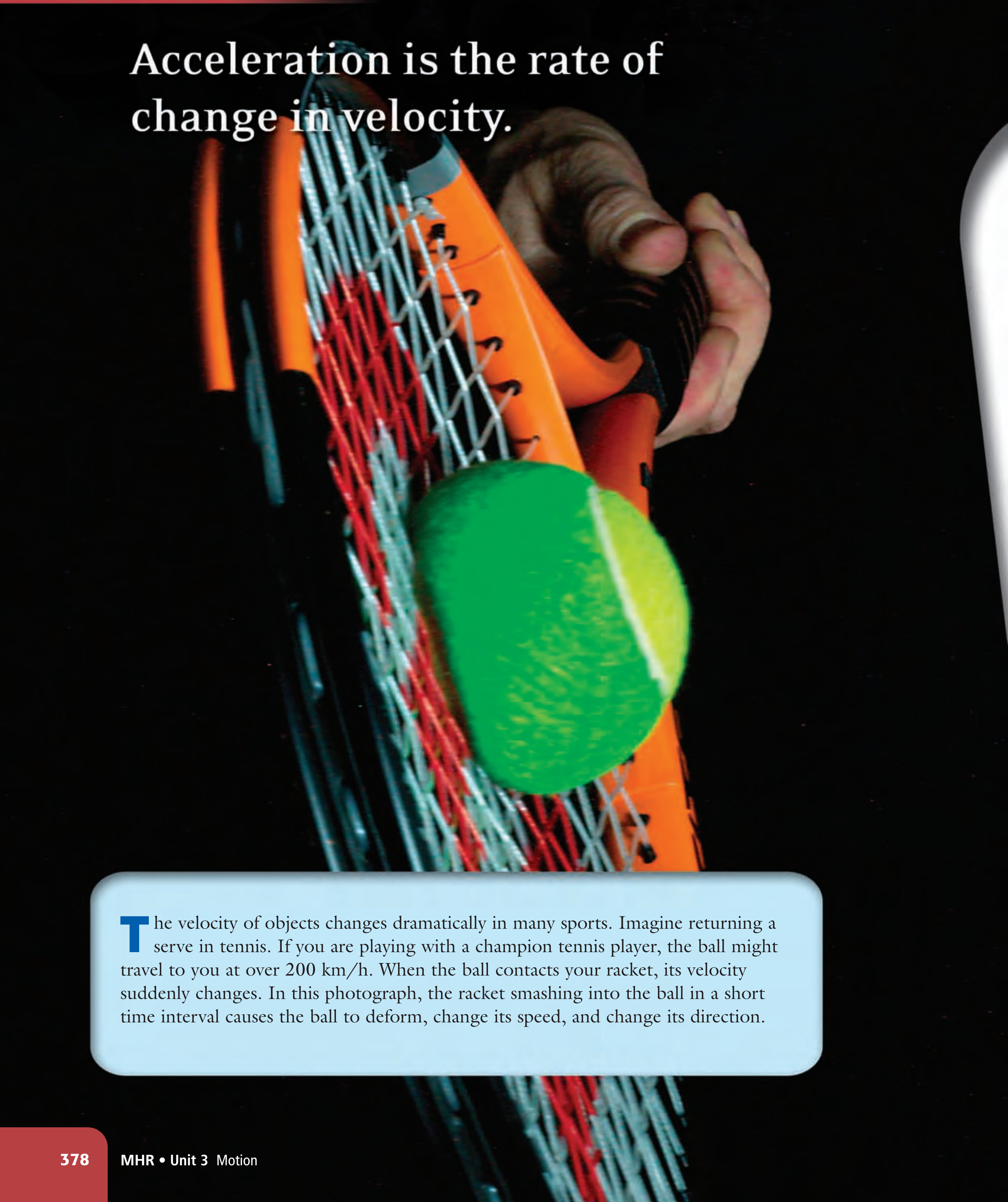
Acceleration is the rate of change in velocity.



The velocity of objects changes dramatically in many sports. Imagine returning a serve in tennis. If you are playing with a champion tennis player, the ball might travel to you at over 200 km/h. When the ball contacts your racket, its velocity suddenly changes. In this photograph, the racket smashing into the ball in a short time interval causes the ball to deform, change its speed, and change its direction.

