

Gravitation

Earth attracts everything towards it by an unseen force of attraction. This force of attraction is known as gravitation or gravitation pull.

Universal Law of Gravitation

Every object in the universe attracts other object by a force of attraction, called gravitation, which is directly proportional to the product of masses of the objects and inversely proportional to the square of distance between them. This is called Law of Gravitation or Universal Law of Gravitation.

The distance is considered between the centres of the objects.

Suppose there are two objects having mass M and m respectively.

The distance between their centres is equal to d .

The force of attraction is F .

Therefore, from Law of Gravitation which states that force of attraction by which an object attracts other object is directly proportional to the product of their masses,

$$\text{Thus, } F \propto M.m \text{ ----- (i)}$$

Now, Law of Gravitation also states that force of attraction by which an object attracts other object is inversely proportional to the square of distance between them.

$$\text{Thus, } F \propto \frac{1}{d^2} \text{ ----- (ii)}$$

Now from equation (i) and (ii) we get

$$F \propto \frac{M.m}{d^2}$$
$$\Rightarrow F = G \cdot \frac{M.m}{d^2} \text{ ----- (iii)}$$

Where, G is the proportionality constant and called Universal Gravitation Constant.

From equation (iii)

$$F \times d^2 = G.M.m$$
$$\Rightarrow G = \frac{F d^2}{M.m} \text{ ----- (iv)}$$

The expression (iii) and (iv) are called expression for Universal Law of Gravitation.

This Law is applicable everywhere in universe, thus it is known as UNIVERSAL LAW OF GRAVIATION.

SI Unit of G

The SI unit of G is $N\ m^2\ kg^{-2}$

The accepted value of G is $6.673 \times 10^{-11}\ Nm^2\ kg^{-2}$.

The value of G was found out by Henry Cavendish, a British philosopher and scientist.

Importance of Universal Law of Gravitation –

This Law is applicable to every object in the universe.

This law explains the cause of revolution of moon around earth and revolution of planets around sun.

This law explains the cause of neap and tide due to moon and sun.

Free Fall

When an object falls from any height under the influence of gravitational force only, it is known as free fall. In the case of free fall no change of direction takes place but the magnitude of velocity changes because of acceleration.

This acceleration acts because of the force of gravitation and is denoted by 'g'. This is called acceleration due to gravity.

Expression for acceleration due to gravitation 'g'.

Let mass of the object put under free fall = m.

And acceleration due to gravity = g.

Therefore, according to Newton's Second Law of Motion which states that Force is the product of mass and acceleration,

$$F = m \times g \text{ -----(i)}$$

Now, according to Universal Law of gravitation,

$$F = G \cdot \frac{M \cdot m}{d^2} \text{ ----- (ii)}$$

Thus, from above two expressions, we get

Where, g is acceleration due to gravity,

G is the Universal Gravitational Constant.

M is the mass of earth.

And d is the distance between object and centre of earth.

When object is near the surface of earth

When an object is near the surface of earth, the distance between object and centre of the earth will be equal to the radius of earth because the distance of object is negligible in comparison of the radius of earth.

Let the radius of earth is equal to R .

Therefore, after substituting ' R ' at the place of ' d ' we get,

$$g = \frac{GM}{R^2} \text{----- (iv)}$$

Since, earth is not a perfect sphere rather it has oblique shape. Therefore, radius at the equator is greater than at the poles.

Since, value of ' g ' is reciprocal of the square of radius of earth, thus, the value of ' g ' will be greater at the poles and less at the equator.

And the value of ' g ' will decrease with increase of distance of object from earth.

Calculation of value of ' g '

We know that,

The accepted value of G is $6.673 \times 10^{-11} \text{ Nm}^2\text{kg}^{-2}$

The mass of earth, $M = 6 \times 10^{24} \text{ kg}$

The radius of earth, $R = 6.4 \times 10^6 \text{ m}$

Therefore, by using expression $g = \frac{GM}{R^2}$, the value of ' g ' can be calculated.

Therefore, after substituting the value of G , M and R in the expression for ' g ' we get.

$$g = \frac{6.673 \times 10^{-11} \text{ Nm}^2\text{kg}^{-2} \times 6 \times 10^{24} \text{ kg}}{(6.4 \times 10^6 \text{ m})^2}$$
$$\Rightarrow g = 9.8 \text{ m s}^{-2}$$

Motion of an object under the influence of gravitational force of earth

The expression for 'g' is written as

$$g = \frac{GM}{R^2}$$

Since, the value of 'g' does not depend upon the mass or distance of an object, therefore, all objects fall over the earth with the same rate.

