3 Laws of Motion

Various situations associated with motion are depicted in the above picture. Look at the child catching the cricket ball.

- While catching the ball, why did the child move his hand backwards along with the ball?

Tug of war between two teams is shown in figure 3.1.

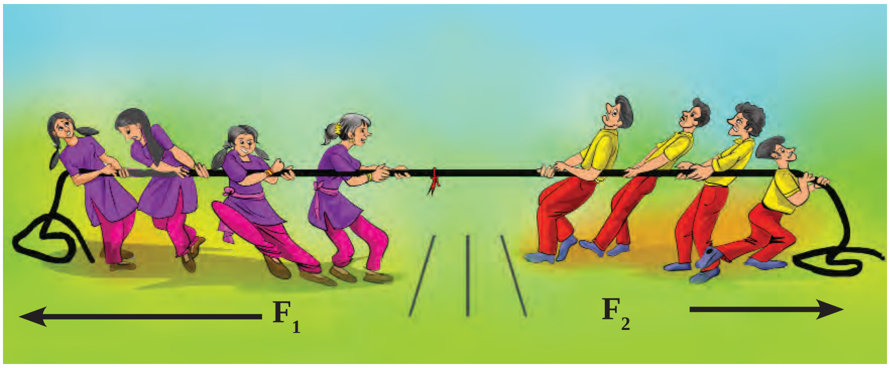


Fig. 3.1

- The rope moves only in one direction even though both the teams are applying force. Why?
- Is the force applied by both teams the same?
- Which team applied more force?
- Wasn't it the excess force that caused the motion?

Here F_1 is acting in the direction of the winning team and F_2 in the opposite direction. If so, the effective force is in the direction of the winning team. If force in a particular direction is considered as positive, the force in the opposite direction is negative. This is because force is a vector quantity.

When more than one force is applied on an object at the same time, the sum of the forces acting on the object will be the effective force or resultant force.

- What will be the resultant force if 100 N force is applied on an object in the east direction and 150 N force in the west direction?

If the force applied in the east direction is considered as positive, then the force in the opposite direction (west) is negative (it can be taken in the reverse order also).

Here, the resultant force = 100 N + (–150 N) = –50 N. Isn't the force applied in the east direction positive? Now you might have understood that the resultant force is 50 N towards west.

Complete the Table 3.1 by analysing the following figures.

Fig. 3.2 (a)

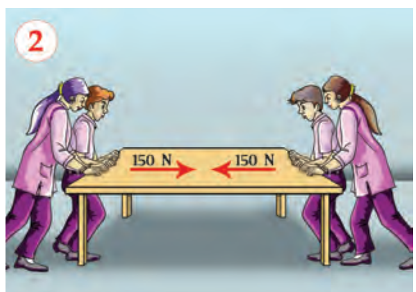


Fig. 3.2 (b)

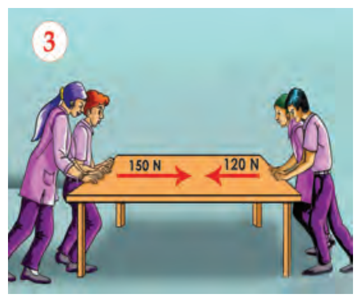


Fig. 3.2 (c)

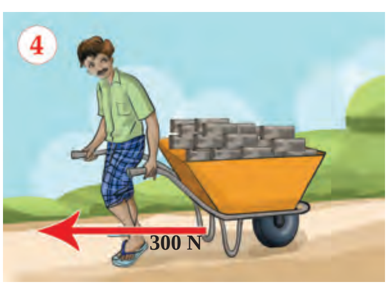


Fig. 3.2 (d)

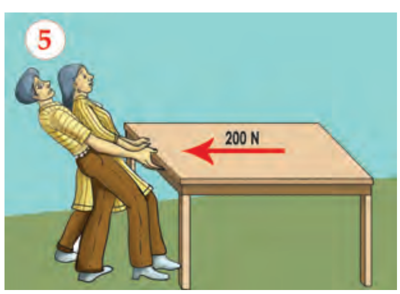


Fig. 3.2 (e)

Fig. 3.2 (f)

Figure	Force F_1 (N)	Force F_2 (N)	Resultant force (N)
1			
2	150	-150	0
3			
4			
5			
6			

Table 3.1

- In which of these situations is the resultant force zero?
- Which are the situations where the resultant force is not zero?
- Which are the situations where there is no motion?

