

CHAPTER – 7



Force And Laws of Motion

We described the motion of an object along a straight line in terms of its position, velocity and acceleration in the previous chapter. But we have not discussed yet the cause of the motion. In this chapter we have to discover – what causes the motion? Why does the speed of an object change with time? Do all the motions require a cause? In this chapter let us make an attempt to quench all the curiosities. For many centuries, the problem related to motion and its causes had puzzled the scientists and philosophers.

You can see in your daily life that on a ball or any inanimate objects of suitable size when given a small kick or hit, it does not remain moving forever. Such observations suggest that rest is the "*natural state*" of inanimate objects. This concept remained the belief until Galileo Galilei and Isaac Newton developed an entirely different approach to understand the motion of inanimate objects. In our everyday life we observed that inanimate objects cannot start moving at their own accord. In other words some effort is always required to put a stationary object into motion or to stop a moving object. We generally use muscular effort in the form of pushing, pulling or hitting on an object to change its state of rest or of motion. The concept of force is based on this push, pull or hit. Let us now try to understand what is a force. In fact no one has seen or tasted a force but we can see or feel the effect of force. Force can be explained by describing the effect after a force is applied to an object. The ways of bringing (inanimate) objects in motion are pushing, hitting and pulling which are shown in Fig.7.1. They move because a force acts on them

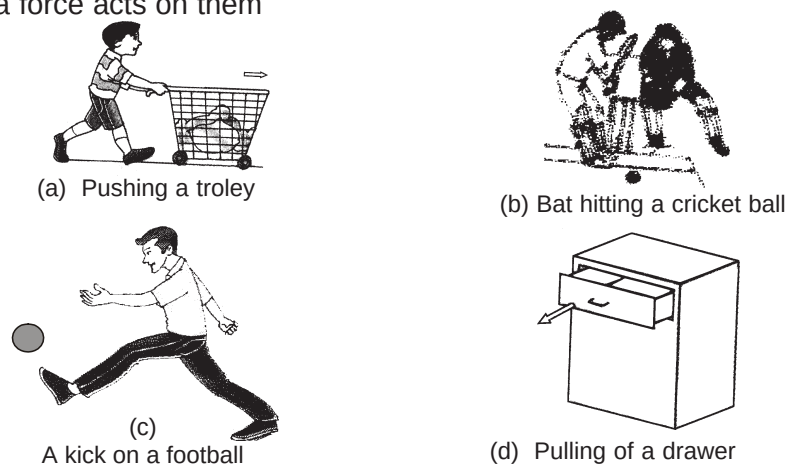


Fig. 7.1

Try also to learn that a force can be used (i) to change the shape and size of objects (ii) to change the magnitude of velocity of an object (that is to make the object move faster or slower) or to change the direction of motion, from the play of football at your school, as shown in Fig.7.2.

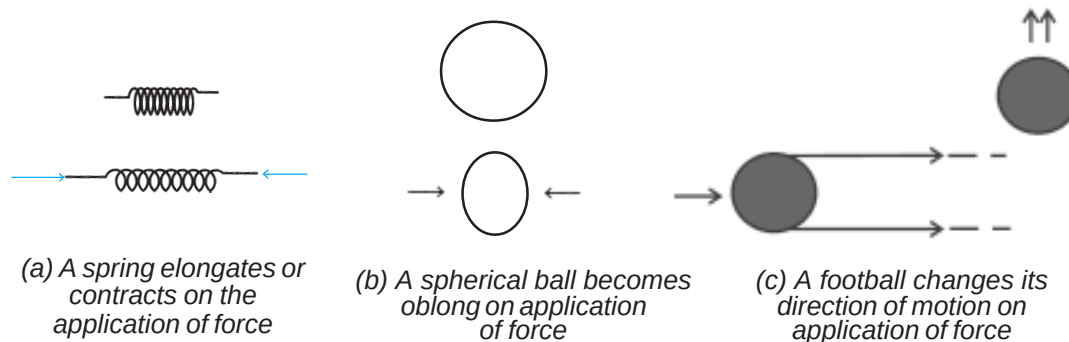


Fig. 7.2

7.1 Balanced and Unbalanced Forces

Let us take a rectangular block of wood on a horizontal table. The strings A and B are tied at its opposite faces, as shown in the Fig. 7.3. Try to apply a force on the block by pulling the string A, then the block will start to move to the right. Similarly, if we pull the string B, then the block will start to move to the left. On the other hand if we pull both strings simultaneously in opposite directions with equal forces, you will find that the block does not move.

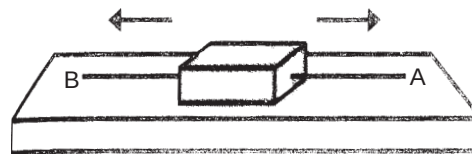


Fig. 7.3: Two forces acting on a wooden block

Let us consider a situation when the opposite forces on the strings A and B are not of equal magnitude. In this situation the block would move in the direction of the force of greater magnitude. Thus the two forces on the block are not balanced i.e. an unbalanced force acts on the block in the direction in which the block moves. The above observation suggests that whenever an unbalanced force acts on a body, then this force will cause the body to move in its direction.

