Chapter 3

Dynamics

Student Learning Outcomes

After completing this chapter, students will be able to:

- Illustrate that mass is a measure of the quantity of matter in an object
- Explain that the mass of an object resists change from its state of rest or motion (inertia)
- Describe universal gravitation and gravity. State Newton's Law of gravitation. (Include problems related to gravitation.)
- Define and calculate weight [Weight is the force exerted on an object having mass by a planet's gravity, and use $w = mg$]
- Define and calculate gravitational field strength [This includes being able to state that a gravitational field is a region in which a mass experiences a force due to gravitational attraction. Students should be able to define gravitational field strength (g) as force per unit mass use the equation gravitational field strength = weight/mass $g = w/m$ (and know that this is equivalent to the acceleration of free fall)]
- Justify and illustrate the use of mechanical and electronic balances to measure mass [understanding the internal workings of the electronic balance is not required; just how to practically use the instrument in appropriate situations]
- Justify and illustrate the use of a force meter (spring balance) to measure weight.
- Differentiate between contact and noncontact forces
- Differentiate between different types of forces [including weight (gravitational force), friction, drag, air resistance, tension (elastic force), electrostatic force, magnetic force, thrust (driving force), and contact force]
- State that there are four fundamental forces and describe them in terms of their relative strengths [These are the gravitational, electromagnetic, strong and weak nuclear forces. Students should know that Pakistani Scientist won the Nobel Prize for helping prove that the weak force and the electromagnetic force are actually unified]
- Represent the forces acting on a body using free body diagrams
- State and apply Newton's first law
- Identify the effect of force on velocity [It may change the velocity of an object by changing its direction of motion or its speed]
- Determine the resultant of two or more forces acting in the same plane.
- State and apply Newton's second law in terms of acceleration
- State and apply Newton's third law
- Explain with examples how Newton's third law describes pairs of forces of the same type acting on different objects
- State the limitations of Newton's laws of motion
- Analyse the dissipative effect of friction
- Analyse the dynamics of an object reaching terminal velocity
- Differentiate qualitatively between rolling and sliding friction
- Justify methods to reduce friction.
- Define and calculate momentum
- Define and calculate impulse [Use the equation Impulse= $F\Delta t = m\Delta V$]
- Apply the principle of the conservation of momentum to solve simple problems in one dimension
- Define resultant force in terms of momentum.

In kinematics, we studied the motion of objects. If the position, velocity and acceleration were known at any time, then the position and velocity of the moving body at another time could be completely described. But one of the things left out of this discussion was the cause of acceleration produced in the body. If a stone is dropped from a height, it is accelerated downward. It is because the Earth exerts a force of gravity on the stone that pulls it down. When we drive a car or motorcycle, the engine exerts a force which produces acceleration. We will observe that whenever there is acceleration, there is always a force present to cause that acceleration. Dynamics is concerned with the forces that produce change in the motions of bodies.

3.1 Concept of Force

A common concept of a force is a push or a pull that starts, stops or changes the magnitude and direction of velocity of a body. We come across many forces in our daily life. Some of them we apply on other bodies and some are acting on us. For example, when we open a door, we push or pull it by applying force. When we are sitting in a car, we push against the seat as the car turns round a corner.

Fig. 3.1

Force transfers energy to an object. Take the example of a man who moves a wheelbarrow with its load. The man first applies force to lift it and then applies force to push it (Fig.3.1). He applies a different amount of force on each handle when turning the wheelbarrow around the corner in order to keep it from tipping over. The examples of forces acting on us are the force of gravity acting downward, the force of friction which helps us to walk on the ground and many others.

Types of Forces

There are two major types of forces:

1. Contact Forces **2. Non-contact Forces**

1. Contact Forces

A contact force is a force that is exerted by one object on the other at the point of contact. Applied forces (push a pull and twist) are contact forces. Some other examples of contact forces are the following:

(i) Friction

It is the force that resists motion when the surface of one object comes in contact with the surface of another.

(ii) Drag

The drag force is the resistant force caused by the motion of a body through a fluid. It acts opposite to the relative motion of any object moving with respect to surrounding fluid.

(iii) Thrust

It is an upward force exerted by a liquid on an object immersed in it. When we try to immerse an object in water, we feel an upward force exerted on the object. This force increases as we push the object deeper into the water. A ship can float in the sea due to this force which balances the weight of the ship.

(iv) Normal Force

It is the force of reaction exerted by the surface on an object lying on it. This force acts outward and perpendicular to the surface. It is also called the support force upon the object.

(v) Air Resistance

It is the resistance (opposition) offered by air when an object falls through it.

(vi) Tension Force

It is the force experienced by a rope when a person or load pulls it.

(vii) Elastic Force

It is a force that brings certain materials back to their original shape after being deformed. Examples are rubber bands, springs, trampoline, etc.

2. Non-contact Forces

A non-contact force is defined as the force between two objects which are not in physical contact. The non-contact forces can work from a distance. That is why, these are sometimes called as action-at-a-distance. There is always a field linked with a non-contact force. Due to this property, non-contact forces are also called field forces. A few examples of non-contact forces are described below:

(i) Gravitational Force

An apple falling down from a tree is one of the best examples of gravitational force (Fig. 3.2). When we throw an object upward, it is the gravitational force of the Earth that brings it back to the Earth. In fact, the gravitational force is an attractive force that exists among all bodies which have mass. It is a long-range force given by Newton's law of gravitation:

$$F = G\frac{m_1 m_2}{r^2}$$ where m_1 and m_2 are two masses distant r apart and G is constant of gravitation. Its value is $6.67 \times 10^{-11}\ \mathrm{N\,m^2\,kg^{-2}}$. The Sun's gravitational force keeps the Earth and all other planets of our solar system in fixed orbits.

Fig. 3.2

Similarly, the gravitational force of the Earth keeps the moon in its orbit. It also keeps the atmosphere and oceans fixed to the surface of the Earth. Even an object resting on a surface exerts a downward force called its weight due to attractive force of the Earth also known as gravity.

(ii) Electrostatic Force

An electrostatic force acts between two charged objects. The opposite charges attract each other and similar charges repel each other as shown in Fig. 3.3. Like gravitational force, electrostatic force is also a long-range force.

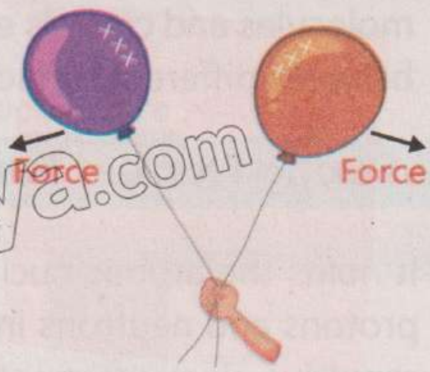


Fig. 3.3

(iii) Magnetic Force

It is a force which a magnet exerts on other magnets and magnetic materials like iron, nickel and cobalt. You might have observed that iron pins attracted in the presence of a magnet without any physical contact (Fig. 3.4). Magnetic force between the poles of two magnets can be either attractive or repulsive. This can be observed very easily by bringing different poles of two magnets close to each other. Like poles repel and unlike poles attract each other.

