05

Motion is an integral part of most of the natural phenomena. Galaxies, Stars, Planets, Satellites all are in continuous motion. Motion of these bodies is governed and regulated by certain laws. Laws hidden behind these motions in nature were discovered first by Issac Newton. Therefore, these laws are known as Newton's laws of motion.

LAWS OF MOTION

Concept Physics classes, for:-11,12,NEET & JEE
By:- Er. S B Choudhary . (B-tech in electrical)
Contact number :- 8076546954, 8130843551

|TOPIC 1|

Newton's Laws of Motion

Motion is the common and most important phenomenon in nature. In case of macroscopic bodies (natural system), it is easily observable. But if we go down to atomic or even nuclear level, motion is not observable but motion is very much there. Motion may be as simple as throwing a ball high up into air. Whatever is the type of motion, we have to study the forces which generate motion.

CHAPTER CHECKLIST

- Force
- Aristotle's Fallacy and Galileo Galilei
- Law of Inertia
- Newton's First Law of Motion
- Momentum
- Newton's Second Law of Motion
- Impulse
  Newton's Third Law of Motion
- Conservation of Momentum
- Equilibrium of a Particle
- Common Forces in Mechanics
- Friction
- Dynamics of Circular Motion

FORCE

Force may be defined as an external agency (a push or a pull) which changes or tends to change the state of rest or of uniform motion or the direction of motion of a body.

The dimensions of force are $[MLT^{-2}]$ and its SI unit is **Newton.**

A force applied on an object can produce four types of effects such as

(i) Force can start or stop a motion.

(ii) Force can change speed of an object, making it to move slower or faster.

(iii) Force can change the direction of motion of an object.

(iv) Force can change the shape of an object.

> ***Some Important Points about Force***
> - A bar magnet can attract an iron nail from a distance. This shows that external agencies of force (gravitational and magnetic forces) can exert force on a body even from a distance.
> - Force is a polar vector as it has a point of application.
> - The vector sum of the forces acting on an object is called the net force.

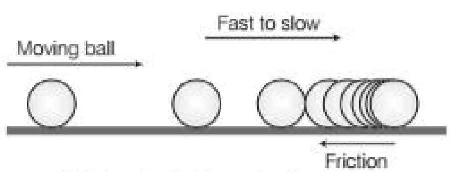
What happens if a body is moving in uniform motion along a straight line, (e.g. if a box is moving with a constant velocity on an ice slab)? Is an external force required to keep a body in uniform motion? For this, we will understand Aristotle's Fallacy and Galileo's law of inertia.

ARISTOTLE'S FALLACY AND GALILEO GALILEI

The Greek philosopher, Aristotle (384 BC-322 BC) gave the view that if a body is moving, some external force is required to keep it moving.

e.g. When an arrow shot from a bow keeps flying since the air behind the arrow keeps pushing it. Thus, according to Aristotelian's law, **an external force is necessary to keep a body in uniform motion.**

Aristotle's statement is based on the fact that ever presenting resistive forces will always stop the motion. So, to keep a body in motion, an external force is needed (i.e. the force to counter the resistive force). An example of rolling ball that stops due to friction could be considered.



Motion of a ball on a horizontal plane

The opposing force such as friction (in case of solids) and viscous forces (in case of fluids) are always present in the natural world. However, Aristotle's views were proved wrong by Galileo about two thousand years later on. It was observed that the external forces were necessary to counter the opposing forces of friction to keep bodies in uniform motion.

If there were no friction, no external force would be needed to maintain the state of uniform motion of a body. Hence, Galileo proposed his **law of inertia.**

LAW OF INERTIA

Galileo first asserted that objects move with constant speed when no external forces act on them. He arrived at this revolutionary conclusion on the basis of following simple experiments

(a) Galileo's Experiments with Single Inclined Plane

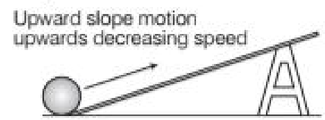
Galileo first studied the motion of objects on an inclined plane.

He observed that

(i) When an object moves down on inclined plane, its speed increases.

Downward motion of the object

(ii) When the object is moved up on the inclined plane, its speed decreases, i.e. retards.



Upward motion of the object

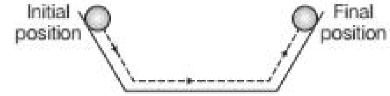
(iii) When an object is moving on a horizontal plane, there should be no acceleration nor retardation, i.e. constant speed.

Horizontal motion of the object

(b) Galileo's Experiments on Two Inclined Planes Combined Together

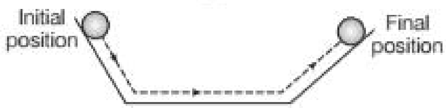
Galileo also observed that in the case of an oscillating pendulum, the bob always reaches the same height on either side of the mean position. Galileo conducted another experiment by using a double inclined plane. In this experiment, two inclined planes are arranged as facing each other.

(i) When an object rolls down one of the inclined planes, it climbs up the other. It almost reaches the same height but not completely because of friction. In ideal case, when there is no friction, the final height of the object is same as the initial height as shown in figure.



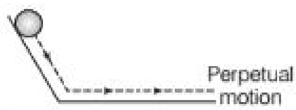
Both planes are inclined at same angle

(ii) When the slope of the second inclined plane is decreased, the object still reaches the same final height but the object has to travel a longer distance to attain the same height.



Inclination of second plane is reduced

(iii) When the slope of the second inclined plane is made zero (i.e. the second plane is made horizontal) the object travels an infinite distance in the ideal situation. This is possible only if the object moves forever with uniform velocity on the horizontal surface.



Inclination of second plane reduced to zero

From his experiments, Galileo concluded the law of inertia and states that the state of rest and the state of motion with constant velocity are equivalent in the absence of external forces.

INERTIA

The term inertia means resistance of any physical object. It is defined as the inherent property of a material body by virtue of which it remains in its state of rest or of uniform motion in a straight line. This term was first used by Galileo.

Various Types of Inertia

The various types of inertia are as below

(i) Inertia of Rest

It is defined as the tendency of a body to remain in its position of rest.

e.g. A person standing in a train falls backward when the train suddenly starts moving forward. It depicts, when train moves, the lower part of his body begins to move alongwith the train while the upper part of his body continues to remain at rest due to inertia.

(ii) Inertia of Motion

It is defined as the tendency of a body to remain in its state of uniform motion in a straight line.

e.g. When a moving bus suddenly stops or apply the brake, a person standing in it falls forward. As the bus stops, the lower part of his body comes to rest alongwith the bus while upper part of his body continues to remain in motion due to inertia and falls forward.

(iii) Inertia of Direction

It is defined as inability of a body to change by itself its direction of motion.

e.g. An umbrella protects us from rain.

The rain drops falling vertically downwards cannot change their direction of motion and wet us, with the umbrella on.

NEWTON'S LAWS OF MOTION

Sir Isaac Newton (1642-1727) made a systematic study of motion and extended the views of Galileo. He arrived at three laws of motion which are called **Newton's law of motion.** These laws are as follows

Newton's First Law of Motion

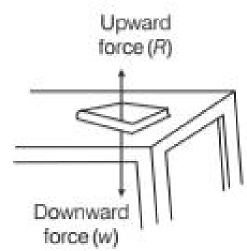
This law states that **every body continues in its state of rest or of uniform motion in a straight line unless it is compelled by some external force to change that state.**

The state of rest or uniform linear motion both imply zero acceleration. The first law of motion can therefore be simply expressed as:

If the net external force on a body is zero, its acceleration is zero. Acceleration can be non-zero, only if there is a net external force on the body. Newton's first law defines force qualitatively.

The Newton's first law is categorised in three parts

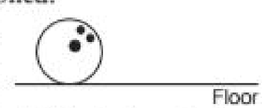
(i) **First part** If a body at rest continues in its state of rest. An external force has to be applied on it to make it move.



Body in a rest

e.g. A book on the table will continue to remain there unless we displace it means a book at rest on a horizontal surface of table, it is subjected to two external forces, the force due to gravity (due to its weight w) acting downward and the upward force on the book by the table, i.e. the normal force R. Since, the book is observed to be at rest, the net external force on it must be zero, i.e. $w = R$ as shown in figure.

(ii) **Second part** If a body is in motion it continues moving in a straight path with a uniform speed unless an external force is applied.



Rolling ball on the floor

This part seems to be contrary to our every day experience. A rolling ball comes to rest on a rough ground. This is because of force of friction. The ball moves through a larger distance on a smooth floor.

If the friction was zero, the ball would continue its motion forever.

This part also depicts that to increase or decrease the speed of a body moving in a straight line, a force has to be applied on it in the direction of motion or opposite to the direction of motion.

(iii) **Third part** says that a body moving with a uniform speed in a straight line cannot change tself its direction of motion.

Moon changes its direction continuously

To change its direction of motion, a force has to be applied normal to this direction of motion.
Consider the motion of the moon continuously changes. The force needed to change the direction is provided by the gravitational attraction of the earth on the moon.

Newton's First Law Defines the Inertia

According to Newton's first law of motion, everybody continues in its state of rest or uniform motion unless an external force acts upon it. This depicts that a body by itself cannot change its state of rest or of uniform motion along a straight line.

Thus, first law defines inertia and so it is rightly inspired by the **law of inertia**.

EXAMPLE |1| A Spaceship

An astronaut accidentally gets separated out of his small spaceship accelerating in interstellar space at a constant rate of 100 m/s^2. What is the acceleration of the astronaut the instant after he is outside the spaceship? (Assume that there are no nearby stars to exert gravitational force on him). **[NCERT]**

Sol. Since, there are no nearby stars to exert gravitational force on him and the small spaceship exerts negligible gravitational attraction on him. The net force acting on the astronaut, once he is out of the spaceship, is zero. By the first law of motion, the acceleration of the astronaut is zero.

MOMENTUM

Momentum of a body is the quantity of motion possessed by the body. It is defined to be the product of its mass m and velocity **v** and is denoted by **p**.

$$\text{Momentum, } \mathbf{p} = m\mathbf{v}$$

Unit and Dimensional Formula

SI unit of momentum = kg m/s or kg ms^{-1}

CGS unit of momentum = g cm/s or g cm s^{-1}

The dimensional formula of momentum is $[MLT^{-1}]$.

It is a vector quantity.

Variation of Momentum

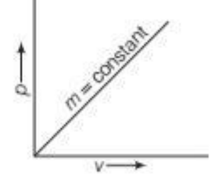
Case I Let two objects each of mass m are moving with different velocities v_1 and v_2 with $v_1 > v_2$, then

$$p_1 = mv_1$$

and $$p_2 = mv_2$$

$\therefore$ $$\frac{p_1}{p_2} = \frac{mv_1}{mv_2} = \frac{v_1}{v_2}$$

$\Rightarrow$ $$\frac{p_1}{p_2} = \frac{v_1}{v_2}$$



As $v_1 > v_2$, so $p_1 > p_2$

Result It is graphically represented in figure. Thus, **the momenta of bodies having equal masses are proportional to their velocities.**

Case II Let a heavier object of mass m_1 and lighter object of mass m_2.
Suppose both the objects are moving with the same velocity v.

Then, $p_1 = m_1 v$ and $p_2 = m_2 v$

$$\therefore \quad \frac{p_1}{p_2} = \frac{m_1 v}{m_2 v} = \frac{m_1}{m_2}$$

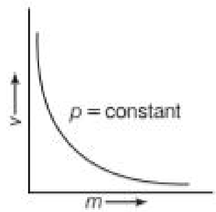
$$\Rightarrow \quad \frac{p_1}{p_2} = \frac{m_1}{m_2}$$

As a result $\quad m_1 > m_2$

So, $\quad p_1 > p_2$

It is graphically represented in figure. Thus, **the momentum of bodies having equal velocities are proportional to their masses.**

Case III Let two objects having equal linear momenta. Thus,



$$p_1 = p_2 = p \Rightarrow m_1 v_1 = m_2 v_2$$

$$\Rightarrow \frac{v_2}{v_1} = \frac{m_1}{m_2}$$

As a result $\quad m_1 > m_2$

So, $\quad v_1 < v_2$

It is graphically represented by figure. Thus, **the velocities of bodies having equal linear momenta are inversely proportional to their masses.**

Some Everyday Phenomena Based on Momentum

The following common examples are

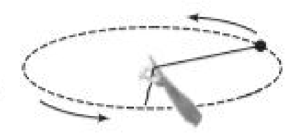
(i) Consider a light-weight vehicle, i.e. car and a heavy weight vehicle i.e. truck parked on a horizontal road. We require a greater force to push the truck than the car to bring at the same speed in same time. Also, a greater opposing force is required to stop the truck than the car at the same time if they are moving with the same speed.

(ii) Speed is another important parameter to consider. A bullet fired by a gun can easily pierce human tissue before it stops, resulting in casuality. The same bullet fired with moderate speed will not cause much damage.

Thus, for a given mass, the greater the speed, the greater is the opposing force needed to stop the body in a certain time. Taken together, the product of mass and velocity, that is momentum eventually is relevant variable of motion. The greater the change in the momentum in a given time, the greater is the force that needs to be applied.

(iii) If two stones, one light and other heavy are dropped from the top of a building, a person on the ground will find it easier to catch the light stone than the heavy stone. This is due to the mass of a body is thus an important parameter that determines the effect of force on its motion.

(iv) Suppose a stone is rotated with uniform speed in a horizontal plane by means of a string, the magnitude of momentum is fixed. But its direction changes. This is due to a force needed to cause this change in momentum vector.



A fastened stone with the string is rotating

This force is provided by our hand through the string. Experience suggests that our hand needs to exert a greater force if the stone is rotated at greater speed or in a circle of smaller radius or both. This corresponds to greater acceleration or greater rate of change in momentum vector. That means the greater rate of change in momentum vector, the greater is the force applied.

Newton's Second Law of Motion

This law states that **the rate of change of momentum of a body is directly proportional to the external force applied on the body and the change takes place in the direction of the applied force.** Let F be external force applied on the body in the direction of motion of the body for time interval Δt, then the velocity of a body of mass m changes from $\mathbf{v}$ to $\mathbf{v} + \Delta \mathbf{v}$, i.e. change in momentum $\Delta \mathbf{p} = m\Delta \mathbf{v}$.

According to Newton's second law,

$$\mathbf{F} \propto \frac{\Delta \mathbf{p}}{\Delta t} \quad \text{or} \quad \mathbf{F} = k\frac{\Delta \mathbf{p}}{\Delta t}$$

where, k is a constant of proportionality.

If limit $\Delta t \to 0$, then the term $\frac{\Delta \mathbf{p}}{\Delta t}$ becomes the derivative $\frac{d\mathbf{p}}{dt}$.

Thus, $$\mathbf{F} = k\frac{d\mathbf{p}}{dt}$$

For a body of fixed mass m, we have

$$\mathbf{F} = k\frac{d(m\mathbf{v})}{dt} = km\frac{d\mathbf{v}}{dt}$$

$$\mathbf{F} = km\mathbf{a} \qquad \left(\because \frac{dv}{dt} = a\right)$$

Let, $k = 1$

So, Force, $\mathbf{F} = m\mathbf{a}$

In scalar form, this equation can be written as

$$F = ma$$

$\therefore$ 1 unit force = 1 unit mass × 1 unit acceleration

A unit force may be defined as the force which produces unit acceleration in a body of unit mass.

The force is a vector quantity and its SI unit is Newton.

One newton is defined as that much force which produces an acceleration of 1 m/s^2 in a body of mass 1 kg.

$$1\,N = 1\,kg \times 1\,m/s^2$$
$$1\,N = 1\,kg\,m/s^2$$

In CGS system, absolute unit of force is dyne. One dyne is that much force which produces an acceleration of 1 cm/s^2 in a body of mass 1 g.

$$1\,dyne = 1\,g \times 1\,cm/s^2$$
$$1\,dyne = 1\,gcm/s^2$$

In SI unit, gravitational unit of force is kilogram weight (kg-wt). It is defined as that much force which produces an acceleration of 9.80 m/s^2 in a body of mass 1 kg.

$$1\text{ kg-wt} = 1\,kgf = 9.8\,N$$

In CGS system, gravitational unit of force is gram weight (g-wt) or gram force (gf). It is defined as that force which produces an acceleration of 980 cm/s^2 in a body of mass 1 g.

$$1\text{ g-wt} = 1\,gf = 980\,gcm/s^2$$

Relation between Newton and Dyne

$$1\,N = 1\,kg \times 1\,m/s^2 = 1000\,g \times 100\,cm/s^2$$
$$= 10^5\,gcm/s^2 \qquad [1\,dyne = 1\,gcm/s^2]$$
$$\mathbf{1\,N = 10^5\,dyne}$$

Note

- A gravitational unit is g times the corresponding absolute unit.
- A gravitational unit of force is used to express the weight of a body. e.g. The weight of a body of mass 10 kg is 10 kg-wt or 10 kgf. For this reason, the gravitational units are also called practical units.

EXAMPLE |2| Playing with the X-ray

If an electron is subjected to a force of 10^{-25} N in an X-ray machine, then find out the time taken by the electron to cover a distance of 0.2 m. Take mass of the electron = 10^{-30} kg.

Sol. The acceleration of the electron

$$a = \frac{F}{m} = \frac{10^{-25}}{10^{-30}} = 10^5\ m/s^2$$

The time taken by the electron (t) to cover the distance (s) of 0.2 m can be given by

$$s = ut + \frac{1}{2}at^2$$

$$0.2 = 0 + \frac{1}{2} \times 10^5 \times t^2$$
$$t^2 = 0.4 \times 10^{-5} = 4 \times 10^{-6}\ s^2$$
$$t = 2 \times 10^{-3}\ s$$

Newton's Second Law in Component Form and its Significance

In terms of their rectangular components, the force, momentum and acceleration vectors can be expressed as

$$\mathbf{F} = F_x\hat{\mathbf{i}} + F_y\hat{\mathbf{j}} + F_z\hat{\mathbf{k}}$$
$$\mathbf{p} = p_x\hat{\mathbf{i}} + p_y\hat{\mathbf{j}} + p_z\hat{\mathbf{k}}$$

and $$\mathbf{a} = a_x\hat{\mathbf{i}} + a_y\hat{\mathbf{j}} + a_z\hat{\mathbf{k}}$$

From the formula of force in vector form, for constant m,

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} = m\mathbf{a}$$

$$\therefore \quad F_x\hat{\mathbf{i}} + F_y\hat{\mathbf{j}} + F_z\hat{\mathbf{k}} = \frac{d}{dt}(p_x\hat{\mathbf{i}} + p_y\hat{\mathbf{j}} + p_z\hat{\mathbf{k}})$$
$$= m(a_x\hat{\mathbf{i}} + a_y\hat{\mathbf{j}} + a_z\hat{\mathbf{k}})$$

Equating the components along the three coordinate axes, we get

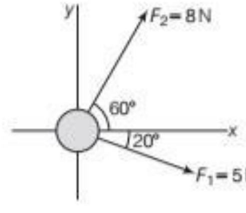
$$F_x = \frac{dp_x}{dt} = ma_x,\ F_y = \frac{dp_y}{dt} = ma_y$$

and $$F_z = \frac{dp_z}{dt} = ma_z$$

The above three equations represent the component form of Newton's second law.

EXAMPLE |3| Acceleration of the Puck

A hockey puck with a mass of 0.3 kg slides on the horizontal frictionless surface of an ice rink. Two forces act on the puck as shown in figure. The force F_1 has a magnitude of 5 N and F_2 has a magnitude of 8 N. Determine the acceleration of the puck.



Using trigonometry, find the x-component and y-component of both the forces exerted on the puck. Add x-components together to get the x-component of the resultant force and then do the same with the y-components. Divide by the mass of the puck to get the accelerations in the x and y-directions.

Sol. Given, $F_1 = 5\text{N}$, $F_2 = 8\text{N}$, $m = 0.3$ kg and acceleration $a = ?$ The resultant force in the x-direction exerted on the puck,

$$\Sigma F_x = F_{1x} + F_{2x} = F_1 \cos 20° + F_2 \cos 60°$$
$$= (5\text{ N})(0.940) + (8\text{ N})(0.500)$$
$$= 8.70\text{ N}$$

The resultant force in the y-direction exerted on the puck,

$$\Sigma F_y = F_{1y} + F_{2y} = -F_1 \sin 20° + F_2 \sin 60°$$
$$= -(5\text{ N})(0.342) + (8\text{ N})(0.8666) = 5.22\text{ N}$$

Now, we can use Newton's second law in component form to find the x and y-components of acceleration

$$a_x = \frac{\Sigma F_x}{m} = \frac{8.70\text{ N}}{0.3\text{ kg}} = 29.0\text{ m/s}^2$$

and $$a_y = \frac{\Sigma F_y}{m} = \frac{5.22\text{ N}}{0.3\text{ kg}} = 17.4\text{ m/s}^2$$

Magnitude, $$a = \sqrt{(29.0)^2 + (17.4)^2}\text{ m/s}^2$$

$= 33.8\text{ m/s}^2$

and its direction is

$$\theta = \tan^{-1}(a_y/a_x) = \tan^{-1}(17.4/29.0) = 31.0°$$

relative to the positive x-axis.

EXAMPLE |4| Magnitude of the Force

A force applied on an object of mass 1 kg produces an acceleration of 8 m/s^2. When a force of the same magnitude is applied to a carton of ice cream of mass m_2, it produces an acceleration of 12 m/s^2. What is the mass of the carton of ice cream and the magnitude of the force?

Apply $\Sigma \mathbf{F} = m\mathbf{a}$ to each object and solve for the mass of the ice cream carton and the magnitude of the force.

Sol. Given, $a_2 = 12\text{m/s}^2$ and Force $F = ?$

Apply $\Sigma \mathbf{F} = m\,\mathbf{a}$ to each object.

$$F_1 = m_1 a_1$$

and $$F_2 = m_2 a_2$$

$$F_1 = F_2 = F$$

or $$m_1 a_1 = m_2 a_2$$

$\Rightarrow$ $$\frac{m_2}{m_1} = \frac{a_1}{a_2} = \frac{8}{12}$$

$$m_2 = \frac{8}{12} = 0.67\text{ kg}$$

$$F = m_1 a_1 = 1 \times 8 = 8\text{N}$$

EXAMPLE |5| Dangerous Bullet

A bullet of mass 0.04 kg moving with a speed of 90 m/s enters a heavy wooden block and is stopped after a distance of 60 cm. What is the average resistive force exerted by the block on the bullet? **[NCERT]**

Sol. Given, $s = 60\text{ cm} = 0.6\text{ m}$, $u = 90\text{ m/s}$

The retardation a of the bullet is given by

$$a = -\frac{u^2}{2s} = \frac{-90 \times 90}{2 \times 0.6}$$

$\Rightarrow$ $$a = -6750\text{ m/s}^2$$

The retarding force by the second law of motion is

$$F = ma$$

where, $$F = 0.04 \times 6750$$

$$F = 270\text{ N}$$

Actual resistive force and retardation of the bullet may not be uniform. It indicates only average force.

EXAMPLE |6| Force Acting on a Particle

The motion of a particle of mass m is described by $y = ut + \frac{1}{2}gt^2$. Find the force acting on the particle. **[NCERT]**

Sol. We know, $y = ut + \frac{1}{2}gt^2$

Now, by differentiating the above equation w.r.t. t, we get

$$v = \frac{dy}{dt} = u + gt$$

and acceleration, $$a = \frac{dv}{dt} = g$$

Then, the force is given by

$$F = ma = mg$$

Thus, the given equation describes the motion of a particle under acceleration due to gravity and y is the position coordinate in the direction of g.

IMPULSE

The measure of the action of a large force acting for a duration of time to produce a finite change in momentum is called an **impulse**. Impulse is defined as the product of the average force and the time interval for which the force acts on the body. It is denoted by **I**.

Thus, Impulse = Average force × time

Impulse is a vector quantity. The direction of impulse is same as that of the force.

Its SI unit is newton-second (N-s).

Its dimensional formula is $[\text{MLT}^{-1}]$.

