SECTION 7

Centripetal Force: Driving on Curves

Section Overview

Students identify and test the nature of centripetal force. A toy car is tied to the end of a string and released. The students then relate factors that control the motion of the toy car in a circular path to the motion of a vehicle traveling around a curve. This section builds on Newton's first law. The formula to calculate the centripetal force is provided at a later stage and sample problems further illustrate how the magnitude of force is determined through the given variables. Students also learn from their investigation what happens to an object moving along a circular path in the absence of a centripetal force.

Background Information

Sir Isaac Newton did more than anyone else to unravel the mysteries of motion. Born on Christmas Day in 1642, this English physicist organized his observations into scientific laws that helped predict motion. Newton noticed objects in motion continued to move until a force acted upon them. A ball rolling would continue to move forever if friction did not eventually slow the ball. A surface, like sandpaper, with great friction would slow the ball faster than a surface with low friction. Newton's first law of motion is often called the law of inertia. The law states that an object in motion or at rest will remain in motion or at rest unless acted upon by an outside, unbalanced force. Therefore, an object moving in a straight path must have an outside unbalanced force acting on it to change its velocity (speed) or its path. Any change in the velocity must involve an acceleration ($a = \Delta v/\Delta t$). The change in velocity can be a change in speed, or a change in direction, as is the case for objects moving in a circular path.

In order for an object to stay in a circular path, there must be a force acting on the object to keep it from moving in a straight line (Newton's first law). This force is the centripetal force (F_c) which always acts toward the center of the circle as shown in the equation $F_c = ma_c$.

A ball on the end of a string stays in a circular path because a force acts on the ball to keep it from going in a straight line. This force is supplied by the tension applied to the string from the center of the circle. Previously, the speed of an object was found by using the formula $v = d/t$.

The same formula is used for an object traveling in a circular path, where the distance is the circumference, $2\pi r$, and the time is the period of one complete rotation (called the period — T). Therefore, the speed of an object is $v = 2\pi r/T$.

To find the period, when you know the frequency, $T = 1/f$.

If a turntable is revolving at 10 revolutions per second, the time (period) for one revolution is

$$T = \frac{1}{f} = \frac{1}{10\ \text{rev/s}} = 0.1\ \text{s/rev} = 0.1\ \text{s}.$$

Centripetal Force

According to Newton's first law of motion, an object in motion will continue in motion unless acted upon by an outside unbalanced force (a push or a pull). Therefore, an object that is moving at a constant speed in a circle must have a force acting on that object to keep it turning. That force is the centripetal force.

The centripetal force is directed toward the center of the circular path. The force is supplied by the tension in the string on a flying ball, friction between the tires and the road of a turning vehicle, and gravity as the space shuttle orbits Earth.

Crucial Physics

- Turning an automobile also produces acceleration.
- A force is required to turn an automobile.
  - The force is toward the center of the circle.
  - The force is always changing direction (since it is always toward the center).

Learning Outcomes	Location in the Section	Evidence of Understanding
Recognize the need for a centripetal force when rounding a curve.	***Investigate*** Steps 2, 5-9	Students make an object go in a curve.
Predict the effect of an inadequate centripetal force.	***Investigate*** Steps 2 and 6	Students calculate speed just before the object slides off the turntable.
Relate speed to centripetal force.	***Investigate*** Step 9	Students change the speed to see a change in the centripetal force.

Section 7 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Stopwatch	2 per group	
Ruler, metric, 30 cm	1 per group	
Car, toy, battery operated	1 per group	
Turn table, heavy duty	1 per group	
Piece, wood, 1 in. x 2 in. x 2 in.	1 per group	
Cork, accelerometer	1 per group	
Ball, bocce	1 per group	
Battery, AA	1 per group	
Sandpaper, 60 grit	1 per group	
Tape, masking		1 per class
String, ball		1 per class
Stool, rotating*		1 per class
Helmet, safety*		1 per class
Pads, knee*		1 set per class
Pads, elbow*		1 set per class
Rolled up newspaper or magazine*	1 per group	

*Additional items needed not supplied

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Stopwatch	2 per group	
Ruler, metric, 30 cm	1 per group	
Car, toy, battery operated	1 per group	
Turn table, heavy duty		1 per class
Piece, wood, 1 in. x 2 in. x 2 in.		1 per class
Cork, accelerometer		1 per class
Ball, bocce	1 per group	
Battery, AA	1 per group	
Sandpaper, 60 grit		1 per class
Tape, masking		1 per class
String, ball		1 per class
Stool, rotating*		1 per class
Helmet, safety*		1 per class
Pads, knee*		1 set per class
Pads, elbow*		1 set per class
Rolled up newspaper or magazine*	1 per group	

*Additional items needed not supplied

Note: Time, Preparation, and Safety requirements are based on Plan A, if using Plan B, please adjust accordingly.

Time Requirement

The approximate time for this investigation will be 30 minutes. Extra time will be required to perform more tests with the block on the turntable, investigating different surfaces.

Teacher Preparation

- Check to be certain that the toy cars the students will be using have batteries that are in good shape.
- You might wish to tape a card to the outer edge of the turntable to help students in counting the revolutions per minute.
- Accelerometers come in several varieties. Make certain you understand how each works.
- Either a rotating stool or chair may be used for *Step 10*. If one is not available in your classroom, you might be able to obtain one from another lab.

Safety Requirements

- If a student will be sitting in the rotating chair when holding the accelerometer, be certain that the student has the necessary safety gear to prevent injury should he or she fall out of the chair (helmet, kneepads, etc.).
- If toy cars are used on the floor in *Steps* 2 and 3, make certain they are picked up immediately to prevent a tripping hazard.
- When the ball is pushed across the floor with a magazine, make certain the area is clear of any obstructions the student might run into while concentrating on the ball. The ball must be picked up immediately upon completion of this part of the investigation.

