

CHAPTER

02

Motion in a Straight Line

General Introduction of Motion • Uniformly Accelerated Motion

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READING KEY

DEFINITION

NOTE

REMEMBER

DERIVATION

STRATEGY

Formulas sit on graph paper • coloured words are the key terms

01

PART 1

General Introduction of Motion

An object is **in motion** when its **position changes** with respect to its **surroundings**. Motion is all around us. Examples: a **train running on its tracks**, a **person walking**, an **insect crawling** and **water flowing** through a dam.

1.1 Motion

DEFINITION

Motion is the **change in position** of an object **with time**, measured from a chosen **reference point**. The reference can also be a group of objects taken together.

• TYPES OF MOTION

BASED ON THE PATH FOLLOWED

Rectilinear Motion

The particle moves along a **straight line**.

Circular Motion

The particle moves along a **circle**.

Oscillatory Motion

The particle moves **back and forth** about a fixed point.

BASED ON HOW MANY COORDINATES ARE NEEDED

One-dimensional (1-D)

Only **one coordinate** is needed to locate the object.

Two-dimensional (2-D)

Two coordinates are needed to locate the object.

Three-dimensional (3-D)

All **three coordinates** are needed to locate the object.

1.2 Point Object

DEFINITION

An object can be treated as a **point object** when the **distance it covers** is **very large** compared with its own **size**.

EXAMPLES

i Example

A **train** on a journey of **hundreds of kilometres**.

ii Example

The **Earth** while it **revolves around the Sun**.

1.3 Scalar and Vector Quantities

Physical quantities are of **two types**: **scalars** and **vectors**.

i Scalars

A quantity that has only **magnitude** (size) is called a **scalar quantity**, or simply a **scalar**.

e.g. Mass, length, time, speed, etc.

ii Vectors

A quantity that has both **magnitude and direction** is called a **vector quantity**, or simply a **vector**.

e.g. Displacement, velocity, acceleration, etc.

1.4 Position

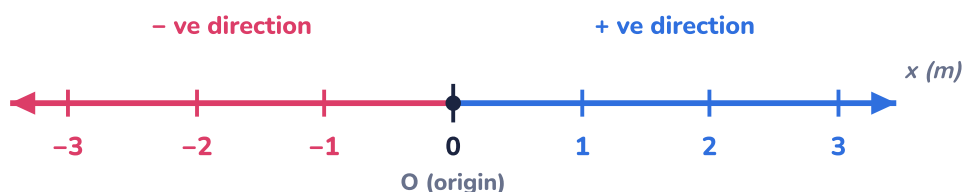
NOTE

Position, Path Length & Displacement

To say where an object is, we need a **reference point**, a set of **axes** and a **frame of reference**.

DEFINITION

Position is the **point where an object is located**. It is measured on a **coordinate axis** marked in **units of length**. This axis has a **positive** and a **negative** direction.



Positions to the right of the origin are positive. Positions to the left are negative

e.g. An object at **-1 m** is on the **negative side** of the origin. The minus sign shows the direction. An object at **0 m** is exactly **at the origin**. Positions are always measured from a convenient origin.

Position to the **right of the origin**

Positive (+)

Position to the **left of the origin**

Negative (-)

● FRAME OF REFERENCE

We usually take **three mutually perpendicular axes** as a **rectangular coordinate system**. These are the x , y and z axes. The point where they meet is the **origin (O)**. It is the **reference point**.

The x , y and z coordinates give the **position of the object** with respect to these axes. A **clock** is used to measure **time**.

Coordinate system + Clock = Frame of Reference

There are **two types** of frames of reference:

i Inertial Frame of Reference

A frame in which **Newton's first law of motion holds true**.

ii Non-inertial Frame of Reference

A frame in which **Newton's first law of motion does not hold**.

