Introduction

Physics, derived from the Greek word physics, meaning "nature," is the study of the fundamental principles governing the behavior of matter, energy, and the forces of nature. It is the foundation of all natural sciences and seeks to understand how the universe works, from the smallest particles to the largest cosmic structures. Physics is essential for explaining how objects move, interact, and change under various conditions, and it provides the conceptual and mathematical framework used in many engineering and technological fields.

The branch of physics that studies the motion of bodies is called mechanics. In antiquity, the science of mechanics (from the Greek mechane, machine) was the study of machines, and this is still what we have in mind when we call an automobile repairperson a mechanic.

In physics, we can categorize motion into three types: translational, rotational, and vibrational. A car traveling on a highway is an example of translational motion, the Earth's spin on its axis is an example of rotational motion, and the back-and-forth movement of a pendulum is an example of vibrational motion.

Position and Displacement

To locate an object means to find its position relative to some reference point, often the origin (or zero point) of an axis such as the x axis in Fig.(1).The positive direction of the axis is in the direction of increasing numbers (coordinates),which is to the right in Fig.(1).The opposite is the negative direction.

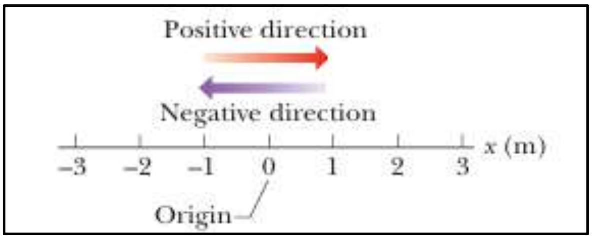


Figure : Show Position on an axis.

The displacement Δx of a particle is defined as its change in position in some time interval. As the particle moves from an initial position x_i to a final position x_f, its displacement is given by:

$$\Delta X = X_f - X_i$$

We use the capital Greek letter delta (Δ) to denote the change in a quantity. From this definition, we see that Δx is positive if X_f is greater than x_i and negative if X_f is less than x_i.

It is very important to recognize the difference between displacement and distance traveled. Distance is the length of a path followed by a particle. Distance is always represented as a positive number, whereas displacement can be either positive or negative. Distance is a scalar quantity that measures the total path length traveled by an object, regardless of direction. Displacement, on the other hand, is a vector and only considers the shortest straight-line distance between the start and end points, along with the direction.

Displacement is an example of a vector quantity, which is a quantity that has both a direction and a magnitude.

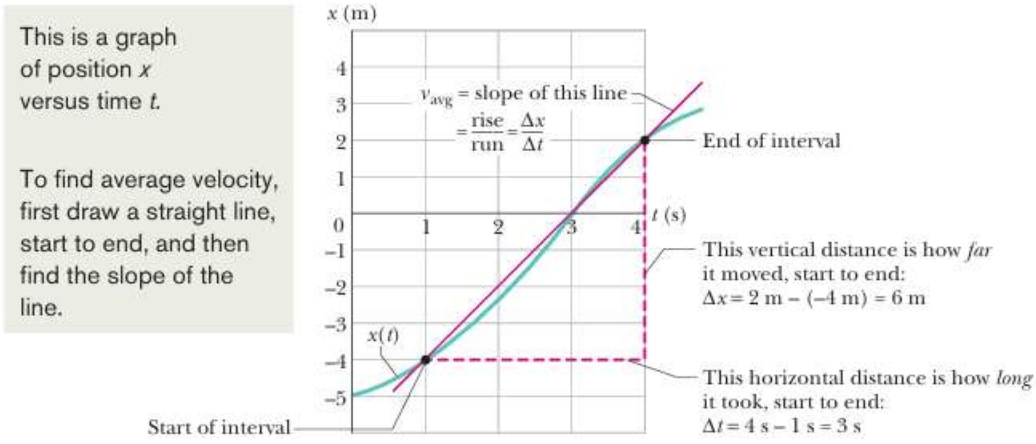
Velocity and Speed

The average velocity is defined as the ratio of this change of position and the time interval:

$$\bar{v} = \frac{x_2 - x_1}{t_2 - t_1}$$

can also be written as

$$\bar{v} = \frac{\Delta x}{\Delta t}$$



The ***average speed*** of a particle, a scalar quantity, is defined as the total distance (d) traveled divided by the total time interval required to travel that distance.

$$v_{avg} \equiv \frac{d}{\Delta t}$$

The SI unit of average speed is the same as the unit of average velocity: meters per second.

