Laws of motion

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Note : The notes given in this file is no substitute to the much detailed discussion held in the online/contact classes with active participation of students. It , at best, serves the purpose of ready reference for important concepts/derivations covered in the classes.

Newtons first law of motion

Every body continues to be in a state of rest or of uniform motion in a straight line unless exerted upon by an external force.

Analysis

- First law gives qualitative introduction of force.
- The property of a body by which it tends to continue its state (of rest or of uniform motion in a straight line) is called inertia.
- Equilibrium is a state characterized by the net force acting on the body being zero. A body in equilibrium continues to remain at rest or move with uniform velocity in a straight line

Inertia

The property of a body by which it tends to continue its state (of rest or of uniform motion in a straight line) is called inertia.

There are three types of inertia

Inertia of rest : The tendency of a body to remain in its state of rest unless acted upon by an external force.
Example : When a bus suddenly starts, a passenger standing in it falls backward.

Inertia of motion : The tendency of a body to continue in its state of uniform motion in a straight line unless acted upon by an external force.
Example : A passenger falls forward when a moving bus stops suddenly.

Inertia of direction : The tendency of a body to continue moving in the same direction unless an external force changes its direction.
Example : When a car takes a sharp turn, passengers are thrown outward.

Note It may be noted that inertia of direction is sometimes considered to be inherent (a part of) the inertia of motion.

Linear momentum (p)

Linear momentum is defined as the product of mass of a body and its velocity.

$$\bar{p} = m\bar{v}$$

- linear momentum is a vector quantity
- SI unit of linear momentum is kg ms^{-1}
- It is also informally called 'quantity of motion' in a body
- Change in linear momentum of a body may be due to
  - (a) Change in its mass
  - (b) Change in magnitude of velocity
  - (c) Change in its direction of velocity

Newton's second law :

Rate of change of linear momentum of a body is directly proportional to the net external force acting on it and takes place in the direction of the applied force.

$$\boldsymbol{F}_{\text{net}} = k\frac{d\boldsymbol{p}}{dt}$$

Analysis

- Newton's 2nd law gives the quantitative introduction of force
- Force is the cause of change in the state of any body
- Force is a vector quantity
- SI unit of force is newton (N)

Derivation of $\boldsymbol{F} = m\boldsymbol{a}$

Considering a body of mass m subjected to a net force $\boldsymbol{F}$. From Newton's second law of motion we get

$$\boldsymbol{F}_{\text{net}} = k\frac{d\boldsymbol{p}}{dt}$$

Using the relation $\boldsymbol{p} = m\boldsymbol{v}$,

$$\boldsymbol{F}_{\text{net}} = k\frac{d(m\boldsymbol{v})}{dt}$$

When mass of the body remains constant during its motion

$$\boldsymbol{F}_{\text{net}} = k\, m\frac{d\boldsymbol{v}}{dt}$$

Using the relation $\boldsymbol{a}$ = d$\boldsymbol{v}$/dt

$$\boldsymbol{F}_{\text{net}} = k\, m\boldsymbol{a}$$

The value of k is set equal to 1 in defining 1 newton as the amount of force required to cause an acceleration of $1 ms^{-2}$ in a body of mass 1 kg. Therefore

$$\boxed{\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}}$$

Impulse (J)

Impulse is defined as the product of force and the small interval of time for which the force acts on a body.

$$\boldsymbol{J} = \boldsymbol{F}\ \mathrm{d}t$$

$$\boldsymbol{F} = \frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t}$$

$$\boldsymbol{J} = \frac{\mathrm{d}\boldsymbol{p}}{\mathrm{d}t}\mathrm{d}t$$

$$\boldsymbol{J} = \mathrm{d}\boldsymbol{p}$$

$$\boldsymbol{J} = \boldsymbol{p}_{\mathrm{f}} - \boldsymbol{p}_{\mathrm{i}}$$

Impulse is equal to change in momentum of the body.

SI unit of impulse is Ns or $kgms^{-1}$

Applications / examples of impulse

- Catching : When a player attempts a catch he draws his hands back. This allows greater time to complete the catch and reduces the force on the ball preventing it from bouncing off the hand and lesser force on the hand to safely complete the catch.

- Shock absorbers : When the vehicle moves over rough terrain it undergoes change in momentum. Due to shock absorbers, this change in momentum takes places over a longer interval of time thereby providing a smooth ride and preventing damage to vehicle.

- Soft packing : Fragile articles are packed by stuffing loose paper or cotton on bubble wrap around them. This is done so that in case of an impact the time of interaction increases and the articles experience less force.

Law of conservation of linear momentum

If the net force acting on a system (or a body) is zero then its total linear momentum remains constant

From Newton's second law of motion, the net force acting on a body and the linear momentum of the body are related as

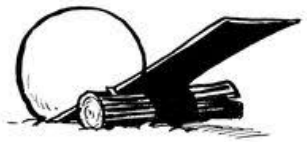
$$\boldsymbol{F}_{\text{net}} = \frac{d\boldsymbol{p}}{dt}$$

If the net force acting on the body is zero, then

$$\frac{d\boldsymbol{p}}{dt} = 0$$

This implies that the momentum of the body or the system is constant

$$\boldsymbol{p}_{\text{final}} = \boldsymbol{p}_{\text{initial}}$$



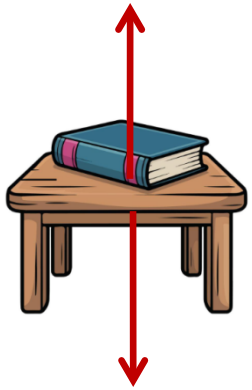
Third law of motion

Action and reaction are two forces of equal magnitude, opposite direction and acting on two different bodies.

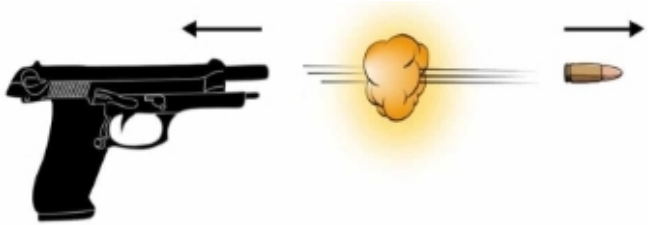
$$F_{\text{action}} = -F_{\text{reaction}}$$

Examples

1. When a book is placed on a table the force exerted by the book on the table is action and the force exerted by the surface of the table n the book is the reaction.



2. When we walk on a ground force exerted by us on the ground is action and the force exerted by the ground on us is the reaction
3. When a bullet is fired from a gun, force exerted by the gun on the bullet fires the bullet and the force exerted by the bullet on the gun causes the gun to recoil .



Third law of motion

When a bouncer hits the helmet, force exerted by the helmet brings the ball to rest and force exerted by the ball causes the impact on the batter !

The players therefore develop the technique to leave it safely !

Contact and non-contact forces

Contact forces : Forces that act between two objects only when they are in physical contact with each other.

They arise due to the direct interaction between the surfaces of the bodies.

Examples : Frictional force, buoyant force, normal reaction, tension in the string, force exerted by a spring etc.

Non-contact forces : Forces that act between two objects without any physical contact or touching.

They act through a field or space surrounding the object.

Examples : Electrostatic force, magnetic force, gravitational force etc.