FORCE & LAWS OF MOTION

CONTENTS

FORCE

The external agent which tends to set a body in motion or which changes the speed and direction of motion of a body or which can change the shape of a body is called force. SI unit of force is newton.

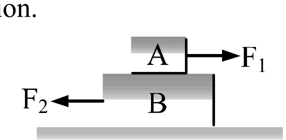
Types of forces :

(a) non contact :

These are the forces in which contact between two objects is not necessary. Gravitational force between two bodies and electrostatic force between two charges are two examples of field forces.

(b) Contact forces :

Two bodies in contact exert equal and opposite forces on each other. If the contact is frictionless the contact force is perpendicular to the common surface and known as normal reaction.



If, however, the objects are in rough contact and move (or have a tendency to move) relative to each other without losing contact then frictional force arise which oppose such motion. Again each object exerts a frictional force on the other and the two forces are equal and opposite. This force is perpendicular to normal reaction. Thus, the contact force (F) between two objects is made up of two forces.

(i) Normal reaction (N) (ii) Force of friction (f) and since these two forces are mutually perpendicular.

$$F = \sqrt{N^2 + f^2}$$

NEWTON'S LAWS OF MOTION

(A) Newton´s Ist law :

A body can not change its state of motion by itself. If the object is at rest it will remain at rest and if it is in uniform motion, it continues to be in motion unless some external force is applied on it.

Inertia :

- There is an inherent property of an object by virtue of which it cannot change its state of motion or rest by itself. This property is called 'inertia'.
- Inertia is of two types– inertia of rest and inertia of motion.

(a) Inertia of rest:

If the body is at rest, it will continue to be at rest unless some external force is applied on it. Examples are following.

Ex. When a train at rest starts moving suddenly, a passenger standing inside the compartment tends to fall backward.

Ex. When a carpet is beaten up with a stick, the dust particles are detached.

Ex. When a bullet is fired into a glass pane, it pierces a hole only at the pt where the bullet hits the glass without breaking the entire glass pane into pieces.

(b) Inertia of motion :

When a body is in uniform motion, it will continue to remain in its uniform motion, i.e. it resists any change in its state of motion due to inertia of motion.

Ex. when a person jumps out of a moving bus, he should run in the direction in which bus is moving otherwise he will fall down.

Ex. A train moving with a uniform speed and if a ball is thrown upwards inside the train by a passenger, then the ball comes back to his hand.

◆ **Relation between mass and inertia :**

Larger the mass of the body, larger is the inertia.

Ex. eg : it is more difficult to stop a cricket ball than a tennis ball.

(B) Newton's second law of motion

Momentum : The product of mass and velocity is called 'momentum'. i.e. $p = m\vec{v}$

(a) Unit : SI unit of momentum is kg-m/s.

(b) It is a vector quantity.

Newton's second law states "the rate of change of momentum of a body is directly proportional to force and takes place in the direction of force."

(a) i.e. $F = \frac{P_2 - P_1}{t}$ or $F = m\left(\frac{v-u}{t}\right) = m\vec{a}$

where p_1 = initial momentum = mu

p_2 = final momentum = mv

(b) Unit of force in SI system is newton.

(c) 1N is equivalent to that force which can produce an acceleration of $1 m/s^2$ in a body of mass 1 kg.

(d) Unit of force in CGS system is dyne.

1 dyne = 1 gm - cm/s^2

1 N = 10^5 dynes

Ex.1 Calculate the force required to produce an acceleration of 5 m/s^2 in a body of mass 2.4 kg.

Sol. We know that force = mass × acceleration

= 2.4 kg × 5 m/s^2

= 12.0N

Ex.2 A body of mass 2.5 kg is moving with a velocity of 20 m/s. Calculate its momentum.

Sol. Momentum, p = mass × velocity

Here, mass m = 2.5 kg

Velocity, v = 20 m/s

∴ Momentum, p = mv = 2.5 × 20 kg-m/s

= 50 kg-m/s

◈Impulse :

◆ If a force F is applied on a body of mass m for a time interval Δt and if the change in velocity is Δv then

∴ Impulse = F dt = m Δ v

Impulse = change in momentum

◆ Unit of impulse is newton × second,

Examples of impulse

Ex. While catching a cricket ball a player moves his hands backwards. Cricket ball coming towards fielder has a large momentum. By doing so he increases the time interval to reduce the momentum of the ball. Rate of change of momentum becomes slow.