NOTE

Accelerated and Unaccelerated Frames

- ◆ A frame that is **accelerating** with respect to the Earth is usually **non-inertial**. A frame that is **not accelerating** is **inertial**.
- ◆ Frames **at rest or moving uniformly** are inertial. Frames in **non-uniform motion** are non-inertial.
- ◆ To use **Newton's second law** in a non-inertial frame, we add an extra imaginary force. It is called the **pseudo force**.

1.5 Path Length / Distance

DEFINITION

The **path length**, or **distance travelled**, is the **total length of the path** that an object actually covers in a given **time interval**. Its **SI unit is the metre (m)**.

EXAMPLE

An object moves **100 m** away from the origin O along the x -axis in time t . So its path length is **100 m**. It then **comes back to the origin** in time t' . Now the total path length is:

$$\text{Path length} = 100 \text{ m} + 100 \text{ m} = 200 \text{ m}$$



Forward and back: total path length = $100 \text{ m} + 100 \text{ m} = 200 \text{ m}$

1.6 Displacement

DEFINITION

Displacement is the **change in position** of an object in a definite **direction**. It is equal to the **final position minus the initial position**. It is written as Δx .

DISPLACEMENT

$$\Delta x = x_2 - x_1$$

where, x_1 = initial position and x_2 = final position of the object

CASES

(i) If $x_2 > x_1$

Δx is positive

(ii) If $x_2 < x_1$

Δx is negative

(iii) If $x_2 = x_1$

Δx is zero

So displacement can be **positive**, **negative** or **zero**. Displacement has both **magnitude and direction**, so it is a **vector quantity**.

NOTE

- The magnitude of the displacement **may or may not be equal** to the **path length**.
- For a trip, the displacement can be **zero**. But the path length of any actual motion is **never zero**.

DIFFERENCES BETWEEN DISTANCE AND DISPLACEMENT

S.NO.	DISTANCE	DISPLACEMENT
1.	The total length of the path covered.	The length of the shortest path from the initial position to the final position.
2.	A scalar quantity.	A vector quantity.
3.	For a moving object it cannot be zero .	It can be zero .
4.	It is never negative .	It can be positive, negative or zero .

1.7 Uniform & Non-uniform Motion

DEFINITION

Uniform Motion in a Straight Line

A body moving along a **straight line** is in **uniform motion** if it covers **equal distances in equal intervals of time**.

e.g. A vehicle moving steadily at **10 m/s** covers **10 m every second**

Uniform

NOTE

In uniform motion along a straight line in one fixed direction, the **magnitude of displacement** is **equal to the distance covered**.

• NON-UNIFORM MOTION

A body is in **non-uniform motion** if it covers **unequal distances in equal intervals of time**.

In such motion, the **speed** of the body, its **direction of motion**, or **both** change with time.

e.g. A vehicle whose velocity is **different at different instants**

Non-uniform

1.8 Speed

DEFINITION

The **speed** of an object is the **distance it covers** divided by the **time taken**.

SPEED

$$\text{Speed} = \frac{\text{Distance travelled}}{\text{Time taken}}$$

Nature

Scalar quantity; always **positive**.

SI Unit

m s^{-1} (MKS / SI); cm s^{-1} (CGS).

Dimensions

$[\text{M}^0\text{L}^1\text{T}^{-1}]$

• TYPES OF SPEED

Uniform Speed

The object covers **equal distances in equal intervals of time**.

Variable / Non-Uniform Speed

The object covers **unequal distances in equal intervals of time**. In other words, it takes unequal times to cover equal distances.

1.9 Velocity

DEFINITION

The **velocity** of an object is the **rate of change of its position** with time.

VELOCITY

$$\text{Velocity} = \frac{\text{Displacement}}{\text{Time}}$$

Nature

Vector quantity.

SI Unit

m s^{-1} (MKS / SI); cm s^{-1} (CGS).

Dimensions

$[\text{M}^0\text{L}^1\text{T}^{-1}]$

• TYPES OF VELOCITY

Uniform Velocity

The object undergoes **equal displacements in equal intervals of time**.

Non-uniform Velocity

The object undergoes **unequal displacements in equal intervals of time**.

