

DYNAMICS - 1

UNIT
3

What force enable us to hold rope tightly?

Student Learning Outcomes (SLOs)

The students will

- [SLO: P-09-B-17] Illustrate that mass is a measure of the quantity of matter in an object.
- [SLO: P-09-B-18] Explain that the mass of an object resists change from its state of rest or motion (inertia).
- [SLO: P-09-B-19] **Define and calculate weight.**
- [SLO: P-09-B-20] **Define and calculate gravitational field strength.**
- [SLO: P-09-B-21] Justify and illustrate the use electronic balances to measure mass.
- [SLO: P-09-B-22] Justify and illustrate the use of a force meter to measure weight.
- [SLO: P-09-B-23] Differentiate between contact and non-contact forces.
- [SLO: P-09-B-24] Differentiate between different types of forces.
- [SLO: P-09-B-25] State that there are three fundamental forces and describe them in terms of their relative strengths.
- [SLO: P-09-B-26] Represent the forces acting on a body using free body diagrams.
- [SLO: P-09-B-27] State and apply Newton's first law.
- [SLO: P-09-B-28] Identify the effect of force on velocity.
- [SLO: P-09-B-29] Determine the resultant of two or more forces acting along the same straight line.
- [SLO: P-09-B-30] State and apply Newton's second law in terms of acceleration.
- [SLO: P-09-B-31] State and apply Newton's third law.
- [SLO: P-09-B-32] Explain with examples how Newton's third law describes pairs of forces of the same type acting on different objects.
- [SLO: P-09-B-33] State the limitations of Newton's laws of motion.
- [SLO: P-09-B-39] Define and calculate momentum.
- [SLO: P-09-B-40] Define and calculate impulse.
- [SLO: P-09-B-41] Apply the principle of the conservation of momentum to solve simple problems in one dimension.
- [SLO: P-09-B-42] Define resultant force in terms of momentum.

In kinematics we have discussed how motion is described in terms of velocity and acceleration. Now we deal with the questions like: How an object at rest begin to move? What causes an object to accelerate or decelerate? What makes an object to moves in a curved path? The simple answer to all these questions is force. In this Chapter, we will study the connection between force and motion, which is the subject called dynamics.

Every motion you observe or experience is related to a force as shown in figure 3.1. We can start moving a trolley by simply applying force on it, we can use this force to speed it up or slow it down and we can even change its direction.

FIGURE 3.1 FORCE



3.1 FORCE

Force is vector quantity which changes or tends to change state of body; start or stop its motion, speed it up or slow it down and can change the direction of its motion.

3.1.1 TYPES OF FORCES

Forces are broadly classified as contact and non contact forces.

A. CONTACT FORCES

The force acting between two objects that are in physical contact are termed as contact forces. For example, in game of cricket a batter hitting a cricket ball (Figure 3.2) is a contact force since there is physical contact is between the bat and the ball.

FIGURE 3.2 CONTACT FORCE



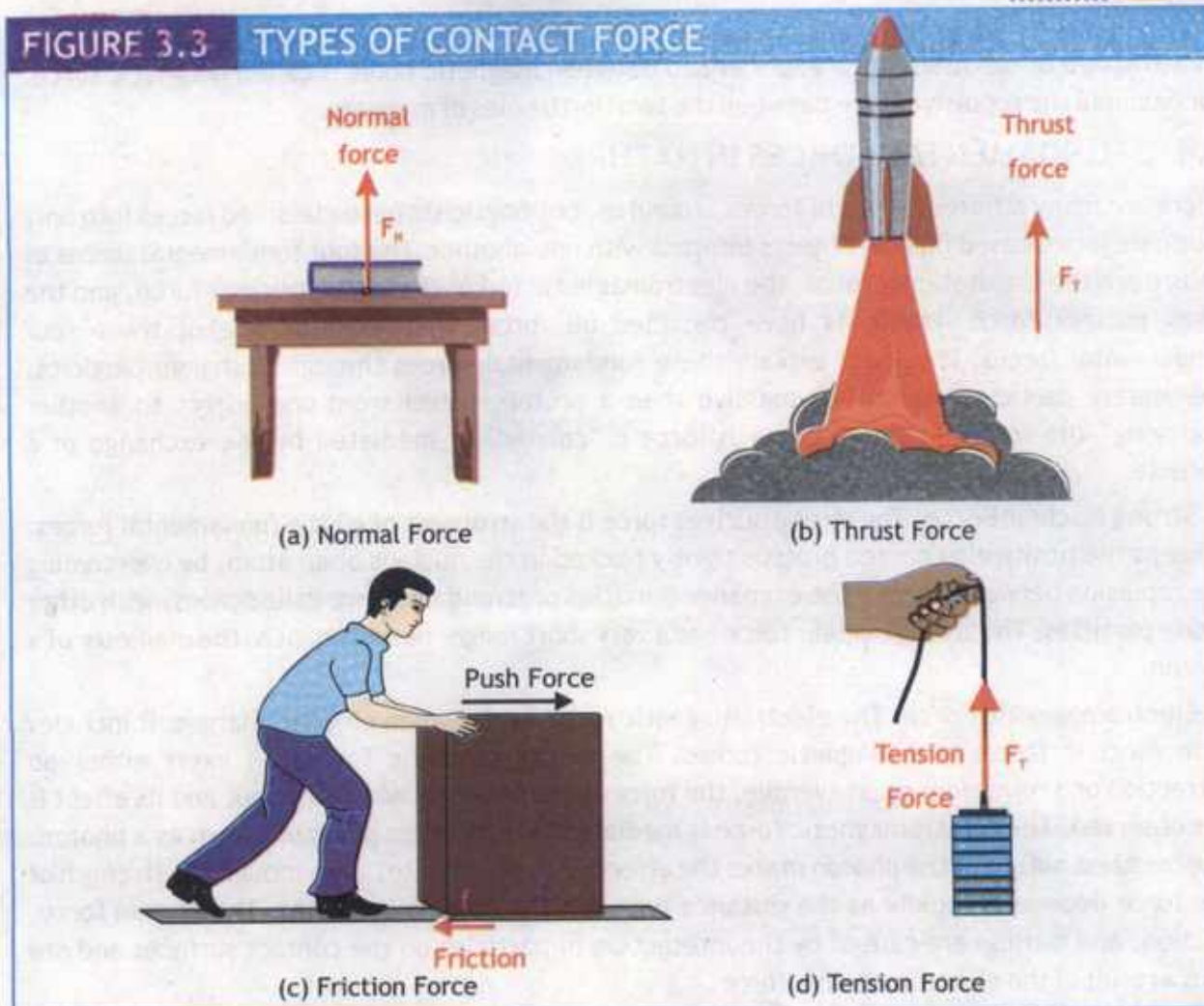
A force perpendicular to the contact surface that keeps objects from passing through each other is called the **normal force** and is represented as F_n . (In geometry, normal means perpendicular). For example the book lying on table, the force perpendicular to the table is normal force figure 3.3 (a).

The force that propels a flying machine in the direction of motion is termed as **thrust**. For example engines produce thrust, the thrust of engine of car cause it to accelerate as shown in figure 3.3 (b).

Force that resist the relative motion of solid surfaces, fluid layers, and material elements in contact and sliding against each other is called **friction**. Friction on an object acts in a direction opposite to the direction of the object's motion or attempted motion figure 3.3 (c).

For example air resistance is also a frictional force which occurs between air and an object. It is the force that the object experiences as it passes through the air. It is a kind of the drag force which resists the motion of a body with fluid.