What You Will Learn

In this chapter, you will
- **define** acceleration
- **demonstrate** the relationship of velocity, time interval, and acceleration
- **determine** acceleration given initial velocity, final velocity, and time interval
- **distinguish** and give examples of positive, negative, and zero acceleration

Why It Is Important

To understand motion, it is important to investigate objects whose velocity is changing. Many living things—including you—change their velocity, speeding up and slowing down many times each day.

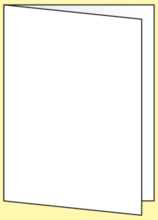
Skills You Will Use

In this chapter, you will
- **measure** velocity and time using appropriate equipment
- **graph** the relationship between velocity and time
- **calculate** using $\vec{a} = \frac{\Delta \vec{v}}{\Delta t}$
- **demonstrate** respect for precision

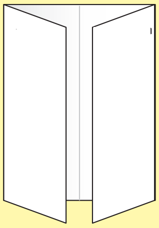
FOLDABLES™
Reading & Study Skills

Make the following Foldable to take notes on what you will learn in Chapter 9.

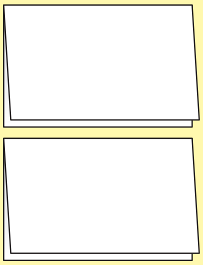
STEP 1 **Fold** a sheet of paper (28 cm by 43 cm) in half lengthwise but instead of creasing the paper, pinch it to show the midpoint.



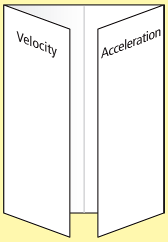
STEP 2 **Flatten** the paper, and **fold** the outer edges of the paper to meet at the pinch, or midpoint, forming a shutterfold.



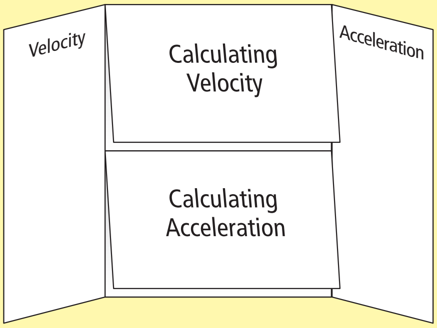
STEP 3 **Fold** two sheets of paper (22 cm by 28 cm) to create two half-books. **Glue** (or staple) them onto the interior centre section. **Use** these half-books to practise calculating velocity and acceleration.



STEP 4 **Label** one exterior tab "Velocity" and the other "Acceleration."



STEP 5 **Label** the interior tabs as shown. As you progress through the chapter, **record** information and take notes under the appropriate tab.



9.1 Describing Acceleration

Acceleration is the rate of change in velocity. A change in velocity is calculated by subtracting the initial velocity from the final velocity. If an object's acceleration is in the same direction as its velocity, the object's speed increases. If an object's acceleration is in the opposite direction to its velocity, the object's speed decreases. Zero acceleration means that the object is moving at a constant velocity.

Words to Know

acceleration
change in velocity
deceleration

The countdown begins. At lift-off time (T) minus 6.6 s, the main engines of the space shuttle are started, one after the other. At T minus 0 s, the solid rocket boosters are ignited and the space shuttle begins its voyage into space (Figure 9.1). The power output needed to launch the space shuttle is 30 times greater than the maximum power output of British Columbia's largest dam.

The space shuttle's motion is not uniform. Within 60 s of launching, the space shuttle is travelling at 350 m/s and is 16 km above Earth. During the next 60 s, the space shuttle increases its speed by over 1200 m/s and travels an additional 30 km away from Earth's surface. In order to launch the space shuttle correctly, scientists need to be able to analyze and predict motion that is changing in speed and direction.

Did You Know?

When astronauts such as Bjarni Tryggvason of British Columbia are orbiting Earth in a space shuttle, they are travelling at 8 km/s. At this speed, it would take less than 10 min to travel across Canada.

internet connect

To find out more about the motion of a space shuttle, go to **www.bcscience10.ca**.

Figure 9.1 A space shuttle is one of the most complex machines ever built. During lift-off, the space shuttle's velocity continuously increases until it reaches a speed of over 27 000 km/h.

9-1A What Is Happening to This Motion?

