Newton's laws of motion

Physics
04

4.1 Nature of force and its effects

You have studied about force in your previous classes. When we push something, we apply a force. When we pull something also, we apply a force. Lifting, compressing are also results of applying forces.

What should we do to move a body which is at rest? We have to apply a force in the direction we need to move the body. However, does it start to move as soon as we apply the force?

Try to push a table as shown in Figure 4.1. If it does not move, increase the force. When you keep increasing the force, at some point, it will begin to move.

Figure 4.1 - Pushing a table

Figure 4.2 - Pushing a bus

If you try to move a bus yourself, in the same manner that you tried to move the table, the bus would not move. But if you push it with the help of a group of people as shown in Figure 4.2, it would move. That is, if we apply a force sufficient to overcome a force that tends to oppose the motion of an object, then it would begin to move. The force that opposes the motion of the object is a resistive force called friction. If the force that we apply is small, it would balance with the resistive force. Since the net force acting on the object at such an instance is zero, the object would not move. If we apply a sufficiently large force, the resistive force would not be able to balance it, and then there would be an **unbalanced force** acting on the object, which could set the object in motion.

If the above mentioned table was on a very smooth surface, such as ice, even a very small force would be sufficient to start the motion. That is because, when there is no resistive force, the whole force that we apply becomes an unbalanced force and contributes to the motion of the table. When ever an unbalanced force acts on an object at rest, the object starts to move.

Figure 4.3 shows a cart loaded with goods being pulled by a bull. If someone applies a force from behind, in the direction that the cart is moving, then the cart would move faster. If a force is applied in the direction opposite to the direction of motion, the cart would slow down. This shows that the result of applying a force depends on the direction of the force.

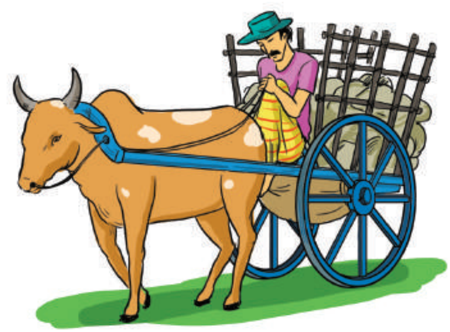

Figure 4.3 - A cart pulled by a bull

This means that the force has both a magnitude and a direction. Since there is a magnitude as well as a direction, the **force is a vector.** The direction of a force acting on some point can be indicated by a straight line drawn from that point. This line is called the line of action of the force.

What we experience about force and motion has been studied in depth by the famous scientist, Sir Isaac Newton. He has formulated three laws of motion based on his studies. Let us now investigate each of these laws.

Newton's first law

Until an unbalanced force is applied on it, bodies at rest remain stationary and bodies in motion continue to move at uniform velocities.

From day to day experience we know that bodies at rest do not start moving without external forces acting on them. However, we often observe that moving bodies come to rest without an external force exerted on them by us. Let us consider the following example in order to understand this.

Consider the case of striking on the carom disc on a carom board with your fingernail as shown in Figure 4.4. Then the disc would move a short distance and come to rest. If we apply some talcum powder on the carom board to make the surface smoother and then repeat the above action by striking on the disc with roughly the same force as before, the disc would move a much longer distance before coming to rest.

Figure 4.4 - Striking a carom disc

The action of the talcum powder on the board is to reduce the resistive forces exerted on the disc by the carom board. The resistive force that opposes the motion of an object on a surface, is called friction. If by some means we could make the frictional force equal to zero, the disc would move without stopping.

Let us consider another example that we experience in daily life, connected to this law. Suppose a passenger is standing on a moving bus without holding any thing for support. If the bus suddenly stops by applying brakes, the passenger would fall towards the forward direction. What is the reason for this?

Since his feet were in contact with the floor board of the bus, the floor board exerts a resistive force on the feet and brings the feet (which too had the speed of the bus) to rest. Since no such force is exerted on the upper parts of his body, their velocity, carries him forward. He falls in the forward direction because of this.

Now suppose that the above passenger is in a bus at rest. If the bus starts to move without his knowledge, the passenger would now fall in the backward direction. As the bus starts, it would exert a force on the feet of the passenger giving the lower part of his body a velocity. The upper part of his body however does not have this velocity and remains at rest, resulting in his falling back.

Seat belts must be worn when riding in a vehicle to prevent the passenger from falling forward upon applying brakes. As the seat belt exerts a force on the upper part of his body as well, the whole body remains at the velocity of the vehicle even when brakes are applied.

Figure 4.5 – Seat belt privents the driver being thrown forward when breaks are applied.

Newton’s second law

The acceleration of a body is directly proportional to the unbalanced force acting on it, while it is inversely proportional to its mass.

