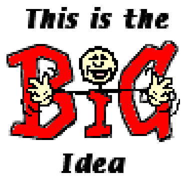
Lesson 1: Describing Motion with Words

Introduction to the Language of Kinematics



A typical physics course concerns itself with a variety of broad topics. One such topic is **mechanics** - the study of the motion of objects. The first six units of The Physics Classroom tutorial will involve an investigation into the physics of motion. As we focus on the language, principles, and laws which describe and explain the motion of objects, your efforts should center around internalizing the meaning of the information. Avoid memorizing the information; and avoid abstracting the information from the physical world which it describes and explains. Rather, contemplate the information, thinking about its meaning and its applications.

Kinematics is the science of describing the motion of objects using words, diagrams, numbers, graphs, and equations. Kinematics is a branch of mechanics. The goal of any study of kinematics is to develop sophisticated mental models which serve to describe (and ultimately, explain) the motion of real-world objects.

In this lesson, we will investigate the words used to describe the motion of objects. That is, we will focus on the *language* of kinematics. The hope is to gain a comfortable foundation with the the language which is used throughout the study of mechanics. The words listed below are used with regularity to describe the motion of objects. Your goal should be to become very familiar with their meaning. You may click on any word now to investigate its meaning or proceed with the lesson in the order listed at the bottom of this page.

Scalars and Vectors

Physics is a mathematical science. The underlying concepts and principles have a mathematical basis. Throughout the course of our study of physics, we will encounter a variety of concepts which have a mathematical basis associated with them. While our emphasis will often be upon the conceptual nature of physics, we will give considerable and persistent attention to its mathematical aspect.

The motion of objects can be described by words. Even a person without a background in physics has a collection of words which can be used to describe moving objects. Words and phrases such as *going fast*, *stopped*, *slowing down*, *speeding up*, and *turning* provide a sufficient vocabulary for describing the motion of objects. In physics, we use these words and many more. We will be expanding upon this vocabulary list with words such as *distance*, *displacement*, *speed*, *velocity*, and *acceleration*. As we will soon see, these words are associated with mathematical quantities which have strict definitions. The mathematical quantities which are used to describe the motion of objects can be divided into two categories. The quantity is either a vector or a scalar. These two categories can be distinguished from one another by their distinct definitions:

- **Scalars** are quantities which are fully described by a magnitude (or numerical value) alone.
- **Vectors** are quantities which are fully described by both a magnitude and a direction.

The remainder of this lesson will focus on several examples of vector and scalar quantities (distance, displacement, speed, velocity, and acceleration). As you proceed through the lesson, give careful attention to the vector and scalar nature of each quantity. As we proceed through other units at The Physics Classroom Tutorial and become introduced to new mathematical quantities, the discussion will often begin by identifying the new quantity as being either a vector or a scalar.

Check Your Understanding

1. To test your understanding of this distinction, consider the following quantities listed below. Categorize each quantity as being either a vector or a scalar. Click the button to see the answer.

Quantity	Category
a. 5 m	
b. 30 m/sec, East	
c. 5 mi., North	
d. 20 degrees Celsius	
e. 256 bytes	
f. 4000 Calories	

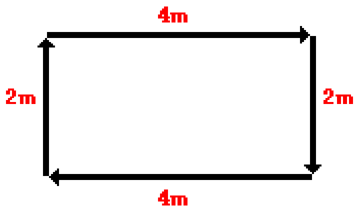
Lesson 1: Describing Motion with Words

Distance and Displacement

Distance and displacement are two quantities which may seem to mean the same thing yet have distinctly different definitions and meanings.

- **Distance** is a scalar quantity which refers to "how much ground an object has covered" during its motion.
- **Displacement** is a vector quantity which refers to "how far out of place an object is"; it is the object's overall change in position.

