1. WHAT IS A FORCE?

To open a drawer of the almirah, we need to pull the drawer. But when we want to close it, we have to push it with our hand. This clearly signifies that an effort of ‘push’ or ‘pull’ is required to move a body. So,

Force is an external effort in the form of a push or pull acting on the body. Forces are used in our everyday actions like pushing, pulling, lifting, stretching, twisting and pressing.

1.1 EFFECTS OF FORCE

A force cannot be seen, tasted or felt. However, we can see or feel the effect of a force. A force can produce following effects :

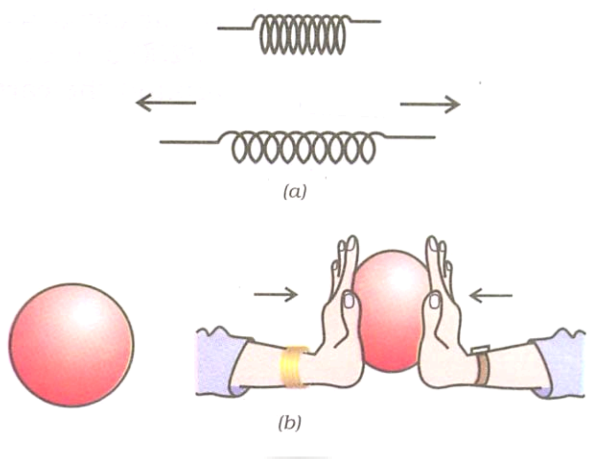
(i) A force can move a stationary body. For e.g. a football at rest moves when it is kicked.

(ii) A force can stop a moving body. For e.g. a moving car stops when the force of brakes is applied.

(iii) A force can change the direction of a moving body. For e.g. when a moving cricket ball is hit by a bat, the ball moves in a different direction due to the force applied by the bat.

(iv) A force can change the speed of a moving body. For e.g. the speed of a falling ball increases because the earth applies a pulling force on it (force of gravity). Whereas, if ball is thrown vertically upwards, the pull of the earth causes the speed of the ball to decrease.

(v) A force can change the size and shape of a body.



(a) A spring expands on application of force;
(b) A spherical rubber ball becomes oblong as we apply force on it.

For e.g. when a spring is pulled at both ends, then the shape and size of the spring changes. A spherical rubber ball becomes oblong as we apply force on it with both hands.

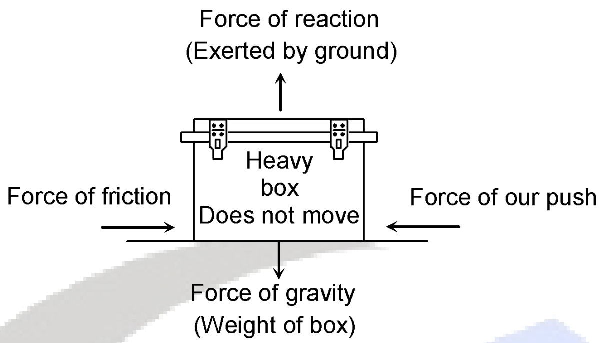
2.1 TYPES OF FORCES

The forces that we come across in our daily life, are divided into two types :

(i) Balanced Forces

(ii) Unbalanced Forces

(i) Balanced Forces : If the resultant of all the forces acting on a body is zero, the forces are called balanced forces.



When balanced forces act on a body (here a heavy box), they do not produce any motion in it.

For example:

(a) a heavy box lying on ground has four forces acting on it as shown in the figure. Since the box does not move at all, the resultant of all the forces acting on it is zero. The force of our push is balanced by the force of friction, and the force of gravity is balanced by the force of the reaction of the ground. So, the forces acting on this stationary box are an example of balanced forces.

(b) Similarly, in a tug of war, i.e. in rope pulling between two teams, if the resultant of forces applied by the two teams is zero, the rope does not move in either direction. The forces exerted by two teams are balanced. From the above example we also conclude that balanced forces do not change the state of rest or of motion of an object i.e. these forces cannot produce motion in a stationary body or stop a moving body. However, they can change the shape of the body. For e.g. when a spherical balloon is pressed between our two hands, its shape changes from spherical to oblong. Here, the balloon does not move, but its shape changes.

(ii) Unbalanced Forces : If the resultant of all the forces acting on a body is not zero, the forces are called unbalanced forces.

