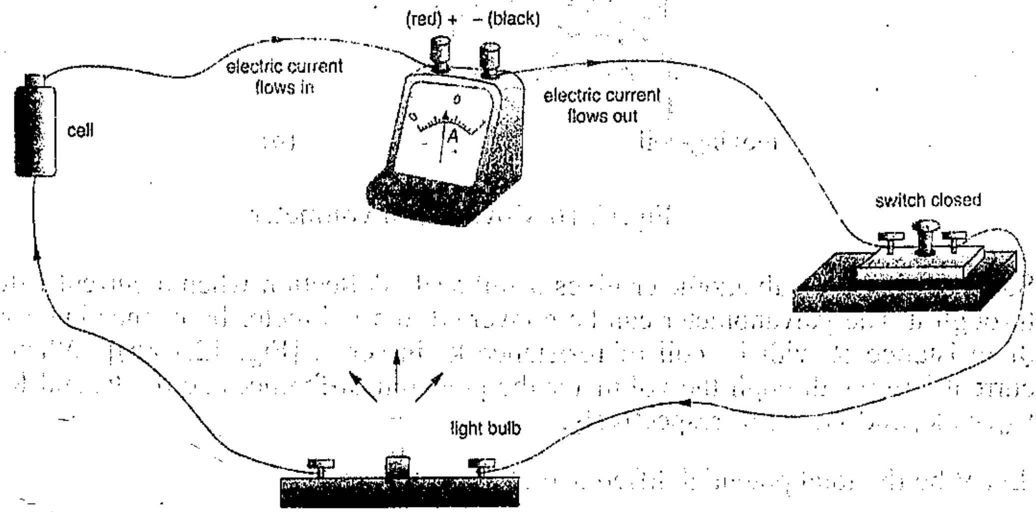


Fig. 12.15 Measuring an electric current using an ammeter

Voltmeter

A voltmeter which measures the potential difference is shown in Fig. 12.16(a). A moving-coil galvanometer functions as a voltmeter when a wire of high resistance is connected in series with its coil. Since the total resistance of the coil and the wire is very high a small current flows through the coil. By Ohm's law, for a given resistance the current is directly proportional to the potential difference. The voltmeter scale is so calibrated that the pointer indicates the potential difference directly.

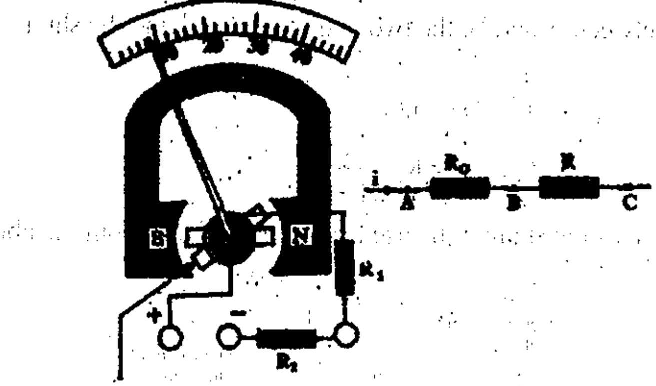


Fig.12.16 Moving-coil voltmeter

Suppose that the galvanometer gives a full-scale deflection when a current i flows through it The galvanometer can be converted to a voltmeter by connecting a wire of resistance R with its coil of resistance R_G in series [Fig. 12.16(b)]. When the current i flows through the voltmeter the potential differences across R_G and R are $V_{AB} = i R_G$ and $V_{BC} = i R$, respectively.

Let V be the total potential difference of the voltmeter.

Then,
$$V = V_{AB} + V_{BC}$$
$$= i R_G + i R$$
$$= i (R_G + R)$$

or
$$R = \frac{V}{i} - R_G \qquad (12.2)$$

The above equation gives the resistance of the wire which must be used in order that the voltmeter may measure the maximum potential difference.

Example (1) A galvanometer has a resistance of 2 Ω and gives a full scale deflection when a current of 1 mA flows through it. How can it be converted for use as (a) an ammeter reading up to 10 A, and (b) a voltmeter reading up to 50 V?

(a)
$$R_G = 2\ \Omega$$
$$i = 1\ \text{mA} = 1.0 \times 10^{-3}\ \text{A}$$
$$I = 10\ \text{A}$$

Let r be the resistance of the wire to be connected in parallel with R_G.

$$r = \frac{i}{I - i} R_G$$

$$= \frac{1.0\times10^{-3}\,A}{10A - 1.0\times10^{-3}\,A} \times 2\Omega$$

$$= 2.0 \times 10^{-4}\ \Omega$$

(b) Let R be the resistance to be connected in series with R_G.

$$R = \frac{V}{i} - R_G$$

$$= \frac{50}{1.0\times10^{-3}} - 2$$

$$= 49\,998\ \Omega$$

$$= 50\ k\ \Omega$$

SUMMARY (ELECTRICITY AND MAGNETISM)

ELECTRICITY

Alternating current (ac) Electric current whose direction alternates (changes) at regular intervals.
Ammeter An instrument used to measure electric current
ampere The unit used to measure electric current.
Capacitor A component of electronic systems which can be charged and discharged, and which may be used to create time delays.
Capacitor in series When capacitors are connected in series each capacitor has the same charge on its plates. The reciprocal of the equivalent capacitance is equal to the sum of the reciprocals of each capacitor.
Capacitor in parallel When capacitors are connected in parallel there is a different amount of charge deposited on its plates of each capacitor, but the potential difference is the same across each of the parallel capacitors. The equivalent capacitance is equal to the sum of the individual capacitance.
Conductors Materials that allow the ready transfer of heat by conduction, or of

electricity by current flow.

coulomb The unit representing the amount of charge passing any point in a circuit when a current of 1 ampere flows past that point for 1 second.

Coulomb's law The electric force between two charges is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. ($\vec{F} = K\frac{Q_1Q_2}{r^2}\hat{r}$)

Direct current (dc) The flow of charge through a circuit in one direction only.

Electric charge A quantity of unbalanced (positive or negative) electricity.

Electric current The rate at which charge flows through a conductor.

Electron current The actual current in a circuit, it is a flow of electrons from a position of low potential to one of high potential.

Conventional current A flow of positive charges in a circuit from a position of high potential to one of low potential.

Electrical energy Energy associated with the flow of charge through any part of a conducting circuit.

Electric field An electric field, can be defined as a region where electrical forces act.

Electric field intensity The electric field intensity at a point in an electric field is the electric force acting upon a unit positive charge placed at that point. The electric field intensity is a vector quantity. The electric field intensity is represented by $\vec{E}$.

$$\vec{E} = \frac{\vec{F}}{q}$$

Electric field intensity from coulomb's law The electric field intensity at a point, a certain distance from the charge, is directly proportional to the magnitude of the charge and inversely proportional to the square of the distance.

$$\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}\hat{r}$$

Electric line of force An electric line of force is a path such that the tangent, drawn at any point on it, indicates the direction of the electric field at that point.

Insulators Materials that prevent, or significantly inhibit, the flow of heat, or electricity, through them.

kilowatt-hour A unit used by electricity supply companies, representing the energy dissipated in one hour by a device with a power of 1 kilowatt.

ohm The unit of electrical resistance. 1 ohm is the resistance of a sample of conducting material across which a potential difference of 1 volt causes a current of 1 ampere to flow.

Ohm s Law A relationship between the current flowing through a conductor and the potential difference across the ends of the conductor: *If a conductor is kept at a* *constant temperature, the current flowing through it is directly proportional to the potential difference between its ends.*

Parallel circuit A circuit in which the circuit elements are connected in such a way that the potential difference across all the elements of the circuit is the same. For a resistive circuit, the potential difference across the resistors are equal.

Series circuit A circuit in which each element of the circuit is connected to an adjacent element of the circuit such that the same amount of charge flows through each and every circuit element. For a resistive circuit, the current is the same through each resistor.

Resistance A property of materials which resist the flow of electric current through them to some greater or lesser degree.

Resistivity The resistance per unit length of unit crosssection of a material.

volt The unit of potential difference. A potential difference of 1 volt exists between two points when 1 joule of work is done in transferring 1 coulomb of charge between the two points. Alternatively, a potential difference of 1 volt exists between two points when 1 ampere of current dissipates 1 watt of power on passing between the two points.

Voltage The value of the potential difference between two points (e.g., the terminals of a cell).

Voltmeter An instrument used to measure potential difference (voltage).

MAGNETISM

Bar magnet A bar magnet has two poles. The one at the north-seeking end is called the north pole, and the other at the south-seeking end is called the south pole. The poles of a magnet have a greater power of attraction than its central portion. Like poles repel each other and unlike poles attract each other.

Right-hand (wire) rule

To determine the direction of the magnetic field around a wire carrying a current, grasp the wire with the right hand, with the thumb in the direction of the current, the fingers will curl around the wire in the direction of the magnetic field.

Electromagnet A soft iron core surrounded by a coil of wire, which acts as a magnet when current flows through the coil.

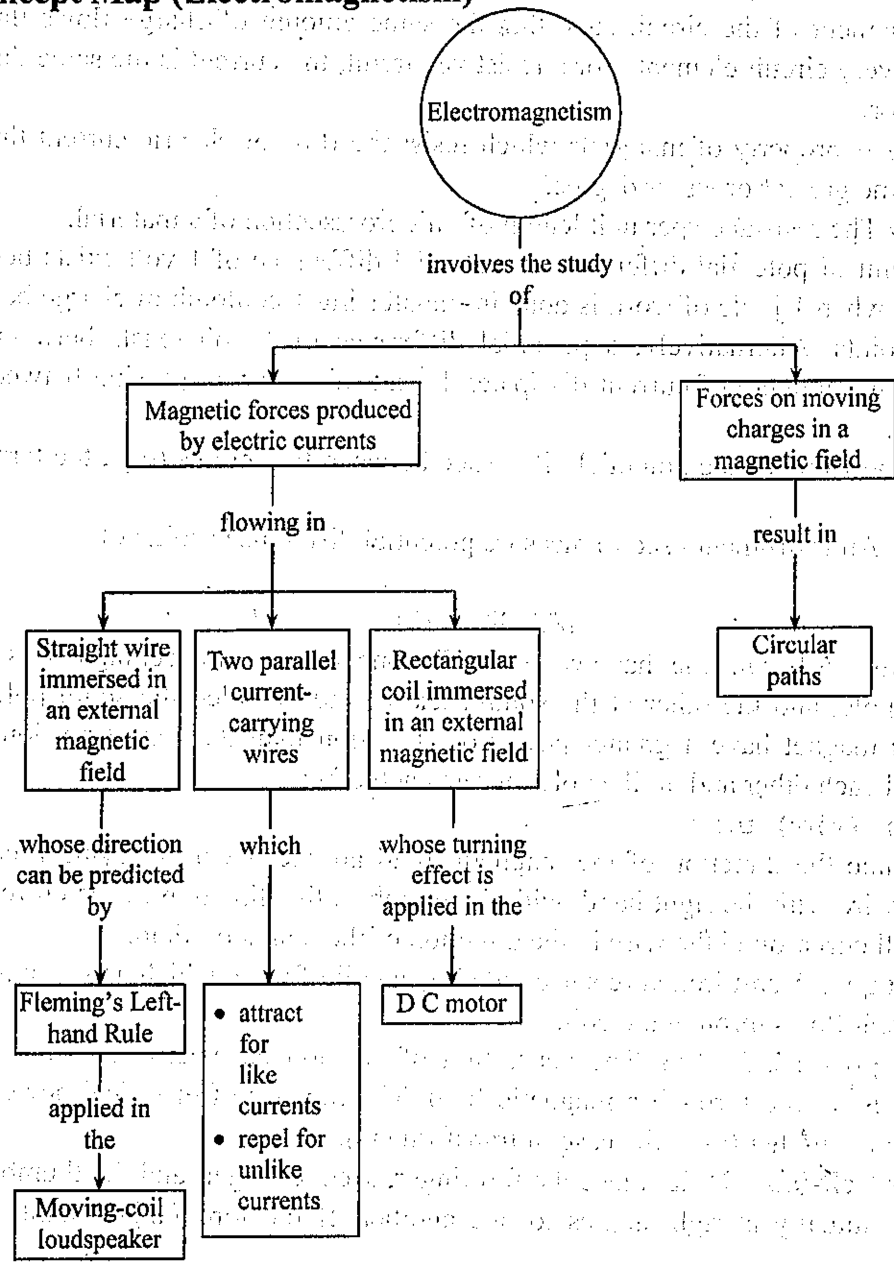
Electromagnetic induction The generation of an induced electric current when a conductor is moved through a magnetic field. The transfer of electrical power from one circuit to another (as in the case of transformers).

Fleming's Left-hand Rule Place the forefinger, second finger, and the thumb of the left hand mutually at right angles to one another. If the fore Finger points in the direction of the Field and the seCond finger in the direction of the Current, then the thuMb will point in the direction of the Motion along which the force acts.

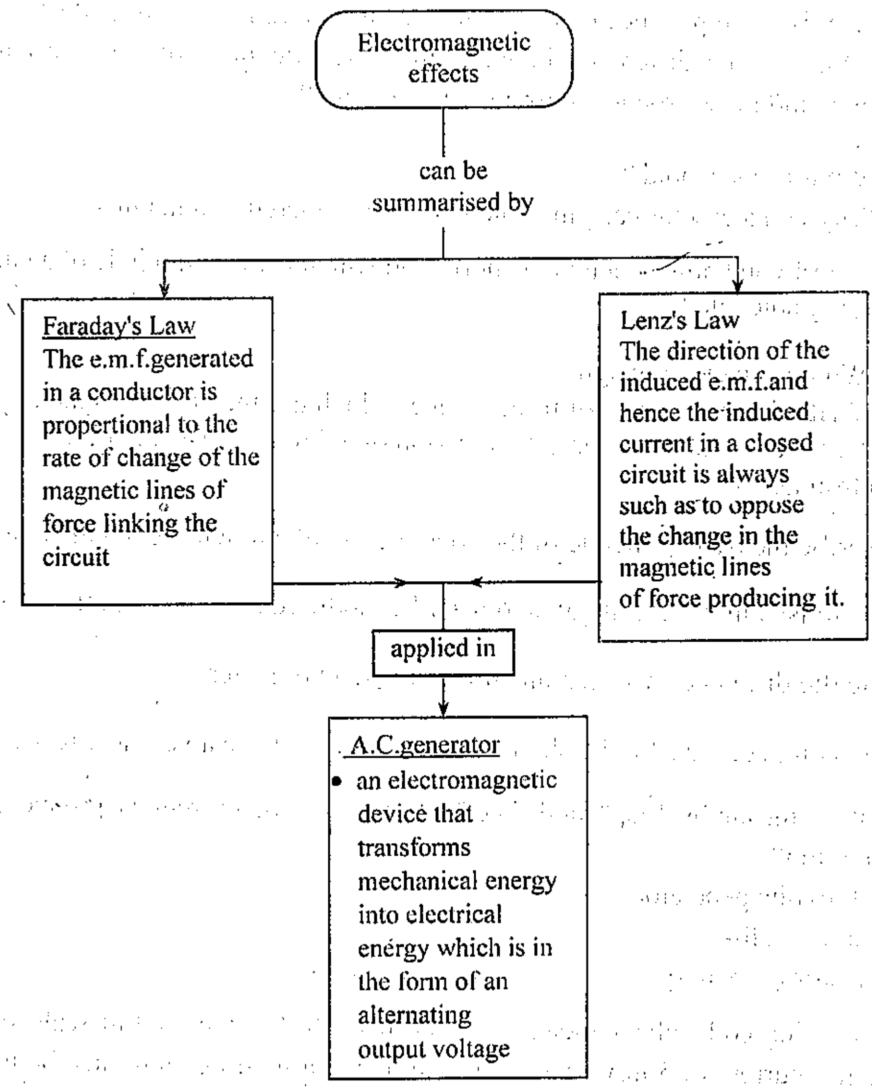
Induced current A current that is induced in a conductor due to the relative motion of the conductor and a magnetic field.

Magnetic field A space in which forces would act on magnetic poles placed within it.

Concept Map (Electromagnetism)



Concept Map (Electromagnetic effects)



EXERCISES

1. (a)Why is a compass needle placed near a current-carrying wire deflected?
   (b) What is the difference between the magnetic lines of force around a bar magnet and those around a current-carrying wire?

2. (a) What is a solenoid ?
   (b)Why can a current-carrying solenoid be considered as a magnet?

3. How will you know which is the north and which is the south pole of a current-carrying solenoid?

4. (a) What is an electromagnet ?
   (b) Write down the name of three devices which use the electromagnet.
   (c) Describe, with a diagram, the function of a device consisting of an electromagnet.

5. Describe the basic principle of the construction of a moving-coil galvanometer.

6. How must a moving-coil galvanometer be modified to convert it into a voltmeter?

7. State the difference between an ammeter and a voltmeter.

8. Why is it necessary for the shunt of an ammeter to have a very low resistance?

9. What is meant by "a.c." and "d.c."? What type of current is produced by the following?
   (a) Lawpita generator
   (b) a dry cell---
   (c) a storage battery

10. A moving-coil galvanometer of resistance 20 Ω gives a full-scale deflection when a current of 5 mA passes through it. What modification must be made to it so that it will give a full-scale deflection for (a) a current of 1 A and (b) a potential difference of 100 V?

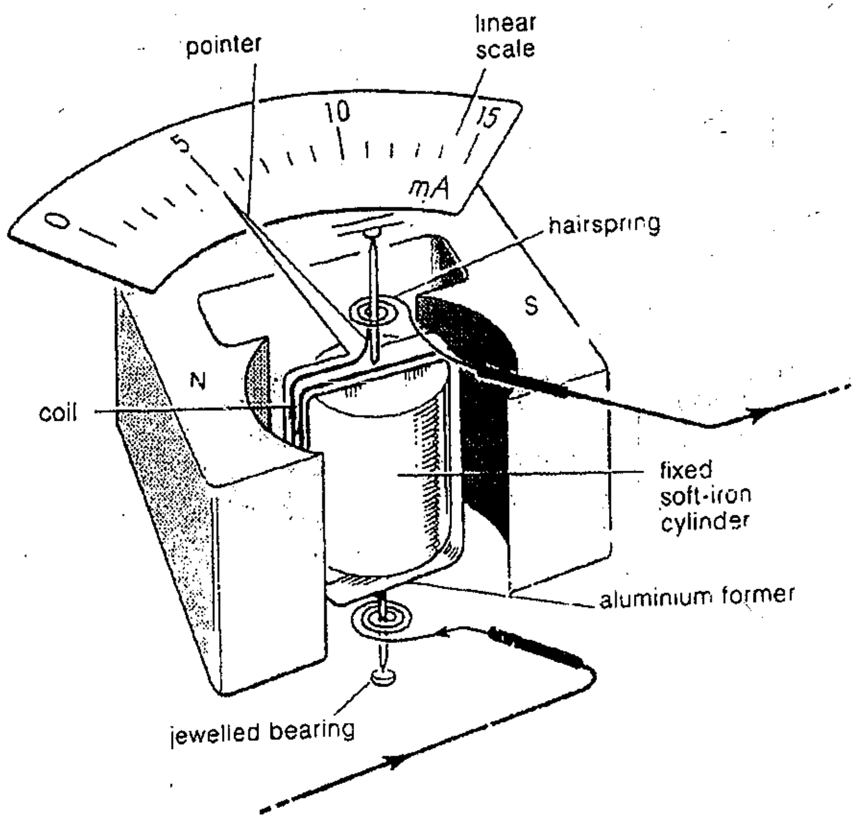
11. The resistance of a moving-coil galvanometer is 25 Ω and the current required for a full-scale deflection is 0.02 A. Find the resistance to be used to convert it into (a) an ammeter reading up to 5 A and (b) a voltmeter reading up to 150 V.

12. When an ammeter is connected in parallel with a current-carrying resistor it reads 5 A. When the ammeter and a 10 Ω resistor are joined in series and the

combination is connected in parallel with the first resistor the ammeter reads 3.5 A. What is the potential difference across the first resistor?

13. A 150 V voltmeter has a resistance of 20 000 Ω. When it is connected in series with a resistor across a 120 V mains line it reads 5 V. What is the resistance of the resistor?

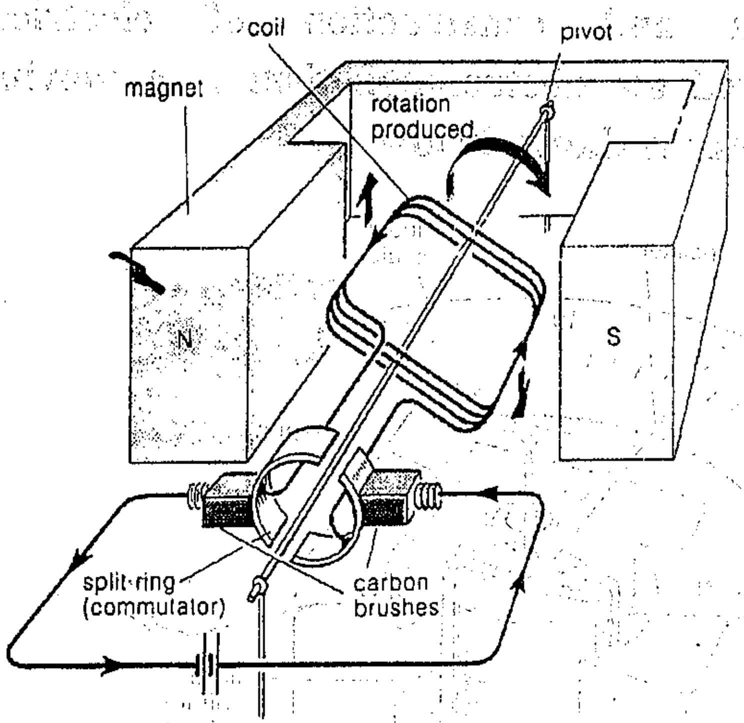
Some more illustrations to help students understand the operation and construction of electrical appliances based on electromagnetism.......a moving coil galvanometer is shown below



Another important device in common use today based on electromagnetism is the motor..shown below

A simple d c motor

D C motors are motors designed to operate from a direct ('one way') current supply such as a battery. A simple type of d.c. motor is shown in figure .