NOTE

Velocity is **positive**, **zero** or **negative** when the displacement is positive, zero or negative, respectively.

1.10 Average Speed and Average Velocity

AVERAGE SPEED

$$v_{av} = \frac{\text{Total distance travelled}}{\text{Total time taken}}$$

The whole distance covered, divided by the whole time taken.

AVERAGE VELOCITY

$$v_{av} = \frac{\Delta x}{\Delta t}$$

The displacement Δx (change in position) divided by the time interval Δt in which it happens.

REMEMBER

Average Velocity vs Average Speed

- ◆ **Average speed** = total **distance** covered $\div$ time taken.
- ◆ **Average velocity** = net **displacement** $\div$ time taken for that displacement.
- ◆ Average velocity can be **zero**, **positive** or **negative**. But the **average speed of a moving body is always positive**.

1.11 Instantaneous Speed and Instantaneous Velocity

DEFINITION

Instantaneous Speed

Instantaneous speed is the speed at a particular instant. It is the **limit of the average speed** as the time interval Δt **approaches zero**. Here Δs is the distance covered in the small time Δt .

$$\text{Speed} = \lim_{\Delta t \rightarrow 0} \frac{\Delta s}{\Delta t} = \frac{ds}{dt}$$

DEFINITION

Instantaneous Velocity

Instantaneous velocity is the velocity at a particular instant. It is the **limit of the average velocity** as the time interval Δt **approaches zero**.

$$v_i = \lim_{\Delta t \rightarrow 0} \frac{\Delta x}{\Delta t} = \frac{dx}{dt}$$

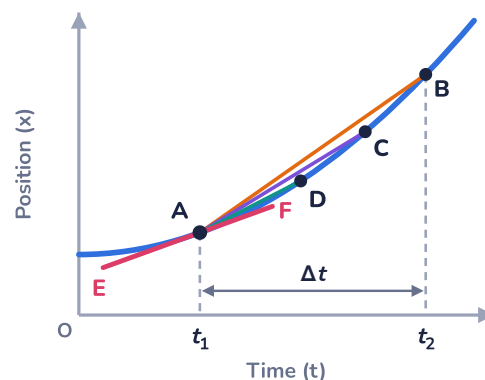
NOTE

- ◆ $\frac{dx}{dt}$ is the **derivative** of position x with respect to time t . Here dx is the tiny displacement in a tiny time dt .
- ◆ At any instant, the **magnitude of the instantaneous velocity** is equal to the **instantaneous speed**.

• GRAPHICAL INTERPRETATION OF INSTANTANEOUS VELOCITY

When the velocity keeps changing, the **position–time graph** is a **curve**. The average velocity between t_1 and t_2 is the **slope of the chord** AB . The time interval is $\Delta t = t_2 - t_1$.

Now make Δt smaller. The chord becomes AC , then AD . As $\Delta t \rightarrow 0$, point B moves closer and closer to A . The chord then becomes the **tangent** to the curve at A . So the **slope of the tangent** at a point gives the **instantaneous velocity** there.



Slope of chord AB = average velocity. The chord ($AC, AD \dots$) finally becomes the tangent EF at A . Its slope = instantaneous velocity

02

PART 2

Uniformly Accelerated Motion

2.1 Acceleration

DEFINITION

Acceleration is the **rate of change of velocity with time**. It tells us how fast the velocity of an object changes. Acceleration is a **vector quantity**.

ACCELERATION

$$\text{Acceleration} = \frac{\text{Change in velocity}}{\text{Time taken}}$$

Nature

Vector quantity.

SI Unit

m s^{-2} (SI); cm s^{-2} (CGS).

Dimensions

$[M^0 L^1 T^{-2}]$

NOTE

An object accelerates when its **speed** changes, when its **direction** changes, or when **both** change.