NOTE :

- Speed is a scalar quantity, meaning it only has magnitude.
- Velocity is a vector quantity, meaning it has both magnitude and direction.

Example/ A runner runs 100 m on a straight track in 11s and then walks back in 80s. What are the average velocity and the average speed for each part of the motion and for the entire motion?

Solution /

The average velocity for the run is:

$$\bar{v} = \frac{\Delta x}{\Delta t} = \frac{+100\ \text{m}}{11\ \text{s}} = +9.1\ \text{m/s}$$

The average velocity for the walk is

$$\bar{v} = \frac{-100\ \text{m}}{80\ \text{s}} = -1.3\ \text{m/s}$$

(Here the minus sign in −100 m indicates that the change of position is in the negative direction.) The average velocity for the entire motion is

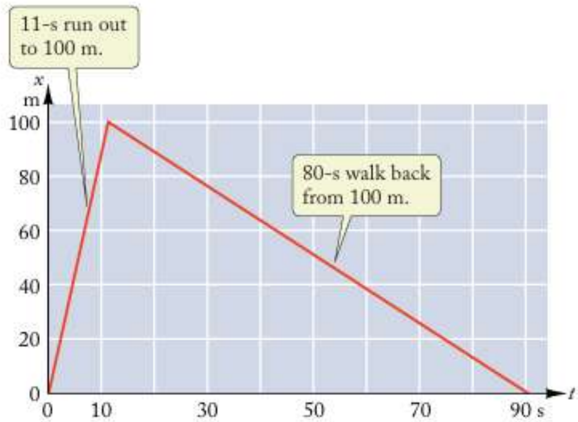
$$\bar{v} = \frac{0\ \text{m}}{91\ \text{s}} = 0\ \text{m/s}$$

This average velocity is zero because the net change of position is zero.

The average speed for the entire motion is the total distance traveled divided by the time taken:

$$[\text{average speed}] = \frac{200\ \text{m}}{91\ \text{s}} = 2.2\ \text{m/s}$$

The average speed differs from the average velocity because the distance traveled (200 m) differs from the net change of position (zero).



Acceleration

Any motion with a change of velocity is accelerated motion. Thus, the motion of an automobile that speeds up is accelerated motion, but so is the motion of an automobile that slows down while braking—in both cases there is a change of velocity. If a particle has velocity v_1 at time t_1 and velocity v_2 at time t_2 ,then the average acceleration for this time interval is defined as the change of velocity divided by the change of time,

$$\bar{a} = \frac{v_2 - v_1}{t_2 - t_1}$$

or

$$\bar{a} = \frac{\Delta v}{\Delta t}$$

Example / A fighter jet being launched by a catapult from the deck of an aircraft carrier. During this launch, the fighter jet attains a speed of 260 km/h in only 1.8 s. What is the average acceleration of the jet during this time interval?

Solution /

$$\Delta v = 260 \text{ km/h} \times \frac{1000 \text{ m}}{1 \text{ km}} \times \frac{1 \text{ h}}{3600 \text{ s}} = 72 \text{ m/s}$$

With $\Delta v = 72$ m/s and $\Delta t = 1.8$ s, the average acceleration is then

$$\bar{a} = \frac{\Delta v}{\Delta t} = \frac{72 \text{ m/s}}{1.8 \text{ s}} = 4.0 \times 10^1 \text{ m/s}^2 = 40 \text{ m/s}^2$$

