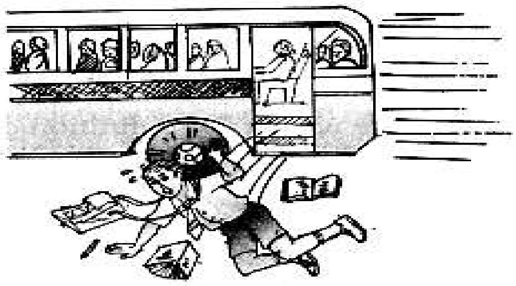
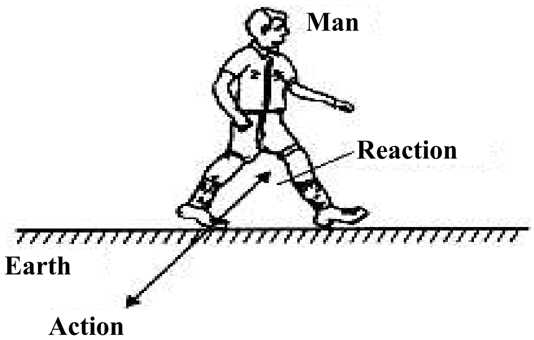
How Forces Affect Motion

Chapter Outline

- ✧ Force
- ✧ Galileo's experiment
- ✧ Inertia
- ✧ Inertia due to motion, rest & direction
- ✧ Newton's first law of motion, momentum
- ✧ Newton's second law of motion
- ✧ Newton's third law of motion
- ✧ Conservation of momentum
- ✧ Friction, types of friction & causes of friction.
- ✧ Methods to increase & decrease friction

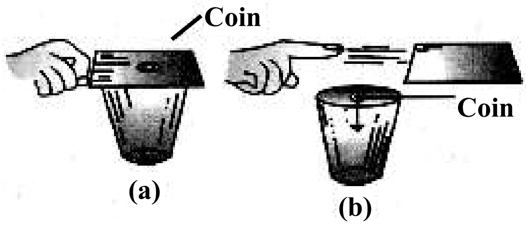


Man jumping carelessly from a moving bus falls forward



Walking man

More the mass
More the inertia



FORCE

Definition of Force :

Force is an external effort in the form of push and pull which :

(i) produces or tries to produce motion in a body at rest

or

(ii) stops or tries to stop a moving body

or

(iii) changes or tries to change the shape and size and the direction of motion of the body.

"Force is the cause which can produce or tries to produces acceleration in the body on which it acts."

Effects of Force :

A force can produce the following effects :

- A force can move a stationary body.
- A force can stop a moving body.
- A force can change the speed of a moving body.
- A force can change the direction of a moving body.
- A force can change the shape (and size) of a body.

There are Four Fundamental Force in Nature :

(i) Gravitational frce

(ii) Electromagnetic force

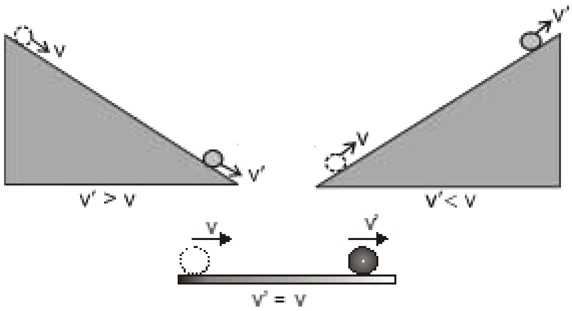
(iii) The strong nuclear force

(iv) Weak force

GALILEO'S EXPERIMENTS

Experiment 1 :

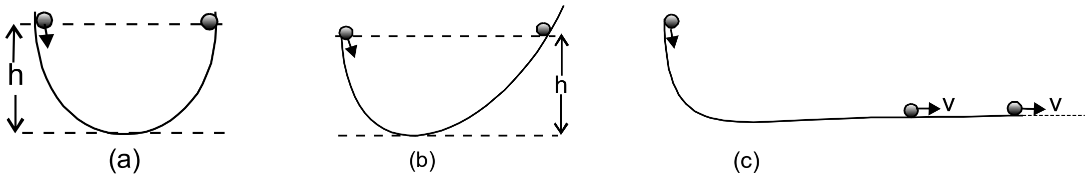
It was observed by Galileo that when a ball is rolled down on an inclined frictionless plane its speed increases, whereas if it is rolled up an inclined frictionless plane its speed decreases .If it is rolled on a horizontal frictionless plane the result must be between the cases describe above i.e. the speed should remain constant. It can be explain as :



- **moving down :** speed increases
- **moving up :** speed decreases
- **moving horizontal :** speed remains constant

Experiments 2 :

When a ball is released on the inner surface of a smooth hemisphere, it will move to the other side and reach the same height before coming to rest momentarily. If the hemisphere is replaced by a surface shown in figure(b) in order to reach the same height the ball will have to move a larger distance.



If the other side is made horizontal, the ball will never stop because it will never be able to reach the same height, it means its speed will not decrease. It will have uniform velocity on the horizontal surface. Thus, if unbalanced forces do not act on a body, the body will either remain at rest or will move with a uniform velocity. It will remain unaccelerated.

Newton concluded the idea suggested by Galileo and was formulated in the laws by Newton.

NEWTON'S FIRST LAW OF MOTION

Everybody remain in its state of rest or uniform motion in a straight line unless it is compelled by some external force.
It means a body remain unaccelerated if and only if, the resultant force on it is zero.
In such a case the body is said to be in equilibrium.

INERTIA

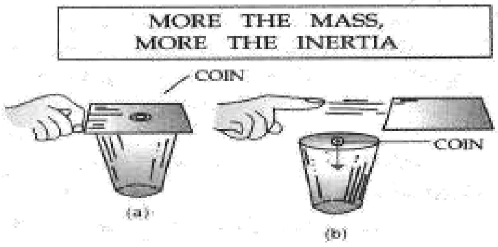
- **Definition of Inertia :**
  The tendency of the body to oppose the change its states of rest or uniform motion in a straight line is called inertia. Newton's first law of motion is also called law of inertia.
- **Description :**
  It follows from first law of motion that in absence of any external force, a body continues to be in its state of rest or in uniform motion along a straight line. In other words, the body cannot change by itself its position of rest or of uniform motion.

Inertia Depends upon Mass :
We know that it is difficult to move a heavier body than the lighter one. Similarly it is difficult to stop a moving heavier body than a lighter body moving with the same velocity. Thus, we conclude that mass of the body is the measure of inertia, more the mass, more the inertia.

