3 LAWS OF MOTION

Syllabus :

(i) *Contact and non-contact forces; C.G.S. and S.I. units.*

Scope – Examples of contact forces (frictional force, normal reaction force, tension force as applied through strings and force exerted during collision) and non-contact forces (gravitational, electric and magnetic). General properties of non-contact forces. C.G.S. and S.I. units of force and their relation. Gravitational unit.

(ii) *Newton's first law of motion (qualitative discussion), introduction of the idea of inertia, mass and force.*

Scope – Newton's first law; statement and qualitative discussion, definitions of inertia and force from first law; examples of inertia as illustration of first law (Inertial mass not included).

(iii) *Newton's second law of motion (including $F = ma$); weight and mass.*

Scope – Detailed study of the second law. Linear momentum $p = mv$; change in momentum $\Delta p = \Delta(mv) = m\Delta v$ for mass remaining constant, rate of change of momentum $\Delta p/\Delta t = m\Delta v/\Delta t = ma \left\{ or\ \frac{p_2 - p_1}{t} = \frac{mv - mu}{t} = \frac{m(v-u)}{t} = ma \right\}$;

Simple numerical problems combining $F = \Delta p/\Delta t = ma$ and equations of motion. Units of force-only CGS and SI.

(iv) *Newton's third law of motion (qualitative discussion only), simple examples.*

Scope – Statement with qualitative discussion, examples of action-reaction pairs (F_{BA} and F_{AB}); action and reaction always act on different bodies.

(v) *Gravitation*

Scope – Universal law of gravitation (statement and equation) and its importance. Gravity, acceleration due to gravity, free fall, weight and mass, weight as force of gravity, comparison of mass and weight; gravitational units of force, simple numerical problems (problems on variation of gravity excluded).

(A) CONTACT AND NON-CONTACT FORCES

3.1 FORCE

We are familiar that a force when applied on a body can produce the following *two* main effects :

(1) *It can change the state of rest or of motion of the body i.e., it can produce motion in the body.*

Examples : The push exerted by a broom moves the trash. A ball lying on the ground moves when it is kicked. The pull exerted by a horse moves a cart. The pull exerted by a steam engine moves a train. The force due to gravity (or the earth's pull) makes an apple fall. A fielder on the ground stops a moving ball by applying force with his hands.

When force is applied on the pedal by a cyclist, the speed of the cycle increases. A freely falling object continuously gains speed due to the earth's pull acting along its direction of motion. The speed of a moving vehicle is slowed down by applying the brakes. A stone tied to one end of a string, whirling at a constant speed in a horizontal circle, changes its direction of motion continuously due to the force of tension in the string (which acts normal to the direction of motion of stone). In cricket, tennis and badminton, the direction of motion and the speed of the ball (or cock) is changed by hitting it in the direction other than its direction of motion. A player applies force with a hockey stick to change the speed and direction of motion of the ball.

(2) *It can change the size or shape of the body i.e., it can change the dimensions of the body.*

Examples : By loading a spring hanging from a rigid support, the length of the spring increases. By hammering a small piece of silver sheet, a big thin foil is made (here the force increases the surface area). The steam pushing out from a pressure cooker occupies a large volume in the atmosphere. On pressing a piece when the piston is lowered, the air is compressed to occupy a smaller volume.

Note : A force when applied on *a rigid object* does not change the inter-spacing between its constituent particles and therefore it does not change the dimensions of the object, but causes only the motion in it. On the other hand, a force when applied on a *non-rigid object,* changes the inter-spacing between its constituent particles and therefore causes a change in its dimensions and can also produce motion in it. Thus

A force is that physical cause which changes (or tends to change) either the size or the shape or the state of rest or of motion of the body.

Kinds of forces : From the point of view of application, the forces are classified in *two* categories, namely, (i) the ***contact forces*** and (ii) the ***non-contact forces.***

3.2 CONTACT FORCES

The forces which are applied on bodies by making a physical contact, are called the contact forces.

These forces are produced and experienced when a body comes in *contact* with another body.

Examples : (1) The force of friction (frictional force), (2) normal reaction force, (3) Force of tension exerted by a string, (4) Force exerted by a spring, (5) Force exerted on two bodies during collision, etc.

(1) **Frictional force :** When a body slides (or rolls) over a rough surface, a force starts acting on the body in a direction *opposite* to the motion of the body, along the surface in contact. This is called the *frictional force* or the *force of friction.* In Fig. 3.1, when a book placed on the table top is pushed to

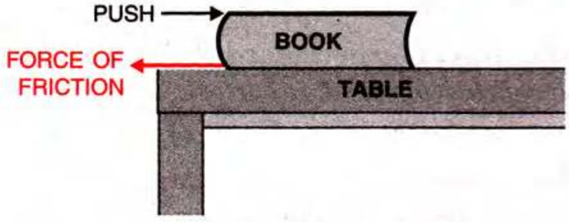


Fig. 3.1 Force of friction

book towards the left. This force *resists* the motion of the book on the table top.

(2) **Normal reaction force :** When a body is placed on a surface, the body exerts a force downwards, equal to its weight, on the surface, but the body does not move (or fall) because the surface exerts an equal and opposite force on the body normal to the surface which is called the *normal reaction force.* For example, in Fig. 3.2, when you hold a block on your palm, the block exerts a force due to its weight downwards on your palm and you have to exert a reaction force upwards on the block normal to the palm to keep the block in position. Similarly in Fig. 3.1, the book exerts a force (= weight) on the table top downwards and the table top exerts an equal reaction force upwards normal to the top of the table.

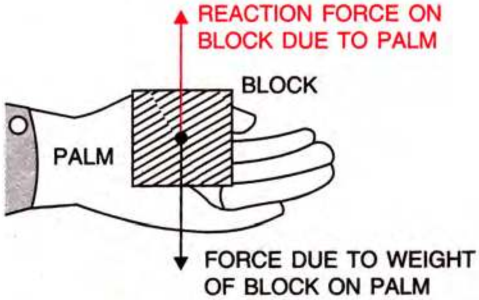


Fig. 3.2 Force of reaction

(3) **Tension force as applied through strings :** When a body is suspended by a string attached to a rigid support, the body, due to its weight *W*, pulls the string vertically downwards and the string in its stretched condition pulls the body upwards by a force which balances the weight of the body. This force developed in the string is called *tension* (or the force of tension) *T*. Fig. 3.3 shows the two forces which are equal and opposite in

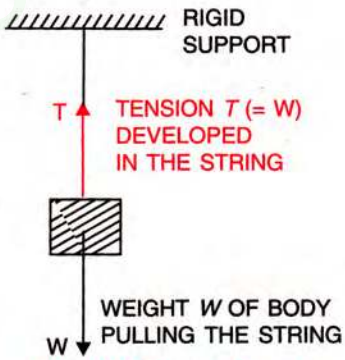
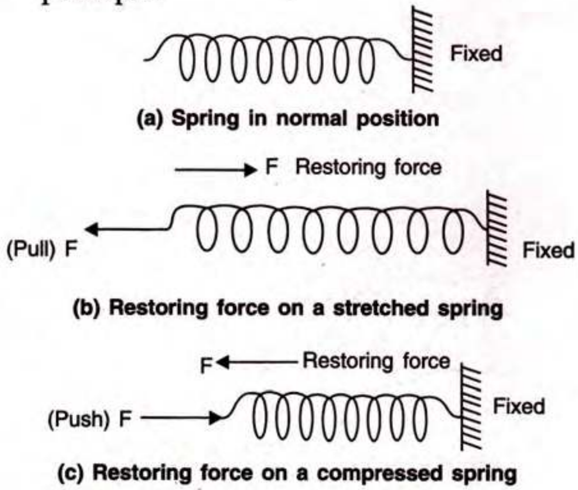


Fig. 3.3 Force of tension

slightly above the body, we see that the string moves slightly upwards with a jerk due to tension in the string acting upwards and then falls downwards due to its own weight.

(4) **Force exerted by a spring :** Consider a spring with its one end kept fixed [Fig. 3.4(a)]. If its other end is either stretched [Fig. 3.4(b)] or compressed [Fig. 3.4(c)], the spring exerts a force F opposite to the direction of displacement of its free end, the magnitude of this force is directly proportional to the magnitude of displacement *i.e.*, its elongation or compression. This force is called *restoring force*. A spring-balance works on this principle.



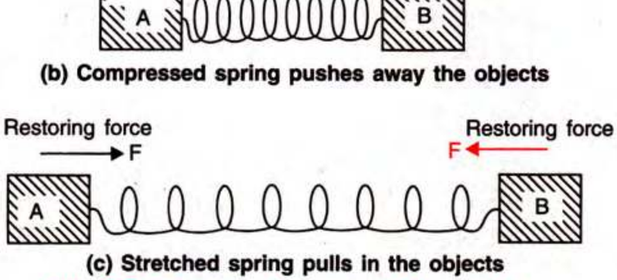
(a) Spring in normal position

(b) Restoring force on a stretched spring

(c) Restoring force on a compressed spring

Fig. 3.4 Restoring force exerted by a spring

Similarly a horizontal spring with two objects A and B attached at its two ends in its normal



(a) Normal form of spring when it exerts no force on any object

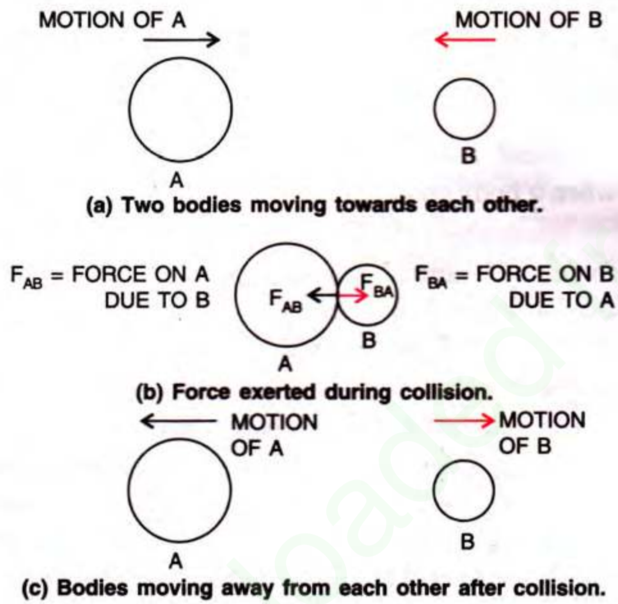
(b) Compressed spring pushes away the objects

(c) Stretched spring pulls in the objects

Fig. 3.5 Restoring force exerted by a spring

attached at its ends [Fig. 3.5(a)]. But if the spring is compressed, it *pushes away* each object with a restoring force F at its ends [Fig. 3.5(b)], while if the spring is stretched, it *pulls in* each object with a restoring force F at its ends [Fig. 3.5(c)]. In each case, the spring has a tendency to come back to its original form.

(5) **Force exerted during collision :** When two bodies collide, they push each other. As a result, equal and opposite forces act on each body. These forces are the force of action and force of reaction. In Fig. 3.6, a body B while in motion, collides with a moving body A and exerts a force F_{AB} on the body A which is called the force of action. *At the same instant*, the body A also exerts an equal and opposite force of reaction F_{BA} on the body B. As a result of these forces, the two bodies move apart after the collision.



(a) Two bodies moving towards each other.

(b) Force exerted during collision.

(c) Bodies moving away from each other after collision.

Fig. 3.6 Collision between two bodies

3.3 NON–CONTACT FORCES

The forces experienced by bodies even without being physically touched, are called the non-contact forces or the forces at a distance.

Examples : (1) Gravitational force, (2) Electrostatic force and (3) Magnetic force.

(1) **Gravitational force :** In universe, each particle attracts the other particle due to its mass. This force of attraction between them is called the *gravitational force*.

