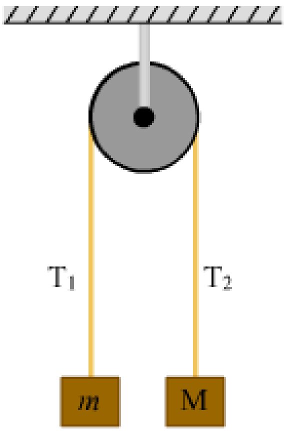
Laws of Motion

Pulleys

- A pulley is a massless wheel with an axle. It is designed to support the movement of a rope or a string along its circumference.
- Pulleys are used to lift loads to change the direction of force.

For the given system with two masses and a light string passing over a pulley:
(*M*>*m*)



- The tension (*T*) in the string= $\left(\frac{2mM}{M+m}\right)g$
- The magnitude of the acceleration (*a*) of the blocks= $\left(\frac{M-m}{M+m}\right)g$
  - The acceleration of the block of mass *M* is $\left(\frac{M-m}{M+m}\right)g$ in downward direction.
  - The acceleration of the block of mass *m* is $\left(\frac{M-m}{M+m}\right)g$ in upward direction.

Frame of reference:

- To locate the physical quantities like position, velocity and acceleration of a particle, a frame of reference is needed. Generally, a set of three mutually-perpendicular axes is taken as the frame of reference .

There are two types of frames of reference:

I Inertial frame of reference:

- A frame of reference moving with constant velocity or at rest with respect to the ground is called inertial frame of reference. In this frame, Newton’s laws of motion are valid. For example: earth

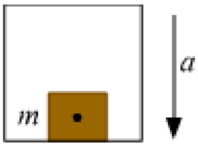
II Non-inertial frame of reference:

- A frame of reference moving with an acceleration is called a non-inertial frame of reference.

Newton’s laws of motion are not valid in a non-inertial frame of reference. For example: a rotating frame

Pseudo Force:

- Pseudo forces arise when Newton’s laws of motion are applied in a non-inertial $accelerating$ frame of reference.
- These forces have no real existence but must be taken into account in an accelerating frame of reference to make Newton’s laws of motion applicable to the system.
- Centrifugal force is the pseudo force for a body in circular motion. The real force in this case is centripetal force, which is directed inwards.
- For a block of mass m placed in an elevator moving down with constant acceleration, a:



Case I

For an inertial frame of reference or ground:
⇒N = m $g - a$

Case (II)

For a non-inertial frame of reference or lift:
⇒ N = m $g - a$

- **Inertia**
  - The property of a body to resist any change is called inertia e. g. when a horse starts suddenly, the rider falls backwards due to the inertia of rest of the upper part of his body.

- **Newton’s First Law**
  - Every body continues to be in its state of rest or uniform motion in a straight line, unless compelled by some external force acting on it.
  - Example: Any object continues lying where it is, unless it is moved.
  - Newton’s first law gives the definition of Inertia.

Momentum:

- Momentum of a body is the product of its mass, *m* and velocity, *v*, and is denoted by *P*.
- It is a vector quantity.
- SI unit → kg ms^{-1}

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 always in the direction of force applied.

  i.e. $\frac{\Delta p}{\Delta t} \alpha F_{\text{ext}}$

- Second law is the real law of motion.

Impulse

- Impulse of a force is a measure of the total effect of the force.

  Impulse = Force × Time

- SI unit of impulse are N-s and kg-ms^{-1}
- Forces which act on bodies for a short time are called impulsive forces.

- **Third Law of motion**
  - **Statement:** To every action, there is always an equal and opposite reaction.

- **Some Important Points about the Third Law**
  - Forces always occur in pairs. Force exerted on a body A by a body B is equal and opposite to the force exerted on body B by body A.
  - There is no cause-effect relationship implied in the third law. The force on body A by body B, and the force on body B by body A act at the same instant.
  - Forces of action and reaction act always on different bodies. Hence, they never cancel each other.

- **Friction** – Friction is the property due to which a force is set up at the surface of contact of two bodies, preventing any relative motion between them.
- **Cause of friction** – Irregularities of the two surfaces get interlocked restricting the motion

when one body moves or tends to move over the other.

- **Types of friction:**
    - Sliding friction
    - Rolling friction
- **Sliding friction** – Whenever a body slides or tends to slide over the surface of another body, the friction that comes into play is called sliding friction. It is of two types:
    - Static friction – It is the opposing force that comes into play when a body tends to slide over the surface of another body.
    - Dynamic friction – It is the opposing force that comes into play when a body is actually sliding over the surface of another body. Dynamic friction is also called kinetic friction.

The maximum value of static friction that comes into play when a body is just on the point of sliding is called limiting friction.

Laws of static friction

- The magnitude of the limiting force of static friction (F_s) between any two bodies in contact is given by $F_s = \mu_s N$.

Here, N is the normal reaction between the bodies and μ_s is the proportionality constant and is called the coefficient of static friction.

- The limiting force of static friction depends on the nature of material of the surfaces in contact.

Laws of kinetic friction

- The magnitude of force of kinetic friction (F_k) between any two bodies in contact is directly proportional to the normal reaction (N) between them.

$$F_k \propto N$$

$$F_k = \mu_k N$$

- The force of kinetic friction is independent of the area of contact, as long as the normal reaction between two surfaces in contact remains the same.
- The force of kinetic friction depends on the nature and material of the surfaces in contact.
- The force of kinetic friction is approximately independent of the relative velocity between the surfaces in contact.

- **Friction force**, $F = \mu N$

  Where, N is the normal reaction of the body

    - Coefficient of friction

($\mu_{static} > \mu_{sliding} > \mu_{rolling}$)

- **Circular motion**

For a level curved road

- $F = \mu_s N \geq \frac{mv^2}{R}$ (R = Radius of curvature of the road)
- $v^2 \leq \mu_s Rg$ (As, $N = mg$)

Tha maximum speed of a car is,

$$v_{max} = \sqrt{\mu_s Rg}$$

For a banked curved road

- Car can be parked, if $\tan\theta \leq \mu_s$.

The maximum speed of a car is,

- $v_{\max} = \left(\frac{Rg(\mu_s + \tan\theta)}{(1 - \mu_s \tan\theta)}\right)^{1/2}$

- **Momentum:** Momentum of a body is the product of its mass, *m* and velocity, *v* and is denoted by *P*.

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

- **Conservation of momentum:** 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. That is,

  Initial momentum of the system = Final momentum of the system

- **Examples of conservation of momentum**

  1. Recoil of a gun on firing a bullet
  2. Backward movement of a boat when a person jumps out of it
  3. Upward motion of a rocket due to downward motion of exhaust gases

- **Equilibrium of particles**
  - Equilibrium of a particle in mechanics refers to the situation when the net external force on the particles is zero. According to the first law, this means that the particle is either at rest or in uniform motion.

- **Equilibrium under Concurrent Forces**
  - Concurrent forces are those forces that act in the same plane.
  - Equilibrium under three concurrent forces $\vec{F_1}$, $\vec{F_2}$, and $\vec{F_3}$ requires that the vector sum of the three forces is zero.

$$\vec{F_1} + \vec{F_2} + \vec{F_3} = 0$$