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GENERAL SCIENCE

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CHAPTER

11

UNITS AND MEASUREMENTS

11.1 Physical Quantities

Anything that can be expressed in numbers is called quantity. Different events in nature take place in accordance with some basic laws. Revealing these laws of nature from the observed events, we need some quantities which are known as physical quantities. E.g. - length, mass, time, temperature, velocity, force etc.

11.2 Units

Measurement of any physical quantity involves comparison with a certain basic, arbitrarily chosen, internationally accepted reference standard called unit. The result of a measurement of a physical quantity is expressed by a number (or numerical measure) accompanied by a unit.

e.g. M = 5 kg.

Here, Kg is unit and it is used 5 times to measure a mass of 5 kg.W

Fundamental or Base Units

Although the number of physical quantities appears to be very large, we need only a limited number of units for expressing all the physical quantities, since they are interrelated with one another.

The units for the fundamental or base quantities are called fundamental or base units. There are 7 fundamental units - **Metre**, **Kilogram**, **Second**, **Ampere**, **kelvin**, **Mole** and **Candela**.

Derived Units

The units of all other physical quantities except fundamental quantities can be expressed as combinations of the base units. Such units obtained for the derived quantities are called derived units. e.g. - Force, Energy, Area, Volume, Power, Work, etc.

Supplementary Units

These are special class of derived units that are regarded as dimensionless. It presently contains only two, purely geometric units – ***radian*** (unit of plane angle) and ***steradian*** (unit of solid angle).

International System of Units (SI)

- The system of units which is at present internationally accepted for measurement is the International System of Units.
- It is built on the earlier MKS (Metre-Kilogram-Second) System and contains **both the base units and derived units.**
- The International System of Units (SI) was formalised in 1960 and has been updated several times to account for development in measurement technology. The recent modifications came in 2018.
- In November 2018, a resolution to redefine four of the seven base units was passed by representatives of 60 countries at the General Conference on Weights and Measures (CGPM) of the International Bureau of Weights and Measures (BIPM).
    - The world's definition of the kilogram, the ampere, the kelvin and the mole were changed and defined in terms of constants that describe the natural world.
        - **The kilogram (kg)** – defined by the Planck constant (h)
        - **The ampere (a)** – defined by the elementary electrical charge (e)
        - **The kelvin (k)** – defined by the Boltzmann constant (k)
        - **The mole (mol)** – defined by the Avogadro constant (NA)
    - The second, metre, and candela were already defined by physical constants and were not subject to correction to their definitions.
- The changes came into force on 20 May 2019 and brought an end to the use of physical objects to define measurement units. India also adopted the same.

Fundamental Units and their Symbols in SI System			
Name of Quantity	**Unit Name**	**Symbol**	**Definition**
Length	Meter	m	It is defined by taking the fixed numerical value of the **speed of light in vacuum c** to be 299,792,458 when expressed in the unit m s^{-1}
Mass	Kilogram	kg	It is defined by taking the fixed numerical value of the **Planck constant h** to be 6.62607015 $\times 10^{-34}$ when expressed in the unit J s, which is equal to kg $m^2 s^{-1}$
Time	Second	s	It is defined by taking the fixed numerical value of the **cesium frequency ∆vCs**, the unperturbed ground-state hyperfine transition frequency of the cesium-133 atom, to be 9,192,631,770 when expressed in the unit Hz
Electric Current	Ampere	A	It is defined by taking the fixed numerical value of the **elementary charge e to be 1.602176634 $\times$ 10^{-19}** when expressed in the unit C
Thermodynamic Temperature	Kelvin	K	It is defined by taking the fixed numerical value of the **Boltzmann constant k** to be 1.380 649 $\times 10^{-23}$ when expressed in the unit J K^{-1}, which is equal to kg m^2 s^{-2} K^{-1}
Amount of Substance	Mole	mol	One mole contains exactly 6.02214076 $\times$ 10^{23} elementary entities. This number is the fixed numerical value of the **Avogadro constant**, when expressed in the unit mol^{-1} and is called the Avogadro number.
Luminous Intensity	Candela	cd	The candela is defined by taking the fixed numerical value of the **luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz, Kcd,** to be 683 when expressed in the unit lm W^{-1}, which is equal to cd sr W^{-1}, or cd sr $kg^{-1}m^{-2}s^3$

Some practical units of length, mass and time

Time	1 solar day = 86400 sec.
	1 year = 365 1/2 solar days
	1 lunar month = 27.3 solar days.
	Tropical year = It is the year in which total solar eclipse occurs.
	Leap year = It is the year in which the month of February is of 29 days. Leap year repeats for every 4 years.

