Section 1 Velocity and Acceleration: The Big Thrill

What Do You See?

Learning Outcomes

In this section, you will

- **Sketch** and interpret a top view and a side view of a roller-coaster ride.
- **Identify** whether thrills in roller-coaster rides come from speeds, accelerations, or changes in each.
- **Define** acceleration as a change in velocity with respect to time and recognize the units of acceleration.
- **Calculate** and measure velocity and acceleration.

What Do You Think?

The tallest wooden roller coaster has a height of about 66 m (218 ft). The tallest steel roller coaster is 128 m (420 ft) high. This is as tall as a 40-story high-rise building.

- **Which part of the roller-coaster ride produces the loudest screams? Why?**

Record your ideas about these questions in your *Active Physics* log. Be prepared to discuss your responses with your small group and the class.

Investigate

Part A: Sketch of the Roller Coaster

1. Sketch a roller coaster with a first hill of 15 m that quickly descends to 6 m and then turns to the right in a big circle (radius of 10 m) and then descends back to the ground.

   a) Include a copy of the sketch in your *Active Physics* log.

2. Compare the sketch of your roller-coaster design with those of others on your design team.

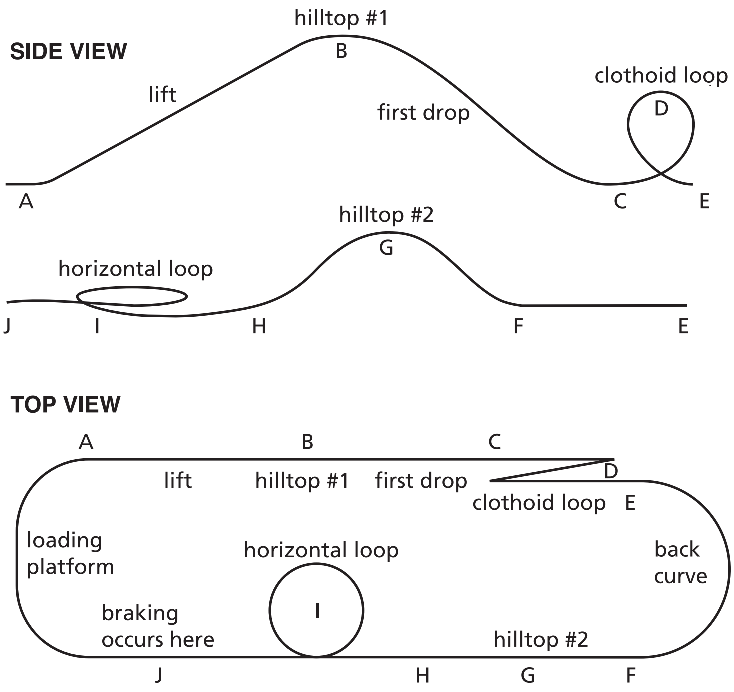
   a) Which sketch do you like the best? Provide three reasons why you prefer that sketch.

3. Create two sketches with different views for the same roller coaster. The first sketch should be a side view. The second sketch should be a view from the sky.

   a) What are the advantages of having two sketches?

4. Below is the roller coaster that has been designed by the professional team that is asking for your help. It is called The Terminator Express. There are two views of the roller coaster. The first view is a side view. The second view is a view from the sky (a top view).

The Terminator Express



   a) Sketch the side and top view in your *Active Physics* log.

5. The Terminator Express roller-coaster car begins from the loading platform at A and then rises along the lift. It reaches the top of hilltop # 1 at B and then makes its first drop. It then goes into a vertical loop at C. This clothoid loop (it has a big radius at the bottom and a small radius at the top) allows the riders to be safely upside down. The coaster car then goes along the track starting at E, moves through the back curve to F, rises over hilltop # 2 at G and then swings into a horizontal loop at I. The brakes are applied after the loop and the roller coaster comes to a stop at J.

