# 3.3 Acceleration

Constant speed is easy to understand. However, almost nothing moves with constant speed for long. When the 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.

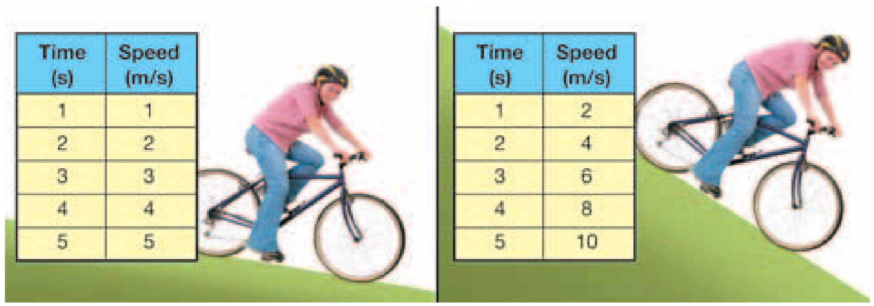
**VOCABULARY**

**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 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 |

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

**Steeper hills**

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 each second. If the hill is steeper, your acceleration is greater, perhaps 2 m/s per second. On the gradual hill, your speed increases by 1 m/s every second. On the steeper hill, it increases by 2 m/s every 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 3.16). The graph on the top shows constant speed. There is zero acceleration at constant speed because the speed does not change.

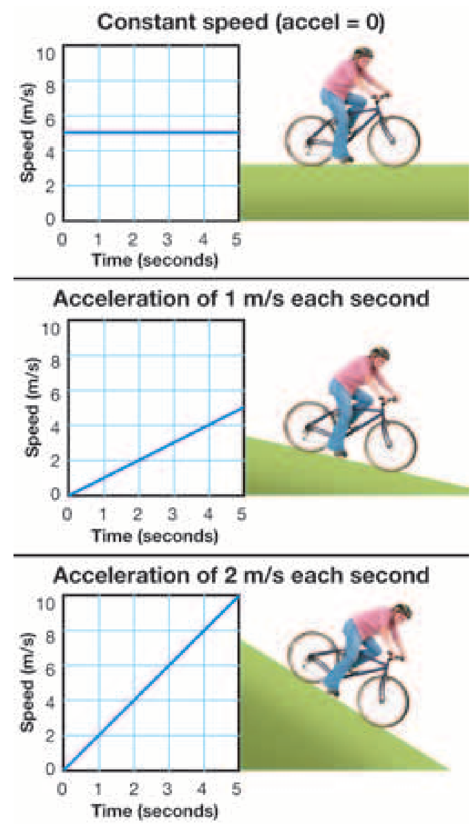



**Figure 3.16:** *Speed vs. time graphs showing constant speed (top) and acceleration (middle and bottom).*

## Speed and acceleration

**The difference between speed and acceleration**

Speed and acceleration are not the same thing. You can be moving (non-zero speed) and have no acceleration (think *cruise control*). You can also be accelerating and not moving! Think about dropping the car down the ramp. In the instant you release it, the car has zero speed because it is not moving yet. But, it is *accelerating* because its speed is already changing.

**Example: acceleration in cars and trucks**

Acceleration is the change in speed divided by the change in time. Acceleration describes how quickly speed changes. High acceleration means speed changes rapidly. A powerful sports car can change its speed from 0 to 60 mph in 5 seconds (Figure 3.17). The car has an acceleration of 12 mph/s. Low acceleration means speed changes slowly. A loaded garbage truck takes 15 seconds to get up to a speed of 60 mph. It has an acceleration of 4 mph/s.

**Acceleration in metric units**

To calculate acceleration, you divide the change in speed by the amount of time it takes for the change to happen. If the change in speed is in meters per second, and the time is in seconds, then the acceleration is in m/s/s or *meters per second per second*. An acceleration of 50 m/s/s means that the speed increases by 50 m/s *every second*.

**What does "units of seconds *squared*" mean?**

An acceleration in m/s/s is often written as m/s$^2$ (meters per second squared). The steps below show you how to simplify the fraction m/s/s to get m/s$^2$. Saying *seconds squared* is just a math-shorthand way of talking. It is better to think about acceleration in units of speed change per second (that is, meters per second *per second*).

