2 Force and Motion

In your previous class you have learnt that a force is needed to set a body in motion or to bring a moving body to rest. A force can also change the speed of a moving body or change its direction of motion. The force acting on a body has a definite relation with its motion, about which you will learn later. In this chapter, we will only discuss motion.

MOTION

Everything that we see around us is either in motion or at rest. Thus, while roads, houses, trees, etc., are stationary, vehicles and people on the road are usually moving. All this is so common that we never stop to think about the exact nature of what we call motion.

Motion is Relative

Usually, we figure out whether an object is in a state of rest or of motion by comparing its position with stationary landmarks in its surroundings. When the position of an object with respect to the other objects around it does not change, we say that it is at rest. For example, the distance of your study table from the walls of the room, or from the roof or floor does not keep changing. Therefore, you conclude that it is at rest. On the other hand, when the position of an object relative to its surroundings changes, we say that it is in motion. For example, when you walk about in your room, your position relative to the things in the room keeps changing. You are then in motion.

(a) (b)

Fig. 2.1 Motion is relative. (a) The background appears to be moving relative to the motorcycle. (b) The motorcycle appears to be moving relative to the background.

To take this idea a little further, think of a boy sitting in a moving bus. Is he in motion or at rest? His position *relative* to the bus does not change. He is, therefore, stationary relative to the bus. On the other hand, his position *relative* to the road, and to the houses along the road, changes continuously. He is in motion relative to these landmarks. In general, we can say that all motion is relative.

We may look upon this idea in a different manner. While looking out of a moving train, you must have noticed that the trees outside seem to be moving away rapidly in the opposite direction. The trees appear to be in motion because an observer judges his surroundings assuming that he himself is at rest. Thus, when he moves in a certain direction, he feels that everything around him is moving in the opposite direction. This is precisely why the sun appears to move from the east to the west when, in reality, it is the earth that rotates from the west to the east.

Types of Motion

Things can move in many different ways, or motion can be of many different types. When the motion of a body does not have any pattern, e.g., the motion of a kite or of a mosquito, we call it random motion. On the other hand, any motion that follows some sort of pattern is called regular motion. Regular motion can be of three types, viz., (1) translatory motion, (2) rotatory motion, and (3) oscillatory motion.

Translatory motion

When an object moves from one point to another along a straight line or a smooth curve, its motion is called translatory. Usually, this term is used when the object moves in only one direction along the path. Translatory motion can be of two types—rectilinear and curvilinear, depending on the path followed.

The motion of a body along a straight line is called rectilinear motion. Examples of this are vehicles moving on a straight road, athletes running on a straight track, and any object thrown straight up or falling vertically down under gravity.

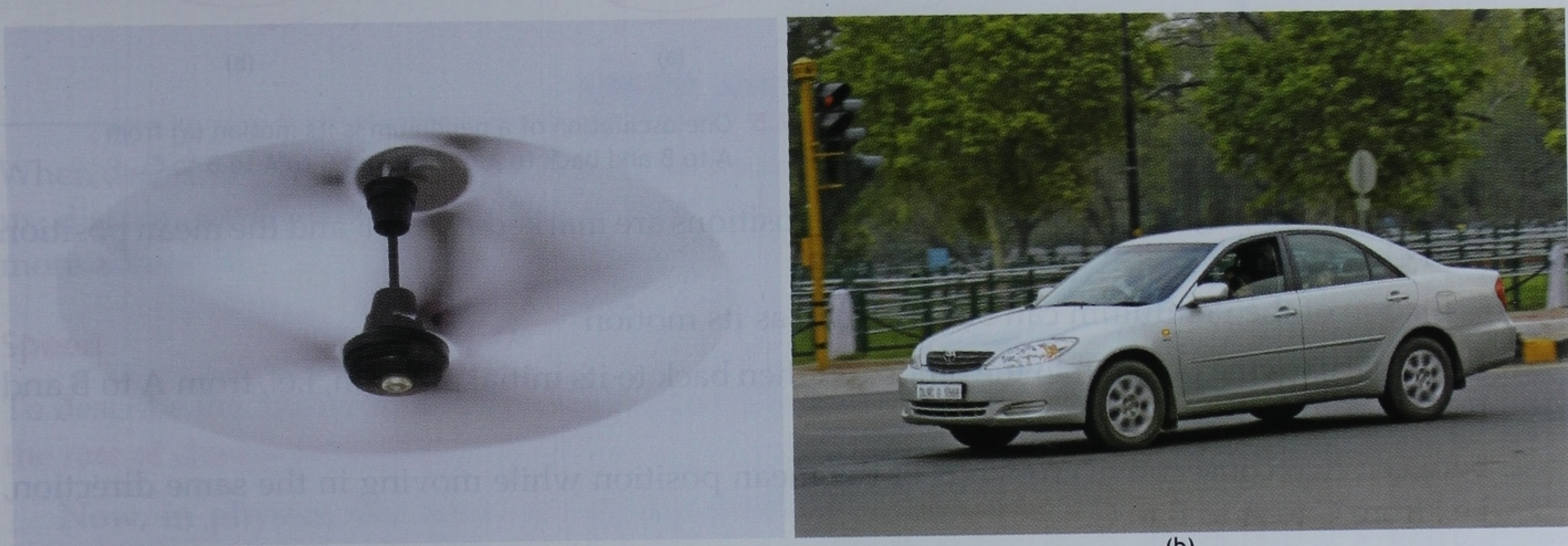
The motion of a body along a curved path is called curvilinear motion. Whenever a vehicle turns from one road into another, it follows a short curved path. Any object thrown in any direction other than the vertical also follows a curvilinear path.