Velocity and acceleration have the **same sign**

Body speeds up

Velocity and acceleration have **opposite signs**

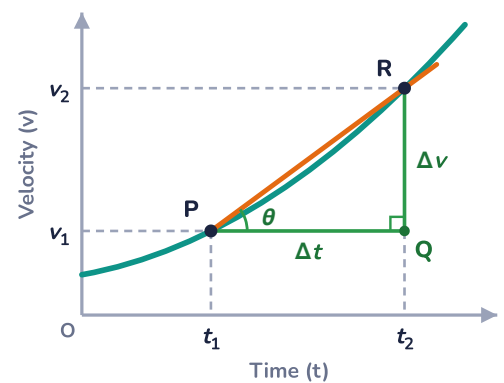
Body slows down (retards)

• AVERAGE ACCELERATION

Let the velocity of a body be v_1 at time t_1 and v_2 at a later time t_2 . Its average acceleration is the **change in velocity** divided by the **time interval**:

$$a_{av} = \frac{\Delta v}{\Delta t} = \frac{v_2 - v_1}{t_2 - t_1}$$

So acceleration is the **slope of the velocity-time graph**.



$$\text{Slope of secant } PR = \frac{RQ}{PQ} = \frac{\Delta v}{\Delta t} = \tan \theta = \text{average acceleration}$$

• INSTANTANEOUS ACCELERATION

DEFINITION

Instantaneous acceleration is the acceleration of a body at a **particular instant**. It is the **limit of the average acceleration** as the time interval approaches zero.

$$a_{inst} = \lim_{\Delta t \rightarrow 0} \frac{\Delta v}{\Delta t} = \frac{dv}{dt}$$

Here $\frac{dv}{dt}$ is the derivative of v with respect to t .

REMEMBER**Differentiate or Integrate?**

Since $v = \frac{dx}{dt}$ and $a = \frac{dv}{dt} = \frac{dv}{dx} \cdot \frac{dx}{dt}$:

- ◆ If the **displacement is given** and you need velocity and acceleration, **differentiate**.
- ◆ If the **acceleration is given** and you need velocity and displacement, **integrate**.

2.2 Uniform and Non-uniform Acceleration**Uniform Acceleration**

The velocity changes by **equal amounts in equal intervals of time**.

Non-uniform Acceleration

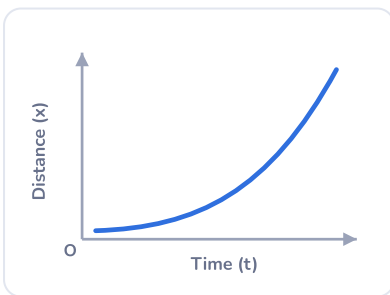
The velocity changes by **unequal amounts in equal intervals of time**.

2.3 Position-Time Graphs for Positive, Negative and Zero Acceleration

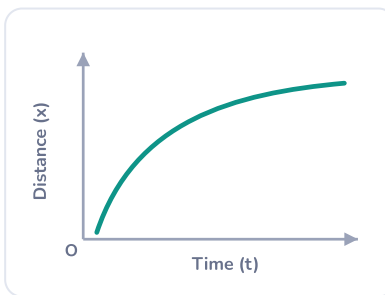
The **shape** of a position–time (distance–time) graph tells us whether the acceleration is **positive**, **negative** or **zero**.

i Positive Acceleration

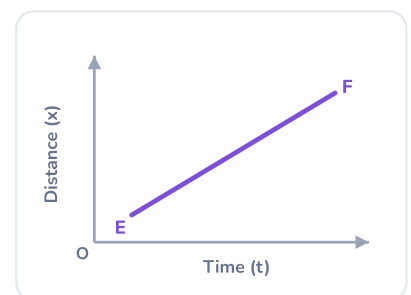
The object covers **more and more distance** in each equal time interval. So the graph curves **upward**.

**ii Negative Acceleration**

The object covers **less and less distance** in each equal time interval. So the graph gets **flatter** with time.

