NEWTON'S LAWS OF MOTION

Aristotle's Fallacy – Aristotle held the view that 'an external force is required to keep a body in motion'.

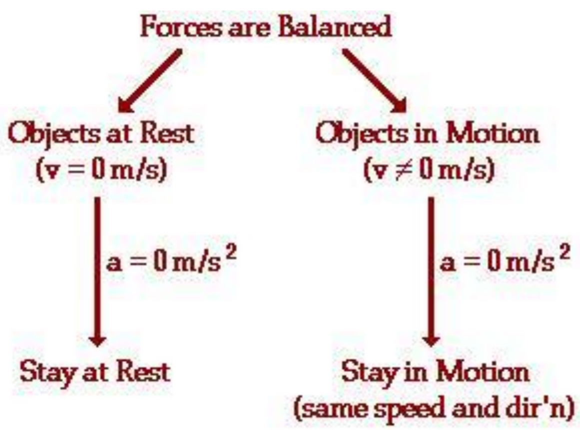
Galileo's Law of inertia – If the net force is zero, then a body at rest continues to remain at rest and a body in motion continues to move with uniform velocity. This property of the body is known as **inertia**. Galileo's idea dethroned Aristotelian mechanics. Newton built on Galileo's ideas and laid the foundation of mechanics in terms of three laws known as Newton's laws of motion.

NEWTON'S FIRST LAW OF MOTION

"Every body continues in its state of rest or of uniform motion in a straight line unless it is compelled by an external force to change that state"

Newton' First law is also called law of Inertia as it defines inertia.

There are two parts to this statement – one which predicts the behavior of stationary objects and the other which predicts the behavior of moving objects. These two parts are summarized in the following diagram.



Illustrations of First law:

1. When a bus or a train starts suddenly, the passengers sitting inside tend to fall backwards. This is so because the lower part of his body starts moving with the bus or train but the upper part tries to remain at rest due to inertia of rest.
2. The dust particles in a carpet fall off when it is beaten with a stick. This is because the beating sets the carpet in motion whereas the dust particles tend to remain at rest and hence separate.
3. When a bus or train stops suddenly, a passenger sitting inside tends to fall forward. This is because the lower part of his body comes to rest with the bus or train but the upper part tends to continue its motion due to inertia of motion.
4. A person jumping out of a speeding train may fall forward. This is because his feet come to rest on touching ground and the remaining body continues to move due to inertia of motion.

5. When a stone tied to one end of a string is whirled and the string breaks suddenly, the stone files off along the tangent to the circle.This is because the pull in the string was forcing the stone to move in a circle. As soon as the string breaks, the pull vanishes. The stone in a bid to move along the straight line files off tangentially.

Question 1. Is it possible to have motion in the absence of force?

Ans. Motion requires no force and body can move with constant velocity even if the force acting on it is zero.

Question 2. A 10 kg object is moving horizontally with a speed of 2 m/s. How much net force is required to keep the object moving at this speed and in the same direction?

Ans. 0 N.

Momentum

Momentum is the measure of motion contained in a body. It is measured by the product of mass and velocity of the body.

NEWTON'S SECOND LAW OF MOTION

"The rate of change of linear momentum of a body is directly proportional to the external force applied on the body, and this change takes place in the direction of the applied force"

Mathematically:

$$\vec{F} \,\alpha\, \frac{d\vec{P}}{dt}$$

$$\vec{F} \,\alpha\, m\frac{d\vec{v}}{dt}$$

$$\vec{F} = Km\vec{a}, \; K = 1$$

$$\therefore \vec{F} = m\vec{a}$$

Consequences of Newton second law of motion

1. No force is required to move a body uniformly in a straight line

According to Newton's second law of motion

F = ma

If $F = 0$, then $a = 0$ Thus velocity of body is constant.

2. Accelerated motion is always due to an external force

Force is required for acceleration i.e. for changing speed, direction or both.

Question 1. An object is accelerating at 2 m/s2. If the net force is tripled and the mass of the object is halved, what is the new acceleration?

Ans. $a = \frac{F}{m}$

$a \propto F$ & $a \propto 1/m$

$\therefore$ a will become 6 times i.e. $6 \times 2 = 12 m/s^2$

Impulse

The forces which act on a body for a short time are called impulsive forces. Impulse of a force is a measure of total effect of a force. It is given by the product of force and time for which the force acts on the body.

