Unit 3

Dynamics

STUDENT'S LEARNING OUTCOMES

After studying this unit, the students will be able to:

- define momentum, force, inertia, friction and centripetal force.
- solve problems using the equation
  Force = change in momentum / change in time.
- explain the concept of force by practical examples of daily life.
- state Newton's laws of motion.
- distinguish between mass and weight and solve problems using $F = ma$, and $w = mg$.
- calculate tension and acceleration in a string during motion of bodies connected by the string and passing over frictionless pulley using second law of motion.
- state the law of conversation of momentum.
- use the principle of conservation of momentum in the collision of two objects.
- determine the velocity after collision of two objects using the law of conservation of momentum.
- explain the effect of friction on the motion of a vehicle in the context of tyre surface, road conditions including skidding, braking force.
- demonstrate that rolling friction is much lesser than sliding friction.
- list various methods to reduce friction.

This unit is built on
Force and Motion
- Science-IV

This unit is leads to:
Motion and Force
- Physics-XI

Major Concepts

3.1 Momentum

3.2 Newton's laws of motion

3.3 Friction

3.4 Uniform circular motion

- explain that motion in a curved path is due to a perpendicular force on a body that changes direction of motion but not speed.
- calculate centripetal force on a body moving in a circle using mv^2/r.
- state what will happen to you while you are sitting inside a bus when the bus
  - (i) starts moving suddenly
  - (ii) stops moving suddenly
  - (iii) turns a corner to the left suddenly
- write a story about what may happen to you when you dream that all frictions suddenly disappeared. Why did your dream turn into a nightmare?

INVESTIGATION SKILLS

The students will be able to:

- identify the relationship between load and friction by sliding a trolley carrying different loads with the help of a spring balance on different surfaces.

SCIENCE, TECHNOLOGY AND SOCIETY CONNECTION

The students will be able to:

- identify the principle of dynamics with reference to the motion of human beings, objects, and vehicles (e.g. analyse the throwing of a ball, swimming, boating and rocket motion).
- identify the safety devices (such as packaging of fragile objects, the action of crumple zones and seatbelts) utilized to reduce the effects of changing momentum.
- describe advantages and disadvantages of friction in real - world situations, as well as methods used to increase or reduce friction in these situations (e.g. advantages of friction onthe surface of car tyres (tyre tread), cycling parachute, knots in string; disadvantages of friction, and methods for reducing friction

Figure 3.1: The food vendor on move

between moving parts of industrial machines and on wheels spinning on axles).

- identify the use of centripetal force in (i) safe driving by banking roads (ii) washing machine dryer (iii) cream separator.

In kinematics, we have studied the changes in motion only. Our understanding about the changes in motion is of little value without knowing its causes. The branch of mechanics that deals with the study of motion of an object and the cause of its motion is called **dynamics.** In this unit, we shall study momentum and investigate what causes a change in the motion of a body and what role the mass of a body plays in its motion. This inquiry leads us to the concept of force. We shall also study the laws of motion and their applications.

Figure 3.2: Ball is turned into different direction as it is pushed by the batsman.

3.1 FORCE, INERTIA AND MOMENTUM

Newton's laws of motion are of fundamental importance in understanding the causes of motion of a body. Before we discuss these laws, it is appropriate to understand various terms such as force, inertia and momentum.

Figure 3.3: A boy is pushing the wall.

FORCE

We can open a door either by pushing or pulling it Figure 3**.1** shows a man pushing a cart. The push may move the cart or change the direction of its motion or may stop the moving cart. A batsman in figure 3.2 is changing the direction of a moving ball by pushing it with his bat.

A force may not always cause a body to move. Look at the picture shown in figure 3.3. A boy is pushing a wall and is thus trying to move it. Could he move the wall? A Goalkeeper needs a force to stop a ball coming to him as shown in figure 3.4. Thus, we understand that

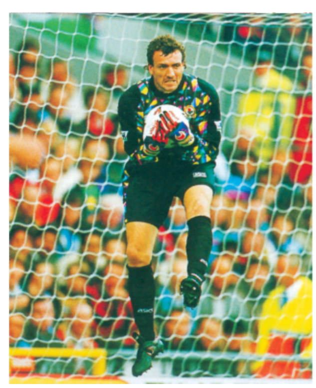


Figure 3.4: Goalkeeper is stopping the ball.

A force moves or tends to move, stops or tends to stop the motion of a body. The force can also change the direction of motion of a body.

What happens when you press a balloon?

You can cut an apple with a knife by pushing its sharp edge into the apple. Thus a force can also change the shape or size of a body on which it acts.

INERTIA

Galileo observed that it is easy to move or to stop light objects than heavier ones. Heavier objects are difficult to move or if moving then difficult to stop. Newton concluded that everybody resists to the change in its state of rest or of uniform motion in a straight line. He called this property of matter as inertia. He related the inertia of a body with its mass; greater is the mass of a body greater is its inertia.

Inertia of a body is its property due to which it resists any change in its state of rest or motion.

Let us perform an experiment to understand inertia.

Figure 3.5: The coin fails into the glass as the card flicks away.

EXPERIMENT 3.1

Take a glass and cover it with a piece of cardboard. Place a coin on the cardboard as shown in figure 3.5. Now flick the card horizontally with a jerk of your finger.

Does the coin move with the cardboard?

The coin does not move with the cardboard due to inertia.

Where does the coin go as the cardboard flies away?

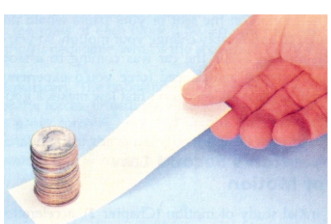


Figure 3.6: Coins stacked over remain undisturbed on pulling. the paper strip quickly

Consider another example of inertia. Cut a strip of paper. Place it on the table. Stack a few coins at its one end as shown in figure 3.6. Pull out the paper strip under the coins with a jerk.

Do you succeed in pulling out the paper strip under the stacked coins without letting them to fall?
Why do the coins remain stacked on pulling out the paper strip quickly under the stack?

MOMENTUM

A bullet has a very small inertia due to its small mass. But why does its impact is so strong when it is fired from the gun?

On the other hand, the impact of a loaded truck on a body coming its way is very large even if the truck is moving slowly. To explain such situation, we define a new physical quantity called momentum.

Momentum of a body is the quantity of motion it possesses due to its mass and velocity.

The momentum *P* of a body is given by the product of its mass m and velocity *v*. Thus

$$P = mv \qquad \dots \dots \dots \dots \dots \qquad (3.1)$$

Momentum is a vector quantity. Its SI unit is $kgms^{-1}$.

3.2 NEWTON'S LAWS OF MOTION

Newton was the first to formulate the laws of motion known as Newton's laws of motion.

NEWTON'S FIRST LAW OF MOTION

First law of motion deals with bodies which are either at rest or moving with uniform speed in a straight line. According to Newton's first law of motion, a body at rest remains at rest provided no net force acts on it. This part of the law is true as we observe that objects do not move by themselves unless someone moves them. For example, a book lying on a table remains at rest as long as no net force acts on it.