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

***How we get units of m/s²***

| Plug in values | | Clear the compound fraction | | Final units |
|---|---|---|---|---|
| $\dfrac{50\,\frac{m}{s}}{s}$ | $=$ | $50\,\frac{m}{s} \times \frac{1}{s} = 50\,\frac{m}{s \times s}$ | $=$ | $50\,\frac{m}{s^2}$ |

**ACCELERATION**

$$\underset{\text{Acceleration (m/s}^2)}{a} = \frac{\overbrace{v_{finish} - v_{start}}^{\text{Change in speed (m/s)}}}{\underbrace{t}_{\text{Time (s)}}}$$

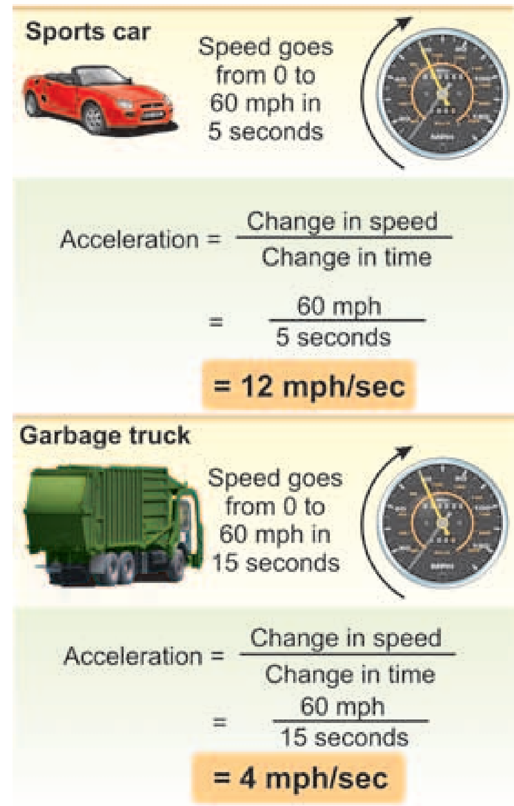



**Figure 3.17:** *The acceleration of a sports car and a garbage truck.*

## Acceleration on motion graphs

**Acceleration on a speed vs. time graph**

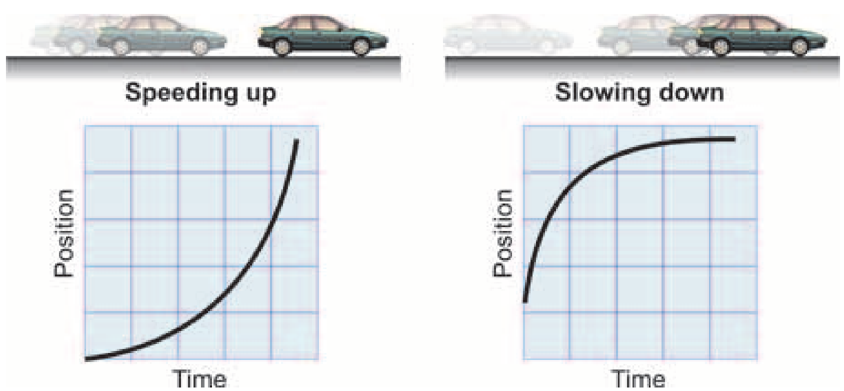
A speed vs. time graph is useful for showing how the speed of a moving object changes over time. Think about a car moving on a straight road. If the line on the graph is horizontal, then the car is moving at a constant speed (top of Figure 3.18). The upward slope in the middle graph shows increasing speed. The downward slope of the bottom graph tells you the speed is decreasing. The word "acceleration" is used for any change in speed, up or down.

**Positive and negative acceleration**

Like velocity, acceleration can be positive or negative. Positive acceleration adds more speed each second. Things get faster. Negative acceleration 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 that is accelerating (speeding up). Its speed increases each second. That means 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 flat when the car is stopped.



