Part–1: Introduction & Force

Introduction

हम अपने दैनिक जीवन में अनेक प्रकार की गतियाँ देखते हैं। कोई गेंद लुढ़कती है, वाहन चलता है, व्यक्ति दौड़ता है, रॉकेट अंतरिक्ष में जाता है तथा पक्षी उड़ते हैं। इन सभी गतियों के पीछे मुख्य कारण **बल (Force)** होता है।

यदि किसी वस्तु की गति या विराम की अवस्था में परिवर्तन होता है, तो उसके पीछे कोई न कोई बाहरी बल अवश्य कार्य करता है।

गतियों के नियमों का वैज्ञानिक अध्ययन सबसे पहले **Sir Isaac Newton** ने किया तथा तीन प्रसिद्ध नियम दिए, जिन्हें **Newton's Laws of Motion** कहा जाता है।

ये नियम सम्पूर्ण Classical Mechanics की नींव हैं।

Learning Objectives

इस अध्याय के अध्ययन के बाद विद्यार्थी

- Force का अर्थ समझेंगे।
- Balanced एवं Unbalanced Force में अंतर जानेंगे।
- Newton के तीनों नियम समझेंगे।
- Inertia का अर्थ जानेंगे।
- Momentum एवं Impulse समझेंगे।
- Friction का अध्ययन करेंगे।
- Circular Motion में Force का उपयोग समझेंगे।
- Numericals हल करना सीखेंगे।

Force (बल)

Definition

Force is an external agency which changes or tends to change the state of rest or uniform motion of a body.

हिन्दी:

बल वह बाहरी प्रभाव है जो किसी वस्तु की विराम अथवा समान वेग से चलने की अवस्था में परिवर्तन करता है अथवा करने का प्रयास करता है।

SI Unit: **Newton (N)**

CGS Unit: dyne

Dimensional Formula:

$$[M\,L\,T^{-2}]$$

Formula:

$$F = ma$$

Nature of Force

Force is

- Vector Quantity
- Has magnitude
- Has direction

Effects of Force

बल

- वस्तु को चलाता है।
- रोक सकता है।
- गति बढ़ा सकता है।
- गति घटा सकता है।
- दिशा बदल सकता है।
- आकार बदल सकता है।

Types of Force

(A) Contact Forces

- Muscular Force
- Friction
- Normal Reaction
- Tension
- Spring Force

(B) Non-contact Forces

- Gravitational Force
- Electrostatic Force
- Magnetic Force

Balanced Forces

यदि दो या दो से अधिक बलों का परिणामी (Resultant Force) शून्य हो, तो वे Balanced Forces कहलाते हैं।

$$\Sigma F = 0$$

Result

- वस्तु की गति नहीं बदलती।
- त्वरण शून्य रहता है।

Example

दो व्यक्ति रस्सी को समान बल से विपरीत दिशाओं में खींचते हैं।

Net Force = 0

Unbalanced Forces

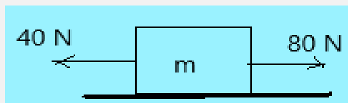
यदि परिणामी बल शून्य न हो

$$\Sigma F \neq 0$$

तो वस्तु में त्वरण उत्पन्न होता है।

Example

Net Force
= 40 N (Right)



Characteristics of Force

Force is characterized by

- Magnitude
- Direction
- Point of Application

Representation of Force

$\vec{F} = 20\ N$

Arrow indicates

- Direction
- Magnitude (by scale)

Important Points

- Force cannot exist alone; it acts due to interaction between two bodies.
- Force is always exerted by one object on another.
- Balanced force does not produce acceleration.
- Unbalanced force always produces acceleration.

Quick Formula Summary

$$F = ma$$
$$1N = 1\ kgm/s^2$$
$$1\ dyne = 10^{-5}N$$

Solved Numerical – 1

Question:

A body of mass **5 kg** accelerates at **2 m/s²**. Find the force acting on it.

Solution:

Given

m = 5 kg

a = 2 m/s²

Using

$$F = ma$$
$$F = 5 \times 2 = 10\ N$$

Answer: 10 N

Solved Numerical – 2

Question:

A force of **30 N** acts on a **10 kg** body. Find its acceleration.

Solution

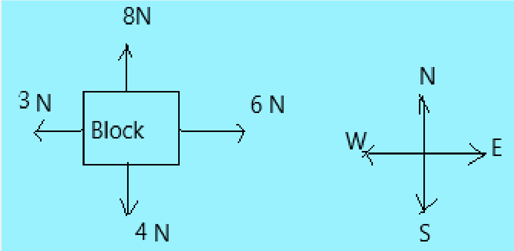
$$a = \frac{F}{m}$$
$$a = \frac{30}{10} = 3ms^{-2}$$

Answer: 3 m/s²

Solved Numerical – 3

Question:

From the figure below, state whether block will move or not. If moves, in which direction and what is the magnitude of force?



Solution:

Net Horizontal Force

$$F_x = 6 - 3 = 3\ N$$

Net Vertical Force

$$F_y = 8 - 4 = 4\ N$$

Resultant Force

$$F = \sqrt{3^2 + 4^2} = 5\ N$$

Direction is towards N-E.

Part – 2: Inertia and Newton's First Law of Motion

4.1 Inertia

Definition

Inertia is the inherent property of a body by virtue of which it resists any change in its state of rest or state of uniform motion in a straight line.

In simple words,

Inertia is the tendency of a body to oppose any change in its state of motion.

Key Points

- Every object possesses inertia.
- Inertia is **not a force**.
- It is a natural property of matter.
- Greater the mass of a body, greater is its inertia.
- SI Unit: **No unit** (Inertia is a property, not a physical quantity.)
- Inertia depends only on the **mass** of the body.

Types of Inertia

(i) Inertia of Rest

It is the tendency of a body to remain at rest unless acted upon by an external unbalanced force.

Examples

1. A passenger falls backward when a bus starts suddenly.
2. Dust particles come out when a carpet is beaten.
3. Fruits fall when the branch of a tree is shaken.
4. A coin drops into a glass when the card beneath it is flicked quickly.

Diagram

```
      Coin
       ●
 ─────────────── Card
      Glass

Card pulled quickly →
Coin falls vertically ↓
```

(ii) Inertia of Motion

It is the tendency of a moving body to continue moving with the same velocity unless acted upon by an external unbalanced force.

Examples

1. A passenger falls forward when a moving bus stops suddenly.
2. A person jumping from a moving bus falls forward.
3. Luggage on the roof of a vehicle tends to move forward when brakes are applied.