Length	Light year (ly) = distance travelled by light in one year in vaccum.
	1 light year = 9.46 x 1015m
	1 astronomical unit (A.U.) = 1.5 x 1011m
	1 parsec = 3.26 ly = 3.08 x 1016m
	1 nautical mile or seamile = 6076 ft = 1852 m.
	1 micron = 1μm =10-6 m
	1 Angstron (A°) = 10-10 m
Mass	1 Quintol = 102 kg
	1 metric ton =103 kg
	1 Atomic mass unit (amu) or dalton = 1.66 x 10-27 kg
	1 slug 14.59 kg
	1 pound = 0.4537 kg
	1 Chandrashekhar limit = 1.4 times the mass of sun = 2.8 x 1030) kg

TRY SOME QUESTIONS

1. Which of the following is a measure of the rate of change of velocity?
(a) Speed (b) Acceleration
(c) Distance (d) Time

Ans. (b)

2. What is the SI unit of speed?
(a) Metres per second
(b) Kilometres per hour
(c) Miles per hour
(d) Feet per second

Ans. (a)

3. Amongst the following options, which is a unit of time?
(a) Light year (b) Parsec
(c) Year (d) None of these

Ans. (c)

4. The quantity having the same unit in all system of unit is
(a) mass (b) time
(c) length (d) temperature

Ans. (b

5. Average distance of the Sun from the Earth
(a) light year (b) astronomical unit
(c) fermi (d) parsec

Ans. (b)

6. The base quantity among the following is,
(a) Speed (b) area
(c) length (d) weight

Ans. (c)

CHAPTER 12

FORCE AND LAWS OF MOTION

12.1 Force

Any action that causes pull or push on a body is called force. Force is needed in everyday life to push, carry or throw objects, deform or break them.

Force produces any of the following effects on the body. It can

- Change the state of rest or motion – move a stationery body or stop a moving body
- Increase or decrease the speed of the body
- Change the shape and size of the body
- Change the direction of the motion of a moving body.

Force is a **vector quantity** and its SI unit is **Newton**.

1 newton = 1 kg ms^{-2}.

DO YOU KNOW?

- **Scalar quantity -** A quantity that has only magnitude but no particular direction is described as a scalar quantity. Every scalar quantity is one-dimensional. E.g – Speed, volume, mass, time etc.
- **Vector quantity -** A quantity that has both magnitude and direction is described as vector. Vector quantity can be one, two or three-dimensional. E.g. – Force, velocity, acceleration, momentum etc.

12.2 Fundamental or Basic Forces in Nature

Fundamental forces, also called fundamental interactions, in physics are the basic forces that govern how objects or particles interact and how certain particles decay. All the known forces of nature arise from only a small number of these fundamental forces.

At the present stage of our understanding, we know of the following four fundamental forces in nature

- **Gravitational Force (Weakest Force but Infinite Range)**
    - It is the force of mutual attraction between any two objects by virtue of their masses. **It is a universal force**. Every object experience this force due to every other object in the universe.
    - **It is the weakest force** among all existing forces but is **very long-ranged (infinite range).** It is negligible for all lighter and smaller bodies but becomes significant and considerable in all celestial bodies.
    - **Significance:** It governs the motion of the moon and artificial satellites around the earth, motion of the earth and planets around the sun, and, of course, the motion of bodies falling to the earth. It plays a key role in the large-scale phenomena of the universe, such as formation and evolution of stars, galaxies and galactic clusters.
- **Weak Nuclear Forces (Next Weakest but very short range)**
    - These are the forces of interaction between elementary particles of short life times like electron and neutrino. It is not as weak as the gravitational force, but is much weaker than the strong nuclear and electromagnetic forces.
    - **Significance:** It is responsible for radioactive decay and neutrino interactions. It appears only in certain nuclear processes such as β-decay of a nucleus. In β-decay, the nucleus emits an electron and an uncharged particle called neutrino.
- **Electromagnetic Force (Stronger, with infinite range)**
    - Matter consists of elementary charged particles like protons and electrons. Electromagnetic force is the force between such charged particles.
        - When charges are at rest, the electrostatic force is governed by **Coulomb's Law**: There are attractive forces between

unlike charges and repulsive forces between like charges.

- Charges in motion produce magnetic effects and a magnetic field gives rise to a force on a moving charge. Thus, the electric and magnetic effects are inseparable and hence the name electromagnetic.

Electromagnetic force acts over large distances and does not need any intervening medium. It is much stronger than gravitational force and dominates all phenomena at atomic and molecular scales.

- **Significance:** It governs the structure of atoms and molecules, the dynamics of chemical reactions and the mechanical, thermal and other properties of materials. It underlies the macroscopic forces like 'tension', 'friction', 'normal force', 'spring force', etc.

