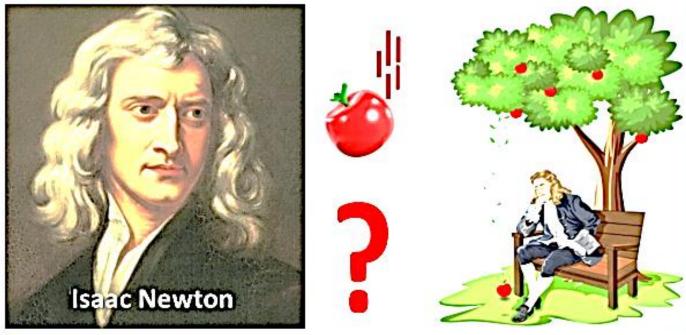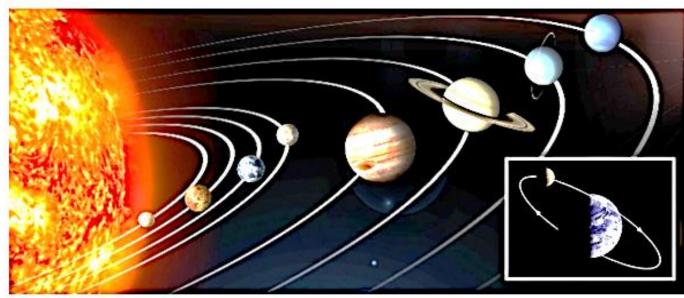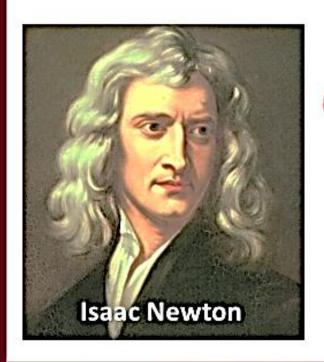- **Gravitation** is a natural phenomenon by which objects with mass are attracted to each other.

- The force of attraction between two objects with mass due to gravitation is called the **gravitational force.** E.g., falling of an object towards the earth, rotation of planets around the Sun, rotation of moon around the earth etc. are due to gravitational force.
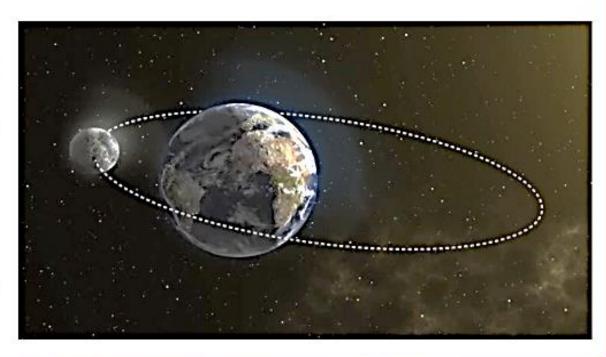
- This was first discovered by **Isaac Newton.**

Isaac Newton

GRAVITATION

- **Isaac Newton** proposed that an apple and the moon are attracted to the earth by same type of force.

- He argued that the **moon,** at each point of its orbit, **falls towards the earth,** instead of moving in a straight line. So, it must be attracted by the earth.

GRAVITATION
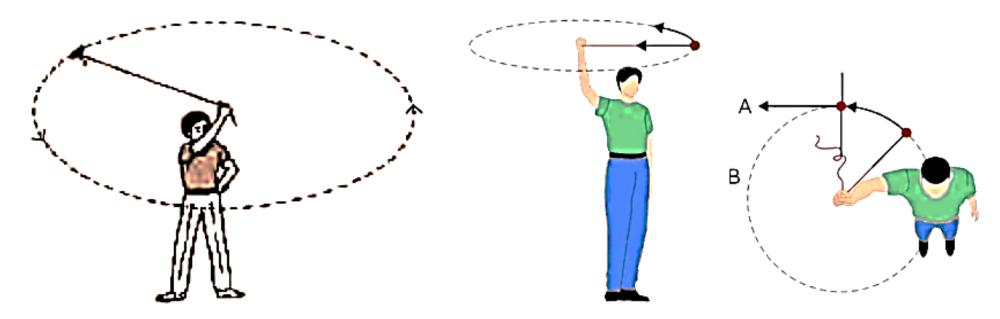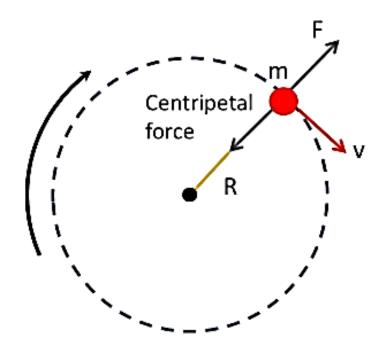
Activity

❖ Tie a stone to a piece of thread and whirl it around.