Let us again consider a situation of pushing a box on a floor of rough surface. If you push the block with a small force the box may not move because of the friction in a direction opposite to that of the push, Fig. 7.4 (a). This friction force exists between the two surfaces in contact, in this case between the lower surface of the box and the floor's rough surface. Since the friction force balances the push, the box does not move. Now you increase the amount of push i.e. try to push the box harder but the box may not move. If it is so, the friction force still balances the pushing force as shown in Fig. 7.4 (b). If you push box harder still by engaging one of your friends in the same direction, the pushing force may be bigger than the friction force as shown in Fig. 7.4 (c) then an unbalanced force acts on the box. So the box will start moving in the direction of unbalanced force which is the direction of push.

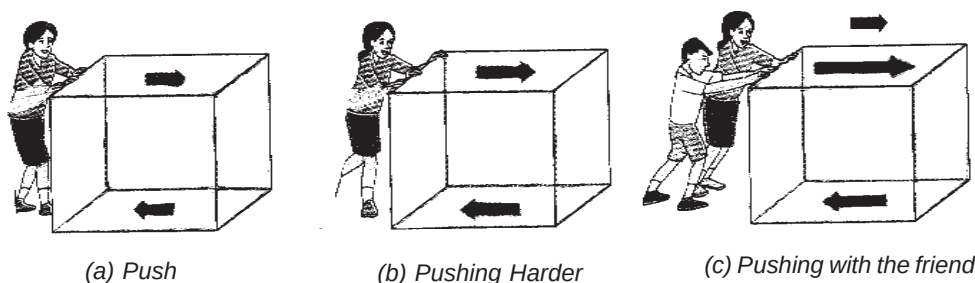


Fig. 7.4

Let us consider another example in our daily life. Suppose you are riding a bicycle. What happens when you stop pedalling? The bicycle will begin to slow down and finally will come to rest. This is because of the force of friction acting opposite to the direction of motion. In order to keep the bicycle moving you have to start pedalling again as earlier. From this you know that an object maintains its motion under the continuous application of an unbalanced force. However it is not true. An object moves at a uniform speed when there is no net external force applying on it, i.e. when the forces like push or pull and frictional force acting on the object are balanced. If an unbalanced force acts on an object, there will be a change either in its speed or its direction of motion or both i.e. there will always occur an acceleration of the motion. Thus to accelerate the motion of an object, an unbalanced force is required and the change in the speed or in the direction of motion would continue as long as the unbalanced force is acting on the object. However, the object will continue to move with the velocity acquired by it at the instant when the unbalanced force is removed.

7.2 First Law of Motion

Through the observations of 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 is made to roll down an inclined plane-I, its velocity increases in magnitude, [Fig.7.5. (a)]. (Here, the marble rolls down under the unbalanced force due to gravity. That is why its velocity is increasing to attain a definite velocity at the bottom of the inclined plane.). However, the velocity of the marble decreases when it climbs up the other inclined plane-II as shown in Fig.7.5. (b). Thus in the case of planes that slope downwards, there is present a cause of acceleration (force of gravity) while on planes sloping upwards there is acceleration opposite to the direction of motion. In second set of experiments Galileo combined two inclined planes I and II together facing each other and highly polished to minimise the friction.

He (Galileo) argued that when a marble is made to roll down the inclined plane I from a height 'h' it would rise up the plane-II to almost the same height (Fig.7.5 c).

He then decreased the inclination or

slope of plane-II and repeated the experiment. This time the marble had to travel a longer distance on the plane II to reach almost the same height. If the friction was totally eliminated, the final height reached on the plane-II would be equal to the initial height in plane-I, as a limiting case. If the slope of plane-II is made zero [Fig. 7.5. (c)] i.e. horizontal, the marble should move forever because it will never attain the initial height. The unbalanced forces on the marble are zero in this situation. In actual practice, it is difficult to achieve a zero unbalanced force. Thus in practice the marble comes to rest after travelling some distance.

Later Sir Issac Newton made a systematic study of Galileo's ideas on force and motion of bodies. He summed up Galileo's findings 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 is actually a reformulation of Galileo's law of inertia and is stated as:

"Every body continues in its state of rest or of uniform motion in a straight line unless compelled to change that state by an external unbalanced force (applied force)."

The word external specifies that the force must act from outside the body in order to have a change in the velocity or state of rest.

According to the above law all bodies resist a change in their state of motion. The tendency of undisturbed objects to remain at rest or to continue moving with the same velocity is called inertia. Because of this tendency, the first law is also called law of *inertia*. Certain experiences that you come across while travelling in the school bus or van can be explained on the basis of law of inertia. You tend to remain at rest with respect to the seat until the driver applies a breaking force to stop the bus. While doing so your body tends to continue in the same state of motion. That is why your body moves forward. A sudden application of brakes may thus cause injury to us by the impact with the front seat. The passengers are advised to wear safety belts to prevent such accidents while travelling in a car or aeroplane because the safety belts exert a force on our body to make the forward motion slower. An opposite experience is encountered when you are standing in a bus at rest and when it begins to move suddenly. In this situation your body falls backwards. The reason is that your feet being in contact with the floor of the bus, share the motion of the bus but the upper part of the body is still in a tendency of rest.