The earth also, because of its mass, attracts all other masses around it. The force on a body due to earth's attraction is called the *force of gravity* or the *weight of the body*. It causes motion in the body towards the earth (*i.e.,* downwards) if the body is free to move. Thus, it is the force due to gravity that makes a body fall, when released from a height. The body also attracts the earth by an equal force, but no motion is caused in the earth because of its huge mass.

Examples : (i) A ball placed on a table starts rolling down when the table is tilted.

(ii) If a body is thrown up in air, it goes up, reaches to a height and then returns to the ground.

(iii) A coin falls down when it is released at a height.

(2) **Electrostatic force :** Two like charges repel, while two unlike charges attract each other. The force between the charges is called the *electrostatic force*. This force acts between the charged objects even when they are separated.

Example : When a comb is rubbed on dry hairs, it gets charged. If this comb is brought near the small bits of paper, opposite charges are induced on the bits of paper and they begin to move towards the comb. The motion of paper bits is due to the electrostatic force of attraction exerted between the unlike charges on the comb and the paper bits.

(3) **Magnetic force :** Two like magnetic poles repel, while two unlike magnetic poles attract each other. The force between the magnetic poles is called the *magnetic force*. This force acts even when the magnetic poles are at a separation.

Example : When a pole of a magnet is brought near a small iron nail (without touching it), an opposite polarity is induced on the nail and it moves towards the magnet. The motion of nail is due to the magnetic force of attraction exerted between the unlike poles on the magnet and the nail.

General character of non-contact forces

(i) The gravitational force is always of attractive nature, while the electrostatic force and the magnetic force can be either attractive or repulsive.

(ii) *The magnitude of non-contact forces on the two bodies depends on the distance of separation between them. It decreases with the increase in separation and increases as the separation decreases.* It varies inversely as the square of distance of separation *i.e.*, on doubling the separation, the force becomes one-fourth.

EXERCISE 3(A)

1. Explain giving *two* examples each of :
   (a) Contact forces, and (b) Non-contact forces.
2. Classify the following amongst contact and non-contact forces :
   (a) frictional force,
   (b) normal reaction force,
   (c) force of tension in a string,
   (d) gravitational force,
   (e) electrostatic force,
   (f) magnetic force.

   Ans. Contact force : (a), (b) and (c),
   Non-contact force : (d), (e) and (f)
3. Give *one* example in each case where :
   (a) the force is of contact, and
   (b) force is at a distance.
4. (a) A ball is hanging by a string from the ceiling of the roof. Draw a neat labelled diagram showing the forces acting on the ball and the string.

   (b) A spring is compressed against a rigid wall. Draw a neat and labelled diagram showing the forces acting on the spring.

   (c) A wooden block is placed on a table top. Name the forces acting on the block and draw a neat and labelled diagram to show the point of application and direction of these forces.

5. State *one* factor on which the magnitude of a non-contact force depends. How does it depend on the factor stated by you ?

Ans. Distance; Magnitude of force decreases as the distance increases

6. The separation between two masses is reduced to half. How is the magnitude of gravitational force between them affected ?

Ans. Force will become four times

7. State the effects of a force applied on (i) a non-rigid, and (ii) a rigid body. How does the effect of the force differ in the two cases ?

8. Give *one* example in each of the following cases where a force :
   (a) stops a moving body.
   (b) moves a stationary body.
   (c) changes the size of a body.
   (d) changes the shape of a body.

Multiple Choice Type

1. Which of the following is a contact force :
   (a) electrostatic force (b) gravitational force
   (c) frictional force (d) magnetic force.

   Ans. (c) frictional force

2. The non-contact force is :
   (a) force of reaction (b) force due to gravity
   (c) tension in string (d) force of friction

   Ans. (b) force due to gravity

(B) NEWTON'S FIRST LAW OF MOTION AND INERTIA

3.4 NEWTON'S FIRST LAW OF MOTION

In chapter 2, we have read the linear motion. Now the question arises : what is the cause of motion (*i.e.*, what produces motion in an object) ? It is our common experience that a force is to be applied on an object to produce motion in it.

Examples : To move a cycle, the cyclist has to apply force on its pedal. In a car, the petrol engine provides the force needed to move the car. To move a horse-cart, the horse applies force by stretching its muscles. To move a boat ahead, a force is applied by the oar on the water to push it backward and the force of reaction exerted by water moves the boat ahead.

Before Galileo, the scientists were of view that a force is needed not only to start a motion but also to keep an object moving even with uniform velocity. In other words, an object remains in motion so long as the external force applied to produce motion remains present (*i.e.*, a force must apply continuously to keep the body in motion). This view was based on the observation that the motion of a body ceases when force is withdrawn from it.

Examples : A cycle remains moving so long the force is applied on its pedal. If we stop pushing the pedal, the cycle stops. Similarly, if we put off the engine of a car, the car stops. The horse-cart stops after the horse stops moving and the boat stops after we stop pushing the oar.

Galileo did not approve the above view. From his experiments, he found that no force is needed to continue the motion of a moving body. If a body is set in motion, it will remain in motion even when the force applied to set the body in motion is withdrawn, *provided that there is no other force such as friction etc., to oppose the motion.* From our everyday life experience, we know that a cycle does not stop at once as we stop pedalling, but it moves a certain distance before coming to rest. In fact it stops due to the force of friction between its tyres and road, and also due to friction between its moving parts. If friction between its moving parts is reduced by proper oiling (or greasing) and it is made to move on a smooth road, it travels comparatively a much longer distance before coming to rest, after pedalling is stopped. If somehow it would have been possible to reduce the force of friction completely, the cycle would have remained in motion forever even when pedalling is stopped. Thus, it is concluded that in the absence of the force of friction, no force is required to keep an object moving after bringing it in motion. In other words, *an object, if once set in motion, moves with uniform velocity if no force acts on it.* Thus a body continues to be in the state of rest or in the state of uniform motion unless an external force is applied on it. This is called the *Galileo's law of inertia.*

From the above discussion, we note that :

(i) *If a body is at rest, it remains at rest unless a force is applied on it.*

(ii) *If a body is moving, it will continue to move with the same speed in the same direction unless a force is applied on it.*

Newton put the above observations in the form of a law which is called the Newton's first law of motion.

Statement : According to Newton's first law of motion, if *a body is in a state of rest, it will remain in the state of rest and if it is in the state of motion, it will remain moving in the same direction with the same speed unless an external force is applied on it.*

Qualitative discussion

Newton's first law can be understood in the following *two* parts :

(i) definition of inertia, and

(ii) definition of force.

(i) ***Definition of inertia :*** In the first part, Newton's first law gives the definition of inertia, according to which *an object cannot change its state by itself.* If the object is in the state of rest, it will remain in the state of rest and if it is moving in some direction, it will continue to move with the same speed in the same direction unless an external force is applied on it.

Examples : A book lying on a table top will remain placed at its place unless it is displaced. Similarly, a ball rolling on a horizontal plane keeps on rolling unless the force of friction between the ball and the plane stops it.

The property of an object by virtue of which it neither changes its state nor it tends to change the state, is called ***inertia.*** It is the inherent property of each object.

(ii) ***Definition of force :*** The second part of Newton's first law defines the force, according to which *force is that external cause which can move a stationary object or which can change the state of motion of a moving object.*

Examples : A book lying on a table gets displaced from its place when it is pushed. A moving bicycle stops when a retarding force is applied by the brakes on its wheels.

Thus force is qualitatively defined as follows :

Force is that external cause which tends to change the state of rest or the state of motion of an object.

Note : (i) Force is a vector quantity. (ii) The sum of two equal and opposite forces is zero. (iii) A body acted upon by several forces can also have the resultant net force on it, equal to zero.

3.5 MASS AND INERTIA

Inertia is an inherent property of each body by virtue of which it has a tendency to resist the change in its state of rest or state of motion. The property of inertia is because of the mass of the body. *The greater the mass, the greater is the inertia of body.* Thus, a lighter body has less inertia than a heavier body. In other words, more the mass of a body, more difficult it is to move the body from rest (or to stop the body if it is initially in motion). Thus *mass is a measure of inertia.*

Examples : (1) A cricket ball is more massive than a tennis ball. The cricket ball acquires much smaller velocity than a tennis ball when the two balls are pushed with equal force for the same duration. In case when they are moving with the same velocity, it is more difficult to stop the cricket ball (which has more mass) in comparison to the tennis ball (which has less mass).

(2) It is difficult (*i.e.*, a larger force is required) to set a loaded trolley (which has more mass) in motion than an unloaded trolley (which has less mass). Similarly, it is difficult to stop a loaded trolley than an unloaded one, if both are moving initially with the same velocity.

3.6 KINDS OF INERTIA AND ITS EXAMPLES AS ILLUSTRATION OF FIRST LAW

Inertia is of the following *two* kinds :

(1) *Inertia of rest*, and (2) *Inertia of motion*.

(1) *Inertia of rest*

If a body is at rest, it will remain at rest unless an external force is applied to change its state of rest. This property of body is called the inertia of rest.

(1) ***When a train suddenly starts moving forward, the passenger standing in the compartment tends to fall backwards :*** The reason is that the lower part of the passenger's body is in close contact with the train. As the train starts moving, his lower part shares the motion at once, but the upper part due to inertia of rest cannot share the motion simultaneously and so it tends to remain at the same place. Consequently, the lower part of the body moves ahead and the upper part is left behind, so the passenger tends to fall backwards.

(2) ***When a hanging carpet is beaten with a stick, the dust particles start falling out of it :*** The reason is that the part of the carpet where the stick strikes, comes in motion at once, while the dust particles settled on its fur, remain in position due to inertia of rest. Thus, the part of the carpet moves ahead with the stick, leaving behind the dust particles which fall down due to the earth's pull.

(3) ***On shaking (or giving jerks to) the branches of a tree, the fruits fall down :*** The reason is that when the stem (or branches) of the tree are shaken, they come in motion, while the fruits due to inertia, remain in the state of rest. Thus, the massive and weakly attached fruits get detached from the branches and fall down due to the pull of gravity.

(4) ***On striking the coin at the bottom of a pile of carrom coins with a striker, lowest coin only moves away, while the rest of the pile remains intact :*** The reason is that as the striker hits the lowest coin, it moves (*i.e.*, changes its state of rest), while the remaining pile due to inertia of rest remains where it is and ultimately takes the place of the original pile due to the force of gravity.

(5) ***When a smooth card placed over the mouth of a tumbler is flicked sharply in the horizontal direction, the card flies away, but the coin kept over the card falls into the tumbler :*** The reason is that when the card is flicked [Fig. 3.7(a)], a momentary force acts on the card, so it moves away [Fig. 3.7(b)]. But the

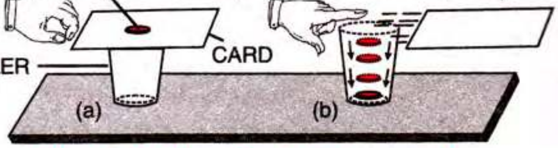


Fig. 3.7 Falling of coin kept on card

coin kept on it does not share the motion at once and it remains at its place due to inertia of rest. The coin then falls down into the tumbler due to the pull of gravity.

(6) ***When a corridor train suddenly starts, the sliding doors of some compartments may open :*** The reason is that the frame of sliding door being in contact with the floor of the train also comes in motion on start of the train, but the sliding door remains in its position due to inertia. Thus the frame moves ahead with the train while door slides opposite to the direction of motion of the train. Thus the door may open.

(2) *Inertia of motion*

A body in a state of motion, continues to be in the state of motion with the same speed in the same direction in a straight line unless an external force is applied on it to change its state. This property of body is called the inertia of motion.

