1. Details of Module and its Structure

Module Detail	
Subject Name	Physics
Course Name	Physics 01 (Physics Part-1, Class XI)
Module Name/Title	Unit 3, Module 4, Types of Forces Chapter 5, Laws of Motion
Module Id	Keph_10504_eContent
Pre-requisites	Resolution of forces, Newton's laws of motion, Kinematics, Basic trigonometry
Objectives	After going through this lesson, the learners will be able to • Identify different types of forces and know their effects • Understand equilibrium of concurrent forces • Draw Free body diagrams and use them to solve problems
Keywords	Tension, Friction, weight, normal force Equilibrium, Concurrent forces, Coplanar, Free body diagram.

2. Development Team

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1. UNIT SYLLABUS

Chapter 5: Laws of Motion

Intuitive concept of force, Inertia, Newton's first law of motion, momentum and Newton's second law of motion, Impulse; Newton's third law of motion.

Law of conservation of linear momentum and its applications.

Equilibrium of concurrent forces, Static and kinetic friction, laws of friction, rolling friction, lubrication.

Dynamics of uniform circular motion: Centripetal force, examples of circular motion (vehicle on a level circular road, vehicle on banked road).

2. MODULE-WISE DISTRIBUTION OF UNIT SYLLABUS 7 Modules

The above unit is divided into seven modules as follows:

Module 1	• Force • inertia • First law of motion
Module 2	• Momentum • Second law • Impulse • F=ma

	• Constant and variable force
Module 3	• Third law • Conservation of linear momentum and its applications
Module 4	• Types of forces (tension, normal, weight, …) • Equilibrium of concurrent forces • FBD
Module 5	• Friction • Coefficient of friction • Static friction • Kinetic friction • Rolling friction • Role of friction in daily life
Module 6	• Dynamics of circular motion • Centripetal force • Banking of roads
Module 7	• Using laws of motion to solve problems in daily life

MODULE 4

3. WORDS YOU MUST KNOW

- Rest: A body is said to be at rest if it does not change its position with time with respect to its surroundings.
- Motion: A body is said to be in motion if it changes its position with time with respect to its surroundings.
- Velocity: The time rate of change of displacement is called velocity.
- Uniform motion: When a particle has equal displacements, in equal intervals of time, (howsoever small this time interval may be) it is said to have a uniform motion. The acceleration for a particle in uniform motion would be zero.
- Momentum (**p**): An indicator of the impact capacity of a moving body. We have **p**= m**v**
- Acceleration: Time rate of change of velocity of a particle, equals its acceleration.
- Vector: A physical quantity that needs both a magnitude and a direction for its specification.
- Vector Algebra: The branch of mathematics that deals with computations involving addition, subtraction, and multiplication of vectors.

- Force: A body will continue in its state of rest, or uniform motion until and unless it is acted upon by an external unbalanced force.

- Inertia: An inherent property of all objects; an object continues in its state of rest or uniform motion unless and until a non-zero external force acts on it.
- Impulse: Rate of change of momentum.

- Equations of motion: A set of equations relating initial velocity final velocity, acceleration, time elapsed and distance travelled. these are used for calculation of any of the physical quantities mentioned for a moving object

- Laws of motion three rules/ laws formulated by Newton to show the cause of motion

- Newton's first law of motion: Everybody continues to be in its state of rest or of uniform motion in a straight line, unless compelled by some external force to act otherwise". In simple terms, the First Law is "If external force on a body is zero, its acceleration is zero".

- Newton's second law of motion: The rate of change of momentum of a body is proportional to the applied force and takes place in the direction in which the force acts. Thus

$$F = k\frac{dp}{dt} = kma$$

Where F is the net external force on the body and 'a' its acceleration. We set the constant of proportionality k =1 in SI units. Then

$$F = \frac{dp}{dt} = ma$$

The SI unit of force is newton: 1 N = 1 kg m s^{-2}.
(a) The second law is consistent with the First Law (F = 0 implies a = 0)
(b) It is a vector equation
(c) It is applicable to a particle, and also to a body or a system of particles, provided F is the total external force on the system and 'a' is the acceleration of the system as a whole.
(d) F at a point at a certain instant determines 'a' at the same point at that instant.
That is the Second Law is a local law; a at an instant does not depend on the history of motion

- Newton's third law of motion

  To every action, there is always an equal and opposite reaction. In simple terms, the law can be stated thus:
  - ✓ Forces in nature always occur between pairs of bodies.
  - ✓ Action and reaction forces are simultaneous forces.
  - ✓ There is no cause-effect relation between action and reaction.
  - ✓ Any of the two mutual forces can be called action and the other reaction.
  - ✓ Action and reaction act on different bodies and so they cannot be cancelled out.
  - ✓ The internal action and reaction forces between different parts of a body do, however, sum to zero.