Constant Acceleration

Constant acceleration refers to the situation in which an object's velocity changes at a constant rate over time. In simpler terms, it means the object’s acceleration remains the same (does not change) during the period of motion.

$$v_{xf} = v_{xi} + a_x t \quad \text{(2.13)}$$

$$v_{x,\text{avg}} = \frac{v_{xi} + v_{xf}}{2} \quad \text{(2.14)}$$

$$x_f = x_i + \tfrac{1}{2}(v_{xi} + v_{xf})t \quad \text{(2.15)}$$

$$x_f = x_i + v_{xi}t + \tfrac{1}{2}a_x t^2 \quad \text{(2.16)}$$

$$v_{xf}^{\,2} = v_{xi}^{\,2} + 2a_x(x_f - x_i) \quad \text{(2.17)}$$

Free-fall acceleration

A body released near the surface of the Earth will accelerate downward under the influence of the pull of gravity exerted by the Earth. If the frictional resistance of the air has been eliminated (by placing the body in an evacuated container),then the body is in free fall, and the down ward motion proceeds with constant acceleration. Show Fig.(2)

Figure (2): Stroboscopic photograph of an apple and a feather in free fall in a partially evacuated chamber. The apple and feather were released simultaneously from the trapdoor at the top. The photograph was made by leaving the shutter of the camera open and triggering a flash of light at regular intervals.

The downward acceleration of a freely falling body near the surface of the Earth is usually denoted by g. The numerical value of g approximately:

$$g \approx 9.81 \text{ m/s}^2$$

$$v = v_0 - gt \qquad (2.27)$$

$$x = x_0 + v_0 t - \frac{1}{2}gt^2 \qquad (2.28)$$

$$-g\,(x - x_0) = \frac{1}{2}(v^2 - v_0^2) \qquad (2.29)$$

Examples/ During a catapult launch from the deck of an aircraft carrier (see the photo),the average acceleration of a fighter jet is 40 m/s2during a time interval of 1.8s. Assuming the motion proceeds with constant acceleration, how far does the fighter jet travel along the deck during this time interval?

Solution / For motion with constant acceleration. To solve this problem, we must decide which of these equations we need. The unknown quantity is the distance, and the known quantities are the acceleration, the final and initial speeds, and the time. For convenience, we assume that the origin of our coordinates is at the initial position of the aircraft, so x0= 0.Then the known and the unknown quantities are as follows:

UNKNOWN	KNOWN
x	$a = 40\ \text{m/s}^2$ $v_0 = 0$ $x_0 = 0$ $t = 1.8\ \text{s}$

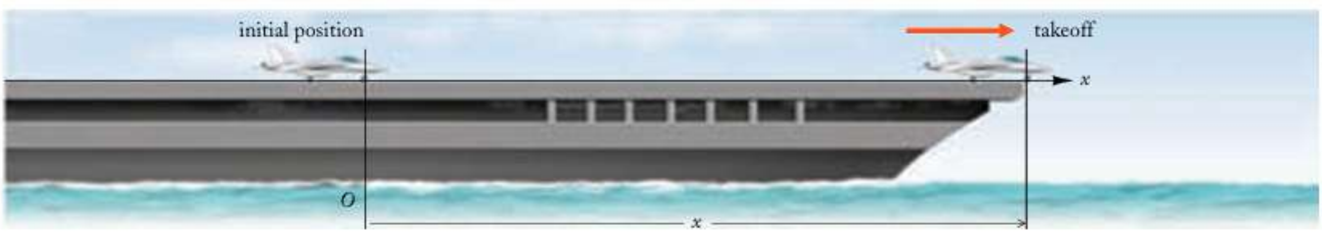


Fig.: catapulted jet. The origin of coordinates is at the initial position of the jet.

$$x = x_0 + v_0 + \frac{1}{2}at^2 = 0 + 0 + \frac{1}{2} \times (40\ \text{m/s}^2) \times (1.8\ \text{s})^2$$
$$= 65\ \text{m}$$

Example/ An automobile is traveling at 86 km/h on a straight road when the driver spots a wreck ahead and slams on the brakes. The reaction time of the driver, that is, the time interval between seeing the wreck and stepping on the brakes, is 0.75 s. Once the brakes are applied, the automobile decelerates at 8.0 m/s^2.What is the total stopping distance (see Fig.)?