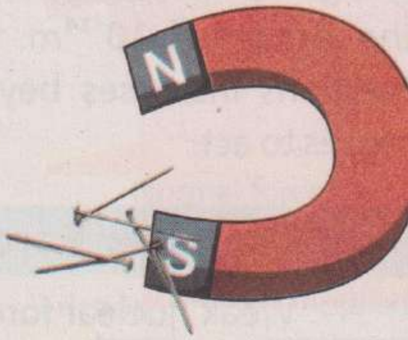


Fig. 3.4

(iv) Strong and Weak Nuclear Forces

These are also non-contact forces acting between the subatomic particles. We will study these forces in the next section.

3.2 Fundamental Forces

There are four fundamental forces in nature. These are:

1. Gravitational force
2. Electromagnetic force
3. Strong nuclear force
4. Weak nuclear force

Every force comes under any of these forces.

Gravitational Force

The gravitational force has been discussed in the previous section. We often talk about this force. It is the weakest one among all four forces. Being a long range force, it extends to infinite distance although it becomes weaker and weaker.

Electromagnetic Force

It is the force that causes the interaction between electrically charged particles. Electrostatic and magnetic forces come under this category. These are long-range forces. The areas in which these forces act are called electromagnetic fields. Electromagnetic forces are stronger than gravitational and weak

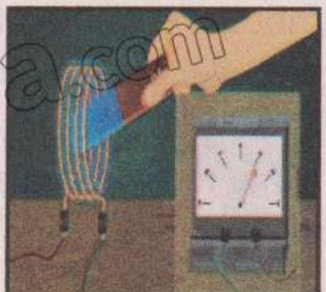


Fig. 3.5
A moving magnet produces electric current

nuclear forces. This force causes all chemical reactions. It binds together atoms, molecules and crystals etc. At macroscopic level, it is a possible cause of friction between different surfaces in relative motion.

Strong Nuclear Force

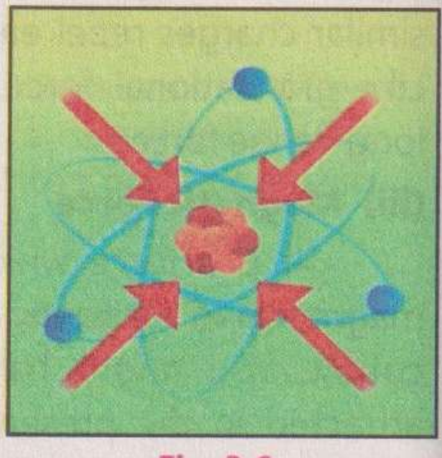


Fig. 3.6
The binding force of protons and neutrons in the nucleus

It holds the atomic nuclei together by binding the protons and neutrons in the nucleus over coming repulsive electromagnetic force between positively charged protons. It is also a short-range force with the order of 10^{-14}m. If the distance between nucleons increases beyond this range, this force ceases to act.

Weak Nuclear Force

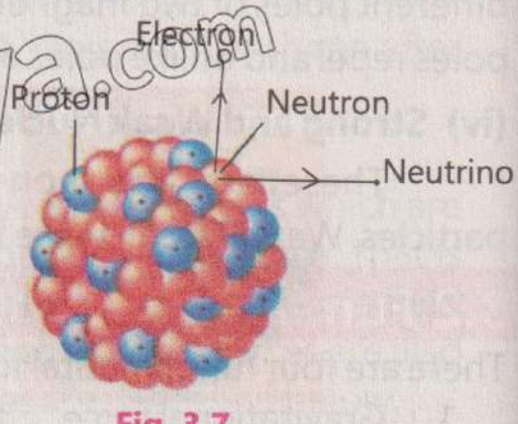


Fig. 3.7

Weak nuclear force is responsible for the disintegration of a nucleus. For example, the weak nuclear force executes the β-decay (beta decay) of a neutron, in which a neutron transforms into a proton (Fig.3.7). In the process, a β-particle (electron) and an uncharged particle called antineutrino are emitted. In other words, we can say that due to weak nuclear force radioactive decay of atoms occurs. However, weak nuclear force is stronger than the gravitational force but weaker than the electromagnetic force. It is a short-range force of the order 10^{-17} m.

Unification of Weak Nuclear and Electromagnetic Forces

A Pakistani scientist Dr. Abdus Salam along with Sheldon Glashow and Steven Weinberg were awarded in 1979 Nobel Prize in Physics for their contributions to the unification of the weak nuclear force and electromagnetic force as electroweak force. Although these two forces appear to be different in everyday phenomena, but the theory models them as two different aspects of the same force. Its effects are observed for the interactions taking place at very high energy.

3.3 Forces in a Free- Body Diagram

External forces acting on an object may include friction, gravity, normal force, drag, tension in a string or a human force due to pushing or pulling.

Suppose a book is pushed over the surface of a table top as shown in Fig.3.8(a). Then how can we represent the forces acting on the body using free-body diagram?

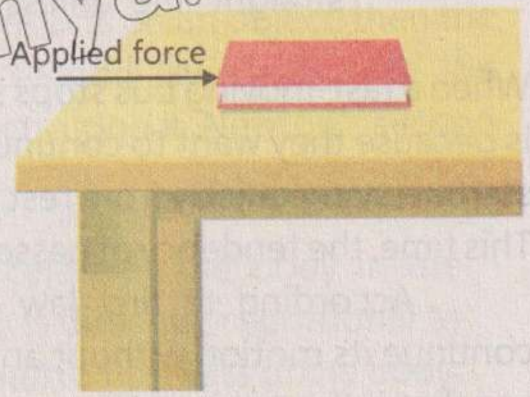


Fig. 3.8 (a)

Free-body diagrams are used to show the relative magnitudes and directions of all the forces acting on an object in a given situation. In other words, a free-body diagram is a special example of the vector diagrams.

Usually, the object is represented by a box and the force arrows are drawn outward from the centre of the box in the directions of forces as shown in Fig.3.8(b). The length of a force arrow (line) reflects the magnitude of the force and the arrow head indicates the direction in which the force acts. Each force is labelled to indicate the exact type of force.

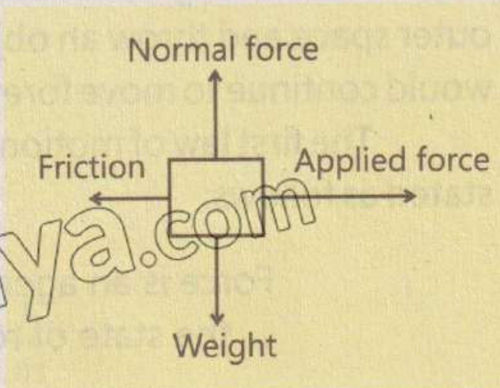


Fig. 3.8 (b)

3.4 Newton's Laws of Motion

Newton's First Law of Motion

It is our common observation that a force is required to move or to stop a body. A book placed on a table remains there unless a force is applied to move it (Fig.3.9). A ball rolling on floor should continue to move with the same velocity in the absence of an applied force. But practically, we see that it is not true. The ball stops after covering some distance. In fact, an opposing force (friction) causes the ball to stop. Newton expressed such observations in his first law of motion which states that:

Do You Know?

