Solution:

We have been given
$u = 0$; $v = 72$ km h^{-1} = 20 m s^{-1} and
$t = 5$ minutes = 300 s.

(i) From Eq. (8.5) we know that

$$a = \frac{(v - u)}{t}$$

$$= \frac{20\ \text{m s}^{-1} - 0\ \text{m s}^{-1}}{300\ \text{s}}$$

$$= \frac{1}{15}\ \text{m s}^{-2}$$

(ii) From Eq. (8.7) we have
$2\,a\,s = v^2 - u^2 = v^2 - 0$
Thus,

$$s = \frac{v^2}{2a}$$

$$= \frac{(20\ \text{m s}^{-1})^2}{2 \times (1/15)\ \text{m s}^{-2}}$$

$= 3000$ m
$= 3$ km

The acceleration of the train is $\frac{1}{15}$ m s^{-2} and the distance travelled is 3 km.

Example 8.6 A car accelerates uniformly from 18 km h^{-1} to 36 km h^{-1} in 5 s. Calculate (i) the acceleration and (ii) the distance covered by the car in that time.

Solution:

We are given that
u = 18 km h^{-1} = 5 m s^{-1}
v = 36 km h^{-1} = 10 m s^{-1} and
t = 5 s .

(i) From Eq. (8.5) we have

$$a = \frac{v - u}{t}$$

$$= \frac{10\ \text{m s}^{-1} - 5\ \text{m s}^{-1}}{5\ \text{s}}$$

$= 1$ m s^{-2}

(ii) From Eq. (8.6) we have

$$s = u\,t + \frac{1}{2} a\,t^2$$

$$= 5\ \text{m s}^{-1} \times 5\ \text{s} + \frac{1}{2} \times 1\ \text{m s}^{-2} \times (5\ \text{s})^2$$

$= 25$ m + 12.5 m

$= 37.5$ m

The acceleration of the car is 1 m s^{-2} and the distance covered is 37.5 m.

Example 8.7 The brakes applied to a car produce an acceleration of 6 m s^{-2} in the opposite direction to the motion. If the car takes 2 s to stop after the application of brakes, calculate the distance it travels during this time.

Solution:

We have been given
$a = -6$ m s^{-2} ; $t = 2$ s and $v = 0$ m s^{-1}.
From Eq. (8.5) we know that
$v = u + at$
$0 = u + (-6\ \text{m s}^{-2}) \times 2$ s
or $u = 12$ m s^{-1} .
From Eq. (8.6) we get

$$s = u\,t + \frac{1}{2}\,a\,t^2$$

$$= (12\ \text{m s}^{-1}) \times (2\ \text{s}) + \frac{1}{2}\,(-6\ \text{m s}^{-2})\,(2\ \text{s})^2$$

$= 24$ m – 12 m
$= 12$ m

Thus, the car will move 12 m before it stops after the application of brakes. Can you now appreciate why drivers are cautioned to maintain some distance between vehicles while travelling on the road?

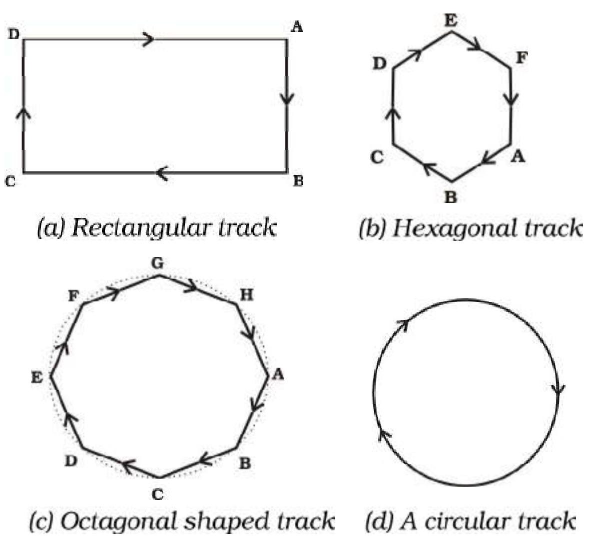
Questions

1. *A bus starting from rest moves with a uniform acceleration of 0.1 m s^{-2} for 2 minutes. Find (a) the speed acquired, (b) the distance travelled.*

2. *A train is travelling at a speed of 90 km h^{-1}. Brakes are applied so as to produce a uniform acceleration of – 0.5 m s^{-2}. Find how far the train will go before it is brought to rest.*
3. *A trolley, while going down an inclined plane, has an acceleration of 2 cm s^{-2}. What will be its velocity 3 s after the start?*
4. *A racing car has a uniform acceleration of 4 m s^{-2}. What distance will it cover in 10 s after start?*
5. *A stone is thrown in a vertically upward direction with a velocity of 5 m s^{-1}. If the acceleration of the stone during its motion is 10 m s^{-2} in the downward direction, what will be the height attained by the stone and how much time will it take to reach there?*

8.6 Uniform Circular Motion

When the velocity of an object changes, we say that the object is accelerating. The change in the velocity could be due to change in its magnitude or the direction of the motion or both. Can you think of an example when an object does not change its magnitude of velocity but only its direction of motion?



(a) Rectangular track *(b) Hexagonal track*

(c) Octagonal shaped track *(d) A circular track*

Fig. 8.9: *The motion of an athlete along closed tracks of different shapes.*

Let us consider an example of the motion of a body along a closed path. Fig 8.9 (a) shows the path of an athlete along a rectangular track ABCD. Let us assume that the athlete runs at a uniform speed on the straight parts AB, BC, CD and DA of the track. In order to keep himself on track, he quickly changes his speed at the corners. How many times will the athlete have to change his direction of motion, while he completes one round? It is clear that to move in a rectangular track once, he has to change his direction of motion four times.

Now, suppose instead of a rectangular track, the athlete is running along a hexagonal shaped path ABCDEF, as shown in Fig. 8.9(b). In this situation, the athlete will have to change his direction six times while he completes one round. What if the track was not a hexagon but a regular octagon, with eight equal sides as shown by ABCDEFGH in Fig. 8.9(c)? It is observed that as the number of sides of the track increases the athelete has to take turns more and more often. What would happen to the shape of the track as we go on increasing the number of sides indefinitely? If you do this you will notice that the shape of the track approaches the shape of a circle and the length of each of the sides will decrease to a point. If the athlete moves with a velocity of constant magnitude along the circular path, the only change in his velocity is due to the change in the direction of motion. The motion of the athlete moving along a circular path is, therefore, an example of an accelerated motion.

We know that the circumference of a circle of radius r is given by $2\pi r$. If the athlete takes t seconds to go once around the circular path of radius r, the speed v is given by

$$v = \frac{2\pi r}{t} \qquad (8.13)$$

When an object moves in a circular path with uniform speed, its motion is called uniform circular motion.

Activity 8.11

- Take a piece of thread and tie a small piece of stone at one of its ends. Move the stone to describe a circular path with constant speed by holding the thread at the other end, as shown in Fig. 8.10.

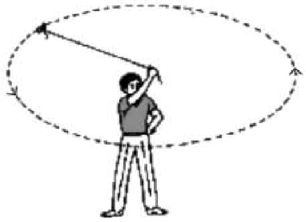


Fig. 8.10: *A stone describing a circular path with a velocity of constant magnitude.*

- Now, let the stone go by releasing the thread.
- Can you tell the direction in which the stone moves after it is released?
- By repeating the activity for a few times and releasing the stone at different positions of the circular path, check whether the direction in which the stone moves remains the same or not.

If you carefully note, on being released the stone moves along a straight line tangential to the circular path. This is because once the stone is released, it continues to move along the direction it has been moving at that instant. This shows that the direction of motion changed at every point when the stone was moving along the circular path.

When an athlete throws a hammer or a discus in a sports meet, he/she holds the hammer or the discus in his/her hand and gives it a circular motion by rotating his/her own body. Once released in the desired direction, the hammer or discus moves in the direction in which it was moving at the time it was released, just like the piece of stone in the activity described above. There are many more familiar examples of objects moving under uniform circular motion, such as the motion of the moon and the earth, a satellite in a circular orbit around the earth, a cyclist on a circular track at constant speed and so on.

What you have learnt

- Motion is a change of position; it can be described in terms of the distance moved or the displacement.
- The motion of an object could be uniform or non-uniform depending on whether its velocity is constant or changing.
- The speed of an object is the distance covered per unit time, and velocity is the displacement per unit time.
- The acceleration of an object is the change in velocity per unit time.
- Uniform and non-uniform motions of objects can be shown through graphs.
- The motion of an object moving at uniform acceleration can be described with the help of the following equations, namely

$$v = u + at$$
$$s = ut + \frac{1}{2} at^2$$
$$2as = v^2 - u^2$$

where u is initial velocity of the object, which moves with uniform acceleration a for time t, v is its final velocity and s is the distance it travelled in time t.

- If an object moves in a circular path with uniform speed, its motion is called uniform circular motion.

Exercises

1. An athlete completes one round of a circular track of diameter 200 m in 40 s. What will be the distance covered and the displacement at the end of 2 minutes 20 s?
2. Joseph jogs from one end A to the other end B of a straight 300 m road in 2 minutes 30 seconds and then turns around and jogs 100 m back to point C in another 1 minute. What are Joseph's average speeds and velocities in jogging (a) from A to B and (b) from A to C?
3. Abdul, while driving to school, computes the average speed for his trip to be 20 km h^{-1}. On his return trip along the same route, there is less traffic and the average speed is 30 km h^{-1}. What is the average speed for Abdul's trip?
4. A motorboat starting from rest on a lake accelerates in a straight line at a constant rate of 3.0 m s^{-2} for 8.0 s. How far does the boat travel during this time?
5. A driver of a car travelling at 52 km h^{-1} applies the brakes and accelerates uniformly in the opposite direction. The car stops in 5 s. Another driver going at 3 km h^{-1} in another car applies his brakes slowly and stops in 10 s. On the same graph paper, plot the speed versus time graphs for the two cars. Which of the two cars travelled farther after the brakes were applied?
6. Fig 8.11 shows the distance-time graph of three objects A,B and C. Study the graph and answer the following questions:

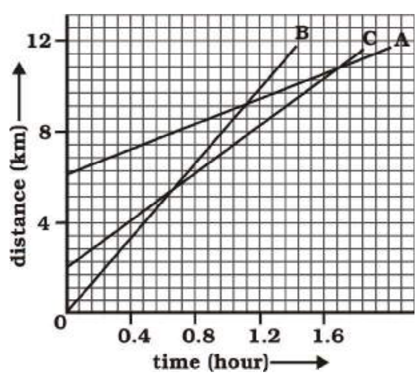


Fig. 8.11

(a) Which of the three is travelling the fastest?

(b) Are all three ever at the same point on the road?

(c) How far has C travelled when B passes A?

(d) How far has B travelled by the time it passes C?

7. A ball is gently dropped from a height of 20 m. If its velocity increases uniformly at the rate of 10 m s^{-2}, with what velocity will it strike the ground? After what time will it strike the ground?

8. The speed-time graph for a car is shown is Fig. 8.12.

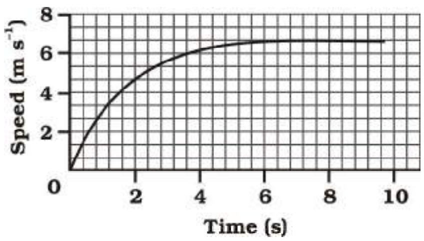


Fig. 8.12

(a) Find how far does the car travel in the first 4 seconds. Shade the area on the graph that represents the distance travelled by the car during the period.

(b) Which part of the graph represents uniform motion of the car?

9. State which of the following situations are possible and give an example for each of these:

(a) an object with a constant acceleration but with zero velocity

(b) an object moving with an acceleration but with uniform speed.

(c) an object moving in a certain direction with an acceleration in the perpendicular direction.

10. An artificial satellite is moving in a circular orbit of radius 42250 km. Calculate its speed if it takes 24 hours to revolve around the earth.

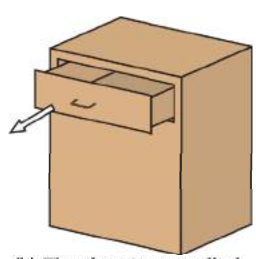
Chapter 9

Force and Laws of Motion

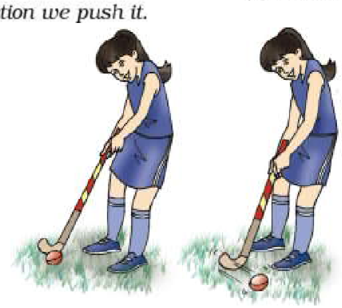
In the previous chapter, we described the motion of an object along a straight line in terms of its position, velocity and acceleration. We saw that such a motion can be uniform or non-uniform. We have not yet discovered what causes the motion. Why does the speed of an object change with time? Do all motions require a cause? If so, what is the nature of this cause? In this chapter we shall make an attempt to quench all such curiosities.

For many centuries, the problem of motion and its causes had puzzled scientists and philosophers. A ball on the ground, when given a small hit, does not move forever. Such observations suggest that rest is the "natural state" of an object. This remained the belief until Galileo Galilei and Isaac Newton developed an entirely different approach to understand motion.

(a) The trolley moves along the direction we push it.



(b) The drawer is pulled.

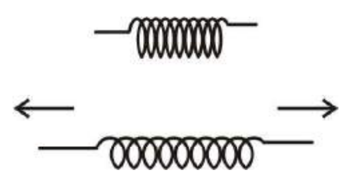


(c) The hockey stick hits the ball forward

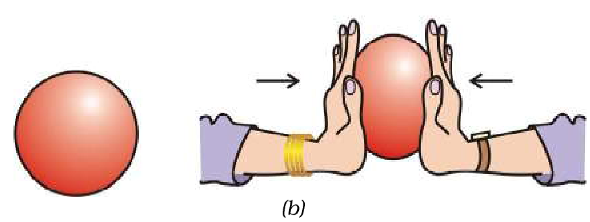
Fig. 9.1: *Pushing, pulling, or hitting objects change their state of motion.*

In our everyday life we observe that some effort is required to put a stationary object into motion or to stop a moving object. We ordinarily experience this as a muscular effort and say that we must push or hit or pull on an object to change its state of motion. The concept of force is based on this push, hit or pull. Let us now ponder about a 'force'. What is it? In fact, no one has seen, tasted or felt a force. However, we always see or feel the effect of a force. It can only be explained by describing what happens when a force is applied to an object. Pushing, hitting and pulling of objects are all ways of bringing objects in motion (Fig. 9.1). They move because we make a force act on them.

From your studies in earlier classes, you are also familiar with the fact that a force can be used to change the magnitude of velocity of an object (that is, to make the object move faster or slower) or to change its direction of motion. We also know that a force can change the shape and size of objects (Fig. 9.2).



(a)



(b)

Fig. 9.2: (a) *A spring expands on application of force;* *(b) A spherical rubber ball becomes oblong as we apply force on it.*

9.1 Balanced and Unbalanced Forces

Fig. 9.3 shows a wooden block on a horizontal table. Two strings X and Y are tied to the two opposite faces of the block as shown. If we apply a force by pulling the string X, the block begins to move to the right. Similarly, if we pull the string Y, the block moves to the left. But, if the block is pulled from both the sides with equal forces, the block will not move. Such forces are called balanced forces and do not change the state of rest or of motion of an object. Now, let us consider a situation in which two opposite forces of different magnitudes pull the block. In this case, the block would begin to move in the direction of the greater force. Thus, the two forces are not balanced and the unbalanced force acts in the direction the block moves. This suggests that an unbalanced force acting on an object brings it in motion.

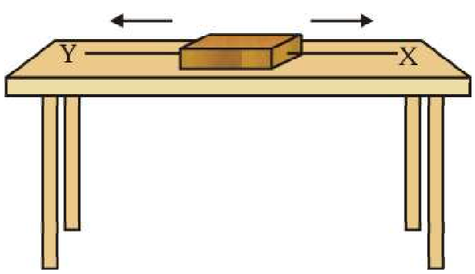


Fig. 9.3: *Two forces acting on a wooden block*

What happens when some children try to push a box on a rough floor? If they push the box with a small force, the box does not move because of friction acting in a direction opposite to the push [Fig. 9.4(a)]. This friction force arises between two surfaces in contact; in this case, between the bottom of the box and floor's rough surface. It balances the pushing force and therefore the box does not move. In Fig. 9.4(b), the children push the box harder but the box still does not move. This is because the friction force still balances the pushing force. If the children push the box harder still, the pushing force becomes bigger than the friction force [Fig. 9.4(c)]. There is an unbalanced force. So the box starts moving.

What happens when we ride a bicycle? When we stop pedalling, the bicycle begins to slow down. This is again because of the friction forces acting opposite to the direction of motion. In order to keep the bicycle moving, we have to start pedalling again. It thus appears that an object maintains its motion under the continuous application of an unbalanced force. However, it is quite incorrect. An object moves with a uniform velocity when the forces (pushing force and frictional force) acting on the object are balanced and there is no net external force on it. If an unbalanced force is applied on the object, there will be a change either in its speed or in the direction of its motion. Thus, to accelerate the motion of an object, an unbalanced force is required. And the change in its speed (or in the direction of motion) would continue as long as this unbalanced force is applied. However, if this force is

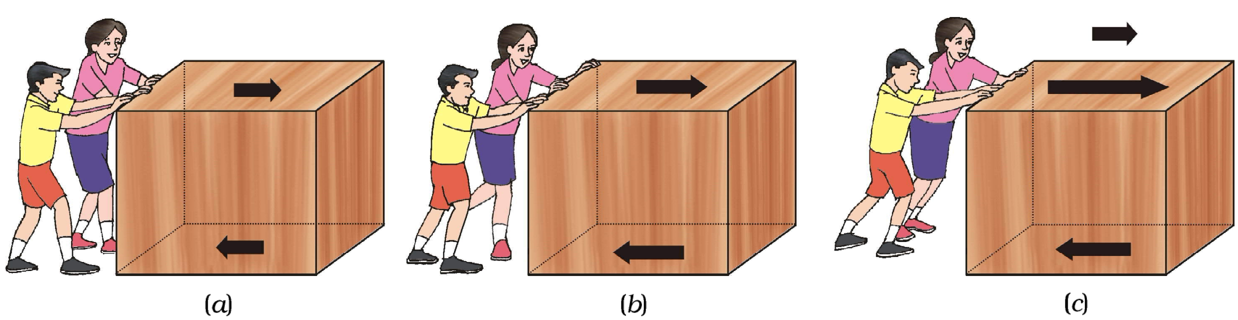


Fig. 9.4

removed completely, the object would continue to move with the velocity it has acquired till then.

