UNIT 5 FORCE AND MOTION

Structure

5.1 INTRODUCTION

If you find that a watch placed by you on a table in your room is neither on the table nor anywhere near it you begin to suspect that somebody has picked it up. Could it be that nobody entered your room and the watch moved on its own? Your answer would definitely be 'NO' and you are perfectly correct. You know that a non-living body cannot change its position or state of motion (or rest) without an external force acting on it. Long back, Newton also had similar notions and he formulated some generalisations which are now known as 'Laws of Motion' and form the backbone of Physics. They have wide applications in different branches of science and have tremendous contributions in the growth of science. They are among the very few basic concepts which form the foundation for the development of different branches of science. Although some modifications are needed in them to describe motion involving speeds close to the speed of light yet they are applicable in most of common cases where speeds are very small in comparison to the speed of light.

The three laws of motion and the law of conservation of momentum are fundamental concepts that have helped us in understanding the secrets of nature and in analysing and describing its behaviour.

5.2 OBJECTIVES

This unit will enable you to :

- demonstrate that inertia is a property of all bodies having mass;
- show the relation between Force and Motion;
- generalise that an unbalanced force acting on a body produces acceleration in the body;
- explain that action and reaction are equal and opposite;
- illustrate that action and reaction act on different bodies;
- verify that a set of forces which just make balance and produce no motion are in equilibrium;
- establish the law of conservation of momentum;

- describe the various applications of the laws of motion in daily life; and
- infer the principles underlying various physical phenomena related to motion in daily life.

5.3 RELATION OF MOTION AND FORCE

Main Teaching Points

- Force acts in the form of push or pull.
- Force tends to produce or change motion or change the position or shape of a body.
- Force is a vector quantity.
- Motion is relative.
- Friction plays an important role in motion.

5.3.1 What is Force?

Teaching-Learning Process

You have seen automobiles accelerating and stopping on the road, objects thrown up coming down eventually, twigs and leaves of trees moving this way and that way, the stars, the sun and the moon changing position across the sky. All the above are examples of motion and change in direction of motion. What causes this change? You know from experiences that a body at rest cannot move unless something pulls or pushes it. Similarly a moving body cannot stop unless again a force (push or pull) is exercised on it. You can easily demonstrate this by applying a force on a toy car or a ball.

Direction of Force	**Diagram showing application of force**	**Direction of motion**
Left to right (L) (R) →		L to R →
Right to left	 ←	R to L ←

Fig. 5.1

If you want to change the direction of motion of a rolling ball on a plane surface you would have to give it a sidewise push or pull or hit it head-on.

Similarly when you compress or stretch a spring, bend a metal wire or break a rod or flatten a metal sheet, you change the shape of a body by applying force. What do you conclude about force? Yes, it is a push or pull. How can you define force? You can describe it by mentioning what it does. It can be said that:-

'A force is that which tends to produce or change the state of motion or change the position or shape of a body'.

How are forces measured?

A force can be measured by using its effect as implied in its definition. One common way of measuring force depends on the following principle enunciated by Robert Hooke (1635-1703):

"The amount of change in the shape of an elastic body is proportional to the force applied, provided the elastic limit is not exceeded". A force can be measured using a spring balance. The gravitational pull exerted on the body by the earth is the weight of the body. Since weight is a force it can be measured using a spring balance. The change in the length of the spring is directly proportional to the force (weight) applied on it.

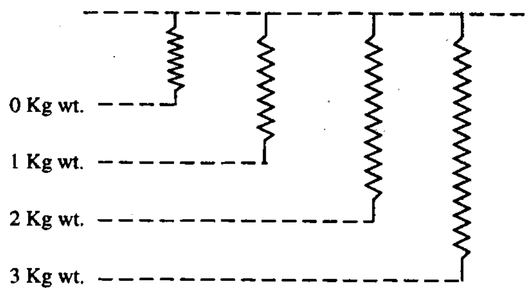

Fig. 5.2 : Force α change in length

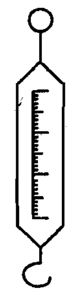

Fig. 5.3 : A Spring Balance

5.3.2 Balanced and Unbalanced Forces

Force is a vector quantity. It has magnitude and direction Therefore, forces can be added or substracted using the law of addition of vectors.