Expression for an Impulse

Consider a constant force **F** which acts on a body for time dt. The impulse is given by

$$d\mathbf{I} = \mathbf{F}\,dt$$

If the force acts on the body for a time interval from t_1 to t_2, the impulse is given by

$$\mathbf{I} = \int d\mathbf{I} = \int_{t_1}^{t_2} \mathbf{F}\,dt$$

If $\mathbf{F}_{av}$ is the average force, then

$$\mathbf{I} = \mathbf{F}_{av} \int_{t_1}^{t_2} dt = \mathbf{F}_{av} [t]_{t_1}^{t_2}$$

$$\mathbf{I} = \mathbf{F}_{av} [t_2 - t_1]$$

$$\text{Impulse, } \mathbf{I} = \mathbf{F}_{av} \Delta t$$

According to Newton's second law of motion,

$$\mathbf{F} = \frac{d\mathbf{p}}{dt}$$

$$\Rightarrow \quad \mathbf{F}\,dt = d\mathbf{p}$$

Integrating both sides with limits, we get

$$\int_0^t \mathbf{F}\,dt = \int_{\mathbf{p}_1}^{\mathbf{p}_2} d\mathbf{p}$$

$$\Rightarrow \quad \mathbf{F} \times t = \mathbf{p}_2 - \mathbf{p}_1$$

$$\Rightarrow \quad \text{Impulse, } \mathbf{I} = \mathbf{p}_2 - \mathbf{p}_1$$

Thus, **the impulse of a force is equal to the total change in momentum produced by the force.**

(Following are some of the practical aspects of impulse.

(i) When a ball hits a wall and bounces back, the force on the ball by the wall acts for a very short time. When the two are in contact, the force is large enough to reverse the momentum of the ball. Often, in these situations, the force and the time duration are difficult to ascertain separately.

However, the product of force (F) and time (t) which is the change in momentum of the body remains measurable quantity.

(ii) An athelete is advised to stop slowly after finishing a fast race, so that time of stop increases and hence force experienced by him decreases.

(iii) Boggies of a train are provided with buffers to avoid severe jerks during shunting of the train. Due to presence of buffers, time of impact increases. Thus, force during jerks decreases.

In all the examples described above, the formula for impulse that is $m(v-u) = F \times t$ is utilised. I_0 achieve the same change in momentum, when t is increased, F required decreases. It results into less injury to body.

(iv) A cricket player lowers his hands while catching a ball. This is due to the player has to apply a retarding force to stop the moving ball (i.e. to change the momentum of the moving ball).

If the player does not lower his hands while catching the ball, the time to reduce the momentum of ball to zero, is small.

So, a large retarding force has to be applied to change the momentum of the moving ball $\left(\because \mathbf{F} = \frac{d\mathbf{p}}{dt}\right)$.

Hence, his hands are injured. On the other hand, when the player lowers his hands while catching the ball, the time to stop the ball is increased.

Hence, less retarding force has to be applied to cause the same change in the momentum of the moving ball. Therefore, the hands of the player are not injured as shown in given figure.

Change in momentum of the ball

EXAMPLE |7| A Straight Drive

A batsman hits back a ball straight in the direction of the bowler without changing its initial speed of 12 m/s. If the mass of the ball is 0.15 kg, determine the impulse imparted to the ball. (Consider a ball in linear motion). **[NCERT]**

Sol. Given, $m = 0.15$ kg, $v = 12$ m/s, $u = -12$ m/s

Change in momentum $= \mathbf{p}_2 - \mathbf{p}_1 = m[v - u]$

$= 0.15\,[12 - (-12)] = 0.15 \times 24$

$\mathbf{p}_2 - \mathbf{p}_1 = 3.60$ kg-m/s

Impulse, $\quad \mathbf{I} = \mathbf{p}_2 - \mathbf{p}_1 \Rightarrow \mathbf{I} = 3.6$ N-s

EXAMPLE |8| Fall of a Ball

Consider a ball falling from a height of 2 m and rebounding to a height of 0.5 m. If the mass of the ball is 60 g, find the impulse and the average force between the ball and the ground. The time for which the ball and the ground remained in contact was 0.2 s.

Sol. The initial velocity of the ball at P is zero. Let the final velocity of the ball at Q is v.

Given $s = 2$ m, then

$$v^2 = u^2 + 2as$$
$$v^2 = 0 + 2 \times 9.8 \times 2 = 4 \times 9.8$$
$$v = \sqrt{39.2} \text{ m/s} = 6.26 \text{ m/s}$$

Let u' be the velocity of rebound of the ball.

Given, $s' = 0.5$ m, the final velocity at R is zero

$$v'^2 = u'^2 + 2as$$
$$0 = u'^2 + 2 \times (-9.8) \times 0.5$$
$$u' = -\sqrt{9.8} \text{ m/s} = -3.13 \text{ m/s}$$

Now, Impulse = Change in momentum

$$= mv - (-mu') = m(v + u')$$
$$= \frac{60}{1000}(6.26 + 3.13)$$
$$= 0.06 \times 9.39 = 0.563 \text{ N-s}$$

$$\because \text{ Average force} = \frac{\text{Impulse}}{\text{Time}} = \frac{0.563}{0.2} = 2.817 \text{ N}$$

Newton's Third Law of Motion

When we press a coiled spring, the spring is compressed by the force of our hand. In turn, the compressed spring exerts a force on our hand, and we can feel it. Also, the earth pulls a stone downwards due to gravity. But according to Newton, the stone exerts an equal and opposite force on the earth. We do not notice it since the earth is very massive and the effect of a small force on its motion is negligible.

Thus, forces always occur in pairs as a result of mutual interaction between two bodies. Thus, **Newton's third law states that for every action, there is always an equal and opposite reaction.**

In simple terms, the third law can be stated as follows

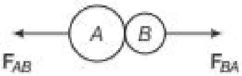
Force in nature always occurs in pairs. Force on body A by body B is equal and opposite to the force on the body B by A.

As shown in figure if $\mathbf{F}_{BA}$ is the force exerted by body A on B and $\mathbf{F}_{AB}$ is the force exerted by B on A, then according to Newton's third law,

$$\mathbf{F}_{AB} = -\mathbf{F}_{BA}$$

Force on A by B = − Force on B by A

The condition is shown in figure.



Forces acting on bodies A and B
(A colliding with B)

Some important implications about the third law of motion

(i) **Newton's third law of motion is applicable irrespective of the nature of the forces** The forces of action and reaction may be mechanical, gravitational, electric or of any other nature.

(ii) **Action and reaction always act on two different bodies** If they acted on the same body, the resultant force would be zero and there could never be accelerated motion.

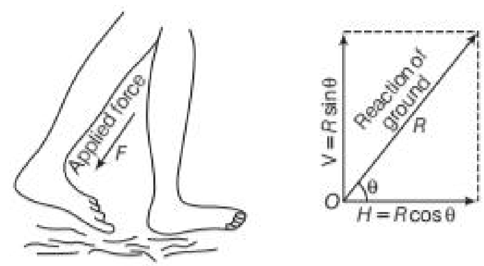
(iii) **The force of action and reaction cannot cancel each other** This is because action and reaction, though equal and opposite forces always act on different bodies and so cannot cancel each other.

(iv) **No action can occur in the absence of a reaction** In a tug of war, one team can pull the rope only if the other team is pulling the other end of the rope, no force can be exerted if the other end is free.

One team can exert the force of action because the other team provides the force of reaction.

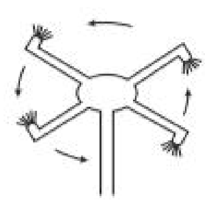
Some Important Concepts about Newton's Third Law of Motion

(i) While walking we press the ground (action) with our feet slightly slanted in the backward direction. The ground exerts an equal and opposite force on us. The vertical component of the force of reaction balances our weight and the horizontal component enables us to move forward as shown in figure.



Applied force by the feet and its reaction force along with its components

(ii) **Rotatory lawn sprinkler** The action of rotatory lawn sprinkler is based on third law of motion. As water forces way its of the nozzle, it exerts an equal and opposite force in the backward direction, causing the sprinkler to rotate in the opposite direction. Thus, water is scattered in all directions as shown in figure.



Water rotatory lawn sprinkler

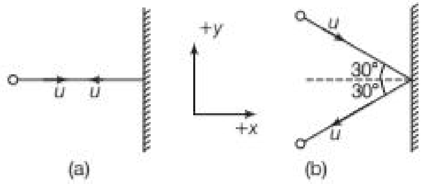
EXAMPLE |9| Play with Billiard Ball

Two identical billiard balls strike a rigid wall with the same speed but at different angles and get reflected without any change in a speed as shown in figure.

(i) What is the direction of the force on the wall due to each ball?

(ii) What is the ratio of the magnitudes of impulses imparted to the balls by the wall? **[NCERT]**

Sol. Let m be the mass of the ball and u be the speed of each ball before and after collision with the ball. Choosing xy- axes as shown in figure.



(i) **Case** (a) In Fig. (a),

$$\left.\begin{aligned} p_{x_{\text{initial}}} &= mu \\ p_{x_{\text{final}}} &= -mu \end{aligned}\right\} \text{on } x\text{-axis}$$

On y-axis $p_{y_{\text{initial}}} = 0$, $p_{y_{\text{final}}} = 0$
and we know that impulse

I = change in momentum $(p_2 - p_1)$

$\therefore$ x-component of impulse

$$= p_{x_{\text{final}}} - p_{x_{\text{initial}}} = -mu - mu = -2mu$$

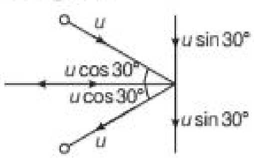
y-component of impulse

$$= p_{y_{\text{final}}} - p_{y_{\text{initial}}} = 0 - 0 = 0$$

Since, impulse and force are in the same direction, therefore, force on the ball due to the wall is along negative x-axis.

By Newton's third law of motion, the force on the wall due to the ball is normal to wall along the positive x-direction.

Case (b) In Fig. (b),



On x-axis, $p_{x_{\text{initial}}} = mu \cos 30°$
$p_{x_{\text{final}}} = -mu \cos 30°$

On y-axis $p_{y_{\text{initial}}} = -mu \sin 30°$
$p_{y_{\text{final}}} = -mu \sin 30°$

x-component of impulse $= p_{x_{\text{final}}} - p_{x_{\text{initial}}}$
$= -mu \cos 30° - mu \cos 30°$
$= -2mu \cos 30°$

y-component of impulse $= p_{y_{\text{final}}} - p_{y_{\text{initial}}}$
$= -mu \sin 30° + mu \sin 30° = 0$

The direction of force on the wall is same as in case (a) i.e. normal to wall along positive x-direction.

(ii) The ratio of the magnitude of the impulse imparted to the balls in cases a and b is

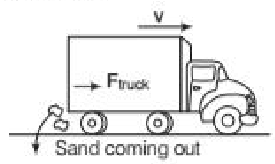
$$= \frac{-2mu}{-2mu \cos 30°}$$

$$= \frac{1}{\cos 30°} = \frac{1}{\sqrt{3}/2} = \frac{2}{\sqrt{3}} = 1.2$$

EXAMPLE |10| Change in Momentum

A truck is moving with a speed of 20 m/s along a straight line. Suddenly, some sand starts falling from the back side of the truck at the rate of 20 g/s. Find the value of external force required to make the truck move with the constant velocity of 20 m/s.

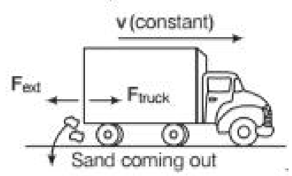
Sol. Since, truck is losing weight or mass without any change in velocity, its momentum changes. When there is a change in momentum, there is creation of force (according to Newton's second law applied in reverse). Since, truck is becoming lighter, it will be accelerated in forward direction. That means force in it will be created in forward direction.



The value of this force could be found out with the formula of Newton's second law, when v is constant (at an instant) but mass is varying.

$$|\mathbf{F}|_{\text{truck}} = |\mathbf{v}| \frac{dm}{dt}$$

That much amount of force have to be applied on the truck in the backward direction to keep the truck moving with constant velocity



$$\mathbf{F}_{\text{ext}} = \mathbf{F}_{\text{truck}} = v\frac{dm}{dt}$$

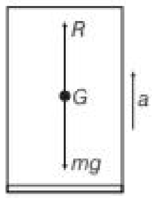
$$\mathbf{F}_{\text{ext}} = 20 \text{ m/s } [20 \times 10^{-3} \text{ kg /s}] = 0.4 \text{ N (backward)}$$

Apparent Weight of a Man in a Lift

Let us consider a man of mass m is standing on a weighing machine placed in an elevator/lift. The actual weight mg of the man acts on the weighing machine and offers a reaction R given by the reading of the weighing machine.

This reaction R exerted by the surface of contact on the man is the apparent weight of the man. Now, we consider how R is related to mg in the different conditions.

(i) When the lift moves upwards with acceleration a as shown in figure, the net upward force on the man is

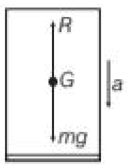


$$R - mg = ma \quad \Rightarrow \quad R = ma + mg$$

$$\boxed{\text{Apparent weight, } R = m(g + a)}$$

So, when a lift accelerates upwards, the apparent weight of the man inside it increases.

(ii) When the lift moves downwards with acceleration a as shown in figure, net downward force on the man is

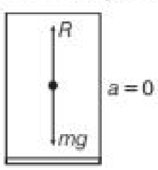


$$mg - R = ma$$

$$\boxed{\text{Apparent weight, } R = m(g - a)}$$

So, when a lift accelerates downwards, the apparent weight of the man inside it decreases.

(iii) When the lift is at rest or moving with uniform velocity v downward or upward as shown in figure.



Then, acceleration $a = 0$. So, net force on the man is

$$R - mg = m \times 0 \quad \Rightarrow \quad R = mg$$

or $\boxed{\text{Apparent weight = actual weight}}$

So, **when the lift at rest and the apparent weight of the man is the actual weight of him.**

(iv) When the lift falls freely under gravity if the supporting cable of the lift breaks. Then, $a = g$.

The net downward force on the man is

$$R = m(g - g) \quad \Rightarrow \quad \boxed{R = 0}$$

Thus, **the apparent weight of the man becomes zero.**

This is because both the lifts are moving downwards with the same acceleration g and so there are no forces of action and reaction exists between the man and lift. Hence, a person develops a feeling of weightlessness when the lift falls freely under gravity.

EXAMPLE |11| Feeling Weightlessness

A man of mass 70 kg stands on a weighing scale in a lift which is moving

(i) upwards with uniform speed of 10 m/s?

(ii) downwards with a uniform acceleration of 5 m/s^2?

(iii) upwards with uniform acceleration of 5 m/s^2.
What would be the readings on the scale in each case?

(iv) What would be the reading if the lift mechanism failed and it hurtled down freely under gravity? **[NCERT]**

When a man is standing on a weighing scale, it will read the normal reaction R as apparent weight.

Sol. Given, mass of man $(m) = 70$ kg

In each case the weighing scale will read the reaction R, i.e. the apparent weight.

(i) As lift is moving upward with a uniform speed, therefore, its acceleration $a = 0$

$\therefore$ Normal reaction $w = R = mg = 70 \times 10\text{ N} = 700\text{ N}$

w acts vertically downwards and R acts vertically upwards.

$\therefore$ Reading on weighing scale $= \dfrac{700}{10} = 70$ kg

(ii) Acceleration of the lift, $a = 5\text{ m/s}^2(\downarrow)$

$\therefore$ Normal reaction, $R = m(g - a) = 70(10 - 5)\text{ N}$
$= 70 \times 5\text{ N} = 350\text{ N}$

$\therefore$ Reading on weighing scale $= \dfrac{350\text{ N}}{10\text{ m/s}^2} = 35$ kg

(iii) Acceleration of the lift, $a = 5\text{ m/s}^2(\uparrow)$

$\therefore$ Normal reaction, $R = m(g + a)$
$= 70(10 + 5) = 1050\text{ N}$

$\therefore$ Reading on weighing scale $= \dfrac{1050\text{ N}}{10\text{ m/s}^2} = 105$ kg

(iv) Acceleration of the lift when it is falling freely under gravity

$$a = g\,(\downarrow)$$

$\therefore$ Normal reaction, $R = m(g - a) = m(g - g) = 0$

$\therefore$ Reading on weighing scale = 0

Note

There will be feeling of weightlessness. We feel our weight because of reaction force. When reaction is zero, we feel weightlessness, though our weight is still there.

CONSERVATION OF MOMENTUM

This principle is a consequence of Newton's second and third law of motion.

According to this principle

"In the absence of an external force the total momentum of a system remains constant or conserved and does not change with time"

If $\quad\quad F_{ext} = 0$

Or in an isolated system (i.e. a system having no external force) mutual forces (called internal forces) between pairs of particles in the system causes momentum change in individual particle. But as the mutual forces for each pair are equal and opposite, the linear momentum of individual particle cancel in pairs and the total momentum remains unchanged. This fact is known as the **law of conservation of momentum.**

The total momentum of an isolated system of interacting particle is conserved. Now, we will show that the total momentum of a system remains constant in the absence of external force. Internal forces acting among constituent particles of a system do not affect momentum of system as a whole.

Explanation of Conservation of Momentum

Let us consider the momenta of two particles system of masses m_1 and m_2 are $\mathbf{p}_1$ and $\mathbf{p}_2$ respectively, then the net momentum of the whole system

$$\mathbf{p} = \mathbf{p}_1 + \mathbf{p}_2 \quad \text{...(i)}$$

Suppose $\mathbf{F}_1$ and $\mathbf{F}_2$ are two forces acting on particles of masses m_1 and m_2. Let in a small time interval Δt the change produced by the forces $\mathbf{F}_1$ and $\mathbf{F}_2$ are $\Delta\mathbf{p}_1$ and $\Delta\mathbf{p}_2$.

Thus, net change in momentum

$$\Delta\mathbf{p} = \Delta\mathbf{p}_1 + \Delta\mathbf{p}_2$$

or $$\frac{\Delta\mathbf{p}}{\Delta t} = \frac{\Delta\mathbf{p}_1}{\Delta t} + \frac{\Delta\mathbf{p}_2}{\Delta t}$$

or $$\frac{d\mathbf{p}}{dt} = \frac{d\mathbf{p}_1}{dt} + \frac{d\mathbf{p}_2}{dt} \quad [\text{as } \Delta t \to 0]$$

or $$\frac{d\mathbf{p}}{dt} = \mathbf{F}_1 + \mathbf{F}_2 \quad \text{...(ii)}$$

where, $$\mathbf{F}_1 = \mathbf{F}_{1\,ext} + \mathbf{F}_{1\,int}$$

and $$\mathbf{F}_2 = \mathbf{F}_{2\,ext} + \mathbf{F}_{2\,int}$$

$$\frac{d\mathbf{p}}{dt} = (\mathbf{F}_{1\,ext} + \mathbf{F}_{1\,int}) + (\mathbf{F}_{2\,ext} + \mathbf{F}_{2\,int})$$

or $$\frac{d\mathbf{p}}{dt} = (\mathbf{F}_{1\,ext} + \mathbf{F}_{2\,ext}) + (\mathbf{F}_{1\,int} + \mathbf{F}_{2\,int}) \quad \text{...(iii)}$$

From Newton's third law, the internal forces always occur in pair so

$$(\mathbf{F}_{1\,int} + \mathbf{F}_{2\,int}) = 0$$

or $$(\mathbf{F}_{1\,int} = -\mathbf{F}_{2\,int})$$

From Eq. (iii), we get

Thus, $$\frac{d\mathbf{p}}{dt} = (-\mathbf{F}_{2\,int} + \mathbf{F}_{2\,int}) + (-\mathbf{F}_{1\,ext} + \mathbf{F}_{2\,ext})$$

or $$\frac{d\mathbf{p}}{dt} = 0 + \mathbf{F}_{1\,ext} + \mathbf{F}_{2\,ext} \quad \text{or} \quad \frac{d\mathbf{p}}{dt} = \mathbf{F}_{ext}$$

where, $$\mathbf{F} = \mathbf{F}_{1\,ext} + \mathbf{F}_{2\,ext},\ \mathbf{F}_{ext} = 0$$

Then, $$\frac{d\mathbf{p}}{dt} = 0$$

or $\quad\quad$ Momentum, $\mathbf{p}$ = constant

This equation shows that the law of conservation of linear momentum holds true, i.e. linear momentum of the system remains conserved.

Conservation of momentum theorem is applicable for $\mathbf{F}_{ext} = 0$, it does not depend on internal forces.

e.g.

(i) Let us consider a bullet fired from a gun. Then, force on the bullet by the gun is $\mathbf{F}$ and according to third law of motion, the force on the gun by bullet will be $-\mathbf{F}$. The two forces act for a common interval of time Δt.

According to second law, $\mathbf{F}\,\Delta t$ is the change in momentum of the bullet and $-\mathbf{F}\,\Delta t$ is the change in momentum of the gun. Because bullet and gun are initially at rest and then change in momentum of the system is zero, so the sum of their final momenta must be zero.

Thus, if $\mathbf{p}_b$ is the momentum of the bullet after firing and $\mathbf{p}_g$ is the recoil momentum of the gun, then $\mathbf{p}_g = -\mathbf{p}_b$ or $\mathbf{p}_b + \mathbf{p}_g = 0$

(ii) Let a bomb be at rest, then its momentum will be zero. If the bomb explodes into two equal parts, then the parts fly off in exactly opposite directions with the same speed so that the total momentum is still zero. Here no external force is applied on the system of particles (bomb). Forces created are internal only.

EXAMPLE |12| Newton's Third Law from Newton's Second Law

Show that Newton's third law of motion is contained in the second law.

Sol. Let F_{BA} be the force (action) exerted by A on B and $\frac{d\mathbf{p}_B}{dt}$ be the resulting change of the momentum of B.

Let $\mathbf{F}_{AB}$ be the force (reaction) exerted by B on A and $\frac{d\mathbf{p}_A}{dt}$ be the resulting change of momentum of A.

According to Newton's second law, $F = \frac{d\mathbf{p}}{dt}$

Then, $\mathbf{F}_{BA} = \frac{d\mathbf{p}_B}{dt}$ and $\mathbf{F}_{AB} = \frac{d\mathbf{p}_A}{dt}$

$$\therefore \quad \mathbf{F}_{BA} + \mathbf{F}_{AB} = \frac{d\mathbf{p}_B}{dt} + \frac{d\mathbf{p}_A}{dt} = \frac{d}{dt}(\mathbf{p}_B + \mathbf{p}_A) \quad \text{...(i)}$$

Without any external force, the rate of change of momentum of the whole system must be zero.

i.e. $$\frac{d}{dt}(\mathbf{p}_B + \mathbf{p}_A) = 0$$

So, $$\mathbf{F}_{BA} + \mathbf{F}_{AB} = 0 \text{ or } \mathbf{F}_{BA} = -\mathbf{F}_{AB}$$

or $$\text{Action} = -\text{reaction}$$

and it is a Newton's third law of motion. Hence, Newton's third law of motion is contained in the second law of motion.

So, Newton's second law of motion is the real law of motion.

EXAMPLE |13| Conservation of Momentum

A moving neutron with speed 10^6 m/s collides with a deuteron at rest and sticks to it. Find the speed of the combination if masses of the neutron and deuteron are 1.67×10^{-27} kg and 3.34×10^{-27} kg, respectively.

Sol. Given, for neutron,

Mass, $m_1 = 1.67 \times 10^{-27}$ kg

Speed, $u_1 = 10^6$ m/s

For deuteron,

Mass, $m_2 = 3.34 \times 10^{-27}$ kg

Speed, $u_2 = 0$ [$\because$ the deuteron is at rest]

From principle of conservation of momentum,

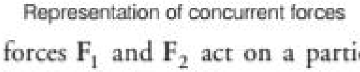
$$m_1 u_1 + m_2 u_2 = (m_1 + m_2) v$$

$$1.67 \times 10^{-27} \times 10^6 + 3.34 \times 10^{-27} \times 0 = (3.34 + 1.67) \times 10^{-27} \times v$$

$$v = \frac{1.67 \times 10^{-27} \times 10^{+6}}{5.01 \times 10^{-27}} = 33.33 \times 10^4 \text{ m/s}$$

Equilibrium of a Particle

Forces which are acting at the same point or on a particle are called **concurrent forces**. These forces are said to be in equilibrium when their resultant is zero.