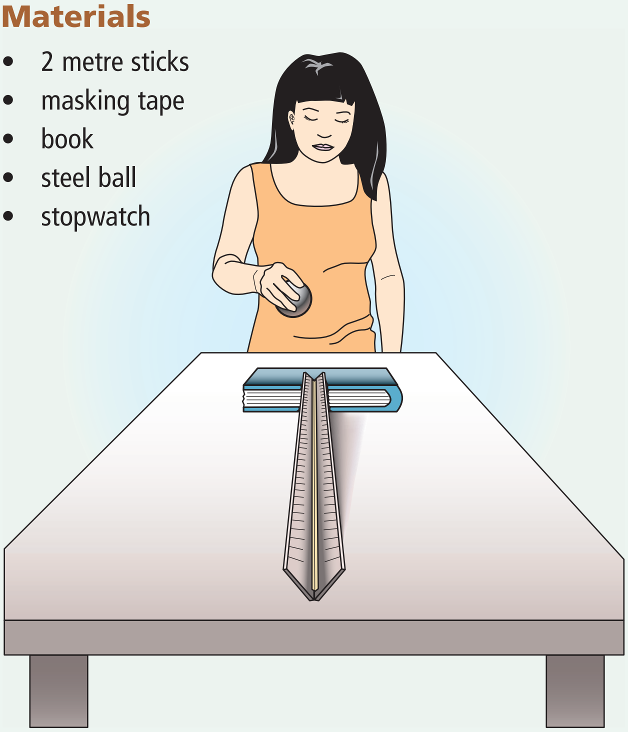
Find Out ACTIVITY

An object travelling with uniform motion has equal displacements in equal time intervals.

In this activity, you will investigate the motion of a ball rolling down a ramp. You will then analyze your data to examine the basis for determining whether the motion has equal displacements in equal time intervals.

Materials

- 2 metre sticks
- masking tape
- book
- steel ball
- stopwatch



What to Do

1. Copy the following data table into your notebook. Give your data table a title.

Displacement (cm [down the ramp])	Time (s)				
	Predicted Time	Trial 1	Trial 2	Trial 3	Average Time
50					
100					
Average time to travel from 0 cm to 50 cm = __________					
Average time to travel from 50 cm to 100 cm = _________					

2. Tape two metre sticks together along their edges to make a V-shaped channel. Set up one end of the metre sticks on a book so that they act a ramp.
3. Predict how much time it would take the ball to roll 50 cm. Record your prediction in your data table.
4. Release the steel ball from 0 cm so that it rolls down the ramp. Using a stopwatch, measure the time it takes to roll 50 cm. Record the time in your data table. Repeat twice more, and average your result of the three trials.
5. Write a sentence describing the motion of the ball.
6. Predict how much time it would take the ball to roll 100 cm. Record your prediction.
7. Release the steel ball from 0 cm so that it rolls down the ramp. Using a stopwatch, measure the time it takes to roll 100 cm. Record the time in your data table. Repeat twice more, and average your results of the three trials.
8. Determine the time it takes the ball to travel from 50 cm to 100 cm by subtracting your average time in step 4 from your average time in step 7. Record this time.
9. Clean up and put away the equipment you have used.

What Did You Find Out?

1. How does the time it took the ball to roll 0 cm to 50 cm compare to the time it took the ball to roll 50 cm to 100 cm?
2. Was the ball's motion down the ramp uniform? Explain, using the data you obtained.

Positive and Negative Changes in Velocity

A **change in velocity** ($\Delta\vec{v}$) occurs when the speed of an object changes, or its direction of motion changes, or both (Figure 9.2). Changes in velocity can be classed as either positive or negative. To find a change in velocity, subtract the initial velocity ($\vec{v}_i$) from the final velocity ($\vec{v}_f$).

$$\Delta\vec{v} = \vec{v}_f - \vec{v}_i$$

Positive changes in velocity

Suppose you are riding a bicycle travelling forward at 6 m/s. You need to get somewhere in a hurry, so you increase your velocity to 9 m/s forward. You would calculate your change in velocity as shown below. In this example, + represents the forward direction.

$$\begin{aligned}\Delta\vec{v} &= \vec{v}_f - \vec{v}_i \\ &= +9\text{ m/s} - (+6\text{ m/s}) \\ &= +3\text{ m/s}\end{aligned}$$

The change in velocity is 3 m/s in the forward direction. In other words, you are speeding up by 3 m/s in the original direction. Your initial forward direction is *positive*, so your change in velocity is *positive* when you speed up.

Figure 9.2 Cyclists riding in the middle of a pack have to be very careful when they make changes to their velocity.

