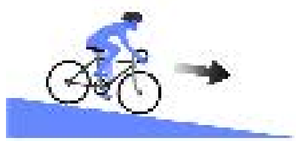
2.3 Acceleration

The speed of things is always changing. Your car speeds up and slows down. If you slow down gradually, it feels very different from slamming on the brakes and stopping fast. In this section we will learn how to measure and discuss changes in speed. Specifically, we will investigate objects rolling downhill. You already know that an object rolling downhill speeds up. The rate at which its speed changes is called acceleration.

Acceleration

You accelerate coasting downhill

What happens if you coast your bicycle down a long hill without pedaling? You accelerate, that is your speed increases steadily. If your bike has a speedometer you find that your speed increases by the same amount every second!



Time (seconds)	Speed (mph)
1 second	1 mph
2 seconds	2 mph
3 seconds	3 mph
4 seconds	4 mph
5 seconds	5 mph

Time (seconds)	Speed (mph)
1 second	[illegible]
2 seconds	4 mph
3 seconds	[illegible]
4 seconds	[illegible]
5 seconds	10 mph

Steeper hills

On a steeper hill, your findings are similar. Your speed increases every second, but by a bigger amount. On the first hill your speed increased by 1 mph every second. On the steeper hill you find your speed increases by 2 mph every second.

Acceleration is the amount that your speed increases, compared to how long it takes. Increasing speed by 1 mph every second means you accelerated at 1 mph per second. Every second your speed increased by 1 mile per hour. It is common to describe acceleration in units of speed (changed) per second.

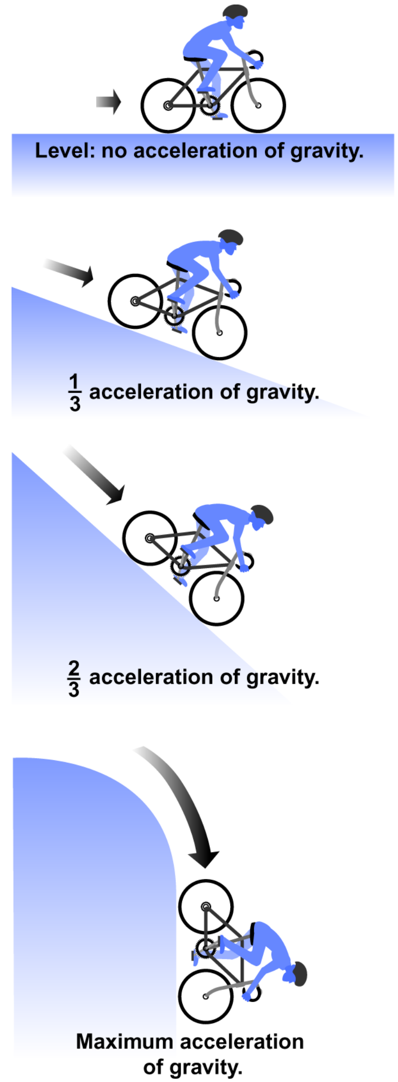
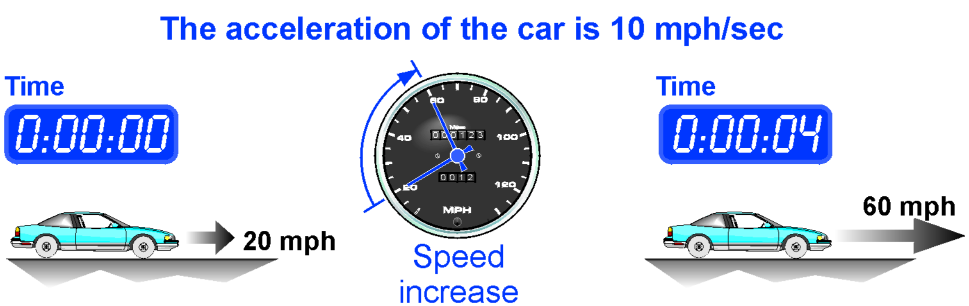


Figure 2.13: *How much of the acceleration of gravity you experience depends on the angle of the hill.*

Acceleration when speed is in miles per hour

Acceleration

Acceleration is the rate of change in the speed of an object. Rate of change means the ratio of the amount of change divided by how much time it took to change.



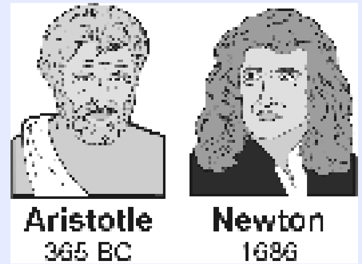
An example of acceleration

Suppose you are driving and your speed goes from 20 mph to 60 mph in four seconds. The amount of change is 60 mph minus 20 mph, or 40 miles per hour. The time it takes to change is 4 seconds. The acceleration is 40 mph divided by 4 seconds, or 10 mph/sec. Your car accelerated 10 mph per second. That means your speed increased by 10 miles per hour each second. Table 2.1 shows how your speed changed during the four seconds of acceleration.