Examples :

(1) ***A cyclist riding along a level road does not come to rest immediately after he stops pedalling :*** The reason is that the bicycle continues to move due to inertia of motion even after the cyclist stops applying the force on the pedal. The bicycle comes to rest afterwards as a result of the retarding force of friction between the tyres of bicycle and the ground.

(2) ***When a passenger jumps out of a moving train, he falls down :*** This is so because inside the train, his whole body was in a state of motion with the train. On jumping out of the moving train, as soon as his feet touch the ground, the lower part of his body comes to rest, while the upper part still remains in motion due to inertia of motion. As a result, he falls in the direction of motion of the train and gets hurt.

To avoid falling, as the passenger's feet touch the ground, he should start running on some distance.

(3) ***When a running car stops suddenly, the passenger tends to lean forward :*** The reason is that in a running car, the whole body of the passenger is in the state of motion. When the car stops suddenly, the lower part of his body, being in contact with the car, comes to rest immediately but his upper part remains in the state of motion, due to inertia. Thus his body leans forward.

(4) ***An athlete often runs before taking a long jump :*** The reason is that by running he brings his body in motion, it becomes easier to take a long jump.

(5) ***A ball thrown vertically upwards by a person in a moving train comes back to his hand:*** The reason is that at the moment when ball was thrown, it was in motion alongwith the person and the train. It remains in the same state of forward motion even during the time the ball remains in air. The person, the inside air and the ball, all move ahead by the same distance due to inertia and so the ball falls back into his palm on its return.

EXERCISE 3(B)

1. Name the physical quantity which causes motion in a body. **Ans.** Force
2. Is force needed to keep a moving body in motion ? **Ans.** No
3. A ball moving on a table top eventually stops. Explain the reason.
   Ans. Force of friction between the ball and table top opposes the motion
4. A ball is moving on a perfectly smooth horizontal surface. If no force is applied on it, will its speed decrease, increase or remain unchanged ? **Ans.** will remain unchanged
5. What is the Galileo's law of inertia ?
6. State the Newton's first law of motion.
7. State and explain the law of inertia (or Newton's first law of motion).
8. What is meant by the term inertia ?
9. Give qualitative definition of force on the basis of Newton's first law of motion.
10. Name the factor on which inertia of a body depends and state how does it depend on the factor stated by you.
    Ans. Mass; more the mass, more is the inertia
11. Give *two* examples to show that greater the mass, greater is the inertia of the body.
12. 'More the mass, more difficult it is to move the body from rest'. Explain this statement by giving an example.
13. Name the *two* kinds of inertia.
14. Give *one* example of each of the following :
    (a) inertia of rest, and (b) inertia of motion.
15. Two equal and opposite forces act on a stationary body. Will the body move ? Give reason to your answer.
    Ans. No. Net force on the body is zero, so the body will remain stationary due to inertia of rest
16. Two equal and opposite forces act on a moving object. How is its motion affected ? Give reason.
    Ans. Motion remains unaffected.
    Reason : Net force on the object is zero.
17. An aeroplane is moving uniformly at a constant height under the action of *two* forces (i) upward force (lift) and (ii) downward force (weight). What is the net force on the aeroplane.
    Ans. Zero
18. Why does a person fall when he jumps out from a moving train ?
19. Why does a coin placed on a card, drop into the tumbler when the card is rapidly flicked with the finger ?
20. Why does a ball thrown vertically upwards in a moving train, come back to the thrower's hand ?
21. Explain the following :
    (a) When a train suddenly moves forward, the passenger standing in the compartment tends to fall backwards.
    (b) When a corridor train suddenly starts, the sliding doors of some compartments may open.
    (c) People often shake branches of a tree for getting down the fruits.
    (d) After alighting from a moving bus, one has to run for some distance in the direction of bus in order to avoid falling.
    (e) Dust particles are removed from a carpet by beating it.

jump.

Multiple choice type :

1. The property of inertia is more in :
   (a) a car (b) a truck
   (c) a horse cart (b) a toy car.
   Ans. (b) a truck

2. A tennis ball and a cricket ball, both are stationary. To start motion in them :
   (a) a less force is required for the cricket ball than for the tennis ball
   (b) a less force is required for the tennis ball than for the cricket ball
   (d) nothing can be said.
   Ans. (b) a less force is required for the tennis ball than for the cricket ball

3. A force is needed to :
   (a) change the state of motion or state of rest of the body
   (b) keep the body in motion
   (c) keep the body stationary
   (d) keep the velocity of body constant.
   Ans. (a) change the state of motion or state of rest of the body

(C) LINEAR MOMENTUM AND NEWTON'S SECOND LAW OF MOTION

3.7 LINEAR MOMENTUM ($p = mv$)

It is our common experience that if two bodies of different masses are moving with the same velocity and they are brought to rest in same time, the force needed to stop the heavier body is more than that for the lighter body. Similarly, if two bodies of the same mass are moving with different velocities, then to stop them in the same time, the force needed for the faster moving body is more than for the slower moving body. Thus, the *force needed to stop a moving body in a definite time depends both on the mass of the body and its velocity.* Actually the force needed to stop a moving body in a given time depends on the product of both the mass and velocity which is called the ***linear momentum*** of the moving body. Thus

Linear momentum of a body is the product of its mass and velocity.

The linear momentum of a body is denoted by the letter p. Generally the word momentum is used for linear momentum.

For a body of mass m moving with velocity v, linear momentum p is expressed as

$$\boxed{p = mv} \qquad ...(3.1)$$

It is a **vector quantity** in the direction of motion of the body (*i.e.*, along the velocity of body).

Unit : From relation $p = mv$,

Unit of momentum = unit of mass × unit of velocity

Thus, the S.I. unit of momentum is kg m s^{-1} and the C.G.S. unit is g cm s^{-1}.

3.8 CHANGE IN MOMENTUM ($\Delta p = m\Delta v$)

From eqn. (3.1), change in momentum

$$\Delta p = \Delta(mv) \qquad ....(3.2)$$

Here the symbol Δ (called del or delta) before a quantity denotes a small change in that quantity.

The change in product mv can be either due to change in mass m or due to change in velocity v or due to change in both the mass m and velocity v. If mass remains constant, then change in momentum is due to change in velocity v alone. Then from eqn. (3.2), for constant mass, change in momentum

$$\Delta p = \Delta(mv) = m\Delta v \qquad ....(3.3)^*$$

In case of atomic particles moving with velocity comparable to the velocity of light c (= 3×10^8 m s^{-1})**, it was observed that the mass of the particle does not remain constant, but it increases with increase in velocity, according to the relation $m = m_0 \sqrt{1-(v/c)^2}$ where m_0 is the mass of the particle when it is at rest (*i.e.*, $v = 0$). In such a case, we cannot write $\Delta(mv) = m\Delta v$. The relation $\Delta p = m\Delta v$ is true only if the velocity v of the

*** The symbol Δ before mv denotes a small change in the product of m and v. If mass m does not change, the product mv will change only due to change in v, and so m can be written before the symbol Δ. The quantity Δv now represents a small change in v only.**

**** c is the ultimate speed. No material particle can acquire a speed equal to or greater than c.**

moving particle is much smaller than the velocity of light c (or $v << c$). It happens when the velocity of particle is of the order of 10^6 m s^{-1} or less than this, then the variation in mass with velocity is small enough and mass can be considered to be constant. However the relation $\Delta p = \Delta(mv)$ is always true, whether mass m varies* or it remains constant.

3.9 RATE OF CHANGE OF MOMENTUM

When a force is applied on a moving body, its velocity changes. Due to change in velocity of the body, its momentum also changes.

Let a force F be applied on a body of mass m for time t due to which its velocity changes from u to v. Then

Initial momentum of the body = mu

Final momentum of the body = mv

Change in momentum of the body in t second

$$= mv - mu = m(v - u)$$

Rate of change of momentum

$$= \frac{\text{Change in momentum}}{\text{Time}} = \frac{m(v-u)}{t}$$

But acceleration $a = \dfrac{\text{Change in velocity}}{\text{Time}} = \dfrac{v-u}{t}$

$\therefore$ Rate of change of momentum $= m\,a$

$= \text{mass} \times \text{acceleration}$ ... (3.4)

This relation holds true when mass of the body remains constant.

Thus when a force acts on a body, the rate of change in momentum of body is equal to the product of mass of the body and acceleration produced in it due to that force, provided that the *mass of the body remains constant.*

Alternative method

For a body of mass m moving with velocity v, its linear momentum is $p = mv$. In time Δt, if its linear momentum changes by Δp on applying a force on it, then the rate of change of linear momentum is

$$\frac{\Delta p}{\Delta t} = \frac{\Delta(mv)}{\Delta t} = m\frac{\Delta v}{\Delta t} \text{ (if mass } m \text{ remains constant)}$$

But $\dfrac{\Delta v}{\Delta t} = a$ (acceleration),

so rate of change of momentum

$$\frac{\Delta p}{\Delta t} = ma = \text{mass} \times \text{acceleration.}$$

The above eqn. is same as eqn. (3.4).

3.10 NEWTON'S SECOND LAW OF MOTION (DERIVATION OF $F = ma$)

Newton's first law of motion defines the force only qualitatively. A force changes the state of motion of a body when it is applied on it. It means that *the force produces acceleration in the body i.e.*, the force is the cause of acceleration. Now we shall see that the Newton's second law of motion gives the quantitative value of force, *i.e.*, it relates force to the measurable quantities like acceleration and mass.

It is our common experience that if we push a tennis ball gently, a small acceleration is produced and it acquires a small velocity in a certain time, but if the same tennis ball is pushed hard, a larger acceleration is produced in it and it acquires a large velocity in the same time interval. Thus the magnitude of two forces can be compared by measuring the accelerations produced by them when they are applied one by one on the same body. If a force F_1 produces an acceleration of 5 m s^{-2} and a force F_2 produces an acceleration of 10 m s^{-2} on the same body, then the magnitude of force F_2 is two times the magnitude of force F_1. Experimentally Newton found that *the acceleration produced in a body is directly proportional to the force applied on it.*

Similarly if we try to produce same change in velocity in the same time (*i.e.*, to produce same acceleration) in a football and a tennis ball, initially both at rest, we need to apply a large force on the football than on the tennis ball. Thus the force needed to produce same acceleration in two bodies of different masses is not same. It is more for the body of larger mass and less for the body of smaller mass. If a force F is needed to produce an acceleration of 5 m s^{-2} in a body of mass 2 kg, then to produce same acceleration (= 5 m s^{-2}) in a body of mass 4 kg, the force needed is of double the magnitude *i.e.* $2F$. Experimentally Newton found that the *force needed to produce same acceleration in different bodies is proportional to their masses.*

*** For example in rocket motion, the mass of rocket decreases as the burnt gases expel out of the nozzle, so the mass does not remain constant.**

concluded that

(i) *The acceleration produced in a body of given mass is directly proportional to the force applied on it. i.e.,*

$a \propto F$ (if mass remains constant) ...(3.5)

A graph plotted for acceleration a against force F is a straight line as shown in Fig. 3.8.

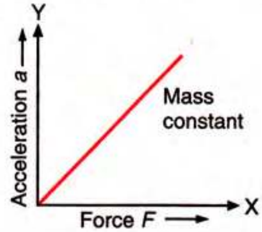


Fig. 3.8 Graph showing the variation of acceleration with force

(ii) *The force needed to produce a given acceleration in a body is directly proportional to the mass of the body. i.e.,*

$F \propto m$ (if acceleration remains the same) ...(3.6)

A graph plotted for force F against mass m is a straight line as shown in Fig. 3.9.

