# Lesson 4: Vertical motion

## Key Terms and Concepts

- Terminal velocity is the maximum velocity of a freely falling body where its velocity no more increases, or the acceleration of the motion is zero.
- Reaction time is the time taken for a person to react to a sudden event.
- The acceleration of free-falling objects is called the acceleration due to gravity, since objects are pulled towards the center of the earth.
- The acceleration due to gravity is constant on the surface of the Earth and has the value of 9.80 $m/s^{2.}$

## Freely Falling Bodies

**Definition of Freefall**

When a body exclusively moves under the influence of the Earth's gravity, the body is said to be in a **freefall**.


## Examples of free fall

A few of the common examples of free fall are given below –

- A stone falling into an empty well.
- Ball thrown in a **projectile motion**.
- A spacecraft in a continuous orbit.
- The fruit that has been removed from the tree then falls to the ground in a free fall

Hence, we can understand that when an object is thrown from a given height, gravity causes it to descend towards the surface of the Earth in a free fall **motion**.

"In a state of free fall" refers to any item that is moving and being affected solely by gravity. A downward **acceleration** of 9.8 $ms^{-2}$ is experienced by such an object.

**Note that** If the item is solely influenced by gravity, its acceleration value will always be 9.8 ms-2, whether it is falling or climbing towards its peak. So, in free fall, 'a' always equals 'g,' according to the free-fall acceleration formula.

Consider an object body falling freely from a height ‘h’ with a final **velocity** ‘v’ for‘t’ seconds due to gravity ‘g’. It will move according to the following equations:

**Free Fall Formula**

| General equation of motion | Equations of motion freely falling bodies |
|---|---|
| (i) $v = u + at$ changes to | $v = u + gt$ |
| (ii) $s = ut + \frac{1}{2}at^2$ changes to | $h = ut + \frac{1}{2}gt^2$ |
| (iii) $v^2 = u^2 + 2as$ changes to | $v^2 = u^2 + 2gh$ |

**Note that:-g is positive downward and g is negative upward**

Free fall formula is $v^2 = 2gh$. $v=gt$. Free Fall Equations of Motion are specified below:

- **First Law of Motion**

Because the object's starting velocity in free fall is 0 m/sec and the **acceleration** acted upon is gravity's acceleration ($g= 9.8$ m/sec$^2$), The equation will be

$v=u+ at$

$u=0$m/sec, $a= g= 9.8$ m/sec$^2$

**v= gt**

- **The Second Law of Motion**

$S = ut+ 1/2(at^2)$

$S = H$, $u=0$m/sec, $a= g= 9.8$ m/sec$^2$

**$H = 1/2(gt^2)$**

**Also read: Newton’s second law of motion**

- **Motion's third equation**

$v^2 = u^2+ 2aS$

S= H, u=0m/sec, a= g= 9.8m/sec$^2$

**$V^2 = 2gH$**, the third equation of motion in free fall.

**Also read: Newton's third law of motion**

Where,

H= height travelled

V= final velocity

g =acceleration due to gravity

t =time taken

## Things to Remember

- A state of free fall is defined as an object that is only affected by the force of gravity.
- Air resistance doesn't really exist for free-falling objects.
- On Earth, all free-falling objects accelerate at a velocity of 9.8 m/s/s.
- Since objects are pulled towards the centre of the earth ,the acceleration of free-falling objects is called the acceleration due to gravity,
- In free fall, a body travels an orbit in which the total of **gravitational** and inertial forces is zero.

### Examples 4.1:-When a ball is dropped from a specific height and takes 10 seconds to reach the ground, what is the final velocity of the ball? There is no consideration for air resistance. [Take g=10 m/sec2]

**Ans.** Using the first equation of motion in free fall

u= 0m/sec, S=H, a= g= 10 m/sec2, (given)

v= u+ at

v= gt

v= 10 x 10

v= 100m/sec

### Examples 4.2:- Alex threw his ball from a height of 5 meters and then dashed downstairs to see if he could grab it; it took him one minute to get to the ground. Will he be able to catch the ball? Note that air friction is not taken into account.

**Ans.** Using the second equation of motion in free fall,

$S= ut+ 1/2(at^2)$

u=0 m/sec, a= g= 9.8 m/sec2, S=H

$H= 1/2(gt^2)$

$5= 1/2(9.8\ t^2)$

$t^2= 10/9.8$

t= 1.01 second,

As can be seen, Rohan takes an entire minute to reach the ground, whilst the ball takes only 1.01 seconds. Hence, he will be unable to catch the ball.

### Examples 4.3:-Find the height at which a toy is dropped if it is in free fall and the toy's ultimate velocity is 20 meters per second.