Similarly, when a motor car makes a sharp turn at high speed, we tend to get thrown outwards i.e. to one side. This is also due to the law of inertia, since we are

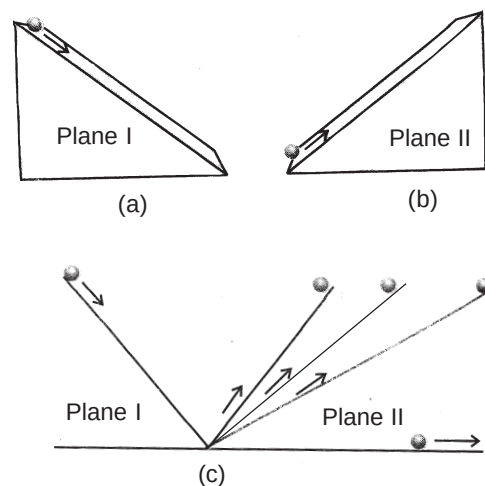


Fig. 7.5: (a) downward motion of marble.

(b) upward motion of marble on an inclined plane

(c) motion of marble on combined inclined planes at different inclinations of plane II

tending to continue in our straight line motion. The change in direction of motion of the motor car is brought by the unbalanced force generated by the engine.

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

Activity7.1

Make a pile of carom coins on a carom board as shown in Fig.7.6. Try to hit at the bottom coin of the pile using striker. If the hit is strong enough the bottom coin only will move out quickly. Once the lowest coin is removed, the other coins make them fall vertically due to inertia.

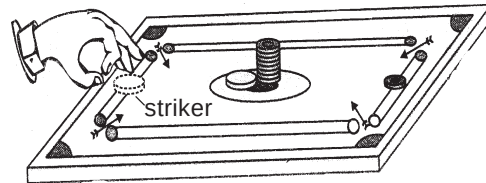


Fig. 7.6: Only the bottom carom coin is removed from the pile, when the fast moving striker hits it

Activity7.2

Place a coin A on a plane paper B lying over a table as shown in Fig.7.7. Now pull the paper slowly, the coin will be in contact with the paper. If the paper is pulled quickly, on one side as shown, the coin will fall on the table. Another similar activity can be taken up by placing a coin A on a cardboard sheet B over a tumbler. When the cardboard sheet is suddenly pulled on one side or is flicked with the finger, the coin will fall into the tumbler. This is due to the fact that the coin remains at rest because of the inertia even when B is removed quickly or flicked off.

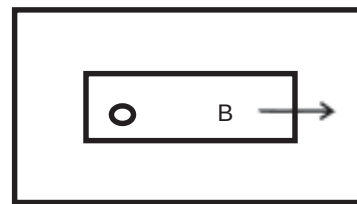


Fig 7.7

Activity7.3

Place a water-filled tumbler on a tray and hold the tray and turn around a little faster. Then you will find that water spills. Why?

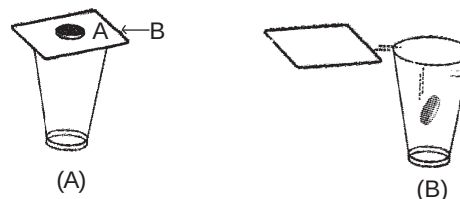


Fig. 7.8: When the card is flicked off with the figure, the coin A falls in the tumbler

7.3 Inertia and Mass

From the examples and activities, it is known that if the body is moving it tends to keep moving; if it is at rest it tends to remain at rest. This property of a body or an object is called its inertia. Do all bodies have the same inertia irrespective of their respective masses? We know that it is easier to push or pull an empty box on a floor than when

the same box is filled with some books or stones on the same floor. Similarly, when you kick a rubber ball it flies away. But if you kick a stone of the size as that of the ball with the same force, it hardly moves. In fact you may get an injury in the foot while doing so. Similarly, in activity (7.2) if lighter coin was used a lesser force would be required to perform the activity. Now you can ascertain that a force that is just enough to cause a smaller mass to pick up a large velocity will produce a negligible change in the motion of a larger mass. This is because, in comparison to the rubber ball the stone has a much lesser tendency to change its state of motion. Now you are clear that more massive bodies offer larger inertia. In other words the inertia of a body or an object is related to its mass. We may thus express inertia and mass in the following way: Inertia is the natural tendency of a body to resist a change in its state of rest or of uniform motion. The mass of an object or a body is a measure of its inertia.

Attempt to answer:

1. Which one has greater inertia:
 - (i) a rubber ball and a stone having the same size?
 - (ii) a bicycle and a scooter?
 - (iii) a five rupee coin and a one-rupee coin?
2. Some of the leaves of a tree may get detached if we vigorously shake its branch. Explain why.