If a body is at rest it can be concluded that the sum of the forces acting in one direction is balancing the sum of forces acting in the opposite direction. Let us now study the situation when body is not at rest.

All Motion is Relative

When you are sitting in a fast moving bus on a road you observe that the trees and buildings on either side of the road are moving in the opposite direction while your co-passengers seated in the bus are at rest with respect to you. For a person sitting on a chair in front of his house near the road you are moving, all your co-passengers in the bus are moving but the person on the chair is at rest. What do you conclude now? You will agree that all motion is relative. If 'A' is moving relative to 'B' it can be said that 'B' is moving relative to 'A'. When two trains are standing side by side on adjacent rail tracks and one of them starts moving persons of either trains observe the other as 'moving' relative to their own train.

Motion and Frictional Force

Do you know why grease and lubricating oil are used in the machines? When the surface of one body is rubbed on the surface of another body, a force known as friction resists the motion. If the surfaces are rough the resistance will be more. Grease and oil reduce the frictional force between the two surfaces. There are other ways also that help us in reducing friction e.g. use of ball bearings, rollers and wheels. Friction results in wear and tear of the surfaces and the energy used up in overcoming the resistance goes as waste mostly in the form of sound and heat. The machine does less work than the energy supplied to it. Friction cannot be completely reduced and therefore no machine can be cent per cent efficient.

However friction is also useful as it plays an important role in all motion. No automobiles can move or stop if friction were not there. You cannot move if there is no friction between your feet and the surface on which you move.

Can friction be thus, called a necessary evil?

Methodology used: The topic was introduced by using the previous experience of children regarding motion and inertia without using the word inertia. Some interesting demonstrations were done using a toy car or a ball to generalise that any change in motion requires some force. The students' experiences in a moving bus were used to explain that all motion is relative. A body at rest may be seen moving by an observer in another frame of reference, moving relative to the body.

The idea of balanced forces was given using concrete examples where forces were acting but the body was at rest. The concept of friction was developed using familiar examples, questions and discussions.

Check Your Progress

Notes: a) Write your answers in the space given below.
b) Compare your answers with those given at the end of the unit.

1. If a body is at rest can we conclude that no force or forces are acting on it? Give arguments in support of your answer.

....
....
....
....
....

2. Suggest one activity for measurement of the magnitude of force.

....

3. Show that friction has advantages as well as disadvantages by giving two examples of each case.

....
....
....
....
....
....

5.4 NEWTON'S LAWS OF MOTION

Main Teaching Points

i) Newton's first law of motion states that in the absence of a net force, a body at rest will remain at rest and a body in motion will continue in a straight line at constant speed.

ii) Newton's second law states that when a net force acts on a body, it will be accelerated in the direction of the force with an acceleration proportional to the magnitude of the force.

iii) The term 'Inertia' refers to the apparent resistance a body offers to change in its state of motion or rest.

iv) The property of matter that manifests itself as inertia is its mass.

v) Newton's third law of motion states that when a body exerts a force on another body, the second body exerts a force on the first body. The forces exerted are of the same magnitude but they act in the opposite direction.

vi) The forces of action and reaction act on two different bodies.

Teaching-Learning Process

Aristotle, on the basis of his experience concluded that the heavier a body is, the faster it falls freely. According to his belief a 1 Kg. ball falls twice as fast a 1/2 Kg. ball. Do you agree with this? Galileo dropped a large cannon ball and a small musket ball from the top of 183 feet high

Leaning Tower of Pisa and demonstrated that both fell at the same rate and hit the ground at the same time. Who is correct, Aristotle or Galileo?