**iii Zero Acceleration**

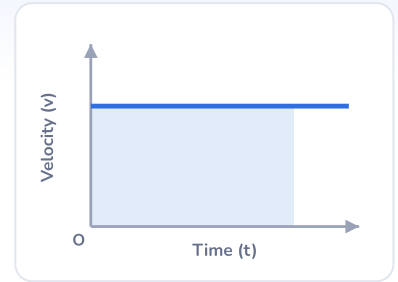
The object covers **equal distances in equal times**. So the graph is a **straight line**.

**2.4 Velocity-Time Graphs for an Accelerated Motion**

The shape of a **velocity–time (v–t) graph** shows what kind of **acceleration** the object has.

• ZERO ACCELERATION

With **zero acceleration**, the **velocity stays constant** with time. So the graph is a horizontal line.



NOTE

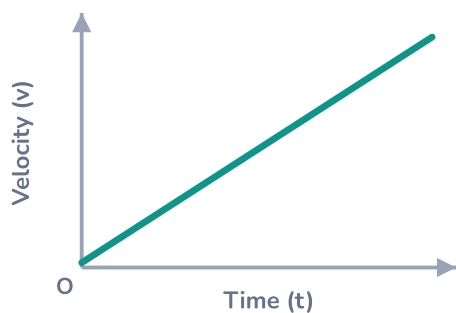
The **area under a v-t graph** gives the **displacement**.

• POSITIVE ACCELERATION

With positive acceleration, the velocity of the object keeps **increasing** with time.

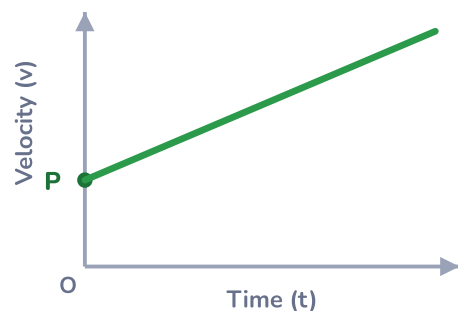
a Zero initial velocity

Starting from **rest**, the velocity-time graph is a **straight line through the origin**.



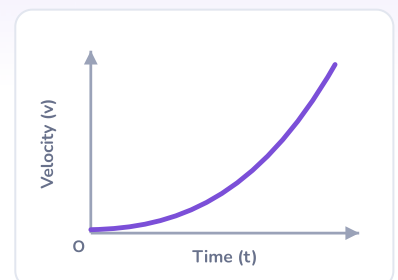
b Some initial velocity

Starting with **some velocity**, the velocity-time graph is a **straight line beginning at P** on the velocity axis.



• INCREASING ACCELERATION

When the acceleration itself keeps increasing, the velocity rises **faster and faster (non-linearly)**. The graph shows an object starting from **rest**. The **slope of the v-t graph** at any point gives the **instantaneous acceleration** at that point.

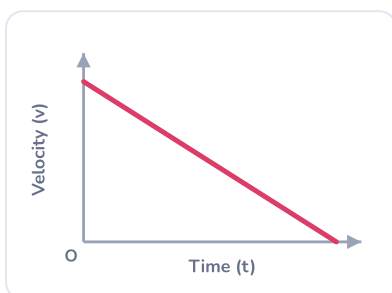


● NEGATIVE ACCELERATION

With uniform negative acceleration, the velocity of the object **decreases steadily (linearly)** with time.

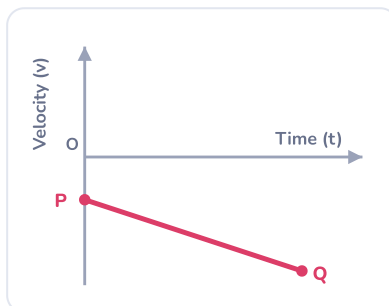
a Positive initial velocity

Starting with a **positive velocity**, the graph is a **straight line sloping downwards** (negative slope).