7.4 Second Law of Motion

From the study of First law of motion we have found that when an unbalanced force acts on a body, there occurs a change in velocity, that is the body gets an acceleration. We would like to know how the acceleration of a body depends on force applied on it and how to measure a force. Let us think some situation from our everyday life. During the game of table tennis at your school or local club, you must have noticed that if the ball hits a player it does not hurt him, although the velocity or speed of the ball is very high. On the other hand, when a fast moving cricket as fast as the table tennis ball hits a player or a spectator, it may hurt him. We do not pay any attention to a truck when parked along a roadside. But a moving truck at a very low speed, may kill a person when it hits. A small mass such as a pebble from a catapult may hurt a person to some extent whereas a bullet having the mass as that of the pebble fired from a pistol may kill a person. These observations suggest that the impact produced by the objects depends on their mass and velocity together. In other words there should exist some quantity of importance that combines the mass of the object and its velocity. One such property called *momentum* was first introduced by Newton in 1687 and the momentum 'p' is defined as the quantity of motion associated with the body. It is measured by the product of the mass 'm' of the body and its velocity, 'v'.

That is **$p = mv$(7.1).**

Momentum has both direction and magnitude. Its direction is the same as that of the velocity. The SI unit of momentum is kilogram-metre per second (kgms^{-1}). Since,

an unbalanced force acting on a body can produce a change in the velocity of the body, it is therefore clear that an applied unbalanced force will produce a change of momentum.

Let us take up an example which you might have observed frequently that when it is not possible to start an engine of a car with weak battery, the car is pushed with the help of two or more persons. Does the engine start with the sudden push (unbalanced force)? Not yet. But a continuous push over some time, will result a gradual acceleration of the car to a speed which is sufficient to start the engine. This shows that the change in momentum of the car in the above observation is not only determined by the magnitude of applied force but also by the time during which the force is exerted. Thus we can conclude that the force necessary to change the momentum of a body 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 a body is proportional to the applied unbalanced force in the direction of force.

7.4.1 Mathematical Formulation of Newton's Second Law of Motion

Suppose an object of mass 'm' is moving along a straight line at an initial velocity 'u'. Now, a constant force F is applied on it which accelerates it uniformly to a velocity 'v' in time 't'. The initial momentum of the body before applying the force, $P_i = mu$ while its final momentum after time 't' is $P_f = mv$.

$$\text{The change in momentum} = P_f - P_i = mv - mu = m(v - u)$$

$$\therefore \text{The rate of change of momentum} = \frac{m \times (v - u)}{t}$$

Or, the applied force, $F \propto$

$$F = \quad = km a \dots\dots\dots(7.2)$$

Here, $a =$ which is the acceleration, the rate of change of velocity.

The quantity 'k' is a constant of proportionality. The unit of force is chosen in such a way that the value of constant k becomes unity. The SI units of mass and acceleration are kg and ms^{-2} respectively. Accordingly, one unit force is defined as the amount that produces an acceleration of 1ms^{-2} in an object of mass 1 kg. That is

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

Thus the value of k becomes 1. From equation (7.2)

$$\mathbf{F = ma} \dots\dots\dots(7.3)$$

The unit of force is kgms^{-2} or newton which has the symbol N. Thus, second law of motion provides us a method to measure the force acting on a body.

The second law of motion is often seen in action in our daily life. While playing a game of cricket, you might have experienced that it is easier to catch the fast moving ball by pulling the arms back as soon as the ball touches your palms. This increases

the time during which the high velocity of the ball decreases to zero. Thus the acceleration of the ball is decreased and therefore the impact of catching the fast moving ball is reduced. On the other hand, if you keep your palms stationary as you catch the ball then its high velocity decreases to zero in a very short interval of time. Thus the rate of change of momentum is larger. Therefore a larger force would have to be applied for the catch that may hurt very much your palms.

In another observation, the athletes participating in high jump are made to fall either on a thick cushion of sponge or on a sand bed. This is to increase the time of the athlete's fall to stop after the jump. As a result, the rate of change of momentum is decreased and hence the force also. Try to think over how a karate player hits a slab of ice in order to break with a single blow.

The first law of motion can be treated mathematically as a special case of second law of motion, given in Eq.7.3. as,

$$F = ma = \frac{m(v - u)}{t} \dots\dots\dots(7.4)$$

$$\text{or, } Ft = m(v - u) = mv - mu \dots\dots\dots(7.5)$$

Thus, when $F = 0$ i.e. there is no unbalanced force acting on the body, $v = u$ for whatever time, t is taken. This means that the body will continue to move with uniform velocity ' u ' throughout the time ' t ' or will remain at rest if $u = 0$.

In Eq.7.5, the quantity ' Ft ' is called the impulse of the force ' F ' in the time interval ' t ' and denoted by $\vec{I}$. as

$$\vec{I} = Ft \dots\dots\dots(7.6)$$

From Eq.7.5, we see that the impulse of a force acting on a body is equal to the change in momentum of the body produced by the force. The SI unit of impulse is Ns or kgms^{-1} .

Example 7.1

A constant force of 4 N acts on a body of mass 2 kg for 4 s. Assuming the body to be initially at rest, find (i) its velocity when the force stops acting (ii) distance covered in 4 s after the force starts acting (iii) distance covered in the next 5s after the force ceases to act.