4. INTRODUCTION

This course serves as an introduction to the different types of forces we encounter in our daily life. Of the four fundamental forces in nature, only the gravitational and electromagnetic forces are relevant in the context of mechanics. We will learn how to recognize these forces and study the effect they produce.

5. COMMON FORCES

In mechanics, we encounter several kinds of forces. The gravitational force is, of course, all pervasive. Every object on the earth or close to it, experiences the force of gravity due to the earth. Gravity also governs the motion of celestial bodies. The gravitational force can act at a distance without the need of any intervening medium.

a) **Field forces (Action at a distance):**

- **Gravitational Force**: The *gravitational force* is an attractive force that acts between any objects with mass.
- **Electric Force**: Force of attraction or repulsion between the two point charges.
- **Magnetic Force**: Force of attraction or repulsion between the poles of a magnet.

Here, we will deal with gravitational force, which is called weight (denoted by symbol W).
If m is the mass, g the acceleration due to gravity at a place, then mg gives the weight so that
$W = mg$.
Mass is constant but weight of a body is not constant, it depends upon the value of g at a place.

b) Contact forces:

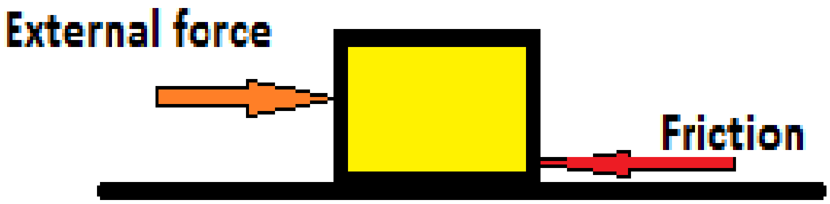
- **Friction (f):**

Frictional force is a force exerted on a body when the body slides or attempts to slide along a surface.

It is represented by symbol f.

This force acts parallel to the surface at the contact and is directed opposite to the motion of the body.

It arises due to electromagnetic interactions of atoms in two objects, we will learn about this later.



- **Air resistance:**

The air resistance or air drag is a type of frictional force that acts upon objects when they travel through air.

The force of air resistance opposes the motion of an object.

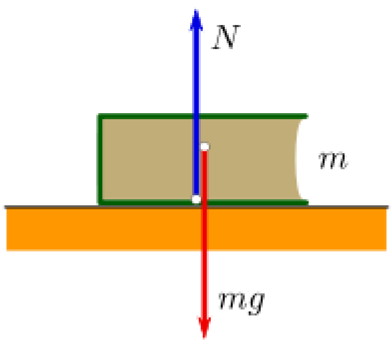
A parachute works by creating a large air resistance/friction opposite to it's as it moves down.

Open the link: (https://www.youtube.com/watch?v=lZsl0FbMjy4)

- **Normal Force(N) :**

When a body presses against a surface, the surface pushes on the body with a force that is perpendicular to the surface. It is called normal reaction or simply normal force.

It is electromagnetic in nature.



