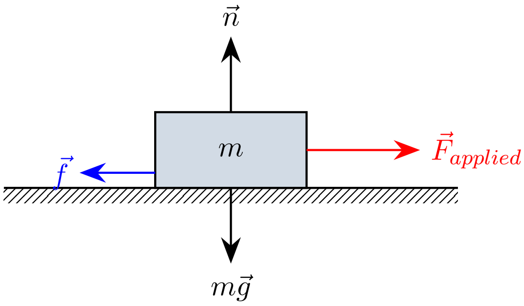
Physics Instructional Material

Unit 3: Forces and Newton's Laws of Motion

Dynamics and Gravitational Interactions



Course Objectives:
After completing this unit, students will be able to:

- Explain the concept of force and find the resultant of multiple forces.
- Construct Free-Body Diagrams (FBD) for various physical systems.
- Apply Newton's Three Laws of Motion to solve complex dynamical problems.
- Analyze friction forces in static and kinetic regimes.
- Calculate gravitational forces using Newton's Law of Universal Gravitation.

Synthesized for Academic Excellence
Based on the National Physics Curriculum (Grade 10)

Contents

1 Nature of Force and Resultant Forces

Force is a vector quantity that represents the interaction between two objects. It can cause an object to change its state of motion (velocity) or its shape.

1.1 Types of Forces

Forces are generally classified into two categories:

1. **Contact Forces:** Forces that occur when objects are physically touching (e.g., Tension, Friction, Normal force).
2. **Non-contact Forces (Field Forces):** Forces that act through a distance (e.g., Gravitational force, Magnetic force, Electric force).

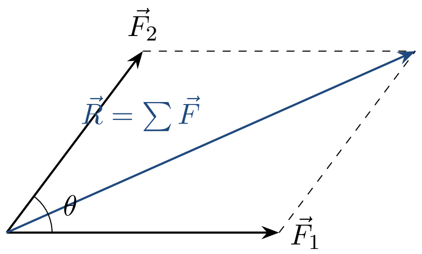
1.2 Resultant Force ($\sum \vec{F}$)

Since force is a vector, multiple forces acting on a single point must be added using vector addition rules.

Vector Addition of Forces

The resultant force $\vec{R}$ of two forces $\vec{F}_1$ and $\vec{F}_2$ separated by an angle θ can be calculated using the Law of Cosines:

$$R = \sqrt{F_1^2 + F_2^2 + 2F_1F_2\cos\theta}$$



1.3 Free-Body Diagrams (FBD)

A Free-Body Diagram is a simplified representation of an object and all the external forces acting upon it. This is the most crucial step in solving physics problems in dynamics.

2 Newton's First Law: The Law of Inertia

Newton's First Law

An object at rest remains at rest, and an object in motion continues in motion with a constant velocity (constant speed in a straight line) unless acted upon by a non-zero resultant force.

$$\sum \vec{F} = 0 \implies \vec{v} = \text{constant}$$

2.1 Concept of Inertia

Inertia is the inherent tendency of an object to resist changes in its state of motion. The measure of inertia is **Mass (m)**. An object with more mass has more inertia.

2.2 Equilibrium

When the resultant force acting on an object is zero, the object is said to be in **translational equilibrium**. This applies to both objects at rest (static equilibrium) and objects moving at constant velocity (dynamic equilibrium).

3 Newton's Second Law: Force and Acceleration

When a non-zero resultant force acts on an object, the object's velocity changes, meaning it accelerates.

Newton's Second Law

The acceleration of an object is directly proportional to the resultant force acting on it and inversely proportional to its mass.

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

Where:

- $\sum \vec{F}$ is the resultant force vector (Newtons, N).
- m is the mass of the object (kilograms, kg).
- $\vec{a}$ is the acceleration vector (m/s^2).

3.1 Mass vs. Weight

It is vital to distinguish between mass and weight:

- **Mass (m):** Scalar quantity, constant regardless of location.
- **Weight ($\vec{w}$):** Vector quantity, representing the gravitational pull on an object. $\vec{w} = m\vec{g}$.

3.2 Problem Solving Strategy

1. Define the system of interest. 2. Draw a complete Free-Body Diagram. 3. Establish a coordinate system (usually x and y axes). 4. Resolve forces into components if necessary ($F_x = F\cos\theta, F_y = F\sin\theta$). 5. Apply $\sum F_x = ma_x$ and $\sum F_y = ma_y$.