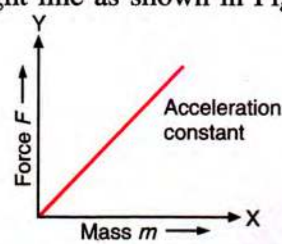


Fig. 3.9 Graph showing the variation of force with mass

Combining eqns. (3.5) and (3.6),

$$\boxed{F = K m a} \quad ...(3.7)$$

Here K is a constant. The unit of force is so chosen that K becomes 1, when $m = 1$ and $a = 1$. Thus, that amount of force is taken as one unit of force which when applied on a body of unit mass, produces a unit acceleration in the body.

With the unit of force so choosen, eqn. (3.7) takes the following form :

$$\boxed{\begin{aligned} F &= m \times a \\ \text{or} \quad \textit{force} &= \textit{mass} \times \textit{acceleration} \end{aligned}} \quad ...(3.8)$$

This is the mathematical expression of Newton's second law of motion.

Note : If a given force is applied on bodies of different masses, the acceleration produced in them is inversely proportional to their masses *i.e.,* $a \propto \frac{1}{m}$ (for a given force F). A graph plotted for acceleration a against mass m is a curve (hyperbola) as shown in Fig. 3.10.

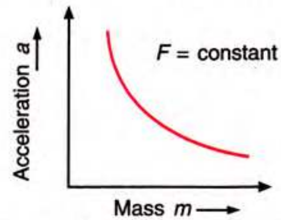


Fig. 3.10 Graph showing the variation of acceleration with mass

3.11 C.G.S. AND S.I. UNITS OF FORCE

The force is related to mass and acceleration as :

Force = mass × acceleration

or $F = m\,a$

On this basis, *the S.I. unit of force is* **newton**.

One newton is the force which when acts on a body of mass 1 kg, *produces an acceleration of* 1 m s^{-2}. *i.e.,* **1 newton = 1 kg × 1 m s^{-2}**

The standard symbol of newton is N.

In C.G.S. system, the unit of force is **dyne**.

One dyne is the force which when acts on a body of mass 1 g, *produces an acceleration of* 1 cm s^{-2}. *i.e.,* **1 dyne = 1 g × 1 cm s^{-2}**

Relationship between newton and dyne

$$\begin{aligned} 1 \text{ newton} &= 1 \text{ kg} \times 1 \text{ m s}^{-2} \\ &= 1000 \text{ g} \times 100 \text{ cm s}^{-2} = 10^5 \text{ g} \times \text{cm s}^{-2} \\ &= 10^5 \text{ dyne.} \end{aligned}$$

Thus $\boxed{1 \text{ newton} = 10^5 \text{ dyne}}$ .... (3.9)

3.12 NEWTON'S SECOND LAW OF MOTION IN TERMS OF RATE OF CHANGE OF MOMENTUM

When force is applied on a body, it produces acceleration in the body due to which the velocity and hence the momentum of body changes.

From eqn. (3.4), the rate of change of momentum is equal to the product of mass and acceleration *i.e.,*

$$\frac{\Delta p}{\Delta t} = ma \text{ (if mass remains constant).}$$

From eqn. (3.8), by Newton's second law of motion, force $F = ma$.

or $\quad F = \dfrac{\Delta p}{\Delta t} = \dfrac{\Delta(mv)}{\Delta t}$

$= ma$ (if mass remains constant) ...(3.10)

Thus Newton's second law of motion can be stated in terms of change in momentum as follows.

Statement : According to Newton's second law of motion, *the rate of change of momentum of a body is directly proportional to the force applied on it and the change in momentum takes place in the direction in which the force is applied.*

Explanation

According to Newton's second law of motion, $F = \dfrac{\Delta p}{\Delta t} = \dfrac{\Delta(mv)}{\Delta t}$. This is the general form of Newton's second law of motion when the momentum changes either due to change in mass or due to change in velocity or due to change in both the mass and velocity.

It is observed that the mass of a particle increases with increase in velocity but it becomes perceptible only when the velocity v of the particle is comparable with the speed of light c (3×10^8 m s^{-1}). At velocities $v << c$ (*i.e.*, when $v << 10^6$ m s^{-1}), the change in mass is not perceptible*. At such velocities ($v << c$), mass m can be considered to be constant. Then Newton's second law takes the form $F = m\dfrac{\Delta v}{\Delta t} = ma$.

Thus, for the relation $F = m\dfrac{\Delta v}{\Delta t} = ma$ *to hold, two conditions are needed : (i) when velocities are much smaller than the velocity of light, and (ii) when mass remains constant.*

Newton's second law is the fundamental law of motion. The first law of motion is also included in the second law. This we can see as follows.

To obtain Newton's first law of motion from second law of motion

From Newton's second law, $F = m\,a$

If $F = 0$, then $a = 0$

This means that if no force is applied on the body, its acceleration will be zero. If the body is at rest, it will remain at rest and if it is moving, it will remain moving in the same direction with the same speed. Thus *a body not acted upon by any external force, does not change its state of rest or of motion.* This is the statement of Newton's first law of motion.

* When $v = 10^6$ m s^{-1}, $m = 1{\cdot}0000056\ m_0$ and when $v = 10^7$ m s^{-1}, $m = 1{\cdot}0005561\ m_0$. Here m_0 is the mass at $v = 0$.

The mathematical expression of the second law of motion is $F = \Delta p/\Delta t$. It gives $\Delta p = F\Delta t$, so a given change in momentum of a body can be brought about either by applying a large force for a small duration or by applying a small force for a long duration. For example, in hitting a cricket ball by a bat, hammering a nail, hitting the ping-pong ball by a racket, *etc.* a required momentum is imparted to the body by applying a force of large magnitude for a short duration. On the other hand in the following examples the momentum of a moving body is brought to zero in a large duration so as to reduce the effect of force exerted by the moving body.

Examples :

(1) While catching a ball, the cricketer withdraws his hands along with the ball

Let u be the velocity of the ball of mass m when it reaches the hands of the player catching it.

The initial momentum of ball = $m\,u$

When the cricketer stops the ball ($v = 0$), its final momentum = $m \times 0 = 0$.

Change in momentum

= final momentum – initial momentum

= $0 - mu = -\,mu = mu$ (numerically)

Here –ve sign shows that the change in momentum is in direction opposite to the initial direction of motion.

If the cricketer does not pull back his hands and stops the ball as soon it touches his hands, he gets very little time t_1 to stop the ball. Then the force exerted by the ball on the hands of the cricketer is $F_1 = \dfrac{\text{Change in momentum}}{\text{Time interval}} = \dfrac{mu}{t_1}$. But if the cricketer pulls back his hands along with the ball, he takes a longer time t_2 to stop the ball. The force now exerted by the ball on his hands is $F_2 = \dfrac{mu}{t_2}$. Since $t_2 > t_1$, therefore $F_2 < F_1$ or the force exerted on the hands of cricketer by the fast moving ball is less when he withdraws his hands. Thus cricketer avoids the chances of injury to his palms by withdrawing his hands alongwith the moving ball while catching it.

(2) Athletes often lands on sand (or foam) after taking a high jump

When an athlete lands from a height on a come to rest almost instantenously (*i.e.*, in a very short interval of time), so a very large force is exerted by the floor on his feet. On the other hand, when he lands on sand (or foam), his feet push the sand (or foam) for some distance, therefore the time duration in which his feet come to rest, increases. As a result, the force exerted on his feet decreases and he is saved from getting hurt.

they break, but they do not break when they fall on a carpet (or sand)

When a glass vessel falls from a height on a hard floor, it comes to rest almost instantenously (*i.e.*, in a very short time) so the floor exerts a large force on the vessel and it breaks. But if it falls on a carpet (or sand), the time duration in which the vessel comes to rest, increases and so the carpet (or sand) exerts a less force on the vessel and it does not break.

EXAMPLES

1. How much force is required to produce an acceleration of 2 m s^{-2} in a body of mass 0·8 kg ?

Given, $m = 0{\cdot}8$ kg, $a = 2$ m s^{-1}

$$\text{Force } F = m\,a = 0{\cdot}8 \text{ kg} \times 2 \text{ m s}^{-2} = \mathbf{1{\cdot}6 \text{ newton}} \text{ (or } \mathbf{1{\cdot}6 \text{ N}}).$$

2. A force acts for 0·1 s on a body of mass 1·2 kg initially at rest. The force then ceases to act and the body moves through 2 m in the next 1·0 s. Find the magnitude of force.

When force ceases to act, the body will move with a constant velocity. Since it moves a distance 2 m in 1·0 s, therefore its uniform velocity is 2 m s^{-1}. Thus under the influence of force, the body acquires a velocity 2 m s^{-1} in 0·1 s.

i.e., $u = 0$, $v = 2$ m s^{-1}, $t = 0{\cdot}1$ s and $m = 1{\cdot}2$ kg

$$\text{Now acceleration } a = \frac{\text{Change in velocity}}{\text{Time}}$$

or
$$a = \frac{v-u}{t} = \frac{(2-0)\text{ m s}^{-1}}{0{\cdot}1 \text{ s}} = 20 \text{ m s}^{-2}$$

From the relation $F = ma$,

$$\text{Force } F = 1{\cdot}2 \text{ kg} \times 20 \text{ m s}^{-2} = \mathbf{24 \text{ N}}$$

3. A ball of mass 10 g is moving with a velocity of 50 m s^{-1}. On applying a constant force on ball for 2·0 s, it acquires a velocity of 70 m s^{-1}. Calculate :

(i) the initial momentum of ball,

(ii) the final momentum of ball,

(iii) the rate of change of momentum,

(iv) the acceleration of ball, and

(v) the magnitude of force applied.

Given, $m = 10 \text{ g} = \frac{10}{1000} \text{ kg} = 0{\cdot}01 \text{ kg}$, $u = 50$ m s^{-1}, $t = 2{\cdot}0$ s, $v = 70$ m s^{-1}.

(i) Initial momentum of ball = mass × initial velocity

$$= mu = 0{\cdot}01 \text{ kg} \times 50 \text{ m s}^{-1} = \mathbf{0{\cdot}5 \text{ kg m s}^{-1}}$$

(ii) Final momentum of the ball = mass × final velocity

$$= mv = 0{\cdot}01 \text{ kg} \times 70 \text{ m s}^{-1} = \mathbf{0{\cdot}7 \text{ kg m s}^{-1}}$$

(iii) Rate of change of momentum

$$= \frac{\text{Final momentum} - \text{Initial momentum}}{\text{Time interval}}$$

$$= \frac{(0{\cdot}7 - 0{\cdot}5)\text{ kg m s}^{-1}}{2{\cdot}0 \text{ s}} = 0{\cdot}1 \text{ kg m s}^{-2} \text{ (or } \mathbf{0{\cdot}1 \text{ N}})$$

(iv) $\text{Acceleration } a = \frac{v-u}{t} = \frac{(70-50)\text{ m s}^{-1}}{2\text{ s}} = \mathbf{10 \text{ m s}^{-2}}$

(v) $\text{Force} = \text{mass} \times \text{acceleration} = ma = 0{\cdot}01 \text{ kg} \times 10 \text{ m s}^{-2} = \mathbf{0{\cdot}1 \text{ N}}$

4. A cricket ball of mass 100 g moving with a speed of 30 m s^{-1} is brought to rest by a player in 0·03 s. Find :

(i) the change in momentum of ball,

(ii) the average force applied by the player.

Given, $m = 100 \text{ g} = \frac{100}{1000} \text{ kg} = 0{\cdot}1 \text{ kg}$, $u = 30$ m s^{-1}, $v = 0$, $t = 0{\cdot}03$ s.