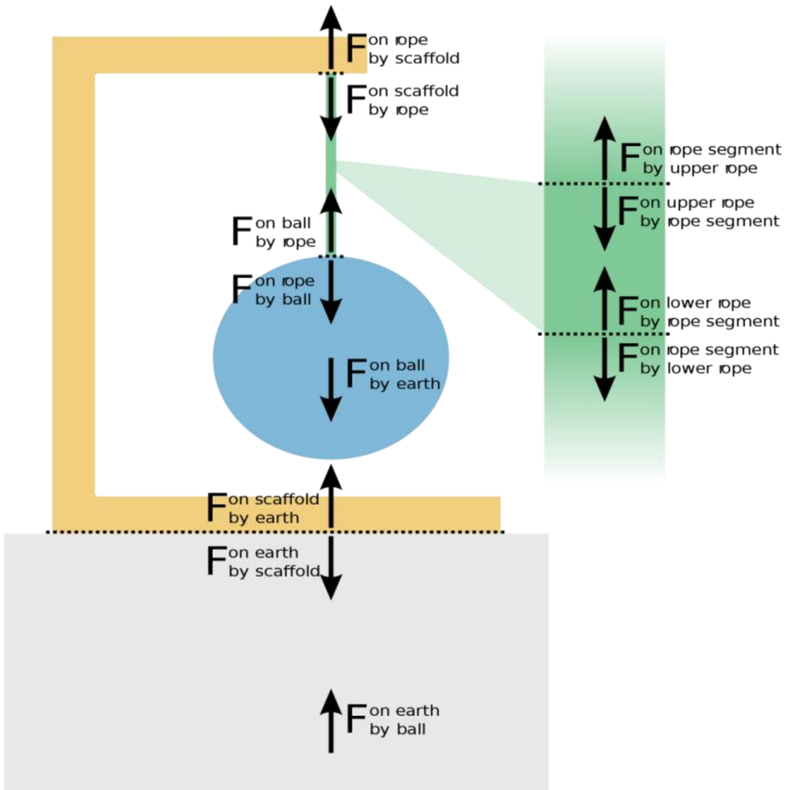
- **Tension (T):**

The tension force is the force that is transmitted through a string, rope, cable or wire when it is pulled tight by forces acting from opposite ends.

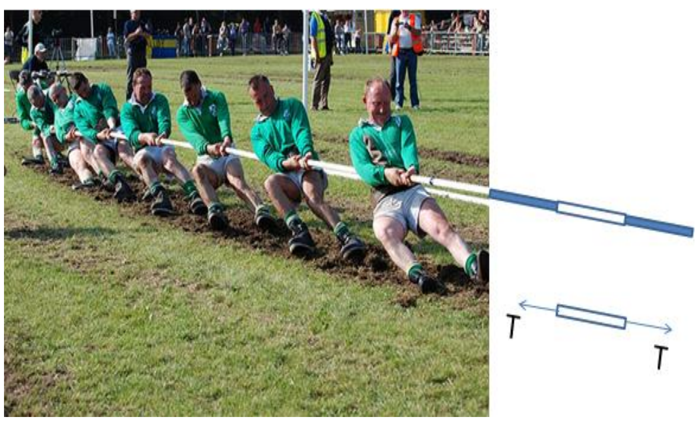
The tension force is directed along the length of the wire and pulls equally on the objects on the opposite ends of the wire (i.e. directed away from the object).

It is electromagnetic in nature and arises due to the intermolecular bonds in the wire or string.

The fig shows a spherical body suspended by a rope

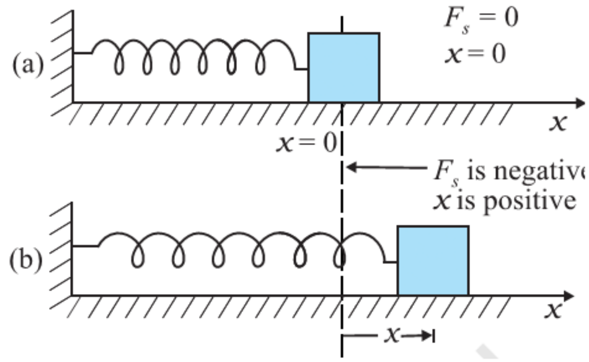


In a game of **tug o war** the rope is pulled by both teams in the opposite direction. Tension in strings, wires and ropes is equal and in opposite direction. We choose the direction when we wish to understand its influence on the body.



- **Spring Force (F_s):**

The spring force is the force exerted by a compressed or stretched spring on an object that is attached to it. Spring force acts in a direction to restore the relaxed state and thus it is also called as restoring force.



We will mainly deal with the following forces:

i. **Weight**

ii. **Normal force**

iii. **Friction**

iv. **Tension**

6. CONCURRENT FORCES

Equilibrium of a particle in mechanics refers to the situation when

- ***The net external force on the particle is zero (F_{net} = 0).***
- ***The net turning effect of all the forces causing clockwise motion must equal turning effect of all the forces causing anti clockwise motion.***

i.e**. the forces will not cause any change in the motion of the object to which they are applied.**