- **Strong Nuclear Force (Strongest but short range)**
  - The force that bind the neutrons and protons together in a nucleus is called the strong nuclear forces. It is the strongest of all fundamental forces but act only if the particles are very close together.
  - It is charge-independent and acts equally between a proton and a proton, a neutron and a neutron, and a proton and a neutron. **It does not act on electrons**.
  - **Significance:** It is responsible for the stability of the nuclei. Recent developments have indicated that protons and neutrons are built of more elementary constituents called **quarks**. These quarks are bound together by the exchange of the strong nuclear force.

Name	Relative Strength	Range	Operates among
Gravitational force	1	Infinite	All objects in universe
Weak nuclear force	10^{25}	Very short, subnuclear size ($\sim 10^{-16}$)	Some elementary particles like electron and neutron
Electromagnetic force	10^{36}	Infinite	Charged particles
Strong nuclear force	10^{38}	Short, nuclear size ($\sim 10^{-15}$)	Nucleons, heavier elementary particles

12.3 Motion

Scalar Quantities: Physical quantities which have magnitude only and no direction are called scalar quantities.

Example: Volume, work, time, power, energy etc.

Vector Quantities: Physical quantities which have magnitude and direction both and which obey triangle law are called vector quantities.

Example: Displacement, acceleration, force, momentum, torque etc.

For example Electric current, though has a direction, is a scalar quantity because it does not obey triangle law.

Note: *Moment of inertia, pressure, refractive index, stress are tensor quantities*.

Distance: Distance is the length of actual path covered by a moving object in a given time interval.

Displacement: Shortest distance covered by a body in a definite direction is called displacement.

- Distance is a scalar quantity whereas displacement is a vector quantity both having the same unit (metre)
- Displacement may be positive, negative or zero whereas distance is always positive. 2- In general, magnitude of displacement $\leq$ distance

Speed: Distance travelled by the moving object in unit time interval is called speed i.e. speed = Distance/Time

It is a scalar quantity and its SI unit is metre/second (m/s).

Velocity: Velocity of a moving object is defined as the displacement of object in unit time interval i.e. velocity = Displacement/Time

It is a vector quantity and its SI unit is metre/second.

Acceleration: Acceleration of an object is defined as the rate of change of velocity of the object i.e. acceleration = Change in Velocity/Time

It is a vector quantity and its SI units is metre / second^2 (m/s^2)

If velocity decreases with time then acceleration is negative and is called *retardation*.

Circular Motion: If an object describes a circular pat (circle) its motion is called circular motion. If the object moves with uniform speed, its motion is uniform circular motion.

Uniform circular motion is an accelerated motion because the direction of velocity changes continuously, though the magnitude of velocity i.e. speed of the body remains unchanged.

Angular Velocity: The angle subtended by the line joining the object from the origin of circle in unit time interval is called angular velocity.

It is generally denoted by ω and $\omega = \theta/t$

If T = time period = time taken by the object to complete one revolution

n = frequency = no. of revolutions in one second.

then $nT = 1$ and $\omega = 2\pi/T = 2\pi n$.

In one revolution, the object travels $2\pi n$ distance.

$\therefore$ Linear speed = $2\pi r/T = \omega r$ = angular speed x radius

12.3 Force and Motion Relation

If an object changes its position or orientation with respect to its surroundings with time, then it is called in motion. E.g., car or bus moves on a road, bird flying in the air etc.

Force and motion are deeply related in nature. It can be said that force is the cause of motion. Suppose something is moving, then it can be easily said that some force must be acting on it or some force must have acted on it which produced this motion.

12.4 Newton's Laws of Motion

The relations between the forces acting on a body and the motion of the body were first formulated by English physicist and mathematician Sir Isaac Newton in 1687.

He gave the following three laws:

Newton's First Law of Motion

Newton's first law states that "**Every Body continues to be in its state of rest or state of motion along a straight line until an external force is applied on it**."

First law is also called law of Galileo or law of inertia.

Inertia: Inertia is the property of a body by virtue of which the body opposes change in its initial state of rest or motion with uniform speed on a straight line.

Inertia is of two types (i) Inertia of rest (ii) Inertia of motion

Some examples of Inertia/first Law:

(i) When a bus starts suddenly, the passengers bend backward. It happens because both the bus and person are at rest. As bus starts moving, the legs of the person start moving along with bus but rest portion of the body has the tendency to remain in rest.

(ii) When a running horse stops suddenly, the rider bends forward.

(iii) When a coat/blanket is beaten by a stick, the dust particles are removed.