9.2 First Law of Motion

By observing the motion of objects on an inclined plane Galileo deduced that objects move with a constant speed when no force acts on them. He observed that when a marble rolls down an inclined plane, its velocity increases [Fig. 9.5(a)]. In the next chapter, you will learn that the marble falls under the unbalanced force of gravity as it rolls down and attains a definite velocity by the time it reaches the bottom. Its velocity decreases when it climbs up as shown in Fig. 9.5(b). Fig. 9.5(c) shows a marble resting on an ideal frictionless plane inclined on both sides. Galileo argued that when the marble is released from left, it would roll down the slope and go up on the opposite side to the same height from which it was released. If the inclinations of the planes on both sides are equal then the marble will climb the same distance that it covered while rolling down. If the angle of inclination of the right-side plane were gradually decreased, then the marble would travel further distances till it reaches the original height. If the right-side plane were ultimately made horizontal (that is, the slope is reduced to zero), the marble would continue to travel forever trying to reach the same height that it was released from. The unbalanced forces on the marble in this case are zero. It thus suggests that an unbalanced (external) force is required to change the motion of the marble but no net force is needed to sustain the uniform motion of the marble. In practical situations it is difficult to achieve a zero unbalanced force. This is because of the presence of the frictional force acting opposite to the direction of motion. Thus, in practice the marble stops after travelling some distance. The effect of the frictional force may be minimised by using a smooth marble and a smooth plane and providing a lubricant on top of the planes.

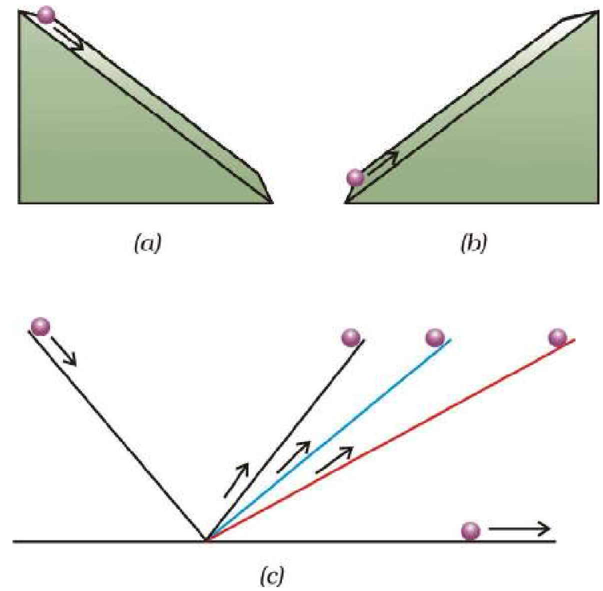


Fig. 9.5: *(a) the downward motion; (b) the upward motion of a marble on an inclined plane; and (c) on a double inclined plane.*

Newton further studied Galileo's ideas on force and motion and presented three fundamental laws that govern the motion of objects. These three laws are known as Newton's laws of motion. The first law of motion is stated as:

An object remains in a state of rest or of uniform motion in a straight line unless compelled to change that state by an applied force.

In other words, all objects resist a change in their *state of motion*. In a qualitative way, the tendency of undisturbed objects to stay at rest or to keep moving with the same velocity is called inertia. This is why, the first law of motion is also known as the law of inertia.

Certain experiences that we come across while travelling in a motorcar can be explained on the basis of the law of inertia. We tend to remain at rest with respect to the seat until the driver applies a braking force to stop the motorcar. With the application of brakes, the car slows down but our body tends to continue in the same state of motion because of its inertia. A sudden application of brakes may thus cause injury to us by

Galileo Galilei was born on 15 February 1564 in Pisa, Italy. Galileo, right from his childhood, had interest in mathematics and natural philosophy. But his father Vincenzo Galilei wanted him to become a medical doctor. Accordingly, Galileo enrolled himself for a medical degree at the University of Pisa in 1581 which he never completed because of his real interest in mathematics. In 1586, he wrote his first scientific book *'The Little Balance [La Balancitta]'*, in which he described Archimedes' method of finding the relative densities (or specific gravities) of substances using a balance. In 1589, in his series of essays – *De Motu*, he presented his theories about falling objects using an inclined plane to slow down the rate of descent.

Galileo Galilei
(1564 – 1642)

In 1592, he was appointed professor of mathematics at the University of Padua in the Republic of Venice. Here he continued his observations on the theory of motion and through his study of inclined planes and the pendulum, formulated the correct law for uniformly accelerated objects that the distance the object moves is proportional to the square of the time taken.

Galileo was also a remarkable craftsman. He developed a series of telescopes whose optical performance was much better than that of other telescopes available during those days. Around 1640, he designed the first pendulum clock. In his book *'Starry Messenger'* on his astronomical discoveries, Galileo claimed to have seen mountains on the moon, the milky way made up of tiny stars, and four small bodies orbiting Jupiter. In his books *'Discourse on Floating Bodies'* and *'Letters on the Sunspots'*, he disclosed his observations of sunspots.

Using his own telescopes and through his observations on Saturn and Venus, Galileo argued that all the planets must orbit the Sun and not the earth, contrary to what was believed at that time.

impact or collision with the panels in front. Safety belts are worn to prevent such accidents. Safety belts exert a force on our body to make the forward motion slower. An opposite experience is encountered when we are standing in a bus and the bus begins to move suddenly. Now we tend to fall backwards. This is because the sudden start of the bus brings motion to the bus as well as to our feet in contact with the floor of the bus. But the rest of our body opposes this motion because of its inertia.

When a motorcar makes a sharp turn at a high speed, we tend to get thrown to one side. This can again be explained on the basis of the law of inertia. We tend to continue in our straight-line motion. When an unbalanced force is applied by the engine to change the direction of motion of the motorcar, we slip to one side of the seat due to the inertia of our body.

The fact that a body will remain at rest unless acted upon by an unbalanced force can be illustrated through the following activities:

Activity _____________ 9.1

- Make a pile of similar carom coins on a table, as shown in Fig. 9.6.
- Attempt a sharp horizontal hit at the bottom of the pile using another carom coin or the striker. If the hit is strong enough, the bottom coin moves out quickly. Once the lowest coin is removed, the inertia of the other coins makes them 'fall' vertically on the table.

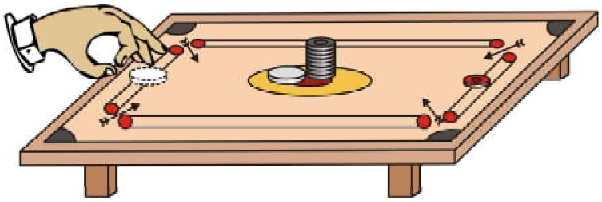


Fig. 9.6: *Only the carom coin at the bottom of a pile is removed when a fast moving carom coin (or striker) hits it.*

Activity _____________ 9.2

- Set a five-rupee coin on a stiff card covering an empty glass tumbler standing on a table as shown in Fig. 9.7.
- Give the card a sharp horizontal flick with a finger. If we do it fast then the card shoots away, allowing the coin to fall vertically into the glass tumbler due to its inertia.
- The inertia of the coin tries to maintain its state of rest even when the card flows off.

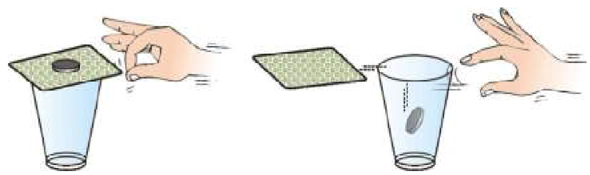


Fig. 9.7: *When the card is flicked with the finger the coin placed over it falls in the tumbler.*

Activity _____________ 9.3

- Place a water-filled tumbler on a tray.
- Hold the tray and turn around as fast as you can.
- We observe that the water spills. Why?

Observe that a groove is provided in a saucer for placing the tea cup. It prevents the cup from toppling over in case of sudden jerks.

9.3 Inertia and Mass

All the examples and activities given so far illustrate that there is a resistance offered by an object to change its state of motion. If it is at rest it tends to remain at rest; if it is moving it tends to keep moving. This property of an object is called its inertia. Do all bodies have the same inertia? We know that it is easier to push an empty box than a box full of books. Similarly, if we kick a football it flies away. But if we kick a stone of the same size with equal force, it hardly moves. We may, in fact, get an injury in our foot while doing so! Similarly, in activity 9.2, instead of a five-rupees coin if we use a one-rupee coin, we find that a lesser force is required to perform the activity. A force that is just enough to cause a small cart to pick up a large velocity will produce a negligible change in the motion of a train. This is because, in comparison to the cart the train has a much lesser tendency to change its state of motion. Accordingly, we say that the train has more inertia than the cart. Clearly, heavier or more massive objects offer larger inertia. Quantitatively, the inertia of an object is measured by its mass. We may thus relate inertia and mass as follows: Inertia is the natural tendency of an object to resist a change in its state of motion or of rest. The mass of an object is a measure of its inertia.

Questions

1. *Which of the following has more inertia: (a) a rubber ball and a stone of the same size? (b) a bicycle and a train? (c) a five-rupees coin and a one-rupee coin?*
2. *In the following example, try to identify the number of times the velocity of the ball changes:*
   "A football player kicks a football to another player of his team who kicks the football towards the goal. The goalkeeper of the opposite team collects the football and kicks it towards a player of his own team".
   Also identify the agent supplying the force in each case.
3. *Explain why some of the leaves may get detached from a tree if we vigorously shake its branch.*
4. *Why do you fall in the forward direction when a moving bus brakes to a stop and fall backwards when it accelerates from rest?*

9.4 Second Law of Motion

The first law of motion indicates that when an unbalanced external force acts on an object, its velocity changes, that is, the object gets an acceleration. We would now like to study how the acceleration of an object depends on the force applied to it and how we measure a force. Let us recount some observations from our everyday life. During the game of table tennis if the ball hits a player it does not hurt him. On the other hand, when a fast moving cricket ball hits a spectator, it may hurt him. A truck at rest does not require any attention when parked along a roadside. But a moving truck, even at speeds as low as 5 m s^{-1}, may kill a person standing in its path. A small mass, such as a bullet may kill a person when fired from a gun. These observations suggest that the impact produced by the objects depends on their mass and velocity. Similarly, if an object is to be accelerated, we know that a greater force is required to give a greater velocity. In other words, there appears to exist some quantity of importance that combines the object's mass and its velocity. One such property called momentum was introduced by Newton. The momentum, p of an object is defined as the product of its mass, m and velocity, v. That is,

$$p = mv \tag{9.1}$$

Momentum has both direction and magnitude. Its direction is the same as that of velocity, v. The SI unit of momentum is kilogram-metre per second (kg m s^{-1}). Since the application of an unbalanced force brings a change in the velocity of the object, it is therefore clear that a force also produces a change of momentum.

Let us consider a situation in which a car with a dead battery is to be pushed along a straight road to give it a speed of 1 m s^{-1}, which is sufficient to start its engine. If one or two persons give a sudden push (unbalanced force) to it, it hardly starts. But a continuous push over some time results in a gradual acceleration of the car to this speed. It means that the change of momentum of the car is not only determined by the magnitude of the force but also by the time during which the force is exerted. It may then also be concluded that the force necessary to change the momentum of an object depends on the time rate at which the momentum is changed.

The second law of motion states that the rate of change of momentum of an object is proportional to the applied unbalanced force in the direction of force.

9.4.1 Mathematical formulation of second law of motion

Suppose an object of mass, m is moving along a straight line with an initial velocity, u. It is uniformly accelerated to velocity, v in time, t by the application of a constant force, F throughout the time, t. The initial and final momentum of the object will be, $p_1 = mu$ and $p_2 = mv$ respectively.

The change in momentum $\propto p_2 - p_1$

$$\propto mv - mu$$

$$\propto m \times (v - u).$$

The rate of change of momentum $\propto \dfrac{m \times (v-u)}{t}$

Or, the applied force,

$$F \propto \frac{m \times (v-u)}{t}$$

$$F = \frac{km \times (v-u)}{t} \tag{9.2}$$

$$= kma \tag{9.3}$$

Here $a\ [= (v - u)/t\ ]$ is the acceleration, which is the rate of change of velocity. The quantity, k is a constant of proportionality. The SI units of mass and acceleration are kg and m s^{-2} respectively. The unit of force is so chosen that the value of the constant, k becomes one. For this, one unit of force is defined as the amount that produces an acceleration of 1 m s^{-2} in an object of 1 kg mass. That is,

$$1 \text{ unit of force} = k \times (1 \text{ kg}) \times (1 \text{ m s}^{-2}).$$

Thus, the value of k becomes 1. From Eq. (9.3)

$$F = ma \tag{9.4}$$

The unit of force is kg m s^{-2} or newton, which has the symbol N. The second law of motion gives us a method to measure the force acting on an object as a product of its mass and acceleration.

The second law of motion is often seen in action in our everyday life. Have you noticed that while catching a fast moving cricket ball, a fielder in the ground gradually pulls his hands backwards with the moving ball? In doing so, the fielder increases the time during which the high velocity of the moving ball decreases to zero. Thus, the acceleration of the ball is decreased and therefore the impact of catching the fast moving ball (Fig. 9.8) is also reduced. If the ball is stopped suddenly then its high velocity decreases to zero in a very short interval of time. Thus, the rate of change of momentum of the ball will be large. Therefore, a large force would have to be applied for holding the catch that may hurt the palm of the fielder. In a high jump athletic event, the athletes are made to fall either on a cushioned bed or on a sand bed. This is to increase the time of the athlete's fall to stop after making the jump. This decreases the rate of change of momentum and hence the force. Try to ponder how a karate player breaks a slab of ice with a single blow.

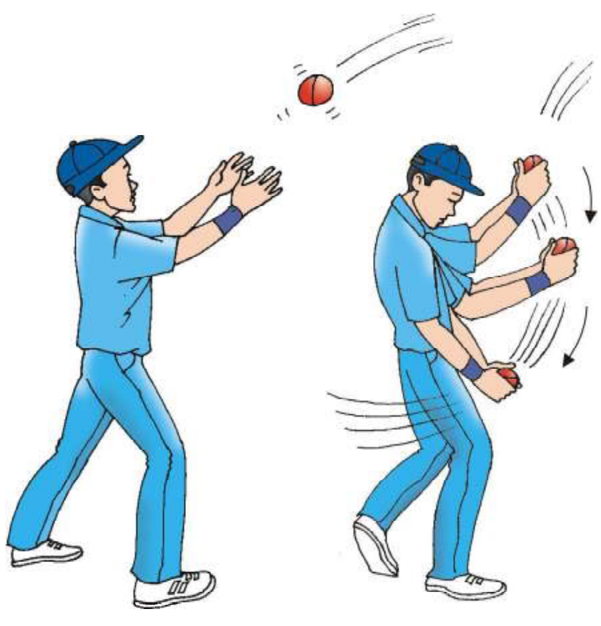


Fig. 9.8: *A fielder pulls his hands gradually with the moving ball while holding a catch.*

The first law of motion can be mathematically stated from the mathematical expression for the second law of motion. Eq. (9.4) is

$$F = ma$$

or $$F = \frac{m(v-u)}{t} \qquad (9.5)$$

or $$Ft = mv - mu$$

That is, when $F = 0$, $v = u$ for whatever time, t is taken. This means that the object will continue moving with uniform velocity, u throughout the time, t. If u is zero then v will also be zero. That is, the object will remain at rest.

Example 9.1 A constant force acts on an object of mass 5 kg for a duration of 2 s. It increases the object's velocity from 3 m s^{-1} to 7 m s^{-1}. Find the magnitude of the applied force. Now, if the force was applied for a duration of 5 s, what would be the final velocity of the object?

Solution:

We have been given that u = 3 m s^{-1} and v = 7 m s^{-1}, t = 2 s and m = 5 kg. From Eq. (9.5) we have,

$$F = \frac{m(v-u)}{t}$$

Substitution of values in this relation gives

F = 5 kg (7 m s^{-1} – 3 m s^{-1})/2 s = 10 N.

Now, if this force is applied for a duration of 5 s (t = 5 s), then the final velocity can be calculated by rewriting Eq. (9.5) as

$$v = u + \frac{Ft}{m}$$

On substituting the values of u, F, m and t, we get the final velocity,

v = 13 m s^{-1}.

Example 9.2 Which would require a greater force — accelerating a 2 kg mass at 5 m s^{-2} or a 4 kg mass at 2 m s^{-2}?

Solution:

From Eq. (9.4), we have $F = ma$.
Here we have m_1 = 2 kg; a_1 = 5 m s^{-2} and m_2 = 4 kg; a_2 = 2 m s^{-2}.
Thus, $F_1 = m_1a_1$ = 2 kg × 5 m s^{-2} = 10 N;
and $F_2 = m_2a_2$ = 4 kg × 2 m s^{-2} = 8 N.
$\Rightarrow F_1 > F_2$.
Thus, accelerating a 2 kg mass at 5 m s^{-2} would require a greater force.

Example 9.3 A motorcar is moving with a velocity of 108 km/h and it takes 4 s to stop after the brakes are applied. Calculate the force exerted by the brakes on the motorcar if its mass along with the passengers is 1000 kg.

Solution:

The initial velocity of the motorcar
u = 108 km/h
= 108 × 1000 m/(60 × 60 s)
= 30 m s^{-1}
and the final velocity of the motorcar
v = 0 m s^{-1}.
The total mass of the motorcar along with its passengers = 1000 kg and the time taken to stop the motorcar, t = 4 s.
From Eq. (9.5) we have the magnitude of the force (F) applied by the brakes as $m(v - u)/t$.
On substituting the values, we get
F = 1000 kg × (0 – 30) m s^{-1}/4 s
= – 7500 kg m s^{-2} or – 7500 N.
The negative sign tells us that the force exerted by the brakes is opposite to the direction of motion of the motorcar.

Example 9.4 A force of 5 N gives a mass m_1, an acceleration of 10 m s^{-2} and a mass m_2, an acceleration of 20 m s^{-2}. What acceleration would it give if both the masses were tied together?

Solution:

From Eq. (9.4) we have $m_1 = F/a_1$; and $m_2 = F/a_2$. Here, a_1 = 10 m s^{-2};
a_2 = 20 m s^{-2} and F = 5 N.
Thus, m_1 = 5 N/10 m s^{-2} = 0.50 kg; and
m_2 = 5 N/20 m s^{-2} = 0.25 kg.
If the two masses were tied together, the total mass, m would be
m = 0.50 kg + 0.25 kg = 0.75 kg.
The acceleration, a produced in the combined mass by the 5 N force would be, $a = F/m$ = 5 N/0.75 kg = 6.67 m s^{-2}.

Example 9.5 The velocity-time graph of a ball of mass 20 g moving along a straight line on a long table is given in Fig. 9.9.