   Have one team member read this description as you move your finger along the roller-coaster track and then have a different team member read the description so that the first reader can follow the coaster car along the track.

   Repeat the procedure with the top view.

Part B: Roller-Coaster Fun

1. In the next part of the *Investigate*, you will blindfold someone in your group in order to observe the thrilling parts of a roller-coaster ride. The blindfolded person will sit in a chair with wheels. This part of the *Investigate* may be done with the whole class viewing one student.

   a) Before you blindfold anyone, write down the safety concerns when one of your team members is blindfolded and you will be pushing him or her. What could go wrong? How can you prevent this? Be sure to check your safety rules with your teacher before proceeding.

2. For each group, choose one person as the rider, one as the recorder, and one as the "driver." The rider should rate each type of move on a 1-to-5 scale (5 being the highest) in terms of its "thrill." The recorder should write a brief description of the move (for example, "sharp left turn") and then record the rider's thrill rating for each move.

3. Have a member of your group sit on the chair with wheels. Blindfold that person. Push on the chair of the blindfolded team member, the rider. While the rider is moving, give the chair another push. Continue pushing the chair but vary the directions of your pushes, for example to the left, to the right, or straight ahead.

a) The recorder should note when the blindfolded team member smiles or laughs or exhibits some emotion as well as the rider's rating of the thrill level.

4. A rider's *velocity* is a measure of the rider's speed and includes information about the direction in which the rider is traveling. The rider's velocity may have been 1.2 m/s north or 1.5 m/s toward the door or 1.0 m/s toward the window. In each case, there is a magnitude or size (1.0 m/s, 1.2 m/s, 1.5 m/s) and a direction (north, toward the door, toward the window).

a) Was the velocity responsible for the "rider's" reactions? Did the blindfolded rider react more when the chair was moving with a fixed velocity (one with the same speed and the same direction) or when the velocity changed, when there was a change in speed or a change in direction of the chair or when there was a change in both the speed and in the direction of the chair?

5. The change in a rider's velocity over time is referred to as *acceleration*. Suppose a rider was moving at 1.1 m/s north and changed velocity to 1.5 m/s north. There is an acceleration because there was a change in speed.

a) In your *Active Physics* log, calculate and record the change in velocity.

6. There would also be acceleration if the rider changed velocity from 1.3 m/s east to 1.3 m/s south. Here the acceleration is due to a change in the direction, with no change in speed.

a) Draw vectors for these two velocities and describe the change in velocity in your log.

7. Suppose a rider was moving at 1.5 m/s toward the door and someone pushed him or her and made the rider move at 1.3 m/s toward the window. There is acceleration because there was a change in speed and a change in direction.

a) Draw a vector to represent the two velocities for the rider in the above example. Make the direction toward the window to be at right angles to the original direction toward the door. Record the change in speed and the change in direction in your *Active Physics* log for the rider in the example above.

b) Was acceleration responsible for the reactions of the blindfolded rider? Did he or she react more when accelerated?

8. Acceleration is a change in velocity in a specific time. For example, the change from 1.1 m/s north to 1.5 m/s north may have taken 1 s.

The change in velocity is 0.4 m/s in one second. There are a number of ways in which this can be stated: The change in velocity is

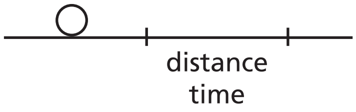
- 0.4 m/s in one second
- 0.4 m/s every second
- 0.4 m/s per second
- 0.4 (m/s)/s
- 0.4 m/s^2

Part C: Measuring Velocities and Calculating Accelerations

1. The value 1.5 m/s north is a velocity. The velocity 1.5 m/s tells you that the object can travel 1.5 m in 1 s. The direction of motion is north.

a) If an object were moving across the table, what instruments would you need for measurements to determine if the object were traveling at 1.5 m/s? Describe how you would go about measuring velocity in your classroom.