Table 2.1: ***Watching your speed while accelerating***

Time	Speed
0 (start)	20 mph
1 second	30 mph
2 seconds	40 mph
3 seconds	50 mph
4 seconds	60 mph

Thinking about acceleration



People have been thinking about acceleration for a long time. In the fourth century BC two Greek scientists, Aristotle and Strato, described free fall as acceleration. In the 1580s European scientists Simon Stevinus and Galileo determined that all objects fall equally fast, if other forces do not act on them.

About 100 years later, Isaac Newton figured out the three laws of motion. Newton's attempts to fully describe acceleration inspired him and others to develop a whole new kind of math, called *calculus*. We will not be learning about calculus in this course, but we will follow some of Newton's experiments with acceleration.

Acceleration in metric units

The units of acceleration The units of acceleration can be confusing. Almost all of the calculations of acceleration you will do will be in metric units. If we measure speed in cm/sec, then the change in speed is expressed in cm/sec as well. For example, 2 cm/sec is the difference between a speed of 3 cm/sec and a speed of 1 cm/sec.

Calculating acceleration Acceleration is the change in speed divided by the change in time. The units for acceleration are units of speed over units of time. If speed is in cm/sec and time in seconds, then the units for acceleration are cm/sec/sec, or *centimeters per second per second*. What this means is that the acceleration is the amount that the speed changes in each second. An acceleration of 50 cm/sec/sec means that the speed increases by 50 cm/sec *every second*. If the acceleration persists for three seconds then the speed increases by a total of 150 cm/sec (3 seconds × 50 cm/sec/sec).

What do units of *seconds squared* mean? To make matters confusing, an acceleration in cm/sec/sec is written cm/sec^2 (centimeters per second squared). Likewise, an acceleration of m/sec/sec is written m/sec^2 (meters per second squared). If you use the rules for simplifying fractions on the units of cm/sec/sec, the denominator ends up having units of seconds times seconds, or sec^2. Saying *seconds squared* is just a math-shorthand way of talking. The units of square seconds do not have physical meaning in the same way that square inches mean surface area. It is better to think about acceleration in units of speed change per second (that is, centimeters per second *per second*).

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

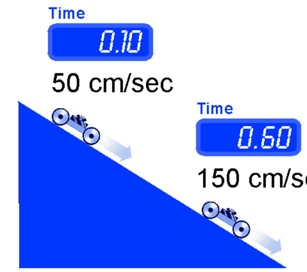
How we get units of cm/sec^2

plug in values	clear the compound fractions	final units
$= \dfrac{50\,\frac{cm}{sec}}{sec}$	$= \dfrac{50\,\frac{cm}{sec}}{sec} \times \dfrac{sec}{sec} = \dfrac{50\,\frac{cm}{\cancel{sec}} \times \cancel{sec}}{sec^2}$	$= 50\,\dfrac{cm}{sec^2}$

Acceleration in m/sec^2 Many physics problems will use acceleration in m/sec^2. If you encounter an acceleration of 10 m/sec^2, this number means the speed is increasing by 10 m/sec every second.

Example

A car rolls down a ramp and you measure times and distances as shown. Calculate the acceleration in cm/sec^2.



Change in speed

$$\begin{array}{r} 150 \text{ cm/sec} \\ -\ \ 50 \text{ cm/sec} \\ \hline = 100 \text{ cm/sec} \end{array}$$

Change in time

$$\begin{array}{r} 0.60 \text{ sec} \\ -\ \ 0.10 \text{ sec} \\ \hline = \ \ 0.50 \text{ sec} \end{array}$$

$$\text{Acceleration} = \frac{\text{Change in speed}}{\text{Change in time}} = \frac{100 \text{ cm/sec}}{0.50 \text{ sec}} = 200 \text{ cm/sec}^2$$