TYPES OF INERTIA

There are three types of Inertia which are :
Inertia of Rest :
The tendency of the body to oppose the change in its state of rest when some external unbalance force is applied on it, is called the inertia of rest.
Example based on Inertia of rest :

- A person sitting in a bus falls backwards when the bus suddenly starts. The reason is that lower part of his body begins to move along with the bus but the upper part of his body tends to remain at rest due to inertia of rest.
- If a coin is placed on a thick card over the mouth of a tumbler and the card is given a sudden jerk, the coin will drop into the tumbler. The reason is that the motion of the card is very quick and it cannot be imparted to the coin due to inertia of rest.



- We beat a carpet with a stick to remove dust particles. When the carpet is beaten, it is suddenly set into motion. The dust particles tend to remain at rest due to inertia of rest and hence fall off.
- When a branch of a tree is shaken, the fruits get separated from the tree due to inertia of rest.
- A bullet fired from a gun makes a small hole in glass of window while passing through it but stone breaks it into pieces.
- A pile of corrom coins remain intact when the lowest coin is struck by a striker forcely.

Inertia of Motion :
The tendency of the body to oppose its state of motion when some unbalance forces are applied on it, is called the inertia of motion.
Example based on Inertia of motion :

- A man carelessly getting down a moving bus falls forward, the reason being that his feet come to rest suddenly, whereas the upper part of his body retains the forward motion.

Man jumping carelessly from a moving bus falls forward.

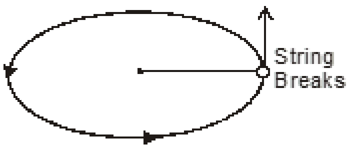
- An athlete runs a certain distance before taking a leap so that the inertia of motion of his body at the time of leaping may help him in his muscular efforts.
- We remove snow or mud from our shoes by striking them against wall. On striking the wall, the feet comes to rest whereas the snow which is still in motion separates from the shoes.

Inertia of Direction :

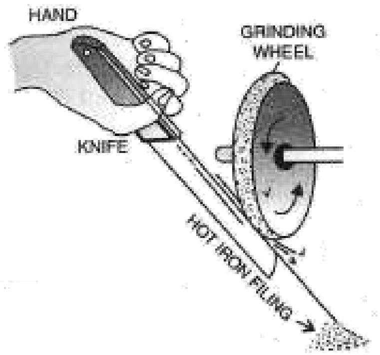
The tendency of a body to oppose any change in its direction of motion is known as inertia of direction.

Example based on Inertia of direction :

- If a car takes a turn along a curved track, the passengers experience a force acting away from the centre of the curved track. This is the result of tendency of the passenger to continue moving along a straight path.
- Tie a stone to one end of a string and holding other end of the string in hand, rotate the stone in a horizontal circle. If during rotation, the string breaks at certain stage, the stone is found to fly off tangentially at that point of the circle.



String breaks, stone goes away tangentially



Sparks produced during sharpening of knife go tangential.

- The water drops sticking to cycle tyre are found to fly off tangentially.
- The sparks produced during sharpening of a knife or a razor against a grinding wheel, leave the rim of the wheel tangentially.

Definition of force from first law of motion :

According to first law of motion, if there is no force, there is no change in state of rest or of uniform motion. In other words, if a force is applied, it may change the state of rest or of uniform motion. If the force is not sufficient, it may not produce a change but only try to do so. Hence force is that which changes or tries to change the state of rest or of uniform motion of a body in straight line.

MOMENTUM

Definition :

Momentum of a particle may be defined as the quantity of motion possessed by it and it is measured by the product of mass of the particle and its velocity.

Momentum is a vector quantity and it is represented by $\vec{p}$

$\therefore \quad \vec{p} = m\vec{v}$

- **Unit of momentum :**

(In C.G.S. system) p=mv gram × cm/s = dyne × s

(In M.K.S. system)p=mv kg × m/s = Newton × s

Description :

Suppose a cricket ball is rolling along the ground. Some force will be required to stop it. If, however it is rolling with larger velocity, a greater force is required to stop it. Again, if a cricket ball and an iron ball of the same size are made to roll with equal velocities, much greater force is required to stop the iron ball than cricket ball because the mass of iron ball is greater than that of cricket ball.

Thus, the force required to stop a moving body is proportional to

(i) its mass

(ii) its linear velocity.

Thus, mass and velocity together increase the motion of the body. The product of two quantities, the mass and velocity which measures the motion of the body, is called momentum.

Can you think why ?

- It is necessary for push and pull to come in contact?

ILLUSTRATION

1. A ball of mass 100 gm. is moving with a velocity of 15 m/s. Calculate the momentum associated with the ball.

Sol. Mass of the ball = 100 gm. = $\frac{100}{1000}$ kg. = 0.1 kg.

Velocity of the ball = 15 m/s

So, momentum = mass of the ball × velocity of the ball

= 0.1 kg. × 15 m/s = 1.5 kg. m/s

NEWTON'S SECOND LAW OF MOTION

The rate of change of momentum of a body is directly proportional to the applied unbalanced forces i.e. Rate of change of momentum $\propto$ Force applied

Let a body is moving with initial velocity **u** and after applying a force **F** on it, its velocity becomes **v** in time **t**.

Initial momentum of the body $p_1 = mu$

Final momentum of the body $p_2 = mv$

Change in momentum in time t is mv – mu

So rate of change of momentum = $\frac{mv - mu}{t}$

But according to Newton's second law $\frac{mv - mu}{t}$, $\propto F$

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

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

So $F \propto ma$

or $F = kma$ (Here k is proportionality constant.

If 1N force is applied on a body of mass 1 kg and the acceleration produced in the body is 1 m/s^2, then $1 = k \times 1 \times 1$ or $k = 1$

Hence, F = ma

So the magnitude of the resultant force acting on a body is equal to the product of mass of the body and the acceleration produced. Direction of the force is same as that of the acceleration.

ILLUSTRATION

2. What force would be needed to produce an acceleration of 4.0 m/s^2 in a ball of mass 6 kg.?

Sol. Acceleration of the ball (a) = 4.0 m/s^2

Mass of the ball (m) = 6 kg.

So, Force (F) = mass (m) × Acceleration (a)

F = 6 kg. × 4.0 m/s^2 $\Rightarrow$ F = 24 kg. m/s^2 $\Rightarrow$ F = 24 N.

UNITS OF FORCE

In C.G.S. System :

$\therefore$ F = ma $\rightarrow$ gm × cm/s^2 = Dyne

- **Definition of one dyne :**

  If m = 1 gm, a = 1 cm/s^2, then F = 1 dyne.

  When a force is applied on a body of mass 1 gram and the acceleration produced in the body is 1 cm/s^2, then the force acting on the body will be one dyne.

In S.I. System :

F = ma $\rightarrow$ kg × m/s^2 = Newton

- **Definition of one Newton :**

  If m = 1 kg and a = 1 m/s^2 then by, F = ma

  F = 1 × 1 = 1 kg × m/s^2 = 1 N.

  If a force is applied on a body of mass 1 kg and acceleration produced in the body is 1 m/s^2, then the force acting on the body will be one Newton.