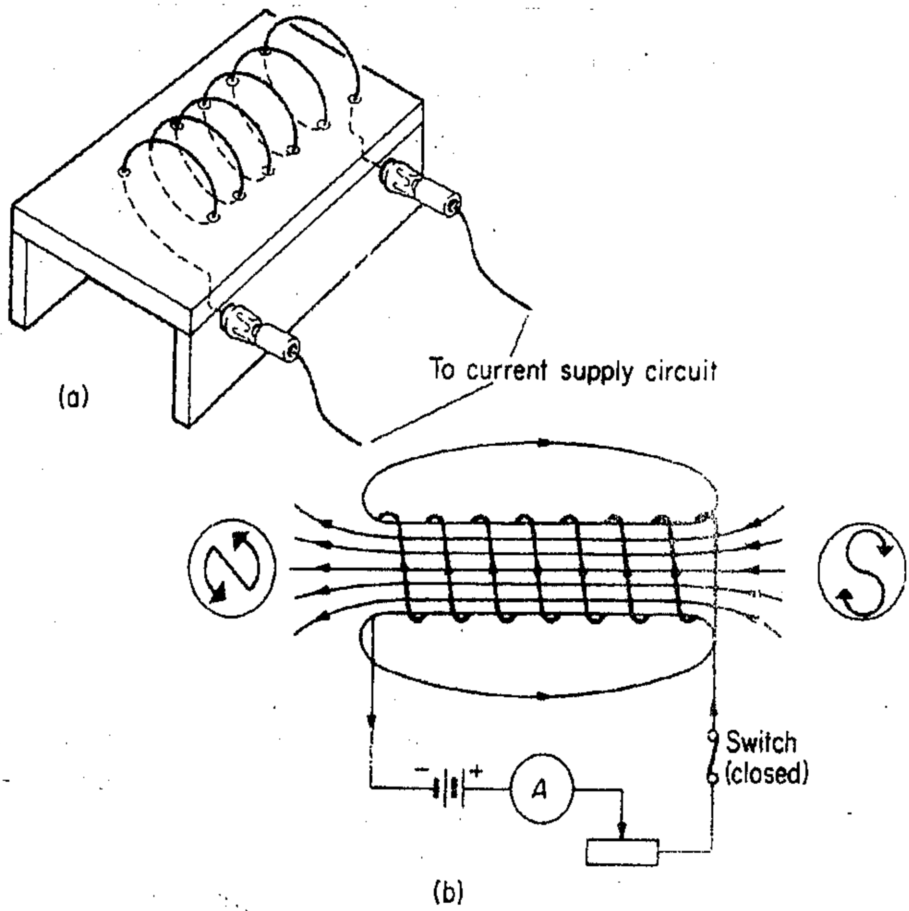


Fig. Magnetic flux pattern due to current in a solenoid

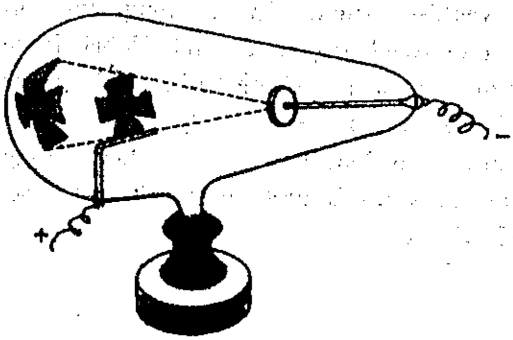
Above figure gives a good illustration to improve the understanding of the reader regarding the magnetic field produced in a solenoid......a very important concept in physics and engineering. Now to learn something about the fathers of electromagnetism remember a great many scientists besides Faraday and Maxwell contributed to the subject.....

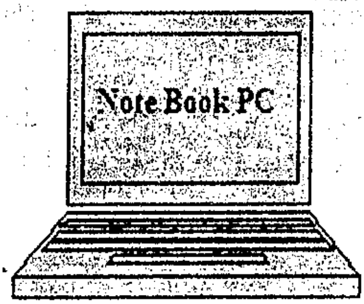
FATHERS OF ELECTRICITY AND MAGNETISM

Michael Faraday (1791-1876) DLit, FRS Professor, Royal Institution A founding father of electricity and magnetism, electrical engineering and electro-chemistry. Faraday though not a mathematical physicist but an excellent experimental physicist, introduced the concept of fields and lines of force using geometry to explain physics. The field concept in electricity and magnetism appears very similar to that used by Newton in his theory of gravitation. The interdisciplinary nature of physics was evident since the days of Faraday and Maxwell. Although totally self taught apart from the training he obtained under Sir Humphrey Davy, his scientific contributions were duly recognised by the award of an FRS and a DLit, he was also a splendid lecturer. "Faraday lectures" at the Royal Institution are given to honour him.

J C Maxwell (1831-1879) MA,DLit, Laboratoy, Cambridge. Sir James Maxwell, invented electromagnetic theory and in particular was able to unify optics and electricity and magnetism. He also worked on dynamical theory of gases. He was one of the first physicists to introduce laboratory work into physics curriculum. The Cavendish became world famous later but it was Maxwell who started the laboratory work at Cambridge. He was a great mathematical physicist and was a competent experimentalist. He introduced the concept of displacement current and wrote " A Treatise on Electricity and Magnetism" in 1873 which is often compared with Newton's "Principia". He was succeeded in the

FRS Professor of Natural Philosophy, King's College, London (1860),the first Professor of Experimental Physics(1974-1879), and Director of the Cavendish	Cavendish Chair by a long line of distinguished physicists and Nobel Prize Winners: Lord Rayleigh DLit, OM,FRS, Sir JJ Thomson DSc, OM,FRS, Lord Rutherford OM,FRS,Sir Lawrence Bragg ScD, FInstP, FRS and Sir Neville Mott DSc, FInstP, FRS.





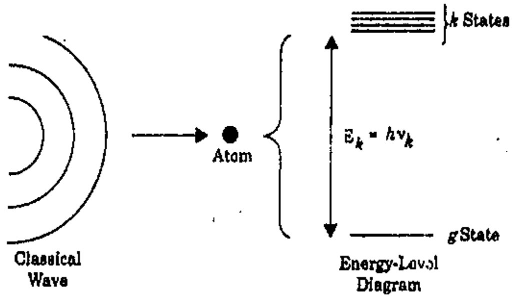
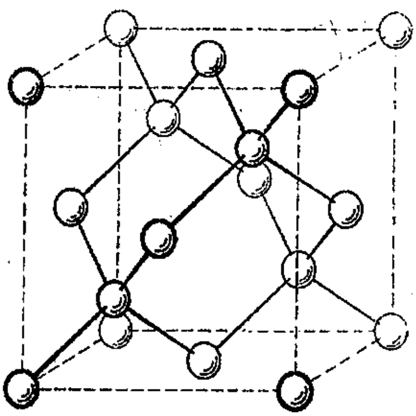
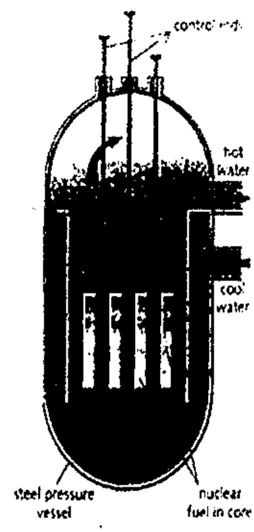


FIG (B) ENERGY LEVEL DIAGRAM OF AN ATOM INTERACTING WITH A CLASSICAL WAVE

MODERN PHYSICS



The arrangement of the silicon / germanium atoms in the diamond crystal. Each atom has four near neighbors, which are arranged about it at the corners of a regular tetrahedron. [Structure of semiconductor crystals.]



A pressurized water reactor(PWR)

CHAPTER 13

MODERN PHYSICS

At the tail end of the nineteenth century, physics was considered by many physicists to be a complete science. However, the few unsolved problems existing at that time proved to be unexplainable by the physical theories of that time; they could be explained only by drastic assumptions that had no historical precedents. The illusion of a complete science proved to be a result of man's lack of experience with atomic-size particles and with objects that move at nearly the speed of light. In this chapter we shall take up the discovery of cathode rays, transistors, models of the atom, quantum theory (it will pay good dividends to revise topics on interference and diffraction in chapter 6) and other topics of modern physics.

13.1 THERMIONIC EMISSION

In 1883, an American scientist, Thomas' Edison, an inventor of the electric light bulb, observed a strange phenomenon from his experiment. The arrangement of his experiment is shown in (Fig. 13.1), A small metal plate is mounted near a filament in an evacuated glass bulb. The filament lamp glows when the filament is connected to a battery. The metal plate can be connected to a positive or negative terminal of the battery through a galvanometer G. Edison found that a small current flowed through the galvanometer G when the metal plate was connected to the positive terminal of the battery. However, there was no current when the metal plate was connected to the negative terminal. This finding is known as the Edison effect.

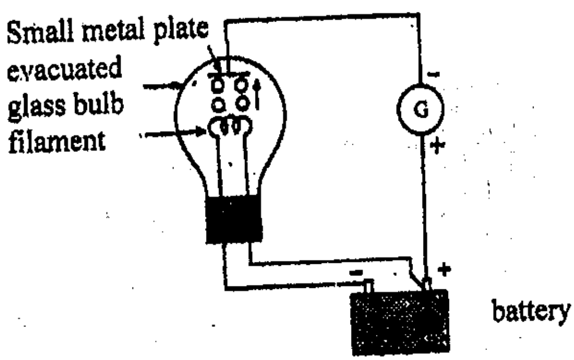


Fig. 13.1 Edison's experiment

Since the filament was not in contact with the plate, no current could be expected to pass through the galvanometer. But Edison found that the galvanometer showed the existence of a small current and he could not explain it.

Early in the twentieth century, Richardson discovered that electrons were liberated from hot bodies and he was able to explain the Edison effect. When a current flows through the filament it becomes hot. When the filament is at a high temperature it liberates electrons. These electrons are attracted by the metal plate (the positive plate) which is connected to the positive terminal of the battery. The drift of electrons from the filament to the plate means the flow of current from the plate to the filament. A small current, then, flows through the galvanometer although the filament is not in contact with the plate.

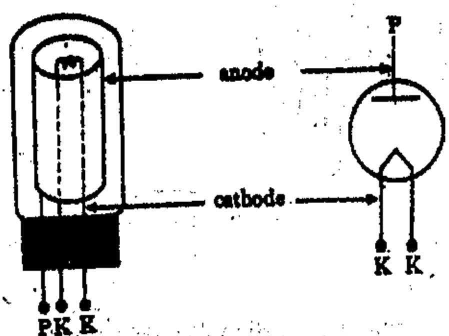
The emission of electrons from the filament at high temperature is similar to the emission of vapour molecules from a hot liquid. Metals contain large numbers of free electrons, When the metal is heated the electrons acquire energy.

When the temperature of the filament becomes high the electrons which acquire sufficient energy escape from the filament. Such emission of electrons from the surface of metal at high temperature is called thermionic emission.

13.2 DIODE, TRANSISTOR AND INTEGRATED CIRCUIT

Vacuum Diode

In 1904, Fleming invented a diode using the principle of thermionic emission. It is an evacuated glass bulb which consists of a metal filament surrounded by a metal cylinder. The structure of a diode is shown in Fig. 13.2(a).



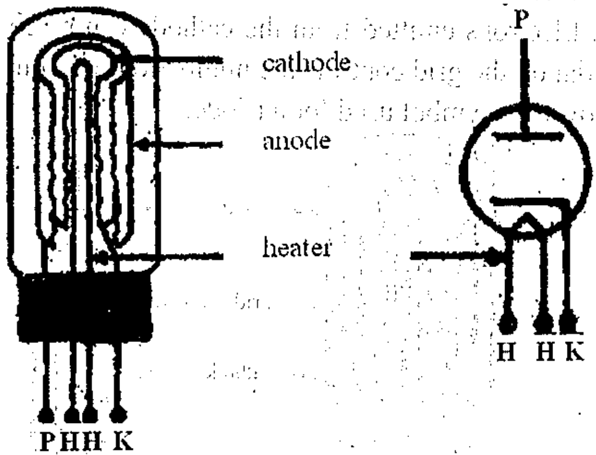
(a) (b)

Fig. 13.2 Structure of a diode

The filament in the diode shown in Fig. 13.2(a) is used as a source of electrons. In the commonly used diodes, the filament is used as a heater [Fig. 13.3(a)]. The symbol used for the vacuum diode is shown in Fig. 13.3(b).

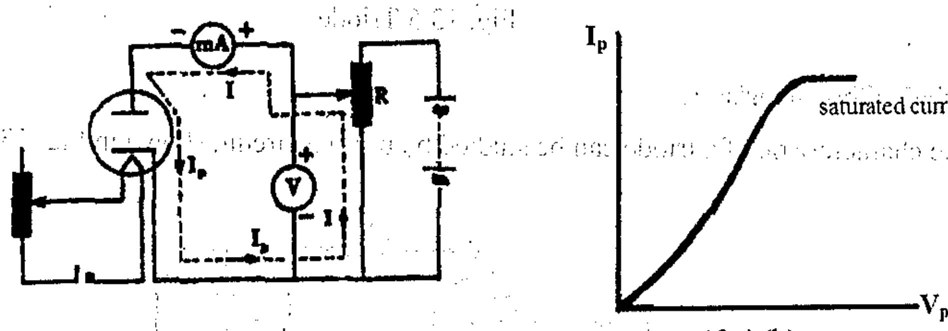
Diode Characteristic

The characteristic of a diode is a graph which shows the relation between the plate current, I_p, and the potential difference, V_p, between anode and cathode.



(a) (b)

Fig. 13.3 Diode



13.4 (a) 13.4 (b)

Fig. 13.4 Characteristics of a diode: diode circuit on the left and I_p - V_p graph on the right.

The I_p - V_p graph is not a straight line. This shows that V_p is not directly proportional to I_p. The vacuum diode therefore does not obey Ohm's law.

Nowadays, a p-n junction diode which is called crystal diode is used instead of a vacuum diode. It is very much smaller than a vacuum diode. The cathode in a vacuum diode has to be heated but it is not necessary to heat a crystal diode.

Triode

In 1907, De Forest invented a vacuum tube called a triode. It consists of three electrodes. An electrode between the cathode and the anode is called a grid [Fig. 13.5 (a)]. The grid is usually a helix of wire or a wire mesh. It is kept nearer to the cathode than the anode. Electrons emitted from the cathode can reach the anode through the grid. The potential on the grid controls the number of electrons which pass through it. Fig. 13.5 (b) shows the symbol used for a triode.

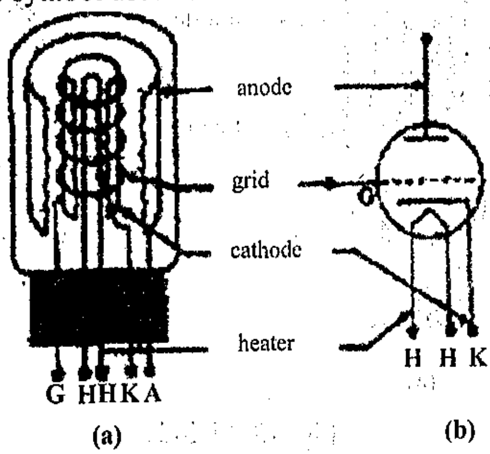


Fig. 13.5 Triode

Triode Characteristics

The characteristic of a triode can be studied by using a circuit, shown in Fig. 13.6.

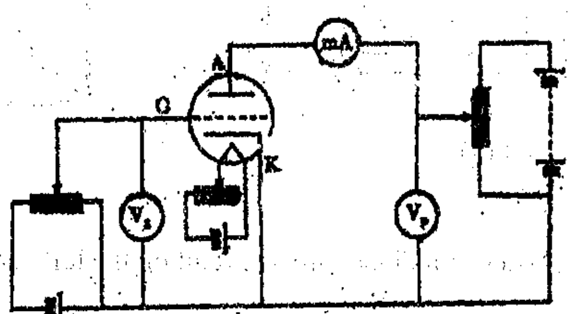


Fig. 13.6 Circuit of the triode

Fig. 13.7 is called the characteristic curve of a triode. They show that Ip is not directly proportional to V_p. Therefore, a triode is a device which does not obey Ohm's law.

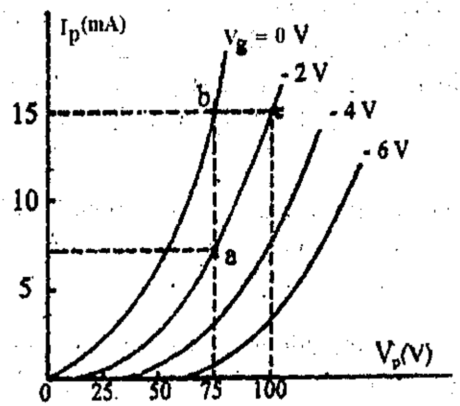


Fig. 13.7 Characteristic curves of a triode

p-n Junction Diode

A p-n junction diode or simply a junction diode is a semiconductor diode. Materials which have an electrical resistance that lies between the high resistance values of insulators and the low resistance values of metals are called semiconductors. For example, germanium and silicon are commonly used semiconductors.

In metals, electrons are the charge carriers. In the case of semiconductors, both electrons and positive holes are the charge carriers. Of the several atoms in a semiconductor, three atoms A, B and C are shown in Fig. 13.8.

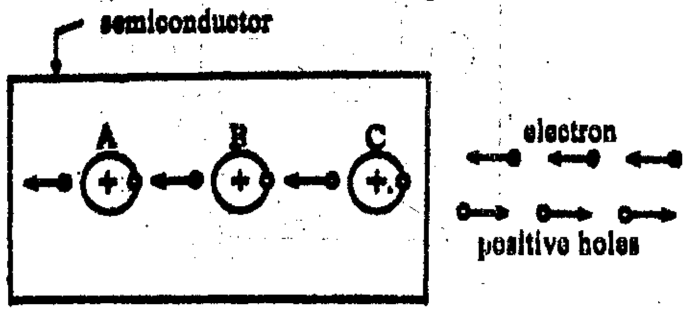
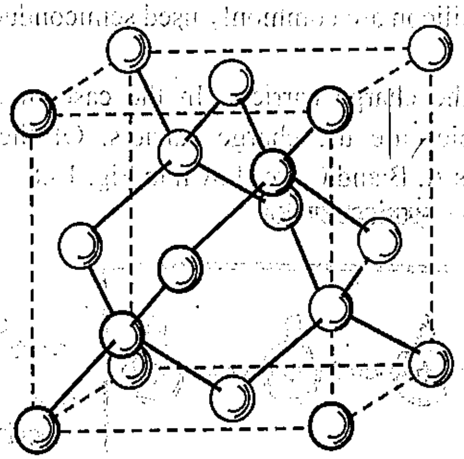


Fig. 13.8 Electron and hole charge carriers in semiconductor

Suppose that an electron leaves the atom A as it acquires sufficient energy. The atom A now has a net positive charge which is equal in magnitude to the charge of an electron. A vacancy which is left with the atom A is called a positive hole. An electron from the atom B moves into that hole so that a positive hole is left with B. Again, when an electron from the atom C moves into that hole a positive hole is left with C. In this way, a positive hole will be left with the neighbouring atom of C and so on. A positive hole appears to move from one place to another. Because the movement of an electron from an atom leaves a vacancy or positive hole in that atom, the, movement of a positive charge is described as the movement of a positive hole. Therefore, in semiconductors, electrons and positive holes are charge carriers. This means that the current is carried by both electrons and holes in the case of semiconductors.

Pure semiconductors have equal numbers of electrons, and positive holes. Since these are relatively few in number at normal temperature, semiconductors have poor conductivity.

When a few impurity atoms are added to the pure semiconductor its conductivity increases. Arsenic, aluminium and indium atoms are used as impurity atoms. When arsenic atoms, having five valence electrons, are added to the germanium (Ge) atoms having four valence electrons(see periodic table), the conductivity of germanium increases. Since the number of electrons is greater than that of positive holes in this impure semiconductor it is called an n-type semiconductor, ('n' stands for 'negative'). In the n-type semiconductor electrons are the majority carriers of electric current.See below to learn how Ge atoms are arranged in a crystal :



The arrangement of the silicon/germanium atoms in the diamond crystal. Each atom has four near neighbours, which are arranged about it at the corners of a regular tetrahedron. [Structure of semiconductor crystals.]

Fig. 13.8 Arrangement of Ge atoms in a diamond type crystal.

When indium atoms having three valence electrons are added to pure germanium a p-type semiconductor is obtained. ('p' stands for 'positive'). In a p-type semiconductor the number of positive holes is greater than that of electrons. Thus in a p-type semiconductor that positive holes are the majority carriers (See illustrations below).

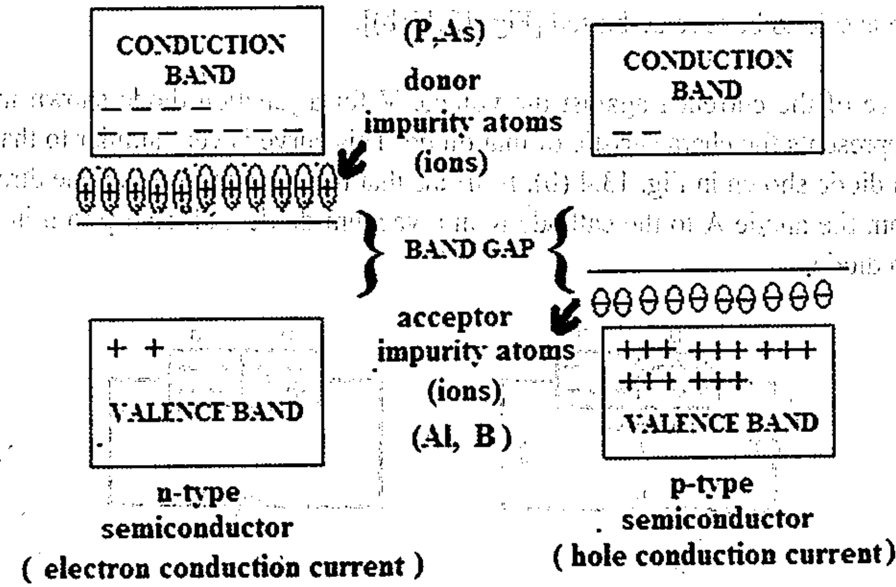


Fig. 13.9 n-type and p-type semiconductors

By a special melting process, p-and n-type semiconductors can be made in contact so that a boundary or junction is formed between them. This junction is called a p-n junction. A device which consists of a p-n junction is called a p-n junction diode. The structure of a p-n junction diode is shown in Fig. 13.10(a) and its symbol is shown in Fig. 13.10(b).

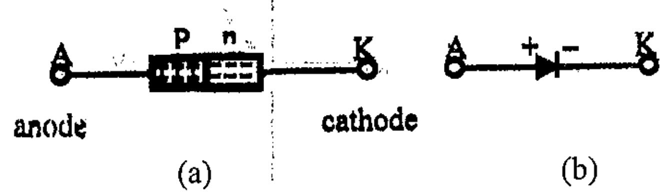
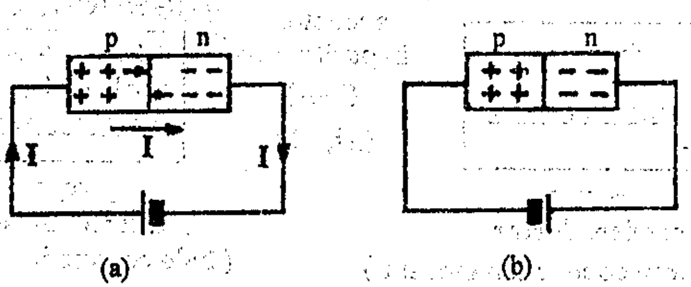


Fig. 13.10 Junction diode and its symbol.

The function of a p-n junction diode can be studied by means of electric circuits shown in Fig. 13.11. When a battery is joined with its positive terminal to the p-type semiconductor and its negative terminal to the n-type semiconductor as shown in Fig.

