# Newton’s Laws of Motion

## 3.1 Limitations of Newton’s Laws in Accelerating Frames

### Activity 3.1: Let us observe

Consider the following situations:

- A passenger standing in a bus that suddenly accelerates forward feels pushed backward, even though no one is actually pushing.
- When a vehicle takes a sharp turn, passengers feel pushed outward.

Why does this happen? Is there really a force pushing the passenger backward or outward? Can these effects be explained only by the usual forces like gravity or friction?

### Understanding the Limitations

According to Newton’s First Law of Motion, a body continues to remain at rest or in uniform motion in a straight line unless acted upon by an external force. This law is strictly valid only in a non-accelerating frame.

However, when the frame itself is accelerating, objects seem to move without any visible external force acting on them.

To maintain consistency with Newton’s laws, let us examine an additional concept.

### Pseudo Force (Fictitious Force)

A force which does not arise due to physical contact or interaction (unlike gravitational, frictional, or tension forces). A pseudo force (also called a fictitious force) is an apparent force that is observed only when motion is described from an accelerating frame of reference.

Now understanding the scenario: What does a passenger fall backwards when a bus starts suddenly?

**Observer 1: Standing on the road (inertial frame)**

- Sees the bus accelerate forward
- Sees the passenger trying to remain at rest (inertia)

Explanation uses only real physics:

- No backward force exists
- Passenger's body just resists motion

This follows Newton's First Law of Motion perfectly.

**Observer 2: Inside the accelerating bus (non-inertial frame)**

- Sees the passenger "move backward"
- But doesn't see any real force causing it

To make Newton's Laws of Motion still work, we **introduce the concept of pseudo force**: From the ground (an inertial frame), no force pushes the passenger backward — the bus simply accelerates away from under them. But if we describe the situation from inside the accelerating bus (a non-inertial frame), we must add a pseudo force of magnitude **m*a** directed backward to make Newton's First Law appear valid within that frame. This force has no physical source and no reaction pair.

When a frame accelerates forward, it exerts an influence on objects inside it. From within that accelerating frame, we introduce an imaginary force acting in the opposite direction to explain the observed motion. Thus, in an accelerating frame:

- The frame accelerates in one direction.
- An apparent force (pseudo force) is considered to act on the body in the opposite direction.

This ensures that Newton's First Law still appears valid within that frame.

**Definition:**

A pseudo force is an apparent force observed only in an accelerating frame of reference.
It is always opposite to the acceleration of the frame and does not arise due to any physical interaction.

**Formula**

$$F_{pseudo} = -ma_{frame}$$

where:

- $m$= mass of the object
- $a_{frame}$= acceleration of the frame
- The negative sign indicates that the pseudo force acts opposite to the acceleration of the frame.

**Quick Check**

1. In which type of reference frame are Newton's laws valid?
2. Define pseudo force and write its formula.
3. A lift accelerates upward at $4.5m\,s^{-2}$. Calculate the pseudo force experienced by a 60 kg person inside the lift.
4. Why does pseudo force disappear in an inertial frame?

## 3.2 Gravitation

Orbital Motion: Why the Earth and Moon Do Not Fall Despite Gravity?

### Concept of Centripetal and Centrifugal forces

The Sun and the Earth both have mass, so they attract each other with a gravitational force. According to Newton's law of gravitation, the force between them is equal in magnitude and opposite in direction. However, because the Sun's mass is much greater than the Earth's mass, the Earth experiences a much larger acceleration as compared to the Sun. That is why the Earth appears to revolve around the Sun.

The Sun's gravitational pull on the Earth provides the centripetal force needed to keep the Earth in its orbit.

Earth is revolving around the Sun and it is moving with very high tangential velocity. So, due to its inertia, it should tend to continue moving in a straight line. On the other hand, the gravitational force of the sun is continuously attracting it towards the centre of the sun. This changes its direction of motion. As a result of these two aspects, the Earth does not move in a straight line but follows a fixed curved path called an orbit.

**Let us think:** Imagine the Earth suddenly slows down. Take a moment to picture what would happen if its forward (tangential) speed decreases, but the Sun's gravitational pull remains just as strong as before. Would the balance still exist? How would this change affect the Earth's path? Think about why slowing down would cause the Earth to drift closer to the Sun instead of continuing smoothly along its usual orbit.