2. Place a track flat on the top of your table. Place a steel ball in the track and give it a small push to get it moving along the track.



a) Measure the distance the steel ball rolls and the time it takes to reach the end of the track using a ruler and a stopwatch. Record this data in your log and calculate the velocity of the steel ball. The equation for calculating average velocity is

$$\text{velocity} = \frac{\text{displacement}}{\text{time elapsed}}$$

$$v = \frac{\Delta d}{\Delta t},$$

where v is the velocity,

Δd is the displacement (change in position), and

Δt is the time elapsed.

The symbol Δ (delta) signifies "change in." Δ always means "final value" – "initial value." So $\Delta t = t_{final} - t_{initial}$.

Remember: a velocity must have a direction. The average velocity will be in the direction of the displacement.

Displacement is itself a vector quantity. For example, you might say that you moved 1.5 m north; so your displacement was 1.5 m north. The change in your position, which is the displacement, is represented as Δd.

3. Do another run with the steel ball but change the speed of the steel ball this time.

a) Record the data and calculate the velocity of the steel ball again.

4. Your teacher will demonstrate the use of a velocimeter that you will use in *Step* 6. A velocimeter (photogate) has two sensors inside and computes the speed of the ball for you. Each sensor can either start or stop the timer when the rolling ball intercepts the beam.

a) How do you think the velocimeter is able to compute the speed?

b) A velocimeter with only a single beam starts when an object breaks a light beam across the opening of the gate. The timer stops when the beam is no longer broken. The time interval can be measured very accurately. The computer measures the opening and closing of the gate as an elapsed time. To determine the velocity of the steel ball, what additional information would you (or the computer) need to know?

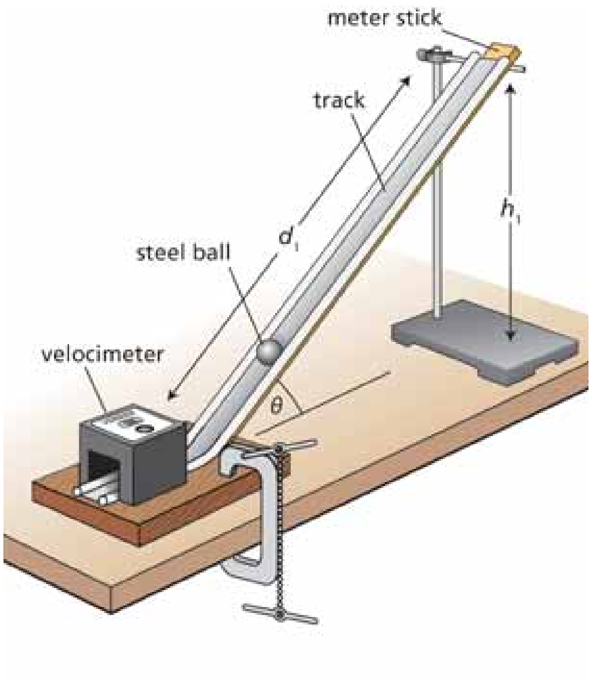
5. A large steel ball travels 6 cm. The elapsed time recorded on the velocimeter timer is 2 s.

a) Calculate the speed of the ball. (Since the speed is requested, you do not have to worry about the direction of motion. Speed is a *scalar* — it has no direction. Velocity is a vector — it has direction).

6. Roll a steel ball along a horizontal track. Use the velocimeter to help you find the speed of the steel ball traveling along the track. Place the velocimeter in a position where the ball must intercept the timer's beam. If you don't have a velocimeter available, you may find the speed by using a stopwatch to determine how long it takes the ball to travel a specified distance, say 0.3 m.

7. Raise the track to create a slope for the steel ball to travel down. Allow the steel ball to roll down this ramp. Make certain to start the ball from the same position during your trials when the ramp was horizontal.

a) Measure the speed of the steel ball at two different points. It is easiest to start the ball at rest (speed equals zero) and then use the velocimeter to measure the speed near the bottom of the track. You will also need to measure the time it takes the ball to go from where it starts to when you measure the "final" speed.



