Section 7 Circular Motion: Riding on the Curves

What Do You See?

Learning Outcomes

In this section, you will

- **Recall** the idea that an object in motion remains in motion with a constant velocity unless acted upon by a force - Newton's first law.
- **Explain** how a force directed toward a center (a centripetal force) will allow a roller-coaster cart to travel in circular motion.
- **Describe** how the centripetal force is dependent on the speed and the radius of the curve and the mass of the cart.
- **Solve** problems using the equation for centripetal force.
- **Recognize** that safety considerations limit the acceleration of a roller coaster to below 4 *g*.

What Do You Think?

The first looping coaster was built in Paris, France. It had about a 4-m (13 ft) diameter loop. One of the largest loops today is about 35 m (120 ft) wide.

- **Why don't you fall out of the roller-coaster cart when it goes upside down during a loop?**

Record your ideas about this question in your *Active Physics* log. Be prepared to discuss your response with your small group and the class.

Investigate

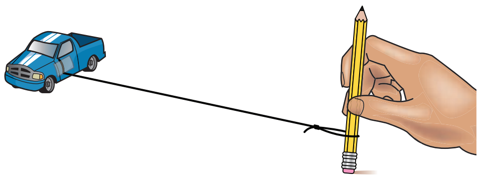
In this *Investigate*, you will explore the behavior of the roller coaster on horizontal curves where you feel pushed to the side and on vertical curves where you find yourself upside down. The more you understand about the requirements of curves on roller coasters, the better your roller-coaster design will be.

Part A: Moving on Curves

1. A battery-operated car can move when you turn on the switch. Investigate the toy car's motion under different circumstances.

a) Turn on the car and let the car run on the floor. Describe its motion in your *Active Physics* log.

b) Attach one end of a string to the side of the car. Loosely tie the other end of the string around a pencil, and hold the eraser end of the pencil firmly on the floor. Turn on the car, and describe the car's motion.



c) Predict what will happen to the motion of the car when you let go of the pencil end of the string. Provide a reason for your prediction.

d) Test your prediction and record your observations in your log.

Be sure to pick up the car from the floor when it is not in use so it does not present a hazard for people walking in the room.

2. Your investigation with the toy car demonstrates that a force is needed for circular motion. This is a big idea that takes some getting used to. Whenever you see anything moving in a circle or on any curve, you should remind yourself of the movement of the toy car and the string. Without the force of the string, the car moves in a straight line.

If something moves in a circle, there must be a force that constantly veers it away from the straight line to keep it moving in a circle.

a) What force kept the toy car moving in a circle?

b) In which direction must this force point?

3. There is no string that keeps a real automobile moving around a curve. However, if the automobile is to move around the curve, there must be a force pointing toward the center of the curve. Imagine a curved road surface covered with slick ice. The automobile would not "make the curve" but would keep moving in a straight line and go off the road. It wouldn't matter which way you pointed the wheels — no turning would occur. What is the force that keeps a real automobile moving around a curve in normal traffic conditions?

4. In a roller coaster, there are horizontal curves similar to those on the road.

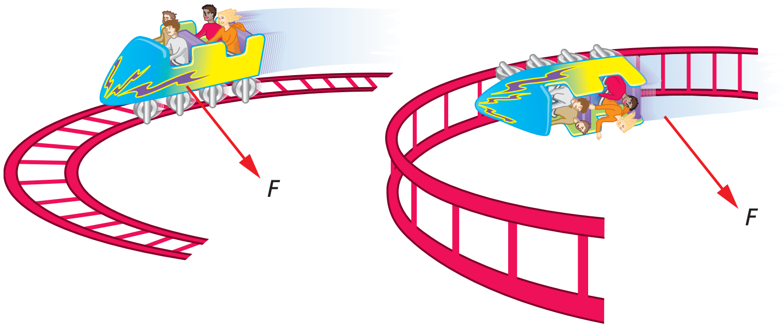
a) Sketch the coaster moving around a horizontal curve.

b) Draw an arrow coming from the coaster car that shows the direction of the velocity of the coaster when the car is part way around the curve. (Remember, the toy car went straight when you released the string.)

c) Now, add another arrow to the coaster car showing the direction of the force that keeps the coaster moving in a circle. Note that the arrow in *b*) represents the velocity vector. In this case, the arrow represents a force vector.

5. There are two orientations of the roller-coaster car you will investigate as it travels in a horizontal circle. The passengers can be sitting up as they would in an automobile with the wheels of the roller coaster down. They could also be on their sides with the wheels of the roller coaster facing away from the center of the circle. In each of these orientations, the force moving the cart in a circle will be toward the center of the circle.

a) Look at the diagrams on the next page. Is this the way that you drew the force arrow in *Step 4.c*)?



Make any changes necessary to your diagram and talk your ideas over with your team if you have questions.