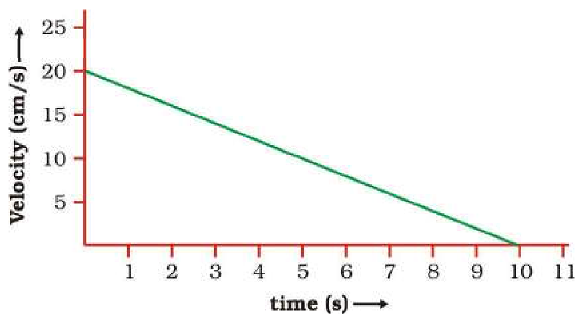


Fig. 9.9

How much force does the table exert on the ball to bring it to rest?

Solution:

The initial velocity of the ball is 20 cm s^{-1}. Due to the frictional force exerted by the table, the velocity of the ball decreases down to zero in 10 s. Thus, u = 20 cm s^{-1}; v = 0 cm s^{-1} and t = 10 s. Since the velocity-time graph is a straight line, it is clear that the ball moves with a constant acceleration. The acceleration a is

$$a = \frac{v - u}{t}$$
= (0 cm s^{-1} – 20 cm s^{-1})/10 s
= –2 cm s^{-2} = –0.02 m s^{-2}.

The force exerted on the ball F is,

$F = ma = (20/1000)\ \text{kg} \times (-\ 0.02\ \text{m s}^{-2})$
$= -\ 0.0004\ \text{N}.$

The negative sign implies that the frictional force exerted by the table is opposite to the direction of motion of the ball.

9.5 Third Law of Motion

The first two laws of motion tell us how an applied force changes the motion and provide us with a method of determining the force. The third law of motion states that when one object exerts a force on another object, the second object instantaneously exerts a force back on the first. These two forces are always equal in magnitude but opposite in direction. These forces act on different objects and never on the same object. In the game of football sometimes we, while looking at the football and trying to kick it with a greater force, collide with a player of the opposite team. Both feel hurt because each applies a force to the other. In other words, there is a pair of forces and not just one force. The two opposing forces are also known as action and reaction forces.

Let us consider two spring balances connected together as shown in Fig. 9.10. The fixed end of balance B is attached with a rigid support, like a wall. When a force is applied through the free end of spring balance A, it is observed that both the spring balances show the same readings on their scales. It means that the force exerted by spring balance A on balance B is equal but opposite in direction to the force exerted by the balance B on balance A. Any of these two forces can be called as *action* and the other as *reaction*. This gives us an alternative statement of the third law of motion i.e., to every action there is an equal and opposite reaction. However, it must be remembered that the action and reaction always act on two different objects, simultaneously.

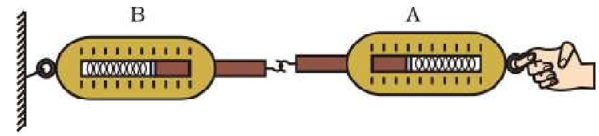


Fig. 9.10: *Action and reaction forces are equal and opposite.*

Suppose you are standing at rest and intend to start walking on a road. You must accelerate, and this requires a force in accordance with the second law of motion. Which is this force? Is it the muscular effort you exert on the road? Is it in the direction we intend to move? No, you push the road below backwards. The road exerts an equal and opposite force on your feet to make you move forward.

It is important to note that even though the action and reaction forces are always equal in magnitude, these forces may not produce accelerations of equal magnitudes. This is because each force acts on a different object that may have a different mass.

When a gun is fired, it exerts a forward force on the bullet. The bullet exerts an equal and opposite force on the gun. This results in the recoil of the gun (Fig. 9.11). Since the gun has a much greater mass than the bullet, the acceleration of the gun is much less than the acceleration of the bullet. The third law of motion can also be illustrated when a sailor jumps out of a rowing boat. As the sailor jumps forward, the force on the boat moves it backwards (Fig. 9.12).

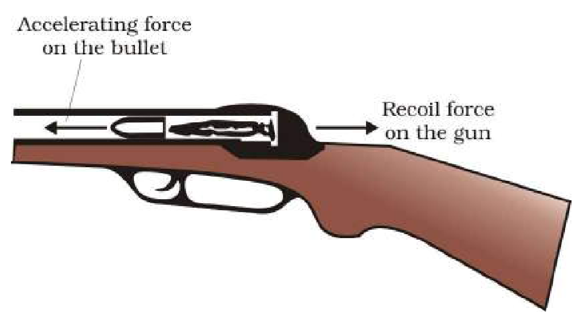


Fig. 9.11: *A forward force on the bullet and recoil of the gun.*

Fig. 9.12: *As the sailor jumps in forward direction, the boat moves backwards.*

Activity ______________ 9.4

- Request two children to stand on two separate carts as shown in Fig. 9.13.
- Give them a bag full of sand or some other heavy object. Ask them to play a game of catch with the bag.
- Does each of them experience an instantaneous force as a result of throwing the sand bag?
- You can paint a white line on cartwheels to observe the motion of the two carts when the children throw the bag towards each other.

Fig. 9.13

Now, place two children on one cart and one on another cart. The second law of motion can be seen, as this arrangement would show different accelerations for the same force.

The cart shown in this activity can be constructed by using a 12 mm or 18 mm thick plywood board of about 50 cm × 100 cm with two pairs of hard ball-bearing wheels (skate wheels are good to use). Skateboards are not as effective because it is difficult to maintain straight-line motion.

9.6 Conservation of Momentum

Suppose two objects (two balls A and B, say) of masses m_A and m_B are travelling in the same direction along a straight line at different velocities u_A and u_B, respectively [Fig. 9.14(a)]. And there are no other external unbalanced forces acting on them. Let $u_A > u_B$ and the two balls collide with each other as shown in Fig. 9.14(b). During collision which lasts for a time t, the ball A exerts a force F_{AB} on ball B and the ball B exerts a force F_{BA} on ball A. Suppose v_A and v_B are the velocities of the two balls A and B after the collision, respectively [Fig. 9.14(c)].

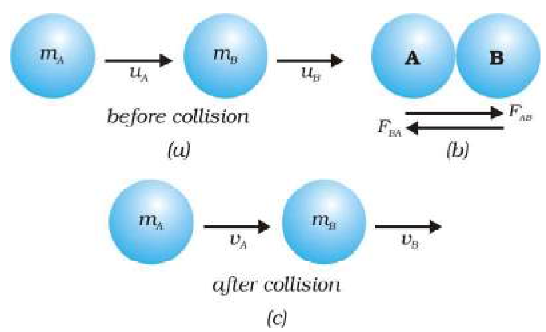


Fig. 9.14: *Conservation of momentum in collision of two balls.*

From Eq. (9.1), the momenta (plural of momentum) of ball A before and after the collision are $m_A u_A$ and $m_A v_A$, respectively. The rate of change of its momentum (or F_{AB}) during the collision will be $m_A \dfrac{(v_A - u_A)}{t}$.

Similarly, the rate of change of momentum of ball B (= F_{BA}) during the collision will be

$m_B \dfrac{(v_B - u_B)}{t}$.

According to the third law of motion, the force F_{AB} exerted by ball A on ball B and the force F_{BA} exerted by the ball B on ball A must be equal and opposite to each other. Therefore,

$$F_{AB} = -F_{BA} \quad (9.6)$$

or

$$m_A \frac{(v_A - u_A)}{t} = -m_B \frac{(v_B - u_B)}{t}.$$

This gives,

$$m_A u_A + m_B u_B = m_A v_A + m_B v_B \quad (9.7)$$

Since $(m_A u_A + m_B u_B)$ is the total momentum of the two balls A and B before the collision and $(m_A v_A + m_B v_B)$ is their total momentum after the collision, from Eq. (9.7) we observe that the total momentum of the two balls remains unchanged or conserved provided no other external force acts.

As a result of this ideal collision experiment, we say that the sum of momenta of the two objects before collision is equal to the sum of momenta after the collision provided there is no external unbalanced force acting on them. This is known as the law of conservation of momentum. This statement can alternatively be given as the total momentum of the two objects is unchanged or conserved by the collision.

Activity 9.5

- Take a big rubber balloon and inflate it fully. Tie its neck using a thread. Also using adhesive tape, fix a straw on the surface of this balloon.
- Pass a thread through the straw and hold one end of the thread in your hand or fix it on the wall.
- Ask your friend to hold the other end of the thread or fix it on a wall at some distance. This arrangement is shown in Fig. 9.15.
- Now remove the thread tied on the neck of balloon. Let the air escape from the mouth of the balloon.
- Observe the direction in which the straw moves.

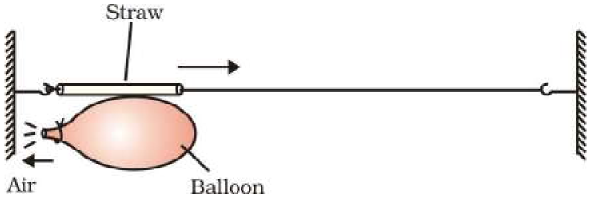


Fig. 9.15

Activity 9.6

- Take a test tube of good quality glass material and put a small amount of water in it. Place a stop cork at the mouth of it.
- Now suspend the test tube horizontally by two strings or wires as shown in Fig. 9.16.
- Heat the test tube with a burner until water vaporises and the cork blows out.
- Observe that the test tube recoils in the direction opposite to the direction of the cork.

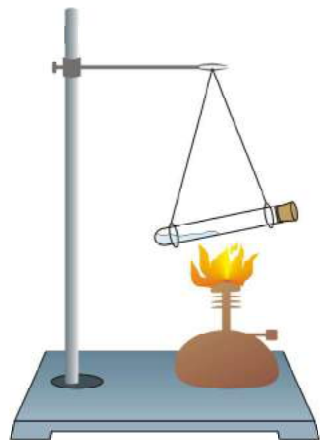


Fig. 9.16

- Also, observe the difference in the velocity the cork appears to have and that of the recoiling test tube.

Example 9.6 A bullet of mass 20 g is horizontally fired with a velocity 150 m s^{-1} from a pistol of mass 2 kg. What is the recoil velocity of the pistol?

Solution:

We have the mass of bullet, m_1 = 20 g (= 0.02 kg) and the mass of the pistol, m_2 = 2 kg; initial velocities of the bullet (u_1) and pistol (u_2) = 0, respectively. The final velocity of the bullet, v_1 = + 150 m s^{-1}. The direction of bullet is taken from left to right (positive, by convention, Fig. 9.17). Let v be the recoil velocity of the pistol.

Total momenta of the pistol and bullet before the fire, when the gun is at rest

$= (2 + 0.02)\ \text{kg} \times 0\ \text{m s}^{-1}$

$= 0\ \text{kg m s}^{-1}$

Total momenta of the pistol and bullet after it is fired

$= 0.02\ \text{kg} \times (+\ 150\ \text{m s}^{-1}) + 2\ \text{kg} \times v\ \text{m s}^{-1}$

$= (3 + 2v)\ \text{kg m s}^{-1}$

According to the law of conservation of momentum

Total momenta after the fire = Total momenta before the fire

$3 + 2v = 0$

$\Rightarrow v = -1.5\ \text{m s}^{-1}$.

Negative sign indicates that the direction in which the pistol would recoil is opposite to that of bullet, that is, right to left.

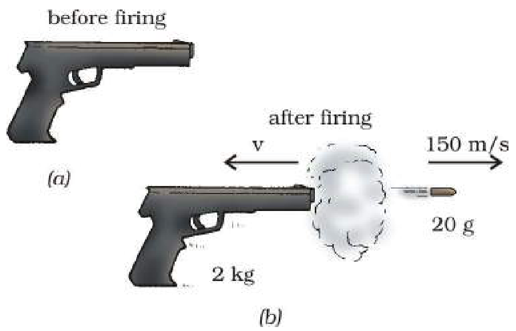


Fig. 9.17: *Recoil of a pistol*

Example 9.7 A girl of mass 40 kg jumps with a horizontal velocity of 5 m s^{-1} onto a stationary cart with frictionless wheels. The mass of the cart is 3 kg. What is her velocity as the cart starts moving? Assume that there is no external unbalanced force working in the horizontal direction.

Solution:

Let v be the velocity of the girl on the cart as the cart starts moving.

The total momenta of the girl and cart before the interaction

$= 40\ \text{kg} \times 5\ \text{m s}^{-1} + 3\ \text{kg} \times 0\ \text{m s}^{-1}$

$= 200\ \text{kg m s}^{-1}$.

Total momenta after the interaction

$= (40 + 3)\ \text{kg} \times v\ \text{m s}^{-1}$

$= 43\ v\ \text{kg m s}^{-1}$.

According to the law of conservation of momentum, the total momentum is conserved during the interaction. That is,

$43\ v = 200$

$\Rightarrow v = 200/43 = +\ 4.65\ \text{m s}^{-1}$.

The girl on cart would move with a velocity of 4.65 m s^{-1} in the direction in which the girl jumped (Fig. 9.18).

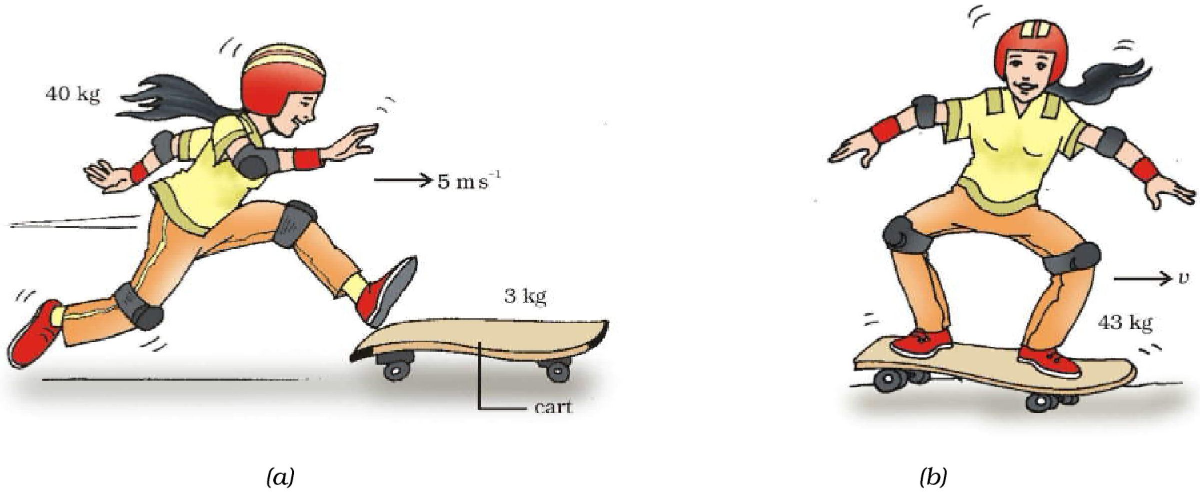


Fig. 9.18: *The girl jumps onto the cart.*

Example 9.8 Two hockey players of opposite teams, while trying to hit a hockey ball on the ground collide and immediately become entangled. One has a mass of 60 kg and was moving with a velocity 5.0 m s^{-1} while the other has a mass of 55 kg and was moving faster with a velocity 6.0 m s^{-1} towards the first player. In which direction and with what velocity will they move after they become entangled? Assume that the frictional force acting between the feet of the two players and ground is negligible.

Solution:

If v is the velocity of the two entangled players after the collision, the total momentum then

$= (m_1 + m_2) \times v$

$= (60 + 55)$ kg $\times v$ m s^{-1}

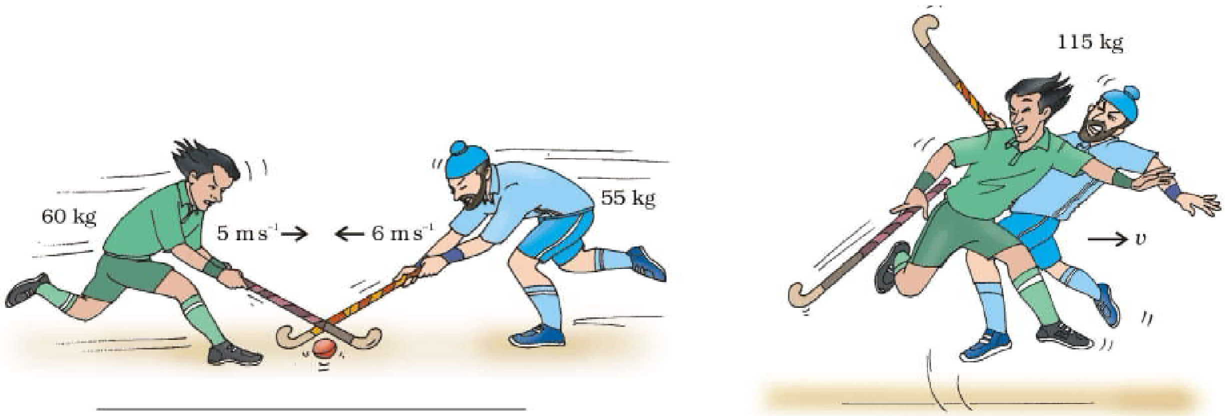
$= 115 \times v$ kg m s^{-1}.

Equating the momenta of the system before and after collision, in accordance with the law of conservation of momentum, we get

$v = -30/115$

$= -0.26$ m s^{-1}.

Thus, the two entangled players would move with velocity 0.26 m s^{-1} from right to left, that is, in the direction the second player was moving before the collision.



(a) (b)

***Fig. 9.19**: A collision of two hockey players: (a) before collision and (b) after collision.*

Let the first player be moving from left to right. By convention left to right is taken as the positive direction and thus right to left is the negative direction (Fig. 9.19). If symbols m and u represent the mass and initial velocity of the two players, respectively. Subscripts 1 and 2 in these physical quantities refer to the two hockey players. Thus,

$m_1 = 60$ kg; $u_1 = +5$ m s^{-1}; and

$m_2 = 55$ kg; $u_2 = -6$ m s^{-1}.

The total momentum of the two players before the collision

$= 60$ kg $\times (+5$ m $s^{-1}) +$
55 kg $\times (-6$ m $s^{-1})$

$= -30$ kg m s^{-1}

Questions

1. *If action is always equal to the reaction, explain how a horse can pull a cart.*
2. *Explain, why is it difficult for a fireman to hold a hose, which ejects large amounts of water at a high velocity.*
3. *From a rifle of mass 4 kg, a bullet of mass 50 g is fired with an initial velocity of 35 m s^{-1}. Calculate the initial recoil velocity of the rifle.*

4. *Two objects of masses 100 g and 200 g are moving along the same line and direction with velocities of 2 m s^{-1} and 1 m s^{-1}, respectively. They collide and after the collision, the first object moves at a velocity of 1.67 m s^{-1}. Determine the velocity of the second object.*

CONSERVATION LAWS

All conservation laws such as conservation of momentum, energy, angular momentum, charge etc. are considered to be fundamental laws in physics. These are based on observations and experiments. It is important to remember that a conservation law cannot be proved. It can be verified, or disproved, by experiments. An experiment whose result is in conformity with the law verifies or substantiates the law; it does not prove the law. On the other hand, a single experiment whose result goes against the law is enough to disprove it.