Sir Isaac Newton was born in Lincolnshire on January 4, 1643. The name of his famous book is "Principia Mathematica".

Fig. 3.9

A body continues its state of rest or of uniform motion in a straight line unless acted upon by some external force.

When a fast-moving bus stops suddenly, the passengers tend to bend forward. It is because they want to continue their motion. On the other hand, when the bus starts moving quickly from rest, the passengers are pushed back against the seat. This time, the tendency of passengers is to retain their state of rest.

According to first law of motion, a bus moving on the road should continue its motion without any force exerted by the engine. But practically, we see that if the engine stops working, the bus comes to rest after covering some distance. It is because of the friction between the tyres of the bus and the road. All the bodies moving on the Earth are stopped by the force of friction. If you were in outer space and throw an object away where no force is acted upon it, the object would continue to move forever with constant velocity.

The first law of motion also provides us another definition of force which is stated as follows:

Force is an agency which changes or tends to change the state of rest or of uniform motion of a body.

In simple words, we can say that force causes acceleration.

Inertia

A net force is required to change the velocity of objects. For instance, a net force may cause a bicycle to pick up speed quickly. But when the same force is applied to a truck, any change in the motion may not be observed. We say that the truck has more inertia than a bicycle. The **mass** of an object is a measure of its inertia. The greater the mass of an object, the greater is its inertia.

The property of a body to maintain its state of rest or of uniform motion in a straight line is called inertia.

As a result of the role of inertia in Newton's first law, this law is sometimes called as law of inertia.

A Demonstration of Property of Inertia

When the table cloth is pulled abruptly, the objects remain in their original position on the table.

Newton's Second Law of Motion

Newton's first law indicates that if no net force acts on an object, then the velocity of the object remains unchanged. The second law deals with the acceleration produced in a body when a net force acts upon it. Newton's second law can be stated as:

If a net external force acts upon a body, it accelerates the body in the direction of force. The magnitude of acceleration is directly proportional to the magnitude of force and is inversely proportional to the mass of the body.

If a net force of magnitude *F* acts on a body of mass *m* and produces an acceleration of magnitude *a*, then the second law can be written mathematically as:

$$a \propto F$$

and

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

So

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

or

$$a = (\text{constant}) \frac{F}{m}$$

According to SI units, if $m = 1$ kg, $a = 1\ \text{m s}^{-2}$, $F = 1$ N, then the value of the constant will be 1. Therefore, the above equation can be written as:

$$a = 1 \times \frac{F}{m}$$

or

$$F = m\,a \qquad \text{.......(3.1)}$$

First law of motion provides the definition of force, i.e., a force produces an acceleration in a body. By the second law of motion ($F = ma$), we can calculate mathematically, the amount of force required to produce a certain amount of acceleration in a body of known mass. The SI unit of force is newton (N).

One newton is the force which produces an acceleration of $1\ \text{m s}^{-2}$ in a body of mass 1 kg.

From Eq 3.1 $\quad 1\ \text{N} = 1\ \text{kg m s}^{-2}$

Effect of Force on Velocity

Newton's second law also tells that a force can change the velocity of a body by producing acceleration or deceleration in it. As velocity is a vector quantity, so the change may be in its magnitude, direction or in both of them.

Newton's Third Law of Motion

Whenever there is an interaction between two bodies A and B, such that the body A exerts a force on body B, the force is known as action of A on B. In response to this action, the body B exerts a force on the body A. This force is known as reaction of B on A. For example, when we press a spring, the force exerted by our hand on the spring is action. Our hand also experiences a force exerted by the spring. This is the force of reaction (Fig.3.10). Newton expressed these action and reaction forces in his third law of motion. It is stated as:

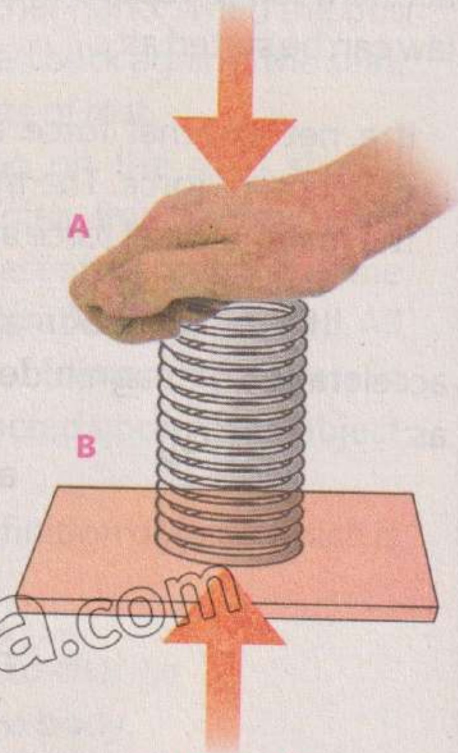


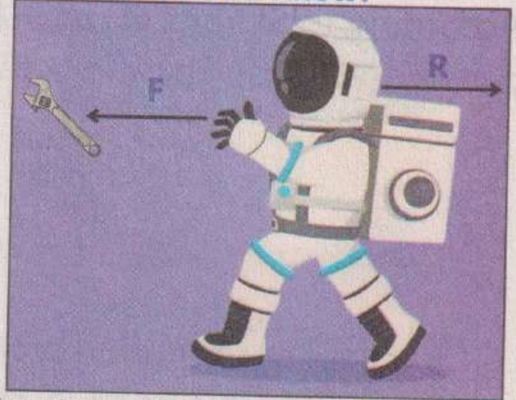
Fig. 3.10

For every action, there is always an equal and opposite reaction.

Since, action and reaction do not act on the same body but they act on two different bodies, so they can never balance each other. Thus, Newton's third law can also be expressed as follows:

If one body exerts a force on a second body, the second body also exerts an equal and opposite force on the first body.

Do You Know?



In space, an astronaut throws a wrench, as a reaction he moves in opposite direction.

Forces Act in Pairs

We have studied that forces act in pairs when two objects interact, i.e., action and reaction forces. We often notice a force that seems to make something happen but usually we do not notice the other force involved. Here are some examples of pairs of forces involved in accordance with Newton's third law of motion.

(i) Consider a block lying on a table as shown in Fig. 3.11.

The force acting downward on the block is the weight. The block exerts a downward force on the table equal to its weight **w**. The table also exerts a reaction force $\mathbf{F_n}$ on the block. The two forces on the block balance each other and the block remains at rest.

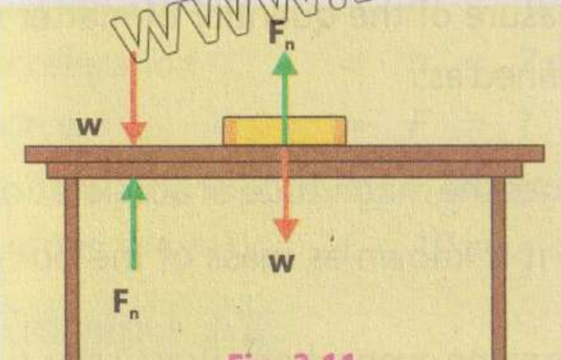


Fig. 3.11

Fig. 3.12

(ii) When a bullet is fired from a gun, the bullet moves in the forward direction with a force **F**. This is the force of action. The gun recoils in the backward direction with a reaction force **R** (Fig. 3.12).