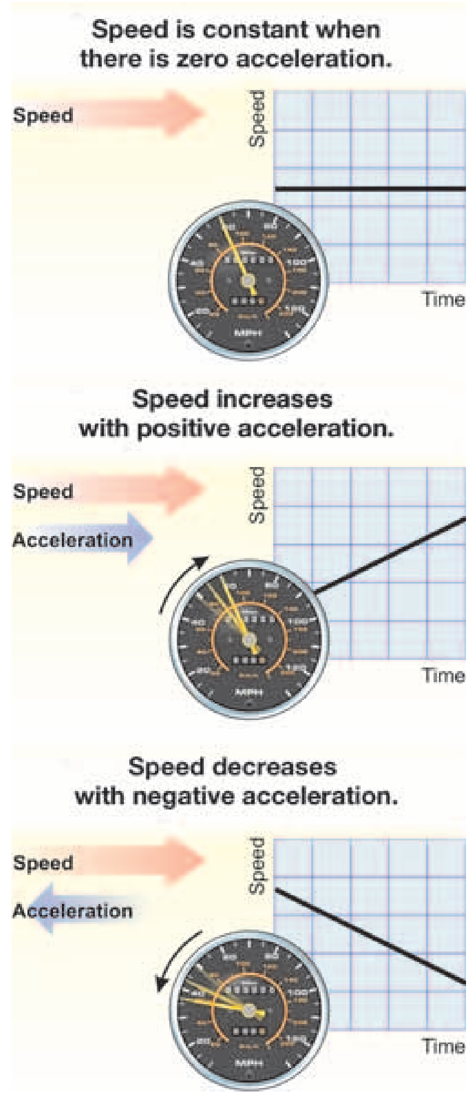




**Figure 3.18:** *Three examples of motion showing constant speed (top) and acceleration (middle, bottom).*

## Free fall

**The definition of free fall**

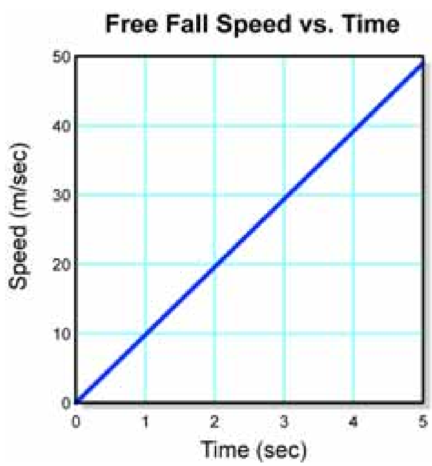
An object is in **free fall** if it is accelerating due to the force of gravity and no other forces are acting on it. A dropped ball is in free fall from the instant it leaves your hand until it reaches the ground. A ball thrown upward is also in free fall after it leaves your hand. Although you might not describe the ball as “falling,” it is still in free fall. Birds, helicopters, and airplanes are *not* normally in free fall because forces other than gravity act on them.

**The acceleration of gravity**

Objects in free fall on Earth accelerate downward, increasing their speed by 9.8 m/s every second (Figure 3.19), The value 9.8 m/s$^2$ is called the **acceleration due to gravity**. The small letter *g* is used to represent its value. When you see the letter *g* in a physics question, you can substitute the value 9.8 m/s$^2$.

**Constant acceleration**

The speed vs. time graph below is for a ball in free fall. Because the graph is a straight line, the speed increases by the same amount each second. This means the ball has a *constant acceleration*. Make sure you do not confuse constant speed with constant acceleration! Constant acceleration means an object’s *speed* changes by the same amount each second.




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

**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 the Earth’s surface, usually represented by the small letter *g*.

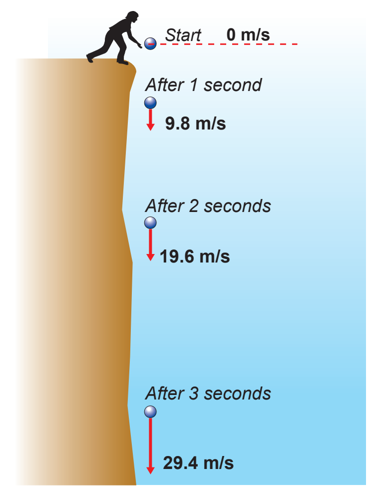



**Figure 3.19:** *A dropped ball increases its speed by 9.8 m/s each second, so its acceleration is 9.8 m/s$^2$.*

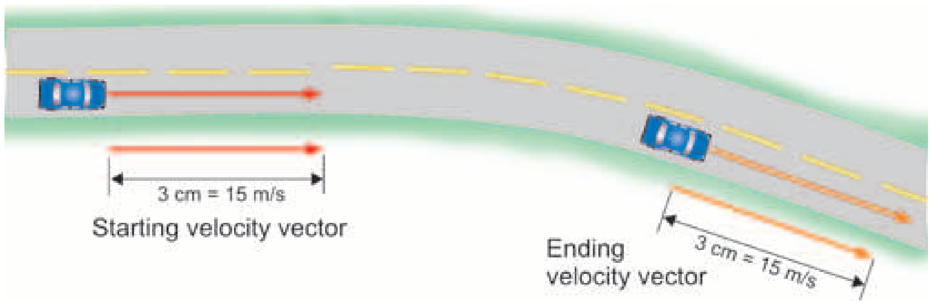
## Acceleration and direction

**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 3.20). Acceleration occurs whenever there is a change in speed, direction, or both.