- First law gives the definition of force.
- **Force:** Force is that external cause which when acts on a body changes or tries to change the initial state of the body.

  * Push, Pull, tension in a string, tension in a coiled spring, action, reaction, normal reaction, friction are forces;

Momentum: Momentum is the measure of amount/ quantity of motion contained in body. Clearly it is the property of a moving body and is defined as the product of mass and velocity of the body. i.e.

momentum = mass x velocity.

It is a vector quantity. Its SI unit is kgm/s.

- The state of rest or uniform linear motion **both imply zero acceleration**. Thus, the first law of motion can, therefore, be simply expressed as - **"If the net external force on a body is zero, its acceleration is zero. Acceleration can be non-zero only if there is a net external force on the body**."

• Newton's Second Law of Motion

The second law of motion refers to the general situation when there is a **net external force acting on the body**. It relates the net external force to the acceleration of the body and is **based on the Law of conservation of Momentum.**

Momentum: The momentum of a moving body is equal to the product of its mass and its velocity. **It is a vector quantity** having SI unit kg-m/s.

If a body of mass (m) moves with a velocity (v), then momentum (p) is given by p=mv.

Law of conservation of Momentum: if no external force acts upon a system of two (or more) bodies, then the total momentum of the system remains constant.

e.g. – When a man jumps out of a boat to the shore, the boat is pushed slightly away from the shore. The momentum of the boat is equal and opposite to that of the man in accordance with the law of the conservation of the momentum.

The second law of motion states that:

- The rate of change of momentum (dp) of a body is directly proportional to the applied force (F) and takes place in the direction in which the force acts.
- Thus, according to the Newton's second Law,

  Force F ∝ rate of change of momentum

  F ∝ dp/dt (dp = change in momentum and dt = change in time)
- On further simplification,

  force F = ma (m = mass of the body, a = acceleration of the body)

  Thus, if F = 0, Acceleration = 0 and hence, the second law is consistent with the first law.
- **Phenomena based on Second Law:** A cricket player moves his hand backwards on catching a fast cricket ball, because the cricket player increases the time during which the high velocity of moving ball decreases to zero. Thus, the acceleration of the ball is decreased and therefore, the impact of catching the fast-moving ball is also reduced.

If the ball is stopped suddenly then its high velocity decreases to zero in a very short interval of time. Thus, the rate of change of momentum of the ball will be large. Therefore, a larger force would have to be applied for holding the catch that may hurt the palm of the player.

Impulse

If a large force is acting on a body for a very short time, then the product of this large force and time is known as impulse and large force itself is called impulsive force.

Impulse = Change in momentum

= Force × Time duration

It's a vector quantity. Its SI unit is N-s or kg-m/s.

Phenomena based on Impulse: An athlete is advised to come to stop slowly after finishing a fast race, so that the time to stop increases and hence force experienced by him decreases.

Newton's Third Law of Motion

According to **Newtonian mechanics**, force never occurs singly in nature. Force is the mutual interaction between two bodies. Forces always occur in pairs.

Newton's third law explains the relations between these forces and states that - **To every action, there is always an equal and opposite reaction.**

It simply means that **Force on a body A by B is equal and opposite to the force on the body B by A.** The forces on both the bodies act at the same instant and anyone of them may be called an action and the other reaction.

Phenomena based on Third Law: While walking a person presses the ground in the backward direction (action) by his feet, the ground pushes the person in forward direction (reaction) with equal force making a person to walk.

12.5 Common Forces in Mechanics

The several kinds of forces that we encounter in mechanics are broadly divided into **contact or non-contact o**f the two interacting objects.

Contact forces: Normal force, Applied force, Frictional force, Tension force, Spring force, Air Resistance force.

Non-contact forces: Gravitational force, electro-magnetic force, nuclear forces (Discussed earlier)

Small description of contact forces	
Applied Force	It is a force that is applied to an object by a person or another object.
Normal Force	It is the support force exerted upon an object that is in contact with another stable object. It acts perpendicular to the surface.

Small description of contact forces	
Frictional Force	It is the force exerted by a surface as an object moves across it or makes an effort to move across it. Types of frictional force • **Static Friction:** It comes into play between two surfaces in contact before the actual motion starts. It is a self-adjusting force which increases as the applied force is increased. • **Limiting Friction:** It is the maximum force of static friction that comes into play before a body just begins to slide over the surface of another body. It does not depend on the area of contact but on their nature, i.e., smoothness or roughness. • **Kinetic Friction:** When a body moves over the other body, then the force of friction acting between two surfaces in contact in relative motion is called kinetic friction.
Tension Force	It is the force that is transmitted through a string, rope, cable or wire when it is pulled tight by forces acting from opposite ends
Spring Force	It is the force exerted by a compressed or stretched spring upon any object that is attached to it
Air Resistance Force	It is a special type of frictional force that acts upon objects as they travel through the air.

