4.3 Acceleration

Constant speed is easy to understand. However, almost nothing moves with constant speed for long. When a driver steps on the gas pedal, the speed of the car increases. When the driver brakes, the speed decreases. Even while using cruise control, the speed goes up and down as the car's engine adjusts for hills. Another important concept in physics is acceleration. Acceleration is how we describe changes in speed or velocity.

VOCABULARY

acceleration - the rate at which velocity changes.

An example of acceleration

Definition of acceleration What happens if you coast down a long hill on a bicycle? At the top of the hill, you move slowly. As you go down the hill, you move faster and faster—you accelerate. **Acceleration** is the rate at which your speed (or velocity) changes. If your speed increases by 1 meter per second (m/s) each second, then your acceleration is 1 m/s per second.

Time (s)	Speed (m/s)
1	1
2	2
3	3
4	4
5	5

Acceleration = 1 m/s each second

Time (s)	Speed (m/s)
1	2
2	4
3	6
4	8
5	10

Acceleration = 2 m/s each second

Acceleration can change Your acceleration depends on the steepness of the hill. If the hill is a gradual incline, you have a small acceleration, such as 1 m/s per second. If the hill is steeper, your acceleration is greater, perhaps 2 m/s per second.

Acceleration on a speed vs. time graph Acceleration is easy to spot on a speed vs. time graph. If the speed changes over time then there is acceleration. Acceleration causes the line to slope up on a speed vs. time graph (Figure 4.10). The graph on the top shows constant speed. There is zero acceleration at constant speed because the speed does not change.

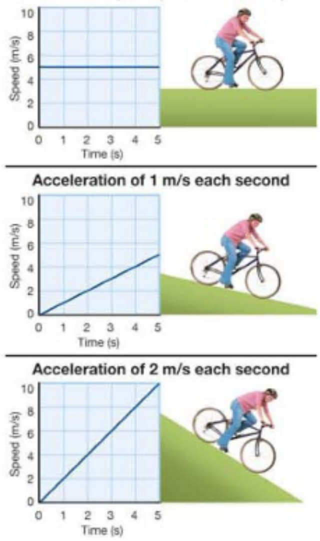


Figure 4.10: *Speed vs. time graphs showing constant speed (top) and acceleration (middle and bottom).*

Speed and acceleration

The difference between speed and acceleration Speed and acceleration are not the same thing. You can be moving in one direction (nonzero speed) and have no acceleration (think cruise control). But if the brakes are applied and the car slows down, it is accelerating because the speed is now changing (faster to slower).

Example: Acceleration in cars Acceleration describes how quickly speed changes. More precisely, acceleration is the change in velocity divided by the change in time. For example, suppose a powerful sports car changes its speed from 0 to 60 mph in 5 seconds. In English units, the acceleration is 60 mph ÷ 5 seconds = 12 mph/s. In SI units, 60 mph is about the same as 100 km/h. The acceleration is 100 km/h ÷ 5 seconds, or 20 km/h/s (Figure 4.11). A formula you can use to calculate acceleration is shown below.

ACCELERATION

$$a = \frac{v_{finish} - v_{start}}{t}$$

Acceleration (m/s²) = Change in velocity (m/s) / Time (s)

Acceleration units To calculate acceleration, you divide the change in velocity by the amount of time it takes for the change to happen. If the change in speed is in kilometers per hour, and the time is in seconds, then the acceleration is in km/h/s or *kilometers per hour per second*. An acceleration of 20 km/h/s means that the speed increases by 20 km/h *every* second.

What is a meter per second squared? The time units for acceleration are often written as seconds squared or s^2. For example, acceleration might be 50 meters per second squared or 50 m/s^2. The steps in Figure 4.12 show how to simplify the fraction m/s/s to get m/s^2. Saying *seconds squared* is just a math-shorthand way of speaking. It is better to think about acceleration in units of speed change per second (that is, meters per second *per second*).

Sports car

Speed goes from 0 to 100 km/h in 5 seconds

$$\text{Acceleration} = \frac{\text{Change in speed}}{\text{Time}}$$

$$= \frac{60 \text{ mph}}{5 \text{ seconds}}$$

$$= \frac{100 \text{ km/h} - 0 \text{ km/h}}{5 \text{ s}}$$

= 20 km/h per second

= 20 km/h/s

Figure 4.11: *The acceleration of a sports car.*

Plug in values:

$$\frac{50 \text{ m/s}}{\text{s}}$$

Clear the compound fraction:

$$\frac{50 \text{ m}}{\text{s}} \times \frac{1}{\text{s}} = \frac{50 \text{ m}}{\text{s} \times \text{s}}$$

Find units:

$$50 \frac{\text{m}}{\text{s}^2}$$

Figure 4.12: *How do we get m/s²?*

Solving Problems: Acceleration

A sailboat moves at 1 m/s. A strong wind increases its speed to 4 m/s in 3 seconds (Figure 4.13). Calculate the acceleration.