Ex.3 A force acts for 0.2 s on a body of mass 2.5 kg initially at rest. The force then ceases to act and the body moves through 4m in the next one second. Calculate the magnitude of force.

Sol. When the force ceases to act, the body will move with a constant velocity. Since it moves a distance of 4 m in 1 s, therefore, its uniform velocity = 4m/s.

Now, initial velocity, u = 0

Final velocity, v = 4 m/s

Time interval Δt = 0.2 s

∴ Acceleration, $a = \frac{v-u}{\Delta t} = \frac{4-0}{0.2} = 20 m/s^2$

Force, F = 2.5 × 20 = 50 N

Ex.4 A ball of mass 20 gm is initially moving with a velocity of 100 m/s. On applying a constant force on the ball for 0.5s, it acquires a velocity of 150 m/s. Calculate the following :

(i) Initial momentum of the ball

(ii) Final momentum of the ball

(iii) Rate of change of momentum

(iv) Acceleration of the ball

(v) Magnitude of the force applied

Sol. Given, $m = 20\text{ gm} = \frac{20}{1000}\text{ kg} = 0.02\text{ kg}$

Initial velocity, $u = 100$ m/s

Time interval, $t = 0.5$ s

Final velocity, $v = 150$ m/s

(i) Initial momentum of the ball

= mass × initial velocity

or $P_1 = mu = 0.02\text{ kg} \times 100\text{ m/s}$

$= 2\text{ kg-ms}^{-1}$

(ii) Final momentum of the ball

= mass × final velocity

or $P_2 = mv = 0.02\text{ kg} \times 150\text{ m/s}$

$= 3\text{ kg-ms}^{-1}$

(iii) Rate of change of momentum

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

or $\frac{\Delta P}{\Delta t} = \frac{3-2}{0.5} = \frac{1}{0.5} = 2.0\text{ kg-ms}^{-1} = 2.0\text{N}$

(iv) Acceleration, $a = \frac{v-u}{t} = \frac{150-100}{0.5}$

$= 100\text{ms}^{-2}$

(v) Force, F = mass × acceleration

$= 0.02 \times 100 = 2.0$ N

Ex.5 A cricket ball of mass 200 gm moving with a speed of 40 m/s is brought to rest by a player in 0.04s. Calculate the following :

(i) change in momentum of the ball,

(ii) average force applied by the player.

Sol. Mass, $m = 200\text{ gm} = \frac{200}{1000}\text{ kg} = 0.2\text{ kg}$

Initial velocity, u = 40 m/s

Final velocity, v = 0

Time, t = 0.04 s

(i) Initial momentum, $p_1 = mu = 0.2\text{ kg} \times 40\text{ m/s}$

$= 8.0\text{ kg-ms}^{-1}$

Final momentum, $p_2 = m \times v = 0.2 \times 0$

$= 0\text{ kg-ms}^{-1}$

Change in momentum, $\Delta p = p_2 - p_1$

$= 0 - 8.0\text{ kg ms}^{-1} = -8.0\text{ kg-ms}^{-1}$

(ii) Average force $= \frac{\text{Change in momentum}}{\text{Time}}$

$= \frac{-8.0-0}{0.04} = -200$ N

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

Ex. 6 A motorcycle is moving with a velocity of 108 km/hr and it takes 5 s to stop it after the brakes are applied. Calculate the force exerted by the brakes on the motorcycle if its mass along with the rider is 250 kg.

Sol. Given that initial velocity of the motorcycle = 108 km/hr = 30 m/s

Final velocity = 0 m/s

Time taken to stop = 5s, the mass of the motorcycle with rider = 250 kg.

The change in the velocity of the motorcycle in 5s = 0 – 30 = –30 m/s

Therefore, the acceleration of the motorcycle,

$a = \frac{-30}{5} = -6\text{ m/s}^2$

The magnitude of the force applied by the brakes is given by the equation,

F = mass × acceleration

$= 250\text{ kg} \times (6)\text{m/s}^2 = 1500$ N

(C) Newton's third law of motion

Newton's first law of motion gives a qualitative idea of force, while the second law provides us an idea to measure the force.

- **Newton's third law of motion states that** " if a body A exerts a force on the body B, the body B will also exert an equal and opposite force on A."