Solution:

We have been given that $u = 0 \text{ ms}^{-1}$ and $m = 2 \text{ kg}$ and $F = 4 \text{ N}$; $t = 4 \text{ s}$.

$$\begin{aligned} \text{The acceleration } a &= \frac{F}{m} = \frac{4 \text{ N}}{2.0 \text{ kg}} = \frac{4 \text{ kg ms}^{-2}}{2 \text{ kg}} \\ &= 2 \text{ ms}^{-2} \end{aligned}$$

The final velocity at the end of 4 s can be calculated as

$$\begin{aligned} v &= u + at = 0 \text{ ms}^{-1} + 2 \text{ ms}^{-2} \times 4 \text{ s} \\ &= 8 \text{ ms}^{-1} \end{aligned}$$

The distance covered during 4 s can be calculated as

$$s = \frac{v^2 - u^2}{2a} = \frac{(8 \text{ ms}^{-1})^2 - (0 \text{ ms}^{-1})^2}{2 \times 2 \text{ ms}^{-2}} = \frac{8^2 \text{ m}^2 \text{ s}^{-2}}{4 \text{ ms}^{-2}} = 16 \text{ m}.$$

After the force ceases to act, the body will continue to move at the uniform vel. $v = 8 \text{ ms}^{-1}$. The distance s' covered in the next 5 s after the force ceases to act can be calculated as

$$\begin{aligned} s' &= vt = 8 \text{ ms}^{-1} \times 5 \text{ s} \\ &= 40 \text{ m}. \end{aligned}$$

Example 7.2

A motor car is moving with a velocity of 144 kmh^{-1} and it takes 5 s to stop after the application of a braking force. Assuming the total mass of the motor car and passenger as 1800 kg, calculate the force exerted by the brakes on the motorcar.

Solution:

The initial velocity of the motorcar, $u = 144 \text{ kmh}^{-1}$

$$\text{or, } u = \frac{144 \times 1000 \text{ m}}{60 \times 60 \text{ s}} = 40 \text{ ms}^{-1}$$

The final velocity of the motorcar, $v = 0 \text{ ms}^{-1}$, since it is stopped by the braking force.

The total mass of motorcar with the passenger = 1800 kg and time taken to stop it = 5 s.

From Eq. 7.4, we get the magnitude of the force exerted by the brakes as $\frac{m(v - u)}{t}$

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

$$\begin{aligned} \text{Thus, on substitution, we have } F &= \frac{1800 \text{ kg} \times (0 - 40) \text{ ms}^{-1}}{5 \text{ s}} = -14400 \text{ kgms}^{-2} \\ &= -14400 \text{ N}. \end{aligned}$$

The negative sign tells us that the force exerted by the brakes is opposite to the direction of motion.

Example 7.3

A constant force of 10 N is applied on two masses m_1 and m_2 in turn and the respective accelerations produced are 10 ms^{-2} and 20 ms^{-2} . What acceleration would this force give, if both the masses are tied together?

Solution:

$$\text{From Eq. 7.3; We have } m_1 = \frac{F}{a_1} \text{ and } m_2 = \frac{F}{a_2}$$

Here, $a_1 = 10 \text{ ms}^{-2}$; $a_2 = 20 \text{ ms}^{-2}$ and $F = 10 \text{ N}$.

$$\text{Thus } m_1 = \frac{10 \text{ N}}{10 \text{ ms}^{-2}} = \frac{10 \text{ kgms}^{-2}}{10 \text{ ms}^{-2}} = 1.0 \text{ kg}$$

$$\text{And } m_2 = \frac{10 \text{ N}}{20 \text{ ms}^{-2}} = \frac{10 \text{ kgms}^{-2}}{20 \text{ ms}^{-2}} = 0.5 \text{ kg}$$

When the two masses are tied together, total mass, $m = 1.0 \text{ kg} + 0.5 \text{ kg}$.
 $= 1.5 \text{ kg}$.

Hence, the acceleration 'a' produced in the combined mass 'm' is

$$a = \frac{F}{m} = \frac{10 \text{ N}}{1.5 \text{ kg}} = \frac{10 \text{ kgms}^{-2}}{1.5 \text{ kg}} = \frac{20}{3} \text{ ms}^{-2} = 6.67 \text{ ms}^{-2}.$$

Example 7.4

The velocity-time graph of a body of mass 1.0 kg sliding along a straight path on a platform is shown in Fig. 7. 9. Obtain the force exerted by the platform on the body.

Solution:

The initial velocity of the body is 15 ms^{-1} . Due to the friction force exerted by the platform, the velocity of the body becomes zero in 30 s. Thus $u = 15 \text{ ms}^{-1}$; $v = 0 \text{ ms}^{-1}$; $t = 30 \text{ s}$. Since the graph is a straight line, the acceleration is uniform but against the direction of motion.

Thus the acceleration,

$$a = \frac{v - u}{t} = \frac{0 \text{ ms}^{-1} - 15 \text{ ms}^{-1}}{30 \text{ s}} \\ = -0.5 \text{ ms}^{-2}$$

Hence, the force F exerted on the body is $F = ma = 1.0 \text{ kg} \times (-0.5 \text{ ms}^{-2})$
 $= -0.5 \text{ N}$.

The negative sign implies that the force due to friction exerted by the platform is opposite to the direction of sliding motion.

