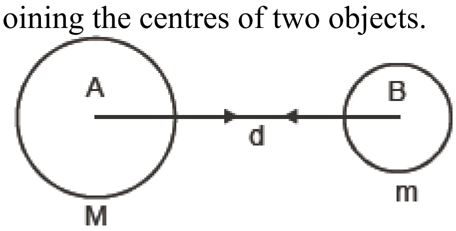
GRAVITATION

Definition: The force of attraction between any two particles in the universe is known as gravitational force or gravity.

Universal law of gravitation:

It states that, "Every object in the universe attracts every other object with a force which is 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 of d from each other as shown in the figure.

Let F be the force of attraction between two objects.

According to the universal law of gravitation

F

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

$$F = G\frac{Mm}{d^2} \qquad \because G = \text{universal gravitational constant}$$

$$G = \frac{Fd^2}{Mm}$$

- G is called a universal constant because its value does not depend on the nature of intervening medium or temperature or any other physical variable.

Definition of Universal gravitational constant:

We have $G = Fd^2/ M \times m$

If M= m= 1 unit and d = 1 unit

Then $G = F \times 1^2/ 1 \times 1$

$G = F$

Hence Gravitational constant is numerically equal to the force of gravitation acting between two bodies having unit masses separated by unit distance.

S.I. unit of G = Nm^2/kg^2
Value of G = 6.673×10^{-11} Nm^2/kg^2

Importance of The Universal Law of Gravitation

- It binds us to the earth.
- It is responsible for the motion of the moon around the earth.
- It is responsible for the motion of planets around the Sun.
- Gravitational force of moon causes tides in seas on earth.

Free Fall

When an object falls from any height under the influence of gravitational force only, it is known as free fall. Such objects are called freely falling objects.

Acceleration Due to Gravity

The acceleration with which an object falls towards the earth only due to the gravitational pull of the earth is called acceleration due to gravity.

The acceleration due to gravity is denoted by g.

The unit of g is same as the unit of acceleration, i.e., ms^{-2}

Mathematical Expression for g:

Consider an object of mass m placed near the surface of the earth.

From the Universal Law of Gravitation

The force of attraction between the object and the earth is given by

$F = G\,Mm/R^2$ ….(i)

(Where M – is mass of earth ; R – radius of the earth)

This force produces an acceleration ‘a’ in the object. From the second law of motion.

$F = ma$

For free fall, acceleration is replaced by acceleration due to gravity. Therefore, force becomes:

$F = mg$ ….(ii)

From (i) and (ii)

$G\,Mm/R^2 = mg$

$g = GM/R^2$

Note : This implies that g does not depend on the mass of an object . All objects irrespective of their masses fall with a constant acceleration towards the earth.

To Calculate the Value of g

Value of universal gravitational constant, $G = 6.7 \times 10^{-11}$ N m^2/kg^2,

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

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

Putting all these values in equation (iii), we get:

$$g = \frac{6.7\times10^{-11}\text{Nm}^2/\text{kg}^2\times6\times10^{24}\text{kg}}{(6.4\times10^6\text{m})^2} = 9.8\,\text{m/s}^2$$

Thus, the value of acceleration due to gravity of the earth, $g = 9.8\ ms^{-2}$

Factors Affecting the Value of g

- As the radius of the earth increases from the poles to the equator, the value of *g* becomes greater at the poles than at the equator.
- As we go at large heights, value of *g* decreases.

Motion of Objects Under the Influence of Gravitational Force of the Earth

- Consider an object falling towards earth with an initial velocity *u*. Let its velocity, under the effect of gravitational acceleration *g*, changes to *v* after covering the height *h* in time *t*.

- Then the three equations of motion can be represented as:

$$v = u + gt$$
$$h = ut + 1/2gt^2$$
$$v^2 = u^2 + 2gh$$

The value of g is taken as positive in the case of object moving towards earth and taken as negative in the case of object is thrown in opposite direction of earth

Difference between Gravitational Constant (G) and Gravitational Acceleration (g)

S. No.	Gravitation Constant (G)	Gravitational acceleration (g)
1.	It is numerically equal to the force of gravitation acting between two bodies having unit masses separated by unit distance.	The acceleration with which an object falls towards the earth only due to the gravitational pull of the earth is called acceleration due to gravity.
2.	Its value is $6.67 \times 10^{-11} Nm^2/kg^2$.	Its value is $9.8\ m/s^2$.
3.	It is a scalar quantity.	It is a vector quantity.
4.	Its value remains constant always and everywhere.	Its value varies at various places.
5.	Its unit is Nm^2/kg^2.	Its unit is m/s^2.