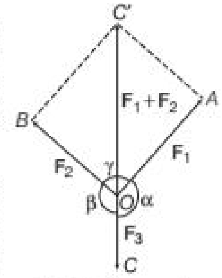


Representation of concurrent forces

(i) If two forces $\mathbf{F}_1$ and $\mathbf{F}_2$ act on a particle, then they will be in equilibrium if $\mathbf{F}_1 = -\mathbf{F}_2$ i.e. two forces on the particle must be equal and opposite.

(ii) Three concurrent forces $\mathbf{F}_1, \mathbf{F}_2$ and $\mathbf{F}_3$ will be in equilibrium when the resultant of two forces $\mathbf{F}_1$ and $\mathbf{F}_2$ is equal and opposite to the third force $\mathbf{F}_3$.

Given, figure shows that three concurrent forces $\mathbf{F}_1, \mathbf{F}_2$ and $\mathbf{F}_3$ are acting at a point O and represented by OA, OB and OC, respectively. Let us complete the parallelogram $OAC'B$.



Equilibrium under concurrent forces

The diagonal OC' of the parallelogram represents $\mathbf{F}_1 + \mathbf{F}_2$, the resultant of $\mathbf{F}_1$ and $\mathbf{F}_2$ from law of parallelogram of forces.

If OC' is equal and opposite to OC, then

$$\mathbf{F}_1 + \mathbf{F}_2 = -\mathbf{F}_3 \text{ or } \mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3 = 0$$

i.e. three concurrent forces are in equilibrium when the resultant of any two of them is equal and opposite to the third.

A particle under the action of forces $\mathbf{F}_1, \mathbf{F}_2, \mathbf{F}_3, \ldots, \mathbf{F}_n$ will be in equilibrium if these forces can be represented by the sides of a closed n sided polygon in the same sense, i.e.

$$\mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3 + \ldots\ldots + \mathbf{F}_n = 0$$

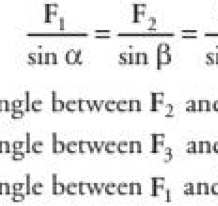
This equation implies that

$$\mathbf{F}_{1x} + \mathbf{F}_{2x} + \mathbf{F}_{3x} + \ldots\ldots + \mathbf{F}_{nx} = 0$$
$$\mathbf{F}_{1y} + \mathbf{F}_{2y} + \mathbf{F}_{3y} + \ldots\ldots + \mathbf{F}_{ny} = 0$$
$$\mathbf{F}_{1z} + \mathbf{F}_{2z} + \mathbf{F}_{3z} + \ldots\ldots + \mathbf{F}_{nz} = 0$$

where, $\mathbf{F}_{1x}, \mathbf{F}_{1y}$ and $\mathbf{F}_{1z}$ are the rectangular components of $\mathbf{F}_1$ along x, y and z-directions.

LAMI'S THEOREM

According to this theorem, when three concurrent forces $\mathbf{F}_1, \mathbf{F}_2$ and $\mathbf{F}_3$ acting on a body are in equilibrium, then



Three concurrent forces acting at some angles

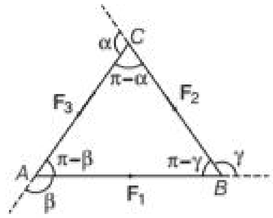
$$\frac{\mathbf{F}_1}{\sin \alpha} = \frac{\mathbf{F}_2}{\sin \beta} = \frac{\mathbf{F}_3}{\sin \gamma}$$

where, α = angle between $\mathbf{F}_2$ and $\mathbf{F}_3$

β = angle between $\mathbf{F}_3$ and $\mathbf{F}_1$

γ = angle between $\mathbf{F}_1$ and $\mathbf{F}_2$

Proof



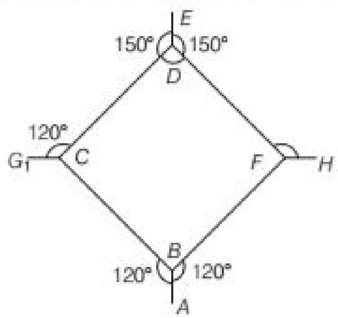
As shown in above figure, the forces $\mathbf{F}_1, \mathbf{F}_2$ and $\mathbf{F}_3$ can be represented by sides of ΔABC, taken in the same order. Applying law of sines to ΔABC, we get

$$\frac{\mathbf{F}_1}{\sin(\pi - \alpha)} = \frac{\mathbf{F}_2}{\sin(\pi - \beta)} = \frac{\mathbf{F}_3}{\sin(\pi - \gamma)}$$

or $$\frac{\mathbf{F}_1}{\sin \alpha} = \frac{\mathbf{F}_2}{\sin \beta} = \frac{\mathbf{F}_3}{\sin \gamma} \quad [\because \sin(\pi - \theta) = \sin \theta]$$

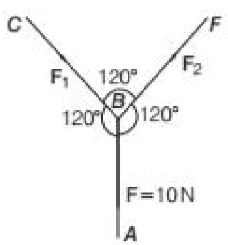
EXAMPLE |14| Lami's Theorem

The below figure is the part of a horizontal stretched net. Section AB is stretched with a force of 10 N, then determine the forces in the sections BC and BF.



Sol. By drawing the free body diagram of point B.

Let the force in the section BC and BF are F_1 and F_2 respectively.



Three concurrent forces acting at some angles

$$\frac{F_1}{\sin 120^\circ} = \frac{F_2}{\sin 120^\circ} = \frac{F}{\sin 120^\circ}$$

From Lami's theorem $F_1 = F_2 = F = 10$ N

TOPIC PRACTICE 1

OBJECTIVE Type Questions

1. Suppose the earth suddenly stops attracting objects placed near surface. A person standing on the surface of the earth will

(a) remain standing
(b) fly up
(c) sink into earth
(d) Either (b) or (c)

Sol. (a) If downward force on the earth stops, so upward self adjusting force also stop. In vertical direction, there is no force. Due to inertia person resists any change to its state of rest. Person will remain standing.

2. An astronaut accidentally gets separated out of his small spaceship accelerating in interstellar space at a constant rate of 100 ms^{-2}. What is the acceleration of the astronaut at the instant after he is outside the spaceship? (Assume that there are no nearby starts to exert gravitational force on him)

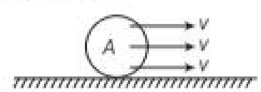
(a) 0
(b) 1
(c) ∞
(d) Data insufficient

Sol. (a) Since, there are no near by stars to exert gravitational force on him and the small spaceship exert negligible gravitational attraction on him, the net force acting on the astronaut, once he is out of the spaceship is zero.

3. A ball is travelling with uniform translatory motion. This means that **[NCERT Exemplar]**

(a) it is at rest
(b) the path can be a straight line or circular and the ball travels with uniform speed
(c) all parts of the ball have the same velocity (magnitude and direction) and the velocity is constant
(d) the centre of the ball moves with constant velocity and the ball spins about its centre uniformly

Sol. (c) In a uniform translatory motion, all parts of the ball have the same velocity in magnitude and direction and this velocity is constant.



The situation is shown in adjacent diagram, where a body A is in uniform translatory motion.

4. A metre scale is moving with uniform velocity. This implies **[NCERT Exemplar]**

(a) the force acting on the scale is zero, but a torque about the centre of mass can act on the scale
(b) the force acting on the scale is zero and the torque acting about centre of mass of the scale is also zero
(c) the total force acting on it need not be zero but the torque on it is zero
(d) neither the force nor the torque need to be zero

Sol. (b) To solve this question we have to apply Newton's second law of motion, in terms of force and change in momentum.

We known that, $F = \frac{dp}{dt}$

given that meter scale is moving with uniform velocity, hence, $dp = 0$

Force, $F = 0$.

As all part of the scale is moving with uniform velocity and total force is zero, hence, torque will also be zero.

5. Conservation of momentum in a collision between particles can be understood from **[NCERT Exemplar]**

(a) conservation of energy
(b) Newton's first law only
(c) Newton's second law only
(d) Both Newton's second and third law

Sol. (d) In case of collision between particles equal and opposite forces will act on individual. (by Newton's third law)

From second law of motion, if external force is zero, then momentum is consered.

6. A body of mass 2kg travels according to the law $x(t) = pt + qt^2 + rt^3$ where, $q = 4\text{ms}^{-2}$, $p = 3\text{ms}^{-1}$ and $r = 5\text{ms}^{-3}$. The force acting on the body at $t = 2\text{s}$ is **[NCERT Exemplar]**

(a) 136 N (b) 134 N
(c) 158 N (d) 68 N

Sol. (a) Given, mass = 2 kg

$$x(t) = pt + qt^2 + rt^3$$

$$v = \frac{dx}{dt} = p + 2qt + 3rt^2$$

$$a = \frac{dv}{dt} = 0 + 2q + 6rt$$

at $t = 2\text{s}$; $a = 2q + 6 \times 2 \times r$

$$= 2q + 12r$$
$$= 2 \times 4 + 12 \times 5$$
$$= 8 + 60 = 68 \text{ m/s}$$

Force $= F = ma$

$$= 2 \times 68 = 136 \text{ N}$$

7. In equilibrium of particle when net external force of the particle is zero. Then, the particle is

(a) at rest
(b) moving with uniform velocity
(c) moving with uniform acceleration
(d) Both (a) and (b)

Sol. (d) In equilibrium, net force is zero, there force, acceleration is zero, hence particle is either at rest or in motion with uniform velocity.

VERY SHORT ANSWER Type Questions

8. Bodies of larger mass need greater initial effort to put them in motion. Why?

Sol. According to the Newton's second law of motion, $F = ma$, for given acceleration a, if m is large, F should be more i.e. greater force will be required to put a larger mass in motion.

9. A force of 1 N acts on a body of mass 1 g. Calculate the acceleration produced in the body.

Sol. Given, $F = 1\text{N}$, $m = 1\text{ g} = 10^{-3}\text{kg}$

Now, $F = ma$

$$\Rightarrow \quad a = \frac{F}{m} = \frac{1}{10^{-3}} = 10^3 \text{ m/s}^2$$

10. Calculate the force acting on a body which changes the momentum of the body at the rate of 1 kg-m/s^2.

Sol. We know that, F = rate of change of momentum

$$F = 1 \text{ kg-m/s}^2 = 1\text{N}$$

11. The distance travelled by a moving body is directly proportional to time. Is any external force acting on it?

Sol. When $S \propto t$, so acceleration = 0, Therefore, no external force is acting on the body.

12. A force of 36 dyne is inclined to the horizontal at an angle of 60°. Find the acceleration in a mass of 18 g that moves in a horizontal direction.

Sol. Given, $F = 36$ dyne at an angle of 60°.

$\therefore$ Component of force along x-direction

$$F_x = F\cos 60° = 36 \times \frac{1}{2} = 18 \text{ dyne}$$

But $F_x = ma_x$,

$$a_x = \frac{F_x}{m} = \frac{18}{18} = 1 \text{ cm/s}^2$$

13. A body is acted upon by a number of external forces. Can it remain at rest?

Sol. Yes, if the external forces acting on the body can be represented in magnitude and direction by the sides of a closed polygon taken in the same order.

14. If force is acting on a moving body perpendicular to the direction of motion, then what will be its effect on the speed and direction of the body?

Sol. No change in speed, but change in direction is possible. Forces acting on a body in circular motion is an example.

15. An impulse is applied to a moving object with a force at an angle of 20° w.r.t. velocity vector, what is the angle between the impulse vector and change in momentum vector?

Sol. Impulse and change in momentum are along the same direction. Therefore, angle between these two vectors is zero degree.

SHORT ANSWER Type Questions

16. Why are porcelain objects wrapped in paper or straw before packing for transportation? **[NCERT]**

Sol. Porcelain objects are wrapped in paper or straw before packing to reduce the chances of damage during transportation. During transportation sudden jerks or even fall can take place. Forces are created at the point of collision and the force takes longer time to reach the porcelain objects through paper or straw for same change in momentum as $F = \Delta p / \Delta t$ and therefore a lesser force acts on object.

17. A woman throws an object of mass 500 g with a speed of 25 m/s.

(i) What is the impulse imparted to the object?

(ii) If the object hits a wall and rebounds with half the original speed, what is the change in momentum of the object? **[NCERT]**

Sol. Given, Mass of the object $(m) = 500\text{ g} = 0.5\text{ kg}$

Speed of the object $(v) = 25\text{ m/s}$

(i) Impulse imparted to the object

= change in the momentum

$= mv - mu = m(v - u)$

$= 0.5(25 - 0) = 12.5\text{ N-s}$

(ii) Velocity of the object after rebounding $= -\frac{25}{2}\text{ m/s}$

$v' = -12.5\text{ m/s}$

$\therefore$ Change in momentum $= m(v' - v)$

$= 0.5(-12.5 - 25) = -18.75\text{ N-s}$

18. A passenger of mass 72.2 kg is riding in an elevator while standing on a platform scale. What does the scale read when the elevator cab is (i) descending with constant velocity (ii) ascending with constant acceleration, 3.5 m/s^2?

Sol. Given, mass, $m = 72.2\text{ kg}$

Gravity acceleration, $g = 9.8\text{ m/s}^2$

Scale reading = apparent weight = R = ?

(i) While descending with constant velocity, $a = 0$

$\therefore \quad R = mg$

$R = 72.2 \times 9.8$

$\Rightarrow \quad R = 707.56\text{ N}$

(*ii*) While ascending with $a = 3.2\text{ m/s}^2$

$R = m(g + a)$

$R = 72.2(9.8 + 3.2) = 938.6\text{ N}$

19. A person of mass 50 kg stands on a weighing scale on a lift. If the lift is descending with a downwards acceleration of 9 m/s^2, what would be the reading of the weighing scale? $(g = 10\text{ m/s}^2)$

When a lift descends with a downward acceleration a, the apparent weight of a body of mass m is given by $w' = R = m(g - a)$ **[NCERT Exemplar]**

Sol. Given, Mass of the person, $m = 50\text{ kg}$

Descending acceleration, $a = 9\text{ m/s}^2$

Acceleration due to gravity, $g = 10\text{ m/s}^2$

Apparent weight of the person,

$$R = m(g - a) = 50(10 - 9) = 50\text{ N}$$

$\therefore$ Reading of the weighing scale $= \frac{R}{g} = \frac{50}{10} = 5\text{ kg}$

20. A person driving a car suddenly applies the brakes on seeing a child on the road ahead. If he is not wearing seat belt, he falls forward and hits his head against the steering wheel. Why? **[NCERT]**

Sol. When a person driving a car suddenly applies the brakes, the lower part of the body slower down with the car while upper part of the body continues to move forward due to inertia of motion. If driver is not wearing seat belt, then he falls forward and his head hit against the steering wheel.

21. Why does a child feel more pain when she falls down on a hard cement floor, than when she falls on the soft muddy ground in the garden? **[NCERT]**

Sol. When a child falls on a cement floor, her body comes to rest instantly.

But $F \times \Delta t$ = change in momentum = constant.

As time of stopping Δt decreases, therefore. F increases and hence child feel more pain. When she falls on a soft muddy ground in the garden, the time of stopping increases and hence F decreases and she feels lesser pain.

LONG ANSWER Type I Questions

22. A pebble of mass 0.05 kg is thrown vertically upwards. Give the direction and magnitude of the net force on the pebble

(i) during its upward motion.

(ii) during its downward motion.

(iii) at the highest point where it is momentarily at rest.

Do your answer change if the pebble was thrown at an angle of 45° with the horizontal direction? Ignore air resistance. **[NCERT]**

Sol. When an object is thrown vertically upward or it falls vertically downward under gravity, then an acceleration $g = 10 \text{ m/s}^2$ acts downward due to the earth's gravitational pull.

Mass of pebble $(m) = 0.05$ kg

(i) **During upward motion**

Net force acting on pebble $(F) = ma = 0.05 \times 10$ N

$= 0.50$ N (vertically downward)

(ii) **During downward motion**

Net force acting on pebble $(F) = ma = 0.05 \times 10$ N

$= 0.50$ N (vertically downward)

(iii) **At the highest point**

Net force acting on pebble

$(F) = ma = 0.05 \times 10$ N

$= 0.50$ N (vertically downward)

If pebble was thrown at an angle of 45° with the horizontal direction, then acceleration acting on it and therefore force acting on it will remain unchanged, i.e. 0.50 N (vertically downward). In case (c), at the highest point the vertical component of velocity will be zero but horizontal component of velocity will not be zero.

23. A stream of water flowing horizontally with a speed of 15 m/s gushes out of a tube of cross-sectional area 10^{-2} m^2 and hits a vertical wall nearby. What is the force exerted on the wall by the impact of water, assuming it does not rebound? **[NCERT]**

Sol. Given, speed of the stream of water, $v = 15$ m/s

Area of cross-section of the tube, $A = 10^{-2} \text{ m}^2$

Volume of water coming out per second from the tube

$$V = Av = 10^{-2} \times 15 = 15 \times 10^{-2} \text{ m}^3$$

Density of water $= 10^3 \text{ kg/m}^3$

$\therefore$ Mass of the water coming out of the tube per second

$$m = V\rho \qquad \left[\because \text{Density} = \frac{\text{mass}}{\text{volume}}\right]$$

$$= 15 \times 10^{-2} \times 10^3 \text{ kg}$$

$$= 150 \text{ kg/s}$$

Force exerted on the wall by the impact of water

= change in momentum per second

$$= mv = 150 \times 15 \text{ N}$$

$$= 2250 \text{ N}$$

24. Ten one-rupee coins are put on top of each other on a table. Each coin has mass m. Give the magnitude and direction of

(i) the force on the 7th coin (counted from the bottom) due to all the coins on its top,

(ii) the force on the 7th coin by the 8 coin, (counted from the bottom)

(iii) the reaction of the 6th coin on the 7th coin. (counted from the bottom) **[NCERT]**

Sol. $\because$ Mass of each coin $= m$

Number of total coins = 10

(i) Force acting on 7th coin (counted from the bottom)

= Weight of the coins above it

= Weight of 3 coins

$= 3\,mg$ N (downward)

(ii) Force acting on 7th coin by the 8th coin = weight of the 8 coins + weight of two coins supported by 8 coins

$= mg + 2mg$

$= 3\,mg$ N (downward)

(iii) Reaction of the 6th coin on the 7th coin

= − (force exerted on 6th coin)

= − (weight of 4 coins)

$= -4\,mg$ N (vertically upward)

25. A helicopter of mass 1000 kg rises with a vertical acceleration of 15 m/s^2. The crew and the passengers weigh 300 kg. Give the magnitude and direction of the

(i) force on floor by the crew and passengers.

(ii) action of the rotor of the helicopter on the surrounding air

(iii) force on the helicopter due to the surrounding air, take $g = 10 \text{ m/s}^2$. **[NCERT]**

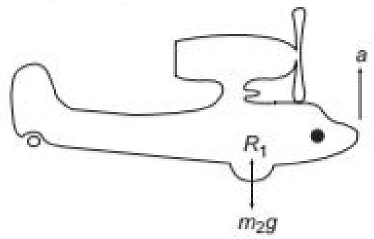
Sol. $\because$ Mass of the helicopter, $m_1 = 1000$ kg

Mass of the crew and the passengers, $m_2 = 300$ kg

Acceleration of the helicopter, $a = 15 \text{ m/s}^2$

Acceleration due to gravity, $g = 10 \text{ m/s}^2$

(i) Let R_1 be the reaction applied by the floor on the crew and the passengers.



$\therefore \quad R_1 - m_2g = m_2a$

or $\quad R_1 = m_2g + m_2a = m_2(g + a) = 300\,(10 + 15)$

$= 7500$ N (upward direction)

(ii) Action of the rotor of the helicopter on the surrounding air

$= (m_1 + m_2)\,g + (m_1 + m_2)a$

$= (m_1 + m_2)(g + a)$

$= (1000 + 300) \times (10 + 15)$

$= 1300 \times 25 = 32500$ N

Force (action) of the rotor of the helicopter on the surrounding air $= 32500$ N (downward)

(iii) According to Newton's third law of motion, for every action there is an equal and opposite reaction.

$\therefore$ Force on the helicopter due to the surrounding air

$= 32500$ N (upward direction)

26. A girl riding a bicycle along a straight road with a speed of 5 m/s throws a stone of mass 0.5 kg which has a speed of 15 m/s with respect to the ground along her direction of motion. The mass of the girl and bicycle is 50 kg. Does the speed of the bicycle change after the stone is thrown? What is the change in speed, if so? **[NCERT Exemplar]**

Sol. Total mass of girl, bicycle and stone,

$m_1 = (50 + 0.5)$ kg $= 50.5$ kg

Velocity of bicycle, $u_1 = 5$ m/s

Mass of stone, $m_2 = 0.5$ kg

Velocity of stone, $u_2 = 15$ m/s

Mass of girl and bicycle, $m = 50$ kg

Yes, the speed of the bicycle changes after the stone is thrown.

Let, after throwing the stone the speed of bicycle be v m/s.

According to the law of conservation of linear momentum,

$$m_1u_1 = m_2u_2 + mv$$

$$50.5 \times 5 = 0.5 \times 15 + 50 \times v$$

$$252.5 - 7.5 = 50v \quad \text{or} \quad v = \frac{245.0}{50}$$

$$v = 4.9 \text{ m/s}$$

Change in speed $= 5 - 4.9 = 0.1$ m/s

LONG ANSWER Type II Questions

27. Give the magnitude and direction of the net force acting on

(i) a drop of rain falling down with a constant speed.

(ii) a cork of mass 10 g floating on water.

(iii) a kite skillfully held stationary in the sky.

(iv) a car moving with a constant velocity of 30 km/h on a rough road.

(v) a high speed electron in space far from all gravitational (material) objects and free of electric and magnetic fields. **[NCERT]**

Force $F = ma$, therefore force acting on a particle in unaccelerated ($a = 0$) motion is zero.

Sol. (i) As drop of rain is falling downward with a constant speed, therefore its acceleration is zero.

According to Newton's second law of motion, net force acting on drop $F = ma = 0$.

(ii) In floating condition, the weight of the body is balanced by the upthrust. Therefore, net force acting on a cork floating on water $= 0$.

(iii) As kite is held stationary in the sky, therefore acceleration of the kite is zero. Therefore, net force acting on the kite $F = ma = 0$.

(iv) As car is moving with a constant velocity, therefore, its acceleration is zero i.e. $a = 0$ therefore, net force acting on the car $F = ma = 0$.

(v) As electron is in a space where there is no electric field, magnetic field and gravitational (material) objects, therefore, no electric, magnetic and gravitational force is acting on it. Hence, net force acting on electron is zero.

28. Give the magnitude and direction of the net force acting on a stone of mass 0.1 kg.

(i) Just after it is dropped from the window of a stationary train.

(ii) Just after it is dropped from the window of a train running at a constant velocity of 36 km/h.

(iii) Just after it is dropped from the window of a train accelerating with 1 m/s^2.

(iv) Lying on the floor of a train which is accelerating with 1 m/s^2, the stone being at rest relative to the train. Neglect air resistance throughout. **[NCERT]**

When any object is thrown from a train, the influence of train on the object becomes zero at the same moment, i.e. there is no effect of acceleration of train on the object.

Sol. $\because$ Mass of stone $(m) = 0.1$ kg

(i) When stone is dropped from the window of a stationary train, it falls freely under gravity.

$\therefore$ Net force acting on stone (F)

$$= mg = 0.1 \times 10$$
$$= 1.0 \text{ N (vertical downward)}$$

(ii) Just after the stone is dropped from the window of a train running at a constant velocity, i.e. acceleration of the train is zero. So, no force acts on the stone due to motion it falls freely under gravity.