❖ The stone moves in a circular path.

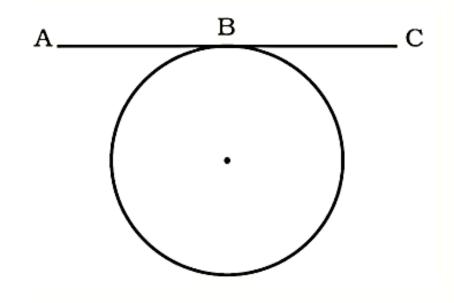❖ Release the thread. The stone moves in a straight line, tangential to the circular path.

A stone describing a circular path with a velocity of constant magnitude

GRAVITATION

- The motion of stone in a circular path involves changes in direction and velocity or acceleration. The force that causes this acceleration is acting towards the center and keeps the body moving along the circular path. It is called **centripetal** ('centre-seeking') **force.**

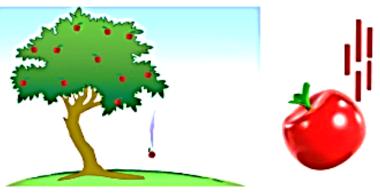- Without this force, the stone moves in a straight line, tangential to the circular path.

Tangent to a circle

It is a straight line that meets the circle at only one point. Line ABC is a tangent to the circle at point B.

GRAVITATION

- The **moon's motion** around the earth is due to **centripetal force** from the attraction of the earth. Without this force, the moon would move in a uniform straight line.

- According to the **Third law of motion,** the apple attracts the earth. But according to the **Second law of motion,** acceleration is inversely proportional to the mass ($F = ma$). The mass of an apple is negligible compared to the earth. So, the earth doesn't move towards the apple. Similarly, the earth does not move towards the moon.

- Newton concluded that all objects in the universe attract each other. This is called **gravitational force.** E.g., In the solar system, planets orbit the Sun due to gravitation.

GRAVITATION
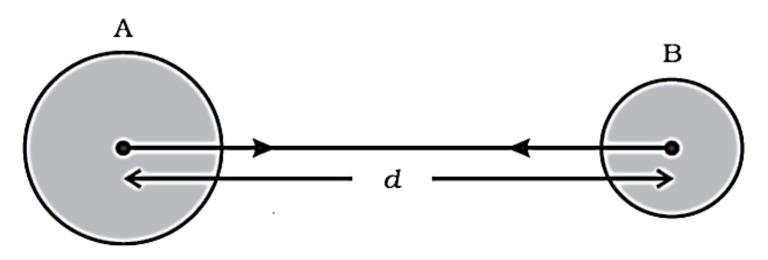
UNIVERSAL LAW OF GRAVITATION

- Every object in the universe attracts every other object with a force proportional to the product of their masses and inversely proportional to the square of the distance between them. The force is along the line joining the centres of two objects.
- Let two objects A and B of masses M and m lie at a distance d from each other.

The gravitational force between two uniform objects is directed along the line joining their centres.
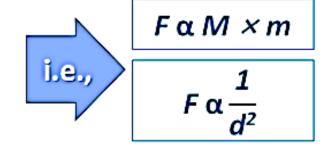
GRAVITATION

UNIVERSAL LAW OF GRAVITATION

According to the universal law of gravitation, the **force F** between two objects is **directly proportional** to the product of their **masses** and **inversely proportional** to the **square of the distance** between them.

i.e.,

$$F \propto M \times m$$

$$F \propto \frac{1}{d^2}$$

Combining both equations,
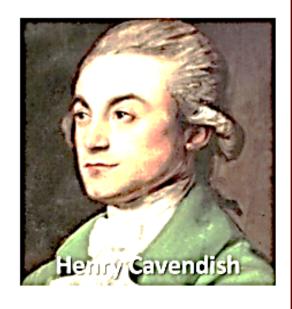
$$F \propto \frac{M \times m}{d^2} \quad \text{or} \quad F = G \frac{M \times m}{d^2}$$

Where *G* is the constant of proportionality and is called the **universal gravitation constant.**

$$G = \frac{F d^2}{M \times m}$$

SI unit of *G* is

$$N \, m^2 \, kg^{-2}$$

Henry Cavendish

Henry Cavendish (1731 – 1810) found out the value of *G* using a sensitive balance.

It is **6.673×10^{-11} N m² kg⁻².**

GRAVITATION

UNIVERSAL LAW OF GRAVITATION

Example

Mass of the earth is 6×10^{24} kg and that of the moon is 7.4×10^{22} kg. If the distance between the earth and the moon is 3.84×10^{5} km, calculate the force exerted by the earth on the moon. ($G = 6.7 \times 10^{-11}$ N m² kg⁻²).