  The force exerted by A on B is called action while the force exerted by B on A is called the reaction.
- Newton's third law is also stated as "to every action there is an equal and opposite reaction."
- Forces always occur in pairs.
- Action and reaction always act on different bodies.

Ex. by hitting a table with palm we apply a force. The table also exerts a force on palm on hitting it.

Applications of Newtons III law :

- Recoil of a gun – when the bullet is fired from a gun, an equal and opposite force is applied on the gun, due to which the gun recoils in backward direction.
- Application in walking : while moving in forward direction we push the ground backwards that is the action. An equal and opposite force is applied by the ground on the man, thus the reaction due to which man moves forward.

◆ Rowing a boat in river : when we push the water backward with the help of oars (applying a force backward), an equal and opposite force acts on the boat. This is the reaction which moves the boat forward.

◆ Launching Rocket : In rocket, gases are produced in large amount. Due to internal combustion they come out and move backwards with an equal and opposite force which in turn acts on the rocket and moves it forward.

➢ LAW OF CONSERVATION OF MOMENTUM

◆ According to law of conservation of momentum "if there is no force acting on a system, the momentum of the system remains unchanged."

◆ Generalizing the situation " if a group of bodies are exerting force on each other, their total momentum remains conserved before and after the interaction provided there is no external force acting on them."

i.e. $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$

Ex.7 A rifle of mass 5 kg fires a bullet of mass 40 gm. The bullet leaves the barrel of the rifle with a velocity 200 m/s. If the bullet takes 0.004 s to move through the barrel, calculate the following:

(i) recoil velocity of the rifle and

(ii) the force experienced by the rifle due to its recoil.

Sol. (i) Given mass of the rifle, $m_1 = 5$ kg

Mass of the bullet, $m_2 = 40$ gm = 0.04 kg

Initial velocities, $u_1 = 0$, $u_2 = 0$

After firing velocity of the bullet, $v_2 = 200$ m/s

Velocity of the rifle, $v_1 = ?$

Applying the law of conservation of momentum, we get

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

or $0 + 0 = 5 \times v_1 + 0.04 \times 200$

or $v_1 = -\dfrac{0.04 \times 200}{5} = -1.6$ m/s

(ii) Initial momentum of the rifle = 0

Final momentum of the rifle = 5 kg ×(–1.6)

= –B kg-m/s

Time interval = 0.004 s

$\therefore$ Force = $\dfrac{\text{Change in momentum}}{\text{Time interval}}$

$= \dfrac{-8\text{kg}-\text{ms}^{-1}}{0.004} = -2000$ N

Ex.8 A bullet of mass 20 gm moving with a velocity 200 m/s gets embedded into a wooden block of mass 980 gm suspended by a string. Calculate velocity acquired by the combined system.

Sol. Mass of the bullet, $m_1 = 20$ gm

$= \dfrac{20}{1000}$ kg = 0.02 kg

Velocity of the bullet, $u_1 = 200$ m/s

Momentum of the bullet = m_1u_1

= 0.02 × 200 kg-m/s = 4 kg-m/s

Now, the bullet gets embedded into a wooden block of mass 980 gm. The mass of the block and bullet = 980 + 20

= 1000 gm = 1kg

Let the velocity of the combined system = v

$\therefore$ Momentum of the combined system

= 1 × v kg-m/s = v kg-m/s

Now, applying the law of conservation of momentum,

$$m_1u_1 = (m_1 + m_2)v$$

or 4 = v $\therefore$ v = 4 m/s = 4 kg m/s

Ex.9 A rifle man, who together with his rifle has a mass of 100 kg, stands on a smooth surface fires 10 shots horizontally. Each bullet has a mass 10 gm a muzzle velocity of 800 m/s. What velocity does rifle man acquire at the end of 10 shots?

Sol Let m_1 and m_2 be the masses of bullet and the rifleman and v_1 and v_2 their respective velocities after the first shot. Initially the rifleman and bullet are at rest, therefore initial momentum of system = 0.

As external force is zero, momentum of system is constant

i.e. initial momentum = final momentum

$= m_1v_1 + m_2v_2$

or $v_2 = \frac{m_1v_1}{m_2} = -\frac{(10\times10^{-3}\text{kg})(800\text{ m/s})}{100\text{kg}}$

$= -0.08$ m/s

Velocity acquired after 10 shots

$= 10\ v_2 = 10 \times (-0.08)$

$= -0.8$ m/s.

i.e, the velocity of rifle man is 0.8 m/s in a direction opposite to that of bullet.