Solution / The motion has two parts. The first part, before the brakes are applied, is motion at constant velocity; the second part, after the brakes are applied, is motion with constant (negative) acceleration.

The first part of the motion lasts for a time $\Delta t = 0.75$ s, with a constant velocity $v_0 = 86$ km/h, that is,

$$v_0 = 86\frac{\text{km}}{\text{h}} \times \frac{10^3\ \text{m}}{1\ \text{km}} \times \frac{1\ \text{h}}{3600\ \text{s}} = 24\ \text{m/s}$$

With this velocity, the automobile travels a distance

$$v_0\,\Delta t = 24\ \text{m/s} \times 0.75\ \text{s} = 18\ \text{m}$$

The second part of the motion therefore has an initial position $x_0 = 18$ m, an initial velocity $v_0 = 24$ m/s, a final velocity $v = 0$, and an acceleration $a = -8.0\ \text{m/s}^2$ (the acceleration is negative since the automobile is decelerating while moving in the positive x direction). The final distance is the unknown:

UNKNOWN	KNOWN
x	$a = -8.0\ \text{m/s}^2$ $v = 0$ $v_0 = 24\ \text{m/s}$ $x_0 = 18\ \text{m}$

$$x = x_0 + \frac{v^2 - v_0^2}{2a}$$
$$= 18\ \text{m} + \frac{0 - (24\ \text{m/s})^2}{2 \times (-8.0\ \text{m/s}^2)} = 18\ \text{m} + 36\ \text{m} = 54\ \text{m}$$

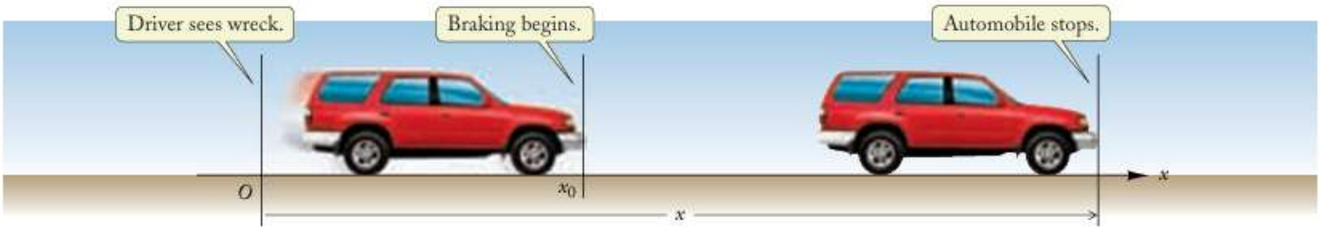


Fig.: braking automobile. The origin of coordinates is at the point where the driver spots wreck.

Example/ On a foggy day, a minivan is traveling at 80 km/h along a straight road when the driver notices a truck ahead traveling at 25 km/h in the same direction. The driver begins to brake when the truck is 12 m ahead, decelerating the minivan at 8.0 m/s2,while the truck continues at a steady 25 km/h. How long after this instant does the minivan collide with the truck? What is the speed of the minivan at the instant of collision?

Solution/ We designate the position, velocity, and acceleration of the minivan by x, v, and a and the position,velocity,and acceleration of the truck by x, v ,and a. We reckon the x and x coordinates from the point at which braking begins.