NOTES

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Creating a table to record data	***Investigate*** Steps 4-9	**Augmentation** • Students with organizational and graphomotor issues struggle to create a data table without a model. They are asked to record the type of surface, the radius from the block to the center of the turntable, the time required for 10 revolutions, the number of revolutions per minute, the time for one revolution, the circumference of the circle, and the speed of the block. All this data must be recorded for a number of scenarios. Instruct students to turn their page to landscape format. Then model how to draw a table that will fit all of the required information. Make sure that students draw their tables large enough to include all the data. **Accommodation** • Provide students with a table to tape into their *Active Physics* logs. Provide a ruler or index card to assist students in tracking columns and rows to record data.
Completing calculations with data collected in an investigation	***Investigate*** Steps 4-9	**Augmentation** • Model one example of the correct way to collect the data needed for this *Investigate*. Then show students how to complete one row of calculations that they can use as a reference to complete the *Investigate*.
Understanding vocabulary	***Investigate*** Step 11	**Augmentation** • Students are asked to push the ball with a motion that is perpendicular to the motion of the ball. Students may not remember what perpendicular means. Explain the definition and provide an example. • Model how to push the ball with a motion that is perpendicular to the ball's motion.
Using text to find answers	***Checking Up***	**Augmentation** • Students with reading comprehension issues struggle to use texts effectively or efficiently to understand new information. Instruct students to read the *Checking Up* questions before they read the *Physics Talk* section. This creates a purpose for the reading that will help students focus on the main points needed to answer the questions. **Accommodation** • Give students a copy of the *Physics Talk* and tell them to highlight the answers to the *Checking Up* questions. This allows students to focus only on the reading, instead of both reading and writing at the same time. Also, students can see the reading passage and questions side-by-side.
Understanding vocabulary	***Physics Essential Questions*** Why should you care?	**Augmentation** • This question uses many words that may confuse students, such as "consequences," "exceeding," "imposed," and "road-tire interface." Ask students to restate the question in their own words to check for understanding, or assist a confused classmate before students try to answer the question on their own.
Solving word problems	***Physics to Go*** Steps 1-3, 8	**Augmentation** • Remind students to use their work from the *Investigate* to help them solve these problems.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Following complex procedures	***Investigate***	Break down the *Investigate* into smaller chunks that allow students to comprehend each portion of the investigation before moving on to the next one. This will allow them to get comfortable following the procedures outlined within each step, and also to internalize new concepts and any new vocabulary that is introduced within a step. Lead a brief class discussion after each step to allow students opportunities to demonstrate knowledge and use the vocabulary.
Calculating with pi (π)	***Investigate,*** Step 7	Collaborate with the students' math teachers to determine what level of familiarity students have with pi (π). Also, decide on the value of π you would like students to use for the calculations in this section.
Inferences, Vocabulary comprehension	***Physics Essential Questions*** Why should you care?	Ask students to infer the meaning of "road-tire interface." Using context clues, students can infer that it means the common boundary of the road and the tires. Explain that "interface" is a combination of the base word "face" and the prefix "inter," meaning "between two faces." It may help to connect with the geometrical meaning of "face": a flat surface of a solid.
Vocabulary comprehension	***Inquiring Further*** Question 1	Students may not know the term "banking" in the context of a curve: to build a road upward from the curve's inside edge. A car on a banked curve is not on a horizontal surface. You can model a car traveling on a banked curve with a toy car or even just your hand.

Cloze Activity

Consider finishing this section with a cloze activity. Cloze activities are useful tools for summarizing material and for giving English-language learners an opportunity to practice vocabulary using science words in context. Write the following paragraph on the board, replacing the underlined words with write-on-lines. Encourage volunteers to fill in the blanks.

1-7a Blackline Master

<u>Centripetal acceleration</u> involves a change in a vehicle's <u>velocity</u>, but not necessarily a change in <u>speed</u>. In the equation, $a = v^2/r$, a is <u>acceleration</u>, v is <u>velocity</u>, and r is the <u>radius</u> of the curve. In the equation for centripetal force, $F = mv^2/r$, F is <u>force</u> and m is <u>mass</u>. Circular motion requires a <u>force</u> toward the center of the circle, called the <u>centripetal force</u>. In the case of a car going around a curve, the <u>force</u> is the <u>friction</u> between the tires and the road surface. The smaller the <u>radius</u> of a curve, the <u>lower</u> the maximum safe speed for driving around that curve.

SECTION 7

Teaching Suggestions and Sample Answers

What Do You See?

A vehicle speeding around a curve conveys the topic of this section in a strong visual to stimulate students' curiosity. You might want to ask them why the illustrator has depicted such a scene and how it might relate to concepts they have learned in the previous sections. Expect a range of responses and prompt students by encouraging them to share their perceptions. Have them focus on the illustration and assure them that the purpose of the *What Do You See?* section is to engage them in an inquiry-based discussion and not to determine the accuracy of their responses.

What Do You Think?

Students will come up with various answers. List all the answers on the board, and emphasize the importance of previous concepts in the chapter. Point out that the new concepts they are about to learn hinge on their understanding of factors influencing the motion of objects. While it is not necessary for all answers to be correct, they should be relevant to the context of the question. *The What Do You Think?* questions should lead to a formative discussion.