(a) The heavy box shown in figure can be moved with a very strong force. This is because in that case the force of push will become greater than the opposing force of friction. An unbalanced force will then act on the heavy box and make it move.

(b) A ball rolling on the ground stops after some time because an unbalanced force of friction acts on it.

(c) When we stop pedaling, the bicycle begins to slow down. This is again because of the unbalanced friction force acting opposite to the direction of motion.

From the above examples, we also conclude that unbalanced forces can change the state of rest or state of uniform motion or the direction of the body or the size and shape of the body.

2. NEWTON'S LAWS OF MOTION

Newton further studied Galileo's ideas on force and motion and presented three fundamental laws that govern the motion of objects. These three laws are known as Newton's laws of motion.

2.1 NEWTON'S FIRST LAW OF MOTION

According to this law : A body continues to be in a state of rest or in a state of uniform motion along a straight line unless compelled by an external force to change its state of rest or of uniform motion.

This statement of the first law is divided into two parts :

(i) A body continues to be in a state of rest unless compelled by an external force to change its state of rest. For e.g. a book lying on a table continues to be there unless it is removed by us. The book will not move by itself till we apply force to move it.

(ii) A body continues in its state of uniform motion in a straight line unless compelled by some external force to change this state of the body. In other words, a moving body cannot come to rest by itself. This part of the law is difficult to realise as we find that a ball rolling on the ground does stop after some time. Similarly, when the engine of a moving car is switched off, it stops after travelling some distance. In fact, motion of everybody is being opposed by the invisible forces like air resistance and friction between the body and the ground. If these opposing forces were removed, a body in uniform motion will continue to move uniformly, and never stop on its own.

2.1.1 Newton's First Law Defines Force

From the above discussion, it is clear that Newton's first law of motion gives us the definition of force. It says that a force is needed to change the state of rest or of uniform motion of the body. Thus force is defined as an external effort which changes or tends to change the state of rest or of uniform motion of the body in a straight line.

2.2 INERTIA

From Newton's first law of motion, it is clear that a body is unable to change its state of rest or motion by itself i.e. all objects resist a change in their state. This property of the body is known as inertia. Hence, Inertia is a tendency of a body to resist a change in its state of rest or of uniform motion.

2.2.1 Relationship between mass of the body and inertia

Inertia of a body is measured by the magnitude of force required to change the state of the body. Greater the inertia of a body, greater will be the force required to bring a change in its state of rest or of uniform motion. If a body is heavy, force required to change its state is large and therefore the inertia of the body is also large. Hence, mass of the body is a measure of inertia of the body. For example, when we kick a football, it moves away. Whereas when a stone of same size is kicked with an equal force, the stone hardly moves. The stone being heavier than football has larger inertia.

2.2.2 Types of Inertia

Inertia can be divided into three types:

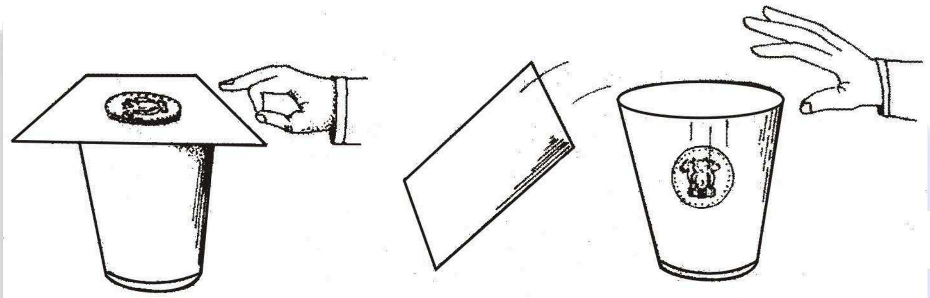
(i) Inertia of rest
(ii) Inertia of motion
(iii) Inertia of direction

(i) Inertia of Rest : The tendency of a body to oppose any change in its state of rest is known as inertia of rest.

Examples of inertia of rest

(a) When a bus suddenly starts moving forward, the passengers in the bus fall backward. This is because the lower part of the bodies of the passengers being in contact with the floor of the bus come in motion along with the bus. On the other hand, the upper part of their bodies remain at rest due to inertia of rest. Hence the passengers fall backward.