Negative changes in velocity

Suppose as you are riding you apply the brakes to slow down. If you slow down from 9 m/s forward to 2 m/s forward, your change in velocity is

$$\begin{aligned}\Delta\vec{v} &= \vec{v}_f - \vec{v}_i \\ &= +2\text{ m/s} - (+9\text{ m/s}) \\ &= -7\text{ m/s}\end{aligned}$$

Your change in velocity is 7 m/s opposite the forward motion. In other words, you are slowing down by 7 m/s in the original direction. Your initial forward direction is *positive*, so your change in velocity is *negative* when you slow down.

Constant velocity

If you were to pedal at a constant velocity, your initial and final velocities would be equal. Therefore, the change in velocity for that time interval would be zero. Any object travelling with uniform motion in a straight line would have zero change in velocity.

9-1B Change in Velocity

Think About It

In this activity, you will analyze data for an object's velocity at given times. You will then calculate the object's change in velocity for specified time intervals.

What to Do

1. Copy the following data table into your notebook. Give your table a title.

Time (s)	0	20	40	60	80	100
Velocity (m/s [forward])	11	16	18	18	14	11

2. Calculate the change in velocity ($\Delta\vec{v}$) for each of the following time intervals. Let the forward direction represent positive (+) velocity.
   (a) 0 s–20 s
   (b) 20 s–40 s
   (c) 40 s–60 s
   (d) 60 s–80 s
   (e) 80 s–100 s

What Did You Find Out?

1. During which of the 20 s time intervals was the object speeding up?
2. During which of the 20 s time intervals was the object slowing down?
3. During which of the 20 s time intervals was the change in velocity zero?

Non-Uniform Motion

You can feel the difference between motion that is nearly uniform and motion that is changing in speed or direction. Imagine that you are riding on a roller coaster. The chain pulls the roller coaster car up the first hill with a constant velocity and relatively uniform motion. If you closed your eyes, it would feel as though you were hardly moving at all (Figure 9.3A). Once the cars of the roller coaster have travelled over the top of the first hill, your velocity quickly increases as you travel down the other side of the hill. Whether your eyes are open or closed, you know your motion is changing. For the rest of the ride, your velocity keeps on changing as the roller coaster car turns in different directions and speeds up and slows down. You feel pushed and pulled from side to side and forward and backward (Figure 9.3B).

Figure 9.3A Passengers have a smooth ride with relatively uniform motion.

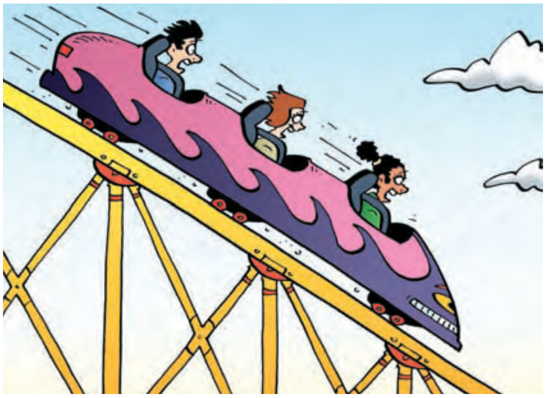


Figure 9.3B Passengers feel pushed and pulled as the velocity of the roller coaster car changes.

Acceleration

The rate at which an object changes its velocity is called **acceleration**. Another way to say this is that acceleration is a way of calculating how the velocity of a moving object changes. Velocity is a vector, so it has two parts: the speed at which the object is moving and also the direction in which the object is moving. A change in velocity can be a change in either speed or direction (Figure 9.4). When we talk about acceleration, we need to include the magnitude of the change in the velocity of the moving object. We also need to indicate the change in direction of the object's velocity.

Did You Know?

A cheetah can run short distances at speeds greater than 90 km/h. What is even more impressive is that it can accelerate from 0 to 70 km/h in less than 2 s.

Figure 9.4 A predator needs to accelerate quickly and make rapid changes in velocity.

Comparing acceleration

There is more to accelerating than just changing velocity. Imagine two cars are going to have a race (Figure 9.5). One car is a powerful dragster. The other is an old car. This race is not about how fast the cars can go but instead about how quickly they can get to a forward velocity of 60 km/h. Even though both cars will have the same change in velocity, the dragster will be able to change velocity faster and therefore will have a greater acceleration. When comparing the acceleration of two objects, the object with the greater acceleration changes its velocity in a shorter time interval or has a greater change in velocity during the same time interval.