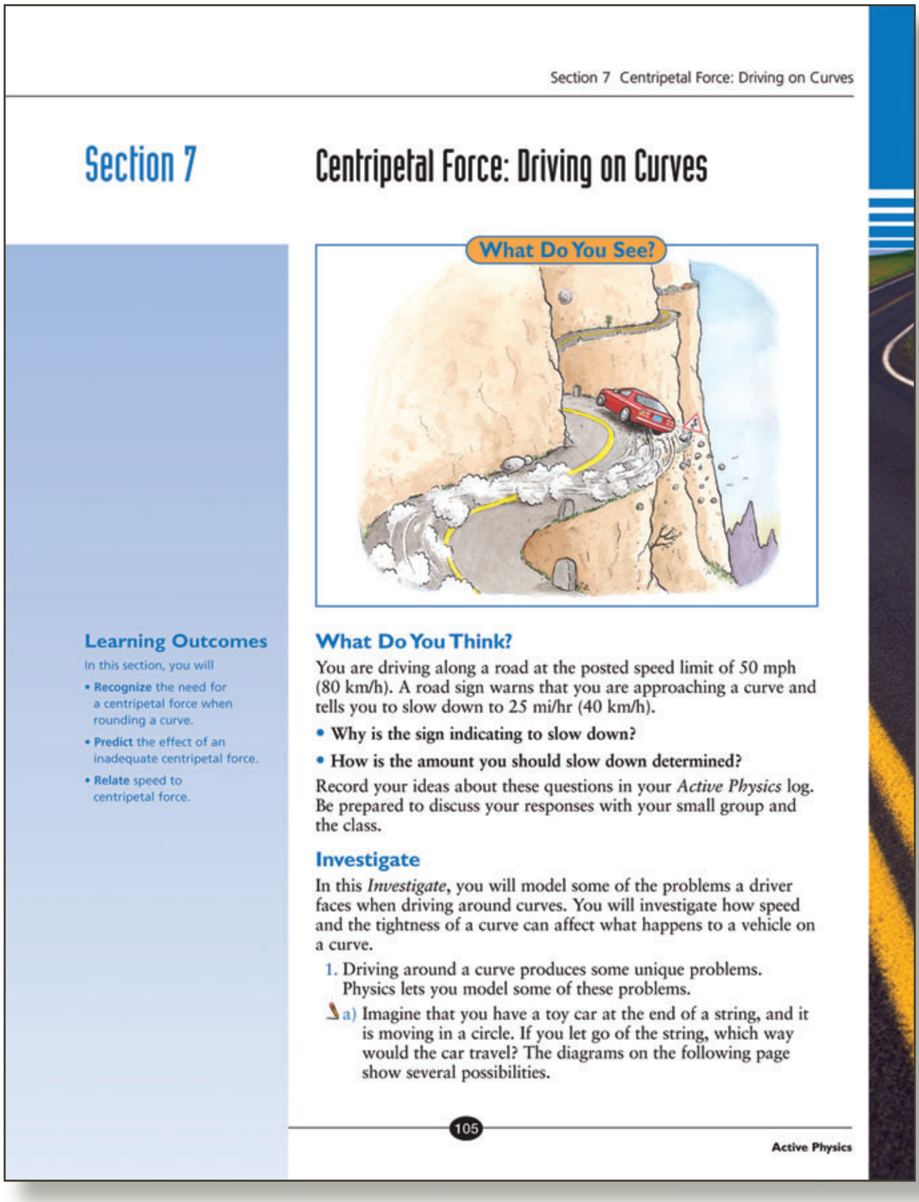
What Do You Think?

A Physicist's Response

The sign is indicating to slow down because at the posted speed limit, which is okay for the straight road, there will not be enough friction to make the curve. From the banking angle of the road, and the friction between road and tires, and from Newton's second law, one can find the maximum velocity with which one can negotiate the curve.

Students' Prior Conceptions

1. **A force is needed to keep an object moving with a constant speed.** Students should explore what happens to the motion of the vehicle when the force maintaining motion along the curve ceases to exist. For example, the friction between the tires and the road diminishes drastically, such as in a skid on an icy road. A classroom demonstration to promote brainstorming on this topic is to twirl a foam ball attached to a string overhead and then quickly release the string from the hand. Describe the motion of the foam ball immediately as it is released from the hand.
2. **Students tend to think of force as a property of an object rather than as a relation between objects.** This section offers another opportunity to explore the nature of pairs of action-reaction forces, as they apply to the friction between the wheels of the vehicle and the surface of the road. Encourage students to identify the pair of forces involved and to correlate them with the objects interacting with each other. What forces act on which objects?
3. **Students may confuse friction with inertia.** When explaining the feelings experienced by the human body when riding as a passenger in a vehicle traveling quickly around a tight curve. Inertia wants the passenger's body to continue moving along a straight line tangent to the path of the circular motion, whereas the friction between the seat and the clothes, and the force of the seatbelt maintain the inward centripetal pull on the passenger.



Section 7 Centripetal Force: Driving on Curves

What Do You See?

Learning Outcomes

In this section, you will

- **Recognize** the need for a centripetal force when rounding a curve.
- **Predict** the effect of an inadequate centripetal force.
- **Relate** speed to centripetal force.

What Do You Think?

You are driving along a road at the posted speed limit of 50 mph (80 km/h). A road sign warns that you are approaching a curve and tells you to slow down to 25 mi/hr (40 km/h).

- **Why is the sign indicating to slow down?**
- **How is the amount you should slow down determined?**

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

In this *Investigate*, you will model some of the problems a driver faces when driving around curves. You will investigate how speed and the tightness of a curve can affect what happens to a vehicle on a curve.

1. Driving around a curve produces some unique problems. Physics lets you model some of these problems.

   a) Imagine that you have a toy car at the end of a string, and it is moving in a circle. If you let go of the string, which way would the car travel? The diagrams on the following page show several possibilities.

Investigate

1.a)

Student answers will demonstrate their misconceptions. The correct answer is diagram B. The toy car continues on the way it was going (in a straight line after the string was released). Do not expect or offer the correct answer.

Students often say that there is a force pushing them outward, away from the center of the motion along the curve; they believe this force, due to friction, is pressing them against the door. With investigation and analysis, students should alter this prior conception to align with the theory that identifies the vehicle as pushing inward on the passenger's body to maintain circular motion, while inertia wants the body to go straight at every point along the curve.

4. **Students may say that the force required to accelerate an object at rest is working against friction, not inertia.** This section is helpful in reviewing this prior conception of students, and to reinforce scientific explanations on inertia—perhaps to even mention the historical scientific developments on inertia and motion promoted by Galileo Galilei.

5. **Students may believe that the effects of inertia while rounding a curve are due to a "centrifugal force" or one that pushes an object outward, away from the center of the circular motion.** This prior conception correlates with the notion of "feeling" something pushing your body against the door of the vehicle while rounding a curve. As mentioned before, inertia wants the body to continue to move in a straight line, tangent to the curve of the traveling vehicle, while the centripetal forces act to push the body inward along a radial line of the curve. Students interpret this interaction as being pushed outward.