Mass & weight

Mass (m)

- The mass of a body is the quantity of matter contained in it.
- Mass is a scalar quantity which has only magnitude but no direction.
- Mass of a body always remains constant and does not change from place to place.
- SI unit of mass is kilogram (kg).
- Mass of a body can never be zero.

Weight (W)

- The force with which an object is attracted towards the centre of the earth, is called the weight of the object OR The force exerted by the earth on an object is called weight of the object.

  Now, Force = $m \times a$
  But in case of earth, $a = g$
  $F = m \times g$
  But the force of attraction of earth on an object is called its weight (W).
  & therefore ; $W = mg$

- As weight always acts vertically downwards, therefore, weight has both magnitude and direction and thus it is a vector quantity.
- The weight of a body changes from place to place, depending on mass of object.
- The SI unit of weight is newton(N).
- Weight of the object becomes zero if g is zero.

Weight of an Object on the Surface of Moon

Mass of an object is same on earth as well as on moon. But weight is different.

Weight of an object is given as,

$$W = mg$$

Where $W = \frac{GMm}{R^2}$

⇒ Let weight of object on earth be given as:

$$W_e = \frac{GM_e m}{R_e^2}$$

Where, G = Gravitational constant
M_e = Mass of earth
R_e = Radius of earth
And m = Mass of object

And, weight of object on moon be given as:

$$W_m = \frac{GM_m m}{R_m^2}$$

Where, M_m = Mass of earth
R_m = Radius of earth

$$\frac{W_e}{W_m} = \frac{GM_e m}{R_e^2} \times \frac{R_m^2}{GM_m m}$$

$$\Rightarrow \quad \frac{W_e}{W_m} = \frac{M_e}{M_m} \times \left(\frac{R_m}{R_e}\right)^2$$

Now, We know that mass of earth is 100 times the mass of the moon.

⇒ $M_e = 100\, M_m$

And radius of earth is 4 times the radius of moon.

⇒ $R_e = 4R_m$

$$\Rightarrow \quad \frac{W_e}{W_m} = \frac{100M_m}{M_m} \times \left(\frac{R_m}{4R_m}\right)^2$$

$$\Rightarrow \quad \frac{W_e}{W_m} = \frac{100}{16} = 6.25 \approx 6(\text{approx.})$$

$$\Rightarrow \quad W_m = \frac{1}{6} W_e$$

Hence, weight of the object on the moon = (1/6) × its weight on the earth.

Gravitation Numerical (Physics – Class IX)

1. The 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 × 10–11 N m2 kg-2. [2.01×10^{20} N]

2. What is the magnitude of the gravitational force between the earth and a 1 kg object on its surface? (Mass of the earth is 6×10^{24} kg and radius of the earth is 6.4×10^{6} m.) [9.8 N]

3. Calculate the force of gravitation between the earth and the Sun, given that the mass of the earth = 6×10^{24} kg and of the Sun = 2×10^{30} kg. The average distance between the two is 1.5×10^{11} m. [3.57×10^{22} N]

4. A car falls off a ledge and drops to the ground in 0.5 s. Let g = 10 m/s^2 (for simplifying the calculations).

   (i) What is its speed on striking the ground? [5 m/s]
   (ii) What is its average speed during the 0.5 s? [2.5 m/s]
   (iii) (iii)How high is the ledge from the ground? [1.25 m]

5. 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. [14 m/s]
   (ii) the time taken by the object to reach the highest point. [1.43 s]

6. A ball is thrown vertically upwards with a velocity of 49 m/s. Calculate

   (i) the maximum height to which it rises, [122.5 m]
   (ii) the total time it takes to return to the surface of the earth. [10 sec]

7. A stone is released from the top of a tower of height 19.6 m. Calculate its final velocity.

   [19.6 m/s]

8. A stone is thrown vertically upward with an initial velocity of 40 m/s. Taking g = 10 m/s2, find the maximum height reached by the stone. What is the net displacement and the total distance covered by the stone? [0 and 80 m]

9. A stone is allowed to fall from the top of a tower 100 m high and at the same time another stone is projected vertically upwards from the ground with a velocity of 25 m/s. Calculate when and where the two stones will meet. [after 4 sec at 21.6 m from ground]

10. A ball thrown up vertically returns to the thrower after 6 s. Find

    (i) the velocity with which it was thrown up, [29.4 m/s]
    (ii) the maximum height it reaches, [44.1 m]
    (iii) its position after 4 s. [39.2 m from ground]

Chapter 10 - Gravitation

Thrust and Pressure

Thrust : force exerted by an object perpendicular to the surface is called thrust.