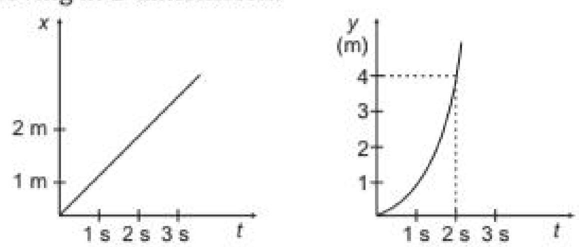
The force acts on it is due to its weight only, i.e. acceleration of the train is zero, so no force acts, on the stone due to this motion.

(iii) The train accelerates horizontally by 1 m/s^2, but as the stone is left it moves under gravity only so the net force on it will be due to gravity only.

(*iv*) As the stone is accelerating with the train, so there must be a net horizontal force on it. Its weight also acts but is balanced by reaction force of the floor.

$$F = m \times a_{(\text{train})} = 0.1 \times 1 = 0.1 \text{ N}$$

29. Figure shows (x, t), (y, t) diagram of a particle moving in 2-dimensions.



(a) (b)

If the particle has a mass of 500 g, find the force (direction and magnitude) acting on the particle. **[NCERT Exemplar]**

Sol. Given, mass of the particle $(m) = 500 \text{ g} = 0.5$ kg

x-t graph of the particle is a straight line.

Hence, particle is moving with a uniform velocity along x-axis, i.e. its acceleration along x-axis is zero and hence, force acting along x-axis is zero.

y-t graph of particle is a parabola. Therefore, particle is in accelerated motion along y-axis.

At $t = 0$, $u_y = 0$

Along y-axis, at $t = 2$s, $y = 4$m

Using equation of motion, $y = u_y t + \frac{1}{2} a_y t^2$

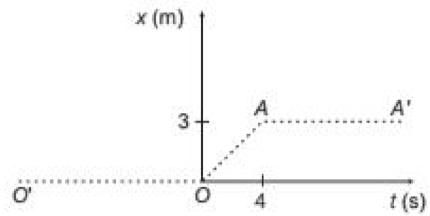
$$4 = 0 \times 2 + \frac{1}{2} \times a_y \times (2)^2$$

or $\quad a_y = 2 \text{ m/s}^2$

$\therefore$ Force acting along y-axis $(f_y) = ma_y$

$$= 0.5 \times 2 = 1.0 \text{ N (along } y\text{-axis)}$$

30. Figure below shows the position-time graph of a particle of mass 4 kg. What is the (i) force on the particle for $t < 0$, $t > 4$s, $0 < t < 4$s? (ii) impulse at $t = 0$ and $t = 4$s? (Consider one-dimensional motion only).



[NCERT]

Velocity = slope of position-time graph and impulse = change in momentum = $mv - mu$.

Sol. (i) (a) For $t < 0$, the position-time graph is OO', for which displacement of the particle is zero, therefore, particle is at rest at the origin. Hence, acceleration and force acting on particle will also be zero.

(b) For $t > 4$s, the position-time graph AA' is parallel to time axis. Therefore, for $t > 4$s particle remains at a fixed distance of 3m from the origin. It means particle is at rest. Therefore, acceleration and force acting on particle will be zero.

(c) For $0 < t < 4$s, the position-time graph OA is a straight line inclined at an angle from time axis, which is representing uniform motion of the particle, i.e. the particle is moving with a constant velocity. Therefore, acceleration and force acting on the particle will be zero.

(ii) Impulse at $t = 0$

(a) Impulse = change in momentum

$$= mv - mu = m(v - u)$$

Before $t = 0$, particle is at rest, hence $u = 0$

After $t = 0$, particle is moving with a constant velocity.

Velocity of the particle = slope of position-time graph

$$= \frac{3 \text{ m}}{4 \text{ s}} = 0.75 \text{ m/s}$$

$\therefore$ Impulse = change in momentum

$$= 4(0.75 - 0) = 3 \text{ kg-m/s}$$

(b) Impulse at $t = 4$s

Before $t = 4$s, particle is moving with a constant speed, $u = 0.75$ m/s

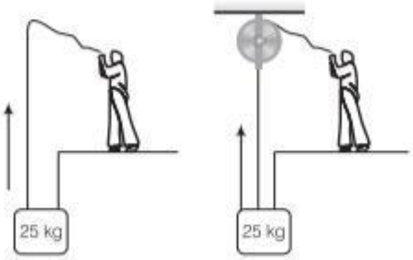
After $t = 4$s, particle is again at rest

$\because \quad v = 0$

$\therefore \quad$ Impulse = Change in momentum = $m(v - u)$

$$= 4(0 - 0.75)$$
$$= -3 \text{ kg-m/s}$$

31. **A block of mass 25 kg is raised by a 50 kg man in two different ways as shown in figure. What is the action on the floor by the man in the two cases? If the floor yields a normal force of 700 N, which mode should the man adopt to lift the block without the floor yielding?** **[NCERT]**



(a) (b)

Sol. $\because$ Mass of block, $m = 25\,\text{kg}$

Mass of the man, $M = 50\,\text{kg}$

Force required to lift the block (F) = weight of the block

$$F = mg = 25 \times 10 = 250\,\text{N}$$

Weight of the man, $w = Mg = 50 \times 10 = 500\,\text{N}$

Case (a)

If the block is raised by the man as shown in Fig. (a), then, force is applied by the man in the upward direction due to which apparent weight of the man increases. When man applies force on block in upward direction, block applies force on man in downward direction, according to 3rd law of motion. Therefore, action on the floor by the man $= F + w$

$$= 250 + 500 = 750\,\text{N}$$

Case (b)

If the block is raised by the man as shown in Fig. (b), then, force is applied by the man in the downward direction due to which apparent weight of the man decreases. Therefore, action on the floor by the man

$$= mg - F$$

$$= 500 - 250 = 250\,\text{N}$$

The floor yields a normal force of 700 N. Action on the floor in case (a) exceeds 700 N, and less than 700 N in case (b). Therefore, mode (b) has to be adopted by the man to lift the block.

32. **Explain why?**

(i) **A horse cannot pull a cart and run in empty space.**

(ii) **Passengers are thrown forward from their seats when a speeding bus stops suddenly.**

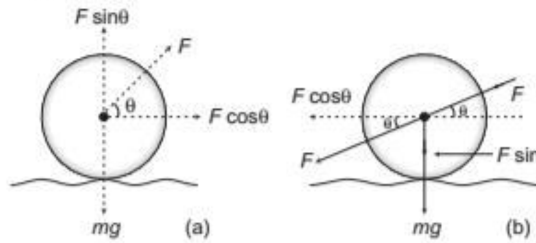
(iii) It is easier to pull a lawn mower than to push it.

(iv) A cricketer moves his hands backwards while holding a catch. **[NCERT]**

Sol. (i) When a horse is trying to pull a cart, he pushes the ground backward at an angle from the horizontal. According to Newton's third law of motion, the ground also apply equal reaction force on the feet of the horse in opposite direction. The vertical component of reaction balances the weight of the horse and horizontal component is responsible for motion of the cart. In empty space, there is no reaction force, therefore, a horse cannot pull a cart.

(ii) When bus is moving, the passengers sitting in it are also in motion and moving with the speed of the bus. When bus stops suddenly then lower part of the body of passengers which is in contact with the bus slow down with the bus but upper part of the bodies of the passengers continue to remain in motion in initial direction due to its inertia of motion and hence are thrown forward.

(iii) In pulling a lawn mower, a force F is applied in upward direction, making an angle θ with the horizontal [Fig. (a)]. Its vertical component in upward direction decreasing the effective weight of the mower.



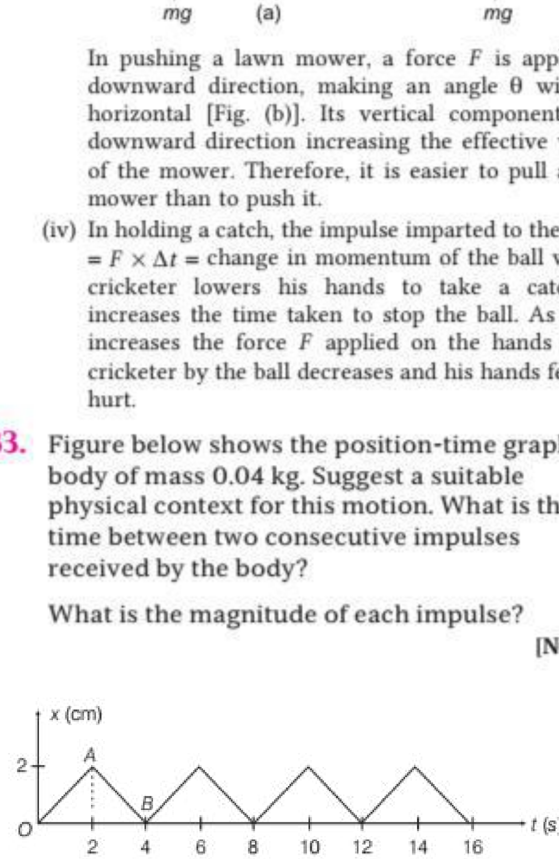
In pushing a lawn mower, a force F is applied in downward direction, making an angle θ with the horizontal [Fig. (b)]. Its vertical component is in downward direction increasing the effective weight of the mower. Therefore, it is easier to pull a lawn mower than to push it.

(iv) In holding a catch, the impulse imparted to the hands $= F \times \Delta t$ = change in momentum of the ball when a cricketer lowers his hands to take a catch, he increases the time taken to stop the ball. As time t increases the force F applied on the hands of the cricketer by the ball decreases and his hands feel less hurt.

33. **Figure below shows the position-time graph of a body of mass 0.04 kg. Suggest a suitable physical context for this motion. What is the time between two consecutive impulses received by the body?**

What is the magnitude of each impulse?

[NCERT]



Sol. Mass of the body, $m = 0.04$ kg

The position-time graph OA from $t = 0$ to $t = 2$s is a straight line, therefore body is moving with a constant velocity.

Velocity of the body, v = Slope of x - t graph

$$= \frac{2-0}{2-0} = 1 \text{ cm/s}$$

$$= 10^{-2} \text{m/s} \quad [\because 1 \text{ cm} = 10^{-2} \text{m}]$$

Part AB of position-time graph is also a straight line, therefore, velocity of the body

$$v' = \frac{0-2}{0-2} = -1 \text{ cm/s} \quad = -10^{-2} \text{cm/s}$$

Negative sign shows that the direction of velocity is reversed after 2s and it is being repeated.

A suitable physical context for this motion is a ball moving with a constant velocity of 10^{-2}m/s between two walls located at $x = 0$ and at $x = 2$m and rebounded repeatedly on striking each wall.

Magnitude of the impulse imparted to the ball after every two seconds

= change in momentum of the ball

$= mv - mv' = m(v - v')$

$= 0.04\, [10^{-2} - (-10^{-2})]$

$= 8 \times 10^{-4}$ kg- m/s

ASSESS YOUR TOPICAL UNDERSTANDING

OBJECTIVE Type Questions

1. If the running bus stop suddenly our feet stop due to friction which does not allow relative motion between the feet and floor of the bus. But the rest of the body continues to move forward due to

(a) momentum (b) force
(c) inertia (d) impulse

2. A cricket ball of mass 150 g has an initial velocity $\mathbf{u} = (3\hat{\mathbf{i}} + 4\hat{\mathbf{j}})\text{ ms}^{-1}$ and a final velocity $\mathbf{v} = -(3\hat{\mathbf{i}} + 4\hat{\mathbf{j}})\text{ ms}^{-1}$, after being hit. The change in momentum (final momentum–initial momentum) is (in kg-ms^{-1}) **[NCERT Exemplar]**

(a) zero
(b) $-(0.45\hat{\mathbf{i}} + 0.6\hat{\mathbf{j}})$
(c) $-(0.9\hat{\mathbf{j}} + 1.2\hat{\mathbf{j}})$
(d) $-5(\hat{\mathbf{i}} + \hat{\mathbf{j}})\hat{\mathbf{i}}$

3. In the previous problem (2), the magnitude of the momentum transferred during the hit is **[NCERT Exemplar]**

(a) zero (b) 0.75 kg-m s^{-1}
(c) 1.5 kg-m s^{-1} (d) 14 kg-m s^{-1}

4. A body with mass 5 kg is acted upon by a force $\mathbf{F} = (-3\hat{\mathbf{i}} + 4\hat{\mathbf{j}})$ N. If its initial velocity at $t = 0$ is $v = (6\hat{\mathbf{i}} - 12\hat{\mathbf{j}})\text{ms}^{-1}$, the time at which it will just have a velocity along the y-axis is

(a) never (b) 10 s (c) 2 s (d) 15 s

5. Which of the following statements is not true regarding the Newton's third law of motion?

(a) To every action there is always an equal and opposite reaction
(b) Action and reaction act on the same body
(c) There is no cause-effect relation between action and reaction
(d) Action and reaction forces are simultaneous

6. A book is lying on the table. What is the angle between the action of the book on the table and reaction of the table on the book?

(a) 0° (b) 30°
(c) 45° (d) 180°

7. Two forces $F_1 = 3\hat{\mathbf{i}} - 4\hat{\mathbf{j}}$ and $F_2 = 2\hat{\mathbf{i}} - 3\hat{\mathbf{j}}$ are acting upon a body of mass 2 kg. Find the force F_3 which when acting on the body will make it stable.

(a) $5\hat{\mathbf{i}} + 7\hat{\mathbf{j}}$ (b) $-5\hat{\mathbf{i}} - 7\hat{\mathbf{j}}$
(c) $-5\hat{\mathbf{i}} + 7\hat{\mathbf{j}}$ (d) $5\hat{\mathbf{i}} - 7\hat{\mathbf{j}}$

Answer

1. (c)	2. (c)	3. (c)	4. (b)	5. (b)
6. (d)	7. (c)			

VERY SHORT ANSWER Type Questions

8. According to Newton's third law, every force is accompanied by an equal and opposite force. How can a movement ever take place?

9. A man suspends a fish from the spring balance held in his hand and the balance reads 9.8 N. While shifting the balance to his other hand, the balance slips and falls down. What will be the reading of the balance during the fall? **[Ans.** zero]

10. Action and reaction are equal and opposite. Why cannot they cancel each other?

11. Calculate the impulse necessary to step 1500 kg car travelling at 90 km/h. **[Ans.** 37500 kg-m/s]

SHORT ANSWER Type Questions

12. A force of 128 If acts on a mass of 490 g for 10 s. What velocity will it give to the mass?

[**Ans.** 25.6 m/s]

13. A force of 16 N acts on a ball of mass 80 g for 1 μs. Calculate the acceleration and the impulse.

[**Ans.** 200 m/s^2, 1.6×10^{-5} kg-m/s]

14. Two billiard balls each of mass 0.5 kg moving in opposite directions with speed 6 m/s collide and rebound with the same speed. What is the impulse imparted to each ball due to the other?

[**Ans.** 3 kg-m/s]

15. A body of mass 25 kg is moving with a constant velocity of 5 m/s on a horizontal frictionless surface in vacuum. What is the force acting on the body?

[**Ans.** zero]

LONG ANSWER Type I Questions

16. A body of mass 5 kg is acted upon by two perpendicular forces 8 N and 6 N. Find the magnitude and direction of the acceleration.

[**Ans.** 2 m/s^2, Making an angle $\tan^{-1}(4/3)$ from 6 N force]

17. A batsman deflects a ball by an angle of 45° without changing its initial speed, which is equal to 54 km/h. What is the impulse imparted to the ball? Mass of the ball is 0.15 kg. [**Ans.** 4.16 kg-m/s]

18. Earth is rotating frame of reference, even then it is considered as inertial frame of reference for all practical purposes. Explain why?

19. Given the action force, describe the reaction force for each situation.

(i) You push forward on a book with 5.2 N.

[**Ans.** 5.2 N backward]

(ii) A boat exerts a force of 450 N on the water.

[**Ans.** 450 N on the boat]

(iii) A hockey player hits the boards with a force of 180 N toward the boards.

[**Ans.** 180 N on the hockey stick]

LONG ANSWER Type II Questions

20. A hammer weighing 1 kg moving with the speed of 20 m/s strikes the head of a nail driving it 20 cm into a wall. Neglecting the mass of the nail, calculate

(i) the acceleration during the impact

[**Ans.** -2000 m/s^2]

(ii) the time interval during the impact and

[**Ans.** 0.01s]

(iii) the impulse [**Ans.** −20 N]

21. A male astronaut 82 kg and a female astronaut 64 kg are floating side by side in space.

(i) Determine the acceleration of each astronaut if the woman pushes on the man with a force of 16 N (left).

[**Ans.** $a_M = 0.2 \text{ m/s}^2$, $a_W = .25$ m]

(ii) How will your answers change if the man pushes with 16 N (Right) on the woman instead?

[**Ans.** No change]

(iii) How will your answers change if they both reach out and push on each other's shoulders with a force of 16 N?

[**Ans.** $a_M = 2.62 \text{ m/s}^2$, $a_W = 2 \text{ m/s}^2$]

|TOPIC 2 |

Common Forces in Mechanics and Circular Motion

COMMON FORCES IN MECHANICS

In mechanics, we encounter several kinds of forces.

(i) The gravitational force is all pervasive. Every object on the earth experiences the force of gravity due to earth. It is a **non-contact force**.

(ii) All the other forces common in mechanics are **contact forces**. A contact force on an object arises due to contact with some other object solid or fluid.

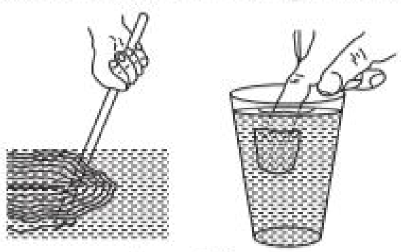
When bodies are in contact (e.g. a book resting on a table, a system of rigid bodies connected by rods), there are mutual contact forces (for each pair of bodies) satisfying the third law of motion.

The component of contact force normal to the surfaces in contact is called **normal reaction**. The component parallel to the surfaces in contact is called **friction**.

(iii) Contact forces arise also when solids are in contact with fluids.

e.g. For a solid immersed in a fluid, there is an upward force exerted by the fluid on the solid which is known as **buoyant force** and it is equal to the weight of the fluid displaced.

The viscous force, (i.e. force opposing the motion of the fluid), air resistance are examples of contact force.



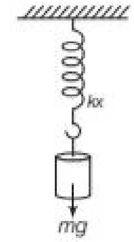
Buoyant force

(iv) Two other common contact forces are tension in the string and force due to spring.

i.e. When a spring is compressed or extended by an external force, a restoring force is generated. This restoring force (F) is usually proportional to the compression and elongation (for small displacements).

It is expressed as $F = kx$, where k is a spring constant and x is the displacement.

Tension force When a body of mass m is fastened with the string, then the weight of the body acts downwards while a force acts just opposite to the downwards force for balancing the downwards force, this force is called **tension.**

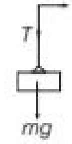


Spring force

$$T = mg$$

where,

g = acceleration due to gravity,
T = tension in the string.



Tension force

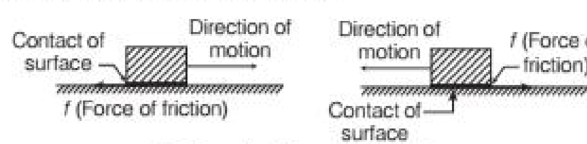
Note

- Gravitational force is the only non-contact force that we use in mechanics.
- If the rope is not light, we will consider its weight as well.

FRICTION

Whenever a body moves or tends to move over the surface of another body, a force comes into play which acts parallel to the surface of contact and opposes the relative motion. This opposing force is called **friction**.

Consider a wooden block placed on a horizontal surface and give it a gentle push. The block slides through a small distance and comes to rest, then according to Newton's second law, a retarding force must be acting on the block. This retarding force or opposing force is called **friction** or **friction force**. As shown in figure, the force of friction always acts tangential to the surface in contact and in a direction opposite to the direction of (relative) motion of the body.



Friction in different directions

TYPES OF FRICTION

There are mainly two types of friction such as

1. Internal Friction

It arises on account of relative motion between two layers of a liquid. Internal friction is also referred as **viscosity** of liquid.

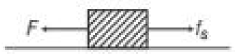
2. External Friction

It arises when two bodies in contact with each other try to move or there is an actual relative motion between the two bodies. This external friction is also called **contact friction**.

Further, external friction is of three types as given below

(i) Static Friction

Let us consider a wooden block placed over a horizontal table. Apply a small force F on it as shown in figure. The block does not move. The force of friction f_s comes into action which balances the applied force F.



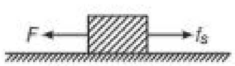
Static friction

Thus, force of friction which comes into play between two bodies before one body actually starts moving over the other is called **static friction** and it is denoted by f_s.

Therefore, static friction opposes the **impending motion** i.e. the motion that would take place under the applied force, if friction were absent. The static friction does not exist by itself. When there is no applied force, there is no static friction. It is a self adjusting force.

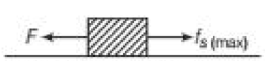
(ii) Limiting Friction

As we increase the applied force on the block, static friction f_s also increases to balance the applied force and the block does not move.



Static friction

Once the applied force is increased beyond a certain limit, the block just begins to move. At this stage, static friction is maximum.



Maximum limiting friction acting on a body

Hence, maximum force of static friction which comes into play when a body just starts moving over the surface of another body is called **limiting friction**. Thus, $f_s \le f_{s\,(\max)}$.

There are four laws of limiting friction such as

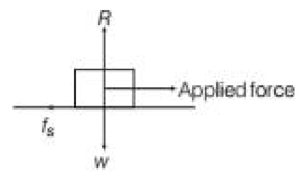
(a) The value of the limiting friction depends upon the nature of the two surfaces in contact and their state of roughness.

(b) The force of limiting friction is tangential (parallel) to the two surfaces in contact and acts opposite to the direction in which the body would start moving on applying the force.

(c) The value of limiting friction is independent of the area of the surface in contact so long as the normal reaction remains the same.

(d) The value of limiting friction $(f_{s(\max)})$ between two given surfaces is directly proportional to the normal reaction (R) between the two surfaces

i.e. $\quad f_{s\,(\max)} \propto R \quad$ or $\quad f_{s\,(\max)} = \mu_s R$



where, $R = w = mg$, m = mass of the block

or $$\mu_s = \frac{f_{s(\max)}}{R} = \frac{\text{Limiting friction}}{\text{Normal reaction}}$$

The proportionality constant μ_s is called **coefficient of static friction**. It is defined as the ratio of limiting friction to the normal reaction.

EXAMPLE |1| A Force Applied on a Sledge

A horizontal force of 980 N is required to slide a sledge weighing 1200 kgf over a flat surface. Calculate the coefficient of friction.

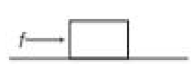
Sol. Given, $f_s = 980$ N, $R = Mg = 1200\,\text{kgf} = 1200 \times 9.8$ N

Now, coefficient of static friction

i.e. $$\mu_s = \frac{f_s}{R} = \frac{980}{1200 \times 9.8} = 0.83$$

EXAMPLE |2| A Force of Friction

A block of mass 2 kg is placed on the floor, the coefficient of static friction is 0.4. A force of 2.5 N is applied on the block as shown in figure. Calculate the force of friction between the block and the floor.



Sol. Here $m = 2$ kg, $\mu_s = 0.4$, $g = 9.8\ m/s^2$

The value of limiting friction

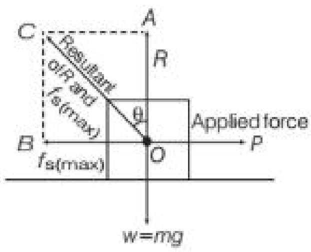
$$F_{s(max)} = \mu_s R = \mu_s\ mg = 0.4 \times 2 \times 9.8 = 7.84\ N$$

As the applied force of 2.5 N is less than the limiting friction (7.84 N), so the block does not move.

In this situation, Force of friction = Applied force = 2.5 N

Angle of Friction

The angle of friction may be defined as the angle which the resultant of the limiting friction and the normal reaction makes with the normal reaction.