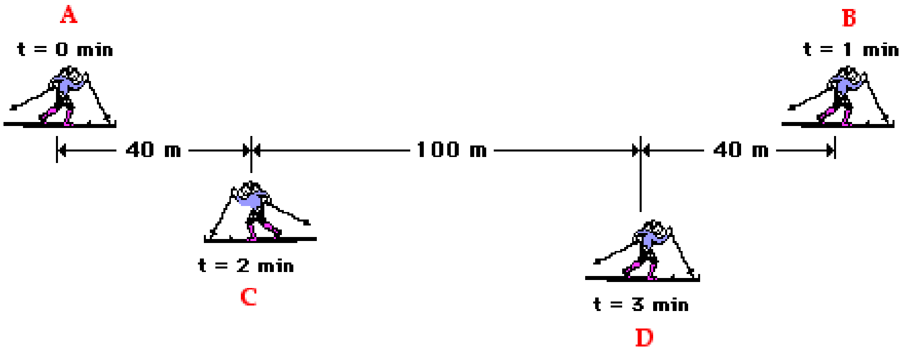
To test your understanding of this distinction, consider the motion depicted in the diagram below. A physics teacher walks 4 meters East, 2 meters South, 4 meters West, and finally 2 meters North.



Even though the physics teacher has walked a total distance of 12 meters, her displacement is 0 meters. During the course of her motion, she has "covered 12 meters of ground" (distance = 12 m). Yet when she is finished walking, she is not "out of place" - i.e., there is no displacement for her motion (displacement = 0 m). Displacement, being a vector quantity, must give attention to direction. The 4 meters east is *canceled* by the 4 meters west; and the 2 meters south is *canceled* by the 2 meters north. Vector quantities such as displacement are *direction aware*. Scalar quantities such as distance are ignorant of direction. In determining the overall distance traveled by the physics teachers, the various directions of motion can be ignored.

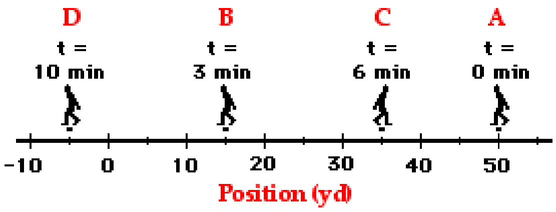
Now consider another example. The diagram below shows the position of a cross-country skier at various times. At each of the indicated times, the skier turns around and reverses the direction of travel. In other words, the skier moves from A to B to C to D.

Quick Quiz Use the diagram to determine the resulting displacement and the distance traveled by the skier during these three minutes. Then click the button to see the answer.



Now for a final example. A football coach paces back and forth along the sidelines. The diagram below shows several of coach's positions at various times. At each marked position, the coach makes a "U-turn" and moves in the opposite direction. In other words, the coach moves from position A to B to C to D.

Quick Quiz What is the coach's resulting displacement and distance of travel? Click the button to see the answer.



To understand the distinction between distance and displacement, you must know the definitions and also know that a vector quantity such as displacement is *direction-aware* and a scalar quantity such as distance is *ignorant of direction*. When an object changes its direction of motion, displacement takes this direction change into account; heading the opposite direction effectively begins to *cancel* whatever displacement there once was.

Check Your Understanding

1. What is the displacement of the cross-country team if they begin at the school, run 10 miles and finish back at the school?

2. What is the distance and the displacement of the race car drivers in the Indy 500?

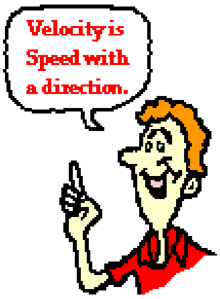
Lesson 1: Describing Motion with Words

Speed and Velocity

Just as distance and displacement have distinctly different meanings (despite their similarities), so do speed and velocity. **Speed** is a scalar quantity which refers to "how fast an object is moving." Speed can be thought of as the rate at which an object covers distance. A fast-moving object has a high speed and covers a relatively large distance in a short amount of time. A slow-moving object has a low speed and covers a relatively small amount of distance in a short amount of time. An object with no movement at all has a zero speed.

Velocity is a vector quantity which refers to "the rate at which an object changes its position." Imagine a person moving rapidly - one step forward and one step back - always returning to the original starting position. While this might result in a frenzy of activity, it would result in a zero velocity. Because the person always returns to the original position, the motion would never result in a change in position. Since velocity is defined as the rate at which the position changes, this motion results in zero velocity. If a person in motion wishes to maximize their velocity, then that person must make every effort to maximize the amount that they are displaced from their original position. Every step must go into moving that person further from where he or she started. For certain, the person should never change directions and begin to return to the starting position.