(i) Initial momentum $= mu = 0{\cdot}1 \times 30 = 3{\cdot}0$ kg m s^{-1}

Final momentum $= mv = 0{\cdot}1 \times 0 = 0$

Change in momentum = Final momentum − Initial momentum

$= 0 - 3{\cdot}0 = \mathbf{-3{\cdot}0 \text{ kg m s}^{-1}}$

(ii) Average force

$$F = \frac{\text{Change in momentum}}{\text{Time } t} = \frac{-3{\cdot}0 \text{ kg m s}^{-1}}{0{\cdot}03 \text{ s}} = \mathbf{-100 \text{ N}}$$

(Negative sign here shows that the force is applied in a direction opposite to the direction of motion of ball).

1. Name the *two* factors on which the force needed to stop a moving body in a given time, depends.
2. Define linear momentum and state its S.I. unit.
3. A body of mass m moving with a velocity v is acted upon by a force. Write expression for change in momentum in each of the following cases : (i) when $v << c$, (ii) when $v \to c$, and (iii) when $v << c$ but m does not remain constant. Here c is the speed of light.
Ans. (i) $m\,\Delta v$ (ii) $\Delta(mv)$ (iii) $\Delta(mv)$
4. Show that the rate of change of momentum = mass × acceleration. Under what condition does this relation hold ?
5. Two bodies A and B of same mass are moving with velocities v and $2v$ respectively. Compare their (i) inertia, (ii) momentum.
Ans. (i) 1 : 1 (ii) 1 : 2
6. Two balls A and B of masses m and $2m$ are in motion with velocities $2v$ and v respectively. Compare : (i) their inertia, (ii) their momentum, and (iii) the force needed to stop them in the same time. **Ans.** (i) 1 : 2 (ii) 1 : 1 (iii) 1 : 1
7. State Newton's second law of motion. What information do you get from it ?
8. How does Newton's second law of motion differ from first law of motion ?
9. Write the mathematical form of Newton's second law of motion. State condition if any.
10. State Newton's second law of motion. Under what condition does it take the form $F = ma$?
11. How can Newton's first law of motion be obtained from the second law of motion ?
12. Draw graphs to show the dependence of (i) acceleration on force for a constant mass, and (ii) force on mass for a constant acceleration.
13. How does the acceleration produced by a given force depend on mass of the body ? Draw graph to show it.
14. Name the S.I. unit of force and define it.
15. What is the C.G.S. unit of force ? How is it defined ?
16. Name the S.I. and C.G.S. units of force. How are they related ?
17. Why does a glass vessel break when it falls on a hard floor, but it does not break when it falls on a carpet ?
18. Use Newton's second law of motion to explain the following :
    (a) A cricketer pulls his hands back while catching a fast moving cricket ball.
    (b) An athlete prefers to land on sand instead of hard floor while taking a high jump.

Multiple choice type :

1. The linear momentum of a body of mass m moving with velocity v is :
   (a) v/m (b) m/v
   (c) mv (d) $1/mv$ **Ans.** (c) mv
2. The unit of linear momentum is :
   (a) N s (b) kg m s^{-2}
   (c) N s^{-1} (d) kg^2 m s^{-1} **Ans.** (a) N s
3. The correct form of Newton's second law is :
   (a) $F = \frac{\Delta p}{\Delta t}$ (b) $F = m\frac{\Delta v}{\Delta t}$
   (c) $F = v\frac{\Delta m}{\Delta t}$ (d) $F = mv$ **Ans.** (a) $F = \frac{\Delta p}{\Delta t}$
4. The acceleration produced in a body by a force of given magnitude depends on
   (a) size of the body (b) shape of the body
   (c) mass of the body (d) none of these.
   Ans. (c) mass of the body

Numericals :

1. A body of mass 5 kg is moving with velocity 2 m s^{-1}. Calculate its linear momentum.
Ans. 10 kg m s^{-1}
2. The linear momentum of a ball of mass 50 g is 0·5 kg m s^{-1}. Find its velocity. **Ans.** 10 m s^{-1}
3. A force of 15 N acts on a body of mass 2 kg. Calculate the acceleration produced.
Ans. 7·5 m s^{-2}
4. A force of 10 N acts on a body of mass 5 kg. Find the acceleration produced. **Ans.** 2 m s^{-2}
5. Calculate the magnitude of force which when applied on a body of mass 0·5 kg produces an acceleration of 5 m s^{-2}. **Ans.** 2·5 N
6. A force of 10 N acts on a body of mass 2 kg for 3 s, initially at rest. Calculate : (i) the velocity acquired by the body, and (ii) change in momentum of the body.
Ans. (i) 15 m s^{-1}, (ii) 30 kg m s^{-1}.
7. A force acts for 10 s on a stationary body of mass 100 kg after which the force ceases to act. The body moves through a distance of 100 m in the next 5 s. Calculate : (i) the velocity

produced by the force, and (iii) the magnitude of the force.

Ans. (i) 20 m s^{-1}, (ii) 2 m s^{-2}, (iii) 200 N

8. Fig. 3.11 shows the velocity-time graph of a particle of mass 100 g moving in a straight line. Calculate the force acting on the particle.

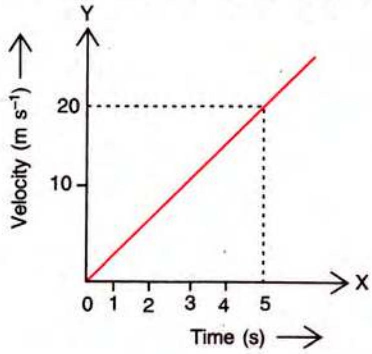


Fig. 3.11

(**Hint :** Acceleration = slope of v–t graph)

Ans. 0·4 N

9. A force acts for 0·1 s on a body of mass 2·0 kg initially at rest. The force is then withdrawn and the body moves with a velocity of 2 m s^{-1}. Find the magnitude of force. **Ans.** 40 N

10. A cricket ball of mass 100 g moving at a speed ... 0·03 s. Find the average force applied by the player. **Ans.** 100 N

11. A car of mass 480 kg moving at a speed of 54 km h^{-1}, is stopped by applying breaks in 10 s. Calculate the force applied by the brakes. **Ans.** 720 N

12. A bullet of mass 50 g moving with an initial velocity 100 m s^{-1}, strikes a wooden block and comes to rest after penetrating a distance 2 cm in it. Calculate : (i) initial momentum of the bullet, (ii) final momentum of the bullet, (iii) retardation caused by the wooden block, and (iv) resistive force exerted by the wooden block

Ans. (i) 5 kg m s^{-1}, (ii) zero, (iii) $2{\cdot}5 \times 10^5$ m s^{-2}, (iv) 12500 N

13. A force causes an acceleration of 10 m s^{-2} in a body of mass 500 g. What acceleration will be caused by the same force in a body of mass 5 kg ? **Ans.** 1 m s^{-2}

14. A car is moving with a uniform velocity 30 m s^{-1}. It is stopped in 2 s by applying a force of 1500 N through its brakes. Calculate : (a) the change in momentum of car, (b) the retardation produced in car, and (c) the mass of car.

Ans. (a) 3000 kg m s^{-1} (b) 15 m s^{-2} (c) 100 kg

(D) NEWTON'S THIRD LAW OF MOTION

3.13 NEWTON'S THIRD LAW OF MOTION

Newton's first law tells us that to bring a change in the state of rest or in the state of motion of an object, a force is needed *i.e.*, a force produces a change in velocity of the object. Newton's second law tells us the magnitude of acceleration produced by the force when applied on the object. These two laws do not explain how does the force act on the object ? This question is answered by the Newton's third law, which is stated as follows.

Statement : According to Newton's third law of motion, *to every action there is always an equal and opposite reaction.*

Examples :

(i) Consider a book lying on a table. The weight of the book acts vertically downwards, but the book does not move downwards. It implies that the resultant force on the book is zero, which is possible only if the table exerts an equal upward force on the book equal to the weight of the book. This force on the book balances the weight of the book.

(ii) While moving on the ground, we exert a force by our feet to push the ground backwards, the ground exerts a force of the same magnitude on our feet forward which makes us to move forward.

Explanation : In the above stated examples, we observe that there are two objects and two forces. In the first example, the weight of the book acting on the table downwards is the *force of action* and the force exerted by table on the book upwards is the *force of reaction*. In the second example, the force exerted by our feet on the ground is the *force of action* and the force exerted by the ground on our feet is the *force of reaction*.

Thus Newton's third law of motion states :

In an interaction of two bodies A and B, the magnitude of reaction (i.e., the force F_{AB} applied by the body B on the body A) is equal in magnitude to the action (i.e., the force F_{BA} applied by the body A on the body B), but they are in directions opposite to each other.

Note : The action and reaction never act on the same body, but they always act *simultaneously* on two different bodies *i.e., the forces of interaction are always present in a pair.*

Experimental demonstration of Newton's third law

Experiment : In Fig. 3.12, the ring of a spring balance *B* is attached to a hook fixed in a wall, and then the hook of another spring balance *A* is attached to the hook of the spring balance *B*. Now the ring of spring balance *A* is pulled. We find that *both the balances show the same reading.*

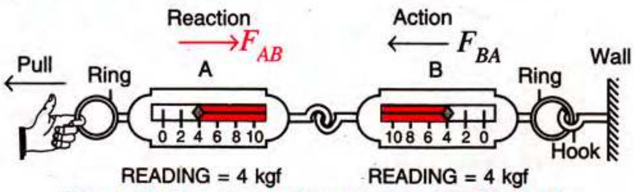


Fig. 3.12 Demonstration of action and reaction

Explanation : The spring of balance *A* pulls the spring of balance *B* due to which we get some reading in balance *B*. The same reading is seen in balance *A* because the spring of balance *B* also pulls the spring of balance *A* by the same force. The pull on the spring *B* by the spring *A* is the *action* F_{BA} and the pull on the spring *A* by the spring *B* is the reaction F_{AB}. This demonstrates that "to every action, there is an equal and opposite reaction" (*i.e.*, in magnitude $F_{AB} = F_{BA}$ but they are in opposite directions) or $\vec{F}_{AB} = -\vec{F}_{BA}$. .....(3.11)

Examples of action and reaction

(1) ***A book on a table :*** When a book is placed on a table top, the book exerts a force equal to its weight *W* (*action*) on the table in direction $\vec{AB}$ downwards and the table balances it by an equal force called the *reaction R* ($R = W$) acting upwards on the book in direction $\vec{AD}$. Fig. 3.13 shows these action and reaction.

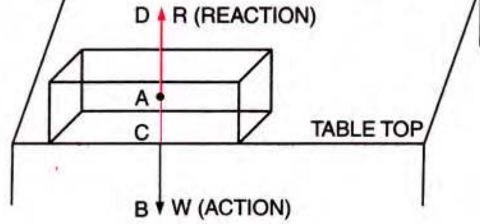


Fig. 3.13 Action and reaction on a book lying on a table

(2) ***Pushing a wall :*** When you exert a force (*action*) on a wall by pushing the palm of your hand against it, you experience a force (*reaction*) exerted by the wall on your palm.

(3) ***Motion of a boat moving away from the shore:*** When a boatman wants to move the boat away from the shore, he pushes the shore by a bamboo or with his oar (*action*). The shore pushes the boatman (along with boat) away with an equal and opposite force (*reaction*).

(4) ***Motion of boat in water :*** To move a boat ahead in water, the boatman pushes (*action*) the water backwards with his oar and the water exerts an equal and opposite force (*reaction*) in the forward direction on the boat due to which the boat moves ahead.

(5) ***Firing a bullet from a gun :*** When a man fires a bullet from a gun, a force *F* is exerted on the bullet (*action*) and the gun experiences an *equal* recoil *R* (*reaction*) as shown in Fig. 3.14.

