Linear Motion, Speed & Velocity

Unit: Kinematics (Motion) in One Dimension

NGSS Standards/MA Curriculum Frameworks (2016): HS-PS2-10(MA)

AP® Physics 1 Learning Objectives/Essential Knowledge (2024): 3.A.1.1, 3.A.1.3

Mastery Objective(s): (Students will be able to…)

- Correctly describe the position, speed, velocity, and acceleration of an object based on a description of its motion (or lack thereof).

Success Criteria:

- Description of vector quantities (position, velocity & acceleration) indicates both magnitude (amount) and direction.
- Description of scalar quantities does not include direction.

Language Objectives:

- Explain the Tier 2 words "position," "distance," "displacement," "speed," "velocity," and "acceleration" and how their usage in physics is different from the vernacular.
- Explain why we do not use the word "deceleration" in physics.

Tier 2 Vocabulary: position, speed, velocity, acceleration, direction

Labs, Activities & Demonstrations:

- Walk in the positive and negative directions (with positive or negative velocity).
- Walk and change direction to show distance *vs.* displacement.

Notes:

coördinate system: a framework for describing an object's ***position*** (location), based on its distance (in one or more directions) from a specifically-defined point (the ***origin***). (You should remember these terms from math.)

direction: which way an object is oriented or moving within its coördinate system. Note that direction can be positive or negative.

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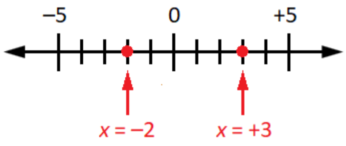
position ($\vec{x}$): [vector*] the location of an object relative to the origin (zero point) of its coördinate system. We will consider position to be a zero-dimensional vector.

If we are representing position in only one dimension (*e.g.,* along the *x*-axis), we represent it as a positive or negative number, which means position can be positive or negative.

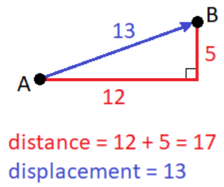


If we are representing position in two dimensions, we can use either cartesian coördinates—the position in each direction (*x*,*y*)—or polar coordinates—the distance from the origin and an angle (*r*,*θ*). See Polar, Cylindrical & Spherical Coördinates starting on page 162 for more information.

distance (*d*): [scalar] the length of the path that an object took when it moved. Distance does not depend on direction and is always positive or zero.

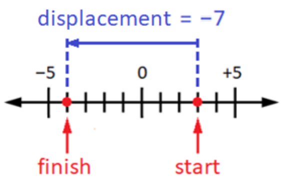
displacement ($\vec{d}$ or $\Delta\vec{x}$): [vector] how far an object's current position is from its starting position ("initial position"). If an object travels in a straight line and does not reverse direction, distance and the magnitude of the displacement will be the same. However, if the object changes direction, then the distance traveled will be greater than the displacement.

For example, suppose an object travelled a distance of 12 units to the east, and then 5 units to the north. The object has travelled a total *distance* of 17 units, However, by the Pythagorean theorem, the object's *displacement* is 13 units from where it started.



Note that because physics problems are usually described in the vernacular, problems will often use the word "distance" when what is actually meant is displacement.

As with position, if motion is in only one dimension (*e.g.,* only along the x-axis), we define one direction along that dimension to be the positive direction and the opposite direction to be negative. Thus displacement will be positive, negative, or zero. For example, the object at the right's displacement is −7 units (7 units in the negative direction) from where it started.



* Position is a zero-dimensional vector. An object's position is a location that, like other vector quantities, can be positive or negative and is dependent on the coördinate system chosen.

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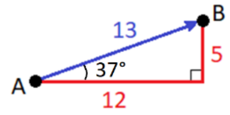
If motion is in two dimensions, the displacement is usually described in polar coördinates, using the straight-line distance from start to finish and the angle from some reference direction (*e.g.,* the *x*-axis). Using the above example, we would describe the object's displacement as 13 at an angle of 37° above horizontal.



<u>rate</u>: the change in any quantity over a specific period of time.

<u>motion</u>: when an object's *position* is changing over time.

<u>speed</u>: [scalar] the rate at which an object is moving at an instant in time. Speed does not depend on direction, and is always positive or zero.

An object's (instantaneous) speed is the distance that it would travel in a given amount of time, divided by that amount of time.

If the object's speed is constant, then its $\text{average speed} = \dfrac{\text{distance}}{\text{time}}$

<u>velocity</u>: ($\vec{\boldsymbol{v}}$) [vector] the rate of change of an object's position (its displacement) over a given period of time. Because velocity is a *<u>vector</u>*, it has a *<u>direction</u>* as well as a *<u>magnitude</u>*; think of velocity as the vector equivalent of speed.

An object's instantaneous velocity is the same as its instantaneous speed, with the addition of some way to indicate the direction it is moving.