1. Looking for: You are asked for the acceleration in m/s^2.

2. Given: You are given the initial speed in m/s (v_1), final speed in m/s (v_2), and the time in seconds.

3. Relationships: Use the formula for acceleration: $a = \frac{v_2 - v_1}{t}$

4. Solution:

$$a = \frac{4\ \text{m/s} - 1\ \text{m/s}}{3\ \text{s}} = \frac{3\ \text{m/s}}{3\ \text{s}} = 1\ \text{m/s}^2$$

Your turn...

a. Calculate the acceleration of an airplane that starts at rest and reaches a speed of 45 m/s in 9 seconds.

b. Calculate the acceleration of a car that slows from 50 m/s to 30 m/s in 10 seconds.

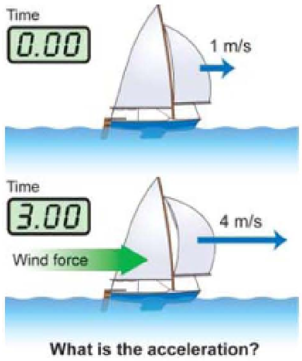


Figure 4.13: *An acceleration example.*

SOLVE FIRST LOOK LATER

a. $5\ m/s^2$

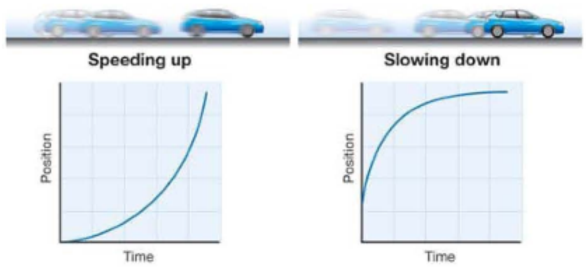
b. $-2\ m/s^2$

Acceleration on motion graphs

Acceleration on a speed vs. time graph A speed vs. time graph is useful for showing how the speed of a moving object changes over time. Think about a car moving on a straight road. If the line on the graph is horizontal, then the car is moving at a constant speed (top of Figure 4.14). The upward slope in the middle graph shows increasing speed. The downward slope of the bottom graph tells you the speed is decreasing. The word *acceleration* is used for any change in velocity, either an increase or a decrease.

Positive and negative acceleration Acceleration can be positive or negative. Positive acceleration in one direction adds more speed each second. Things get faster. Negative acceleration in one direction subtracts some speed each second, Things get slower. People sometimes use the word *deceleration* to describe slowing down.

Acceleration on a position vs. time graph The position vs. time graph is a *curve* when there is acceleration. Think about a car with a speed that increases each second. Because it is speeding up, it covers more distance each second. The position vs. time graph gets steeper each second. The opposite happens when a car is slowing down. The speed decreases so the car covers less distance each second. The position vs. time graph gets shallower with time, becoming horizontal when the car is stopped.



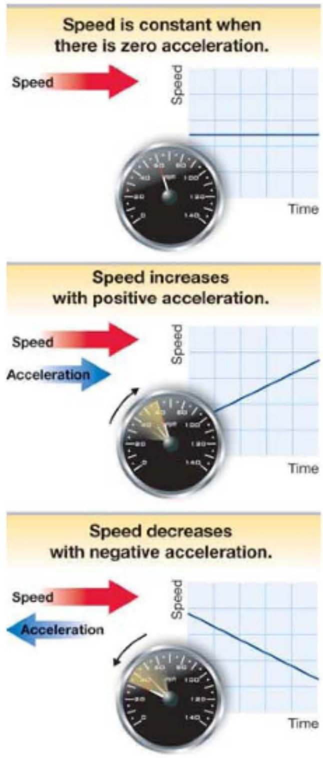


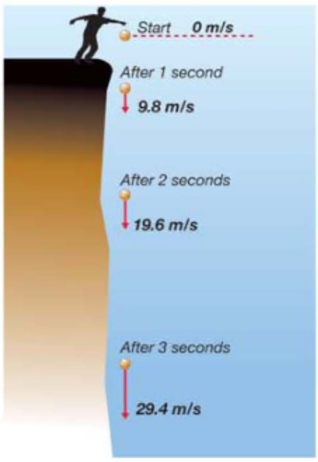
Figure 4.14: *Three examples of motion showing constant speed (top) and acceleration (middle, bottom).*

Free fall

The definition of free fall

An object is in **free fall** if it is accelerating due to the force of gravity and no other forces are acting on it. A dropped ball is almost in free fall from the instant it leaves your hand until it reaches the ground. The "almost" is because there is a little bit of air friction that *does* make an additional force on the ball. A ball thrown upward is also in free fall after it leaves your hand. Even going up, the ball is in free fall because gravity is the only significant force acting on it.