The equations for motion are as follows:

$$v = u + at \text{ -----(i)}$$

$$s = ut + \frac{1}{2} at^2 \text{ -----(ii)}$$

$$v^2 = u^2 + 2as \text{ -----(iii)}$$

Therefore, the equations of motion are also applied to calculate the velocity, distance, etc by replacing 'a' by 'g'. After substituting 'g' at the place of 'a' we get above equations as follows:

$$v = u + gt \text{ -----(iv)}$$

$$s = ut + \frac{1}{2} gt^2 \text{ -----(v)}$$

$$v^2 = u^2 + 2gs \text{ -----(vi)}$$

In the calculation; initial velocity (u), final velocity (v), time taken (t), or distance covered (s), 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.

Mass

Mass is the measurement of inertia and inertia is the property of any object which opposes the change in state of the object. It is inertia because of which an object in rest has tendency to remain in rest and an object in motion has tendency to remain in motion.

Inertia depends upon the mass of an object. Object having greater mass has greater inertia and vice versa. Mass of an object remains constant everywhere, i.e. mass will remain same whether that object is at the moon, at the earth or anywhere in the universe.

Weight:

Earth attracts every object towards it. We know that force is the product of mass and acceleration due to gravity.

This means, $F = m \times g$ -----(i)

The force by which earth attracts an object towards it is called the weight of the object, which is the product of mass (m) of the object and acceleration due to gravity (g).

Weight is denoted by 'W'.

Therefore, by substituting in the expression 'F = mg' we get,

$W = m \times g$ -----(ii)

Since weight is the force which is acting vertically downwards, therefore, weight has both magnitude and direction and hence it is a vector quantity.

Since the value of 'g' is always constant at a given place,

Therefore, expression 'W = m x g' can be written as follows:

$W \propto m$ -----(iii)

This means weight of any object is directly proportional to its mass, i.e. weight will increase with the increase of mass and decrease with decrease in mass.

This is the cause that weight of any object is the measure of its mass.

The unit of weight

Since, weight of an object is equal to the force by which an object is attracted towards earth, therefore, unit of weight is same as the unit of force.

Therefore, Unit of weight is 'newton (N)'.

Weight of an Object on the Surface of Moon

Since, weight of an object on the earth is the force by which earth attracts that very object towards it. In similar way, weight of an object on the surface of moon or any other planet is the force by which moon or any other planet will attract the object towards it.

We know that,

The Mass of Earth = 5.98×10^{24} kg

Radius of earth = 6.37×10^6 m

Mass of moon = 7.36×10^{22} kg

Radius of moon = 1.76×10^6 m

Since, mass of the moon is less than that of earth, therefore, moon will exert less force of attraction on any object; in comparison to the earth.

Let mass of an object is 'm'

The weight of the object on earth is W_e

The weight of the object on moon is W_m

Mass of the earth is M

Mass of the moon is M_m

Radius of earth is R

Radius of moon is R_m

Acceleration due to gravity on earth is 'g'

Acceleration due to gravity on moon is ' g_m '.

Therefore,

Weight of the object on earth $W_e = m \times g$

By substituting the value of 'g' from the expression of Universal Law of Gravitation we get

$$\begin{aligned}
W_e &= m \cdot \frac{GM}{R^2} \\
\Rightarrow W_e &= \frac{m \times G \times 5.98 \times 10^{24} \text{ kg}}{(6.37 \times 10^6 \text{ m})^2} \\
\Rightarrow W_e &= \frac{m \times G \times 5.98 \times 10^{24} \text{ kg}}{6.37 \times 6.37 \times 10^6 \times 10^6 \text{ m}^2} \\
\Rightarrow W_e &= \frac{m \times G \times 5.98 \times 10^{24} \text{ kg}}{40.57 \times 10^{12} \text{ m}^2} \\
\Rightarrow W_e &= \frac{m \times G \times 5.98 \times 10^{12} \text{ kg}}{40.57 \text{ m}^2} \\
\Rightarrow W_e &= m \times G \times 0.1474 \times 10^{12} \text{ kg m}^{-2} \\
\Rightarrow W_e &= m \times G \times 1.474 \times 10^{11} \text{ kg m}^{-2}
\end{aligned}$$

Weight of the object on moon $W_m = m \times g_m$

By the expression of universal law of gravitation,

$$\begin{aligned}
W_m &= m \frac{GM_m}{R_m^2} \\
\Rightarrow W_m &= \frac{m \times G \times 7.36 \times 10^{22} \text{ kg}}{(1.74 \times 10^6 \text{ m})^2} \\
\Rightarrow W_m &= \frac{m \times G \times 7.36 \times 10^{22} \text{ kg}}{1.74 \times 1.74 \times 10^6 \times 10^6 \text{ m}^2} \\
\Rightarrow W_m &= \frac{m \times G \times 7.36 \times 10^{22} \text{ kg}}{3.0276 \times 10^{12} \text{ m}^2} \\
\Rightarrow W_m &= \frac{m \times G \times 7.36 \times 10^{10} \text{ kg}}{3.0276 \text{ m}^2} \\
\Rightarrow W_m &= m \times G \times 2.4309 \times 10^{10} \text{ kg m}^{-2} \\
\text{Now, } \frac{W_m}{W_e} &= \frac{m \times G \times 2.4309 \times 10^{10} \text{ kg m}^{-2}}{m \times G \times 1.474 \times 10^{11} \text{ kg m}^{-2}} \\
\Rightarrow \frac{W_m}{W_e} &= \frac{2.4309}{1.474 \times 10} = \frac{2.4309}{14.74} \\
\Rightarrow \frac{W_m}{W_e} &= \frac{1}{6.030} \approx \frac{1}{6}
\end{aligned}$$