FIGURE 3.3 TYPES OF CONTACT FORCE



The forces exerted by two or more physical objects that are in contact, through string, rope, cable or spring, we call such force as **tension**. For example tension keeps spider web together consists of numerous fine strands that pull on one another. The tension in cord attached to a string is shown in the figure 3.3 (d). The forces that an object exerts to resist a change in its shape are called **elastic forces**; they arise from forces between the particles in the material. For example when force is applied to a spring or rubber band it will stretch and at same time resists being stretched. It must be noted that the tension is the elastic only during extension not compression.

B. NON-CONTACT FORCES

Have you seen magnets exerting push or pull on other magnets at some distance? The force which acts at a distance, without any physical contact between bodies is termed as non-contact force. This force acts even if the objects involved are not touching, also termed as action at a distance force. The attractive force between two objects with mass is called **gravitational force**. For example, the force experienced by moon because of earth. An attractive or repulsive force experienced by charged objects is called **electrostatic force**. For example the attractive force between a positively charged nucleus and negatively charged electron.



An attractive or repulsive force experienced between magnetic poles is called **magnetic force**. For example the repulsive force between the two North poles of magnets.

3.1.2 FUNDAMENTAL FORCES IN NATURE

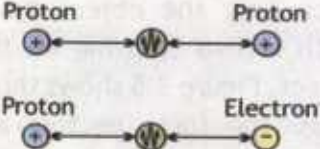
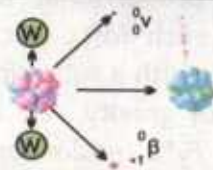
There are many different types of forces around us, but physicists have classified forces into only four categories based on how objects interact with one another. The four fundamental forces of nature are the gravitational force, the electromagnetic force, the strong nuclear force, and the weak nuclear force. Physicists have classified all forces that exist as one of these four fundamental forces. Physicists explain these fundamental forces through exchange particles. Elementary particles, much less massive than a proton, travel from one object to another "carrying" the force. In this way, each force is 'carried' or mediated by the exchange of a particle.

A. Strong Nuclear Force: The strong nuclear force is the strongest of all the fundamental forces. It keeps the positively charged protons tightly packed in the nucleus of an atom, by overcoming the repulsion between them. The exchange particles of strong force are called pions, with other heavy particles. The strong nuclear force has a very short range, nearly equal to the diameter of a proton.

B. Electromagnetic Force: The electromagnetic force act between electric charges. It includes both electric forces and magnetic forces. The electromagnetic force can exert either an attraction or a repulsion, so on average, the forces tend to cancel each other out and its effect is not observed. The electromagnetic force is mediated by a massless particle known as a photon. **The massless nature of the photon makes the effective range infinite, even though the strength of the force decreases rapidly as the distance between the objects increases.** The normal force, friction, and tension are caused by the interaction of particles on the contact surfaces and are thus a result of the electromagnetic force.

C. Gravitational Force: The gravitational force, or the force of gravity, is the force of attraction between all objects in the universe. Gravity is by far the weakest of the four fundamental forces (with least relative strength), the force of gravity between two objects is noticed only if at least one of the objects has a large mass such as stars, planets, and moons. It holds them together and controls their motions in the same way that it controls the motion of falling objects here on Earth. Gravitational force is theorized to be an exchange force with a massless mediating particle 'graviton'. The massless nature of the graviton allows gravity to have infinite range similar to the electromagnetic force. However, the graviton is the only exchange particle not detected yet.

D. Weak Nuclear force: The weak nuclear force is very weak, 10 000 times weaker than the strong nuclear force and has the shortest range of any of the fundamental forces. Despite this, the weak nuclear force plays a major role in the structure of the universe. It is an exchange force mediated by the exchange of three different particles called vector bosons. The weak nuclear force is responsible for radioactive decay. Specifically, the weak force changes the flavour (type) of an elementary particle called a quark. When this process occurs, a neutron in the nucleus transforms into a proton.

TABLE 3.1: FUNDAMENTAL FORCES IN NATURE				
Fundamental Force	Range (metre)	Relative strength	Function	Exchange Particles
Strong Force	10^{-15} (diameter of proton)	1		Pions (π) or others
Electromagnetic Force	infinite	7.3×10^{-3}		Photons (massless)
Weak Force	10^{-17}	10^{-6}		W^+ , W^- , Z_0 (vector bosons)
Gravitational Force	infinite	6×10^{-39}		graviton (not yet detected)

For years physicists have sought to show that the four basic forces are simply different manifestations of the same fundamental force. The most successful attempt at such a unification is the electroweak theory, proposed during the late 1960s by Abdus Salam (Pakistani physicist), Steven Weinberg, and Sheldon Lee Glashow. This theory, which incorporates quantum electrodynamics (the quantum field theory of electromagnetism), treats the electromagnetic and weak forces as two aspects of a more-basic electroweak force that is transmitted by four carrier particles, the so-called gauge bosons.

FIGURE 3.4 ABDUS SALAM



One of these carrier particles is the photon of electromagnetism, while the other three—the electrically charged W^+ and W^- particles and the neutral Z_0 particle—are associated with the weak force. Unlike the photon, these weak gauge bosons are massive, and it is the mass of these carrier particles that severely limits the effective range of the weak force.



3.1.3 FORCE DIAGRAMS

In order to study forces and their effects on the objects, we should familiarize ourselves with the skill of drawing force diagrams. Commonly two types of force diagrams, 'system diagrams' and 'free-body diagrams', are used. A system diagram (SD) is a visual expression of all the objects required. A free-body diagram (FBD) is a schematic representation in which only the object being analyzed is drawn, with arrows showing all the forces acting on the object. Figure 3.5 shows three examples SDs and FBDs: the force vectors are drawn with their lengths proportional to the magnitudes of the forces; each force vector is labelled with the symbol ' $\vec{F}$ ', with a subscript (for example, ' $\vec{F}_g$ ' is the force of gravity, ' $\vec{F}_N$ ' is the normal force, ' $\vec{F}_f$ ' is friction, ' $\vec{F}_T$ ' is tension, and ' $\vec{F}_A$ ' is the applied force).

3.1.4 CONCEPT OF NET FORCE

Different forces can affect an object, and the net force is the total effect of all these forces. It is calculated by adding up all the forces acting on the object.

The net force helps us determine if the forces on the object are balanced or unbalanced. If the net force is 0 N, it means the forces are balanced, and there will be no change in the object's motion.

FIGURE 3.5 FORCE DIAGRAMS

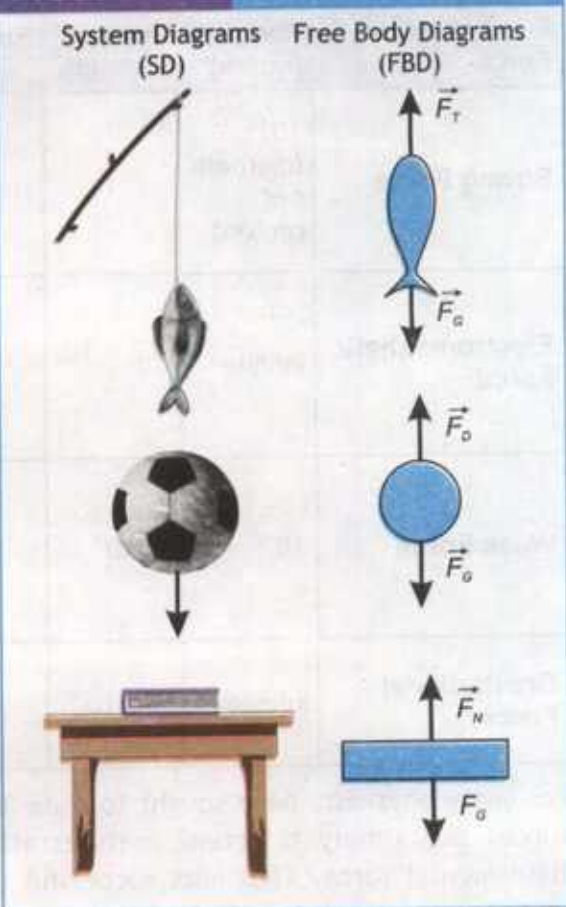


FIGURE 3.6 NET FORCE



For example, in a tug of war shown in figure 3.6 (a) the forces ' $\vec{F}_1$ ' and ' $\vec{F}_2$ ' are equal in magnitude and opposite in direction, the forces cancel the effect of each other and there is no net force. However, when the net force on an object is not 0 N, the forces are unbalanced and produce a change in motion of an object. For example, for tug of war in figure 3.6 (b) one force ' $\vec{F}_2$ ' exceeds the other force ' $\vec{F}_1$ ', and there is a net force ' $\vec{F}_{net}$ ' to the right.

