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CHAPTER – 9

GRAVITATION

Gravitation

The force with which the earth pulls the objects towards it is called the gravitational force of earth or gravity (of earth). It is due to the gravitational force of earth that all the objects fall towards the earth when released from a height.

The gravitational force of earth (or gravity of earth) is responsible for holding the atmosphere above the earth; for the rain falling to the earth; and for the flow of water in the rivers. It is also the gravitational force of earth (or gravity of earth) which keeps us firmly on the ground (and we do not float here and there).

Similarly, a ball thrown upwards also falls back to the earth due to the gravitational force of the earth. Since the gravitational force of earth (or gravity of earth) pulls the objects in the downward direction, therefore, a force has to be applied by us to raise an object to a height above the surface of earth (to overcome the gravitational force of earth).

Gravitational force

According to Newton, every object in this universe attracts every other object with a certain force. The force with which two objects attract each other is called gravitational force (or gravity).

The gravitational force between two objects acts even if the two objects are not connected by any means. If the masses of the objects (or bodies) are small, then the gravitational force between them is very small (which cannot be detected easily).

For example, 'two stones' lying on the ground attract each other but since their masses are small, the gravitational force of attraction between them is small and hence we do not see one stone moving towards the other stone. If, however, one of the objects (or bodies) is very big (having a very large mass), then the gravitational force becomes very large (and its effect can be seen easily).

For example, a stone (lying at a height) and the earth attract each other, and since the earth has a very large mass, the gravitational force of attraction between them is very large due to which when the stone is dropped, it moves down towards the earth. Please note that the 'gravitational force' or 'gravity' is always a force of attraction between two objects (or two bodies).

UNIVERSAL LAW OF GRAVITATION

The universal law of gravitation was given by Newton. So, it is also known as Newton's law of gravitation.

According to universal law of gravitation Every body in the universe attracts every other body with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

The direction of force is along the line joining the centres of the two bodies. Suppose two bodies A and B of masses m, and m, are lying at a distance r from each other. Let the force of attraction between these two bodies be F. Now according to the universal law of gravitation :

(i) the force between two bodies is directly proportional to the product of their masses. That is

$F \ \alpha \ m1 \times m2$ (1)

(ii) the force between two bodies is inversely proportional to the square of the distance between them.

$F\alpha \ 1/r2$ (2)

Combining (1) and (2), we get:

$F\alpha \ (m1 \times m2)/r2$

Gravitational force,

$F=G \times (m1 \times m2)/r2$

where G is a constant known as "universal gravitational constant".

The value of gravitational constant G does not depend on the medium between the two bodies. It also does not depend on the masses of the bodies or the distance between them.

The above formula gives the gravitational force of attraction F between two bodies of masses m, and m2 which are at a distance r from one another.

This formula is applicable anywhere in this universe, and it is a mathematical expression of universal law of gravitation. Since the gravitational force between two bodies is inversely proportional to the square of the distance between them, therefore, if we double the distance between two bodies, the gravitational force becomes one-fourth and if we have the distance between two bodies, then the gravitational force becomes four times.

Unit Of Gravitational Constant G

According to universal law of gravitation the gravitational force F between two bodies of masses m_1 and m_2 placed at the distance r a part is given by

$F = G \ (m_1 \times m_2)/r^2$

Rearrange to get an expression for the gravitational constant G

$G = F \times r^2/(m_1 \times m_2)$

Unit of force is F is newton (N) unit of distance r is (m), unit of masses m_1& m_2 is (kg)

SI unit of gravitational constant G

(newton (meter)^2)/(kilogram)^2 or Nm^2/Kg^2

Thus, the gravitational constant G is numerically equal to the force of gravitation which exists between two bodies of unit masses kept at a unit distance from each other.

The value of universal gravitational constant G has been found to be $6.67 \times 10^{-1} NM^2/kg^2$.

The extremely small value of gravitational constant (G) tells us that the force of gravitation between any two ordinary objects will be very, very weak

Gravitational Force Holds the Solar System Together

In the solar system, planets move in almost circular orbits around the sun ; and satellites move in circular orbits around the planets. A force (called centripetal force) is needed to make an object move in a circular orbit (or circular path). In the case of planets moving around the sun, the centripetal force is provided by the gravitational force of the sun.