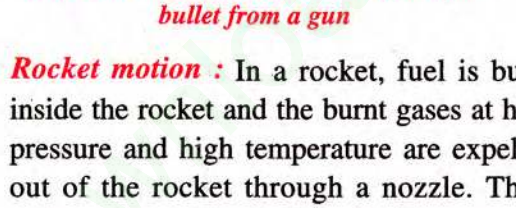


Fig. 3.14 Action and reaction on firing a bullet from a gun

(6) ***Rocket motion :*** In a rocket, fuel is burnt inside the rocket and the burnt gases at high pressure and high temperature are expelled out of the rocket through a nozzle. Thus, rocket exerts a force *F* (*action*) on gases to expel them through a nozzle backwards. The outgoing gases exert an equal and opposite force *R* (*reaction*) on the rocket due to which it moves in the forward direction (Fig. 3.15).

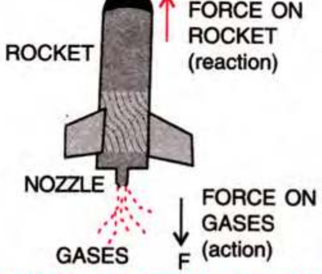


Fig. 3.15 Action and reaction in rocket motion

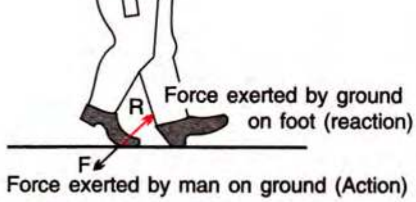


Fig. 3.16 Action and reaction while a man moves on ground

(7) ***Motion of man on ground :*** When a man applies a force F (*action*) backward by his foot on the ground against the force of friction, the ground exerts an equal and opposite force R (*reaction*) forward on his foot. The horizontal component of the force of reaction R enables the man to move forward (Fig. 3.16). Obviously it will be difficult for a man to move on a slippery road where friction is less.

(8) ***Motion of boat away from the shore while stepping down from it :*** When a man exerts a force (*action*) on the boat, its force of *reaction* enables him to step out of the boat. At the same instant, the boat tends to leave the shore due to the force exerted by the man (*i.e.*, action).

(9) ***Catching a ball :*** While catching a ball, the ball exerts a force (*action*) on the hand of cricketer and the cricketer exerts an equal force (*reaction*) on the ball to stop it.

EXERCISE 3(D)

1. State the usefulness of Newton's third law of motion.
2. State Newton's third law of motion.
3. State and explain the law of action and reaction, by giving *two* examples.
4. Name and state the action and reaction in the following cases :
   (a) firing a bullet from a gun,
   (b) hammering a nail,
   (c) a book lying on a table,
   (d) a moving rocket,
   (e) a person walking on the floor,
   (f) a moving train colliding with a stationary train.
5. Explain the motion of a rocket with the help of Newton's third law.
6. When a shot is fired from a gun, the gun gets recoiled. Explain.
7. When you step ashore from a stationary boat, it tends to leave the shore. Explain.
8. When two spring balances joined at their free ends, are pulled apart, both show the same reading. Explain.
9. To move a boat ahead in water, the boatman has to push the water backwards by his oar. Explain.
10. A person pushing a wall hard is liable to fall back. Give reason.
11. 'The action and reaction both act simultaneously.' Is this statement true ? **Ans.** Yes
12. 'The action and reaction are equal in magnitude'. Is this statement true ? **Ans.** Yes
13. A light ball falling on ground, after striking the ground rises upwards. Explain the reason.
14. Comment on the statement 'the sum of action and reaction on a body is zero'.
    [**Hint :** The statement is wrong]

Multiple choice type :

1. Newton's third law :
   (a) defines the force qualitatively
   (b) defines the force quantitatively
   (c) explains the way the force acts on a body
   (d) gives the direction of force.
   Ans. (c) explains the way the force acts on a body
2. Action and reaction act on the :
   (a) same body in opposite directions
   (b) different bodies in opposite directions
   (c) different bodies, but in same direction
   (d) same body in same direction.
   Ans. (b) different bodies in opposite directions

Numericals :

1. A boy pushes a wall with a force of 10 N towards east. What force is exerted by the wall on the boy ? **Ans.** 10 N towards west
2. In Fig. 3.17, a block of weight 15 N is hanging from a rigid support by a string. What force is exerted by
   (a) block on the string,
   (b) string on the block.
   Name them and show them in the diagram.

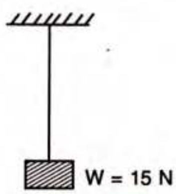


Fig. 3.17

Ans. (a) 15 N downwards (weight), (b) 15 N upwards (tension)

3.14 UNIVERSAL LAW OF GRAVITATION

Each mass particle of the universe attracts the other mass particle. The force of attraction between the two particles because of their masses, is called the *gravitational force of attraction*. For the magnitude of this force, Sir Issac Newton gave a law, known as *Newton's law of gravitation*.

According to Newton, *the force of attraction acting between the two particles is (i) directly proportional to the product of their masses and (ii) inversely proportional to the square of the distance between them.* This force acts along the line joining the two particles.

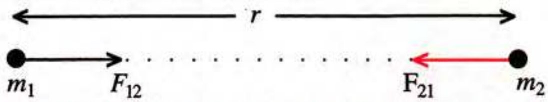


Fig. 3.18 Gravitational force between two particles

In Fig. 3.18, let there be two particles of masses m_1 and m_2 at a separation r. The magnitude of force of attraction F acting between them is

$$F \propto m_1 m_2 \text{ and } F \propto 1/r^2$$

Combining the two relations,

$$F \propto \frac{m_1 m_2}{r^2}$$

or $$\boxed{F = G\frac{m_1 m_2}{r^2}} \qquad ...(3.12)$$

where G is a constant of proportionality which is known as *gravitational constant.* The value of G remains same at all places and it is independent of the nature of particles, temperature, medium, *etc*. Therefore, it is a *universal constant* and is known as universal gravitational constant.

It may be mentioned here that force is a vector quantity, hence it is necessary to indicate its direction also. The direction of force $\vec{F}_{12}$ on mass m_1 is towards m_2 along the line joining the masses m_1 and m_2, whereas the force $\vec{F}_{21}$ on mass m_2 is towards mass m_1 along the same line. Both these forces are equal in magnitude, but opposite in direction (*i.e.*, $\vec{F}_{12} = -\vec{F}_{21}$). Thus it is an action-reaction force *i.e.*, a particle exerts a force on other particle, equal and opposite to the force that the second particle exerts on the first particle.

Unit and value of universal gravitational constant

From eqn. (3.12), $G = \dfrac{F \times r^2}{m_1 \times m_2}$

$$\therefore \quad \text{S.I. unit of } G = \frac{\text{newton} \times \text{metre}^2}{\text{kilogram} \times \text{kilogram}} = \text{N m}^2 \text{kg}^{-2}$$

The value of G is $6{\cdot}67 \times 10^{-11}$ N m^2 kg^{-2}.

In eqn. (3.12), if $m_1 = 1$ kg, $m_2 = 1$ kg and $r = 1$ m, then $G = F$. Thus

> *Gravitational constant G is numerically equal to the magnitude of force of attraction between the two masses each of* 1 kg *placed at a separation of* 1 m.

Examples : (1) The gravitational force of attraction between two bodies of masses $m_1 = 1$ kg and $m_2 = 1$ kg kept at a separation of $r = 1$ m is

$$F = \frac{(6{\cdot}67 \times 10^{-11}) \times 1 \times 1}{(1)^2} = 6{\cdot}67 \times 10^{-11} \text{ N.}$$

(2) The gravitational force of attraction between the moon (mass = $7{\cdot}36 \times 10^{22}$ kg) and the earth (mass = $5{\cdot}96 \times 10^{24}$ kg), taking the distance of moon from the earth to be $3{\cdot}80 \times 10^8$ m, is

$$F = \frac{(6{\cdot}67 \times 10^{-11}) \times (5{\cdot}96 \times 10^{24}) \times (7{\cdot}36 \times 10^{22})}{(3{\cdot}80 \times 10^8)^2}$$
$$= 2 \times 10^{20} \text{ N.}$$

From the above two examples, it is clear that the gravitational force of attraction is significant between the heavenly bodies, but it is insignificant between the ordinary bodies.

In fact, regarding the gravitational force, it is important to note that the gravitational force between the two masses :

(i) is always *attractive*.

(ii) is directly proportional to the *product of the masses*.

(iii) is inversely proportional to the square of separation between them, *i.e.* it obeys the inverse square law. Thus, by doubling the separation between the two masses, the force of attraction between them is reduced to one-fourth.

(iv) is significant between heavenly bodies, but is insignificant between ordinary bodies because of small magnitude of G.

used this law to explain the motion of planets around the sun, the motion of the moon (satellite) around the earth and the motion of a freely falling body.

3.15 FORCE DUE TO GRAVITY

According to the law of gravitation, the earth attracts each object around it, towards its centre. The force with which the earth attracts a body is called the ***force due to gravity*** on the body, which can be taken to act vertically downwards at the centre of gravity of the body. In vertical motion *near* the earth surface for height much smaller than the radius of earth, the force of gravity on the body is assumed to be *same* throughout.

The force due to gravity on a body of mass m kept on the surface of earth of mass M and radius R, is equal to the force of attraction between the earth and that body. It is given as

$$F = \frac{GMm}{R^2} \qquad \text{....(3.13)}$$

Taking the mass of earth $M = 5{\cdot}96 \times 10^{24}$ kg and the radius of earth $R = 6{\cdot}37 \times 10^6$ m, the force of gravity on a body of mass $m = 1$ kg on the surface of earth will be

$$F = \frac{(6{\cdot}67\times10^{-11})\times(5{\cdot}96\times10^{24})\times1}{(6{\cdot}37\times10^6)^2} = 9{\cdot}8 \text{ N.}$$

Thus earth attracts a body of mass 1 kg by a force of 9·8 N towards its centre.

Note : As earth attracts an object towards it, the object also attracts the earth towards it by an equal force. Since the object is free to move, it starts moving towards the earth, but the earth because of its large inertia, does not move towards the object.

3.16 ACCELERATION DUE TO GRAVITY

Galileo was the first scientist to study the motion of different bodies under the force of attraction of earth (*i.e.*, gravity). From his experiments, Galileo found that if bodies of different masses and sizes (or shapes) are simultaneously made to fall in vacuum (*i.e.*, in absence of air)* from the same height, they all reach the earth surface simultaneously and with same velocity. Thus, all bodies travel the same distance in the same interval of time. Moreover, he found that the velocity of a freely falling body does not remain constant, but it *freely falling body is a uniformly accelerated motion*. This acceleration is same for all bodies. In other words, *the acceleration of a freely falling body does not depend on the mass of the body, its size and its shape, etc.* This acceleration is called the *acceleration due to gravity*. Thus

> *The rate at which the velocity of a freely falling body increases, is called the acceleration due to gravity.* In other words, *it is the acceleration produced in a freely falling body due to the gravitational force of attraction of the earth.*

The acceleration due to gravity is denoted by the letter g. Its S.I. unit is m s^{-2}. It is a **vector** quantity directed vertically downwards towards the centre of earth.

Experimentally, it is found that the value of acceleration due to gravity g does not remain constant. On the earth's surface, the value of g varies from place to place. On equator, it is slightly less as compared to that at poles. The mean value of g on the earth surface is 9·8 m s^{-2}. At altitudes above the earth's surface or at depth below the earth surface, the value of g decreases. The value of g is zero at the centre of earth.

Note : The value of g is different on different planets and satellites. The value of g on moon's surface is nearly one-sixth the value of g on earth's surface.