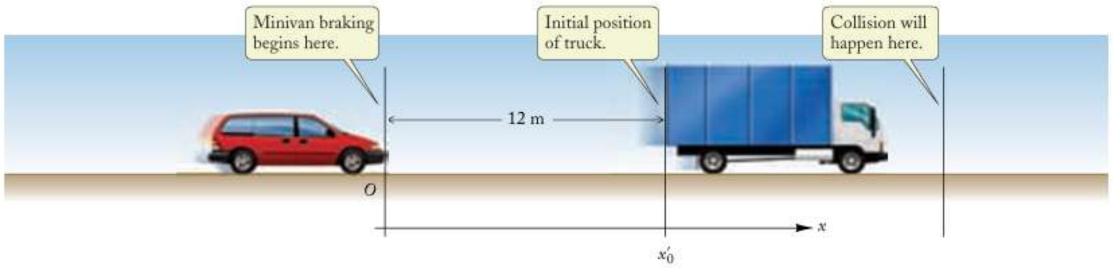


Fig.: braking minivan and a truck traveling at constant velocity. The origin of coordinates is at the point where braking begins. The initial position of the minivan is x_0=0,and the initial position of the truck (measured to the rear of the truck) is x'_0 =12 m.

The time t of the collision and the positions x and x' at that time are unknown. The initial positions x_0 and x'_0, velocities v_0 and v'_0, and accelerations a and a' are known:

UNKNOWN	KNOWN
t	$x_0 = 0$
x	$x'_0 = 12$ m
x'	$v_0 = 80$ km/h
	$v'_0 = 25$ km/h
	$a = -8.0$ m/s^2
	$a' = 0$

To relate the unknowns x and x' to the known quantities, we use Eq. (2.22) for the minivan:

$$x = x_0 + v_0 t + \tfrac{1}{2}at^2 = v_0 t + \tfrac{1}{2}at^2$$

and for the truck:

$$x' = x'_0 + v'_0 t + \tfrac{1}{2}a' t^2 = x'_0 + v'_0 t$$

Here we have two equations but three unknowns (t, x, x'). We can extract the unknown time t from these equations by taking into account that when the vehicles collide, $x = x'$. This condition tells us that

$$v_0 t + \tfrac{1}{2}at^2 = x'_0 + v'_0 t$$

This is a quadratic equation. Before proceeding with the solution, it is convenient to substitute the known numbers $a = -8.0$ m/s^2, $v_0 = 80$ km/h $= 80 \times 1000$ m/3600 s $=$ 22.2 m/s, $x'_0 = 12$ m, and $v'_0 = 25$ km/h $= 25 \times 1000$ m/3600 s $= 6.9$ m/s. Since the acceleration values are in m/s^2 and the velocity values in m/s, the time will be in seconds. Omitting the units, we obtain

$$22.2t - 4.0t^2 = 12 + 6.9t$$

and if we shift all the terms to the left side, we obtain

$$-4.0t^2 + 15.3t - 12 = 0$$

$$at^2 + bt + c = 0$$

with the two solutions (see Appendix 2)

$$t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$= \frac{-15.3 \pm \sqrt{(15.3)^2 - 4 \times (-4.0) \times (-12)}}{2 \times (-4.0)} = 1.1 \text{ s or } 2.7 \text{ s}$$

Of these two solutions, only the first is relevant (the second solution would require that the minivan pass through the truck while continuing to brake at 1.1 s and that the truck then again approach the minivan when the minivan has nearly stopped at 2.7 s). Thus, the collision occurs at a time 1.1 s.

The speed of the minivan at this time is

$$v = v_0 + at = 22.2 \text{ m/s} - 8.0 \text{ m/s}^2 \times 1.1 \text{ s} = 13 \text{ m/s}$$

Example/ A powerful bow, like one of those used to establish world records in archery, can launch an arrow at a velocity of 90 m/s. How high will such an arrow rise if aimed vertically upward? How long will it take to return to the ground? What will be its velocity when it hits the ground? For simplicity, ignore air friction and treat the arrow as an ideal particle.