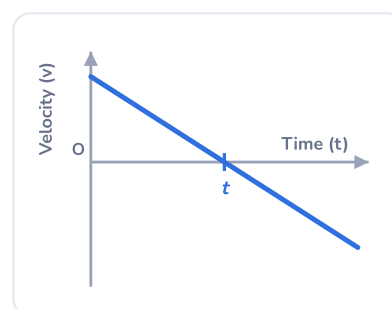
b Negative initial velocity

Starting with a **negative velocity**, the graph is a **straight line that begins at P**. P is a point of **negative velocity** below the time axis.



c Positive initial velocity – direction reverses

Starting with a **positive velocity**, the velocity can fall to zero and then become negative. So the **direction of motion reverses** at time t . For uniform acceleration, the **slope of the graph stays the same** throughout.



2.5 Kinematic Equations for Uniformly Accelerated Motion

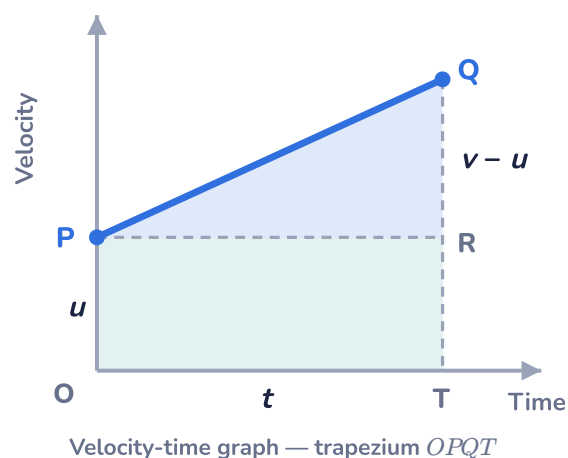
DEFINITION

Uniformly Accelerated Motion

When the velocity of an object changes by the **same amount in every unit of time**, it has **constant acceleration**. Such motion is called **uniformly accelerated motion**.

SETUP – GIVEN INFORMATION

- ◆ The object moves along a straight line with **constant acceleration a** .
- ◆ Initial velocity = u (at $t = 0$). Final velocity = v (after time t).
- ◆ The **slope** of the v - t graph = a (acceleration).
- ◆ The **area** under the v - t graph = displacement x .



• (I) VELOCITY-TIME RELATION

DERIVATION

The **slope** of the velocity-time graph is equal to the **acceleration**:

1

$$a = \text{Slope of } PQ = \frac{QR}{PR} = \frac{v - u}{t}$$

2

$$\Rightarrow v - u = at$$

VELOCITY-TIME RELATION

$$v = u + at$$

• (II) POSITION-TIME RELATION

DERIVATION

The **area** under the velocity-time graph is equal to the **displacement**. For a time interval t :

1

$$x = \text{Area of } \triangle PQR + \text{Area of rectangle } OPRT$$

2

$$= \frac{1}{2} QR \times PR + OP \times PR$$

3

$$= \frac{1}{2}(v - u)t + ut$$

4

$$= \frac{1}{2}(at)t + ut \quad [\because v - u = at]$$

5

$$= \frac{1}{2}at^2 + ut$$

6

$$\Rightarrow x = \frac{1}{2}at^2 + ut$$

POSITION-TIME RELATION

$$x = ut + \frac{1}{2}at^2$$

• (III) POSITION-VELOCITY RELATION

DERIVATION

The displacement in time t is also equal to the **area of the trapezium** $OPQT$:

1

$$x = \frac{1}{2}(OP + QT) \times OT = \frac{1}{2}(u + v)t \quad \dots (i)$$

2

$$\text{From } v - u = at \Rightarrow t = \frac{v - u}{a} \quad \dots (ii)$$

3

$$\text{Substituting (ii) in (i): } x = \frac{1}{2}(u + v) \times \frac{v - u}{a} \Rightarrow v^2 - u^2 = 2ax$$

POSITION-VELOCITY RELATION

$$v^2 = u^2 + 2ax$$

2.6 Displacement of the Particle in n^{th} Second

CONCEPT

Consider an object with initial velocity u and **constant acceleration** a . To find its displacement **during the n^{th} second**, take its position at the end of n **seconds**. Then subtract its position at the end of $(n - 1)$ **seconds**.