In the above figure, OA represents the normal reaction R which balances the weight of the body. OB represents the limiting friction. P is the applied force and OC is the resultant of limiting friction and normal reaction. The angle θ between the normal reaction R and the resultant OC is the angle of friction.

The value of angle of friction depends on the nature of materials of the surfaces in contact and the nature of the surfaces (smooth or rough).

Relation between angle of friction (θ) and coefficient of friction (μ_s).

In ΔAOC, $\tan\theta = \dfrac{AC}{OA} = \dfrac{OB}{OA} = \dfrac{f_{s(max)}}{R}$

But $\dfrac{f_{s(max)}}{R} = \mu_s$ = coefficient of static friction

$\therefore$ $\tan\theta = \mu_s$ or $\theta = \tan^{-1}(\mu_s)$

Hence, **coefficient of static friction is equal to tangent of the angle of friction.**

EXAMPLE |3| Angle of Friction

A force of 49 N is just sufficient to pull a block of wood weighing 10 kg on a rough horizontal surface, so calculate the coefficient of friction and angle of friction.

Sol. Here, F = applied force= 49 N

$m = 10$ kg, $g = 9.8\ m/s^2$

Coefficient of friction, $\mu = \dfrac{F}{R} = \dfrac{F}{mg} = \dfrac{49}{10 \times 9.8} = 0.5$

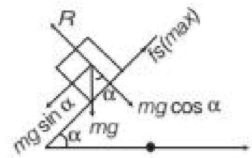
As $\tan\theta = \mu = 0.5$

$\therefore$ $\theta = \tan^{-1}(0.5) = 26°34'$

Angle of Repose

Angle of repose is defined as the minimum angle of inclination of a plane with the horizontal, such that a body placed on the plane just begins to slide down the incline. It is represented by α and its value depends on material and nature of the surfaces in contact.

Consider a body of mass m placed on an inclined plane. The angle of inclination α of the inclined plane is so adjusted that a body placed on it just begins to slide down. Thus, α is the angle of repose the various forces acting on the body are



(i) The weight mg of the body acting vertically downwards.

(ii) The limiting friction $f_{s(max)}$ acting along the inclined plane in the upward direction. It balances the component $mg\sin\alpha$ of the weight mg perpendicular to the inclined plane. Thus,

$$f_{s(max)} = mg\sin\alpha \qquad \ldots(i)$$

(iii) The normal reaction R acting at right angle to the inclined plane in the upward direction. It balances the weight $mg\cos\alpha$ of the weight mg perpendicular to the inclined plane. Thus

$$R = mg\cos\alpha \qquad \ldots(ii)$$

Dividing the Eq. (i) by Eq. (ii), we get

$$\frac{f_{s\ (max)}}{R} = \frac{mg\sin\alpha}{mg\cos\alpha}$$

or $\mu_s = \tan\alpha$

Thus, the coefficient of static friction is equal to the tangent of the angle of repose.

As $\mu_s = \tan\theta = \tan\alpha$

$\therefore$ $\theta = \alpha$

Thus, the angle of friction is equal to the angle of repose.

(iii) Kinetic Friction

When we increase the applied force slightly beyond limiting friction, the actual motion starts and force of friction decreases. This means that the applied force is now greater than the force of limiting friction. The force of friction at this stage is called **kinetic friction** or **dynamic friction** which is actually a little bit less than the value of limiting friction.

Hence, kinetic friction or dynamic friction is the opposing force that comes into play when one body is actually moving over the surface of another body. Thus, kinetic friction opposes the **relative motion**.

There are four laws of kinetic friction such as

(a) The kinetic friction opposes the relative motion and has a constant value which depends on the nature of two surfaces in contact.

(b) The value of kinetic friction f_k is independent of the area of contact so long as the normal reaction remains the same.

(c) The kinetic friction does not depend on velocity.

(d) The value of kinetic friction f_k is directly proportional to the normal reaction R between the two surfaces.

i.e. $f_k \propto R$

or $f_k = \mu_k R$

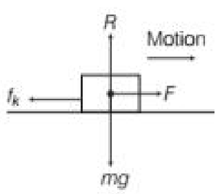
$$\mu_k = \frac{f_k}{R} = \frac{\text{Kinetic friction}}{\text{Normal reaction}}$$

The proportionality constant μ_k is called **coefficient of kinetic friction** and it is defined as the ratio of kinetic friction to the normal reaction.

Note

- This can be shown as $f_k < f_{s(max)}$ or $\mu_k R < \mu_s R$
  $\therefore \quad \mu_k < \mu_s$
- Thus, the coefficient of kinetic friction is less than the coefficient of static friction.

EXAMPLE |4| Coefficient of Kinetic Friction



A hockey puck is given an initial speed of 20 m/s on a frozen pond as shown in figure. The puck remains on the ice and slides 120 m before coming to rest. Determine the coefficient of kinetic friction between the puck and the ice.

After the puck is given an initial velocity, the external forces acting on it are the weight mg, the normal force R and the force of kinetic friction f_k. The acceleration of the puck can be found from $v^2 = u^2 + 2ax$, with the final speed v equal to zero because after 120 m the puck comes to rest.

Sol. Given,

The initial speed, $u = 20$ m/s

Distance travelled, $x = 120$ m

$$v^2 = u^2 + 2ax \qquad \text{[third equation of motion]}$$

$$0 = (20\text{ m/s})^2 + 2a\,(120\text{ m})$$

$$a = -1.67\text{ m/s}^2$$

The negative sign shows that the acceleration is towards left, i.e. opposite the direction of the velocity.

$$\Sigma F_y = R - w = 0 \Rightarrow R = w = mg$$

Thus, $\quad f_k = \mu_k R = \mu_k mg$

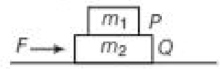
$$\Sigma F_x = -f_k = ma$$

$$\Rightarrow \quad \mu_k mg = m\,(-1.67\text{ m/s}^2)$$

$$\mu_k = \frac{1.67\text{ m/s}^2}{9.80\text{ m/s}^2} = 0.170$$

EXAMPLE |5| Force on the Block

A block P of mass 4 kg is placed on another block Q of mass 5 kg, and the block Q rests on a smooth horizontal table. For sliding block P on Q, horizontal force of 12 N is required to be applied on P. How much maximum force can applied on Q so that both P and Q move together? Also, find out acceleration produced by this force.



Sol. Here, $m_1 = 4$ kg, $m_2 = 5$ kg

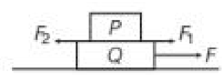
Force applied on block $P = 12$ N

This force must be equal to the kinetic friction applied on P by Q.

$\therefore \quad 12 = F_k = \mu_k R = \mu_k m_1 g$

or $\quad 12 = \mu_k \times 4g \;$ or $\; \mu_k = \dfrac{12}{4g} = \dfrac{3}{g}$

acceleration of $P = \dfrac{12}{4} = 3$ m/s



When force F is applied on Q to create common motion in P & Q, the forces created (friction) is shown in the diagram above. F_1 force will be created on P and F_2 force will be created on Q.

Considering forces on Q, we have

$$F - F_2 \text{ (net force)} = m_2 \times a = m_2 \times 3$$

Since, $F_1 = F_2 = \mu_1 m_1 g$

$$F - \mu_k m_1 g = m_2 \times 3$$

$$F = \mu_k m_1 g + m_2 \times 3 = \frac{3}{g} \times 4 \times g + 5 \times 3 = 12 + 15 = 27\text{ N}$$

As this force moves both the blocks together on a smooth table, so the acceleration produced is

$$a = \frac{F}{m_1 + m_2} = \frac{27}{4+5} = 3\text{ m/s}$$

EXAMPLE |6| Kinetic Friction Between Deck and the Disc

Consider a shuffleboard cue which is being used by a cruiseship passenger. To push the shuffleboard disc of mass 0.50 kg horizontally along the deck so that the disc leaves the cue with a speed of 6 m/s, what will be the coefficient of kinetic friction between the deck and the disc if the disc slides a distance of 10 m before coming to rest?

When the disc is separated from the cue, the force of kinetic friction is the only horizontal force acting on the disc. Since, the frictional force is constant, the acceleration is also constant.

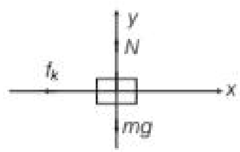
Sol. $\because$ Mass of the disc, $m = 0.50$ kg

Initial velocity, $u = 6$ m/s

Displacement, $x = 10$ m

Coefficient of kinetic friction, $\mu_k = ?$

Draw a FBD for the disc after it leaves the cue.



Apply $\sum F_y = ma_y$ to the disc and solve for normal reaction N.

$$\sum F_y = ma_y$$
$$N - mg = 0$$
$$N = mg = 0.5 \times 9.8 = 4.9 \text{ N}$$

The kinetic friction f_k can be found out by using the equation given below $f_k = \mu_k mg$

Now, apply $\sum F_x = ma_x$ to the disc and solve for a_x.

$$-f_k = ma_x \quad \text{or} \quad -\mu_k mg = ma_x$$
$$a_x = -\mu_k g$$

Now, use the third equation of motion.

$$v^2 = u^2 + 2ax \quad 0 = 6^2 + 2(-\mu_k g)10$$
$$\mu_k = \frac{36}{2 \times 9.8 \times 10} = \frac{36}{196} = 0.184$$

Types of Kinetic Friction

(i) Sliding Friction

The force of friction that comes into play when a body slides over the surface of another body is called **sliding friction**.

e.g. When a flat block is moved over the flat surface of a table, then the opposing force acting on it is known as sliding friction.

Laws of sliding friction are

(a) The sliding friction opposes the applied force and has a constant value, depending upon the nature of the two surfaces in relative motion.

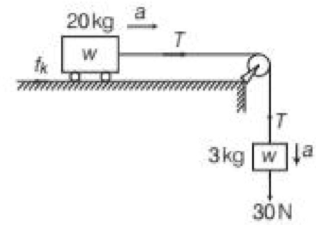
(b) The force of sliding friction is directly proportional to the normal reaction R.

(c) The sliding frictional force is independent of the area of the contact between the two surfaces so long as the normal reactions remain the same.

(d) The sliding friction does not depend upon the velocity.

EXAMPLE |7| Enjoy the Ride of a Trolley

What is the acceleration of the block and trolley system shown in a figure. If the coefficient of kinetic friction between the trolley and the surface is 0.04, what is the tension in the string? (take $g = 10 \text{ ms}^{-2}$). Neglect the mass of the string. **[NCERT]**



As the string is inextensible and the pulley is smooth, the 3 kg block and the 20 kg trolley both have same magnitude of acceleration.

Sol. Applying the second law of motion to the block.

$$30 - T = 3a \quad \text{...(i)}$$

Apply the second law of motion to the trolley.

$$T - f_k = 20a$$

Now, $f_k = \mu_k R = \mu_k mg$

Here, $\mu_k = 0.04$

$$f_k = 0.04 \times 20 \times 10 = 8 \text{ N}$$

Thus, the equation for the motion of the trolley is

$$T - 8 = 20a \quad \text{...(ii)}$$

On adding Eqs.(i) and (ii), we get

$$22 = 23a$$

or $a = \frac{22}{23} = 0.96 \text{ m/s}^2$

From Eq. (i),

$$30 - T = 3 \times 0.96$$
$$T = 30 - 2.88 = 27.12 \text{ N}$$

(ii) Rolling Friction

The force of friction that comes into play when a body rolls over the surface of another body is called **rolling friction**. e.g. When a wheel, circular disc or a ring or a sphere or a cylinder roll over a surface, the force that opposes it is the rolling friction.

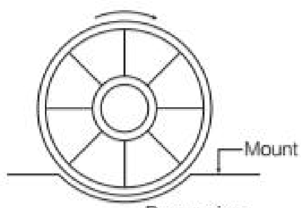
When a wheel rolls without slipping over a horizontal plane, the surfaces at contact do not rub each other. The relative velocity of the point of contact of the wheel with respect to the plane is zero, if there is no slipping. There is no sliding or static friction in such an ideal situation.

We need to overcome rolling friction only which is much smaller than sliding friction. For this reason, wheel has been considered as one of the greatest inventions. It conversly sliding into rolling friction thus lowers friction.

Cause of Rolling Friction Let us consider a wheel rolling along a road. As the wheel rolls, it exerts a large pressure due to its small area.

This causes a depression in the surface below and a mount or bump in front of it is shown in figure. In addition to this, the rolling wheel has a continuously detach itself from the surface on which it rolls. This is opposed by the adhesive force between the two surfaces in contact.

On account of these factors, a force originates which retards the rolling motion. This retarding force is known as **rolling friction**.



Cause of rolling friction

Ways for Reducing Friction

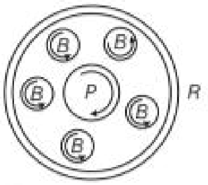
The various ways of reducing friction are

(i) **Lubrication** They are used to reduce kinetic friction in a machine. Lubricants like oil, grease, etc. fill the irregularities of the surface to make them smoothers. Thus, friction decreases.

(ii) **Polishing** They are used to make the surface smoother.

(iii) **Ball Bearing** The ball bearing arrangement consists of two co-axial cylinders P and R between which suitable number of hard steel balls are arranged. When the wheel rotates the ball B rotates in the direction as shown.

The wheel thus rolls on the balls instead of sliding on the axle. Thus, power dissipation is reduced.



Ball bearing arrangement

(*iv*) A thin cushion of air maintained between solid surfaces in relative motion.

(*v*) **Streamlining** Friction due to air is considerably reduced by streamlining the shape of the body moving through air.

DYNAMICS OF CIRCULAR MOTION

Earlier, we have studied that acceleration of a body moving in a circle of radius r with uniform speed v is $\frac{v^2}{r}$ directed towards the centre. From second law of motion, the force F_c is given by

$$\text{Centripetal force, } F_c = \frac{mv^2}{r}$$

where, m is the mass of the body. This force directed forward the centre is called **centripetal force**.

But $\frac{v^2}{r}$ is centripetal acceleration or radial acceleration.

$$\therefore \quad \boxed{\text{Centripetal force, } F_c = mr\omega^2} \qquad [\because v = \omega r]$$

For a stone rotated in a circle by a string, the centripetal force is provided by the tension in the string.

The centripetal force for motion of a planet around the sun is the gravitation force on the planet due to the sun.

For a car taking a circular turn on a horizontal road, the centripetal is the force of friction.

EXAMPLE |8| Check out the Revolving Satellite

An artificial satellite of mass 2500 kg is orbiting around the earth with a speed of $4\ \text{kms}^{-1}$ at a distance of 10^4 km from the earth. Calculate the centripetal force acting on it.

Sol. Given, $r = 10^4\ \text{km} = 10^4 \times 1000\ \text{m} = 10^7\ \text{m}$,

$m = 2500$ kg,

$v = 4\ \text{kms}^{-1} = 4 \times 10^3\ \text{ms}^{-1}$

Now, centripetal force is $F = \frac{mv^2}{r}$

$$F = \frac{2500 \times (4 \times 10^3)^2}{10^7} = \frac{2500 \times 16 \times 10^6}{10^7}$$

$$F = \frac{250 \times 16 \times 10^7}{10^7} = 4000\ \text{N}$$

Interesting Applications of Laws of Motion

The circular motion of a car on a flat and banked road are explained below

(i) Circular Motion of a Car on Level Road

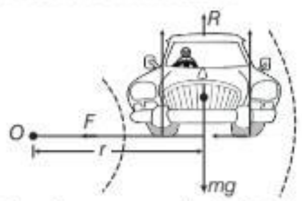
When a vehicle goes round a curved road, it requires some centripetal force. While rounding the curve, the wheels of the vehicle have a tendency to leave the curved path and regain the straight line path. The force of friction between the road and the tyres provided the centripetal force required to keep the car in motion around the curve.

There are three forces acting on the car such as

(i) The weight of the car mg, acting vertically downwards.

(ii) Normal reaction R of the road on the car, acting vertically upwards.

(iii) Frictional force F, along the surface of the road, i.e. towards the centre of the turn.



Motion of a car on a circular level road

Let us consider a car of weight mg going around a circular level road of radius r with velocity v as shown in figure. While taking the turn, the tyres of the car tend to leave the road and go away from the centre of the curve.

The force of friction F is acting on the tyre and R is the normal reaction of the ground.

As there is no acceleration in the vertical direction, then

$$R - mg = 0 \Rightarrow R = mg$$

For circular motion, the centripetal force is along the surface of the road towards the centre of the turn. The static friction opposes the impending motion of the car moving away from the circle. Thus, $\frac{mv^2}{r} \le F$

where v is the velocity of car while turning and r is the radius of the circular track.

As, $F = \mu_s R = \mu_s mg$

F is limiting friction here to get maximum velocity possible of car

where, μ_s is the coefficient of static friction between the tyres and the road.

$$\therefore \quad \frac{mv^2}{r} \le \mu_s mg \Rightarrow v \le \sqrt{\mu_s rg}$$

or Maximum velocity of the vehicle, $v_{max} = \sqrt{\mu_s rg}$

Hence, the maximum velocity with which a vehicle can go round a level curve without skidding is

$$v = \sqrt{\mu_s rg}.$$

EXAMPLE |9| Rounding off a Flat Curve

A bend in a level road has a radius of 100 m. Find the maximum speed which a car turning this bend may have without skidding, if the coefficient of friction between the tyres and road is 0.8.

Sol. The maximum speed which the car can have without skidding is given by

$$\mu = \frac{v^2}{rg} \Rightarrow v = \sqrt{\mu rg}$$

Here, $r = 100\text{ m}, \mu = 0.8, g = 9.8\text{ ms}^{-2}$

$$v = \sqrt{0.8 \times 100 \times 9.8} = \sqrt{4 \times 2 \times 2 \times 49}$$

$$v = 2 \times 2 \times 7 = 28\text{ m/s}$$

EXAMPLE |10| Cyclist Slip on Turn

A cyclist speeding at 18 km/h on a level road takes a sharp circular turn of radius 3m without reducing the speed. The coefficient of static friction between the tyres and the road is 0.1. Will the cyclist slip while taking the turn? **[NCERT]**

Sol. Here, $v = 18\text{ km/h} = \frac{18 \times 1000}{60 \times 60} = 5\text{ m/s}$

$r = 3\text{ m}, \mu_s = 0.1$

On a level road, frictional force alone can provide the centripetal force.

Therefore, condition for the cyclist not to slip is that

$$\frac{mv^2}{r} \le F_s \ (= \mu_s R = \mu_s \text{ mg}); \ v^2 \le \mu_s rg$$

As $v^2 = (5)^2 = 25\text{ m}^2\text{s}^{-2}$

and $\mu_s rg = 0.1 \times 3 \times 10 = 3\text{ m}^2\text{s}^{-2}$

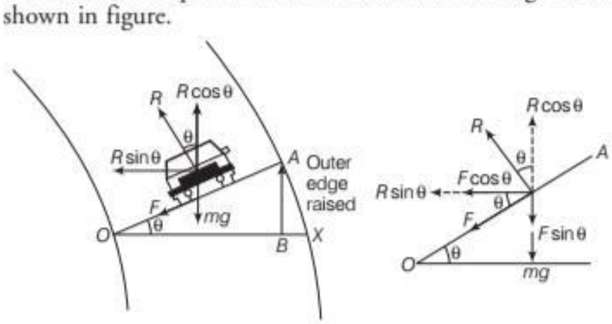
$\therefore$ The condition is not satisfied. Hence, the cyclist will slip.

(ii) Motion of a Car on a Banked Road

The large amount of friction between the tyres and the road produces considerable wear and tear of the tyres. To avoid this, the curved road is given an inclined sloping upwards towards the outer circumference. This reduces wearing out of the tyres because the horizontal component of normal reaction provides the necessary centripetal force.

The system of raising the outer edge of a curved road above its inner edge is called **banking of the curved road.** So, the angle through which the outer edge of the curved road is raised above the inner edge is called **angle of banking.**

Let us consider a car of weight mg going along a curved path of radius r with speed v on a road banked at an angle θ, as shown in figure.



Circular motion of a car on a banked road

The forces acting on the car are

(i) Weight mg acting vertically downwards.

(ii) Normal reaction R acting upwards in a direction perpendicular to inclined plane making angle θ with the horizontal plane.

(iii) Force of friction F acting downwards along the inclined plane because car tends to slip outwards.

Reaction R can be resolved into two rectangular components

(i) $R\cos\theta$, along vertically upward direction.

(ii) $R\sin\theta$, along the horizontal towards the centre of the curved road .

Force of friction F, can also be resolved into two rectangular components.

(i) $F\cos\theta$, along the horizontal, towards the centre of curved road.

(ii) $F\sin\theta$, along vertically downward direction.

Since, there is no motion along vertical, so

$$R\cos\theta = mg + F\sin\theta \qquad \ldots\text{(i)}$$

Let v is velocity of the car. The centripetal force is now provided by the components $R\sin\theta$ and $F\cos\theta$, i.e.

$$R\sin\theta + F\cos\theta = \frac{mv^2}{r} \qquad \ldots\text{(ii)}$$

We know $F = \mu_s R$, then we can write Eqs. (i) and (ii) as

$$R\cos\theta = mg + \mu_s R\sin\theta \qquad \ldots\text{(iii)}$$

and $$R\sin\theta + \mu_s R\cos\theta = \frac{mv^2}{r} \qquad \ldots\text{(iv)}$$

From Eq. (iii), we get

or $$R\cos\theta - \mu_s R\cdot\sin\theta = mg$$

or $$R(\cos\theta - \mu_s\sin\theta) = mg$$

or $$R = \frac{mg}{\cos\theta - \mu_s\sin\theta} \qquad \ldots\text{(v)}$$

From Eq. (iv), we get

$$R(\sin\theta + \mu_s\cos\theta) = \frac{mv^2}{r} \qquad \ldots\text{(vi)}$$

From Eq. (v) and (vi), we get

$$\frac{mg(\sin\theta + \mu_s\cos\theta)}{\cos\theta - \mu_s\sin\theta} = \frac{mv^2}{r}$$

$\therefore$ $$v^2 = \frac{rg(\sin\theta + \mu_s\cos\theta)}{(\cos\theta - \mu_s\sin\theta)}$$

$$v^2 = \frac{rg\cos\theta\left(\dfrac{\sin\theta}{\cos\theta} + \dfrac{\mu_s\cos\theta}{\cos\theta}\right)}{\cos\theta\left(\dfrac{\cos\theta}{\cos\theta} - \mu_s\dfrac{\sin\theta}{\cos\theta}\right)}$$

$$v^2 = \frac{rg\cos\theta(\tan\theta + \mu_s)}{\cos\theta(1 - \mu_s\tan\theta)}$$

$$v^2 = \frac{rg(\tan\theta + \mu_s)}{(1 - \mu_s\tan\theta)}$$

Maximum velocity of vehicle on banked road, $$v = \sqrt{\frac{rg(\mu_s + \tan\theta)}{(1 - \mu_s\tan\theta)}} \qquad \ldots\text{(vii)}$$

Special case When there is no friction between the road and the tyres, then the safe limit for maximum velocity is $\mu_s = 0$,

Substituting the value of μ_s in Eq. (vii), we get

$$v = \sqrt{\frac{rg(0 + \tan\theta)}{1 - (0 \times \tan\theta)}}$$

$$v = \sqrt{rg\tan\theta} \qquad \ldots\text{(viii)}$$

This is the speed at which car does not slide down even if, track is smooth. If track is smooth and speed is less than $\sqrt{rg\tan\theta}$, vehicle will move down so that r gets decreased and if speed is more than this vehicle will move up.

The angle of banking θ for minimum wear and tear of tyres is given by Eq. (viii), we get

$$\tan\theta = \frac{v^2}{rg} \quad \text{or} \quad \boxed{\text{Angle of banking, } \theta = \tan^{-1}\left(\frac{v^2}{rg}\right)}$$

EXAMPLE |11| Formula One Racing Track

A circular race track of radius 300 m is banked at angle of 15°. If the coefficient of friction between the wheels of a race car and the road is 0.2, what is the (i) optimum speed of the race car to avoid wear and tear on its tyres and (ii) maximum permissible speed to avoid slipping?