The law of conservation of momentum has been deduced from large number of observations and experiments. This law was formulated nearly three centuries ago. It is interesting to note that not a single situation has been realised so far, which contradicts this law. Several experiences of every-day life can be explained on the basis of the law of conservation of momentum.

What you have learnt

- First law of motion: An object continues to be in a state of rest or of uniform motion along a straight line unless acted upon by an unbalanced force.
- The natural tendency of objects to resist a change in their state of rest or of uniform motion is called inertia.
- The mass of an object is a measure of its inertia. Its SI unit is kilogram (kg).
- Force of friction always opposes motion of objects.
- Second law of motion: The rate of change of momentum of an object is proportional to the applied unbalanced force in the direction of the force.
- The SI unit of force is kg m s^{-2}. This is also known as newton and represented by the symbol N. A force of one newton produces an acceleration of 1 m s^{-2} on an object of mass 1 kg.
- The momentum of an object is the product of its mass and velocity and has the same direction as that of the velocity. Its SI unit is kg m s^{-1}.
- Third law of motion: To every action, there is an equal and opposite reaction and they act on two different bodies.
- In an isolated system (where there is no external force), the total momentum remains conserved.

Exercises

1. An object experiences a net zero external unbalanced force. Is it possible for the object to be travelling with a non-zero velocity? If yes, state the conditions that must be placed on the magnitude and direction of the velocity. If no, provide a reason.
2. When a carpet is beaten with a stick, dust comes out of it. Explain.
3. Why is it advised to tie any luggage kept on the roof of a bus with a rope?
4. A batsman hits a cricket ball which then rolls on a level ground. After covering a short distance, the ball comes to rest. The ball slows to a stop because
   (a) the batsman did not hit the ball hard enough.
   (b) velocity is proportional to the force exerted on the ball.
   (c) there is a force on the ball opposing the motion.
   (d) there is no unbalanced force on the ball, so the ball would want to come to rest.
5. A truck starts from rest and rolls down a hill with a constant acceleration. It travels a distance of 400 m in 20 s. Find its acceleration. Find the force acting on it if its mass is 7 tonnes (*Hint*: 1 tonne = 1000 kg.)
6. A stone of 1 kg is thrown with a velocity of 20 m s^{-1} across the frozen surface of a lake and comes to rest after travelling a distance of 50 m. What is the force of friction between the stone and the ice?
7. A 8000 kg engine pulls a train of 5 wagons, each of 2000 kg, along a horizontal track. If the engine exerts a force of 40000 N and the track offers a friction force of 5000 N, then calculate:
   (a) the net accelerating force and
   (b) the acceleration of the train.
8. An automobile vehicle has a mass of 1500 kg. What must be the force between the vehicle and road if the vehicle is to be stopped with a negative acceleration of 1.7 m s^{-2}?
9. What is the momentum of an object of mass m, moving with a velocity v?
   (a) $(mv)^2$ (b) mv^2 (c) ½ mv^2 (d) mv
10. Using a horizontal force of 200 N, we intend to move a wooden cabinet across a floor at a constant velocity. What is the friction force that will be exerted on the cabinet?
11. Two objects, each of mass 1.5 kg, are moving in the same straight line but in opposite directions. The velocity of each object is 2.5 m s^{-1} before the collision during which they

stick together. What will be the velocity of the combined object after collision?

12. According to the third law of motion when we push on an object, the object pushes back on us with an equal and opposite force. If the object is a massive truck parked along the roadside, it will probably not move. A student justifies this by answering that the two opposite and equal forces cancel each other. Comment on this logic and explain why the truck does not move.
13. A hockey ball of mass 200 g travelling at 10 m s^{-1} is struck by a hockey stick so as to return it along its original path with a velocity at 5 m s^{-1}. Calculate the magnitude of change of momentum occurred in the motion of the hockey ball by the force applied by the hockey stick.
14. A bullet of mass 10 g travelling horizontally with a velocity of 150 m s^{-1} strikes a stationary wooden block and comes to rest in 0.03 s. Calculate the distance of penetration of the bullet into the block. Also calculate the magnitude of the force exerted by the wooden block on the bullet.
15. An object of mass 1 kg travelling in a straight line with a velocity of 10 m s^{-1} collides with, and sticks to, a stationary wooden block of mass 5 kg. Then they both move off together in the same straight line. Calculate the total momentum just before the impact and just after the impact. Also, calculate the velocity of the combined object.
16. An object of mass 100 kg is accelerated uniformly from a velocity of 5 m s^{-1} to 8 m s^{-1} in 6 s. Calculate the initial and final momentum of the object. Also, find the magnitude of the force exerted on the object.
17. Akhtar, Kiran and Rahul were riding in a motorcar that was moving with a high velocity on an expressway when an insect hit the windshield and got stuck on the windscreen. Akhtar and Kiran started pondering over the situation. Kiran suggested that the insect suffered a greater change in momentum as compared to the change in momentum of the motorcar (because the change in the velocity of the insect was much more than that of the motorcar). Akhtar said that since the motorcar was moving with a larger velocity, it exerted a larger force on the insect. And as a result the insect died. Rahul while putting an entirely new explanation said that both the motorcar and the insect experienced the same force and a change in their momentum. Comment on these suggestions.
18. How much momentum will a dumb-bell of mass 10 kg transfer to the floor if it falls from a height of 80 cm? Take its downward acceleration to be 10 m s^{-2}.

Additional Exercises

A1. The following is the distance-time table of an object in motion:

Time in seconds	Distance in metres
0	0
1	1
2	8
3	27
4	64
5	125
6	216
7	343

(a) What conclusion can you draw about the acceleration? Is it constant, increasing, decreasing, or zero?

(b) What do you infer about the forces acting on the object?

A2. Two persons manage to push a motorcar of mass 1200 kg at a uniform velocity along a level road. The same motorcar can be pushed by three persons to produce an acceleration of 0.2 m s^{-2}. With what force does each person push the motorcar? (Assume that all persons push the motorcar with the same muscular effort.)

A3. A hammer of mass 500 g, moving at 50 m s^{-1}, strikes a nail. The nail stops the hammer in a very short time of 0.01 s. What is the force of the nail on the hammer?

A4. A motorcar of mass 1200 kg is moving along a straight line with a uniform velocity of 90 km/h. Its velocity is slowed down to 18 km/h in 4 s by an unbalanced external force. Calculate the acceleration and change in momentum. Also calculate the magnitude of the force required.

Chapter 10

GRAVITATION

In Chapters 8 and 9, we have learnt about the motion of objects and force as the cause of motion. We have learnt that a force is needed to change the speed or the direction of motion of an object. We always observe that an object dropped from a height falls towards the earth. We know that all the planets go around the Sun. The moon goes around the earth. In all these cases, there must be some force acting on the objects, the planets and on the moon. Isaac Newton could grasp that the same force is responsible for all these. This force is called the gravitational force.

In this chapter we shall learn about gravitation and the universal law of gravitation. We shall discuss the motion of objects under the influence of gravitational force on the earth. We shall study how the weight of a body varies from place to place. We shall also discuss the conditions for objects to float in liquids.

10.1 Gravitation

We know that the moon goes around the earth. An object when thrown upwards, reaches a certain height and then falls downwards. It is said that when Newton was sitting under a tree, an apple fell on him. The fall of the apple made Newton start thinking. He thought that: if the earth can attract an apple, can it not attract the moon? Is the force the same in both cases? He conjectured that the same type of force is responsible in both the cases. He argued that at each point of its orbit, the moon falls towards the earth, instead of going off in a straight line. So, it must be attracted by the earth. But we do not really see the moon falling towards the earth.

Let us try to understand the motion of the moon by recalling activity 8.11.

Activity 10.1

- Take a piece of thread.
- Tie a small stone at one end. Hold the other end of the thread and whirl it round, as shown in Fig. 10.1.
- Note the motion of the stone.
- Release the thread.
- Again, note the direction of motion of the stone.

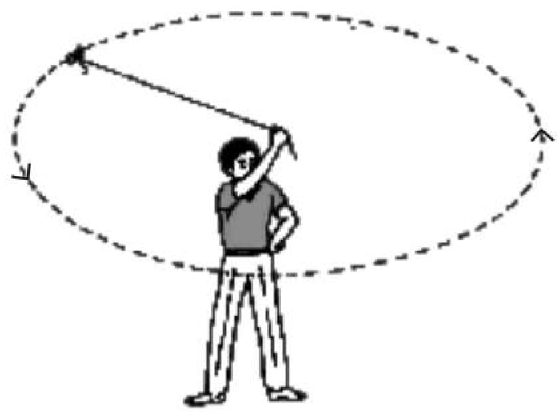
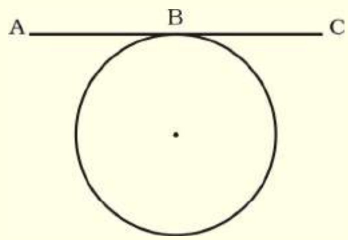


Fig. 10.1: *A stone describing a circular path with a velocity of constant magnitude.*

Before the thread is released, the stone moves in a circular path with a certain speed and changes direction at every point. The change in direction involves change in velocity or acceleration. The force that causes this acceleration and keeps the body moving along the circular path is acting towards the centre. This force is called the centripetal (meaning 'centre-seeking') force. In the absence of this force, the stone flies off along a straight line. This straight line will be a tangent to the circular path.

> More to know
>
> **Tangent to a circle**
>
> 
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>
> A straight line that meets the circle at one and only one point is called a tangent to the circle. Straight line ABC is a tangent to the circle at point B.

The motion of the moon around the earth is due to the centripetal force. The centripetal force is provided by the force of attraction of the earth. If there were no such force, the moon would pursue a uniform straight line motion.

It is seen that a falling apple is attracted towards the earth. Does the apple attract the earth? If so, we do not see the earth moving towards an apple. Why?

According to the third law of motion, the apple does attract the earth. But according to the second law of motion, for a given force, acceleration is inversely proportional to the mass of an object [Eq. (9.4)]. The mass of an apple is negligibly small compared to that of the earth. So, we do not see the earth moving towards the apple. Extend the same argument for why the earth does not move towards the moon.

In our solar system, all the planets go around the Sun. By arguing the same way, we can say that there exists a force between the Sun and the planets. From the above facts Newton concluded that not only does the earth attract an apple and the moon, but all objects in the universe attract each other. This force of attraction between objects is called the gravitational force.

10.1.1 Universal law of gravitation

Every object in the universe attracts every other object with a force which is proportional to the product of their masses and inversely proportional to the square of the distance between them. The force is along the line joining the centres of two objects.

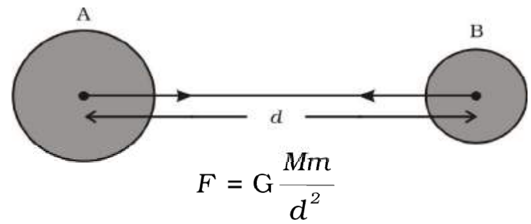


Fig. 10.2: *The gravitational force between two uniform objects is directed along the line joining their centres.*

Let two objects A and B of masses M and m lie at a distance d from each other as shown in Fig. 10.2. Let the force of attraction between two objects be F. According to the universal law of gravitation, the force between two objects is directly proportional to the product of their masses. That is,

$$F \propto M \times m \qquad (10.1)$$

And the force between two objects is inversely proportional to the square of the distance between them, that is,

$$F \propto \frac{1}{d^2} \qquad (10.2)$$

Combining Eqs. (10.1) and (10.2), we get

$$F \propto \frac{M \times m}{d^2} \qquad (10.3)$$

or, $$F = G\frac{M \times m}{d^2} \qquad (10.4)$$

where G is the constant of proportionality and is called the universal gravitation constant. By multiplying crosswise, Eq. (10.4) gives

$$F \times d^2 = G\, M \times m$$

Isaac Newton
(1642 – 1727)

Isaac Newton was born in Woolsthorpe near Grantham, England. He is generally regarded as the most original and influential theorist in the history of science. He was born in a poor farming family. But he was not good at farming. He was sent to study at Cambridge University in 1661. In 1665 a plague broke out in Cambridge and so Newton took a year off. It was during this year that the incident of the apple falling on him is said to have occurred. This incident prompted Newton to explore the possibility of connecting gravity with the force that kept the moon in its orbit. This led him to the universal law of gravitation. It is remarkable that many great scientists before him knew of gravity but failed to realise it.

Newton formulated the well-known laws of motion. He worked on theories of light and colour. He designed an astronomical telescope to carry out astronomical observations. Newton was also a great mathematician. He invented a new branch of mathematics, called calculus. He used it to prove that for objects outside a sphere of uniform density, the sphere behaves as if the whole of its mass is concentrated at its centre. Newton transformed the structure of physical science with his three laws of motion and the universal law of gravitation. As the keystone of the scientific revolution of the seventeenth century, Newton's work combined the contributions of Copernicus, Kepler, Galileo, and others into a new powerful synthesis.

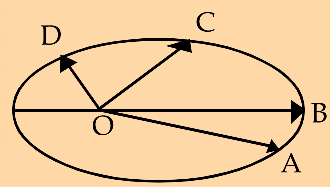
It is remarkable that though the gravitational theory could not be verified at that time, there was hardly any doubt about its correctness. This is because Newton based his theory on sound scientific reasoning and backed it with mathematics. This made the theory simple and elegant. These qualities are now recognised as essential requirements of a good scientific theory.

How did Newton guess the inverse-square rule?

There has always been a great interest in the motion of planets. By the 16th century, a lot of data on the motion of planets had been collected by many astronomers. Based on these data Johannes Kepler derived three laws, which govern the motion of planets. These are called Kepler's laws. These are:

1. The orbit of a planet is an ellipse with the Sun at one of the foci, as shown in the figure given below. In this figure O is the position of the Sun.
2. The line joining the planet and the Sun sweep equal areas in equal intervals of time. Thus, if the time of travel from A to B is the same as that from C to D, then the areas OAB and OCD are equal.
3. The cube of the mean distance of a planet from the Sun is proportional to the square of its orbital period T. Or, r^3/T^2 = constant.

It is important to note that Kepler could not give a theory to explain the motion of planets. It was Newton who showed that the cause of the planetary motion is the gravitational force that the Sun exerts on them. Newton used the third law of Kepler to calculate the gravitational force of attraction. The gravitational force of the earth is weakened by distance. A simple argument goes like this. We can assume that the planetary orbits are circular. Suppose the orbital velocity is v and the radius of the orbit is r. Then the force acting on an orbiting planet is given by $F \propto v^2/r$.



If T denotes the period, then $v = 2\pi r/T$, so that $v^2 \propto r^2/T^2$.

We can rewrite this as $v^2 \propto (1/r) \times (r^3/T^2)$. Since r^3/T^2 is constant by Kepler's third law, we have $v^2 \propto 1/r$. Combining this with $F \propto v^2/r$, we get, $F \propto 1/r^2$.

or $$G = \frac{F d^2}{M \times m} \qquad (10.5)$$

The SI unit of G can be obtained by substituting the units of force, distance and mass in Eq. (10.5) as N m^2 kg^{-2}.

The value of G was found out by Henry Cavendish (1731 – 1810) by using a sensitive balance. The accepted value of G is 6.673×10^{-11} N m^2 kg^{-2}.

We know that there exists a force of attraction between any two objects. Compute the value of this force between you and your friend sitting closeby. Conclude how you do not experience this force!

More to know

The law is universal in the sense that it is applicable to all bodies, whether the bodies are big or small, whether they are celestial or terrestrial.

Inverse-square

Saying that *F* is inversely proportional to the square of *d* means, for example, that if *d* gets bigger by a factor of 6, *F* becomes $\frac{1}{36}$ times smaller.

Example 10.1 The mass of the earth is 6×10^{24} kg and that of the moon is 7.4×10^{22} kg. If the distance between the earth and the moon is 3.84×10^5 km, calculate the force exerted by the earth on the moon. (Take $G = 6.7 \times 10^{-11}$ N m^2 kg^{-2})

Solution:

The mass of the earth, $M = 6 \times 10^{24}$ kg

The mass of the moon,

$m = 7.4 \times 10^{22}$ kg

The distance between the earth and the moon,

$$\begin{aligned} d &= 3.84 \times 10^5 \text{ km} \\ &= 3.84 \times 10^5 \times 1000 \text{ m} \\ &= 3.84 \times 10^8 \text{ m} \\ G &= 6.7 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2} \end{aligned}$$

From Eq. (10.4), the force exerted by the earth on the moon is

$$F = G\frac{M \times m}{d^2}$$

$$= \frac{6.7 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2} \times 6 \times 10^{24} \text{ kg} \times 7.4 \times 10^{22} \text{ kg}}{(3.84 \times 10^8 \text{ m})^2}$$

$= 2.02 \times 10^{20}$ N.

Thus, the force exerted by the earth on the moon is 2.02×10^{20} N.

Questions

1. *State the universal law of gravitation.*
2. *Write the formula to find the magnitude of the gravitational force between the earth and an object on the surface of the earth.*

10.1.2 Importance of the universal law of gravitation

The universal law of gravitation successfully explained several phenomena which were believed to be unconnected:

(i) the force that binds us to the earth;
(ii) the motion of the moon around the earth;
(iii) the motion of planets around the Sun; and
(iv) the tides due to the moon and the Sun.

10.2 Free Fall

Let us try to understand the meaning of free fall by performing this activity.

Activity _______________ *10.2*

- Take a stone.
- Throw it upwards.
- It reaches a certain height and then it starts falling down.

We have learnt that the earth attracts objects towards it. This is due to the gravitational force. Whenever objects fall towards the earth under this force alone, we say that the objects are in free fall. Is there any change in the velocity of falling objects? While falling, there is no change in the direction of motion of the objects. But due to the earth's attraction, there will be a change in the magnitude of the velocity. Any change in velocity involves acceleration. Whenever an object falls towards the earth, an acceleration is involved. This acceleration is due to the earth's gravitational force. Therefore, this acceleration is called the acceleration due to the gravitational force of the earth (or acceleration due to gravity). It is denoted by *g*. The unit of *g* is the same as that of acceleration, that is, m s^{-2}.

We know from the second law of motion that force is the product of mass and acceleration. Let the mass of the stone in activity 10.2 be *m*. We already know that there is acceleration involved in falling objects due to the gravitational force and is denoted by *g*. Therefore the magnitude of the gravitational force *F* will be equal to the product of mass and acceleration due to the gravitational force, that is,

$$F = m\,g \tag{10.6}$$

From Eqs. (10.4) and (10.6) we have

$$m\,g = G\,\frac{M \times m}{d^2}$$

or

$$g = G\,\frac{M}{d^2} \tag{10.7}$$

where *M* is the mass of the earth, and *d* is the distance between the object and the earth.