Solution

Mass of the earth, $M = 6 \times 10^{24}$ kg

Mass of the moon, $m = 7.4 \times 10^{22}$ kg

Distance between earth and moon, $d = 3.84 \times 10^{5}$ km

$= 3.84 \times 10^{5} \times 1000$ m $\quad = 3.84 \times 10^{8}$ m

$G = 6.7 \times 10^{-11}$ N m² kg⁻²

$$F = G \frac{M \times m}{d^2}$$

$$= \frac{6.7 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2} \times 6 \times 10^{24} \text{ kg} \times 7.4 \times 10^{22} \text{ kg}}{(3.84 \times 10^{8} \text{ m})^2}$$

$$= \underline{2.02 \times 10^{20} \text{ N}}$$

GRAVITATION

UNIVERSAL LAW OF GRAVITATION

Importance of the Universal Law of Gravitation

It can explain several phenomena such as

i.　the force that binds us to the earth.

ii.　the motion of the moon around the earth.

iii.　the motion of planets around the Sun.

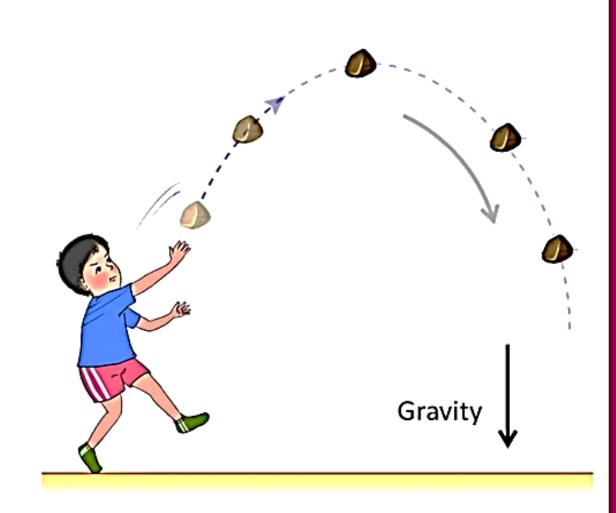iv.　the tides due to the moon and the Sun.

FREE FALL

- When a stone is thrown upwards, it reaches a certain height and then falls down.

- If an object falls towards the earth under **gravitational force alone,** it is called **free fall.**

- While falling, the **direction of motion** remains **unchanged.** But the earth's attraction causes a change in the magnitude of **velocity,** leading to **acceleration.**

- The acceleration experienced during free fall due to the earth's gravitational force is called **acceleration due to gravity (g).** Its unit is **ms⁻².**

Gravity

FREE FALL

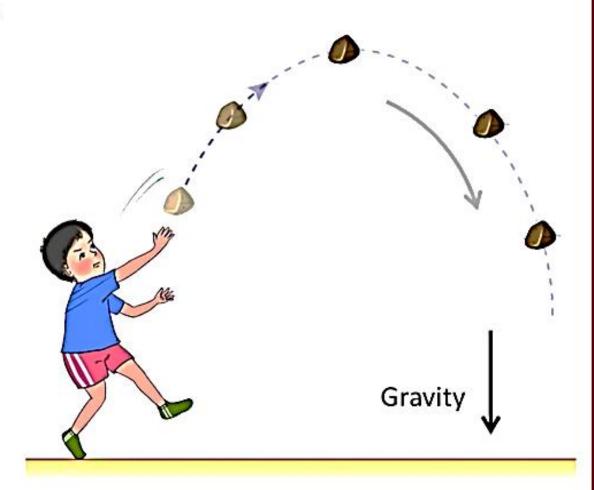- According to the Second law of motion, $F = m\,a$.

- If the mass of the stone is m and acceleration due to gravity is g, the magnitude of the gravitational force F will be the product of mass & acceleration due to gravity.

$$F = m\,g$$

$$mg = G\,\frac{M \times m}{d^2}$$ or $$g = G\,\frac{M}{d^2}$$

M = mass of the earth.

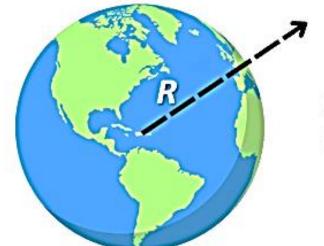d = distance between the object and the earth.

Gravity

FREE FALL

For an object on or near the Earth's surface, the **distance d** equals the **Earth's radius R.** Thus,

$$mg = G\,\frac{M \times m}{R^2}$$ or $$g = G\,\frac{M}{R^2}$$

Radius of earth
$R = 6.4 \times 10^6$ m
(average)

The earth is not a perfect sphere. As the **radius** of the earth **increases from the poles to the equator,** the value of **g becomes greater at the poles.** For most calculations, g is considered constant on or near the earth.