Ex.10 A body of mass 1 kg strikes elastically with another body at rest and continues to move in the same direction with one fourth of the initial velocity. What will be the mass of the other body ?

Sol . Given that,

Initial velocity = u

Final velocity = $\frac{u}{4}$

So by conservation of momentum, we have

$1 \times u + 0 = 1 \times \frac{u}{4} + m \times v_2$

$\Rightarrow mv_2 = \frac{3u}{4}$ ...(1)

and by conservation of energy, we have

$\frac{1}{2} \times 1 \times u^2 + 0 = \frac{1}{2} \times 1 \left(\frac{u}{4}\right)^2 + \frac{1}{2} mv_2^2$

or $mv_2^2 = \frac{15}{16}u^2$ ...(2)

from equation (1) and (2),

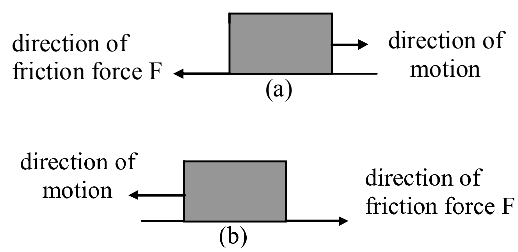
$= \frac{(mv_2)^2}{mv_2^2} = \frac{(9/16)u^2}{(15/16)u^2}$

or $m = 0.6$ kg

FRICTION

If the switch off the engine of car it will stop after moving a certain distance. It means that some retarding force is acting on the car which stops it. The force opposing the motion of the car is called "force of friction".

- The frictional force is tangential to the surface in contact and always in a direction opposite to the direction of motion of the object.



- Frictional force is a force opposing the relative motion between two surfaces which are in contact with each other.

Reducing friction

Frictional force can be reduced in the following ways:

- **Use of lubricants :** In machines, friction can be reduced by applying lubricants between the contact surfaces to fill the fine pores or depressions in the surfaces and make them smooth thereby reducing friction.
- **Polishing :** unevenness of the surfaces can be reduced by polishing, thereby reducing the friction.
- **Use of ball bearings :** In rotating machines, shafts are mounted on ball bearings. By doing so, rolling friction occurs lesser than sliding friction, thereby reducing the friction.
- **By streamlining :** Air friction is reduced by designing streamlined bodies of cars or aeroplanes. Similarly, if the bodies of boats and ships are streamlined, friction of water can be reduced.

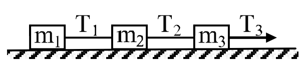
◈ Disadvantages of friction :

- Wear and Tear : In machine parts like gears, brakes when they come in contact with each other continuously, they wear out gradually, which should be replaced time to time.
- Friction reduces efficiency of the machine.
- Friction in machine produces heat and undesirable noise which damages the machine. To avoid excessive heating, water is circulated in machines generally.

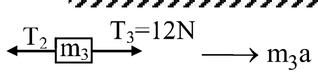
◈ Applications of frictional forces

- We would not be able to walk if there had been no friction between the soles of our shoes and the ground.
- If there had been no friction, the wheels of a car will slip instead of rotating and stop moving. For that we have to increase the friction by making the tyres corrugated to get better grip of tyres on the road. Also, the friction is increased.
- When brakes are applied, the vehicle stops due to the force of friction between the brake lining and the drum.
- In the absence of friction, we cannot write on a blackboard with a chalk stick because the chalk stick will slide off the board without leaving any mark on the board.

Ex.11 Three blocks are tied together with strings as shown. They are lying on a horizontal frictionless table. These are pulled to the right with T_3 = 12N force. If m_1 = 1 kg, m_2 = 2kg, and m_3 = 3 kg, calculate the tension T_1.

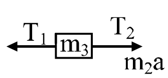


Sol.



$m_3a = T_3 - T_2$

$\Rightarrow$ $3a = 12 - T_2$ ...(1)



$m_2a = T_2 - T_1$

$\Rightarrow$ $2a = T_2 - T_1$ ...(2)

from (1) & (2)

$5a = 12 - T_1$ ...(3)

$m_1a = T_1 \Rightarrow a = T_1$ ...(4)

from (3) & (4)

$5T_1 = 12 - T_1 \Rightarrow T_1 = 2N$

➤ THRUST AND PRESSURE

(A) Thrust :

- The force acting normally on surface is called 'thrust'.
- This is a vector quantity.
- It is measured in newton (N).