(b) The carpet is beaten with a stick to remove the dust particles. When the carpet is beaten with a stick, the fibres of the carpet come in motion and hence move forward. On the other hand, the dust particles remain at rest due to inertia of rest. Therefore, they fall down.



(c) Place a fifty paise coin on a piece of a card-board covering the glass. Strike the card board with a finger. The card board flies away and the coin falls into the glassdue to inertia of rest.

(d) When a tree is vigorously shaken, some of the fruits fall from the tree. When a tree is vigorously shaken, the branches of the tree come in motion but the fruits tend to continue in their state of rest due to inertia of rest. As a result of this, fruits get separated from the branches of the tree.

(ii) Inertia of motion : The tendency of a body to oppose any change in its state of uniform motion is known as inertia of motion.

Examples of inertia of motion

(a) The passengers fall forward when a fast moving bus stops suddenly. This is because the lower part of the bodies of the passengers comes to rest as soon as the bus stops. But the upper parts of their bodies continue to move forward due to inertia of motion.

(b) A person falls forward while getting down from a moving bus or train. This is because as the foot of the person touches the ground, the lower part of his body comes to rest while the upper part of his body remains in motion due to inertia of motion.

(c) **A luggage is usually tied with a rope on the roof of buses.** When a moving bus suddenly stops, the luggage on its roof tends to continue in the state of motion due to inertia of motion. Hence the luggage fall down from the roof of the bus. Similarly, when a bus suddenly starts, the luggage on the roof of the bus tends to continue in the state of rest and hence fall down from the roof of the bus. Thus, to avoid the falling of the luggage, it is tied with a rope on the roof of a bus.

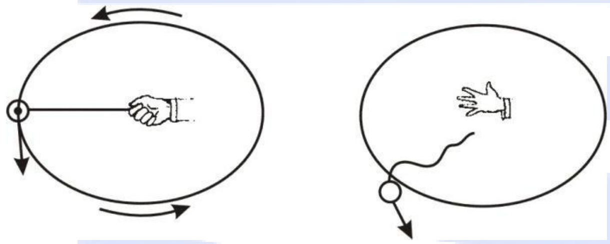
(iii) **Inertia of Direction :** The tendency of a body to oppose any change in its direction of motion is known as inertia of direction.

Examples of inertia of direction

(a) **When a fast moving bus negotiates a curve on the road, passengers fall towards the centre of the curved road.** This is due to the tendency of the passengers to continue to move in a straight line.

(b) **The sparks produced during sharpening of a knife** against a grinding wheel leave the rim of the wheel tangentially. This is because of the inertia of direction.

(c) **A stone tied to a string is whirling in a horizontal circle. If the string breaks, the stone flies away tangentially.** The stone moving in a circular path has the direction of motion along the tangent at any point of the circle. The pull of hand keeps it in a circular path. As soon as the string breaks, the force acting on the string ceases and the stone continues to move along the tangent of the point of the circle due to inertia of direction.



(d) **An umbrella protects us from rain.** It is based on the property of inertia of direction. The rain drops falling vertically cannot change their direction of motion on their own and wet us, with umbrella on, they move along the surface of umbrella and fall down.

2.3 MOMENTUM

To understand its meaning, let us recount some observations from our everyday life:

(i) During the game of table-tennis, if the ball hits a player, it does not hurt him. On the other hand, when a fast moving cricket ball hits a spectator, it may hurt him. This is because cricket ball is much heavier than the table tennis ball.

(ii) A truck at rest does not require any attention when parked along a roadside. But a moving truck, even at speed as low as 5 m/s, may kill a person standing in its path. This is because of heavy mass of the truck.

(iii) A bullet of small mass may kill a person when fired from a gun.

These observations suggest that the impact produced by the objects depends on their mass and velocity. Therefore, there must be some quantity that combines mass of a body and velocity of the body.

One such quantity called momentum was introduced by Newton. The momentum, *p*, of an object is defined as the product of its mass and velocity.

Momentum = Mass × Velocity

That is,

$P = m \times v$

Where p = Momentum

m = Mass

v = Velocity

It is a vector quantity as it has both direction and magnitude. Its direction is same as that of velocity.

The SI unit of momentum is kilogram metre per second (Kg ms^{-1})

2.4 NEWTON'S SECOND LAW OF MOTION

According to this law, the rate of change of momentum of an object is proportional to the applied unbalanced force in the direction of force.