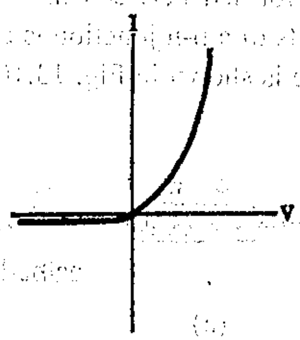
13.11 (a), positive holes from p-type semiconductor pass through the junction easily. Thus a current flows in the circuit. In other words, a current flows through the p-n junction diode. The p-n junction is now said to be forward-biased. When a battery is joined with its negative terminal to the p-type and its positive terminal to the n-type, only a very small current flows through the p-n junction diode. In this case the p-n junction is said to be reverse-biased [Fig. 13.11(b)].

The curve of the current I against the voltage V for a junction diode shown in Fig. 13.12 represents the characteristic of that diode. This curve is very similar to that of a vacuum diode shown in Fig. 13.4 (b). It means that the current flows in one direction only from the anode A to the cathode K in a vacuum diode and from p to n in a p-n junction diode.



A junction diode with forward and reverse bias

Fig. 13.11 A junction diode with (a) forward and (b) reverse bias.



Current-voltage characteristic

Fig. 13.12 Current voltage characteristic.

Therefore, in the symbol of diode shown in Fig. 13.10 (b), the arrow points from A to K. The current flows from A to K only when the potential of A is higher than that of K. This means that the diode must be forward-biased.

Rectifier

A rectifier is a device which converts an alternating current (ac or AC) into a unidirectional current or a direct current (dc or DC). Diodes can be used as rectifiers because the current flows in one direction only from anode A to cathode K.

Half-wave Rectifier

The circuit diagram shown in Fig. 13.13 (a) is that of a half-wave rectifier. There is only one diode in the circuit. Since the secondary or the output coil of the transformer delivers an a.c. voltage, voltages of opposite polarity are induced at the point a and b. The variation of potential difference V_{ab} between a and b with time is shown in Fig. 13.13(b).

During the first half of the cycle, a is at a higher potential than b, so that a current flows in the circuit. During the second half of the cycle, a is at a lower potential than b, so that no current flows in the circuit. The variation of current I with the time is shown in Fig. 13.13 (c). The figure shows that the current I flows in the circuit only when a is at a higher potential than b (only when V_{ab} is positive).

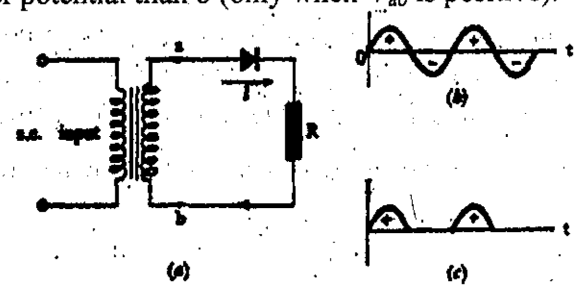


Fig. 13.13 Half-wave rectifier

This happens for every one cycle of a.c.(AC) voltage. The current I flows in one direction only as shown in Fig. 13.13 (a). As the current I flows in the diode for every first half of the cycle of a.c (AC)or for every half wave this device acts as a half-wave rectifier.

Full-wave Rectifier

The circuit diagram shown in Fig. 13.14 (a) is that of a full-wave rectifier. The circuit consists of two diodes. Since the secondary of the transformer delivers an a.c. voltage, voltages of opposite polarity are induced alternately at the points a and b. The variation of the potential difference V_{ab} between a and b with time t is shown in Fig. 13.14(b).

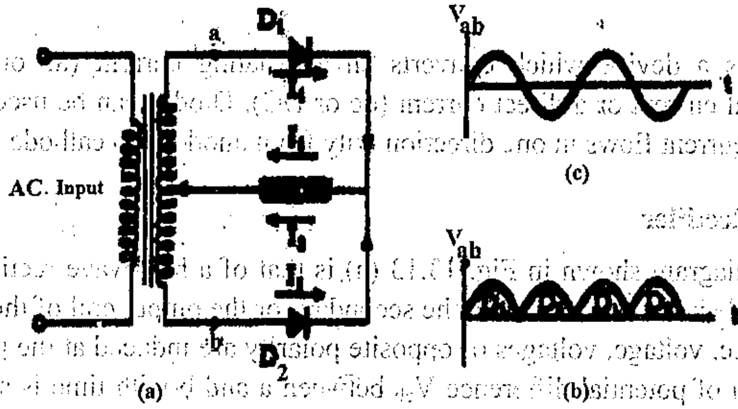


Fig. 13.14 Full-wave rectifier

During the first half of the cycle a is at a higher potential than b. Therefore the current I_1 flows in the diode D_1 and no current flows in the diode D_2. During the second half of that cycle b is at a higher potential than a. Therefore the current I_2 flows in D_2 and no current flows in D_1. Since D_1 and D_2 operate alternately for one cycle of an a.c. voltage, current always flows through the resistor R. This occurs also for other cycles of the output a.c. voltage. The variation of current I passing through R with time is shown in Fig. 13.14(c). As the current flows through R for both half-cycles of the a.c. voltage or for a full-wave, this device is called a full-wave rectifier.

Rectifiers can also be constructed by using vacuum diodes. But the circuits must be modified properly.

Transistor

A transistor (transfer resistor) is a semiconductor device which works as an amplifier. In 1949, three American physicists Shockley, Bardeen and Brattain invented the transistor.

From that time onwards various kinds of electronic equipment which employ transistors were designed and constructed.

The advantages of transistors over the vacuum tubes can be summed up as follows:

- They do not deteriorate with time, whereas vacuum tubes do.
- They are physically much more robust than vacuum tubes.
- They waste much less electrical power than vacuum tubes.
- There is no warm-up period after switching on.
- They are very much smaller than vacuum tubes but they perform a similar function.

A transistor is made of three layers of p-and n-semiconductors. There are two common kinds of transistors called the pnp and the npn transistors. In a pnp transistor a thin layer of n-semiconductor is sandwiched between two layers of p-semiconductors. In a npn transistor a thin layer of p-semiconductor is sandwiched between two layers of n-semiconductors. An electrode is attached to each layer and hence there are three electrodes in a transistor.

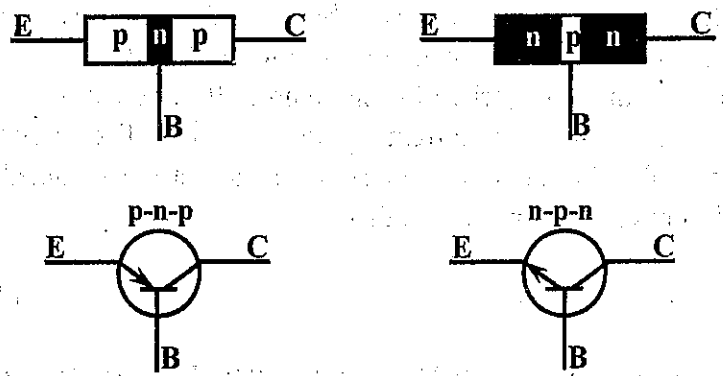


Fig. 13.15 Transistors and their symbols

Fig. 13.15 shows the transistors and their respective circuit symbols. The three electrodes of a transistor are called the emitter (E), the base (B) and the collector (C). In the symbols for the transistors the arrows show the directions of the current flowing between the emitter E and the base B. The direction of current is the same as that of the positive holes. The electrons flow in the direction opposite to that of positive holes.

A transistor consists of two junctions called an emitter junction and a collector junction. When a transistor is in use the emitter junction must be forward-biased and the collector junction must be reverse-biased. In order to be so, a battery must be connected to the pnp and npn transistors as shown in Fig. 13.16.

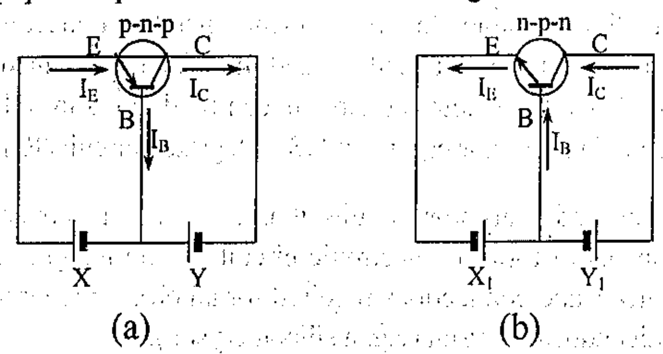


Fig. 13.16 Transistor biasing circuits

In Fig. 13.16 (a) the positive terminal of a battery X is connected to the emitter E and the negative terminal of a battery Y is connected to the collector C of a pnp transistor. Hence, the emitter E is forward-biased and the collector C is reverse-biased. In Fig. 13.16 (b) the negative terminal of a battery X_1 is connected to the emitter E whereas the positive terminal of a battery Y_1 is connected to the collector C.

In Fig. 13.16 (a), the emitter junction is forward-biased and the positive holes which are majority carriers flows across the junction from E to the base B. As the thickness of the base is about 10^{-3} cm the majority of positive holes flow across the base to the collector which is reverse-biased. A current I_C flows in the collector circuit. The remainder of positive holes flows into the base so that a current I_B is obtained there. If I_E is a current which flows across the emitter, then

$$I_E = I_C + I_B \qquad (13.1)$$

However, the base is so thin that $I_B \sim 0.02\, I_E$ and $I_C \sim 0.98\, I_E$. Therefore, the small base current I_B can control a very large collector current I_C. Because of this property a transistor can be regarded as a current amplifier.

The resistance of forward-biased emitter junction is small and that of reverse-biased collector junction is large. But I_C is nearly equal to I_E. Since the electrical power is I^2R, the power in the emitter side is small whereas the power in the collector side is large. Therefore the transistor can be regarded as a power amplifier.

Integrated Circuit

By 1950, various electronic equipment which make use of transistors were widely used. Since these equipment are small and light they can be used quite conveniently. Scientists have been attempting to make the electronic circuits as well as the components as small as possible. An arrangement whereby connections of electronic components such as resistors, capacitors and transistors are made is called an electronic circuit. Generally, electronic circuits can be divided into three groups: (1) vacuum tube circuit (2) transistor circuit and (3) integrated circuit (IC).

In the vacuum tube and transistor circuits it is necessary to connect the separate electronic components to form an electronic circuit. In the integrated circuit all the electronic components and connections required for an electronic circuit are all made on one single semiconductor crystal (e.g. a silicon crystal).

Integrated circuits are so small that about 200 000 electronic components can be fitted into one cubic inch or of less space. In the integrated circuit the resistor, capacitor, diode and transistors are made by using the process of diffusion. Other components are made by employing films deposited on the crystal layers. Fig. 13.17 shows an integrated circuit. Integrated circuits are used in televisions, computers and advanced electronic equipment.

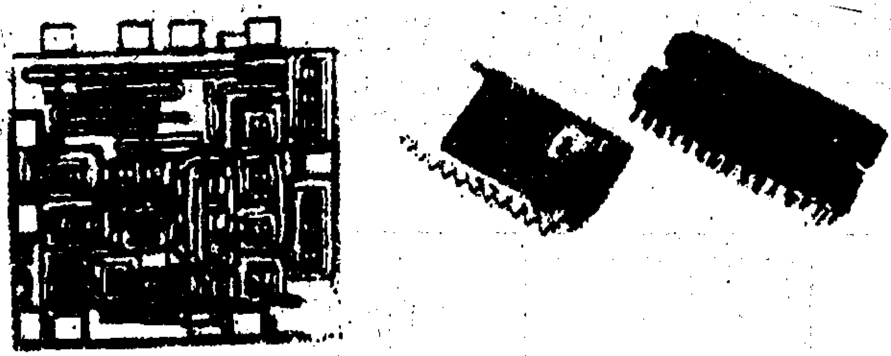


Fig. 13.17 Integrated circuits and their uses

13.3 ELECTRONIC LOGIC GATES

In most electrical appliances, we must input commands for the appliances to carry out their duties. The appliances take in information from the environment, make a decision based on that information and then give out the result. An electronic device which can be used to do this is called a logic gate. The five common logic gates are the AND, OR, NAND, NOR and NOT (inverter) gates.

Different types of logic gates can be built from different arrangements of electronic components. However, the principle of an AND gate can also be demonstrated with a simple circuit such as that in Fig. 14.18. Here, manually pressing one or other or both of the switches acts in the same way as applying an electric signal to a transistor used as a switch.

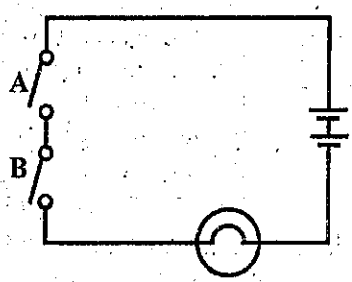


Fig. 13.18 A simple AND gate

Consider the effect of pressing each of the switches. It we press neither or only one of the two switches, the lamp will not light. It will only light when both switch A AND switch B are closed.

Now compare this behaviour with the behaviour of an electronic AND-gate. This could be built up using resistors and transistors, but nowadays it is far more convenient to use small integrated circuits (ICs). Each circuit has all the necessary electronic components already connected together on a tiny piece of silicon.

Fig. 13.19 shows an AND gate IC which contains four (QUAD) AND gates, each having two inputs and one output. Its reference number is TTL 7408; TTL stands for Transistor Transistor Logic. The IC or chip needs a 5V power supply with positive terminal and negative terminal connected to pin 14 and pin 7 respectively. If leads are connected to pin 13 and 12 (inputs), and an LED and protective resistor are connected between pin 11 and pin 7, then the properties of an AND gate can be investigated (Fig. 13.20).

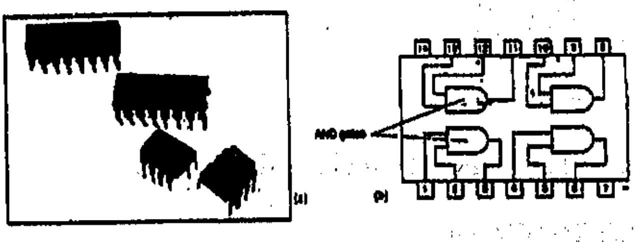


Fig. 13.19 ***(a) Commercial IC's***
(b) The layout of a QUAD 2 input AND gate IC

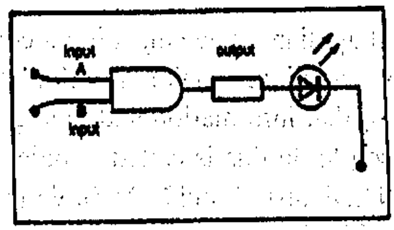


Fig. 13.20 Circuit for investigating an AND gate

A	B	Output
0	0	0
0	1	0
1	0	0
1	1	1

low voltage = logic 0
high voltage = logic 1

Fig. 13.20(a).

When leads A and B are both connected to a negative supply (or low voltage, also known as logic 0), there is no output. If A is connected to the positive supply (or high voltage, also known as logic 1), and B remains at logic 0, then again there is no output (low voltage, logic 0). When B is at logic 1 and A is at logic 0 there is still no output (logic 0). But when both A and B are at logic 1 there is a high voltage (logic 1) at the output and the LED which serves as an indicator lights up.

These practical results can be summarized in a **truth table** as shown in Fig. 13.20(a). Obviously, the only way that the LED will light up (output is high or logic 1), is when both input A **AND** input B are at logic 1. This is why it is called an AND gate.

Similar experiments can be carried out with other gates and the results can be tallied with the truth tables shown in Fig. 13.21.

AND gate

A	B	Output
0	0	0
0	1	0
1	0	0
1	1	1

NAND gate

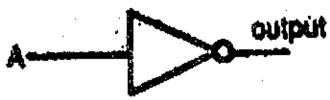
A	B	Output
0	0	1
0	1	1
1	0	1
1	1	0

OR gate

A	B	Output
0	0	0
0	1	1
1	0	1
1	1	1

NOR gate

A	B	Output
0	0	1
0	1	0
1	0	0
1	1	0



NOT gate

A	Output
0	1
1	0

Fig.13.21 Symbols and truth tables for AND, NAND, OR, NOR and NOT (inverter) gates

The actions of different types of gates can be memorized as follows:

AND gate - The output is high only when A and B are high.

NAND gate - The output is not high when both A and B are high. (The gate gets its name from this NOT AND behaviour).

OR gate - The output is high when either A or B or both are high.

NOR gate - The output is not high when either A or B or both are high.

NOT gate - The output is high if the input is not high. Whatever the input the gate inverts it.

NAND gates and NOR gates are called universal gates because they alone can be used to build up all other types of gates.

Combination of gates

Figure 13.22 shows two NOT gates and a NAND gate. To deduce the logical output Q of the system, we have to work out first the intermediate outputs C and D from the NOT gates, which act as the two inputs to the NAND gate. Check the truth table given to confirm whether this system is equivalent to an OR gate.

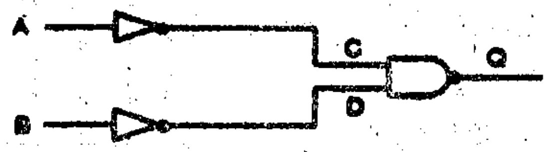


Fig 13.22(a)

A	B	C	D	Q
0	0	1	1	0
0	1	1	0	1
1	0	0	1	1
1	1	0	0	1

Fig 13.22(b) **shows some of the possible arrangements of NAND gates to form other types of logic gates. You may construct a stage-by-stage truth table to confirm their actions.**

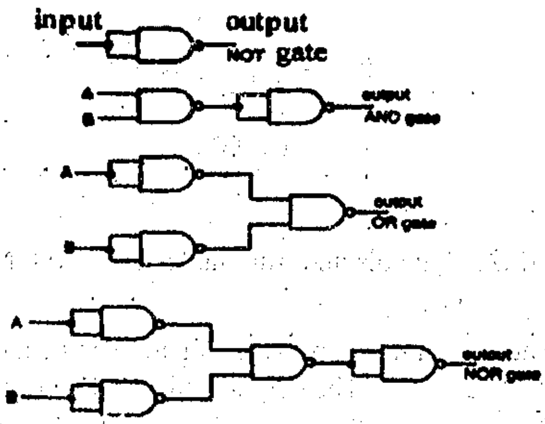


Fig 13.23 ***Combining NAND gates to build other types of logic gates***

Using Logic Gate

Example 1: A security lock

In this example, a security lock is designed using a two-switch system. If a hidden switch is turned on first, a main switch will open the door lock. However if the hidden switch is not turned on, turning on the main switch will turn on an alarm instead. Fig. 13.24 shows the system of logic gates, together with its truth table.

A	B	C	P	Q
0	0	1	0	0
0	1	0	0	0
1	0	1	0	1
1	1	0	1	0

A – main switch
B – hidden lock
P – lock
Q – alarm

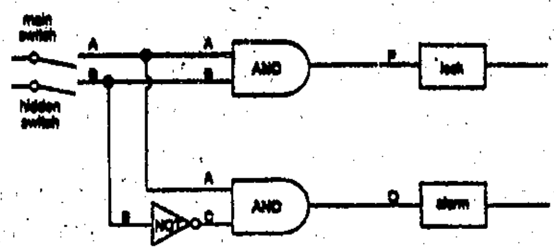


Fig 13.24 A security lock

Example 2: A fire alarm

In this example, the fire alarm will turn on when smoke or heat is detected. If both the smoke and heat are detected, the fire extinguisher will also be set to operate. Fig. 13.25 shows the system of logic gates, together with its truth table.

A	B	P	Q
0	0	0	0
0	1	1	0
1	0	1	0
1	1	1	1

A – smoke detector
B – heat detector
P – alarm
Q – extinguisher

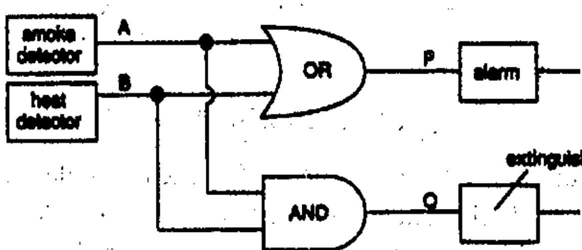


Fig 13.25 A fire alarm

13.4 CATHODE RAYS

During the last decade of the nineteenth century scientists performed experiments on the conduction of electric charges through gases and electrolytes. These experiments resulted in the discovery of the electron.

Streams of electrons moving at high speed are called cathode rays. Their properties can be studied using special cathode ray tubes. A cathode ray tube is an evacuated glass tube which mainly consists of an electron gun and a fluorescent screen. When electrons strike the screen, fluorescence takes place with a green light. More detailed descriptions of cathode ray tubes will be given later. We shall now study the electric discharge through gases at low pressure.

Under normal conditions air is an insulator and thus no electric discharge can occur in it. It is known from experiments that a voltage of 30 000 V is required for the electric discharge between two plates in air which are 1 cm apart. It is found that the lower the pressure of the air the lesser is the voltage required for the electric discharge. Crookes first studied the electric discharge through air at low pressure. The apparatus used in his experiment is illustrated in Fig. 13.26.

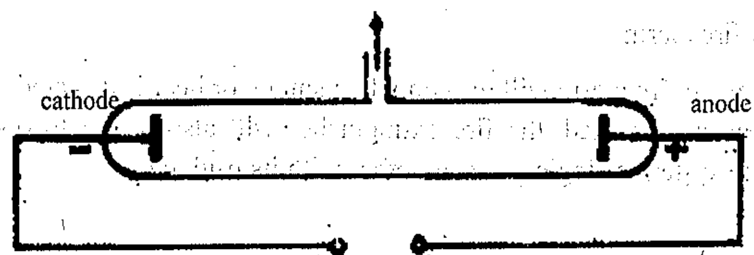


Fig 13.26 Electric discharge tube.

The metal electrodes are sealed at the ends of a glass tube which is about 15 cm long. To apply a high voltage between the electrodes they are connected to an induction coil. The tube is connected to a vacuum pump through a side tube to pump the air out of the tube. The electrode at a higher voltage is called an anode and the other electrode is called a cathode. A voltage higher than 1000 V is applied between the cathode and the anode while the air inside the tube is slowly pumped out.

The first electric discharge appears in the tube at about 20 mm Hg pressure. This first discharge consists of thin violet streamers [Fig. 13.26 (a) below].

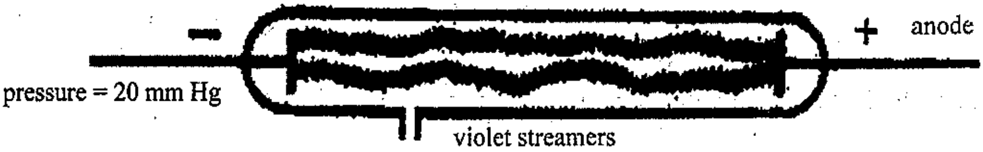


Fig. 13.26(a)

On further reduction of pressure the streamers broaden out into a pink discharge which fills the space between the electrodes.

At 5 mm Hg pressure a dark region appears near the Cathode. That dark region is called the Faraday dark space. A blue negative glow appears between the cathode and the Faraday dark space and the pink positive column appears between the anode and the Faraday dark space [Fig. 13.26 (b)].