But for objects far from the earth, the acceleration due to gravity is given by **g = G M /R².**
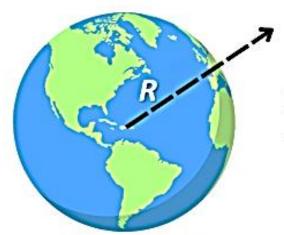
Polar radius - 6357 km

Equatorial radius
6378 km

FREE FALL

TO CALCULATE THE VALUE OF g

- Universal gravitational constant, $G = 6.7 \times 10^{-11}$ N m^2 kg^{-2}

- Mass of the earth, $M = 6 \times 10^{24}$ kg

- Radius of the earth, $R = 6.4 \times 10^6$ m

$$g = G \frac{M}{R^2}$$

$$g = \frac{6.7 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2} \times 6 \times 10^{24} \text{ kg}}{(6.4 \times 10^6 \text{ m})^2}$$

$$= \underline{9.8 \text{ m s}^{-2}}$$

Radius of earth
$R = 6.4 \times 10^6$ m
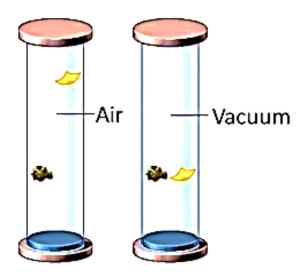(average)

Polar radius - 6357 km
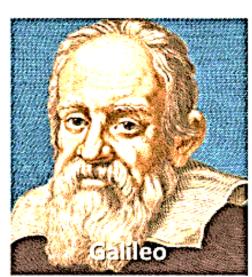
Equatorial radius
6378 km

FREE FALL
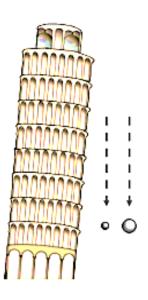
MOTION OF OBJECTS UNDER THE INFLUENCE OF GRAVITATIONAL FORCE OF THE EARTH

Activity

❖ Drop a sheet of **paper** and a **stone** simultaneously from the first floor of a building.

❖ The paper falls slower due to air resistance, which is greater for the paper than the stone. Air resistance creates friction to the motion of the falling objects.

❖ In a vacuum glass jar, the paper and the stone fall at the same rate.

It shows that **acceleration due to gravity is independent of its mass.** i.e., all objects fall at the same rate. This was proved by **Galileo** by dropping different objects from the top of the **Leaning Tower of Pisa** in Italy.

FREE FALL

MOTION OF OBJECTS UNDER THE INFLUENCE OF GRAVITATIONAL FORCE OF THE EARTH
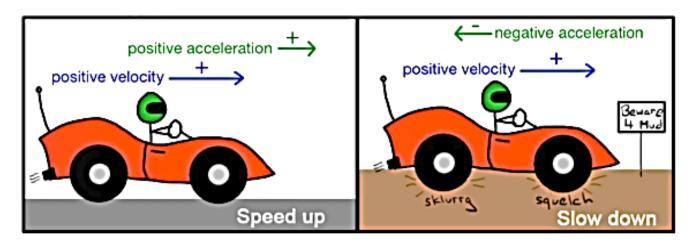
- As **g is constant** near the earth, all the equations for the **uniformly accelerated motion** of objects become valid with **acceleration *a*** replaced by *g*. The equations are:

$$v = u + at \qquad\qquad s = ut + \tfrac{1}{2}at^2 \qquad\qquad v^2 = u^2 + 2as$$

- When applying these equations, **acceleration, *a* is positive** if it is **in the direction of velocity** (direction of motion) and **negative** when it **opposes the motion.**

FREE FALL

Problem

A car falls off a ledge and drops to the ground in 0.5 s. Let $g = 10$ m s^{-2}

i.   What is its speed on striking the ground?

ii.   What is its average speed during the 0.5 s?

iii.   How high is the ledge from the ground?

> g is taken as 10 m s^{-2} to simplify the calculations.

Solution

Time, t = ½ second

Initial velocity, $u = 0$ m s^{-1}

Acceleration due to gravity, $g = 10$ m s^{-2}

Acceleration of the car, $a = +10$ m s^{-2}

(downward)

(i) speed, $v = a\,t$

$v = 10$ m s^{-2} × 0.5 s = **5 m s^{-1}**

(ii) average speed $= \dfrac{u + v}{2}$

$= (0$ m s$^{-1} + 5$ m s$^{-1})/2 =$ **2.5 m s^{-1}**

(iii) distance travelled, $s = $ ½ at^2

$= $ ½ × 10 m s^{-2} × $(0.5$ s$)^2 =$ **1.25 m**

Thus height of the ledge from the ground = **1.25 m.**

FREE FALL

Problem

An object is thrown vertically upwards and rises to a height of 10 m. Calculate

(i) the velocity with which the object was thrown upwards.