5.4.1 First Law of Motion

You might have experienced that you are thrown from your bicycle if it stops suddenly. You might have seen people running along a moving bus while boarding it or alighting from it. You might have seen dust coming out of a duster when it is given a jerk. Clothes dry faster when waved quickly. Why does that happen? It is because of the tendency of a body to resist any change in its motion. This tendency is termed as Inertia. These are examples of Newton's first law of motion, which is stated as follows:

"A body in motion continues to remain in its state of rest or of uniform motion in a straight line unless it is acted upon by a net external force".

Galileo arrived at the above conclusion using an experiment described below:

What happens to the speed of a ball rolling down on an inclined plane as shown in Fig. 5.4 (a)?

[Ans: The speed increases.]

What happens when the ball goes up on an inclined plane as shown in Fig. 5.4 (b)?

[Ans: The speed decreases.]

What do you observe if the ball moves on a plane which is neither inclined upward nor downward?

[Ans: The speed is unchanged.]

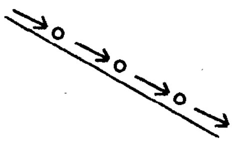

Fig. 5.4(a)

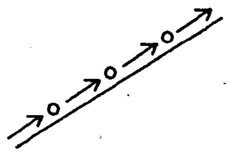

Fig. 5.4(b)

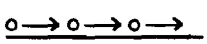

Fig. 5.4(c)

Besides the above you can also try the following.

1. Place a stack of coins on a strip of paper, put near the edge of a table, and try to remove the paper from beneath the stack. First pull the paper gently. What happens? Then pull the paper very quickly. What happens? Remember the paper has to be pulled in horizontal direction only. If you have difficulty in doing so hold the other end of the paper horizontally and strike it with you finger in vertical direction.
2. Repeat the experiment with a rupee coin kept on the paper in the standing position.
3. Hang a banana on a long thread. Keep a knife touching the banana. Can you cut the banana without moving the knife backwards unless there is a space in between the banana and the knife? No. You may not be able to cut it. The banana can be cut only if either the banana or the knife moves quickly but the other one is kept stationary.

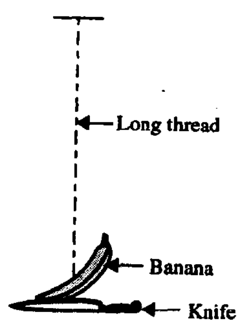

Fig. 5.5

5.4.2 Second Law of Motion

A smooth-running cart is attached to a pan by a string passing over a pully as shown in the figure. A weight is placed in the pan so that the cart begins to move. You will find the cart first moves slowly and then moves with ever increasing speed. If the experiment is repeated with a heavier weight on the pan there will be a faster change in motion of the cart. In other words the acceleration of the cart is proportional to the force that pulls the cart.

Mathematically,

Acceleration (a) α Force (F)..................(1)

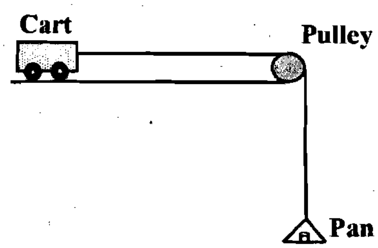

Fig. 5.6

The same experiment is repeated with the same weight on the pan by varying the mass of the cart by putting weights on it.

It will be observed that

acceleration of the cart (a) $\alpha \dfrac{1}{\text{Total mass of the cart (m)}}$ ....(2)

Combining eq. (1) & (2) we get

$$a \; \alpha \; \frac{F}{m}$$

or $F \; \alpha \; ma$

or $F = Kma$

Where K is a constant of proportionality. If we choose units in such a way that a force of one Newton causes an acceleration of $1 m/S^2$ in a mass of 1 Kg.
we have

$$1N = K\frac{1m}{S^2} \times 1Kg$$

$\therefore \; K = 1$

Hence second law of motion can be stated as

Force = Mass × acceleration
(F) (m) (a)

5.4.3 Third Law of Motion

Let the hooks of two spring balances A and B be fastened to each other as shown in the figure.