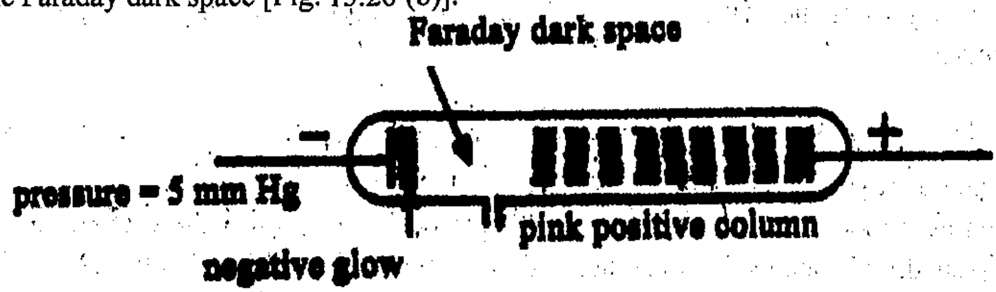


Fig. 13.26(b)

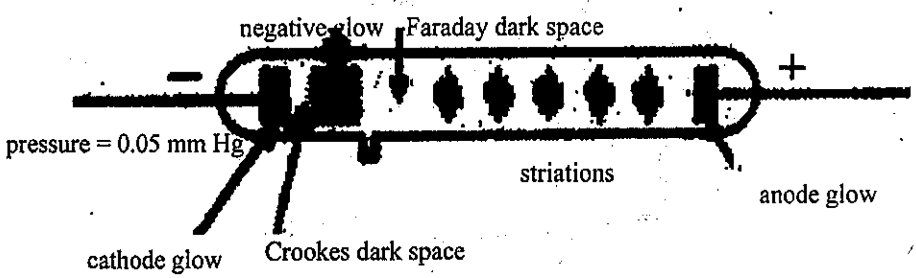


Fig. 13.26 (c)

At 0.05 mm Hg pressure the positive column shrinks towards the anode and begins to break up into striations. The Faraday dark space and the negative glow increase in length and another dark region appears between the cathode and the negative glow. That dark region is called the Crookes dark space [Fig.13.26(c)].

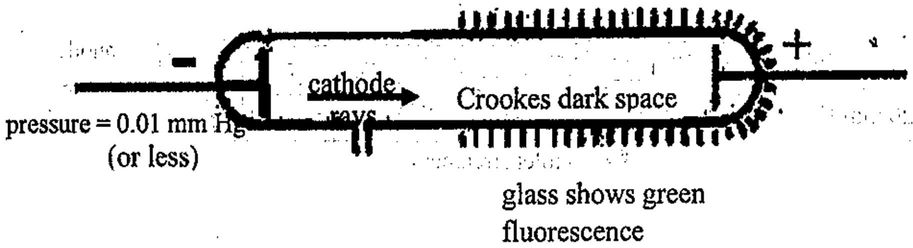


Fig. 13.26(d)

When the pressure reaches 0.01 mm Hg the positive column and the negative glow disappear. At this stage the Crookes dark space extends to fill the whole of the tube and the walls of the tube show a green fluorescence [Fig. 13.26(d)]. This is due to the invisible rays, from the cathode, striking the walls of the tube. These invisible rays emanating from the cathode are called "cathode rays". The name was given by Crookes.

The Properties of Cathode Rays

1. Cathode rays travel in straight lines.

When an anode in the shape of a cross is placed in the path of the cathode rays a sharp shadow is obtained at the other end of the tube (Fig.13.27). This shows that the cathode rays travel in straight lines.

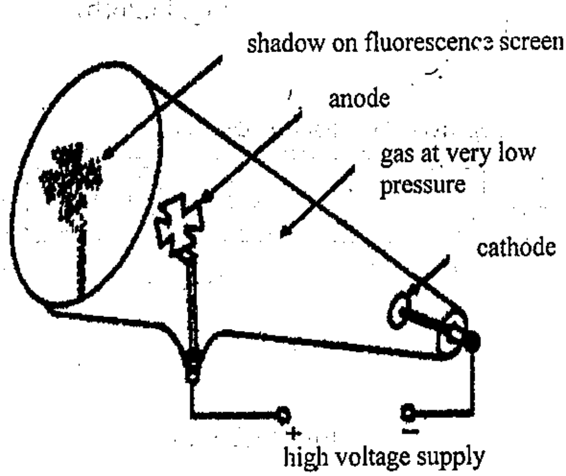


Fig. 13.27 Path of cathode rays (Maltese cross tube)

2. Cathode rays have momentum and kinetic energy

A light wheel having mica vanes rotates towards the anode when it is placed in the path of cathode rays (Fig. 13.28). This experiment shows that the cathode rays consist of fast-moving particles which strike the vanes and make the wheel rotate. It can be concluded that the cathode rays have momentum, and that they therefore have mass, velocity and kinetic energy.

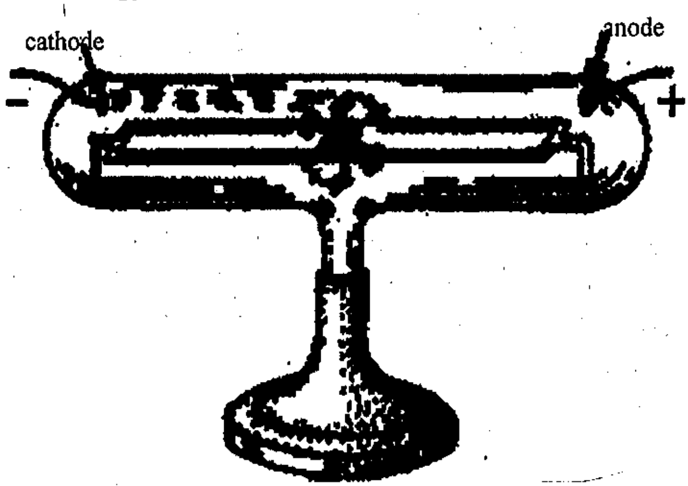


Fig. 13.28 Paddle-wheel discharge tube

3. Cathode rays consist of negatively charged particles.

In Fig. 13.29 a narrow slit is placed in front of the cathode. The cathode rays passing through the slit are allowed to strike a long strip of metal coated with a fluorescence paint. The path of the cathode rays can be seen on the strip. The path is found to be a straight line. By placing a horseshoe magnet across the tube, as illustrated, the path of the cathode rays is deflected downward. When the poles of the magnet are reversed the path is deflected upward. The deflection shows that the cathode rays are charged and the direction of deflection determines the kind of charge. It has been mentioned that the direction of the force acting on a charged particle moving in a magnetic field can be found by using Fleming's left-hand rule. By application of this rule the cathode rays are found to be negatively charged particles. Cathode rays are deflected by a magnetic field as well as by an electric field.

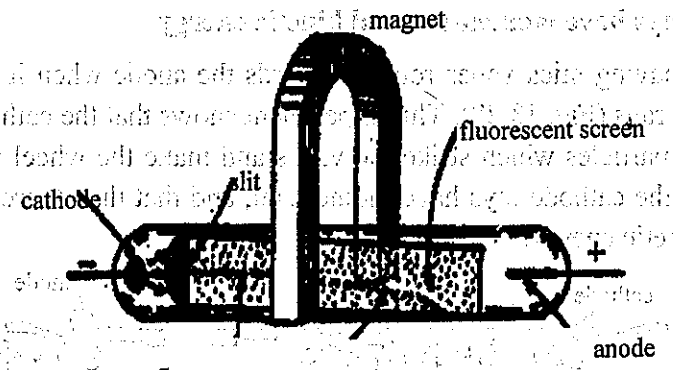


Fig. 13.29 Deflection of cathode rays by a magnetic field

In 1895, J.J. Thomson performed experiments on the deflection of cathode rays by applying both the electric and magnetic fields simultaneously. From these experiments he could determine the charge (e) to mass (m) ratio for the cathode rays. The value he obtained was

$$\frac{e}{m} = 1.7589 \times 10^{11}\ C\ kg^{-1}$$

Therefore, it is found that the mass of a cathode ray particle is extremely small and its charge is extremely large. J.J. Thomson called the particle "the electron".

In 1906, Millikan determined the magnitude of the charge of an electron. The value obtained was $e = 1.602 \times 10^{-19}$ C. From the values of e/m and e, the mass of an electron m is found to be 9.1×10^{-31} kg.

The above experimental results can be summarized as follows. Cathode rays consist of fast moving electrons. These electrons are liberated from the surface of the cathode. They move very fast because an electric field between the cathode and anode accelerates them.

13.5 CATHODE RAY OSCILLOSCOPE

A cathode ray oscilloscope (CRO) consists of a cathode ray tube to which is connected an appropriate electronic circuit. The cathode ray tube is the principal part of the CRO; it is an evacuated glass tube containing the following essential elements:

(1) the electron gun
(2) the deflection system, and
(3) the fluorescent screen.

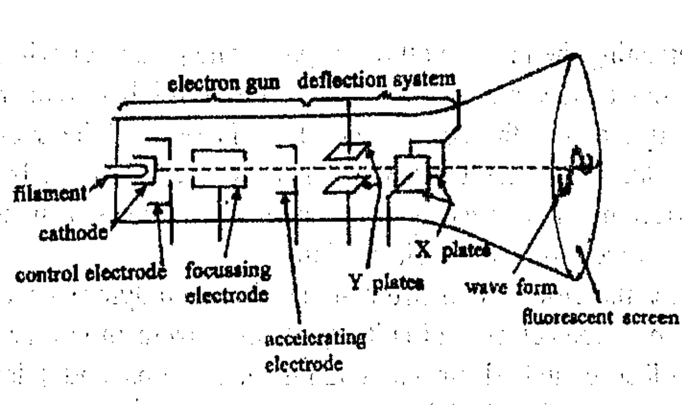


Fig. 13.30 Cathode ray tube.

Fig. 13.30 shows how a cathode ray tube is constructed. The electron gun is made up of a filament-cathode complex which emits electrons that are accelerated by an anode placed at the other end of the gun. In between the cathode and the anode are placed control electrodes and focussing electrodes which converge and concentrate the electrons into a fine beam.

The electron gun is followed by an arrangement consisting of two pairs of deflecting plates: the first pair, called Y plates; has two horizontal parallel flat plates which deflect the electron beam vertically when a potential difference is applied across them and the second pair, called X plates, has two vertical parallel flat plates which deflect the electron beam horizontally when a potential difference exists between them.

The electron beam after emerging from the deflection system will reach the fluorescent screen at the end of the Cathode ray tube. This screen is coated with phosphor and when the electron beam strikes the screen a bright sharp spot is produced. If no potential difference exists between the deflecting plates when the electron beam passes through the deflection system, the bright spot formed on the fluorescent screen will be stationary.

Let us now see how CRO works. The bright spot is first formed on the screen. Then the sweep-generator or the time-base circuit, which is the appropriate electronic circuit mentioned above, is switched on. This circuit is connected to the X plates and the switching on of this circuit results in a potential difference across the X plates. The potential difference builds up uniformly to a maximum and the process repeats at regular intervals. This has the effect of moving the spot horizontally across the screen and bringing it back again to the starting point when it reached the end of the screen and then repeating the process all over again. The person viewing the screen will see a moving spot at low sweep frequencies, but at higher frequencies he will see a continuous line across the screen. The line, instead of the spot, is seen at higher frequencies due to an effect called the persistence of vision. If now an alternating potential difference is applied to the Y plates, the spot will trace out a path which displays, the wave forms of the alternations.

The CRO is, therefore, an instrument used for studying the current and voltage waveforms in various electric circuits. Such an instrument is very useful for checking laboratory electric and electronic equipments, radios and televisions. In fact, a primary component of a television set is a cathode ray tube.

13.6 X-RAYS

In 1895, William Roentgen discovered X-rays (xrays , x-rays) by observing that some crystals glowed brightly near a working cathode ray tube. He also found that wrapped photographic plates were fogged as if exposed to light. The tube evidently emitted some rays which affected the photographic plates. These rays are now called x rays.

The X-ray tube

The schematic diagram of a xray tube is given in Fig. 13.31. A high potential difference is applied between the anode and the cathode to accelerate electrons emitted from the cathode. Xrays are emitted when electrons strike the target, which is made of tungsten to withstand high temperatures.

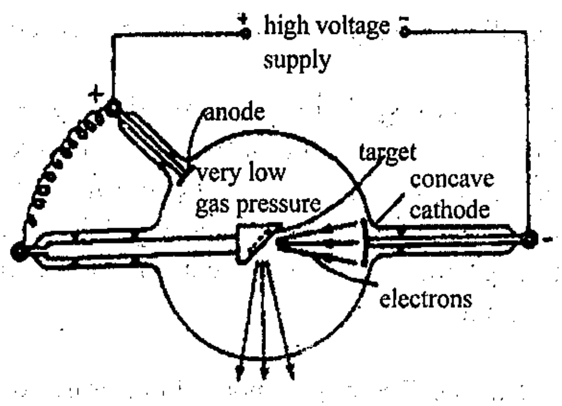


Fig. 13.31 The X-ray tube

Production of X-rays

To understand X-rays properly we need to consider the structure of the atom. The atom has a very heavy central core called the nucleus. The nucleus is made up of positively charged particles called protons (p) and uncharged or neutral particles called neutrons (n). Around the nucleus there are negatively charged particles called electrons (e) moving in closed orbits which are often circular in shape.

The electron is the lightest particle in the atom. The charge on the proton is the same as that on the electron but is positive. The mass of proton and that of the neutron are approximately equal; $m_p \approx m_n \approx 1840\ m_e$. They are not elementary particles like the electron or the muon since a proton or a neutron may be considered as composed of more fundamental particles called quarks(p = uud, n= udd). Quarks (u=up, d=down) carry fractional charges .

The simplest atom is the hydrogen atom written, ${}^{1}_{1}H$. The top 1 represents the mass number, A and the bottom 1 represents the atomic number, Z. It has one proton inside the

nucleus (A = 1) and an electron moving in a circular orbit around it. There are heavier versions of the hydrogen atom called the deuterium written as ${}^{2}_{1}H$ and tritium written as ${}^{3}_{1}H$. There are thus three isotopes of hydrogen each having a single proton inside the nucleus but differing in the number of neutrons that each has inside the nucleus. Could you think of another light atom which has more than two isotopes? The most abundant radioactive isotopes of uranium are ${}^{234}_{92}U$, ${}^{235}_{92}U$, and ${}^{238}_{92}U$. There are in fact six isotopes of uranium having A = 232, 233, 234, 235, 236, 238 all with Z = 92.

On this atomic model one can explain the production of X-rays. X-rays are produced by accelerating electrons through a potential drop, V of about 10 to 100 kV in a high vacuum and then stopping them suddenly in a target of some dense material.

Radiation consists of (a) intense sharp lines or characteristic X-rays and (b) continuous background or white X-rays. High energy electrons emitted from the cathode in bombarding the target may knock an electron completely out of its atom. Electrons from orbit having higher energy will fall back into the vacant position emitting the characteristic X-radiation.

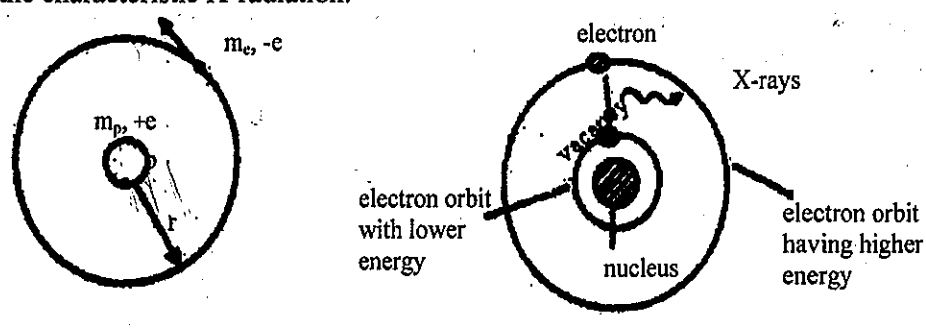


Fig. 13.32 A circular orbit for an electron in H-atom and production of X-rays on this model

To explain the continuous spectrum one can assume that as the electron passes through the atoms of the target material, it will suffer a series of deflections in the Coulomb field of the nuclei of the target. Each time the electron is deflected it is given a brief acceleration which produces a small burst of radiation. This gives rise to the continuous spectrum.

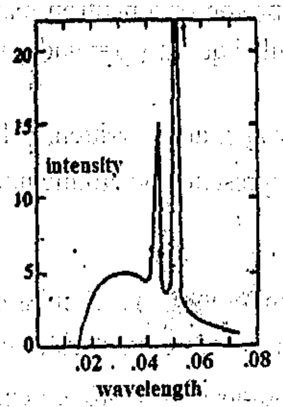


Fig.13.33 A continuous xray spectrum with two characteristic lines superimposed (schematic)

Properties of X-rays

X-rays are electromagnetic waves like light. But their wavelengths are much shorter than those of light. They can penetrate solid materials including metals, but a few millimetres of aluminium will stop most X-rays. They can cause ionization by stripping electrons from the atoms.

Uses of X-rays

X-rays with low penetrating power are called, soft X-rays. The soft X-rays can penetrate flesh easily but not bones. This fact is used to take X-ray photographs of some parts of human body for medical diagnosis.

Hard X-rays which have high penetrating power are used to destroy cancer cells. Extreme care is necessary in this treatment because X-rays can also damage normal cells. X-rays are also used in industries for finding defects in welded joints and metal castings.

13.7 RADIOACTIVITY

In 1896, Henri Becquerel discovered that uranium salts emitted radiations which affected photographic plates and caused ionizations. This effect is called radioactivity and uranium is said to be a radioactive material. Later Marie Curie discovered two more radioactive elements called polonium and radium. Since then many radioactive materials have been identified.

The rays emitted from radioactive materials are of three types: namely alpha rays, beta rays and gamma rays. Emission of some or all of these rays from the nucleus of an atom is called radioactivity.

Alpha rays

Alpha rays consist of positively charged particles and thus can be deflected by electric and magnetic fields. They have the most strongly ionizing power of the three rays. But they are the least penetrating and can be stopped by a thick sheet of paper.

Beta rays

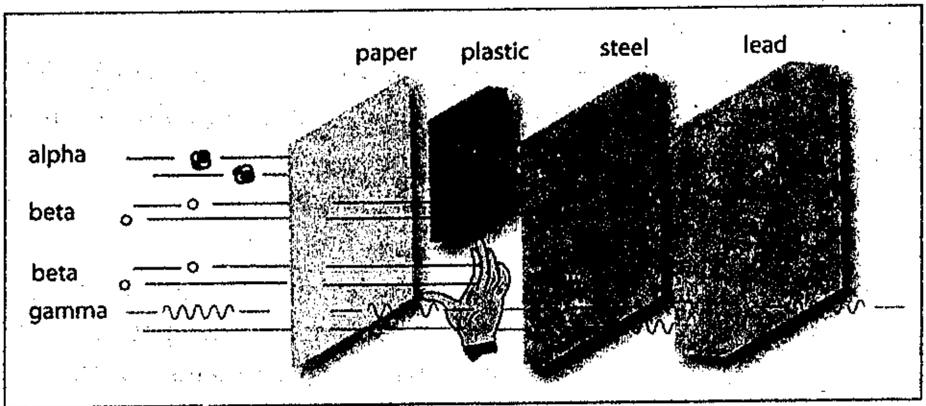
Beta rays consist of electrons with varying speeds. They carry negative charge and can be deflected by electric and magnetic fields. They are much less ionizing than alpha rays but have more penetrating power. It needs a few millimetres of aluminium to stop them.

Beta rays may also consist of positively charged electrons or positrons first predicted by theoretical physicist PAM Dirac in 1931 a year before its discovery by Anderson of the USA in 1932 and confirmed by Blackett of Great Britain a little later. The positrons carry positive charge ($e = +1.602 \times 10^{-19}$ C) but possesses an identical mass as the electron.

Gamma rays

Gamma rays are electromagnetic waves like light and X-rays but have much shorter wavelength. Gamma rays are the least ionizing but most penetrating of three rays. Their intensity is greatly reduced by several centimetres of lead but they are never completely stopped. They may also be considered as high energy (frequency) photons. Gamma rays are also produced when electrons collide with positrons (a process called electron positron annihilation).

Radioactive substances such as radium and polonium occur in nature. Radioactive substances can also be made artificially. Nuclear reactors, cyclotrons and other accelerators are used for the production of these artificial radioactive samples. Radioactive isotopes find wide and varied applications in medicine, agriculture, industry and in other areas.



Relative penetrating powers of the three kinds of radiation

Half-life

Radioactive samples are unstable; some decay spontaneously and others decay gradually. In other words, they decay at different rates.

Radioactive atoms of an element change into atoms of other elements when alpha or beta particles are emitted. The rate of decay of a radioactive sample is called its activity. The SI unit for activity is the becquerel which is abbreviated to Bq and 1 Bq = 1 event s^{-1}. In practice activities are quite high so that larger units; MBq (10^6 Bq) and GBq (10^9 Bq), are used. These larger units are more appropriate. A unit that is still being used today is the curie.

The curie and the becquerel are related as follows:

$$1 \text{ curie} = 3.7 \times 10^{10} \text{ events } s^{-1}$$

$$= 37 \text{ GBq}$$

Sub-multiples of the curie are the millicurie (10^{-3} curie) and the microcurie (10^{-6} curie). The activity of radium used in watch dials amounts to many microcuries. 1 curie or more than 1 curie of cobalt 60 ($^{60}_{27}Co$) is used in radiation therapy.

The rate of decay is unaffected by temperature but is a characteristic of the radioactive atoms, which is described by its half-life. The half-life is defined as the time for half the atoms in radioactive sample to decay.

Radium has a half-life of 1620 years. This means that if we start with N_0 atoms, then only $N_0/2$ atoms will remain after a time of 1620 years has elapsed. After another 1620 years the number remaining will be $N_0/4$. And it goes on decaying at that same rate. We, thus, see that after each half-life period the number of atoms is reduced to one half of the number present at the beginning of the period.
Fig. 13.34 shows the decay of the radioactive substance radon. Initially, at time t = 0, there was 1 g of radon. Since the half-life of radon is only 3.8 days, 1/2 g of it will remain after a period of 3.8 days. After 7.6 days, a period of two half-lives 1/4 g (= $1/2 \times 1/2$ g) will be left, after 11.4 days (= 3×3.8 days), 1/8 g (= $1/2 \times 1/2 \times 1/2$ g) will be left and so on. Can you find out how much radon will remain after 19 days?

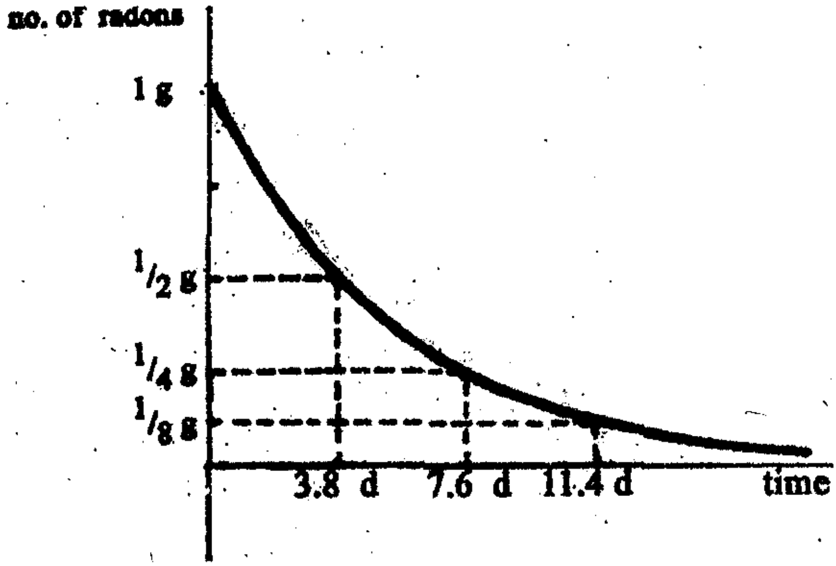


Fig. 13.34 Graph to illustrate the exponential nature of radioactive decay

13.8 MODELS OF THE ATOM

Matter is composed of atoms. These atoms were once assumed to be the smallest elementary particles or indivisible particles.