DERIVATION

1

$$s_{n^{\text{th}}} = s_n - s_{n-1}$$

2

$$= [un + \frac{1}{2}an^2] - [u(n-1) + \frac{1}{2}a(n-1)^2]$$

3

$$= u + \frac{a}{2} [n^2 - (n-1)^2]$$

4

$$= u + \frac{a}{2} (2n - 1)$$

DISPLACEMENT IN N^{TH} SECOND

$$s_{n^{\text{th}}} = u + \frac{a}{2} (2n - 1)$$

where, $s_{n^{\text{th}}}$ = displacement in the n^{th} second, u = initial velocity, a = constant acceleration

2.7 Steps to Solve Problems Based on Accelerated Motion

A simple method to solve problems on **accelerated motion**:

PROBLEM SOLVING STRATEGY

Accelerated Motion

I Check the Units

Make sure all the **units match**. If distances are in **metres**, velocities must be in **m/s** and accelerations in **m/s²**.

II List Knowns and Unknowns

Write down all the **given quantities**. Separately, write the quantities you **need to find**.

III Pick the Right Equation(s)

Think about what is happening **physically**. Then choose the **kinematic equation(s)** that connect the given quantities to the **unknowns**.

2.8 Non-uniformly Accelerated Motion

DEFINITION

In **non-uniformly accelerated motion**, the **acceleration** of a particle is **not constant**. For example, it may change with **time**. We describe such one-dimensional motion with these **calculus (differential) relations**.

VELOCITY

$$v = \frac{dx}{dt}$$

ACCELERATION

$$a = \frac{dv}{dt} = \frac{d^2x}{dt^2}$$

VELOCITY-DISPLACEMENT

$$v \, dv = a \, dx$$

NOTE

These relations come from **calculus** and work for **uniform** as well as **non-uniform** acceleration.

2.9 Equations of Motion for an Object Under Gravity

DEFINITION

Motion Under Gravity

A body is said to be in **motion under gravity** when it is **thrown upwards** or **falls towards the Earth**. Whether it moves up or down, its **acceleration is the acceleration due to gravity** ($g \approx 9.8 \text{ m/s}^2$).

So the equations of motion still apply. Just replace the acceleration a by $(\pm g)$ and the displacement by the height h :

VELOCITY-TIME ... (I)

$$v = u + (\pm g) t$$

POSITION-TIME ... (II)

$$h = ut + \frac{1}{2}(\pm g) t^2$$

POSITION-VELOCITY ... (III)

$$v^2 = u^2 + 2(\pm g) h$$

The **sign of g** depends on the direction of motion:

Moving **upward** — gravity **opposes** the motion

g is negative ($-g$)

Moving **downward** — gravity acts **along** the motion

g is positive ($+g$)

REMEMBER

Feeling Weightlessness

Many people think that no force acts on us in free fall, because we cannot feel our weight. In fact, we "feel" our weight through the **reaction force from the ground**. In free fall, we are **pressing on nothing**. So there is **no reaction force** (Newton's third law), and we feel **weightless**. But gravity still acts on us.

2.10 Galileo's Law of Odd Numbers

LAW

Galileo was the first to study free fall with careful measurements. He found that the **distances covered by a freely falling body in successive equal intervals of time** are in the **ratio of the odd numbers starting from 1**, i.e. $1 : 3 : 5 : 7 \dots$

RATIO OF DISTANCES IN SUCCESSIVE EQUAL TIME INTERVALS

$$1 : 3 : 5 : 7 : \dots : (2n - 1)$$

distances covered in the 1st, 2nd, 3rd, ... equal time intervals τ , in the ratio of odd numbers starting from 1