3.5 Limitations of Newton's Laws of Motion

We have already explained that Newton's laws of motion can be applied with very high degree of accuracy to the motion of objects and velocities which we come across in everyday life.

The problems arise when we deal with the motion of elementary particles having velocities close to that of light. For that purpose, relativistic mechanics developed by Albert Einstein is applicable.

After all this discussion, we can say that Newton's laws of motion are not exact for all types of motion, but provide a good approximation, unless an object is small enough or moving close to the speed of light.

Mini Exercise

Look at the photographs below. Identify the pairs of forces acting in each photograph.

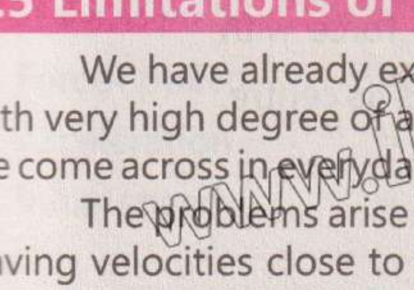


Fig. 3.13

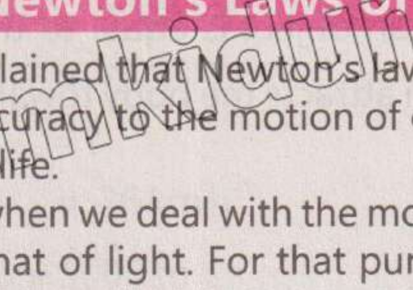


Fig. 3.14

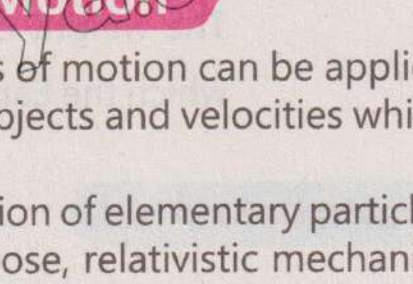


Fig. 3.15

3.6 Mass and Weight

Commonly, we consider mass and weight as the same quantities but scientifically, mass and weight are two different quantities. When we say that the weight of this object is 5 kg, it is not true. In fact, 5 kg is the mass of the object. The simplest definition of mass is that it is a measure of the quantity of matter in a body. Scientifically, mass of a body can be defined as:

The characteristic of a body which determines the magnitude of acceleration produced when a certain force acts upon it is known as mass of the body.

Mass is a scalar quantity. It remains the same everywhere. Practically, mass is measured by an ordinary balance. The SI unit of mass is kilogram (kg).

Weight is a gravitational force acting on the object. It is a vector quantity directed downward, towards the centre of the Earth.

The weight of an object is equal to the force with which the Earth attracts the body towards its centre.

Gravitational Field

The gravitational field is a space around a mass in which another mass experiences a force due to gravitational attraction. The gravitational field strength is defined as the gravitational force acting on unit mass. Thus, mass m on the surface of the Earth exerts a force known as its weight $\mathbf{w}$ given by $\mathbf{w} = m\,\mathbf{g}$, where $\mathbf{g}$ is the gravitational field strength. Its value is 10 N kg^{-1}.

As the value of **g** varies from place to place and also with altitude, therefore, the value of weight does not remain the same everywhere.

It varies from place to place according to variation in **g**. Though an object's weight may vary from one place to another, but at any particular location, its weight is proportional to its mass. Thus, we can conveniently compare the masses of two objects at a given location by comparing their weights. The weight cannot be measured by an ordinary balance. A spring balance can be used to measure the weight. The SI unit of weight is newton (N).

Example 3.1

A 10 kg block moves on a frictionless horizontal surface with an acceleration of $2\ m\ s^{-2}$. What is the force acting on the block?

Solution

Mass of a block $= m = 10\ kg$

Acceleration $= a = 2\ m\ s^{-2}$

Force $= F = ?$

By Newton's second law of motion, $F = ma$

Putting the values, $F = 10\ kg \times 2\ m\ s^{-2} = 20\ kg\ m\ s^{-2} = 20\ N$

Example 3.2

A force of 7500 N is applied to move a truck of mass 3000 kg. Find the acceleration produced in the truck. How long will it take to accelerate the truck from $36\ km\ h^{-1}$ to $72\ km\ h^{-1}$ speed?

Solution

Mass of truck $= m = 3000\ kg$

Force applied $= F = 7500\ N$

Acceleration $= a = ?$

Initial speed $= v_i = 36\ km\ h^{-1}$

$$= \frac{36 \times 1000\ m}{60 \times 60\ s} = 10\ m\ s^{-1}$$

Final speed $= v_f = 72\ km\ h^{-1} = \frac{72 \times 1000\ m}{60 \times 60\ s} = 20\ m\ s^{-1}$

Time $= t = ?$

By Newton's second law, $F = ma$

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

Putting the values, $a = \frac{7500\ N}{3000\ kg} = 2.5\ m\ s^{-2}$

Now, using first equation of motion,

$$v_f = v_i + at$$

or $t = \frac{v_f - v_i}{a}$

Putting the values, $t = \frac{20\ m\ s^{-1} - 10\ m\ s^{-1}}{2.5\ m\ s^{-2}} = 4\ s$

3.7 Mechanical and Electronic Balances

Balance scales are commonly used to compare masses of objects or to weigh objects by balancing them with standard weights.

Mechanical Balances

A mechanical balance consists of a rigid horizontal beam that oscillates on a central knife edge as a fulcrum. It has two end knife edges equidistant from the centre. Two pans are hung from bearings on the end knife edges (Fig.3.16). The material to be weighed is put in one pan. Standard weights are put on the other pan. The deflection of the balance may be indicated by a pointer attaches to the beam. The weights on the pan are adjusted to bring the beam in equilibrium.

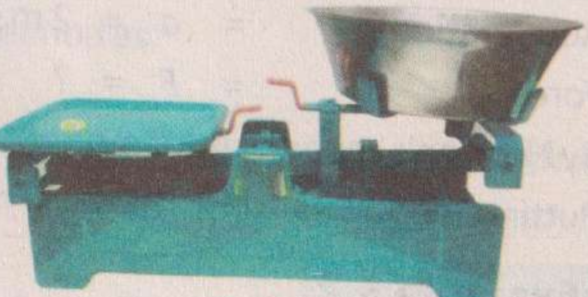


Fig. 3.16

There is another type of mechanical balances which are used to weigh heavy items like flour bags, cement bags, steel bars, etc. These are called mechanical platform balances (Fig.3.17). Standard weights are not required to use this balance. Its reason is that the fulcrum of the beam of such a balance is kept very near to its one end. Therefore, much smaller weights have to be put at the other end of beam to bring it to equilibrium. These smaller weights have already been calibrated to the standard weights.

Fig. 3.17

Electronic Balances

No standard weights are required to use in an electronic balance (Fig.3.18). Only it has to be connected to a power supply. There are some models which can operate by using dry cell batteries. An electronic balance is more precise than mechanical balance. When an object is placed on it, its mass is displayed on its screen. Now-a-days,

Fig. 3.18

electronic balances also display the total price of the material if the rate per kg is fed to the balance.