In 1897, J.J. Thomson discovered that cathode rays were negatively charge electrons and that the mass of an electron was very much smaller than that of the lightest atom. Therefore it was concluded that the mass of an electron was just a fraction of the mass of an atom and that the electrons could be considered as elementary particles of matter.

Normally, an atom is electrically neutral. As an atom consists of negatively charged electrons it must also consist of positively charged particles. Since the mass of an electron is very much smaller than that of an atom, almost all the mass of an atom must be due to the total mass of the positively charged particles. J. J. Thomson introduced an atomic model which explains the configuration of the charged particles in the atom.

Thomson's Atomic Model

In 1906, Thomson proposed a model of an atom. In this model, the positive charge was supposed to be uniformly distributed throughout a sphere in which the electrons were embedded (Fig. 13.35). A normal atom is electrically neutral and hence the sum of the positive and negative charges is zero.

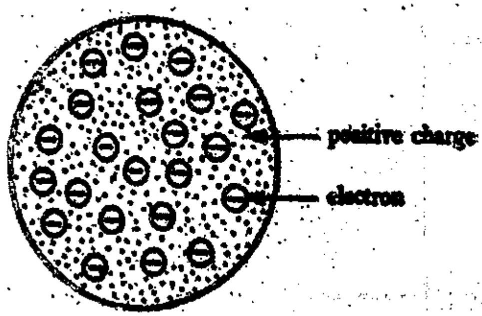
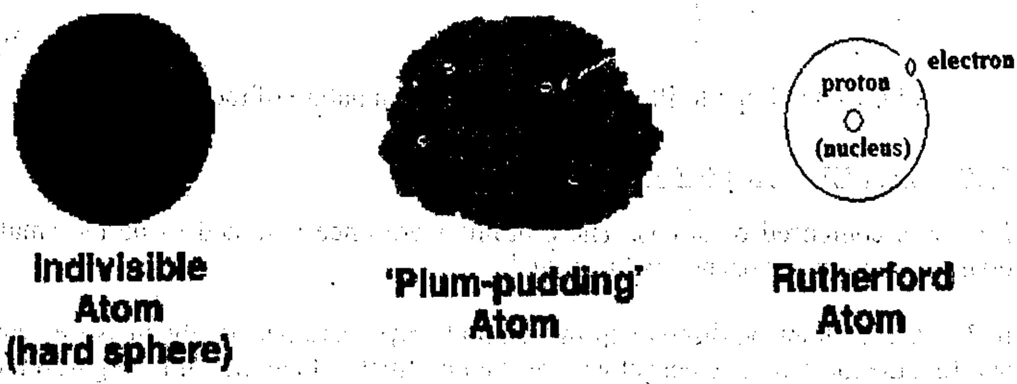


Fig. 13.35 Thomson's atom

At that time, Rutherford was devoting much of his time to the study of radioactivity. One of his most important discoveries was the spontaneous emission of α - particles by some heavy radioactive elements.



The α - particle emitted by the radioactive element has a charge of + 2e. Rutherford and his co-workers investigated the scattering of α - particles by a thin gold foil by bombarding it with α - particles. The experimental apparatus used is shown schematically in Fig. 13.36.

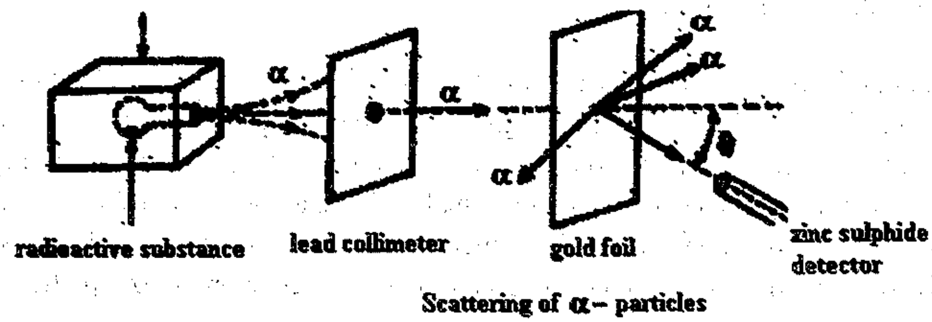


Fig. 13.36 Alpha scattering

It was found that most of the α - particles were scattered through very small angles. However, some α - particles were scattered through much larger angles. Occasionally an α - particle was stopped and thrown back along its original path. That was a rather strange phenomenon.

According to Thomson's atomic model, the positive charge of an atom is distributed uniformly over its volume so that the magnitude of the repulsive force exerted upon the positively charged α - particle should be very small. In addition the magnitude of the attractive force exerted upon the α - particle by the electrons distributed in the atom should also be very small. Therefore most of the a- particle should pass almost straight through the very thin gold foil [Fig.13.37(a)]. This means that the α - particles could be scattered through very small angles. That did not agree with the experiment. Therefore, Thomson's atomic model became an unacceptable model.

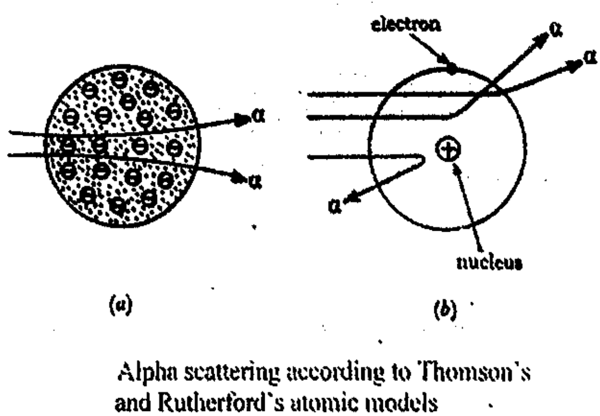


Fig. 13.37(a), (b) Alpha scattering on Thomson's and Rutherford's atomic models.

Rutherford's Atomic Model

To explain the results of a α - scattering Rutherford made the following assumptions. An α - particle may be scattered through a large angle only if it experiences a strong repulsive force. In order to be so the positive charge should not be spread throughout the atom but should be concentrated in a small volume at the centre of the atom. This positively charged volume is called the nucleus which is surrounded by electrons. The positively charged nucleus can now exert a repulsive force upon the α - particles.

The α - particle which travels directly toward the nucleus experiences a strong repulsive force. Hence the α - particle is stopped near the nucleus and is thrown or scattered back along its original path [Fig. 13.37(b)]. This explanation is an acceptable one. Thus, Rutherford's atomic model became an acceptable atomic model. According to this model the space inside an atom is mostly empty.

However, Rutherford's atomic model presented some difficulties. If the electrons in an atom were assumed to be stationary, they would fall into the nucleus because they would be attracted by the nucleus. On the other hand, if the electrons were assumed to move around the nucleus they would have centripetal acceleration. The accelerated electrons would radiate energy according to electromagnetic theory. As a result they would lose energy gradually and its orbit would get smaller and smaller. Finally electrons would fall into the nucleus and the atom could no longer exist (Fig. 13.38 below). This problem was resolved by Bohr in 1913.

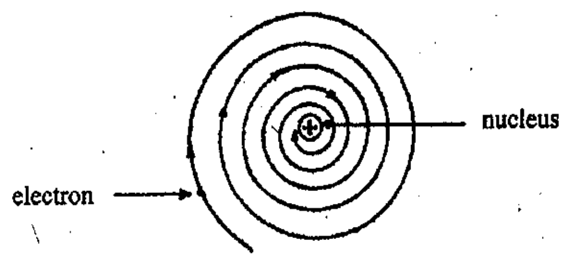
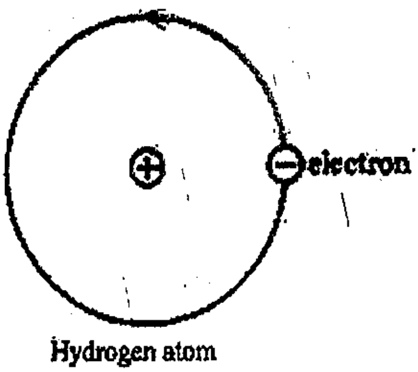


Fig. 13.38 Instability of Rutherford's model.

Bohr's Atomic Model

Bohr, accepting Rutherford's model of the atom, proposed another atomic model. In this model, electrons are moving around the nucleus in circular orbits. In addition, he made the following basic assumptions. The electrons which are moving around the nucleus should be restricted to allowed orbits. If an electron is moving in a certain orbit it does not absorb or radiate energy. But it may absorb or radiate energy when it jumped from one orbit to another.



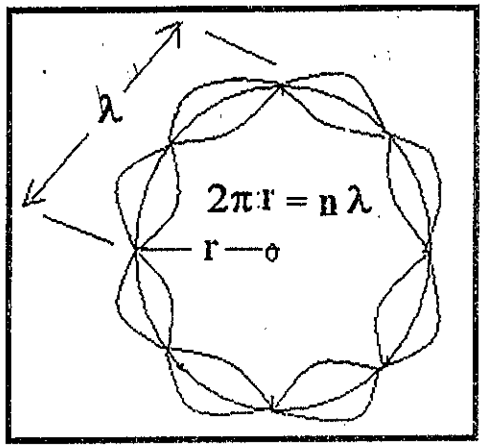


Fig. 13.39 (left) Hydrogen atom. Fig 13.39 (right) Bohr orbital radius "r" and wavelength " λ"associated with the electron of mass m with n=1,2,3....Due to the relation $k = 2\pi/\lambda$ corresponding to angular "frequency" $\omega = 2\pi/T$ these terms give rise to $p = \hbar k = h/\lambda$ and $E = \hbar\,\omega = h\,\nu$.

Using his assumptions Bohr obtained a formula (13.6) from which the energy levels of the hydrogen atom can be calculated. The formula gives values which agree with the experimental results obtained for the spectrum of hydrogen atom. Consider an electron of charge e and mass m moving in a circular orbit of radius "r" under the influence of centripetal force mv^2/r $[ML^2T^{-2}L^{-1}]$ balanced by the Coulomb force e^2/r^2 :

$$mv^2/r = e^2/r^2 \text{ or } mv^2r = e^2 \qquad (13.1)$$

but Bohr assumed that the angular momentum mvr could take integral values of $h/2\pi$.

$$mvr = n\,\hbar \qquad (13.2)$$

thus, dividing (13.1) by (13.2) we get

$$v = e^2/n\hbar \qquad (13.3)$$

From which we have

$$r = (n\hbar)^2 / me^2 \quad (13.4)$$

The total energy of the H-atom is $E = KE + PE$

$$\tfrac{1}{2} mv^2 - e^2/r = E \quad (13.5)$$

But $PE = -me^4/(n\hbar)^2$ and $KE = \tfrac{1}{2} me^4/(n\hbar)^2$

Thus

$$E = -\tfrac{1}{2} me^4/(n\hbar)^2 \quad (13.6)$$

That is

$$E_n = -13.6/n^2 \ \text{(eV)} \quad (13.7)$$

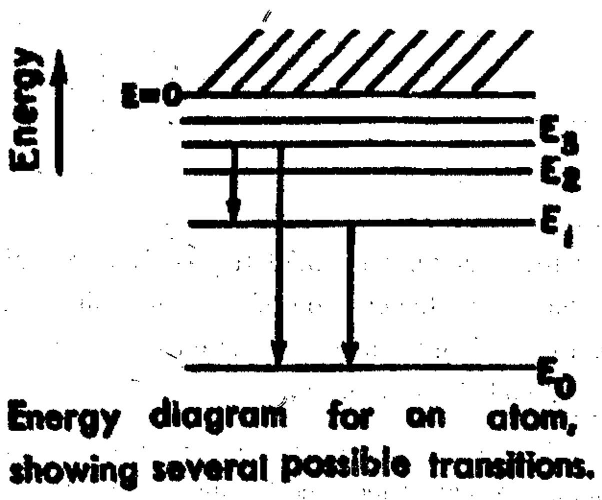


Fig. 13 .40 Energy level diagram for an atom showing possible transitions

In the tenth grade you have already learnt that there exists what is known as wave particle duality for light , here we assume that it is true for all atomic particles and write $k = 2\pi/\lambda$ in much the same way as we wrote $\nu = 1/T$(frequency is 1/period) and $\omega = 2\pi/T$. In quantum theory,energy comes in packets $E = h\nu = \hbar\omega$(energy packet) , similarly $p = \hbar k = h/\lambda$ where $h/2\pi = \hbar$ and is a unit of angular momentum (defined as mvr) in quantum theory in any case $\hbar k$ has the dimension of momentum just as $\hbar\omega$ has the dimension of energy . From $p = \hbar k = h/\lambda$ and the fact that any Bohr's orbit contains an integral number of λ , $2\pi r = n\lambda$, using the value of $\lambda = 2\pi r/n$ in p , we get $mvr = n\hbar$, the Bohr condition for the angular momentum of the electron (n=integer).

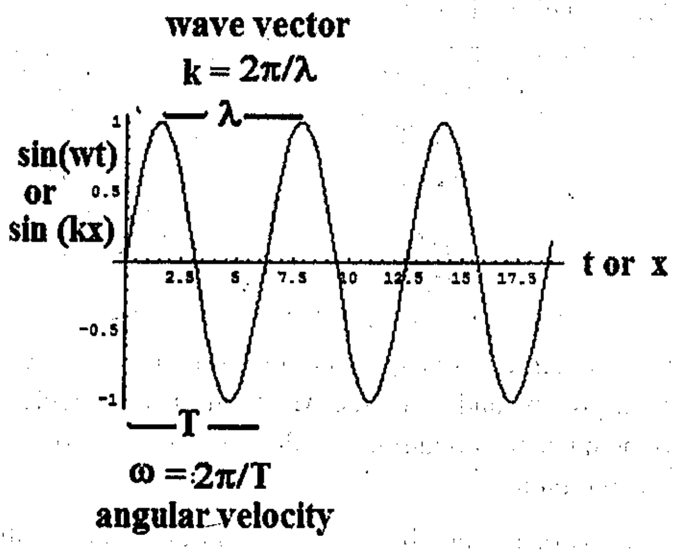


Fig. 13.41 The angular frequency and the wave vector in a periodic motion.

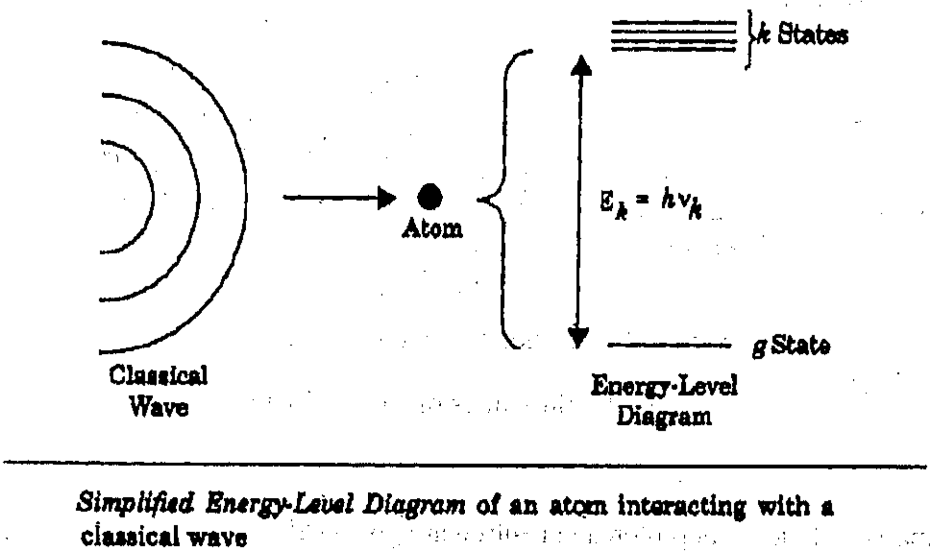


Fig. 13.42 Simplified energy-level diagram of an atom interacting with a classical wave.

Bohr's atomic model is a useful model. This model can be used not only for the hydrogen atom but also for hydrogen-like atoms.

Table of energy levels in eV and joules

n	Energy/eV	Energy/J
1	−13.60	-2.18×10^{-18}
2	−3.39	-5.42×10^{-19}
3	−1.51	-2.42×10^{-19}
4	−0.85	-1.36×10^{-19}
5	−0.54	-8.71×10^{-20}

Although a simple hydrogen atom has no neutron in its nucleus, the nuclei of other atoms consist of both protons and neutrons. Although in some nuclei the number of protons is equal to the number of neutrons in other nuclei, that form a majority, there are more neutrons than protons.

The number of electrons or the number of protons in an atom is called the atomic number. The total number of protons and neutrons in the nucleus of an atom is called the mass number. Thus the atomic number and mass number of an ordinary hydrogen atom are both 1 .

The atomic number of helium atom is 2 and that of lithium atom is 3. The structures of these atoms are shown in Fig. 13.43.

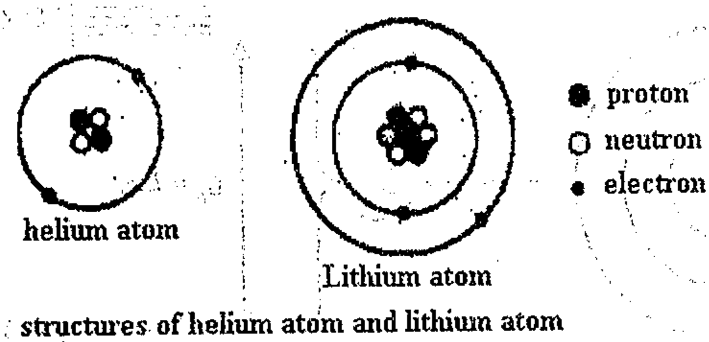


Fig. 13.43 Structures of He and Li atoms.

The masses of electron, proton and neutron are given below:

mass of electron $= 9.1091 \times 10^{-31}$ kg

mass of proton $= 1.6725 \times 10^{-27}$ kg

mass of neutron $= 1.6748 \times 10^{-27}$ kg

From these values it can be assumed that

mass of proton ≈ mass of neutron

mass of proton ≈ 1840 × mass of electron.

All the mass of an atom is concentrated in its nucleus.

In a normal atom the number of electrons, negatively-charged particles, is always equal to the number of protons, positively-charged particles. An electron and a proton have the same magnitude of electric-charge: 1.60×10^{-19} C. A neutron is an uncharged-particle. Therefore, a normal atom is electrically neutral.

Isotopes

We have already learnt about the structure of an atom; it is a system with a central, core called the nucleus, and an electron cloud surrounding that nucleus. The nucleus in turn is made up of protons and neutrons. Are all atoms of the same chemical element structured in the same way? The answer is a definite no.

Let us look at a particular element, say, copper. There are two kinds of naturally occurring atoms for this element; these two kinds of atoms have the same atomic number but different mass numbers.

That is, an atom of one kind has the same number of protons and electrons as an atom of another kind; but the masses are different. It means that the two have different number of neutrons. These atoms are called the isotopes of copper. Isotopes, then, are atoms of the same element that have different masses. In the case of copper one isotope has 29 protons and 34-neutrons while the other has the same number of protons but 36 neutrons. They are represented by the symbols $^{63}_{29}Cu$ and $^{65}_{29}Cu$ respectively.

The element hydrogen with atomic number one has three known isotopes. These three are hydrogen ($^{1}_{1}H$), deuterium ($^{2}_{1}H$) and tritium ($^{3}_{1}H$).

Naturally occurring isotopes do not occur in equal amounts. For instance, there occur in nature about twice as many $^{63}_{29}Cu$ as $^{65}_{29}Cu$. Of the over 1000 isotopes known thus far, the most abundant one in the entire universe is the hydrogen isotope. All of the known isotopes are not found in nature; many of them are made artificially.

Isotopes of a single element have the same chemical properties since they have the same distribution of electrons and it is this electronic distribution that determines the chemical properties. They, however, have considerably different physical properties because of the difference in mass.

13.9 USES OF RADIOACTIVITY

Radioactivity isotopes are called radioisotopes (or radio nuclides).Some are produced artificially in a nuclear reactor when nuclei absorb neutrons or gamma radiation. For example, all natural cobalt is cobalt-59, which is stable. If cobalt-59 absorbs a neutron, it becomes cobalt-60, which is radioactive.

Here are some of the practical uses of radioisotopes.

Tracers

Radioisotopes can be detected in very small (and safe) quantities, so they can be used as **tracers** – their movements can be tracked. Examples include:

- Checking the function of body organs. For example, to check thyroid function, a patient drinks a liquid containing iodine-123, a gamma emitter. Over the next 24 hours, a detector measures the activity of the tracer to find out how quickly it becomes concentrated in the thyroid gland.
- Tracking a plant's uptake of fertilizer from roots to leaves by adding a tracer to the soil water.
- Detecting leaks in underground pipes by adding a tracer to the fluid in the pipe.

For tests like those above, artificial radioisotopes with short half-lives are used so that there is no detectable radiation after a few days.

Radiotherapy

Cobalt-60 is a strong gamma emitter. Gamma rays can penetrate deep into the body and kill living cells. So a highly concentrated beam from a cobalt-60 source can be used to kill cancer cells in a tumour. Treatment like this is called **Radiotherapy**.

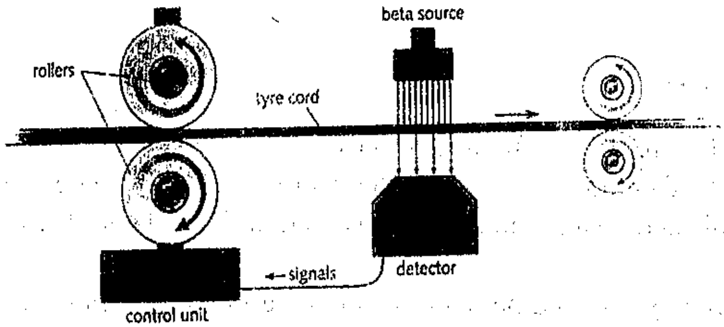
Testing for cracks

Gamma rays have the same properties as short-wavelength X-rays, so they can be used to photograph metals to reveal cracks. A cobalt-60 gamma source is compact and does not need electrical power like an X-ray tube.

Thickness monitoring

In some production processes a steady thickness of material has to be maintained. The diagram below shows one way of doing this.

Fig 13. 44



◄ The moving band of tyre cord has a beta source on one side and a detector on the other. If the cord from the rollers becomes too thin, more beta radiation reaches the detector. This sends signals to the control unit, which adjusts the gap between the rollers.