Figure 2.14: *An example of calculating acceleration for a car on a ramp.*

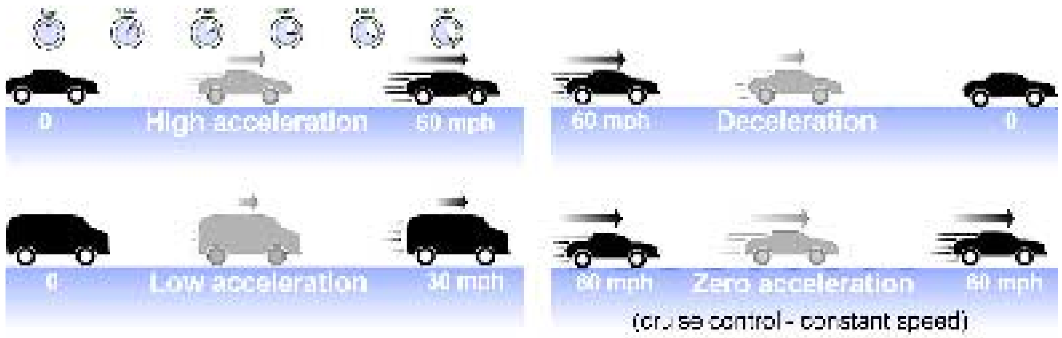
Different examples of acceleration

Any change in speed means acceleration

Acceleration means changes in speed or velocity. *Any* change in speed means there is acceleration. If you put on the brakes and slow down, your speed changes. In the example of slowing down, the acceleration is in the negative direction. We also use the term **deceleration** to describe this situation. *Acceleration occurs whenever the speed changes, whether the speed increases or decreases.*

Zero acceleration

An object has zero acceleration if it is traveling at constant speed in one direction. You might think of zero acceleration as "cruise control." If the speed of your car stays the same at 60 miles per hour, your acceleration is zero.



Acceleration when turning

If you change direction, some acceleration happens. When you turn a sharp corner in a car you feel pulled to one side. The pull you feel comes from the acceleration due to turning. To explain this, you need to remember velocity encompasses speed *and direction*. Any time you change either speed or direction, you are accelerating.

Steep hills and acceleration

You have probably noticed that the steeper the hill, the faster you accelerate. You may already know this effect has to do with **gravity**. Gravity pulls everything down toward the center of the Earth. The steeper the hill, the greater the amount of gravity pulling you forward, and the greater your acceleration.

Free fall

If you drop something straight down it accelerates in free fall. The speed of a free falling object in a vacuum increases by 9.8 meters per second for every second it falls (figure 2.15). This special acceleration is called the acceleration of gravity because it is the acceleration of objects under the influence of the Earth's gravity. The acceleration of gravity would be different on the moon or on other planets.

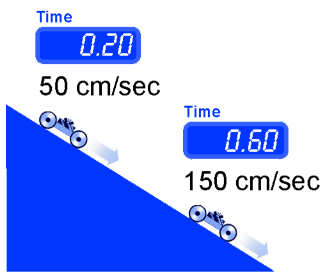
Figure 2.15: *In free fall, the speed of objects increases by 9.8 m/sec each second. Free fall is most accurately measured in a vacuum, since air friction changes the rate of fall of different objects in different ways.*

Acceleration and the speed vs. time graph

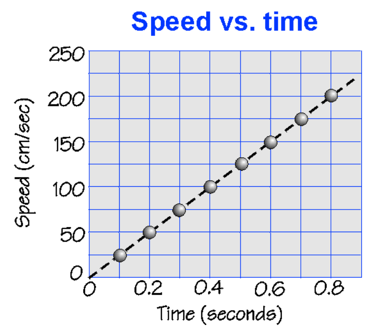
The speed vs. time graph

Another motion graph we need to understand is the graph of speed vs. time. This is the most important graph for understanding acceleration because it shows how the speed changes with time.

The graph below shows an example from an experiment with a car rolling down a ramp. The time is the time between when the car was first released and when its speed was measured after having moved farther down the ramp. You can see that the speed of the car increases the longer it rolls down.



Time (sec)	Speed (cm/sec)
0.1	25
0.2	50
0.3	75
0.4	100
0.5	125
0.6	150
0.7	175
0.8	200



The graph shows a straight line

The graph shows a straight line. This means that the speed of the car increases by the same amount every second. The graph (and data) also shows that the speed of the car increases by 25 cm/sec every one-tenth (0.1) of a second.

Acceleration

You should be thinking of acceleration. This graph shows an acceleration of 250 cm/sec/sec or 250 cm/sec^2. This is calculated by dividing the change in speed (25 cm/sec) by the change in time (0.1 seconds).

Seeing acceleration on a graph

If you see a slope on a speed vs. time graph, you are seeing acceleration. Figure 2.16 shows some examples of graphs with and without acceleration. *Any time* the graph of speed vs. time is not perfectly horizontal, it shows acceleration. If the graph slopes down, it means the speed is decreasing. If the graph slopes up, the speed is increasing.