Diagram

```
Moving Bus →
```

```
Passenger

     O
    /|\
    / \

Bus stops suddenly

Passenger moves forward →
```

(iii) Inertia of Direction

It is the tendency of a body to resist any change in the direction of its motion.

Examples

1. A passenger is pushed outward when a car takes a sharp turn.
2. Mud flies off the rotating tyre of a vehicle.
3. A stone tied to a string moves in a circular path because the string continuously changes its direction.

Diagram

```
Car turning left

      Car
     ______
----->

Passenger tends to move straight
```

Mass and Inertia

Mass is the measure of inertia.
Therefore,

- Larger mass → Greater inertia
- Smaller mass → Smaller inertia

Example

A truck is more difficult to push than a bicycle because the truck has much greater mass and hence greater inertia.

Newton's First Law of Motion

Statement

Every body continues in its state of rest or of uniform motion in a straight line unless compelled by an external unbalanced force to change that state.
This law is also known as the **Law of Inertia**.

Mathematical Interpretation

If the net external force acting on a body is zero,

$$\sum \vec{F} = 0$$

then,

$$\vec{a} = 0$$

Therefore,

- Velocity remains constant.
- The body remains either at rest or moves with uniform velocity in a straight line.

Explanation

Suppose a body is at rest.
If no external unbalanced force acts on it,

```
Net Force = 0

↓

Acceleration = 0

↓

Body remains at rest
```

Similarly, if a body is moving with constant velocity,

```
Net Force = 0

↓

Acceleration = 0

↓

Velocity remains constant
```

External Unbalanced Force

An external unbalanced force is a force whose resultant is not zero.
When such a force acts,

- Speed may increase.
- Speed may decrease.
- Direction may change.
- Both speed and direction may change.

Importance of Newton's First Law

The First Law:

- Defines the concept of force.
- Explains the concept of inertia.
- Forms the basis of Newton's Second Law.
- Explains many day-to-day observations.

Everyday Applications

Seat Belt

When a moving car stops suddenly, passengers tend to move forward due to inertia of motion.
The seat belt prevents injury by applying the necessary force to stop the passenger safely.

Beating a Carpet
Dust particles remain at rest while the carpet moves suddenly.
Hence, dust separates from the carpet due to inertia of rest.

Shaking Tree Branches
When branches are shaken suddenly, the branch moves but the fruits tend to remain at rest.
Hence, fruits fall due to inertia of rest.

Pulling a Table Cloth Quickly
When the table cloth is pulled rapidly, utensils tend to remain at rest because of inertia of rest.

Conceptual Questions
Q1. Why does a passenger fall forward when a bus stops suddenly?
Answer:
Due to inertia of motion, the upper part of the passenger's body continues to move forward even after the bus stops.

Q2. Why is it difficult to stop a moving truck compared to a motorcycle?
Answer:
A truck has greater mass and therefore greater inertia.

Q3. Why is mass called the measure of inertia?
Answer:
Because inertia depends directly on the mass of the body. Greater mass means greater resistance to change in motion.

Solved Numerical 1
A body of mass **12 kg** and another body of mass **3 kg** are initially at rest. Which body possesses greater inertia?
Solution
Since inertia depends only on mass.
Mass of first body = **12 kg**
Mass of second body = **3 kg**
Therefore, the **12 kg body** has greater inertia.

Solved Numerical 2
A body moves with a constant velocity of **8 m s^{-1}**. What is the net external force acting on it?
Solution
Since velocity is constant,

$$a = 0$$

Using Newton's Second Law,

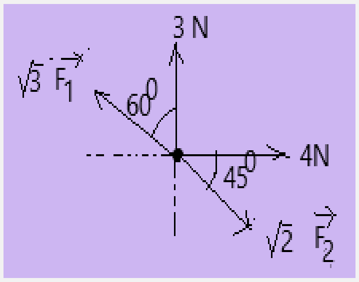
$$F = ma$$
$$F = 0$$

Answer: 0 N

Numerical Based on Newton's First law-

(i) Two or more forces acting at a point (Concurrent Coplanar Forces)

Q.1. Four forces are acting at a point of mass m as shown in the figure. The mass is in equilibrium. Find the magnitude of forces $\vec{F}_1$ and $\vec{F}_2$.



Solution:

Since the mass m is in equilibrium, then net force acting on body in x- and y-direction is zero.

In x-direction,

$$\sum F_x = 0$$

Resolving components of $\sqrt{2}\vec{F}_2$ and $\sqrt{3}\vec{F}_1$ in x-direction and adding 4 N in it to make all equal to zero.

Then,

$$\sqrt{2}F_2 \cos 45^0 + 4 - \sqrt{3}F_1 \sin 60^0 = 0$$

Or,

$$F_2 + 4 - \frac{3F_1}{2} = 0\ Or, 3F_1 - 2F_2 = 8 - - - (i)$$

Resolving components of $\sqrt{2}\vec{F}_2$ and $\sqrt{3}\vec{F}_1$ in y-direction and adding 3 N in it to make all equal to zero.

Then,

$$-\sqrt{2}F_2 \sin 45^0 + 3 + \sqrt{3}F_1 \cos 60^0 = 0$$

Or,

$$-F_2 + 3 + \frac{\sqrt{3}}{2}F_1 = 0$$

Or,

$$\sqrt{3}F_1 - 2F_2 = -6 - -(ii)$$

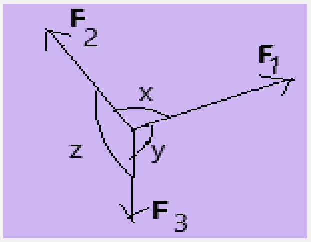
Solving equation (i) and (ii), we get

$$F_1 = \frac{14}{3-\sqrt{3}}\ N = 11.04\ N$$

And

$$F_2 = \frac{9-4\sqrt{3}}{3-\sqrt{3}} N = 1.63\ N$$

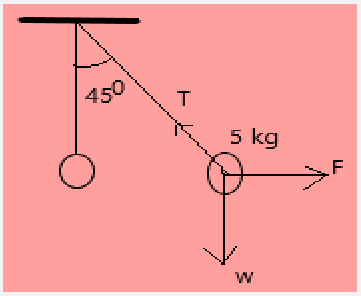
(ii) Lami's Theorem



When three forces are acting at a point in equilibrium, making angle x, y *and* z between two forces respectively as shown in the figure,
'The ratio of magnitude of each force and sin (trigonometry ratio) of opposite angle between remaining two forces is constant'. That is,

$$\frac{F_1}{\sin z} = \frac{F_2}{\sin y} = \frac{F_3}{\sin x} = Constant\ (C)$$

Q.2. As shown in the figure, find the tension in the string. Here w is the weight and F is external force. Take g = 10 m/s^2.