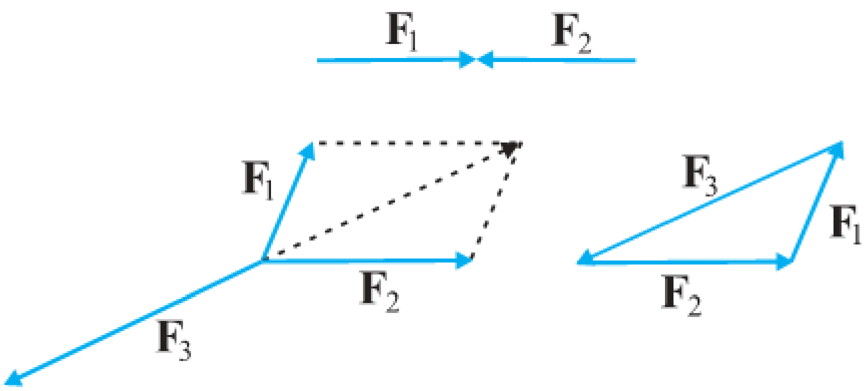
From Newton's first law, there are two cases when a body can be in equilibrium:

$F_{net} = 0$ (Equilibrium)

Body at rest   Body in uniform motion

- **Concurrent Forces**: Forces acting simultaneously on a body at the same point. When forces are concurrent, all the vectors are added together to obtain the resultant force.

- **Collinear Forces**: Forces acting along same line or close parallel lines.
- **Coplanar Forces**: Forces acting in the same plane.
- **Equilibrium under concurrent forces:**



If two forces F_1 and F_2 act on a particle, equilibrium requires $F_1 = -F_2$ i.e. the two forces on the particle must be equal and opposite.

Equilibrium under three concurrent forces F_1, F_2 and F_3 requires that the vector sum of the three forces is zero i.e.$F_1 + F_2 + F_3 = 0$.

In other words, the resultant of any two forces, say F_1 and F_2, obtained by the parallelogram law of forces must be equal and opposite to the third force, F_3.

The three forces in equilibrium can be represented by the sides of a triangle with the vector arrows taken in the same order/sense.

The result can be generalized to any number of forces.
A particle is in equilibrium under the action of forces F_1, F_2,... F_n if they can be represented by the sides of a closed *n*-sided polygon with arrows directed in the same sense, making the resultant zero.

7. EQUILIBRIUM OF CONCURRENT COPLANAR FORCES

If an object is in equilibrium under two or more concurrent forces, the algebraic sum of the components of forces in any two mutually perpendicular should be zero. The set of forces must be such that:

a. **The algebraic sum of components parallel to x-axis is** $F_x = 0$**.**

b. **The algebraic sum of components parallel to y-axis is** $F_y = 0$**.**

∴ **For the equilibrium of two or more forces:** Fx = **0 and** Fy = **0.**

Also the turning effect of forces (Torque) should be balanced, so turning effect of forces causing clockwise motion must equal turning effect of forces causing anti clockwise motion. We will study this in our course later.

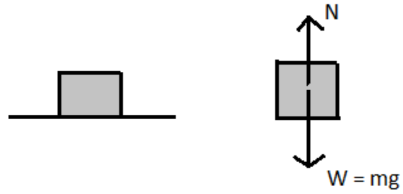
8. FREE BODY DIAGRAM (FBD):

No system, natural or man-made, consists of a single body alone m there is some environment for objects. A single body or a part of the system can, however, be isolated from the rest by appropriately accounting for its effect on the remaining system.

A free body diagram (FBD) consists of a diagrammatic representation of a single body or sub-system of bodies isolated from its surroundings showing all the forces acting on it.

Consider the simplest example of a book lying on a horizontal table surface.

A free body diagram of the book alone would consist of its weight (W = mg), acting downwards through the centre of gravity and the normal force (N) exerted on the book by the surface.



9. SOLVING PROBLEMS USING FREE BODY DIAGRAMS:

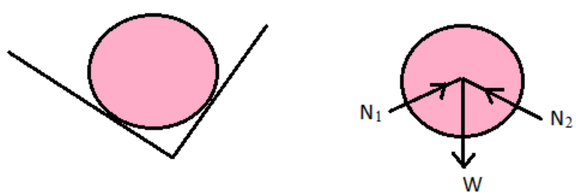
EXAMPLE:

A cylinder (cross-section) of weight W is resting on a V-shaped groove as shown. Draw the free body diagram.