Gravitational Unit of force :

- **Kilogram Force (kgf) :**

  Kilogram force (kgf) or Kilogram weight (kg. wt.) is force with which a mass of 1 kg is attracted by the earth towards its centre.

  1kgwt = 1kgf = 9.8 N

- **Gram Force (gf) :**
  Gram force or gram weight is the force with which a mass of 1 gram is attracted by the earth towards its centre.

  1gwt = 1gf = 981 dyne

Relation between Newton and dyne.

We know :

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

or $1 \text{ N} = 1000 \text{ g} \times 100 \text{ cms}^{-2}$

or $1 \text{ N} = 10^5 \text{ g cms}^{-2} = 10^5$ dyne

$1 \text{ N} = 10^5$ dyne

ILLUSTRATION

3. A force acts for 0.2 s on a body of mass 2.5 kg initially at rest. The force then ceases to act and the body moves through 4m in the next one second. Calculate the magnitude of force.

Sol. When the force ceases to act, the body will move with a constant velocity. Since it moves a distance of 4 m in 1 s, therefore, its uniform velocity = 4m/s.

Now, initial velocity, $u = 0$

Final velocity, $v = 4$ m/s

Time interval $\Delta t = 0.2$ s

$\therefore$ Acceleration, $a = \dfrac{v-u}{\Delta t} = \dfrac{4-0}{0.2} = 20\text{m/s}^2$

Force, $F = 2.5 \times 20 = 50$ N

4. A ball of mass 20 gm is initially moving with a velocity of 100 m/s. On applying a constant force on the ball for 0.5s, it acquires a velocity of 150 m/s. Calculate the following :

(i) Initial momentum of the ball
(ii) Final momentum of the ball
(iii) Rate of change of momentum
(iv) Acceleration of the ball
(v) Magnitude of the force applied

Sol. Given , $m = 20 \text{ gm} = \dfrac{20}{1000} \text{ kg} = 0.02 \text{ kg}$

Initial velocity, $u = 100$ m/s

Time interval, $t = 0.5$ s

Final velocity, $v = 150$ m/s

(i) Initial momentum of the ball = mass × initial velocity

or $P_1 = mu = 0.02 \text{ kg} \times 100 \text{ m/s}$

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

(ii) Final momentum of the ball = mass × final velocity

or $P_2 = mv = 0.02 \text{ kg} \times 150 \text{ m/s}$

$= 3 \text{ kg-ms}^{-1}$

(iii) Rate of change of momentum = $\dfrac{\text{Final momentum} - \text{Initial momentum}}{\text{Time}}$

or $\dfrac{\Delta P}{\Delta t} = \dfrac{3-2}{0.5} = \dfrac{1}{0.5} = 2.0 \text{ kg-ms}^{-1} = 2.0\text{N}$

(iv) Acceleration, $a = \dfrac{v-u}{t} = \dfrac{150-100}{0.5} = 100\text{ms}^{-2}$

(v) Force, F = mass × acceleration

$= 0.02 \times 100 = 2.0$ N

5. A motorcycle is moving with a velocity of 108 km/hr and it takes 5 s to stop it after the brakes are applied. Calculate the force exerted by the brakes on the motorcycle if its mass along with the rider is 250 kg.

Sol. Given that initial velocity of the motorcycle

= 108 km/hr = 30 m/s

Final velocity = 0 m/s

Time taken to stop = 5s, the mass of the motorcycle with rider = 250 kg.

The change in the velocity of the motorcycle in 5s = 0 – 30 = –30 m/s

Therefore, the acceleration of the motorcycle,

$a = \dfrac{-30}{5} = -6 \text{ m/s}^2$

The magnitude of the force applied by the brakes is given by the equation,

F = mass × acceleration = 250 kg × (6)m/s^2 = 1500 N

FIRST LAW OF MOTION BY SECOND LAW OF MOTION

Description:
According to first law of motion, if there is no force, there is no change in state of rest or of uniform motion. In other words, if a force is applied, it may change the state of rest or of uniform motion. If the force is not sufficient, it may not produce a change but only try to do so. Hence force is that which changes or tries to change the state of rest or of uniform motion of a body in straight line.
Hence we get the definition of force from Newton's first law of motion.
Newton's first law of motion can be deduced from Newton's second law of motion.
According to second law of motion,

$$F = \frac{p_2 - p_1}{\Delta t} = \frac{mv - mu}{\Delta t}$$

if applied force is zero

$$\frac{mv - mu}{t} = 0 \Rightarrow mv - mu = 0 \Rightarrow mv = mu$$

$v = u \Rightarrow$ it shows inertia of motion
If $u = 0$, $v = 0$
Then, $v = u \Rightarrow$ show the inertia of rest
$\vec{v} = \vec{u}$
$\Rightarrow$ show the inertia of direction, it means if applied force is zero direction remains the same.
Thus, it follows that a body will continue to be in the state of rest or of uniform motion along a straight line if no external force acts on it and this is the first law. Thus, first law can be deduced from second law of motion.

ILLUSTRATION

6. A force F_1 acting on a body of 2 kg produces an acceleration of 2.5 m/s^2. An other force F_2 acting on the another body of mass 5 kg produces an acceleration of 2 m/s^2. Find the ratio $\frac{F_2}{F_1}$.

Sol. For first body $F = ma \Rightarrow F_1 = 2 \times 2.5 = 5N$
For second body $F_2 = 5 \times 2 = 10N$
So $\frac{F_2}{F_1} = \frac{10}{5} = 2$.

7. A force of 20N acting on a mass m_1 produces an acceleration of 4 ms^{-2}. The same force is applied on mass m_2 then the acceleration produced is 0.5 ms^{-2}. What acceleration would the same force produce, when both masses are tied together?

Sol. **For mass m_1:** $F = 20N$, $a = 4$ ms^{-2}
then $m_1 = \frac{F}{a} = \frac{20}{4} = 5$ kg
For mass m_2 : $F = 20N$, $a = 0.5$ ms^{-2}
then $m_2 = \frac{F}{a} = \frac{20}{0.5} = 40$ kg
When m_1 and m_2 are tied together :

Total mass $= m_1 + m_2 = 45$ kg, $F = 20N$
then $a = \frac{F}{(m_1 + m_2)} = \frac{20}{45} = 0.44$ ms^{-2}

IMPULSE OF FORCE

A large force acting for a short time to produce a finite change in momentum is called impulsive force.
The product of force and time is called impulse of force.
i.e., Impulse = Force × Time
or $I = F\Delta t$
The S.I. unit of impulse is Newton-second (**N-s**) and the C.G.S unit is dyne- second (**dyne-s**)

◈ **Impulse and Momentum :**
From Newton's second law of motion

Force, $F = \frac{p_2 - p_1}{\Delta t}$ or $F\Delta t = p_2 - p_1$

i.e., Impulse = Change in momentum
This relation is called impulse equation or momentum-impulse theorem. It has an important application in our everyday life.

