9 FORCE AND LAWS OF MOTION

INTRODUCTION

- The basic idea Newton taught us is that motion is caused by forces which is easy enough to understand: kick a ball (the force) and it flies into the air (the motion). But forces don't always make things move: a bridge has lots of forces acting on it, but it doesn't go anywhere.
- Also, the "motion" forces produce is sometimes a shift in the direction in which something is moving or a change in its shape. So what exactly are forces and how they do they produce these different kinds of motion? It's time to take a closer look at the science of moving things!
- "May the force be with you" is a strange thing to say to someone, because there's a never a moment when forces aren't. Forces are the hidden power behind everything that happens in our world and beyond. Forces make your heart race and your lungs pump; they swing the planets round the Sun and bind atoms tight.
- Think of anything, absolutely anything, that's going on in the universe right now, and you can guarantee that somewhere, somehow forces are responsible

1 FORCE

In our everyday life, we observe that some efforts are required to put a stationary object into motion or to stop a moving object. We ordinarily experience this as a muscular effort and say that we must push, hit or pull on an object to change its state of motion. The concept of force is based on this push, hit or pull.

1.1 Force

Any action which requires one to pull, hit or push on a body is called a force. Forces cannot be seen and can only be judged by the effects which they produce on bodies around us. Some effects of force are given below:

(1) A force can move a stationary body

(2) A force can stop a moving body

(3) A force can change the direction and speed of a moving body

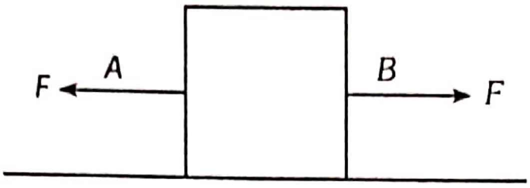
(4) A force can change the shape an

1.2 Types of Force

Forces can be categorised as balanced forces and unbalanced forces. This section takes a look at these forces and some everyday life examples where we encounter them.

(1) **Balanced forces:** When the net effect produced by a number of forces acting on a body is zero, then the forces are said to be balanced forces. We can also say that the body is balanced. Balanced forces can only bring a change in the shape of the body and do not affect its motion.

Example: A block of wood is placed on a horizontal surface and two strings A and B are connected to it as shown in the figure:



The block is initially at rest. If we pull strings A and B with equal magnitude of forces, then the block does not change its state of rest. Then we can say that the forces are balanced. Balanced forces do not change the following:

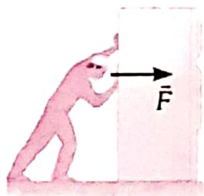
- The state of rest of a body
- The state of motion of a body

Example: In a tug of war when both the teams apply equal force from both sides, rope does not move either side, i.e. the resultant force is zero. Hence, it is a case of balanced forces.

(2) **Unbalanced forces:** When the net effect produced by a number of forces acting on a body is non-zero, then the forces are said to be unbalanced.

Example: A boy wants to relocate the refrigerator in his house as shown in the figure.

He pushes the refrigerator with a small force, the refrigerator does not move due to frictional force acting in a direction opposite to the push. If he pushes the refrigerator harder, then the pushing force becomes more than the friction and due to this the refrigerator starts moving in the direction of push as shown in the figure.



In the above example there is an unbalanced force which causes motion of the refrigerator. Unbalanced forces change the following:

- The state of rest of a body
- The state of uniform motion of a body

Example: In a tug of war when one of the teams suddenly releases the rope, then an unbalanced force acts on the other team due to which they fall backwards.

> If an unbalanced force is applied on a moving object, there will be a change either in its speed or in the direction of its motion. Thus, to accelerate the motion of an object, an unbalanced force is required.

2 NEWTON'S FIRST LAW OF MOTION

Isaac Newton studied the ideas of Galileo concerning the motion of an object. He formulated the fundamental laws that govern the motion of objects. These three laws are known as Newton's laws of motion, which we will discuss in this chapter.

2.1 Newton's First Law of Motion

It states that an object will continue to remain in a state of rest or of uniform motion along a straight line path unless acted upon by an external force(s). This means all objects resist change in their state. The state of any object can be changed by applying external forces only.

Examples:

(1) A person standing in a bus falls backward when the bus starts moving suddenly. This happens because the person and bus are both initially at rest. When the bus starts moving the legs of the person start moving along with the bus, but the rest of his body has a tendency to remain at rest. Because of this, the person falls backwards if he is not alert.