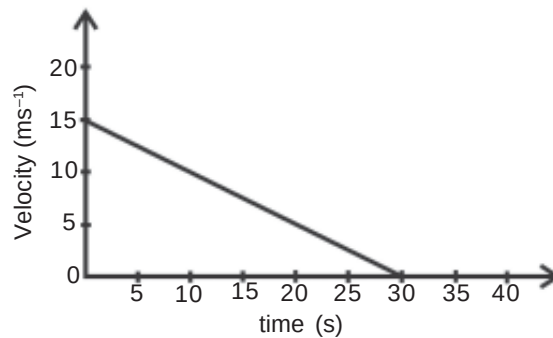


Fig. 7.9

7.5 Newton's Third Law of Motion

We have seen that Newton's first and second laws deal with the effect of forces when they act on a body. The first law states that unbalanced forces produce a change in the velocity of the body and the second law gives the exact amount of force needed to produce a given acceleration. Unlike the two laws stated above, Newton's third law

of motion is the relation between the forces themselves and it **states that when one body exerts a force on another body, the other body also exerts a force on the first body. These forces are always equal in magnitude but opposite in direction.** These forces act on different bodies and never act on the same body. This means that forces always occur in pairs. Let us consider an example associated in our daily life. In a football match a player looking at the football and trying to kick it with a greater force sometimes collide with a player of the opposite team. Both feel hurt because each of them applies a force on the other, thereby indicating a pair of forces. These two opposing forces are known as action and reaction forces.

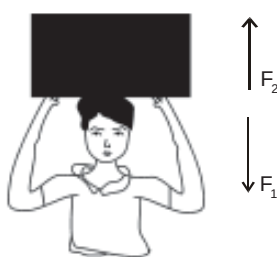


Fig. 7.10

Let us consider some more examples. When you hit a wall with your fist, the wall also hits your fist with same force and you can feel it. If you hit the same wall stronger than the earlier, you can feel more hurting than earlier. Suppose, a heavy load is put on the head of a porter Fig.7.10. The load presses the head in the downward direction. The porter's head pushes the load in the upward direction. These forces are equal in magnitude.

$F_1 \rightarrow$ Force applied by the load on the head

$F_2 \rightarrow$ Force applied by the head on the load.

Let us consider another example of two identical spring balances connected together as shown in Fig.7.11.

The fixed end of the balance B is attached to a rigid support such as a rigid wall. When the free end of balance A is pulled, it is observed that both the balances show the same reading on their scales. This phenomenon shows that force exerted by the balance A on balance B is equal but opposite in direction to that exerted by the balance B on A. The force exerted by balance A on the balance B is called the *action* while the force exerted by balance B on A is called the *reaction*. This illustration gives us an alternative statement of Newton's third law of Motion i.e. to every action there is an equal and opposite reaction. It is to be remembered that the action and reaction always act on two different bodies.

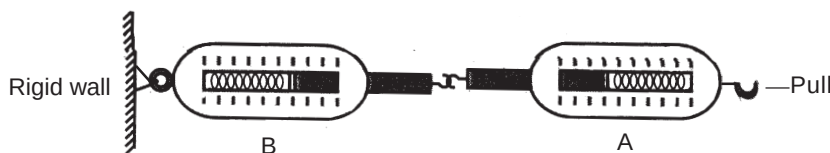


Fig.7.11: Action force and Reaction force are equal

Let us again consider an example that we have experienced in our day to day life. Suppose you are standing at rest and intend to start walking. You have to accelerate and this requires a force in accordance with the second law of motion. Here the force exerted by you is the muscular effort. Is it in the same direction you intend to walk? No, you push the ground backwards. The ground exerts an equal and opposite reaction force on your feet in order to make you walk forward. In fact you are walking in the direction of reaction force. Does the ground also accelerate to the same amount? No, this is because each force of equal magnitude acts on different bodies that may have a different mass. It will be clear from the following illustrations.

(1) When a gun is fired, it exerts a forward force on the bullet. At the same time, the bullet exerts an equal and opposite reaction force on the gun (Fig. 7.12). Since the mass of the gun is much larger than that of the bullet, the acceleration of the gun is much less than that of the bullet.

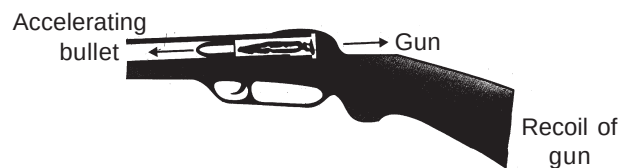


Fig. 7.12: A forward force on the bullet and recoil of gun

(2) When a sailor of a boat jumps forward to the bank of river, the force exerted on the boat makes it move backwards, as shown in (Fig. 7.13)

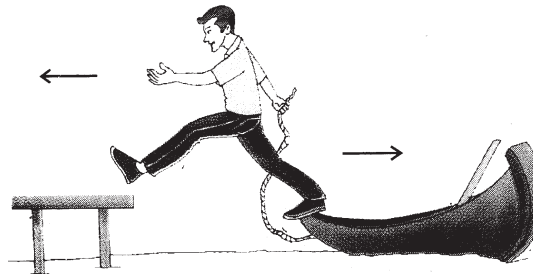


Fig. 7.13: As the sailor jumps forward the boat moves backwards

7.6 Conservation of Momentum

Suppose two bodies such as two balls marked 1 and 2 having masses m_1 and m_2 are moving along a straight line in the same direction at different velocities u_1 and u_2 respectively. Let us assume that $u_1 > u_2$, so that m_1 will collide m_2 as shown in the Fig. 7.14 (a) and (b)