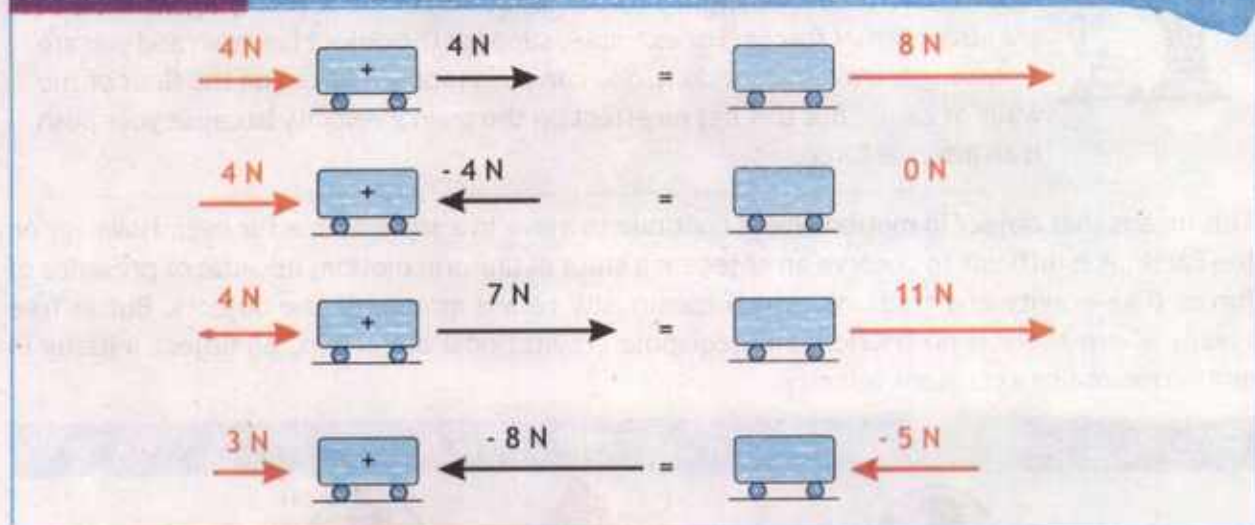


FREE-BODY DIAGRAMS AND RESULTANT (NET) FORCES

To study the effects of forces acting on any object, we can apply the skill of drawing force diagrams. Since force is a vector quantity, the vector sum of all the forces acting on an object is the resultant force. The resultant force can also be called the net force. These two terms can be used interchangeably. They will be represented by the same symbol, ' $\vec{F}_{net}$ ', in this text.

The net force or resultant force can be obtained by simply adding forces. A resultant force is a single force that has the same effect as the combined effect of all the forces to be added. Forces are vector quantities which require both magnitude with proper unit as well as direction for its complete description. Therefore it is required that we should draw the forces to a common scale as vectors (arrow diagrams). Simply add the magnitudes of vectors in case of like parallel forces and subtract the magnitudes of vectors in case of unlike parallel forces. Few examples are shown in the figure 3.7.

FIGURE 3.7 NET FORCE FOR LIKE AND UNLIKE PARALLEL FORCES

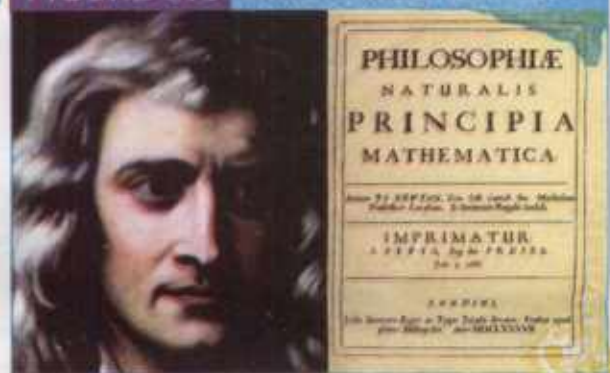


However, we cannot make such algebraic addition of vectors when vectors are making certain angle. In such cases we draw vectors on a coordinate axis and then according to the same scale we can add them by head to tail rule of vector addition.

3.2 NEWTON'S LAWS OF MOTION

In 1686 English Scientist Sir. Isaac Newton (1642-1727) presented his three laws of motion in a book *Philosophiae Naturalis Principia Mathematica* (English: Principles of Natural Mathematics) as shown in the figure 3.8. This book is considered as the greatest scientific work ever written.

FIGURE 3.8 SIR. ISAAC NEWTON



3.2.1 NEWTON'S FIRST LAW OF MOTION

In a soccer game, players kick the ball to each other. When a player kicks the ball, the kick is an unbalanced force. It sends the ball in a new direction with a new speed. What keeps the ball rolling? To answer we have to look into statement of Newton's first law of motion.

If the net external force acting on an object is zero, the object will maintain its state of rest or uniform motion (constant velocity).

It means that in absence of external net force, an object at rest, it will remain at rest; While an object in motion will continue to move with constant velocity (no change in velocity or no acceleration). Mathematically,

$$\vec{F}_{\text{net}} = 0 \quad \text{then} \quad \Delta \vec{v} = 0 \quad \text{or} \quad \vec{a} = 0$$



SCIENCE TIDBITS

An external force is an applied force, applied on to the object or system. There are also internal forces. For example, suppose the object is a train and you are a passenger traveling inside it. You can push (apply a force) on the floor or the walls of cabin, but this has no effect on the train's velocity because your push is an internal force.

This means that object in motion would continue to move in a straight line for ever. However on the Earth, it is difficult to observe an object in a state of uniform motion, because of presence of forces (like gravity and friction), which continually retard motion of the objects. But in free space, where there is no friction and negligible gravitational attraction, an object initially in motion maintains a constant velocity.

FIGURE 3.9 NEWTON'S FIRST LAW OF MOTION



An object at rest will remain at rest



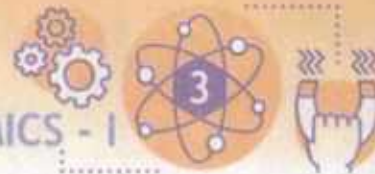
Unless acted on by an unbalance force



The object will continue to move at constant speed and direction



Unless acted upon by another unbalance force



An object can continue to move when the unbalanced forces are removed. For example, when a soccer ball is kicked, it experiences an unbalanced force. The ball keeps rolling on the ground until another unbalanced force alters its movement as shown in figure 3.9.

POINT TO PONDER



Why is it more difficult to push large man on swing compared to a small child?

There is a difference in the resistance to a change in motion between the man and the child. Also, when you try to stop their motions, you would again notice a difference in the resistance to a change in motion. Because large man has more inertia due to more mass.

First law of motion specifies that there is a natural tendency of an object to remain in a state of rest or in uniform motion in a straight line termed as **inertia**. Does all objects have equal tendency to resist its state of rest or uniform motion? Absolutely not, the object with more mass (the measure of the amount of matter in a body) has greater resistance to change (inertia), is the reason why it is difficult to move massive objects. Mass is a quantity that is dependent on inertia (the greater the mass of an object, the greater its inertia, and vice versa).