Since the direction of the steel ball down the track can be considered to be along a straight path, your measurement is also a velocity. The direction does not change. In your log, record the speeds and the time it took for the ball to go from the starting point to the velocimeter.

b) Calculate the acceleration of the ball from the two speed (velocity) measurements. Acceleration is the change in velocity with respect to time. The equation to calculate acceleration is

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time elapsed}}$$

$$a = \frac{\Delta v}{\Delta t},$$

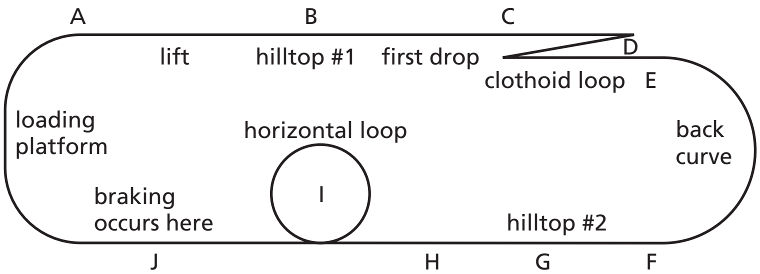
where a is the acceleration,
v is the velocity,
t is time,
$\Delta v = v_{\text{final}} - v_{\text{initial}}$, change in velocity,
$\Delta t = t_{\text{final}} - t_{\text{initial}}$, time elapsed.

The initial velocity is zero and you recorded the final velocity. You need to know the time it took the steel ball to travel from the start position to the final position. This will provide the change in time necessary for the acceleration calculation. You may have to repeat *Step 7.a)* again in order to measure this time. It may be good to do this several times so that you can compare your measurements and evaluate them.

Part D: Acceleration on the Roller Coaster—Pulling *g*'s

1. On a roller coaster, you often feel heavier or lighter as you whip around curves or go up or down hills. You can feel the accelerations with your body. This is often called "pulling *g*'s." Recall that *g* stands for acceleration due to gravity. The Terminator Express has a number of places where a rider would be pulling *g*'s. Try to imagine a ride on the roller coaster shown in the diagram below.

Top View of the Terminator Express



a) Make a new copy of the drawing of The Terminator Express. Indicate where the riders might feel light, and where they might feel heavy. Also indicate on the diagram where you think the coaster is speeding up and where it is slowing down.

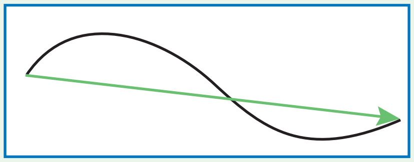
Physics Talk

MEASURING VELOCITY AND ACCELERATION

In this section, you were introduced to some terms that you will need to understand in order to redesign The Terminator Express.

Distance, a **scalar** quantity, can be measured with a flexible piece of string or a metric tape measure placed along a path. The unit of measurement used is usually a meter. For example, an object travels 3 m.

Displacement is a measured distance with a direction included. Displacement depends only on the endpoints, not on the detailed path. If an object travels 3.5 m in an eastern direction, the displacement is recorded as 3.5 m, east. Displacement, a **vector**, has magnitude (size or length—3.5 m and direction—east. In the diagram shown, the curve represents the actual path of an object. The straight line represents the displacement.



If you were to walk from your home to school and back again, the distance traveled may be 5 km. The total displacement would be zero because your final position and your initial position are identical.

Speed is the distance traveled divided by the time elapsed. An object's speed may be 4 m/s. This means that the object moves 4 m every second if it continues to move with this speed. Speed is a scalar. It has no direction.

Velocity is the displacement divided by the time elapsed. The object's velocity may be 4 m/s south. Velocity is a vector. It has magnitude (4 m/s) and direction (south).