2.a)

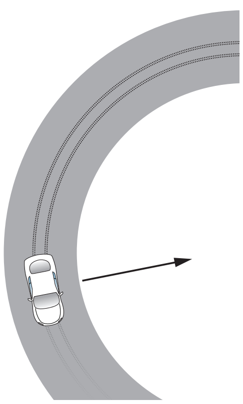
The string pulls the car toward the center of the circle.

2.b)

Along the tangent to the circle — note that it is not a radial path.

3.a)

Make sure students realize the car is travelling in a circular curve. Students' diagram should resemble the one below.

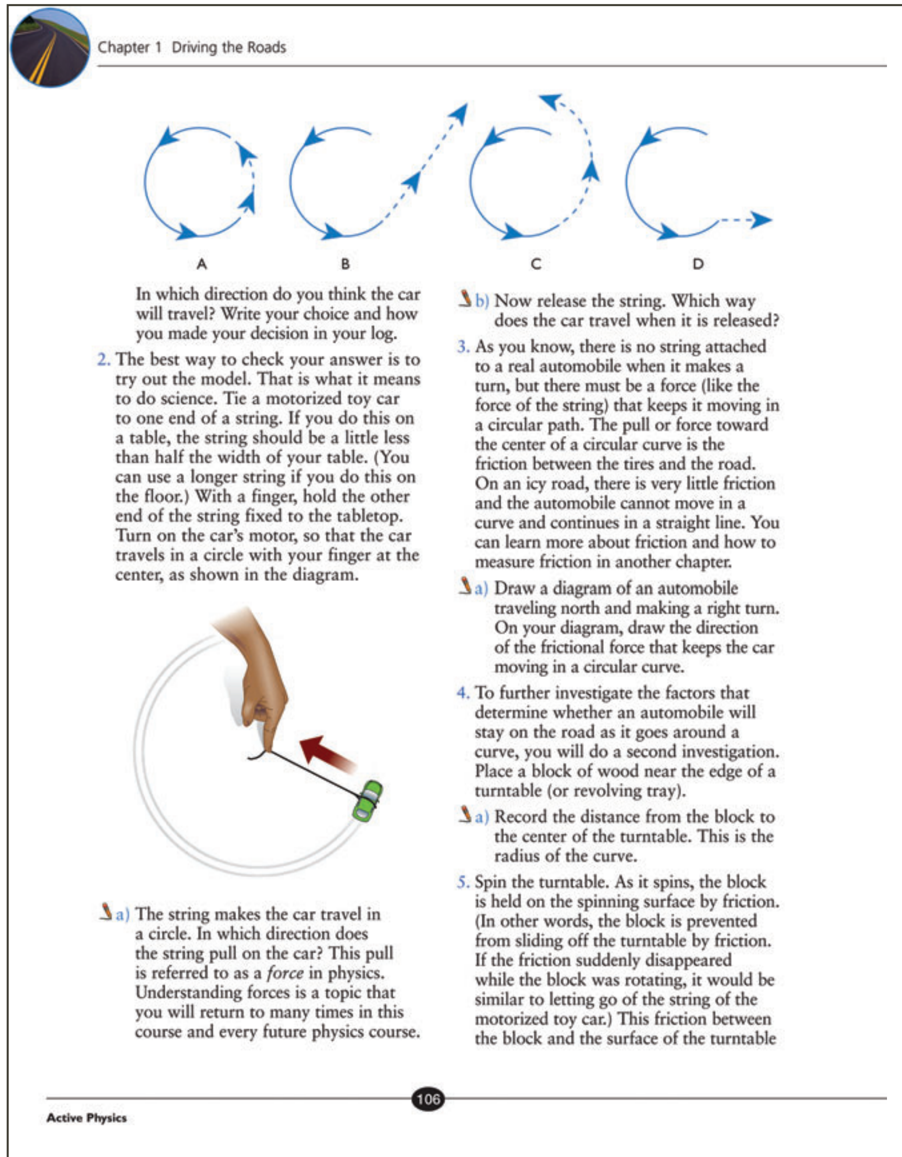


4.a)

Students record the data.

5.

Students spin the turntable to observe the property of friction.



Chapter 1 Driving the Roads

In which direction do you think the car will travel? Write your choice and how you made your decision in your log.

2. The best way to check your answer is to try out the model. That is what it means to do science. Tie a motorized toy car to one end of a string. If you do this on a table, the string should be a little less than half the width of your table. (You can use a longer string if you do this on the floor.) With a finger, hold the other end of the string fixed to the tabletop. Turn on the car's motor, so that the car travels in a circle with your finger at the center, as shown in the diagram.

a) The string makes the car travel in a circle. In which direction does the string pull on the car? This pull is referred to as a *force* in physics. Understanding forces is a topic that you will return to many times in this course and every future physics course.

b) Now release the string. Which way does the car travel when it is released?

3. As you know, there is no string attached to a real automobile when it makes a turn, but there must be a force (like the force of the string) that keeps it moving in a circular path. The pull or force toward the center of a circular curve is the friction between the tires and the road. On an icy road, there is very little friction and the automobile cannot move in a curve and continues in a straight line. You can learn more about friction and how to measure friction in another chapter.

a) Draw a diagram of an automobile traveling north and making a right turn. On your diagram, draw the direction of the frictional force that keeps the car moving in a circular curve.

4. To further investigate the factors that determine whether an automobile will stay on the road as it goes around a curve, you will do a second investigation. Place a block of wood near the edge of a turntable (or revolving tray).

a) Record the distance from the block to the center of the turntable. This is the radius of the curve.