ACTIVITY



Place a stack of coins over a small sheet of paper. Quickly remove the sheet without toppling the stack of coins. Increase the number of coins and see who wins the game.



Newton's first law of motion is applied when we ride standing in the aisle of a bus holding a pole as shown in figure 3.10 (a). As the bus begins to move, we tend to remain at rest, therefore we feel a push to back (as our lower body start moving with the bus, but the upper part of body maintains the state of inertia). The same principle is again at work when the bus start to slow down or stops, we feel to move forward due to inertia as shown in the figure 3.10 (b).

FIGURE 3.10 INERTIA AND SUDDEN MOTION OF BUS



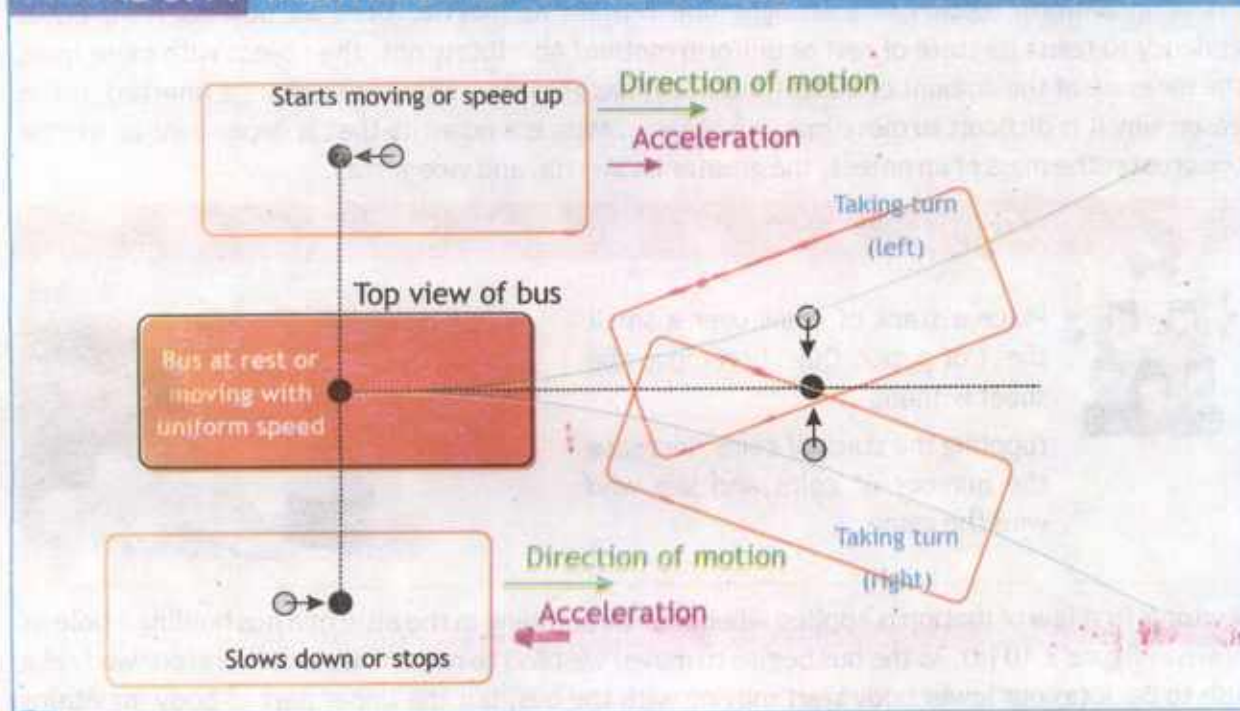


ACTIVITY



Place a card on top of a glass, and put a coin above this arrangement. If you quickly flick the card horizontally, the inertia of the coin will keep it at rest horizontally. The vertical force of gravity will pull it straight down into the glass.

FIGURE 3.11 INERTIA ON AN OBJECT IN BUS



As the bus start moving with uniform speed if we hold on to the pole, it supplies the forces needed to give us the same motion as the bus, we no longer feel pushed. But when the bus goes around a curve, again we feel a tendency to move to the side of the bus. The bus has changed its straight line motion, but we tend to move straight ahead. The same principle is again at work when the bus start to slow down or stops, we feel to move forward as shown in the figure 3.11. Thus the forces we feel when the bus starts moving, speeds up, slows down or turn around a corner are a result of our tendency to remain at rest or follow a straight path.



3.2.2 NEWTON'S SECOND LAW OF MOTION

What causes acceleration (change in velocity)? We can get this answer from Newton's first law of motion as 'external, unbalanced net force is required to produce a change in velocity'. Newton went further and related acceleration to inertia (or mass), that it tends to reduce this acceleration.

The acceleration produced by a net force acting on an object (or mass) is directly proportional to the magnitude of the force ($a \propto F_{\text{net}}$) and in the direction of the force (the $\propto$ symbol is a proportionality sign). In other words, the greater the unbalanced net force, the greater the acceleration.

The acceleration of an object being acted on by a net force is inversely proportional to the mass of the object ($a \propto 1/m$). That is, for a given unbalanced net force, the greater the mass of an object, the smaller the acceleration.

Combining these effects of net force and mass on acceleration gives

$$\text{acceleration} = \frac{\text{net force}}{\text{mass}}$$

Using appropriate units we can write

$$\vec{a} = \frac{\vec{F}_{\text{net}}}{m}$$

This is Newton's second law of motion which can be formally stated as, The acceleration of an object as produced by a net force is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the object.

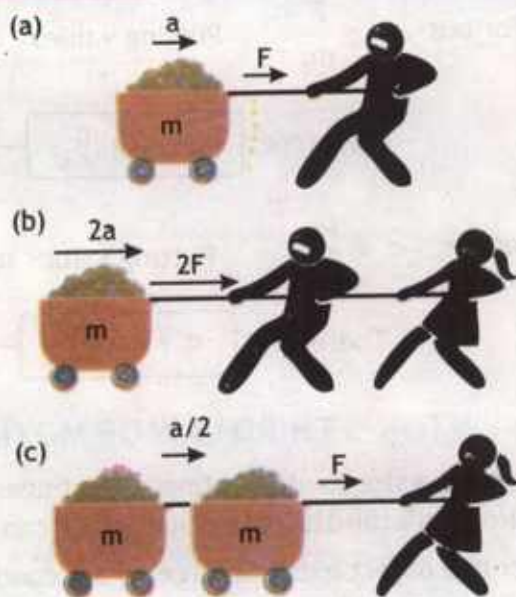
Commonly written in terms of force in magnitude form, we have Newton's second law of motion:

$$\vec{F}_{\text{net}} = m\vec{a} \quad \text{--- 3.1}$$

As an example consider the figure 3.12 (a), mass m is the mass of the system, when net force acts it produces an acceleration ' a '. In figure 3.12 (b) the force is doubled by keeping the mass same, the acceleration also doubles where as in figure 3.12 (c) the mass is doubled while force is kept the same the acceleration is halved.

Newton's second law of motion also enable us to define System International (SI) unit of force newton represented by symbol N.

FIGURE 3.12 NEWTON'S SECOND LAW



One newton is defined as the force that produces acceleration of one meter per second squared ($a = 1 \text{ m/s}^2$) in a body of mass one kilogram (1 kg).

$$1 \text{ N} = 1 \text{ kg} \times 1 \text{ m/s}^2 \quad \text{or} \quad \text{N} = \text{kgm/s}^2$$

EXAMPLE 3.1: BUS AND CAR ACCELERATIONS

If the same engine is installed in a bus and car that applies a force of 3000 N. What acceleration will this engine produce in a bus of mass 12,000 kg and a car of mass 1200 kg?