Relationship between g and G : Let g be the acceleration due to gravity at a planet (or satellite) of mass M and radius R. By Newton's law of motion, the force due to gravity on a body of mass m on its surface will be

$$F = \text{mass} \times \text{acceleration due to gravity}$$

or
$$F = mg \qquad \text{....(3.14)}$$

By Newton's gravitational law, this attractive force is given by
$$F = \frac{GMm}{R^2} \qquad \text{...(3.15)}$$

From eqns. (3.14) and (3.15),

$$\frac{GMm}{R^2} = mg$$

or
$$\boxed{\text{acceleration due to gravity } g = \frac{GM}{R^2}} \qquad \text{...(3.16)}$$

The above eqn. (3.16) relates the acceleration due to gravity g with the gravitational constant G. Obviously *the value of g on a planet (or satellite)*

* In presence of air, viscous force and force due to buoyancy act on the body upwards. These forces depend on size, shape and velocity of the body, so they are different in magnitude for different bodies. Therefore downward acceleration will not remain same (equal to g) for all bodies, so they will not reach simultaneously.

(or satellite).

Examples : (1) Taking the mass of earth $M = 5{\cdot}96 \times 10^{24}$ kg and the radius of earth $R = 6{\cdot}37 \times 10^6$ m, the acceleration due to gravity at a place on the surface of earth comes out to be

$$g_{earth} = \frac{(6{\cdot}67\times10^{-11})\times(5{\cdot}96\times10^{24})}{(6{\cdot}37\times10^{6})^2} = 9{\cdot}8 \text{ m s}^{-2}.$$

(2) On the surface of moon (mass $M = 7{\cdot}36 \times 10^{22}$ kg and radius $R = 1{\cdot}75 \times 10^6$ m), the acceleration due to gravity at the surface of moon is

$$g_{moon} = \frac{(6{\cdot}67\times10^{-11})\times(7{\cdot}36\times10^{22})}{(1{\cdot}75\times10^{6})^2} = 1{\cdot}6 \text{ m s}^{-2}.$$

Obviously, $g_{moon} = \frac{1}{6}\, g_{earth}$ nearly.

3.17 FREE FALL

In chapter 2, we have studied one dimensional motion. The motion of a freely falling body from a height or the motion of a body thrown vertically upwards from the surface of earth, is the one dimensional motion under gravity. The acceleration of a vertically falling body is $a = + g$ and that of a body going vertically upwards is $a = - g$.

If a body *falls from rest* freely from a height h, under gravity then $u = 0$ and acceleration a is replaced by g (acceleration due to gravity), then equations of motion are :

$$\left.\begin{array}{lrcl} \text{(i)} & v & = & gt \\ \text{(ii)} & h & = & \frac{1}{2}gt^2 \\ \text{(iii)} & v^2 & = & 2gh \end{array}\right\} \qquad ...(3.17)$$

But if the initial velocity of fall of the body is u, then equations of motion are :

$$\left.\begin{array}{lrcl} \text{(i)} & v & = & u + gt \\ \text{(ii)} & h & = & ut + \frac{1}{2}gt^2 \\ \text{(iii)} & v^2 & = & u^2 + 2gh \end{array}\right\} \qquad ...(3.18)$$

If a body is thrown vertically up with an initial velocity u to a height h, there will be retardation ($a = - g$), then equations of motion are:

$$\left.\begin{array}{lrcl} \text{(i)} & v & = & u - gt \\ \text{(ii)} & h & = & ut - \frac{1}{2}gt^2 \\ \text{(iii)} & v^2 & = & u^2 - 2gh \end{array}\right\} \qquad ...(3.19)$$

At the highest point of reach, final velocity $v = 0$, thus maximum height reached $h_{max} = \frac{u^2}{2g}$ (from equation $v^2 = u^2 - 2gh$) and the time taken by the body to rise to the highest point $t = \frac{u}{g}$ (from equation $v = u - gt$). The same will be the time it takes to come back to the initial point after reaching the highest point. So the total time of journey $t' = 2t = \frac{2u}{g}$ and the total distance travelled by the body $h' = 2h_{max} = \frac{u^2}{g}$.

3.18 MASS AND WEIGHT

(a) Mass

The mass of a body is the quantity of matter it contains.

The mass is a **scalar** quantity. Its S.I. unit is kilogram (symbol kg). It is constant for a given body at rest and does not change by changing the place of the body. It is an intrinsic property of the body. It is measured by a physical balance (or beam balance) because the value of g (acceleration due to gravity) is same on both the pans. The mass of a body increases with its velocity*, but this change is perceptible only when the velocity of the body v becomes more than 10^6 m s^{-1} *i.e.*, reaches close to the speed of light c ($= 3 \times 10^8$ m s^{-1}), so for a body moving with velocity less than 10^6 m s^{-1}, its mass is taken to be constant.

(b) Weight

The weight of a body is the force with which the earth attracts it. In other words, weight of a body is the force of gravity on it.

The weight is a **vector** quantity. Its direction is downwards towards the centre of earth.

Unit of weight : The S.I. unit of weight is newton (N) and the C.G.S. unit is dyne where

$$1 \text{ N} = 10^5 \text{ dyne.}$$

Relationship between weight and mass : The weight of a body is related to its mass as follows :

Weight = mass × acceleration due to gravity

or $W = m \times g$ *i.e.*, $\boxed{W = mg}$ ... (3.20)

* $m = m_0/\sqrt{1 - (v/c)^2}$ where m_0 is the mass of the body at rest.

Note : From eqn. (3.20), the S.I. unit of acceleration due to gravity g can also be written as newton per kilogram (or N kg^{-1}) in place of metre/second^2 (or m s^{-2}).

Since the value of g varies from place to place, the weight of a given body also varies from place to place.

The gravitational unit of weight in M.K.S. system is kilogram force (kgf) and in C.G.S. system is gram force (gf), where

$$1 \text{ kgf} = 9{\cdot}8 \text{ N}$$

and $$1 \text{ gf} = 980 \text{ dyne}$$

Obviously a body of mass m kg will weigh m kgf.

The weight of a body can be measured by a spring balance directly in newton and also by a physical balance in kgf.

Comparison of mass and weight

Mass	Weight
1. It is a measure of the quantity of matter contained in the body, at rest.	1. It is the force with which the earth attracts the body.
2. It is a scalar quantity.	2. It is a vector quantity
3. Its S.I. unit is kg.	3. Its S.I. unit is newton (N).
4. It is measured by a physical (or beam) balance.	4. It is measured by a spring balance which is calibrated to read in newton.
5. It is constant for a body and does not change with the change in place.	5. It is not constant for a body, but varies from place to place due to change in the value of g.

In M.K.S. system, the gravitational unit of force is *kilogram force* (kgf).

One kilogram force is the force due to gravity on a mass of 1 kg.

i.e., 1 kgf = force due to gravity on a mass of 1 kg
= mass 1 kg × acceleration due to gravity g m s^{-2}
= g newton

Since average value of g is 9·8 m s^{-2},

∴ 1 kgf = 9·8 newton (or 9·8 N)

In C.G.S. system, the gravitational unit of force is *gram force* (gf).

One gram force is the force due to gravity on a mass of 1 g.

i.e., 1 gf = force due to gravity on a mass of 1 g
= mass 1g × acceleration due to gravity g cm s^{-2}
= g dyne

Since average value of g is 980 cm s^{-2},

∴ $\boxed{1 \text{ gf} = 980 \text{ dyne}}$

Further, 1 kgf = 1000 gf

To an approximation 1 kgf is assumed to be nearly equal to 10 N. Then 1 N = 0·1 kgf or 100 gf. Thus one can feel a force of 1 N by holding a mass of 100 g on his palm as shown in Fig. 3.19.

Obviously, if we say that 1 kgf = 9·8 N, we mean that we have to exert a force of 9·8 N to hold a mass of 1 kg on our palm.

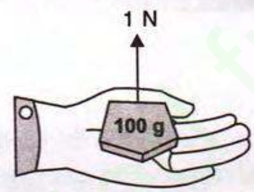


Fig. 3.19 Force of 1 N exerted by palm on a mass of 100 gramme to hold it

EXAMPLES

1. Calculate the gravitational force of attraction between the two bodies of masses 40 kg and 80 kg separated by a distance 15 m. Take $G = 6{\cdot}7 \times 10^{-11}$ N m^2 kg^{-2}.

Given, $m_1 = 40$ kg, $m_2 = 80$ kg, $G = 6{\cdot}7 \times 10^{-11}$ N m^2 kg^{-2}, $r = 15$ m

Gravitational force of attraction

$$F = \frac{G\, m_1 m_2}{r^2}$$
$$= \frac{(6{\cdot}7\times10^{-11})\times40\times80}{(15)^2} = \mathbf{9{\cdot}5 \times 10^{-10}\ N}$$

2. Taking the mass of earth equal to 6×10^{24} kg and its radius equal to $6{\cdot}4 \times 10^6$ m, calculate the value of acceleration due to gravity at a height of 2000 km above the earth surface. Take $G = 6{\cdot}7 \times 10^{-11}$ N m^2 kg^{-2}.

When the body is at a height h = 2000 km = 2000 × 10^3 m = 2 × 10^6 m above the earth surface, the distance of body from centre of earth will be $r = R + h$ = (6·4 × 10^6) + (2 × 10^6) = 8·4 × 10^6 m. Then

$$g = \frac{GM}{r^2} = \frac{GM}{(R+h)^2}$$

or $g = \frac{\quad}{(8.4 \times 10^6)^2}$ $= \mathbf{5.7\ m\ s^{-2}}$.

3. A body of mass 10 kg is taken from the earth to the moon. If the value of g on earth is $9.8\ m\ s^{-2}$ and on moon is $1.6\ m\ s^{-2}$, find : (i) the weight of the body on earth, (ii) the mass and weight of the body on moon.

Given, mass on earth $m = 10$ kg,

$g_{earth} = 9.8\ m\ s^{-2}$; $g_{moon} = 1.6\ m\ s^{-2}$.

(i) Weight of the body on earth = mass × g_{earth}

$= 10 \times 9.8 = \mathbf{98\ N}$

(ii) Mass of the body on moon

= Mass of the body on earth = **10 kg**

Weight of the body on moon = $m \times g_{moon}$

$= 10 \times 1.6 = \mathbf{16\ N}$

4. A stone is dropped from rest and falls freely under gravity. Calculate the distance covered by it in the first two seconds. ($g = 9.8\ m\ s^{-2}$)

Given, $u = 0, a = g = 9.8\ m\ s^{-2}$ and $t = 2$ s.

From equation of motion $h = ut + \frac{1}{2}gt^2$

∴ Distance covered $h = 0 \times 2 + \frac{1}{2} \times 9.8 \times (2)^2$

$= 0 + 19.6 = \mathbf{19.6\ m}$.

5. A stone is dropped freely in a river from a bridge. It takes 5 s to touch the water surface in the river. Calculate : (i) the height of the bridge from the water level, (ii) the distance covered by the stone in 2 s ($g = 9.8\ m\ s^{-2}$).

Given, $u = 0$, $a = g = 9.8\ m\ s^{-2}$, $t = 5$ s

(i) From equation of motion $h = ut + \frac{1}{2}gt^2$

$h = 0 \times 5 + \frac{1}{2} \times 9.8 \times (5)^2$

$= 9.8 \times \frac{25}{2} = 122.5$ m

∴ Height of the bridge = **122·5 m**

(ii) Distance covered by the stone in $t = 2$ s

$S = ut + \frac{1}{2}gt^2 = 0 + \frac{1}{2} \times 9.8 \times (2)^2 = \mathbf{19.6\ m}$.

6. A body is dropped freely under gravity from the top of a tower of height 78·4 m. Calculate :

(i) the time to reach the ground, and

(ii) the velocity with which it strikes the ground. Take $g = 9.8\ m\ s^{-2}$.

Given, $u = 0$, $h = 78.4$ m, $a = g = 9.8\ m\ s^{-2}$.