The equation to calculate average velocity is

$$\text{average velocity} = \frac{\text{displacement}}{\text{time elapsed}}$$

$$v = \frac{\Delta d}{\Delta t},$$

where v is the average velocity,

Δd is the displacement, and

Δt is the time elapsed.

The symbol Δ (delta) signifies "change in."
The symbol Δ always means final value – initial value.

So, $\Delta d = d_{final} - d_{initial}$, or change in position,

and $\Delta t = t_{final} - t_{initial}$, or time elapsed.

Physics Words

scalar: a quantity that has magnitude (size/amount), but no direction.

displacement: the difference in position between a final position and an initial position; it depends only on the endpoints, not the path; displacement is a vector quantity, it has magnitude (size) and direction.

vector: a quantity that has both magnitude (size/amount) and direction.

speed: distance traveled divided by the time elapsed; speed is a scalar quantity, it has no direction.

velocity: displacement divided by the time elapsed; velocity is a vector quantity, it has magnitude (size) and direction.

This is the method you used to measure the speed of the ball in the *Investigate*. If you also recorded the direction in which the ball was moving, then you have the information needed to describe the ball's velocity.

For a person walking one lap around a city block, the distance is equal to the perimeter of the city block. The speed is equal to this distance divided by the time to complete the walk. The displacement for the entire trip equals zero (since the person ended up where she started) and the velocity equals zero as a result.

You will find that in some cases it is distance that is important and in other cases displacement is important. It will be important to keep the difference between the two ideas in mind. It may seem that defining both distance and displacement as well as speed and velocity complicates things. However, scientists occasionally introduce terms and distinctions that seem to make simple things more complicated because they are then able to make very difficult things much easier to explain and understand.

Physics Words

acceleration: the change in velocity divided by the time elapsed; acceleration is a vector quantity, it has magnitude (size) and direction.

Acceleration is the change in velocity divided by the time elapsed. An object's acceleration may be 5 m/s per second. If the direction stays the same, this means that the object changes its speed by 5 m/s every second if it continues with the same acceleration. The speed will increase from 0 m/s to 5 m/s to 10 m/s to 15 m/s with each change requiring one second. The acceleration of 5 m/s every second is also written as 5 m/s^2 (five meters per second squared).

The equation to calculate acceleration is

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time elapsed}}$$

$$a = \frac{\Delta v}{\Delta t},$$

where a is the acceleration,

Δv is the change in velocity, and

Δt is the time elapsed.

Note that the acceleration (a vector quantity) will be in the direction of the change in velocity.

When you measured the acceleration of the ball rolling down the incline in the *Investigate*, you measured the velocity of the ball at two different times. The acceleration is then given by the change in velocity divided by the time interval between the two velocity measurements. In *Active Physics Plus*, you will explore acceleration when the direction of the velocity changes.

Checking Up

1. Explain the difference between distance and displacement.
2. You went to school and back home, a total distance of 2 km. What is your displacement?
3. What is the difference between speed and velocity?
4. How can you find the acceleration of an object?

Active Physics Plus

+Math	+Depth	+Concepts	+Exploration
◆◆	◆◆		

Subtracting Vectors

In *Part C* of the *Investigate*, you found the acceleration when a steel ball speeds up or slows down while traveling in a straight line. In *Part B*, you probably found that riders get a "thrill" when their velocity changes direction even if they do not speed up or slow down. Whenever velocity changes direction, acceleration occurs. How do you find acceleration when only the direction of the velocity changes and the speed remains the same?

Assume that you are traveling east at 1 m/s and that 1 s later you are traveling north at 1 m/s. Your speed (1 m/s) has not changed but your velocity changed because its direction changed.