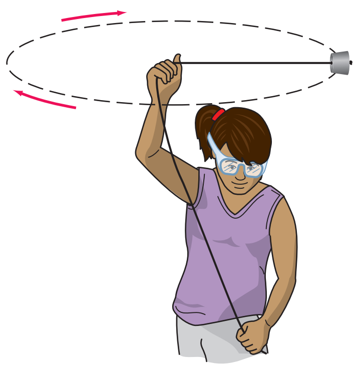
b) Identify the force that causes the roller coaster to move in the circle in each of the following cases: with passengers sitting in the usual sitting position, and with passengers and the coaster cart turned sideways.

c) The coaster car, whether stationary or moving also has forces in the vertical direction – its weight and the force of the ground pushing up. Draw a small box to represent the coaster car and the passengers. Attach arrows to this box that represent all of the forces acting on the coaster and passengers as it goes in a circle.

Part B: How Much Force is Required?

1. Your teacher will supply you with three rubber stoppers and a string. Put on your safety goggles. Twirl the stopper at a slow speed in a horizontal circle like helicopter blades. Gradually increase the speed.

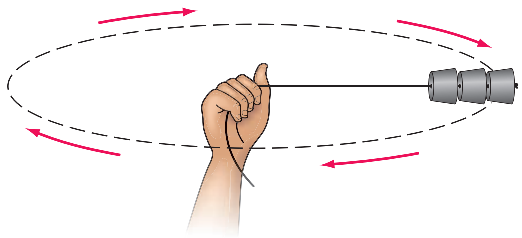
Wear safety glasses to protect your eyes in case the string should break or your partner accidentally loses grip of the string. Everyone must be wearing safety glasses. Stand clear of anything that is breakable, such as glass.



a) Observe and record the force that your fingers are applying to the string at a slow speed and as you increase the speed of the stopper.

b) Write down a description of what you observed about the relationship between the speed of the stopper and the force of your fingers.

2. Now twirl a string with two or three rubber stoppers attached. Hold the string so that the length of the string for the multiple stopper is the same as the length of the string for one stopper.



a) Compare the force that your fingers applied to a string with one rubber stopper and a string with more than one stopper.

b) In comparing one stopper with three, why did you keep the speeds and radii (length of string) of the circular twirls identical?

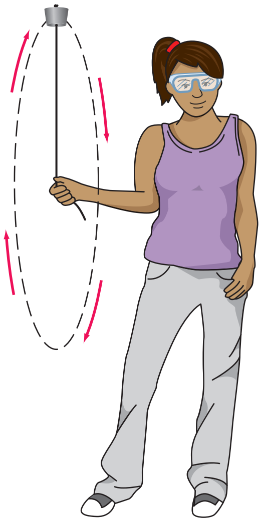
c) Write down your observations about the force of your fingers and the mass of the stoppers.

3. Twirl one stopper, but this time, change the length of the string.

a) Write down a description of what you observed concerning the length of the string and the force on your fingers.

b) What properties of the twirling stopper must you keep constant if you wish to compare only how changes in length affect the required force?

4. Now twirl the stopper in a vertical circle.



a) Observe how the force your fingers exert on the string is different when the stopper is near the top of the circle and when it is at the bottom of the circle.

b) Write down a description of how this force changes. Is it larger when the stopper is at the top of the loop or when it is at the bottom?

c) Twirl the stopper in a vertical circle and gradually reduce the speed of the stopper. At some point, the speed will be so low that the string goes slack and the stopper no longer moves in a circular path. When the string goes slack, it is no longer exerting a force on the stopper. Record your observation of where the string goes slack.

5. To keep a roller coaster moving in a circle, a force is required toward the center of the circle. The track pushing on the edges of the wheels, the surface of the track pushing on the rims of the wheels, the force of gravity on the coaster car, or some combination of these forces can supply this force.

a) How does the required force change when the speed of the roller coaster changes?

b) How does the required force change when the mass of the roller coaster changes?

c) How does the required force change when the radius of the curve changes?

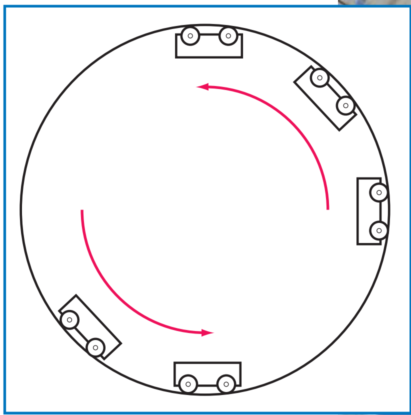
d) If the speed of a roller coaster were increased, how might you strengthen the track to provide the additional force required?

6. In physics, scientists often look at "limiting cases" (or "extreme cases") to help understand a concept better. A limiting case is the most extreme case that you may imagine. For instance, analyze the limiting cases for a roller coaster going around a horizontal curve that is not banked. If the coaster car's speed got much larger, an extreme case would be a very high speed.

a) If the coaster car were going at a very high speed, would the force required from the track to keep the car moving in the curve be very large or very small? Write your response down in your *Active Physics* log.

b) The other extreme case is a coaster car with zero speed. Would the force that the track would have to provide if the car were moving very slowly around a curve be very large or very small? Write your response down in your *Active Physics* log.