Here, "the acceleration is **directly proportional** to the unbalanced force" means that when the magnitude of the unbalanced force is increased or decreased by a certain ratio then the acceleration also increases or decreases by the same ratio.

This is symbolically written as $a \propto F$.

Similarly "the acceleration is **inversely proportional** to the mass" means that if the mass is increased by a certain ratio, then the acceleration decreases by the same ratio, and if the mass is decreased by a certain ratio, then the acceleration increases by the same ratio.

This statement is symbolically written as, $a \propto \frac{1}{m}$.

Therefore Newton’s second law can be written as

$$a \propto F \text{ and}$$

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

$$\text{or, } a \propto \frac{F}{m}$$

Therefore we have, $\frac{F/m}{a} = \text{constant}$

The unit of force is defined in such a way that the above constant is equal to one. That is, if the unit of force is defined in such a way that the force required to produce a unit acceleration (1 m s^{-2}) in a body of unit mass (1 kg) is equal to 1 Newton (1 N), Then the value of the left hand side of the above equation becomes 1, That means when

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

then the constant will also become 1. Therefore, Newton's second law can be written as

$$F = ma$$

A force is acting on an object, gives rise to an acceleration.

Let us consider the following experiment in order to verify Newton's second law.

Figure 4.6 - Demonstrating that the acceleration of a trolley increases with force

- Place a trolley on a horizontal surface, attach a rubber band to the trolley and hold the trolley with one hand.
- Hold the free end of the rubber band with the other hand as shown in Figure 4.6 and pull it until it is extended to the other end of the trolley.
- Next, release the trolley and move your hand along with the trolley, without changing the extension of the rubber band. You will notice that the trolley moves with an acceleration.
- Attach another rubber band similar to the first one to the trolley and stretch both to the other end of the trolley as before and repeat the experiment. As the force on the trolley is now twice the force in the previous step, you will be able to observe that the trolley moves with a larger acceleration than before.
- Repeat the experiment with three rubber bands and observe that the acceleration is even larger than that in the second time. Since there are three rubber bands, the force exerted on the trolley is three times as large as in the first time.
- Accordingly, it can be observed that the acceleration of the trolley increases as the force exerted on it is increased.

- Now place a mass on the trolley and repeat the experiment with one rubber band and observe the motion of the trolley. You will observe that the acceleration has decreased.

- Then repeat the experiment with another mass placed on the trolley and you will notice that the acceleration decreases further.

From this it will be clear that the acceleration decreases with increasing mass if the force is constant.

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

It is clear from the above equation that for a constant force, the acceleration increases if the mass is decreased and the acceleration decreases if the mass is increased.

Example 1

What is the force required to give an acceleration of 2 m s^{-2} to a 5 kg mass?

$$\begin{aligned} F &= ma \\ &= 5 \text{ kg} \times 2 \text{ m s}^{-2} \\ &= 10 \text{ N} \\ &\quad (1 \text{ kg m s}^{-2} = 1 \text{ N}) \end{aligned}$$

Example 2

A force of 12 N is applied on a body of mass 6 kg, moving at a uniform velocity, in the direction of its motion. Find the acceleration of the body.

$$\begin{aligned} F &= ma \\ 12 &= 6 \times a \\ a &= \frac{12}{6} \\ a &= 2 \text{ m s}^{-2} \end{aligned}$$

Example 3

If an acceleration of 2 m s^{-2} results when a force of 8 N is applied on a certain object, find the mass of the object.

$$F = ma$$
$$8 = m \times 2$$
$$m = \frac{8}{2}$$
$$m = 4 \text{ kg}$$

Exercise 4.1

Fill in the blanks in the table given below.

(1)

Force (N)	**Mass (kg)**	**Acceleration (m s^{-2})**
....	3 kg	2 m s^{-2}
40 N	10 kg	....
30 N	....	1.5 m s^{-2}
2 N	500 kg	....

(2) (a) If a force of 6 N is applied on a body of mass 4 kg, moving at a uniform velocity, in the direction of its motion, find the resulting acceleration.

(b) If the above force is applied in the direction opposite to the direction of motion of the body, find its deceleration.

Newton's third law

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

Here, an **action** means a force exerted by an object on another object. Then the **reaction** is a force exerted on the first object, by the second object.

Expulsion of air from an inflated balloon is a practical situation where this law can be applied. Hold a balloon filled with air, with its opening turned downwards.

Loosen the hold on the opening and release the balloon as shown in Figure 4.7. You will notice that the balloon would initially move upwards rapidly and later fall down. Air leaves the balloon as its rubber walls push the air molecules downwards. The balloon moves upward due to the reaction force exerted on the rubber walls by the air molecules moving out.