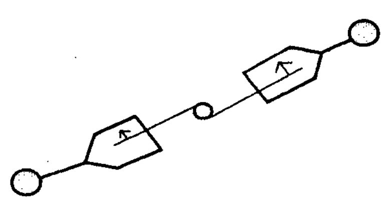

Fig 5.7

Now force is applied to spring B keeping spring A at the same place. What is the relation between the readings of the two balances? Pull B with a stronger force. What is the relation between the readings of the two balances?

Now keep spring balance B stationary and apply force to spring balance A. What is the relation between the readings now?

Repeat the experiment by pulling both springs. What is the relation between the readings of the two? Pull them apart with greater forces and you will observe that in each case the readings of the two balances remain equal irrespective of which one is pulled. It can be concluded that:

A always exerts a force on B as B does on A. The magnitudes of the forces are equal while their directions are opposite. If one force is known as action, the other one can be called reaction.

The third law can be stated as follows :

Every action has an equal and opposite reaction.

The forces of actions and reactions are equal in magnitude though opposite in direction and they act on different bodies.

You may try following activities also.

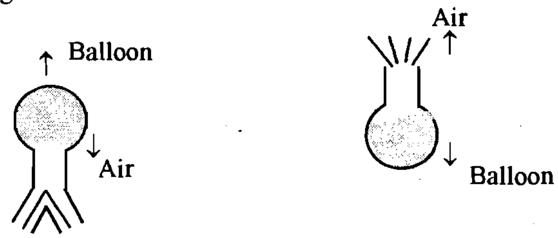

Fig. 5.8

i) Air is allowed to escape from an inflated balloon keeping its open end downwards. In which direction does it move? Repeat the experiment keeping the open end upward. What happens now? Repeat the experiment by keeping the open end in any direction and note the direction of motion of the balloon. It will be found that the balloon moves in a direction opposite to that of the escaping air.

ii) A small amount of water is put into a pyrex test-tube. A cork is loosely fitted on the mouth of the test-tube keeping the tube nearly horizontal by means of two loops as shown. Heat the tube from below. What happens when steam is formed? The cork moves in one direction while the test-tube moves in the opposite direction.

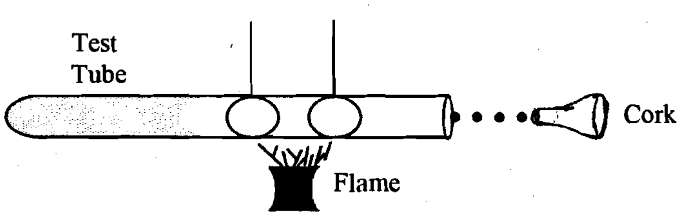

Fig. 5.9

The principle of action and reaction holds good whenever a force is applied. Can we say that **forces operate in pairs?** Can you imagine a situation where this principle is violated? Certainly not.

If there are always equal and opposite forces why do things move? Why do the forces not cancel each other? It is because they act on two different bodies. In Fig. 5.8 the air moved in one direction while the balloon in the reverse direction. Similarly the cork and the test-tube move in reverse directions in Fig. 5.9.

Can you explain the working of a rocket or a jet plane now?

Newtonian Mechanics (using the above three laws) explain almost all the cases involving speeds encountered in daily life situations. However at very high speeds comparable to the velocity of light these laws break down and some corrections are needed. In such situations relativistic mechanics is applicable.

Methodology used : The topic was introduced using simple demonstrations or student activities. The observations and students' experiences were used to arrive at generalisations. More examples were elicited from students. The first law was illustrated using Galileo's experiment which involves reasoning. At attempt was made to seek active cooperation of the students in developing new concepts.

Check Your Progress

Notes : a) Write your answers in the space given below.

b) Compare your answers with those given at the end of the unit.

4. Why can an aeroplane not take us to the moon? Why can a rocket do so?

....