The forces acting on a body are said to be balanced forces, if the resultant force is zero. Such forces can neither move an object at rest nor change the direction or speed of an object in motion.

The forces acting on a body are said to be unbalanced forces if the resultant force is not zero. Such forces can either move an object at rest or change the direction or speed of an object in motion.

In the tug of war shown in the figure 3.1, is the resultant force experienced on the rope balanced or unbalanced?

Do all forces cause motion?

Let's do an activity.

Fix a pulley each at the both ends of a wooden plank of length about 1.2 m and breadth 10 cm. Keep this plank on a table. Place a toy car in the middle of the plank as shown in figure 3.3. Hang pans of equal mass on strings attached to the two ends of the toy car. Place 200 g weight each in both the pans.

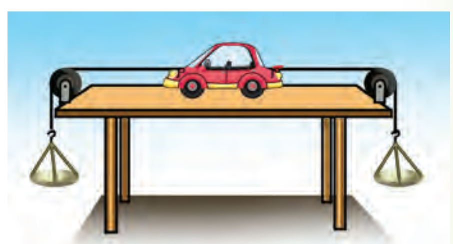


Fig. 3.3

PhET→ Forces and Motion : Basics

PhET→ Friction

- Does the toy car move?
- Are these forces balanced or unbalanced?
- Add 50 g more to any one of the pans. What do you observe?
- Are the forces balanced or unbalanced in this case?
- When the toy car is moving, if 50 g more is added to the pan in the direction in which the car moves, what change can be observed in the motion of the car?
- When the car is moving, a mass of 200 g more is added to the pan attached to the string in the opposite direction of the motion of the car. What is the change observed?
- Are the forces balanced or unbalanced in the above situation?
- What do you understand from these activities?
- Does the body move in the direction of resultant force?

  (moves / does not move)
- When does the speed of the car increase?

  (when the magnitude of the resultant force increases / decreases)
- Was the force that moved the car applied from inside the car or from outside?
- In which situation does the direction of motion change?

In all these cases the force was given externally. Hence all of them are external forces. An external force can be balanced or unbalanced.

An unbalanced external force acting on an object either changes or tends to change its state of rest, state of motion, direction or speed of motion. This change will be in the direction of the unbalanced force.

Fig. 3.4

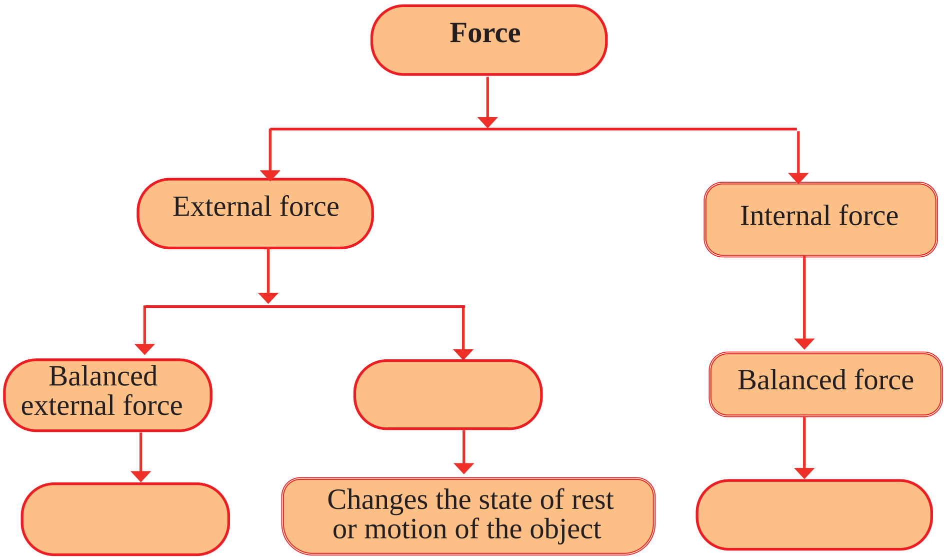
Observe the figure.

- Can a vehicle move if pushed from inside?
- Isn't it an internal force?
- All internal forces are - - - - - - - - - - - - - - -

  (balanced / unbalanced)

All internal forces are balanced forces. Hence the state of rest or motion of a body does not change on applying an internal force.

Complete the chart and redraw it in the science diary.



Galileo's Observations

A revised version of the experiment done by Galileo, almost four decades ago is given below.