Net force is the resultant of all the forces acting on a body.

Similarly, a moving object does not stop moving by itself. A ball rolled on a rough ground stops earlier than that rolled on a smooth ground. It is because rough surfaces offer greater friction. If there would be no force to oppose the motion of a body then the moving body would never stop. Thus Newton's first law of motion states that:

A body continues its state of rest or of uniform motion in a straight line provided no net force acts on it.

DO YOU KNOW?

When a bus takes a sharp turn, passengers fall in the outward direction. It is due to inertia that they want to continue their motion in a straight line and thus fall outwards.

Since Newton's first law of motion deals with the inertial property of matter, therefore, Newton's first law of motion is also known as law of inertia.

We have observed that the passengers standing in a bus fall forward when its driver applies brakes suddenly. It is because the upper parts of their bodies tend to continue their motion, while lower parts of their bodies in contact with the bus stop with it. Hence, they fall forward.

NEWTON'S SECOND LAW OF MOTION

Newton's second law of motion deals with situations when a net force is acting on a body. It states that:

When a net force acts on a body, it produces acceleration in the body in the direction of the net force. The magnitude of this acceleration is directly proportional to the net force acting on the body and inversely proportional to its mass.

If a force produces an acceleration a in a body of mass m, then we can state mathematically that

$$a \propto F$$

and $$a \propto \frac{1}{m}$$

or $$a \propto \frac{F}{m}$$

or $$F \propto ma$$

Putting k as proportionality constant, we get

$$F = kma \quad \dots \quad \dots \quad \dots \quad (3.2)$$

In SI units, the value of k comes out to be 1. Thus Eq. 3.2 becomes

$$F = m\,a \quad \dots \quad \dots \quad \dots \quad (3.3)$$

SI unit of force is newton (N). According to Newton's second law of motion:

One newton (1 N) is the force that produces an acceleration of 1 ms^{-2} in a body of mass of 1 kg.

Thus, a force of one newton can be expressed as

$$1N = 1\text{ kg} \times 1\text{ ms}^{-2}$$

or $$1N = 1\text{ kg ms}^{-2} \quad \dots \quad \dots \quad (3.4)$$

EXAMPLE 3.1

Find the acceleration that is produced by a 20 N force in a mass of 8 kg.

SOLUTION

Here $m = 8\text{ kg}$

$F = 20\text{N}$

$a = ?$

using the formula $F = m\,a$

$20\text{N} = 8\text{ kg} \times a$

or $a = \dfrac{20\text{N}}{8\text{kg}}$

$a = 2.5\ \dfrac{\text{kg ms}^{-2}}{\text{kg}}$

$= 2.5\text{ ms}^{-2}$

Thus acceleration produced by the force is 2.5 ms^{-2} .

EXAMPLE 3.2

A force acting on a body of mass 5 kg produces an acceleration of 10 ms^{-2}. What acceleration the same force will produce in a body of mass 8 kg?

SOLUTION

Here $m_1 = 5\text{kg}$

$m_2 = 8\text{kg}$

$a_1 = 10\text{ ms}^{-2}$

$a_2 = ?$

Applying Newton's second law of motion, we get

$F = m_1 a_1$

$F = m_2 a_2$

Comparing the equations, we get

$m_1 a_1 = m_2 a_2$

$(5\text{kg})\ (10\text{ms}^{-2}) = (8\text{kg})\ a_2$

or $a_2 = 6.25\text{ ms}^{-2}$

Hence, the acceleration produced is 6.25 ms^{-2}.

EXAMPLE 3.3

A cyclist of mass 40 kg exerts a force of 200 N to move his bicycle with an acceleration of 3 ms^{-2}. How much is the force of friction between the road and the tyres?

SOLUTION

Here $m = 40 \text{ kg}$

$a = 3 \text{ ms}^{-2}$

$F_o = 200 \text{ N}$

Net Force $F = ?$

Force of friction $f = ?$

As net Force $F = m\,a$

$= 40 \text{ kg} \times 3 \text{ ms}^{-2}$

$= 120 \text{ N}$

$\therefore$ Net force = Applied Force - Force of friction

$120 \text{ N} = 200\text{N} - f$

Hence $f = 80 \text{ N}$

Thus, the force of friction between the road and the tyres is 80 N.

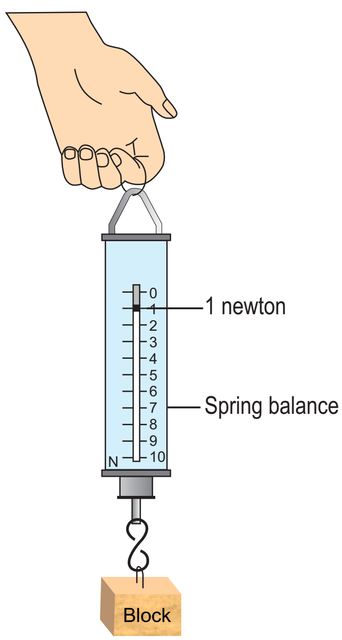


Figure 3.7: Spring balance is used to measure the force or weight of a body.

MASS AND WEIGHT

Generally, mass and weight are considered similar quantities, but it is not correct. They are two different quantities. Mass of a body is the quantity of matter possessed by the body. It is a scalar quantity and does not change with change of place. It is measured by comparison with standard masses using a beam balance.

On the other hand, weight of a body is the force equal to the force with which Earth attracts it. It varies depending upon the value of ***g***, acceleration due to gravity. Weight woi a body of mass m is related by the equation

$$w = mg \quad .... \quad (3.5)$$

Weight is a force and thus it is a vector quantity. Its SI unit is newton (N); the same as force. Weight is measured by a spring balance.

NEWTON'S THIRD LAW OF MOTION

Newton's third law of motion deals with the reaction of a body when a force acts on it. Let a body Aexerts a force on another body B, the body B reacts against this force and exerts a force on body A. The force exerted by body A on B is the action force whereas the force exerted by body B on A is called the reaction force. Newton's third law of motion states that:

To every action there is always an equal but opposite reaction.

According to this law, action is always accompanied by a reaction force and the two forces must always be equal and opposite. Note that action and reaction forces act on different bodies.

Consider a book lying on a table as shown in figure 3.8. The weight of the book is acting on the table in the downward direction. This is the action. The reaction of the table acts on the book in the upward direction. Consider another example. Take an air-filled balloon as shown in figure 3.9. When the balloon is set free, the air inside it rushes out and the balloon moves forward. In this example, the action is by the balloon that pushes the air out of it when set free. The reaction of the air which escapes out from the balloon acts on the balloon. It is due to this reaction of the escaping air that moves the balloon forward.

A rocket such as shown in figure 3.10 moves on the same principle. When its fuel burns, hot gases escape out from its tail with a very high speed. The

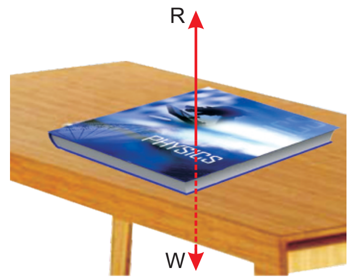


Figure 3.8: Action of the book and reaction on it.