12.6 Circular Motion Forces

Centripetal Force

A body performing circular motion is acted upon by **a force directed along the radius** towards the centre of the circle. This force is called centripetal force. It is a net force that acts on an object to **keep it moving along a circular path**.

Centripetal force = Mass × Centripetal acceleration

$$F = (mv^2)/r = mr\omega^2$$

Where v = linear velocity of the body in circular motion and ω = angular velocity

Example of Centripetal Force

1. If a stone attached to a string is whirled in a circular path, the required centripetal force is supplied by the tension in the string.
2. For the motion of planets around the sun, the required centripetal force is supplied by the gravitational attraction of sun.

Centrifugal Force

It is a force that arises when a body is moving actually along a circular path, by virtue of tendency of the body to regain its natural straight-line path. It is the **apparent outward force** and is regarded as the **reaction of centripetal force**. It acts along the radius and away from the centre of the circle.

Coriolis Force

If the ordinary Newtonian laws of motion of bodies are to be used in a **rotating frame of reference**, **an inertial force**—acting to the right of the direction of body motion for counterclockwise rotation of the reference frame or to the left for clockwise rotation—must be included in the equations of motion. This inertial force is called Coriolis force, **also called Coriolis effect**.

Coriolis force can thus be described as an apparent force caused by a rotating object.

Application: The Coriolis effect is responsible for many large-scale weather patterns on earth. It describes the pattern of deflection taken by objects not firmly connected to the ground as they travel long distances around Earth.

For e.g., Once air has been set in motion by the pressure gradient force, it undergoes an apparent deflection from its path, as seen by an observer on the earth. This apparent deflection is called the "Coriolis force" and is a result of the earth's rotation.

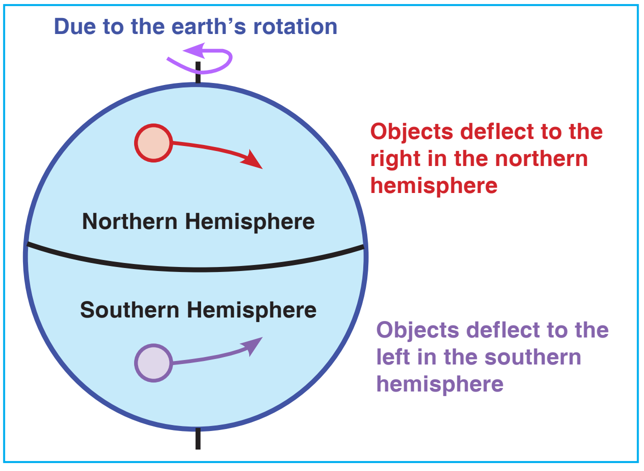


Figure: Coriolis force

As air moves from high to low pressure in the northern hemisphere, it is deflected to the right by the Coriolis force. In the southern hemisphere, air moving from high to low pressure is deflected to the left by the Coriolis force.

TRY SOME QUESTIONS

1. **Which of the following is a measure of the rate of change of velocity?**
(a) Speed
(b) Acceleration
(c) Distance
(d) Time

Ans. (b)

2. **In a rocket, a large volume of gases produced by the combustion of fuel is allowed to escape through its tail nozzle in the downward direction with the tremendous speed and makes the rocket to move upward**
(a) Moment of inertia
(b) Conservation of momentum
(c) Newton's third law of motion
(d) Newton's law of gravitation

Ans. (b)

3. **When a balloon held between the hands is pressed, its shape changes. This happens because:**
(a) Balanced forces act on the balloon
(b) Unbalanced forces act on the balloon
(c) Frictional forces act on the balloon
(d) Gravitational force acts on the balloon

Ans. (a)

4. **Which of the following situations involves the Newton's second law of motion?**
(a) A force can stop a lighter vehicle as well as a heavier vehicle which are moving
(b) A force exerted by a lighter vehicle on collision with a heavier vehicle results in both the (vehicles coming to a standstill
(c) A force can accelerate a lighter vehicle more easily than a heavier vehicle which are moving
(d) A force exerted by the escaping air from a balloon in the downward direction makes the balloon to go upwards

Ans. (c)

5. **A passenger in a moving train tosses a coin which falls behind him. Observing this statement what can you say about the motion of the train?**
(a) Accelerated
(b) Retarded
(c) Along circular tracks
(d) Uniform

Ans. (a)

CHAPTER 13

GRAVITATION

13.1 Gravitation

Gravitation is defined as the *non-contact force of attraction* between any two bodies in the universe (no matter how far the bodies are). The earth attracts (or pulls) all the bodies towards its centre. The force with which the earth pulls the bodies towards it, is called the gravitational force of earth or the gravity of the earth.