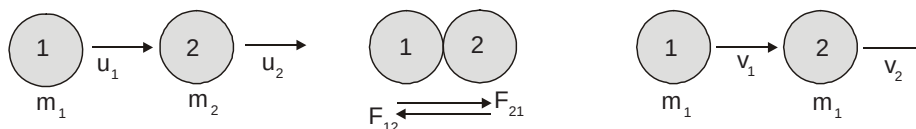


Fig. 7.14. (a) Before collision

(b) During collision

(c) After collision

The collision may last for a time 't' and during this interval ball 1 exerts a force F_{21} on the ball 2 and the ball 2 will also exert a force F_{12} on the ball 1. Let ' v_1 ' and ' v_2 ' be the velocities of ' m_1 ' and ' m_2 ' respectively after the collision, shown in Fig.7.14 (c). From the definition of momentum, the momenta of ball 1 before and after collision are $m_1 u_1$ and $m_1 v_1$ respectively. The change in momentum of ball 1 due to collision is $(m_1 v_1 - m_1 u_1)$ during the time t. Thus the rate of change of momentum which is equal to F_{12} during the collision will be $\frac{m_1 (v_1 - u_1)}{t}$. Similarly, the rate of change of momentum of ball

2 which is equal to F_{21} during the collision, is $\frac{m_2 (v_2 - u_2)}{t}$. As there are no other unbalanced forces acting on the balls, we can apply Newton's Third Law of Motion, according to which the force F_{12} exerted by ball 2 on ball 1 (Action force) and the force F_{21} exerted by ball 1 on ball 2 (Reaction force) must be equal and opposite to each other.

That is $F_{12} = -F_{21}$(7.7)

$$\text{or, } \frac{m_1 (v_1 - u_1)}{t} = - \frac{m_2 (v_2 - u_2)}{t}$$

$$m_1 v_1 - m_1 u_1 = - m_2 v_2 + m_2 u_2$$

This gives

$$m_1 v_1 + m_2 v_2 = m_2 u_2 + m_1 u_1$$

$$\text{or } m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2 \text{.....(7.8)}$$

i.e. Total momentum before collision = Total momentum after collision.

From Eq.7.8 we observe that total momentum of the two colliding balls remains unchanged or conserved provided no external unbalanced force acts. This is known as the law of conservation of momentum. The above can be stated as — "Momentum can neither be created nor destroyed – in a closed system consisting of number of bodies colliding with one another, the total momentum of the system remains constant".

7.6.1 Basic Working Principle of Toy Rocket

We have already seen the firing of toy rockets in certain festivals such as Diwali or Panthoibi Iratpa. The movement of the toy rocket is based on Newton's Third Law of motion as well as on the principle of conservation of momentum. In such a rocket, the hot gases produced by rapid burning of fuel rush out as a jet at the bottom and opposite reaction force of the downward going gases pushes the rocket upward with a great speed, as shown in Fig.7.15. Here the momentum of the rocket is equal to that of the hot gases.

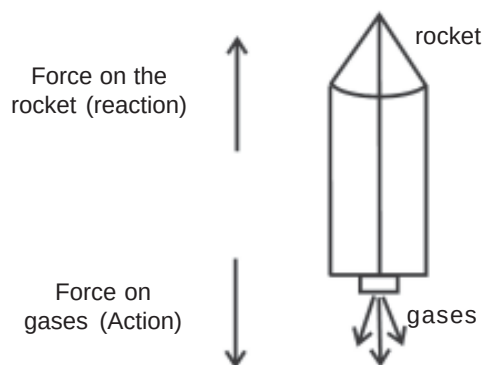


Fig. 7.15: Diagram showing action and reaction in the case of a toy rocket

Again, final vel. of the bullet after firing, $v_1 = 200 \text{ ms}^{-1}$.

Let 'v' be the velocity of recoil of the pistol.

Total momentum of the bullet and pistol after firing

$$= 0.02 \text{ kg} \times 200 \text{ ms}^{-1} + 3.00 \text{ kg} \times v \text{ ms}^{-1} = (4 + 3v) \text{ kgms}^{-1}$$

According to the law of conservation of momentum, we have

Total momentum after firing = Total momentum before firing

$$4 + 3v = 0$$

$$\Rightarrow v = -\frac{4}{3} = -1.33 \text{ ms}^{-1}$$

The negative sign shows that the direction of recoil of the pistol is opposite to that of the bullet.

Example 7.6

A boy of mass 25 kg jumps on a stationary skateboard fitted with frictionless wheels having a mass of 3 kg. If the velocity of the boy on jumping is 3m/s horizontally, what is the velocity of the skateboard with the boy? Assume that there is no other external force on the system.

Solution:

Let v be the velocity of the boy and skateboard together at the moment of starting.