And in the case of satellites moving around the planets, the centripetal force is provided by the gravitational force of the planets. We will now discuss the case of 'the sun and the earth' and that of 'the earth and the moon'. Since the masses of the sun (which is a star) and the earth (which is a planet) are very, very large, they exert very large force on one another.

It is the gravitational force between the sun and the earth which keeps the earth in uniform circular motion around the sun. Similarly, the gravitational force between the earth and the moon makes the moon revolve at uniform speed around the earth. Thus, the gravitational force is responsible for the existence of our solar system.

The tides in the sea formed by the rising and falling of water level in the sea, are due to the gravitational force of attraction which the moon and the sun exert on the water surface in the sea. Thus, Newton used his theory of gravitation to give the first satisfactory explanation of many natural phenomena such as : motion of planets around the sun; motion of moon around the earth ; and formation of tides in the sea (or ocean).

KEPLER'S LAWS OF PLANETARY MOTION

Kepler's first law states that :

The planets move in elliptical orbits around the sun, with the sun at one of the two foci of the elliptical orbit. This law means that the orbit (or path) of a planet around the sun is an ellipse (oval-shaped) and not an exact circle.

An elliptical path has two foci, and the sun is at one of the two foci of the elliptical path (foci is the plural of focus). A planet P is moving around the sun S in an elliptical orbit.

The elliptical orbit has two foci F1 and F2. The sun is situated at the focus F1

2. Kepler's second law states that :

Each planet revolves around the sun in such a way that the line joining the planet to the sun sweeps over equal areas in equal intervals of time. We know that a planet moves around the sun in an elliptical orbit with sun at one of its focus. Now, since the line joining the planet and the sun sweeps over equal areas in equal intervals of time, it means that a planet moves faster when it is closer to the sun, and moves slowly when it is farther from the sun.

3.Kepler's third law states that :

The cube of the mean distance of a planet from the sun is directly proportional to the square of time it takes to move around the sun.

r^(3) α T^2

r^3=constant×T^2

r^3/T^2 =constant

r = mean distance of planet from sun

T = time period of planet (around the sun)

Newton Inverse-Square Rule

The statement made by Newton in his universal law of gravitation that 'the force between two bodies is inversely proportional to the square of distance between them' is called the inverse-square rule.

Consider a planet of mass m moving with a velocity (or speed) v around the sun in a circular orbit of radius r. A centripetal force F acts on the orbiting planet (due to the sun) which is given by:

$F = mv^2/r$

Since the mass m of a given planet is constant, so we can write the above equation as

$F \alpha v^2/r$ ...(1)

Now, if the planet takes time T to complete one revolution (of 2nr) around the sun, then its velocity v is given by :

$v \alpha 2\pi r/T$

Factor 2π is constant $v \alpha r/T$

Take square on both side $v^{2} \alpha r^2/T^2$

By multiply and divide this equation by r

$v^2 \alpha r^3/T^2 \times 1/r$

r^3/T^2 is constant by Keplers 3rd law

$v^2 \alpha 1/r$ ..... (2)

In equation (1) putting 1/r in palce 0f v^2 we get

$$F \alpha 1/r^2$$

FREE FALL

The falling of a body (or object) from a height towards the earth under the gravitational force of earth (with no other forces acting on it) is called free fall. And such a body is called 'freely falling body' (or 'freely falling object'). So, whenever a body (or object) falls towards the earth on its own, we say that it is under free fall or that it is a freely falling body (or freely falling object).

Acceleration due to Gravity (g)

When an object is dropped from some height, its velocity increases at a constant rate. In other words, when an object is dropped from some height, a uniform acceleration is produced in it by the gravitational pull of the earth and this acceleration does not depend on the mass of the falling object.

The uniform acceleration produced in a freely falling body due to the gravitational force of the earth is known as acceleration due to gravity and it is denoted by the letter g .

The value of g does not depend on the mass of the body. T

he value of g changes slightly from place to place but for most of the purposes it is taken as 9.8 m/s. Thus, the acceleration due to gravity, g-9.5 m/s.

