Newton's Laws

Newton's Laws are not applicable in the following two situations:

1. When the speed of objects is close to the speed of light, we have to apply Einstein's special theory of relativity.

2. When the size of objects is on the scale of atomic structure, we have to apply quantum mechanics.

Earlier people felt that a moving body has an inherent tendency to come to rest.

This wrong concept was corrected by Galileo who gave us the concept of inertia. He realized that a moving body comes to rest because of external forces like friction etc. This understanding formed the basis of Newton's First Law of Motion.

First Law (Law of Inertia)

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

Important Points

- Newton's first law is applicable to every body
- State of rest and State of uniform motion in a straight line are both natural states of a body.
- The tendency of a body at rest to remain at rest unless acted upon by an external force is called ***Inertia of Rest***.
- The tendency of a moving body to continue moving with uniform motion in a straight line unless acted upon by an external force is called ***Inertia of Motion.***
- Only an external unbalanced force can cause acceleration. Internal forces cannot accelerate a body.
- **Balanced forces:** If the resultant of all forces acting on a body is equal to null vector, then the forces are said to be balanced. Balanced Forces cannot accelerate a body. Balanced Forces can deform a body.

- **Unbalanced forces:** If the resultant of the forces acting on a body is not zero, then the forces are said to be unbalanced. Unbalanced external forces can accelerate a body.
- Newton's First Law defines an inertial frame of reference

What is a force?

A force is an interaction that can cause acceleration of a body.

A body is said to accelerate when its velocity changes either in magnitude or direction or both.

Question to think?

Which external force makes a car accelerate?

What is momentum?

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

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

Second Law

The rate of change of momentum is directly proportional to impressed force and takes place in the same direction as the force.

Key Concepts

Newton's Second Law $\boldsymbol{\vec{F}_{net} = \frac{d\vec{p}}{dt}}$

When m is constant the above equation simplifies to

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

The above vector equation is equivalent to three scalar equations

$F_x = ma_x$ $F_y = ma_y$ $F_z = ma_z$

X-components of forces can cause acceleration along X-axis only and not along Y or Z axis. Same is true for Y or Z axis .

- What is mass?

  Mass (Inertial Mass) is defined by Newton’s second law. It is a scalar quantity that relates the force the force acting on a body to the resulting acceleration.

  If a force of 1 N produces an acceleration of 1 ms^{-2} then the mass of the body is 1 kg.

  If a force of 2 N produces an acceleration of 1 ms^{-2} then the mass of the body is 2 kg.

Question to think?

Why is momentum mass*velocity?

Third Law

Every action has an equal and opposite reaction, but they act on different bodies.

Questions to think?

- If action and reaction are equal and opposite, how is a horse able to pull a cart? (Whatever force the horse applies, the cart will pull back the horse with an equal and opposite force!)
- Newton’s Fist Law and Third Law can be derived mathematically from Newton’s Second Law. Then why are the first and third law required.
- First Law is required to define an inertial frame of reference. Without defining an inertial frame of reference Newton’s Second Law cannot be stated.
- Third Law is required to understand that always Action = - Reaction

Frame of Reference

Frame of reference refers to the perspective from which an observer views a situation. There is no absolute frame of reference in the universe, no stationary platform from where we can observe all motion.

There are two types of frames of reference:

1. Inertial frame of reference
2. Non-inertial frame of reference (Accelerated frame of reference)

An inertial frame of reference is a frame of reference in which Newton's Laws can be directly applied.

An inertial frame of reference is a frame of reference that is either at rest or moving with uniform velocity with respect to another inertial frame of reference.

Is the earth an inertial frame of reference?

The earth is actually not an inertial frame of reference because the earth rotates and revolves around the Sun.

We are living in a spaceship called earth that is rotating at a speed of 1600 km/hr at the equator, and going around the Sun at a speed of 100,000 km/hr. The Sun along with the entire solar system is going around the centre of the Milky way galaxy at a speed of 900,000 km/hr. The milky way galaxy is moving through inter galactic space.