13.2 Universal Law of Gravitation (Newton's Law)

Newton gave the Universal Law of gravitation after observing an apple falling from the tree. According to this law.

The attractive force between any two objects in the universe is directly proportional to the product of their masses and inversely proportional to the square of distance between them.

Consider two bodies A and B having masses m_1 and m_2, whose centres are at a distance r from each other.

Gravitational Force, $F \propto (m_1 m_2)/r^2$

$$\Rightarrow \quad F = (G\, m_1 m_2)/r^2$$

Where, G is universal gravitational constant. The value of G is 6.67×10^{-11} Nm^2kg^{-2}.

The law of gravitation is applicable for all the bodies, irrespective of their size, shape and position.

Gravitational force between hollow sphere and a point mass

- The force of attraction between a hollow spherical shell of uniform density and a point mass situated outside is just as if the entire mass of the shell is concentrated at the centre of the shell.
- The force of attraction due to a hollow spherical shell of uniform density, on a point mass situated inside it is zero.

Acceleration Due to Gravity (g)

Whenever an object falls towards the earth, an acceleration is involved. This acceleration is due to the earth's gravitational force and is called the acceleration due to gravity. It is independent of size, shape and mask of the body.

It is denoted by g and its SI unit is m/s^2. It is a vector quantity and its direction is towards the centre of the earth.

Relation Between 'G' and 'g' (Acceleration Due to Gravity)

Let g be the acceleration due to gravity on the earth's surface. Let M be the mass of the earth of radius R and m be the mass of the body.

On the surface of earth:

Weight of the body = gravitational force of attraction.

$$mg = G.Mm/R^2$$

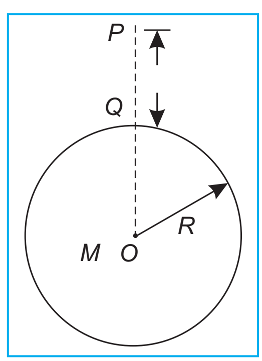
$$\mathbf{g = G\, M/R^2}$$

The value of g changes slightly from place to place. The value of g is taken to be 9.8 m/s^2 for all the practical purposes at the earth's surface

Variations of g

The value of acceleration due to gravity (g) varies as we go above or below the surface of the earth.

Variation of g with Altitude



Consider earth to be a sphere of radius R and mass M.

The acceleration due to gravity on the surface of earth (point Q in Fig.) is

$$g = G\, M/R^2 \qquad (1)$$

Consider a point P at a height h above the surface of the earth. The acceleration due to gravity at point P is

$$g_h = G\,M/(R + h)^2 \qquad (2)$$

Dividing (2) by (1)

$$g_h/g = R^2/(R + h)^2$$

$$g_h = (R^2/(R + h)^2) \times g$$

$$\therefore \quad \boldsymbol{g_h < g}$$

Thus, as we go above the earth's surface acceleration due to gravity goes on decreasing.

On solving the above relation

$$\boldsymbol{g_h/g = (1 + h/R)^{-2}}$$

When h < < < R higher powers of h/R can be neglected

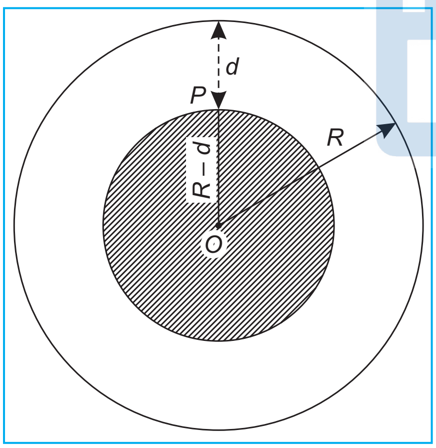
∴ sing binomial theorem

$$g_h = \left(1 - \frac{2h}{R}\right) g$$

Using this relation value of acceleration due to gravity can be determined when h is small as compared to R.

Variation of g with Depth

Consider earth to be a sphere of radius R and mass M.



The acceleration due to gravity at the surface of the earth is $g = G\,M/R^2$

If ρ is the density of the earth, density (ρ) = mass (M) /volume (V)

$$V \text{ of earth} = (4/3)\,\pi\,R^3$$

$$\therefore \quad M = (4/3)\,\pi\,R^3\,\rho$$

$$\boldsymbol{g = (4/3)\,\pi\,R\,\rho\,G}$$

Consider a point P which is inside the earth below the earth's surface at depth d. Its distance from point O is (R–d).