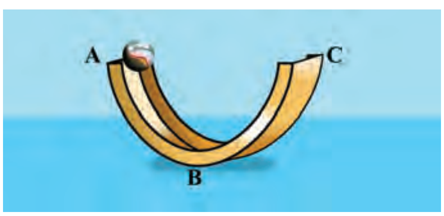


Fig. 3.5 (a)

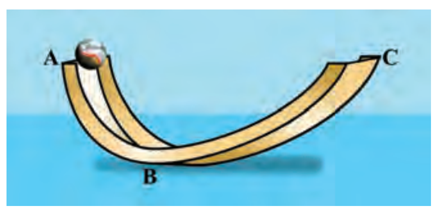


Fig. 3.5 (b)

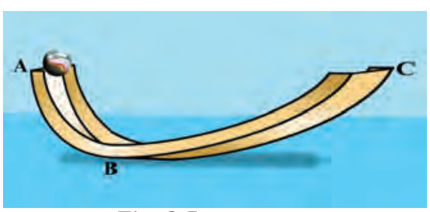


Fig. 3.5 (c)

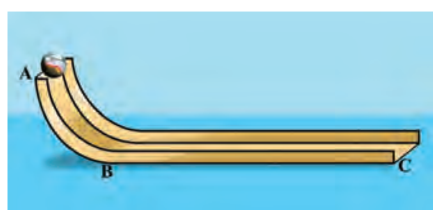


Fig. 3.5 (d)

A wiring channel is used for doing this experiment. The end C of the wiring channel is gradually lowered to horizontal level as shown in the figures.

- What do you observe, if in each case, a marble is rolled from the end A in the wiring channel?

Galileo Galilei

Lifetime : 1564 - 1642

Place of Birth : Pisa in Italy

From early childhood Galileo was interested in Mathematics and Philosophy. In 1581, in his first science book, 'The Little Balance', he mentioned the Archimedes' method of finding relative density. He observed the Saturn and Venus using his own telescope and argued that all the planets were revolving around the Sun. He was able to give some ideas about inertia through his inclined plane experiment.

- Does the distance travelled by the marble increase or decrease in each situation?
- When did the marble travel the longest distance?

The marble covers more distances as the slope decreases.

When the marble falls down it has a tendency to reach the original height. This tendency makes the marble move longer distances as the slope decreases.

- Why did the marble come to rest after traversing some distance?
- What would have happened if the force of friction was absent?
- What would have happened if no external force was applied to the marble?
- Write your inference from the above observation.

An unbalanced external force is to be applied in the opposite direction of motion of a body to bring it to rest. An unbalanced external force is not required to maintain uniform motion along a straight line.

This was Galileo's inference.

We can summarise the information acquired from the toy car experiment and Galileo's experiment as follows.

An unbalanced external force is essential to change the state of rest or uniform motion of a body.

Newton's First Law of Motion

Newton analysed and consolidated the scientific observations of predecessors such as Galileo. This enabled him to put forward new ideas and inferences on the motion of bodies subjected to forces. This paved the way for the formulation of Newton's laws of motion.

Every body will continue in its state of rest or uniform motion in a straight line unless and until an unbalanced external force acts on it. This is Newton's first law of motion.

The first law of motion helps us to define the physical quantities inertia and force.

- What is force?

Force is that which can change or tend to change the state of rest or uniform motion of a body along a straight line.

Inertia

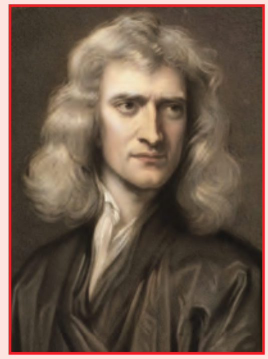
Did you notice that passengers standing in a bus tend to fall backwards when the bus at rest moves forward suddenly? Before the bus moved forward, weren't the passengers and the bus stationary? When the bus moves forward suddenly, the passengers tend to fall backwards because of the tendency to continue in the state of rest. This tendency is the inertia of rest.

- Why do the passengers standing in a bus tend to fall forward when the moving bus stops suddenly?
    - A body at rest cannot change its state of rest by itself. This is inertia of rest.
    - A body in uniform motion cannot change its state of motion by itself. This is inertia of motion.

Analyse the above ideas and write down a practical definition for inertia.

Compare it with the definition given below.

Sir Isaac Newton



Life time : 1643 - 1727

Place of Birth : England

Sir Isaac Newton was a philosopher, physicist, mathematician and an astronomer.