....

....

....

....

....

5. Why do we shake a wet handkerchief when we want it to become dry quickly?

....

....

....

....

....

6. Why is the base of a field gun of Army kept heavy?

....

....

....

....

....

7. Write three methods of reducing friction.

....

....

5.5 CONSERVATION OF MOMENTUM

Main Teaching Points

- The linear momentum of a body is the product of its mass and velocity.
- Momentum is a vector having the direction of the body's velocity.
- The impulse of a force is the product of the force and the time during which it acts.
- Impulse is a vector quantity having the direction of the body's velocity.
- When a force acts on a body that is free to move, its change in momentum equals the impulse given to it.
- When the net external force on a system is zero, the total linear momentum of the system remains constant.

5.5.1 Law of Conservation of Momentum

The law of conservation of momentum is a very general law applicable in all collisions, explosions and interactions and for all types of moving bodies — massive or tiny. It has tremendous importance for all branches of science.

You have seen pictures of rockets, space vehicles sent to space by many countries including India. Collect their pictures and descriptions. Do you know their principle of operation ? Well, you can learn it now.

You can easily stop a toy car but not a truck moving slowly. You need a big hammer to drive a nail into a wooden plank, as a light one is not that useful. You may try to catch a ball coming towards you but certainly you would not dare to stop a bullet fired from a gun. Obviously mass and velocity of moving body have something to do with the difficulty encountered in starting or stopping a body.

Sometimes we apply a force only for a small period of time. The product of force and the time interval is known as Impulse. It is a vector quantity and its direction is the direction of force.

Try the following activities:

1. Toss rubber balls of medium size to different heights vertically upwards and catch these balls on return. Repeat this using ball bearings of different sizes and masses. What do you generalise regarding the forces experienced by your hand in different cases?
2. Collect pictures of jet planes and rockets and describe the principle of their operation.
3. Keep five marbles (identical) in a smooth groove in a wooden board or in an angular shaped smooth body made of card board, plastic or metal such that each marble touches the next one and keeping the apparatus horizontal move the first marble to the left. Now strike it with a pencil so that it collides with the marbles in front of it. What happens?

   Repeat the experiment again, this time let two marbles be taken to the left and keeping them in contact they be pushed to strike the remaining stationary marbles. What happens now? Repeat the experiment by taking three marbles to the left.

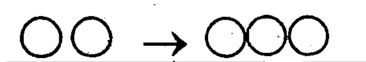

Fig. 5.10

How can you explain the observations? Is the principle of conservation of momentum valid here? Is this principle alone sufficient to explain the observations ? The answer is 'No' because another principle applicable here is the law of conservation of energy.

The law of conservation of momentum can be derived using the third law of motion.

Suppose two bodies A and B collide together for a time Δt resulting in the change of momenta ΔP_A and ΔP_B respectively. According to third law of motion:
Force on A = – Force on B
(Force on A). Δt = – (Force on B). Δt
Impulse acting on A = – Impulse acting on B
Change in momentum of A = – Change in momentum of B

$$\Delta P_A = -\Delta P_B$$

$$\text{or } \Delta P_A + \Delta P_B = 0$$

Hence the total momentum remains unchanged.

Methodology used: This topic is very important as it is one of the basic laws operating universally. The topic was introduced through simple student activities like tossing balls upwards and catching them. Instead of balls any other object could be used provided it is safe to handle it. The objects were thrown to various heights. The experiences were used to draw conclusions. Conservation of momentum was explained mathematically also.

For motivation the teacher can ask students to collect pictures of some rockets or spaceships or missiles and their working was discussed.

Check Your Progress

Notes : a) Write your answers in the space given below.

b) Compare your answers with those given at the end of the unit.

8. Prove that impulse equals change in momentum.

....

....

....

....

....

9. A ball of mass 50g moving at a speed of 6 m/s is struck by a racket. It leaves in the reverse direction at a speed of 10 m/s What is the impulse applied to the ball by the racket? What is the change in the momentum of the ball ?