A body at point P will experience force only due to the portion of earth of radius (R–d). The outer spherical shell, whose thickness is d, will not exert any force on the body at point P.

Let **M'** be the mass of the earth of portion of radius (R-d)

$$\therefore \quad M' = (4/3)\,\pi\,(R - d)^3\,\rho$$

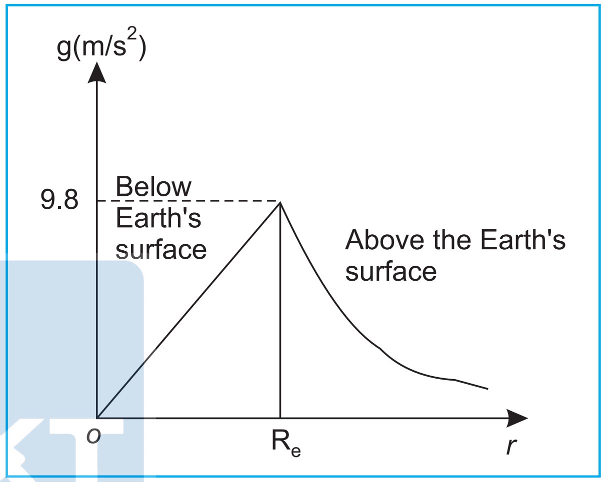
Then $\quad g_d = GM'/(R - d)^2$

$$\therefore \quad \boldsymbol{g_d = (4/3)\,\pi\,(R\text{-}d)\,\rho\,G}$$

Dividing g_d and g

$$g_d/g = (R - d)/R \quad \Rightarrow \quad \boldsymbol{g_d = (1 - d/R)g}$$

Therefore, the value of acceleration due to gravity decreases with depth.



- **At centre:** The acceleration due to gravity at the centre of earth can be found by substituting d = R in

$$g_d = (1 - d/R)g$$

$$\Rightarrow \quad g_d = (1 - R/R)g$$

$$\Rightarrow \quad \boldsymbol{g_{centre} = 0}$$

- **At poles:** Earth is flattened at poles. Thus, radius of earth is less at poles than at equator. Hence, the value of g is less at equator than poles.

INTERESTING FACTS

Variation in *g* (weight = mg):

(i) Value of *g* decreases with height or depth from earth's surface.

(ii) *g* is maximum at poles.

(iii) *g* is minimum at equator.

(iv) *g* decreases due to rotation of earth.

(v) *g* decreases if angular speed of earth increases and increases if angular speed of earth decreases.

If angular speed of earth becomes 17 times its present value, a body the equator becomes weightless.

Weight of a body in a lift

1. If lift is stationary or moving with uniform speed (either upward or downward), the apparent weight of a body is equal to its true weight.
2. If lift is going up with acceleration, the apparent weight of a body is less than the true weight.
3. If lift is going down with acceleration, the apparent weight of a body is less than the true weight
4. If the cord of the lift is broken, it falls freely. In this situation the weight of a body in the lift becomes zero. This is the situation of weightlessness.
5. While going down, if the acceleration of lift is more than acceleration due to gravity, a body in the lift goes in contact of the ceiling of lift.

Some Major Applications of Gravitational Force and Gravity

Gravitational force governs the motion of the moon and artificial satellites around the earth, motion of the earth and planets around the sun, and, of course, the motion of bodies falling to the earth

Kepler's Laws of Planetary Motion

Johannes Kepler gave three laws regarding motion of the planets around the sun.

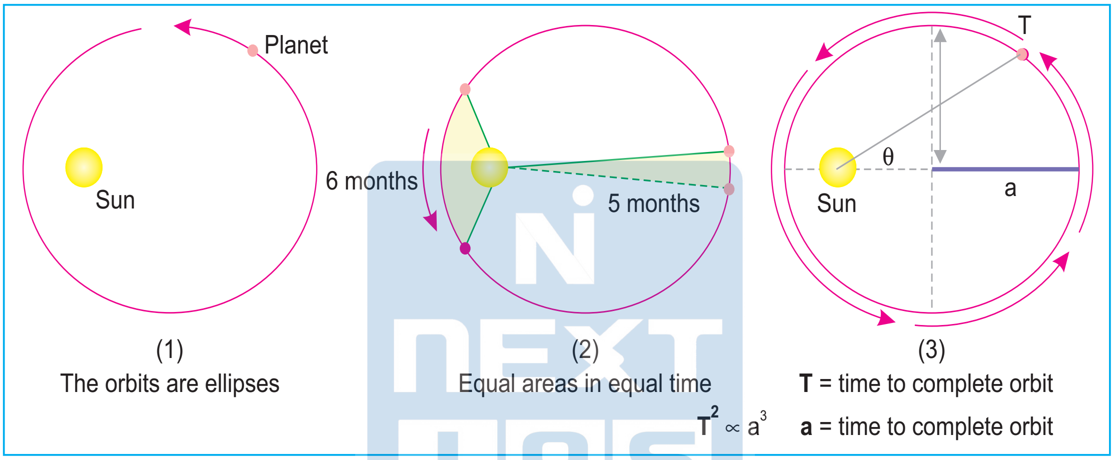


Figure: Kepler's 3 Laws of Planetary Motion

First Law (Law of Orbits)