(2) A person standing in a moving bus falls forward, when the driver applies brakes, suddenly.

3 INERTIA

3.1 Inertia

The unwillingness (or inability) of an object to change its state of rest or of uniform motion along a straight line is called inertia of the object. A few properties and facts about inertia are stated below:

- It is an inherent property of all objects
- Newton's first law of motion is also known as Galileo's law of inertia
- Inertia of an object is measured by its mass, it is directly proportional to the mass of the object. It means that inertia increases with increase in mass and decreases with decreases in mass. A heavy object will have more inertia than a lighter one.

3.2 Types of Inertia

There are three types of inertia:

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

Examples:

- When a bus suddenly starts moving forward, then the passengers in the bus fall backward.
- A carpet is beaten with a stick to remove the dust particles.
- When a tree is vigorously shaken, then some of the leaves fall from the tree.

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

Examples:

- Passengers in a bus fall forward when a fast moving bus stops suddenly.
- A person falls forward while getting down from a moving bus or train.
- Luggage is usually tied with a rope on the roof of a bus otherwise it will fall off when the bus stops suddenly.

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

Examples:

- When a fast moving bus navigates a curve on the road, then passengers fall away from the centre of the curved road.
- The sparks produced during sharpening of a knife against a grinding wheel leaves tangentially to its rim.
- A stone tied to a string is whirling in a circle. If the string breaks, then the stone flies away tangentially.

4 NEWTON'S SECOND LAW OF MOTION

4.1 Momentum

Momentum measures the quantity of motion possessed by a body. It is defined as the product of a mass and velocity of the body. Besides magnitude, momentum also has a direction. At any instant, its direction is the same as the direction of the velocity. It is a vector quantity.

If a body of mass m moves with a velocity v, then momentum p is given by:

$$p = mv$$

The SI unit of momentum is kg m/s.

If a body is at rest its velocity is zero and therefore, its momentum is also zero.

Example : A car of mass 1000 kg is moving with a velocity of 72 km/h. Find its momentum.

Solution: Mass of the car, $m = 1000$ kg, velocity of the car, $v = 72$ km/h = 20 m/s

The momentum of the car can be found as: $p = mv = 1000 \times 20 = 20000$ kg m/s

4.2 Newton's Second Law of Motion

The second law of motion states that the rate of change of momentum of an object is directly proportional to the applied external force.

(1) **Mathematical formula for second law of motion:** If a body of mass m moving at initial velocity u, accelerates uniformly with an acceleration a for time t, so that its final velocity change to v, then:

Initial momentum, $p_1 = mu$, Final momentum, $p_2 = mv$

$$\Delta p = p_2 - p_1 = mv - mu = m(v-u)$$

According to the second law of motion:

$$F \propto \frac{\text{Change in momentum}}{\text{Time}} \Rightarrow F \propto \frac{\Delta p}{t} \Rightarrow F \propto \frac{m(v-u)}{t}$$

$$F \propto ma \Rightarrow F = kma$$

The quantity k is a constant of proportionality. One unit of force is defined as the amount that produces an acceleration of 1 m/s² on an object of 1 kg mass, i.e., 1 unit of force $= k \times 1\,\text{kg} \times 1\,\text{m/s}^2 \Rightarrow k = 1$

Therefore, the second law of motion can be rewritten as: $F = ma$

The SI unit of force is Newton, which is denoted by the symbol N and it is equivalent to kg m/s².

When the applied force is zero, then the acceleration is also zero and the body remains in its state of rest or of uniform motion.

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(2) **Application of Newton's second law of motion :** The following applications are based on Newton's second law of motion:

- A cricket player (or fielder) moves his hands backward while catching a fast cricket ball
- During athletics meets, athletes doing high jump and long jump land on foam or a heap of sand to decrease the force on the body and the landing is comfortable and safe

(3) **Newton's first law from mathematical expression of second law:** The first law of motion can be mathematically understood from the mathematical expression of the second law of motion.

As we know,

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

From this equation if $F = 0$, then $v = u$ for any value of time. This means that in the absence of an external force, the object will continue moving with uniform velocity u throughout the time t and if u is zero, then v will also be zero. This means that the object will stay at rest.