....

....

....

....

....

....

....

....

....

....

5.6 APPLICATION OF THE LAWS OF MOTION IN DAILY LIFE

Motion is the essence of life. Motion is a relative phenomenon and absolute motion has little meaning for us. Only motion relative to material bodies is of use to us. Motion of heavy bodies has not only fascinated man but has intrigued man since times immemorial. In order to explain the observed phenomena some explanations were given. It was Newton who gave us the three laws of motion that formed the backbone of classical mechanics. We now know that these laws have to be modified for speeds close to the speed of light but for most of the practical purposes they are found to give satisfactory explanation.

Main Teaching Points

- Newton's laws form the backbone of Physics.
- Newton's laws have many applications in daily life.
- A knowledge of the laws of motion can enable a person to solve many problems.
- Newton's laws need correction for cases having velocity comparable to the velocity of light.

5.6.1 Application of First Law of Motion

Do you know why a car cannot stop immediately after its engine is switched off? Similarly a train takes time in gaining its maximum speed. Why so ?

If we give a jerk to a duster or a wet cloth why do particles of dust or water come out of it?

A brick is hung by means of a thread as shown. The thread can be broken at a point above the brick or below it by gently pulling the thread or by giving a swift jerk to it respectively.

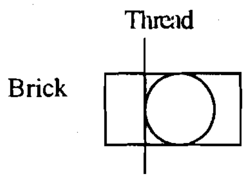

Fig. 5.11

A bicycle rider is thrown in the forward direction if breaks are applied suddenly. An astronaut is pushed to his seat with tremendous force when the rocket accelerates.

Can you add to this list similar cases where the law of inertia holds good ?

5.6.2 Application of Second Law of Motion

If mass is constant the acceleration produced in a body is directly proportional to the force applied. It is because of this law that a freely falling body comes to the ground with ever increasing speed until the terminal velocity is reached. Also we need a more powerful rocket to put a satellite into a higher orbit around the earth.

Newton's second law of motion, being the key relation between Force and Motion, is needed in dealing with projectiles, rockets, trains and machinery.

5.6.3 Application of Third Law of Motion

Can you push me without finding that I push you back ? No, you cannot do that. Any attempt to push leads to two forces or none. Suppose you push me with a force of 100 N eastward. Automatically I push you with a force of 100 N in the opposite direction. The forces still remain equal and opposite when we move or accelerate. The fact that I am pushing you back does not constitute a force on me. Only your push acts on me and I feel it. If I am on roller skates your push will accelerate me. You must run faster and faster to keep up with me as you push me.

All jet engines and rockets are based on the third law. Our country has developed missiles and rockets like Agni, Prithvi, PSLV etc. Collect information about them. As a consequence of third law we have law of conservation of momentum which has helped scientists to explain many observations and has even helped in making predictions.

The discovery of particles like neutrino would not have been possible if the law of conservation of momentum was not known. The gun recoils as it fires a bullet and the same thing happens when we fire huge bombs but this time the gun has to be very heavy. So in war as well as in daily life the third law cannot be underestimated. In all collisions like collisions between vehicles on roads, or a collision between a bullet and target the law of conservation of momentum holds good. Similarly it holds good in all types of explosions also.

Methodology used : Newton's laws have many applications in daily life and the teacher should ask students to perform simple activities and to recall their experiences. Models, pictures and diagrams can probably be used to explain important concepts/principles and applications. The students may be asked to collect information about the attempts made by our country to launch satellites, and missiles.

Check Your Progress

Notes : a) Write your answers in the space given below.

b) Compare your answers with those given at the end of this unit.

10. What unbalanced force will accelerate a 25 kg bicycle from 5 m/s to 10 m/s in 5 seconds ?

....

....

....

....

....

....

....

11. Describe the efforts of ISRO in making our country pioneer in space research.

....

....

....

12. Explain the statement 'Forces always occur in pairs'.

....

....