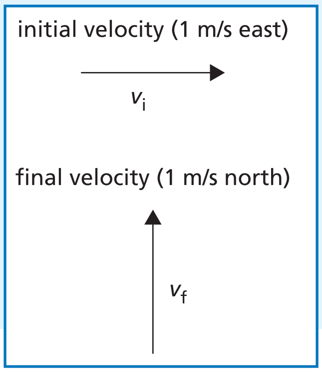
$$\text{Acceleration} = \frac{\text{change in velocity}}{\text{time elapsed}}$$

$$a = \frac{\Delta v}{\Delta t}$$

Δv is the change in velocity

$$\Delta v = \text{final velocity} - \text{initial velocity}$$

You can represent the velocities by arrows (vectors). Here are the vectors for the situation described: The length of the arrow represents the speed. The arrow is drawn to scale, in this case 1 m/s = 2 cm.

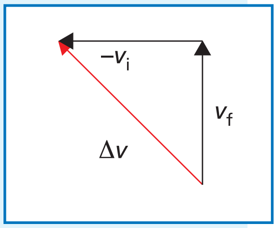


To find the change in velocity you need to subtract vectors, but you have only learned how to add vectors. You can turn your subtraction problem into an addition problem. Recall from algebra that subtracting a number is equivalent to adding the negative of the number. For vectors, the negative is represented by an arrow pointed in the the direction opposite to that of the original vector.

$$\Delta v = \text{final velocity} - \text{initial velocity}$$

$$\Delta v = \text{final velocity} + (-\text{initial velocity})$$

You can add the final velocity and the negative of the initial velocity. The negative of the initial velocity has the same magnitude but the opposite direction.



The change in velocity is represented by the red vector in the diagram to the right.

The acceleration (strictly speaking, the average acceleration) will point in the direction of the red arrow Δv and its magnitude will be given by the magnitude (length) of Δv divided by the time elapsed (in this case 1 s).

a) Use the Pythagorean theorem to find the length of Δv.

b) Compute the value of the (average) acceleration.

c) The direction of the acceleration will be in the direction of Δv. What is the angle between Δv and the eastward direction?

d) Suppose the initial velocity is 4 m/s north and the final velocity 2 s later is 3 m/s west. Draw a diagram showing the change in velocity. Use the Pythagorean theorem to find the magnitude of Δv and then find the magnitude of the acceleration. Use a protractor to measure the angle of Δv with respect to the westward direction. That will specify the direction of the acceleration.

What Do You Think Now?

At the beginning of this section, you were asked the following:

- **Which part of the roller-coaster ride produces the loudest screams? Why?**

Given what you have learned about velocity and acceleration and what you observed with the student riding in the moving chair, where will the riders in your roller-coaster ride experience acceleration? Which parts will produce the greatest "thrills"?

Physics

Essential Questions

What does it mean?

Scientists need to develop a precise vocabulary to talk about motion. You used the terms speed, velocity, and acceleration to describe the motion of a ball rolling down a ramp. Explain what each of these terms means.

How do you know?

Physicists often find that one concept is particularly important in understanding a given situation. You probably found that the blindfolded rider rated the "thrills" highest while being accelerated. What was the evidence for that? How do you know when the rider is being accelerated?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Forces and motion	* Change and constancy	Makes mathematical sense

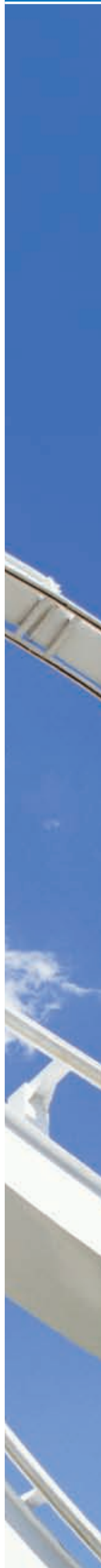
* It is important to distinguish between scientific concepts that are often used interchangeably in everyday language. Speed and velocity are two such concepts. The speedometer in your car indicates the car's speed (usually in miles per hour or kilometers per hour or both). What instrument could cars have that allows you to observe the car's velocity?

Why should you care?