Impulse = force x time = change in momentum

Applications of the Concept of Impulse

1. A cricket player lowers his hands while catching a cricket ball to avoid injury. In this way, he increases the time of catch to reduce the momentum of the ball to zero. As

Impulse = force x time = change in momentum

Or force = change in momentum/time, thus player has to apply a smaller force against the ball in order to stop it.

2. An athlete is advised to come to stop slowly, after finishing a fast race, so that time of stop increases and hence force experienced by him decreases.

Question 1. If the net force of 10 N was continuously applied on 5 kg object at rest, how long will it take to raise its velocity to 80 m/s?

Ans. $u = 0$, $v = 80$ m/s, $F = 10$ N, $m = 5$ kg, $t = ?$

F=ma=m(v-u)/t

t=m(v-u)/F=5x(80-0)/10=40s

Question 2. A batsman hits back a ball straight in the direction of the bowler without changing its initial speed of 12 m/s. If the mass of the ball is 0.15 kg, determine the impulse imparted to the ball.

Ans. m = 0.15 kg, u = 12 m/s, v = - 12 m/s

Impulse=m(v-u)=0.15(-12–12)=-3.6Ns

*The negative sign indicates that the direction of the impulse is from batsman to the bowler.

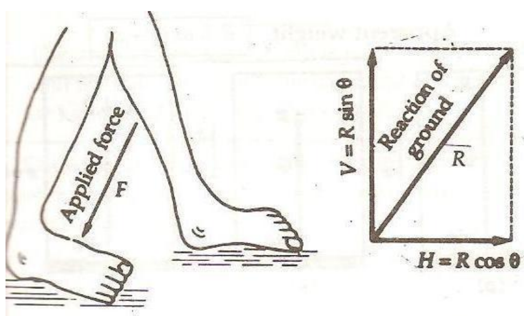
NEWTON'S THIRD LAW OF MOTION

"To every action, there is an equal and opposite reaction"

This means that if a body A applies a force F on body B, then the body B will also exert force –F on the body A.

Illustration of Newton's Third Law:

1. Walking: While walking a person presses the ground in the backward direction (action) by his feet. The ground pushes the person in forward direction with an equal force (reaction). The component of reaction in the horizontal direction makes the person move forward.

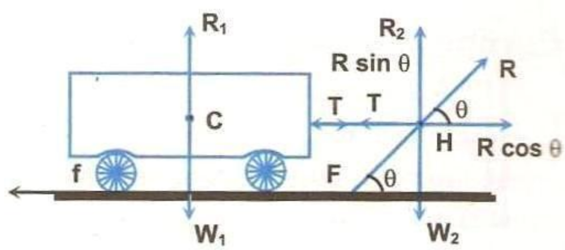


2. Swimming: A swimmer pushes the water backwards (action). The water pushes the swimmer forward (reaction) with the same force. Hence the swimmer swims.

3. Firing from a gun: When a gun is fired, the bullet moves forward (action). The gun recoils backwards (reaction).

4. Horse and Cart Problem: Horse pulls the cart and in turn cart pulls the horse with equal and opposite force. Then how is horse able to move the cart?

The various forces acting on a system of horse and cart at rest are shown in the figure. Here, the weight (W_1) of the cart C is balanced by the reaction (R_1) of the ground on the cart. The weight W_2 of the horse H is balanced by the reaction R_2 of the ground on the horse. The horse pulls the cart with a force T in the forward direction. The cart, in turn, pulls the horse with the same force T in the backward direction. These two forces are balanced. While pulling the cart, the horse pushes the ground backwards with its foot by a Force F inclined at an angle q with the horizontal. As a reaction, the ground exerts force R on the horse equal and opposite to F.



R can be resolved into two rectangular components:

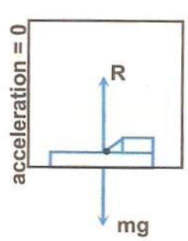
R sin q vertically upwards, and R cos q along the horizontal.

The component RCosq tends to move the cart forward. This motion is opposed by the force of friction f between the cart and the ground. The cart will move only when RCosq > f.

5. Apparent weight of a Man in an Elevator

Suppose a person of mass m is standing on weighing machine placed in an elevator. The actual weight of the person is equal to mg. This acts on the weighing machine which offers a reaction R given by the reading of the weighing machine. This reaction exerted by the surface of contact on the person is the apparent weight of the person. R will depend on the acceleration of the elevator.