Fig. 2.2 Water coming out of a garden hose follows a curvilinear path.

Rotatory motion

When an object turns or rotates or spins about an axis, its motion is called rotatory. The rotation of the earth about its own axis is of this nature. Electrical fans, food processors, wheels, pulleys and ferris wheels are some things that show rotatory motion.

Many things around us have two different types of motion at the same time. For example, the wheels of a moving car have the same translatory motion as the car. In addition, each wheel has a rotatory motion about its own axis. Other common examples of a body showing more than one type of motion at the same time are a spinning top and a drill.



(a) (b)

Fig. 2.3 (a) The motion of a fan is rotatory. (b) The wheels of a car have translatory as well as rotatory motion.

Oscillatory motion

When a body moves to and fro between two points, repeatedly, its motion is called oscillatory. A child on a swing and the pendulum of a clock are common examples of oscillatory motion.

ACTIVITY Make a list of the motions that you see around you. Most of these motions will fit into one of the categories we have discussed. Make separate lists of (a) motions that do not fit into any of these groups, and (b) motions which are combinations of different categories.

SIMPLE PENDULUM

A simple pendulum consists of a small, heavy sphere, called the bob, suspended by a light string from a fixed support in such a way that it can oscillate freely. The sphere is about 1 cm to 2 cm in diameter, and has a hook to which the string can be tied. The length of the string can be altered, and is usually kept between 30 cm and 120 cm.

When the pendulum is at rest, with the string vertical, it is said to be at its mean position. The distance from the point of support to the centre of the bob is called the effective length, or simply the length (l) of the pendulum. To set the pendulum oscillating, the bob is pulled to one side gently, such that the string makes a small angle (less than 4°) with the vertical. This angle is called the amplitude of the oscillations.

When the bob is released, the pendulum oscillates between two extreme positions on either side of