Example 1: A force acts on an object of mass 4 kg and changes its velocity from 10 m/s to 20 m/s in 5 s. Find the magnitude of the force.

Solution: Mass of the object, $m = 4$ kg, Initial velocity of the object, $u = 10$ m/s,

Final velocity of the object, $v = 20$ m/s, Time taken, $t = 5$ s

The force can be found using Newton's second law of motion as:

$$F = \frac{m(v-u)}{t} = \frac{4 \times (20-10)}{5} = 8\text{N}$$

Example 2: A force of 50 N acts on a stationary body of mass 10 kg for 2 s. Find the acceleration produced in the body and velocity attained by it.

Solution: Force acting on the body, $F = 50$ N, Mass of the body, $m = 10$ kg

Time taken, $t = 2$s, Initial velocity, $u = 0$ m/s

Using the Newton's second law of motion, the acceleration of the body can be found as: $50 = 10 \times a \Rightarrow a = 5\,\text{m/s}^2$

The velocity attained can now be found as: $a = \frac{v-u}{t} \Rightarrow 5 = \frac{v-0}{2} \Rightarrow v = 10\,\text{m/s}$

Example 3: A bullet train is moving with a velocity of 180 km/h and it takes 5 s to stop after the brakes are applied. Find the force exerted by the brakes on the wheel of the train, if its mass with the wagan is 2000 kg.

1 Initial velocity of the train, $u = 180$ km/h = 50 m/s, Final velocity of the train, $v = 0$ m/s

Time taken, $t = 5$ s, Mass of the train and wagon system, $m = 2000$ kg

The force exerted by the brakes on the wheel of the train can be found using Newton's second law of motion:

$$F = m(v-u) = \frac{2000 \times (0-50)}{5} = -20000\text{N}$$

The negative sign shows that the direction of force is opposite to the motion of the train.

Example 4: A force of 6 N gives a mass m_1 an acceleration of 18 m/s² and a mass m² an acceleration of 24m/s². What acceleration would it give if both the masses were tied together?

Solution: Force applied, $F = 6$ N, Acceleration of first mass, $a_1 = 18$ m/s², Acceleration of second mass, $a_2 = 24$ m/s²

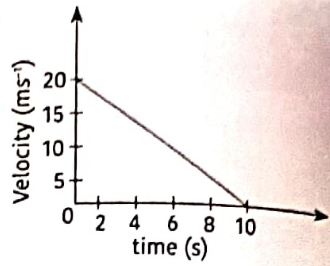
Applying Newton's second law of motion to the first mass: $F = m_1 a_1 \Rightarrow 6 = m_1 \times 18 \Rightarrow m_1 = \frac{1}{3}$kg

Applying Newton's second law of motion to the second mass: $F = m_2 a_2 \Rightarrow 6 = m_2 \times 24 \Rightarrow m_2 = \frac{1}{4}$kg

Now applying Newton's second law of motion to the combined system we get:

$$F = (m_1 + m_2)a \Rightarrow 6 = \left(\frac{1}{3} + \frac{1}{4}\right) \times a \Rightarrow 6 = \frac{7}{12} \times a \Rightarrow a = 10.28\,\text{m/s}^2$$

Example 5: The velocity-time graph of a ball of mass 20 g moving along a straight line on a long table is given. How much force does the table exert on the ball to bring it to rest?



Solution: Mass of the ball, $m = 20\text{ g} = 0.02\text{ kg}$,
From the graph, we can see that: Initial velocity of the ball, $u = 20$ m/s
Final velocity of the ball, $v = 0$ m/s, Time taken, $t = 10$ s
The force exerted by the table on the ball such that the ball comes to rest can be found using

Newton's second law of motion as: $F = \frac{m(v-u)}{t} = \frac{0.02\times(v-u)}{t} = \frac{0.02\times(0-20)}{10} = -0.04\text{N}$

The negative sign indicates that the force is acting opposite to the direction of motion of the ball.

4.3 Impulse:

It is termed as the total impact of force. This is equal to the change in momentum of the body. In other words, impulse is defined as the product of force and the small time in which the force acts.

According to Newton's second law: $F = ma = \frac{m(v-u)}{t} \Rightarrow Ft = mv - mu$

Impluse, $I = Ft = p_2 - p_1$

The SI unit of impulse is N s or kg m/s.