7. The roller coaster may also do a loop as it travels in a vertical circle. If the loop were a perfect circle, as illustrated to the right, there would always have to be a force toward the center of circle.



a) Make a sketch of the loop in your *Active Physics* log.

b) Draw the velocity vector for the coaster at each of the positions shown in the diagram.

c) Draw the centripetal force vectors at each position. This is the force toward the center of the circle that keeps the roller-coaster car moving in a circle at each position in a circle.

8. The gravitational force F_w is acting on the coaster car at all times. To move in a circle, there must be a force toward the center of the circle. At the top of the circle, the gravitational force is down toward the center of Earth and acts toward the center of the circle. For a coaster car at the bottom of the circle, the gravitational force remains down toward the center of Earth. However, at the bottom, the gravitational force is in the opposite direction to the force required for circular motion. The only other force at the bottom of the loop is the force due to the track pushing up on the car. This upward force must be responsible for the car moving in a circle.

a) Draw the gravitational force and the force of the track on the coaster car when the car is at the bottom of the loop and moving in a circle.

9. Check your force diagram for the coaster car at the bottom by answering the following questions.

a) Is the gravitational force (weight force) vector pointing down?

b) Is the force of the track pointing up?

c) Is the force of the track pointing up larger than the weight force pointing down? (Hint: at the bottom of the circular loop, the coaster car's net force is up toward the center of the circle.)

10. The force of the track on the coaster car is called the *normal force*, F_N, because it is "normal" or "perpendicular" to the track. This normal force must be present on the car when it rounds the loop at the bottom.

11. A roller-coaster car in a vertical loop always requires a net force toward the center of the loop. At the top of the loop, the car requires a force toward the center of the loop, which is straight down. This net force can be supplied by a combination of the downward force of gravity, and by the downward normal force of the track.

a) In the extreme case, where the coaster car is traveling at very high speed, would the force required to keep it moving in the circle be very large or very small? Since the force of gravity is mg and doesn't change its value, what produces most of the very large force?

b) Describe how the construction of a roller-coaster track in a vertical loop is impacted by the speed of the roller coaster. Enter comments and ideas into your engineering design process, too.

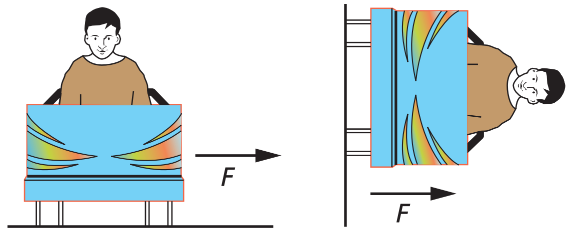
Physics Talk

CENTRIPETAL FORCE AND ACCELERATION

A battery-operated car can move in a straight line at constant speed. As you saw in the *Investigate*, this same car can move in a circle if a string is attached to the car and the end of the string is held fixed at a point on the floor. The string supplied a force toward the center of the circle that kept the car moving in a circle. All objects moving in circles or curves must have a force toward the center of the circle.

Much of the fun of riding a roller coaster comes from whipping around the turns and flipping upside down. All objects moving in circles are accelerating and require a force toward the center of the circle. In a roller coaster moving around a horizontal curve, there is no string toward the center, but there is a force due to the track pushing on the wheels of the roller-coaster car.

In a roller-coaster curve where the car tilts vertically and the wheels face the outside of the circle, the force toward the center is the **normal force** of the track on the wheels. Of course, there must be some support that holds the track in place, but it is the track that acts directly on the wheels of the car. It is called a normal force, F_N, because it is normal (perpendicular) to the track.



Force toward center supplied by the indentation of the track on the wheels

Force toward center supplied by the vertical walls

In any circular motion when the object is moving at constant speed, the force that keeps the object moving in a circle is called the **centripetal force**. The centripetal force is always directed toward the center. Centripetal means "center seeking." The toy car moving in a circle had a centripetal force that was the force of tension in the attached string acting on the toy car. An automobile moving around a curve has the force of friction between the tires and road as the centripetal force. Earth moving around the Sun has a force of gravity toward the Sun. The clothes in a dryer have the walls of the dryer keeping the clothes moving in a circle (the water flies out in straight lines through the holes). The roller-coaster car rounding a turn on its side may have the force of the track as the centripetal force. *The centripetal force is not an additional force.* It is the name given to a force like friction, tension, gravity, or the normal force when that force causes an object to move in a circle. The centripetal force could be a combination of these forces.

In your experiments with the rubber stoppers on the string, you experienced producing the centripetal force (acting via the string) required to keep the stopper moving in a circle. You observed that the centripetal force is larger if the speed of the stopper increases. Also, you observed that the centripetal force is larger if the mass of the stoppers is larger. Finally, you observed that the centripetal force is larger if the radius of the circle is smaller (with the mass and speed remaining the same).