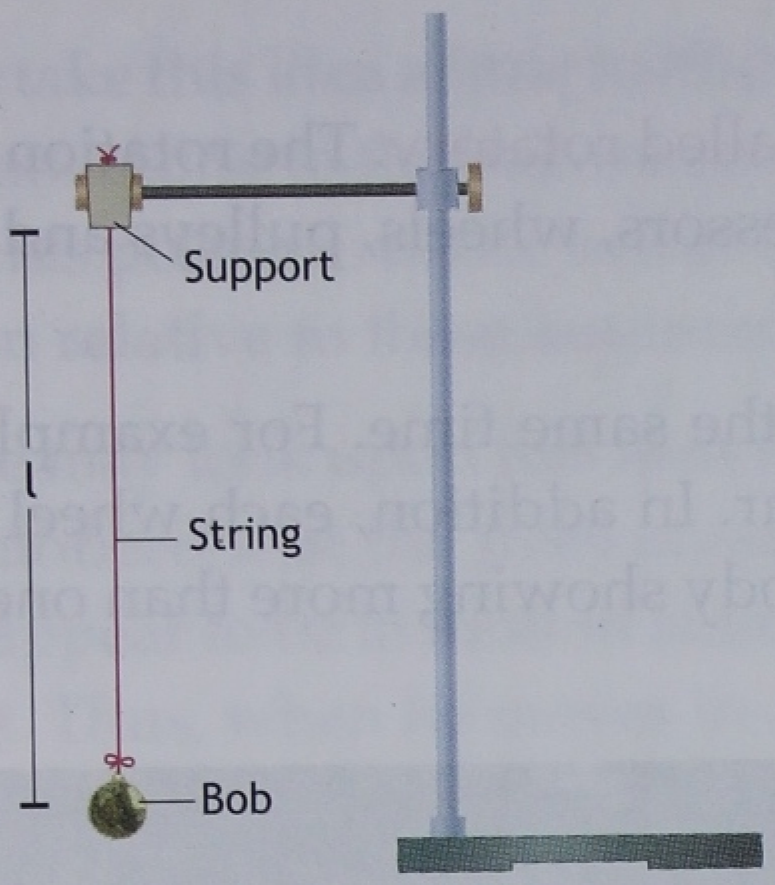


Fig. 2.4 Simple pendulum

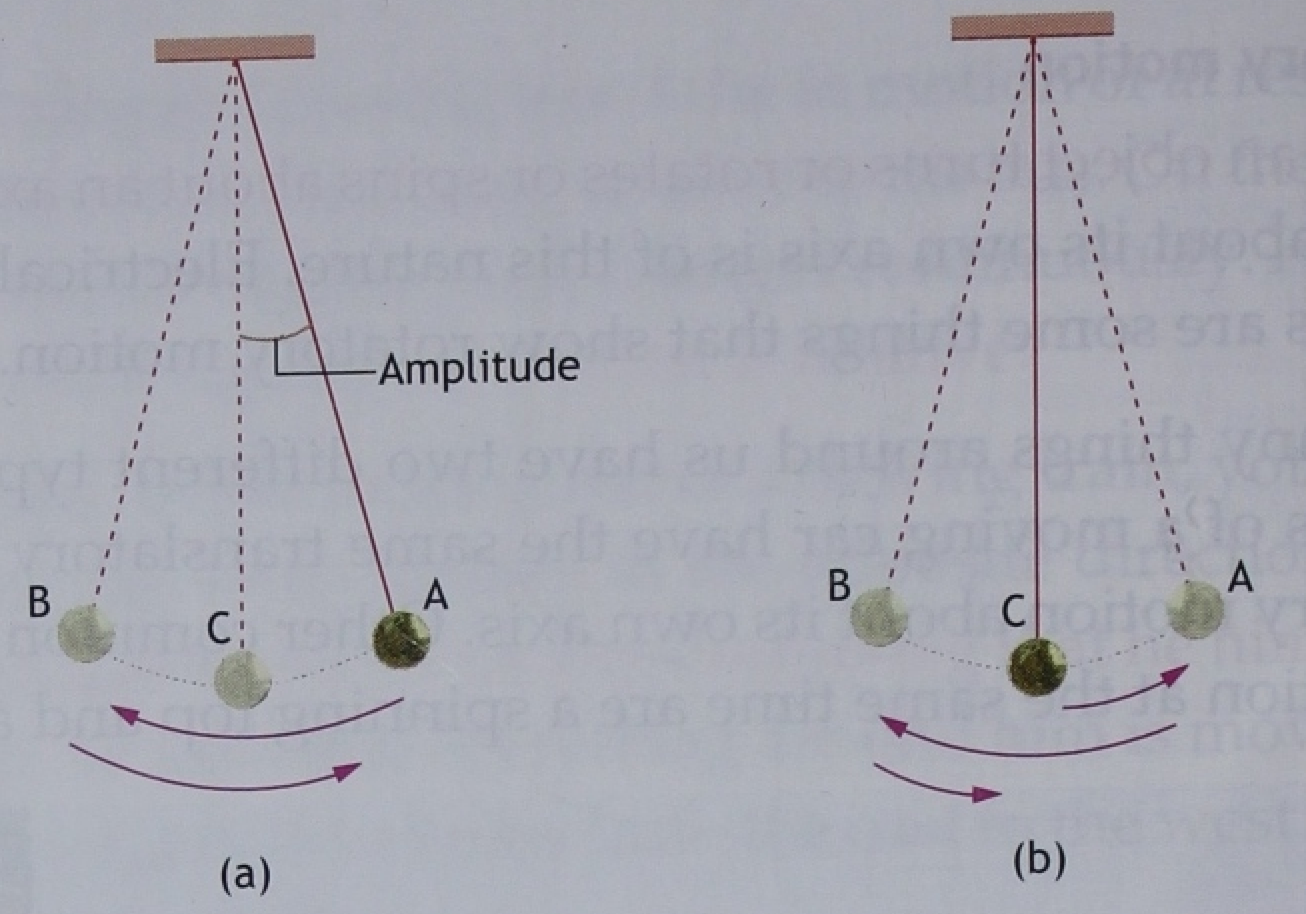


Fig. 2.5 One oscillation of a pendulum is its motion (a) from A to B and back to A or (b) from C to A to B to C.

the mean position. In Figure 2.5, the two extreme positions are marked A and B and the mean position is marked C.

One oscillation of the pendulum can be described as its motion

1. from one extreme position to the other and then back to its initial position, i.e., from A to B and back to A, or
2. between two consecutive crossings of the mean position while moving in the same direction, i.e., from C to A to B to C.

Time Period

The total time taken by a pendulum to complete one oscillation is called its time period (T). It can be shown, both through experiments and by calculations, that the time period of a pendulum is related to its characteristics as follows.

1. T depends on the length of the pendulum. It increases when l is increased. It is found to be about 1 s for $l = 30$ cm, which increases to about 2.2 s for $l = 120$ cm.
2. T does not depend on the amplitude, as long as the amplitude is small. When a pendulum is allowed to oscillate for some time, the amplitude of its oscillations decreases gradually due to air resistance. However, its time period does not change due to this decrease in amplitude.
3. T does not depend on the mass of the bob. This means that so long as the length of a pendulum remains constant, its time period will be the same even if bobs of different masses are used.