Now, Rate of change of momentum $= \dfrac{\text{change in momentum}}{\text{time taken for the change}}$

So, according to this law,

$$\frac{\text{change in momentum}}{\text{time taken}} \propto \text{force applied}$$

2.4.1 Mathematical formulation of Newton's second law of motion

Suppose of an object

m = mass

u = initial velocity along a straight line

F = constant external force

t = time for which the force is applied

v = final velocity along the same straight line after time, t.

Initial momentum of the object, $p_1 = mu$

Final momentum of the object, $p_2 = mv$

Change in the momentum = $p_2 - p_1$

$= mv - mu$

$= m(v - u)$

Rate of change of momentum $= \dfrac{\text{change in momentum}}{\text{time taken}}$

$$= \frac{m(v-u)}{t} \qquad \ldots\text{(i)}$$

But we know

$$\frac{v-u}{t} = \frac{\text{change in velocity}}{\text{time taken}}$$

= rate of change of velocity
= acceleration of the object (a)

i.e. $\frac{v-u}{t} = a$ …(ii)

Putting $\frac{v-u}{t} = a$ from equation (ii) into (i)

We get,
Rate of change of momentum = $m \times a$
According to Newton's second law of motion rate of change of linear momentum ∝ Force applied

∴ $m \times a \propto F$
or $F \propto m\,a$
or $F = k\,m\,a$

Where k is a constant of proportionality. The value of constant k in S.I. units is 1, so the above equation becomes :

$F = m \times a$

or Force = mass × acceleration

The S.I. unit of force is Newton which is denoted by N. A Newton is that force which when acting on a body of mass 1 kg produces an acceleration of 1 m/s^2 in it.

We know $F = m \times a$

IN = 1 kg × 1 m/s^2

The second law of motion gives us a method to measure the force acting on an object as a product of its mass and acceleration.

2.4.2 Applications of Newton's second law of motion

Some of our day-to-day observations can be explained in terms of Newton's second law of motion.

As $F = ma = \frac{m\,(v-u)}{t}$

∴ the force F can be reduced by increasing the time taken t for the change in momentum of the body. For example :

(i) Catching a cricket ball : To catch a fast cricket ball, a player pulls his hands backwards to prevent injury to his hands. By doing so, the player increases the time during which high velocity of the cricket ball reduces to zero. Thus, the acceleration of the ball $a = \frac{(v-u)}{t}$ is decreased, and therefore, the impact of catching the fast ball (i.e., $F = ma$) is reduced, i.e., the player has to apply a smaller force against the ball in order to stop it. The ball, in turn, exerts a smaller force on his hands and the hands are not injured.

If the ball was stopped suddenly, the high velocity of the ball would be reduced to zero in a very short interval of time, *t*. Therefore, rate of change of linear momentum of the ball would be large, and therefore, a large force would have to be applied for holding the catch. The hands of the player would be hurt.

(ii) High Jump : In the athletic event 'High Jump', the athletes are made to fall either on a cushioned bed or on a sand bed. This is done to avoid injury to the athlete. Falling on a cushioned bed or on a sand bed will increase the time during which high velocity of the athlete would be reduced to zero. This would decrease the rate of change of momentum of the athlete and hence the force on the athlete. The injury to the athlete is thus avoided.

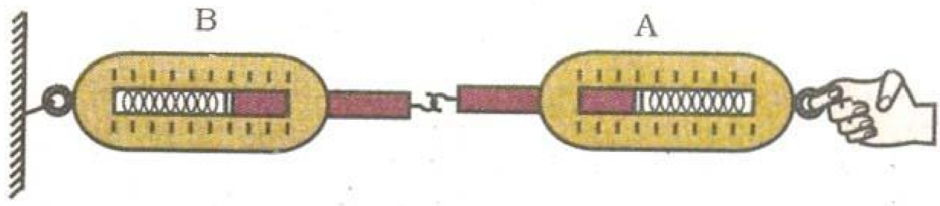
(iii) Use of seat belts in cars : All the cars these days are provided with seat belts for the passengers, which are rightly called safety belts. The purpose of seat belts is to prevent injuries to the passengers in case of an accident or in case of sudden application of brakes. In both the cases, the momentum of the car reduces to zero in a very short interval of time resulting in the development of a large force causing injuries. The stretchable safety belts worn by the passengers of the car exert a force on their body and make the forward motion slower. Thus, the time taken by the passengers to fall forward increases. Therefore, rate of change of momentum of passengers is reduced. Hence, the stopping force acting on the passengers is reduced. They may not get injuries at all or they may get away with minor injuries.