Major contributions : Proved that the motion of all objects on the Earth and celestial spheres are based on the same laws of nature. The force of gravitation and laws of motion are well explained in his book 'Principia Mathematica'. Even today, this book is the foundation stone of Mechanics. The corpuscular theory of light and calculus are his contributions. He is known as the Father of Calculus. He invented the reflecting telescope.

Inertia of a body is the tendency of the body to continue in its state of rest or uniform motion.

Do the following activities and write down the observations in the science diary.

Fig. 3.6 (a)

Fig. 3.6 (b)

Place a paper on a table. Keep a closed flat bottomed bottle filled with water over the paper. Quickly pull the paper horizontally.

- What happened to the bottle?
- Name the inertia possessed by the bottle.

Fig. 3.7 (a)

Place a glass filled with water on a desk. Slowly move it forward and gradually increase its speed. Stop it suddenly.

- What do you observe? Name the inertia possessed by the water.

Stack some carrom coins, one above the other, as shown in figure 3.7 (b). Place a plastic cup filled with water above it. Using a long plastic scale, quickly strike out the carrom coins one by one from the bottom.

Fig. 3.7 (b)

- Does the cup possess inertia? Which type?

Based on the knowledge gained from the activities you have done, write down the following statements related to inertia in the table (Table 3.2) appropriately.

- On shaking the branch of a mango tree, the mangoes get detached and fall down.
- A participant in long jump competition, runs some distance and then jumps.
- Travelling in a car without wearing seat belt is dangerous.
-

Inertia of rest	Inertia of motion
• When a bus moves forward suddenly, the standing passengers tend to fall backward. •	• A ball set rolling on a horizontal floor keeps moving forward. •

Table 3.2

Expand the table by including more examples for inertia of rest and inertia of motion.

Is there any relation between the mass of a body and inertia?

Mass and Inertia

Place a paper on a table. Take two identical flat bottomed bottles. Fill one of them with sand. Place the bottles vertically on the paper. Quickly pull the paper horizontally.

Fig. 3.8

- Which bottle does not topple over?
- Which bottle has a higher mass?
- Which bottle possesses more inertia?
- Based on the above observations, what is the relation between mass and inertia?

? Which one possesses greater inertia-an empty barrel or a tar filled barrel? Give reason.

? Why should people run in a zig-zag manner to escape from an elephant attack?

? From the following, write the situations where an unbalanced force is experienced.

a) Brakes are applied on a car moving with a velocity of 20 m/s.

b) A book is supported by the hand.

c) An artificial satellite travels with uniform speed.

A force of 200 N is applied on a body in one direction and another force of 250 N in the opposite direction.

a) Calculate the resultant force.

b) If it moves, what will be the direction of motion?

Let's examine some facts related to bodies in motion.

Momentum

Have you ever seen pits formed when coconuts fall on the loose soil in coconut plantations? Isn't it due to the impact made by the coconut on the soil? Will a pit of the same depth be formed if the coconut is placed gently? Such an impact can be exerted only by a body in motion. This property of a body in motion is momentum.

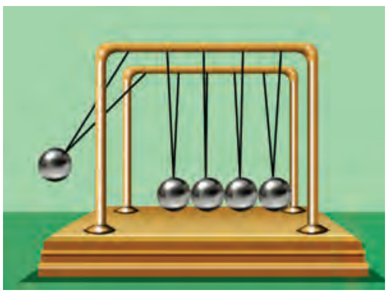


Fig. 3.9

Observe figure 3.9.

A device known as Newton's cradle is shown.

Pull back the balls in a Newton's cradle and release them in the following order. Write down the observations in the science diary.

- First ball alone
- First two balls
- First three balls
- First four balls

When the first ball alone hits the next ball, the momentum thus transferred by it reaches the last ball through the other balls and results in the last ball being tossed off.

When the first two balls together hit the next ball, they form a moving system and the momentum of this system is transferred to the last two balls. Hence the last two balls are tossed off.

What are the factors that influence this momentum?

In the Newton's cradle, pull back one ball alone to a small distance and release it. What do you see? The last ball moves out only a little. When the same ball is pulled back further and released, it hits with a greater velocity. Now we can see that the last ball covers a greater distance on moving out. Isn't it due to the increase in the velocity of the first ball?

- If so, which factor influenced the momentum of the ball?

We have seen that when a system of two balls together hit the others in the Newton's cradle, the last two balls are tossed out. This is due to the increase in the mass of the hitting system.

- In this case, what decided the momentum of the balls?

We have seen that the impact produced by a body in motion increases with the increase in its mass or velocity.