Carbon dating

There is carbon in the atmosphere (in carbon dioxide) and in the bodies of animals and plants. A small proportion is radioactive carbon-14 (half-life 5730 years). Although carbon-14 decays, the amount in the atmosphere changes very little because more is continually being formed as nitrogen in the upper atmosphere is bombarded by comic radiation from space. While plants and animals are living, feeding, and breathing, they absorbed and give out carbon, so the proportion of carbon-14 is gradually reduced by radioactive decay. By measuring the activity of a sample, the age of the remains can be estimated. This is called carbon dating. It can be used to find the age of organic materials such as wood and cloth. However, it assumes that the proportion of carbon-14 in the atmosphere was the same hundreds or thousands of years ago as it is today.

Human remains from a Danish peat bog. Carbon dating showed that this man died around 220-240BC.

Dating rocks

When rocks are formed, some radioisotopes become trapped in them. For example, potassium-40 is trapped when molten material cools to form igneous rock. As the potassium-40 decays, more and more of its stable decay product, argon-40 is created. Provided none of this argon gas has escaped, the age of the rock (which may be hundreds of millions of years) can be estimated from the proportions of potassium-40 to argon-40. Igneous rock can also be dated by the proportion of uranium to lead isotopes – lead being the final, stable product of a series of a series of decays that starts with uranium.

13.10 NUCLEAR ENERGY

When alpha or beta particles are emitted by a radioactive isotope, they collide with surrounding atoms and make them move faster. In other words, the temperature rises as nuclear energy (potential energy stored in the nucleus) is transformed into thermal energy (heat).

In radioactive decay, the energy released per atom is around a million times greater than that from a chemical change such as burning. However, the rate of decay is usually very slow. Much faster decay can happen if nuclei are made more unstable by bombarding them with neutrons. Whenever a particle penetrates and changes a nucleus, this is called a **nuclear reaction**.

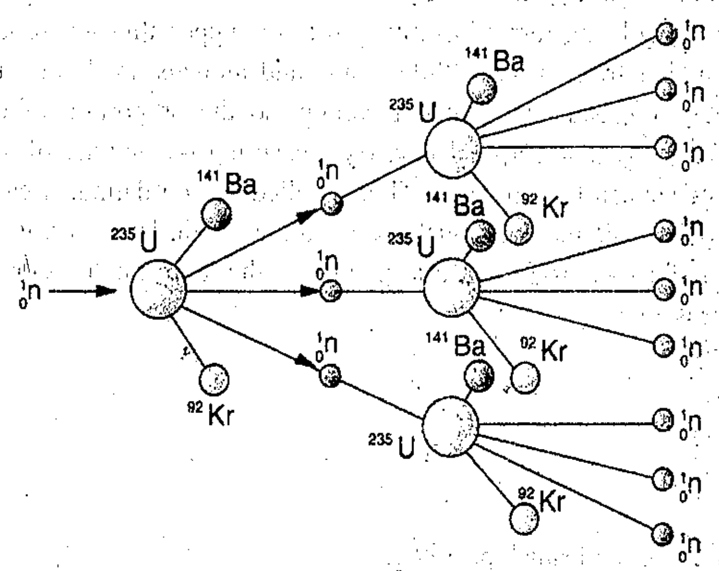


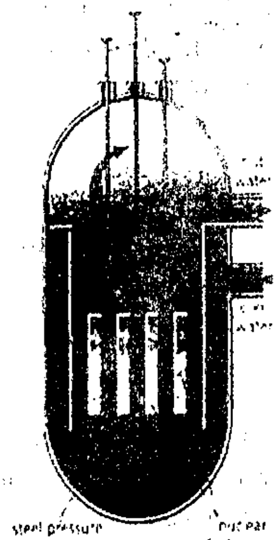
Fig. 13.45 Nuclear Fission

Fission

Natural uranium is a dense radioactive metal consisting mainly of two isotopes: uranium-238 (over 99%) and uranium-235 (less than 1%). The diagram (Fig 13.45) shows what can happen if a neutron strikes and penetrates a nucleus of uranium-235. The nucleus becomes highly unstable and splits into two lighter nuclei, shooting out two or three neutrons as it does so. The splitting process is called **fission**, and the fragments are thrown apart as energy is released. If the emitted neutrons go on to split other nuclei ... and so on, the result is a **chain reaction**, and a huge and rapid release of energy.

For a chain reaction to be maintained, the uranium-235 has to be above a certain **critical mass,** otherwise too many neutrons escape. In the first atomic bombs, an uncontrolled chain reaction was started by bringing two lumps of pure uranium-235 together so that the critical mass was exceeded. In present-day nuclear weapons, plutonium-239 is used for fission.

The steel flasks on this train contain waste from a nuclear reactor.



pressurized water reactor(PWR)

Fission in a nuclear reactor

In a nuclear reactor in a nuclear power station, a controlled chain reaction takes place and thermal energy (heat) is released at a steady rate. The energy is used to make steam for the turbines, as in a conventional power station. In many reactors, the nuclear fuel is uranium dioxide, the natural uranium being enriched with extra uranium-235. The fuel is in sealed cans (or tubes).

To maintain the chain reaction in a reactor, the neutrons have to be slowed down, otherwise many of them get absorbed by the uranium-238. To slow them, a material called a **moderator** is needed. Graphite is used in some reactors, water in others. The rate of the reaction is controlled by raising or lowering **control rods**. These contain boron or cadmium, materials which absorb neutrons.

Nuclear waste

After a fuel can has been in a reactor for three of four years, it must be removed and replaced. The amount of uranium-235 in it has fallen and the fission products are building up. Many of these products are themselves radioactive, and far too dangerous to be released into the environment. They include the following isotopes, none of which occur naturally.

- Strontium-90 and iodine-131, which are easily absorbed by the body. Strontium becomes concentrated in the bones; iodine in the thyroid gland.
- Plutonium-239, which is produced when uranium-238 is bombarded by neutrons. It is itself a nuclear fuel and is used in nuclear weapons. It also highly toxic. Breathed in as dust, the smallest amount can kill.

Spent fuel cans are taken to a reprocessing plant where unused fuel and plutonium are removed. The remaining waste, now a liquid, is sealed off and stored with thick shielding around it. Some of the isotopes have long half-lives, so **safe storage** will be needed for thousands of years. The problem of finding acceptable sites for long-term storage has still not been solved.

Energy and mass

According to Albert Einstein (1905), energy itself has mass. If an object gains energy, its mass increases; if it loses energy, its mass decreases. The mass change *m* (kg) is linked to the energy change E (joules) by this equation:

$$E = mc^2 \text{ (where c is the speed of light, } 3 \times 10^8 \text{ m/s)}$$

The value of c^2 is so high that energy gained or lost by everyday objects has a negligible effect on their mass. However, in nuclear reactions, the energy changes per atom are much larger, and produce detectable mass changes. For example, when the fission products of uranium-235 are slowed down in a nuclear reactor, their total mass is found to be reduced by about 0.1 %.

EXERCISES

1. Explain the following.

   (a) Edison effect,

   (b) Thermionic emission.

2. (a) Explain how an n-type semiconductor and a p-type semiconductor can be obtained.

   (b) What are the majority carriers in the above semiconductors?

3. (a) Describe the constructions of a vacuum diode and a p-n junction diode.

   (b) Do these diodes obey Ohm's law? Explain.

4. (a) What is a positive hole? What is the difference between a positive hole and an electron? (b) What are the carriers of charge in a metal and in a semiconductor?

5. What is meant by "forward-biased" and "reverse-biased"? Explain these terms using circuit diagrams.

6. (a) What is a rectifier? (b) Describe the function of a full-wave rectifier.

7. (a) Describe the construction of a triode. (b) When does a triode behave like a diode?

   (c) Does a triode obey Ohm's law?

8. (a) What is a transistor? (b) Mention some types of transistors.

9. Why do people use transistors instead of vacuum tubes?

10. Explain how a transistor can be used as a current amplifier and as a power amplifier.

11. Multiple Choice Questions

    (i). Thermionic emission requires which of the following?

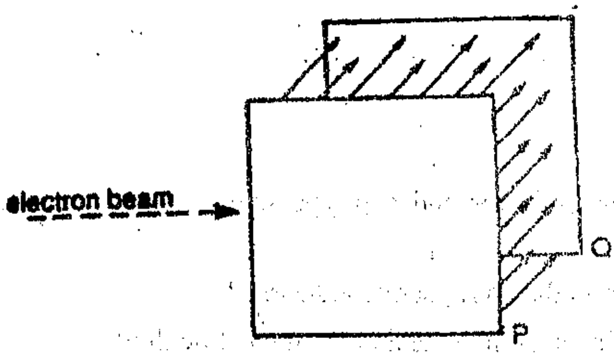
    A An anode and a cathode

    B A hot filament

    C An evacuated bulb

    D Ions

    (ii). An electric field is set up between plates P and Q as shown in the Fig. An electron beam is then directed through the field. In which direction will the electron beam be deflected?



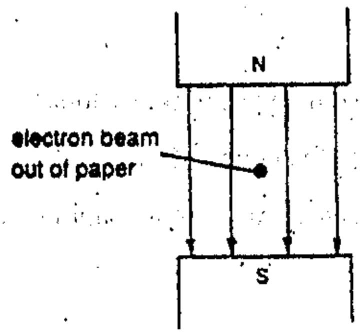
A Out of the paper

B Into the paper

C Up

D Down

(iii). An electron beam is directed out of the paper. When it passes between the poles of the two magnets which direction will it be deflected in?



electron beam out of paper

A Left

B Right

C Up

D Down

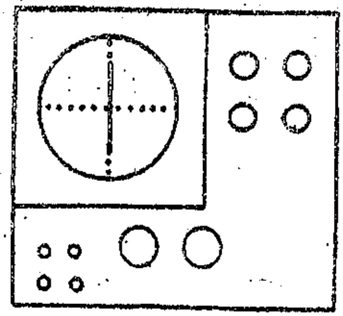
(iv). An Oscilloscope is used to measure an a.c. voltage and gives the following reading. The trace is 5 cm long and the Y gain is set at 0.1 V cm^{-1}. The peak voltage, therefore, is

A 0.25V

B 0.5V

C 2.5

D 5 V



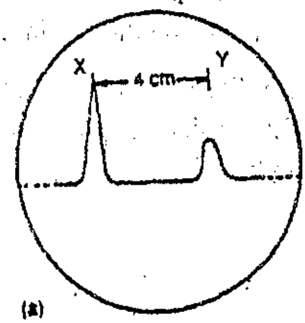
(v). The two peaks X arid Y, shown in Fig. were produced on the screen of a cathode ray oscilloscope when high frequency radio waves (radar) were sent out (X) and returned (Y) after bouncing off an aeroplane. The time-base was set at 0.5 millisecond per cm and XY measured 4 cm long. What was the time taken for the radio wave from the radar station to reach the aeroplane?

A 1 ms

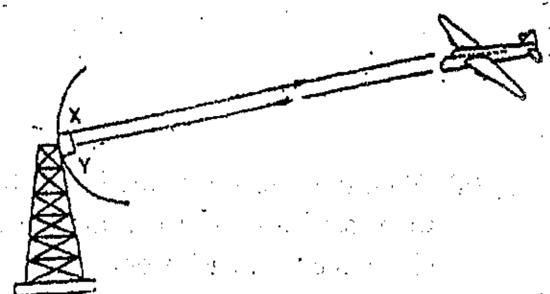
B 2 ms

C 2 s

D 20 ms



(a)



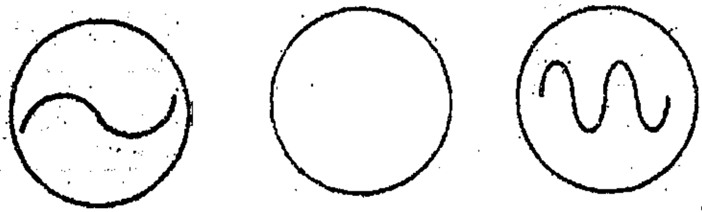
12. Structured Questions

(i) (a) What is meant by the phrase the thermionic emission of electrons?

(b) Draw a labelled diagram of a cathode ray tube as used in an oscilloscope.

(c) Explain how the beam is produced, how it may be deflected and how it is made visible. How do the brightness and focus controls effect the beam.

(ii)A microphone connected to a cathode ray oscilloscope is placed in front of a vibrating tuning fork. The waveform of the output from the microphone is shown in Fig.(a)

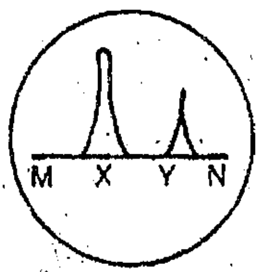


(a) (b) (c)

(a) Assuming that the controls of the C.R.O. are unaltered, draw, in Fig.(b) the trace that would be obtained if the same tuning fork gave a louder note.

(b) What adjustment has to be made in order to obtain the trace as shown in Fig. (c) using the original tuning fork?

(iii)Figure shows the screen of a cathode ray oscilloscope. The time-base is set at 2.0 microseconds per mm and the length of the time-base sweep MN is 100 mm.



(a) What time span does the length MN represent? A radar signal sent from a radar station to a distant aircraft is displayed on the C.R.O. at X and the signal received back from the aircraft, by reflection, is displayed at Y where the distance XY is 80 mm.

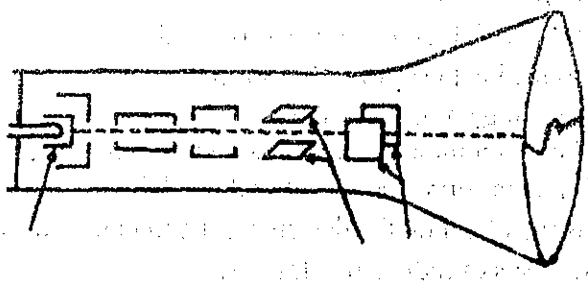
(b) How far is the aircraft from the radar station? The speed of radar waves is 3.0×10^8 ms^{-1}.

13. Draw the symbols and give the truth tables for the five common logic gates.
14. Suggest how two NAND gates can be connected to behave as an AND gate.
15. Describe the different stages of electric discharge at various pressures when the air inside the cathode ray tube is pumped out.
16. a) What are cathode rays? (b) State the properties of cathode rays.

17. How can it be known that cathode rays are electrically charged particles ?

18. Why do the walls of the cathode ray tube show a green fluorescence?

19. Label the diagram.



20. (a) What are X-rays (xrays)?

(b) How are X-rays produced?

(c) Give two properties of X-rays.

(d) How do X-rays and gamma rays similar?

(e) Are the wavelengths of X-rays longer than those of light?

21. (a) What is radioactivity ?

(b) Who discovered radioactivity?

(c) What are the properties of alpha, beta and gamma rays?

22. Define half-life of a substance.

23. What is meant by "Radium has a half-life of 1620 years"?

24. Explain Thomson's atomic model and Rutherford's atomic model.

25. Why was Rutherford's atomic model unacceptable? Explain.

26. Explain Bohr's atomic model.

27. State Bohr's basic assumptions. Why does an electron moving around the nucleus not fall into the nucleus?

28. What are the mass numbers and atomic numbers of the following elements?

(1) $^{206}_{82}Pb$ (ii) $^{235}_{92}U$ (iii) $^{193}_{80}Hg$

29. Distinguish between half-wave and full-wave rectification.

30. If a piece of either an- n-type or p-type semiconductor were placed in a battery

circuit, would there be conduction in each case? Explain. What if the polarity were reversed ?

EXERCISES: USING RADIOACTIVITY

1. (a) What are radioisotopes?
   (b) How are artificial radioisotopes produced?
   (c) Give two medical uses of radioisotopes.
2. Give two uses of gamma radiation.
3. In the thickness monitoring system shown in Fig 14. 55 :
   (a) Why is a beta source used, rather than alpha or gamma source?
   (b) What is the effect on the detector if the thickness of the tyre cord increases?
4. (a)Give two uses of radioactive tracers.
   (b)Why is it important to use radioactive tracers with short half-lives?
5. Carbon-14 is a radioactive isotope of carbon.
   (a)What happens to the proportion of carbon-14 in the body of a plant or an animal while alive?
   (b)Why does the proportion of carbon-14 in the remains of dead plants and animals give clues about their age?

Appendix : A Glossary of Nuclear Terms

activity: The rate of radioactive decay.

alpha particle (alpha radiation, alpha ray): A ^4He nucleus. It is made up of two neutrons and two protons. It is the least penetrating of the three common form of radiation, being stopped by a thin sheet of paper. It is not dangerous to living things unless the alpha-emitting substance is inhaled or ingested or comes into contact with the lens of the eye.

atom: A particle of matter indivisible by chemical means. It is the fundamental building block of molecules. It consists of a positively charged nucleus and orbiting electrons. The number of electrons is the same as the number of protons in the nucleus.

atomic mass (sometimes mistakenly called atomic weight): The mass of a neutral atom. Its value in atomic mass units (u) is approximately equal to the sum of the number of protons and neutrons in the nucleus of the atom.

atomic mass number: A, the total number of nucleons (protons and neutrons) found in a nucleus.

atomic number: Z, the total number of protons found in a nucleus.

atomic mass unit (amu or u): Unit of mass defined by the convention that the atom ^{12}C has a mass of exactly 12 u; the mass of 1 u is 1.67×10^{-27} kg.

becquerel (Bq): Unit of activity in the International System—one disintegration per second; 1 Bq = 27 pCi.

beta particle (beta radiation, beta ray): An electron of either positive charge (e^+ or β^+) or negative charge (e, e^- or β^-) emitted by an atomic nucleus or neutron in the process of a transformation. Beta particles are more penetrating than alpha particles but less than gamma rays or xrays. Electron capture is a form of beta decay.

curie (Ci): The original unit used to describe the intensity of radioactivity in a sample of material. One curie equals thirty-seven billion disintegrations per second, or approximately the radioactivity of one gram of radium. This unit is no longer recognized as part of the International System of units. The becquerel has replaced it.

decay (radioactive): The change of one radioactive nuclide into a different nuclide by the spontaneous emission of radiation such as alpha, beta, or gamma rays, or by electron capture. The end product is a less energetic, more stable nucleus. Each decay process has a definite half-life.

decay rate: The ratio of activity to the number of radioactive atoms of a particular species.

decay time: The time required for a quantity to fall to *1/e* times the original value.

detector: A device or series of devices used to measure nuclear particles and radiations.

electromagnetic radiation: Radiation consisting of electric and magnetic fields that travel at the speed of light. Examples: light, radio waves, gamma rays, x-rays.

electron: An elementary particle with a unit electrical charge and a mass 1/1837 that of the proton. Electrons surround an atom's positively charged nucleus and determine that atom's chemical properties.

electron-volt (eV): Energy unit used as the basis of measurement for atomic (eV),

electronic (keV), nuclear (MeV), and subnuclear processes (GeV or TeV). One electron-volt is equal to the amount of energy gained by an electron dropping through a potential difference of one volt, which is 1.6×10^{-19} joules.

gamma ray: A highly penetrating type of nuclear radiation, similar to x-radiation, except that it comes from within the nucleus of an atom, and, in general, has a shorter wavelength.

half-life: The time in which half the (large number of) atoms of a particular radioactive nuclide disintegrate. The half-life is a characteristic property of each radioactive isotope.

ion: An atomic particle that is electrically charged, either negatively or positively.

ionizing radiation: Radiation that is capable of producing ions either directly or indirectly.

isotope: Isotopes of a given element have the same atomic number (same number of protons in their nuclei) but different mass numbers (different number of neutrons in their nuclei). ^{238}U and ^{235}U are isotopes of uranium.

mass number: The total number of protons and neutrons in the nucleus: $A=Z+N$. This is also the total nucleon number of the nucleus.

MeV: One (million) mega electron volts.

neutrino: An electrically neutral particle with negligible mass. It is produced in processes such as beta decay and reactions that involve the weak force.

neutron: One of the basic particles that make up a nucleus. A neutron and a proton have about the same mass, but the neutron has no electrical charge.

nuclear reactor: A device in which a fission chain reaction can be initiated, maintained, and controlled. Its essential components are fissionable fuel, moderator, shielding, control rods, and coolant.

nucleon: A constituent of the nucleus; that is, a proton or a neutron.

nucleus: The core of the atom, where most of its mass and all of its positive charge is concentrated. Except for ^1H, the nucleus consists of a combination of protons and neutrons.

nuclide: Any species of atom that exists for a measurable length of time. Its atomic mass, atomic number, and energy state can distinguish a nuclide.

photon: A packet of electromagnetic energy. Photons have momentum and energy, but no rest mass or electrical charge.

proton: One of the basic particles that makes up an atom. The proton is found in the nucleus and has a positive electrical charge equal to the negative charge of an electron and a mass similar to that of a neutron: a hydrogen nucleus.

proton number: The total number of protons in the nucleus, Z.

QCD: Quantum chromodynamics, the gauge theory describing the color strong interaction.

QED: Quantum electrodynamics, the gauge theory describing electromagnetism.

quark: A strongly interacting fermion that is a building block of hadronic matter. Quarks come in six flavors: up, down, charm, strange, top, and bottom.

radioactive waste: Materials that are radioactive and for which there is no further use.

radioactivity: The spontaneous decay or disintegration of an unstable atomic nucleus accompanied by the emission of radiation.

radioisotope: A radioactive isotope. A common term for a radionuclide.

radionuclide: A radioactive nuclide. An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation.

source: A radioactive material that produces radiation for experimental or industrial use.

stable: Non-radioactive.

tracer: A small amount of radioactive isotope introduced into a system in order to follow the behavior of some component of that system.

Ultraviolet radiation: Electromagnetic radiation having wavelengths between the visible part of the spectrum and x-rays.

x-radiation: Electromagnetic radiation usually produced in transitions of the inner electrons of atoms. The wavelength is between ultraviolet and gamma rays.

x-ray: Electromagnetic radiation with wavelengths between ultraviolet and gamma rays.

x-ray: Electromagnetic radiation with wavelengths between ultraviolet and gamma rays.