Let an object be on or near the surface of the earth. The distance *d* in Eq. (10.7) will be equal to *R*, the radius of the earth. Thus, for objects on or near the surface of the earth,

$$mg = G\,\frac{M \times m}{R^2} \tag{10.8}$$

$$g = G\,\frac{M}{R^2} \tag{10.9}$$

The earth is not a perfect sphere. As the radius of the earth increases from the poles to the equator, the value of *g* becomes greater at the poles than at the equator. For most calculations, we can take *g* to be more or less constant on or near the earth. But for objects far from the earth, the acceleration due to gravitational force of earth is given by Eq. (10.7).

10.2.1 To calculate the value of *g*

To calculate the value of *g*, we should put the values of G, *M* and *R* in Eq. (10.9), namely, universal gravitational constant, G = 6.7×10^{-11} N m^2 kg^{-2}, mass of the earth, *M* = 6×10^{24} kg, and radius of the earth, *R* = 6.4×10^6 m.

$$g = G\,\frac{M}{R^2}$$

$$= \frac{6.7 \times 10^{-11}\,\text{N m}^2\,\text{kg}^{-2} \times 6 \times 10^{24}\,\text{kg}}{(6.4 \times 10^6\,\text{m})^2}$$

$$= 9.8\ \text{m s}^{-2}.$$

Thus, the value of acceleration due to gravity of the earth, *g* = 9.8 m s^{-2}.

10.2.2 Motion of objects under the influence of gravitational force of the earth

Let us do an activity to understand whether all objects hollow or solid, big or small, will fall from a height at the same rate.

Activity ____________ 10.3

- Take a sheet of paper and a stone. Drop them simultaneously from the first floor of a building. Observe whether both of them reach the ground simultaneously.
- We see that paper reaches the ground little later than the stone. This happens because of air resistance. The air offers resistance due to friction to the motion of the falling objects. The resistance offered by air to the paper is more than the resistance offered to the stone. If we do the experiment in a glass jar from which air has been sucked out, the paper and the stone would fall at the same rate.

We know that an object experiences acceleration during free fall. From Eq. (10.9), this acceleration experienced by an object is independent of its mass. This means that all objects hollow or solid, big or small, should fall at the same rate. According to a story, Galileo dropped different objects from the top of the Leaning Tower of Pisa in Italy to prove the same.

As g is constant near the earth, all the equations for the uniformly accelerated motion of objects become valid with acceleration a replaced by g (see section 8.5). The equations are:

$$v = u + at \quad (10.10)$$

$$s = ut + \frac{1}{2}at^2 \quad (10.11)$$

$$v^2 = u^2 + 2as \quad (10.12)$$

where u and v are the initial and final velocities and s is the distance covered in time, t.

In applying these equations, we will take acceleration, a to be positive when it is in the direction of the velocity, that is, in the direction of motion. The acceleration, a will be taken as negative when it opposes the motion.

Example 10.2 A car falls off a ledge and drops to the ground in 0.5 s. Let g = 10 m s^{-2} (for simplifying the calculations).

(i) What is its speed on striking the ground?
(ii) What is its average speed during the 0.5 s?
(iii) How high is the ledge from the ground?

Solution:

Time, t = ½ second
Initial velocity, u = 0 m s^{-1}
Acceleration due to gravity, g = 10 m s^{-2}
Acceleration of the car, a = + 10 m s^{-2} (downward)

(i) speed $v = a\,t$
v = 10 m s^{-2} × 0.5 s
= 5 m s^{-1}

(ii) average speed $= \frac{u+v}{2}$
= (0 m s^{-1} + 5 m s^{-1})/2
= 2.5 m s^{-1}

(iii) distance travelled, $s = \frac{1}{2}\,a\,t^2$
= ½ × 10 m s^{-2} × $(0.5\text{ s})^2$
= ½ × 10 m s^{-2} × 0.25 s^2
= 1.25 m

Thus,
(i) its speed on striking the ground = 5 m s^{-1}
(ii) its average speed during the 0.5 s = 2.5 m s^{-1}
(iii) height of the ledge from the ground = 1.25 m.

Example 10.3 An object is thrown vertically upwards and rises to a height of 10 m. Calculate (i) the velocity with which the object was thrown upwards and (ii) the time taken by the object to reach the highest point.

Solution:

Distance travelled, s = 10 m
Final velocity, v = 0 m s^{-1}
Acceleration due to gravity, g = 9.8 m s^{-2}
Acceleration of the object, a = –9.8 m s^{-2} (upward motion)

(i) $v^2 = u^2 + 2a\,s$
$0 = u^2 + 2 \times (-9.8\text{ m s}^{-2}) \times 10\text{ m}$
$-u^2 = -2 \times 9.8 \times 10\ \text{m}^2\,\text{s}^{-2}$
$u = \sqrt{196}\ \text{m s}^{-1}$
$u = 14\ \text{m s}^{-1}$

(ii) $v = u + a\,t$
$0 = 14\ \text{m s}^{-1} - 9.8\ \text{m s}^{-2} \times t$
t = 1.43 s.

Thus,
(i) Initial velocity, u = 14 m s^{-1}, and
(ii) Time taken, t = 1.43 s.

Questions

1. *What do you mean by free fall?*
2. *What do you mean by acceleration due to gravity?*

10.3 Mass

We have learnt in the previous chapter that the mass of an object is the measure of its inertia (section 9.3). We have also learnt that greater the mass, the greater is the inertia. It remains the same whether the object is on the earth, the moon or even in outer space. Thus, the mass of an object is constant and does not change from place to place.

10.4 Weight

We know that the earth attracts every object with a certain force and this force depends on the mass (m) of the object and the acceleration due to the gravity (g). The weight of an object is the force with which it is attracted towards the earth.

We know that

$$F = m \times a, \qquad (10.13)$$

that is,

$$F = m \times g. \qquad (10.14)$$

The force of attraction of the earth on an object is known as the weight of the object. It is denoted by W. Substituting the same in Eq. (10.14), we have

$$W = m \times g \qquad (10.15)$$

As the weight of an object is the force with which it is attracted towards the earth, the SI unit of weight is the same as that of force, that is, newton (N). The weight is a force acting vertically downwards; it has both magnitude and direction.

We have learnt that the value of g is constant at a given place. Therefore at a given place, the weight of an object is directly proportional to the mass, say m, of the object, that is, $W \propto m$. It is due to this reason that at a given place, we can use the weight of an object as a measure of its mass. The mass of an object remains the same everywhere, that is, on the earth and on any planet whereas its weight depends on its location because g depends on location.

10.4.1 Weight of an object on the moon

We have learnt that the weight of an object on the earth is the force with which the earth attracts the object. In the same way, the weight of an object on the moon is the force with which the moon attracts that object. The mass of the moon is less than that of the earth. Due to this the moon exerts lesser force of attraction on objects.

Let the mass of an object be m. Let its weight on the moon be W_m. Let the mass of the moon be M_m and its radius be R_m.

By applying the universal law of gravitation, the weight of the object on the moon will be

$$W_m = G\frac{M_m \times m}{R_m^2} \qquad (10.16)$$

Let the weight of the same object on the earth be W_e. The mass of the earth is M and its radius is R.

Table 10.1

Celestial body	Mass (kg)	Radius (m)
Earth	5.98×10^{24}	6.37×10^{6}
Moon	7.36×10^{22}	1.74×10^{6}

From Eqs. (10.9) and (10.15) we have,

$$W_e = G\frac{M \times m}{R^2} \qquad (10.17)$$

Substituting the values from Table 10.1 in Eqs. (10.16) and (10.17), we get

$$W_m = G\frac{7.36 \times 10^{22}\,\text{kg} \times m}{\left(1.74 \times 10^{6}\,\text{m}\right)^2}$$

$$W_m = 2.431 \times 10^{10}\,G \times m \qquad (10.18a)$$

and $$W_e = 1.474 \times 10^{11}\,G \times m \qquad (10.18b)$$

Dividing Eq. (10.18a) by Eq. (10.18b), we get

$$\frac{W_m}{W_e} = \frac{2.431 \times 10^{10}}{1.474 \times 10^{11}}$$

or $$\frac{W_m}{W_e} = 0.165 \approx \frac{1}{6} \qquad (10.19)$$

$$\frac{\text{Weight of the object on the moon}}{\text{Weight of the object on the earth}} = \frac{1}{6}$$

Weight of the object on the moon

= (1/6) × its weight on the earth.

Example 10.4 Mass of an object is 10 kg. What is its weight on the earth?

Solution:

Mass, m = 10 kg
Acceleration due to gravity, $g = 9.8$ m s^{-2}
$W = m \times g$
$W = 10 \text{ kg} \times 9.8 \text{ m s}^{-2} = 98 \text{ N}$
Thus, the weight of the object is 98 N.

Example 10.5 An object weighs 10 N when measured on the surface of the earth. What would be its weight when measured on the surface of the moon?

Solution:

We know,
Weight of object on the moon
= (1/6) × its weight on the earth.
That is,

$$W_m = \frac{W_e}{6} = \frac{10}{6} \text{ N.}$$

= 1.67 N.

Thus, the weight of object on the surface of the moon would be 1.67 N.

Questions

1. *What are the differences between the mass of an object and its weight?*
2. *Why is the weight of an object on the moon $\frac{1}{6}^{th}$ its weight on the earth?*

10.5 Thrust and Pressure

Have you ever wondered why a camel can run in a desert easily? Why an army tank weighing more than a thousand tonne rests upon a continuous chain? Why a truck or a motorbus has much wider tyres? Why cutting tools have sharp edges? In order to address these questions and understand the phenomena involved, it helps to introduce the concepts of the net force in a particular direction (thrust) and the force per unit area (pressure) acting on the object concerned.

Let us try to understand the meanings of thrust and pressure by considering the following situations:

Situation 1: You wish to fix a poster on a bulletin board, as shown in Fig 10.3. To do this task you will have to press drawing pins with your thumb. You apply a force on the surface area of the head of the pin. This force is directed perpendicular to the surface area of the board. This force acts on a smaller area at the tip of the pin.

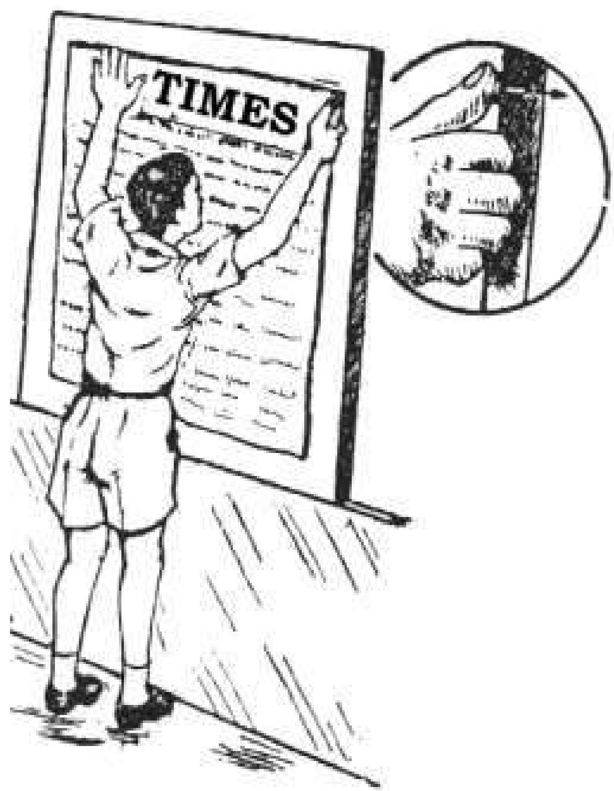


Fig. 10.3: *To fix a poster, drawing pins are pressed with the thumb perpendicular to the board.*

Situation 2: You stand on loose sand. Your feet go deep into the sand. Now, lie down on the sand. You will find that your body will not go that deep in the sand. In both cases the force exerted on the sand is the weight of your body.

You have learnt that weight is the force acting vertically downwards. Here the force is acting perpendicular to the surface of the sand. The force acting on an object perpendicular to the surface is called thrust.

When you stand on loose sand, the force, that is, the weight of your body is acting on an area equal to area of your feet. When you lie down, the same force acts on an area equal to the contact area of your whole body, which is larger than the area of your feet. Thus, the effects of forces of the same magnitude on different areas are different. In the above cases, thrust is the same. But effects are different. Therefore the effect of thrust depends on the area on which it acts.

The effect of thrust on sand is larger while standing than while lying. The thrust on unit area is called pressure. Thus,

$$\text{Pressure} = \frac{\text{thrust}}{\text{area}} \quad (10.20)$$

Substituting the SI unit of thrust and area in Eq. (10.20), we get the SI unit of pressure as N/m^2 or $N\ m^{-2}$.

In honour of scientist Blaise Pascal, the SI unit of pressure is called pascal, denoted as Pa.

Let us consider a numerical example to understand the effects of thrust acting on different areas.

Example 10.6 A block of wood is kept on a tabletop. The mass of wooden block is 5 kg and its dimensions are 40 cm × 20 cm × 10 cm. Find the pressure exerted by the wooden block on the table top if it is made to lie on the table top with its sides of dimensions (a) 20 cm × 10 cm and (b) 40 cm × 20 cm.

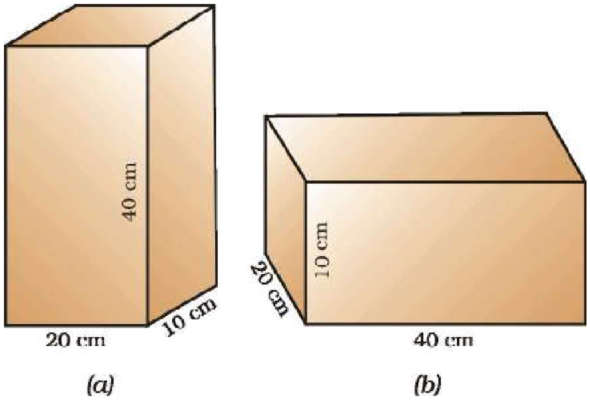


Fig. 10.4

Solution:

The mass of the wooden block = 5 kg

The dimensions

= 40 cm × 20 cm × 10 cm

Here, the weight of the wooden block applies a thrust on the table top.

That is,

$$\text{Thrust} = F = m \times g$$
$$= 5\ \text{kg} \times 9.8\ \text{m s}^{-2}$$
$$= 49\ \text{N}$$

Area of a side = length × breadth

= 20 cm × 10 cm

= 200 cm^2 = 0.02 m^2

From Eq. (10.20),

$$\text{Pressure} = \frac{49\,\text{N}}{0.02\,\text{m}^2}$$

$$= 2450\ \text{N m}^{-2}.$$

When the block lies on its side of dimensions 40 cm × 20 cm, it exerts the same thrust.

Area = length × breadth

= 40 cm × 20 cm

= 800 cm^2 = 0.08 m^2

From Eq. (10.20),

$$\text{Pressure} = \frac{49\,\text{N}}{0.08\,\text{m}^2}$$

$$= 612.5\ \text{N m}^{-2}$$

The pressure exerted by the side 20 cm × 10 cm is 2450 N m^{-2} and by the side 40 cm × 20 cm is 612.5 N m^{-2}.

Thus, the same force acting on a smaller area exerts a larger pressure, and a smaller pressure on a larger area. This is the reason why a nail has a pointed tip, knives have sharp edges and buildings have wide foundations.

10.5.1 Pressure in fluids

All liquids and gases are fluids. A solid exerts pressure on a surface due to its weight. Similarly, fluids have weight, and they also exert pressure on the base and walls of the container in which they are enclosed. Pressure exerted in any confined mass of fluid is transmitted undiminished in all directions.

10.5.2 Buoyancy

Have you ever had a swim in a pool and felt lighter? Have you ever drawn water from a well and felt that the bucket of water is heavier when it is out of the water? Have you ever wondered why a ship made of iron and steel does not sink in sea water, but while the same amount of iron and steel in the form of a sheet would sink? These questions can be answered by taking buoyancy in consideration. Let us understand the meaning of buoyancy by doing an activity.

Activity 10.4

- Take an empty plastic bottle. Close the mouth of the bottle with an airtight stopper. Put it in a bucket filled with water. You see that the bottle floats.
- Push the bottle into the water. You feel an upward push. Try to push it further down. You will find it difficult to push deeper and deeper. This indicates that water exerts a force on the bottle in the upward direction. The upward force exerted by the water goes on increasing as the bottle is pushed deeper till it is completely immersed.
- Now, release the bottle. It bounces back to the surface.
- Does the force due to the gravitational attraction of the earth act on this bottle? If so, why doesn't the bottle stay immersed in water after it is released? How can you immerse the bottle in water?

The force due to the gravitational attraction of the earth acts on the bottle in the downward direction. So the bottle is pulled downwards. But the water exerts an upward force on the bottle. Thus, the bottle is pushed upwards. We have learnt that weight of an object is the force due to gravitational attraction of the earth. When the bottle is immersed, the upward force exerted by the water on the bottle is greater than its weight. Therefore it rises up when released.

To keep the bottle completely immersed, the upward force on the bottle due to water must be balanced. This can be achieved by an externally applied force acting downwards. This force must at least be equal to the difference between the upward force and the weight of the bottle.

The upward force exerted by the water on the bottle is known as upthrust or buoyant force. In fact, all objects experience a force of buoyancy when they are immersed in a fluid. The magnitude of this buoyant force depends on the density of the fluid.

10.5.3 Why objects float or sink when placed on the surface of water?

Let us do the following activities to arrive at an answer for the above question.

Activity 10.5

- Take a beaker filled with water.
- Take an iron nail and place it on the surface of the water.
- Observe what happens.

The nail sinks. The force due to the gravitational attraction of the earth on the iron nail pulls it downwards. There is an upthrust of water on the nail, which pushes it upwards. But the downward force acting on the nail is greater than the upthrust of water on the nail. So it sinks (Fig. 10.5).

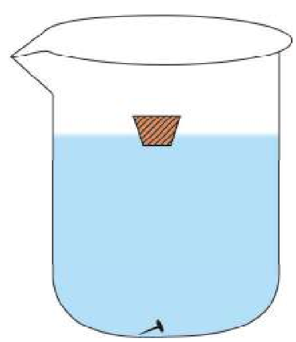


Fig. 10.5: *An iron nail sinks and a cork floats when placed on the surface of water.*

Activity ______________ 10.6

- Take a beaker filled with water.
- Take a piece of cork and an iron nail of equal mass.
- Place them on the surface of water.
- Observe what happens.

The cork floats while the nail sinks. This happens because of the difference in their densities. The density of a substance is defined as the mass per unit volume. The density of cork is less than the density of water. This means that the upthrust of water on the cork is greater than the weight of the cork. So it floats (Fig. 10.5).