The momentum of a body in motion is the product of its mass (m) and velocity (v). ie., momentum, $p = mv$. Momentum is a vector quantity. The direction of momentum is the same as that of its velocity.

Unit of momentum = Unit of mass × Unit of velocity
= .... × .... = ...

Calculate the momentum of a body of mass 200 kg moving with a velocity 16 m/s.

The momentum of a body moving with a velocity 20 m/s is 200 kgm/s. What is its mass?

Calculate the momentum of a bullet of mass 60 g moving with a velocity 200 m/s. What is its momentum when it is at rest?

Rate of Change of Momentum

- A body of mass 20 kg is at rest. When a force is applied on it for 5 s, its velocity changes to 30 m/s. Find the change in momentum of the body.

Initial momentum = $mu = 20\ \text{kg} \times 0 = 0$

Final momentum = $mv = 20\ \text{kg} \times 30\ \text{m/s} = 600\ \text{kgm/s}$

Change in momentum = $mv - mu = 600\ \text{kgm/s} - 0 = 600\ \text{kgm/s}$

What will be its change in momentum in unit time or its rate of change of momentum?

$$\text{Rate of change of momentum} = \frac{\text{Change of Momentum}}{\text{Time}}$$

$$= \frac{600\ \text{kgm/s}}{5\ \text{s}}$$

$$= 120\ \text{kgm/s}^2$$

A body of mass 100 kg starts from rest and acquires a velocity of 30 m/s in the fourth second. If so,

a) what is its initial momentum?

b) what is its final momentum?

c) what is the change in momentum?

d) what is the rate of change of momentum?

A body of mass 20 kg is at rest. The velocity at various instances when a force of varying magnitude is applied on it for a time interval of 5 s is given. Calculate the initial momentum, final momentum and the rate of change of momentum of the body in each case.

Force N	Velocity acquired m/s	Initial momentum kgm/s	Final momentum kgm/s	Change in momentum kgm/s	Rate of change of momentum kgm/s^2
F	30	0	20 kg ×30 m/s = 600	600 – 0 = 600	$\frac{600\ kgm/s}{5\ s} = 120$
$\frac{F}{2}$	15				
2F	60				

Table 3.3

Complete the table and find the relation between the rate of change of momentum and the force applied on them.

Newton's Second Law of Motion

The rate of change of momentum of a body increases with the increase in the applied force. This was first enunciated by Sir Isaac Newton. This is Newton's second law of motion.

The rate of change of momentum of a body is directly proportional to the unbalanced force acting on the body. The change of momentum takes place in the direction of the resultant force.

Let's try to express it mathematically.

Let a body of mass m move with a velocity u. On applying a force F for a time t, the velocity changes to v.

Initial velocity of the body = u Final velocity = ...

Initial momentum = mu Final momentum = ...

Change in momentum = ...

Rate of change of momentum = $\frac{m(v-u)}{t}$ = ma

According to Newton's second law of motion $F \propto ma$

So, F = k ma

where k is a constant

The SI unit of force is newton (N). A force of 1 N is defined as the force required to produce an acceleration of 1 m/s^2 on an object of mass 1 kg. That is, m = 1 kg, a = 1 m/s^2. Then, F = 1 N

Therefore, F = kma ; 1 N = k × 1 kg × 1 m/s^2 ; k = 1

F = ma

This is the equation for calculating force.

A body of mass 12 kg is moving with an acceleration of 4 m/s^2. Calculate the force applied.

A force of 40 N is applied on a body of mass 20 kg. Calculate the acceleration produced.

A vehicle of mass 1000 kg is travelling with a velocity of 90 km/h. The vehicle comes to rest when brakes are applied for 5 s. Calculate the force applied.

Initial velocity u = 90 km/h

$$= 90 \times \frac{5}{18} \text{ m/s}$$

$$= 25 \text{ m/s}$$

Final velocity v = 0

Mass m = 1000 kg

F = ma

$$= \frac{m(v-u)}{t}$$

$$= \frac{1000(0-25)}{5} \text{ N}$$

$$= -5000 \text{ N}$$

Oh! There is a negative sign for this force. Why?

Force is a vector quantity. The negative sign indicates that the force applied is in a direction opposite to the motion of the vehicle.