Figure 3.9: Reaction of the air pushed out of the balloon moves it.

Figure 3.10: A Rocket taking off.

reaction of these gases on the rocket causes it to move opposite to the gases rushing out of its tail.

> **Quick Quiz**
>
> Stretch out your palm and hold a book on it.
>
> 1. How much force you need to prevent the book from falling?
> 2. Which is action?
> 3. Is there any reaction? If yes, then what is its direction?

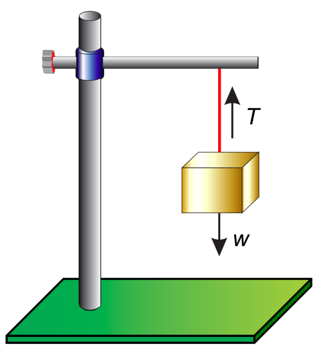


Figure 3.11: Weight of the block pulls the string downwards.

TENSION AND ACCELERATION IN A STRING

Consider a block supported by a string. The upper end of the string is fixed on a stand as shown in figure 3.11. Let *w* be the weight of the block. The block pulls the string downwards by its weight. This causes a tension *T* in the string. The tension *T* in the string is acting upwards at the block. As the block is at rest, therefore, the weight of the block acting downwards must be balanced by the upwards tension *T* in the string. Thus the tension *T* in the string must be equal and opposite to the weight w of the block.

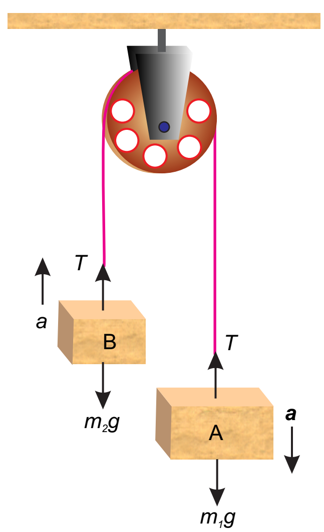


Figure 3.12: Bodies attached to the ends of a string that passes over a frictionless pulley.

VERTICAL MOTION OF TWO BODIES ATTACHED TO THE ENDS OF A STRING THAT PASSES OVER A FRICTIONLESS PULLEY

Consider two bodies A and B of masses m_1 and m_2 respectively. Let m_1 is greater than m_2. The bodies are attached to the opposite ends of an inextensible string. The string passes over a frictionless pulley as shown in figure 3.12. The body *A* being heavier must be moving downwards with some acceleration. Let this acceleration be *a*. At the same time, the body *B* attached to the other end of the string moves up with the same acceleration *a*. As the pulley is frictionless, hence tension will be the same throughout the string. Let the tension in the string be *T*.

Since the body *A* moves downwards, hence its weight m_1g is greater than the tension *T* in the string.

$\therefore$ Net force acting on body $A = m_1g - T$

According to Newton s second law of motion;

$$m_1 g - T = m_1 a \quad \ldots \quad \ldots \quad \ldots \quad (3.6)$$

As body B moves upwards, hence its weight m_2g is less than the tension T in the string.

$\therefore$ Net force acting on body B = T- $m_2 g$

According to Newton's second law of motion;

$$T - m_2 g = m_2 a \quad \ldots \quad \ldots \quad \ldots \quad (3.7)$$

Adding Eq. 3.6 and Eq.3.7, we get acceleration a.

$$a = \frac{m_1 - m_2}{m_1 + m_2} g \quad \ldots \quad \ldots \quad (3.8)$$

Divide Eq. 3.7 by Eq. 3.6, to find tension T in the string.

$$T = \frac{2m_1 m_2}{m_1 + m_2} g \quad \ldots \quad \ldots \quad (3.9)$$

The above arrangement is also known as Atwood machine. It can be used to find the acceleration *gdue* to gravity using Eq 3.8,

$$g = \frac{2m_1 + m_2}{m_1 - m_2} a$$

EXAMPLE 3.4

Two masses 5.2 kg and 4.8 kg are attached to the ends of an inextensible string which passes over a frictionless pulley. Find the acceleration in the system and the tension in the string when both the masses are moving vertically.

SOLUTION

m_1 = 5.2 kg

m_2 = 4.8 kg

as $a = \frac{m_1 - m_2}{m_1 + m_2} g$

$= \frac{5.2\,\text{kg} - 4.8\,\text{kg}}{5.2\,\text{kg} + 4.8\,\text{kg}} \times 10\ \text{ms}^{-2}$

$\therefore$ a = 0.4 ms^{-2}

as $T = \frac{2m_1 m_2}{m_1 + m_2} g$

DO YOU KNOW?

An Atwood machine is an arrangement of two objects of unequal masses such as shown in figure 3.12. Both the objects are attached to the ends of a string. The string passes over a frictionless pulley. This arrangement is sometime used to find the acceleration due to gravity.

$$= \frac{2 \times 5.2\,\text{kg} \times 4.8\,\text{kg}}{5.2\,\text{kg} + 4.8\,\text{kg}} \times 10\ \text{ms}^{-2}$$

$$\therefore \quad T = 50\ \text{N}$$

Thus the acceleration in the system is 0.4 ms^{-2} and tension in the string is 50 N.

MOTION OF TWO BODIES ATTACHED TO THE ENDS OF A STRING THAT PASSES OVER A FRICTIONLESS PULLEY SUCH THAT ONE BODY MOVES VERTICALLY AND THE OTHER MOVES ON A SMOOTH HORIZONTAL SURFACE

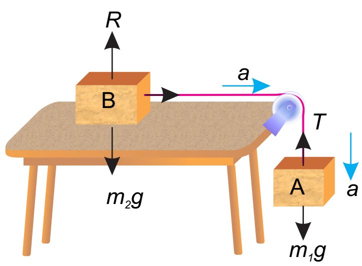


Figure 3.13: Motion of masses attached to a string that passes over a frictionless pulley.

Consider two bodies *A* and *B* of masses m_1 and m_2 respectively attached to the ends of an inextensible string as shown in figure 3.13. Let the body *A* moves downwards with an acceleration **a**. Since the string is inextensible, therefore, body B also moves over the horizontal surface with the same acceleration **a**. As the pulley is frictionless, hence tension *T* will be the same throughout the string.

Since body *A* moves downwards, therefore, its weight m_1g is greater than the tension *T* in the string.

Net force acting on body *A* = $m_1g - T$

According to Newton's second law of motion;

$$m_1 g - T = m_1 a \quad \ldots \quad \ldots \quad \ldots \quad (3.10)$$

The forces acting on body *B* are:

i. Weight m_2g of the body *B* acting downward.

ii. Reaction *R* of the horizontal surface acting on body *B* in the upwards direction.

iii. Tension *T* in the string pulling the body *B* horizontally over the smooth surface.

As body *B* has no vertical motion, hence resultant of vertical forces(m_2g and *R*) must be zero.

Thus, the net force acting on body *B* is *T*.