Therefore, $\frac{\text{Weight of an object on moon}}{\text{Weight of an object on earth}} = \frac{1}{6}$

Or, Weight of an object on the moon = 1/6 of the weight of the object on earth.

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.

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

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

$$\text{Or, } p = \frac{F}{A} \text{ ----- (i)}$$

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

Since, 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 of Pressure

The unit of force is newton (N) and unit of area is square meter

Therefore, by substituting the unit of force and are in equation (i) we get

$$p = \frac{N}{m^2} \text{ or } N m^{-2}$$

Thus, unit of pressure is $N m^{-2}$

In the honour of Blaise Pascal, the SI unit of pressure is known as pascal.

One pascal is equal to the 1 newton per square meter.

Or, 1 pascal = $N m^{-2}$

Thrust and pressure in everyday life

(a) **Pressure exerted by a brick** - A stretched brick kept on the ground exerts less pressure than a brick kept on the ground in standing position. This happens because the surface area of contact of brick in stretched position is more in comparison to the brick in standing position. And we know that pressure increases with decrease in surface area and vice versa. Thus, in the case of stretched position a brick exerts less thrust over the ground in comparison to the brick kept in standing position.

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

(c) **Tank easily can run over sand and mud.** Caterpillar tracks; surrounding the wheels provide a larger surface area. Due to this, a tank can move on any terrain without sinking.

(d) **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 decreases with increase in surface area or contact and hence easily runs over the muddy field.

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

(f) **The straps of school bag are broader** – Since larger surface area exerts less pressure, therefore school bags with broader straps exert 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.

(g) **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 than a knife with blunt edge.

Pressure in Fluids

Any solid object exerts pressure because of weight. Similarly, since fluids also have weight, thus they exert pressure.

Gas and liquid both are considered as fluids. Fluids exert pressure in all directions over the inner walls of a container in which they are kept.

Buoyancy

Buoyancy is the upward force exerted by fluids over the surface are of contact of an object which is immersed in fluids. 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 buoyancy by water, the object sinks in water otherwise it floats over water.

Buoyancy in everyday life –

(a) **Swimming in water** :– Anyone can be able to swim in water because of upward thrust exerted by water.

(b) **Flying of bird or aero plane** :– Since air is a fluid, thus it also exerts upward thrust over the object. Therefore, because of upward thrust of air a bird or aero plane can fly in air.

Factors which affect buoyancy

- Volume of the object
- Density of the fluid

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 increase the density and hence it exerts more upward thrust than fresh water.

Density

Mass per unit volume of an object is called density or mass density. Density is denoted by Greek letter rho (ρ).

$$\text{Density } (\rho) = \frac{\text{Mass}}{\text{Volume}} = \frac{m}{V}$$
$$\text{Or, } \rho = \frac{m}{V}$$

Where, m is mass of object and V is the volume of that object.

SI Unit of density

The SI unit of mass is kg and SI unit of volume is cubic meter.

Therefore, by substituting the unit of mass and volume in the expression of density we get

$$\rho = \frac{\text{kg}}{\text{m}^3}$$

Therefore, SI unit of density (ρ) is kg m^{-3}

Relative density

For convenience the density of water is expressed in comparison of water. Thus, when density of a substance is expressed in comparison with water, it is called relative density.

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

Relative density has no unit, because it is the ratio of similar quantity.

Practical application of density

Water is taken as reference material because it is easily available at most of the places and it is easy to carry out the measurement related to density in field visit.

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.

Archimedes' Principle

Archimedes' Principle 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 liquid displaced by the object.

Application of Archimedes' Principle

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

(a) In submarines – In submarines, there is a tank which can be filled or emptied as per requirement. It is called buoyancy tank.

When submarines have to go inside the water, the buoyancy tank is filled with water, so that, the weight of the submarines would become more than the weight of water displaced by it. And when submarines have to come over the surface of water, the buoyancy tank is emptied and water is replaced by air. In this condition, the weight of water displaced by submarines will become more than the weight of submarines and submarine comes over the surface of water.

(b) **Air balloons** – To raise the air balloon in air; the air inside the balloon is heated. Air expands because of heat and becomes lighter. Thus, the balloon gets an upward thrust from the surrounding air and rises up.

(c) **Ships** – A ship is much heavier than water, yet it floats on water. This happens because of the 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.

SHASHI SIR'S CLASSES