Try to get the answer with the help of the following activity.

**Activity 3.2:**
**Steps**:

1. Tie the ring/bob securely to one end of the thread of length approx. 1 m.
2. Hold the other end of the thread firmly with your finger.
3. Swing the ring/bob in a horizontal circle at a steady speed.

4. Observe how the bob moves in a circular path.
5. Now slowly reduce the speed of rotation.
6. Continue decreasing the speed further and observe what happens to the circular motion.

**Observation:**

At an appropriate speed, the thread provides the centripetal force that pulls the stone/ bob inward, keeping it in a circular path. At the same time, due to its inertia, the stone tends to move in a straight line along the tangent. The balance between this outward tendency and the inward centripetal force results in circular motion.

When the speed decreases, the **required centripetal force also decreases**. However, the tension in the thread may reduce to the point where it can no longer keep the stone moving in a circular path. As a result, the string may become slack, and the motion is no longer circular—the stone begins to move inward or fall.

**Conclusion:**

Circular motion requires a balance between inward pulling force (centripetal force) and tangential speed (which provides necessary centrifugal force). If speed decreases too much, the balance is disturbed, and the object can no longer continue in the same circular path.

## Effect of Cross-Sectional Area (Air Resistance) on Falling Objects of Equal Mass

Let us imagine two objects with the same mass but different cross-sectional areas These are dropped from the same height, an important question arises: *Will they reach the ground at the same time?*

### Case 1: When Air Is Present

Both objects have the same mass, so the gravitational force acting on them is the same:

**F = mg**

Since mass (m) is the same, the force of gravity on both objects is equal. This means gravity pulls both objects downward equally.

However, another force also acts on the objects — **air resistance (air drag)**. This is an upward force that opposes motion.

Air resistance mainly depends on the **cross-sectional area** of the object (and shape, speed and density of air). The larger the cross-sectional area, the greater the air resistance.

Because of this:

- The object with a **larger cross-sectional area** experiences more air resistance.
- The object with a **smaller cross-sectional area** faces less opposition.
- Therefore, it has a greater net downward force and falls faster.

**Conclusion:**
In air, the object with the **smaller cross-sectional area** reaches the ground first.

**Case 2: In a Vacuum (No Air)**

Since there is no air in a vacuum, there is **no air resistance either**.

$$a = \frac{F}{m} = \frac{mg}{m} = g$$

**Conclusion:**
In a vacuum, both objects reach the ground at the **same time**, regardless of their shape or size.

## Variation of acceleration due to Gravity with Altitude and Depth (without using Binomial Theorem)

- When we throw a ball upward, it comes back down.
- When we jump, we return to the ground.

This happens because the Earth pulls everything toward its centre due to gravity.

But why do astronauts float inside a spacecraft?
Does gravity disappear in space?
Is the value of gravity the same everywhere?

We know that as we go higher above the Earth's surface, we move farther away from the centre of the Earth. We know that gravitational force depends on distance. As distance increases, force decreases.

Astronauts in the International Space Station appear weightless.

So clearly, gravity decreases with height, but it does not become zero.

Now let us derive the expression for the acceleration due to gravity at point A, which is at a height of *h* from the surface of the earth.

## Derivation – Acceleration Due to Gravity at Height

Let:

- Mass of object = m
- Radius of Earth = R
- Height above surface = h
- Distance from centre of Earth = (R + h)

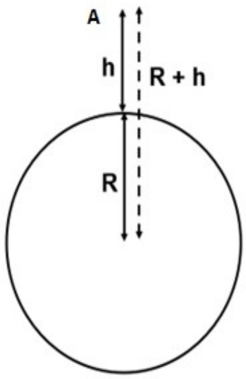



Fig: 3.1 Acceleration due to gravity at height h

The acceleration due to gravity at height h is:

$$g_h = \frac{GM}{(h)^2}$$

Where:

- G = Universal Gravitational Constant
- M = Mass of Earth

On Earth's surface:

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

Dividing both equations:

$$\frac{g_h}{g} = \frac{R^2}{(h)^2}$$

This shows clearly that:

$$g_h < g$$

**Example**

Calculate acceleration due to gravity at a height of 800 km above Earth.