Pressure : force exerted by any object per unit area is called pressure.

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$\text{Pressure} = \frac{\text{Thrust}}{\text{Area}}$$

$$p = \frac{F}{A}$$

Where p is pressure, F is thrust or force and A is surface area of the object.

Since the pressure is indirectly proportional to the surface area of the object, thus, pressure increases with decrease in surface area and decreases with increase in surface area.

SI unit - $N m^{-2}$ / N/m^2 or Pascal 1 Pa = 1 N/m^2

Thrust and Pressure in everyday life

1) Pressure exerted by a brick: A stretched brick keep on the ground exerts less pressure than a brick kept on the ground in standing position. Thus, in the case of stretched position a brick exerts less thrust over the ground in comparison to the brick kept in standing position.

2) Camel can run easily over the sand. The feet of a camel are large. Larger feet means larger area which results in low pressure. Due to this camel can easily walk on sand without sinking its feet.

3) Tank can easily run over sand and mud. Continous chains, surrounding the wheel provide a larger surface area. Due to this, a tank can move on any terrain without sinking.

4) Tractor has broader tyres: Tractors are made mainly for agriculture purpose. Because of broader tyres, a tractor exerts less pressure over the ground as pressure decrease with increase in surface area and hence easily runs over the muddy field.

5) One end of nail is pointed – When a nail is pushed in a wall or wood, it is pushed from pointed side. Because of the pointed shape, nail exerts more pressure over the wall or wood and is easily pushed by hammering.

(6) The straps of school bag are broader :- Since larger surface area exerts less pressure, therefore school bags with broader straps exerts less pressure over the shoulder of a student while being slung over the shoulder and a student feels it easy to carry even a heavy bag with more books.

7) Knife with sharp edge cuts easily compare to one with blunt edge - Knife with sharp edge exerts more pressure because of less area in contact with an object, such as vegetable and hence it cuts more easily.

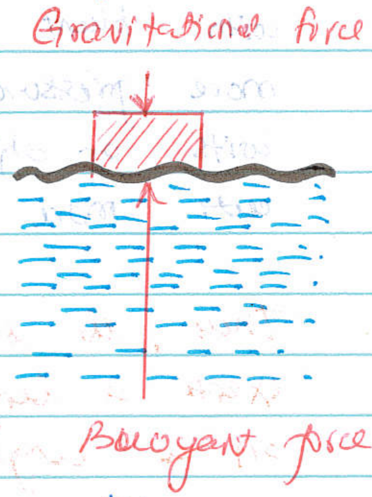
Thus, the same force acting on a smaller area exerts a larger pressure, and a smaller pressure on a larger area.

PRESSURE in FLUIDS

Any solid objects exerts pressure because of weight. Similarly, since fluids also have weight, thus they exert pressure.
Gases and liquids both are considered as fluids. Fluids exert pressure in all direction over the inner walls of a container in which they are kept.

BUOYANCY

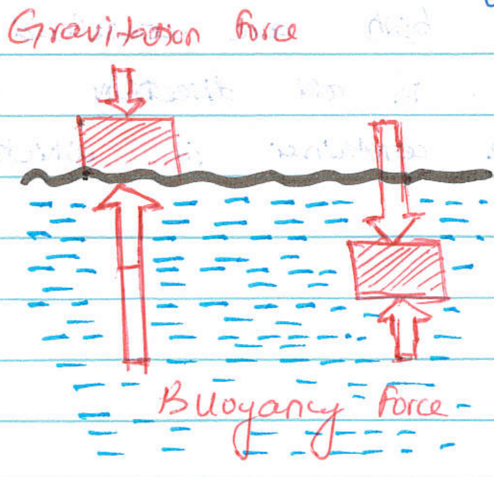
The upward force exerted by fluids (liquid or gas) on objects when they are immersed in them is called buoyant force and the phenomenon is called buoyancy.



Buoyancy is also known as upward thrust.

Why does an object sink or float over water?

When an object is immersed in water, it exerts pressure over water due to its weight. At the same time water also exerts upward thrust over the object. If the force exerted by the object is greater than the upward thrust or buoyance by water, the object sink in water otherwise it floats over water.