ILLUSTRATION

8. A car of mass 1000 kg moving with a velocity of 36 km/h hits a wall and comes to rest in 5 s. Find the force exerted by the car on the wall.

Sol. Here, m = 1000 kg

Initial velocity, u = 36 km/h

$= 36 \times \frac{5}{18}$ ms^{-1} = 10 ms^{-1} (1 km/h = $\frac{5}{18}$ ms^{-1})

Final velocity, v = 0

Time, t = 5 s.

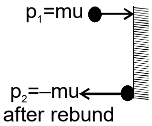
F = ?

Using, F = ma, we get $F = m\left(\frac{v-u}{\Delta t}\right) = 1000\left(\frac{0-10}{5}\right) = -2000N$

Thus, force exerted by the car on the wall = 2000 N.

9. When a ball of mass m kg strikes a wall with a speed 'u' m/s. and rebound at the same speed them find the charge in momentum.

Sol. Change in momentum = final momentum – initial momentum



Change in momentum=(–mu)– (mu)= (–2mu) kgm/s

> **Boost your knowledge**
> - Due to action and reaction acting on different bodies that why they cannot cancel each other.

APPLICATIONS OF IMPULSE EQUATION IN DAILY LIFE

(i) Catching the ball by a cricketer :

While catching a fast moving cricket ball, the player moves his hands backward after catching the ball. By moving his hands, the cricketer increases the time. As a result he has to apply a small force on the ball. In reaction, the ball also applies lesser force and the hands of the player are not injured.

(ii) Jumping on a heap of sand :

If someone jumps from a height on a heap of sand then, his feet move inside the sand very slowly. His momentum changes slowly requiring a lesser force of action from the sand and the man is not injured.

(iii) Jumping down of a passenger from a moving train or bus :

A passenger sitting in a moving train or bus has momentum. When he jumps down and stands on platform or road, his momentum becomes zero.

If he jumps down suddenly from the moving train or bus and tries to stand on his feet, his body will fall forward due to inertia of motion. He will be injured.

He is advised to run over some distance on the platform or road along with (in direction of) the train or bus. This will slow down his rate of change of momentum and lesser force will be involved.

(iv) Springs in vehicles :

The vehicles are fitted with springs to reduce the hardness of the shocks. When vehicles move over an uneven road, they experience impulses exerted by the road. The springs increase the duration of impulse and hence reduce the force.

(v) Springs in seats :

The seats are also fitted with springs to reduce their hardness. When we sit on them all of a sudden, the seats are compressed. The compression increases duration of our coming to rest on the seat. The reaction force of seats becomes negligible.

(vi) Soft material packing :

China and glass wares are packed with soft material when transported. They collide during transportation but soft packing material slows down their rate of change of momentum. The force of impact is reduced and the items are not broken.

(vii) Athletes :

Athletes are advised to come to stop slowly after finishing a fast race. In general, all changes of momentum must be brought slowly to involve lesser forces of action and reaction to avoid injury.

IMPULSE DURING AN IMPACT OR COLLISION

The impulsive force acting on the body produces a change in momentum of the body on which it acts. We know, Ft = mv – mu, therefore the maximum force needed to produce a given impulse depends upon time. If time is short, the force required in a given impulse or the change in momentum is large and vice-versa.

NEWTON'S THIRD LAW

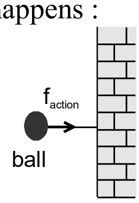
Newton's third law states that every action is associated with an equal and opposite reaction. Thus in nature force always occur between pairs of bodies. An one of them called the action and the other reaction. It is clear from third law that a single force can never exist.

So. according to newton's third law for every action there is an equal and opposite reaction.

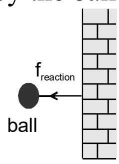
$F_{action} = -F_{reaction} \Rightarrow$ negative sign indicats that the reaction force is opposite to the direction of force.

◈ **Practical Demonstration :**

- when a ball strikes a wall, the following happens :

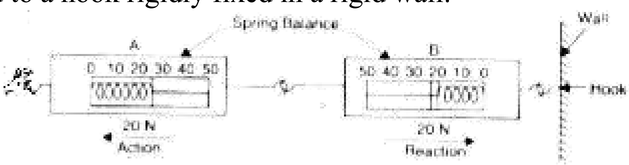


F_{action} = action force = force exerted by the ball on the wall.



$F_{reaction}$ = reaction force = force exerted by the wall on the ball due to reaction force, the ball bounces back.

- Two similar spring balances A and B joined by hook as shown in the figure. The other end of the spring balance B is attached to a hook rigidly fixed in a rigid wall.



Demonstration- Newton's third law of motion

The other end of the spring balance A is pulled out to the left. Both balances show the same reading (20 N) for the force.

The pulled balance A exerts a force of 20N on the balance B. It acts as action, B pulls the balance A in opposite direction with a force of 20 N. This force is known as reaction.

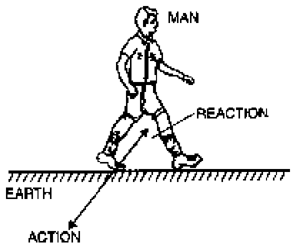
We conclude that action-reaction forces are equal and opposite and act on two different bodies.

◈ **Explanation :**

It may be noted that action and reaction occur simultaneously. Action and reaction never act on same body. Since action and reaction occur in pairs and act on two different bodies, it is impossible to have a single isolated force.

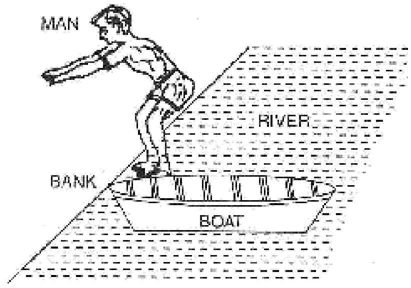
◈ **Examples :**

- **Swimming of a man :** The man swims because he pushes water behind (action), water pushes man forward (reaction).
- **Walking of a man :** Man pushes the earth behind from right foot (action). Earth pushes the man forward (reaction). Then the man walks.



Walking man.

- **Flight of jet or rocket :** The burnt gases are exhausted from behind with high speed giving the gases backward momentum (action). The exhausted gases impart the jet or rocket a forward momentum (reaction). Then jet or rocket moves.
- **Gun and bullet :** A loaded gun has a bullet inside it. When the gun's trigger is pressed, the powder inside cartage explodes. A force of action acts on the bullet and makes the light bullet come out of the barrel with a high velocity. The heavy gun moves behind (recoils) with a small velocity due to force of reaction. This is also an example of law of conservation of linear momentum.
- **Man and boat :** A man in a boat near a river bank is at rest. To reach the bank, the man pushes the boat behind (action), the boat pushes the man forward (reaction). Then man lands on the bank.