GIVEN

Mass of bus $m_b = 12000 \text{ kg}$

Mass of Car $m_c = 1200 \text{ kg}$

Force $F = 3000 \text{ N}$

REQUIRED

Acceleration in bus $a_b = ?$

Acceleration in car $a_c = ?$

SOLUTION:

From Newton 2nd law of motion $a = \frac{F}{m}$

For bus $a_b = \frac{F}{m_b}$ Putting values $a_b = \frac{3000 \text{ N}}{12000 \text{ kg}} = \frac{3000 \text{ kgm/s}^2}{12000 \text{ kg}}$

Therefore $a_b = 0.25 \text{ m/s}^2$ ——— **Answer**

For car $a_c = \frac{F}{m_c}$ Putting values $a_c = \frac{3000 \text{ N}}{1200 \text{ kg}} = \frac{3000 \text{ kgm/s}^2}{1200 \text{ kg}}$

Therefore $a_c = 2.5 \text{ m/s}^2$ ——— **Answer**

3.2.3 NEWTON'S THIRD LAW OF MOTION

When we press a stone with our finger, the finger is also pressed upon by the stone. The reason is given by Newton's third law of motion, which can be stated as

Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first object.

When an object 'A' exerts force on object 'B' written as ' $\vec{F}_{AB}$ ', object 'B' also exerts equal force on object 'A' written as ' $\vec{F}_{BA}$ ' but in opposite direction:

$$\vec{F}_{AB} = - \vec{F}_{BA} \quad \text{—————} \quad \mathbf{3.3}$$

Here the negative sign shows that force ' $\vec{F}_{BA}$ ' is opposite to force ' $\vec{F}_{AB}$ '.

These two forces are termed as action - reaction pair. Action and reaction cannot cancel each other because they act on different bodies (action on one body and reaction on another body). When we kick a football as shown in figure 3.13, the foot exerts the action force F_{AB} on the football and as a reaction the foot ball exerts an equal and opposite force F_{BA} on our foot. Both these forces are equal in magnitude and opposite in direction.

FIGURE 3.13 NEWTON'S THIRD LAW OF MOTION



Examples of Newton's third law of motion are present every where, because when we talk of force we also consider its reaction.

For example, when we jump, our legs apply a force to the ground, and the ground applies an equal and opposite reaction force that pushes us into the air. When we punch an object or kick something as an action, we also get a force onto our hands and legs as a reaction force. That is why we feel pain when punching a wall, or falling on the ground. The exhaust from the rocket creates a downward force which creates an equal and opposite thrust in the upward direction as shown in figure 3.14. Applying Newton's third law of motion allow us to explore two important forces normal force and tension force.

FIGURE 3.14 NEWTON'S THIRD LAW



3.2.4 LIMITATIONS OF NEWTON'S LAWS OF MOTION

Although Newton's laws of motion are a fundamental set of principles and are applied in variety of situations. While they are very useful for describing the behavior of everyday objects, there are some limitations to their applicability.

- Newton's laws are not readily applied on the very small scale: As one goes to extremely low energies on the atomic scale, position and acceleration are not well defined, where the concepts of quantum mechanics takes over.

- Newton's laws are not applied for objects moving at high speed (speeds close to the speed of light) relativistic effects complicate the dynamics at high speeds and high energies. In such situations we would require to use relativistic mechanics.

However, Newton's laws are not exact but provide a good approximation on the large (macroscopic) scale and over the vast range of practical energies and forces. Newton's laws are still work spectacularly well in physics and engineering.

3.3 MASS AND WEIGHT

In our daily life we use the term mass and weight in almost the same meaning. However, mass is the amount of matter an object contains (and a measure of inertia). Weight is the gravitational force acting on a mass or object. Newton's second law can be used to relate the two quantities.

On the surface of the Earth, where the acceleration due to gravity is relatively constant ($g = 9.80 \text{ m/s}^2$), the weight W is

weight = mass $\times$ acceleration due to gravity

$$\vec{w} = m\vec{g} \quad \text{--- 3.2}$$

Note that this equation is a special case of $\vec{F} = m\vec{a}$ where different symbols, W and g , have been used for force and acceleration.

3.3.1 MEASURING FORCE AND MASS:

Two devices used to measure force in the laboratory are the spring scale and the force sensor, as shown in figure 3.15.

Spring scale is a device used for measuring the force acting on an object. It consists of a spring which gets stretched when a force is applied to it. Stretching of the spring is measured by a pointer moving on a graduated scale. The reading on the scale gives the magnitude of the force.

The force sensor uses an electronic gauge to measure force measure force with a high degree of accuracy. It gives a digital readout or a graph of the forces when interfaced with a computer.

Weight is the effect that gravitational force has on an object. Mass is the amount of matter in an object irrespective of the gravitational force. If we to move to the Moon, our weight would be reduced roughly by 5/6, but our mass would stay the same.

However by using Newton's laws convert our weight into mass easily.

FIGURE 3.15 FORCE AND MASS MEASUREMENT





Equation 3.2 can be written as:

$$m = \frac{\vec{W}}{g}$$

Thus if we somehow measure the force of gravity as weight ' W ' and divide the value by acceleration due to gravity ' g ' we could easily find our mass ' m '. Weighing-scales (actually force-measurers) as shown in figure 3.16 are therefore graduated in kg to show mass. Thus every time you stand on weight machine it gives your mass in '*kilograms*', not your weight in '*newtons*'.

FIGURE 3.16 WEIGHT MACHINE



Weight machine can be calibrated to measure mass

EXAMPLE 3.2: WEIGHT OF SCHOOL BAG ON EARTH AND MOON

Mass of your school bag is 8 kg. How much will it weigh (a) here on Earth and on (b) the surface of moon? [Take acceleration due to gravity for Earth as $g_e = 9.8 \text{ m/s}^2$ and for Moon as $g_m = 1.625 \text{ m/s}^2$]

GIVEN

Mass of school bag ' m ' = 8 kg

acceleration due to gravity for Earth $g_e = 9.8 \text{ m/s}^2$ and
acceleration due to gravity for Moon as $g_m = 1.625 \text{ m/s}^2$

REQUIRED

- (a). Weight on surface of Earth $w_e = ?$
(b). Weight on surface of Moon $w_m = ?$

SOLUTION: Weight of a body is given by: $W = mg$

(a) The weight on surface of earth is $W_e = m g_e$

Putting values $W_e = 8 \text{ kg} \times 9.8 \text{ m/s}^2$

$$W_e = 78.4 \text{ kg m/s}^2 = 78.4 \text{ N}$$

Answer

(b) The weight on surface of Moon is $W_m = m g_m$

Putting values $w_m = 8 \text{ kg} \times 1.625 \text{ m/s}^2$

$$w_m = 13 \text{ kg m/s}^2 = 13 \text{ N}$$

Answer

Due to low value of " g " on Moon's surface, it will be much easy for you to carry your bag to school. Similarly, it will be easy for you to do the routine works and will not get tired easily on Moon's surface.

3.4 GRAVITATIONAL FIELD

The region around a non contact forces where a magnetic force is operative is termed as force field. Whereas the region around a massive object (such as earth, sun etc.) where gravitational force is operative is termed as gravitational field.

The gravitational field strength is the amount of force per unit mass acting on objects in the gravitational field. The value of 'g' is equal to the magnitude of the gravitational force exerted on a unit mass at that point, mathematically

$$g = F_g / m.$$

The gravitational field strength (g) is a vector with a magnitude of 'g' that points in the direction of the gravitational force.

The gravitational field strength 'g' for earth is shown in the figure 3.17. Since, from newton's second law of motion:

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

similarly $\vec{a}_g = \frac{\vec{F}_g}{m} = \vec{g}$ — 3.3

In SI units, gravitational field strength is measured in newton per kilogram (N/kg). It is a vector quantity that has the direction downward or toward the centre of Earth.