Calculation of acceleration due to gravity (g)

If we drop a body (say, a stone) of mass m from a distance R from the centre of the earth of mass M, then the force exerted by the earth on the body is given by universal law of gravitation as :

$F=G\times(M\times m)/R^2$ ...(1)

G = gravitational constant

$F = M \times a$

So $a = F/M$ .....(2)

Put value of F from eq (1) into eq (2)

$a = (G\times M\times m)/(R^2\times m)$

$a = (M)/R^2$

a is known as acceleration due to gravity represented by g

putting g in eq we get

$g=G\times M/R^2$

G = gravitational constant

M = mass of earth

R = radius of earth

Now putting value in above equation

$g=(6.7\times 10^{(-11)})/((6.4\times10^{(6)2}))\ (\times 6\times10^{24})/.$

$g=9.8\ m/s^2$

Equation of motion of freely falling body

For freely falling bodies, the acceleration due to gravity is 'g', so we replace the acceleration 'a' of the equations by 'g'

and since the vertical distance of the freely falling bodies is known as height 'h', we replace the distance 's' in our equations by the height h'.

This gives us the following modified equations for the motion of freely falling bodies:

(i) $v = u + at$ changes to $v = u + gt$

(ii) $s = ut + \frac{1}{2}at^2$ changes to $h = ut + \frac{1}{2}gt^2$

(iii) $v^2 = u^2 + 2as$ changes to $v^2 = u^2 + 2gh$

(a) When a body is falling vertically downwards, its velocity is increasing, so the acceleration due to gravity, g, is taken as positive. That is, Acceleration due to gravity = + 9.8 m/s for a freely falling body

(b) When a body is thrown vertically upwards, its velocity is decreasing, so the acceleration due to gravity, g, is taken as negative. Acceleration due to gravity: for a body thrown upwards That is, 9.8 m/s2

(c) When a body is dropped freely from a height, its initial velocity 'u' is zero.

(d) When a body is thrown vertically upwards, its final velocity 'v' becomes zero.

(e) The time taken by a body to rise to the highest point is equal to the time it takes to fall from the same height

MASS

The mass of a body is the quantity of matter (or material) contained in it. Mass is a scalar quantity which has only magnitude but no direction.

The mass of a body (or object) is commonly measured by an equal arm balance.

The SI unit of mass is kilogram which is written in short form as kg.

Weight

The earth attracts every object with a certain force and this force depends on the mass (m) of the object and the acceleration due to the gravity (g). The weight of an object is the force with which it is attracted towards the earth.

Force = mass x acceleration due to gravity

Force = m x g

the force of attraction of earth on a body is known as weight W of the body,

writing weight W in place of force in the above equation, we get :

Weight, W= m x g

where m = mass of the body

g = acceleration due to gravity

Weight is measured in the same units as force.

SI unit of force is newton (N).

So, the SI unit of weight is also newton which is denoted by the letter N.

Let us calculate the weight of 1 kilogram mass.

Weight is a vector quantity having magnitude as well as direction.

The weight of a body acts in vertically downward direction. The weight of a body is usually denoted by W.

The weight of a body is given by W = m x g, and since the value of g (the acceleration due to gravity) changes from place to place,

therefore, the weight of a body also changes from place to place. Thus, the weight of a body is not constant.

In the interplanetary space, where $g = 0$, the weight of a body becomes zero and we feel true weightlessness. Thus, the weight of a body can be zero.

Weight of an object on Moon

Let the mass of an object be m.

Let its weight on the moon be W^m

Let the mass of the moon be M and its radius be R

By applying the universal law of gravitation, the weight of the object on the

moon will be

$W^m = G \times (M \times m)/R^2$ (1)

Weight actually force with which moon attract the object

Let the weight of the same object on the earth be We. The mass of the earth is 100 times that of moon.

Radius of earth 4times that of moon

Mass of moon is M and mass of earth will be 100M

Radius of moon is R Radius of Earth is 4R

Apply universal law of gravitation

Weight of earth $W_e = G \times (100M \times m)/(4R)^2$

$W_e = G \times (100M \times m)/(16R)^2$ **(2)**

Putting equation (1) and (2)

$W_m/W_e = (G \times M \times m \times (16R^2))/(R^2 \times G \times 100M \times m)$

$W_m/W_e = 16/100$

$W_m/W_e = 1/6$

Weight on moon =1/6 th the weight of earth

Thrust & Pressure

Pressure is the force acting perpendicularly on a unit area of the object. To obtain the value of pressure, we should divide the force acting on an object by the area of the object on which it acts. So, the formula for calculating pressure is

Pressure =Force/Area

This formula gives the relation between pressure, force and area.