? The velocity of a body of mass 10 kg changes from 6 m/s to 18 m/s in 4 s.

a) What is the rate of change of momentum?

b) What is the force applied?

c) Calculate the acceleration of the body.

d) What will be its velocity if this force is applied for 6 s?

mass m = 10 kg, initial velocity u = 6 m/s, final velocity v = 18 m/s

a) Rate of change of momentum $= m\frac{(v-u)}{t}$

$$= \frac{10\ kg\ (18\ m/s - 6\ m/s)}{4\ s} = 30\ N$$

b) Force F = Rate of change of momentum = 30 N

c) Acceleration $a = \frac{F}{m} = \frac{30\ N}{10\ kg} = 3\ m/s^2$

d) Final velocity $v = u + at = 6\ m/s + 3\ m/s^2 \times 6\ s = 24\ m/s$

Fig. 3.10

? A shot of mass 7 kg rolled on a level ground, with a velocity 2 m/s, came to rest in 5 s.

a) Which force brought it to rest?

b) Calculate the magnitude of this force.

Have you ever thought about the time interval required for the force to be transferred to the nail when a nail is hammered? Didn't this occur in a fraction of a second? Let's examine the peculiarities of this type of force.

Impulsive Force and Impulse of Force

Can you find out the peculiarities of the forces applied in the following situations?

- hitting the ball with a cricket bat
- kicking the ball while playing football

Aren't large forces applied here for a very short interval of time? Such forces are the impulsive forces.

Impulsive force is a very large force applied for a very short interval of time. The product of the force and the time is the impulse of the force.

Impulse of force (I) = Force (F) × Time (t), $I = F \times t$.

The unit of impulse of force = unit of force × unit of time

= .... × .... = ...

The impulse of force $= F\,t = \frac{m(v-u)\,t}{t} = mv - mu$

The impulse of force is equal to the change in momentum. This is impulse–momentum principle.

A ball of mass 200 g is moving with a velocity of 30 m/s. A person catches the ball.

a) If the time taken to bring the ball to rest is as follows, what will be the force felt on the arm in each case? i) 0.3 s ii) 0.2 s iii) 0.1 s

b) In all the answers you arrived at, the magnitude of the force is negative. What does this indicate?

c) Analyse the answers and arrive at a common conclusion.

Based on the conclusions formulated, find the reason for the following statements.

a) Cricket players move their hands backwards along with the ball while catching a fast moving ball.

b) In the game of football, while the goal keeper catches the ball coming into the goal post, he moves his hands backwards along with the ball.

c) A foam bed is placed in a pole vault pit.

d) Sponge or hay is kept between glass vessels while packing.

Fig. 3.11

Think about a situation in which no force is applied while considering the second law of motion.

$F = ma$ $\qquad a = \frac{F}{m}$

$F = 0$ then $\qquad a = 0$

There will be no acceleration if no force is applied. An object in motion with no acceleration will continue in its motion in a straight line or an object at rest will continue in its state of rest. Isn't this the first law of motion? Does it not mean that the second law of motion is on par with the first law of motion?

Have you ever run on the sand on a beach? Have you ever felt any difficulty in walking through a muddy terrain? What if you are walking on a firm ground? You are able to walk fast on a firm ground and find it difficult to walk through a muddy terrain. What may be the reason? In which direction do you apply force while walking on a ground? What is the direction of motion? To know more about this, let's familiarise with Newton's third law of motion.

Newton's Third Law of Motion

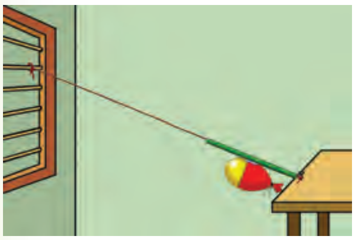


Fig. 3.12 (a)

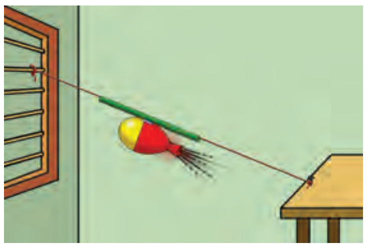


Fig. 3.12 (b)

As shown in the figure, a straw is passed through a smooth plastic thread tied diagonally. Attach an inflated balloon to the straw with cello tape and release the air from the balloon. What do you observe?

- What is the direction of air flow from the balloon?
- What is the direction of motion of the balloon?

A and B are two identical spring balances.

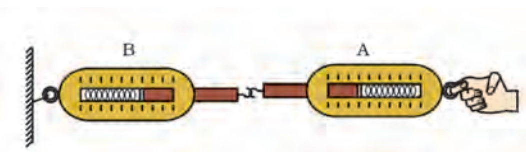


Fig. 3.13

Fix one end of the spring balance B firmly to the grill of a window. Apply a force 40 N on the spring balance B using A. What is the reading shown by each spring balance? Aren't they the same?