(ii) the time taken by the object to reach the highest point.

Solution

Distance travelled, s = 10 m

Final velocity, v = 0 ms^{-1}

Acceleration due to gravity, g = 9.8 m s^{-2}

Acceleration of the object, a = −9.8 m s^{-2}

(upward motion)

(i) $v^2 = u^2 + 2as$

$0 = u^2 + 2 \times (-9.8 \text{ m s}^{-2}) \times 10 \text{ m}$

$-u^2 = -2 \times 9.8 \times 10 \text{ m}^2\text{s}^{-2}$

Initial velocity, $u = \sqrt{196}$ m s^{-1} = **14 m s^{-1}**

(ii) $v = u + at$

$0 = 14 \text{ ms}^{-1} - 9.8 \text{ m s}^{-2} \times t$

$t =$ **1.43 s**

MASS & WEIGHT
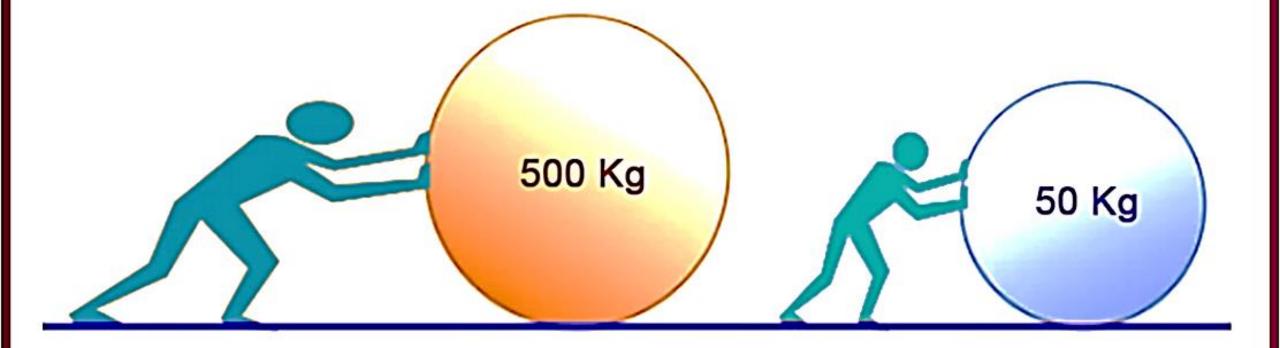
- The mass of an object is the measure of its **inertia.**

- **Greater the mass, the greater is the inertia.** It remains the same whether the object is on the earth, the moon or in outer space. Thus, mass of an object is constant.

500 Kg

50 Kg

MASS & WEIGHT

WEIGHT
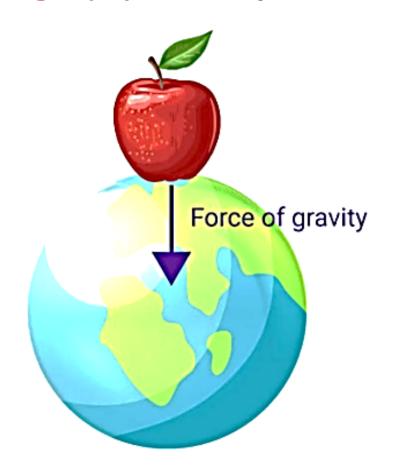
- The force of attraction of the earth on an object is called the **weight (W)** of the object.

- Substituting the Eq. $F = m \times g$,

$$W = m \times g$$

- As the weight is the force, its SI unit is **newton (N).**

- The weight is a force acting vertically downwards; it has both **magnitude** and **direction.**

- The value of g is constant at a given place. So, the weight is directly proportional to the mass (m) of the object.

$$W \propto m$$

- So, weight can be used to measure mass at a given place.

- Mass remains constant, but weight varies with location due to changes in g.

Force of gravity

MASS & WEIGHT

WEIGHT OF AN OBJECT ON THE MOON
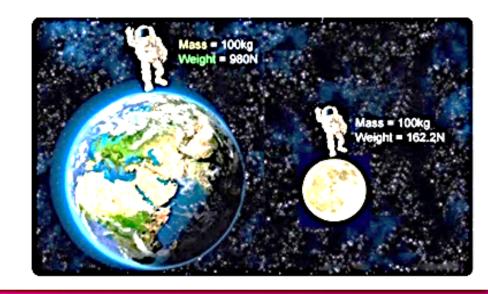
- The weight of an object on the moon is the force with which the moon attracts that object.

- Mass of the moon is less than that of the earth. So the moon exerts lesser force of attraction on objects.

- Applying the universal law of gravitation, the weight of the object on the moon will be

$$W_m = G \frac{M_m \times m}{R_m^2}$$

- Let the weight of the same object on the earth be W_e. The mass of the earth is M and its radius is R.

$$W_e = G \frac{M \times m}{R^2}$$

m = mass of an object.