ACTIVITY To find the time period of a simple pendulum, set it up as shown in Figure 2.4. In addition, you will require a stop watch to record time.

Choose any length for the pendulum. Make a chalk mark on the side of the table to mark the mean position of the pendulum. Then pull the bob to one side through a few centimetres and release it. When it crosses the chalk mark, say "zero" and start the stop watch. When it next crosses the mark, moving in the same direction, count "one". Continue this for 20 oscillations and stop the watch. The reading of the watch divided by 20 will give you the time period.

If you want to do this activity at home, use a lock tied to a string as a pendulum and a watch that has a seconds hand instead of a stop watch. Hang the string off the edge of a table by placing its free end under a couple of heavy books. Alternatively, hang it off a door knob or handle.

Seconds Pendulum

A pendulum with a time period of exactly 2 s is called a seconds pendulum. Its length is very close to 1 m. Such pendulums take exactly 1 s to swing from one side to the other, and were used in clocks at one time.

You can make a seconds pendulum by keeping the length of the string close to 99 cm. Find the time period of the pendulum in the same way as in the preceding activity. If it is slightly different from 2 s, alter the length of the string by a few millimeters at a time until you get the exact value.

SPEED AND VELOCITY

When describing the motion of an object, we use general terms such as 'slow', 'fast' and 'smooth'. Let us discuss some physical quantities that can be used to describe different kinds of motion more accurately.

Speed

To describe the 'fastness' or 'slowness' of a moving body we use the term speed. Speed is defined as the rate of change of distance.

Now, in physics, the term rate always means per unit time. Also, the quantity distance can have some meaning only if it is measured from a fixed point. Thus, the speed of a body means the change in its distance, measured from some fixed point, in unit time. This will become clear with the following example.

Figure 2.6 shows a small box moving along a fixed line AB. O is a fixed point on AB. Let the box move from position P to position Q in time t. The distance from O to P is x_1 and from O to Q is x_2. Thus, the change in its distance, measured from O, is $(x_2 - x_1)$, which is equal to x in the figure. The speed of the box, v, according to our definition, is

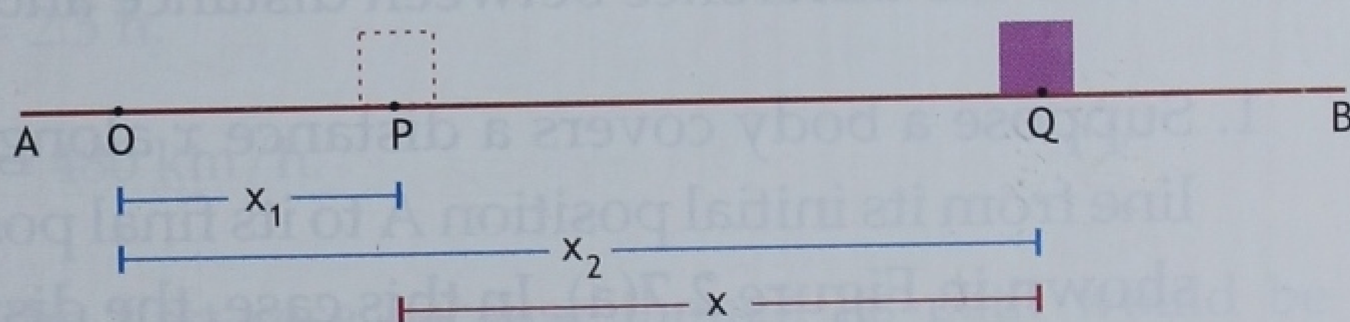


Fig. 2.6

$$v = \frac{(x_2 - x_1)}{t} = \frac{x}{t}$$

We can now simplify our definition of speed further.

$$\text{The speed of a body} = \frac{\text{distance covered by the body}}{\text{time taken to cover the distance}}$$

Units of speed

The SI units of distance and time are the metre and second respectively. Hence, the SI unit of speed = metre/second = m/s. The speed of vehicles is usually expressed in kilometres per hour, which is written as km/h. This can be converted to m/s as follows.

$$1\text{ km/h} = \frac{1000}{3600}\text{ m/s} = \frac{1}{3.6}\text{ m/s}.$$

It follows that 1 m/s = 3.6 km/h.

EXAMPLE 1. A schoolboy covers a distance of 90 m in 15 s. Find his speed.

$$\text{Speed} = \frac{\text{distance}}{\text{time}} = \frac{90\text{ m}}{15\text{ s}} = 6\text{ m/s}.$$

EXAMPLE 2. The maximum speed of an athlete over short distances is 36 km/h. Find the minimum time in which he can cover a distance of 100 m.