[tan 15° = 0.2679] **[NCERT]**

On a banked road, the horizontal component of the normal force and the frictional force contribute to provide centripetal force to keep the car moving on a circular turn without slipping. At the optimum speed, the normal reaction's component is enough to provide the needed centripetal force and the frictional force is not needed. Friction force increases the slope of increasing the velocity on banked surface.

Sol. The optimum speed v_o is given by equation

$$v_o = (R\,g\tan\theta)^{1/2}$$

Here, $R = 300$ m, $\theta = 15°$, $g = 9.8\ \text{ms}^{-2}$, $\mu_s = 0.2$,

We have

$$v_o = 28.1\ \text{m s}^{-1}$$

The maximum permissible speed v_{max} is given by equation.

$$v_{max} = \left(Rg \frac{\mu_s + \tan\theta}{1 - \mu_s \tan\theta} \right)^{1/2}$$

$$v_{max} = \left(\frac{300 \times 9.8 \times (0.2 + \tan 15^\circ)}{1 - (0.2 \times \tan 15^\circ)} \right)^{1/2}$$

$$v_{max} = \left(\frac{2940 \times (0.4679)}{0.9464} \right)^{1/2}$$

$$= (1453.535)^{1/2} = 38.1 \text{ ms}^{-1}$$

EXAMPLE |12| Train goes over Circular Path

The radius of curvature of a railway track at a place, where the train is moving at a speed of 72 kmh^{-1} is 625 m. The distance between the rails is 1.5 m. Find the angle and the elevation of the out rail so that there may be no side pressure on the rails. Take, $g = 9.8 \text{ m/s}^2$

$[\tan^{-1} (0.00653) = 3.74^\circ, \ \sin 3.74^\circ = 0.06522]$

Sol. Here, $r = 625$ m, $v = 72 \text{ kmh}^{-1}$

$$v = 72 \times \frac{5}{18} \text{ m/s}$$

$$v = 20 \text{ m/s}, \ g = 9.8 \text{ m/s}^2, \ l = 1.5 \text{ m}$$

Now, angle of elevation of outer rail

i.e $\quad . \tan\theta = \dfrac{v^2}{rg}$

$$\tan\theta = \frac{20 \times 20}{625 \times 9.8} = .00653$$

$$\theta \ \tan^{-1} = (0.00653)$$

$$\theta = 3.74^\circ$$

Also, elevation of outer rail $h = l \sin\theta$

$$h = 1.5 \sin 3.74^\circ$$

$$h = 0.0978 \text{ m} = 9.78 \text{ cm}$$

EXAMPLE |13| Banked Curve

If a car having speed 50 km/h can round the curve banked at an angle θ. Find out the value of θ, if radius of the curve is 40 m and consider the friction is negligible. $[\tan^{-1}(0.5) = 26.5]$

In the given case, only two forces act on the car i.e. gravity and the normal force. Since, the car is travelling in a circle at constant speed, the acceleration is in the centripetal direction. The vector sum of the two forces is in the direction of the acceleration.

Sol. Write the given quantity and the quantity to be known.

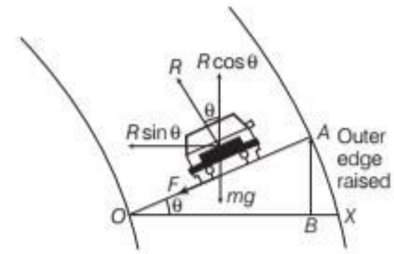
$$v = 50 \text{ km/h} = 50 \times \frac{5}{18} \text{ m/s} = 13.88 \text{ m/s}$$

$$r = 40 \text{ m}, \ \theta = ?$$

Draw the FBD of the car.

Now, apply $\sum F_g$ = may to the car

$$R\cos\theta - mg = 0 \ \Rightarrow \ R = \frac{mg}{\cos\theta}$$



Similarly, apply $\sum F_x = ma_x$ to the car

$$R\sin\theta = \frac{mv^2}{r}$$

Put the value of R and then solve for θ.

$$\frac{mg}{\cos\theta} \cdot \sin\theta = \frac{mv^2}{r}$$

$$\Rightarrow \quad \tan\theta = \frac{v^2}{rg}; \theta = \tan^{-1}\left(\frac{v^2}{rg}\right)$$

Put the all given values to get θ.

$$\theta = \tan^{-1}\left[\frac{(13.88)^2}{40 \times 9.8}\right] = \tan^{-1}(0.4917)$$

$$\theta = 26.18^\circ$$

Solving Problems in Mechanics

A typical problem in mechanics usually does not merely involve a single body under the action of given forces. More often, we will need to consider an assembly of different bodies exerting forces on each other. Besides, each body in the assembly experiences the force of gravity. To solve a typical problem in mechanics, we use the following steps

- Draw a diagram showing schematically the various parts of the assembly of bodies, the links, supports, etc.
- Choose a convenient part of the assembly as one system.
- Draw a separate diagram which shows this system and all the forces on the system by the remaining part of the assembly. Also include the forces on the system by other agencies. A diagram of this type is known as **free body diagram**.
- In free body diagram, mark the magnitude and direction of the forces that are either given or you are sure of and the rest should be treated as unknowns to be determined using laws of motion.
- If necessary, we can follow the same procedure for any other part of the system. The equations of laws of motion obtain for different parts of the system can be solved to obtain the desired results.

EXAMPLE |14| Action-reaction Pairs

A wooden block of mass 2 kg rests on a soft horizontal floor. When an iron cylinder of mass 25 kg is placed on top of the block, the floor yields steadily and the block and the cylinder together go down with an acceleration of 0.1 m/s^2. What is the action of the block on the floor (i) before and (ii) after the floor yields? Take $g = 10 \text{ m/s}^2$. Identify the action-reaction pairs in the problem. **[NCERT]**

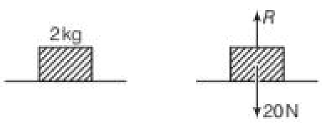
Sol. $\because$ Mass of the block = 2 kg

Mass of the cylinder = 25 kg

Acceleration of the system = 0.1 m/s^2

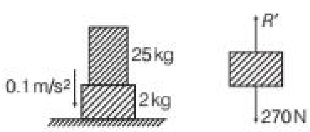
$$g = 10 \text{ m/s}^2$$

The force of gravitational attraction of the earth, i.e. weight of the block is equal to mg.



$$w = mg \Rightarrow w = 2 \times 10 \Rightarrow w = 20 \text{ N}$$

According to Newton's first law, net force on the block is zero, i.e. $R = 20$ N



Force of gravity due to the earth, i.e.

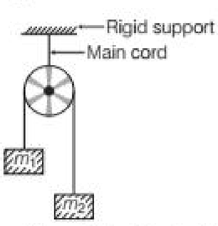
$$w = mg = (25 + 2) \times 10 = 270 \text{ N}$$

$$270 - R' = 27 \times 0.1$$

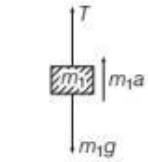
$$\Rightarrow \quad R' = 270 - 2.7 = 267.3 \text{ N}$$

EXAMPLE |15| Pulley-block System

Consider two masses m_1 and m_2 connected by a light and inextensible string passing over a smooth light pulley which is fixed by a rigid cord, from a rigid support as shown in figure. This device is also known as Atwood's machine. Find the tension in the rope and acceleration of each block.

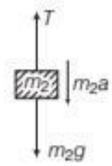


Sol. To study the motion of the blocks, let us draw the free body diagram (FBD) of various parts of the system, by assuming $m_2 > m_1$. FBD and dynamics of block m_1



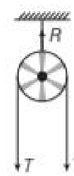
$$T - m_1 g = m_1 a \quad \text{...(i)}$$

FBD and dynamics of block m_2,



$$m_2 g - T = m_2 a \quad \text{...(ii)}$$

FBD of pulley



$$R - 2T = 0 \quad \text{...(iii)}$$

where, R is reaction on the axle of pulley. Since, pulley is fixed, therefore, $a = 0$ for it.

From the solution of simultaneous Eqs. (i), (ii) and (iii) we get, the value of acceleration a, tension T and pressure R on the axle of pulley.

Thus, from adding Eqs. (i) and (ii), we get acceleration a

$$T - m_1 g = m_1 a$$

and $$m_2 g - T = m_2 a$$

or $$T - m_1 g + m_2 g - T = m_1 a + m_2 a$$

$$m_2 g - m_1 g = a(m_1 + m_2)$$

or $$a = \frac{(m_2 - m_1) g}{(m_1 + m_2)} \quad \text{...(iv)}$$

On substituting a in Eqs. (i) or (ii), we get

$$T = \left(\frac{2 m_1 m_2 g}{m_1 + m_2} \right) \quad \text{...(v)}$$

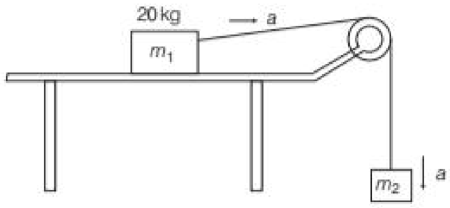
and pressure on pulley from Eq. (iii), we get

$$R = 2T$$

$$R = 2 \times \frac{2 m_1 m_2 g}{m_1 + m_2} = \frac{4 m_1 m_2 g}{m_1 + m_2} \quad \text{...(vi)}$$

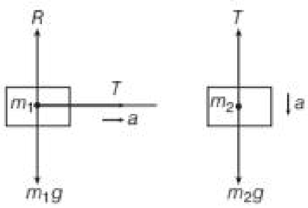
EXAMPLE |16| Motion of Two Bodies

A body of mass m_1 equal to 20 kg is placed on a smooth horizontal table. This body is connected to a string which passes over a frictionless pulley. The string also carries another body of mass m_2 equal to 10 kg at the other end. Find out the acceleration which will be produced when the nail fixed on the table is removed, also find out the tension in the string during the motion of the bodies. What is the result, when the bodies stop? Take $g = 10$ N/kg.



Sol. When the nail fixed on the table is removed, system of two bodies moves with an acceleration a in the forward direction. The acceleration can be found by using Newton's second law.

Draw the FBD for each body as shown in the figure



For mass m_1,

$$T = m_1 a \quad \text{...(i)}$$

For mass m_2,

$$m_2 g - T = m_2 a \quad \text{...(ii)}$$

Adding Eqs. (i) and (ii), we get

$$m_1 a + m_2 a = m_2 g$$

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

$$= \frac{10 \times 10}{20 + 10} = \frac{100}{30}$$

$$= 3.33 \text{ m/s}^2$$

Tension, $T = m_1 a = 10 \times 3.33 = 33.3$ N

When the bodies stop, acceleration, a will be zero. Suppose, the tension becomes T. As the net force on each body is zero, so for body m_2

$$T = m_2 g$$

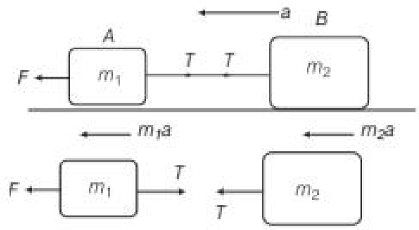
$$= 10 \times 10$$

$$= 100 \text{ N}$$

EXAMPLE |17| Connected Bodies

Two bodies of masses 10 kg and 20 kg respectively kept on a smooth, horizontal surface are tied to the ends of a light string. A horizontal force $F = 600$ N is applied to (i) A, (ii) B along the direction of string. What is the tension in the string in each case? **[NCERT]**

Sol. (*i*) **When force is applied on** A, then



$\because$ Mass of body $A\ (m_1) = 10$ kg

Mass of body $B\ (m_2) = 20$ kg

Force applied $(F) = 600$ N

For body A, $F - T = m_1 a$ ...(i)

For body B, $T = m_2 a$ ...(ii)

Adding Eqs. (i) and (ii), we get

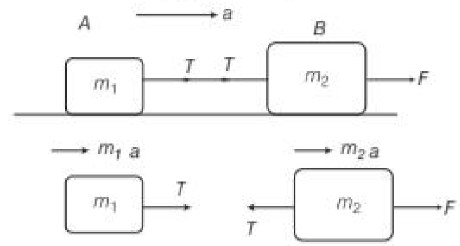
$$F = (m_1 + m_2)a$$

or $$a = \frac{F}{m_1 + m_2} = \frac{600}{(10 + 20)} = 20 \text{ m/s}^2$$

Substituting value of a in Eq. (ii), we get

$$T = m_2 a = 20 \times 20 \text{ N} = 400 \text{ N}$$

(*ii*) **When force is applied on** B, then



For body A, $T = m_1 a$ ...(iii)

For body B, $F - T = m_2 a$ ...(iv)

Adding Eqs. (iii) and (iv), we get

$$F = (m_1 + m_2)a$$

or $$a = \frac{F}{m_1 + m_2}$$

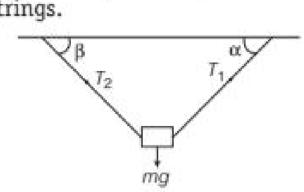
$$= \frac{600}{10 + 20} = 20 \text{ m/s}^2$$

Substituting the value of a in Eq. (iii), we get

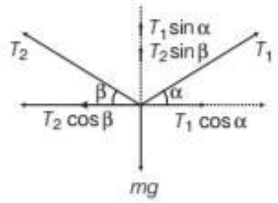
$$T = m_1 a = 10 \times 20 = 200 \text{ N}$$

EXAMPLE |18| Tension in the Strings

Consider the body of mass m is suspended by two strings making angles α and β with the horizontal as shown in figure. If the body is in equilibrium, then find out the tension in the strings.



Sol. Draw the free body diagram firstly as shown in figure. Mention all the horizontal and vertical components of tensions T_1 and T_2.



As the body is in equilibrium, the various forces must add to zero. Taking horizontal components of forces.

$$T_1 \cos \alpha = T_2 \cos \beta$$

$$\Rightarrow \quad T_2 = T_1 \frac{\cos \alpha}{\cos \beta}$$

Now, taking the vertical components of forces.

$$T_1 \sin \alpha + T_2 \sin \beta = mg$$

$$T_1 \sin \alpha + T_1 \frac{\cos \alpha}{\cos \beta} \sin \beta = mg$$

Now, solve the equations for T_1 to find out the value of T_1.

$$T_1 = \frac{mg}{\sin \alpha + \frac{\cos \alpha}{\cos \beta} \sin \beta}$$

$$= \frac{mg \cos \beta}{\sin \alpha \cos \beta + \cos \alpha \sin \beta}$$

$$\therefore \quad T_1 = \frac{mg \cos \beta}{\sin (\alpha + \beta)}$$

$$[\because \sin(A+B) = \sin A \cos B + \cos A \sin B]$$

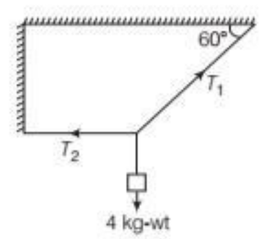
Now, find out the value of T_2 by using above equation.

$$T_2 = T_1 \frac{\cos \alpha}{\cos \beta} = \frac{mg \cos \beta}{\sin (\alpha + \beta)} \times \frac{\cos \alpha}{\cos \beta}$$

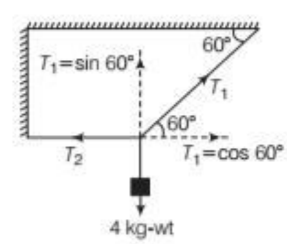
$$= \frac{mg \cos \alpha}{\sin (\alpha + \beta)}$$

EXAMPLE |19| Tension in the Strings

Determine the tensions T_1 and T_2 in the strings as shown in the figure.



Sol. We redraw the above figure



While resolving the tension T_1 along horizontal and vertical directions. As, in equilibrium,

$$T_1 \sin 60° = 4 \text{kg-wt} = 4 \times 9.8 \text{N} \quad \text{...(i)}$$

$$T_1 \cos 60° = T_2 \quad \text{...(ii)}$$

Solving Eq. (i), we get

$$T_1 = \frac{4 \times 9.8}{\sin 60°} = 45.26 \text{N}$$

Solving Eq. (ii), we get

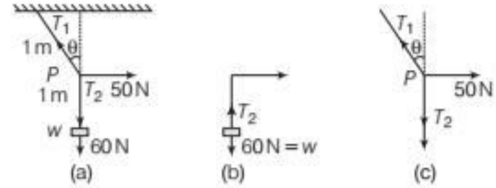
$$T_2 = T_1 \cos 60°$$

$$= 45.26 \times 0.5$$

$$= 22.63 \text{N}$$

EXAMPLE |20| Horizontal Force Applied on Rope Hanging Vertically

See in figure a mass of 6 kg is suspended by a rope of length 2 m from the ceiling. A force of 50 N in the horizontal direction is applied at the mid-point P of the rope as shown. What is the angle, the rope makes with the vertical in equilibrium? (Take $g = 10 \text{ ms}^{-2}$). Neglect the mass of the rope. **[NCERT]**



Sol. Fig. (b) is the free body diagram of w and Fig. (c) is the free body diagram of point P.

Consider the equilibrium of the weight w. Clearly,

$$T_2 = 6 \times 10 = 60 \text{N}$$

Consider the equilibrium of the point P under the action of three forces, the tensions T_1 and T_2 and the horizontal force 50 N. The horizontal and vertical components of the resultant force must vanish separately.

$$T_1 \cos \theta = T_2 = 60 \text{N}$$

and

$$T_1 \sin \theta = 50 \text{N}$$

Which gives that $\tan \theta = \frac{5}{6}$

or

$$\theta = \tan^{-1}\left(\frac{5}{6}\right) = 40°$$

TOPIC PRACTICE 2

OBJECTIVE Type Questions

1. Which force is dissipative force?

(a) Electrostatic force (b) Magnetic force
(c) Gravitational force (d) Frictional force

Sol. (d) Frictional force is a non-conservative force because work done by it is dissipated (wasted) as heat energy. This is not the case with other forces.

2. A trolley is carrying a box on its surface having coefficient of static friction equal to 0.3. Now the trolley starts moving with increasing acceleration. Find the maximum acceleration of the trolley so that the box does not slide back on the trolley.

(a) 2 ms^{-2} (b) 3 ms^{-2}
(c) 4 ms^{-2} (d) 5 ms^{-2}

Sol. (b) As trolley accelerates forward, a pseudo force acts on the box in reverse. It prevents its slippage in backward direction, as friction starts acting on it. But as friction can be increased to a maximum value of μmg. So maximum acceleration that is possible for block before it starts slipping $= \mu g = 0.3 \times 10 = 3\ ms^{-2}$

3. If a car is moving in uniform circular motion, then what should be the value of velocity of a car, so that car will not moving away from the circle,

(a) $v < \sqrt{\mu_s Rg}$ (b) $v \le \sqrt{\mu_s Rg}$
(c) $v < \sqrt{\mu_k Rg}$ (d) None of these

Sol. (b) For car moving in circle of radius R, with velocity v, mass $= m$,

centripetal force required $=$ Frictional force $\le \mu_s N$

$$\frac{mv^2}{R} \le \mu_s mg \qquad (\because N = mg)$$

$$v \le \sqrt{\mu_s Rg}$$

4. A particle of man 2 kg is moving on a circular path of radius 10 m with a speed of 5 ms^{-1} and its speed is increasing at rate of 3 ms^{-1}. Find the force acting on the particle.

(a) 5 N (b) 10 N
(c) 12 N (d) 14 N

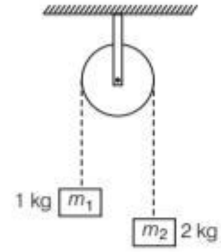
Sol. (a) Radial acceleration (centripetal acceleration)

$$= \frac{v^2}{r} = \frac{5 \times 5}{10} = 2.5\ ms^{-2}$$

Force acting = mass $\times$ acceleration

$$= 2 \times 2.5 = 5\ N$$

5. Two masses $m_1 = 1$ kg and $m_2 = 2$ kg are connected by a light inextensible string and suspended by means of a weightless pulley as shown in figure.



Assuming that both the masses start from rest, the distance travelled by 2 kg mass in 2 s is

(a) $\frac{20}{9}$ m (b) $\frac{40}{9}$ m
(c) $\frac{20}{3}$ m (d) $\frac{1}{3}$ m

Sol. (c) Given, $m_1 = 1$ kg, $m_2 = 2$kg and $g = 10\ ms^{-2}$

Acceleration, $a = \left(\frac{m_2 - m_1}{m_1 + m_2}\right)g$

$$= \left(\frac{2-1}{1+2}\right)10 = \frac{10}{3}$$

$$\left[\because s = ut + \frac{1}{2}at^2 \text{ and } u = 0\ ms^{-1}\right]$$

Distance, $s = \frac{1}{2} \times a \times t^2$

$$= \frac{1}{2} \times \frac{10}{3} \times 4 = \frac{20}{3}\ m$$

6. If a box is lying in the compartment of an accelerating train and box is stationary relative to the train. What force cause the acceleration of the box?

(a) Frictional force in the direction of train
(b) Frictional force in the opposite direction of train
(c) Force applied by air
(d) None of the above

Sol. (a) Frictional force in the direction of train causes the acceleration of the box lying in the compartment of an accelerating train.

VERY SHORT ANSWER Type Questions

7. Why is static friction called a self-adjusting force?

Sol. As the applied force increases, the static friction also increases and becomes equal to the applied force to make the object stationary. That is why static friction is called a self-adjusting force.

8. A body is moving in a circular path such that its speed always remains constant. Should there be a force acting on the body?

Sol. When a body is moving along a circular path, speed always remains constant and a centripetal force is acting on the body.

9. What is the acceleration of a train travelling at 50 ms^{-1} as it goes round a curve of 250 m radius?

Sol. Given, velocity, $v = 50 \text{ ms}^{-1}$

Radius, $r = 250$ m

Centripetal acceleration, $a = \frac{v^2}{r}$

$$a = \frac{50 \times 50}{250} = 10 \text{ ms}^{-2}$$

10. A heavy point mass tied to the end of string is whirled in a horizontal circle of radius 20 cm with a constant angular speed. What is angular speed if the centripetal acceleration is 980 cms^{-2}?

Sol. Here, radius $r = 20$ cm

Centripetal acceleration, $= 980 \text{ cms}^{-2}$

We know that centripetal acceleration, $a = r\omega^2$

$$\omega = \sqrt{\frac{a}{r}} = \sqrt{\frac{980}{20}}$$

$$\omega = \sqrt{49} = 7 \text{ rad/s}$$

11. Carts with rubber tyres are easier to ply than those with iron tyres. Explain.

Sol. The carts with rubber tyres are easier to ply than those with iron types because the coefficient of friction between rubber and concrete is less than that between iron and the road.

12. The mountain road is generally made winding upwards rather than going straight up. Why?

Sol. When we go up a mountain, the opposing force of friction $F = \mu R = \mu mg \cos\theta$.

where θ is angle of slope with horizontal. To avoid skidding, F should be large.

$\therefore \cos\theta$ should be large and hence, θ must be small. Therefore, mountain roads are generally made winding upwards. The road straight up would have large slope.

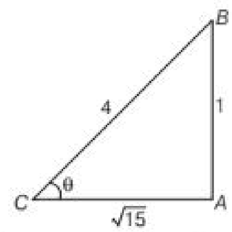
13. The outer rail of a curved railway track is generally raised over the inner. Why?

Sol. When the outer rail of a curved railway track is raised over the inner, the horizontal component of the normal reaction of the rails, provides the necessary centripetal force for the train to enable it moving along the curved path.

SHORT ANSWER Type Questions

14. A body placed on a rough inclined plane just begins to slide, when the slope of the plane equal to 1 in 4. Calculate the coefficient of friction.