....

....

5.7 LET US SUM UP

All motions are relative.

A force acts in the form of a push or a pull.

Newton's first law states that in the absence of a net force, a body at rest will remain at rest and a body in motion will continue in motion in a straight line at constant speed.

According to second law of motion the acceleration produced in a body is proportional to the force acting on it.

The terms inertia refers to the apparent resistance a body offers to changes in its state of motion.

Friction opposes relative motion between two surfaces in contact.

Newton's third law of motion states that when a body exerts a force on another body, the second body exerts a force on the first body of the same magnitude but in the opposite direction.

Momentum is the product of the mass and the velocity of a body.

Momentum is a vector having the direction of the body's velocity.

Momentum is conserved in all collisions and explosions.

Laws of motion as described by Newton need correction when speeds are close to the speed of light.

5.8 UNIT-END EXERCISES

1. Describe three demonstrations to explain the inertia of rest.
2. Define force in your own words.
3. How will you show that an unbalanced force produces acceleration in a body?
4. List at least five demonstrations (other than those given in this text) to explain third law of motion.
5. Write down the various applications of third law of motion in (i) daily life and (ii) scientific research.
6. Prepare charts showing the progress of space programme of ISRO.
7. Describe the limitations of Newton's laws of motion.

5.9 ANSWERS TO CHECK YOUR PROGRESS

1. No. All that we can conclude is that no net (unbalanced) force is acting on the body. The forces action on the body might be such that there resultant is zero.
2. Elongation of an elastic band or a rubber band can be used to measure force.
3. **Advantages:**
   a) In enabling vehicles to move
   b) In walking on the road
   c) In enabling machines to do work like grinding of wheat

   Disadvantages :
   a) It causes wear and tear in machines
   b) It reduces efficiency of machines
   c) Machines become hot after they have done work.
4. There is no air after some height above the earth to provide buoyant force to an aeroplane. A rocket needs no extra air as it operates on the principle of action and reaction.
5. So that loosely bound water particles leave the threads of the handkerchief when it is moved suddenly.
6. When a heavy bomb is fired the forward momentum of the bomb gives equal momentum to the gun and if the base of the gun is light it will recoil with considerable velocity.
7. Greasing, using ball bearings and wheels.
8. Impulse = Force × Time duration

$$= \frac{\text{Change in Momentum}}{\text{Time duration}} \times \text{Time duration}$$

$$= \text{Change in Momentum}$$

9. Change in Momentum

$$= \frac{50}{1000} \text{ Kg} \times [6 \text{ m/s} + 10 \text{ m/s}]$$

$$= \frac{50}{1000} \times 16 \text{ Kg.m/s}$$

$$= \frac{800}{1000} \text{ Kg. m/s}$$

$$= 0.8 \text{ Kg m/s}$$

= Impulse applied to the ball

10. Force $=$ Mass $\times$ Acceleration
$= 25\ Kg \times (10^{-5}/50)\ m/s$
$= 25\ Kg.\ m/s^2 = 25\ N$

11. Development of launching vehicles, tracking systems and missiles is being done by ISRO.

12. An action force causes a reaction force automatically and hence according to third law of motion a single force cannot occur.

5.10 SUGGESTED READINGS

NCERT (1988) : *SCIENCE, A Text Book for Class IX.*

Fensham P.J. (1994) et.al : *The Content of Science: A Constructive Approach to its Teaching and Learning.* The Falmer Press, Washington D.C.

Carin/Sund : *Teaching Science Through Discovery,* C.E. Merrill Publishing Co., London.

Craig (1958) : *Science for the Elementary School Teacher,* Ginn & Co., New York.

Cleaveland, J.M. (1964) : *Physical Science,* C.E. Merrill Publishing Co., Ohio.

Leckstein, John Murrey (1988) : *Basic Skills - SCIENCE,* John Murrey.

Jennings Terry (1987) : *The Young Scientist Investigates : The Teachers Manual,* Oxford University Press.