Case 1: When the elevator is at rest or moves with uniform velocity



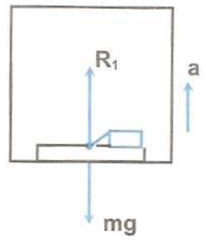
Acceleration of the person = 0

Net force on the person F = 0

i.e. R –mg = 0 or R = mg

i.e. apparent weight is equal to the actual weight of the person.

Case 2: When the elevator is accelerating upwards



Suppose uniformly upward acceleration of the person in the elevator is ‘a’

or $R_1 = mg + ma = m\,(g + a)$ . .....(i)

Hence apparent weight of the person becomes more than the actual weight, when the elevator is accelerating upwards.

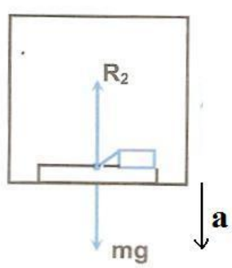
Case 3: When the elevator is accelerating downwards

Suppose uniform downward acceleration of the person in the elevator = a

$R_2 = mg - ma = m\,(g - a)$ ....(ii)

Thus $R_2 < mg$

Hence apparent weight of the person becomes less than the actual weight when the elevator is accelerating downwards.



Case 4: In free fall of a body under gravity, a = g

Therefore, $R_2 = m\,(g\text{-}g) = 0$

i.e. apparent weight of the person becomes zero or the body becomes weightless.

Case 5: When downward acceleration is greater than g.

i.e. $a > g$, then $R_2 = m(g-a)$, R_2 becomes negative. In that event, the person will rise from the floor of the elevator and stick to the ceiling of the lift.

Question 1. In tug of war, if one team exerts a force on the second team, then the second team also exerts an equal and opposite force on the first. Then how is it possible that one team wins?

Ans. The team which exerts a greater force on the ground gets greter reaction from the ground and is able to win.

LAW OF CONSERVATION OF LINEAR MOMENTUM

"When no external force acts on a system of several interacting particles, the total linear momentum of the system remains conserved"

Practical applications of the law of conservation of linear momentum

(i) Recoil of a gun. Let M be the mass of the gun and m be the mass of the bullet. Before firing, both the gun and the bullet are at rest. After firing, the bullet moves with the velocity v and the gun moves with the velocity V. As no external force acts on the system, linear momentum is conserved.

Total momentum before firing = Total momentum after firing

$0 = mv + MV$

Or $V = -mv/M$

The negative sign shows that V and v are in opposite directions.

(ii) When a man jumps out of a boat to the shore, the boat slightly moves away from the shore. Initially, the total momentum of the boat and the man is zero. As the man jumps from the boat to the shore, he gains a momentum in the forward direction. To conserve momentum, the boat also gains an equal momentum in the opposite direction.

Q1. A shell of mass 0.02 kg is fired by a gun of mass 100 kg. If the muzzle speed of the gun is 80 m/s, what is the recoil speed of the gun?

Ans. $m = 0.02$ kg, $M = 100$ kg, $v = 80$ m/s

Let V be the recoil speed of the gun

According to the law of conservation of momentum,

Initial momentum = Final momentum

$0 = mv + MV$

$V = - mv/M = - 0.02 \times 80/100 = - 0.016$ m/s

*Negative sign indicates that the gun moves backward as the bullet moves forward.

Q2. Can a sailboat be propelled by air blown at the sails from a fan attached to the boat?

Ans. No. When the fan pushes the sail by blowing air, the air also pushes the fan in opposite direction. As the fan is a part of the boat, the vector sum of the momenta of the fan and the boat is zero. The boat will only move if some external agency applies force on it.

WORK

The meaning of work in our daily life is quite different than that in physics. For example, we may exert a large force on the wall, but if the wall remains intact in its position, then we have not done any work in the language of physics.

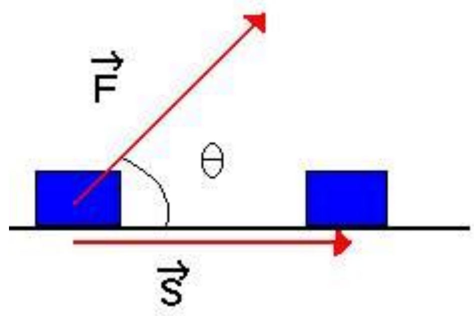
In the language of physics, "whenever force acting on a body is actually able to move it through some distance in the direction of force, then work is said to be done by the force".