Force Meter

A force meter is a scientific instrument that measures force. It is also called as a newton meter or a spring balance (Fig.3.19). Now-a-days digital force meters are also available. You have already learnt about mechanical and electronic balances. They measure mass of the objects in kilograms or its multiples. On the other hand, force meter measures force directly in newtons (N).

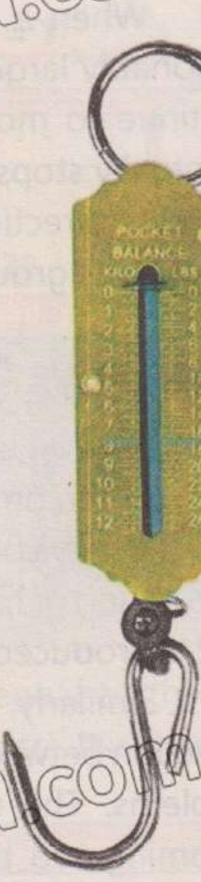


Fig. 3.19

An ordinary force meter has a spring inside it. Upper end of the spring is attached to a handle. A hook is attached to the lower end the spring that holds the object. A pointer is also attached to the spring at its upper end. A scale in newtons is provided along the spring such that the pointer coincides with zero of the scale when nothing is hung with the hook.

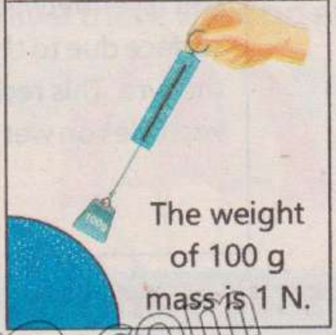
The object to be weighed is hung with the hook. The mass of the object causes the spring to compress. The pointer indicates the weight of the object. However, some force meters are also based on the stretching of the spring when a load is hung. In this case, the pointer is attached at the lower end of the spring.

In some spring balances, the scale measures the mass which can be readily converted into newtons by multiplying the mass in kg with the value of $g = 10\,m\,s^{-2}$.

A digital force meter measures directly the weight of the object in newtons (Fig. 3.20).

Fig. 3.20

Do You Know?



The weight of 100 g mass is 1 N.

3.8 Friction

When a cricket ball is hit by the bat, it moves on the ground with a reasonably large velocity. According to Newton's first law of motion, it should continue to move with constant velocity. But, practically, we observe that it eventually stops after covering some distance. Does any force act on the ball in opposite direction that stops the ball? Yes, it is the force of friction between the ball and the ground that opposes the motion of the ball.

Dissipative Effect of Friction

Friction is a dissipative force due to which the energy is wasted in doing work to overcome against friction. The lost energy appears in the form of heat.

A very common example of energy dissipation is the rubbing of hands (Fig.3.21). When we rub our hands, heat is produced due to friction and our hands become warm. Similarly, the temperature of machines rises due to friction between its moving parts that can cause many problems. The tyres of vehicles also wear out after becoming too hot due to friction between tyres and road.

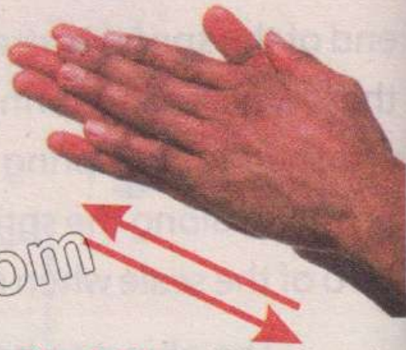


Fig. 3.21 Rubbing hands

Shooting of stars seen in the sky at night also happen due to friction of air. These are actually asteroids that enter the Earth's atmosphere. As they are moving, air resistance causes generation of heat. Their temperature becomes so high that they start burning and ultimately disintegrate.

Do You Know?

On a wet road, the water does not form wet layer between the tyre surface and the road surface due to the spaces in the tread pattern on the tyre. This reduces the chances of skidding of vechicles on wet roads.

Sliding Friction

The friction between two solid surfaces is called sliding friction which can be divided into two categories.

1. Static friction   2. Kinetic friction

Static Friction

Let us consider the motion of a block on a horizontal surface. The arrangement is shown in Fig. 3.22. When a weight is put in the pan, a force **F** = **T** equal to the sum of this weight and weight of the pan acts on the block. This force tends to pull the block. At the same time an opposing force appears that does not let the block move. This opposing force is the static friction $\mathbf{F}_s$.

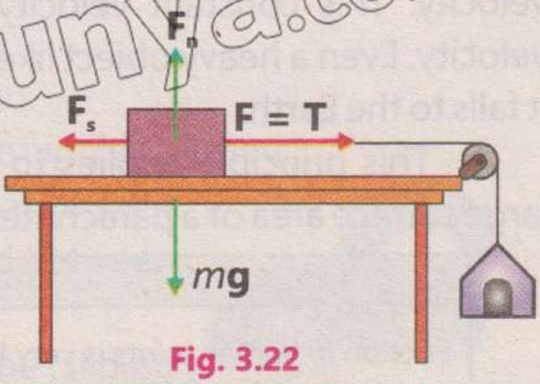


Fig. 3.22

For Your Information!

Some frogs can cling to a vertical surface, such as this leaf, because of the static friction between their feet and the surface.

Kinetic Friction

If we go on adding more weights in the pan one by one in small steps, a stage will come when the block starts sliding on the horizontal surface. This is the limit of static friction that is equal to the total weights including pan. When the block is sliding, friction still exists. It is known as kinetic friction.

Do You Know?
When a shuttle re-enters the Earth's atmosphere, the friction caused by the atmosphere raises the surface temperature of the shuttle to over 950°C.

Terminal Velocity

When an object falls freely, it is accelerated by an amount $g = 10\ \text{m s}^{-2}$. But practically the acceleration may be different. Air resistance plays an important role in determining how fast an object accelerates when it falls.

If we drop a cricket ball and a piece of Styrofoam of the same weight from a certain height, they will hit the ground at the same time only if there were no air resistance. Both would fall with the same acceleration $g = 10\ \text{m s}^{-2}$. Practically, the ball in air, would drop faster. The Styrofoam having larger surface would face greater opposing force of the air and thus moves slowly.

Experiments have been made in this respect and it was found that the faster an object falls the more air resistance will be exerted on it. A speed is finally attained at which the upward force of air resistance balances the downward force of gravity. When this happens, the object stops accelerating. It keeps falling at a constant

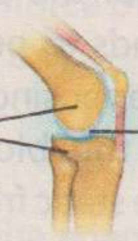
Fig. 3.23
A paratrooper falling with terminal velocity

velocity. This constant velocity achieved by an object is called its terminal velocity. Even a heavy object like a meteorite does not gain an infinite velocity as it falls to the Earth.

This principle applies to paratroopers. Air resistance acting against the large surface area of a parachute allows for descent at a safer velocity (Fig.3.23).

Do You Know?

Friction in human joints is very low because our bodies contain a natural lubricating system. Consequently,, though our bones rub against each other at the points as we move, yet bones do not normally wear out, even after many years of use.