Planet revolves in an elliptical path around the sun, the sun being at one of the two foci of the ellipse.

Second Law (Law of Areas)

The radius vector of any planet relative to the sun sweeps out equal area in equal time.

A consequence of this law is that the speed of planet increases when the planet is closer to the sun and decreases when the planet is far away from sun.

Speed of a planet is maximum when it is at perigee and minimum when it is at apogee.

Third Law (Law of Periods)

The square of the period of revolution of any planet around the sun is proportional to the cube of the semi-major axis of the elliptical orbit.

i.e., $T^2 \alpha a^3$ $T^2 = Ka^3$

where, a= length of semi-major axis and T= time period of the planet and K = Kepler's constant.

Clearly distant planets have larger period of revolution. The time period of nearest planet Mercury is 88 days where as time period of farthest planet Pluto is 247.7 years.

Orbital Velocity

Orbital velocity of a satellite is the maximum velocity required to put the satellite into a given orbit around the earth. It is denoted by V_o and given by

$$V_o = R \sqrt{(g/R_e+h)}$$

Where, R_e = radius of earth

h = height of the satellite from the earth's surface.

If the satellite is revolving near the earth's surface, then orbital velocity = $\sqrt{(g Re)}$ = 7.92 km/hr.

Note: If v is the speed of a satellite in its orbit and V_o is the orbital velocity required orbital velocity to move in the orbit, then

- If $v < V_o$, then satellite will move on a parabolic path and satellite falls back to the earth.
- If $v = V_o$, then satellite will revolve in a circular path/orbit around the earth.

Orbital speed of a satellite

(i) Orbital speed of a satellite is independent of its mass. Hence satellites of different masses revolving in the orbit of same radius have same orbital speed.

(ii) Orbital speed of a satellite depends upon the radius of orbit (height of satellite from the surface of earth). Greater the radius of orbit, lesser will be the orbital speed.

The orbital speed of a satellite revolving near the surface of earth is 7.9 km/sec.

Period of Revolution of a satellite: Time taken by a satellite to complete one revolution in its orbit is called its period of revolution.

i.e. period of revolution = circumference of orbit / orbital speed

(i) Period of revolution of a satellite depends upon the height of satellite from the surface of earth. Greater the height, more will be the period of revolution.

(ii) Period of revolution of a satellite is independent of its mass.

The period of revolution of satellite revolving near the surface of earth is 1 hour 24 minute (84 minute)

Escape Velocity / Escape Speed / second cosmic velocity

Escape speed on the earth (or any other planet) is defined as the **minimum speed** with which a body is to be projected vertically upwards from the surface of the earth (or any other planet), so that it just crosses the gravitational field of the earth and never returns on its own.

Escape velocity or speed Ve = $\sqrt{(2gR)}$

Where, g = acceleration due to gravity on the earth or planet

R = radius of earth or planet

Interesting Facts

- Escape velocity is independent of the mass, shape and size of the body and its direction of projection.
- For earth, escape velocity = 11.2 km / s.
- For moon, escape velocity = 2.4 km/s.
- If the orbital velocity of a satellite is increased to $\sqrt{2}$ times (increased by 41%), the satellite will leave the orbit and escape.

TRY SOME QUESTIONS

1. The law of gravitation describes the gravitational force between
(a) any two bodies having mass
(b) earth and point mass only
(c) earth and Sun only
(d) two charged bodies only

Ans. (a)

2. The Earth's atmosphere is held by the
(a) Wind
(b) Clouds
(c) Earth's magnetic field
(d) Gravity

Ans. (d)

3. Which of the following is true when a Mango falls from a Mango Tree?
(a) Only the Earth attracts the Mango.
(b) Only the Mango attracts the Earth.
(c) Both Mango and Earth attract each other
(d) Both Mango and Earth repel each other

Ans. (c)

4. The gravitational force between two bodies does not depend on
(a) their masses
(b) their separation
(c) the product of their masses
(d) the medium between two bodies

Ans. (d)