Solution

By using Lami's theorem

$$\frac{T}{\sin 90^0} = \frac{w}{\sin 135^0}$$

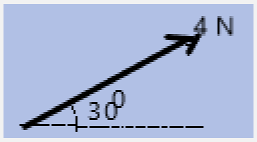
Or

$$T = \frac{mg}{1/\sqrt{2}}\ or\ T = 50\sqrt{2}\ N$$

Answer

$\boxed{50\sqrt{2}N}$

Q.3. Resolve the 4 N in its horizontal and vertical components as shown below.



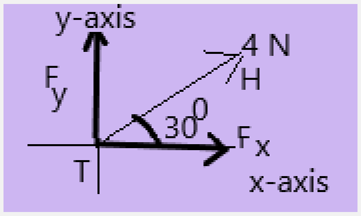
Solution:

Tracing horizontal line and vertical line from the Point of Tail as shown below and then finding the horizontal and vertical components. The solution is made below.

$F_x = 4\cos 30^0$ Or, $F_x = 4 \times \frac{\sqrt{3}}{2} = 2\sqrt{3}\ N$

And

$F_y = 4\sin 30^0$ Or, $F_y = 4 \times \frac{1}{2} = 2\ N$



Answer: Horizontal component = $2\sqrt{3}\ N$ and Vertical Component = 2 N

Chapter Summary (Part–2)

- Inertia is the property of matter that resists any change in its state of motion.
- Inertia depends only on mass.
- There are three types of inertia: **Inertia of Rest, Inertia of Motion, and Inertia of Direction**.
- Newton's First Law is also called the **Law of Inertia**.
- If the net external force on a body is zero, its velocity remains constant.
- An unbalanced external force is required to change the state of motion of a body.

Part – 3: Linear Momentum and Newton's Second Law of Motion

4.2 Linear Momentum

Definition

Linear momentum is the quantity of motion possessed by a body. It is defined as the product of the mass of the body and its velocity.
Mathematically,

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

where,

- $\vec{p}$ = Linear momentum
- mmm = Mass of the body
- $\vec{v}$ = Velocity of the body

Since velocity is a vector quantity, **momentum is also a vector quantity**.

SI Unit

$$\boxed{kgms^{-1}}$$

Dimensions

$$\boxed{[MLT^{-1}]}$$

Direction of Momentum

The direction of momentum is always the **same as the direction of velocity**.
Example:
If a particle moves towards the east, its momentum is also directed towards the east.

Important Points

- Momentum depends upon both **mass** and **velocity**.
- If either mass or velocity is zero, momentum is zero.
- Larger the momentum, greater is the difficulty in stopping the body.
- A heavy truck moving slowly may possess greater momentum than a fast-moving motorcycle.

Examples

Example 1

A body of mass **5 kg** moves with velocity **4 m s⁻¹**.

$$p = mv$$
$$p = (5)(4) = 20\ kgm/s$$

Example 2
A stationary body has

$$v = 0$$

Hence,

$$p = 0$$

Change in Momentum

Suppose
Initial velocity = u
Final velocity = v
Mass remains constant.
Initial momentum,

$$p_i = mu$$

Final momentum,

$$p_f = mv$$

Therefore,

$$\Delta p = mv - mu$$

$$\boxed{\Delta p = m(v - u)}$$

Rate of Change of Momentum

If the change in momentum occurs in time t,

$$\frac{\Delta p}{\Delta t} = \frac{m(v-u)}{t}$$

Since,

$$a = \frac{v-u}{t}$$

Therefore,

$$\boxed{\frac{\Delta p}{\Delta t} = ma}$$

This result forms the basis of **Newton's Second Law of Motion**.

Newton's Second Law of Motion

Statement

The net external force acting on a body is directly proportional to the rate of change of its linear momentum and acts in the direction of the applied force.
Mathematically,

$$\boxed{\vec{F} \propto \frac{d\vec{p}}{dt}}$$

Introducing the proportionality constant,

$$\boxed{\vec{F} = \frac{d\vec{p}}{dt}}$$

(In SI units, the proportionality constant is unity.)

Derivation of F= ma

For a body of constant mass,

$$p = mv$$

Differentiating with respect to time,

$$\frac{dp}{dt} = m\frac{dv}{dt} = F$$

But,

$$\frac{dv}{dt} = a$$

Hence,

$$\boxed{F = ma}$$

This equation is valid when the mass of the body remains constant.

Physical Meaning of F = ma

The equation shows that:

- Force is directly proportional to acceleration.
- For the same force, a larger mass produces a smaller acceleration.
- Greater the force, greater is the acceleration produced.

SI Definition of One Newton

One Newton is the force that produces an acceleration of **1 m s^{-2}** in a body of mass **1 kg**.
Therefore,

$$\boxed{1N = 1kgms^{-2}}$$

Applications of Newton's Second Law

Pushing a Trolley

An empty trolley accelerates more easily than a loaded trolley because the loaded trolley has greater mass.

Kicking a Football

A greater force produces a greater acceleration, so the ball travels faster.

Catching a Cricket Ball

A fielder moves his hands backward while catching the ball, increasing the time of contact. This reduces the average force experienced (Impulse concept, to be discussed later).

Graphical Interpretation

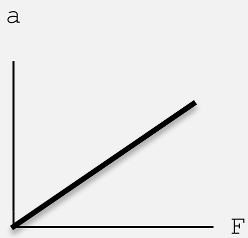
For constant mass,

$$F = ma$$

Thus,

$$a \propto F$$

The graph between force and acceleration is a straight line passing through the origin.



The slope of the graph is:

$$\frac{a}{F} = \frac{1}{m}$$

Hence, a larger mass corresponds to a smaller slope.

Solved Numerical 1

A force of **18 N** acts on a body of mass **6 kg**. Find the acceleration.

Solution

Given,

F=18 N, m = 6 kg

Using,

$$F = ma$$

$$a = \frac{F}{m} = \frac{18}{6} = 3ms^{-2}$$

Answer: $\boxed{3ms^{-2}}$

Solved Numerical 2

A body of mass **4 kg** is moving with a velocity of **5 m s^{-1}**. Calculate its momentum.