Example: If a force of 1000 N is applied on a vehicle of 500 kg, then for how much time will the velocity of the vehicle increase from 2 m/s to 10 m/s. Also find the impulse.

Solution: Force applied on the vehicle, $F = 1000$ N, Mass of the vehicle, $m = 500$ kg
Initial velocity of the vehicle, $u = 2$ m/s, Final velocity of the vehicle, $v = 10$ m/s
The time taken for the velocity of the vehicle to increase from 2 m/s to 10 m/s can be found as:

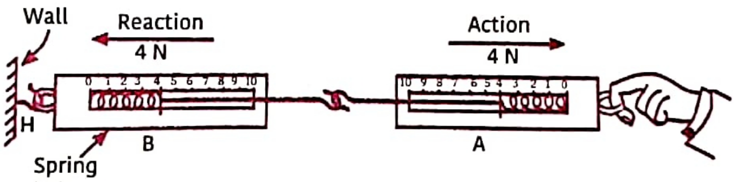
$$F = \frac{m(v-u)}{t} \Rightarrow t = \frac{m(v-u)}{F} = \frac{500\times(10-2)}{1000} = 4\text{s}$$

The impulse can now be found as: $I = Ft = 1000\times 4 = 4000\text{Ns}$.

5 NEWTON'S THIRD LAW OF MOTION

5.1 Newton's Third Law of Motion

The third law of motion states that, when one object exerts a force on another object, then the second object exerts a force equal in magnitude but opposite in direction on the first object. In other words, every action has an equal and opposite reaction.
Example: Spring balance action and reaction forces are equal and opposite. This is illustrated below:



Thus, action and reaction forces are equal in magnitude and opposite in direction. They still do not cancel each other's effect because they act on different objects.

5.2 Application of Newton's third Law of Motion

The following applications are based on Newton's third law of motion:

(1) **Collision of two people:** If two people walking or running in opposite directions collide with each other then both feel hurt. This is because they apply equal forces on each other. Two opposing forces are an action and reaction pair.

(2) **A person walking:** A person is able to walk because of Newton's third law of motion. During walking, a person pushes the ground in the backward direction. The reaction force is due to the ground pushing the person with equal magnitude of force but in the opposite direction. This enables the person to move forward and walk.

(3) **Recoil of a gun:** When a bullet is fired from a gun, then the bullet pushes the gun in the opposite direction of its motion with the same magnitude of force. Since the gun has a greater mass than the bullet, the acceleration of the gun is much less than the acceleration of the bullet.

(4) **Propulsion of a boat in forward direction:** Sailor pushes water with oars in the backward direction resulting water to push the oars in the forward direction. Consequently, the boat is pushed in the forward direction. Force applied by the oars and water are of equal magnitude but in opposite directions.

(5) **Rocket propulsion:** The propulsion of a rocket is based on the principle of action and reaction. The rapid burning of fuel produces hot gases which rush out from the nozzle at the rear end of the rocket at a very high speed. This produces a reaction force which is equal in magnitude and opposite in direction to the escaping gases hence, propelling the rocket forward.

Chapter At Glance

(1) Any pushing or pulling motion is a **force.**

(2) A force can change the state of motion, the shape and size of a body.

(3) If the net effect of multiple forces on a body is zero, then the forces are said to be **balanced.** The body's state of motion does not change in this case.

(4) If the net effect of multiple forces on a body is non-zero, then the forces are said to be **unbalanced.** The body's state of motion changes in this case.

(5) The motion of all bodies in the universe are governed by **Newton's three laws of motion.**

(6) Newton's first law of motion states that an object's state of motion doesn't change unless acted upon by an unbalanced external force.

(7) **Inertia** is the inability of an object to change its state of rest or motion along a straight line.

(8) **Momentum** is a physical quantity that measures the amount of motion possessed by a body. It is mathematically given as:

$$p = mv$$

Here, p is the momentum of the body, m is the mass of the body and v is the velocity of the body.

It is a vector quantity and its SI unit is kg m/s.

(9) Newton's second law of motion states that the rate of **change of momentum for a body is directly proportional to the external force** acting on it. Mathematically it is given as:

$$F = ma$$

Here, F is the external force, m is the mass of the body and a is the acceleration produced by the body due to the external force.

(10) Newton's third law of motion states that **every action has an equal and opposite reaction.**