Since the gravitational field strength and the acceleration due to gravity are equal in magnitude, the same symbol, $\vec{g}$, is used for both. Therefore, on Earth's surface, $\vec{g} = 9.8 \text{ N/kg} [\downarrow]$, or $\vec{g} = 9.8 \text{ m/s}^2 [\downarrow]$.

The gravitational field strength is not the same everywhere. Gravitational force decrease as we move away from the surface of earth, therefore gravitational field strength also decreases. Also on different planets we have different gravitational field strengths as shown in table 3.2.

FIGURE 3.17 FIELD STRENGTH

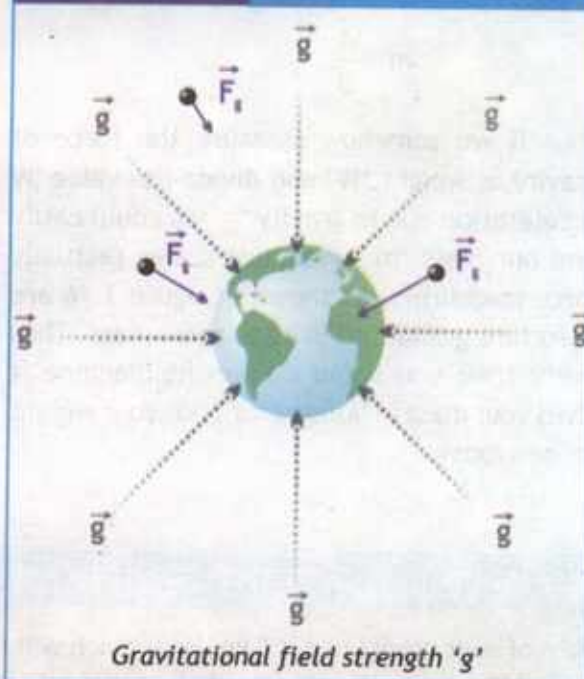


TABLE 3.2: GRAVITATIONAL FIELD STRENGTH IN THE SOLAR SYSTEM

Planet	g (N/kg)
Mercury	3.7
Venus	8.9
Earth	9.8
Mars	3.7
Jupiter	24.7
Saturn	9.0
Uranus	8.7
Neptune	11.0
Sun	274



EXAMPLE 3.2: WEIGHT OF SCHOOL BAG ON EARTH AND MOON

A box weighs 400 N on earth while 150 N on an unknown planet. Find the gravitational field strength on that planet.

GIVEN

Weight on Earth ' W_E ' = 400 N
 unknown planet ' W_N ' = 150 N

Gravitational field strength on Earth ' g_E ' = 9.8 N/kg

REQUIRED

Gravitational field strength on the unknown planet ' g_N ' = ?

SOLUTION

Since, weight of a body is the product of its mass and acceleration due to gravity, given by:

$$W = mg \quad \text{or} \quad m = \frac{W}{g}$$

Since, mass of a body remains constant, therefore,

$$\frac{W_E}{g_E} = \frac{W_N}{g_N} \quad \text{or} \quad g_N = \frac{W_N}{W_E} \times g_E$$

Putting values $g_N = \frac{150 \text{ N}}{400 \text{ N}} \times 9.8 \text{ N/kg}$

Hence

$$g_N = 3.675 \text{ N/kg}$$

Answer

The value 3.675 agrees with the numerical value of gravitational field strength on the surface of Mars. So, the unknown planet is Mars (red planet), the nearest planet to earth.

3.5 MOMENTUM

The product of the object's mass ' m ' and velocity ' $\vec{v}$ ' is called momentum, denoted by ' $\vec{p}$ '. Mathematically

$$\vec{p} = m\vec{v} \quad \text{--- 3.4}$$

Momentum is a vector quantity that points in the same direction as the velocity. SI Unit of momentum is kilogram-meter per second (kgm/s), or newton-second (Ns). Newton's second law is used to relate force and momentum.

EXAMPLE 3.4: GOLF BALL MOMENTUM

A golfer hits a ball having mass 45 g. If after the shot, the ball travels with a speed of 80 m/s, what magnitude of momentum does the golfer imparted to ball?



GIVEN

Mass of ball ' m ' = 45 g = 0.045 kg

Velocity of ball ' v ' = 80 m/s

REQUIRED

Momentum of ball ' P ' =?

SOLUTION

From the mathematical form of linear momentum: $p = mv$

for magnitude ignoring the vector signs: $p = mv$

putting values $p = 0.045 \text{ kg} \times 80 \text{ m/s}$

Therefore

$$p = 3.6 \text{ kg m/s}$$

Answer

In order to increase the speed of ball, the golfer needs to impart a greater momentum to the ball.

3.5.1 FORCE AND CHANGE IN MOMENTUM

A force ' $\vec{F}$ ' produces acceleration ' $\vec{a}$ ' in a body of mass ' m '. By Newton's second law of motion it is written as

$$\vec{F}_{\text{net}} = m\vec{a} \quad \text{--- (1)}$$

The acceleration produced changes the velocity of the body from initial velocity ' $\vec{v}_i$ ' to final velocity ' $\vec{v}_f$ ' during time interval ' Δt '. Then by definition of acceleration

$$\vec{a} = \frac{\vec{v}_f - \vec{v}_i}{\Delta t} \quad \text{--- (2)}$$

Putting equation 2 in equation 1

$$\vec{F}_{\text{net}} = m \frac{\vec{v}_f - \vec{v}_i}{\Delta t} \quad \text{or} \quad \vec{F}_{\text{net}} = \frac{m\vec{v}_f - m\vec{v}_i}{\Delta t}$$

FIGURE 3.18 CATCHING





Hence $\vec{F}_{net} = \frac{\vec{p}_f - \vec{p}_i}{\Delta t} = \frac{\Delta \vec{p}}{\Delta t}$ — 3.5

The time rate of change of linear momentum of a body is equal to the net force acting on the body. This means that for sudden change in momentum force is large and vice versa.

For example, catching a ball with your bare hands will hurt depending on the force of the ball. However, if you allow your hands to move with the ball as you catch it, duration of time ' Δt ' will increase, and force will be smaller, and your hands will hurt less.

EXAMPLE 3.5: FORCE REQUIRED TO STOP A TRUCK AND CAR

What is difficult to stop if their brakes fail and are travelling from an inclined road:

- (a) A car of mass 1200 kg moving with a velocity of 8 m/s in 5 seconds,
- (b) A truck of mass 10,000 kg moving with the same velocity in the same time?

GIVEN

Mass of car $m_c = 1200$ kg

Mass of truck $m_t = 10,000$ kg

Initial Velocity $v_i = 8$ m/s

Change in time $\Delta t = 5$ s

Final Velocity $v_f = 0$ m/s (As both car and truck have to stop finally)

REQUIRED

(a) Average force required to stop car $F_c = ?$

(b) Average Force required to stop truck $F_t = ?$

SOLUTION

From the relation between force and momentum:

$$F_{net} = \frac{\Delta p}{\Delta t} = \frac{mv_f - mv_i}{\Delta t} \quad \text{--- 1}$$

Putting Values in equation 1 for car: $F_c = \frac{(1200 \text{ kg})(0 \text{ m/s}) - (1200 \text{ kg})(8 \text{ m/s})}{5 \text{ s}}$

Therefore,

$$F_c = -1920 \text{ N}$$

Answer

(b) Putting Values in equation 1 for truck: $F_t = \frac{(10,000 \text{ kg})(0 \text{ m/s}) - (10,000 \text{ kg})(8 \text{ m/s})}{5 \text{ s}}$

Therefore,

$$F_t = -16,000 \text{ N}$$

Answer

The negative sign shows that force is applied opposite to the direction of motion i.e., velocity.