The SI unit of measuring force is newton (N), and the

SI unit of measuring area is 'square metre' (m^2),

therefore, the SI unit of measuring pressure is 'newtons per square metre' (N/m^2 or $N\ m^{-2}$) which is also called pascal (Pa).

Thus, 1 pascal = 1 newton per square metre or 1 Pa = 1 N/m2

In the above formula for pressure, if we put the value of force in newtons (N) and the value of area in square metres (m2), then we will get the value of pressure in newtons per square metre (N/m2) or pascals (Pa).

PRESSURE IN FLUIDS

Water is a liquid. When we pour some water on a table, it flows'.

Air is a gas (or rather a mixture of gases). Air flows from one place to another. Those substances which can flow easily are called fluids. All the liquids and gases are fluids. Water and air are the two most common fluids. We have already studied that solids exert pressure on a surface due to their weight. Fluids also have weight. So, fluids (liquids and gases) also exert pressure on the container in which they are enclosed. A fluid liquid or gas) exerts pressure in all directions-even upwards .

BUOYANCY

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

Now to keep the object immersed we have to apply external force from upward direction to overcome buoyant force

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

Take a beaker filled with water. Take an iron nail and place it on the surface of the water . Observe what happens. The nail sinks. The force due to the gravitational attraction of the earth on the iron nail pulls it downwards. There is an up thrust of water on the nail, which pushes it upwards. But the downward force acting on the nail is greater than the up thrust of water on nail so it sinks.

The cork floats while the nail sinks. This happens because of the difference in their densities. The density of a substance is defined as the mass per unit volume. The

density of cork is less than the density of water. This means that the upthrust of water

on the cork is greater than the weight of the cork. So it floats.

The density of an iron nail is more than the density of water. This means that the

upthrust of water on the iron nail is less than the weight of the nail. So it sinks.

Therefore 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.

Archimedes 'Principle

Archimedes' principle states that the upward buoyant force that is exerted on a body immersed in a fluid, whether fully or partially submerged, is equal to the weight of the fluid that the body displaces and acts in the upward direction at the center of mass of the displaced fluid.

When an object is partially or fully immersed in a liquid, the apparent loss of weight is equal to the weight of the liquid displaced by it. If you look at the figure, the weight due to gravity is opposed by the thrust provided by the fluid. The object inside the liquid only feels the total force acting on it as the weight. Because the actual gravitational force is decreased by the liquid's upthrust, the object feels as though its weight is reduced. The apparent weight is thus given by:

Apparent weight= Weight of object (in the air) – Thrust force (buoyancy)

Archimedes's principle tells us that this loss of weight is equal to the weight of liquid the object displaces. If the object has a volume of V, then it displaces a volume V of the liquid when it is fully submerged. If only a part of the volume is submerged, the object can only displace that much of liquid.

Archimedes Principle Formula

In simple form, the Archimedes law states that the buoyant force on an object is equal to the weight of the fluid displaced by the object. Mathematically written as:

$F_b = \rho \times g \times V$.

Where,

- **F_b is the buoyant force**
- **ρ is the density the fluid**
- **V is the submerged volume**
- **g is the acceleration due to gravity**

Archimedes Principle Derivation

The mass of the liquid displaced is.

Mass = Density × Volume = $\rho \times V$

This is because density (ρ) is defined as

Density,ρ = MassVolume = MV

Thus the weight of that displaced liquid is:

Weight = Mass × Acceleration due to gravity

$W = M \times g = \rho \times V \times g$

Thus, from the Archimedes principle, we can write:

The apparent loss of weight = weight of water displaced = $\rho \times V \times g$

Thus, the Thrust force is,

Thrust = $\rho \times V \times g$

Where,

- **ρ is the density of liquid**

V is the volume of liquid displaced

The thrust force is also called the buoyant force because it is responsible for objects to float. Thus, this equation is also called the law of buoyancy.