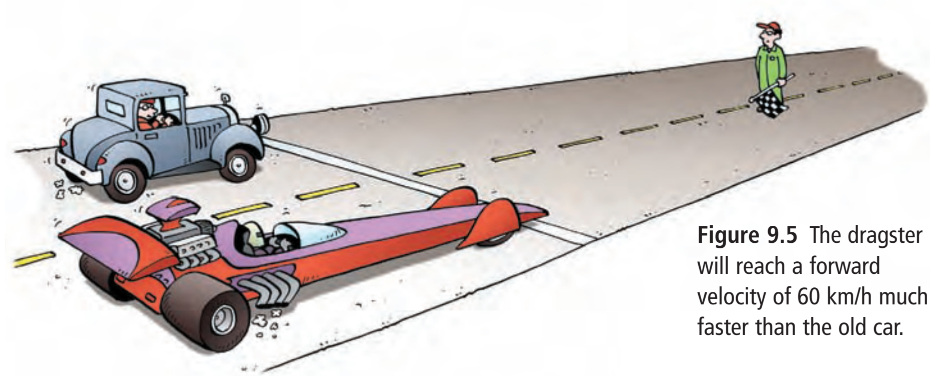


Figure 9.5 The dragster will reach a forward velocity of 60 km/h much faster than the old car.

Suggested Activity

Find Out Activity 9-1C on page 387

Reading Check

1. What two aspects of motion can change when velocity changes?
2. What is the definition of acceleration?
3. How can you tell which of two objects has the greater acceleration?

Positive and Negative Acceleration

Whenever the velocity of an object changes, its motion is not uniform, and we say that the object is accelerating. Acceleration occurs when the speed of an object changes, or its direction of motion changes, or both.

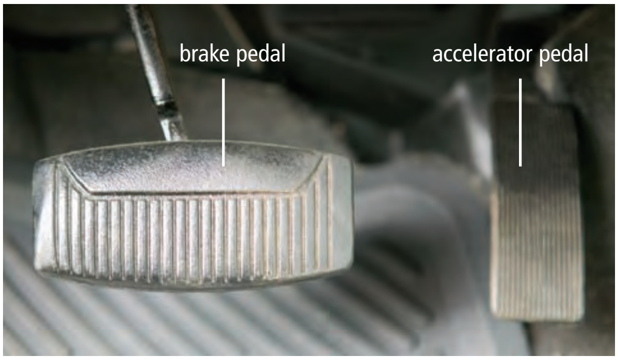


Figure 9.6 A more common name for the accelerator pedal is the gas pedal.

Positive acceleration

When you think of acceleration, you probably think of something speeding up. However, an object that is slowing down is also changing its velocity and therefore is accelerating. In straight-line motion, acceleration can be either positive or negative.

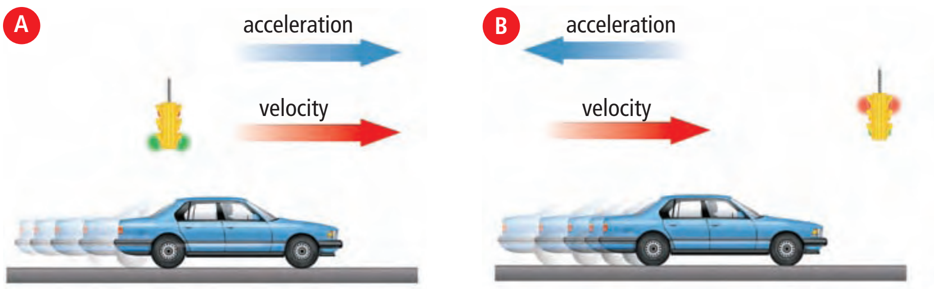
Imagine you are driving along a straight, level road at 40 km/h. Since your velocity is constant, you are travelling with a relatively uniform motion and passengers in your car will be experiencing a smooth ride. If you need to speed up to 60 km/h, you must press on the accelerator pedal (Figure 9.6). Suppose the forward motion of the car is represented as positive (+). When the car's speed is *increasing*, the car has a *positive* acceleration.

Negative acceleration

If you need to slow down, you press on the brake pedal (Figure 9.6). Again, suppose the forward motion of the car is represented as positive (+). When the car's speed is *decreasing,* the car has a *negative* acceleration.

Acceleration is the rate of change in velocity. Therefore, the direction of the acceleration is the same direction as the change in velocity. If an object's acceleration is in the same direction as its velocity, the object's speed increases (Figure 9.7A). If the acceleration is in an opposite direction to its velocity, the object's speed decreases (Figure 9.7B). Acceleration that is opposite to the direction of motion is sometimes called **deceleration** (Figure 9.8 on the next page).