5. Spin the turntable. As it spins, the block is held on the spinning surface by friction. (In other words, the block is prevented from sliding off the turntable by friction. If the friction suddenly disappeared while the block was rotating, it would be similar to letting go of the string of the motorized toy car.) This friction between the block and the surface of the turntable

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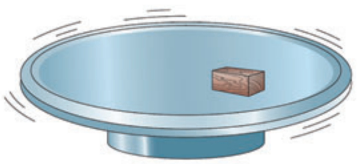
Students' Prior Conceptions *(continued)*

6. **Acceleration is always in a straight line.** In order to apply Newton's second law of motion to motion along a curve, it is helpful for the teacher to interpret the mathematical statement, $\Sigma F = ma$, as the sum of the net forces acting on an object equals the product of its mass and acceleration. Both force and acceleration are vectors, whereas mass is a scalar. The mass of the student remains constant for the short duration of motion; mathematically, this enables the teacher to highlight the direct relationship between the net force and acceleration. They must be in the same direction, parallel to one another. In order to have centripetal motion, a force acts upon an object to push or to pull it in toward the center of the curve; hence, the acceleration also acts inward, toward the center of the curve, perpendicular to the straight-line motion at every point along the curve.

7. **Students may not recognize that a force perpendicular to the straight-line motion of a vehicle is needed at every point along the motion in order for a vehicle to travel along a curve.** Centripetal force, which is a radial force acting toward the center of the curve, confuses students. Prior student knowledge discussed above directly resolves this confusion.

CHAPTER 1

is not identical to the friction that holds an automobile on the road, but it is similar to the friction between the surface of the road and an automobile's tires.



6. Gradually increase the rotational speed of the turntable until the block just begins to slide. To repeat the experiment after the block slides, place it back on the turntable at the original distance from the center. Now practice until you find the fastest speed that allows the block to stay in place.
   - a) Measure and record the time required for 10 revolutions.
   - b) Record the number of revolutions per minute made by the block when the friction is strong enough to keep the block going in a circle.
   - c) How much time goes by during one revolution?
   - d) How fast (revolutions per second) is the turntable turning when friction can no longer hold the block in place?

7. To calculate the speed of the block, divide the distance traveled by the time needed to go that distance.

   When an object moves in a circle, the distance traveled in one revolution is the circumference (distance around the outside) of a circle.

   Circumference = $2\pi \times$ radius of circle

   $C = 2\pi r$

   - a) What was the speed of the block when it stayed on the turntable?
   - b) What was the block's speed when it slid off the turntable? Record your results in a table in your log.

Note: You may not be able to find the exact speed at which the block leaves the turntable. You can find a maximum speed at which the block stays in place. You can call this a safe speed. Any speed lower than the safe speed will also be safe. You can also find the minimum speed at which the block is not able to stay on the turntable. You can call this an unsafe speed. Any speed higher than this will also be unsafe.

8. Tape some sandpaper or place a rubber mat on top of the turntable. Place the block on the sandpaper or the mat. Repeat the entire investigation. Keep the distance between the block and the turntable's center the same as it was previously.
   - a) Record all the necessary data.
   - b) Calculate the greatest speed at which the block can stay on the sandpaper or rubber mat.
   - c) Compare the maximum safe speed with the sandpaper or mat to the maximum safe speed without it. How does the surface affect the maximum speed?

9. In addition to the speed and the road surface, you also need to look at the curvature of the road (how tight the turn happens to be). Curves come in many shapes. The arc of a circle is a good approximation for at least a segment of any curve. The arc of a large circle (a circle with a large radius) can represent a gentle curve. The arc of a small circle (a circle with a small radius) can represent a tight curve.
   - a) Investigate the effect of the amount of curve by placing the block at various distances from the center of the turntable.

6.a)

By timing 10 revolutions, the error in starting and stopping the clock is spread out over a longer time, resulting in less fractional error and higher precision.

6.b)

Write the answer of *6.a)* in rev/s. To convert rev/s into rev/min, multiply by 60 s/min.

6.c)

Time for one revolution or period is equal to 1/frequency. Therefore, from the example above, 1 period = $\frac{1}{2}$ s/rev or 0.5 s.

6.d)

Students observe when the block slides off and records the rpm.

7.a)

Students use $v = 2\pi r/t$ to calculate the speed.

7.b)

Students use $v = 2\pi r/t$.

8.a)

Students record data.

8.b)

Students use $v = 2\pi r/t$ to calculate the speed.

8.c)

The greater the force of friction, supplied by the sandpaper or rubber mat, the greater the speed of the turntable before the block flies off. On a surface with higher friction, an automobile has a higher safe speed while rounding a curve.

9.a)

The students should find that the block will stay on the turntable if the speed remains the same when at a larger radius. If the revolutions per minute are kept the same, the velocity will be greater at the edge, and the block will fly off sooner due to the increased speed and increased radius.

9.b)

As the radius increases, the speed at which the block can travel around the circle without flying off will increase. Make certain the students actually calculate the speed and do not substitute the rpm. The turntable must spin at fewer rpms for the block to have the same linear speed at a larger radius.

9.c)

As the radius of the curve decreases, the cart will fly off at progressively lower speeds.

10.a)

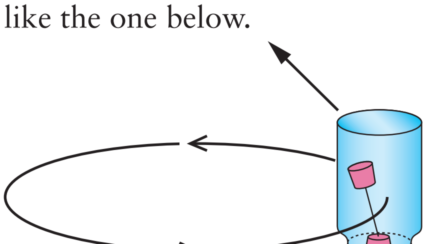
When the automobile brakes, the necklace swings forward; when the automobile speeds up, the necklace swings backward; when the automobile turns, the necklace swings to one side.