2.5 NEWTON'S THIRD LAW OF MOTION

The first law of motion tells us about force that how an applied force changes the motion. The second laws of motion provide us with a method of determining the force.

The third law of motion tells us about the nature of force.

According to third law, 'To every action, there is an equal and opposite reaction.' This means when one object exerts a force an another object, the second object instantaneously exerts a force back on the first. These two forces are always equal in magnitude but opposite in direction. These two forces act on **different objects** and never on the same object. The two opposing forces are also known as action and reaction forces. Let's study a simple experiment to prove Newton's third law of motion.



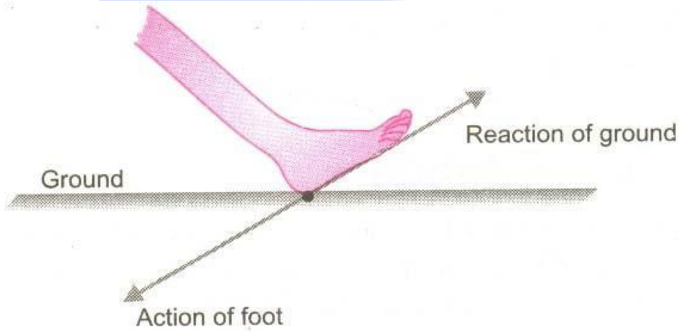
Action and reaction forces are equal and opposite

Let us consider two spring balances connected together as shown in figure. The fixed end of balance B is attached with a rigid support, like a wall. When a force is applied through the free end of spring balance A, it is observed that both the spring balance show the same readings on their scales. It means that the force exerted by spring balance A on balance B is equal but opposite in direction to the force exerted by the balance B on balance A. The force which balance A exerts on balance B is called the action and the force of balance B on balance A is called the reaction. It must be remembered that the action and reaction always act on two different objects.

2.5.1 Examples of Newton's Third Law of Motion

Some of our day-to-day observations can be explained in terms of Newton's third law of motion as follows :

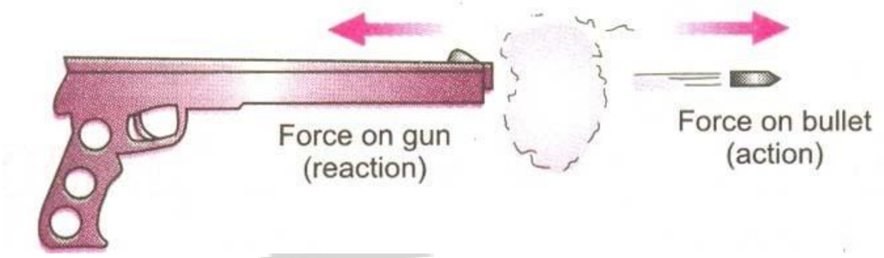
(i) Walking : To walk on the ground, we push the ground backwards with our foot. As a reaction, the ground pushes our foot forward with the same force. It is this forward reaction force of the ground that enables us to walk forward.



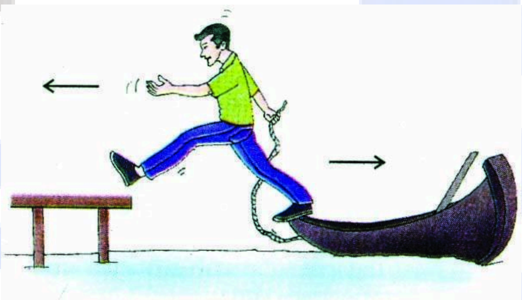
Walking becomes difficult when the ground is slippery or it is covered with snow or sand. This is because we can exert much smaller force in the form of backward action on the ground. The forward reaction of the ground will reduce accordingly.

(ii) Swimming : While trying to swim, a swimmer pushes the water backwards with his hands and feet. This is the force of action. The water pushes the swimmer forward with the same force (of reaction).

