CHAPTER NOTES - GRAVITATION

INTRODUCTION

We know that an object in circular motion keeps on changing its direction.
Due to this, the velocity of the object also changes.
A force called **Centripetal Force** acts upon the object that keeps it moving in a circular path.
The centripetal force is exerted from the center of the path.
Without the Centripetal Force objects cannot move in circular paths, they would always travel straight.
For Example, The rotation of Moon around the Earth is possible because of the centripetal force exerted by Earth.

Newton's Observations

Why does Apple fall on Earth from a tree? – Because the earth attracts it towards itself.

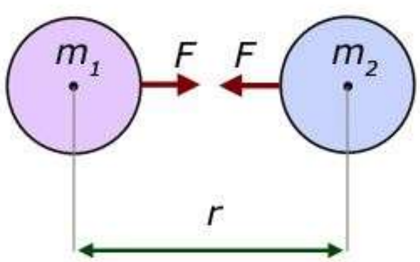
Can Apple attract the earth? - Yes. It also attracts the earth as per Newton's third law (every action has an equal and opposite reaction). But the mass of the earth is much larger than Apple's mass thus the force applied by Apple appears negligible and Earth never moves towards it.
Newton thus suggested that all objects in this universe attract each other. This force of attraction is called **Gravitational Force**.

Universal Law of Gravitation by Newton

According to the universal law of gravitation,

- Every object attracts every other object with a force.
- This force is directly proportional to the product of their masses.
- This force is inversely proportional to the square of distances between them.

Consider the figure given below. It depicts the force of attraction between two objects with masses m_1 and m_2 respectively that are 'r' distance apart.



The figure below describes how the universal law of gravitation is derived mathematically.

$$F \propto m_1 \text{ ------ (i)}$$

$$F \propto m_2 \text{ ------ (ii)}$$

$$F \propto \frac{1}{r^2} \text{ ------ (iii)}$$

From the above equation we can rewrite them as the following:

$$F \ \alpha \ \frac{m_1 m_2}{r^2} ------(iv)$$

If we remove the proportionality we get proportionality constant G as the following:

$$F = G\frac{m_1 m_2}{r^2}$$

The above equation is the mathematical representation of Newton’s universal Law of gravitation

Hence, $G = Fr^2/ m_1 m_2$

SI Unit: $Nm^2 \ kg^{-2}$

Value of **$G = 6.673 \times 10^{-11}$ $Nm^2 \ kg^{-2}$** (was found out by Henry Cavendish (1731- 1810))

The proportionality constant G is also known as the **Universal Gravitational Constant**

<u>Why we study the universal law of gravitation?</u>

It explains many important phenomena of the universe –

- Earth’s gravitational force
- Why the moon always moves in a circular motion around the earth and the sun
- Why all planets revolve around the sun
- How the sun and moon can cause tides

<u>Free Fall</u>

When an object falls down towards the earth under the gravitational force alone, we say the object is in free fall.

The velocity of a freely falling body changes and is said to be accelerated.

- **Acceleration due to gravity** – Whenever an object falls towards the Earth there is an acceleration associated with the movement of the object. This acceleration is called acceleration due to gravity.
- Denoted by: g
- SI Unit: $m \ s^{-2}$

<u>Equations of motion in an object under freefall</u>

1. $v=u+gt$ (coming down)

   $v=u-gt$ (going up)

2. $h= ut + ½ gt^2$ (coming down)

   $h = ut- ½ gt^2$ (going up)

3. $v^2-u^2 =2gh$

[NOTE- At maximum height, v=0 when an object is thrown up]

MATHEMATICAL DERIVATION OF ‘g'

Let an object of mass m is on or near the surface of the earth, and d is the distance between the object and the earth.

As $F = ma \quad (\because a = g) \quad ...(i)$

$F = mg \quad ...(ii)$

and $F = G\frac{Mm}{d^2} \quad (\therefore \text{ Universal law of gravitation}) \quad ...(iii)$

From (*ii*) and (*iii*)

$\therefore \quad mg = G\frac{Mm}{d^2}$

$\therefore \quad g = \frac{GM}{d^2}$

M = Mass of the earth

d = Distance between the object and the earth

G = Gravitational constant

If the object is placed on the earth then $d = R$

(R = radius of the earth)

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

$G = 6.67 \times 10^{-11}\ Nm^2/kg^2$

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

$R = 6.4 \times 10^6\ m$

On substituting the given values

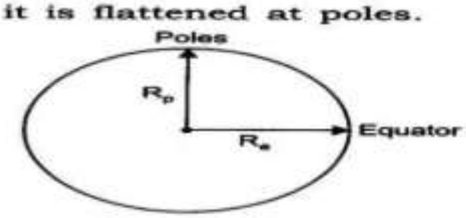
$$g = \frac{6.7 \times 10^{-11} Nm^2\ kg^{-2} \times 6 \times 10^{24} kg}{(6.4 \times 10^6 m)^2}$$

$g = 9.8\ m/s^2.$

Value of ‘g' may vary at different parts of the earth –

- From the equation g = GM/ R^2 it is clear that the value of ‘g' depends upon the distance of the object from the earth's center.
- The value of ‘g’ decreases with height from the surface of earth.
- The value of ‘g’ decreases with depth from the surface of Earth.
- At center of the Earth ‘g’ value is zero.
- This is because the shape of the earth is not a perfect sphere. It is rather flattened at poles and bulged out at the equator.
- Hence, the value of ‘g' is greater at the poles and lesser at the equator.