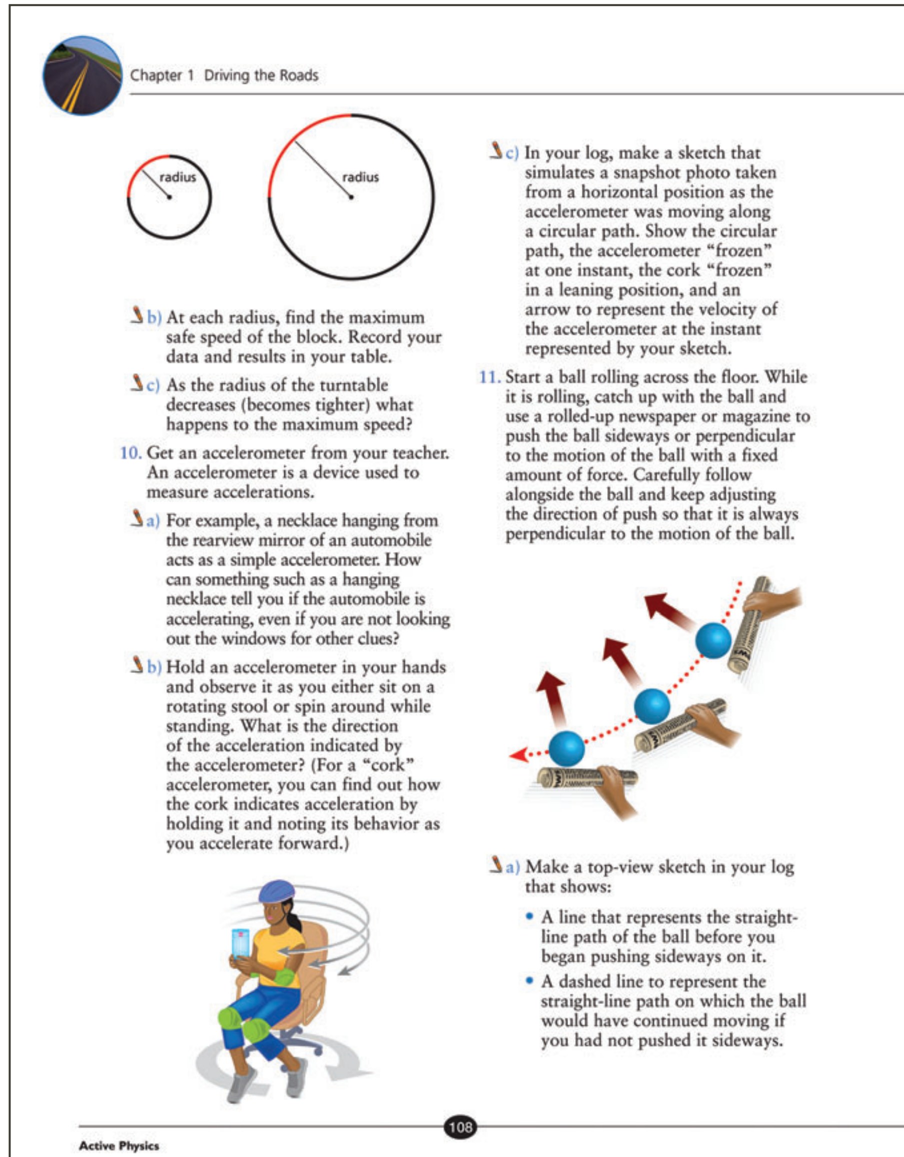
10.b)

For a cork-level accelerometer, students should see the cork pointing toward the center of the circle. Have students compare the direction of their acceleration with the indication on the accelerometer.

10.c)

Students' sketches should look like the one below.





Chapter 1 Driving the Roads

radius

radius

b) At each radius, find the maximum safe speed of the block. Record your data and results in your table.

c) As the radius of the turntable decreases (becomes tighter) what happens to the maximum speed?

10. Get an accelerometer from your teacher. An accelerometer is a device used to measure accelerations.

a) For example, a necklace hanging from the rearview mirror of an automobile acts as a simple accelerometer. How can something such as a hanging necklace tell you if the automobile is accelerating, even if you are not looking out the windows for other clues?

b) Hold an accelerometer in your hands and observe it as you either sit on a rotating stool or spin around while standing. What is the direction of the acceleration indicated by the accelerometer? (For a "cork" accelerometer, you can find out how the cork indicates acceleration by holding it and noting its behavior as you accelerate forward.)

c) In your log, make a sketch that simulates a snapshot photo taken from a horizontal position as the accelerometer was moving along a circular path. Show the circular path, the accelerometer "frozen" at one instant, the cork "frozen" in a leaning position, and an arrow to represent the velocity of the accelerometer at the instant represented by your sketch.

11. Start a ball rolling across the floor. While it is rolling, catch up with the ball and use a rolled-up newspaper or magazine to push the ball sideways or perpendicular to the motion of the ball with a fixed amount of force. Carefully follow alongside the ball and keep adjusting the direction of push so that it is always perpendicular to the motion of the ball.

a) Make a top-view sketch in your log that shows:

- A line that represents the straight-line path of the ball before you began pushing sideways on it.
- A dashed line to represent the straight-line path on which the ball would have continued moving if you had not pushed it sideways.