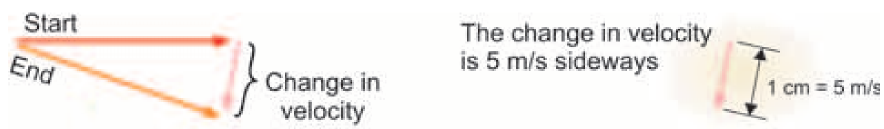
**What "change in direction" means**

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




**Turns are caused by sideways accelerations**

The change in velocity is the small pink arrow that connects the old velocity and the new velocity. This arrow represents the difference in velocity before and after the turn. The change vector is 1 cm 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*.

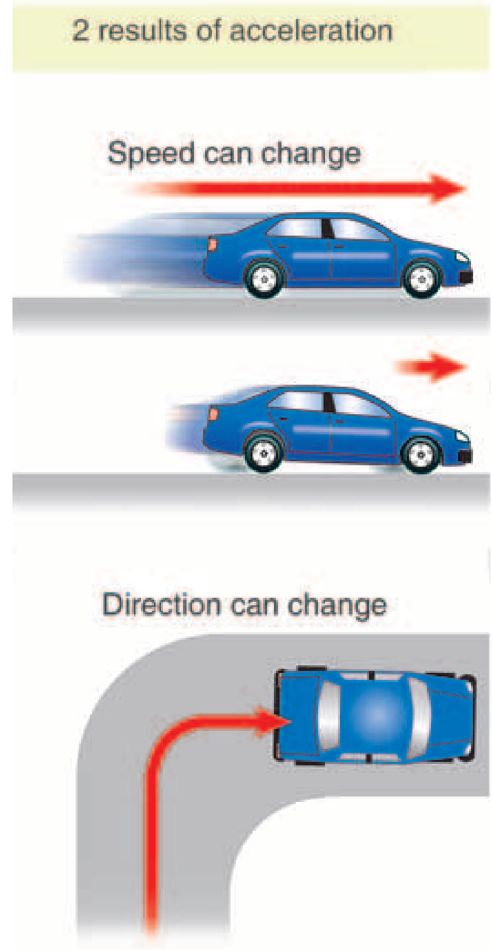



**Figure 3.20:** *A car can change its velocity by speeding up, slowing down, or turning.*

## Curved motion

**Acceleration and curved motion**

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

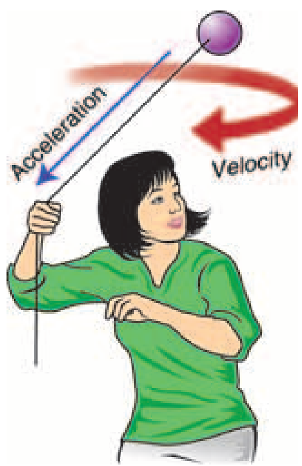
**An example of curved motion**

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 3.21). Gravity accelerates the ball downward as it flies. The acceleration of gravity bends the velocity vector more toward the ground during each second the ball is in 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 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.

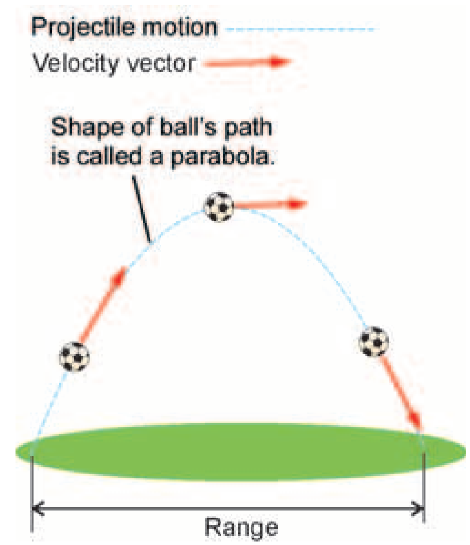



**Figure 3.21:** *A soccer ball in the air is a projectile. The path of the ball is a bowl-shaped curve called a parabola.*