Velocity is a vector quantity. As such, velocity is *direction aware*. When evaluating the velocity of an object, one must keep track of direction. It would not be enough to say that an object has a velocity of 55 mi/hr. One must include direction information in order to fully describe the velocity of the object. For instance, you must describe an object's velocity as being 55 mi/hr, **east**. This is one of the essential differences between speed and velocity. Speed is a scalar quantity and does not *keep track of direction*; velocity is a vector quantity and is *direction aware*.



The task of describing the direction of the velocity vector is easy. The direction of the velocity vector is simply the same as the direction which an object is moving. It would not matter whether the object is speeding up or slowing down. If an object is moving rightwards, then its velocity is described as being rightwards. If an object is moving downwards, then its velocity is described as being downwards. So an airplane moving towards the west with a speed of 300 mi/hr has a velocity of 300 mi/hr, west. Note that speed has no direction (it is a scalar) and velocity at any instant is simply the speed with a direction.

As an object moves, it often undergoes changes in speed. For example, during an average trip to school, there are many changes in speed. Rather than the speed-o-meter maintaining a steady reading, the needle constantly moves up and down to reflect the stopping and starting and the accelerating and decelerating. One instant, the car may be moving at 50 mi/hr and another instant, it might be stopped (i.e., 0 mi/hr). Yet during the trip to school the person might average 32 mi/hr. The average speed during an entire motion can be thought of as the average of all speedometer readings. If the speedometer readings could be collected at 1-second intervals (or 0.1-second intervals or ...) and then averaged together, the average speed could be determined. Now that would be a lot of work. And fortunately, there is a shortcut. Read on.

Calculating Average Speed and Average Velocity

The average speed during the course of a motion is often computed using the following formula:

$$\text{Average Speed} = \frac{\text{Distance Traveled}}{\text{Time of Travel}}$$

Meanwhile, the average velocity is often computed using the equation

$$\text{Average Velocity} = \frac{\Delta\,\text{position}}{\text{time}} = \frac{\text{displacement}}{\text{time}}$$

Let's begin implementing our understanding of these formulas with the following problem:

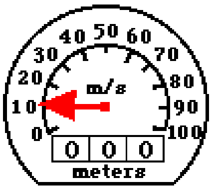
While on vacation, Lisa Carr traveled a total distance of 440 miles. Her trip took 8 hours. What was her average speed?

To compute her average speed, we simply divide the distance of travel by the time of travel.

$$v = \frac{d}{t} = \frac{440\text{ mi}}{8\text{ hr}} = 55\text{ mi/hr}$$

That was easy! Lisa Carr averaged a speed of 55 miles per hour. She may not have been traveling at a constant speed of 55 mi/hr. She undoubtedly, was stopped at some instant in time (perhaps for a bathroom break or for lunch) and she probably was going 65 mi/hr at other instants in time. Yet, she averaged a speed of 55 miles per hour. The above formula represents a shortcut method of determining the average speed of an object.

Average Speed versus Instantaneous Speed



Since a moving object often changes its speed during its motion, it is common to distinguish between the average speed and the instantaneous speed. The distinction is as follows.

Instantaneous Speed - the speed at any given instant in time.

Average Speed - the average of all instantaneous speeds; found simply by a distance/time ratio.

You might think of the instantaneous speed as the speed which the speedometer reads at any given instant in time and the average speed as the average of all the speedometer readings during the course of the trip. Since the task of averaging speedometer readings would be quite complicated (and maybe even dangerous), the average speed is more commonly calculated as the distance/time ratio.

Moving objects don't always travel with erratic and changing speeds. Occasionally, an object will move at a steady rate with a constant speed. That is, the object will cover the same distance every regular interval of time. For instance, a cross-country runner might be running with a constant speed of 6 m/s in a straight line for several minutes. If her speed is constant, then the distance traveled every second is the same. The runner would cover a distance of 6 meters every second. If we could measure her position (distance from an arbitrary starting point) each second, then we would note that the position would be changing by 6 meters each second. This would be in stark contrast to an object which is changing its speed. An object with a changing speed would be moving a different distance each second. The data tables below depict objects with constant and changing speed.