- **Hose pipe :** Water rushes out of the hose pipe with a large velocity due to force of action of the compressor from behind. The rushing out jet of water pushes the hose pipe behind due to force of reaction. Then pipe has to be held tightly.

Can you think why ?
- Why compartments of train are provided with the buffers?

NO ACTION IS POSSIBLE WITHOUT REACTION

Examples :

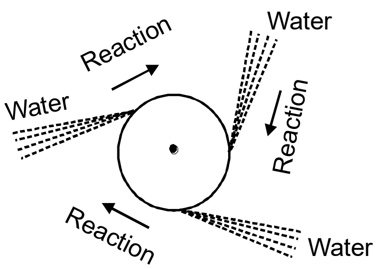
(i) A nail cannot be fixed on a suspended wooden ball.
(ii) A paper cannot be cut by scissors of single blade.
(iii) A hanging piece of paper cannot be cut by blade.
(iv) Writing on a hanging page is impossible.
(v) Hitting on a piece of sponge does not produce reaction. You do not enjoy hitting.

ACTION AND REACTION ARE NOT BALANCED

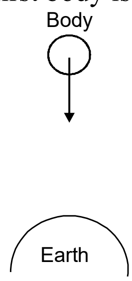
Action and reaction, though equal and opposite are not balanced because they act on two different bodies. In case when they act on two different bodies forming a single system, they become balanced.

INTERACTION BETWEEN BODIES AT A DISTANCE

We have up till now considered examples where the two bodies are in direct contact with each other. But interaction takes place even when the two bodies are not in actual contact with each other. For example, a comb rubbed with dry hair can interact with a piece of paper from a distance. Similarly a magnet can interact with an iron piece from a distance. Interaction between a falling stone and the earth also takes place although these are not in actual contact with each other. Thus when one body influences another body by applying force with or without contact, we say that the first body is interacting with the second body.

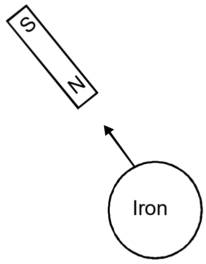


Lawn Sprayer



(a)

Earth attracts a body at a distance

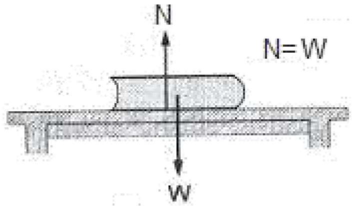


(b)

Magnet attracts iron at a distance

ANY PAIR OF EQUAL & OPPOSITE FORCES IS NOT AN ACTION-REACTION PAIR

Consider a book kept on a table. We have seen that the table pushes the book in the upward direction. Then why does not the book fly up? It does not fly up because there is another force on the book pulling it down. This is the force exerted by the earth on the book, which we call the weight of the book. So, there are two forces on the book– the normal force, N acting upwards, applied by the table and the force, W acting downwards, applied by the earth. As the book does not accelerate, we conclude that these two forces are balanced. In other words, they have equal magnitudes but opposite directions.



Can we call N the action and W the reaction? We cannot. This is because, although they are equal and opposite, they are not forces applied by two bodies on each other. The force N is applied by the table on the book, its reaction will be the force applied by the book on the table. Weight W is the force applied by the earth on the book, its reaction will be the force applied by the book on the earth.

So, although N and W are equal and opposite, they do not form an action–reaction pair.

PRINCIPLE OF CONSERVATION OF LINEAR MOMENTUM

By Newton's second law, the rate of change of momentum is equal to the applied force.

$$\frac{\text{Change in momentum}}{\text{time}} = \text{Force}$$

Change in momentum = F × t

If F = 0 then,

Change in momentum = 0

If the force applied on the body is zero then its momentum will be conserved, this law is also applicable on the system. If in a system the momentum of the objects present in the system are P_1, P_2, P_3........... and external force on the system is zero, then–

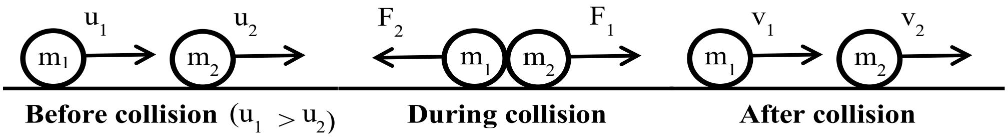
$P_1 + P_2 + P_3 + ... = \text{Constant}$

NOTE : If only internal forces are acting on the system then its linear momentum will be conserved.

❖ **The Law of Conservation of Linear Momentum by Third Law of Motion :**

Suppose A and B are two objects of masses m_1 and m_2 are moving in the same direction with velocity u_1 and u_2 respectively ($u_1 > u_2$). Object A collides with object B and after time t both move in their original direction with velocity v_1 and v_2 respectively.

The change in momentum of object A = $m_1v_1 - m_1u_1$



The force on B by A is

$$F_1 = \frac{\text{Change in momentum}}{\text{time}}$$

$$= \frac{m_1v_1 - m_1u_1}{t} \quad ....(1)$$

The change in momentum of object B = $m_2v_2 - m_2u_2$

The force on A by B is

$$F_2 = \frac{\text{Change in momentum}}{\text{time}}$$

$$= \frac{m_2v_2 - m_2u_2}{t} \quad ....(2)$$

By Newton's third law, $F_1 = -F_2$

$$\frac{m_1v_1 - m_1u_1}{t} = -\left(\frac{m_2v_2 - m_2u_2}{t}\right) \Rightarrow m_1v_1 - m_1u_1$$

$$= -m_2v_2 + m_2u_2$$

or $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$

or Initial momentum = Final momentum

ILLUSTRATION

10. A rifle of mass 5 kg fires a bullet of mass 40 gm. The bullet leaves the barrel of the rifle with a velocity 200 m/s. If the bullet takes 0.004 s to move through the barrel, calculate the following:
(i) recoil velocity of the rifle and
(ii) the force experienced by the rifle due to its recoil.

Sol. (i) Given mass of the rifle, $m_1 = 5$ kg
Mass of the bullet, $m_2 = 40$ gm $= 0.04$ kg
Initial velocities, $u_1 = 0$, $u_2 = 0$
After firing velocity of the bullet, $v_2 = 200$ m/s
Velocity of the rifle, $v_1 = ?$
Applying the law of conservation of momentum, we get
$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$
or $0 + 0 = 5 \times v_1 + 0.04 \times 200$
or $v_1 = -\dfrac{0.04 \times 200}{5} = -1.6$ m/s

(ii) Initial momentum of the rifle = 0
Final momentum of the rifle = 5 kg $\times(-1.6)$
$= -8$ kg-m/s
Time interval = 0.004 s

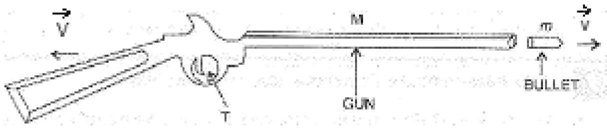
$$\therefore \quad \text{Force} = \frac{\text{Change in momentum}}{\text{Time interval}}$$

$$= \frac{-8\text{kg} - \text{ms}^{-1}}{0.004} = -2000 \text{ N}$$

SOME ILLUSTRATIONS ON CONSERVATION OF MOMENTUM

(a) Recoil of Gun :

A loaded gun (rifle) having bullet inside it forming one system is initially at rest. The system has zero initial momentum.