Sol. The slope of the plane equal to 1 in 4 implies that if $BC = 4$ and $AB = 1$. Suppose that the plane is inclined at angle θ with the horizontal AC. From the relation between the coefficient of friction and angle of repose, we have



$\mu = \tan\theta$ [here, θ is angle of repose]

$$\mu = \frac{AB}{AC} = \frac{AB}{\sqrt{BC^2 - AB^2}}$$

$$= \frac{1}{\sqrt{4^2 - 1^2}} = \frac{1}{\sqrt{16-1}}$$

$$\mu = \frac{1}{\sqrt{15}}$$

$$\mu = 0.258$$

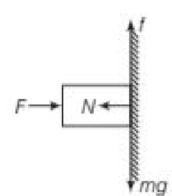
15. A block of mass m is held against a rough vertical wall by pressing it with a finger. If the coefficient of friction between the block and the wall is μ and the acceleration due to gravity is g, calculate the minimum force required to be applied by finger to hold the block against the wall? **[NCERT Exemplar]**

Sol. Given, mass of the block $= m$

Coefficient of friction between the block and the wall $= \mu$

Let a force F be applied on the block to hold the block against the wall. The normal reaction of mass be N and force of friction acting upward be f.

In equilibrium, vertical and horizontal forces should be balanced separately.



$\therefore$ $f = mg$ ...(i)

and $F = N$ ...(ii)

But force of friction $(f) = \mu N$

$$= \mu F \text{ [using Eq. (ii)]} \qquad \text{...(iii)}$$

From Eqs. (i) and (iii), we get

$$\mu F = mg \quad \text{or} \quad F = \frac{mg}{\mu}$$

16. A body of mass 2 kg is being dragged with a uniform velocity of 2 ms^{-1} on a rough horizontal plane. The coefficient of friction between the body and the surface is 0.2. Calculate the amount of heat generated per second. Take $g = 9.8 \text{ ms}^{-2}$ and $J = 4.2 \text{ Jcal}^{-1}$.

Sol. Given, $m = 2 \text{ kg}, u = 2\text{ms}^{-1}, \mu = 0.2$

Force of friction, $F = \mu R$

$$F = \mu mg \qquad [\because R = mg]$$

$$F = 0.2 \times 2 \times 9.8$$

$$F = 3.92 \text{ N}$$

Distance moved per second $s = ut$

$$s = 2 \times 1 = 2$$

Work done by friction per second, $W = Fs$

$$W = 3.92 \times 2 = 7.84 \text{ J}$$

Heat produced, $H = \dfrac{W}{J} \Rightarrow H = \dfrac{7.84}{4.2}$

$$H = 1.87 \text{ cal}$$

17. If the speed of stone is increased beyond the maximum permissible value and the string breaks suddenly, which of the following correctly describes the trajectory of the stone after the string breaks

(i) the stone moves radially outwards,

(ii) the stone flies off tangentially from the instant the string breaks,

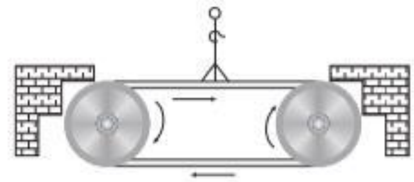
(iii) the stone flies off at an angle with the tangent whose magnitude depends on the speed of the particle? **[NCERT]**

Sol. The second part correctly describes the trajectory of the stone after the spring breaks because when a stone tied to one end of a string is whirled round in a circle then velocity of the stone at any point is along the tangent at that point. If the string breaks suddenly, then stone flies off tangentially, along the direction of its velocity.

LONG ANSWER Type I Questions

18. Figure below shows a man standing stationary with respect to a horizontal conveyor belt that is accelerating with 1 m/s^2.

What is the net force on the man? If the coefficient of static friction between the man's shoes and the belt is 0.2, up to what acceleration of the belt can the man continue to be stationary relative to the belt? (Mass of the man = 65 kg). **[NCERT]**



Sol. Acceleration of the conveyor belt, $a = 1 \text{ m/s}^2$

As man is standing stationary with respect to the horizontal conveyor belt therefore, acceleration of the man = acceleration of the belt

$$\therefore \qquad a = 1 \text{ m/s}^2$$

Mass of the man, $m = 65$ kg

$\therefore$ Net force acting on the man $F = ma = 65 \times 1 = 65$ N

This force is actually the force of friction (static) between man and the belt. Force of friction is actually supporting motion of man.

The direction of this force is in the direction of motion of the belt. Coefficient of friction between the man's shoes and the belt $\mu = 0.2$

Let a' be the acceleration of the belt upto which the man can continue to be stationary relative to the belt.

In this condition

$\therefore \quad ma' =$ maximum static friction

$$ma' = \mu R = \mu mg \qquad \left[\because \mu = \frac{\text{Limiting friction}}{\text{Normal reaction}}\right]$$

or $\quad a' = \mu g = 0.2 \times 9.8 = 1.96 \text{ m/s}^2$

19. A stone of mass 0.25 kg tied to the end of a string is whirled round in a circle of radius 1.5 m with speed 40 rev/min in a horizontal plane. What is the tension in the string? What is the maximum speed with which the stone can be whirled around if the string can withstand a maximum tension of 200 N? **[NCERT]**

When a stone tied to one end of a string is whirled in a circle, then required centripetal force is provided by the tension in the string.

Sol. Mass of stone, $m = 0.25$ kg, Radius of the string, $r = 1.5$ m

Frequency, $\nu = 40 \text{ rev/min} = \dfrac{40}{60} \text{ rev/s} = \dfrac{2}{3} \text{ rev/s}$

Centripetal force required for circular motion is obtained from the tension in the string.

$\therefore$ Tension in the string = centripetal force

$$T = mr\omega^2$$

$$= mr(2\pi\nu)^2 \qquad [\because \omega = 2\pi\nu]$$

$$= mr4\pi^2\nu^2$$

$$T = 0.25 \times 1.5 \times 4 \times \left(\frac{22}{7}\right)^2 \times \left(\frac{2}{3}\right)^2 = 6.6 \text{N}$$

Maximum tension which can be withstand by the string

$$T_{max} = 200\text{ N} = \frac{m{v^2}_{max}}{r}$$

$$v_{max} = \sqrt{\frac{T_{max} \times r}{m}} = \sqrt{\frac{200 \times 1.5}{0.25}}$$

$$= 34.6\text{ m/s}$$

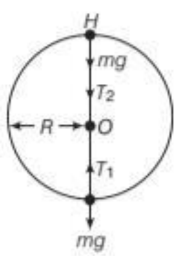
20. A stone of mass m tied to the end of a string revolves in a vertical circle of radius R. The net forces at the lowest and highest points of the circle directed vertically downwards are (choose the correct alternative).

Lowest point	**Highest point**
(i) $mg - T_1$	$mg + T_2$
(ii) $mg + T_1$	$mg - T_2$
(iii) $mg + T_1 - (mv_1^2)/R$	$mg - T_2 + (mv_2^2)/R$
(iv) $mg - T_1 - (mv_1^2)/R$	$mg + T_2 + (mv_2^2)/R$

Here, T_1, T_2 and (v_1, v_2) denote the tension in the string (and the speed of the stone) at the lowest and the highest point respectively. **[NCERT]**

Sol. Let tension in the string be T_1 and T_2 at lowest and highest points of the vertical circle.

At lowest point T_1 acts towards the centre of the circle
($\because$ at the lowest point string will be stretched downward due to weight of the stone) and mg acts vertically downward (weight of an object always acts downward)



$\therefore$ Net force acting on the stone in downward direction $(F_L) = mg - T_1$

At highest point Both T_2 and mg act vertically downward ($\because$ at the highest point string is stretched away from the centre) towards the centre of the vertical circle. Net force acting on the stone in downward direction $(F_H) = mg + T_2$

$\therefore$ Correct option is (i).

21. An aircraft executes a horizontal loop at a speed of 720 km/h with its wings banked at 15°. What is the radius of the loop? **[NCERT]**

If wings of the aircraft are inclined at an angle θ at turn, then $\tan\theta = \frac{v^2}{rg}$ where v is the speed of the aircraft and r is the radius of the circular turn.

Sol. Speed of the aircraft, $v = 720$ km/h

$$= 720 \times \frac{5}{18}\text{ m/s} \left[\because 1\text{ km/h} = \frac{5}{18}\text{ m/s}\right]$$

$$= 200\text{ m/s}$$

Angle of banking, $\theta = 15°$

Acceleration due to gravity, $g = 9.8\text{ m/s}^2$

At turn, $\tan\theta = \frac{v^2}{rg}$

or $$r = \frac{v^2}{g\tan\theta} = \frac{(200)^2}{9.8 \times \tan 15°} = \frac{40000}{9.8 \times 0.2679}$$

$$r = 15240\text{ m} = 15.24 \times 10^3\text{ m} = 15.24\text{ km}$$

22. A train rounds an unbanked circular bend of radius 30 m at a speed of 54 km/h. The mass of the train is 10^6 kg. What provides the centripetal force required for this purpose, the engine or the rails? What is the angle of banking required to prevent wearing out of the rail? **[NCERT]**

The centripetal force required by the train to cross the circular bend is provided by the lateral thrust exerted by the outer rails on the wheels. According to Newton's third law of motion, the train also exerts an equal and opposite force on the rails causing its wear and tear.

Sol. Radius of circular bend, $r = 30$ m

Speed of the train, $v = 54$ km/h

$$= 54 \times \frac{5}{18}\text{ m/s} \left[\because 1\text{ km/h} = \frac{5}{18}\text{ m/s}\right]$$

$$= 15\text{ m/s}$$

Mass of the train, $m = 10^6$ kg

Let θ be the angle of banking required to prevent wearing out the rails, then

$$\tan\theta = \frac{v^2}{rg} = \frac{(15)^2}{30 \times 9.8}$$

$$= \frac{225}{30 \times 9.8} = 0.7653$$

$$\theta = \tan^{-1}(0.7653) = 37.4°$$

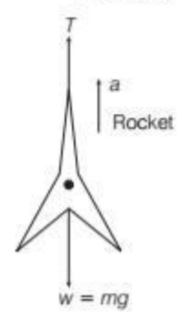
23. A rocket with a lift-off mass 20000 kg is blasted upwards with an initial acceleration of 5.0 m/s^2. Calculate the initial thrust (force) of the blast. **[NCERT]**

Sol. Initial mass of the rocket,

$m = 20000$ kg

Initial acceleration $a = 5.0\text{ m/s}^2$ in upwards direction

Let initial thrust of the blast be T.



$\therefore \quad T - mg = ma$

or $$T = mg + ma$$

$$= m(g + a)$$

$$= 20000 \times (9.8 + 5.0)$$

$$= 2 \times 10^4 \times 14.8\text{ N}$$

$$= 29.6 \times 10^4\text{ N} = 2.96 \times 10^5\text{ N}$$

24. You may have seen in a circus a motorcyclist driving in vertical loops inside a death well (a hollow spherical chamber with holes, so the spectators can watch from outside). Explain clearly, why the motorcyclist does not drop down when he is at the uppermost point, with no support from below. What is the minimum speed required at the uppermost position to perform a vertical loop if the radius of the chamber is 25 m? **[NCERT]**

Sol. When the motorcyclist is at the uppermost point of the death well, then weight of the cyclist as well as the normal reaction R of the ceiling of the chamber is in downward direction. These forces are balanced by the outward centrifugal force acting on the motorcyclist.

$$\therefore \quad R + mg = \frac{mv^2}{r}$$

where, v = speed of the motorcyclist

m = mass of (motorcycle + driver)

r = radius of the death well.

As the forces acting on the motorcyclist are balanced, therefore, motorcyclist does not fall down.

The minimum speed required to perform a vertical loop is given by

$$mg = \frac{mv_{min}^2}{r}$$

[$\because$ In the case weight of the object = centripetal force]

or $$v_{min} = \sqrt{rg} = \sqrt{25 \times 9.8}$$

$$= 15.65 \text{ m/s}$$

LONG ANSWER Type II Questions

25. A block of mass 15 kg is placed on a long trolley. The coefficient of static friction between the block and the trolley is 0.18. The trolley accelerates from rest with 0.5 m/s^2 for 20s and then moves with uniform velocity. Discuss the motion of the block as viewed by (i) stationary observer on the ground (ii) an observer moving with the trolley. **[NCERT]**

Sol. Mass of the block, $m = 15$ kg

Coefficient of friction between the block and the trolley

$$\mu = 0.18$$

Acceleration of the trolley, $a = 0.5 \text{ m/s}^2$

Time, $t = 20$ s

(i) As block is placed on the trolley, therefore, friction force is applied on the block by the trolley

$$F = ma = 15 \times 0.5 = 7.5 \text{ N}$$

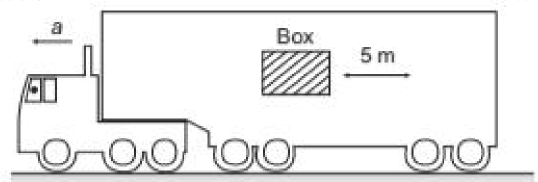
Force on the block is the friction applied by trolley on the block, its direction is in the direction of motion of the trolley.

For the stationary observer on the ground, the block will appear to move with acceleration initially and then with uniform velocity as given in the question.

(ii) For an observer on the trolley, the block is always at rest either initially or finally. Trolley always becomes inertial frame with respect to block because both have the same acceleration initially and same velocity finally.

26. The rear side of a truck is open and a box of 40kg mass is placed 5 m away from the open end as shown. The coefficient of friction between the box and the surface below it, is 0.15. On a straight road, the truck starts from rest and accelerates with 2 m/s^2.

At what distance from the starting point does the box fall off the truck? (ignore the size of the box). **[NCERT]**



Sol. $\because$ Mass of the box, $m = 40$ kg

Coefficient of friction between the box and the surface,

$$\mu = 0.15$$

Acceleration of the truck, $a = 2 \text{ m/s}^2$

Truck is a non-inertial frame for the box, so motion of box can be studied by assuming a pseudo force acting on it in a direction opposite to the direction of acceleration of truck i.e. in backward direction.

pseudo force applied by the truck on the box due to its accelerated motion, $F = ma = 40 \times 2 = 80$ N

Due to this pseudo force on the box, the box tries to move in backward direction but limiting friction force opposes its motion.

Limiting friction force between the box and the surface

$$= \mu R = \mu mg$$

$$f = 0.15 \times 40 \times 9.8 \text{ N}$$

$$= 58.8 \text{ N} \quad \text{[in forward direction]}$$

Net force acting on box in backward direction

$$F' = F - f = 80 - 58.8 \text{ N}$$

$$= 21.2 \text{ N}$$

Acceleration produced in the box in backward direction

$$a' = \frac{F'}{m} = \frac{21.2}{40} \text{ ms}^{-2}$$

$$a' = 0.53 \text{ ms}^{-2}$$

Using equation of motion for travelling $s = 5$ m to fall off the truck, $$s = ut + \frac{1}{2}at^2$$

$$5 = 0 \times t + \frac{1}{2} \times 0.53 \times t^2$$

or $$t = \sqrt{\frac{5 \times 2}{0.53}} = \sqrt{\frac{1000}{53}} = 4.34 \text{ s}$$

Distance travelled by the truck in time,

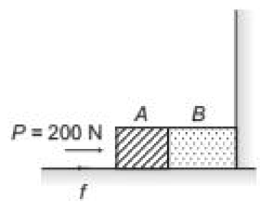
$t = 4.34$ s

$$s' = ut + \frac{1}{2}at^2 = 0 \times t + \frac{1}{2} \times 2 \times (4.34)^2$$

$$= (4.34)^2 = 18.84 \text{ m}$$

27. Two bodies A and B of masses 5 kg and 10 kg in contact with each other rest on a table is against a rigid wall as shown in figure. The coefficient of friction between the bodies and the table 0.15. A force of 200 N is applied horizontally at A.

What are (i) the reaction of the partition or wall (ii) the action- reaction forces between A and B? What happens when the partition is removed? Does the answer to (ii) change, when the bodies are in motion? Ignore difference between μ_s and μ_k. **[NCERT]**



Sol. Mass of body $A(m_1) = 5$ kg

Mass of body $B(m_2) = 10$ kg

Coefficient of friction between the bodies and the table $(\mu) = 0.15$

Force applied horizontally at A, $F = 200$ N

(i) **Reaction of partition**

Limiting friction acting to the left

$$f = \mu R = \mu(m_1 + m_2)g$$
$$= 0.15\,(5 + 10) \times 9.8 = 22.05 \text{ N}$$

$\therefore$ Net force acting on the partition towards the right

$$F' = F - f$$
$$= 200 - 22.05 = 177.95 \text{ N}$$

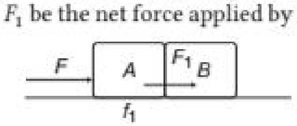
According to the Newton's third law of motion,

Reaction of partition = Net force acting on the partition

= 177.95 N [towards the left]

(ii) **Action-reaction forces between A and B**

Let f_1 be the force of limiting friction acting on body A and F_1 be the net force applied by body A on body B.



$$f_1 = \mu R_1$$
$$= \mu m_1 g \qquad [\because R_1 = m_1 g]$$
$$= 0.15 \times 5 \times 9.8$$
$$= 7.35 \text{ N (towards the left)}$$

$\therefore$ Net force applied by body A on body B,

$$F_1 = F - f_1 = 200 - 7.35$$
$$= 192.65 \text{ N} \qquad \text{[towards the right]}$$

According to Newton's third law of motion, reaction force applied by body B on body, i.e.

$$A = F_1 = 192.65 \text{ N (towards left)}$$

28. A disc revolves with a speed of $33\frac{1}{3}$ rev/min and has a radius of 15 cm. Two coins are placed at 4 cm and 14 cm away from the centre of the record. If the coefficient of friction between the coins and the record is 0.15, which of the coins will revolve with the record? **[NCERT]**

Sol. Given, $(\nu) = 33\frac{1}{3} = \frac{100}{3}$ rev/min $= \frac{100}{3 \times 60}$ rev/s $= \frac{5}{9}$ rev/s

$\therefore$ Angular velocity $(\omega) = 2\pi\nu = 2 \times \frac{22}{7} \times \frac{5}{9} = \frac{220}{63}$ rad/s

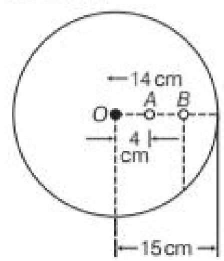
Radius of the disc $(r) = 15$ cm.

Distance of first coin A from the centre $(x_1) = 4$ cm

Distance of the second coin B from the centre $(x_2) = 14$ cm

Coefficient of friction between the coins and the record = 0.15.

If force of friction between the coin and the record is sufficient to provide the centripetal force, then coil will revolve with the record.



$\therefore$ To prevent slipping (or to revolve the coin alongwith record) the force of friction $f \geq$ centripetal force (f_c)

or $$\mu mg \geq mr\omega^2$$

or $$\mu g \geq r\omega^2$$

For first coin A

$$r\omega^2 = \frac{4}{100} \times \left(\frac{220}{63}\right)^2 = \frac{4 \times 220 \times 220}{100 \times 63 \times 63}$$
$$= 0.488 \text{ m/s}^2$$

and $$\mu g = 0.15 \times 9.8 = 1.47 \text{ m/s}^2$$

Here, $\mu g > r\omega^2$, therefore, this coin will revolve with the record.

For second coin B

$$r\omega^2 = \frac{14}{100} \times \left(\frac{220}{63}\right)^2 = \frac{14 \times 220 \times 220}{100 \times 63 \times 63} = 1.707 \text{ m/s}$$

and $$\mu g = 1.47 \text{ m/s}$$

Here, $\mu g < r\omega^2$, therefore, centripetal force will not be obtained from the force of friction, hence this coin will not revolve with the record.

29. A 70 kg man stands in contact against the inner wall of a hollow cylindrical drum of radius 3 m rotating about its vertical axis with 200 rev/min. The coefficient of friction between the wall and his clothing is 0.15. What is the minimum rotational speed of the cylinder to enable the man to remain stuck to the wall (without falling) when the floor is suddenly removed? **[NCERT]**

Sol. Given, Radius of the cylindrical drum $(r) = 3$ m

Coefficient of friction between the wall and his clothing $(\mu) = 0.15$. Frequency $(\nu) = 200$ rev/ min

$$= \frac{200}{60} \text{ rev/s} = \frac{10}{3} \text{ rev/s}$$

The normal reaction of the wall on the man acting horizontally provides the required centripetal force.

$$R = mr\omega^2 \quad \text{...(i)}$$

The frictional force F, acting upwards balances his weight

i.e. $$F = mg \quad \text{...(ii)}$$

The man will remain stuck to the wall without slipping, if

$$\mu R \geq F \quad \text{or} \quad F \leq \mu R$$

$$mg \leq \mu \times mr\omega^2 \quad \text{or} \quad \omega^2 \geq \frac{g}{\mu r}$$

$$\omega \geq \sqrt{\frac{g}{\mu R}}$$

For minimum angular speed of rotation,

$$\omega_{\min} = \sqrt{\frac{g}{\mu R}} = \sqrt{\frac{9.8}{0.15 \times 3}} = 4.67 \text{ rad/s}$$

30. When a body slides down from rest along a smooth inclined plane making an angle of 45° with the horizontal, it takes time T. When the same body slides down from rest along a rough inclined plane making the same angle and through the same distance, it is seen to take time pT, where p is some number greater than 1. Calculate the coefficient of friction between the body and the rough plane. **[NCERT Exemplar]**

Sol. **On smooth inclined plane** Acceleration of a body sliding down a smooth inclined plane, $a = g\sin\theta$

Here, $\theta = 45°$

$$\therefore \quad a = g\sin 45° = \frac{g}{\sqrt{2}}$$

Let the travelled distance be s.

Using the equation of motion, $s = ut + \frac{1}{2}at^2$, we get

$$s = 0.t + \frac{1}{2}\frac{g}{\sqrt{2}}T^2 \quad \text{or} \quad s = \frac{gT^2}{2\sqrt{2}} \quad \text{...(i)}$$

On rough inclined plane

Acceleration of the body,

$$a = g(\sin\theta - \mu\cos\theta)$$
$$= g(\sin 45° - \mu\cos 45°)$$
$$= \frac{g(1-\mu)}{\sqrt{2}} \quad \left[\text{as } \sin 45° = \frac{1}{\sqrt{2}}\right]$$

Again using equation of motion, $s = ut + \frac{1}{2}at^2$, we get

$$s = 0(pT) + \frac{1}{2}\frac{g(1-\mu)}{\sqrt{2}}(pT)^2$$

or $$s = \frac{g(1-\mu)p^2T^2}{2\sqrt{2}} \quad \text{...(ii)}$$

From Eqs. (i) and (ii), we get

$$\frac{gT^2}{2\sqrt{2}} = \frac{g(1-\mu)p^2T^2}{2\sqrt{2}}$$

or $$(1-\mu)p^2 = 1 \quad \text{or} \quad 1-\mu = \frac{1}{p^2}$$

or $$\mu = \left(1 - \frac{1}{p^2}\right)$$

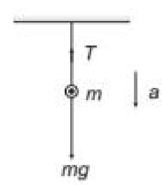
31. A monkey of mass 40 kg climbs on a rope which can stand a maximum tension of 600 N. In which of the following cases will the rope break? The monkey

(i) climbs up with an acceleration of 6 m/s^2.
(ii) climbs down with an acceleration of 4 m/s^2.
(iii) climbs up with a uniform speed of 5 m/s.
(iv) falls down the rope nearly freely under gravity. (Ignore the mass of the rope) and take $g = 10 \text{ m/s}^2$. **[NCERT]**

Tension in the rope will be equal to the apparent weight of the monkey (R).

Sol. Given, Mass of the monkey, $m = 40$ kg

Maximum tension which can be withstood by the rope $(T)_{\max} = 600$ N



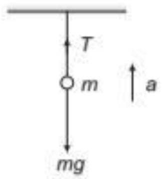
(i) When monkey climbs up with an acceleration $a = 6 \text{ m/s}^2$, then

$$T - mg = ma\,; \; T = mg + ma$$

$$T = m(g + a) = 40(10 + 6) = 640\text{ N}$$

In this condition, $T > T_{max}$ therefore, the rope will break.