SOLUTION: At the ground, the initial velocity is positive, $v_0 = 90$ m/s (see Fig. 2.21). The arrow moves upward while its velocity decreases at the rate of 9.81 m/s^2. At the highest point of the motion, the arrow ceases to move upward and is momentarily at rest; at this point the instantaneous velocity is zero, $v = 0$. For the upward motion, we can therefore regard the initial and final velocities as known. The height reached and the time are unknown:

UNKNOWN	KNOWN
$x - x_0$	$v_0 = 90$ m/s
t	$v = 0$
	$g = 9.81$ m/s^2

$$x - x_0 = \frac{-(v^2 - v_0^2)}{2g} = \frac{-0 + (90 \text{ m/s})^2}{2 \times 9.81 \text{ m/s}^2} = 4.1 \times 10^2 \text{ m}$$

$$t = \frac{v_0 - v}{g} = \frac{90 \text{ m/s} - 0}{9.81 \text{ m/s}^2} = 9.2 \text{ s}$$

The downward motion is simply the reverse of the upward motion—during the downward motion, the arrow accelerates at the rate of 9.81 m/s^2, just as it decelerated at this same rate during the upward motion. The downward motion therefore takes exactly as long as the upward motion, and the total time required for the arrow to complete the up and down motion is twice the time required for the upward motion, that is, 2×9.2 s = 18.4 s.

The velocity of the arrow when it hits the ground is simply the reverse of the initial velocity; thus, it is −90 m/s.

COMMENT: Keep in mind that although the instantaneous velocity of the arrow is zero at the highest point of the motion, the acceleration is still the same as that at any other point, $a = -g$. The arrow is momentarily at rest, but it is still accelerating!

Example/ The speed of nerve pulses in mammals is typically 10^2 m/s. If a shark bites the tail of a 30-m-long whale ,roughly how long will it take before the whale knows of this?

Solution/

$$t = \frac{d}{t}$$

$$t = \frac{30\,\text{m}}{100\,\text{m/s}} = 0.3\,\text{seconds}$$

Example/ A kinesiologist is studying the biomechanics of the human body. (Kinesiology is the study of the movement of the human body. Notice the connection to the word kinematics.) She determines the velocity of an experimental subject while he runs along a straight line at a constant rate. The kinesiologist starts the stopwatch at the moment the runner passes a given point and stops it after the runner has passed another point 20 m away. The time interval indicated on the stopwatch is 4.0 s.

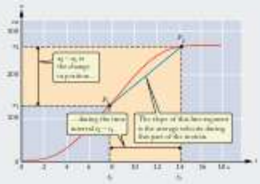
(A) What is the runner's velocity?

$$v_x = \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{\Delta t} = \frac{20\text{ m} - 0}{4.0\text{ s}} = 5.0\text{ m/s}$$

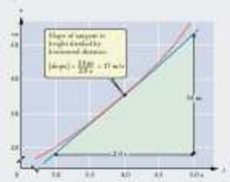
(B) If the runner continues his motion after the stopwatch is stopped, what is his position after 10 s have passed?

$$x_f = x_i + v_x t = 0 + (5.0\text{ m/s})(10\text{ s}) = 50\text{ m}$$

AVERAGE VELOCITY $$\bar{v} = \frac{\Delta x}{\Delta t}$$



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



AVERAGE ACCELERATION $$\bar{a} = \frac{\Delta v}{\Delta t}$$

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

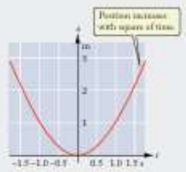
MOTION WITH CONSTANT ACCELERATION

$$v = v_0 + at$$

$$x - x_0 = \tfrac{1}{2}(v_0 + v)t$$

$$x - x_0 = v_0 t + \tfrac{1}{2}at^2$$

$$a(x - x_0) = \tfrac{1}{2}(v^2 - v_0^2)$$



ACCELERATION OF FREE FALL $g \approx 9.81\ \text{m/s}^2$

STANDARD g 1 standard $g = 9.81\ \text{m/s}^2$

MOTION OF FREE FALL (x axis is upward)

$$v = v_0 - gt$$

$$x - x_0 = v_0 t - \tfrac{1}{2}gt^2$$

$$-g(x - x_0) = \tfrac{1}{2}(v^2 - v_0^2)$$