Solution

$$p = mv$$

$$p = 4 \times 5 = 20\ kgm/s$$

Answer: $\boxed{20\ kgm/s}$

Concept Check

Q1. Can a body have momentum even when no force acts on it?

Answer: Yes. A body moving with constant velocity has momentum even though the net external force acting on it is zero.

Q2. Is force required to maintain uniform motion?

Answer: No. According to Newton's First Law, no net external force is required to maintain uniform motion in a straight line.

Part – 4: Impulse, Impulsive Force, Newton's Third Law and Conservation of Linear Momentum

4.3 Impulse

Definition

Impulse is the product of the average force acting on a body and the time interval for which the force acts.
Mathematically,

$$\boxed{\vec{J} = \vec{F}\Delta t}$$

where,

- $\vec{J}$ = Impulse
- $\vec{F}$ = Average force
- Δt = Time interval

Impulse is a **vector quantity**, and its direction is the same as that of the applied force.

SI Unit

$$\boxed{Ns}$$

Since,

$$1N = 1kgm/s^2$$

Therefore,

$$\boxed{1Ns = 1kgm/s}$$

Thus, the SI unit of impulse is numerically equal to the SI unit of momentum.

Dimensional Formula

$$\boxed{[MLT^{-1}]}$$

Impulse–Momentum Theorem

According to Newton's Second Law,

$$F = \frac{\Delta p}{\Delta t}$$

Multiplying both sides by Δt\Delta tΔt,

$$F\Delta t = \Delta p$$

Hence,

$$\boxed{\vec{J} = \Delta\vec{p}}$$

Statement:
Impulse imparted to a body is equal to the change in its linear momentum.
This is known as the **Impulse–Momentum Theorem**.

Impulsive Force

Definition

An **impulsive force** is a very large force acting on a body for a very short interval of time.
Examples:

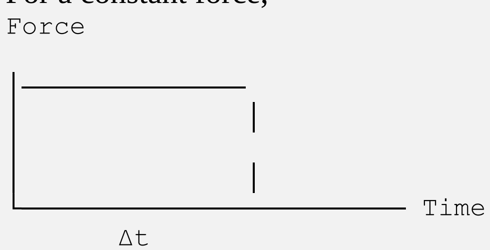
- A bat hitting a cricket ball.
- A hammer striking a nail.
- A football being kicked.
- Collision between two vehicles.
- A tennis racket hitting a ball.

Characteristics of Impulsive Force

- Magnitude is very large.
- Time of action is very small.
- Produces a finite change in momentum.
- Usually acts during collisions.

Force–Time Graph

For a constant force,



The **area under the Force–Time graph** represents the impulse.

$$\boxed{Impulse = Area\ Under\ F - t\ graph}$$

Applications of Impulse

(i) Airbags in Cars

Airbags increase the time during which the passenger comes to rest.
Since,

$$F = \frac{\Delta p}{\Delta t}$$

an increase in Δt decreases the average force, thereby reducing injuries.

(ii) Catching a Ball

A cricketer pulls his hands backward while catching a fast-moving ball.
This increases the stopping time and reduces the force experienced.

(iii) Thick Foam Mattresses

High jumpers land on thick foam mattresses to increase the stopping time and reduce the impact force.

(iv) Bending the Knees
While jumping from a height, bending the knees increases the stopping time and decreases the force acting on the body.

Newton's Third Law of Motion

Statement

To every action, there is an equal and opposite reaction.
Or,
Whenever one body exerts a force on another body, the second body exerts an equal and opposite force on the first body.

Mathematical Form

$$\boxed{\vec{F}_{AB} = -\vec{F}_{BA}}$$

where,

- $\vec{F}_{AB}$ = Force exerted by A on B
- $\vec{F}_{BA}$ = Force exerted by B on A

Characteristics of Action–Reaction Forces

- They are always equal in magnitude.
- They act in opposite directions.
- They act on **different bodies**.
- They occur simultaneously.
- They are of the same type (both gravitational, both normal, both frictional, etc.).

Important Note: Since action and reaction act on different bodies, they **do not cancel each other**.

Examples of Newton's Third Law

Walking

When we walk, our foot pushes the ground backward. The ground exerts an equal and opposite force on us, pushing us forward.

```
Foot pushes ground  ←

Ground pushes person →
```

Swimming

A swimmer pushes water backward.
Water pushes the swimmer forward.

Recoil of a Gun

When a bullet moves forward, the gun recoils backward due to the reaction force.

Rocket Propulsion

Hot gases are expelled downward at high speed.

The reaction force pushes the rocket upward.

Rowing a Boat
The oar pushes water backward.
Water exerts a reaction force that moves the boat forward.

Conservation of Linear Momentum
Statement
If no external force acts on a system, the total linear momentum of the system remains constant.
This law is based on Newton's Third Law.

Mathematical Proof (Two-Body System)
Consider two bodies of masses m_1 and m_2.
Initial velocities:

$$u_1, u_2$$

Final velocities:

$$v_1, v_2$$

Initial momentum:

$$p_i = m_1u_1 + m_2u_2$$

Final momentum:

$$p_f = m_1v_1 + m_2v_2$$

If no external force acts,

$$\boxed{p_i = p_f}$$

Therefore,

$$\boxed{m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2}$$

This is the mathematical expression for the **Law of Conservation of Linear Momentum**.

Applications of Conservation of Momentum
Explosion of a Bomb
Initially, the bomb is at rest, so total momentum is zero.
After the explosion, fragments move in different directions, but their vector sum of momenta remains zero.

Recoil of a Gun
Before firing,
Total momentum = 0.
After firing,
Forward momentum of the bullet = Backward momentum of the gun.

Rocket Motion
The gases expelled downward carry downward momentum.

The rocket gains equal upward momentum.

Solved Numerical 1

A force of **80 N** acts on a body for **0.2 s**. Calculate the impulse.

Solution

Given,

$F = 80$ N, $\Delta t = 0.2$ s

Using,

$$J = F\Delta t$$
$$J = 80 \times 0.2 = 16\ Ns$$

Answer: $\boxed{16\ Ns}$

Solved Numerical 2

A **2 kg** body is initially at rest. A constant force of **10 N** acts on it for **3 s**.

Find:

1. Impulse
2. Final momentum
3. Final velocity

Solution

Impulse,

$$J = F\Delta t$$
$$J = 10 \times 3 = 30\ Ns$$

Since,

$$J = \Delta p$$

Final momentum,

$$p = 30 \text{ kg m s}^{-1}$$

Using,

$$p = mv$$
$$30 = 2 \times v$$
$$v = 15\ m/s$$

Answers:

- Impulse = 30 N s
- Final Momentum = 30 kg m s^{-1}
- Final Velocity = 15 m s^{-1}

Conceptual Questions

Q1. Why does a gun recoil when fired?