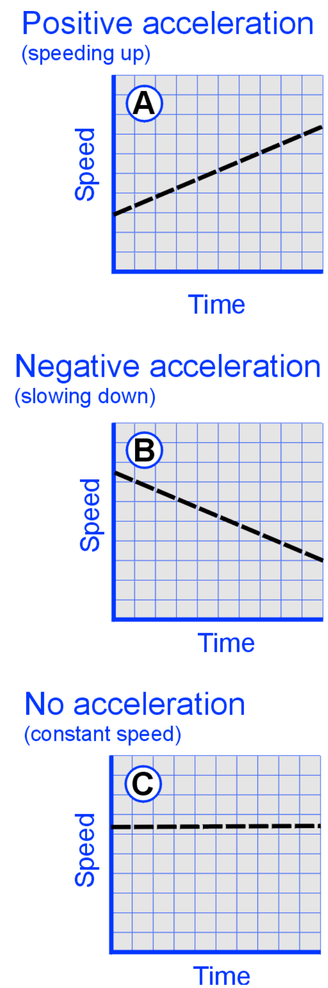


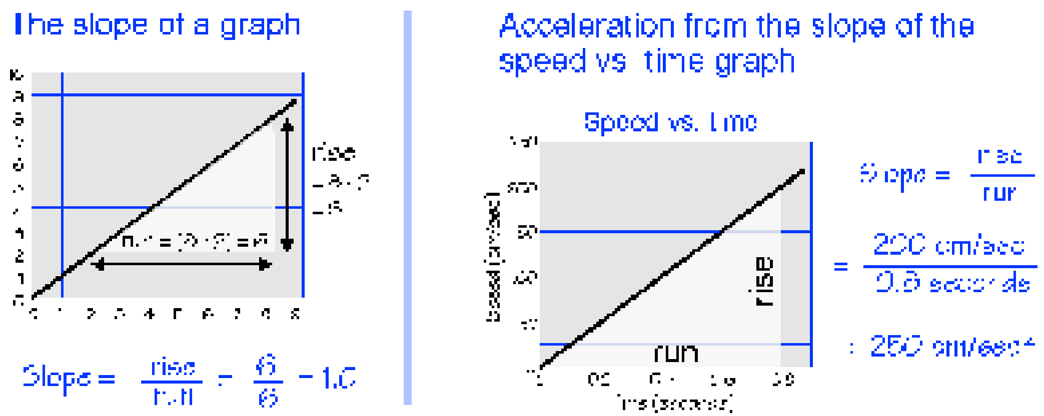
Figure 2.16: *Examples of graphs with different amounts of acceleration.*
Graph **A** *shows positive acceleration, or speeding up.*
Graph **B** *shows negative acceleration, or slowing down.*
Graph **C** *shows zero acceleration.*

Calculating acceleration from the speed vs. time graph

Slope From the last section, you know that the slope of a graph is equal to the ratio of *rise* to *run*. On the speed vs. time graph, the rise and run have special meanings, as they did for the distance vs. time graph. The *rise* is the amount the speed changes. The *run* is the amount the time changes.

Acceleration and slope Remember, acceleration is the change in speed over the change in time. This is *exactly the same* as the rise over run for the speed vs. time graph. The slope of the speed vs. time graph is the acceleration.

Acceleration is the slope of the speed vs. time graph



Make a triangle to get the slope To determine the slope of the speed vs. time graph, take the rise or change in speed and divide by the run or change in time. It is helpful to draw the triangle shown above to help figure out the rise and run. The rise is the height of the triangle. The run is the length of the base of the triangle.

Complex speed vs. time graphs You can use slope to recognize when there is acceleration in complicated speed vs. time graphs (figure 2.17). Level graphs mean the speed does not change, which means the acceleration is zero.

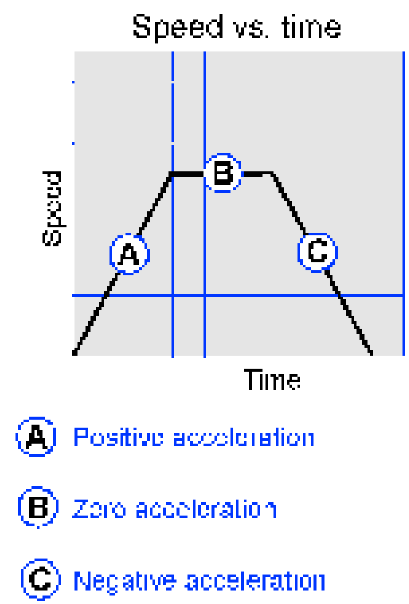


Figure 2.17: *How to recognize acceleration on speed vs. time graphs.*

(A) Positive slope means positive acceleration (speeding up)

(B) No slope (level) means zero acceleration (constant speed)

(C) Negative slope means negative acceleration (slowing down)