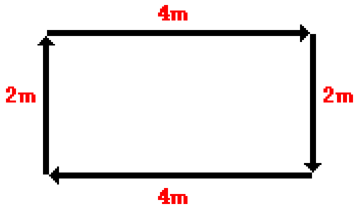
An object moving with
a constant speed of 6 m/s

Time (s)	Position (m)
0	0
1	6
2	12
3	18
4	24

An object moving with
a changing speed

Time (s)	Position (m)
0	0
1	1
2	4
3	9
4	16

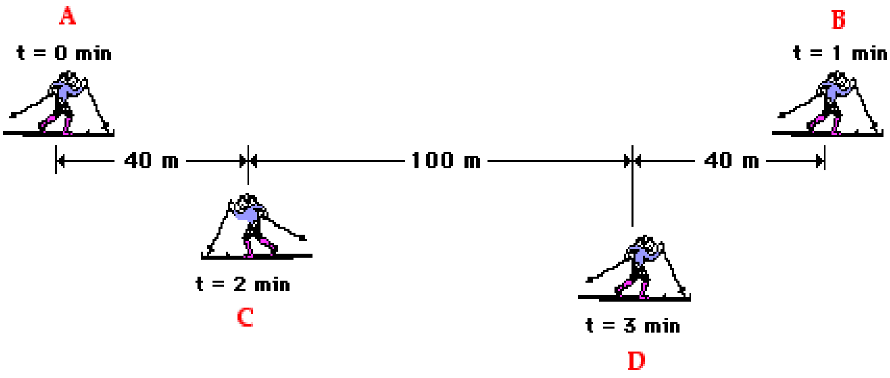
Now let's consider the motion of that physics teacher again. The physics teacher walks 4 meters East, 2 meters South, 4 meters West, and finally 2 meters North. The entire motion lasted for 24 seconds. Determine the average speed and the average velocity.



The physics teacher walked a distance of 12 meters in 24 seconds; thus, her average speed was 0.50 m/s. However, since her displacement is 0 meters, her average velocity is 0 m/s. Remember that the displacement refers to the change in position and the velocity is based upon this position change. In this case of the teacher's motion, there is a position change of 0 meters and thus an average velocity of 0 m/s.

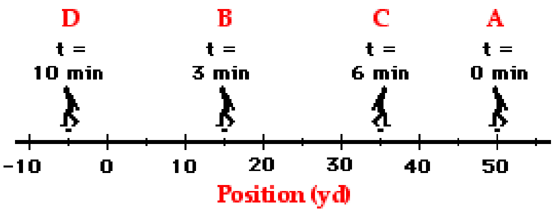
Here is another example similar to what was seen before in the discussion of distance and displacement. The diagram below shows the position of a cross-country skier at various times. At each of the indicated times, the skier turns around and reverses the direction of travel. In other words, the skier moves from A to B to C to D.

Quick Quiz Use the diagram to determine the average speed and the average velocity of the skier during these three minutes. When finished, click the button to view the answer.



And now for the last example. A football coach paces back and forth along the sidelines. The diagram below shows several of coach's positions at various times. At each marked position, the coach makes a "U-turn" and moves in the opposite direction. In other words, the coach moves from position A to B to C to D.

Quick Quiz What is the coach's average speed and average velocity? When finished, click the button to view the answer.



In conclusion, speed and velocity are kinematic quantities which have distinctly different definitions. Speed, being a scalar quantity, is the rate at which an object covers distance. The average speed is the distance (a scalar quantity) per time ratio. Speed is *ignorant of direction*. On the other hand, velocity is a vector quantity; it is *direction-aware*. Velocity is the rate at which the position changes. The average velocity is the displacement or position change (a vector quantity) per time ratio.

Average vs. Instantaneous Speed

A GIF Animation

During a typical trip to school, your car will undergo a series of changes in its speed. If you were to inspect the speedometer readings at regular intervals, you would notice that it changes often. The speedometer of a car reveals information about the instantaneous speed of your car. It shows your speed at a particular instant in time.