According to Newton's second law of motion;

$$T = m_2 a \quad \ldots \quad \ldots \quad \ldots \quad (3.11)$$

Adding Eqs. 3.10 and 3.11, we get acceleration a as

$$a = \frac{m_1}{m_1 + m_2} g \quad \ldots \quad \ldots \quad (3.12)$$

Putting the value of a in equations 3.11 to get tension T as

$$T = \frac{m_1 m_2}{m_1 + m_2} g \quad \ldots \quad \ldots \quad (3.13)$$

EXAMPLE 3.5

Two masses 4 kg and 6 kg are attached to the ends of an inextensible string which passes over a frictionless pulley such that mass 6 kg is moving over a frictionless horizontal surface and the mass 4 kg is moving vertically downwards. Find the acceleration in the system and the tension in the string.

SOLUTION

$$m_1 = 4 \text{ kg}$$

$$m_2 = 6 \text{ kg}$$

as $$a = \frac{m_1}{m_1 + m_2} g$$

$$= \frac{4 \text{ kg}}{4 \text{ kg} + 6 \text{ kg}} \times 10 \text{ ms}^{-2}$$

$$\therefore \quad a = 4 \text{ ms}^{-2}$$

as $$T = \frac{m_1 m_2}{m_1 + m_2} g$$

$$= \frac{4 \text{ kg} \times 6 \text{ kg}}{4 \text{ kg} + 6 \text{ kg}} \times 10 \text{ ms}^{-2}$$

$$\therefore \quad T = 24 \text{ N}$$

Thus the acceleration in the system is 4 ms^{-2} and tension in the string is 24N.

FORCE AND THE MOMENTUM

Consider a body of mass m moving with initial velocity v_i. Let a force F acts on the body which produces an acceleration a in it. This changes the velocity of the body. Let its final velocity after time becomes v_f. If P_i and P_f be the initial momentum and

USEFUL INFORMATION

Fragile objects such as glass wares etc. are packed with suitable materials such as styrofoam rings, balls, polythene sheets with air sacks etc.

Air enclosed in the cavities of these materials makes them flexible and soft. During any mishap, they increase the impact time on fragile objects. An increase in impact time lowers the rate of change of momentum and hence lessens the impact of force. This lowers the possible damage due to an accident.

USEFUL INFORMATION

In an accident at high speed, the impact force is very large due to the extremely short stopping time. For safety purposes, vehicles have rigid cages for passengers with crumple zones at their front and rear ends.

During an accident, crumple zones collapse. This increases the impact time by providing extra time for crumpling. The impact of force is highly reduced and saves the passengers from severe injuries.

final momentum of the body related to initial and final velocities respectively, then

$$P_i = mv_i$$

and $$P_f = mv_f$$

$\therefore$ Change in momentum = final momentum − initial momentum

or $$P_f - P_i = mv_f - mv_i$$

Thus the rate of change in momentum is given by:

$$\frac{P_f - P_i}{t} = \frac{mv_f - mv_i}{t}$$

$$= m\,\frac{v_f - v_i}{t}$$

since $\frac{v_f - v_i}{t}$ is the rate of change of velocity equal to the acceleration a produced by the force F.

$$\therefore \quad \frac{P_f - P_i}{t} = m\,a$$

According to Newton's second law of motion,

$$F = ma$$

or $$\frac{P_f - P_i}{t} = F \qquad \ldots \ldots \ldots \ldots \quad (3.14)$$

Equation 3.14 also defines force and states Newton's second law of motion as

When a force acts on a body, it produces an acceleration in the body and will be equal to the rate of change of momentum of the body.

SI unit of momentum defined by equation 3.14 is newton-second (Ns) which is the same as kgms^{-1}.

EXAMPLE 3.6

A body of mass 5 kg is moving with a velocity of 10ms^{-1}. Find the force required to stop it in 2 seconds.

SOLUTION

$$m = 5\text{ kg}$$

$$v_i = 10\text{ ms}^{-1}$$

$$v_f = 0\text{ ms}^{-1}$$

$$t = 2\ \text{s}$$
$$F = ?$$
$$P_i = 5\ \text{kg} \times 10\ \text{ms}^{-1}$$
$$= 50\ \text{Ns}$$
$$P_f = 5\ \text{kg} \times 0\ \text{ms}^{-1}$$
$$= 0\ \text{Ns}$$

since $$F = \frac{P_f - P_i}{t}$$

$$= \frac{50\ \text{Ns} - 0\ \text{Ns}}{2\ \text{s}}$$

$$= 25\ \text{N}$$

Thus 25 N force is required to stop the body.

LAW OF CONSERVATION OF MOMENTUM

Momentum of a system depends on its mass and velocity. A system is a group of bodies within certain boundaries. An **isolated system** is a group of interacting bodies on which no external force is acting. If no unbalanced or net force acts on a system, then according to equation 3.14 its momentum remains constant. Thus the momentum of an isolated system is always conserved. This is the Law of Conservation of Momentum. It states that:

The momentum of an isolated system of two or more than two interacting bodies remains constant.

Consider the example of an air-filled balloon as described under the third law of motion. In this case, balloon and the air inside it form a system. Before releasing the balloon, the system was at rest and hence the initial momentum of the system was zero. As soon as the balloon is set free, air escapes out of it with some velocity. The air coming out of it possesses momentum. To conserve momentum, the balloon moves in a direction opposite to that of air rushing out.

Consider an isolated system of two spheres of masses m_1 and m_2 as shown in figure 3.14. They are moving in a straight line with initial velocities u_1 and u_2

USEFUL INFORMATION

In case of an accident, a person not wearing seatbelt will continue moving until stopped suddenly by something before him. This something may be a windscreen, another passenger or back of the seat in front of him/her. Seatbelts are useful in two ways:

- They provide an external force to a person wearing seatbelt.
- The additional time is required for stretching seat belts. This prolongs the stopping time for momentum to change and reduces the effect of collision.

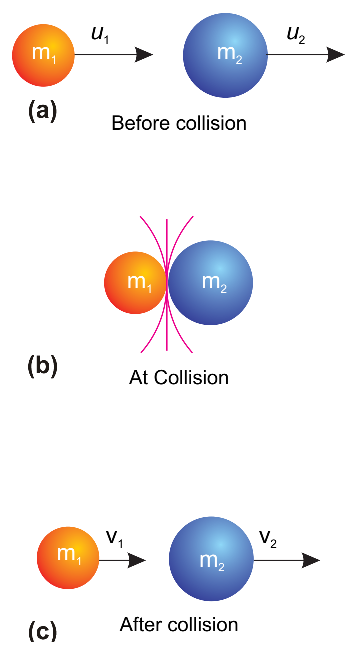


Figure 3.14: Collision of two bodies of spherical shapes.

respectively, such that u_1 is greater than u_2. Sphere of mass m_1 approaches the sphere of mass m_2 as they move.