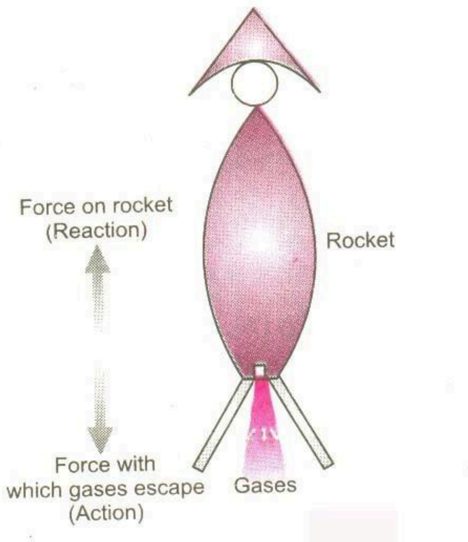
(iii) Recoiling of gun : When a bullet is fired from a gun, the gun recoils, *i.e.,* the gun moves backwards through a small distance, giving jerk to the shoulder of the gunman. This is because on firing, the gun exerts some force on the bullet (*i.e.,* action) in forward direction. In turn, the bullet exerts an equal force on the gun (*i.e.,* reaction) in the backward direction. The distance moved by the gun is small because gun is much heavier than the bullet, figure.



(iv) Man and boat : When a man jumps from the boat to the river bank, the boat is pushed away from the bank. This happens due to equal forces of action and reaction.



(v) The flying of rockets and jet planes : In a rocket and jet plane the fuel burnt appears in the form of hot and highly compressed gases. These are made to escape jet planes in the downward direction. As a reaction, the rocket moves upwards with the same force. The forces of action and reaction are shown in figure.



(vi) The case of hose pipe : To put out fire, the firemen direct a powerful stream of water on fire, from a hosepipe. While doing so, the hosepipe is to be held strongly because of its tendency to move backwards. As the water rushes out at a great speed from the hose pipe in the forward direction (action), the hosepipe tends to move backwards, due to an equal force of reaction.

2.5.2 Application of Third Law of Motion

(i) Recoil of a gun : When a bullet is fired from a gun, the gun recoils i.e. it moves backward.

The bullet inside the gun and the gun itself forms a system. Thus, the system is gun + bullet. Before firing, the gun and the bullet are at rest, therefore, momentum of the system is zero.

When the bullet is fired, it leaves the gun in the forward direction with certain momentum. Since no external force acts on the system, so the momentum of the system (gun + bullet) must be zero after firing. This is possible only if the gun moves backward with a momentum equal to the momentum of the bullet. This is why gun recoils or moves backward.

(ii) Rocket propulsion (Movement of a rocket in the upward direction) : Rocket works on the basis of the law of conservation of momentum.

The momentum of the rocket before it is fired is zero. When the rocket is fired, gases are produced in the combustion chamber of the rocket. 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. To conserve the momentum of the system (rocket + gases), the rocket moves upward with a momentum equal to the momentum of the gases.

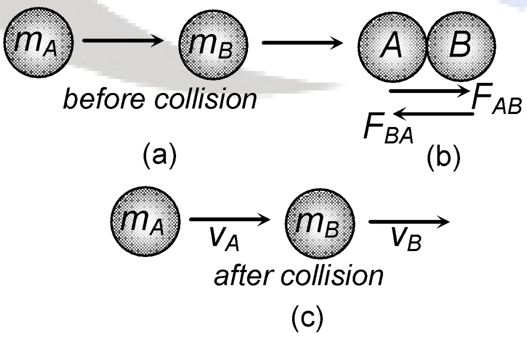
The rocket continues to move upward as long as the gases are ejected out of the rocket.

(iii) Inflated balloon lying on the surface of a floor moves forward when pierced with a pin : The momentum of the inflated balloon before it is pierced with a pin is zero. When it is pierced with a pin, air in it comes out with a speed in the backward direction. To conserve the momentum of the balloon, it moves in the forward direction.

2.6 LAW OF CONSERVATION OF MOMENTUM

According to this law, the total momentum of a system or a body remains constant if no net external force acts on the system. In other words, momentum is never created or destroyed. It has been deduced from Newton's third law of motion.

2.6.1 Proof of the law of conservation of momentum by ideal collision experiment.



Suppose two balls *A* and *B* are moving in the same direction along a straight line with different velocities.