W_m = its weight on the moon.

M_m = mass of the moon.

R_m = radius of moon.

MASS & WEIGHT   WEIGHT OF AN OBJECT ON THE MOON

Celestial body	Mass (kg)	Radius (m)
Earth	5.98×10^{24}	6.37×10^{6}
Moon	7.36×10^{22}	1.74×10^{6}

$$W_m = G \frac{M_m \times m}{R_m^2} \qquad W_e = G \frac{M \times m}{R^2}$$

$$W_m = G \frac{7.36 \times 10^{22} \text{ kg} \times m}{(1.74 \times 10^6 \text{ m})^2} \qquad W_e = G \frac{5.98 \times 10^{24} \text{ kg} \times m}{(6.37 \times 10^6 \text{ m})^2}$$

$$W_m = 2.431 \times 10^{10} \; G \times m \qquad\qquad W_e = 1.474 \times 10^{11} \; G \times m$$

$$\frac{\text{Weight of the object on the moon } (W_m)}{\text{Weight of the object on the earth } (W_e)} = \frac{2.431 \times 10^{10}}{1.474 \times 10^{11}} = 0.165 \approx \frac{1}{6}$$

$$W_m = (1/6) \times W_e$$

MASS & WEIGHT | WEIGHT OF AN OBJECT ON THE MOON

Problem	Problem
Mass of an object is 10 kg. What is its weight on the earth?	An object weighs 10 N when measured on the surface of the earth. What would be its weight when measured on the surface of the moon?

Solution	Solution

Solution (left):

Mass, m = 10 kg

g = 9.8 ms^{-2}

Weight of the object, $W = m \times g$

W = 10 kg × 9.8 ms^{-2} = **98 N**

Solution (right):

$$W_m = (1/6) \times W_e$$

$$W_m = \frac{W_e}{6} = \frac{10}{6} N$$

$$= \underline{1.67 \text{ N}}$$

THRUST AND PRESSURE

The force acting on an object perpendicular to the surface is called **thrust.** E.g.,

➢ When fixing a poster with a drawing pin, a force is directed perpendicular to the surface of the board and acts on a smaller area at the tip of the pin.

➢ Standing on loose sand sinks the feet due to the force (body weight) on a small area (feet). When lie down, distributes the same force over a larger area, preventing sinking.
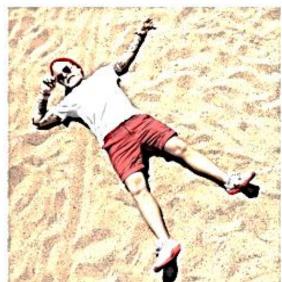
Here, thrust is the same. But effects are different.

Therefore, the effect of thrust depends on the area on which it acts. The effect of thrust on sand is larger while standing than while lying.
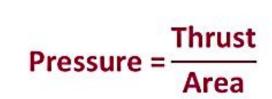
THRUST AND PRESSURE

- The thrust on unit area is called **pressure.**
- The SI unit of pressure= **N/m² or N m⁻²**, or the **pascal (Pa)** in honor of scientist **Blaise Pascal.**
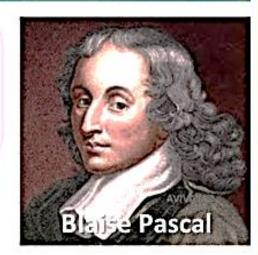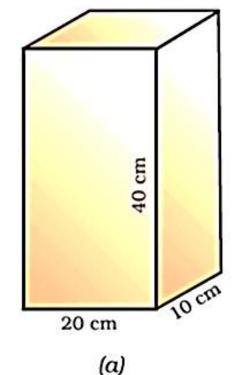
$$\text{Pressure} = \frac{\text{Thrust}}{\text{Area}}$$

Blaise Pascal

Problem

A block of wood is kept on a tabletop. The mass of wooden block is 5 kg and its dimensions are 40 cm × 20 cm × 10 cm.
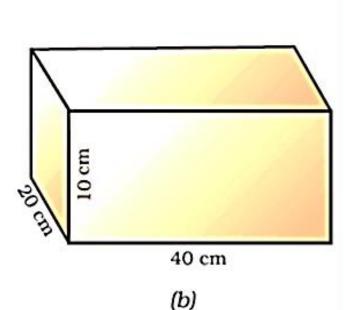
Find the pressure exerted by the wooden block on the table top if it is made to lie on the table top with its sides of dimensions

(a) 20 cm × 10 cm and   (b) 40 cm × 20 cm.