**Ans.** Using the third equation of motion.

$v^2= u^2+ 2aS$

Under free fall,

u= 0m/sec, a= g= 9.8m/sec2, S=H

$v^2= 2gH$

202 = 2 x 9.8 x H

400 = 19.6 x H

H = 20.40 meters

## Terminal velocity

- When a solid body is inside a liquid or gas, its entire surface is in contact with the particles of the fluid. For this reason, during its motion in a fluid, the body experiences a resistive force.
- These resistance forces which the fluid exerted on the body are called fluid friction or drag force.
- Thus, a body falling in air moves under the action of two forces (ignoring buoyancy): the downward gravitational force (its weight) and the upward drag force.
- At the beginning of the fall the downward gravitational force would be larger than the drag force ( mg > F ) and hence it will make an accelerated downward motion,
- This resulted to an increase in velocity. As the velocity the falling object increases, so does the drag force. At some velocity, the drag force of resistance will be equal to the gravitational pull on the object. At this point the object stops accelerating and continues falling at a constant velocity called the terminal velocity. Thus, terminal velocity is defined as the point at which the velocity of a falling object is no longer getting greater.
- An object at terminal velocity has zero acceleration.
- Besides weight, terminal velocity depends on other factors such as shape and cross section area of the falling object and the nature of the fluid.
- When a thing falls from a height, we find:
- **At first, it falls at a fast speed, as the force of gravity causes it to speed up rapidly.**
- Its body weight acts downward, air resistance pushes upward, and **gravitational force** pulls downward.
- After a while, it falls at a certain constant **speed.**
- **This happens as the air drag force is exactly equal to the gravitational force.**
- **The object will no longer speed up or decelerate if these two forces are perfectly balanced.**
- However, it will continue to descend at a steady pace.
- **This steady speed is terminal velocity.**

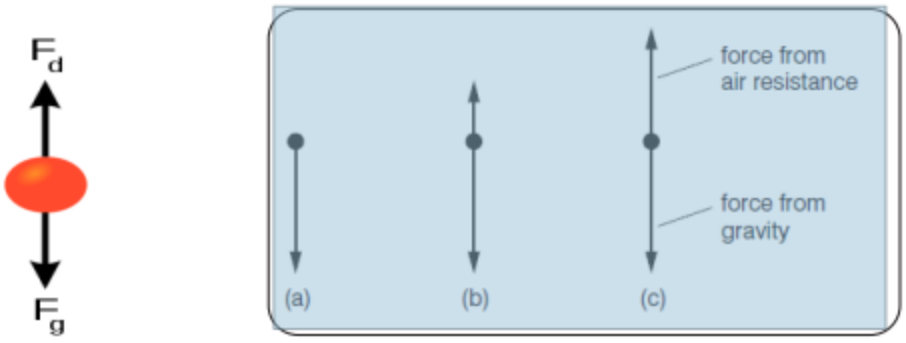


*Figure 3.13: A free body diagram showing the forces on a particle at different times during its fall: (a) at the start of the fall; (b) during the fall; (c) at the end of the fall.*

## Drag Force

- **Drag force is a resistive force that works in the opposite direction of an object's relative motion in relation to a fluid. It depends on the object's velocity as it falls through the fluid, which makes it different from other resistive forces.**
- **Factors affecting Drag Force**

## The factors affecting drag force are as follows:

- Density
- Compressibility
- Viscosity of the fluid
- Square of the object's velocity
- Shape and size of the body
- Leaning of the body towards the flow

## Galileo Galilee and the Motion of Objects

- In contrary to Aristotle (384–322 B.C.) view of motion, which states that heavier objects fell faster than lighter ones, Galileo Galilee (1564–1642) Italian Physicist and Astronomer postulated that, regardless of their size and mass all bodies falling through empty space (vacuum) have the same acceleration.
- He was the first person to determine the correct mathematical law for acceleration: the total distance covered, starting from rest, is proportional to the square of the time.
- Galileo also investigated the motion of an object on an inclined plane, established the concept of relative motion, invented the thermometer, and discovered that the motion of a swinging pendulum could be used to measure time intervals.
- After designing and constructing his own telescope, he discovered four of Jupiter's moons, found that our own Moon's surface is rough, discovered sunspots and the phases of Venus, and showed that the Milky Way consists of an enormous number of stars.
- He is also known for the assertion that the Sun is at the center of the Universe (the heliocentric system), not Earth.
- **Reaction time** is the time a person takes to observe, think and act. Reaction time is the time it takes you to react to a hazard.
- For example, if a person is driving and suddenly a boy appears on the road, then the time elapsed before he/she applies the brakes of the car is the reaction time.
- calculate the reaction time using the equation:
- $t=\sqrt{\frac{2d}{g}}$
- Reaction distance is the distance you travel during your reaction time. It depends on the reaction time and speed. It is calculated as:
- Reaction Distance = Reaction Time x Speed
- **s = $vt$.**