WORK DONE BY A CONSTANT FORCE

(i) **Measurement of work done when the force acts along the direction of motion**
If a force 'F' acting on a body produces a displacement 's' in the direction of the force, then the work done by the force is given by

$$W = F\,s$$

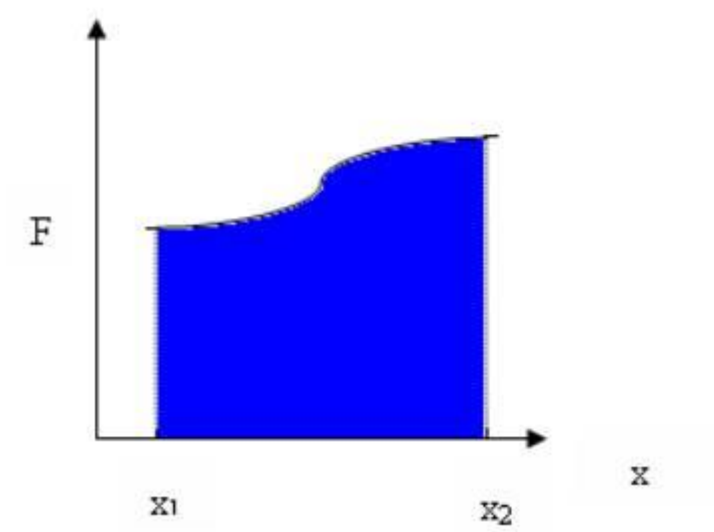
(ii) **Measurement of work done when the force and displacement are inclined at an angle to each other**



W = Fs cos q

WORK DONE BY A VARIABLE FORCE

Suppose a variable force acts on a body along the fixed direction, say x axis.



The work done in moving the body from $x = x_1$ to $x = x_2$ under the action of this variable force is given by

W = Area under the curve between force and x axis from $x= x_1$ to $x = x_2$

$x1$
$\int F dx$

$= x2$

UNITS OF WORK DONE

(i) **S.I. unit :** Joule (1J = 1 N-m)
(ii) **CGS unit:** erg (1 erg = 1 dyne-cm)

1 J = 10^7 erg

NATURE OF WORK DONE

(a) Positive work

As W = Fs cos q

When q is acute (< 90°) cos q is positive. Hence work done is positive.

Examples of positive work

(i) When a body falls freely under gravity, force of gravity and displacement are in the same direction (q = 0°) and the work done by force of gravity is positive.

(ii) When a spring is stretched, the work done by the stretching force is positive.

(b) Negative work

When q is obtuse (>90°), cos q is negative. Hence work done is negative.

Examples of negative work

(i) When a body is made to slide over a rough surface, the work done by frictional force is negative.

(ii) When brakes are applied on a moving vehicle, the work done by the breaking force is negative.

(iii) When a positive charge is moved towards another positive charge, work done by electrostatic force of repulsion between the charges is negative.

(iv) When a body is lifted, the work done by gravitational force is negative.

(c) Zero work

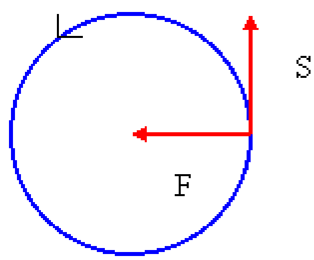
When the force applied or the displacement or both are zero, or force and displacement are perpendicular to each other, the work done is zero.

Examples of zero work

(i) When we push hard against a wall, the force we exert on the wall does no work, because s = 0. However, in this process, our muscles are contracting and relaxing alternately and internal energy is used. That is why we get tired.

(ii) When a porter carrying some load on his head moves on a horizontal platform, q = 90°,, therefore the work done by the porter is zero.

(iii) For a body moving in a circular path, the centripetal force and displacement are perpendicular to each other. So the work done by the centripetal force is zero.