The density of an iron nail is more than the density of water. This means that the upthrust of water on the iron nail is less than the weight of the nail. So it sinks.

Therefore objects of density less than that of a liquid float on the liquid. The objects of density greater than that of a liquid sink in the liquid.

Questions

1. *Why is it difficult to hold a school bag having a strap made of a thin and strong string?*
2. *What do you mean by buoyancy?*
3. *Why does an object float or sink when placed on the surface of water?*

10.6 Archimedes' Principle

Activity ______________ 10.7

- Take a piece of stone and tie it to one end of a rubber string or a spring balance.
- Suspend the stone by holding the balance or the string as shown in Fig. 10.6 (a).
- Note the elongation of the string or the reading on the spring balance due to the weight of the stone.
- Now, slowly dip the stone in the water in a container as shown in Fig. 10.6 (b).

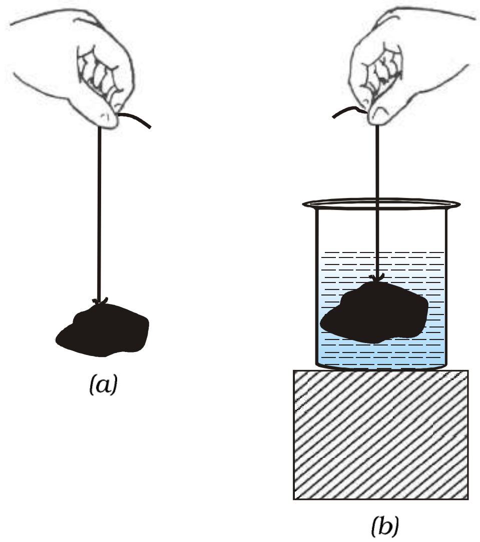


Fig. 10.6: *(a) Observe the elongation of the rubber string due to the weight of a piece of stone suspended from it in air. (b) The elongation decreases as the stone is immersed in water.*

- Observe what happens to elongation of the string or the reading on the balance.

You will find that the elongation of the string or the reading of the balance decreases as the stone is gradually lowered in the water. However, no further change is observed once the stone gets fully immersed in the water. What do you infer from the decrease in the extension of the string or the reading of the spring balance?

We know that the elongation produced in the string or the spring balance is due to the weight of the stone. Since the extension decreases once the stone is lowered in water, it means that some force acts on the stone in upward direction. As a result, the net force on the string decreases and hence the elongation also decreases. As discussed earlier, this upward force exerted by water is known as the force of buoyancy.

What is the magnitude of the buoyant force experienced by a body? Is it the same in all fluids for a given body? Do all bodies in a given fluid experience the same buoyant force? The answer to these questions is contained in Archimedes' principle, stated as follows:

When a body is immersed fully or partially in a fluid, it experiences an upward force that is equal to the weight of the fluid displaced by it.

Now, can you explain why a further decrease in the elongation of the string was not observed in activity 10.7, as the stone was fully immersed in water?

Archimedes

Archimedes was a Greek scientist. He discovered the principle, subsequently named after him, after noticing that the water in a bathtub overflowed when he stepped into it. He ran through the streets shouting "Eureka!", which means "I have got it". This knowledge helped him to determine the purity of the gold in the crown made for the king.

His work in the field of Geometry and Mechanics made him famous. His understanding of levers, pulleys, wheels-and-axle helped the Greek army in its war with Roman army.

Archimedes' principle has many applications. It is used in designing ships and submarines. Lactometers, which are used to determine the purity of a sample of milk and hydrometers used for determining density of liquids, are based on this principle.

Questions

1. *You find your mass to be 42 kg on a weighing machine. Is your mass more or less than 42 kg?*
2. *You have a bag of cotton and an iron bar, each indicating a mass of 100 kg when measured on a weighing machine. In reality, one is heavier than other. Can you say which one is heavier and why?*

10.7 Relative Density

As you know, the density of a substance is defined as mass of a unit volume. The unit of density is kilogram per metre cube (kg m^{-3}). The density of a given substance, under specified conditions, remains the same. Therefore the density of a substance is one of its characteristic properties. It is different for different substances. For example, the density of gold is 19300 kg m^{-3} while that of water is 1000 kg m^{-3}. The density of a given sample of a substance can help us to determine its purity.

It is often convenient to express density of a substance in comparison with that of water. The relative density of a substance is the ratio of its density to that of water:

$$\text{Relative density} = \frac{\text{Density of a substance}}{\text{Density of water}}$$

Since the relative density is a ratio of similar quantities, it has no unit.

Example 10.7 Relative density of silver is 10.8. The density of water is 10^3 kg m^{-3}. What is the density of silver in SI unit?

Solution:

Relative density of silver = 10.8

Relative density

$$= \frac{\text{Density of silver}}{\text{Density of water}}$$

Density of silver

$$= \text{Relative density of silver} \times \text{density of water}$$

$$= 10.8 \times 10^3 \text{ kg m}^{-3}.$$

What you have learnt

- The law of gravitation states that the force of attraction between any two objects is proportional to the product of their masses and inversely proportional to the square of the distance between them. The law applies to objects anywhere in the universe. Such a law is said to be universal.
- Gravitation is a weak force unless large masses are involved.
- The force of gravity decreases with altitude. It also varies on the surface of the earth, decreasing from poles to the equator.
- The weight of a body is the force with which the earth attracts it.
- The weight is equal to the product of mass and acceleration due to gravity.
- The weight may vary from place to place but the mass stays constant.
- All objects experience a force of buoyancy when they are immersed in a fluid.
- Objects having density less than that of the liquid in which they are immersed, float on the surface of the liquid. If the density of the object is more than the density of the liquid in which it is immersed then it sinks in the liquid.

Exercises

1. How does the force of gravitation between two objects change when the distance between them is reduced to half ?
2. Gravitational force acts on all objects in proportion to their masses. Why then, a heavy object does not fall faster than a light object?
3. What is the magnitude of the gravitational force between the earth and a 1 kg object on its surface? (Mass of the earth is 6×10^{24} kg and radius of the earth is 6.4×10^{6} m.)
4. The earth and the moon are attracted to each other by gravitational force. Does the earth attract the moon with a force that is greater or smaller or the same as the force with which the moon attracts the earth? Why?
5. If the moon attracts the earth, why does the earth not move towards the moon?

6. What happens to the force between two objects, if
   (i) the mass of one object is doubled?
   (ii) the distance between the objects is doubled and tripled?
   (iii) the masses of both objects are doubled?
7. What is the importance of universal law of gravitation?
8. What is the acceleration of free fall?
9. What do we call the gravitational force between the earth and an object?
10. Amit buys few grams of gold at the poles as per the instruction of one of his friends. He hands over the same when he meets him at the equator. Will the friend agree with the weight of gold bought? If not, why? [*Hint*: The value of g is greater at the poles than at the equator.]
11. Why will a sheet of paper fall slower than one that is crumpled into a ball?
12. Gravitational force on the surface of the moon is only $\frac{1}{6}$ as strong as gravitational force on the earth. What is the weight in newtons of a 10 kg object on the moon and on the earth?
13. A ball is thrown vertically upwards with a velocity of 49 m/s. Calculate
   (i) the maximum height to which it rises,
   (ii) the total time it takes to return to the surface of the earth.
14. A stone is released from the top of a tower of height 19.6 m. Calculate its final velocity just before touching the ground.
15. A stone is thrown vertically upward with an initial velocity of 40 m/s. Taking $g = 10\ m/s^2$, find the maximum height reached by the stone. What is the net displacement and the total distance covered by the stone?
16. Calculate the force of gravitation between the earth and the Sun, given that the mass of the earth = 6×10^{24} kg and of the Sun = 2×10^{30} kg. The average distance between the two is 1.5×10^{11} m.
17. A stone is allowed to fall from the top of a tower 100 m high and at the same time another stone is projected vertically upwards from the ground with a velocity of 25 m/s. Calculate when and where the two stones will meet.
18. A ball thrown up vertically returns to the thrower after 6 s. Find
   (a) the velocity with which it was thrown up,
   (b) the maximum height it reaches, and
   (c) its position after 4 s.

19. In what direction does the buoyant force on an object immersed in a liquid act?
20. Why does a block of plastic released under water come up to the surface of water?
21. The volume of 50 g of a substance is 20 cm^3. If the density of water is 1 g cm^{-3}, will the substance float or sink?
22. The volume of a 500 g sealed packet is 350 cm^3. Will the packet float or sink in water if the density of water is 1 g cm^{-3}? What will be the mass of the water displaced by this packet?

Chapter 11

Work and Energy

In the previous few chapters we have talked about ways of describing the motion of objects, the cause of motion and gravitation. Another concept that helps us understand and interpret many natural phenomena is 'work'. Closely related to work are energy and power. In this chapter we shall study these concepts.

All living beings need food. Living beings have to perform several basic activities to survive. We call such activities 'life processes'. The energy for these processes comes from food. We need energy for other activities like playing, singing, reading, writing, thinking, jumping, cycling and running. Activities that are strenuous require more energy.

Animals too get engaged in activities. For example, they may jump and run. They have to fight, move away from enemies, find food or find a safe place to live. Also, we engage some animals to lift weights, carry loads, pull carts or plough fields. All such activities require energy.

Think of machines. List the machines that you have come across. What do they need for their working? Why do some engines require fuel like petrol and diesel? Why do living beings and machines need energy?

11.1 Work

What is work? There is a difference in the way we use the term 'work' in day-to-day life and the way we use it in science. To make this point clear let us consider a few examples.

11.1.1 Not much 'work' in spite of working hard!

Kamali is preparing for examinations. She spends lot of time in studies. She reads books, draws diagrams, organises her thoughts, collects question papers, attends classes, discusses problems with her friends, and performs experiments. She expends a lot of energy on these activities. In common parlance, she is 'working hard'. All this 'hard work' may involve very little 'work' if we go by the scientific definition of work.

You are working hard to push a huge rock. Let us say the rock does not move despite all the effort. You get completely exhausted. However, you have not done any work on the rock as there is no displacement of the rock.

You stand still for a few minutes with a heavy load on your head. You get tired. You have exerted yourself and have spent quite a bit of your energy. Are you doing work on the load? The way we understand the term 'work' in science, work is not done.

You climb up the steps of a staircase and reach the second floor of a building just to see the landscape from there. You may even climb up a tall tree. If we apply the scientific definition, these activities involve a lot of work.

In day-to-day life, we consider any useful physical or mental labour as work. Activities like playing in a field, talking with friends, humming a tune, watching a movie, attending a function are sometimes not considered to be work. What constitutes 'work' depends on the way we define it. We use and define the term work differently in science. To understand this let us do the following activities:

Activity ______________ *11.1*

- We have discussed in the above paragraphs a number of activities which we normally consider to be work in day-to-day life. For each of these activities, ask the following questions and answer them:

(i) What is the work being done on?
(ii) What is happening to the object?
(iii) Who (what) is doing the work?

11.1.2 Scientific conception of work

To understand the way we view work and define work from the point of view of science, let us consider some situations:

Push a pebble lying on a surface. The pebble moves through a distance. You exerted a force on the pebble and the pebble got displaced. In this situation work is done.

A girl pulls a trolley and the trolley moves through a distance. The girl has exerted a force on the trolley and it is displaced. Therefore, work is done.

Lift a book through a height. To do this you must apply a force. The book rises up. There is a force applied on the book and the book has moved. Hence, work is done.

A closer look at the above situations reveals that two conditions need to be satisfied for work to be done: (i) a force should act on an object, and (ii) the object must be displaced.

If any one of the above conditions does not exist, work is not done. This is the way we view work in science.

A bullock is pulling a cart. The cart moves. There is a force on the cart and the cart has moved. Do you think that work is done in this situation?

Activity 11.2

- Think of some situations from your daily life involving work.
- List them.
- Discuss with your friends whether work is being done in each situation.
- Try to reason out your response.
- If work is done, which is the force acting on the object?
- What is the object on which the work is done?
- What happens to the object on which work is done?

Activity 11.3

- Think of situations when the object is not displaced in spite of a force acting on it.
- Also think of situations when an object gets displaced in the absence of a force acting on it.
- List all the situations that you can think of for each.
- Discuss with your friends whether work is done in these situations.

11.1.3 Work done by a constant force

How is work defined in science? To understand this, we shall first consider the case when the force is acting in the direction of displacement.

Let a constant force, F act on an object. Let the object be displaced through a distance, s in the direction of the force (Fig. 11.1). Let W be the work done. We define work to be equal to the product of the force and displacement.

$$\text{Work done} = \text{force} \times \text{displacement}$$

$$W = F\,s \qquad (11.1)$$

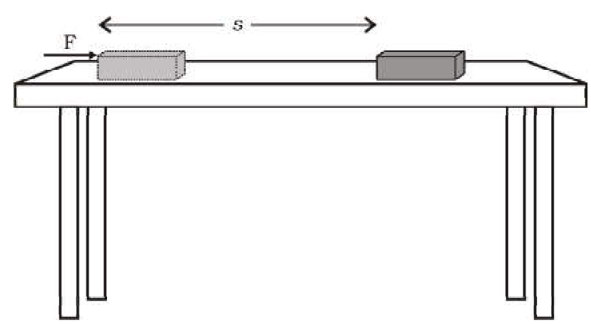


Fig. 11.1

Thus, work done by a force acting on an object is equal to the magnitude of the force multiplied by the distance moved in the direction of the force. Work has only magnitude and no direction.

In Eq. (11.1), if F = 1 N and s = 1 m then the work done by the force will be 1 N m. Here the unit of work is newton metre (N m) or joule (J). Thus 1 J is the amount of work done on an object when a force of 1 N displaces it by 1 m along the line of action of the force.

Look at Eq. (11.1) carefully. What is the work done when the force on the object is zero? What would be the work done when the displacement of the object is zero? Refer to the conditions that are to be satisfied to say that work is done.

Example 11.1 A force of 5 N is acting on an object. The object is displaced through 2 m in the direction of the force (Fig. 11.2). If the force acts on the object all through the displacement, then work done is 5 N × 2 m =10 N m or 10 J.

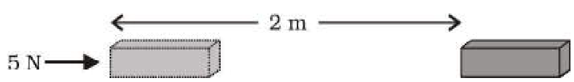


Fig. 11.2

Question

1. *A force of 7 N acts on an object. The displacement is, say 8 m, in the direction of the force (Fig. 11.3). Let us take it that the force acts on the object through the displacement. What is the work done in this case?*

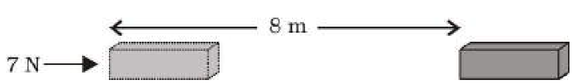


Fig. 11.3

Consider another situation in which the force and the displacement are in the same direction: a baby pulling a toy car parallel to the ground, as shown in Fig. 11.4. The baby has exerted a force in the direction of displacement of the car. In this situation, the work done will be equal to the product of the force and displacement. In such situations, the work done by the force is taken as positive.

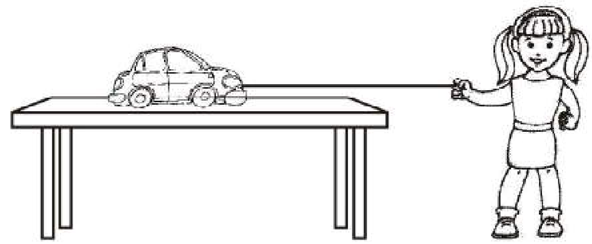


Fig. 11.4

Consider a situation in which an object is moving with a uniform velocity along a particular direction. Now a retarding force, F, is applied in the opposite direction. That is, the angle between the two directions is 180º. Let the object stop after a displacement *s*. In such a situation, the work done by the force, *F* is taken as negative and denoted by the minus sign. The work done by the force is $F \times (-s)$ or $(-F \times s)$.

It is clear from the above discussion that the work done by a force can be either positive or negative. To understand this, let us do the following activity:

Activity _____________ *11.4*

- Lift an object up. Work is done by the force exerted by you on the object. The object moves upwards. The force you exerted is in the direction of displacement. However, there is the force of gravity acting on the object.
- Which one of these forces is doing positive work?
- Which one is doing negative work?
- Give reasons.

Work done is negative when the force acts opposite to the direction of displacement. Work done is positive when the force is in the direction of displacement.

Example 11.2 A porter lifts a luggage of 15 kg from the ground and puts it on his head 1.5 m above the ground. Calculate the work done by him on the luggage.

Solution:

Mass of luggage, m = 15 kg and displacement, s = 1.5 m.

$$
\begin{aligned}
\text{Work done, } W &= F \times s = mg \times s \\
&= 15\ \text{kg} \times 10\ \text{m s}^{-2} \times 1.5\ \text{m} \\
&= 225\ \text{kg m s}^{-2}\ \text{m} \\
&= 225\ \text{N m} = 225\ \text{J}
\end{aligned}
$$

Work done is 225 J.

Questions

1. *When do we say that work is done?*
2. *Write an expression for the work done when a force is acting on an object in the direction of its displacement.*
3. *Define 1 J of work.*
4. *A pair of bullocks exerts a force of 140 N on a plough. The field being ploughed is 15 m long. How much work is done in ploughing the length of the field?*

11.2 Energy

Life is impossible without energy. The demand for energy is ever increasing. Where do we get energy from? The Sun is the biggest natural source of energy to us. Many of our energy sources are derived from the Sun. We can also get energy from the nuclei of atoms, the interior of the earth, and the tides. Can you think of other sources of energy?

Activity 11.5

- A few sources of energy are listed above. There are many other sources of energy. List them.
- Discuss in small groups how certain sources of energy are due to the Sun.
- Are there sources of energy which are not due to the Sun?

The word energy is very often used in our daily life, but in science we give it a definite and precise meaning. Let us consider the following examples: when a fast moving cricket ball hits a stationary wicket, the wicket is thrown away. Similarly, an object when raised to a certain height gets the capability to do work. You must have seen that when a raised hammer falls on a nail placed on a piece of wood, it drives the nail into the wood. We have also observed children winding a toy (such as a toy car) and when the toy is placed on the floor, it starts moving. When a balloon is filled with air and we press it we notice a change in its shape. As long as we press it gently, it can come back to its original shape when the force is withdrawn. However, if we press the balloon hard, it can even explode producing a blasting sound. In all these examples, the objects acquire, through different means, the capability of doing work. An object having a capability to do work is said to possess energy. The object which does the work loses energy and the object on which the work is done gains energy.

How does an object with energy do work? An object that possesses energy can exert a force on another object. When this happens, energy is transferred from the former to the latter. The second object may move as it receives energy and therefore do some work. Thus, the first object had a capacity to do work. This implies that any object that possesses energy can do work.

The energy possessed by an object is thus measured in terms of its capacity of doing work. The unit of energy is, therefore, the same as that of work, that is, joule (J). 1 J is the energy required to do 1 joule of work. Sometimes a larger unit of energy called kilo joule (kJ) is used. 1 kJ equals 1000 J.