- Are the forces in the same direction or in the opposite direction?

The reading shown by one spring balance is action and the other is reaction.

That is, every action has a reaction. One of these forces is action and the other is reaction.

We can formulate Newton's third law of motion from these findings.

For every action (force) there is an equal and opposite reaction. This is Newton's third law of motion.

A car will not move if we push it sitting inside. But we can move the front seat by pushing it sitting on the back seat. How is it possible?

An option for sliding the front seats is provided. While sitting in the back seat and pushing the front seat, we are totally outside the front seat. Hence we are able to exert an unbalanced external force. But when we are pushing the car sitting inside, the same force that is exerted on the car is transferred through our body to the platform of the car. Thus the force becomes balanced. Hence the car will not move. On pushing the car by standing on the road, the car moves as an unbalanced external force is acting on it.

Which happens first – action or reaction?

Action and Reaction

Action and reaction act on two different bodies simultaneously. When force acts on two different bodies, the force on one body can be considered as the action and the force acting in the opposite direction on the other body as the reaction force. They occur in pairs only. Whenever there is an action, there is a reaction.

Find the reason for the following statements and record them in the science diary.

- **While rowing a boat the water is pushed back, but the boat moves forward.**
- **When a rocket is launched, gases are produced in its chamber by the combustion of fuels. These gases which are at high pressure move in one direction at high speed. But the rocket is propelled in the opposite direction.**
- **When a person jumps from a boat onto a shore, the boat moves backwards.**

Fig. 3.14

In the previous experiment using spring balance, aren't the forces equal in both the directions?

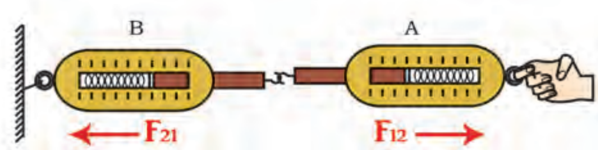


Fig. 3.15

Forces occur only in pairs. F_{12} is the force exerted by the first body on the second body. What about F_{21}? It is the force exerted by the second body on the first body. If so, according to Newton's third law of motion $F_{12} = - F_{21}$.

Static | Motion in accordance with the third law of motion | Continues in motion due to inertia

Fig. 3.16

Answer the following questions and justify them.

a) Action and reaction are equal and opposite. If so, will they cancel each other?

b) If you are pushing a vehicle standing on ice, will the vehicle move?

Based on the third law of motion, establish how an internal force becomes a balanced force. (Hint : When an internal force is applied, both the action and reaction are experienced on the same object.)

Let's Assess

1. A body of mass 5 kg travelling with a velocity 144 km/h comes to rest in 4 s. Calculate its

   a) initial momentum b) final momentum

   c) change in momentum d) rate of change of momentum

2. A hockey ball of mass 200 g hits a hockey stick with a speed 20 m/s and returns with the same speed through the same path. What is the change in momentum?

3. What is the rate of change of momentum of a loaded truck of mass 10,000 kg, if its velocity changes from 15 m/s to 12 m/s in 4 s?

4. Which of the following does not belong to the group?

   (force, momentum, velocity, speed)

5. A cup is covered with a cardboard and a coin is kept on the cardboard.

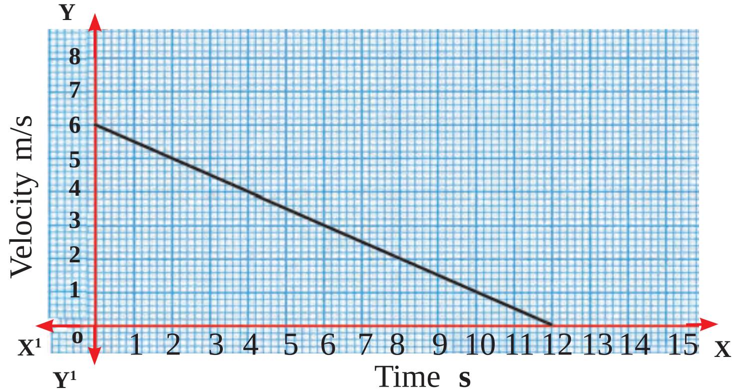
   a) What happens to the coin when the cardboard is struck off suddenly?

   b) Why does it happen?