Given:

R = 6400 km

h = 800 km

g = 9.8 m/s²

$$g_h = g\left(\frac{R^2}{(h)^2}\right) g_h = 9.8\left(\frac{6400^2}{7200^2}\right) g_h = 9.8\left(\frac{64}{72}\right)^2 \; g_h = 7.74\, m/s^2$$

### Acceleration Due to Gravity Below the Surface of Earth

Now, consider a point **A** located at a depth **d** inside the Earth. Assuming the Earth has uniform density, let us determine the acceleration due to gravity at that interior point.
Let:

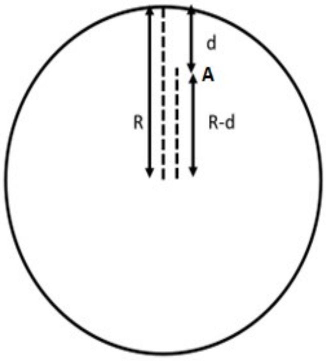



Fig: 3.2 Acceleration due to gravity at depth d

- Radius of Earth = R
- Depth below surface = d
- Distance from centre = (R − d)
- Density of Earth = ρ (uniform)

If density is uniform, then mass of the earth can be calculated by

$$Mass\ of\ Earth = M = \frac{4}{3}\pi R^3 \rho$$

At depth d, the object is at a distance (R − d) from the centre, only the mass inside radius (R − d) contributes to gravity. (This is By Newton's Shell theorem, the gravitational effect of a uniform spherical shell on a point inside it is exactly zero. Therefore, at depth d, only the sphere of radius (R–d) centred at Earth's core contributes to gravity— the outer shell of thickness d has no net effect)

$$M_d = \frac{4}{3}\pi (R-d)^3 \rho$$

From Newton's Law of Gravitation

$$g_d = \frac{GM_d}{(d)^2}$$

Substitute $M_d$:

$$g_d = \frac{G\left(\frac{4}{3}\pi(R-d)^3\rho\right)}{(d)^2}$$

$$g_d = \frac{4}{3}\pi G\rho(R-d)$$

Compare with gravity at earth's surface i.e.

At Earth's surface:

$$g = \frac{4}{3}\pi G\rho R$$

Dividing the two equations:

$$\frac{g_d}{g} = \frac{R-d}{R}$$

Therefore,

$$g_d = g\left(\frac{d}{R}\right)$$

We conclude from the above derivations that acceleration due to gravity is maximum at the Earth's surface and decreases as we go up/down. It will become zero at the centre of the earth.

**Example:**

At what depth does g become 1/10th of its surface value?

Given:

$$g_d = \frac{g}{10}$$

Using the formula:

$$g\left(\frac{d}{R}\right) = \frac{g}{10} 1 - \frac{d}{R} = \frac{1}{10}\frac{d}{R} = \frac{9}{10} d = \frac{9R}{10}$$

## Quick Check

1. Where does the acceleration due to gravity reach its maximum value—on the surface, above, or below the Earth?
2. What happens to g at the centre of the Earth?
3. Calculate g at a height of 400 km if R = 6400 km.
4. At what depth will g become half of its surface value?
5. Why does gravity decrease both above and below the surface of the earth?

## 3.3 Turning Forces (Moment of Force/Torque)

### Activity 3.3: Let us observe

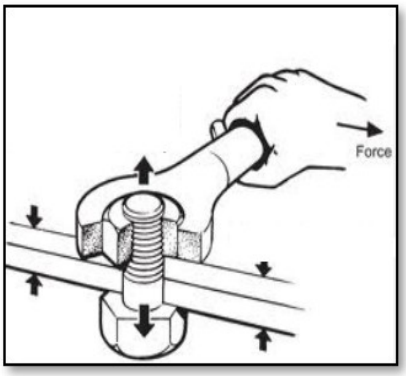
Look at the picture of a boy trying to enter his classroom. He pushes the door to open it.