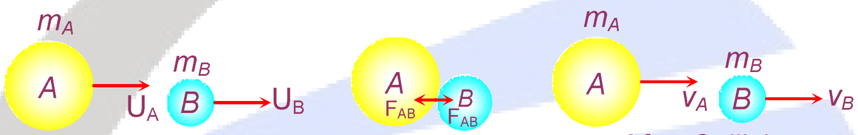
Let m_A = mass of ball A
m_B = mass of ball B
u_A = initial velocity of A
u_B = initial velocity of B

If $u_A > u_B$, the two balls collide with each other as shown in figure. Let this collision last for a short time t. During collision, suppose

F_{AB} = force exerted by A on B, and
F_{BA} = force exerted by B on A.

We shall assume that no other external unbalanced forces are acting on the balls.

After collision for t seconds, the balls move separately. Let
v_A = velocity of A after collision,
v_B = velocity of B after collision.



Before Collision (a) During Collision (b) After Collision (c)

Change in momentum of A = momentum of A after collision – momentum of A before collision

$$= m_A v_A - m_A u_A$$

Rate of change of momentum of $A = \dfrac{\text{change in momentum of } A}{\text{time taken}}$

$$= \frac{m_A v_A - m_A u_A}{t}$$

This is equal to force exerted by B on A, i.e., F_{BA} (as per Newton's second law of motion).

$$\therefore \quad F_{BA} = \frac{m_A v_A - m_A u_A}{t} \qquad \ldots\text{(i)}$$

Similarly, rate of change of momentum of $B = \dfrac{m_B v_B - m_B u_B}{t}$

This must be equal to force exerted by A on B, i.e., F_{AB}.

$$\therefore \quad F_{AB} = \frac{m_B v_B - m_B u_B}{t} \qquad \ldots\text{(ii)}$$

According to Newton's third law of motion, the force F_{AB} exerted by ball A on ball B (say, action) and the force F_{BA} exerted by ball B on ball A, (the reaction) must be equal and opposite to each other. Therefore, $F_{AB} = -F_{BA}$

Using equations (i) and (ii), we get

$$\frac{m_B v_B - m_B u_B}{t} = -\frac{(m_A v_A - m_A u_A)}{t}$$

or $m_B v_B - m_B u_B = -m_A v_A + m_A u_A$

$$\boldsymbol{m_B v_B + m_A v_A = m_B u_B + m_A u_A} \quad \text{...(iii)}$$

Now, $(m_A v_A + m_B v_B) =$ total momentum of the two balls after collision, and

$(m_B u_B + m_A u_A) =$ total momentum of the two balls before collision.

Therefore, equation (iii) shows that total momentum of the two balls remains unchanged on collision, i.e., total linear momentum is conserved and is not affected by the mutual action and reaction of the balls. This is the law of conservation of linear momentum.

2.6.2 Applications of The Law of Conservation of Momentum

As the law of conservation of (linear) momentum has been deduced from Newton's third law of motion, therefore, all the applications/examples of Newton's third law of motion can be explained in terms of the law of conservation of momentum.

(a) For example, ***flight of jet planes and rockets*** can be understood in terms of the law of conservation of momentum. Before firing, the momentum of the rocket is zero. On firing, the burnt gases rush out through the nozzle in the downward direction. The rocket moves such that
Momentum of rocket + momentum of escaping gases = 0.

∴ momentum of rocket = – momentum of escaping gases.

(b) Similarly the case of the gun can also be understood
Let
m_1 = mass of bullet,
m_2 = mass of gun,
v_1 = velocity of bullet,
v_2 = velocity of gun,
Total momentum of bullet and gun on firing = $m_1v_1 + m_2v_2$
Before firing, both the gun and the bullet are at rest, therefore total momentum of bullet and gun = 0.
As no external forces are involved in the process, therefore, applying the law of conservation of momentum,
$m_1v_1 + m_2v_2 = 0$

$$m_2v_2 = -m_1v_1$$

$$\boldsymbol{v_2 = -\frac{m_1v_1}{m_2}}$$

Negative sign in equation shows that v_2 is in a direction opposite to v_1, i.e., the gun recoils or moves backwards when the bullet moves forward. Further, as $m_2 >> m_1$, therefore, $v_2 << v_1$, i.e., as the gun is much heavier than the bullet, **the recoil velocity of the gun is much smaller than the velocity of the bullet.**