(a)

(b)

THRUST AND PRESSURE

Solution

- The mass of the wooden block = 5 kg
- The dimensions = 40 cm × 20 cm × 10 cm

- Here, the weight of the wooden block applies a thrust on the table top. i.e.,

  Thrust = $F = m \times g$

  = 5 kg × 9.8 ms^{-2} = **49 N**

(a) Area of a side = length × breadth

  = 20 cm × 10 cm = 200 cm^2 = **0.02 m²**

$$\text{Pressure} = \frac{\text{Thrust}}{\text{Area}} = \frac{49 \text{ N}}{0.02 \text{ m}^2} = \textbf{2450 N m}^{-2}$$

(b) When the block lies on its side of dimensions 40 cm × 20 cm, it exerts the same thrust.

  Area = length × breadth

  = 40 cm × 20 cm = 800 cm^2 = **0.08 m²**

$$\text{Pressure} = \frac{\text{Thrust}}{\text{Area}} = \frac{49 \text{ N}}{0.08 \text{ m}^2} = \textbf{612.5 N m}^{-2}$$

Thus, the same force on a smaller area exerts a larger pressure, and a smaller pressure on a larger area. This explains why a nail has a pointed tip, knives have sharp edges and buildings have wide foundations.

THRUST AND PRESSURE

❖ **A camel can run easily in a desert due to its wide, padded feet.** These distribute camel's weight over a larger area, reducing pressure on the sand and preventing it from sinking.

❖ **An army tank rests upon a continuous chain to distribute its weight over a larger area.** This reduces pressure and prevents the tank from sinking into soft terrain.

❖ **Trucks and buses have wider tires to distribute their weight over a larger area.** This reduces pressure on the road and minimizes wear and tear.

THRUST AND PRESSURE

PRESSURE IN FLUIDS

- All **liquids** and **gases** are **fluids.**

- A solid exerts pressure on a surface due to its weight. Similarly, fluids exert pressure on the base and walls of the container in which they are enclosed.

- Pressure exerted in any confined mass of fluid is transmitted undiminished in all directions.
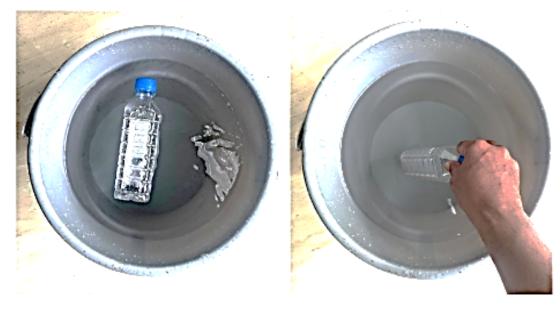
THRUST AND PRESSURE

BUOYANCY

It is the tendency of an object to **float in a fluid.**

Activity

❖ Place a closed, airtight plastic bottle in a bucket of water. It floats.

❖ Push the bottle into the water. An **upward force** is felt, and it becomes harder to push further. This shows that water exerts an increasing upward force as the bottle is pushed deeper until fully immersed.

❖ Release the bottle. It bounces back to the surface.

The **gravitational force** pulls the bottle downward while the water exerts an upward **buoyant force,** pushing the bottle up. Since the buoyant force is greater than the bottle's weight, the bottle rises when released.

THRUST AND PRESSURE

BUOYANCY

- To keep the bottle fully immersed, an external downward force is needed to balance the upward force. This force must at least be equal to the difference between the upward force and the bottle's weight.

- The upward force exerted by a fluid on an immersed object is called **upthrust** or **buoyant force.** This makes the object feel lighter and helps it float. E.g.,

  ❖ Swimming in a pool makes the body feel lighter.

  ❖ A bucket of water feels lighter underwater but heavier when lifted out.

  ❖ A ship made of iron & steel floats on water.
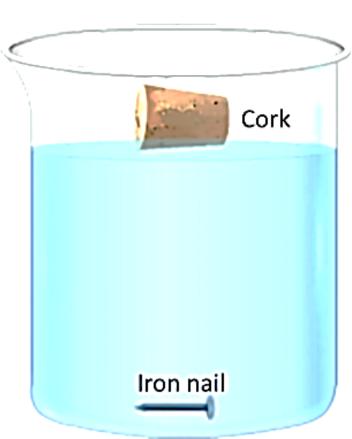
THRUST AND PRESSURE

WHY OBJECTS FLOAT OR SINK WHEN PLACED ON THE SURFACE OF WATER?

- Place an iron nail on the water in a beaker. The nail sinks because the **gravitational force** on the **nail** is **greater** than the **buoyant force.**

- Take a cork and an iron nail of equal mass. Place them on water. The cork floats and the nail sinks. It is due to the difference in their densities.

- **Density** of a substance is defined as the *mass per unit volume.*

- Magnitude of **buoyant force depends on the density** of the fluid.

- **Density** of **cork** is **less** than that of water. i.e., **upthrust** of **water** is **greater** than the weight of cork. So it floats.