Even though speed of the earth is huge, but acceleration of the earth is small.

The acceleration of earth due to rotation is 0.034 m/s^2 *at equator and the acceleration of earth is 0.006* m/s^2 *due to revolution around the Sun.*

Therefore the earth approximately behaves like an inertial frame of reference.

Some Important Forces:

1. **Weight**
   For any object having mass, weight acts vertically downwards.
   The weight of a body is the magnitude of the gravitational force due to the earth on the body.
   W = mg
   Mass does not vary from place to place. Weight varies from place to place as 'g' varies from place to place..
   A massless body means a body whose mass can be neglected.
   The weight of a body must be measured when the body is not accelerating vertically w.r.t. ground. For e.g. in an accelerating lift we get the apparent weight, not the actual weight.

2. **Normal Reaction**
   When a body pushes against a surface, the surface gets deformed and pushes on the body with a force called normal reaction that always acts perpendicular to the surface.

   Are N and mg action reaction forces ?

3. **Friction**
   If we slide or attempt to slide a body over a rough surface, the relative sliding is opposed by friction.
   Friction does not oppose motion always but it opposes relative sliding.
   If normal reaction is zero, cold welds are not formed and hence friction is zero.
   A smooth surface means a frictionless surface.
   However if a surface is made perfectly smooth, friction becomes very high.

4. **Tension**
   When a string (cord, rope or cable) is attached to a body and pulled tight, the string pulls on the body with a force called tension directed away from the body and along the string.

Properties of Tension:

1. Tension always acts away from the body. A string can pull, it cannot push.

2. Tension always acts along the string.
3. For a massless string, Tension is same at all points if all the pulleys in the path are also massless. One string, one tension.

Types of Forces:

1. Field Forces – Physical contact is not required.
   E.g. Gravitational Force, Electrostatic Force, Magnetic Force
2. Contact Forces – Physical Contact is required.
   E.g. Normal Reaction, Friction
   The vector sum of Normal Reaction and Frictional Force is called Contact Force.
3. Attachment to a body
   Tension, Spring Force
   Spring force
   $F = -kx$
   k = spring constant = force constant of spring = restoring force per unit extension or compression (N/m). k varies from spring to spring. If spring is more stiff, k is more.
   Energy stored in spring = U= $\frac{1}{2}kx^2$

For a force, three things are important

1. Magnitude
2. Direction
3. Point of Application

System: A collection of two or more bodies is called system. If two or more bodies are having the same acceleration, they can be taken as a system.

Free Body Diagram (FBD): In a free body diagram, a sketch of the body is drawn and all the forces acting on it are shown. Other bodies and supports are not shown. The direction of acceleration is also shown.

When we are drawing FBD of an object we should only at that object and not bother at other objects.

While drawing FBD of a system**, o**nly external forces are shown. Internal forces are not shown as different parts of the system experience equal and opposite internal forces.

How to systematically show forces in an FBD (so that we do not miss out any forces):

1. If a body has mass, weight acts vertically downwards towards at the centre of gravity. The line of action of weight cannot shift.

2. If a body is pushing against a surface, Normal Reaction acts perpendicular to the surface. The line of action of normal reaction can shift to keep a body in rotational equilibrium.

3. When a body is connected by a taut (tight) string, Tension acts along the string away from the body.

4. When a body is trying to slide or sliding on a rough surface, friction acts along the surface opposing relative sliding. Friction acts if the surface is rough and normal reaction is present. As long as the body is static, the magnitude of static friction can adjust to keep a body in translational equilibrium. Static friction is a self adjusting force.

5. When we are looking at two bodies/parts exerting forces on one another, we need to show equal and opposite forces on both the bodies/parts, as every action has equal and opposite reaction.