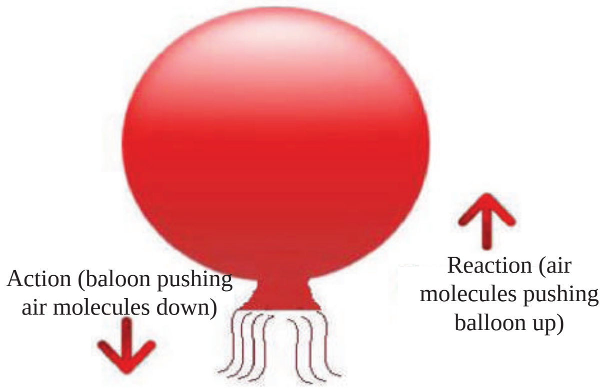

Figure 4.7 –Air inside the balloon leaving it and the balloon moving upwards.

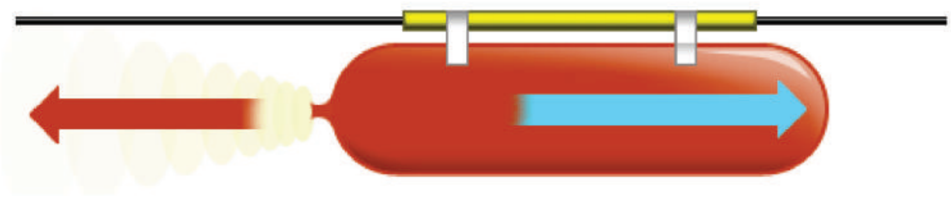

Figure 4.8 – Air leaving the balloon and the balloon moving in the opposite direction

A balloon moving due to air leaving the balloon can also be illustrated as shown in Figure 4.8. Attach a straw to an air filled balloon as shown in Figure 4.8, using sellotape. Insert a metal wire through the straw and fix it horizontally from the two ends. Allow the air in the balloon to leave by removing the thread that closes the opening of the balloon.

You will be able to observe the balloon moving on the metal wire in the direction opposite to that of the air leaving the balloon.

Another instance illustrating the action and reaction is shown in Figure 4.9. Place two planks of wood on a few glass balls. Let two children sit on the two planks. If they push each other with their palms as shown, it would be possible to observe them moving in opposite directions.

Figure 4.9 - Two children being pushed in opposite directions when pushing each other with their palms.

A few other instances where Newton's third law is applied are mentioned below.

When rowing a boat (Figure 4.10), water is pushed in the backward direction using the oars. That is, a force is applied on water by the oars. Then the boat moves forward due to the reaction force applied on the oars by water.

Figure 4.10 – Force applied on the water by the oars and the reaction force acting on the boat.

In swimming (Figure 4.11), the swimmer exerts a force on water in the backward direction. Then water exerts the reaction force on the swimmer's body in the forward direction. Because of this, the swimmer moves forward. The action in this case is the backward force applied by the hands. The reaction is the forward thrust exerted by water.

Figure 4.11 - Hands applying a force on water and an equal and opposite force exerted on the hands by water.

4.2 Momentum

The momentum of a moving body is a measure of how difficult it is to stop the motion of that body.

It would be an easy task to catch a pen or pencil thrown to you by a friend. If however, somebody throws a putt or some other heavy object towards you, it would not be so easy to catch it. If the same object is handed over to you without throwing then it would not be difficult to take it to your hand.

The reason for the difficulty in catching such an object is not only its large mass but also the speed with which it is moving. A bullet fired from a gun has very small mass. But once it is fired, we cannot even think of catching it.

Therefore, we can conclude that the level of difficulty in stopping a moving body depends on two factors; mass and velocity.

In physics, the momentum of a body is defined as the product of the mass (m) of the object and its velocity (v).

Momentum = mass × velocity

$$= m \times v$$

The unit of mass is kg. The unit of velocity is m s^{-1}. Therefore, the unit of momentum is kg m s^{-1}.

Since the velocity is a vector, the momentum is also a vector.

When a motor vehicle is moving fast, it possesses a large momentum. When it reduces its velocity, the momentum decreases. When it speeds up, the momentum increases.

Example 1

What is the momentum of a body of mass 2000 kg moving at a velocity of 20 m s^{-1}?

$$\text{Momentum} = m \times v$$
$$= 2000 \text{ kg} \times 20 \text{ m s}^{-1}$$
$$= 40000 \text{ kg m s}^{-1}$$

Example 2

A bullet of mass 10 g fired by a gun moves at a velocity of 400 m s^{-1}. Find its momentum.