Total initial momentum

$$= 25 \text{ kg} \times 3 \text{ ms}^{-1} + 3 \text{ kg} \times 0 \text{ ms}^{-1}$$

$$= 75 \text{ kgms}^{-1}$$

Total final momentum after the boy has jumped onto the skateboard

$$= (25 + 3) \text{ kg} \times v \text{ ms}^{-1} = 28 v \text{ kgms}^{-1}$$

According to the law of conservation of momentum, the total momentum is conserved, before and after jumping onto the skateboard.

$$\text{Thus } 28 v = 75$$

$$\therefore v = \frac{75}{28} = +2.678 \text{ ms}^{-1}$$

Points to remember

- (i) Force is that cause which produces *the change in the* state of rest or uniform motion of the body on which it acts.
- (ii) A force or a set of forces can (a) change the speed of the body (b) change the direction of motion of the body (c) also change the shape of deformable bodies.
- (iii) If forces acting on a body produce no acceleration in it, the forces are said to be balanced. If, on the other hand they produced a non-zero acceleration, the forces are called unbalanced.
- (iv) The natural tendency of objects/bodies resisting a change in their state of rest or of uniform motion is called inertia. The mass of the body is a measure of its inertia and its SI unit is kilogram (kg).

- (v) A stretched spring pulls the bodies connected to its ends whereas a compressed spring pushes the bodies connected to its ends.
- (vi) Friction between two surfaces is due to the lack of smoothness.
- (vii) Force of friction always opposes the direction of applied force.
- (viii) The rate of change of momentum of an object is directly proportional to the applied unbalanced force and takes place in the direction of force.
- (ix) The SI-unit of force is kgms^{-2} or newton, represented by the symbol N. A force of 1N produces an acceleration of 1 ms^{-2} on a body of mass 1 kg.
- (x) The momentum of a body is the product of its mass and velocity and has the same direction as that of the velocity. Its SI unit is kgms^{-1} . The change in momentum of a body is equal to the impulse of the applied force. The SI unit of impulse is N s.
- (xi) To every action there is an equal and opposite reaction and they act on two different bodies. So, when there is action there is reaction.
- (xii) The total momentum of a system, where there is no external force, remains conserved.

EXERCISES

1. Define balanced and unbalanced forces.
2. Can non-living objects exert a force? If yes, give two examples.
3. Why does the striker move through longer distances when some powder is sprinkled on a carromboard?
4. Explain Newton's laws of motion with example.
5. Give an example to demonstrate Newton's third law of motion.
6. Explain the meaning of inertia. Give appropriate examples to explain the inertia of rest and inertia of motion.
7. When you pull your arms back while catching a fast moving cricket ball, the chance of your hand getting hurt is less. Explain on the basis of Newton's laws of Motion.
8. When a hung carpet is beaten with a stick, dust particles come out of it. Explain.
9. A truck starting from rest travels down a hill with a constant acceleration. It travels a distance of 300 metres in 15 sec. Calculate its acceleration. Find the force acting on it, if its mass is 10 metric tonnes. (1 metric tone = 1000 kg)
10. A force of 15 N acts on a body of mass 0.5 kg. Find the acceleration of the particle. (30 ms^{-2})
11. The velocity of a body of mass 125 g changes from 10 m/s to 5 m/s in 5 second. Assuming that a constant force acts on it, find the magnitude of the force.

12. A coin of mass 25 g is pushed on a table. The coin starts moving at a speed of 25 cm s^{-1} and stops in 5 s. Find the force of friction exerted by the table on the coin.
(0.00125 N)
13. A hockey ball of mass 200 g travelling at 10 ms^{-1} is struck by a hockey stick so as to return it along its original path with a velocity of 5 ms^{-1} . Calculate the change in momentum occurred in the motion of the ball by the force applied by the hockey stick.
(3 kg ms^{-1})
14. A horizontal force of 200 N is required to move a wooden cabinet across a floor at a constant velocity. Calculate the friction force exerted on the cabinet.
(200 N)
15. Two bodies having each of mass 2 kg are moving in the same straight line but in opposite directions. The velocity of each before collision is 3 ms^{-1} . In the collision they stick together. What will be the velocity of the combined body after collision?
(Zero)
16. A sharp object of mass 0.5 kg travelling horizontally at a velocity of 100 ms^{-1} strikes a stationary wooden block of mass 2.5 kg. Thereafter the two move together in the same straight line. Calculate the total momentum before and after the impact. Also calculate the velocity of the combined system.
(50 kg ms^{-1} ; ms^{-1})
17. A ball of iron of mass 10 kg falls from a height of 0.8 m. If the downward acceleration of the ball is 10 ms^{-2} , calculate the momentum transfer to the floor by the ball, provided the ball does not rebound.
(40 kg ms^{-1})
18. An unbalanced force acts on a body. The body must
(a) remain at rest (b) move with uniform velocity
(c) be accelerated (d) move along a circle
(c)
19. When a bus suddenly starts, the standing passengers lean backwards in the bus. It is an example of Newton's
(a) first law of motion (b) second law of motion
(c) third law of motion (d) any one of the above laws of motion
(a)
20. Action-reaction forces act
(a) on the same body (b) on different bodies
(c) in the same direction (d) along different lines.
(b)
22. Suppose a constant force acts on a body initially kept at rest. The distance covered by the body in time t from start is proportional to
(a) t (b) t^{-1} (c) t^2 (d) t^3 .
(c)