Answer: Due to Newton's Third Law and conservation of linear momentum. The bullet gains forward momentum, while the gun acquires equal backward momentum.

Q2. Why do airbags reduce injuries?

Answer: Airbags increase the time of impact. Since $F = \Delta p / \Delta t$, increasing the time reduces the average impact force.

Q3. Why don't action and reaction forces cancel each other?
Answer: Because they act on **different bodies**, not on the same body.

Important Formulae (Part–4)

$$\boxed{J = F\Delta t}$$

$$\boxed{J = \Delta p}$$

$$\boxed{F = \frac{\Delta p}{\Delta t}}$$

$$\boxed{\vec{F}_{AB} = -\vec{F}_{BA}}$$

Part–4 Summary

- **Impulse** is the product of force and the time interval for which it acts.
- The **Impulse–Momentum Theorem** states that impulse equals the change in linear momentum.
- **Impulsive forces** are large forces acting for a very short duration.
- **Newton's Third Law** states that action and reaction are equal in magnitude, opposite in direction, and act on different bodies.
- In the absence of external forces, the **total linear momentum of a system remains conserved**.

Part – 5: Types of Forces, Free Body Diagram (FBD), Weight, Normal Reaction, Tension and Spring Force

4.5 Types of Forces

A **force** is an interaction between two bodies that can change or tends to change the state of rest or uniform motion of a body.
Forces are broadly classified into two categories:

1. Contact Forces
2. Non-Contact (Field) Forces

1. Contact Forces

A **contact force** acts only when two bodies are in physical contact with each other.

Examples

- Normal Reaction
- Frictional Force
- Tension in a String
- Spring Force
- Muscular Force
- Air Resistance (Drag Force)

2. Non-Contact (Field) Forces

A **field force** acts even when two bodies are not in physical contact.

Examples

- Gravitational Force
- Electrostatic Force
- Magnetic Force

Comparison

Contact Force	Field Force
Requires physical contact	No physical contact required
Acts only at the point of contact	Acts through a field
Example: Friction	Example: Gravity

Weight of a Body

Definition

The gravitational force with which the Earth attracts a body is called its **weight**.
It acts vertically downward towards the centre of the Earth.

Formula

$$\boxed{\vec{w} = m\vec{g}}$$

where

- m = mass
- g = acceleration due to gravity

SI Unit

Newton (N)

Direction

Always vertically downward.

Diagram

```
        ↑
        N
______________

      □
      |
      ↓  W = mg
```

Important Difference Between Mass and Weight

Mass	Weight
Amount of matter	Gravitational force on the body
Scalar quantity	Vector quantity
Constant everywhere	Changes with the value of g
SI Unit: kg	SI Unit: N

Normal Reaction (Normal Force)

Definition

The force exerted by a surface on a body in contact with it, **perpendicular to the surface**, is called the **normal reaction**.

Symbol:

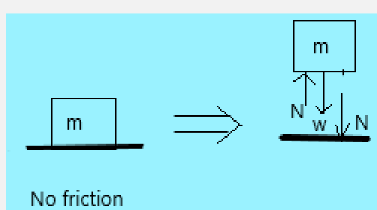
$\boxed{N}$

Characteristics

- Acts perpendicular to the surface.
- It is a contact force.
- It is **not always equal to the weight**.
- Its magnitude depends on the situation.

Horizontal Surface

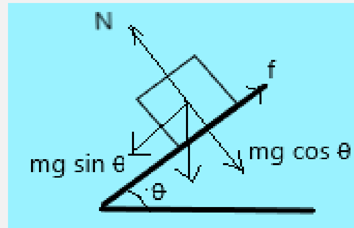
```
        ↑  N
           |
      ┌─────┐
      │ Box │
      └─────┘
           |
           ↓  W = mg
____________________
```



If no other vertical force acts,

$\boxed{N = mg}$

Inclined Plane



On an incline,

$$\boxed{N = mg\cos\theta}$$

(when no other force acts perpendicular to the plane)

Tension in a String

Definition

The pulling force transmitted through a stretched string, rope or cable is called **tension**.
It acts away from a block along a string.
Symbol:

$$\boxed{T}$$

Characteristics

- Tension always acts **along the string**.
- A string can pull but **cannot push**.
- In an ideal string (light and inextensible), tension is the same throughout its length.

Diagram

← T ——————□—————— T →

Ideal String

An ideal string is

- Massless (light)
- Inextensible
- Perfectly flexible

Hence,
Same tension throughout the string\boxed{\text{Same tension throughout the string}}Same tension throughout the string

Spring Force

When a spring is stretched or compressed, it exerts a restoring force opposite to the displacement.

Hooke's Law

Within the elastic limit,
The restoring force of a spring is directly proportional to its extension or compression.

Mathematically,

$$\boxed{F \propto (-x)}$$

Or

$$\boxed{F = -kx}$$

where

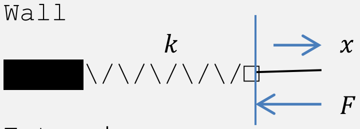
- k = spring constant
- x = extension/compression
- Negative sign indicates that the spring force acts opposite to the displacement.

SI Unit of Spring Constant

$$\boxed{Nm^{-1}}$$

Diagram

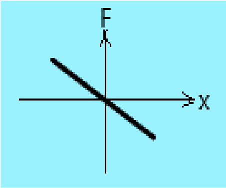
Wall



Extension = x

Spring force ←

Graph Between Force and Extension



The graph is a straight line passing through the origin.
Its slope is

$$\boxed{-k}$$

Drag Force (Air Resistance)

When a body moves through air or any fluid, the fluid opposes its motion.
This opposing force is called **drag force** or **air resistance**.
Properties:

- Opposite to the direction of motion.
- Depends on the speed of the body.
- Increases with increasing speed.

Free Body Diagram (FBD)

Definition

A **Free Body Diagram (FBD)** is a simplified diagram in which a body is isolated from its surroundings and **all the external forces acting on it are represented by arrows**.
It is one of the most important tools in mechanics.

Rules for Drawing an FBD

1. Isolate the body.
2. Replace all contacts by the corresponding forces.

3. Show only **external forces**.
4. Indicate the correct direction of each force.
5. Do not include forces exerted by the body on other objects.