SOLUTION

The Free body diagram of the cylinder can be drawn:

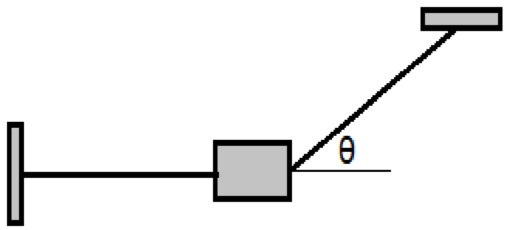
W: weight of the cylinder, N_1 and N_2 are the normal forces by the two inclined walls of the groove on the cylinder.



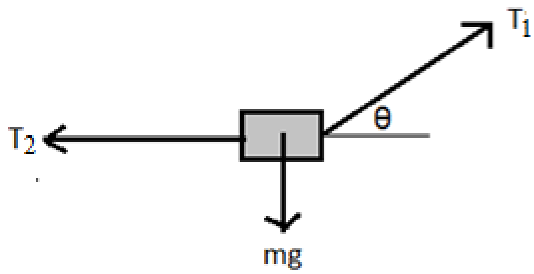
(FBD)

EXAMPLE:

A block of mass m is attached with two strings as shown in the figure. Draw the free body diagram considering the forces acting on the block.



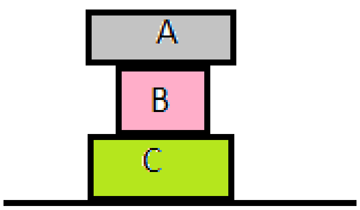
SOLUTION



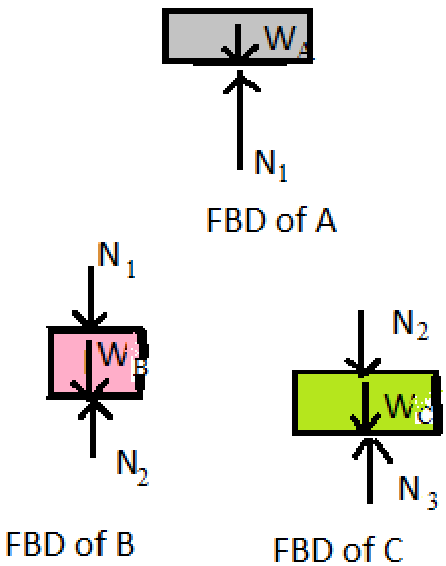
(FBD)

EXAMPLE:

Three blocks A, B and C are placed one over the other as shown. Draw the Free body diagrams for each block considering the forces acting on them.



SOLUTION



Where, **N_1: normal force between A and B**
N_2: normal force between B and C
N_3: normal force between C and base/Surface.

W_A: weight of A
W_B: weight of B
W_C: weight of C

EXAMPLE

A mass of 6 kg is suspended by a rope of length 2 m from the ceiling. A force of 50 N in the horizontal direction is applied at the midpoint P of the rope, as shown. What is the angle the rope makes with the vertical in equilibrium?

(Take g = 10 ms^{-2}).
Neglect the mass of the rope.

SOLUTION:

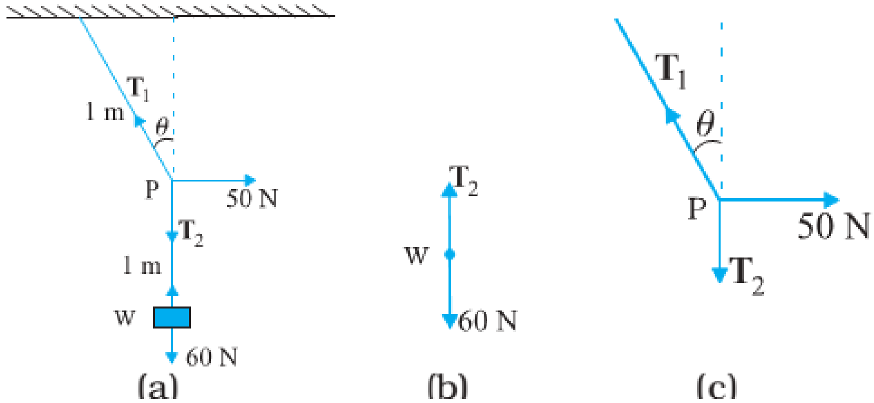


Fig (b) and (c) are the free-body diagrams.
Fig. (b) is the free body diagram of W and
Fig. (c) is the free-body diagram of point P.

Consider the equilibrium of the weight W.

Clearly, T_2 = 6 x 10 N = 60 N.