Earth is not a sphere it is flattened at poles.



Hence R_p – Radius at pole and R_e – Radius at equator

$$R_e > R_p$$

$$g \propto \frac{1}{R}$$

$\therefore$ The value of 'g' is more at poles = (9.9 m/s^2) and less at equator = (9.8 m/s^2)

Mass and Weight

Mass is the measure of object's inertia, more the mass more the inertia.

- It is a property of material , so it does not change with place.
- SI unit is 'kg'.
- It is a scalar quantity.

Weight of an object on earth is the force by which it is attracted towards earth.

- As it is force so it has both magnitude and direction (i.e. downwards).
- SI unit 'N'.
- W = mass x g.
- g changes with location, so does weight.

Weight of an object on the Moon

Just like the Earth, the Moon also exerts a force upon objects. Hence, objects on moon also have some weight. The weight will not be same as than on the earth. So, weight on the Moon can be calculated as -

$$W_M = \frac{GM_M m}{R_M^2}$$

Now,

$$\Rightarrow \frac{W_M}{W_E} = \frac{M_M R_E^2}{M_E R_M^2}$$

Where,

$M_E = 5.98 \times 10^{24}\ kg$
$M_M = 7.36 \times 10^{22}\ kg$
$R_E = 6.4 \times 10^6\ m$
$R_M = 1.74 \times 10^6\ m$

$$\Rightarrow \frac{W_M}{W_E} = \frac{7.36 \times 10^{22} \times (6.4 \times 10^6)^2}{5.98 \times 10^{24} \times (1.74 \times 10^6)^2} = 0.165 \approx \frac{1}{6}$$

Therefore, weight of an object on the moon is $\frac{1}{6}$ of its weight on the Earth.

EXTENDED LEARNING (FOR PRACTICAL ACTIVITY)

Thrust

- The force that acts in the perpendicular direction is called thrust.
- It is similar to force applied to an object
- It is a vector quantity.

Pressure

- The force that acts per unit area of the object is pressure.
- It is the thrust per unit area.
- Pressure is denoted by ‘P'
- P = thrust/ area = force/ area = F/A
- SI unit: N/m^2 or Pa (Pascal)

Why do nails have sharp edges?

We know that pressure is inversely proportional to area. As area increases, pressure decreases and vice versa. So, nails' sharp edges make it easier for them to get into the wall because more pressure is exerted on the wall from a single point.

- **Solids** - They exert pressure on the surface because of their weight.
- **Fluids (gases and liquids)** - They also have weight, therefore, they exert pressure on the surface and the walls of the container in which they are put in.

Buoyancy

- Whenever an object is immersed in a liquid, the liquid exerts a buoyant force or upthrust in the opposite direction of the gravitational force. This is also called the **Force of Buoyancy**.
- It depends upon the density of the fluid.
- Therefore an object is able to float in water when the gravitational force is less than the buoyant force.
- Similarly, an object sinks into the water when the gravitational force is larger than the buoyant force.

Why does an object sink or float on water?

- An object can sink or float on water based on its density with respect to water. The density is defined as mass per unit volume.
- Objects having a density less than water float in it. **For Example**, Cork flows in water because its density is lower than that of water.
- Objects that have a density higher than water sink in it. **For Example**, Iron nail sinks in water because the density of iron is more than water's density.

- Thus, we can conclude that buoyancy depends upon:
  - The density of the liquid
  - The volume of the object (as the volume of object increases, its density decreases and vice-versa)

Archimedes Principle

According to the Archimedes principle, whenever an object is immersed in a liquid (fully or partially), the liquid exerts an upward force upon the object. The amount of that force is equivalent to the weight of the liquid displaced by the object.

This means that if the weight of an object is greater than the amount of liquid it displaces, the object will sink into the liquid. However, if the weight of an object is less than the amount of water it displaces, the object will sink.

- Submarines have a tank called **Buoyancy Tank**. Whenever the submarine needs to be taken inside water the tank is filled which thus increases the weight of the submarine. Similarly, when the submarine is to appear above water the tank is emptied and the weight of the submarine becomes lighter and it rises above the water.
- Ships are heavier than water but their unique shape gives them a large volume. Their volume is larger than their weight and hence the water displaced by a ship provides it with the right upthrust so that it can float on water.

Applications of Archimedes Principle

- In evaluating relative density
- In designing ships and submarines
- In making lactometers and hydrometers

What is relative density?
When density can be expressed in comparison with water's density it is called **Relative Density**. It has no unit because it is a ratio of two similar quantities.

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

$$\text{Relative Denisty} = \frac{\text{Denisty of Substance}}{\text{Denisty of Water}}$$

Why water is chosen as a reference?

Water is present everywhere on earth so it becomes easier to evaluate the density of a substance in relation to water.

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