(B) Pressures :

- The thrust on an unit area of a surface is called 'pressure'.
- Pressure = $\frac{\text{Thrust}}{\text{Area}}$ or $P = \frac{F}{A}$
- Unit : The SI unit of pressure is newton per meter square or N/m^2, other units of pressure are pascal and bar.
- One Pascal : One pascal is defined as the pressure exerted on a surface area of $1m^2$ by a thrust of 1 newton.

  i.e. 1 Pascal = 1 N/m^2

◈ Some examples based on pressure

Ex. Inserting a pointed nail in a wooden block is an easier task than to insert a rod inside a wooden block with the same force because the nail has a smaller area and thus it will experience more pressure even with the same force.

Ex. A sharp knife cuts better than a blunt knife.

Ex. While walking, a man exerts more pressure on the ground in comparison to when he is standing.

◈ Pressure in fluids

- A substance that can flow is called a 'fluid'.

  liquid and gases are considered as fluids

◈ Laws of pressure

- Pressure exerted by the liquid is the same in all directions about a point.
- Pressure exerted is the same at all points in a horizontal plane as well as in a stationary liquid.
- Pressure at a particular depth is P = hdg

  where, h = height of the column of liquid.

  d = density of the liquid

  g = acceleration due to gravity

Different types of Pressure :

(A) Hydrostatic Pressure :

The normal force (or thrust) exerted by a liquid at rest per unit area of the surface in contact with it is called "pressure of liquid or hydrostatic pressure."

(B) Atmospheric Pressure :

- The pressure exerted by atmosphere is called atmospheric pressure.
- At sea level, atmospheric pressure is the pressure exerted by 0.76 m of mercury column i.e. h = 0.76 m equal to 10 pascal
- 1 atm = 10^5 Pascal

Ex.12 What will be the pressure in N/m^2 at a depth of 1.5 m in brine of density 120 kg/cm^3 ?

Sol. P = hdg

$=15 \times 120 \times 10$

= 1800 N/m^2

Ex.13 Calculate the density of a liquid if the pressure at a point 30 m below its surface is 32×10^4 N/m^2.

Sol. P = hdg

$$\Rightarrow \quad d = \frac{P}{hg} = \frac{32 \times 10^4}{30 \times 10} = 1066.6 \text{ kg/m}^3$$

Ex.14 A force of 150 N is applied on an area of 1.5 m^2. Calculate the pressure exerted.

Sol. Force, F = 150 N; area, A = 1.5 m^2

Now, $\quad \text{Pressure} = \frac{\text{Force}}{\text{Area}}$

or $\quad P = \frac{F}{A} = \frac{150\text{N}}{1.5\text{m}^2} = 100 \text{ N/m}^2$

Ex.15 A force of 500 dynes is applied on an area of 20 cm^2. Calculate the pressure exerted.

Sol. Force, F = 500 dynes = 500×10^{-5} newton

Area, A = 20 cm^2 = 20×10^{-4} m^2

$$\text{Pressure, } P = \frac{F}{A} = \frac{500 \times 10^{-5}\text{N}}{20 \times 10^{-4}\text{m}^2} = 2.5 \text{ N/m}^2$$

➤ BUOYANCY

When a body is immersed in a liquid, the liquid exerts an upward force on the body called as the 'upthrust' or 'buoyant force.'

Factors affecting upthrust :

- Larger the volume of the body submerged in the liquid, greater is the upthrust.
- Larger the density of the liquid, greater is the upthrust.

Archimedes principle :

'Archimedes' principle states that when a body is immersed in liquid partially or completely, it experiences an upthrust equal to the weight of the liquid displaced."

or

The loss in weight of the block, i.e. buoyant force acting on the block is equal to the weight of the liquid displaced.

i.e. $\quad F = Vdg$

where V = volume of the body

d = density of the liquid

g = acceleration due to gravity

Ex.16 A body weighs 300 gmf in air and 260 gmf when completely immersed in water. Calculate the following :

(i) loss in weight of the body

(ii) upthrust on the body.