Consider the equilibrium of the point P under the action of three forces –

i. **the tensions T_1 and T_2,** and
ii. **the horizontal force 50 N.**

The horizontal and vertical components of the resultant force must vanish separately:

$T_1 \cos\theta = T_2 = 60$ N

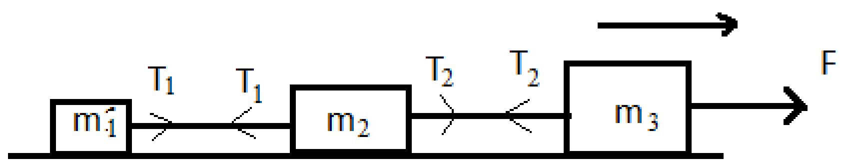
$T_1 \sin\theta = 50$ N, which gives that

tan θ = 5/6

Note
the answer does not depend on the length of the rope (assumed massless or of negligible mass) nor on the point at which the horizontal force is applied.

EXAMPLE:

As shown, three blocks are connected together, and lie on a horizontal frictionless table and pulled to right with a force F = 50 N. If m_1 = 5 kg, m_2 = 10 kg and m_3 = 15 kg, find the tensions T_1 and T_2.



SOLUTION:

All the blocks move with the common acceleration a under the effect of force F = 50 N.

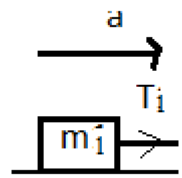
$F = (m_1 + m_2 + m_3)\,a$

$a = 5/3\ ms^{-2}$

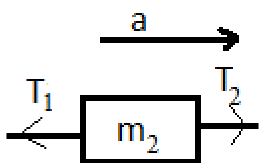
To determine T_1 and T_2, consider free body diagrams for m_1, m_2 and m_3.

Applying Newton's second law, $T_1 = m_1 a$

$T_1 = 5 \times 53 = 8.33$ N



Applying Newton's second law, $T_2 - T_1 = m_2 a$

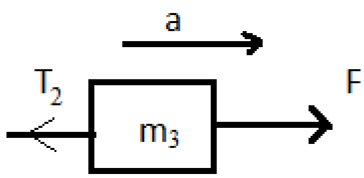


OR

$F - T_2 = m_3 a$

$50 - T_2 = 15 \times 5/3$

$T_2 = 25$ N



EXAMPLE:

A person of mass *m* is standing on the floor of a lift elevator. Find the apparent weight when the lift is

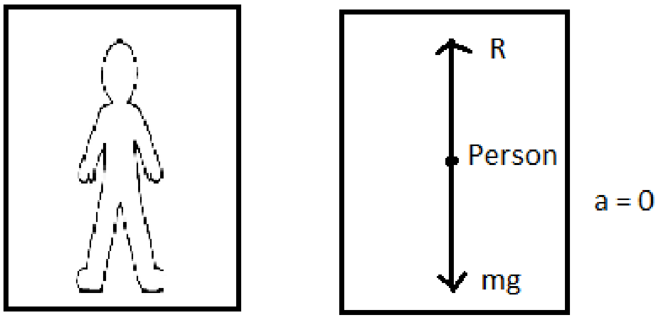
i. **at rest or moving with uniform velocity 'v'**
ii. **going upwards with a uniform acceleration 'a'**
iii. **going downwards with uniform acceleration 'a',**
iv. **Falling freely.**

SOLUTION

A person with mass, m, who is located on the surface of the Earth will always have some weight W = mg. When a person stands on a scale, the reading on the scale is actually the normal force that the scale exerts back towards the person to support the person's weight. This weight is called apparent weight of the person.

(The person and the scale are always in contact with each other, so they always have equal and opposite action and reaction forces acting between them.)

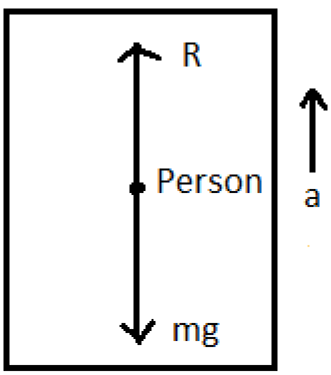
Case (i) when the elevator is at rest or moving with uniform velocity (i.e. zero acceleration)



FBD of the person

If the **acceleration of the elevator is zero**, in this case, the action and reaction force pair between the person and the scale is just the weight. The person pushes down on the scale with a force of W = mg (downward direction) and the scale pushes up against the man with a normal force of F_N = W = mg (upward direction). As the reading on the scale is the magnitude of the normal force, the scale will read the true weight when the elevator is **NOT** accelerating.