Objects of density less than that of a liquid float on the liquid.

The objects of density greater than that of a liquid sink in the liquid.

Buoyancy in everyday life

Swimming in water : Anyone can be able to swim in water because of upward thrust exerted by water.

Flying of bird or aeroplane : Since air is a fluid, thus it also exerts upward thrust over the object. Therefore, because of upward thrust of air a bird or aeroplane can fly in air.

Factors which affect buoyancy

Volume of the object : Buoyancy or upward thrust exerted by a fluid increases with the volume of the object immersed in it.

Density of the fluid : The buoyant force or upward thrust increases with increase in density of the fluid. Denser liquid exert more upward thrust.

This is the cause that it is easier to swim in sea water rather than fresh water. Sea water is saline. Salts dissolved in sea water increases the density and hence it exerts more upward thrust than fresh water.

Density (ρ)

Mass per unit volume of an object is called density or mass density

$$\text{Density } (\rho) = \frac{\text{Mass}}{\text{Volume}} = \frac{m}{V} \Rightarrow \boxed{\rho = \frac{m}{V}} \quad kg/m^3$$

Relative Density

When density of a substance is expressed in comparison with water, it is called relative density.

$$\text{Relative density} = \frac{\text{Density of substance}}{\text{Density of water}}$$

Practical application of density:

When the relative density of a substance is less than 1, it will float in water otherwise it will sink in water.

The relative density of ice is 0.91, thus it floats in water.

If the relative density of an object is less than 1, compare to the liquid in which it is immersed, the object will sink otherwise object will float.

ARCHIMEDE'S PRINCIPLE

It states that – "When an object is immersed fully or partially in a liquid, it experiences an upward force which is equal to the weight of the liquid displaced by the object."

Aplication of Archimedes Principle

When the weight of displaced liquid by an object is greater than the weight of the object, the object will float in the liquid and when the weight of liquid will be smaller than that of the weight of the object, the object will sink in liquid.

In submarines, there is a tank which can be filled or emptied as per requirement. It is called buoyancy tank. When submarine have to go inside the water, the buoyancy tank is filled with water, so that weight of the submarines would become more than the weight of water displaced by it.

Air Ballons :- To raise the air balloon in air, the air inside the ballon is heated. Air expands because of heat and becomes lighter. Thus, balloon gets upward thrust from surrounding air and rises up.

Ships: A ship is much heavier than water, yet it floats on water. This happens because of unique shape of the ship. Because of its shape, the volume of the ship is larger compared to its weight. Due to this, water displaced by the ship provides a proper upward thrust to the ship and the ship floats on water.

Numerical: A block of wood is kept on a tabletop. The mass of wooden block is 5 kg and its dimensions are 40 cm X 20 cm X 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 dimension

(a) 20 cm X 10 cm (b) 40 cm X 20 cm.

Soln: The mass of wooden block $m = 5$ kg

Thrust $F = mg = 5 \times 9.8 = 49$ N

(a) Area of side $= 20 \times 10$ cm^2 $= 200$ cm^2 $= 0.02$ m^2

$$\text{Pressure} = \frac{F}{A} = \frac{49}{0.02} = 2450 \text{ Nm}^2$$

(b) Area of side $= 40 \times 20$ cm^2 $= 800$ cm^2 $= 0.08$ m^2

$$\text{Pressure} = \frac{F}{A} = \frac{49}{0.08} = 612.5 \text{ Nm}^2$$

Ans. (*a*) The cube will experience a greater buoyant force in the saturated salt solution because the density of the salt solution is greater than that of water.

The smaller cube will experience lesser buoyant force as its volume is lesser than the initial cube.

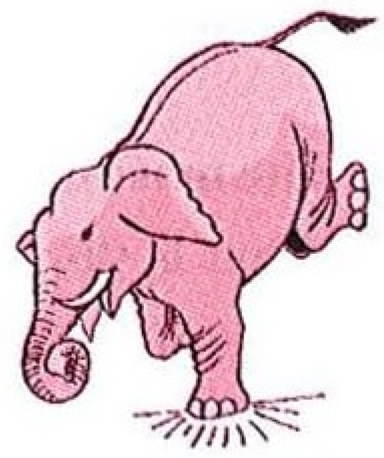
(*b*) Buoyant force = Weight of the liquid displaced

= Density of water × Volume of water displaced × g

$$= 1{,}000 \times \frac{4}{4{,}000} \times 10 = 10 \text{ N}$$

Numericals

Q. 1. An elephant weighing 50,000 newton stands on one foot of area 1000 cm². What is the pressure exerted on the ground?