When the trigger (T) is pressed, the bullet is fired due to internal force of explosion of powder in cartidge inside. The bullet moves forward with a high velocity and the gun move behind (recoils) with a lesser velocity.
Let the bullet and the gun have masses m and M respectively. Let the bullet move forward with velocity v and the gun recoils with velocity V.
Then final momentum of the gun and bullet is MV + mv
By the law of conservation of momentum–
Initial momentum of the system = Final momentum of the system.

$0 = MV + mv$ or $V = -\dfrac{mv}{M}$

Hence the recoil velocity of gun $= \dfrac{mv}{M}$

and the velocity of the gun is $= -\dfrac{mv}{M}$

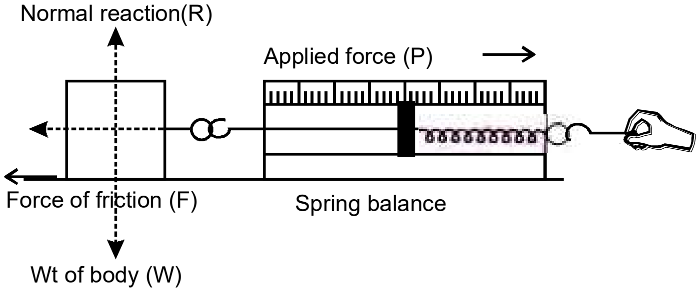
(b) The Working of a Rocket :

the momentum of a rocket before it is fired is zero. When the rocket is fired, gases are produced. These gases come out of the rear of the rocket with high speed. The direction of the momentum of the gases coming out of the rocket is in the downward direction. Thus, to conserve the momentum of the system i.e., (rocket + gases), the rocket moves upward with a momentum equal to the momentum of the gases. So, the rocket continues to move upward as long as the gases are ejected out of the rocket. Thus a rocket works on the basis of the law of conservation of momentum.

Boost your knowledge
- The direction of momentum is same as direction of velocity.

FRICTION AND ITS INTRODUCTION

- Consider a block of wood placed on a wooden table, such that the weight of the block W acting vertically downward is equal to the reaction of the table R, acting vertically upward as shown in Figure, Now, if this block is attached to a spring balance and the spring balance is pulled towards the right gently, it is observed that the block initially does not move. However, when the applied force is gradually increased which is indicated by reading of spring balance, a stage comes when the block just starts sliding. The question arises why does not the block move with a gentle force ?
  The answer to the above question is, that an equal and opposite force is applied on the block by the surface of the table. This force which resists motion, is called the force of friction.

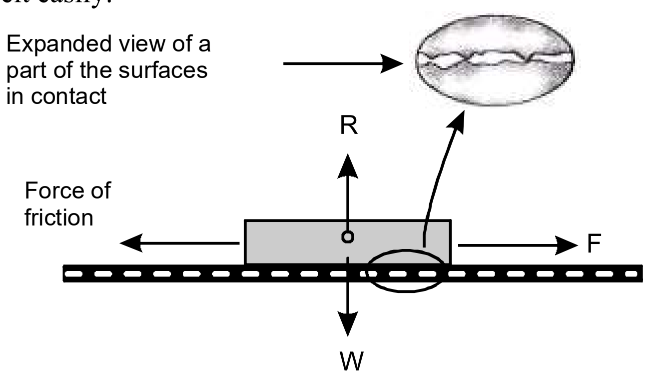


- Roll a ball down a floor and observe it moving. It moves for a while, slows down, and then stops. Why does the ball first slows down and then stop ? Apparently, we have not applied any force on it. Yet we know that it is force that speeds up or slows down an object. Therefore, the ball rolling down the floor must have experienced a force that opposed its motion.
  We call this opposing force exerted by the floor on the ball as the force of friction.
  Therefore, from these two observations it follows that an opposing force always acts between the two objects, whenever one object tends to move or moves over another objects. Apparently, this opposing force depends on the nature of surfaces of the two bodies in contact and such an opposition offered to the motion is called friction.

(a) Definition :
Friction is the opposing force that is set up between the surfaces of contact, when one body slides or rolls or tends to do so on the surface of another body.

(b) Direction of Frictional Force :
When a block is pulled by force F towards the right, the force of friction acts towards the left and when the block is pulled by force F towards the left, the force of friction acts towards the right.
So we can say that force of friction always acts in the direction opposite to that of motion or intended motion.

(c) Causes of Friction :
The friction between any two surfaces is mainly caused by the following factors :
(i) Due to the interlocking of surfaces :
No solid surface is perfectly smooth. This means all solid surfaces are rough. The degree of roughness varies from surface to surface. Some are more rough, while some others are less. Even a surface which looks smooth to the naked eyes is actually rough. In the case of highly rough surfaces, the surface roughness can be seen, felt easily.



Roughness of the surfaces in contact can be seen as the presence of hills and valleys in expanded view of a part of the surface is shown in figure.
In the case of surfaces which appear to be smooth, the surface roughness can be seen only with the help of a microscope. A magnified view of the surface roughness is shown alongside.
When a body (say, a wooden block) is pulled over another, these 'hills' and 'valleys' interlock with each other and oppose the relative motion between the two bodies. This gives rise to a frictional force. Thus, friction is due to the roughness of the two surfaces in contact.

(ii) Due to force of adhesion between the two surfaces:

Two rough surfaces when placed together meet only at certain points. The atoms or molecules present at such points of contact attract each other due to electrostatic attractions. These attractions are called forces of adhesion.

When one body is made to move over the other, the force of adhesion opposes the motion. This force which opposes the motion also gives rise to frictional force. So, the force of adhesion between the two surfaces gives rise to friction.

(d) Factors on which Friction Force Depends:

The force of friction depends upon the following factors.

(i) On a horizontal surfaces, the force of friction is directly proportional to the weight of the body which moves.

(ii) The force of friction depends on the nature of surface in contact. For example, the force of friction between a pair of polished surfaces is very small as compared to the force of friction between two rough surfaces.