Example 1: Block on a Horizontal Surface

```
        ↑ N
        |
     ┌───────┐
     │ Block │
     └───────┘
        |
        ↓ W = mg

→ Applied Force (F)

← Friction (f)
```

Example 2: Hanging Block

```
    T
    ↑
    |
    □
    |
    ↓
   mg
```

Solved Numerical 1

A block of mass **8 kg** is placed on a horizontal table. Calculate its weight.
Take
$g=9.8\ \mathrm{m\ s^{-2}}$
Solution

$$w = mg$$

$$w = 8 \times 9.8 = 78.4\ N$$

Answer: $\boxed{78.4\ N}$

Solved Numerical 2

A spring of spring constant **250 N m⁻¹** is stretched by **8 cm**. Find the restoring force.
Solution
Given,
$k=250\ \mathrm{N\ m^{-1}}$, $x = 8\ \mathrm{cm} = 0.08\ \mathrm{m}$
Using Hooke's law,
$F = kx = 250 \times 0.08 = 20\ \mathrm{N}$
The restoring force acts opposite to the extension.
Answer: $\boxed{250\ N}$

Important Points to Remember

- Weight always acts vertically downward.
- Normal reaction is always perpendicular to the surface.
- Tension always acts along the string.
- A string can pull but cannot push.
- Spring force is a restoring force and obeys Hooke's law within the elastic limit.
- A correct **Free Body Diagram (FBD)** is the key to solving problems involving connected bodies, pulleys and friction.

Part–5 Summary

- Forces are classified into **contact** and **non-contact (field)** forces.
- Important contact forces include **normal reaction, tension, spring force, friction and drag**.
- Important field forces include **gravitational, electrostatic and magnetic forces**.
- The weight of a body is given by $w = mg$
- **Normal reaction** acts perpendicular to the surface, while **tension** acts along the string.
- **Hooke's Law** is expressed as $F=-kx$
- Drawing a proper **Free Body Diagram (FBD)** is essential before applying Newton's laws.

Part – 6: Free Body Diagram (Advanced), Connected Bodies and Mass–Pulley Systems

4.6 Free Body Diagram (FBD)

Definition

A **Free Body Diagram (FBD)** is a diagram in which a body is isolated from its surroundings and **all the external forces acting on it are represented by arrows**.

An FBD helps us apply **Newton's Second Law** correctly.

Golden Rule:

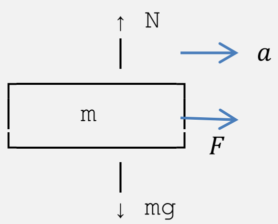
Draw the FBD before writing any equation of motion.

Steps for Drawing an FBD

1. Isolate the body from its surroundings.
2. Replace every contact by the corresponding force.
3. Draw all external forces only.
4. Mark the positive direction.
5. Apply Newton's Second Law separately to each body.

Example 1: Block on a Smooth Horizontal Surface

Figure



Applied Force → F

Forces Acting

- Weight mg (downward)
- Normal reaction N (upward)
- Applied force F (horizontal)

Since the surface is smooth,

$$\boxed{friction = 0}$$

Equation of Motion

Horizontal direction

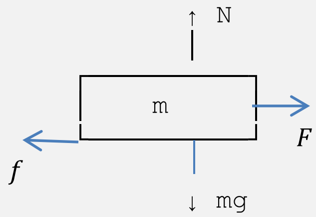
$$F = ma$$

Vertical direction

$$N = mg$$

Example 2: Block on a Rough Horizontal Surface

Figure



← Friction

Applied Force →

Horizontal equation

$$F - f = ma$$

Vertical equation

$$N = mg$$

Example 3: Hanging Body

Figure

```
 T
 ↑
 |
 □
 |
 ↓
mg
```

If the body moves upward,

$$T - mg = ma$$

If it moves downward,

$$mg - T = ma$$

Choose the sign convention carefully.

Connected Bodies

Two or more bodies connected by a light string move with the **same magnitude of acceleration** as long as the string remains taut.

Assumptions

For an ideal system,

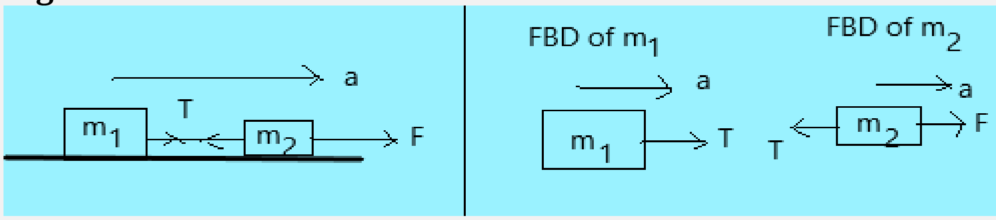
- String is light (massless).
- String is inextensible.
- Pulley is smooth (frictionless).
- Pulley has negligible mass.

Therefore,

- Tension is the same throughout the string.
- All connected bodies have the same magnitude of acceleration.

Two Blocks on a Smooth Surface

Figure



Free Body Diagram

For block m_2
Applied force F
Backward tension T
Hence,

$$F - T = m_2 a$$

For block m_1
Only tension acts horizontally.

$$T = m_1 a$$

Adding the two equations,

$$F = (m_1 + m_2)a$$

Therefore,

$$\boxed{a = \frac{F}{m_1 + m_2}}$$

Tension in the String

Substitute

$$\boxed{a = \frac{F}{m_1 + m_2}}$$

into

$$T = m_1 a$$

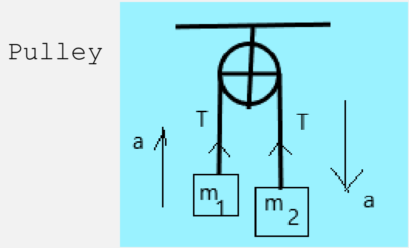
Hence,

$$\boxed{T = \frac{m_1 F}{m_1 + m_2}}$$

Atwood Machine

One of the most important pulley systems,

Figure



Suppose $m_1 > m_2$

Then,

- m_2 moves downward.
- m_1 moves upward.

Free Body Diagram

For m_1,

Upward T and weight m_1g downward

Equation is

$$T - m_1g = m_1a$$

For m_2

Upward T, Downward m_2g

Equation is

$$m_2g - T = m_2a$$

Adding,

$$(m_2 - m_1)g = (m_2 + m_1)a$$

Therefore,

$$\boxed{a = \frac{(m_2 - m_1)g}{(m_2 + m_1)}}$$

Tension in Atwood Machine

Substitute the value of acceleration into either equation.