PERIODIC TABLE OF ELEMENTS (Simplified Form)

	H 1	He 2

O	I	II	III	IV	V	VI	VII	O
He 2	Li 3	Be 4	B 5	C 6	N 7	O 8	F 9	Ne 10
Ne 10	Na 11	Mg 12	Al 13	Si 14	P 15	S 16	Cl 17	Ar 18

O	I(a)	II(a)	IIIa		IVa	Va	VIa	VIIa	VIII			Ib	IIb	IIIb	IV(b)	V(b)	VI(b)	VII(b)	O
Ar 18	K 19	Ca 20	Sc 21		Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Kr 36	Rb 37	Sr 38	Y 39		Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Xe 54	Cs 55	Ba 56	La 57	*	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Rn 86	Fr 87	Ra 88	Ac 89	**	Th 90	Pa 91	U 92												

* Rare-earth metals	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
** Uranium metals	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	E 99	Fm 100	Mv 101	No 102	Lw 103

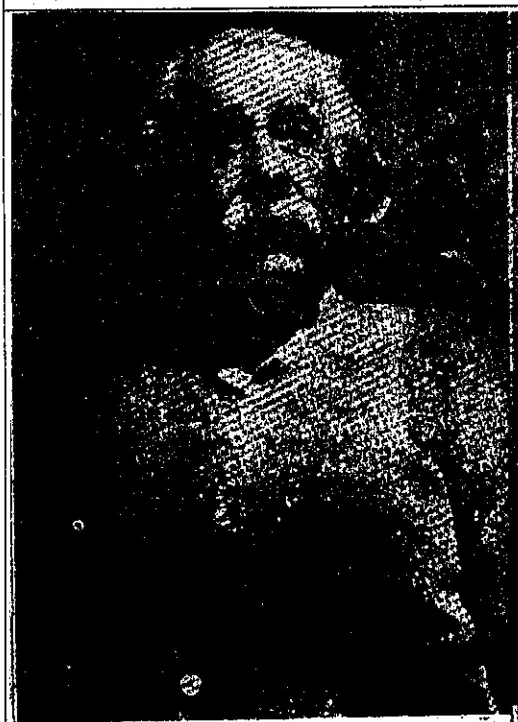
PERIODIC TABLE OF ELEMENTS

Element Name
Atomic No. Symbol
Atomic weight ← Solids & Liquids (g/cm3) Gases (g/l)
Density
M.pt./B.pt.(°C) ← Melting point (Solids & Liquids) • Boiling point (Gases)

1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Hydrogen 1 H 1.0079 0.090 -252.87																		Helium 2 He 4.0026 0.177 -268.93
Lithium 3 Li 6.941 0.54 180.5	Beryllium 4 Be 9.0122 1.85 1287												Boron 5 B 10.811 2.46 2076	Carbon 6 C 12.011 2.27 3900	Nitrogen 7 N 14.007 1.251 -195.79	Oxygen 8 O 15.999 1.429 -182.95	Fluorine 9 F 18.998 1.696 -188.12	Neon 10 Ne 20.180 0.900 -246.08
Sodium 11 Na 22.990 0.97 97.7	Magnesium 12 Mg 24.305 1.74 650												Aluminium 13 Al 26.982 2.70 660.3	Silicon 14 Si 28.086 2.33 1414	Phosphorus 15 P 30.974 1.82 44.2	Sulphur 16 S 32.065 1.96 115.2	Chlorine 17 Cl 35.453 3.214 -34.04	Argon 18 Ar 39.948 1.784 -185.85
Potassium 19 K 39.098 0.86 63.4	Calcium 20 Ca 40.078 1.55 842		Scandium 21 Sc 44.956 2.99 1541	Titanium 22 Ti 47.867 4.51 1668	Vanadium 23 V 50.942 6.11 1910	Chromium 24 Cr 51.996 7.14 1907	Manganese 25 Mn 54.938 7.47 1246	Iron 26 Fe 55.845 7.87 1538	Cobalt 27 Co 58.933 8.90 1495	Nickel 28 Ni 58.693 8.91 1455	Copper 29 Cu 63.546 8.92 1084.6	Zinc 30 Zn 65.39 7.14 419.5	Gallium 31 Ga 69.723 5.90 29.8	Germanium 32 Ge 72.64 5.32 938.3	Arsenic 33 As 74.922 5.73 816.9	Selenium 34 Se 78.96 4.82 221	Bromine 35 Br 79.904 3.12 -7.3	Krypton 36 Kr 83.80 3.733 -153.22
Rubidium 37 Rb 85.468 1.53 39.3	Strontium 38 Sr 87.62 2.63 777		Yttrium 39 Y 88.906 4.47 1526	Zirconium 40 Zr 91.224 6.51 1855	Niobium 41 Nb 92.906 8.57 2477	Molybdenum 42 Mo 95.94 10.28 2623	Technetium 43 Tc [98] 11.5 2157	Ruthenium 44 Ru 101.07 12.37 2334	Rhodium 45 Rh 102.91 12.45 1964	Palladium 46 Pd 106.42 12.02 1554.9	Silver 47 Ag 107.87 10.49 961.8	Cadmium 48 Cd 112.41 8.65 321.1	Indium 49 In 114.82 7.31 156.6	Tin 50 Sn 118.71 7.31 231.9	Antimony 51 Sb 121.76 6.70 630.6	Tellurium 52 Te 127.60 6.24 449.5	Iodine 53 I 126.90 4.94 113.7	Xenon 54 Xe 131.29 5.887 -108.05
Caesium 55 Cs 132.91 1.88 28.4	Barium 56 Ba 137.33 3.51 727	57-70 *	Lutetium 71 Lu 174.97 9.84 1652	Hafnium 72 Hf 178.49 13.31 2233	Tantalum 73 Ta 180.95 16.65 3017	Tungsten 74 W 183.84 19.25 3422	Rhenium 75 Re 186.21 21.02 3186	Osmium 76 Os 190.23 22.61 3033	Iridium 77 Ir 192.22 22.65 2466	Platinum 78 Pt 195.08 21.09 1768.3	Gold 79 Au 196.97 19.30 1064.2	Mercury 80 Hg 200.59 13.55 -38.83	Thallium 81 Tl 204.38 11.85 304	Lead 82 Pb 207.2 11.34 327.5	Bismuth 83 Bi 208.98 9.78 271.3	Polonium 84 Po [209] 9.20 254	Astatine 85 At [210] - 302	Radon 86 Rn [222] 9.73 -61.85
Francium 87 Fr [223] - -	Radium 88 Ra [226] 5.0 700	89-102 **	Lawrencium 103 Lr [262] - 1627	Rutherfordium 104 Rf [262] - -	Dubnium 105 Db [262] - -	Seaborgium 106 Sg [266] - -	Bohrium 107 Bh [264] - -	Hassium 108 Hs [277] - -	Meitnerium 109 Mt [268] - -	Darmstadtium 110 Ds [281] - -	Unununium 111 Uuu [272] - -	Ununbium 112 Uub [285] - -	Ununtrium 113 Uut [284] - -	Ununquadium 114 Uuq [289] - -	Ununpentium 115 Uup [288] - -	Ununhexium 116 Uuh [292] - -		

* Lanthanoids	Lanthanum 57 La 138.91 6.146 920	Cerium 58 Ce 140.12 6.689 795	Praseodymium 59 Pr 140.91 6.64 935	Neodymium 60 Nd 144.24 6.80 1024	Promethium 61 Pm [145] 7.264 1100	Samarium 62 Sm 150.36 7.353 1072	Europium 63 Eu 151.96 5.244 826	Gadolinium 64 Gd 157.25 7.901 1312	Terbium 65 Tb 158.93 8.219 1356	Dysprosium 66 Dy 162.50 8.551 1407	Holmium 67 Ho 164.93 8.795 1461	Erbium 68 Er 167.26 9.066 1497	Thulium 69 Tm 168.93 9.321 1545	Ytterbium 70 Yb 173.04 6.57 824
** Actinoids	Actinium 89 Ac [227] 10.07 1050	Thorium 90 Th 232.04 11.72 1842	Protactinium 91 Pa 231.04 15.37 1568	Uranium 92 U 238.03 19.05 1132	Neptunium 93 Np [237] 20.45 637	Plutonium 94 Pu [244] 19.816 639	Americium 95 Am [243] - 1176	Curium 96 Cm [247] 13.51 1340	Berkelium 97 Bk [247] 14.78 986	Californium 98 Cf [251] 15.1 900	Einsteinium 99 Es [252] - 860	Fermium 100 Fm [257] - 1527	Mendelevium 101 Md [258] - 827	Nobelium 102 No [259] - 827

THE MAN WHO "DISCOVERED" CURVED SPACETIME IN THE UNIVERSE



ALBERT EINSTEIN

Albert Einstein(1879-1955). Diplom(Phys)(1900),PhD(1905,Zurich, Academician(PAC)

Einstein and Planck proposed the law $E=h\nu = \hbar\omega$ in 1900. Einstein explained the Brownian motion as a kind of "atomic agitation" mathematically in his PhD thesis and in a research paper on heat and thermodynamics submitted to *Annalen der Physik* in1901. He obtained his PhD in 1905 four years after his initial submission to the University of Zurich. He was at that time working as an Engineer Class III in the Patent Office he was promoted to Engineer Class II after the award of his doctorate and became Professor in 1909 in Zurich and was working as a Lecturer(Privatdozent) at Bern a year before. Between 1900 and 1905 he developed theories related to the photon as a packet of energy, Brownian motion, photo-electric effect, special relativity (including the famous formula $E = mc^2$ which is of importance in nuclear fission and fusion)and in 1915 he discovered general relativity a theory of curved spacetime applicable to the Universe (the largest physical system).

THE MEN WHO BUILT ATOMIC MODELS

Lord Rutherford and Niels Bohr in Cambridge,1930. Front row left to right Lady Rutherford , Mrs Oliphant and Mrs Bohr.

Ernest Rutherford (1871-1937)MA, DLit, FRS,OM

Professor of Physics at McGill (1898-1907) at Manchester(1907-199) Cavendish Lab (1919-1937)

Father of nuclear physics, famous for Bohr-Rutherford model, splitting the atom with Cockcroft and Walton , experimental researches in radioactive transformations and training nuclear physicists of Nobel Laureate calibre. He won Nobel Prize in chemistry although he had never worked or studied chemistry! He was instrumental in awarding overseas scholars PhD's at Cambridge after two to three years of successful research. The degree was instituted at Cambridge and London in 1920.

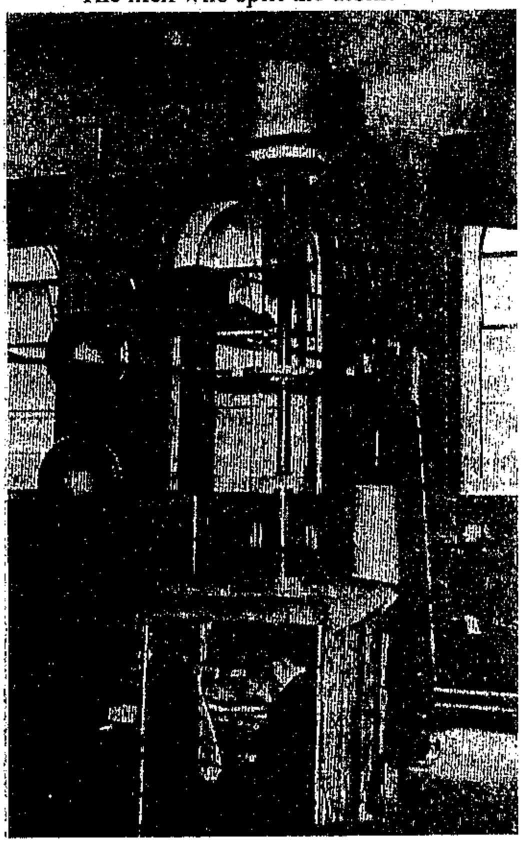
Before that there were much tougher earned senior doctorates DSc, DLit or FRS or FInstP for lifelong devotion to physics research !

Niels Bohr(1885-1962)PhD(1911 , University of Copenhagen) Professor (1916-1962) and Director of Institute of Theoretical Physics(1920-1962) ,Copenhagen

Father of quantum theory and famous for his investigations of the atomic structure of matter and the radiation which emanates from them. Also famous for Bohr-Wheeler model of the nucleus and work on the atomic bomb. Almost all the then famous theoretical physicists including Dirac, Heisenberg, and Pauli spent post doctoral years with Bohr and for the experimental physicists a visit to the Cavendish to do research under Rutherford was "a must" at that time.

THE MEN WHO SPLIT THE ATOM

The men who split the atom!



The Cockcroft-Walton Accelerator

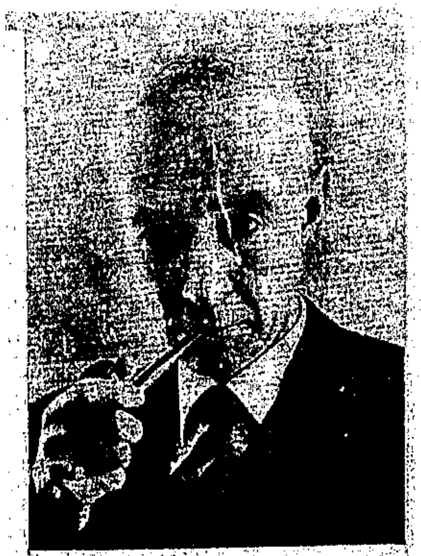
Lord Rutherford, Walton and Cockcroft were Cavenish physicists who split the atom using the Cockcroft – Walton accelerator. Cockcroft and Walton shared the 1951 Nobel Prize for physics on the pioneering work on the transmutation of atomic nuclei by artificially accelerated atomic particles.

Shown below is such an accelerator with Dr Cockcroft doing experiments inside the chamber. In 1919 Rutherford discovered how to change one element into another by bombardment with alpha particles from a radium source. However only a few transmutations could be produced by the natural projectiles, and at first it seemed that the enormous energies required might not be attainable for artificially accelerated atomic particles. But using the laws of modern quantum theory as discovered by Dirac, Heisenberg and Schroedinger if one attributes wave properties to the bombarding particles one finds that they have a minute but finite probability of "tunnelling" through the potential barrier around the nucleus if protons have about 0.3 MeV for a target nucleus like boron.

Using Li as target protons were found to knock off alpha particles from the Li nucleus. The alphas revealed themselves bright scintillations on a ZnS screen.

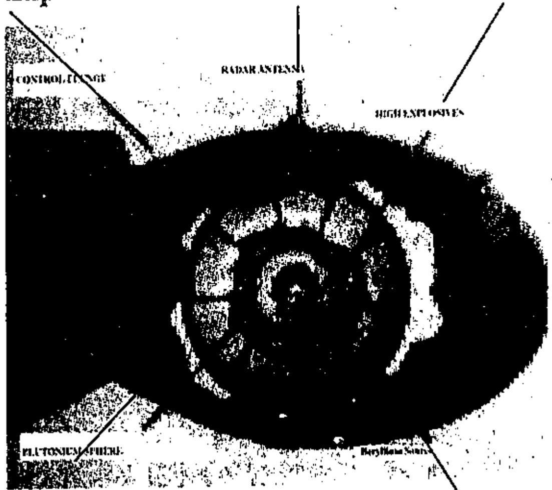
In the accelerator that they built, Cockcroft and Walton arranged a high-voltage transformer, voltage-doubling circuits and rectifying tubes in a four-stage system to apply up to $6x10^5V$ to the evacuated tube down which the protons were accelerated.

THE MAN WHO MADE THE ATOMIC BOMB



J Robert Oppenheimer

Control Flunge   Radar Antenna   High Explosives



Plutoniam Sphere   Beryllium Source

Robert Oppenheimer (1904–1967) a physicist who wrote a PhD thesis on quantum mechanics under Max Born in Germany (1926-1927) was able to make an atom bomb at Los Alamos in which many physicists contributed.

THE MAN WHO BUILT THE NUCLEAR REACTOR

Fermi and Robert Oppenheimer

Fermi and Oppenheimer

Dr Enrico Fermi (1901–1954) was a physicist who was equally at home with quantum theory and experimental nuclear physics. To his credit he was not only able to build the first nuclear reactor but also to construct his own innovations for experimental work like the target holder for a cyclotron.

He was awarded the Nobel Prize for the discovery of the new radioactive elements produced by neutron irradiation, and for the discovery of nuclear reactions induced by slow neutrons. Look for the photo of a nuclear reactor somewhere in the text.

THE MAN WHO DISCOVERED THERMIONIC EMISSION

Sir Owen Willans Richardson

1879–1959

Awarded (in 1929) the 1928 Nobel Prize for physics for his work on thermionic phenomena and especially for discovery of the law which bears his name.

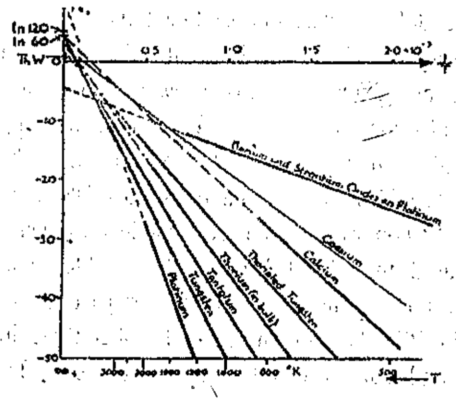
Sir Owen Richardson was awarded the 1928 Nobel Prize for Physics in 1929. Physicists had accepted the concept of the electron before the physical atom. Edison had detected an electric current across the vacuum in a bulb containing a heated filament and a collector.

Richardson's law expresses the dependence of the saturation current emitted per unit area J_s (ampere/m^2)on the temperature T(kelvin) of the filament:

$$J_s = AT^2 \exp(-b/T) \text{ where } A, b=w/k$$

are characteristic constants of emitter, w is electronic work function in joules of the metal and k the Boltzmann constant.

The phenomenon had been used by Fleming to device a rectifier and Lee de Forest to construct a diode. but it was Richardson who worked out the theory of electron and ion emission, and made possible the rapid development of radio, telephony and xray(x-ray) technology. Freely moving electrons in the interior of a hot conductor escape when they reach the surface provided their kinetic energy is great enough to overcome the attraction of the positive charges in the material. Richardson worked on thermionics (a term he coined) for 15 years resulting in the book "The Emission of Electricity from Hot Bodies" in 1910. He was pleased that his basic equation of thermionic emission survived the quantum mechanical revolution of 1920's.



$\uparrow \ln J_s + 2\ln(1/T)$

Richardson's law illustrated

in the form : $\ln J_s + 2\ln(1/T) = \ln A - b(1/T)$

THE MAN WHO INVENTED THE WWW , MEN WHO INVENTED THE TRANSISTOR

Sir Bernard Lees physicist and inventor of World Wide Web;

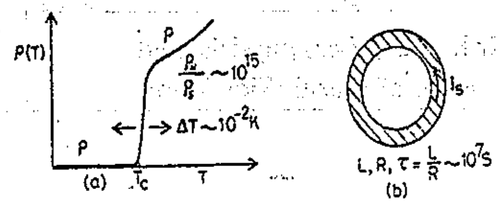
John Bardeen

1908–

It is truism that physicists have a knack of making surprising inventions. The current IT era and following it the Knowledge Age would not have taken place if World Wide Web had not been invented by Sir Bernard Lees a British physicist who had been honoured like Sir Isaac Newton by conferring a knighthood for Science by the British Monarch. It is to be noted that Electronics, Information Technology and Communications form a prominent group in the learned society Institute of Physics , London established in 1879, the same year that the Cavendish Laboratory at Cambridge was established by Sir James Clark Maxwell. The IOP like IEE has the Royal Charter to confer very high qualifications such as CEng (chartered engineer) to scientists and engineers.

Below the critical temp T_C, the superconductor shows (a) no resistivity and a superconducting loop shows persistent current (b) that lasts for 10^7 seconds . See figure on the RHS ↔

Professor John Bardeen obtained his PhD in Physics under Eugine Wigner and had the distinction of being awarded the Nobel Prize *twice* for Physics. He was also for many years Professor of Physics and Electrical Engineering (Electronics) at the University of Illinois Champagne Illinois, USA. He first worked on transistor and semiconductor physics and shared the Nobel Prize with Shockley and Brattain for the discovery of the "transistors" in 1956. In 1972 he won his second Nobel Prize in Physics and shared it with L Cooper and J Schrieffer for the quantum theory of super-conductivity known as BCS theory. Super conductors lose resistivity below a certain critical temperature due to the interaction of the electron and a quantum of lattice vibration known as a phonon. In superconductors two electrons form a "Cooper pair" near a state known as a Fermi level as they are weakly attracted to one another by the exchange of phonons(quantum mechanically) . The pairs have a common momentum which is not affected by random scattering of the individual electrons so the effective resistance is zero.



THE MEN WHO INVENTED THE TRANSISTOR

William Shockley

1910–

Shared the 1956 Nobel Prize for physics with John Bardeen and Walter Brattain for their investigations on semiconductors and their discovery of the transistor effect.

William Shockley earned his PhD from MIT and joined the Bell Telephone Laboratory in 1936 until he retired in 1975 as Excutive Consultant (1962-1975). In the meantime he was also Professor of Engineering and Applied Science at Stanford , President of Shockley Transistor Corporation (1958-60) .

Shared the 1956 Nobel Prize with John Bardeen and Walter Brattain for their investigations on semiconductors and their discovery of the transistor effect.

He considered the portable tape recorder as perhaps his own most important application of the transistor,

Shockley invented the junstion transistor which avoided the troublesome metal contact (of the point contact transistor) by controlling the impurity distributions so as to produce an n-p-n or p-n-p transistors.; rectification and amplification occurring inside the crystal.

Brattain worked as a research physicist at Bell Telephone Lab from 1929 to 1967.
He obtained his PhD in Physics in 1928.
He was awarde with the Nobel Prize together with Schokley and Bardeen in 1956 for semiconductor and transistor physics.
A transistor (transfer resistor) is a semiconductor device that will amplify or process electrical signals. The invention of the transistor announced in July 1948, resulted from research of semiconductors at Bell Lab when Brittain and Becker started

Walter Houser Brattain

1902–

Shared the 1956 Nobel Prize for physics with William Shockley and John Bardeen for their investigations on semiconductors and their discovery of the transistor effect.

to investigate them and found that rectification was a surface property.

His main contribution had been the discovery of the photo electric effect free surface of a semiconductor the invention of the point-contact transistor with Bardeen.

Physicists who discovered radioactivity

Antoine Henri Becquerel
1852–1908

AH Bequerel(1852-1908)

Bequerel obtained his doctorate in optical properties of crystals but made a discovery that crystals of potassium uranyl sulphate made a record on a photographic plate wrapped in black paper although both crystals and plate were in total darkness. He thus discovered spontaneous radioactivity.

P Curie (1859-1906), M Curie(1867-1934)

P Curie obtained his doctorate on magnetic properties of crystals There is a law named after him and also Curie point is well known in magnetism and with his wife M Curie, he isolated and discovered radium and induced radioactivity in the action of polonium or radium on inert substances. M Curie did her PhD in the field of radioactivity (emission of radiation from uranium) under P Curie .

Becquerel and the Curies were awarded the Nobel Prize for physics in 1903 for their work in radioactivity.

Marie Curie was awarded again with the 1911 Nobel Prize for chemistry after the death of her husband for discovering polonium and radium.