$36\text{ km/h} = (1/3.6) \times 36\text{ m/s} = 10\text{ m/s}.$

$$\text{Minimum time} = \frac{\text{distance}}{\text{maximum speed}} = \frac{100\text{ m}}{10\text{ m/s}} = 10\text{ s}.$$

EXAMPLE 3. An ant starts from the floor and moves straight up along a wall with a speed of 1.5 cm/s. It reaches the ceiling in 4 minutes. Find the height of the room.

$\text{Distance} = \text{speed} \times \text{time} = (1.5\text{ cm/s}) \times (4 \times 60\text{ s}) = 360\text{ cm} = 3.6\text{ m}.$

Displacement

The displacement of a body is defined as the separation between its initial and final positions. This separation is taken as the distance between the two positions measured along a straight line between them, irrespective of the actual path followed by the body. The following examples will help you understand the difference between distance and displacement.

1. Suppose a body covers a distance x along a straight line from its initial position A to its final position B, as shown in Figure 2.7(a). In this case, the displacement of the body from A to B is equal to x. The distance covered by it is also equal to x.

2. Now suppose a body moves from point A to B and then to C, as shown in Figure 2.7(b). The distance covered by the body from A to C = 4 m + 3 m = 7 m. However, the displacement measured along AC = 5 m.

3. If the body moves along the path shown in Figure 2.7(c), from A to P to Q to R and then to C, its displacement is still 5 m, measured from A to C.

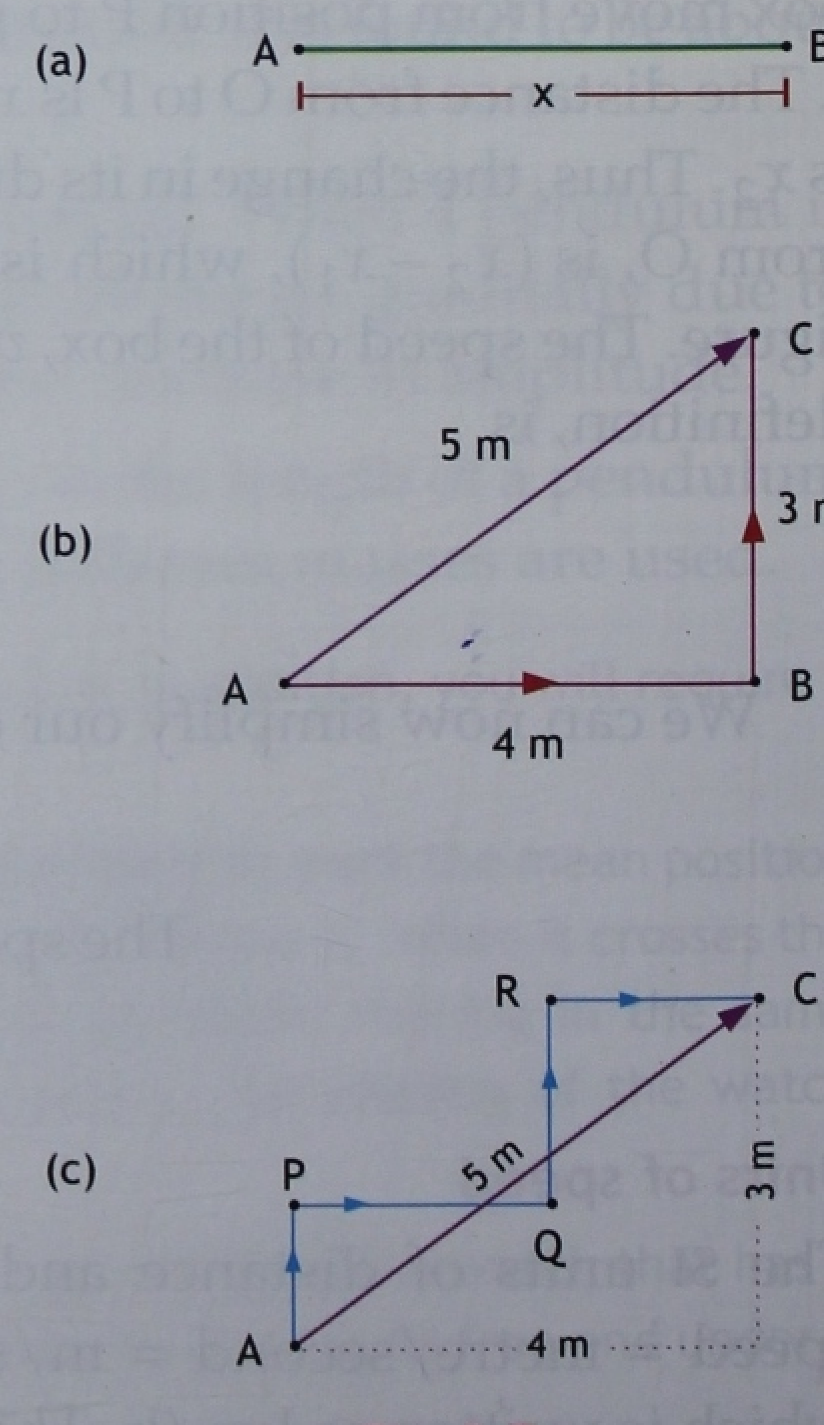


Fig. 2.7

Three things should be clear to you.