Figure 9.7 The speed of both cars is changing, so they are both accelerating.



If forward motion is represented as positive, the speed of this car is increasing so the car has positive acceleration (A).

If forward motion is represented as positive, the speed of this car is decreasing so the car has negative acceleration (B).

Figure 9.8 A parachute reduces the landing run of a space shuttle, reducing wear on the brakes and providing increased directional stability.

Direction

Positive (+) and negative (−) acceleration are also dependent upon the direction of an object's motion. Suppose a car driving forward increases its velocity from 2 m/s to 6 m/s (Figure 9.9A). If forward motion is positive (+), then the change in velocity would be +4 m/s. Because the change in velocity is positive (+), which represents forward, the acceleration must also be forward.

Suggested Activity

Conduct an Investigation 9-1D on page 388

Figure 9.9A Since the car speeds up in a forward direction, its sign is positive (+).

Suppose that a different car is increasing its speed going backward (Figure 9.9B). If we define forward motion as positive (+), then backward motion must be negative (−). If the car's velocity as it travels backward changes from −1 m/s to −4 m/s, the change in velocity would be −3 m/s. Because the change in velocity is negative (−), which represents backward, the direction of the change in velocity, and therefore acceleration, must also be backward.

Explore More

Find out more about the effects of acceleration on the human body. Start your search at **www.bcscience10.ca**.

Figure 9.9B Since the car speeds up in a backward direction, its sign is negative (−).

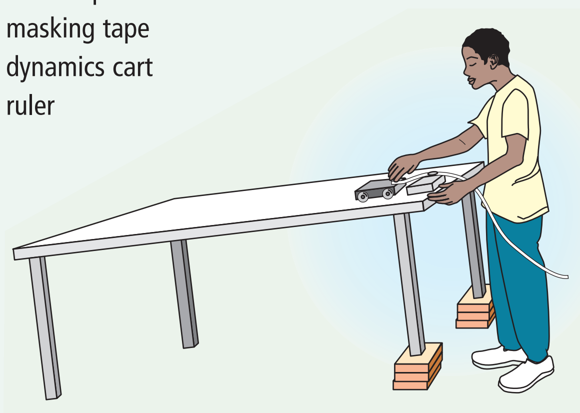
9-1C Accelerated Motion

Find Out ACTIVITY

In this activity, you will analyze accelerated motion using a recording timer and ticker tape.

Materials

- lab table
- several books or other flat objects
- C-clamp
- recording timer
- ticker tape
- masking tape
- dynamics cart
- ruler



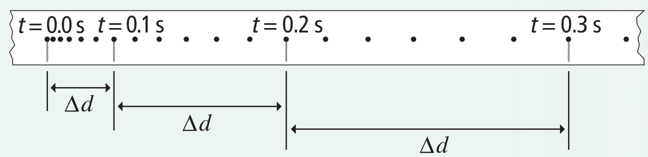
Step 3

What to Do

1. Copy the following data table into your notebook. Give the table a title.

Time interval (s)	0.0 to 0.1	0.1 to 0.2	0.2 to 0.3	0.3 to 0.4	0.4 to 0.5	0.5 to 0.6	0.6 to 0.7	0.7 to 0.8
Displacement (cm/s)								
Average velocity (cm/s [forward])								

2. Raise one end of a lab table 10 cm to 15 cm by placing several books or other flat objects under the back legs.
3. Use the C-clamp to fasten a recording timer to the raised end of the table. Cut a piece of ticker tape 1 m long. Insert the ticker tape into the timer, and use the masking tape to attach the ticker tape to the back of a dynamics cart.
4. Hold the dynamics cart stationary next to the timer and release it after the timer is turned on. Have a partner catch the cart before it falls off the table.
5. Draw a line through the first dot on the tape and label it $t = 0.0$ s. Count six dots from the $t = 0.0$ s line, and draw another line through the sixth dot. Label this line $t = 0.1$ s. Measure the distance between these two lines, and record this value in the table as the displacement during the time interval $t = 0.0$ to $t = 0.1$ s.



An example of how to mark the ticker tape

6. From the $t = 0.1$ s line, draw a line through the sixth dot. Label this line $t = 0.2$ s. Measure the distance between the $t = 0.1$ s line and the $t = 0.2$ s line. Record this value as the displacement during the time interval $t = 0.1$ to $t = 0.2$ s.
7. Continue measuring and recording the displacements for each of the time intervals in your data table.
8. Using the equation $\vec{v}_{av} = \frac{\Delta \vec{d}}{\Delta t}$, calculate the average velocity for each of the 0.1 s time intervals. Record these values in your data table.
9. Clean up and put away the equipment you have used.