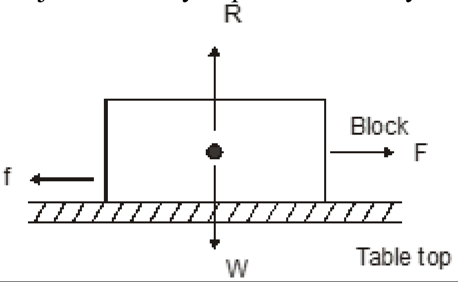
(iii) The force of friction does not depend upon the area of the surfaces in contact till weight remains the same.

(e) Friction is a Self Adjusting Force :

Consider a wooden block lying on a horizontal surface. Push a block by applying a small force. The block remains at rest. It implies that the applied force on the block has been exactly balanced by the force of friction acting at the interface of block and the horizontal surface. Now, increase the push on the wooden block a little. The block may still remain at rest. Obviously, the force of friction has also increased and has become equal and opposite to the applied force. However, a stage comes when the block just starts sliding.

The maximum value of the force of friction which comes into play before a body just begins to slide over the surface of another body is called limiting friction.

The force of friction always adjusts itself equal to the applied force upto the value of limiting friction i.e. as much force of friction comes into play as is just necessary to prevent the body from moving.



> **Can you think why ?**
> - A soda bottle falling freely. Will the bubble of gas rise.

TYPES OF FRICTION

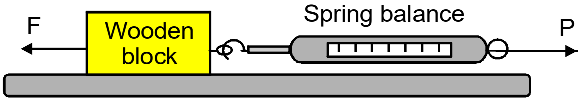
(a) Static friction :

Friction is a self–adjusting force. Thus, when the applied force is gradually increased, the force of friction also increases at the same rate and the body remains stationary. This force of friction is called force of static friction (f_s) or simply static friction. If the applied force is increased further, a stage reaches when the body begins to just move. At this stage the force of static friction is maximum ($f_{s.max}$). The maximum force of friction when the block just starts moving is called the limiting value of the static friction, or limiting friction.

For example :

Place a rectangular block with a hook on one side on a table.

Attach a spring balance to the hook to measure the least horizontal force needed to make the block move.



Static friction

Apply a small force on the block by pulling the spring balance. The block remains at rest because a force of friction, f_r, equal but opposite to the applied pull comes into action between the surfaces. Increase the force a little, the block does not move. This means that the force of friction has increased to balance the pulling force on the block. If the pulling force P is increased further, at a certain stage for the block static friction will be maximum.

(b) Sliding (Kinetic) Friction :

The force of friction between the two surfaces in contact when one surface slides over the other is called **sliding (kinetic) friction**.

For example :

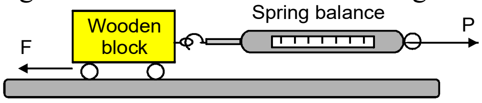
Continue pulling the block with the spring balance, so that it slides at a steady speed. The reading on the spring balance is also steady. Kinetic or sliding friction between the two surfaces is acting.

The force required to keep a body in motion is less than the force required to start the motion. Therefore sliding (kinetic) friction is less than the limiting static friction.

(c) Rolling Friction :

The force of friction between the two surfaces in contact when one of them is rolling on the other is called **rolling friction**.

Provided with wheels on either side, the reading on the spring balance when the block moves with a steady speed is much less than the sliding friction measured above. Rolling friction is less than sliding friction.



Rolling friction

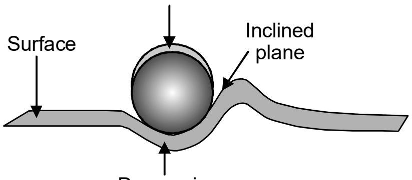
◈ **Examples of Rolling Friction :**

- When a car or bus or bicycle, etc., moves on the road, a part of its wheel and the surface of the road get continuously deformed. Thus, force has to be applied to overcome this deformation and is equivalent to the rolling friction.

  It is for the same reason that more force is required when the tyres do not have sufficient air pressure, conversely, if the tyres are heavily inflated, the deformation produced is very small and hence the rolling friction decreases. However, the ride becomes very bumpy. Furthermore, it becomes difficult to apply brakes as the vehicle does not stay on its path during the application of brakes.
- The wheels of the train are made of steel and so are the railway tracks. Thus, the deformation produced in them is very small and hence, they have very small rolling friction. It is because of this small rolling friction that the trains run very fast.
- These days luggage, such as suitcases, are provided with tiny wheels. These wheels offer very small amount of rolling friction and are easy to move.
- Roller skates have tiny wheels these wheels have very small rolling friction and help in fast motion of the skater.

◈ **Causes of Rolling Friction :**

The roller or the wheel deforms (changes the shape) the surface on which it is rolling temporarily, thereby causing a depression, on account of its weight. In this process the roller or the wheel itself gets deformed temporarily at the point of contact of the surface of the body. Because of the above deformations a kind of inclined plane is formed in the direction of motion of the roller or the wheel. Thus, a force is required to over come this temporary, but continuously forward moving inclined plane. This force applied against the continuously forward moving inclined plane is the equivalent of rolling friction.



From the above discussion it is clear that smaller the depression formed at the point of contact of wheel or roller with a given surface, the lesser is the force of rolling friction and vice versa.

Furthermore, rolling friction is far less than the sliding friction. This is achieved by using wheels, ball bearings, roller bearings, etc.

◈ **Friction plays an important role in our daily life.**

- Without friction we would slip and fall every time we attempt to walk or run. There is very little friction on a wet polished floor. That is why it is easy to slip on such a floor.

- Friction causes nails and screws to hold on to walls.
- It would not be possible to light a matchstick without friction between its head and the side of the match box.
- Cars and buses are able to run on roads because of friction between the tyres and the road.
- Without friction writing on paper would be impossible as the tip of the pen will slip on paper.
- It is because of friction between the brake 'shoes' and wheels that bicycles and automobiles stop when brakes are applied.

Friction is a demerit too in some circumstances:

- The heat produced in the moving parts of machinery due to friction results in wear and tear of the parts.
- Forest fires are caused due to friction between branches of trees rubbing against each other.
- Tyres of vehicles and soles of footwear wear out because of friction (figure 16.8).

Worn out sole of a shoe

- Energy is wasted in overcoming the force of friction.

WHY DOES FRICTION CONSIDERED A NECESSARY EVIL

It may appear that since the force of friction always opposes motion, it is always a curse. This is not so, because very often the force of friction is also a boon or, as we often say, a necessary evil. In fact, life would have been almost impossible if there were no friction. Friction helps us to walk and to drive our vehicles. It also helps us to produce heat.

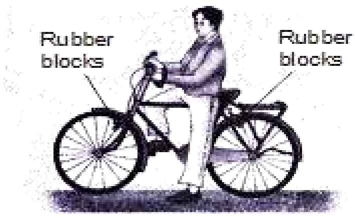
In an effort to walk, we push the earth backward. In return, the earth pushes us forward and we are able to walk. On a highly polished floor, there is a very little grip between the floor and our shoes due to lack of friction. So, on a polished floor, the moment we try to push the earth backward, we slip and fall. So, it is friction that helps our feet to grip the road and enables us to walk. We even provide corrugations on the soles of our shoes to increase friction between our feet and the ground.