- If a body moves between two points along different paths, its displacement is the same for all the paths, though the distance covered by it may be different for the different paths.

- If a body starts moving from a point and returns to the same point, its displacement is zero.
- Since displacement is measured from the *initial position to the final position*, it has a direction. Distance or length, on the other hand, is not measured along any particular direction. Therefore, it is a quantity that has only a magnitude and no direction.

Velocity

The velocity of a body is defined as its rate of change of displacement.

$$\text{Velocity of a body} = \frac{\text{displacement of the body}}{\text{time of travel from initial to final point}}$$

Thus, to find the velocity of a body, we need to know only its displacement, and its time of travel. We do not need to know the actual path followed by the body.

Since displacement has a direction, so also does velocity. For both quantities, the direction is always from the initial position to the final position. Speed, on the other hand, does not have a direction. It is the rate of change of distance, and distance does not have a direction.

EXAMPLE 4. The straight-line distance from Mumbai to Delhi is 1200 km. An aircraft flies from Delhi to Mumbai in 2.5 hours. (a) Find the velocity of the aircraft. (b) If the aircraft takes the same time to fly from Delhi to Agra and then from Agra to Mumbai, would its velocity remain the same? (c) What would its velocity be if it made the return flight from Mumbai to Delhi in the same time?

(a) Given, displacement = 1200 km, time = 2.5 h.

$$\therefore \quad \text{velocity} = \frac{\text{displacement}}{\text{time}} = \frac{1200\text{ km}}{2.5\text{ h}} = 480\text{ km/h}.$$

(b) Its velocity would be the same as in the first case because though its path would be different, its displacement would be the same.

(c) Its velocity would have the same magnitude as in (a), but the opposite direction.

UNIFORM AND NONUNIFORM MOTION

The motion of a body at any time is described by its velocity. This includes its speed as well as the direction of its motion. The motion of a body is said to be uniform when its velocity remains constant. Clearly, the motion of a body is uniform if

1. the speed of the body is constant, and
2. the direction of its motion remains the same.

A body moving along a straight line at a constant speed is, therefore, in uniform motion. Examples of this kind of motion are (1) a vehicle moving along a straight highway at a constant speed and (2) an aircraft or a ship travelling on a straight course at a constant speed. The motion of a body becomes nonuniform when its velocity changes with time. A change in velocity may mean a change in speed, or a change in direction or both. The following are common examples of nonuniform motion.

1. When a vehicle moves through a straight but crowded road, its direction remains the same, but its speed changes continuously due to traffic conditions.
2. If you tie a stone to a light string and whirl it along a circle, its speed remains constant, but the direction of its motion changes continuously.
3. When you walk through a crowded marketplace, you have to make small changes in both your speed and direction all the time.