6. To clean a carpet, we hold it up and hit it with a stick. The dust falls off. Give reason.

7. When a horse pulls the cart, the horse cart moves forward. The cart in turn pulls the horse with an equal and opposite force. But the horse and the cart go ahead. Explain how this is possible.

8. The velocity - time graph of a body of mass 250 g moving on a surface is given. Calculate the force of friction exerted by the surface.



Graph 3.1

9. A body of mass 500 g moves with a velocity of 40 m/s. On applying a force for 4 s, the velocity changes to 80 m/s. Calculate the force applied.

10. A person of mass 50 kg runs with a velocity of 8 m/s and makes a long jump. Another person of mass 60 kg makes the jump with a velocity 7 m/s. Compare their momenta.

11. Calculate the force required to stop a vehicle of mass 14,000 kg by applying a retardation of 1.8 m/s^2.

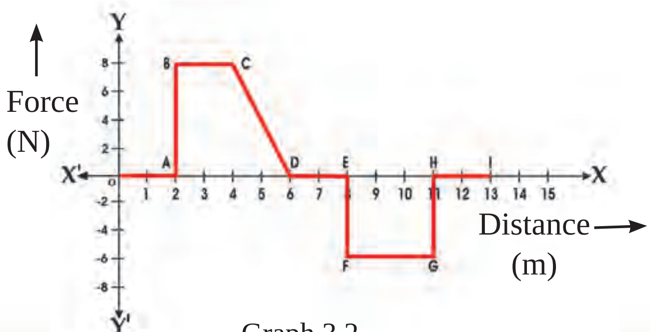
12. A force is applied on a body of mass 20 kg for 2 s and its velocity changes from 10 m/s to 50 m/s. The same force is applied on another body of mass 10 kg moving with a velocity of 20 m/s for 2 s in the direction of its motion. Calculate the final velocity.

13. A bullet of mass 20 g hits a wooden block with a velocity of 100 m/s and comes to rest after penetrating 4 cm.

    a) What is the acceleration of the bullet? b) What is the retardation of the bullet?

    c) Calculate the force exerted by the bullet on the plank.

14. A graph showing the application of force on a body of mass 10 kg is given. The magnitude of force changes as indicated in the graph. (Frictional force need not be considered.)



Graph 3.2

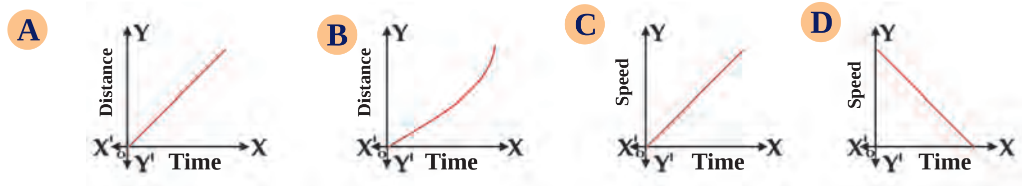
a) What is the acceleration of the body when it is at 3 m?

b) Which are the instances when the body has uniform velocity?

c) Which are the instances when the body has uniform acceleration?

d) Which is the instance when the body has retardation?

15. Which is the graph showing zero resultant force?



Graph 3.3

16. The figure shows forces applied on an object at rest. What is its acceleration? What is its displacement in 2 s?

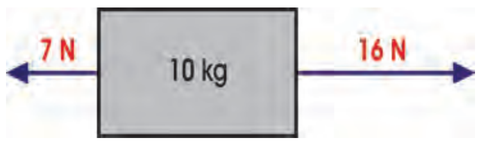


Fig. 3.17

17. Observe the figure.

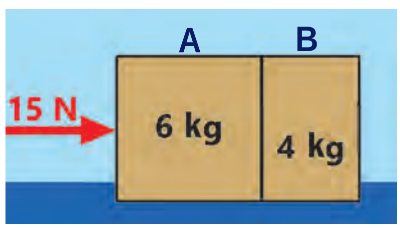


Fig. 3.18

A and B are two objects of masses 6 kg and 4 kg respectively. They are placed touching each other on a frictionless surface. Calculate the force exerted by object B on object A, when a force of 15 N is applied on them.

Extended Activities

1. Prepare and present a seminar paper on how overload and overspeed of vehicles affect road safety.

2. Write a report on how the concept of impulse can be used to explain the working of shock absorber in vehicles and discs in the spinal cord. Present it in the Science Club.

3. Present a seminar on some real life situations in which the concepts related to force are utilised.