The instantaneous speed of an object is not to be confused with the average speed. Average speed is a measure of the distance traveled in a given period of time; it is sometimes referred to as the distance *per* time ratio. Suppose that during your trip to school, you traveled a distance of 5 miles and the trip lasted 0.2 hours (12 minutes). The average speed of your car could be determined as

$$\text{Ave. Speed} = \frac{5\ \text{miles}}{0.2\ \text{hours}} = 25\ \text{miles/hour}$$

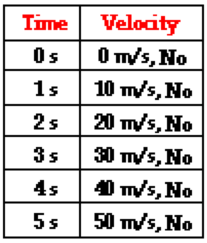
On the average, your car was moving with a speed of 25 miles per hour. During your trip, there may have been times that you were stopped and other times that your speedometer was reading 50 miles per hour. Yet, on average, you were moving with a speed of 25 miles per hour.

Lesson 1: Describing Motion with Words

Acceleration

The final mathematical quantity discussed in Lesson 1 is acceleration. An often confused quantity, acceleration has a meaning much different than the meaning associated with it by sports announcers and other individuals. The definition of acceleration is:

Acceleration is a vector quantity which is defined as the rate at which an object changes its velocity. An object is accelerating if it is changing its velocity.



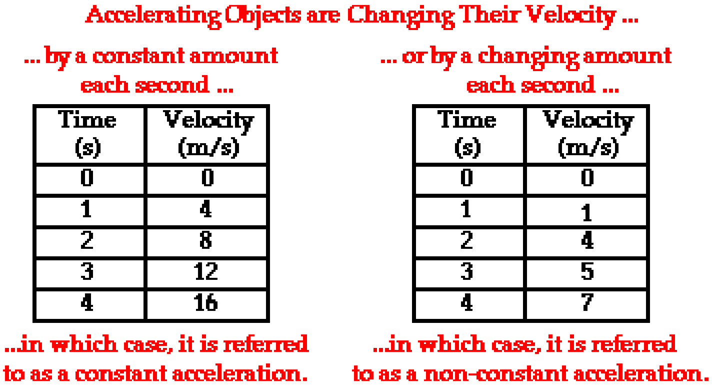
Time	Velocity
0 s	0 m/s, No
1 s	10 m/s, No
2 s	20 m/s, No
3 s	30 m/s, No
4 s	40 m/s, No
5 s	50 m/s, No

Sports announcers will occasionally say that a person is accelerating if he/she is moving fast. Yet acceleration has nothing to do with going fast. A person can be moving very fast and still not be accelerating. Acceleration has to do with changing how fast an object is moving. If an object is not changing its velocity, then the object is not accelerating. The data at the right are representative of a northward-moving accelerating object. The velocity is changing over the course of time. In fact, the velocity is changing by a constant amount - 10 m/s - in each second of time. Anytime an object's velocity is changing, the object is said to be accelerating; it has an acceleration.

Animation

The Meaning of Constant Acceleration

Sometimes an accelerating object will change its velocity by the same amount each second. As mentioned in the previous paragraph, the data table above show an object changing its velocity by 10 m/s in each consecutive second. This is referred to as a **constant acceleration** since the velocity is changing by a constant amount each second. An object with a constant acceleration should not be confused with an object with a constant velocity. Don't be fooled! If an object is changing its velocity -whether by a constant amount or a varying amount - then it is an accelerating object. And an object with a constant velocity is not accelerating. The data tables below depict motions of objects with a constant acceleration and a changing acceleration. Note that each object has a changing velocity.



Accelerating Objects are Changing Their Velocity ...

... by a constant amount each second ...

Time (s)	Velocity (m/s)
0	0
1	4
2	8
3	12
4	16

...in which case, it is referred to as a constant acceleration.

... or by a changing amount each second ...

Time (s)	Velocity (m/s)
0	0
1	1
2	4
3	5
4	7

...in which case, it is referred to as a non-constant acceleration.

Since accelerating objects are constantly changing their velocity, one can say that the distance traveled/time is not a constant value. A falling object for instance usually accelerates as it falls. If we were to observe the motion of a **free-falling object** (free fall motion will be discussed in detail later), we would observe that the object averages a velocity of approximately 5 m/s in the first second, approximately 15 m/s in the second second, approximately 25 m/s in the third second, approximately 35 m/s in the fourth second, etc. Our free-falling object would be constantly accelerating. Given these average velocity values during each consecutive 1-second time interval, we could say that the object would fall 5 meters in the first second, 15 meters in the second second (for a total distance of 20 meters), 25 meters in the third second (for a total distance of 45 meters), 35 meters in the fourth second (for a total distance of 80 meters after four seconds). These numbers are summarized in the table below.