Case (ii) when the **elevator is accelerating upwards with acceleration 'a'**



The elevator accelerates upward. The elevator floor and scale must push up on the person to accelerate him upward along with the elevator.

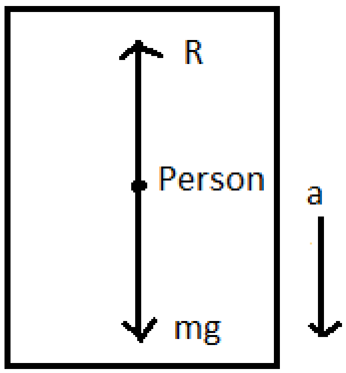
Let's consider Newton's 2nd Law (ΣF=ma) acting on the person. The overall acceleration of the person is upward (with the elevator).

So *ma* is positive (upward). The only external forces acting on the person are the force of gravity acting downwards (W=mg) and the supporting normal force F_N (or R) that the scale applies upward on the person.

Taking upward force to be positive and downward force to be negative:

R – mg = ma
R = mg + ma
Therefore, the **apparent weight of the person increases as the elevator accelerates upwards.**

Case (iii) when the **elevator is accelerating downwards with acceleration 'a'**



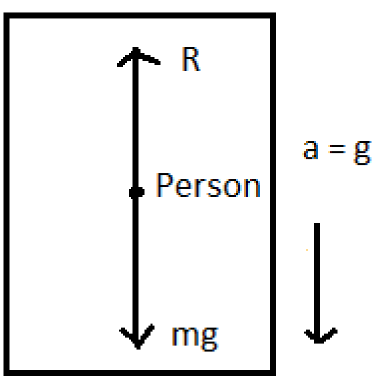
The elevator then speeds up in the downward direction towards a lower floor. The acceleration of the elevator is negative/downward (increasing the velocity magnitude in the downward direction).
Considering Newton's 2nd Law (ΣF=ma) acting on the person.
The overall acceleration of the person is downward (with the elevator).

So *ma* is negative (downward). The only external forces acting on the person are the force of gravity acting downward (W = mg) and the supporting normal force F_N (or R) that the scale applies upward on the person.

R – mg = - ma
R = mg – ma
R = m (g - a)

Therefore, the **apparent weight of a person decreases as the elevator accelerates downward.**

Case (iv) when the **elevator falls freely**



If the elevator falls freely, the whole elevator-scale-person system would all begin to accelerate downward due to the force of gravity.

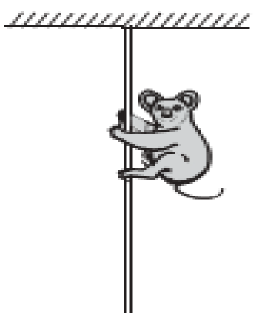
All objects in free fall accelerate downward with the same magnitude (acceleration due to gravity, g).

The scale and the person are free falling together, so there is no contact force (Normal Force) between the scale and the person i.e. no support to the person's weight.)

So the apparent weight of the person will be zero

EXAMPLE:

A monkey of mass 40 kg climbs on a rope which can withstand a maximum tension of 600 N. In which of the following cases will the rope break?



When the monkey:

(a) climbs up with an acceleration of 6 m s^{-2}

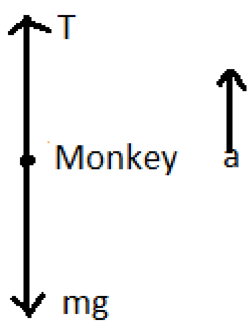
(b) climbs down with an acceleration of 4 m s^{-2}

(c) climbs up with a uniform speed of 5 m s^{-1}

(d) falls down the rope nearly freely under gravity?

(Ignore the mass of the rope)

SOLUTION



a. **FBD of monkey**

Using Newton's second law

$T – m g = ma$

$T= m (g + a)$

$T = 40 (10 + 6)$

$T = 640$ N

b. Downward acceleration: a

$T - m g = - m a$

$T = m g - m a$

$T = m (g - a)$

$T = 40 (10 - 4)$

$T = 240$ N

c. **Uniform speed of 5m/s**: a = 0

$T = mg = 40 \times 10$

$T = 400$ N

d. Free fall, a = g

$T = m (g - a)$

$T = m (g - g)$

$T = 0$ N.

As the tension T in the rope in case (a) is greater than the maximum tension of 600 N, so the rope will break in that case only.