Result,

$$\boxed{T = \frac{2m_1m_2g}{m_2 + m_1}}$$

This formula is valid for an **ideal Atwood machine**.

Constraint Relation

Because the string length remains constant,

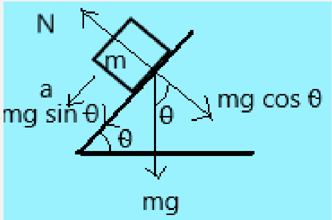
If one body moves upward by x and the other body moves downward by x

Therefore,

- Displacements are equal.
- Velocities are equal in magnitude.
- Accelerations are equal in magnitude.

Motion on an Inclined Plane (Without Friction)

Figure



Weight mg is resolved into two components.

Component Parallel to Plane

$$\boxed{mg\sin\theta}$$

This causes the body to slide down.

Component Perpendicular to Plane

$$\boxed{mg\cos\theta}$$

This is balanced by the normal reaction.
Hence,

$$\boxed{N = mg\cos\theta}$$

Acceleration on a Smooth Inclined Plane

Applying Newton's Second Law,

$$mg\sin\theta = ma$$

Therefore,

$$\boxed{a = g\sin\theta}$$

Solved Numerical 1

Two blocks of masses 3 kg and 2 kg are connected by a light string on a smooth surface. A horizontal force of 20 N acts on the first block. Find the acceleration.

Solution

Total mass = 3+2 = 5kg
Using,

$$a = \frac{F}{m_1 + m_2}$$

Or

$$a = \frac{F}{m_1 + m_2} = \frac{20}{5} = 4\ m/s^2$$

Answer

$\boxed{4m/s^2}$

Solved Numerical 2

Two masses 5kg and 3kg form an Atwood machine. Find the acceleration.
Take g = 9.8m/s^2

Solution
Using,

$$a = \frac{(m_2 - m_1)g}{m_2 + m_1}$$

Larger mass = 5kg, Smaller mass = 3kg

$$a = \frac{(5 - 3) \times 9.8}{5 + 3} = \frac{19.6}{8} = 2.45\ m/s^2$$

Answer
$\boxed{2.45\ m/s^2}$

Common Mistakes

- Forgetting to draw the FBD before solving.
- Taking the wrong direction of acceleration.
- Assuming different accelerations for bodies connected by the same string.
- Using different tensions in an ideal light string.
- Ignoring the components mg sinθ and mg cosθ on an inclined plane.

Important Formulae (Part–6)

$$F = (m_1 + m_2)a$$

$$a = \frac{F}{m_1 + m_2}$$

$$T = \frac{m_2 F}{m_1 + m_2}$$

$$a = \frac{(m_2 - m_1)g}{m_1 + m_2}$$

$$T = \frac{2m_1 m_2 g}{m_1 + m_g}$$

$$N = mg\cos\theta$$

$$a = g\sin\theta$$

Chapter Summary (Part–6)

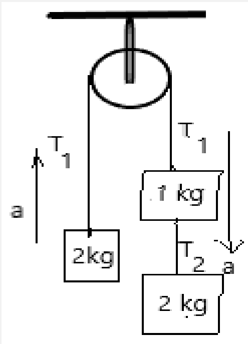
- A correct **Free Body Diagram (FBD)** is the foundation of solving mechanics problems.
- In an **ideal string–pulley system**, the tension is the same throughout the string and all connected bodies have the same magnitude of acceleration.

- For an **Atwood machine**, acceleration and tension are obtained by applying Newton's Second Law to each mass separately.
- On a **smooth inclined plane**, the component mgsinθ causes motion, while mgcosθ determines the normal reaction.

Numerical based on Newton's Second Law

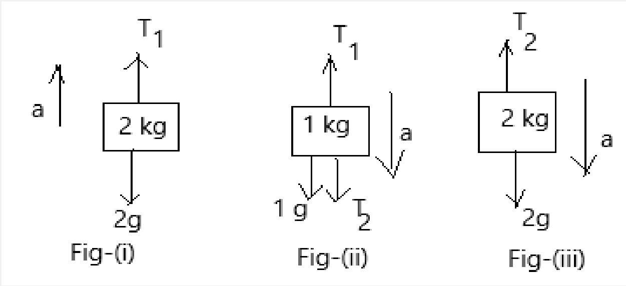
Question 1:

Find the acceleration of each block and tension in each string as shown below. The string is inextensible. Take g = 10 m/s^2



Solution

Free body diagram of each block isolated, by showing all Forces acting on it, is shown below.



In Fig-(i), FBD of 2 kg is shown.
Equation is

$$T_1 - 2g = 2a$$

Or

$$T_1 - 20 = 2a - - - - (i)$$

In Fig-(ii),FBD is shown.
Equation is

$$g + T_2 - T_1 = a$$

Or

$$10 + T_2 - T_1 = a - - - - (ii)$$

In Fig-(iii), FBD is shown.
Equation is

$$2g - T_2 = 2a$$

Or

$$20 - T_2 = 2a - - - (iii)$$

Solving equations (i), (ii) and (iii), we get

$$20 - T_2 = T_1 - 20 \; or \; T_1 + T_2 = 40 - - - (iv)$$

And

$$T_1 - 20 = 20 + 2T_2 - 2T_1 \; Or \; 3T_1 - 2T_2 = 40 - - - - (v)$$

Solving equation (iv) and (v), we get

$$T_1 = 24\ N, T_2 = 16\ N, a = 2\frac{m}{s^2} \;\; Answer$$

Part – 7: Friction (Static, Limiting and Kinetic Friction)

4.7 Friction

Definition

Friction is the contact force that opposes the relative motion or the tendency of relative motion between two surfaces in contact.
In simple words,
Friction always acts parallel to the surfaces in contact and opposite to the direction of relative motion or impending motion.

Why Does Friction Arise?

No surface is perfectly smooth.
Even polished surfaces contain microscopic irregularities called **asperities**.
When two surfaces are pressed together, these irregularities interlock and oppose motion, producing friction.