Steps to solve problems on Newton's Laws

1. **Draw the diagram and write the data.**
2. **Fix a consistent direction of acceleration. The direction may be incorrect but it must be consistent.**
3. **Draw the FBD.**
4. **Resolve forces in the direction of acceleration and perpendicular to acceleration.**
5. **Use the equation Net Force (in the direction of acceleration) = Mass*acceleration along each axis independently.**
6. **Solve for a and T simultaneously.**

Pseudo Force

When the FBD is drawn with respect to an inertial frame of reference (observer with zero acceleration), we apply only real forces (forces which are actually acting on the mass).

However, when the FBD is drawn with respect to a non inertial frame of reference (accelerated frame of reference i.e. observer with acceleration), a pseudo force has to be applied in addition to all real forces. The direction of Pseudo Force is always opposite to the direction of acceleration of non inertial frame of reference. Pseudo force is given by $\vec{F}_p = -m\vec{a}_o$ where $\vec{a}_o$ is the acceleration of the non inertial frame of reference and m is the mass of the body under consideration.

Frame of reference refers to observer.

Pseudo force has got nothing to do with acceleration of body, it is related to acceleration of observer.

Every problem can be solved without using pseudo force as long as we take inertial frame of reference but at times it is convenient to take non-inertial frame of reference and apply pseudo force.

Friction

When relative sliding is attempted or maintained between two solid bodies in contact and exerting normal force on one another, then due to the intermolecular attraction between the bodies at the surface of contact (due to which cold welds are formed) a resisting force called friction acts on both the bodies and it acts along the surface of contact.

Friction does not oppose motion. It opposes relative sliding.

- If a surface is made perfectly smooth, friction will become very high.
- When a problem says surface is smooth, there is no friction.
- When a problem says surface is rough, there is friction.

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- If N = 0, friction = 0

***Static Friction**:* Before the relative sliding between two solid bodies in contact starts due to the resultant external force $\vec{F}$, a self-adjusting frictional force called static friction comes into play, which has a magnitude equal to F and direction opposite to $\vec{F}$.

***Limiting Static Friction*(f_{LS}):**
The frictional force increases as the external force $\vec{F}$ increases, till it reaches a maximum value called limiting static friction (f_{LS}) and if the external force exceeds this, then relative sliding begins.

Kinetic Friction (Dynamic Friction or Sliding Friction f_K) :
When there is relative sliding, kinetic friction f_K comes into play,

Generally $f_K < f_{LS}$

Forces of Limiting Static Friction and Kinetic Friction
1. are independent of the macroscopic area of apparent contact.
2. are dependent on the microscopic area of contact which is proportional to the normal force N between the two surfaces.
3. Depend on the nature of surfaces in contact.

We will assume that Kinetic Friction is independent of the velocity of sliding.

Coefficient of friction:

μ_s = f_{LS} **/ N =** Coefficient of static friction

μ_k = f_K **/ N =** Coefficient of kinetic friction

μ_s and μ_k depend on the nature of surfaces in contact and are independent of the normal reaction.

Generally $\mu_s > \mu_k$ and μ_s and μ_k are less than 1. But they can be greater than 1 (1.2 for rock climbing shoes)

Contact Force: The vector sum of Normal Force and Friction is called Contact Force.

Total Limiting Reaction: The vector sum of Normal Force and Limiting Static Frictional Force is called Total Limiting Reaction.

Limiting Angle of Friction (λ): The angle between the total limiting reaction and normal reaction is called limiting angle of friction.

Cone of friction: It is a cone drawn with the point of contact O between the two bodies as apex , common normal as axis and limiting angle of friction as the semi vertical angle.

The contact force will always lie within or on the surface of this cone. No force P whose line of action lies within the cone of friction can produce sliding motion however large P may be.

Angle of Repose (α) When a solid body is placed on a rough plane whose inclination to the horizontal is gradually increased then at one stage of inclination ($=\alpha$**)** the body just starts sliding down the inclined plane on its own. This angle α of the inclined plane is called Angle of Repose.