Initial momentum of mass $m_1 = m_1u_1$ Initial momentum

of mass $m_2 = m_2u_2$ Total initial momentum of the system before collision $= m_1u_1+m_2u_2$ ... (3.15)

After sometime mass m_1 hits m_2 with some force. According to Newton's third law of motion, m_2 exerts an equal and opposite reaction force on m_1. Let their velocities become v_1 and v_2 respectively after collision. Then

Final momentum of mass $m_1 = m_1v_1$ Final

momentum of mass $m_2 = m_2v_2$

Total final momentum of the system after collision $= m_1v_1+m_2v_2$............ (3.16)

According to the law of conservation of momentum

$$\begin{pmatrix}\text{Total initial momentum of} \\ \text{the system before collision}\end{pmatrix} = \begin{pmatrix}\text{Total final momentum} \\ \text{the system after collision}\end{pmatrix}$$

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2 \quad \ldots \quad (3.17)$$

Equation 3.17 shows that the momentum of an isolated system before and after collisions remains the same which is the law of conservation of momentum. Law of conservation of momentum is an important law and has vast applications.

Consider a system of gun and a bullet. Before firing the gun, both the gun and bullet are at rest, so the total momentum of the system is zero. As the gun is fired, bullet shoots out of the gun and acquires momentum. To conserve momentum of the system, the gun recoils. According to the law of conservation of momentum, the total momentum of the gun and the bullet will also be zero after the gun is fired. Let *m* be the mass of the bullet and v be its velocity on firing the gun; *M* be the mass of the gun and *V* be the velocity with which it recoils. Thus the total momentum of the gun and the bullet after the gun is fired will be;

$$\begin{pmatrix}\text{Total momentum of the}\\ \text{gun and the bullet after}\\ \text{the gun is fired}\end{pmatrix} = M\,V + m\,v \;\ldots\;\ldots\quad\ldots(3.18)$$

According to the law of conservation of momentum

$$\begin{pmatrix}\text{Total momentum of the}\\ \text{gun and the bullet after}\\ \text{the gun is fired}\end{pmatrix} = \begin{pmatrix}\text{Total momentum of the}\\ \text{gun and the bullet before}\\ \text{the gun is fired}\end{pmatrix}$$

$$\therefore \qquad M\,V + m\,v = 0$$

$$\text{or} \qquad M\,V = -\,m\,v$$

$$\text{Hence} \qquad V = -\frac{m}{M}\,v \;\ldots\;\ldots\;\ldots\;(3.19)$$

Equation 3.19 gives the velocity V of the gun. Negative sign indicates that velocity of the gun is opposite to the velocity of the bullet, i.e., the gun recoils. Since mass of the gun is much larger than the bullet, therefore, the recoil is much smaller than the velocity of the bullet.

Rockets and jet engines also work on the same principle. In these machines, hot gases produced by burning of fuel rush out with large momentum. The machines gain an equal and opposite momentum. This enables them to move with very high velocities.

EXAMPLE 3.7

A bullet of mass 20 g is fired from a gun with a muzzle velocity 100 ms^{-1}. Find the recoil of the gun if its mass is 5 kg.

SOLUTION

m = 20 g = 0.02 kg

v = 100 ms^{-1}

M = 5 kg

V = ?

According to the law of conservation of momentum:

$$MV + mv = 0$$

Putting the values, we get

$$\therefore\ 5\text{ kg} \times V + (0.02\text{ kg}) \times (100\text{ ms}^{-1}) = 0$$

$$\text{or} \quad 5\text{ kg} \times V = -(0.02\text{ kg}) \times (100\text{ ms}^{-1})$$

$$\text{or} \quad V = -\frac{(0.2\text{ kg}) \times (100\text{ ms}^{-1})}{5\text{ kg}}$$

$$= -0.4\text{ ms}^{-1}$$

The negative sign indicates that the gun recoils i.e., moves in the backward direction opposite to the motion of the bullet with a velocity of 0.4 ms^{-1}.

Figure 3.15: A cyclist keeps on pedalling to overcome friction.

3.3 FRICTION

Have you noticed why a moving ball stops? Why bicycle stops when the cyclist stops pedalling?

Naturally there must be some force that stops moving objects. Since a force not only moves an object but also stops moving object.

The force that opposes the motion of moving objects is called friction.

Figure 3.16: To walk or to run friction is needed to push the ground backward

Friction is a force that comes into action as soon as a body is pushed or pulled over a surface. In case of solids, the force of friction between two bodies depends upon many factors such as nature of the two surfaces in contact and the pressing force between them. Rub your palm over different surfaces such as table, carpet, polished marble surface, brick, etc. You will find smoother is the surface, easier it is to move over the surface. Moreover, harder you press your palm over the surface, more difficult would it be to move.

Why friction opposes motion? No surface is perfectly smooth. A surface that appears smooth has pits and bumps that can be seen under a microscope. Figure 3.17 shows two wooden blocks with their polished surfaces in contact. A magnified view of two smooth surfaces in contact shows the gaps and

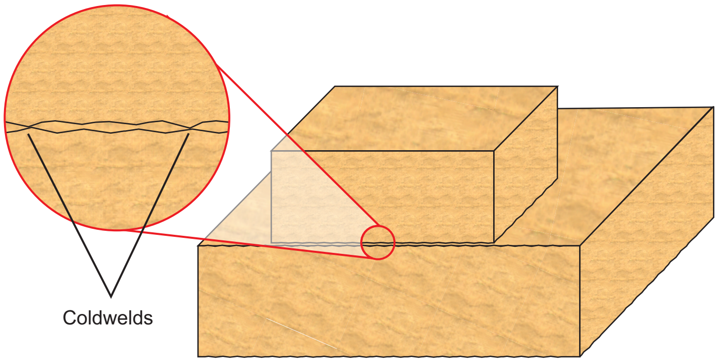


Figure 3.17: A magnified view of the two surfaces in contact.

TIDBITS

Pushing the opposite walls by palms and feet increases friction. This enables the boy to move up on the walls.

contacts between them. The contact points between the two surfaces form a sort of **coldwelds.** These cold welds resist the surfaces from sliding over each other. Adding weight over the upper block increases the force pressing the surfaces together and hence, increases the resistance. Thus, greater is the pressing force greater will be the friction between the sliding surfaces.

Friction is equal to the applied force that tends to move a body at rest. It increases with the applied force. Friction can be increased to certain maximum value. It does not increase beyond this. The maximum value of friction is known as the **force of limiting friction (F_s).** It depends on the normal reaction (pressing force) between the two surfaces in contact. The ratio between the force of limiting friction F_s and the normal reaction R is constant. This constant is called the **coefficient of friction** and is represented by μ.