Figure

```
Microscopic View

Surface A

^^^^^^^^^^^^^^^^

Surface B

~~~~~~~~~~~~~~~~

Interlocking of irregularities produces friction.
```

Nature of Friction

- Friction is a **contact force**.
- It always acts **parallel** to the surface.
- It opposes relative motion or the tendency of relative motion.
- It depends upon the nature of the surfaces.
- It depends upon the normal reaction.

Direction of Friction

Important Rule
Friction acts opposite to the direction of actual motion or the tendency of motion.

Example

```
Applied Force →

 Block

← Friction
```

Types of Friction

There are mainly four types of friction:

1. Static Friction
2. Limiting Friction
3. Kinetic (Sliding) Friction
4. Rolling Friction

Static Friction

Definition

The friction acting between two surfaces at rest with respect to each other is called **static friction**.
Static friction prevents the body from moving.

Important Property

Static friction is **self-adjusting**.
It automatically adjusts its magnitude according to the applied force until it reaches its maximum value.
Mathematically,

$$0 \leq f_s \leq f_l$$

Where,
f_l = Limiting frictional force or maximum of static frictional force

---

Example

Suppose a block is on a table.
Applied force = 10 N
Static friction = 10 N
Result:
Net force = 0
The block does not move.

If the applied force becomes 20 N, Static friction also becomes 20 N, provided its maximum value has not yet been reached.

Limiting Friction
Definition
The maximum value of static friction just before the body starts moving is called **limiting friction**.
It is denoted by f_l.

Formula

$$\boxed{f_s = \mu_s N}$$

Where,
- μ_s = Coefficient of static friction
- N = Normal reaction

Characteristics of Limiting Friction
- It is the maximum possible static friction.
- It acts when motion is about to start.
- Beyond this value, the body begins to move.

Kinetic (Sliding) Friction
Definition
The friction acting when one surface actually slides over another is called **kinetic friction**.

Formula

$$\boxed{f_k = \mu_k N}$$

Where
- μ_k = Coefficient of kinetic friction

Important Relation

$$\boxed{\mu_k < \mu_s}$$

Hence,

$$\boxed{f_k < f_l}$$

Why is Kinetic Friction Smaller?
During sliding, the microscopic irregularities do not remain interlocked for a long time.
Therefore, the opposing force decreases.

Rolling Friction
Rolling friction acts when a body rolls over a surface.
Example

- Bicycle wheel
- Car tyre
- Ball bearing

Rolling friction is much smaller than sliding friction.
Hence,
Rolling is preferred over sliding in machines.

Laws of Dry Friction (Coulomb's Laws)

First Law

Friction acts opposite to the direction of relative motion.

Second Law

Limiting friction is directly proportional to the normal reaction.

$$f_l \propto N$$

Third Law

Friction depends upon the nature of the surfaces in contact.

Fourth Law

For ordinary speeds, friction is nearly independent of the area of contact.
Teacher's Note:
Students often think that increasing the contact area always increases friction. For dry friction between rigid bodies, this is generally **not true** because friction mainly depends on the **normal reaction** and the **coefficient of friction**.

Coefficient of Friction

Definition

The ratio of limiting friction to the normal reaction is called the **coefficient of friction**.

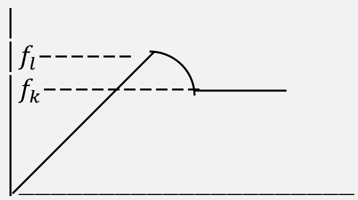
$$\boxed{\mu = \frac{f_l}{N}}$$

Nature

- Dimensionless quantity
- No SI unit
- Depends on the nature of the surfaces

Graph between Applied Force and Friction

Friction

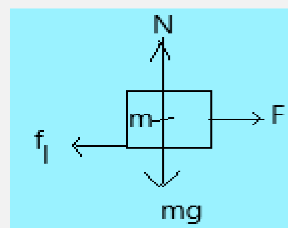


Applied Force

Interpretation

- Initially, friction increases linearly with the applied force (static friction).
- At the limiting value, motion is about to start.
- Once the body starts moving, friction decreases to the kinetic value.

Free Body Diagram on a Rough Surface



↑ N

Block

↓ mg

Applied Force →

← Friction

Solved Numerical 1

A block is placed on a horizontal surface.
Mass = **5 kg**
Coefficient of static friction = **0.4**
Find the maximum static friction.
Take, G = 9.8 m s^{-2}

Solution

Normal reaction,

$$N = mg$$

Or

$$N = 5 \times 9.8 = 49\ N$$

Maximum static friction,

$$f_l = \mu_s N$$

Or

$$f_l = 0.4 \times 49 = 19.6\ N$$

Answer

$\boxed{19.6\ N}$

Solved Numerical 2

A block slides on a horizontal surface.
Mass = **8 kg**
Coefficient of kinetic friction = **0.25**
Calculate the kinetic friction.

Solution
Normal reaction,

$$N = mg$$

Or

$$N = 8 \times 9.8 = 78.4\ N$$

Therefore,

$$f_k = \mu_k N$$

Or

$$f_k = 0.25 \times 78.4 = 19.6\ N$$

Answer
$\boxed{19.6\ N}$

Everyday Applications of Friction

- Walking without slipping.
- Writing with a pen or pencil.
- Braking in vehicles.
- Climbing a ladder.
- Holding objects firmly.
- Lighting a matchstick.

Advantages of Friction

- Helps in walking.
- Enables vehicles to move.
- Allows writing on paper.
- Prevents slipping.
- Helps nails and screws remain fixed.

Disadvantages of Friction

- Causes wear and tear.
- Produces heat.
- Reduces efficiency of machines.
- Wastes energy.
- Increases fuel consumption.

Methods to Reduce Friction

- Lubrication (oil, grease)
- Ball bearings

- Polishing surfaces
- Streamlining of vehicles
- Using wheels instead of sliding

Methods to Increase Friction

- Grooves on tyres
- Spikes in sports shoes
- Roughening surfaces
- Sprinkling sand on slippery roads

Common Mistakes

- Assuming static friction is always equal to$\mu_s N$.
  Correct: Static friction can have **any value from 0 to $\boldsymbol{\mu_s N}$** depending on the applied force.
- Forgetting that kinetic friction is **less than** limiting friction.
- Drawing friction in the wrong direction.
  Always draw it opposite to the actual or impending motion.

Formula Summary

$$\boxed{f_l = \mu_s N}$$

$$\boxed{f_k = \mu_k N}$$

$$\boxed{\mu = \frac{f}{N}}$$

$$\boxed{\mu_k < \mu_s}$$

Chapter Summary (Part–7)

- Friction is a **contact force** that opposes relative motion or the tendency of motion.
- **Static friction** is self-adjusting and varies from zero up to its maximum value.
- **Limiting friction** is the maximum static friction just before motion begins.
- **Kinetic friction** acts during sliding and is smaller than limiting friction.
- **Rolling friction** is the smallest among the common types of dry friction.
- The coefficient of friction is a **dimensionless ratio** and depends on the nature of the contacting surfaces