Velocity and acceleration are the two most important concepts in describing motion of all kinds. Give some examples in everyday life where the distinction between velocity and acceleration is important. Why are velocity and acceleration important in a roller-coaster ride? How will understanding the difference between velocity and acceleration help you in your *Chapter Challenge*?

Reflecting on the Section and the Challenge

A big part of roller-coaster fun comes from the physics of velocity and acceleration. Traveling at a high speed is not enough to give a big thrill. The thrills come from accelerating around the curves and along the straight segments. Acceleration may change your speed or your direction (or both) as you ride along the path of the coaster. More rapid changes require greater accelerations. Additional thrills come from changes in acceleration. In designing your variation of The Terminator Express, you will want to ensure that the speeds and accelerations are right for your riders. You are required to have hills and turns, but the loop may be too much for your riders. There are more safety concerns for younger riders.



You are now able to draw top and side views for your variation of The Terminator Express and to note where the accelerations (and fun) may occur. If you were to build a prototype of part of the roller coaster, you could also make measurements of velocity and calculate accelerations.

Physics to Go

1. Draw a top view and a side view of a new version of The Terminator Express with the following characteristics: The roller coaster car begins from the loading platform and then rises along the lift. It arrives at the top of hilltop #1 and makes its first drop. It then climbs hill # 2 that is half the height of hill # 1. The car then goes along the back curve, rises over hilltop # 3, and swings into a horizontal circle. The coaster then comes out of the circle onto a level plane. The brakes are applied and the roller coaster comes to a stop.
2. Identify where the biggest thrill will be in The Terminator Express roller coaster. Explain why this will be the big thrill.
3. Speed by itself does not produce thrills. Living on Earth, you already have a big speed, since Earth is constantly turning.
   a) Earth makes a complete revolution once every 24 h. La Paz, Bolivia is close to the Equator and travels a large circumference in 24 h. Oslo, Norway is close to the Arctic Circle and travels a smaller circumference in 24 h. Which city has the greater speed?
   b) The circumference of Earth's Equator is about 40,000 km. It requires one day or 24 h to complete one revolution. Calculate the speed you are traveling on Earth if you are at the Equator.
   c) Why do you not get a big thrill going at such a high speed?

4. A roller-coaster rider traveling in a straight line changes from a speed of 4 m/s to 16 m/s in 3 s. Calculate the acceleration of the ride.

5. Identify the following situations as an example of either distance, displacement, speed, velocity, or acceleration.

   a) a car traveling at 50 km/h

   b) a student riding a bike at 4 m/s toward home

   c) a roller-coaster ride whips around a left turn at 5 m/s

   d) a roller-coaster car is dragged up a hill 12 m tall traveling at 3 m/s.

   e) a train ride takes you 150 km northwest

6. A lab cart is 10 cm long. It travels through a velocimeter in 2 s. Calculate the cart's speed.

7. A second lab cart is 5 cm long. If it were traveling at the same speed as the cart in *Question* 6, what would the velocimeter record as the elapsed time?

8. Your vehicle accelerates from 0 to 25 m/s (about 55 mi/h) in 10 s while traveling down a straight street. What is the acceleration of your vehicle?

9. As noted in the *Physics Talk*, physicists often introduce terms and distinctions that seem to make simple things more complicated. As you were told, these distinctions can make very difficult things much easier to explain and understand. Give an example outside of physics where you make a distinction for simple things so that complicated things will be easier to understand?

10. ***Preparing for the Chapter Challenge***

    Suppose you were designing a roller coaster for young preschool children.

    a) Describe two changes you would make to The Terminator Express roller coaster. Explain why you would make these changes.

    b) Draw the top and side view of the roller coaster with these additional changes.

Inquiring Further

Research roller coasters

Research roller coasters on the Internet. Which are the most modern? What are some innovations in newer roller coasters? What features from historic coasters have been retained? Compare wooden and steel roller coasters.