11.2.1 Forms of Energy

Luckily the world we live in provides energy in many different forms. The various forms include mechanical energy (potential energy + kinetic energy), heat energy, chemical energy, electrical energy and light energy.

Think it over !

How do you know that some entity is a form of energy? Discuss with your friends and teachers.

James Prescott Joule
(1818 – 1889)

James Prescott Joule was an outstanding British physicist. He is best known for his research in electricity and thermodynamics. Amongst other things, he formulated a law for the heating effect of electric current. He also verified experimentally the law of conservation of energy and discovered the value of the mechanical equivalent of heat. The unit of energy and work called joule, is named after him.

11.2.2 Kinetic energy

Activity ______________ 11.6

- Take a heavy ball. Drop it on a thick bed of sand. A wet bed of sand would be better. Drop the ball on the sand bed from height of about 25 cm. The ball creates a depression.
- Repeat this activity from heights of 50 cm, 1m and 1.5 m.
- Ensure that all the depressions are distinctly visible.
- Mark the depressions to indicate the height from which the ball was dropped.
- Compare their depths.
- Which one of them is deepest?
- Which one is shallowest? Why?
- What has caused the ball to make a deeper dent?
- Discuss and analyse.

Activity ______________ 11.7

- Set up the apparatus as shown in Fig. 11.5.
- Place a wooden block of known mass in front of the trolley at a convenient fixed distance.
- Place a known mass on the pan so that the trolley starts moving.

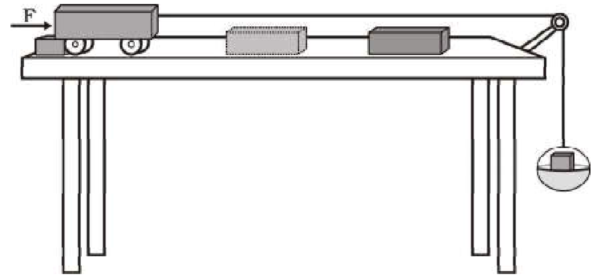


Fig. 11.5

- The trolley moves forward and hits the wooden block.
- Fix a stop on the table in such a manner that the trolley stops after hitting the block. The block gets displaced.
- Note down the displacement of the block. This means work is done on the block by the trolley as the block has gained energy.
- From where does this energy come?
- Repeat this activity by increasing the mass on the pan. In which case is the displacement more?
- In which case is the work done more?
- In this activity, the moving trolley does work and hence it possesses energy.

A moving object can do work. An object moving faster can do more work than an identical object moving relatively slow. A moving bullet, blowing wind, a rotating wheel, a speeding stone can do work. How does a bullet pierce the target? How does the wind move the blades of a windmill? Objects in motion possess energy. We call this energy kinetic energy.

A falling coconut, a speeding car, a rolling stone, a flying aircraft, flowing water, blowing wind, a running athlete etc. possess kinetic energy. In short, kinetic energy is the energy possessed by an object due to its motion. The kinetic energy of an object increases with its speed.

How much energy is possessed by a moving body by virtue of its motion? By definition, we say that the kinetic energy of a body moving with a certain velocity is equal to the work done on it to make it acquire that velocity.

Let us now express the kinetic energy of an object in the form of an equation. Consider an object of mass, m moving with a uniform velocity, u. Let it now be displaced through a distance s when a constant force, F acts on it in the direction of its displacement. From Eq. (11.1), the work done, W is $F\,s$. The work done on the object will cause a change in its velocity. Let its velocity change from u to v. Let a be the acceleration produced.

In section 8.5, we studied three equations of motion. The relation connecting the initial velocity (u) and final velocity (v) of an object moving with a uniform acceleration a, and the displacement, s is

$$v^2 - u^2 = 2a\,s \qquad (8.7)$$

This gives

$$s = \frac{v^2 - u^2}{2a} \qquad (11.2)$$

From section 9.4, we know $F = m\,a$. Thus, using (Eq. 11.2) in Eq. (11.1), we can write the work done by the force, F as

$$W = m\,a \times \left(\frac{v^2 - u^2}{2a}\right)$$

or

$$W = \frac{1}{2} m \left(v^2 - u^2\right) \qquad (11.3)$$

If the object is starting from its stationary position, that is, $u = 0$, then

$$W = \frac{1}{2} m\,v^2 \qquad (11.4)$$

It is clear that the work done is equal to the change in the kinetic energy of an object.

If $u = 0$, the work done will be $\frac{1}{2} m\,v^2$.

Thus, the kinetic energy possessed by an object of mass, m and moving with a uniform velocity, v is

$$E_k = \frac{1}{2} m\,v^2 \qquad (11.5)$$

Example 11.3 An object of mass 15 kg is moving with a uniform velocity of 4 m s^{-1}. What is the kinetic energy possessed by the object?

Solution:

Mass of the object, m = 15 kg, velocity of the object, v = 4 m s^{-1}.
From Eq. (11.5),

$$E_k = \frac{1}{2} m\,v^2$$

$$= \frac{1}{2} \times 15 \text{ kg} \times 4 \text{ m s}^{-1} \times 4 \text{ m s}^{-1}$$

$$= 120 \text{ J}$$

The kinetic energy of the object is 120 J.

Example 11.4 What is the work to be done to increase the velocity of a car from 30 km h^{-1} to 60 km h^{-1} if the mass of the car is 1500 kg?

Solution:

Mass of the car, m =1500 kg,
initial velocity of car, u = 30 km h^{-1}

$$= \frac{30 \times 1000 \text{ m}}{60 \times 60 \text{ s}}$$

$$= 25/3 \text{ m s}^{-1}.$$

Similarly, the final velocity of the car,

$$v = 60 \text{ km h}^{-1}$$
$$= 50/3 \text{ m s}^{-1}.$$

Therefore, the initial kinetic energy of the car,

$$E_{ki} = \frac{1}{2} m\,u^2$$

$$= \frac{1}{2} \times 1500 \text{ kg} \times (25/3 \text{ m s}^{-1})^2$$

$$= 156250/3 \text{ J}.$$

The final kinetic energy of the car,

$$E_{kf} = \frac{1}{2} \times 1500 \text{ kg} \times (50/3 \text{ m s}^{-1})^2$$

$$= 625000/3 \text{ J}.$$

Thus, the work done = Change in kinetic energy

$$= E_{kf} - E_{ki}$$

$$= 156250 \text{ J}.$$

Questions

1. *What is the kinetic energy of an object?*
2. *Write an expression for the kinetic energy of an object.*
3. *The kinetic energy of an object of mass, m moving with a velocity of 5 m s^{-1} is 25 J. What will be its kinetic energy when its velocity is doubled? What will be its kinetic energy when its velocity is increased three times?*

11.2.3 POTENTIAL ENERGY

Activity 11.8

- Take a rubber band.
- Hold it at one end and pull from the other. The band stretches.
- Release the band at one of the ends.
- What happens?
- The band will tend to regain its original length. Obviously the band had acquired energy in its stretched position.
- How did it acquire energy when stretched?

Activity 11.9

- Take a slinky as shown below.
- Ask a friend to hold one of its ends. You hold the other end and move away from your friend. Now you release the slinky.

- What happened?
- How did the slinky acquire energy when stretched?
- Would the slinky acquire energy when it is compressed?

Activity 11.10

- Take a toy car. Wind it using its key.
- Place the car on the ground.
- Did it move?
- From where did it acquire energy?
- Does the energy acquired depend on the number of windings?
- How can you test this?

Activity 11.11

- Lift an object through a certain height. The object can now do work. It begins to fall when released.
- This implies that it has acquired some energy. If raised to a greater height it can do more work and hence possesses more energy.
- From where did it get the energy? Think and discuss.

In the above situations, the energy gets stored due to the work done on the object. The energy transferred to an object is stored as potential energy if it is not used to cause a change in the velocity or speed of the object.

You transfer energy when you stretch a rubber band. The energy transferred to the band is its potential energy. You do work while winding the key of a toy car. The energy transferred to the spring inside is stored as potential energy. The potential energy possessed by the object is the energy present in it by virtue of its position or configuration.

Activity 11.12

- Take a bamboo stick and make a bow as shown in Fig. 11.6.
- Place an arrow made of a light stick on it with one end supported by the stretched string.
- Now stretch the string and release the arrow.
- Notice the arrow flying off the bow. Notice the change in the shape of the bow.
- The potential energy stored in the bow due to the change of shape is thus used in the form of kinetic energy in throwing off the arrow.

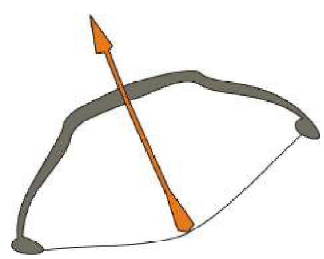


Fig.11.6: *An arrow and the stretched string on the bow.*

11.2.4 Potential energy of an object at a height

An object increases its energy when raised through a height. This is because work is done on it against gravity while it is being raised. The energy present in such an object is the gravitational potential energy.

The gravitational potential energy of an object at a point above the ground is defined as the work done in raising it from the ground to that point against gravity.

It is easy to arrive at an expression for the gravitational potential energy of an object at a height.

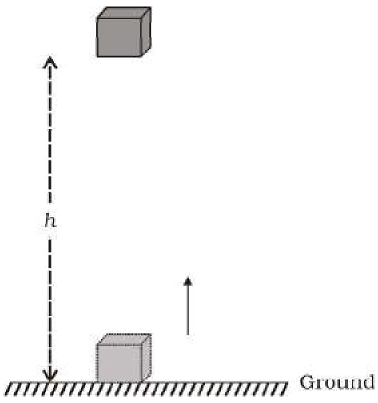


Fig. 11.7

Consider an object of mass, m. Let it be raised through a height, h from the ground. A force is required to do this. The minimum force required to raise the object is equal to the weight of the object, mg. The object gains energy equal to the work done on it. Let the work done on the object against gravity be W. That is,

$$\text{work done, } W = \text{force} \times \text{displacement}$$
$$= mg \times h$$
$$= mgh$$

Since work done on the object is equal to mgh, an energy equal to mgh units is gained by the object. This is the potential energy (E_p) of the object.

$$E_p = mgh \qquad (11.7)$$

More to know

The potential energy of an object at a height depends on the ground level or the zero level you choose. An object in a given position can have a certain potential energy with respect to one level and a different value of potential energy with respect to another level.

It is useful to note that the work done by gravity depends on the difference in vertical heights of the initial and final positions of the object and not on the path along which the object is moved. Fig. 11.8 shows a case where a block is raised from position A to B by taking two different paths. Let the height AB = h. In both the situations the work done on the object is mgh.

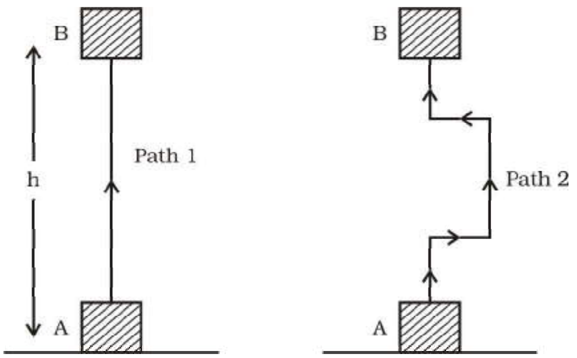


Fig. 11.8

Example 11.5 Find the energy possessed by an object of mass 10 kg when it is at a height of 6 m above the ground. Given, $g = 9.8 \text{ m s}^{-2}$.

Solution:

Mass of the object, m = 10 kg, displacement (height), h = 6 m, and acceleration due to gravity, $g = 9.8 \text{ m s}^{-2}$.

From Eq. (11.6),

Potential energy = mgh

$= 10 \text{ kg} \times 9.8 \text{ m s}^{-2} \times 6 \text{ m}$

$= 588$ J.

The potential energy is 588 J.

Example 11.6 An object of mass 12 kg is at a certain height above the ground. If the potential energy of the object is 480 J, find the height at which the object is with respect to the ground. Given, $g = 10 \text{ m s}^{-2}$.

Solution:

Mass of the object, $m = 12$ kg,
potential energy, $E_p = 480$ J.

$$E_p = mgh$$
$$480 \text{ J} = 12 \text{ kg} \times 10 \text{ m s}^{-2} \times h$$
$$h = \frac{480 \text{ J}}{120 \text{ kg m s}^{-2}} = 4 \text{ m.}$$

The object is at the height of 4 m.

11.2.5 Are various energy forms interconvertible?

Can we convert energy from one form to another? We find in nature a number of instances of conversion of energy from one form to another.

Activity ______________ *11.13*

- Sit in small groups.
- Discuss the various ways of energy conversion in nature.
- Discuss following questions in your group:
  - (a) How do green plants produce food?
  - (b) Where do they get their energy from?
  - (c) Why does the air move from place to place?
  - (d) How are fuels, such as coal and petroleum formed?
  - (e) What kinds of energy conversions sustain the water cycle?

Activity ______________ *11.14*

- Many of the human activities and the gadgets we use involve conversion of energy from one form to another.
- Make a list of such activities and gadgets.
- Identify in each activity/gadget the kind of energy conversion that takes place.

11.2.6 Law of conservation of energy

In activities 11.13 and 11.14, we learnt that the form of energy can be changed from one form to another. What happens to the total energy of a system during or after the process? Whenever energy gets transformed, the total energy remains unchanged. This is the law of conservation of energy. According to this law, energy can only be converted from one form to another; it can neither be created or destroyed. The total energy before and after the transformation remains the same. The law of conservation of energy is valid in all situations and for all kinds of transformations.

Consider a simple example. Let an object of mass, m be made to fall freely from a height, h. At the start, the potential energy is mgh and kinetic energy is zero. Why is the kinetic energy zero? It is zero because its velocity is zero. The total energy of the object is thus mgh. As it falls, its potential energy will change into kinetic energy. If v is the velocity of the object at a given instant, the kinetic energy would be $\frac{1}{2}mv^2$. As the fall of the object continues, the potential energy would decrease while the kinetic energy would increase. When the object is about to reach the ground, $h = 0$ and v will be the highest. Therefore, the kinetic energy would be the largest and potential energy the least. However, the sum of the potential energy and kinetic energy of the object would be the same at all points. That is,

potential energy + kinetic energy = constant

or

$$mgh + \frac{1}{2}mv^2 = \text{constant.} \qquad (11.7)$$

The sum of kinetic energy and potential energy of an object is its total mechanical energy.

We find that during the free fall of the object, the decrease in potential energy, at any point in its path, appears as an equal amount of increase in kinetic energy. (Here the effect of air resistance on the motion of the object has been ignored.) There is thus a continual transformation of gravitational potential energy into kinetic energy.

Activity 11.15

- An object of mass 20 kg is dropped from a height of 4 m. Fill in the blanks in the following table by computing the potential energy and kinetic energy in each case.

Height at which object is located m	Potential energy ($E_p = mgh$) J	Kinetic energy ($E_k = mv^2/2$) J	$E_p + E_k$ J
4			
3			
2			
1			
Just above the ground			

- For simplifying the calculations, take the value of g as 10 m s^{-2}.

Think it over !

What would have happened if nature had not allowed the transformation of energy? There is a view that life could not have been possible without transformation of energy. Do you agree with this?

11.3 Rate of Doing Work

Do all of us work at the same rate? Do machines consume or transfer energy at the same rate? Agents that transfer energy do work at different rates. Let us understand this from the following activity:

Activity 11.16

- Consider two children, say A and B. Let us say they weigh the same. Both start climbing up a rope separately. Both reach a height of 8 m. Let us say A takes 15 s while B takes 20 s to accomplish the task.
- What is the work done by each?
- The work done is the same. However, A has taken less time than B to do the work.
- Who has done more work in a given time, say in 1 s?

A stronger person may do certain work in relatively less time. A more powerful vehicle would complete a journey in a shorter time than a less powerful one. We talk of the power of machines like motorbikes and motorcars. The speed with which these vehicles change energy or do work is a basis for their classification. Power measures the speed of work done, that is, how fast or slow work is done. Power is defined as the rate of doing work or the rate of transfer of energy. If an agent does a work W in time t, then power is given by:

Power = work/time

or $$P = \frac{W}{t} \qquad (11.8)$$

The unit of power is watt [in honour of James Watt (1736 – 1819)] having the symbol W. 1 watt is the power of an agent, which does work at the rate of 1 joule per second. We can also say that power is 1 W when the rate of consumption of energy is 1 J s^{-1}.

1 watt = 1 joule/second or 1 W = 1 J s^{-1}.

We express larger rates of energy transfer in kilowatts (kW).

1 kilowatt = 1000 watts
1 kW = 1000 W
1 kW = 1000 J s^{-1}.

The power of an agent may vary with time. This means that the agent may be doing work at different rates at different intervals of time. Therefore the concept of average power is useful. We obtain average power by dividing the total energy consumed by the total time taken.

Example 11.7 Two girls, each of weight 400 N climb up a rope through a height of 8 m. We name one of the girls A and the other B. Girl A takes 20 s while B takes 50 s to accomplish this task. What is the power expended by each girl?

Solution:

(i) Power expended by girl A:
Weight of the girl, mg = 400 N
Displacement (height), h = 8 m

Time taken, $t = 20$ s
From Eq. (11.8),

$$\text{Power, } P = \text{Work done/time taken} = \frac{mgh}{t} = \frac{400 \text{ N} \times 8 \text{ m}}{20 \text{ s}} = 160 \text{ W.}$$

(ii) Power expended by girl B:
Weight of the girl, $mg = 400$ N
Displacement (height), $h = 8$ m
Time taken, $t = 50$ s

$$\text{Power, } P = \frac{mgh}{t} = \frac{400 \text{ N} \times 8 \text{ m}}{50 \text{ s}} = 64 \text{ W.}$$

Power expended by girl A is 160 W.
Power expended by girl B is 64 W.

Example 11.8 A boy of mass 50 kg runs up a staircase of 45 steps in 9 s. If the height of each step is 15 cm, find his power. Take $g = 10 \text{ m s}^{-2}$.

Solution:

Weight of the boy,
$mg = 50 \text{ kg} \times 10 \text{ m s}^{-2} = 500$ N
Height of the staircase,
$h = 45 \times 15/100 \text{ m} = 6.75$ m
Time taken to climb, $t = 9$ s
From Eq. (11.8),
power, P = Work done/time taken

$$= \frac{mgh}{t} = \frac{500 \text{ N} \times 6.75 \text{ m}}{9 \text{ s}} = 375 \text{ W.}$$

Power is 375 W.

Questions

1. What is power?
2. Define 1 watt of power.
3. A lamp consumes 1000 J of electrical energy in 10 s. What is its power?
4. Define average power.