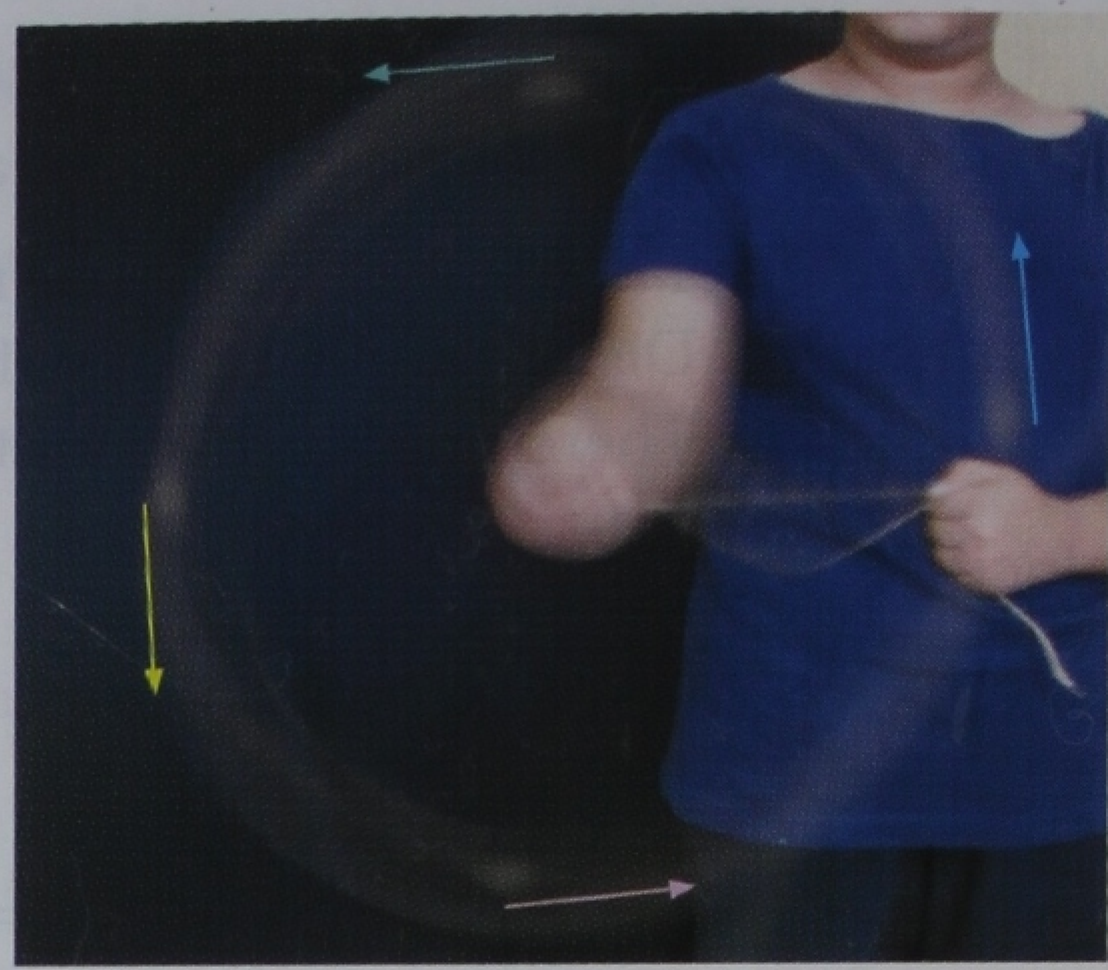


Fig. 2.8 The speed of the stone is constant but its direction of motion changes continuously.

ACCELERATION

In nonuniform motion, the velocity of a body changes with time. When we wish to study the manner in which the velocity changes, we do so with the help of a quantity which we call acceleration. Acceleration is the rate of change of velocity. Like velocity and displacement, acceleration too has a magnitude as well as a direction.

Since the rate of change of any quantity means the change in that quantity per unit time, acceleration is equal to the change in velocity per unit time. Thus,

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{period of time during which the change in velocity takes place}}$$

We use the symbol a to denote acceleration. The unit of acceleration is the unit of speed/the unit of time. This is read as "metres per second square".

Relation between Velocity and Acceleration

Suppose a body is moving with a velocity u to begin with, and that after a time t, its velocity becomes v.

Then the change in its velocity over time t = its final velocity – its initial velocity = $v - u$.

Now,

$$\text{acceleration} = a = \frac{\text{change in velocity}}{\text{time}} = \frac{v-u}{t}.$$

$$\therefore \quad v - u = at.$$

This leads to the relation $\quad v = u + at$

EXAMPLE 5. The initial velocity of a truck is 5 m/s and its acceleration is 0.25 m/s^2. Find the velocity of the truck after 40 s.

Given, $u = 5$ m/s, $a = 0.25$ m/s^2, $t = 40$ s.

$$\therefore \quad v = u + at = 5\text{ m/s} + (0.25\text{ m/s}^2)(40\text{ s}) = 5\text{ m/s} + 10\text{ m/s} = 15\text{ m/s}.$$

EXAMPLE 6. A car is moving at a velocity of 20 m/s when the driver applies the brakes. The velocity of the car then decreases to 10 m/s in 5 s. Find the acceleration of the car during this period.

Given, $u = 20$ m/s, $v = 10$ m/s, $t = 5$ s.

We know that $v = u + at$.

$$\therefore \quad a = \frac{v-u}{t} = \frac{10\text{ m/s} - 20\text{ m/s}}{5\text{ s}} = -\frac{10\text{ m/s}}{5\text{ s}} = -2\text{ m/s}^2.$$

(Notice that the acceleration turns out to be negative. This is so because the velocity is decreasing. Negative acceleration is usually called retardation.)

EXAMPLE 7. A motorcycle moving at 4 m/s begins to accelerate at the rate 0.5 m/s^2. How much time will it take to reach a velocity of 22 m/s?

Given, $u = 4$ m/s, $v = 22$ m/s, $a = 0.5$ m/s^2.

We know that $v = u + at$.

$$\therefore \quad t = \frac{v-u}{a} = \frac{22\text{ m/s} - 4\text{ m/s}}{0.5\text{ m/s}} = 36\text{ s}.$$

POINTS TO REMEMBER

- When the position of an object relative to the other objects around it does not change, we say that it is at rest.
- All motion is relative.
- An observer judges his surroundings assuming that he himself is at rest.
- When a body moves from one point to another along a straight line or a smooth curve, its motion is called translatory.
- Motion along a straight line is called rectilinear motion and motion along a curved path is called curvilinear motion.
- When an object turns or rotates or spins about an axis, its motion is called rotatory.
- When a body moves to and fro between two points, repeatedly, its motion is called oscillatory.
- A simple pendulum consists of a small, heavy sphere, suspended by a light string from a fixed support in such a way that it can oscillate freely.
- When a pendulum is at rest, with the string vertical, it is at its mean position.
- The distance from the point of support to the centre of the bob is called the length (l) of the pendulum.
- The small angle made by the string with the vertical when the pendulum is at either of the two extreme positions is called the amplitude of the oscillations.