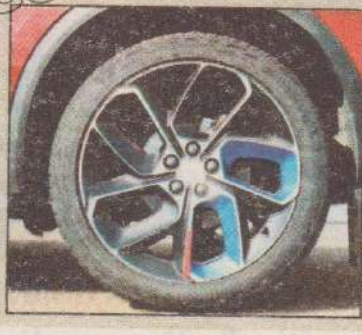
Knee joint

Rolling Friction

The static and kinetic friction which we have studied so far is the sliding friction. There is another type of friction which is called rolling friction. When an object rolls over a surface, the friction produced is called rolling friction. The idea of rolling friction is associated with the concept of wheel. In our everyday life, we observe that a body with wheels faces less friction as compared to a body of the same size without wheels. Ball bearings also play the same role as is played by the wheels. Many machines in industry are designed with ball bearings so that the moving parts roll on the ball bearing and friction is greatly reduced. The rolling friction is about one hundred times smaller than the sliding friction.

For Your Information!

Practically, the contact point is not perfectly circular; it becomes flat under pressure as shown in figure. This flat portion of the wheel has the tendency to slide against the surface and does produce a frictional force.



The reason for the rolling friction to be less than the sliding friction is that there is no relative motion between the wheel and the surface over which it rolls. The wheel touches the surface only at a point. It does not slide.

For Your Information!

A hovercraft is a kind of ship that can move over the surface of water and ground both. Air is ejected underneath by powerful fans forming a cushion of air. The hovercraft moves over the cushion of air which offers very small resistance.

Methods to Reduce Friction

The following methods are used to reduce friction:

(i) The parts which slide against each other are highly polished.

(ii) Since, the friction of liquids is less than that of solid surfaces, therefore, oil or grease is applied between the moving parts of the machinery.

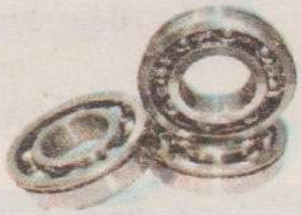


Fig. 3.24

(iii) As rolling friction is much less than the sliding friction, so sliding friction is converted into rolling friction by the use of ball bearings (Fig. 3.24) in the machines and wheels under the heavy objects.

(iv) Frictional force does not act only among solids, high speed vehicles, aeroplanes and ships also face friction while moving through air or water. If the front of a vehicle is flat, it faces more resistance by air or water. Therefore, the bodies moving through air or water are streamlined to minimize air or water friction. In this case, the air passes smoothly over the slanting surface of vehicle. This type of flow of air is known as streamline flow. A streamline flow over the car is shown in Fig. 3.25. The vehicles designed pointed from the front are said to be streamlined.

Fig. 3.25 Streamline air flow over a speedy car

3.9 Momentum and Impulse

Suppose that a bicycle rider and a heavy truck are moving with the same speed, which one can be stopped easily, depends on the quantity of motion of the moving body. It is our common observation that quantity of motion in a moving body depends on its mass and velocity. Greater is the mass, the greater will be the quantity of motion. Similarly, greater is the velocity, the greater will be quantity of motion. This quantity of motion is called momentum and denoted by *p*. It is defined as:

The momentum of a moving body is the product of its mass and velocity.

Therefore, $\mathbf{p} = m \times \mathbf{v}$ .... (3.2)

Like velocity momentum is also a vector quantity. The SI unit momentum is (kg m s^{-1}). It can also be written as (N s).

When a ball is hit by a bat, the force is exerted on the ball for a very short interval of time. In such cases, it is very difficult to calculate the exact magnitude of the force. However, initial velocity $\mathbf{v}_i$ of the ball and final velocity $\mathbf{v}_f$ after collision can be found easily.

During a time interval Δt, the average acceleration **a** is given by

$$\mathbf{a} = \frac{\Delta \mathbf{v}}{\Delta t} = \frac{\mathbf{v}_f - \mathbf{v}_i}{\Delta t} \quad \text{.......................} \quad (3.3)$$

According to Newton's second law of motion, the value of average force acting during the interval Δt will be:

$$\mathbf{F} = m\mathbf{a} = m\left(\frac{\Delta \mathbf{v}}{\Delta t}\right)$$

or

$$\mathbf{F} \times \Delta t = m(\Delta \mathbf{v}) = m(\mathbf{v}_f - \mathbf{v}_i) \quad \text{.......................} \quad (3.4)$$

Equation (3.4) shows that **F** and Δt cannot be exactly known but their product which is equal to the change of momentum ($m\mathbf{v}_f - m\mathbf{v}_i$) can be calculated. For such cases, the product $\mathbf{F} \times \Delta t$ is called as **Impulse** of the force.

When a large force **F** acts on an object for a short interval of time, the impulse of the force is defined as the total change in momentum of the object.

Dividing both sides of Eq.3.4 by Δt, we have

$$\mathbf{F} = \frac{m(\Delta \mathbf{v})}{\Delta t} \quad \text{................} (3.5)$$

where $m(\Delta \mathbf{v})$ is the change in momentum $\Delta \mathbf{p}$. Equation (3.5) gives the value of force in terms of momentum i.e., force acting on an object is equal to the change in momentum of the object per unit time.

$$\mathbf{F} = \frac{\Delta \mathbf{p}}{\Delta t} \quad \text{................} (3.6)$$

Equation (3.6) suggests to define Newton's second law of motion in terms of momentum i.e.,

The rate of change of momentum of a body is equal to the force acting on it.

The direction of change in momentum is that of the force.

Do you know?

A cricketer draws his hands back to reduce the impact of the ball by increasing the time.

For Your Information!

The arrow penetrates into the apple, and in response, the momentum of the apple changes. Conversely, the apple applies an opposing force to the arrow, and in response, the momentum of the arrow changes.

Packing of Fragile Objects

Fragile objects such as glassware may break easily due to jerks or by the direct impact with hard objects during their transportation.

To protect them soft, packing materials are used for these objects. These materials reduce the effect of quick change in momentum. Consequently, the force acting on the fragile objects is greatly reduced. Special materials like Styrofoam, corrugated cardboard sheets, bubble wrap are used for the packing of such objects.

Crumple Zones

A crumple zone of an automobile is a structural feature designed to compress during an accident to absorb deformation energy from the impact. Typically, crumple zones are located in front and behind of the main body of the vehicle.

Crumple zones work by managing crash energy absorbing within the outer parts of the vehicle, rather than being directly transmitted to the occupants. This is achieved by controlled weakling of outer parts (plastic bumpers, etc.) of the vehicle, while strengthening of the passenger cabin.

Example 3.3

A bullet of mass 15 g is fired by a gun. If the velocity of the bullet is 150 m s^{-1}, what is its momentum?

Solution

Mass of bullet $= m = 15\,g = 0.015\,kg$

Velocity of bullet	= v	=	$150\ m\ s^{-1}$
Momentum	= p	=	?

Using the formula, $p = mv$

Putting the value, $p = 0.015\ kg \times 150\ m\ s^{-1}$

or $p = 2.25\ kg\ m\ s^{-1}$

Example 3.4

A cricket ball of mass 160 g is hit by a bat. The ball leaves the bat with a velocity of $52\ m\ s^{-1}$. If the ball strikes the bat with a velocity of $-28\ m\ s^{-1}$ (opposite direction) before hitting, find the average force exerted on the ball by the bat. The ball remains in contact with the bat for 4×10^{-3} s.