In this problem, when we substitue the value of mass to the equation, we must convert the mass to kg.

$$\text{Momentum} = m \times v$$
$$= \frac{10}{1000} \text{ kg} \times 400 \text{ m s}^{-1}$$
$$= 4 \text{ kg m s}^{-1}$$

Exercise 4.2

1. The mass of a motor car is 800 kg. Find its momentum when it is moving at a velocity of 5 m s^{-1}.
2. The mass of an object is 600 g. Find its momentum when it is moving at a velocity of 5 m s^{-1}.
3. A certain object has a mass of 200 g. if it moves with a velocity of 4 m s^{-1} what is the momentum of the object ?
4. The momentum of a moving object is 6 kg m s^{-1}. Find its velocity if it has a mass of 500 g.
5. An object of mass 3 kg is projected upwards. At the beginning of the motion its velocity is 10 m s^{-1}.
   (a) What was its momentum at the moment when it was projected?
   (b) What would be the momentum when it reaches the highest point?

4.3 Mass and weight

The mass of an object is the amount of matter in it. The international unit of mass is the kg.

The weight of an object is the force with which it is attracted towards the earth. That is, the force acting on it due to gravitational attraction of the earth.

According to Newton's second law, the force acting on a body moving at an acceleration is given by,

$$F = m a$$

If it is moving under gravity, then its acceleration would be the gravitational acceleration g. Then, the force exerted on the body is its weight and it is given by,

$$\text{Weight} = \text{mass} \times \text{acceleration} = m g$$

Because the weight is defined as a force, its international unit is the Newton (N).

Since the gravitational acceleration near the surface of the earth at sea level is 9.8 m s^{-2}, the weight of a body of mass *m* is 9.8*m*. The weight of an object of mass 1 kg would be 9.8 N.

Attractive force exerted by the earth on a mass of 3 kg (weight) = 3 kg × 9.8 m s^{-2}
= 29.4 N

When we go up, starting from sea level, the gravitational acceleration gradually decreases. Therefore, if we take an object to the top of a mountain, the weight of the object becomes less, while the mass remains constant. On the moon, the gravitational acceleration is about 1/6 of that on the earth. Therefore, the weight of an object on the moon is about 1/6 of the weight of that object on the earth.

Miscellaneous exercises

(1) (i) State Newton's first law.

(ii) Why are the passengers standing on a moving bus, thrust forward when brakes are suddenly applied?

(iii) A passenger is seated in a bus at rest. If the bus starts to move without his knowledge, why is he pushed backwards?

(iv) What is the benefit of wearing seat belts when travelling in vehicles?

(2) (i) State Newton's second law.

(ii) The mass of a body is 12 kg. What is the resulting acceleration if a force of 6 N is applied on it in the direction of motion?

(3) Fill in the blanks of the table given below.

Force (F)	Mass (m)	Acceleration (a)
....	10 kg	2 m s^{-2}
60 N	12 kg	....
4 N	500 g	....
40 N	....	5 m s^{-2}

(4) The mass of a certain object is 6 kg. What is the force that could have acted on it, if its velocity increased from 5 m s^{-1} to 13 m s^{-1} during 5 s?

(5) (i) State Newton's third law.

(ii) Give three instances where Newton's third law is applied.

(iii) What are the factors affecting the momentum of an object.

(6) What is the momentum of an object of mass 10 kg, moving at a velocity of 4 m s^{-1}?

(7) The mass of an object is 750 g. At a certain instant, its velocity is 8 m s^{-1}. What is its momentum at this instant?

(8) At a certain instant, the momentum of an object is 6 kg m s^{-1}. If its velocity at that instant is 3 m s^{-1}, what is its mass?

(9) (i) The mass of an object is 60 kg. What is its weight? (g = 10 m s^{-2})

(ii) If the gravitational acceleration on the moon is $1/6^{th}$ that of the earth, what would be the weight of the above object on the moon?

(10) The weight of an object is 5 N. At a certain instant, its momentum is 6 kg m s^{-1}. Due to a force applied in the direction opposite to the direction of motion. the velocity is of the object decreased to 4 m s^{-1} during 4 s. what is the force exerted on the object ?

Summary

- According to Newton's first law, until an unbalanced force acts on it, a stationary body remains at rest and a moving body continues its motion at a uniform velocity.
- Newton's second law states that the acceleration of a body is directly proportional to the force acting on it and inversely proportional to its mass.
- Newton's third law states that for every action, there is a reaction equal in magnitude and opposite in direction to the action.
- The weight of an object is the force with which it is attracted to the center of the earth. It is equal to the force that is required to accelerate it with the gravitational acceleration *g*.

Technical terms

Force	බලය	விசை
Unbalanced Force	අසංතුලිත බලය	சமநிலைப்படாத விசை
Uniform acceleration	ඒකාකාර ත්වරණය	சீரான ஆர்முடுகல்
Uniform velocity	ඒකාකාර ප්‍රවේගය	சீரான வேகம்
Mass	ස්කන්ධය	திணிவு
Acceleration	ත්වරණය	ஆர்முடுகல்
Action	ක්‍රියාව	தாக்கம்
Reaction	ප්‍රතික්‍රියාව	மறுதாக்கம்
Momentum	ගම්‍යතාව	உந்தம்