2.2 NEWTON'S LAWS OF MOTION

Sir Isaac Newton (1642-1727) made a systematic study of motion and extended the ideas of Galileo (1564-1642). He summed up Galileo's observation in his three laws of motion which form the foundation of Newtonian mechanics.

Galileo's conclusions are:

a) An object at rest continues to be at rest until and unless a force is exerted by another object.
b) An object set in motion retards and eventually stops if there is a force to oppose its motion.
c) An object set in motion moves with constant velocity if there is no net force acting on it.

These observations are summed up in Newton's first law of motion.
It states that

"Every body continues to be in its state of rest or of uniform motion in a straight line unless compelled by an unbalanced external force."

It is 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.

Mathematically, $\Sigma F = 0 \rightarrow a = 0$
$\Sigma F \neq 0 \rightarrow a \neq 0$

i.e. a body at rest tends to remain at rest and a body which is moving continues to move.

The intrinsic property of material body which resists a change in its state of rest or of uniform motion along a straight line is called **inertia**

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Inertia is a natural tendency of the body. Mass is taken as a quantitative measure of inertia of a material body. The larger the mass of a body the greater the difficulty in bringing about a change in its state of motion, i.e. the mass is a measure of inertia.

There are two types of inertia
a) Inertia of rest
b) Inertia of motion

The tendency of a body at rest to preserve its state of rest is called inertia of rest.

Example:

a) A passenger standing or sitting in a bus or a train falls back, when it starts suddenly. This is because the lower part of the body moves forward with the bus while the upper part of the body continues to be at rest due to inertia.
b) A coin is placed over a card on a tumbler. If we flip the card quickly away with a finger the coin falls into the tumbler as the card moves away quickly.

Inertia of Motion:

The tendency of a moving body to preserve its motion in a straight line with uniform velocity is known as inertia of motion.

Example:

a) A person in a moving vehicle falls forward when it suddenly stops. This is because the lower part of the person comes to rest with the vehicle while the upper part of the body moves forward due to inertia of motion.

b) Before taking a long jump an athlete runs some distance so that the inertia of motion might help him to jump longer distance.

Force:

Force is regarded as the cause of motion we can visualize a force as a push, a pull, a stretch or a squeeze and it can do one or more of the following when applied on an object. It may

1) Produce or tend to produce the motion.
2) Stop or tend to stop the motion
3) Speed up or slow down a moving object
4) Change the direction of the motion

Thus **"Force is a physical cause which changes or tends to change the state of rest or of uniform motion or direction of motion of an object."**

Fundamental forces in nature:

a) **Gravitational force**: It is the force of attraction between any two bodies in the universe. It arises by virtue of their mass.
b) **Electromagnetic force**: It is the force of interaction due to inter between two charged particles.
c) **Strong nuclear forces**: It is the binding force responsible for binding the nucleons together.
d) **Weak nuclear forces**: It arises due to weak interaction.

Momentum:

Consider a car and a truck moving with the same speed. The force required to stop the truck is more than that required to stop the car. The reason being that the truck has a greater mass than the car. Thus the force required to stop a moving object depends on its mass.

It is a matter of common experience that the force required to stop a moving object also depends on its velocity.

Suppose the car is moving slowly a small force is required to stop it. If the car is moving with a high speed a much greater force is required to bring it to rest.

Thus the force required to stop a moving object also depends on its velocity.

Therefore to explain the action of a force on a body Newton introduced the concept known as **momentum**.

Momentum is the quantity of motion associated in the body and it is defined as the product of mass and velocity of a body. **P = m v**

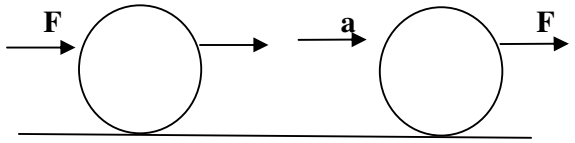
It is a vector quantity and it is the direction of velocity. It is measured in **kg ms^{-1}**.

Newton's Second Law:

The second law of motion deals with the measurement of force. It gives a quantitative relation between the force applied to the body and the resistance effect produced in it.

Statement:

"The rate of change of momentum of a body is directly proportional to the impressed force and takes place in the direction of the force."



Consider a body of mass 'm' moving with an initial velocity 'u' it is accelerated to velocity 'v' in a time 't' by the application of a constant force F. Let 'a' be the acceleration of the body, then

Initial momentum of the body = mu

Final momentum of the body = mv
Therefore, change in momentum in 't' seconds is mv – mu.