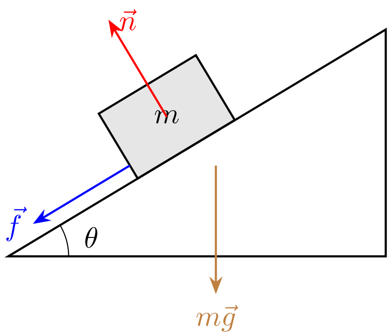


Figure 3.1: FBD on an Inclined Plane

4 Newton's Third Law: Action and Reaction

Force is always an interaction between two objects. They never exist in isolation.

Newton's Third Law

Whenever one object exerts a force on a second object, the second object exerts an equal and opposite force on the first object.

$$\vec{F}_{1\to 2} = -\vec{F}_{2\to 1}$$

4.1 Characteristics of Action-Reaction Pairs

1. They have exactly the same magnitude. 2. They act in exactly opposite directions. 3. They act on **different objects**. Therefore, they can never cancel each other out in a single FBD. 4. They are of the same type of force (e.g., if action is gravitational, reaction is gravitational).

5 Friction Forces

Friction is a force that opposes the relative motion (or the tendency of motion) between two surfaces in contact.

5.1 Static Friction ($\vec{f}_s$)

Static friction acts when there is no relative motion between surfaces. It increases to match the applied force until it reaches a maximum value.

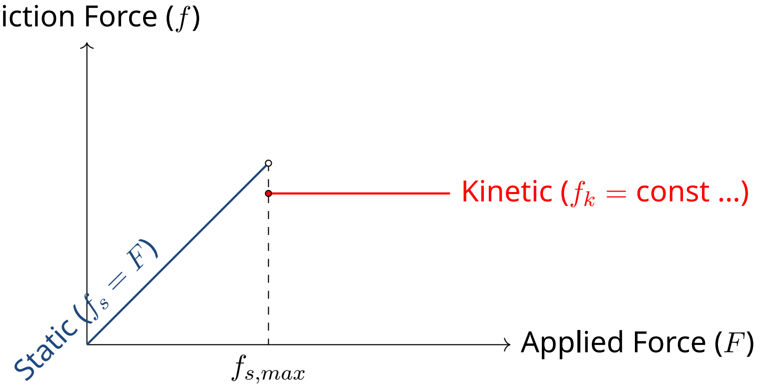
$$f_s \leq f_{s,max} = \mu_s n$$

where μ_s is the coefficient of static friction and n is the normal force.

5.2 Kinetic Friction ($\vec{f}_k$)

Kinetic friction acts once the object is sliding. It is generally constant and slightly less than $f_{s,max}$.

$$f_k = \mu_k n$$



6 Newton's Law of Universal Gravitation

Newton proposed that the force of gravity is not limited to the Earth but exists between all objects in the universe.

Universal Gravitation

Every particle in the universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.

$$F_G = G\frac{m_1 m_2}{r^2}$$

Where:

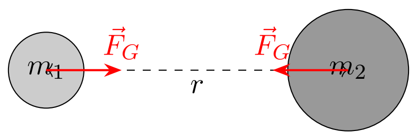
- $G \approx 6.674 \times 10^{-11}\, N \cdot m^2/kg^2$ (Gravitational Constant).
- r is the distance between centers.

6.1 Gravitational Field Strength (g)

On the surface of a planet of mass M and radius R:

$$g = \frac{GM}{R^2}$$

This explains why acceleration due to gravity varies on different celestial bodies.



7 Worked Examples and Practice

7.1 Example 1: The Elevator Problem

A person of mass $60\, kg$ stands on a scale in an elevator. What does the scale read (apparent weight) when: a) The elevator moves at constant speed? b) The elevator accelerates upward at $2\, m/s^2$?

Solution: The scale reads the normal force n. a) $\sum F_y = n - mg = 0 \implies n = mg = 60(9.8) = 588\, N$. b) $\sum F_y = n - mg = ma \implies n = m(g+a) = 60(9.8+2) = 708\, N$.

7.2 Review Exercises

1. Calculate the force required to accelerate a $1500\, kg$ car from 0 to $27\, m/s$ in 6 seconds. 2. A block of mass $5\, kg$ is on a horizontal table. If $\mu_s = 0.4$, what is the minimum horizontal force to start motion? 3. Two masses of $10\, kg$ and $20\, kg$ are connected by a light string over a frictionless pulley. Find the acceleration of the system (Atwood machine).

End of Unit 3 - Prepared by Physics Department