11.3.1 Commercial Unit of Energy

The unit joule is too small and hence is inconvenient to express large quantities of energy. We use a bigger unit of energy called kilowatt hour (kW h).

What is 1 kW h? Let us say we have a machine that uses 1000 J of energy every second. If this machine is used continuously for one hour, it will consume 1 kW h of energy. Thus, 1 kW h is the energy used in one hour at the rate of 1000 J s^{-1} (or 1 kW).

$$1 \text{ kW h} = 1 \text{ kW} \times 1 \text{ h} = 1000 \text{ W} \times 3600 \text{ s} = 3600000 \text{ J}$$

$$1 \text{ kW h} = 3.6 \times 10^6 \text{ J.}$$

The energy used in households, industries and commercial establishments are usually expressed in kilowatt hour. For example, electrical energy used during a month is expressed in terms of 'units'. Here, 1 'unit' means 1 kilowatt hour.

Example 11.9 An electric bulb of 60 W is used for 6 h per day. Calculate the 'units' of energy consumed in one day by the bulb.

Solution:

Power of electric bulb = 60 W
= 0.06 kW.
Time used, t = 6 h
Energy = power × time taken
= 0.06 kW × 6 h
= 0.36 kW h
= 0.36 'units'.

The energy consumed by the bulb is 0.36 'units'.

Activity ______________ 11.17

- Take a close look at the electric meter installed in your house. Observe its features closely.
- Take the readings of the meter each day at 6.30 am and 6.30 pm.
- Do this activity for about a week.
- How many 'units' are consumed during day time?
- How many 'units' are used during night?
- Tabulate your observations.
- Draw inferences from the data.
- Compare your observations with the details given in the monthly electricity bill (One can also estimate the electricity to be consumed by specific appliances by tabulating their known wattages and hours of operation).

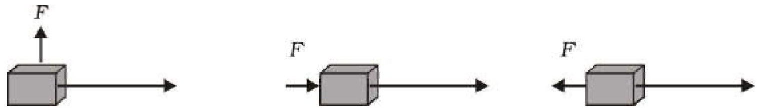
What you have learnt

- Work done on an object is defined as the magnitude of the force multiplied by the distance moved by the object in the direction of the applied force. The unit of work is joule: 1 joule = 1 newton × 1 metre.
- Work done on an object by a force would be zero if the displacement of the object is zero.
- An object having capability to do work is said to possess energy. Energy has the same unit as that of work.
- An object in motion possesses what is known as the kinetic energy of the object. An object of mass, m moving with velocity v has a kinetic energy of $\frac{1}{2}mv^2$.
- The energy possessed by a body due to its change in position or shape is called the potential energy. The gravitational potential energy of an object of mass, m raised through a height, h from the earth's surface is given by $m\,g\,h$.
- According to the law of conservation of energy, energy can only be transformed from one form to another; it can neither be created nor destroyed. The total energy before and after the transformation always remains constant.
- Energy exists in nature in several forms such as kinetic energy, potential energy, heat energy, chemical energy etc. The sum of the kinetic and potential energies of an object is called its mechanical energy.
- Power is defined as the rate of doing work. The SI unit of power is watt. 1 W = 1 J/s.
- The energy used in one hour at the rate of 1kW is called 1 kW h.

Exercises

1. Look at the activities listed below. Reason out whether or not work is done in the light of your understanding of the term 'work'.
   - Suma is swimming in a pond.
   - A donkey is carrying a load on its back.
   - A wind-mill is lifting water from a well.
   - A green plant is carrying out photosynthesis.
   - An engine is pulling a train.
   - Food grains are getting dried in the sun.
   - A sailboat is moving due to wind energy.
2. An object thrown at a certain angle to the ground moves in a curved path and falls back to the ground. The initial and the final points of the path of the object lie on the same horizontal line. What is the work done by the force of gravity on the object?
3. A battery lights a bulb. Describe the energy changes involved in the process.
4. Certain force acting on a 20 kg mass changes its velocity from 5 m s^{-1} to 2 m s^{-1}. Calculate the work done by the force.
5. A mass of 10 kg is at a point A on a table. It is moved to a point B. If the line joining A and B is horizontal, what is the work done on the object by the gravitational force? Explain your answer.
6. The potential energy of a freely falling object decreases progressively. Does this violate the law of conservation of energy? Why?
7. What are the various energy transformations that occur when you are riding a bicycle?
8. Does the transfer of energy take place when you push a huge rock with all your might and fail to move it? Where is the energy you spend going?
9. A certain household has consumed 250 units of energy during a month. How much energy is this in joules?
10. An object of mass 40 kg is raised to a height of 5 m above the ground. What is its potential energy? If the object is allowed to fall, find its kinetic energy when it is half-way down.
11. What is the work done by the force of gravity on a satellite moving round the earth? Justify your answer.
12. Can there be displacement of an object in the absence of any force acting on it? Think. Discuss this question with your friends and teacher.

13. A person holds a bundle of hay over his head for 30 minutes and gets tired. Has he done some work or not? Justify your answer.
14. An electric heater is rated 1500 W. How much energy does it use in 10 hours?
15. Illustrate the law of conservation of energy by discussing the energy changes which occur when we draw a pendulum bob to one side and allow it to oscillate. Why does the bob eventually come to rest? What happens to its energy eventually? Is it a violation of the law of conservation of energy?
16. An object of mass, m is moving with a constant velocity, v. How much work should be done on the object in order to bring the object to rest?
17. Calculate the work required to be done to stop a car of 1500 kg moving at a velocity of 60 km/h?
18. In each of the following a force, F is acting on an object of mass, m. The direction of displacement is from west to east shown by the longer arrow. Observe the diagrams carefully and state whether the work done by the force is negative, positive or zero.



19. Soni says that the acceleration in an object could be zero even when several forces are acting on it. Do you agree with her? Why?
20. Find the energy in kW h consumed in 10 hours by four devices of power 500 W each.
21. A freely falling object eventually stops on reaching the ground. What happenes to its kinetic energy?

Chapter 12

SOUND

Everyday we hear sounds from various sources like humans, birds, bells, machines, vehicles, televisions, radios etc. Sound is a form of energy which produces a sensation of hearing in our ears. There are also other forms of energy like mechanical energy, light energy etc. We have talked about mechanical energy in the previous chapters. You have been taught about conservation of energy, which states that we can neither create nor destroy energy. We can just change it from one form to another. When you clap, a sound is produced. Can you produce sound without utilising your energy? Which form of energy did you use to produce sound? In this chapter we are going to learn how sound is produced and how it is transmitted through a medium and received by our ears.

12.1 Production of Sound

Activity ______________ 12.1

- Take a tuning fork and set it vibrating by striking its prong on a rubber pad. Bring it near your ear.
- Do you hear any sound?
- Touch one of the prongs of the vibrating tuning fork with your finger and share your experience with your friends.
- Now, suspend a table tennis ball or a small plastic ball by a thread from a support [Take a big needle and a thread, put a knot at one end of the thread, and then with the help of the needle pass the thread through the ball]. Touch the ball gently with the prong of a vibrating tuning fork (Fig. 12.1).
- Observe what happens and discuss with your friends.

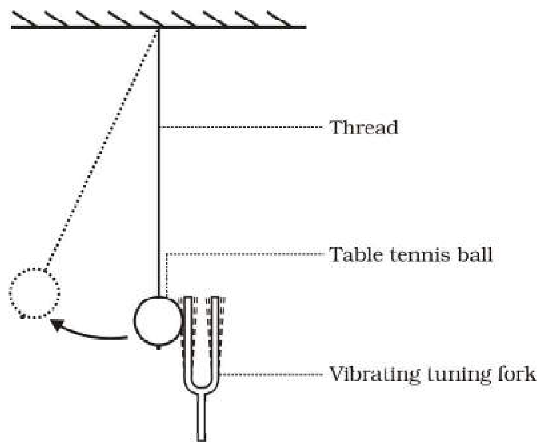


Fig. 12.1: *Vibrating tuning fork just touching the suspended table tennis ball.*

Activity ______________ 12.2

- Fill water in a beaker or a glass up to the brim. Gently touch the water surface with one of the prongs of the vibrating tuning fork, as shown in Fig. 12.2.
- Next dip the prongs of the vibrating tuning fork in water, as shown in Fig. 12.3.
- Observe what happens in both the cases.
- Discuss with your friends why this happens.

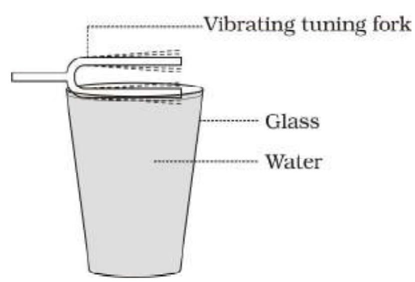


Fig. 12.2: *One of the prongs of the vibrating tuning fork touching the water surface.*

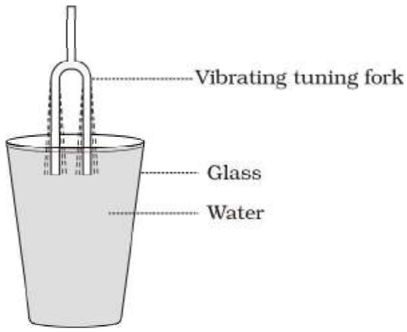


Fig. 12.3: *Both the prongs of the vibrating tuning fork dipped in water.*

From the above activities what do you conclude? Can you produce sound without a vibrating object?

In the above activities we have produced sound by striking the tuning fork. We can also produce sound by plucking, scratching, rubbing, blowing or shaking different objects. As per the above activities what do we do to the objects? We set the objects vibrating and produce sound. Vibration means a kind of rapid to and fro motion of an object. The sound of the human voice is produced due to vibrations in the vocal cords. When a bird flaps its wings, do you hear any sound? Think how the buzzing sound accompanying a bee is produced. A stretched rubber band when plucked vibrates and produces sound. If you have never done this, then do it and observe the vibration of the stretched rubber band.

Activity ____________ *12.3*

- Make a list of different types of musical instruments and discuss with your friends which part of the instrument vibrates to produce sound.

12.2 Propagation of Sound

Sound is produced by vibrating objects. The matter or substance through which sound is transmitted is called a medium. It can be solid, liquid or gas. Sound moves through a medium from the point of generation to the listener. When an object vibrates, it sets the particles of the medium around it vibrating. The particles do not travel all the way from the vibrating object to the ear. A particle of the medium in contact with the vibrating object is first displaced from its equilibrium position. It then exerts a force on the adjacent particle. As a result of which the adjacent particle gets displaced from its position of rest. After displacing the adjacent particle the first particle comes back to its original position. This process continues in the medium till the sound reaches your ear. The disturbance created by a source of sound in

Can sound make a light spot dance?

Take a tin-can. Remove both ends to make it a hollow cylinder. Take a balloon and stretch it over the can, then wrap a rubber band around the balloon. Take a small piece of mirror. Use a drop of glue to stick the piece of mirror to the balloon. Allow the light through a slit to fall on the mirror. After reflection the light spot is seen on the wall, as shown in Fig. 12.4. Talk or shout directly into the open end of the can and observe the dancing light spot on the wall. Discuss with your friends what makes the light spot dance.

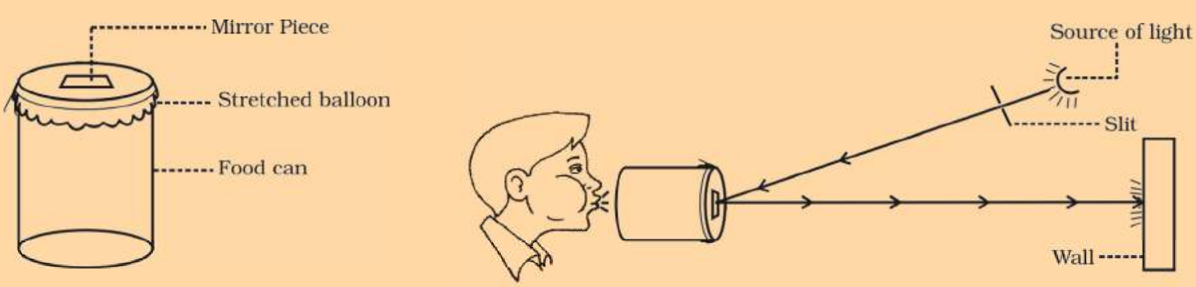


Fig. 12.4: *A beam of light from a light source is made to fall on a mirror. The reflected light is falling on the wall.*

the medium travels through the medium and not the particles of the medium.

A wave is a disturbance that moves through a medium when the particles of the medium set neighbouring particles into motion. They in turn produce similar motion in others. The particles of the medium do not move forward themselves, but the disturbance is carried forward. This is what happens during propagation of sound in a medium, hence sound can be visualised as a wave. Sound waves are characterised by the motion of particles in the medium and are called mechanical waves.

Air is the most common medium through which sound travels. When a vibrating object moves forward, it pushes and compresses the air in front of it creating a region of high pressure. This region is called a compression (C), as shown in Fig. 12.5. This compression starts to move away from the vibrating object. When the vibrating object moves backwards, it creates a region of low pressure called rarefaction (R), as shown in Fig. 12.5. As the object moves back and forth rapidly, a series of compressions and rarefactions is created in the air. These make the sound wave that propagates through the medium. Compression is the region of high pressure and rarefaction is the region of low pressure. Pressure is related to the number of particles of a medium in a given volume. More density of the particles in the medium gives more pressure and vice versa. Thus, propagation of sound can be visualised as propagation of density variations or pressure variations in the medium.

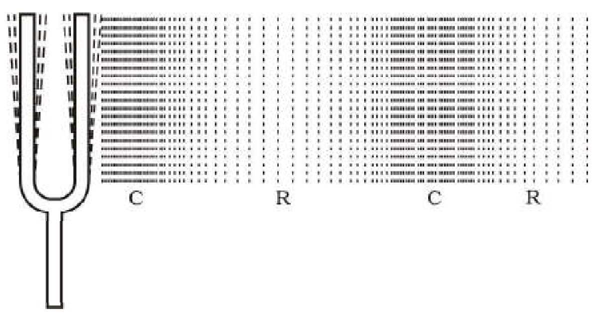


Fig. 12.5: *A vibrating object creating a series of compressions (C) and rarefactions (R) in the medium.*

Question

1. *How does the sound produced by a vibrating object in a medium reach your ear?*

12.2.1 Sound needs a medium to travel

Sound is a mechanical wave and needs a material medium like air, water, steel etc. for its propagation. It cannot travel through vacuum, which can be demonstrated by the following experiment.

Take an electric bell and an airtight glass bell jar. The electric bell is suspended inside the airtight bell jar. The bell jar is connected to a vacuum pump, as shown in Fig. 12.6. If you press the switch you will be able to hear the bell. Now start the vacuum pump. When the air in the jar is pumped out gradually, the sound becomes fainter, although the same current is passing through the bell. After some time when less air is left inside the bell jar you will hear a very feeble sound. What will happen if the air is removed completely? Will you still be able to hear the sound of the bell?

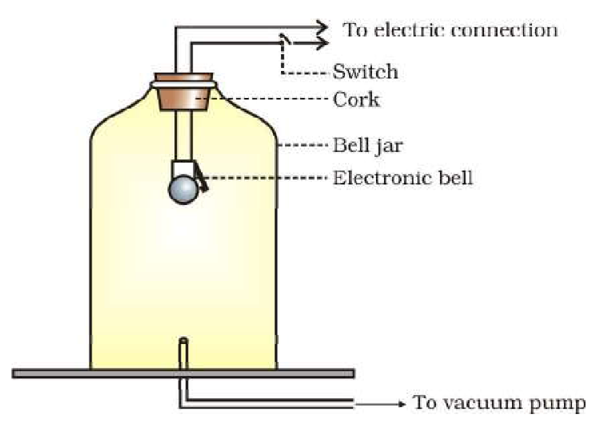


Fig. 12.6: *Bell jar experiment showing sound cannot travel in vacuum.*

Questions

1. *Explain how sound is produced by your school bell.*
2. *Why are sound waves called mechanical waves?*
3. *Suppose you and your friend are on the moon. Will you be able to hear any sound produced by your friend?*

12.2.2 Sound waves are longitudinal waves

Activity ______________ 12.4

- Take a slinky. Ask your friend to hold one end. You hold the other end. Now stretch the slinky as shown in Fig. 12.7 (a). Then give it a sharp push towards your friend.
- What do you notice? If you move your hand pushing and pulling the slinky alternatively, what will you observe?
- If you mark a dot on the slinky, you will observe that the dot on the slinky will move back and forth parallel to the direction of the propagation of the disturbance.

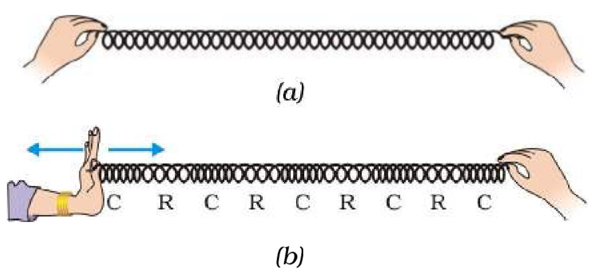


Fig. 12.7: *Longitudinal wave in a slinky.*

The regions where the coils become closer are called compressions (C) and the regions where the coils are further apart are called rarefactions (R). As we already know, sound propagates in the medium as a series of compressions and rarefactions. Now, we can compare the propagation of disturbance in a slinky with the sound propagation in the medium. These waves are called longitudinal waves. In these waves the individual particles of the medium move in a direction parallel to the direction of propagation of the disturbance. The particles do not move from one place to another but they simply oscillate back and forth about their position of rest. This is exactly how a sound wave propagates, hence sound waves are longitudinal waves.

There is also another type of wave, called a transverse wave. In a transverse wave particles do not oscillate along the direction of wave propagation but oscillate up and down about their mean position as the wave travels. Thus, a transverse wave is the one in which the individual particles of the medium move about their mean positions in a direction perpendicular to the direction of wave propagation. When we drop a pebble in a pond, the waves you see on the water surface is an example of transverse wave. Light is a transverse wave but for light, the oscillations are not of the medium particles or their pressure or density – it is not a mechanical wave. You will come to know more about transverse waves in higher classes.

12.2.3 Characteristics of a sound wave

We can describe a sound wave by its
- frequency
- amplitude and
- speed.

A sound wave in graphic form is shown in Fig. 12.8(c), which represents how density and pressure change when the sound wave moves in the medium. The density as well as the pressure of the medium at a given time varies with distance, above and below the average value of density and pressure. Fig. 12.8(a) and Fig. 12.8(b) represent the density and pressure variations, respectively, as a sound wave propagates in the medium.

Compressions are the regions where particles are crowded together and represented by the upper portion of the curve in Fig. 12.8(c). The peak represents the region of maximum compression. Thus, compressions are regions where density as