Now, think carefully and answer the following questions:

- Where will the boy apply force to open the door easily?
  - (a) Near the handle
  - (b) Near the hinges
  - (c) At the centre of the door
- Why are door handles fixed far away from the hinges and not near them?

Now, reflect on the following points:

- The boy applies force in a straight direction, but the door rotates. Why does this happen?
- Even though the door is heavy, it rotates easily when pushed at the handle.
- How is it possible to rotate such a heavy object by applying force at just one end?



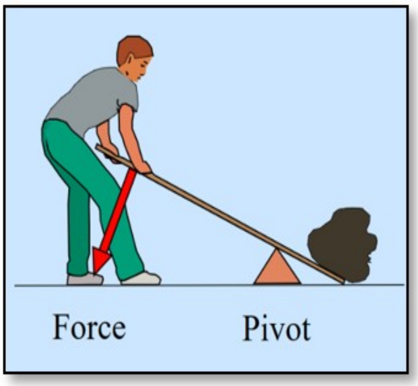




Fig: 3.3 Some examples of turning effects of forces in our daily life

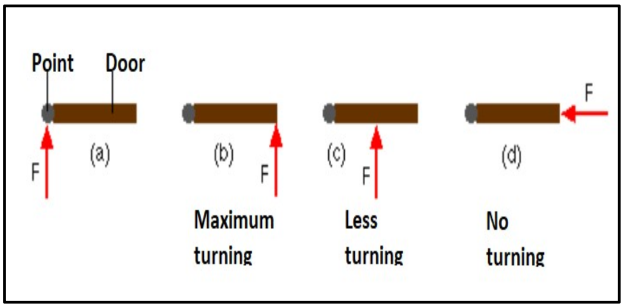
When we apply a force to an object and it starts to rotate, the force produces a turning effect.

This turning effect of a force is called the moment of force.

**Moment of Force (Torque)$\tau$ = F × d × sin θ,** where F is the magnitude of the force, d is the distance from the pivot to the point of application, and θ is the angle between the force and the line joining the pivot to the point of application. Torque is maximum when θ = 90° (force perpendicular to the lever arm) and zero when θ = 0° or 180° (force directed toward or away from the pivot).

Since the turning effect of a force depends on both the magnitude of the force and the distance from the fixed point, its S.I. unit is newton-metre (Nm).

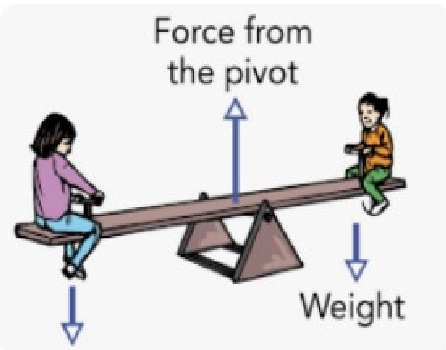
The angle at which force is applied to a door (and the resulting angle of the door itself) is crucial for controlling the turning, efficiency, and safety of the opening motion. The fundamental principle is that turning is maximized when the force is applied perpendicular (at a 90-degree angle) to the door surface, making it the most efficient way to open or close it.




**Check Your Understanding**

1. Why is it easier to open a door when you push at the handle rather than near the hinges?
2. A force is applied to a wrench at different angles. At which angle will the rotating force be maximum? What happens to the turning effect when the force is applied parallel to the wrench?
3. Two students apply the same force to open a gate. One pushes perpendicular to the gate at 20cm from the hinge. The other pushes perpendicular to the gate at 80 cm. Who produces greater torque? Justify
4. Is it possible for a force to act on a body and still produce zero turning about a given fixed point? Give a real-life example.
5. Two forces act on a rod pivoted at its centre:
   I. 10 N downward at 0.5 m on the left
   II. 10 N downward at 0.5 m on the right

   Will the rod rotate? Explain your reasoning




6. How can a mechanic loosen a tight bolt using a long spanner instead of applying a very large force? Explain using the torque formula.
7. A force of 20 N is applied to a door at 0.8 m from the hinge. Calculate the torque when the force is applied at (a) 90°, (b) 60° (c) 30° to the door surface.

*****************************************************************************************