Time Interval	**Ave. Velocity During Time Interval**	**Distance Traveled During Time Interval**	**Total Distance Traveled from 0 s to End of Time Interval**
0 - 1 s	~ 5 m/s	~ 5 m	~ 5 m
1 -2 s	~ 15 m/s	~ 15 m	~ 20 m
2 - 3 s	~ 25 m/s	~ 25 m	~ 45 m
3 - 4 s	~ 35 m/s	~ 35 m	~ 80 m

Note: The ~ symbol as used here means approximately.

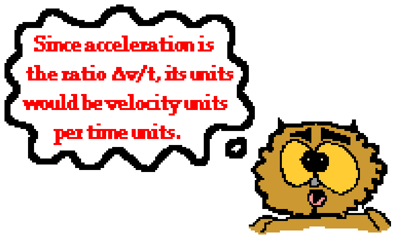
This discussion illustrates that a free-falling object which is accelerating at a constant rate will cover different distances in each consecutive second. Further analysis of the first and last columns of the data above reveal that there is a square relationship between the total distance traveled and the time of travel for an object starting from rest and moving with a constant acceleration. The total distance traveled is directly proportional to the square of the time. As such, if an object travels for twice the time, it will cover four times (2^2) the distance; the total distance traveled after two seconds is four times the total distance traveled after one second. If an object travels for three times the time, then it will cover nine times (3^2) the distance; the distance traveled after three seconds is nine times the distance traveled after one second. Finally, if an object travels for four times the time, then it will cover 16 times (4^2) the distance; the distance traveled after four seconds is 16 times the distance traveled after one second. For objects with a constant acceleration, the distance of travel is directly proportional to the square of the time of travel.

Calculating the Average Acceleration

The average acceleration (**a**) of any object over a given interval of time (**t**) can be calculated using the equation

$$\text{Ave. acceleration} = \frac{\Delta\,\text{velocity}}{\text{time}} = \frac{v_f - v_i}{t}$$

This equation can be used to calculate the acceleration of the object whose motion is depicted by the velocity-time data table above. The velocity-time data in the table shows that the object has an acceleration of 10 m/s/s. The calculation is shown below.



$$a = \frac{v_f - v_i}{t} = \frac{50\text{ m/s} - 0\text{ m/s}}{5\text{ s}} = \frac{10\text{ m/s}}{1\text{ s}}$$

Acceleration values are expressed in units of velocity/time. Typical acceleration units include the following:

m/s/s
mi/hr/s
km/hr/s
m/s^2

These units may seem a little awkward to a beginning physics student. Yet they are very reasonable units when you begin to consider the definition and equation for acceleration. The reason for the units becomes obvious upon examination of the acceleration equation.

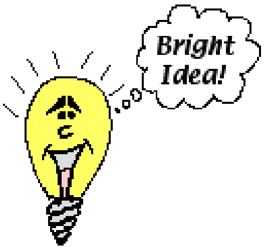
$$a = \frac{\Delta \text{velocity}}{\text{time}}$$

Since acceleration is a velocity change over a time, the units on acceleration are velocity units divided by time units - thus (m/s)/s or (mi/hr)/s. The (m/s)/s unit can be mathematically simplified to m/s^2.

The Direction of the Acceleration Vector

Since acceleration is a vector quantity, it has a direction associated with it. The direction of the acceleration vector depends on two things:

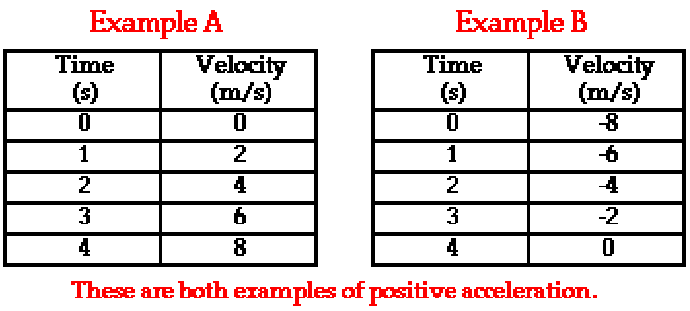
- whether the object is speeding up or slowing down
- whether the object is moving in the + or - direction



The general RULE OF THUMB is:

If an object is slowing down, then its acceleration is in the opposite direction of its motion.