(i) From equation of motion $h = ut + \frac{1}{2}gt^2$

$78.4 = 0 \times t + \frac{1}{2} \times 9.8 \times t^2$

or $t^2 = \frac{78.4}{4.9} = 16$

∴ Time to reach the ground $t = \sqrt{16} = \mathbf{4\ s}$

(ii) From equation of motion $v = u + gt$

$v = 0 + 9.8 \times 4 = 39.2\ m\ s^{-1}$.

i.e., the body strikes the ground with velocity **39·2 m s⁻¹**.

7. A ball is thrown vertically upwards. It goes to a height 19·6 m and then comes back to the ground. Find :

(i) the initial velocity of the ball,

(ii) the total time of journey, and

(iii) the final velocity of the ball when it strikes the ground. Take $g = 9.8\ m\ s^{-2}$.

Given, $h = 19.6$ m, $a = -g = -9.8\ m\ s^{-2}$, $v = 0$

(i) From equation of motion $v^2 = u^2 + 2gh$

$0 = u^2 - 2 \times 9.8 \times 19.6$

or $u^2 = 19.6 \times 19.6$

∴ Initial velocity $u = \mathbf{19.6\ m\ s^{-1}}$.

(ii) Let t s be the time taken by the ball to reach the highest point.

From equation of motion $v = u + gt$

$0 = 19.6 - 9.8\,t$ or $9.8\,t = 19.6$

∴ $t = \frac{19.6}{9.8} = 2$ s

It will take the same time $t = 2$ s to come back from the highest point to the ground.

∴ Total time of journey $t' = 2t = 2 \times 2 = \mathbf{4\ s}$.

(iii) The final velocity of ball when it strikes the ground will be same as the initial velocity with which it was thrown upwards.

∴ Final velocity on reaching the ground $= \mathbf{19.6\ m\ s^{-1}}$.

8. A ball is thrown vertically upwards from the top of a building of height 24·5 m with an initial velocity $19.6\ m\ s^{-1}$. Taking $g = 9.8\ m\ s^{-2}$, calculate : (i) the height to which it will rise before returning to the ground, (ii) the velocity with which it will strike the ground, and (iii) the total time of journey.

Given, $u = 19.6\ m\ s^{-1}$ (upwards), height of building $x = 24.5$ m.

(i) At the highest point, $v = 0$.

For upward journey, from relation $v^2 = u^2 - 2gh$

$0 = u^2 - 2gh$

or $h = \frac{\quad}{2g} = \frac{\quad}{2\times9.8} = \mathbf{19.6\ m}$

(ii) While returning from the highest point, $u = 0$, total height travelled = 19·6 + 24·5 = 44·1 m. Let v be the velocity with which it strikes the ground. Then from relation $v^2 = u^2 + 2\,gh$,

$$v^2 = 0 + 2 \times 9.8 \times 44.1.$$

$$\therefore \quad v = \sqrt{2\times9.8\times44.1} = \mathbf{29.4\ m\ s^{-1}}$$

(iii) If the ball takes time t_1 to go to the highest point from the top of building, then for upward journey, from relation $v = u - gt$,

$0 = 19.6 - 9.8\,t_1$ or $t_1 = \frac{\quad}{9.8} = 2$ s

Now for downward journey from the highest point, if the ball takes time t_2 to reach the ground, then $u = 0$, $v = 29.4$ m s^{-1}.

From relation $v = u + gt$.

$$29.4 = 0 + 9.8\,t_2$$

$$\therefore \quad t_2 = \frac{29.4}{9.8} = 3\ \text{s}$$

Hence total time of journey $t = t_1 + t_2$

$= 2 + 3 = \mathbf{5\ s.}$

EXERCISE 3(E)

1. State Newton's law of gravitation.
2. State whether the gravitational force between *two* masses is attractive or repulsive ?
   Ans. Always attractive
3. Write an expression for the gravitational force of attraction between *two* bodies of masses m_1 and m_2 separated by a distance r.
4. How does the gravitational force of attraction between two masses depend on the distance between them ?
5. How is the gravitational force between two masses affected if the separation between them is doubled ? **Ans.** Force reduces to one-fourth
6. Define gravitational constant G.
7. Write the numerical value of gravitational constant G with its S.I. unit.
8. What is the importance of the law of gravitation ?
9. What do you understand by the term force due to gravity ?
10. Write an expression for the force due to gravity on a body of mass m and explain the meaning of the symbols used in it.
11. Define the term acceleration due to gravity ? Write its S.I. unit.
12. Write down the average value of g on the earth's surface.
13. How is the acceleration due to gravity on the surface of earth related to its mass and radius ?
14. How are g and G related ?
15. A body falls freely under gravity from rest and reaches the ground in time t. Write an expression for the height fallen by the body. **Ans.** $h = \frac{1}{2}gt^2$
16. A body is thrown vertically upwards with an initial velocity u. Write expression for the maximum height attained by the body.
    Ans. $h = u^2/2g$
17. Define the terms mass and weight.
18. Distinguish between mass and weight.
19. State the S.I. units of (a) mass and (b) weight.
20. The value of g at the centre of earth is zero. What will be the weight of a body of mass m kg at the centre of earth ? **Ans.** Zero
21. Which of the following quantity does not change by change of place of a body : mass or weight ? **Ans.** Mass
22. Explain the meaning of the following statement '1 kgf = 9·8 N'.

Multiple choice type :

1. The gravitational force between the two bodies is :
   (a) always repulsive
   (b) always attractive
   (c) attractive only at large distances
   (d) repulsive only at large distances.
   Ans. (b) always attractive
2. The value of G is :
   (a) 9.8 N m^2 kg^{-2}
   (b) 6.7×10^{-11} N m^2 kg^{-2}
   (c) 6.7×10^{-11} m s^{-2}
   (d) 6.7 N kg^{-1}
   Ans. (b) 6.7×10^{-11} N m^2 kg^{-2}
3. The force of attraction between the two masses each of 1 kg kept at a separation of 1 m is :
   (a) 9·8 N (b) 6·7 N
   (c) 980 N (d) 6.7×10^{-11} N
   Ans. (d) 6.7×10^{-11} N
4. A body is projected vertically upward with an initial velocity u. If acceleration due to gravity is g, the time for which it remains in air, is :
   (a) $\frac{u}{g}$ (b) ug
   (c) $\frac{2u}{g}$ (d) $\frac{u}{2g}$ **Ans.** (c) $\frac{2u}{g}$

8. An object falling freely from rest reaches ground in 2 s. If acceleration due to gravity is $9{\cdot}8\ m\ s^{-2}$, the velocity of the object on reaching the ground will be :

(a) $9{\cdot}8\ m\ s^{-1}$ (b) $4{\cdot}9\ m\ s^{-1}$

(c) $19{\cdot}6\ m\ s^{-1}$ (d) zero.

Ans. (c) $19{\cdot}6\ m\ s^{-1}$

Numericals :

1. The force of attraction between the two bodies at a certain separation is 10 N. What will be the force of attraction between them if the separation is reduced to half ? **Ans.** 40 N
2. Write the approximate weight of a body of mass 5 kg. What assumption have you made ?
Ans. 50 N (Assumption : $g = 10\ m\ s^{-2}$).
3. Calculate the weight of a body of mass 10 kg in (a) kgf and (b) newton. Take $g = 9{\cdot}8\ m\ s^{-2}$.
Ans. (a) 10 kgf (b) 98 newton.
4. State the magnitude and direction of the force of gravity acting on a body of mass 5 kg. Take $g = 9{\cdot}8\ m\ s^{-2}$.
Ans. Force of gravity on the body = 49 newton vertically downwards.
5. The weight of a body is 2·0 N. What is the mass of the body ? ($g = 10\ m\ s^{-2}$) **Ans.** 0·2 kg
6. The weight of a body on earth is 98 N where the acceleration due to gravity is $9{\cdot}8\ m\ s^{-2}$. What will be its (a) mass and (b) weight on moon where the acceleration due to gravity is $1{\cdot}6\ m\ s^{-2}$? **Ans.** (a) 10 kg (b) 16 N
7. A man weighs 600 N on earth. What would be his approximate weight on moon ? Give reason for your answer ? **Ans.** 100 N
Reason : The value of g on moon = $\frac{1}{6}$ th the value of g on earth.
8. What is the (a) force of gravity and (b) weight of a block of mass 10·5 kg ? Take $g = 10\ m\ s^{-2}$. **Ans.** (a) 105 N, (b) 105 N
9. A ball is released from a height and it reaches the ground in 3 s. If $g = 9{\cdot}8\ m\ s^{-2}$, find :
(a) the height from which the ball was released,
(b) the velocity with which the ball will strike the ground.
Ans. (a) 44·1 m (b) $29{\cdot}4\ m\ s^{-1}$
10. What force, in newton, your muscles need to apply to hold a mass of 5 kg in your hand ? State the assumption.
Ans. 49 N. **Assumption :** $g = 9{\cdot}8\ N\ kg^{-1}$.
11. A ball is thrown vertically upwards. It goes to a height 20 m and then returns to the ground. Taking acceleration due to gravity g to be $10\ m\ s^{-2}$, find :
(a) the inital velocity of the ball
(b) the final velocity of the ball on reaching the ground and
(c) the total time of journey of the ball.
Ans. (a) $20\ m\ s^{-1}$ (b) $20\ m\ s^{-1}$ (c) 4 s
12. A body is dropped from the top of a tower. It acquires a velocity $20\ m\ s^{-1}$ on reaching the ground. Calculate the height of the tower. (Take $g = 10\ m\ s^{-2}$) **Ans.** 20 m.
13. A ball is thrown vertically upwards. It returns 6 s later. Calculate : (i) the greatest height reached by the ball, and (ii) the initial velocity of the ball. (Take $g = 10\ m\ s^{-2}$)
Ans. (i) 45 m, (ii) $30\ m\ s^{-1}$
14. A pebble is thrown vertically upwards with a speed of $20\ m\ s^{-1}$. How high will it be after 2 s ? (Take $g = 10\ m\ s^{-2}$) **Ans.** 20 m
15. (a) How long will a stone take to fall to the ground from the top of a building 80 m high and (b) what will be the velocity of the stone on reaching the ground ? (Take $g = 10\ m\ s^{-2}$)
Ans. (a) 4 s, (b) $40\ m\ s^{-1}$
16. A body falls from the top of a building and reaches the ground 2·5 s later. How high is the building ? (Take $g = 9{\cdot}8\ m\ s^{-2}$) **Ans.** 30·6 m
17. A ball is thrown vertically upwards with an initial velocity of $49\ m\ s^{-1}$. Calculate : (i) the maximum height attained, (ii) the time taken by it before it reaches the ground again. (Take $g = 9{\cdot}8\ m\ s^{-2}$). **Ans.** (i) 122·5 m, (ii)10 s
18. A stone is dropped freely from the top of a tower and it reaches the ground in 4 s. Taking $g = 10\ m\ s^{-2}$, calculate the height of the tower.
Ans. 80 m
19. A pebble is dropped freely in a well from its top. It takes 20 s for the pebble to reach the water surface in the well. Taking $g = 10\ m\ s^{-2}$ and speed of sound = $330\ m\ s^{-1}$, find : (i) the depth of water surface, and (ii) the time when echo is heard after the pebble is dropped.
Ans. (i) 2000 m (ii) 26·1 s
20. A ball is thrown vertically upwards from the top of a tower with an initial velocity of $19{\cdot}6\ m\ s^{-1}$. The ball reaches the ground after 5 s. Calculate : (i) the height of the tower, (ii) the velocity of ball on reaching the ground. Take $g = 9{\cdot}8\ m\ s^{-2}$.
Ans. (i) 24·5 m (ii) $29{\cdot}4\ m\ s^{-1}$.