3.5.2 IMPULSE AND CHANGE IN MOMENTUM

Newton's second law enable us to write force and change in momentum relation as:

$$\vec{F}_{net} = \frac{\vec{p}_f - \vec{p}_i}{\Delta t} = \frac{\Delta \vec{p}}{\Delta t}$$

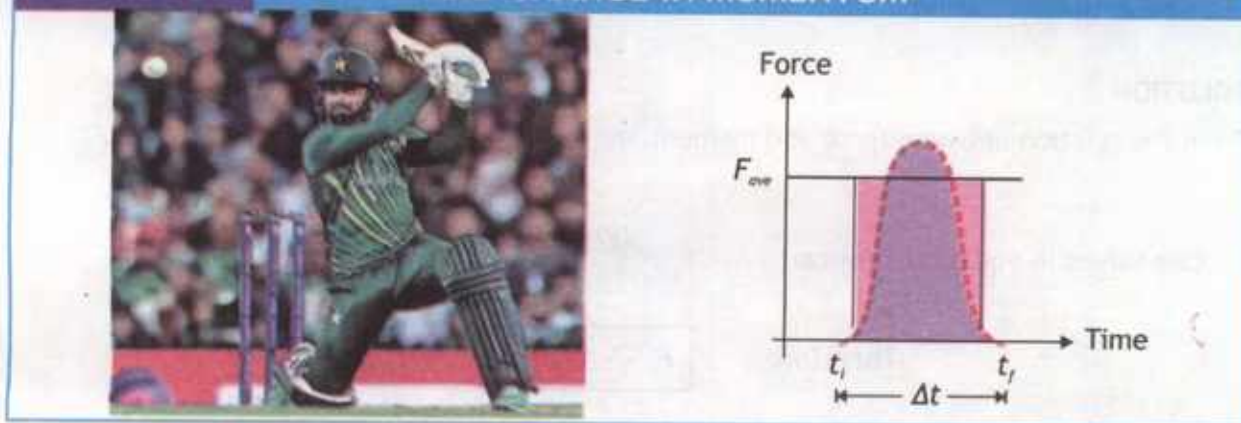
$$\vec{F}_{net} \times \Delta t = \Delta \vec{p} \quad \text{--- 3.6}$$

Equation 3.6 enable us to define a new quantity termed as 'impulse'. Impulse is the product of the force exerted on an object and the time interval over which the force acts, and is often given the symbol 'J'. Impulse is a vector quantity, and the direction of the impulse is the same as the direction of the force that causes it, and have the same SI units as momentum.

In many situations, the net force on the object is not constant and the force applied to an object changes non-linearly during its time of application. The equation 3.8 still applies, provided the net force ' F_{net} ' is equal to the average force acting on the object over the time interval Δt .

For example, when a batter hits a cricket ball, initially the force is very small. Within milliseconds, the force is large enough to deform the ball. The ball then begins to move by return to its original shape and the force soon drops back to zero. Graph in figure 3.19 shows how the force changes with time. We can find the impulse by calculating the area under the curve in force versus time graph.

FIGURE 3.19 IMPULSE AND CHANGE IN MOMENTUM



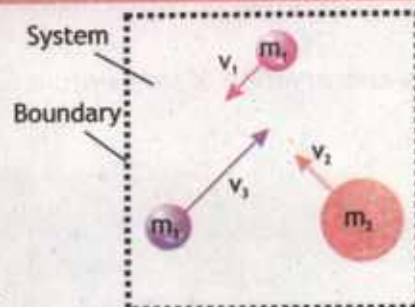
In many collisions, it is difficult to make the precise measurements of force and time that you need in order to calculate the impulse. The relationship between impulse and momentum provides an alternative approach to analyzing such collisions, as well as other interactions. By analyzing the momentum before and after an interaction between two objects, we can determine the impulse.



SCIENCE TIDBITS

Group of bodies or particles, under study separated by a boundary is called as a system. If the net external force on the system is zero, it is termed as isolated system.

An isolated system is a collection of bodies that can interact with each other but whose interactions with the environment have a no effect on their properties is termed as an isolated system.



3.5.3 NEWTON'S LAWS AND CONSERVATION OF MOMENTUM

For an isolated system there is no net force acting ' $F = 0$ ', therefore Newton's second law in terms of momentum (equation 3.) can be written as

$$0 = \frac{\Delta \vec{P}}{\Delta t} \quad \text{or} \quad 0 = \frac{\vec{P}_f - \vec{P}_i}{\Delta t}$$

$$\text{therefore} \quad \vec{P}_f = \vec{P}_i \quad \text{or} \quad m_f \vec{v}_f = m_i \vec{v}_i \quad \text{--- 3.8}$$

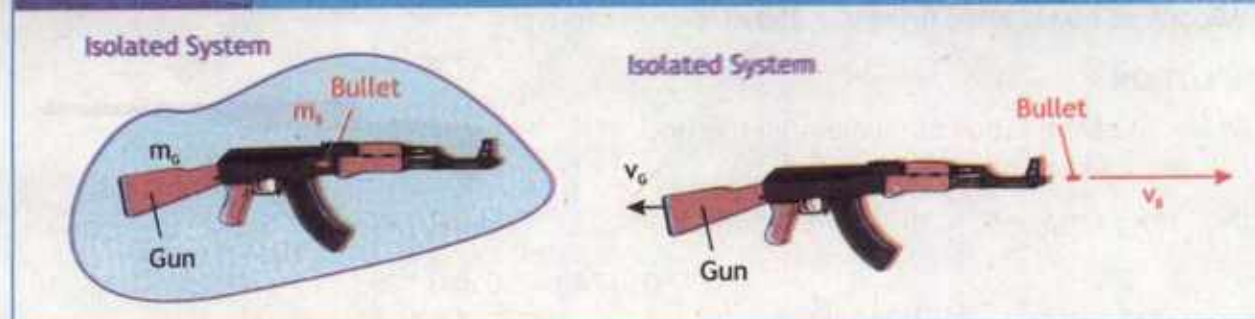
In the absence of external force (isolated system) the final momentum ' $\vec{P}_f$ ' of the system must be equal to initial momentum ' $\vec{P}_i$ '. If no net external force acts on a system of particles, the total momentum of the system cannot change.

This enable us to write the law of conservation of momentum which states:

'The momentum of an isolated system remains constant'.

Consider an isolated system of bullet of mass m_b and gun of mass m_g . Such that before firing the total initial momentum ($p_i = 0$) of the system is zero as shown in figure 3.20.

FIGURE 3.20 RECOIL OF GUN



UNIT 3 DYNAMICS - I

After firing the bullet moves with velocity ' v_b ' in one direction and the rifle recoils with velocity ' v_g ' in the other direction such that the total final momentum ($P_f = 0$) is again zero.

By conservation of momentum $\vec{p}_f = \vec{p}_i = 0$ or $m_b \vec{v}_b + m_g \vec{v}_g = 0$
or $m_g \vec{v}_g = -m_b \vec{v}_b$

Hence $\vec{v}_g = -\frac{m_b \vec{v}_b}{m_g}$ 3.9

Negative sign indicates that velocity of the gun is opposite to the velocity of the bullet, i.e., the gun recoils. Since mass of the gun is much larger than the bullet, therefore, the recoil is much smaller than the velocity of the bullet.

POINT TO PONDER



How rockets accelerate in space as there is no air in space to push against such that as a reaction rocket pushed forward?

In rockets, hot gases produced by burning of fuel rush out with large momentum. The rockets gain an equal and opposite momentum, thereby causing them to accelerate.