- The total time taken by a pendulum to complete one oscillation is called its time period (T). T depends on the length of the pendulum. It increases when l is increased.
- A pendulum with a time period of exactly 2 s is called a seconds pendulum. Its length is very close to 1 m.
- Speed is the rate of change of distance: $v = \frac{x}{t}$. Its unit is m/s.
- The displacement of a body is the distance between its initial and final positions, measured along the straight line joining the two points. It does not depend on the actual path taken by the body.
- The velocity of a body is the rate of change of its displacement.
- The motion of a body is said to be uniform when its velocity remains constant.
- Acceleration is the rate of change of velocity. Its unit is m/s^2.
- $v = u + at$.

EXERCISE

Short-Answer Questions

1. How do we usually judge the state of rest or of motion of a body?
2. Name three types of regular motion.
3. Briefly describe oscillatory motion. Give two examples.
4. What is meant by the mean position of a simple pendulum?
5. What is acceleration? What is its SI unit?

Long-Answer Questions

1. Explain the statement "all motion is relative".
2. Explain translatory, rotatory and oscillatory motions with suitable examples.
3. Can a body have more than one type of motion at the same time? Explain with two examples.
4. What is one oscillation of a simple pendulum? (You can use a sketch to explain your answer.) How does the time period of a simple pendulum depend on its length, the amplitude of its oscillations and the mass of the bob?
5. What is meant by a seconds pendulum? Describe how such a pendulum can be set up.
6. Distinguish between speed and velocity. Explain what is meant by acceleration.

Objective Questions

Choose the correct option.

1. Which of the following is not an example of regular motion?
   (a) A child on a swing
   (b) An object moving in a circle
   (c) A mosquito flying about in a room
   (d) A swinging pendulum
2. A body starts moving from some point and returns to the same point. For this entire motion, its displacement is D and the distance covered by it is S.
   (a) Both D and S are zero.
   (b) D is zero but S is not zero.
   (c) S is zero but D is not zero.
   (d) Neither D nor S is zero.
3. A particle moves from one point to another along a straight line at a constant speed.
   (a) Its velocity is constant.
   (b) Its velocity may be constant.
   (c) Its velocity cannot be constant.
   (d) No conclusion can be drawn about its velocity.
4. The velocity of a particle A is small and increasing. The velocity of another particle B is large and constant. Which of the following statements is correct?
   (a) The acceleration of A is small, while the acceleration of B is large.
   (b) The acceleration of A is large, while the acceleration of B is small.
   (c) The acceleration of A must be smaller than the acceleration of B.
   (d) The acceleration of A may have any value, while the acceleration of B is zero.

5. The total time taken by a seconds pendulum to complete 20 oscillations is
   (a) 20 s (b) 38 s
   (c) 40 s (d) 42 s
6. The time taken by a pendulum to swing from one extreme position to another is 0.5 s. Its time period is
   (a) 0.5 s (b) 1 s
   (c) 2 s (d) 1.5 s
7. Which of the following has a magnitude and a direction?
   (a) Speed (b) Distance
   (c) Length (d) Acceleration

Fill in the blanks.

1. An object is said to be at rest when its position ...... to its surroundings does not change.
2. The amplitude of a simple pendulum should not exceed ...... during experiments.
3. The length of a seconds pendulum is close to ....
4. The distance from the point of support to the ...... of the bob is taken as the length of a simple pendulum.
5. The word ...... always means per unit time.

Write true or false.

1. Rectilinear and curvilinear motions are both examples of translatory motion.
2. When an object moves in a circle with a constant speed, its velocity remains constant.
3. The time period of a simple pendulum is the time in which it moves from one extreme position to the other extreme position.
4. When the velocity of a particle is small, its acceleration must also be small.
5. For a body moving from one point to another, the velocity and speed may be of equal magnitude.
6. The displacement of a body moving from one point to another depends on the path it takes.

Numericals

1. Refer to Figure 2.7(b). An insect flying at a constant speed of 50 cm/s flies from A to B, B to C and C to A. (a) What is its displacement? (b) What is the total distance it covers? (c) How much time does it take to return to A?
2. A soldier marches at the speed of 2 m/s. What distance will he cover in one hour?
3. A car moving at 10 m/s begins to accelerate at the rate of 0.2 m/s^2. After how much time will its speed become double?
4. The speed of a cyclist increases from 2 m/s to 12 m/s in 50 s. Find his acceleration.
5. A simple pendulum completes 20 oscillations in 30 s. How much time does it take to move from an extreme position to the mean position?

Answers

1. (a) 0 (b) 12 m (c) 24 s 2. 7.2 km 3. 50 s
4. 0.2 m/s^2 5. 0.375 s

❑