What Did You Find Out?

1. Use a sentence to describe how the spacing of the dots for the accelerated motion is different from the spacing of the dots you would expect for uniform motion.
2. As the cart moved down the incline, how did the displacement of the cart change for each of the 0.1 s time intervals?
3. As the cart moved down the incline, how did the average velocity of the cart change for each of the 0.1 s time intervals?

9-1D The Direction of Acceleration

Conduct an INVESTIGATION

Inquiry Focus

Skill Check

- Observing
- Measuring
- Controlling variables
- Evaluating information

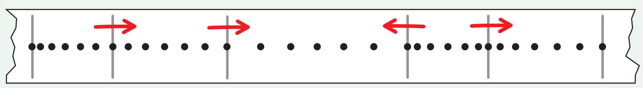
Materials

- 2 m of ticker tape
- recording timer
- C-clamp

We usually define forward motion of an object as positive (+). If an object increases its forward velocity, the acceleration would also be positive (+), which means it is accelerating forward. If the object slows down in its forward motion, then the acceleration is backward or negative (−). In this activity, you will analyze acceleration by comparing average velocity during equal time intervals. Remember, for equal time intervals, greater displacements represent greater average velocity.

Question

How is acceleration represented on a motion diagram created by a recording timer?



An example of how to mark the ticker tape

Procedure

1. Use the C-clamp to fasten the timer to the end of the table. Cut a 2 m length of ticker tape and insert it into the recording timer.
2. Turn on the recording timer, and pull approximately 1.5 m of the tape through the timer with non-uniform motion. Make sure that the speed you pull the tape increases and decreases several times during the time you are pulling.
3. Turn off the timer.
4. Using a pencil, draw a line through the first dot on the tape.
5. Draw a line through every sixth dot all the way along the tape.
6. Make a sketch of the ticker tape in your notebook.
7. Clean up and put away the equipment you have used.

Analyze

1. The displacement for each of these equal time intervals is proportional to the average velocity that the tape was being pulled. If the interval distance is increasing, then the average velocity of the tape is increasing. This indicates the tape is accelerating in the direction of motion. If the interval distance is decreasing, then the average velocity of the tape is also decreasing. This indicates either the tape is accelerating or the direction of the acceleration is opposite the direction of the velocity. Draw an arrow indicating the direction of the acceleration for successive time intervals.

Conclude and Apply

1. Explain why some of the acceleration arrows point in different directions.
2. Turn your ticker tape so that it is backward. Analyze the acceleration arrows that you have marked on your tape. Are they still correct? Explain.

Wild, Weird, Wonderful

www Science

The Motion of a Falling Object

Our understanding of science helps us find answers to real world problems. But you can also use your scientific knowledge to analyze the world of science fiction. Many of our superheroes possess powers and perform stunts that appear out of the ordinary. But does this mean that these feats are not scientifically possible? Mostly science fiction is fantasy, but many times the writers of science fiction get it right. Not only do these fantasy characters sometimes use scientific principles, they also behave like true scientists and learn from their mistakes.

Spider-Man was first introduced in comic books in 1962. After being bitten by a radioactive spider, Peter Parker gains the attributes of a spider, including the ability to shoot a web from his wrist. These spider abilities allow him to save people from villains such as the Green Goblin.

One such event was portrayed in a 1973 Spider-Man comic. Spider-Man's girlfriend, Gwen Stacy, is pushed off a 100 m high tower by the Green Goblin. To save her life, Spider-Man shoots a web that attaches to her ankle. The web stops the girl before she hits the ground, but unfortunately the deceleration is too large for her to survive.

After falling 80 m, Gwen would have a downward velocity of approximately 140 km/h. To safely come to a stop from this velocity, she would need a time interval greater than 1.0 s. Spider-Man's web slowed her down too quickly to come to a stop safely.

Spider-Man learned from his mistake. In the Spider-Man movie of 2002, the Green Goblin pushes Mary Jane Watson from the top of a tall bridge. This time, Spider-Man does not shoot a web to stop her fall. Instead, he dives after the falling girl. Since his initial downward velocity is greater than her initial velocity, he can catch up to her. Once he catches her, he shoots a web to a nearby building and they swing to safety. By swinging to safety, they slow down over a long period of time. This is much the same as slowing down while on a playground swing. Spider-Man was able to save Mary Jane due to understanding the concept of acceleration. In the real world, scientists have used this understanding of acceleration to increase passenger safety in automobiles.