Physics Words

normal force: the force acting perpendicular to the surface.

centripetal force: any force directed toward the center that causes an object to follow a circular path at constant speed.

All of these observations are summarized in the equation for centripetal force.

$$F_c = \frac{mv^2}{r}$$

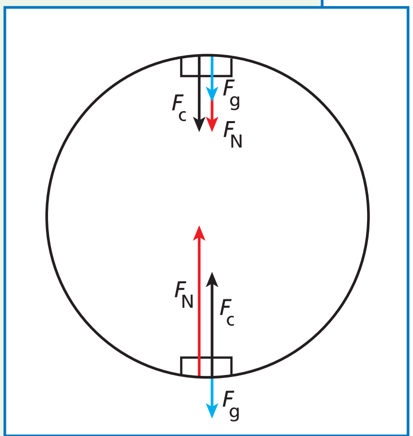
where F_c is the centripetal force,
m is the mass of the object,
v is the speed, and
r is the radius of the circle.

When you are riding in the roller-coaster car and the car goes around a curve, you are also accelerating. You know from Newton's second law that if there is a net force, an object must be accelerating. In the case of circular motion, this force is toward the center of the circle. Therefore, the acceleration must be toward the center of the circle. This is called **centripetal acceleration**. You can feel the contact forces between you and your seat and between you and the side of the coaster car that cause you to accelerate. It is the acceleration and the related contact forces that give you the thrill of riding on the roller coaster.

Physics Words

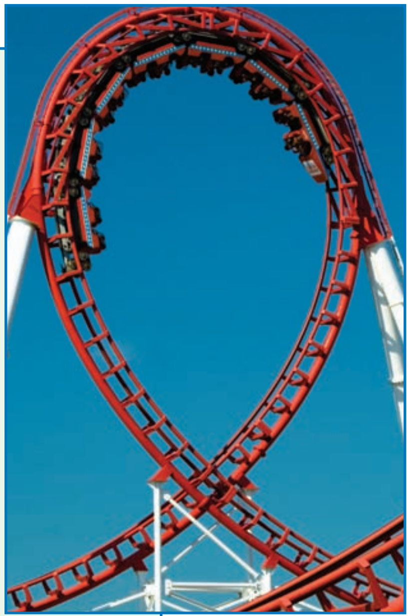
centripetal acceleration: the acceleration directed toward the center of a circle experienced by an object traveling in a circular path at constant speed.

When the roller coaster is in a vertical loop, the direction of the centripetal force is always changing to ensure that the centripetal force vector always points toward the center of the circular track. Pay particular attention to how this is phrased. Although the centripetal force is always toward the center, the direction is always changing since in the circle, the centripetal force may be toward the left or the right or up, but still point toward the center.



In the vertical loop, this centripetal force can be either the gravitational force, the normal force of the track on the coaster car or a combination of the two. When it is a combination of the two, you must add the forces as vectors. At the bottom of the circle, the normal force (red vector) points toward the center of the circle (upward) while the gravitational force (blue vector) points downward. The vector sum of these two forces must be toward the center of the circle. You can therefore conclude that the normal force is larger than the gravitational force. The normal force corresponds to your apparent weight, as it did in the investigation in the previous section. This is why you feel as if you weigh more at the bottom of the loop of the roller coaster.

At the top of the loop-the-loop, the gravitational force (blue vector) and the normal force (red vector) both act downward, toward the center of the loop. The sum of these two vectors provides the required centripetal force.



How much of the normal force required to keep the car moving in a circle will depend on the mass and speed of the car.

The black force vectors show the net centripetal force required to keep the car moving in a circular path at the top and bottom of the loop. Notice that the length of the black vectors is different since the coaster car has a larger speed at the bottom of the loop. The directions are different because the centripetal force must always point toward the center of the circle.

The blue force vector represents the force of gravity or weight of the coaster cars. Both weight vectors are identical because the weights of the roller-coaster car are identical at the top and bottom.

The red vector represents the normal force of the track on the car. The sum of the normal force plus the weight must be equal to the required net (centripetal) force. At the top, the normal force is smaller since the weight contributes to the centripetal force. If the speed decreases, the required net centripetal force would be less and less. There comes a point where the gravitational force (weight) would be all that is required to keep the coaster car moving in a circle. In that case, the normal force is zero. In this special situation, where no normal force is required, you could actually have a small gap at the top between the track and the car. The car would continue to move in a circle. If the car were to slow down more, the car would leave the track completely and no longer travel in a circle. That is something you don't want to have happen with your roller coaster!

At the bottom of the roller-coaster loop, the car would need a normal force of the track on the car greater than the weight since the weight is downward and the car needs a net upward force (toward the center of the circle).

This is summarized in the following tables.