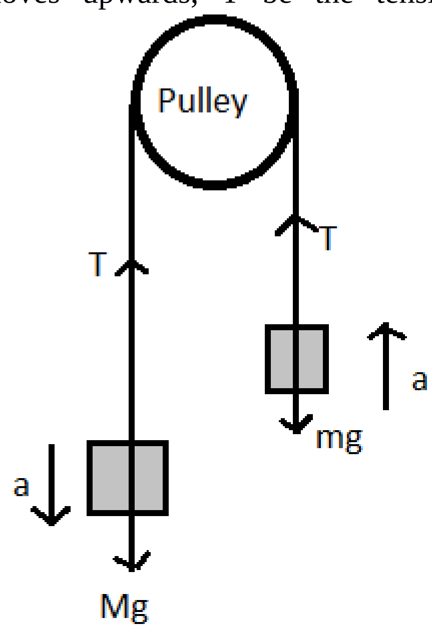
EXAMPLE

Motion of connected Bodies:

Two masses M and m are connected to the ends of an inextensible string. The string passes over a smooth frictionless pulley. Calculate the acceleration of the masses and the tension in the string for M > m.

SOLUTION

Let 'a' be the acceleration with which heavier mass M moves downwards and the lighter mass m moves upwards, T be the tension in the string (assuming the string to be massless)



Using Newton's second law,

According to FBD of mass M (Resultant force on mass M is downward):
T – M g = - M a …… (1)

According to FBD of mass m (Resultant force on mass m is upward):
T – m g = m a ….. …..(2)

Solving equations (1) and (2)

$$a = \frac{(M-m)}{(M+m)}g, \quad \text{where } a < g$$

and $$T = \frac{2Mm}{(M+m)}g$$

10. SUMMARY:

- In mechanics, we encounter several kinds of forces. The gravitational force can act at a distance without the need of any intervening medium. All the other forces common in mechanics are contact forces. The component of contact force normal to the surfaces in contact is called normal force. The component parallel to the surfaces in contact is called force of friction.

- Contact forces arise also when solids are in contact with fluids. For example, for a solid immersed in a fluid, there is an upward buoyant force equal to the weight of the fluid displaced. The viscous force, air resistance, etc are also examples of contact forces.

- Two other common forces are tension in a string and the force due to spring. The restoring force in a string is also called tension. It is customary to use a constant tension *T* throughout the string. This assumption is true for a string of negligible mass.

- The different contact forces of mechanics mentioned above fundamentally arise from electromagnetic forces. This may seem surprising since we are talking of uncharged and non-magnetic bodies in mechanics. At the microscopic level, all bodies are made of charged constituents (nuclei and electrons) and the various contact forces arising due to elasticity of bodies, molecular collisions and impacts, etc. can ultimately be traced to the electromagnetic forces between the charged constituents of different bodies.

- The familiar equation *mg* = *R* for a body on a table is true only if the body is in equilibrium. The two forces *mg* and *R* can be different (e.g. a body in an accelerated lift). The equality of *mg* and *R* has no connection with the third law.

- For applying the second law of motion, there is no conceptual distinction between inanimate and animate objects. An animate object such as a human also requires an external force to accelerate. For example, without the external force of friction, we cannot walk on the ground.

- The practice of drawing free-body diagrams is of great help in solving problems in mechanics. It allows you to clearly define your system and consider all forces on the system due to objects that are not part of the system itself.

- To handle a typical problem in mechanics systematically, one should use the following steps:

i. Draw a diagram showing schematically the various parts of the assembly of bodies, the links, supports, etc.
ii. Choose a convenient part of the assembly as one system.
iii. Draw a separate diagram which shows this system and all the forces on the system by the remaining part of the assembly.
iv. Include also the forces on the system by other agencies. Do not include the forces on the environment by the system. A diagram of this type is known as "free-body diagram". (Note this does not imply that the system under consideration is not acted upon by a net force).
v. In a free-body diagram, include information about forces (their magnitudes and directions) that is either given or you are sure of (e.g., the direction of tension in a string along its length). The rest should be treated as unknowns to be determined using laws of motion.
vi. If necessary, follow the same procedure for another choice of the system. In doing so, employ Newton's third law. That is, if in the free-body diagram of *A*, the force on *A* due to *B* is shown as F, then, in the free-body diagram of *B*, the force on *B* due to *A* should be shown as – F.