Power

Power is the rate of doing work. If an agent does work W in time t, then its average power if given by

$$P_{av} = \frac{W}{t}$$

The power of an agent during a time interval may not be constant. The instantaneous power is defined as the limiting value of the average power of an agent in a small interval, when the time interval approaches zero. If DW is the small amount of work done in a small time interval Dt, then instantaneous power is defined as

$$P = \underset{\Delta t \to 0}{\text{Limit}} \frac{\Delta W}{\Delta t} = \frac{dW}{dt}$$

Now, dW = $\vec{F}.d\vec{S}$

$$P = \vec{F} \cdot \frac{d\vec{S}}{d\vec{t}}$$

But $\frac{d\vec{S}}{d\vec{t}} = \vec{v}$, the instantaneous velocity of the particle. Thus

$$P = \vec{F} . \vec{v}$$

UNITS OF POWER

S.I. Unit: Watt
Other units: Kilowatt, Horse Power

1 KW = 1000w
1H.P. = 746 W

Example 1
A 70 kg man runs up a staircase 3m high in 3.5 s. How much power does he develop?

Answer: Work done = mgh

$$Power = \frac{W}{t} = \frac{mgh}{t} = \frac{70x9.8x3}{3.5}$$
$$= 588 \text{ W}$$

Example 2
A one kilowatt motor pumps out water from a well 10 m deep. Calculate the quantity of water pumped out per second.

Answer: P = 1 kW = 1000 W, h = 10 m, t = 1s, m =?

$$Power = \frac{W}{t} = \frac{mgh}{t}$$
$$\frac{m}{t} = \frac{P}{gh} = \frac{10^3}{9.8x10} = 10.204 \text{ kg/s}$$

Example 3
An elevator weighing 500 kg is to be lifted up at a constant velocity of 0.20 m/s. What would be the minimum horsepower of the motor to be used?

Answer: As the elevator is going up with a uniform velocity, the total work done on it is zero in any time. The work done by the motor is, therefore, equal to the work done by the force of gravity in that interval (in magnitude). Thus the power is

P = Fv = mgv = 500 x 9.8 x 0.2 = 980 W

The minimum horsepower of the motor is
P = 980 W = 980/746 hp = 1.3 hp

ENERGY

Energy of a body is its capacity or ability to do work.

Units of energy: As energy is measured by the amount of work done, it has same units as that of work.

S.I. unit: Joule (1J = 1 N-m)
CGS unit: erg (1 erg = 1 dyne-cm)

Energy has several forms: Mechanical energy, sound energy, heat energy, light energy, chemical energy etc.

Mechanical energy is of two types- **kinetic energy** and **potential energy**.

Kinetic energy: It is the energy possessed by a body by virtue of its motion. The kinetic energy of a body of mass 'm' moving with speed 'v' is given by

$$\text{K.E.} = \tfrac{1}{2} mv^2$$

Examples of Kinetic energy

(a) The kinetic energy of air is used to run the wind mills.

(b) A bullet fired from a gun can pierce through a target due to its kinetic energy.

Potential energy: It is the energy possessed by a body by virtue of its position or configuration.

Examples of potential energy due to position

(a) The potential energy of water stored to great heights in dams is used to run turbines for generating hydroelectricity.

(b) A body lying on the roof of a building has potential energy. When allowed to fall down, it can do work.

Examples of potential energy due to configuration

(a) A stretched bow has elastic potential energy. When released, the bow does work in imparting kinetic energy to the arrow.

(b) When a spring is compressed or stretched, work done in compressing or stretching the spring is stored in the spring in the form of potential energy.

Gravitational Potential Energy

It is the energy possessed by a body by virtue of its position above the surface of earth.

When a body of mass 'm' is raised through height 'h' (h is much smaller than the radius of earth), its potential energy is given by

$$P.E. = mgh$$

Potential energy of a spring

When a spring of spring constant 'k' is stretched or compressed by amount 'x', the potential energy of the spring is given by

$$P.E. = \frac{1}{2} kx^2$$

Work- Energy Theorem

"The work done by the net force in displacing a body is equal to the change in kinetic energy of the body"

$$W = \Delta K.E$$

The kinetic energy of a body increases if net force on it does positive work and the kinetic energy of the body decreases if net force on it does negative work.

LAW OF CONSERVATION OF ENERGY

"Energy can neither be created not destroyed but can be transformed from one form to another, the total amount of energy of the universe remaining constant"

Whenever energy disappears in one form, an equal amount of energy appears in some other form. For example, when a body is dropped from some height, it has potential energy at the top which gets converted to kinetic energy as it reaches the ground.