According to Second law of motion,

$$F \alpha \text{ rate of change of momentum}$$

$$F \alpha \frac{mv - mu}{t}$$

$$F \alpha m \frac{(v - u)}{t}$$

$$F \alpha ma, \quad \text{because, } \frac{v - u}{t}$$

In SI units, k = 1
Therefore, **F = ma**

Thus force is measured as the product of mass and acceleration with which the body moves. The SI unit of force is **newton (N).**

Weight:

We know that any body on the surface of the earth is pulled towards the center even if the body is at rest. This force with which a body is pulled towards the center of the earth is called the weight of the body.

The weight of a body is the gravitational force exerted on it by the earth.

Distinction between mass and weight

Mass	Weight
a) Mass of a body is the amount of substance in the body which measures inertia of the body.	a) Weight of a body is the force with which it is attracted by the earth towards the center.
b) Mass is a scalar quantity	b) Weight is a vector quantity
c) Mass of a body is same at all place.	c) Weight of a body depends on 'g' which varies from place to place.
d) Mass of a body is measured with a common balance.	d) Weight of a body is measured with a spring balance.

Ex ; If m=2kg on the earth surface then weight
W =mg =2x9.8 = 19.6 N.

Newton's third law of motion:

When ever a force is applied, there are two bodies involved in the process, i.e., the body which applying the force and the body on which the force is applied.

Example:
a) When a foot ball is kicked, there are two bodies involved, one the foot ball and the other player.
b) A hammer drilling a nail.

"For every action there is always an equal and opposite reaction."

In the statement action and reaction here refer to forces. When one object exerts a force on a second object, the second object exerts an equal but opposite force on the first.

The two forces are always equal and opposite.

Thus in nature force always occur in pairs, one action and the other reaction. The forces of action and reaction are simultaneous.
Even though the action and reaction are equal and opposite they never cancel each other because they never act on the same body.

Examples:

a) A swimmer while swimming pushes water backwards. In reaction to this water pushes the swimmer forward.

b) The upward thrust of a rocket is caused by the rapidly escaping gases through the nozzles at the rear of the rocket.

c) When one walks the foot pushes backwards on the earth and the earth exerts an equal but opposite force forward on the walker.

Conservation of momentum:

It states that **"If no net external force acts on a system, then the momentum of that system is constant regardless of any interaction between the parts of the system."**

In a closed system containing particles total moment remain constant.

Momentum **P = mv** = constant

Ex: Rockets move upwards using the principle of conservation of momentum.

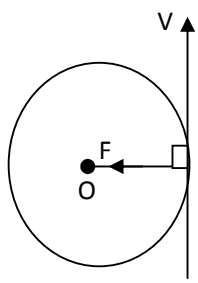
Circular Motion:

In circular motion of an object two kinds of forces occur.

1) **Centripetal force**:

When a body moves along a circular path with uniform speed its direction changes continuously, i.e. velocity keeps on changing on account of a change in direction.

According to Newton's first law of motion, a change in the direction of motion of the body can take place only if some external force acts on the body.



Thus a particle performing circular motion is acted upon by a force directed along the radius towards the center of the circle.

This force is called the centripetal force.

If 'm' is the mass of the particle the magnitude of centripetal force is given by,

Centripetal force = mass x centripetal - acceleration.

$$\mathbf{F = m\,(v^2 / r);\ F = m\,r\,\omega^2} \quad \text{(because } v = r\,\omega\text{)}$$

Centripetal force in different situations:

Situation	Centripetal force
A particle tied to a string and whirled in a horizontal circle.	Tension in the string.
Vehicle taking a turn on a level road.	Frictional force exerted by the road on the tyres.
A vehicle on a speed breaker.	Weight of the body or a component of weight.

Revolution of earth around the sun.	Gravitational force exerted by sun.
Electron revolving around the nucleus in an atom.	Coulomb attraction exerted by the protons on electrons.

Important Features:

a. If a moving particle comes to stand still, i.e. $v \rightarrow 0$, the particle will move along the radius towards the center and if radial acceleration a_r is zero, the body will fly off along the tangent. So, a tangential velocity and a radial acceleration (hence force) is a must for uniform circular motion.

b. The work done by the centripetal force is always zero as it is perpendicular to velocity and displacement.

Further by work-energy theorem as

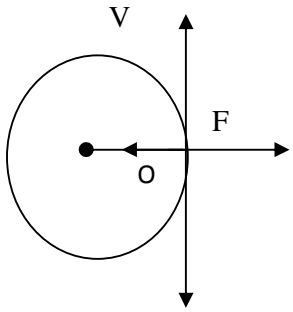
Work done = change in kinetic energy

$\Delta K = 0$ (because $\Delta W = 0$)

i.e. K (KE) remains constant.