Sol. Given : Weight of body in air = 300 gmf

Weight of the body in water = 260 gmf

∴ Loss in weight of the body

= 300 – 260 = 40 gmf

∴ Upthrust of the body = Loss in weight

= 40 gmf

Ex.17 A solid block of volume 2 litres has a weight of 80 N. What will be its weight when immersed completely in water ?

Sol. In order to calculate the weight of the block in water, first calculate the upthrust, i.e. the loss in weight of the body in water, then

Volume of the block = 2 litres = 2000 cc

∴ Volume of water displaced = 2000 cc

Weight of water displaced = 2000 gm

= 2.0 kgf

(Density of water = 1 gm/cc)

= 2.0 × 9.8 N = 19.6 N

∴ Upthrust of water = 19.6 N

Hence, weight of the body fully immersed in water = 80 N – 19.6 N = 60.4 N

Ex.18 A solid block of density D has a weight W in air is fully immersed in a liquid of density d. Calculate its apparent weight when fully immersed in liquid.

Sol. Weight of the block = W

Density of block = D

∴ Volume of the block = $\frac{W}{D}$. d

∴ Upthrust on the block = $\frac{W}{D}$ .d

∴ Loss in weight of the block inside liquid

$$= \frac{W}{D}.d$$

Hence, apparent weight of the block when fully immersed in water

$$= W - \frac{W}{D}d = W\left(1 - \frac{d}{D}\right)$$

➤ DENSITY

- Density = $\frac{\text{Mass}}{\text{Volume}}$ or $d = \frac{M}{V}$

  SI unit of density is kg/m^3 and CGS unit of density is g/cm^3
- 1 gm/cm^3 = 1000 kg/m^3
- Different substances have different densities which gets affected by temperature.
- Respective density of a substance decreases on heating due to the expansion of the substance.
- Water has anomalous expansion. When water is cooled at 4ºC, its volume decreases but on further cooling its volume starts increasing.

  ⇒ the density of water is maximum at 4ºC.

◈ Relative density

Relative density of a substance

$$= \frac{\text{density of substance}}{\text{density of water at } 4°C}$$

$$= \frac{\text{mass of unit volume of substance}}{\text{mass of unit volume of water at } 4°C}$$

$$= \frac{\text{mass of certain volume of substance}}{\text{mass of same volume of water at } 4°C}$$

$$= \frac{\text{weight of certain volume of substance}}{\text{weight of same volume of water at } 4°C}$$

◈ Unit of Relative Density

It has no units.

Note : density of water in CGS system is 1 gm/cm^3.

◈ Relative Density for solids

i.e. $R.D = \frac{W_1}{W_1 - W_2}$

Where W_1 = weight of solid body in air

W_2 = weight of solid body in water

◈ Relative Density for liquids

i.e $R.D. = \frac{W - W''}{W - W'}$

Where.

W' = weight of the body fully immersed in water

W'' = weight of the body fully immersed in liquid.

W = weight of the body in air

Ex.19 A body weighs 30 N in air and 26 N when fully immersed in water. Calculate its relative density.

Sol. Given : Weight of body in air, $W_1 = 30$ N

Weight of body in water, $W_2 = 26$ N

$\therefore$ Relative density $= \dfrac{W_1}{W_1 - W_2}$

$= \dfrac{30}{30-26} = 7.5$

Ex.20 Relative density of copper is 8.8. What is its density in SI system ?

Sol. R.D. $= \dfrac{\text{density of copper}}{\text{density of water}}$

$\therefore$ Density of copper = R.D. × density of water

$= 8.8 \times 10^3$ kg/m^3

Ex.21 A solid weighs 60 gmf in air and 52 gmf when completely immersed in water. Calculate the following :

(i) upthrust,

(ii) volume of the solid,

(iii) relative density of the solid

Sol. Given:

Weight of solid in air = 60 gmf

Weight of solid in water = 52 gmf

$\therefore$ Loss of weight in water = 60 – 52 = 8 gmf

(i) $\therefore$ Upthrust = loss of weight in water = 8 gmf

(ii) Since density of water is 1 gm/cm^3, and weight of equal volume of water = 8 gmf

$\therefore$ Volume of solid = 8 cm^3

(iii) Relative density of solid $= \dfrac{W_1}{W_1 - W_2}$

$= \dfrac{60}{60-52} = 7.5$