The corrugations on the soles of our shoes help us to have a better grip on the road

You must have seen that tyres of all new vehicles have many treads or corrugations on them. The treads on the tyres increase friction between tyre and the road. When the treads on a tyre get worn out, it loses its grip on the road and the vehicle tends to skid.

Treads on tyres help them to have a better grip on the road

Again, we make use of friction while applying brakes to our bicycle. When we apply brakes to our bicycle, we are really clamping rubber blocks against the revolving rim of the wheel. The resulting friction stops the movement of the wheels.



Friction stops the movement

Sometimes, we also use different materials to increase friction. For example, trolley wheels have rubber washers. The use of wet surfaces generally reduces friction. Therefore, friction can be increased by making the surfaces dry. A wet glass tends to slip more easily from our hands than a dry one. We can increase the grip by increasing the pressure on surfaces in contact. Thus, when any object starts slipping from our hand, we hold it more firmly. This results in an increase of friction between that object and our hand.

Can you think why ?

- Actual and virtual force are different?

WAYS TO REDUCE FRICTION

The friction between two surfaces can be reduced by the following methods.

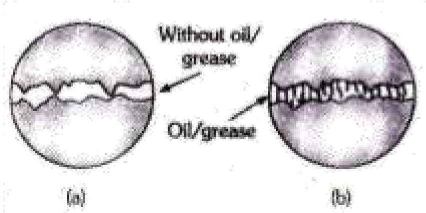
(a) By Polishing the Surfaces :

Rough surfaces can be made smooth by polishing. Polishing removes 'hills' and 'valleys' from the surfaces. Therefore, polishing of the surfaces reduces the friction.

(b) By Applying Oil or Grease on the Surfaces (or by Lubrication) :

Oil/grease forms a thin layer between the two surfaces. Thus, a lubricant separates the two surfaces. This reduces the changes of interlocking of the two surfaces and thus reduces the friction.

Soap solution also acts as a lubricant. That is why we tend to slip on the floor if it is covered with soap solution.



Views of two rough surfaces in contact
(a) without oil/grease (b) with oil/grease

(c) By Sprinkling a Soft, Slippery Fine Powder on the Surfaces :

A small quantity of talcum powder on a wooden surface or floor etc. reduces friction. This is why a small quantity of talcum powder is applied on carrom board. Graphite powder is used in machines to reduce friction.

(d) By Using Ball-Bearings or Roller- Bearings:

When a body rolls over a surface, the force of friction is much less. That is why, friction can be reduced by using ball - bearings or roller - bearings in machines.

(e) By streamlining the body of an object :

Properly shaped bodies (called streamlined) experience less friction from air or water. Bodies of cars, aeroplanes, rockets, ships, etc., are streamlined. Birds and fishes also have streamlined bodies.

Boost your knowledge

- Drop of rain is falling with a constant speed, acceleration is zero, and in accordance with first law of motion, the net force on the drop of rain is zero.

WAYS TO INCREASE FRICTION

The friction between two surfaces can be increased by the following methods.

(a) By making the surface rough : Friction can be increased by increasing the roughness of the surfaces in contact. For example, the surface of the head of a matchstick and the sides of the matchbox are deliberately made rough to increase the friction to produce more heat because of which the matchstick lights up easily.

(b) By making grooves : We can increase the friction in case of tyres of bicycles, cars, buses, etc., by making grooves in them. Due to greater friction, the tyres get a better grip on the road which prevents skidding of the vehicles.

FRICTION DUE TO LIQUIDS AND GASES

We have learnt that solids experience friction when their surfaces move relative to one another. It has been found that when a solid moves in a liquid or a gas the surface of the solid experiences friction. However, it is found that liquids exert less force of friction as compared to the solids. Similarly, the gases exert least force of friction as compared to the solids or liquids. As the most common liquid is water and most common gas is air, therefore, we will discuss friction due to water and friction due to air.

The frictional force exerted by fluids is also called drag.

(a) Friction due to Water :

Before we discuss the friction due to water, let us know about the "streamlined shape". The special shape of a body or an object around which a fluid (air or water) can flow easily offering minimum amount of friction is called **streamlined shape**.

Examples :

(i) The body of ships and boats is streamlined so that they experience minimum amount of friction while moving through water.

(ii) In nature the body of fishes is streamlined, such that they experience least amount of friction in water.

(iii) When a swimmer swims in water he tries to streamline his body as far as possible so that he experiences least friction due to water.

(b) Friction due to Air :

Friction due to air is so small that we hardly feel it. However following activity will show the friction of air. Take a full sheet of paper and allow it to fall down from the level of your head. Record the time in which the sheet of paper reaches the ground level. Now crumple the sheet in the form of a ball and allow it to fall down from the level of your head. You will notice the crumpled ball quickly reaches the ground level. Why?

It is because when the sheet is flat, it has a large surface area which experiences a large force of friction due to air and hence slows down. However, when the sheet is crumpled in the form of ball, it has very small surface area. The small surface area experiences less force of friction due to air and hence reaches the ground level quickly.

Examples :

(i) Nature has shaped the body of birds in such a way, that air offers least resistance and hence they can fly with good speed.

(ii) The body of aeroplanes is streamlined so that the air offers least possible friction.

(iii) The body of automobiles (cars, buses, motorcycles, etc.) is streamlined so that air offers least possible friction.

(iv) The meteors (shooting stars) enter the atmosphere of the earth at a very high speed. At such speeds the friction due to air is extremely high. Due to this high friction the temperature of meteors rises to such a high degree that they catch fire.

Burning meteor

(v) The spaceships are provided with heat shield at their head. It is because when the spaceships enter the atmosphere then due to friction of air they can catch fire, much like the meteors. Thus, to prevent their burn out, a heat shield is provided.

ILLUSTRATION

11. A machine gun has a mass of 30 kg. The machine gun fires 35 g bullets at the rate of 400 bullets per minute with a speed of 400 m/s. What force must be applied to the gun so that the gun is kept in position.

Sol. Mass of the gun, $M = 30$ kg.

Mass of each bullet, $m = 35$ g. $= 35 \times 10^{-3}$ kg.

Velocity of each bullet, $v = 400$ m/s

Let n be the number of bullets fired per second

$$\therefore n = \frac{400}{60} = \frac{200}{3}$$

Required force = rate of change of linear momentum of bullets.

or $$F = \frac{n(mv)}{t} = \frac{20}{3} \times \frac{35 \times 10^{-3} \times 400}{1}$$

$$F = 93.3 \text{ N}$$