Thus $$\mu = \frac{F_s}{R} \quad \ldots \ldots \ldots \quad (3.20)$$

or $$F_s = \mu R \quad \ldots \ldots \ldots \quad (3.21)$$

If m be the mass of the block, then for horizontal surface;

$$R = mg \quad \ldots \ldots \ldots \quad (3.22)$$

Hence $$F_s = \mu\, mg \quad \ldots \ldots \ldots \quad (3.23)$$

Friction is needed to walk on the ground. It is risky to run on wet floor with shoes that have smooth soles. Athletes use special shoes that have extraordinary ground grip. Such shoes prevent them from slipping while running fast. What will we do to stop our bicycle? We will apply brakes. The rubber pads

Coefficient of friction between some common materials

Materials	μ_s
Glass and Glass	0.9
Glass and Metal	0.5 - 0.7
Ice and Wood	0.05
Iron and Iron	1.0
Rubber and Concrete	0.6
Steel and Steel	0.8
Tyre and Road, dry	1
Tyre and Road, wet	0.2
Wood and Wood	0.25 - 0.6
Wood and Metal	0.2 - 0.6
Wood and Concrete	0.62

pressed against the rims provide friction. It is the friction that stops the bicycle.

QUICK QUIZ

1. Which shoe offer less friction?
2. Which shoe is better for walking on dry track?
3. Which shoe is better for jogging?
4. Which sole will wear out early?

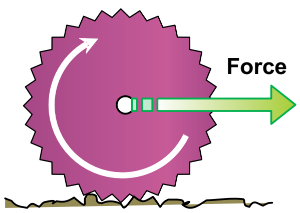


Figure 3.18: Friction may cause the body to roll.

Wheel is one of the most important inventions in the history of mankind. The first thing about a wheel is that it rolls as it moves rather than to slide. This greatly reduces friction. Why?

When the axle of a wheel is pushed, the force of friction between the wheel and the ground at the point of contact provides the reaction force. The reaction force acts at the contact points of the wheel in a direction opposite to the applied force. The wheel rolls without rupturing the cold welds. That is why the rolling friction is extremely small than sliding friction. The fact that rolling friction is less than sliding friction is applied in ball bearings or roller bearings to reduce losses due to friction.

Figure 3.19: A ball bearing

The wheel would not roll on pushing it if there would be no friction between the wheel and the ground. Thus, friction is desirable for wheels to roll over a surface. It is dangerous to drive on a wet road because the friction between the road and the tyres is very small. This increases the chance of slipping the tyres from the road. The threading on tyres is designed to increase friction. Thus, threading improves road grip and make it safer to drive even on wet road.

Figure 3.20: Threading on tyres provides good road grip.

A cyclist applies brakes to stop his/her bicycle. As soon as brakes are applied, the wheels stop rolling and begin to slide over the road. Since sliding friction is much greater than rolling friction. Therefore, the cycle stops very quickly.

QUICK QUIZ

1. Why is it easy to roll a cylindrical eraser on a paper sheet than to slide it?
2. Do we roll or slide the eraser to remove the pencil work from our notebook?

BRAKING AND SKIDDING

The wheels of a moving vehicle have two velocity components:

(i) motion of wheels along the road.
(ii) rotation of wheels about their axis.

To move a vehicle on the road as well as to stop a moving vehicle requires friction between its tyres and the road. For example, if the road is slippery or the tyres are worn out then the tyres instead of rolling, slip over the road. The vehicle will not move if the wheels start slipping at the same point on the slippery road. Thus for the wheels to roll, the force of friction (gripping force) between the tyres and the road must be enough that prevents them from slipping.

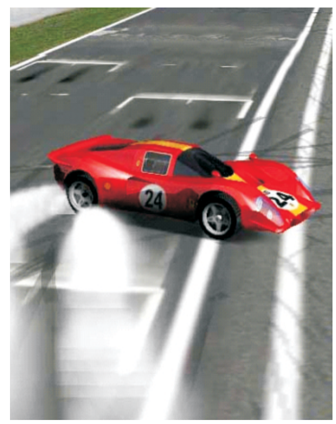


Figure 3.21: A car skidding.

Similarly, to stop a car quickly, a large force of friction between the tyres and the road is needed. But there is a limit to this force of friction that tyres can provide. If the brakes are applied too strongly, the wheels of the car will lock up (stop turning) and the car will skid due to its large momentum. It will lose its directional control that may result in an accident. In order to reduce the chance of skidding, it is advisable not to apply brakes too hard that lock up their rolling motion especially at high speeds. Moreover, it is unsafe to drive a vehicle with worn out tyres.

Mini Exercise

1. In which case do you need smaller force and why?
   (i) rolling (ii) sliding
2. In which case it is easy for the tyre to roll over?
   (i) rough ground
   (ii) smooth ground

ADVANTAGES AND DISADVANTAGES OF FRICTION

Friction has the advantages as well as disadvantages. Friction is undesirable when moving at high speeds because it opposes the motion and thus limits the speed of moving objects. Most of our useful energy is lost as heat and sound due to the friction between various moving parts of machines. In machines, friction also causes wear and tear of their moving parts.

DO YOU KNOW?

Friction is highly desirable when climbing up a hill.

However, sometimes friction is most desirable. We cannot write if there would be no friction between paper and the pencil. Friction enables us to walk on the ground. We cannot run on a slippery ground. A slippery ground offers very little friction. Hence, anybody who tries to run on a slippery ground may meet an accident. Similarly, it is dangerous to apply brakes with full force to stop a fast moving vehicle on a slippery road. Birds could not fly, if there is no air resistance. The reaction of pushed air enables the birds to fly. Thus in many situations, we need friction while in other situations we need to reduce it as much as possible.

Write a dream during which you are driving a car and suddenly the friction disappears. What happened next...?

Figure 3.22: Smooth air flow at high speeds reduces air resistance.

METHODS OF REDUCING FRICTION

The friction can be reduced by:

(i) making the sliding surfaces smooth.

(ii) making the fast moving objects a streamline shape (fish shape) such as cars, aero planes, etc. This causes the smooth flow of air and thus minimizes air resistance at high speeds.

(iii) Lubricating the sliding surfaces.

(iv) Using ball bearings or roller bearings .Because the rolling friction is lesser than the sliding friction.

Figure 3.23: Streamlining the bullet train reduces air resistance at high speed.

3.4 UNIFORM CIRCULAR MOTION

We come across many things in our daily life that are moving along circular path. Take a small stone. Tie it at one end of a string and keep the other end of the string in your hand as shown in figure 3.24.

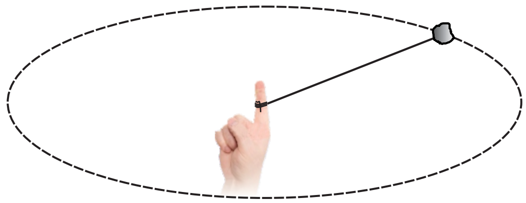


Figure 3.24: Circular motion of a stone attached with a string.

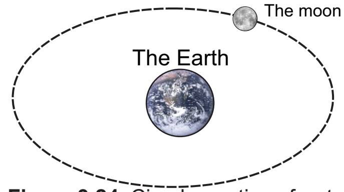


Figure 3.24: Circular motion of a stone attached with a string.

Now rotate the stone holding the string. The stone will move in a circular path. The motion of stone will be called as circular motion. Similarly, motion of the moon around the Earth is circular motion.

The motion of an object in a circular path is known as circular motion.