Fast-moving Roller Coaster

	Required centripetal force	Force of gravity (weight)	Normal force (the force of the track on the car)
at the top of the loop	5000 N	1000 N	4000 N
at the bottom of the loop	9000 N	1000 N	10,000 N

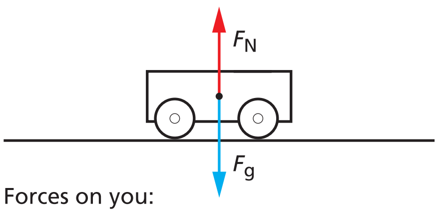
Slow-moving Roller Coaster

	Required centripetal force	Force of gravity (weight)	Normal force (the force of the track on the car)
at the top of the loop	2100 N	1000 N	1100 N
at the bottom of the loop	6100 N	1000 N	7100 N

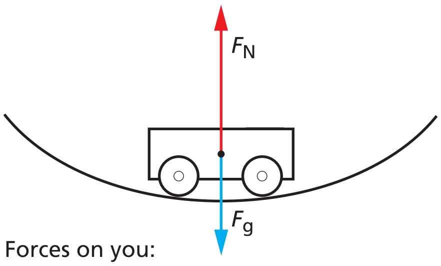
Apparent Weight and the Roller-Coaster Ride

You discovered earlier that an elevator ride could give you a sense of weight changes during accelerations. In the roller coaster loop-the-loop, the passenger will also experience changes in apparent weight. The normal force on the passenger due to the seat is an indication of the apparent weight, as it was in the elevator. A passenger on the roller coaster feels lighter at the top of the loop because the contact force between the passenger and the seat is smaller. This is similar to the elevator because in both cases you feel lighter because acceleration is directed downward. A passenger on the roller coaster feels heavier at the bottom of the loop. Once again, this is similar to the elevator because in both cases you feel heavier because acceleration is upward.

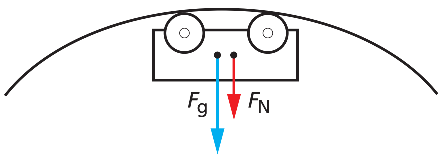
In the slow-moving roller coaster in the chart, the apparent weight (normal force) at the top of the loop may only be 1100 N, while the apparent weight (normal force) at the bottom of the loop may be 7100 N.



Forces on you:
The force of the seat on you = 500 N (apparent weight).
The force of gravity on you is 500 N (weight).



Forces on you:
The force of the seat on you = 1000 N.
The force of gravity on you is 500 N (weight).
You feel as if you weigh 1000 N (apparent weight).



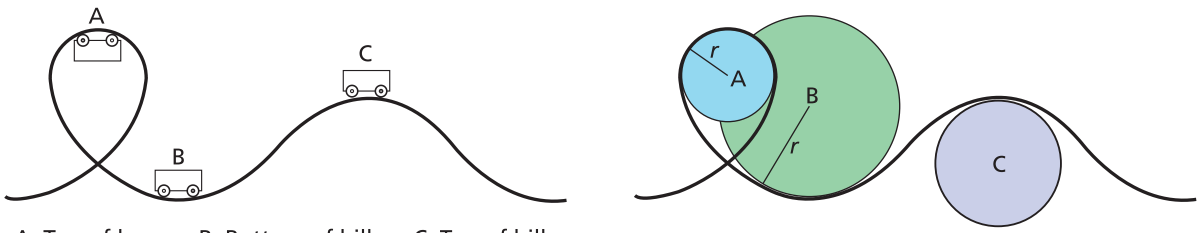
Forces on you:
The force of the seat on you = 100 N.
The force of gravity on you is 500 N (weight).
You feel as if you weigh 100 N (apparent weight).

Three locations can be used to summarize the discussion on forces and weight. On a level track with the coaster car moving at constant speed, the sum of the forces must be zero.

At the bottom of the loop, there must be a net force up toward the center of the circle to keep you moving in a circular path.

At the top of the loop, there must be a net force down toward the center of the circle to keep you moving in a circular path.

Roller coasters do not use loops that are circular. They use a clothoid loop (it has a big radius at the bottom and a small radius at the top). In this way, at the top of the loop the roller coaster is moving in a small circle (smaller radius), while at the bottom it is moving in a larger circle (larger radius). This kind of loop is used to ensure that the roller-coaster car can make the turn at the top but not have an acceleration at the bottom of the loop that exceeds about 4 *g's*. The speed at the bottom is determined by the height of the loop as you saw in *Section 2*. If r is larger at the bottom of the loop, then the acceleration experienced by the riders at the bottom of the loop will be smaller, keeping it within a thrilling but safe range.