A freely falling body: distances $1 : 3 : 5 : 7$ in equal times τ

● PROOF OF THE LAW

Divide the time of **free fall** into many **equal intervals** τ . Then find the distance covered in each interval. Since $u = 0$:

$$y = -\frac{1}{2}gt^2, \quad \text{where } y_0 = \frac{1}{2}g\tau^2$$

t	y	$ y $ IN TERMS OF $y_0 = \frac{1}{2}g\tau^2$	DISTANCE TRAVERSED IN SUCCESSIVE INTERVALS	RATIO OF DISTANCES TRAVERSED
0	0	0	—	—
τ	$-\frac{1}{2}g\tau^2$	y_0	y_0	1
2τ	$-4(\frac{1}{2}g\tau^2)$	$4y_0$	$3y_0$	3
3τ	$-9(\frac{1}{2}g\tau^2)$	$9y_0$	$5y_0$	5
4τ	$-16(\frac{1}{2}g\tau^2)$	$16y_0$	$7y_0$	7
5τ	$-25(\frac{1}{2}g\tau^2)$	$25y_0$	$9y_0$	9
6τ	$-36(\frac{1}{2}g\tau^2)$	$36y_0$	$11y_0$	11

HENCE PROVED

The third column gives the distance fallen $|y|$ in units of y_0 . The fourth column gives the distance covered in each successive interval τ . These distances are in the simple ratio:

$$y_0 : 3y_0 : 5y_0 : 7y_0 : 9y_0 : 11y_0 = 1 : 3 : 5 : 7 : 9 : 11$$

These are the **odd numbers starting from 1**. Hence proved.

2.11 Stopping Distance for a Vehicle

DEFINITION

The **stopping distance** (d_s) of a vehicle is the **distance it travels after the brakes are applied**, until it comes to rest.

NOTE

Stopping distance is very important for **road safety**. It depends on the **speed** of the vehicle and how **efficient its brakes** are.

DERIVATION

Let the vehicle travel a distance d_s before stopping. Use the equation of motion $v^2 = u^2 + 2ax$ with final velocity $v = 0$ and $x = d_s$:

1

$$0 = u^2 + 2a d_s$$

2

$$\Rightarrow d_s = \frac{-u^2}{2a}$$

STOPPING DISTANCE

$$d_s = \frac{-u^2}{2a}$$

where, u = initial speed, a = acceleration (negative when braking, so d_s is positive)

$d_s \propto u^2$, so **doubling** the initial speed (with the same braking)

d_s becomes 4×

2.12 Reaction Time

DEFINITION

When a situation needs **immediate action**, we still take a little time to respond. The time taken to **see**, **think and act** is called **reaction time**.

EXAMPLE

A driver suddenly sees a child run onto the road. The time that passes **before the driver presses the brakes** is the driver's reaction time.

REACTION TIME DEPENDS ON

i Presence of mind

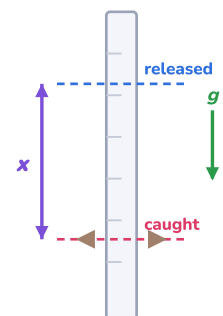
How **alert** the person is.

ii Complexity

How **complicated the situation** is.

● CALCULATION OF REACTION TIME

A simple experiment measures it. A friend holds a **long ruler vertically** between your thumb and forefinger. The friend **releases it** without warning. You catch it as quickly as you can. By the time you react, the ruler has already fallen a distance x .



Ruler-drop test for reaction time

DERIVATION

Suppose $x = 0.21$ m. Here $u = 0$ and $a = g = 9.8 \text{ m/s}^2$. Use $x = ut + \frac{1}{2}at^2$ to find the reaction time t :

1

$$0.21 = 0 + \frac{1}{2} \times 9.8 \times t^2$$

2

$$t = \sqrt{\frac{2 \times 0.21}{9.8}} \approx 0.21 \text{ s}$$

REACTION TIME

$$t = \sqrt{\frac{2x}{g}}$$

where, x = distance the ruler falls before it is caught, g = acceleration due to gravity