EXAMPLE 3.6: RIFLE RECOIL

Ahmad fired a bullet of mass 17 g from his hunting gun, of mass 3 kg. If the velocity of the bullet were 350 m/s, what would be the recoil velocity of the air gun?

GIVEN

Mass of Rifle $m_g = 3$ kg

Mass of bullet $m_b = 17$ g = 0.017 kg

Velocity of bullet after firing $v_b = 350$ m/s

REQUIRED

Velocity of Rifle after firing (Recoil speed) $v_g = ?$

SOLUTION

By law of conservation of momentum the final momentum must be zero, therefore

$$m_b v_b + m_g v_g = 0 \quad \text{or} \quad m_g v_g = -m_b v_b$$

Hence $v_g = -\frac{m_b v_b}{m_g}$

Putting values $v_g = -\frac{0.017 \text{ kg} \times 350 \text{ m/s}}{3 \text{ kg}}$

Therefore

$v_g = -1.98 \text{ m/s}$

Answer



Negative sign is for direction opposite to that of bullet's velocity.

The gun will move in the opposite direction but with a smaller velocity as compared to the bullet because of its greater mass than the bullet..

SUMMARY

Dynamics is the branch of mechanics in which we discuss the motion of bodies along with causes of motion of bodies.

Force is a physical quantity which moves or tends to move a body, stops or tends to stop a moving body or which tends to change the speed and direction of a moving body.

Newton's First Law of Motion states that every body continues in its state of rest or uniform motion in a straight line unless an external net force acts upon it.

Newton's Second Law of Motion states that whenever a net force acts on a body, it produces acceleration in the direction of the net force. The acceleration is directly proportional to the net force and inversely proportional to the mass of the body.

Newton's Third Law of Motion states that to every action there is an equal and opposite reaction.

Mass is the quantity of matter in a body.

Weight is the downward force with which the earth pulls a body towards its center.

Gravitational Field Strength is defined as the force per unit mass that earth exerts on a body.

Momentum is the product of mass and velocity. It is a vector quantity.

Law of Conservation of Momentum states that if there is no external force applied to a system, the momentum of that system remain constant.

EXERCISE



MULTIPLE CHOICE QUESTIONS

Q1. Choose the best possible option.

1. Inertia of a body is related to which of the following quantities

- | | | | |
|---------|----------|-----------|-------------|
| A. mass | B. force | C. weight | D. friction |
|---------|----------|-----------|-------------|

2. A force of 5N is applied to a body weighing 10 N. Its acceleration in m/s^2 is:

- | | | | |
|--------|------|------|-------|
| A. 0.5 | B. 2 | C. 5 | D. 50 |
|--------|------|------|-------|

3. SI unit of linear momentum is:

- | | | | |
|------------------------------------|---------------------------------|--------|-------------------------|
| A. $\text{kg m}^{-1}\text{s}^{-1}$ | B. $\text{kg m}^2\text{s}^{-1}$ | C. N m | D. kg m s^{-1} |
|------------------------------------|---------------------------------|--------|-------------------------|



4. The rate of change of momentum of free falling body is equal to its:
A. momentum B. velocity C. weight D. size
5. Change in momentum of a body is equal to:
A. (force) (velocity) B. (force) (time) C. (mass) (time) D. force
6. A book of mass 5 kg is placed on the table, the magnitude of net force acting on the book is:
A. 50 N B. 5 N C. 25 N D. 10 N
7. Thrust force is a consequence of which law of motion:
A. First B. second C. third D. fourth
8. A force acts on a body for 2 seconds and it produces 50 kgm/s change in its momentum. The force acting on the body is:
A. 100 N B. 50 N C. 25 N D. 2 N
9. At the fairground, the force that balances your weight is:
A. gravitational force B. centripetal force
C. electrostatic force D. frictional force
10. When a hanging carpet is beaten by stick. Dust flies off the carpet. It is mainly due to:
A. Action force on carpet B. Reaction force by carpet
C. Inertia of dust D. Rate of change of momentum of carpet
12. A bucket having some water is revolved in vertical circle. Water does not spill out, even the bucket is upside down, due to:
A. Weight of water
B. Centrifugal force on water
C. Inertia of water
D. Action and Reaction balance each other
13. The force which moves the car is:
A. Force developed by engine B. Force of friction between road and tyre
C. Weight of car D. Water spilt on the road
14. N kg^{-1} is equivalent to:
A. m s^{-1} B. m s^{-2} C. kg m s^{-1} D. kg s^{-2}
15. An object of mass 1 kg placed at earth's surface experiences a force of:
A. 1 N B. 9.8 N C. 100 N D. any value
16. Net force on the body falling in air with uniform velocity is equal to _____.
A. Weight of the body B. air resistance on the body
C. difference of weight of body and air resistance on it D. zero





SHORT RESPONSE QUESTIONS

QII. Give a short response to the following questions

1. When a motor cyclist hit a stationary car, he may fly off the motor cycle and driver in the car may get neck injury. Explain
2. In autumn, when you shake a branch, the leaves are detached. Why?
3. Why it is not safe to apply brakes only on the front wheel of a bicycle?
4. Deduce Newton's first law of motion from Newton's second law of motion.
5. Action and reaction are equal but opposite in direction. These forces always act in pair. Do they balance each other? Can bodies move under action - reaction pair?
6. A man slips on the oily floor; he wants to move out of this area. He is alone. He throws his bag to move out of this slippery area. Why is it so?
7. How would you use Newton's 3rd law of motion and law of conservation of momentum to explain motion of rocket?
8. Why are cricket batter gloves padded with foam?
9. Where will your weight be greater, near earth or near moon? What about mass?
10. When Ronaldo kicks the ball, at the highest point of ball both Earth and ball attract each other with the same magnitude of force. Why then the ball moves towards Earth and not the Earth?

LONG RESPONSE QUESTIONS

QIII. Give a an extended response to the following questions

1. State first law of motion. Explain with the help of examples. Why is it called law of inertia?
2. Define inertia. Why is it important to have knowledge of inertia in our daily life? Elaborate your answer with examples.
3. State and prove Newton's second law of motion. Deduce Newton's second law of motion from its first law?
4. State Newton's 3rd law of motion. Explain with examples from daily life.
5. State the limitations of Newton's laws of motion.
6. Differentiate with examples between contact and non-contact forces. Also, explain fundamental forces and the role of Dr. Abdus Salam from Pakistan in unifying two fundamental forces.
7. Represent the forces acting on a body using free body diagrams.
8. Define momentum. What is its formula and unit? Is it a scalar or vector quantity? Show that units of momentum, Ns and kgm/s are equal.
9. Differentiate between mass and weight of body.



10. What are gravitational field and gravitational field strength? Explain.
11. Justify and illustrate the use of electronic balances to measure mass.
12. State and prove Newton's second law of motion in term of momentum.
13. Define isolated system. State law of conservation of linear momentum. Explain with example.

NUMERICAL RESPONSE QUESTIONS

QIV. Solve the following numerical questions.

1. A boy is holding a book of mass 2 kg. How much force is he applying on the book? If he moves it up with acceleration of 3 m/s^2 , how much should he apply total force on the book?
(Ans. 19.6 N, 25.6 N)
2. A girl of mass 30 kg is running with velocity of 4 m/s. Find her momentum.
(Ans. 120 N)
3. A 2 kg steel ball is moving with speed of 15 m/s. It hits with bulk of sand and comes to rest in 0.2 second. Find force applied by sand bulk on the ball.
(Ans. - 150 N)
4. A 100 grams bullet is fired from 5 kg gun. Muzzle velocity of bullet is 20 m/s. Find recoil velocity of the gun.
(Ans. 0.4 m/s)
5. A robotic car of 15 kg is moving with 25 m/s. Brakes are applied to stop it. Brakes apply constant force of 50 N. How long does the car take to stop?
(Ans. 7.5 s)