CENTRIPETAL FORCE

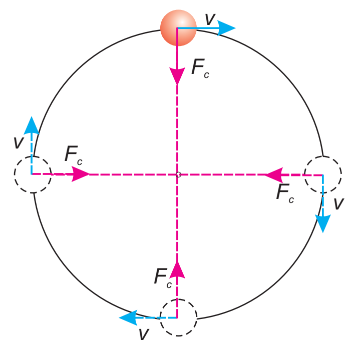


Figure 3.26: Centripetal force is always directed towards the centre and has no component in the direction of motion.

Consider a body tied at the end of a string moving with uniform speed in a circular path. A body has the tendency to move in a straight line due to inertia. Then why does the body move in a circle? The string to which the body is tied keeps it to move in a circle by pulling the body towards the centre of the circle. The string pulls the body perpendicular to its motion as shown in figure 3.26. This pulling force continuously changes the direction of motion and remains towards the centre of the circle. This centre seeking force is called the centripetal force. It keeps the body to move in a circle. Centripetal force always acts perpendicular to the motion of the body.

Centripetal force is a force that keeps a body to move in a circle.

Let us study the centripetal forces in the following examples:

(i) Figure 3.27 shows a stone tied to one end of a string rotating in a circle. The tension in the string provides the necessary centripetal force. It keeps the stone to remain in the circle. If the string is not strong enough to provide the necessary tension, it breaks and the stone

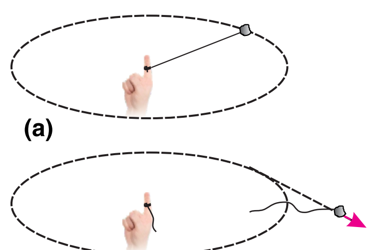


Figure 3.27 (a) A string provides necessary centripetal force.
(b) A string is unable to provide the required centripetal force.

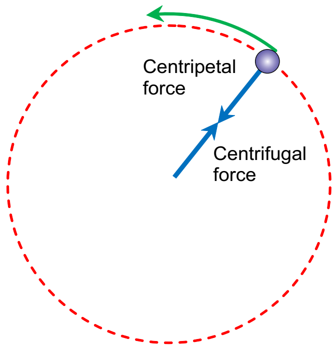


Figure 3.28: centripetal force acting on the stone and the centrifugal force acting on the string

moves away along a tangent to the circle as shown in figure 3.27(b).

(ii) The moon revolves around the Earth. The gravitational force of the Earth provides the necessary centripetal force.

Let a body of mass m moves with uniform speed v in a circle of radius r. The acceleration a_c produced by the centripetal force F_c is given by

$$\text{centripetal acceleration } a_c = \frac{v^2}{r} \quad \ldots \quad \ldots (3.24)$$

According to Newton's second law of motion, the centripetal force F_c is given by

$$F_c = m\,a_c \quad \ldots \quad \ldots \quad \ldots \quad (3.25)$$

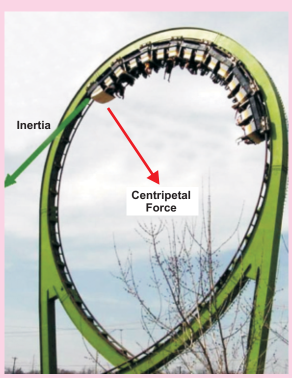
$$F_c = \frac{mv^2}{r} \quad \ldots \quad \ldots \quad \ldots (3.26)$$

Equation (3.26) shows that the centripetal force needed by a body moving in a circle depends on the mass m of the body, square of its velocity v and reciprocal to the radius r of the circle.

CENTRIFUGAL FORCE

Consider a stone shown in figure 3.28 tied to a string moving in a circle. The necessary centripetal force acts on the stone through the string that keeps it to move in a circle. According to Newton's third law of motion, there exists a reaction to this centripetal force. Centripetal reaction that pulls the string outward is sometimes called the centrifugal force.

DO YOU KNOW?



While the coaster cars move around the loop, the track provides centripetal force preventing them to move away from the circle.

EXAMPLE 3.8

A stone of mass 100 g is attached to a string 1m long. The stone is rotating in a circle with a speed of 5 ms^{-1}. Find the tension in the string.

SOLUTION

$$m = 100\text{ g} = 0.1\text{ kg}$$

$$v = 5\text{ ms}^{-1}$$

$r = 1\text{ m}$

$T = F_c = ?$

Tension T in the string provides the necessary centripetal force given by

$$F_c = \frac{mv^2}{r}$$

$$\therefore \quad T = \frac{0.1\ \text{kg} \times (5\ \text{ms}^{-1})^2}{1\ \text{m}}$$

$$T = 2.5\text{ N}$$

Thus, tension in the string will be equal to 2.5 N.

BANKING OF THE ROADS

When a car takes a turn, centripetal force is needed to keep it in its curved track. The friction between the tyres and the road provides the necessary centripetal force. The car would skid if the force of friction between the tyres and the road is not sufficient enough particularly when the roads are wet. This problem is solved by banking of curved roads. Banking of a road means that the outer edge of a road is raised. Imagine a vehicle on a curved road such as shown in figure 3.29. Banking causes a component of vehicle's weight to provide the necessary centripetal force while taking a turn. Thus banking of roads prevents skidding of vehicle and thus makes the driving safe.

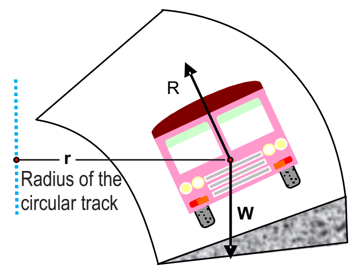


Figure 3.29: Outer edge of the curved road is elevated to prevent skidding.

WASHING MACHINE DRYER

The dryer of a washing machine is basket spinners. They have a perforated wall having large numbers of fine holes in the cylindrical rotor as shown in figure 3.30. The lid of the cylindrical container is closed after putting wet clothes in it. When it spins at high speed, the water from wet clothes is forced out through these holes due to lack of centripetal force.

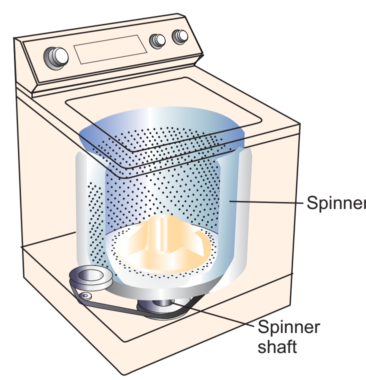


Figure 3.30: Dryer of washing machines has perforated wall.

CREAM SEPARATOR

Most modern plants use a separator to control the fat contents of various products. A separator is a high-speed spinner. It acts on the same principle of centrifuge machines. The bowl spins at very high

Figure 3.31: A Cream separator

speed causing the heavier contents of milk to move outward in the bowl pushing the lighter contents inward towards the spinning axis. Cream or butterfat is lighter than other components in milk. Therefore, skimmed milk, which is denser than cream is collected at the outer wall of the bowl. The lighter part (cream) is pushed towards the centre from where it is collected through a pipe.