- **Density** of **nail** is **more** than that of water. i.e., **upthrust** of **water** is **less** than the weight of the nail. So it sinks.
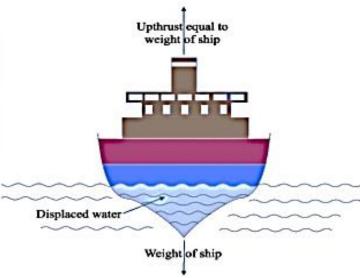
Cork

Iron nail

THRUST AND PRESSURE

WHY OBJECTS FLOAT OR SINK WHEN PLACED ON THE SURFACE OF WATER?

- Objects with lower density than a liquid float. Objects with greater density than a liquid sink.

- A **ship floats** because its **overall density,** including air, is **less than the density of water.** It **displaces more water,** generating **enough buoyant force** to support its weight.

- A **metal sheet sinks** because it has a **higher density** and **displaces less water,** generating **insufficient buoyant force.**

Upthrust equal to weight of ship

Displaced water

Weight of ship

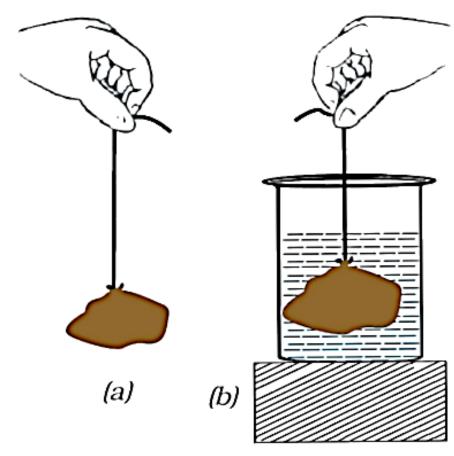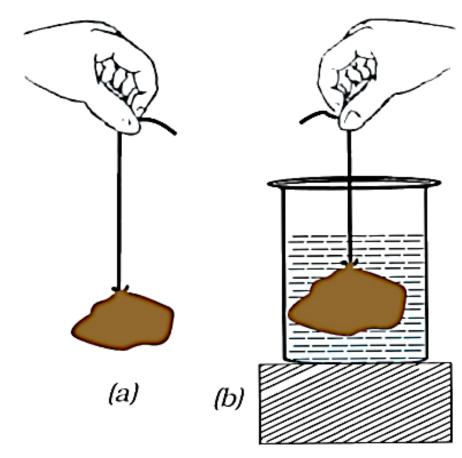Metal sheet

ARCHIMEDES' PRINCIPLE

Activity

- ❖ Tie a stone to a rubber string / spring balance and suspend.

- ❖ The elongation of the string or reading on the balance increases due to the stone's weight.

- ❖ As the stone is slowly dipped in water, the elongation of the string or reading on the balance decreases. However, no further change is observed once the stone gets fully immersed in the water.

(a)   (b)

(a) Elongation of the rubber string due to the weight of stone suspended from it in air.

(b) Elongation decreases as the stone is immersed in water.

ARCHIMEDES' PRINCIPLE
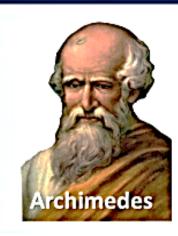
Activity

❖ The elongation is caused by the weight of the stone. When the stone is lowered into water, the extension decreases, indicating that an upward force **(buoyant force)** is acting on the stone. This reduces the net force on the string, causing the elongation to decrease.

❖ Magnitude of buoyant force, its variation in different fluids etc. are explained by **Archimedes' principle.**

(a)   (b)

(a) Elongation of the rubber string due to the weight of stone suspended from it in air.

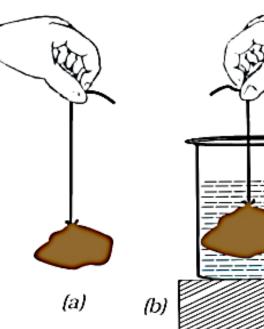(b) Elongation decreases as the stone is immersed in water.

ARCHIMEDES' PRINCIPLE

- **Archimedes' principle:** Proposed by **Archimedes** (a Greek scientist).

- It states that *When a body is immersed fully or partially in a fluid, it experiences an upward force that is equal to the weight of the fluid displaced by it.*

Archimedes

- The elongation of the string does not decrease further once the stone becomes fully immersed in water because the buoyant force reaches its maximum when the body displaces the maximum amount of fluid. Beyond this point, the buoyant force remains constant, so the elongation stays the same.

(a)　(b)

ARCHIMEDES' PRINCIPLE

Applications of Archimedes' principle

❖ It is used in designing **ships** and **submarines**.

❖ **Lactometers** (to determine the purity of milk) and **Hydrometers** (to determine density of liquids) are based on this principle.

Lactometer

Hydrometer