Solution

Mass of ball	$m = 160\ g = 0.16\ kg$
Initial velocity	$v_i = -28\ m\ s^{-1}$
Final velocity	$v_f = 52\ m\ s^{-1}$
Time of contact	$t = 4 \times 10^{-3}\ s$
Average force	$F = ?$

From Eq. (3.6), we have

$$F = \frac{m(v_f - v_i)}{t}$$

Putting the values,

$$F = \frac{0.16\ kg\ [52\ m\ s^{-1} - (-28\ m\ s^{-1})]}{4 \times 10^{-3}\ s}$$

or $F = 3200\ N$

3.10 Principle of Conservation of Momentum

The collection of objects is known as a 'system'. If no external force acts on any object of the system, it is known as isolated system. Consider a system of two balls of masses m_1 and m_2. Suppose that the balls are moving with velocities $\mathbf{v}_1$ and $\mathbf{v}_2$ along a straight line in the same direction. If $\mathbf{v}_1 > \mathbf{v}_2$, the balls will collide as shown in Fig. 3.26. If their velocities become v'_1, and v'_2 respectively after collision, then

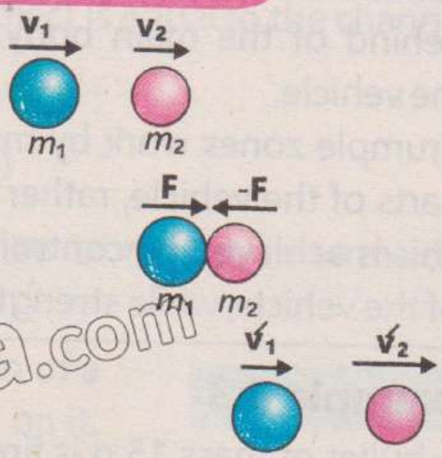


Fig. 3.26

Total momentum of the system before collision $= m_1\mathbf{v}_1 + m_2\mathbf{v}_2$

Total momentum of the system after collision $= m_1 v'_1 + m_2 v'_2$

The principle of conservation of momentum states that:

If no external force acts on an isolated system, the final total momentum of the system is equal to the initial total momentum of the system.

This means that:

$$\text{Total momentum of the system before collision} = \text{Total momentum of the system after collision}$$

$$\text{or} \quad m_1\mathbf{v}_1 + m_2\mathbf{v}_2 = m_1\acute{\mathbf{v}}_1 + m_2\acute{\mathbf{v}}_2$$

To explain this principle, let us consider the collision of two identical balls in which the second ball is at rest.

When there is collision of two balls, there is a transfer of momentum from one ball to another. The ball at rest gains momentum and starts moving whereas the striking ball slows down. If the balls are identical, we will observe that there is a total transfer of momentum. The striking ball comes to rest and the other ball starts moving with the same speed (Fig.3. 27). It means that second ball gains momentum equal to that lost by the first one. If the first ball stops after collision, the second ball moves with the momentum of the first ball. This suggests that the total momentum of the two balls after collision remains the same as total momentum before collision.

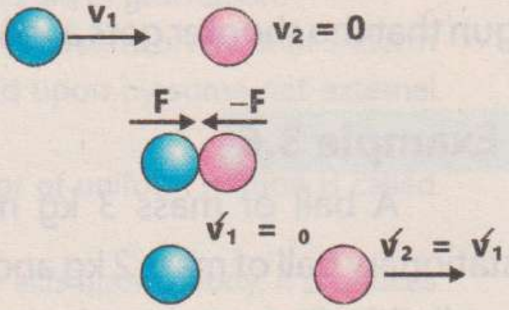


Fig. 3.27

The principle of conservation of momentum is applicable not only to macro-objects but also for micro-objects like atoms and molecules.

Seatbelts

When a moving car stops suddenly, the passengers move forward toward the windshield. Seatbelts prevent the passengers from moving. Thus, chances of hitting the passengers against the windshield or steering wheel are reduced.

Example 3.5

A bullet of mass m_1 is fired by a gun of mass m_2. Find the velocity of the gun in terms of velocity of bullet v_1 just after firing.

Solution

Before firing, the velocity of bullet as well as that of gun was zero. Therefore, total momentum of bullet and gun was also zero. After firing, the bullet moves forward with velocity v_1 whereas the gun moves with velocity v_2.

According to law of conservation of momentum,

Total momentum before firing = Total momentum after firing

Putting the values,
$$0 = m_1v_1 + m_2v_2$$
$$m_2v_2 = -m_1v_1$$
or
$$v_2 = \frac{-m_1v_1}{m_2}$$

The negative sign in this equation, indicates that the gun moves backward, i.e. opposite to the bullet. It is because of the backward motion of the gun that the shooter gets a jerk on his shoulder.

Example 3.6

A ball of mass 3 kg moving with a velocity of 5 ms^{-1} collides with a stationary ball of mass 2 kg and then both of them move together. If the friction is negligible, find out the velocity with which both the balls will move after collision.

Solution

Mass of first ball $= m_1 = 3$ kg

Velocity of first ball before collision $= v_1 = 5$ m s

Mass of second ball $= m_2 = 2$ kg

Velocity of second ball before collision $= v_2 = 0$

Velocity of both the balls after collision $= v = ?$

Total mass of balls after collision $= m_1 + m_2$

By law of conversion of momentum,

Total momentum before collision = Total momentum after collision

or
$$m_1 v_1 + m_2 v_2 = (m_1 + m_2)\, v$$

Putting the values,
$$3\,\text{kg} \times 5\,\text{m s}^{-1} + 0 = (3\,\text{kg} + 2\,\text{kg})\, v$$
$$15\,\text{kg m s}^{-1} = 5\,\text{kg} \times v$$
$$v = 3\,\text{m s}^{-1}$$

KEY POINTS

- A force is a push or a pull that starts, stops and changes the magnitude and direction of velocity of a body.
- A contact force is a force that acts at the point of contact between two objects.
- Non-contact force is a force between two objects which are not in physical contact.
- Gravitational force, electromagnetic force, strong nuclear force and weak nuclear force are the four fundamental forces in nature.
- Every object in the universe attracts every other object with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. This is known as Newton's law of gravitation.
- Newton's first law of motion states that a body continues its state of rest or of uniform motion with the same constant velocity, unless acted upon by some net external force.
- The property of a body to maintain its state of rest or of uniform motion is called inertia.
- The second law of motion states that when a net force acts upon a body, it produces an acceleration in the direction of force and the magnitude of acceleration is directly proportional to the force and is inversely proportional to the mass.
- The third law of motion states that to every action there is an equal but opposite reaction.
- Action and reaction do not act on the same body but act on two different bodies.
- Mass of a body is the quantity of matter in it. It determines the magnitude of acceleration produced when a force acts on it. Mass of a body does not vary. It is a scalar quantity and its unit is kilogram (kg).
- The weight of an object is equal to the force with which the Earth attracts a body towards its centre.
- Force meter is a scientific instrument that measures force in newtons (N).
- Friction is the force that tends to prevent the bodies from sliding over each other.
- The resisting force between the two surfaces before the motion starts is called the static friction. The maximum value of the static friction is called limiting friction.
- The friction during motion is called kinetic friction.
- When a body moves with the help of wheels, the friction in this case is known as rolling friction. Rolling friction is much less as compared to the sliding friction.
- Energy is wasted in doing work against friction that appears in the form of heat.
- When upward air resistance balances the downward force of gravity on a falling object, it falls down with constant (safe) velocity, it is called terminal velocity.
- The product of mass and velocity of a moving body is called momentum.
- The principle of conservation of momentum states that if no external force acts on an isolated system, the final total momentum of the system is equal to the initial total momentum of the system.
- Impulse is defined as the product of $F \times \Delta t = m \times \Delta v$ = total change in momentum.