(ii) When monkey climbs down with an acceleration $a = 4\text{ m/s}^2$, then



$$mg - T = ma$$

or $$T = mg - ma = m(g - a)$$
$$= 40(10 - 4)\text{ N} = 240\text{ N}$$

In this condition, $T < T_{max}$,
Therefore, the rope will not break.

(iii) When monkey climbs up with a uniform speed of 5 m/s, then its acceleration a is zero.

$\therefore$ $$T = mg = 40 \times 10 = 400\text{ N}$$

In this condition $T < T_{max}$, therefore, the rope will not break.

(iv) When monkey falls down freely under gravity, then its acceleration in downward direction is g.

$\therefore$ $$T = m(g - a) = m(g - g) \quad [\because a = g]$$
$$= 0$$

In this condition, monkey will be in a state of weightlessness and tension in the rope is zero.

Therefore, the rope will not break.

In this problem, T actually represents friction force which is generated, when the monkey pushes the rope in downward direction with a view to climb up.

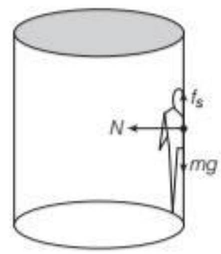
32. In a rotor, a hollow vertical cylinder rotates about its axis and a person rests against the inner wall. At a particular speed of the rotor, the floor below the person is removed and the person hangs resting against the wall without any floor.

If the radius of the rotor is 2 m and the coefficient of static friction between the wall and the person is 0.2.

(i) Find the minimum speed at which the floor may be removed.

(ii) What type of speciality is associated with this question? [take, $g = 10\text{ m/s}^2$]

Sol. The situation is shown in figure below



(i) When the floor is removed, the forces on the person are

(a) weight mg downward.

(b) normal force N due to the wall towards the centre.

(c) frictional force f_s parallel to the wall, upwards.

The person is moving in a circle with a uniform speed, so its acceleration is v^2/r towards the centre.

Newton's law for the horizontal direction (second law) and for the vertical direction (first law) give

$$N = mv^2/r \quad \text{...(i)}$$

and $$f_s = mg \quad \text{...(ii)}$$

For the minimum speed, when the floor may be removed, the friction is limiting one and, so equals $\mu_s N$.

This gives $\mu_s N = mg$

or $$\frac{\mu_s mv^2}{r} = mg \quad \text{[using Eq. (i)]}$$

or $$v = \sqrt{\frac{rg}{\mu_s}} = \sqrt{\frac{2\text{m} \times 10\text{ m/s}^2}{0.2}}$$
$$= 10\text{ m/s}$$

(ii) Speciality is that without the floor an object a body may be 0 align with a vertical wall provided, it is set to be in circular motion (horizontal) with properly required speed.

ASSESS YOUR TOPICAL UNDERSTANDING

OBJECTIVE Type Questions

1. When a box is in stationary position with respect to train moving with no acceleration, then relative motion is opposed by .... Which provides the same velocity to the box as that of the train, keeping it stationary relative to the train.

(a) static friction
(b) kinetic friction
(c) No friction because there will be no relative velocity
(d) None of the above

2. A boy prevents fall of his book on the ground by pressing it against a vertical wall. If weight of his book is 10 kg and μ_s of the wall is 0.2. Find the minimum force needed by him in his attempt.

(a) 300 N (b) 400 N
(c) 500 N (d) 600 N

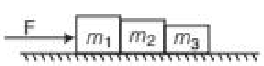
3. When a car is taking a circular turn on a horizontal road, the centripetal force is the force of

(a) friction (b) weight of the car
(c) weight of the tyres (d) None of these

4. When a car is moving along a circle on a level road, then centripetal force is provided by f, where f denotes as

(a) $f < \mu_s N = \frac{mv^2}{r}$ (b) $\frac{mv^2}{r} = f \leq \mu_s N$
(c) $f = \mu_s N = \frac{mv^2}{r}$ (d) $f = \mu_k N = \frac{mv^2}{r}$

5. Three blocks of masses m_1, m_2 and m_3 kg are placed in contact with each other on a frictionless table. A force F is applied on the heaviest mass m_1, so the acceleration of m_3 will be



(a) $\frac{F}{m_1}$ (b) $\frac{F}{m_1 + m_2}$
(c) $\frac{F}{m_2 + m_3}$ (d) $\frac{F}{m_1 + m_2 + m_3}$

Answer

1. (c) | 2. (c) | 3. (a) | 4. (b) | 5. (d)

VERY SHORT ANSWER Type Questions

6. What type of friction is involved when an axle rotates in a sleeve?

7. A stone is tied to one end of a string and rotated in a vertical circle. What is the difference in tension of the string at lowest and highest points of the vertical circle?

8. A ball of 1 g released down an inclined plane describe a circle of radius 10 cm in the vertical plane on reaching the bottom. What is the minimum height of the inclined plane? [**Ans.** 25 cm]

9. For uniform circular motion, does the direction of the centripetal force depend on the sense of rotation, i.e. clockwise or anti-clockwise rotation?

SHORT ANSWER Type Questions

10. Distinguish between sliding friction and rolling friction.

11. A block slides down a rough incline of angle 30° with an acceleration $g/4$. Find the coefficient of kinetic friction. [**Ans.** $1/2\sqrt{3}$]

12. State two advantages of friction in daily life.

13. How sliding friction is converted into rolling friction?

14. State the laws of kinetic friction. Define coefficient of kinetic friction.

LONG ANSWER Type I Questions

15. A body of mass 10 kg is placed on an inclined plane of angle 30°. If the coefficient of static friction is $\frac{1}{\sqrt{3}}$. Find the force required to just push the body up the inclined surface. [**Ans.** 100 N]

16. A block of mass 2 kg is placed on the floor. The coefficient of limiting friction is 0.4. If a force of 3.6 N is applied on the block parallel to the floor. Find the acceleration of the block. What is the force of friction between the block and floor? [**Ans.** zero, 3.6 N]

17. A small body tied to one end of the string is whirled in a vertical circle.

(i) Represent the forces on a diagram when the string makes an angle θ with initial position.

(ii) Find the tension and velocity at the highest and lowest point, respectively.

LONG ANSWER Type II Questions

18. A trolley of mass 20 kg rests on a horizontal surface. A massless string tied to the trolley passes over a frictionless pulley and a load of 5 kg is suspended from other end of string. If coefficient of kinetic friction between trolley and surface be 0.1, find the acceleration of trolley and tension in the string. (take $g = 10\ \text{ms}^{-2}$). **[Ans.** 44 N]

19. A circular motion addict of mass 80 kg sides a ferris wheel around in a vertical circle of radius 10 m at a constant speed of 6.1 m/s. (i) What is the period of motion? What is the magnitude of the normal force on the addict from the seat when both go through (ii) the highest point of the circular path and (iii) lowest point?

[Ans. (i) 10 s, (ii) 4.9×10^2 N and (iii) 1.1×10^3 N]

20. A curve of radius 120 m is banked at an angle of 18°. At what speed can it be negotiated under icy conditions where friction is negligible?

[Ans. 2×10^1 m/s]

21. A stone of mass 0.20 kg is tied to one end of a string of length 80 cm, holding the other end, the stone is whirled into a vertical circle. What is the minimum speed of the stone at the lowest point so that it just completes the circle. What is the tension in string at lowest point of the circular path? ($g = 10\ \text{m/s}^2$)

[Ans. 6.32 m/s, 12 N]

22. Derive an expression for acceleration of a body down a rough inclined plane.

SUMMARY

- Force is an external agency (a pull or a push) which changes or tends to change the state of rest or of uniform motion or the direction of motion of a body. Its SI units is Newton and dimensional formula is $[MLT^{-2}]$.
- Sir Issac Newton made a systematic study of motion and proposed three laws of motion.
- **Newton's first law of motion** states that every body continues in its state of rest or of uniform motion in a straight line unless it is compelled by some external force to change that state.
- **Newton's second law of motion** states that the rate of change of momentum of a body is directly proportional to the external force applied on the body and the change takes place in the direction of the applied force.

$$F = k\frac{dp}{dt} = ma$$

- **Newton's third law of motion** states that for every action there is always an equal and opposite reaction $F_{AB} = -F_{BA}$.
- **Momentum** is quantity of motion possessed by the body. It is the product of its mass and velocity.

$$p = mv$$

SI units is kg-m/s and dimensional formula is $[MLT^{-1}]$.

- **Impulse** is the product of the average force and the time interval for which the force acts on the body

$$I = \mathbf{F}\times\Delta t = \mathbf{p}_2 - \mathbf{p}_1.$$

Its SI unit N-s and dimensional formula is $[MLT^{-1}]$.

- In a lift going upwards or downwards, our feeling of weight (called apparent weight) changes as follows due to different values of reaction force of ground

$R = ma + mg$ [in lift going upwards]

$R = mg - ma$ [in lift going downwards]

$R = 0$ [lift falls freely under gravity]

- **Conservation of momentum**, if there are no external forces acting on a system, the total momentum of the system remains constant .

$$F_{ex} = 0, \text{ then } \Delta \mathbf{p} = \text{constant}$$
$$\mathbf{p} = \mathbf{p}_1 + \mathbf{p}_2$$

- **Equilibrium of a particle** the forces which are acting at the same point or on a particle are called concurrent forces. These forces are said to be in equilibrium when their resultant is zero.
- **Lami's theorm** According to this theorem when three concurrent forces F_1, F_2 and F_3 acting on a body are in equilibrium, then

$$\frac{F_1}{\sin\alpha} = \frac{F_2}{\sin\beta} = \frac{F_3}{\sin\gamma}$$

- **Some common forces in mechanics** are
  Gravitational force $F_g = mg$
  Weight $w = mg$, Tension force, $T = mg$, Spring force $F = k\,x$ and Buoyant force friction.
- **Friction** is the opposing force which comes into play when a body moves or tries to move over the surface of another body.
- **Internal friction** are arises due to relative motion between two layers of liquid.
- **External friction** are arises when two bodies in contact with each other try to move or there is an actual relative motion between the two bodies.
- **Static Friction** The opposing force which comes into play between two bodies before one body actually starts moving over the other. It is denoted by f_s.
- **Limiting friction** The maximum opposing force which comes into play when a body just starts moving over the surface of another body. There are four laws of limiting friction.

$$\mu_s = \frac{f_s}{R} = \frac{\text{Limiting friction}}{\text{Normal reaction}}$$

- **Kinetic friction** The opposing force that comes into existence when one object is actually moving over the surface of the other object. it is also known as dynamic friction.

$$\mu_s = \frac{f_R}{R} = \frac{\text{Kinetic friction}}{\text{Normal reaction}}$$

- **Angle of friction** (θ) may be defined as the angle which the resultant of the limiting friction and the normal reaction makes with the normal reaction.
- **Angle of repose** is defined as the minimum angle of inclination of a plane with the horizontal such that a body placed on the plane just begins to slide down the ineline. It is represented by α
- **Types of kinetic friction sliding friction** The force that comes into play when a body slides over the surface of another body.
- **Rolling Friction** The force of friction that comes into play when a body rolls over the surface of another body.
- For circular motion of car on level road
  Centripetal force $F_c = mr\omega^2 = \dfrac{mv^2}{r}$ and $v_{max} = \sqrt{\mu r_g}$
- For motion of a car on banked road $v_{max} = \sqrt{\dfrac{r_g\,(u_s \tan\theta)}{T - (u_s \tan\theta)}}$

  Angle of banking, $\theta = \tan^{-1}\left(\dfrac{v^2}{r\,g}\right)$

CHAPTER PRACTICE

OBJECTIVE Type Questions

1. Who gave the idea that when a particle is moving with uniform velocity, there is no need of any force, if frictional force is zero?

(a) Aristotle (b) Newton
(c) Galileo (d) Einstein

2. A hockey player is moving northward and suddenly turns westward with the same speed to avoid an opponent. The force that acts on the player is **[NCERT Exemplar]**

(a) frictional force along westward
(b) muscle force along southward
(c) frictional force along south-West
(d) muscle force along south-West

3. A car of mass m starts from rest and acquires a velocity along east, $\mathbf{v} = v\hat{\mathbf{i}}\ (v > 0)$ in two seconds. Assuming the car moves with uniform acceleration, the force exerted on the car is **[NCERT Exemplar]**

(a) $\frac{mv}{2}$ eastward and is exerted by the car engine
(b) $\frac{mv}{2}$ eastward and is due to the friction on the tyres exerted by the road
(c) more than $\frac{mv}{2}$ eastward exerted due to the engine and overcomes the friction of the road
(d) $\frac{mv}{2}$ exerted by the engine

4. If F is the force applied (as $F > f_k$), then acceleration of the body of mass M when body is on horizontal surface **[NCERT Exemplar]**

(a) $\frac{f_k}{M}$ (b) $\frac{F - F_k}{M}$
(c) $\frac{F}{M}$ (d) None of these

5. If 3 forces $\mathbf{F}_1$, $\mathbf{F}_2$ and $\mathbf{F}_3$ act on a particle, then in equilibrium ...

(a) $\mathbf{F}_{21} + \mathbf{F}_2 + \mathbf{F}_3 = 0$ (b) $\mathbf{F}_1 + \mathbf{F}_2 + \mathbf{F}_3 = 0$
(c) $\mathbf{F}_{21} + \mathbf{F}_2 + \mathbf{F}_3$ (d) None of these

6. The coefficient of friction between tyres and the road is 0.1. Find the maximum speed allowed by traffic police for cars to cross a circular turn of radius 10 m to prevent accident.

(a) $\sqrt{10}\ \text{ms}^{-1}$ (b) $\sqrt{20}\ \text{ms}^{-1}$
(c) $5\ \text{ms}^{-1}$ (d) $9\ \text{ms}^{-1}$

7. A particle is moving on a circular path of 10 m radius. At any instant of time, its speed is 5ms^{-1} and the speed is increasing at a rate of $2\ \text{ms}^{-2}$. The magnitude of net acceleration at this instant is

(a) $5\ \text{ms}^{-2}$ (b) $2\ \text{ms}^{-2}$ (c) $3.2\ \text{ms}^{-2}$ (d) $4.3\ \text{ms}^{-2}$

ASSERTION AND REASON

Direction (Q. Nos. 8-17) *In the following questions, two statements are given- one labelled Assertion (A) and the other labelled Reason (R). Select the correct answer to these questions from the codes (a), (b), (c) and (d) as given below*

(a) Both Assertion and Reason are true and Reason is the correct explanation of Assertion.
(b) Both Assertion and Reason are true but Reason is not the correct explanation of Assertion.
(c) Assertion is true but Reason is false.
(d) Assertion is false but Reason is true.

8. **Assertion** A body is momentarily at rest still some force is acting on it at that time.
Reason When a force acts on a body, it may not have some acceleration.

9. **Assertion** During the action of an impulsive force, change in the momentum is very high even though force acts for a very short period.
Reason The amount of force is very high.

10. **Assertion** Action and Reaction forces do not cancel out each other.
Reason It is because both do not act on the same body.

11. **Assertion** Angle of repose is equal to angle of limiting friction.
Reason When a body is just at the point of motion, the force of friction in this stage is called as limiting friction.

12. **Assertion** It is always necessary that external agency of force is in contact with the object while applying force on object.

Reason A stone released from top of a building accelerates downward due to gravitational pull of the earth.

13. **Assertion** At the microscopic level, all bodies are made of charged constituents (nuclei and electrons) and various contact forces arise.

Reason These forces are due to elasticity of bodies, molecular collisions and impacts, etc.

14. **Assertion** Objects in motion generally experience friction, viscous drag, etc.

Reason On the earth, if an object is at rest or in uniform linear motion, it is not because there are no forces acting on it but because the various external forces cancel out, *i.e.* add upto zero net external force.

15. **Assertion** A seasoned cricketer allows a longer time for his hands to stop the ball, while catching the ball. His hand is not hurt.

Reason The novice (new player) keeps his hand fixed and tries to catch the ball almost instantly. He needs to provide a much greater force to stop the ball instantly and this hurts.

16. **Assertion** Product of mass and velocity (*i.e.* momentum) is basic to the effect of force on motion.

Reason Same force for same time causes the same change in momentum for different bodies.

17. **Assertion** Newton's third law of motion is applicable only when bodies are in motion.

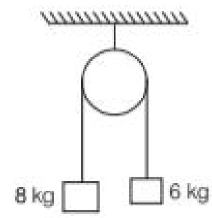
Reason Newton's third law applies to all types of forces, e.g., gravitational, electric or magnetic forces, etc.

CASE BASED QUESTIONS

Direction (Q. Nos. 18-19) *These questions are case study based questions. Attempt any 4 sub-parts from each question.*

18. **Force of Friction on Connected Bodies**

When bodies are in contact, there are mutual contact forces satisfying the third law of motion. The component of contact force normal to the surfaces in contact is called normal reaction. The component parallel to the surfaces in contact is called friction.



In the figure, 8 kg and 6 kg are hanging stationary from a rough pulley and are about to move. They are stationary due to roughness of the pulley.

(i) Which force is acting between pulley and rope?
(a) Gravitational force (b) Tension force
(c) Frictional force (d) Buoyant force

(ii) The normal reaction acting on the system is
(a) 8 g (b) 6 g (c) 2 g (d) 14 g

(iii) The tension is more on side having mass of
(a) 8 kg (b) 6 kg
(c) Same on both (d) Nothing can be said

(iv) The force of friction acting on the rope is
(a) 20 N (b) 30 N (c) 40 N (d) 50 N

(v) Coefficient of friction of the pulley is
(a) $\frac{1}{6}$ (b) $\frac{1}{7}$ (c) $\frac{1}{5}$ (d) $\frac{1}{4}$

19. **Friction**

Starting from rest, a body slides down a $\theta = 45°$ inclined plane of length s in twice the time it takes to slide down the same distance in the absence of friction. The coefficient of friction between the body and the inclined plane is μ.

(i) What is the expression for the acceleration of body?
(a) $a = g(\sin\theta - \mu\cos\theta)$
(b) $a = g(\cos\theta - \mu\sin\theta)$
(c) $a = g\sin\theta$
(d) $a = \mu g\cos\theta$

(ii) Expression for time taken by body to slide down the plane is

(a) $\sqrt{\dfrac{2s}{g(\sin\theta - \mu\cos\theta)}}$

(b) $\sqrt{\dfrac{2s}{g(\sin\theta + \mu\cos\theta)}}$

(c) $\sqrt{\dfrac{2s}{g(\tan\theta - \mu)}}$

(d) None of the above

(iii) When friction is absent, time taken to slide down the plane

(a) $\sqrt{\dfrac{2s}{g\sin\theta}}$ (b) $\sqrt{\dfrac{2s}{g\cos\theta}}$

(c) $\sqrt{\dfrac{2s}{g\tan\theta}}$ (d) $\sqrt{\dfrac{2s}{g\cot\theta}}$

(iv) Which of the following relation is correct?

(a) $3\cos\theta = 4\mu\sin\theta$ (b) $3\sin\theta = 4\mu\cos\theta$

(c) $4\cos\theta = 3\mu\sin\theta$ (d) $4\sin\theta = 3\mu\cos\theta$

(v) Coefficient of friction μ is

(a) 0.5 (b) 0.75 (c) 0.25 (d) 0.35

Answer

1.	(c)	2.	(c)	3.	(b)	4.	(b)	5.	(b)
6.	(a)	7.	(c)	8.	(c)	9.	(a)	10.	(a)
11.	(a)	12.	(a)	13.	(b)	14.	(b)	15.	(a)
16.	(c)	17.	(d)						

18.	(i)	(c)	(ii)	(d)	(iii)	(a)	(iv)	(a)	(v)	(b)
19.	(i)	(a)	(ii)	(a)	(iii)	(a)	(iv)	(b)	(v)	(b)

VERY SHORT ANSWER Type Questions

20. $F = ma$, this expression represents Newton's second law. What is the condition behind this expression?

21. Write the formula of the speed of the car on a banked circular road, when friction force acting on the tyres is zero.

22. A boy is standing on the road, having a box on his head. Find the number of action-reaction pairs.

23. A box is lying on a rough floor. What is the maximum value of F_{ext} so that box do not slip relative to the floor?

[**Ans.** 40 N]

24. A box is lying on the floor of a lift, which is in free fall, what is the value of normal reaction?

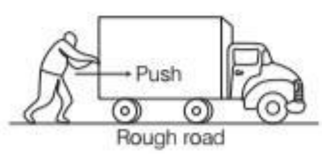
SHORT ANSWER Type Questions

25. Forces of 16 N and 12 N are acting on a mass of 200 kg in mutually perpendicular direction. Find the magnitude of acceleration produced.
[**Ans.** 0.1 m/s^2]

26. The wheel of a truck has a radius of $r = 0.29$ m and is being rotated at 830 revolutions per minute (rpm) on a tyre balancing machine. Determine the speed (in m/s) at which the outer edge of the wheel is moving. [**Ans.** 0.1 m/s]

27. What is the smallest radius of an unbanked (flat) track around which a bicyclist can move if her speed is 29 km/h and the μ_s between tyres and track is 0.32? [**Ans.** 2.1 m]

28. A boy is trying to push a truck but not able to push it. His friend explains the situation with the help of Newton's third law. His friend says that according to Newton's third law action-reaction forces are equal and opposite, so they will cancel each other and the net force on the truck will become zero. That's why the truck will not move. Analyse the explanation of his friend and comment that his explanation is right or wrong.



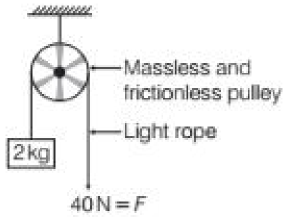
29. A shell of mass 0.020 kg is fired by a gun of mass 100 kg. If the muzzle speed of the shell is 80 m/s, what is the recoil speed of the gun?
[**Ans.** 0.016 m/s]

LONG ANSWER Type I Questions

30. A bullet of mass 0.04 kg moving with a speed of 30 m/s enters a heavy wooden block and is stopped after a distance of 60 cm. What is the average resistive force exerted by the block on the bullet? [**Ans.** 270 N]

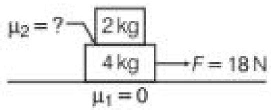
31. Briefly explain static friction, limiting friction and kinetic friction. How do they vary with the applied force?

32. For the given pulley block system, find the acceleration of 2 kg block.



[**Ans.** 20 m/s^2]

33. Two blocks are placed over a horizontal smooth plane as shown in the figure. Find the minimum value of μ_2, so that block could move together.



[**Ans.** 0.6]

34. Find the maximum speed at which a car can turn around a curve of 30 m radius on a level road, given the coefficient of friction between the tyres and the road is 0.4. [$g = 10\ m/s^2$] [**Ans.** 11 m/s]

35. For traffic moving at 60 km/h, if the radius of a curve is 0.1 km, then what is the correct angle of banking of the road? [take $g = 10\ m/s^2$]

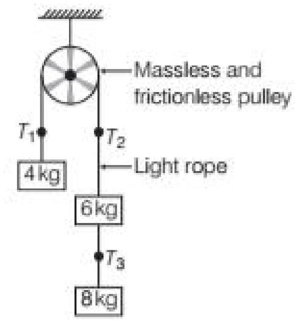
[**Ans.** $\theta = \tan^{-1}\left(\frac{5}{18}\right) = 15°32'$]

36. Discuss the equilibrium of concurrent forces acting on a rigid body.

LONG ANSWER Type II Questions

37. A disc revolves in a horizontal plane at a steady rate of 3 revolutions per second. A coin of mass 6 g just remains on the disc if kept at a mean distance of 2 cm from the axis of rotation. What is the coefficient of friction between the coin and the disc? ($g = 10\ m/s^2$) [**Ans.** 0.725]

38. For the system below, find the values of T_1, T_2 and T_3. Also, find the acceleration of every block.



[**Ans.** $T_1 = \frac{56}{9}g$, $T_2 = \frac{56}{9}g$, $T_3 = \frac{16}{9}g$, $a = \frac{5}{9}g$]