Sol. Here,

Force = 50,000 N

Area = 1,000 cm^2

$$= \frac{1{,}000}{100 \times 100} m^2 = 0.1 \ m^2$$

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{50{,}000 \text{ N}}{0.1 \text{ m}^2} = \mathbf{5{,}00{,}000 \ Nm^{-2}}$$

Q. 2. Calculate the pressure exerted by a girl weighing 500 N standing on one stiletto heel of area 1 cm².

Sol. Here, Force = 500 N

$$\text{Area} = 1 \text{ cm}^2 = \frac{1}{10{,}000} \text{ m}^2$$

$$= 0.0001 \text{ m}^2$$

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$= \frac{500 \text{ N}}{0.0001 \text{ m}^2} = \mathbf{50{,}00{,}000 \ Nm^{-2}}$$

Q. 3. A solid cube of dimensions 50 cm × 50 cm × 50 cm and weighing 25 N is placed on a table. Calculate the pressure exerted on the table.

Sol. Side of cube, l = 50 cm = 0.50 m

Area of base of cube = $l \times l$ = 0.50 × 0.50 = 0.25 m^2

Force on base = Weight of cube = 25 N

$$\therefore \quad \text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{F}{A} = \frac{25}{0.25}$$

$$= \mathbf{100 \ Nm^{-2}} \text{ or } \mathbf{100 \ pascal.}$$

Q. 4. The length and breadth of a rectangular tank are 3.0 m and 2.0 m. It contains water up to height 1.5 m. Calculate the total thrust and pressure at the bottom of tank due to water. Density of water = 1,000 kg/m³ and g = 10 m/s².

Sol. Volume of water = Length × breadth × height

= (3.0 m) × (2.0 m) × (1.5 m)

= 9.0 m^3

Mass of water, M = Volume × Density

= (9.0 m^3) × (1,000 kg/m^3) = 9,000 kg

Weight of water, $W = Mg = 9{,}000 \times 10^4$ N

Total thrust of water on the bottom of tank,

$$F = \text{Weight of water}$$
$$= 9 \times 10^4 \text{ N}$$

$$\text{Area of bottom} = \text{Length} \times \text{Breadth}$$
$$= 3.0 \times 2.0 = 6.0 \text{ m}^2$$

Pressure of water at the bottom,

$$P = \frac{\text{Force}}{\text{Area of bottom}}$$
$$= \frac{9 \times 10^4}{6.0} = \mathbf{1.5 \times 10^4\ N/m^2}$$

Q. 5. The mass of a body is 70 kg. When completely immersed in water, it displaces 2000 cm^3 of water. What is the relative density of the material of the body?

Sol. Mass of body in air, $m = 70$

Weight of body in air $= 70$ kg weight

Loss of weight of body in water = Weight of water displaced by body
= Volume of water × Density of water

Density of water = 1000 kg/m^3

Volume of water displaced = 2000 cm^3

As $1 \text{ cm}^3 = 10^{-6} \text{ m}^3$

$\therefore$ Volume of water displaced $= 2000 \times 10^{-6} \text{ m}^3$
$= 2 \times 10^{-3} \text{ m}^3$

$\therefore$ Loss in weight of body when immersed in water
$= (2 \times 10^{-3}) \times 1000 = 2$ kg weight

$\therefore$ Relative density of material of body

$$= \frac{\text{Weight of body in air}}{\text{Loss of weight of body in water}}$$
$$= \frac{70}{2} = \mathbf{35.}$$

Q. 6. A wooden block floats in glycerine in such a way that its $\frac{2}{5}$ th volume remains above surface. If relative density of wood is 0.78, calculate the relative density of glycerine.

Sol. Relative density of wood $= \dfrac{\text{Density of wood}}{\text{Density of water}}$

$\therefore$ Density of wood = Relative density of wood × Density of water
$= 0.78 \times 1 \text{ g/cm}^3 = 0.78 \text{ g/cm}^3$

Fraction of volume of wood submerged in glycerine

$$= \frac{\text{Density of wood}}{\text{Density of glycerine}}$$

$$\Rightarrow \quad \frac{3}{5} = \frac{0.78}{\text{Density of glycerine}}$$

$$\therefore \quad \text{Density of glycerine} = 0.78 \times \frac{5}{3} = \mathbf{1.30\ g/cm^3}$$