Even a superhero needs to understand the physics of motion.

Science Watch

Human Acceleration

In the late 1940s, there was an increasing emphasis on speed in transportation. Refinements to the design of the jet plane had allowed it to reach speeds of more than 700 km/h. Grand Prix race cars were travelling at more than 150 km/h. However, the faster speeds came with a huge cost: crashes at these speeds were usually fatal due to the large acceleration experienced by pilots, drivers, and passengers.

Colonel John Stapp (1910–1999) was a pioneer in studying the effects of acceleration on the human body. He was called "the fastest man on Earth." Colonel Stapp did most of his research at Edwards Air Force Base, in California, where he was stationed as a medical doctor.

Back in 1947, scientists did not have computers and complex crash-test dummies to use in analyzing accelerations on humans. In order to do his research, Stapp subjected himself to large accelerations. Acceleration of 1 *g* (*g* is the symbol for the value of the acceleration due to gravity) is equivalent to the acceleration of an object dropped near the surface of Earth. It was believed that an acceleration of more than 18 *g* (176 m/s^2) would cause death, but Stapp experienced up to 46 *g* (451 m/s^2) and survived.

The results of John Stapp's research are evident in today's safety features. Stapp was dedicated to safety and took every opportunity to support the use of safety belts in cars. The lap belts and shoulder straps in cars today are a result of Stapp's research. Stapp also discovered that humans can withstand a larger acceleration when riding backward than when riding forward. This finding has led to infant seats being positioned facing backward in the rear seats of cars.

John Stapp even made an impact on our language. You may have heard of Murphy's law, which states "If anything can go wrong, it will." Murphy was a test engineer working with Stapp on his experiments.

In one of the first rides on the "human decelerator," Stapp was fitted with 16 accelerometers placed on various parts of his body. Unfortunately, all 16 were mounted backward. After the very uncomfortable acceleration, no measurements were recorded due to the backward sensors, making Stapp's effort wasted. In future experiments, Stapp was famous for always trying to consider everything that could possibly go wrong before undertaking the experiment.

The "human decelerator" consisted of 610 m of railway track stretching across the air base. Rockets propelled the 680 kg carriage. Once the carriage was moving fast enough, a 14 m long braking system, the most powerful ever constructed, was controlled to stop the passenger with a calculated acceleration.

Questions

1. What was the purpose of John Stapp's research?
2. What maximum acceleration did John Stapp withstand?
3. What modern safety features resulted from John Stapp's research?

Check Your Understanding

Checking Concepts

1. Describe two ways to change the velocity of a moving car.

2. (a) Define "acceleration."
(b) Define "deceleration."

3. In terms of initial velocity ($\vec{v}_i$) and final velocity ($\vec{v}_f$), how is change in velocity ($\Delta\vec{v}$) determined?

4. Determine the change in velocity of a car that starts at rest and has a final velocity of 20 m/s [N].

5. How are the direction of an object's acceleration and the direction of the same object's change in velocity related?

6. Suppose motion toward the east is positive (+). Is the acceleration positive, negative, or zero for each of the following situations?
(a) slowing down while travelling east
(b) travelling with a constant velocity west
(c) increase in speed while travelling east
(d) increase in speed while travelling west
(e) decrease in speed while travelling west

Understanding Key Ideas

7. Given the following data, calculate the change in velocity ($\Delta\vec{v}$) for the following time intervals. Let motion to the north represent positive (+) velocity.
(a) 0 s–5 s
(b) 5 s–10 s
(c) 10 s–15 s
(d) 15 s–20 s
(e) 20 s–25 s

Time (s)	Velocity (m/s [N])
0	0
5	8
10	12
15	12
20	15
25	9

8. (a) If the acceleration is in the same direction as the velocity, what happens to the speed of an object?
(b) If the acceleration is in the opposite direction to the velocity, what happens to the speed of an object?

9. A car travelling forward at 25.0 m/s stops and backs up at 4.0 m/s.
(a) What is the car's change in velocity?
(b) What is the direction of the car's acceleration?

10. Describe the direction of the acceleration for each of the following situations.

A Sliding in to home plate

B Starting the race

Pause and Reflect

Give an example from your own life of two objects that can accelerate to the same speed but have different accelerations. Explain why their accelerations are different.