The acceleration due to gravity



If air friction is ignored, objects in free fall on Earth accelerate downward, increasing their speed by 9.8 m/s every second. The value 9.8 m/s^2 is called the **acceleration due to gravity**. The lowercase letter *g* is used to represent its value. When you see the lowercase letter *g* in a physics question, you can substitute the value 9.8 m/s^2.

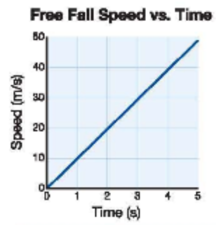
Constant acceleration

The speed vs. time graph in Figure 4.15 is for a ball in free fall. Because the graph is a straight line, we know the speed increases by the same amount each second. This means the ball has a *constant acceleration*. Don't confuse constant speed with constant acceleration! Constant acceleration means an object's *speed* changes by the same amount each second.

VOCABULARY

free fall - accelerated motion that happens when an object falls with only the force of gravity acting on it.

acceleration due to gravity - the value of 9.8 m/s^2, which is the acceleration in free fall at Earth's surface, usually represented by the lowercase letter *g*.



Time (s)	Speed (m/s)
0	0
1	9.8
2	19.6
3	29.4
4	39.2
5	49.0

Figure 4.15: *A dropped ball increases its speed by 9.8 m/s each second, so its constant acceleration is 9.8 m/s^2.*

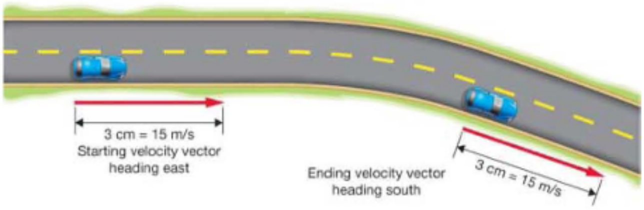
Acceleration and direction

A change in direction is acceleration

If an object's acceleration is *zero*, the object can only move at a constant speed *in a straight line* (or be stopped). A car driving around a curve at a constant speed is accelerating (in the "physics sense") because its direction is changing (Figure 4.16). Acceleration occurs whenever there is a change in speed, direction, or both.

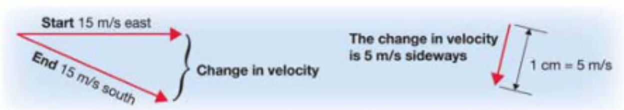
***What change in direction* means**

What do we mean by *change in direction*? Consider a car traveling east. Its velocity is drawn as an arrow pointing east. Now suppose the car turns southward a little. Its velocity vector has a new direction.



Drawing vectors

When drawing velocity vectors, the length represents the speed. A 2 cm vector stands for 10 m/s (22 mph). A 4 cm vector is 20 m/s, and so on. At this *scale*, each centimeter stands for 5 m/s. You can now find the change in velocity by measuring the length of the vector that goes from the old velocity vector to the new one.



Turns are caused by sideways accelerations

The small red arrow in the graphic above represents the difference in velocity before and after the turn. The change vector is 1 centimeter long, which equals 5 m/s. Notice the speed is the same before and after the turn! However, the change in direction is a *sideways* change of velocity. This change is caused by a *sideways acceleration*.

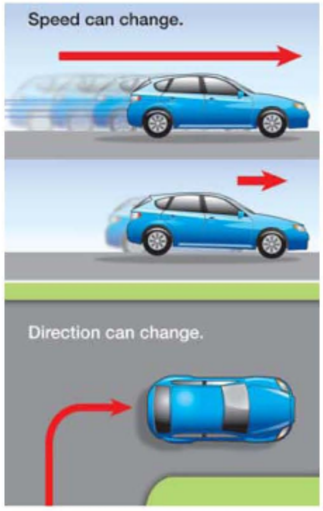


Figure 4.16: *A car can change its velocity by speeding up, slowing down, or turning. The car is accelerating in each of these cases.*

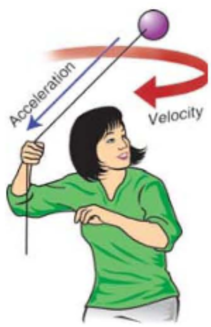
Curved motion

Acceleration and curved motion Like velocity, acceleration has direction and is a vector. Curved motion is caused by sideways accelerations. Sideways accelerations cause velocity to change direction, which results in turning. Turns create curved motion.