This RULE OF THUMB can be applied to determine whether the sign of the acceleration of an object is positive or negative, right or left, up or down, etc. Consider the two data tables below. In each case, the acceleration of the object is in the *positive* direction. In Example A, the object is moving in the *positive* direction (i.e., has a *positive* velocity) and is speeding up. When an object is speeding up, the acceleration is in the same direction as the velocity. Thus, this object has a **positive acceleration**. In Example B, the object is moving in the *negative* direction (i.e., has a negative velocity) and is slowing down. According to our RULE OF THUMB, when an object is slowing down, the acceleration is in the opposite direction as the velocity. Thus, this object also has a **positive acceleration**.



Example A

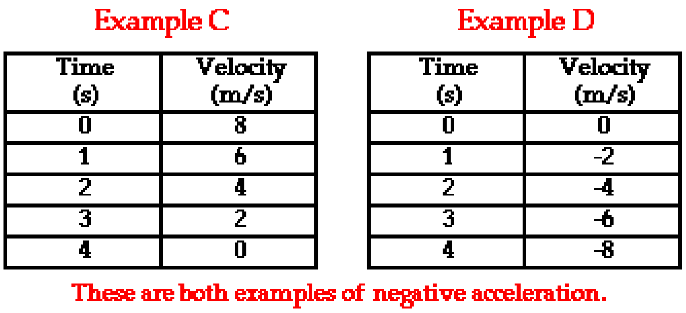
Time (s)	Velocity (m/s)
0	0
1	2
2	4
3	6
4	8

Example B

Time (s)	Velocity (m/s)
0	-8
1	-6
2	-4
3	-2
4	0

These are both examples of positive acceleration.

This same RULE OF THUMB can be applied to the motion of the objects represented in the two data data tables below. In each case, the acceleration of the object is in the *negative* direction. In Example C, the object is moving in the *positive* direction (i.e., has a *positive* velocity) and is slowing down. According to our RULE OF THUMB, when an object is slowing down, the acceleration is in the apposite direction as the velocity. Thus, this object has a **negative acceleration**. In Example D, the object is moving in the *negative* direction (i.e., has a *negative* velocity) and is speeding up. When an object is speeding up, the acceleration is in the same direction as the velocity. Thus, this object also has a **negative acceleration**.



Example C

Time (s)	Velocity (m/s)
0	8
1	6
2	4
3	2
4	0

Example D

Time (s)	Velocity (m/s)
0	0
1	-2
2	-4
3	-6
4	-8

These are both examples of negative acceleration.

▶ Animation

Observe the use of positive and negative as used in the discussion above (Examples A - D). In physics, the use of positive and negative always has a physical meaning. It is more than a mere mathematical symbol. As used here to describe the velocity and the acceleration of a moving object, positive and negative describe a direction. Both velocity and acceleration are vector quantities and a full description of the quantity demands the use of a directional adjective. North, south, east, west, right, left, up and down are all directional adjectives. Physics often borrows from mathematics and uses the + and - symbols as directional adjectives. Consistent with the mathematical convention used on number lines and graphs, positive often means to the right or up and negative often means to the left or down. So to say that an object has a negative acceleration as in Examples C and D is to simply say that its acceleration is to the left or down (or in whatever direction has been defined as negative). Negative accelerations do not refer acceleration values which are less than 0. An acceleration of -2 m/s/s is an acceleration with a magnitude of 2 m/s/s which is directed in the negative direction.

Check Your Understanding

To test your understanding of the concept of acceleration, consider the following problems and the corresponding solutions. Use the equation for acceleration to determine the acceleration for the following two motions.

Practice A

Time (s)	Velocity (m/s)
0	0
1	2
2	4
3	6
4	8

Practice B

Time (s)	Velocity (m/s)
0	8
1	6
2	4
3	2
4	0