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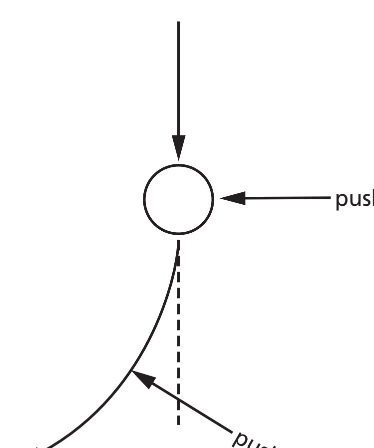
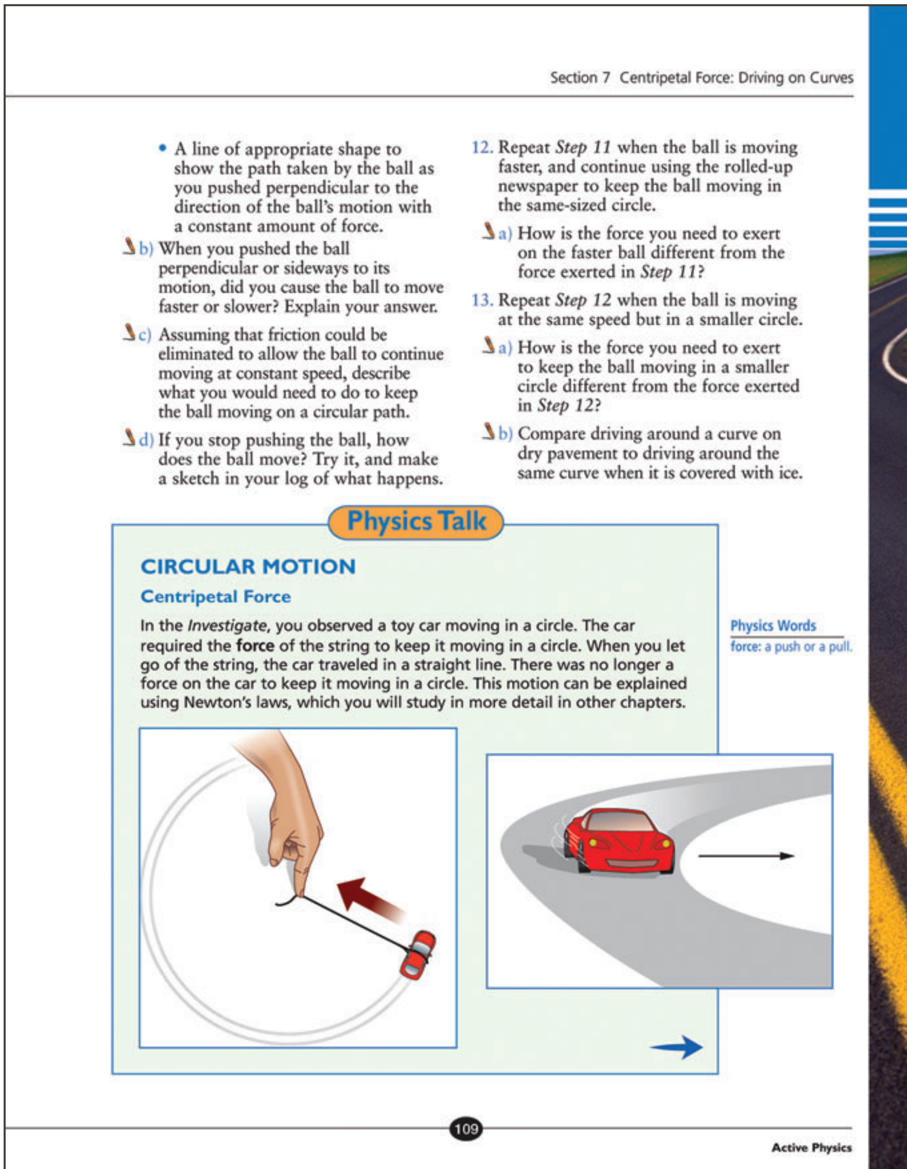
11.a)

Students' sketches should look like the one at right.





Section 7 Centripetal Force: Driving on Curves

- A line of appropriate shape to show the path taken by the ball as you pushed perpendicular to the direction of the ball's motion with a constant amount of force.

b) When you pushed the ball perpendicular or sideways to its motion, did you cause the ball to move faster or slower? Explain your answer.

c) Assuming that friction could be eliminated to allow the ball to continue moving at constant speed, describe what you would need to do to keep the ball moving on a circular path.

d) If you stop pushing the ball, how does the ball move? Try it, and make a sketch in your log of what happens.

12. Repeat *Step 11* when the ball is moving faster, and continue using the rolled-up newspaper to keep the ball moving in the same-sized circle.

a) How is the force you need to exert on the faster ball different from the force exerted in *Step 11*?

13. Repeat *Step 12* when the ball is moving at the same speed but in a smaller circle.

a) How is the force you need to exert to keep the ball moving in a smaller circle different from the force exerted in *Step 12*?

b) Compare driving around a curve on dry pavement to driving around the same curve when it is covered with ice.

Physics Talk

CIRCULAR MOTION

Centripetal Force

In the *Investigate*, you observed a toy car moving in a circle. The car required the **force** of the string to keep it moving in a circle. When you let go of the string, the car traveled in a straight line. There was no longer a force on the car to keep it moving in a circle. This motion can be explained using Newton's laws, which you will study in more detail in other chapters.

Physics Words

force: a push or a pull.

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11.b)

The speed will not change because you are never pushing in or against the direction of motion, but the direction of motion changes.

11.c)

Tether the ball to the center somehow, or always push only toward the center to provide the center-seeking force, keeping it on a circular path.

11.d)

With no friction, the ball continues to move with constant speed in a straight line.

12.a)

As speed of the ball increases, students will have to push harder to keep the ball going in the same-size circle.

13.a)

A larger force is needed to make the ball go in a smaller circle at the same speed.

13.b)

When driving on a curve on dry pavement, friction between the tires and the road provides the force toward the center that is needed to make the car change direction. When driving on ice around a curve, the friction is so low that the tires probably will not have enough friction to make the car change direction and the car will go straight off the road.

Physics Talk

Students gain a clearer understanding of centripetal force through examples of different experiments conducted in the *Investigate*. In order to reinforce the concept of centripetal acceleration, try to come up with additional examples of objects traveling in a circular path, such as clothes spinning in a washing machine or amusement park rides. Ask students to indicate the direction of the velocity at any given point, and the direction of the centripetal force and centripetal acceleration. Engage students in discussing how their knowledge of centripetal force would help them in navigating a curved path while driving. Ask students to explain the factors that must be taken into consideration when they are driving to safely negotiate a curve.

CHAPTER 1

Checking Up

1.

The force that is needed to keep an object moving in a circle is always directed toward the center of the circle along the radius.

2.

The force that keeps an object, moving in a circle, directed toward the center, is called the centripetal force.

3.