A: Top of loop B: Bottom of hill C: Top of hill

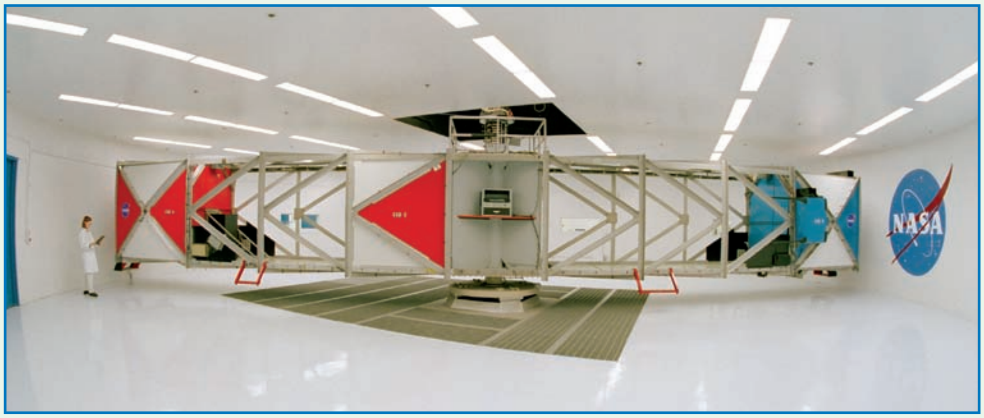
Each of these three situations is basically circular motion.

The type of loop the coaster designers use is called a clothoid. It has a large radius at the bottom, circle *B,* and a smaller radius at the top, circle *A*.

Safety on the Roller Coaster

Test pilots and astronauts experience lots of accelerations during their job performance. To prepare for this, they all go through physical training to see how much acceleration they can endure without getting sick or becoming unconscious. Experiencing an acceleration of more than nine times gravity for a sustained period will cause unconsciousness in most people. Since the acceleration due to gravity is 9.8 m/s^2 or approximately 10 m/s^2, you can refer to other accelerations in terms of 1 *g*. An acceleration of 2 *g's* is approximately 20 m/s^2 while an acceleration of 8 *g's* is approximately 80 m/s^2. Astronauts sometimes experience as much as 6 *g*'s during liftoff.

Safety on a roller coaster requires that you stay below 4 *g's* for the entire ride. You must never go beyond 4 *g's* for even a short time. Changes in small accelerations may make a better ride than one big thrill from a single large acceleration.



Checking Up

1. What is required to make an object travel in a circle?
2. If you are traveling in a circle at constant speed, are you accelerating?
3. At the top of a roller-coaster loop, what two forces provide the centripetal force?
4. What force is responsible for your apparent weight on a roller coaster?
5. How does the centripetal force acting on an object depend upon the object's mass? On the radius of the curve? On the object's speed?

Active Physics **Plus**

+Math	+Depth	+Concepts	+Exploration
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Understanding the Equation for Centripetal Force

The success of physics in describing the world is due to the discovery that mathematics can describe events precisely, accurately, and concisely. You can bring together all of your observations about circular motion into one equation relating the force required to keep an object in circular motion, the object's mass, its speed, and the radius of the circle. First, you note that if there is a net force toward the center of the circle, the object must be accelerating toward the center of the circle. That acceleration is centripetal acceleration. The centripetal acceleration is given by

$$\text{centripetal acceleration} = \frac{\text{speed}^2}{\text{radius of the circle}}$$

$$a_c = \frac{v^2}{r}$$

where a is the object's acceleration,

v is the object's speed, and

r is the radius of the circle.

By Newton's second law there must be a net force in the direction of the acceleration.

$$F_{net} = ma_c$$

$$F_{net} = \frac{mv^2}{r}$$

Recall that the net force F_{net} might be composed of several different forces.

This equation concisely describes your observations. Let's see how this works. If the speed of the object moving around the circle increases, the force required to keep it moving in a circle increases (as the square of the speed). If the radius of the circle is made larger while the speed stays the same, the net force required to keep it moving in a circle gets smaller (r is in the denominator). If the mass of the object increases, the net force required to keep it moving in a circle increases.

The net force, F_{net}, on the left side of the equation is the force required to move something in a circle. It is always directed toward the center of the circle. Such a force is called the centripetal force. When something moves in a circle a force is required. Remember the toy car with the string attached? The string always supplied a force toward the center of the circle and the car moved in a circle. For the toy car, the string force acting on the car was the centripetal force.

$$F_{net} = ma_c$$

$$F_{string} = \frac{mv^2}{r}$$

On the right side of the equation are variables that can change when objects move in circles. They were tested in your investigation as you twirled the cork on a string. The finger force F was equal to mv^2/r.

1. a) As the mass increases on the right side of the equation, then the right side of the equation gets larger. What happens to the F_{net}? Describe in your log how this agrees with your observations.

   b) If the velocity increases on the right side of the equation, what happens to the F_{net}? Describe in your log how this agrees with your observations.

The equation tells you more about how the change in velocity affects the force than you could determine from your qualitative exercise. The equation says that the force increases as the square of the velocity, v^2. If the velocity triples, then v^2 is nine times as large. Tripling the velocity requires nine times the force. If the velocity quadruples (four times as large), then v^2 is sixteen (4×4) times as large. And, if the velocity increases by a factor of 10, then v^2 is 100 times as large.

2. A rollercoaster car going with twice the speed around a banked curve needs a stronger track. Write down in your log how much stronger the track must be for a doubling of the speed.

3. If the radius of the curve increases on the right side of the equation, then the right side of the equation gets smaller since the r is in the denominator of the fraction. What happens to the F_{net}?