An example of curved motion As an example of curved motion, imagine a soccer ball kicked into the air. The ball starts with a velocity vector at an upward angle (Figure 4.17). The acceleration of gravity bends the trajectory more toward the ground during each second the ball is in the air. Therefore, gravity accelerates the ball downward as it moves through the air. Near the end of the motion, the ball's velocity vector is angled down toward the ground. The path of the ball makes a bowl-shaped curve called a *parabola*.

Projectiles A soccer ball is an example of a **projectile**. A projectile is an object moving under the influence of only gravity. The action of gravity is to constantly turn the direction of the velocity vector more and more downward. Flying objects such as airplanes and birds are *not* projectiles, because they are affected by forces generated from their own power.

Circular motion



Circular motion is another type of curved motion. An object in circular motion has a velocity vector that constantly changes direction. Imagine whirling a ball around your head on a string. You have to pull the string to keep the ball moving in a circle. Your pull accelerates the ball toward you. That acceleration is what bends the ball's velocity into a circle with you at the center. Circular motion always has an acceleration that points toward the center of the circle. In fact, the direction of the acceleration changes constantly so it *always* stays pointed toward the center of the circle.

VOCABULARY

projectile - an object moving through space and affected only by gravity.

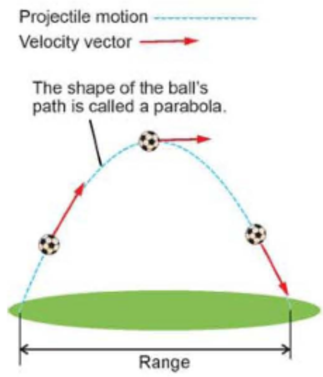
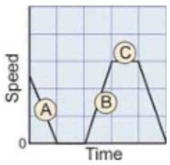


Figure 4.17: *A soccer ball in the air is a projectile. The path of the ball is a bowl-shaped curve called a parabola.*

Section 4.3 Review

1. Nearly all physics problems will use the unit m/s^2 for acceleration. Explain why the seconds are squared. Why isn't the unit given as m/s, as it is for speed?
2. Suppose you are moving forward with a velocity of 10 m/s. What happens to your speed if you have a *negative* acceleration? Do you speed up or slow down?
3. A rabbit starts from a resting position and is moving at 6 m/s after 3 seconds. What is the acceleration of the rabbit? (Figure 4.18)
4. You are running a race and you speed up from 3 m/s to 5 m/s in 4 seconds.
   a. What is your change in speed?
   b. What is your acceleration?
5. Does a car accelerate when it goes around a corner at a constant speed? Explain your answer.
6. A sailboat increases its speed from 1 m/s to 4 m/s in 3 seconds. What will the speed of the sailboat be at 6 seconds if the acceleration stays the same? (Figure 4.19)
7. The graph at the right shows the speed of a person riding a bicycle through a city. Which point (A, B, or C) on the graph is a place where the bicycle has speed but no acceleration? How do you know?



8. What happens to the speed of an object that is dropped in free fall?
9. A ball is in free fall after being dropped. What will the speed of the ball be after 2 seconds of free fall?
10. What happens when velocity and acceleration are at right angles to each other? What kind of motion occurs?
11. The Earth moves in a nearly perfect circle around the Sun. Assume the speed stays constant. Is the Earth accelerating?

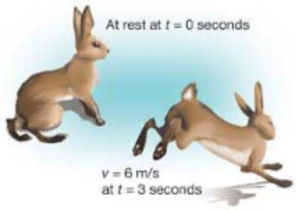


Figure 4.18: *Question 3.*

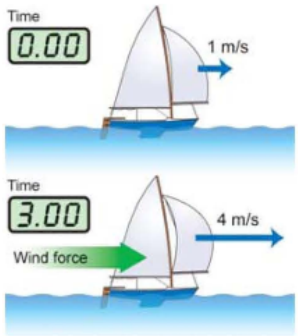


Figure 4.19: *Question 6.*