2) **Centrifugal force**:

Centrifugal force can be defined as the radically directed outward force acting on a body in circular motion, as observed by a person moving with the body.



Centrifugal force on string

Centrifugal force = Mass x centrifugal - acceleration.

$F = m r \omega^2$

Or $F = mv^2 / r$

Or $\mathbf{F = mr\omega^2}$

In an inertial frame, the centrifugal force does not act on the object.

Applications of uniform circular motion

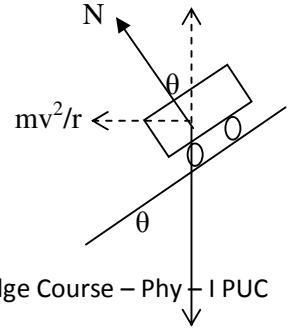
Circular turning of Roads:

When vehicles go through turns, they travel along circular arc. There must be some force which will provide required centripetal acceleration. If the vehicles travel in horizontal circular path, this resultant force is also horizontal. The necessary centripetal force is being provided to the vehicles by the following three ways.

1. By friction only.
2. By banking of roads only.
3. By friction and banking of roads both

In real life the necessary centripetal force is provided by friction and banking of roads both.

By banking of roads, friction is not always relied at circular turns if high speed and sharp turns are involved. To avoid dependence on friction, the roads are banked at the turns so that the outer part of the road is slightly raised comparatively to the inner part.



Applying Newton's second law along the radius and the first law in the vertical direction.

$N \sin \theta = mv^2 / r$

and $N \cos \theta = mg$

From these two equations, we get

$\tan \theta = v^2 / rg$ … (1)

or $\mathbf{v = \sqrt{rg \tan \theta}}$ … (2)

mg

NEWTON'S LAWS OF MOTION

Newton's laws are a set of statements and definitions that we believe to be true because the results they predict are found to be in very exact agreement with experiment over a wide range of conditions.

First Law

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.

INTERTIA
It is the property of a body to resist the change in its state of rest or uniform motion.

Inertia of rest
It is the inability of a body to change by itself, its state of rest. This means a body at rest remains at rest and cannot start moving on its own.

Inertia of motion
It is the inability of a body to change by itself its state of uniform motion, i.e. a body in uniform motion can neither accelerate nor retard on its own and come to rest.

Inertia of direction
It is the inability of a body to change by itself its direction of motion, i.e. a body continues to move along the same straight line unless compelled by some external force to change it.

Second Law

The rate of change of momentum of a body is directly proportional to the applied force and takes place in the direction in which the force acts.

Weight
W = mg

Force
F = ma

Momentum
It is the product of mass and velocity.
p = m x v

Conservation of linear momentum
According to this principle, in an isolated system, the vector sum of the linear momenta of all the bodies of the system is conserved and is not affected due to their mutual action and reaction.

Impulse
It is the change in momentum.
Impulse = Force x time duration
Or, Ft = mv - mu

Third Law

To every action, there is always an equal and opposite reaction.

2.2 Questions:

1. What is the significance of Newton's first law?
2. What is the direction of momentum?
3. Why does an electric fan continue to run after switching off the current?
4. Two bodies of masses in the ratio 2:3 are moving with equal moment in the same direction. What is the ratio of their velocities?
5. Name the basic forces in nature.
6. A person jumping out of a moving bus runs a few steps before coming to rest. Why?
7. Why does a gun recoil after firing?
8. Which principle is used in rocket propulsion?
9. A thief jumps from the roof of a house with a box of weight 'w' on his head. What will be the weight of the box as experienced by the thief during the jump?
10. Can a body remain at rest position when external forces are acting on it?
11. Do action and reaction act on the same body?
12. Why a light rifle gives more jerk than a heavy rifle?
13. A body having a momentum p hits a body and its momentum becomes (-p) what is the change in the momentum of the ball ?
14. A force of 5N acts on a body of mass 2 kg what is the acceleration produced in m/s^2.
15. If the mass and force are doubled, the acceleration will become, same as before

Answers.

2.2 Newton's laws of motion

1. It gives the definition of inertia and explains the importance of force.
2. Momentum is always in the direction of velocity $p = mv$.
2. Due to inertia of motion.
3. $m_1v_1 = m_2v_2$
   $v_1/v_2 = 3/2$.
4. a) Gravitational force . b) Electromagnetic force
   c) Strong nuclear force d) Weak nuclear force .
5. Due to inertia of motion.
6. Due to conservation of momentum.
7. Law of conservation of momentum.
8. zero
9. Yes when net force is zero .
10. No they never act on the same body
11. a=F/m
12. -2p
13. 2 ms^{-2}