SUMMARY

- A force is a push or pull. It moves or tends to move, stops or tends to stop the motion of a body.
- Inertia of a body is its property due to which it resists any change in its state of rest or uniform motion in a straight line.
- Momentum of a body is the quantity of motion possessed by the body. Momentum of a body is equal to the product of its mass and velocity
- The force that opposes the motion of a body is called friction.
- Newton's first law of motion states that a body continues its state of rest or of uniform motion in a straight line provided no net force acts on it.
- Newton's second law of motion states that when a net force acts on a body, it produces acceleration in the body in the direction of the net force. The magnitude of this acceleration is directly proportional to the net force acting on it and inversely proportional to its mass. Mathematically, $F = ma$.
- SI unit of force is newton (N). It is defined as the force which produces an acceleration of 1 ms"^{2} in a body of mass 1 kg.
- Mass of a body is the quantity of matter possessed by it. It is a scalar quantity. SI unit of mass is kilogramme (kg).
- Weight of a body is the force of gravity acting on it. It is a vector quantity. SI unit of weight is newton (N).
- Newton's third law of motion states that to every action there is always an equal and opposite reaction.
- The acceleration and tension in a system of two bodies attached to the ends of a string that passes over a frictionless pulley such that both move vertically are given by:

$$a = \frac{m_1 - m_2}{m_1 + m_2} g \ ; \ T = \frac{2m_1 m_2}{m_1 + m_2} g$$

- The acceleration and tension in a system of two bodies attached to the ends of a string that passes over a frictionless pulley such that one moves vertically and the other moves on a smooth horizontal surface are given by:

$$a = \frac{m_1}{m_1 + m_2} g \; ; \; T = \frac{m_1 m_2}{m_1 + m_2} g$$

- Law of conservation of momentum states that the momentum of an isolated system of two or more than two interacting bodies remains constant.
- A force between the sliding objects which opposes the relative motion between them is called friction.
- Rolling friction is the force of friction between a rolling body and a surface over which it rolls. Rolling friction is lesser than the sliding friction.
- The friction causes loss of energy in machines and much work has to be done in overcoming it. Moreover, friction leads to much wear and tear on the moving parts of the machine. The friction can be reduced by:

  (i) Smoothing the sliding surfaces in contact.

  (ii) Using lubricants between sliding surfaces.

  (iii) Using ball bearings or roller bearings.
- The motion of a body moving along a circular path is called circular motion.
- The force which keeps the body to move in a circular path is called the centripetal force and is given.

  by $F_c = \dfrac{mv^2}{r}$
- According to Newton's third law of motion, there exists a reaction to the centripetal force. Centripetal reaction that pulls the string outward is sometimes called the centrifugal force.

QUESTIONS

3.1 **Encircle the correct answer from the given choices:**

i. Newton's first law of motion is valid only in the absence of:

(a) force (b) net force

(c) friction (d) momentum

ii. Inertia depends upon

(a) force (b) net force

(c) mass (d) velocity

iii. A boy jumps out of a moving bus. There is a danger for him to fall:

(a) towards the moving bus

(b) away from the bus

(c) in the direction of motion

(d) opposite to the direction of motion

iv. A string is stretched by two equal and opposite forces 10 N each. The tension in the string is

(a) zero (b) 5 N

(c) 10 N (d) 20 N

v. The mass of a body:

(a) decreases when accelerated

(b) increases when accelerated

(c) decreases when moving with high velocity

(d) none of the above.

vi. Two bodies of masses m_1 and m_2 attached to the ends of an inextensible string passing over a frictionless pulling such that both move vertically. The acceleration of the bodies is:

(a) $\frac{m_1 \times m_2}{m_1 + m_2} g$ (b) $\frac{m_1 - m_2}{m_1 + m_2} g$

(c) $\frac{m_1 + m_2}{m_1 - m_2} g$ (d) $\frac{2m_1 m_2}{m_1 + m_2} g$

vii. Which of the following is the unit of momentum?

(a) Nm (b) $kgms^{-2}$

(c) Ns (d) Ns^{-1}

viii. When horse pulls a cart, the action is on the:

(a) cart (b) Earth

© horse (d) Earth and cart

ix. Which of the following material lowers friction when pushed between metal plates?

(a) water (b) fine marble powder

(c) air (d) oil

3.2 Define the following terms:
(i) Inertia (ii) Momentum
(iii) Force (iv) Force of friction
(v) Centripetal force

3.3 What is the difference between:
(i) Mass and weight
(ii) Action and reaction
(iii) Sliding friction and rolling friction

3.4 What is the law of Inertia?

3.5 Why is it dangerous to travel on the roof of a bus?

3.6 Why does a passenger move outward when a bus takes a turn?

3.7 How can you relate a force with the change of momentum of a body?

3.8 What will be the tension in a rope that is pulled from its ends by two opposite forces 100 N each?

3.9 Action and reaction are always equal and opposite. Then how does a body move?

3.10 A horse pulls the cart. If the action and reaction are equal and opposite then how does the cart move?

3.11 What is the law of conservation of momentum?

3.12 Why is the law of conservation of momentum important?

3.13 When a gun is fired, it recoils. Why?

3.14 Describe two situations in which force of friction is needed.

3.15 How does oiling the moving parts of a machine lowers friction?

3.16 Describe ways to reduce friction.

3.17 Why rolling friction is less than sliding friction?

3.18 What you know about the following:

(i) Tension in a string
(ii) Limiting force of friction
(iii) Braking force
(iv) Skidding of vehicles
(v) Seatbelts
(vi) Banking of roads
(vii) Cream separator

3.19 What would happen if all friction suddenly disappears?

3.20 Why the spinner of a washing machine is made to spin at a very high speed?

PROBLEMS

3.1 A force of 20 N moves a body with an acceleration of 2 ms^{-2}. What is its mass? (10 kg)

3.2 The weight of a body is 147 N. What is its mass? (Take the value of g as 10 ms^{-2}) (14.7 kg)

3.3 How much force is needed to prevent a body of mass 10 kg from falling? (100 N)

3.4 Find the acceleration produced by a force of 100 N in a mass of 50 kg. (2 ms^{-2})

3.5 A body has weight 20 N. How much force is required to move it vertically upward with an acceleration of 2 ms^{-2}? (24 N)

3.6 Two masses 52 kg and 48 kg are attached to the ends of a string that passes over a frictionless pulley. Find the tension in the string and acceleration in the bodies when both the masses are moving vertically. (500 N, 0.4 ms^{-2})

3.7 Two masses 26 kg and 24 kg are attached to the ends of a string which passes over a frictionless pulley. 26 kg is lying over a smooth horizontal table. 24 N mass is moving vertically downward. Find the tension in the string and the acceleration in the bodies. (125 N, 4.8 ms^{-2})

3.8 How much time is required to change 22 Ns momentum by a force of 20 N? (1.1s)

3.9 How much is the force of friction between a wooden block of mass 5 kg and the horizontal marble floor? The coefficient of friction between wood and the marble is 0.6. (30 N)

3.10 How much centripetal force is needed to make a body of mass 0.5 kg to move in a circle of radius 50 cm with a speed 3 ms^{-1}? (**9** N)