4. Complete the following sentence in your log: The larger the radius for the curve, the _______ the force required to keep the car moving along the curve. If the curve is tight (r is very small) then a _______ force is required.

5. The limiting case of the large curve is where the curve's radius is so very large that the curve and a straight line are hardly distinguishable. On a straight path, no force is required. Describe in your log how this agrees with your observations of the stopper on a string.

Sample Problem

A roller-coaster cart moving at 12.0 m/s enters a horizontal turn with a radius of curvature equal to 20.0 m.

a) What is the centripetal acceleration of the roller coaster?

b) If the mass of the passengers and car is 300 kg, what is the net centripetal force required to keep the car on its tracks?

Strategy: Since you know the speed of the car and the radius of the circle, you can directly calculate the centripetal acceleration. You can then use Newton's second law to calculate the magnitude of the centripetal force. You know that its direction will be in toward the center of the circle.

Given:

$v = 12.0$ m/s

$r = 20.0$ m

$m = 300.0$ kg

Solution:

$$a_c = \frac{v^2}{r}$$

$$= \frac{(12.0 \text{ m/s})^2}{20.0 \text{ m}}$$

$$= 7.2 \text{ m/s}^2$$

Next, find the net centripetal force

$$F_{net} = ma$$

$$= (300.0 \text{ kg})(7.2 \text{ m/s}^2)$$

$$= 2200 \text{ N}$$

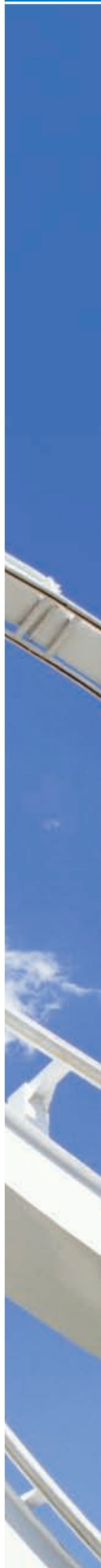
The force will be in the direction of acceleration, toward the center of the circle. Since the track is the only object in contact with the car, this force will have to be supplied by the track to the wheels of the coaster.

What Do You Think Now?

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

- **Why don't you fall out of the roller coaster car when it goes upside down during a loop?**

Review, and if necessary, revise your answer to the question. Use the concepts of circular motion, centripetal force, and force diagrams in your response. Discuss your revisions with other students in your group. How would you explain the answer to a friend who has not done this investigation?



Physics

Essential Questions

What does it mean?

General concepts such as acceleration and force are often given special names for particular circumstances. The crucial concept in this section is centripetal acceleration and centripetal force. Explain the meanings of centripetal acceleration and centripetal force and give some examples of when each applies.

How do you know?

What evidence do you have that a force is required to move a toy car in a circle? Describe the observations you made in this *Investigate* that give evidence that the centripetal acceleration increases if v increases while r stays the same?

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
* Forces and motion	Models	Good, clear explanation, no more complex than necessary

* The toy car had a string to move it in a circle. Tires on the car provide frictional force on the road that allows your car to make a turn and move in a circular path. When you are moving upside down in the loop of a roller coaster, why do you believe that there must be a force pulling you in a circle? What is that force?

Why should you care?

Traveling along curves occurs in many situations. Give some examples of centripetal acceleration in everyday life. How will what you learned in this section about centripetal acceleration help you with your challenge?

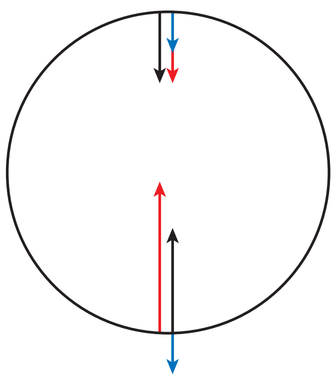
Reflecting on the Section and the Challenge

All objects moving in circles require a centripetal force toward the center. With a toy car attached to a string, the tension in the string is the centripetal force. A roller-coaster car rounding a horizontal turn has the track pushing on the wheels providing the centripetal force. A roller coaster making a turn on its side has the track's normal force as the centripetal force. The upside-down roller coaster has gravity and the normal force from the track combining to produce the centripetal force. At the bottom of the loop, the normal force is larger than the weight force to provide a net centripetal force upward. Since the normal force must be larger than the gravitational force, the passengers feel much heavier at the bottom of the loop. In designing your roller coaster, you will have to ensure that the roller coaster has enough speed to make the full circle. You will also have to ensure that it doesn't have so much speed at the bottom that the apparent weight is too great. You don't want the passengers to be injured!

The loop is one of the big thrills of riding a roller coaster. People are always worried that they will fall out of the roller coaster when it is upside down. This does not happen because they arrive at the top of the loop with a large speed. The gravitational force (weight) at the top of the roller coaster combines with the normal force from the track to serve as the centripetal force that moves the roller coaster in a circular path.