Pierre Curie

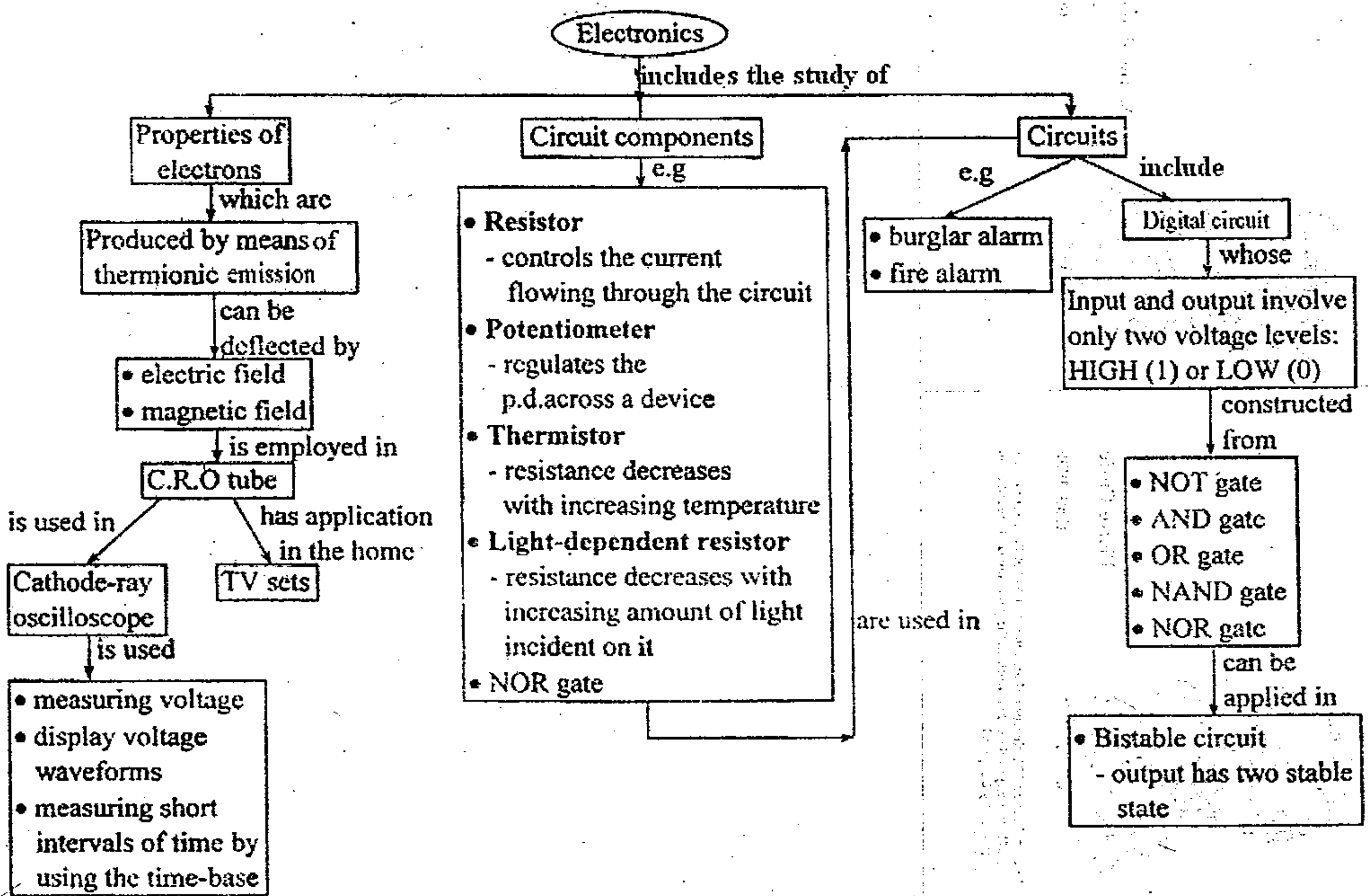
1859–1906

Pierre Curie and Marie Curie shared the 1903 Nobel Prize for physics with Henri Becquerel for their work on the phenomena of the radiation discovered by Becquerel.

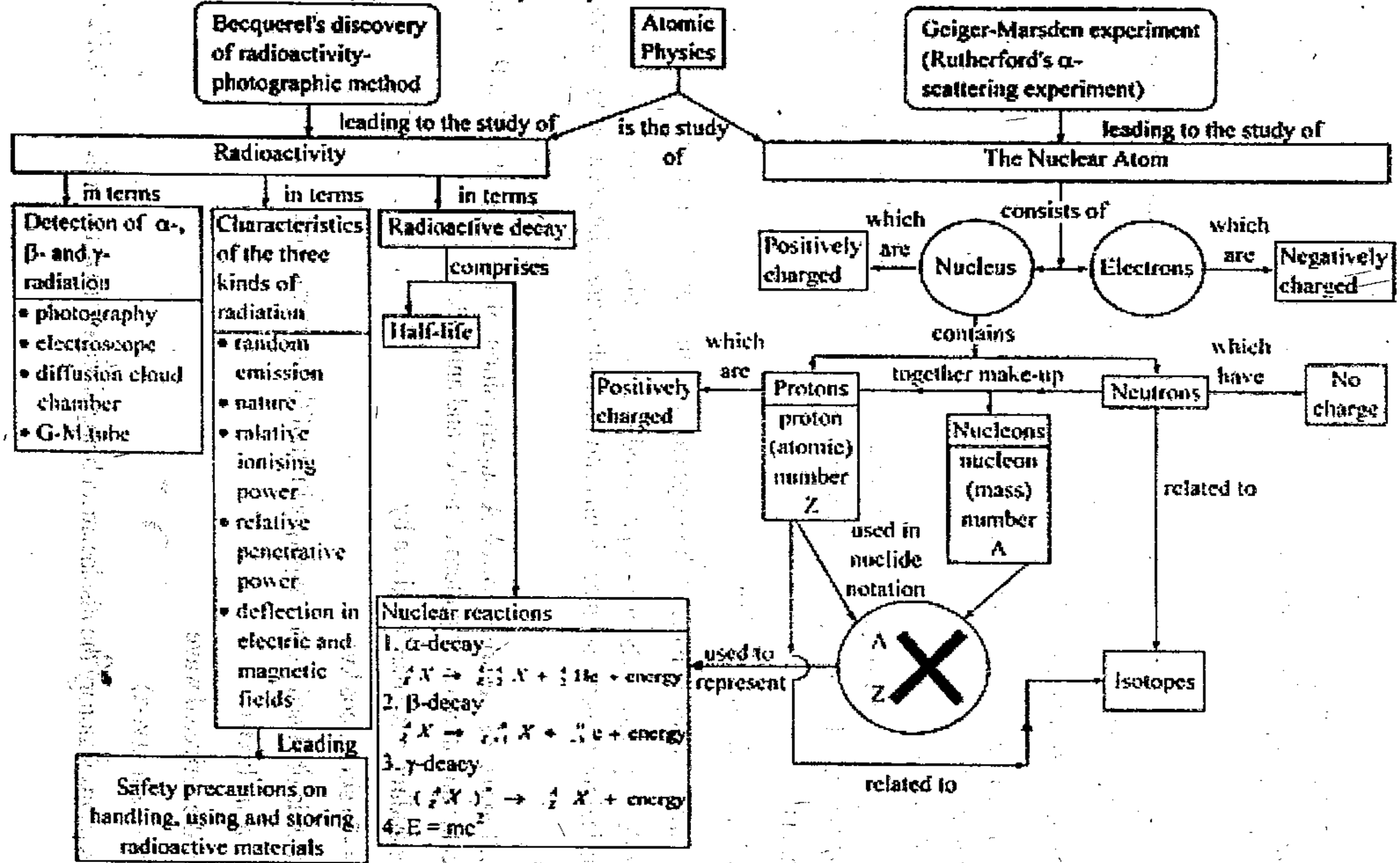
Marie Sklodowska Curie

1867–1934

Concept Map (Electronics)



Concept Map(Atomic Physics)



Addendum and Erratum

Chapter 4, p[54]

Progressive waves Sound waves which travel in air when we speak and water waves which travel on the water surface when a stone is dropped are called progressive waves.

Or

Progressive waves Waves propagating through an infinite [(1)] homogeneous[(2)] medium **Progressive waves** may be represented by a since wave.

y=a sin k(vt-x)=a sin π/λ (vt-x)

where a is the displacemrnt at distance x from a fixed point along the direction of motion v is the wave velocity, λ the wavelength and t is the time measured from a fixed instant.

For a given value of x, the displacement y changes through a complete cycle when $2\pi/\lambda$(vt-x) changes by 2π radians the corresponding change in t is T, the period. That is

$vT\,2\pi/\lambda = 2\pi$ or $T = \lambda/v$

(1)infinite=without limit;(2) homogeneous=of the same kind or nature, uniform

Stationary waves The waves produced in hollow tubes such as flutes and in stringed musical instruments such as violins and mandolins are called stationary waves.

Or

Stationary or standing wave A superposition of an incident and reflected waves creates an interference pattern of nodes and antinodes.

A standing wave may be given by

y = -2a sin kx cos kvt

which is obtained from a superposition of the incident wave

y_1 = a sin k(vt-x)

and the reflected wave

y_2 = - a sin k(vt-x)

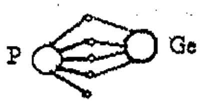
It remains staionary the displacement being always zero at the nodes (x = 0, $\lambda/2$, λ, $3/2\lambda$

etc) and vibrating with amplitude 2a at the antinodes (x $=\lambda/4, 3/4\lambda, 5/4\lambda$ etc). See Fig(4.3).

Addendum to Chapter 13 p246 Fig 13.9 n-type and p-type semiconductors

N-Type Semiconductor: When a donor impurity like P(valency 5) is inserted into Ge(valency 4) crystal lattice the donor dopant becomes a cation (positive ion), located close to the edge of the conduction band, donating an electron to the **conduction band**. For every donor atom introduced into Ge crystal, an electron is created in the conduction band. Many such electrons so created will constitute a majority electron current which flows in the conduction band, under the influence of an apploed electric field. An important energy level called the Fermi-level is respresented by a line close to bottom of the impurity energy levels slightly more than half way up the band gap. Energy band means a **band of energy levels lumped together for electrons or holes inside a crystal.**

P-Type Semiconductor: When an acceptor impurity like Al (valency 3) is inserted into Ge (valency 4) crystal lattice the acceptor becomes an anion (negative ion), located closed to the edge of the valence band, after accepting an electron from the Ge atom of the host germanium crystal. This introduces a hole in the valence band. For every acceptor atom introduced into the Ge crystal, a positive hole is created in the valence band. Many such holes so created will constitute a majority hole current which flows in the valence band., under the influence of an applied electric field. An important energy level called the Fermi-level is represented by a line close to the top of impurity energy levels slightly more than half way down the band gap.



dangling bond

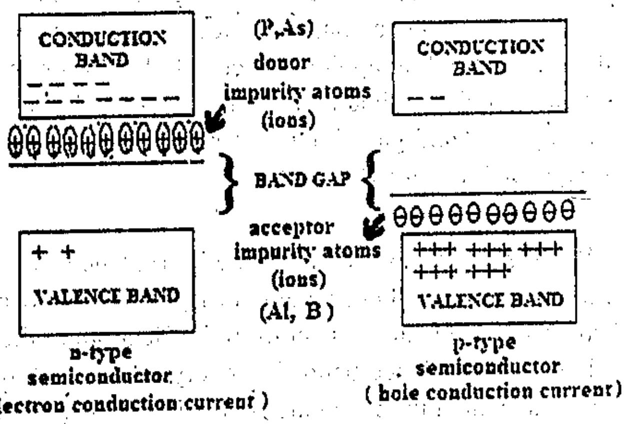
[loose electron]

Phosphorous anion is formed after donating an electron to the conduction band

dangling bond

[loose electron]

Al cation is formed after accepting an electron from germanium crystal producing a + hole in the valence band

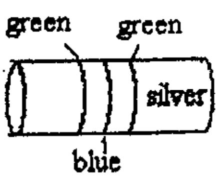


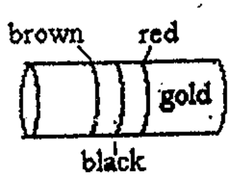
Addendum to Chapter 11

Resistors and Colour Codes

18 What are the resistance values of the given resistrs?

(i)Resistance=56 x $10^5 \pm 10\% \Omega$, (ii) Resistance = 10 x $10^2 \pm 5\% \Omega$





Colour codes for resistors

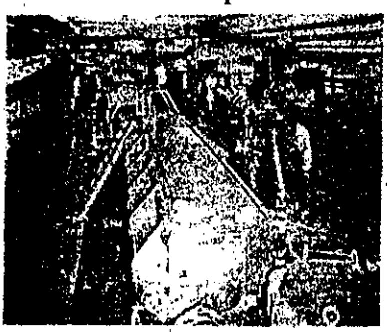
R=AB x $10^C \pm$ D%

A,B,C										D		
black	brown	red	Orange	yellow	green	blue	purple	gray	white	Gold	Ag	white
0	1	2	3	4	5	6	7	8	9	5%	10%	20%

Elements of quantum theory may be found (Bohr atomic theory, wave particle duality of deBroglie, xray diffraction of Bragg and laue, electron diffraction of G P Thomson, Davisson & Germer, Planck-Einstein relation) in the following sections of this text.

- Section on interference experiments of waves, bullets and electrons of Chapter 6 where some differentiation is pointed out between intensity and probability
- See also Chapter 3 Section 3.3 on heat transfer by radiation for a treatment of Stephan-Boltzmann's law, Brownian motion of Einstein
- Section 5.1 The nature of light. Wave particle duality light as corpuscles or particles of light or energy packets or quantum of light or photons (modern terminology)
- Chapter 13 particularly the illustration of band diagrams of n-type and p-type semiconductors figures 13.8 and 13.9, explanation of characteristic xrays and continuous spectrum based on Bohr's theory figures 13.32 and 13.33
- Bohr's atomic model and energy level diagram of hydrogen atom and explanation of $E=\omega\hbar$ (planck-Einstein relation) and p= $k\hbar$ (deBroglie relation) and $\omega = 2\pi/T$ and $k= 2\pi/\lambda$ paticularly figures 13.38 to 13.42.

Addendum to Chapter 13



Injection from the linear accelerator into BeVproton-synchrotron at CERN(The European Organization for Nuclear Research, Geneva, Switzerland). The beam enters from the right, is deflected into the circle of the main accelerator and then completes the 650 meter circumference to rejoin the point of injection. Crossing through the wall separating the linear accelerator from the synchrotron is the ejection line towards the Intersecting Storage Rings started serveral hundred meters to the right.

ANSWERS TO ODD-NUMBERED PROBLEMS

Chapter 1

11. (a) 20
    (b) 80 %
13. (i) 43 cm
    (ii) 30 cm
    (iii) 1.65 N
15. 213.3 W
17. (a) 2000 J
    (b) 333.33 W

Chapter 2

19. 930 N
21. $\frac{1}{10}$
23. (a) 0.4 N
    (b) 0.004 N

Chapter 3

15. 141.21 kJ
17. 1569 J
19. 0.1635 m
21 521.35 K

Chapter 4

3. 0.8 m
   84 ms^{-1}
7. 200 Hz
9. 37.8 Hz
   18.9 Hz
11. 341.4 ms^{-1}

Chapter 5

19. 0.45 μm
21. (a) 70°
    (b) 41°
    (c) 1.432
    (d) 44° 17′
    (e) The ray will not emerge, it will be reflected internally.
23. 27° 55′
25. (a) 1.521
    (b) 52° 12′

Chapter 6

7. (a) 6 cm
   (b) 10 cm
9. 6.67 cm
11. It is not possible to obtain a sharp image larger than the size of the object
13. 0.75 cm (towards the lens)

Chapter 7

3. 12.5 μC
5. 0.082×10^{-6} N
7. 2700 N (toward -1×10^{-4} C)
9. 5.032 m
11. (a) 180 N
    (b) 22.5 N
13. 6.25×10^{10}
23. 36×10^{3} NC^{-1} (toward 4×10^{-6} C)
25. 5.69×10^{-4} NC^{-1} (Opposite to the direction of motion of electron.)
27. 2m
29. (a) 1.325×10^{-13} NC^{-1} (away from the nucleus)
    (b) 2.12×10^{-6} N (toward the nucleus)

Chapter 8

13. (a) 3 m
    (b) 0.1 μC
15. 7.2×10^{-3} NC^{-1} (toward the negative charge)
    - 10.8 mV
17. 1218 V
19. 2.5 kV

Chapter 9

11. (a) 4.425×10^{-11} F
(b) 1.99×10^{-9} C
(c) 4.48×10^{-8} J

13. (a) 447.2 V
(b) 6

17. (a) 3.33 μF, 30 μF
15μF, 6.67 μF

19. 5

21. 2×10^{-4} C, 66.7 V, 20 V
13.3 V

23. 4.25 μF

Chapter 10

3. (a) 1200 C
(b) 75×10^{20}

5. 8 times greater

9. (a) 0.516 Ω
(b) 0.032 Ω

11. 5×10^{-3} °C^{-1}

13. (a) All in series
Two 5 Ω are in parallel and that combination is in series with 10 Ω
(b) 3 Ω
1.5 Ω
0.33 Ω
0.67 Ω
(c) Resistor of less resistance

15. 4

17. (a) 4 A
(b) 5 A

19. 3.75 Ω

23. Resistor R_3 must be increased.
I_3 is decreased when R_3 is increased. Therefore I_2 is increased

25. Reading of A_1 = 4 A, A_5= 6A

27. V_1 = 12 V
A_2 = 1 A
R_1 = 12 Ω
R_2 = 1.5 Ω

Chapter 11

5. 10.29 kcal

7. (a) 48 Ω
(b) 5 A
(c) 285.7 cal
(d) 833.3 W

9. 2.74 cal s^{-1} (by 2 Ω resistor)
1.83 cal s^{-1} (by 3 Ω resistor)
0.91 cal s^{-1} (by 6 Ω resistor)

11. 4.29 cal s^{-1}

13. 1150 W

15 16 lamps

Chapter 12

17. (a) 0.1 Ω
(b) 7.475 kΩ

19. 460 kΩ

APPENDIX

Common SI base unit and derived units

Quantity	Base Units	Symbols
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic	kelvin	K
luminous intensity	candela	cd
substance	mole	mol

Quantity	Drived Units (Selected)	Formula
acceleration	metre per second squared	ms^{-2}
area	square metre	m^2
density	kilogram per cubic metre	kgm^{-3}
electric capacitance	farad (F)	$As\ V^{-1}$
electric charge (quantity of electricity)	Coulomb (C)	As
energy	joule	Nm
force	newton (N)	$kg\ ms^{-2}$
frequency	hertz (Hz)	cycle s^{-1}
magnetic flux density	tesla (T)	$Wb\ m^{-2}$
power	watt (W)	$J\ s^{-1}$
pressure	pascal (Pa)	Nm^{-2}

thermal conductivity	watt per metre per kelvin	$W\ m^{-1}\ K^{-1}$
velocity	metre per second	ms^{-1}
work	joule (J)	N m

SI unit prefixes, symbols and power of ten multiple and submultiple values

Prefix	Symbol	Value as Power of Ten	Multiplication Factor
deka	da	10	10
hecto	h	10^2	100
kilo	k	10^3	1 000
mega	M	10^6	1 000 000
giga	G	10^9	1 000 000 000
tera	T	10^{12}	1 000 000 000 000

Prefix	Symbol	Value as Power of Ten	Multiplication Factor
deci	d	10^{-1}	0.1
centi	c	10^{-2}	0.01
milli	m	10^{-3}	0.001
micro	µ	10^{-6}	0.000 001
nano	n	10^{-9}	0. 000 000 001
pico	p	10^{-12}	0. 000 000 000 001
femto	f	10^{-15}	0. 000 000 000 000 001
atto	a	10^{-18}	0. 000 000 000 000 000 001

Greek Alphabets

α	alpha	λ	lambda
β	beta	μ	mu
γ	gamma	ρ	rho
δ	delta	σ	sigma
ε	epsilon	τ	tau
η	eta	φ	phi
θ	theta	Ω	omega
κ	kappa		

Appendix

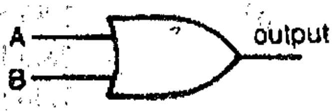
Solutions from chapter 13 no. 13

AND gate

A	B	Output
0	0	0
0	1	0
1	0	0
1	1	1

NAND gate

A	B	Output
0	0	1
0	1	1
1	0	1
1	1	0

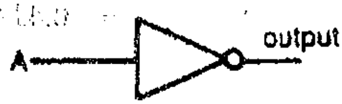


OR gate

A	B	Output
0	0	0
0	1	1
1	0	1
1	1	1

NOR gate

A	B	Output
0	0	1
0	1	0
1	0	0
1	1	0



NOT gate

A	Output
0	1
1	0

CONVERSION FACTORS

Length

1 metre(m) = 39.4 in
= 3.28 ft

1 centimetre(cm) = 0.394 in

1 kilometre(km) = 0.621 in

1 foot(ft) = 0.305 m

1 inch(in) = 0.0833 ft
= 2.54 cm

1 mile(mi) = 1.61 km

Area

1 m^2 = 10^4 cm^2
= 1.55 10^3 in^2
= 10.76 ft^2

1 cm^2 = 10^{-4} m^2
= 0.155 in^2

1 ft^2 = 9.29 x 10^{-2} m^2
= 929 cm^2

Volume

1 m^3 = 10^6 cm^3
= 35.3 ft^2
= 6.10 x 10^4 in^3

1 Imperial gal = 1.2 US gal

1 ft^3 = 2.83 x 10^{-2} m^3
= 28.3 litres
= 7.48 gal

1 US gal = 0.134 ft^3
= 3.79 x 10^{-3} m^3

Mass

1 kilogram(kg) = 0.0685 slug

1 slug(sl) = 14.57 kg

1 lb mass = 454 g
= 0.454 kg

Velocity

1 m s^{-1} = 3.28 ft s^{-1}
= 3.60 km h^{-1} +
= 2.24 mi h^{-1}

1 km h^{-1} = 0.278 m s^{-1}
= 0.913 ft s^{-1}

1 ft s^{-1} = 0.305 m s^{-1}
= 0.682 mi h^{-1}
= 1.10 km h^{-1}

1 mi h^{-1} = 1.47 ft s^{-1}
= 0.447 m s^{-1}

	=	$0.621\ mi\ h^{-1}$		=	$1.61\ km\ h^{-1}$
			$60\ mi\ h^{-1}$	=	$88\ ft\ s^{-1}$

Force

1 newton(N)	=	0.225 lb	1 lb	=	4.45 N
	=	3.60 oz	1 inch(in)	=	4.45×10^5 dynes
	=	10^5 dynes			

Pressure

1 pascal(Pa)	=	$1\ N\ m^{-2}$	$1\ lb\ in^{-2}$	=	6.90×10^3 Pa
	=	$1.45 \times 10^{-4}\ lb\ in^{-2}$			
1 atm	=	$1.013 \times 10^5\ N\ m^{-2}$			
	=	$14.7\ lb\ in^{-2}$			

Energy

1 joule(J)	=	0.738 ft-lb	1 ft-lb	=	1.36 J
	=	2.39×10^{-4} kcal		=	1.29×10^{-3} Btu
	=	6.24×10^{18} eV		=	3.25×10^{-4} kcal
1 kilocalorie(kcl)	=	4184 J	1 Btu	=	778 ft-lb
	=	3.97 Btu		=	0.252 kcal
	=	3077 ft-lb			
1 electron volt (eV)	=	1.60×10^{-19} J			

Power

1 watt(W)	=	$1\ J\ s^{-1}$		=	$0.738\ ft\text{-}lb\ s^{-1}$
1 kilowatt(kW)	=	1.34 hp			
1 horse power(hp)	=	746 W		=	$550\ ft\text{-}lb\ s^{-1}$

Temperature

$$T_K = T_C + 273$$
$$T_C = 5/9\ (T_F - 32)$$
$$T_F = 9/5\ T_C + 32$$

Time

1 day	=	1.44×10^3 min	=	8.64×10^4 s		
1 year	=	8.76×10^3 h	=	5.26×10^6 min	=	3.15×10^7 s

Angle

1 radian(rad)	=	$57^\circ 18' = 57.30^\circ$
1°	=	0.01745 rad
1 rad s^{-1}	=	9.55 rev min^{-1}
1 rev min^{-1} (rpm)	=	0.1047 rad s^{-1}