We use $\vec{\boldsymbol{v}}$ without a subscript to indicate an object's instantaneous velocity. If the object's velocity is changing, we use $\vec{\boldsymbol{v}}_o$ for the initial velocity (the subscript "0" means "at time zero"), and $\vec{\boldsymbol{v}}$ for the final velocity.

If an object is moving in one dimension and does not change direction, then (the magnitude of) its average velocity will be the same as its average speed.

As with average speed, an object's $\text{average velocity} = \dfrac{\text{displacement}}{\text{time}}$

$$\vec{\boldsymbol{v}}_{ave.} = \frac{\vec{\boldsymbol{d}}}{t} = \frac{\Delta \boldsymbol{x}}{t}$$

Note that because the average velocity is neither the initial nor final velocity, we need to use a descriptive subscript to indicate what sort of velocity it is.

Note that if the direction changes, the object's average speed will be greater than its average velocity, because the distance traveled is greater than the object's displacement.

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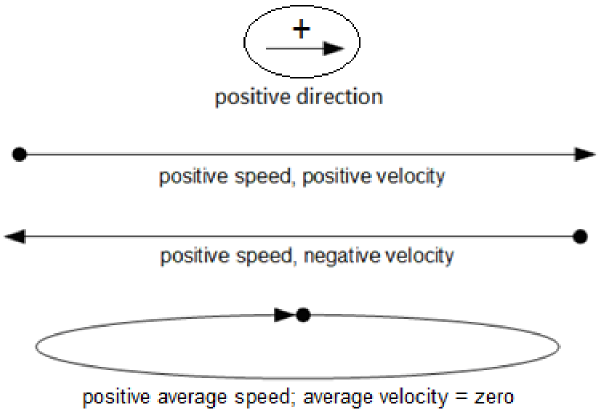
As with position and displacement, if velocity is in one dimension (e.g., along the x-axis), we use positive and negative numbers to indicate the direction. A positive instantaneous velocity means the object is moving in the positive direction; a negative instantaneous velocity means the object is moving in the negative direction; an instantaneous velocity of zero means the object is "at rest" (not moving).

If an object returns to its starting point, its average velocity is zero, because its displacement is zero.



In the MKS system, speed and velocity are measured in meters per second.

$$1\,\frac{\text{m}}{\text{s}} \approx 2.24\,\frac{\text{mi.}}{\text{hr.}}$$

<u>uniform motion</u>: motion at a constant velocity (*i.e.,* constant speed and direction)

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Variables Used to Describe Linear Motion

Variable	Quantity	Unit	Variable	Quantity	Unit
$\vec{x}$	(final) position	m	$\vec{v}$	(final) velocity	$\frac{m}{s}$
$\vec{x}_o$	initial (starting) position	m	$\vec{v}_o$	initial (starting) velocity	$\frac{m}{s}$
d	distance	m	$\vec{v}_{ave.}$	average velocity	$\frac{m}{s}$
$\vec{d}$, $\Delta\vec{x}$	displacement	m	$\vec{a}$	acceleration	$\frac{m}{s^2}$
$\vec{h}$	height	m	$\vec{g}$	acceleration due to gravity	$\frac{m}{s^2}$
			t	time	s

By convention, physicists use the variable $\vec{g}$ to mean acceleration due to gravity of an object in free fall, and $\vec{a}$ to mean acceleration under any other conditions.

The average velocity of an object is its displacement (change in position) divided by the elapsed time.

$$\vec{v}_{ave} = \frac{\vec{d}}{t}$$

The acceleration of an object is its change in velocity divided by the elapsed time. (Acceleration will be covered in detail in the next section.)

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

Signs of Vector Quantities

As described above, for motion in one dimension, the sign of a vector (positive or negative) is used to indicate its direction.

- Displacement is positive if the change in position of object in question is toward the positive direction, and negative if the change in position is toward the negative direction.
- Velocity is positive if the object is moving in the positive direction, and negative if the object is moving in the negative direction.
- Acceleration is positive if the *change* in velocity is positive (*i.e.,* if the velocity is becoming more positive or less negative). Acceleration is negative if the *change* in velocity is negative (*i.e.,* if the velocity is becoming less positive or more negative).

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Sample Problems

Q: A car travels 1200 m in 60 seconds. What is its average velocity?

A: $v_{ave.} = \frac{d}{t} = \frac{1200\,\text{m}}{60\,\text{s}} = 20\,\frac{\text{m}}{\text{s}}$

Q: A person walks 320 m at an average velocity of $1.25\,\frac{\text{m}}{\text{s}}$. How long did it take?

A: "How long" means what length of *time*.

$$\vec{v}_{ave.} = \frac{\vec{d}}{t} \qquad (\vec{v}_{ave.})t = \vec{d} \qquad t = \frac{\vec{d}}{\vec{v}_{ave.}} = \frac{320}{1.25} = 256\,s$$

Notice that when solving for a variable in the denominator, it is safest to do it in two steps—first multiply both sides by the denominator and then divide to isolate the variable in a second step. Many students attempt to rearrange the variables in one step, often with little success.

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