EXERCISE

A Multiple Choice Questions

Tick (✓) the correct answer.

3.1. When we kick a stone, we get hurt. This is due to:

(a) inertia (b) velocity (c) momentum (d) reaction

3.2. An object will continue its motion with constant acceleration until:

(a) the resultant force on it begins to decrease.

(b) the resultant force on it is zero.

(c) the resultant force on it begins to increase.

(d) the resultant force is at right angle to its tangential velocity.

3.3. Which of the following is a non-contact force?

(a) Friction (b) Air resistance

(c) Electrostatic force (d) Tension in the string

3.4. A ball with initial momentum p hits a solid wall and bounces back with the same velocity. Its momentum p' after collision will be:

(a) $p' = p$ (b) $p' = -p$ (c) $p' = 2p$ (d) $p' = -2p$

3.5. A particle of mass m moving with a velocity v collides with another particle of the same mass at rest. The velocity of the first particle after collision is:

(a) v (b) $-v$ (c) 0 (d) $-1/2$

3.6. Conservation of linear momentum is equivalent to:

(a) Newton's first law of motion (b) Newton's second law of motion

(c) Newton's third law of motion (d) None of these

3.7. An object with a mass of 5 kg moves at constant velocity of 10 m s^{-1}. A constant force then acts for 5 seconds on the object and gives it a velocity of 2 m s^{-1} in the opposite direction. The force acting on the object is:

(a) 5 N (b) −10 N (c) −12 N (d) −15 N

3.8. A large force acts on an object for a very short interval of time. In this case, it is easy to determine:

(a) magnitude of force (b) time interval

(c) product of force and time (d) none of these

3.9. A lubricant is usually introduced between two surfaces to decrease friction. The lubricant:

(a) decreases temperature (b) acts as ball bearings

(c) prevents direct contact of the surfaces (d) provides rolling friction

B Short Answer Questions

3.1. What kind of changes in motion may be produced by a force?

3.2. Give 5 examples of contact forces.

3.3. An object moves with constant velocity in free space. How long will the object continue to move with this velocity?

3.4. Define impulse of force.

3.5. Why has not Newton's first law been proved on the Earth?

3.6. When sitting in a car which suddenly accelerates from rest, you are pushed back into the seat, why?

3.7. The force expressed in Newton's second law is a net force. Why is it so?

3.8. How can you show that rolling friction is lesser than the sliding friction?

3.9. Define terminal velocity of an object.

3.10. An astronaut walking in space wants to return to his spaceship by firing a hand rocket. In what direction does he fire the rocket?

C Constructed Response Questions

3.1 Two ice skaters weighing 60kg and 80 kg push off against each other on a frictionless ice track. The 60 kg skater gains a velocity of 4 m s^{-1}. Considering all the relevant calculations involved, explain how Newton's third law applies to this situation.

3.2 Inflatable airbags are installed in the vehicles as safety equipment. In terms of momentum, what is the advantage of airbags over seatbelts?

3.3 A horse refuses to pull a cart. The horse argues, "according to Newton's third law, whatever force I exert on the cart, the cart will exert an equal and opposite force on me. Since the net force will be zero, therefore, I have no chance of accelerating (pulling) the cart." What is wrong with this reasoning?

3.4. When a cricket ball hits high, a fielder tries to catch it. While holding the ball he/she draws hands backward. Why?

3.5. When someone jumps from a small boat onto the river bank, why does the jumper often fall into the water? Explain.

3.6. Imagine that if friction vanishes suddenly from everything, then what could be the scenario of daily life activities?

D Comprehensive Questions

3.1. Explain the concept of force by practical examples.

3.2. Describe Newton's laws of motion.

3.3. Define momentum and express Newton's 2nd law of motion in terms of change in momentum.

3.4. State and explain the principle of conservation of momentum.

3.5. Describe the motion of a block on a table taking into account the friction between the two surfaces. What is the static friction and kinetic friction?

3.6. Explain the effect of friction on the motion of vehicles in context of tyre surface and braking force.

E Numerical Problems

3.1. A 10 kg block is placed on a smooth horizontal surface. A horizontal force of 5 N is applied to the block. Find:

(a) the acceleration produced in the block.

(b) the velocity of block after 5 seconds. ($0.5\ m\ s^{-2}$, $2.5\ m\ s^{-1}$)

3.2. The mass of a person is 80 kg. What will be his weight on the Earth? What will be his weight on the Moon? The value of acceleration due to gravity of Moon is $1.6\ m\ s^{-2}$. (800 N, 128 N)

3.3. What force is required to increase the velocity of 800 kg car from $10\ m\ s^{-1}$ to $30\ m\ s^{-1}$ in 10 seconds? (1600 N)

3.4. A 5 g bullet is fired by a gun. The bullet moves with a velocity of $300\ m\ s^{-1}$. If the mass of the gun is 10 kg, find the recoil speed of the gun. ($-0.15\ m\ s^{-1}$)

3.5. An astronaut weighs 70 kg. He throws a wrench of mass 300 g at a speed of $3.5\ m\ s^{-1}$. Determine:

(a) the speed of astronaut as he recoils away from the wrench.

(b) the distance covered by the astronaut in 30 minutes.

($-1.5 \times 10^{-2}\ m\ s^{-1}$, 27 m)

3.6. A 6.5×10^3 kg bogie of a goods train is moving with a velocity of $0.8\ m\ s^{-1}$. Another bogie of mass 9.2×10^3 kg coming from behind with a velocity of $1.2\ m\ s^{-1}$ collides with the first one and couples to it. Find the common velocity of the two bogies after they become coupled. ($1.03\ m\ s^{-1}$)

3.7. A cyclist weighing 55 kg rides a bicycle of mass 5 kg. He starts from rest and applies a force of 90 N for 8 seconds. Then he continues at a constant speed for another 8 seconds. Calculate the total distance travelled by the cyclist.

(144 m)

3.8. A ball of mass 0.4 kg is dropped on the floor from a height of 1.8 m. The b
rebounds straight upward to a height of 0.8 m. What is the magnitude anc
direction of the impulse applied to the ball by the floor?

(4 N s, upwarc

3.9. Two balls of masses 0.2 kg and 0.4 kg are moving towards each other w
velocities 20 m s^{-1} and 5 m s^{-1} respectively. After collision, the velocity
0.2 kg ball becomes 6 m s^{-1}. What will be the velocity of 0.4 kg ball?

(2 m s^{-1})