Physics to Go

1. A battery-operated toy car is attached to a string.
   a) If the loose end of the string is held to the ground, draw the path of the car while the battery is running.
   b) If the string were to break while the car was moving in a circle, draw the path that the car would follow.
2. Consider a real car on a road making a turn.
   a) What force has replaced the string of the toy car in *Question 1.a*)?
   b) If the car were to hit a section of ice, draw the path that the car probably would follow.
3. A girl twirls a key chain in a circle. If she twirls it faster, she finds that she holds the chain tighter. Explain why this is necessary.
4. It is a cold night and the roads are icy. If your car is filled with friends, will it be easier or more difficult to make a turn? Explain why.
5. The force equation for circular motion at constant speed is $F_{net} = mv^2/r$. Explain what each of the terms represents.
6. A roller-coaster car is traveling east at 20 m/s. After 2 s, it is traveling north at 20 m/s.
   a) Did the speed of the roller-coaster car change?
   b) Did the velocity of the roller-coaster car change?
   c) What was the change in velocity of the roller-coaster car? Give both magnitude and direction for the change in velocity.
7. Active Physics *Plus* A roller-coaster car is traveling east at 20 m/s in a circular path. After 16 s, it is traveling north at 20 m/s. The circular curve had a radius of 200 m. Calculate the acceleration of the car and give its direction.
8. A roller-coaster car is traveling in a circular loop. Identify the six force vectors in the diagram to the right.



9. In explaining circular motion, someone correctly states that the centripetal force is a name for a combination of forces, but it is not an additional force. Explain what this means.

10. Fill in the missing values in the tables that you created in your *Active Physics* log:

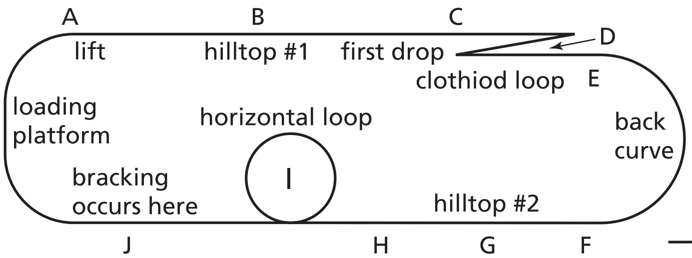
Fast-moving roller coaster			
	Required centripetal force	**Force of gravity (weight)**	**Normal force (the force of the track on the car)**
At the top of the loop	4000 N	500 N	
At the bottom of the loop	6000 N		
Slow-moving roller coaster			
	Required centripetal force	**Force of gravity (weight)**	**Normal force (the force of the track on the car)**
At the top of the loop	800 N		
At the bottom of the loop	2800 N		

11. At which section of a vertical loop would the roller-coaster passengers feel the heaviest? Why?

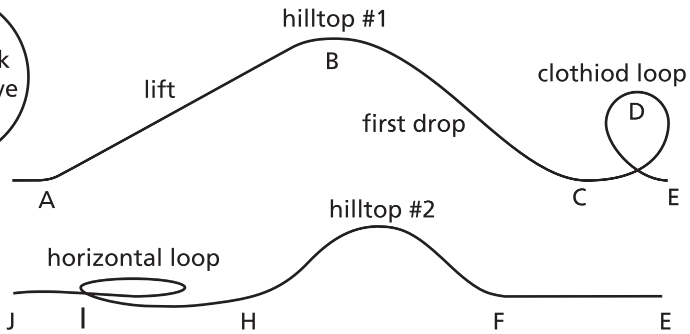
12. Safety requires the roller coaster to be able to make the complete vertical loop and to keep the acceleration under 4 *g*. How can both of these safety features be accomplished at the same time?

13. Use the diagram of the Terminator Express roller coaster. Indicate at which of the following points the passengers will feel heavy, where they will feel light, and where it is uncertain.

The Terminator Express



TOP VIEW



SIDE VIEW

a) C (bottom of hill #1)

b) D (top of the vertical loop)

c) E (bottom of the vertical loop)

d) F (bottom of hill #2)

e) lift hill (going up at constant speed)

14. Using the diagram of the Terminator Express, indicate at which of the following points the centripetal force is up, when it is down, when it is zero, and when it is sideways.

a) C (bottom of hill #1)

b) D (top of the vertical loop)

c) E (bottom of the vertical loop)

d) F (bottom of hill #2)

e) lift hill (going up at constant speed)

f) horizontal loop

g) back curve

15. ***Preparing for the Chapter Challenge***

The *Chapter Challenge* requires you to calculate the accelerations and forces on the roller coaster at different positions. In discussions with your teacher, determine whether the "calculations" should be comparisons of the forces at different positions or involve solving the equations for centripetal acceleration and force.

Inquiring Further

Circular motion on a swing

Imagine that you are swinging back and forth on a playground swing. Use the ideas developed in this section (centripetal acceleration and centripetal force) to explain how the contact force between you and the swing seat changes as you swing back and forth. If you have the opportunity, ride on a swing and pay close attention to how the force that the seat exerts on you changes as you swing back and forth and how that force changes if you get the swing to higher heights.