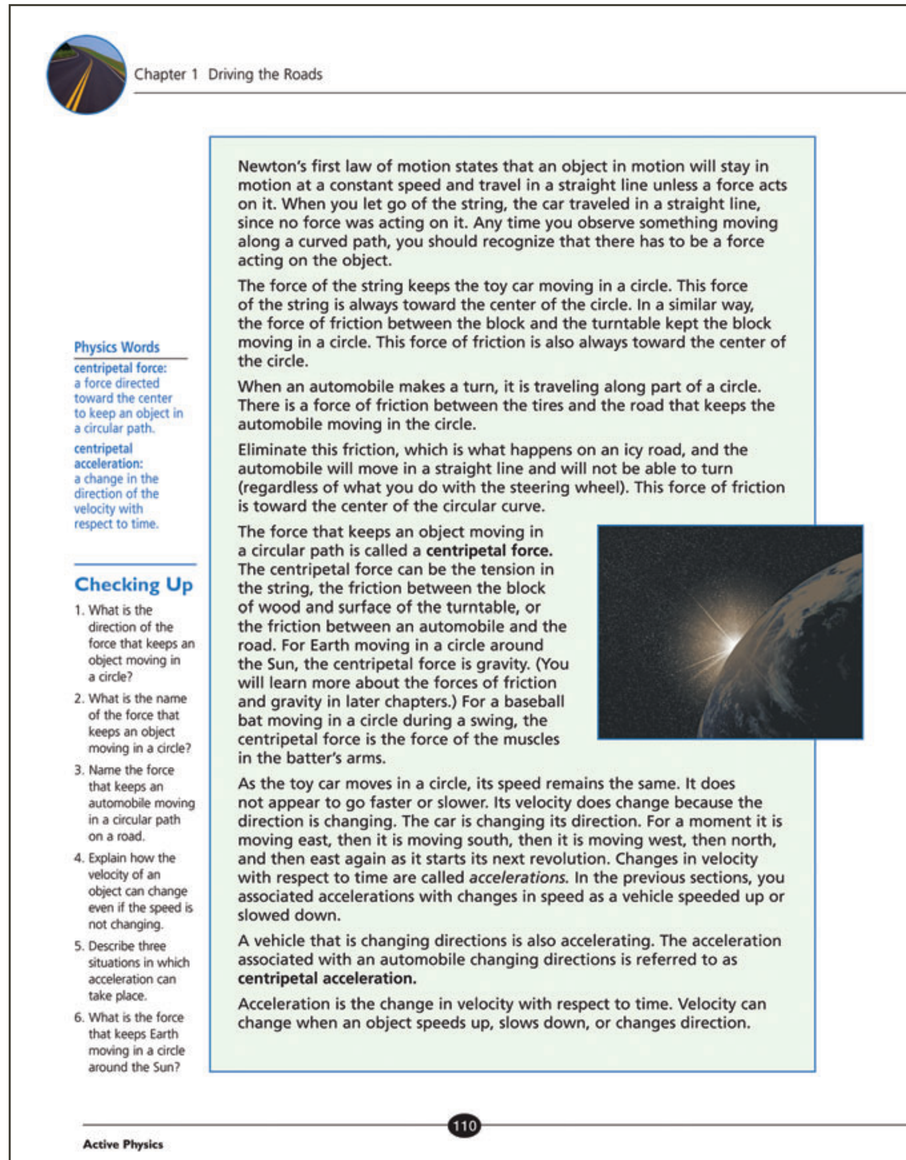
For an automobile going around a circular path on the road, the force of friction between the tires and the road provides the centripetal force.

4.

Velocity is a vector quantity. All vectors have two components — size and direction. The size of the velocity vector is called the speed. When a moving object changes direction, the object's velocity changes whether the speed changes or not.

5.

Acceleration can occur when an object speeds up, slows down, or changes direction. An automobile has three "accelerators" — the gas pedal to speed up, the brake to slow down, and the steering wheel to change direction. All three will cause the velocity to change, and therefore accelerate the automobile.



Chapter 1 Driving the Roads

Newton's first law of motion states that an object in motion will stay in motion at a constant speed and travel in a straight line unless a force acts on it. When you let go of the string, the car traveled in a straight line, since no force was acting on it. Any time you observe something moving along a curved path, you should recognize that there has to be a force acting on the object.

The force of the string keeps the toy car moving in a circle. This force of the string is always toward the center of the circle. In a similar way, the force of friction between the block and the turntable kept the block moving in a circle. This force of friction is also always toward the center of the circle.

When an automobile makes a turn, it is traveling along part of a circle. There is a force of friction between the tires and the road that keeps the automobile moving in the circle.

Eliminate this friction, which is what happens on an icy road, and the automobile will move in a straight line and will not be able to turn (regardless of what you do with the steering wheel). This force of friction is toward the center of the circular curve.

The force that keeps an object moving in a circular path is called a **centripetal force.** The centripetal force can be the tension in the string, the friction between the block of wood and surface of the turntable, or the friction between an automobile and the road. For Earth moving in a circle around the Sun, the centripetal force is gravity. (You will learn more about the forces of friction and gravity in later chapters.) For a baseball bat moving in a circle during a swing, the centripetal force is the force of the muscles in the batter's arms.

As the toy car moves in a circle, its speed remains the same. It does not appear to go faster or slower. Its velocity does change because the direction is changing. The car is changing its direction. For a moment it is moving east, then it is moving south, then it is moving west, then north, and then east again as it starts its next revolution. Changes in velocity with respect to time are called *accelerations.* In the previous sections, you associated accelerations with changes in speed as a vehicle speeded up or slowed down.

A vehicle that is changing directions is also accelerating. The acceleration associated with an automobile changing directions is referred to as **centripetal acceleration.**

Acceleration is the change in velocity with respect to time. Velocity can change when an object speeds up, slows down, or changes direction.

Physics Words

centripetal force: a force directed toward the center to keep an object in a circular path.

centripetal acceleration: a change in the direction of the velocity with respect to time.

Checking Up

1. What is the direction of the force that keeps an object moving in a circle?
2. What is the name of the force that keeps an object moving in a circle?
3. Name the force that keeps an automobile moving in a circular path on a road.
4. Explain how the velocity of an object can change even if the speed is not changing.
5. Describe three situations in which acceleration can take place.
6. What is the force that keeps Earth moving in a circle around the Sun?

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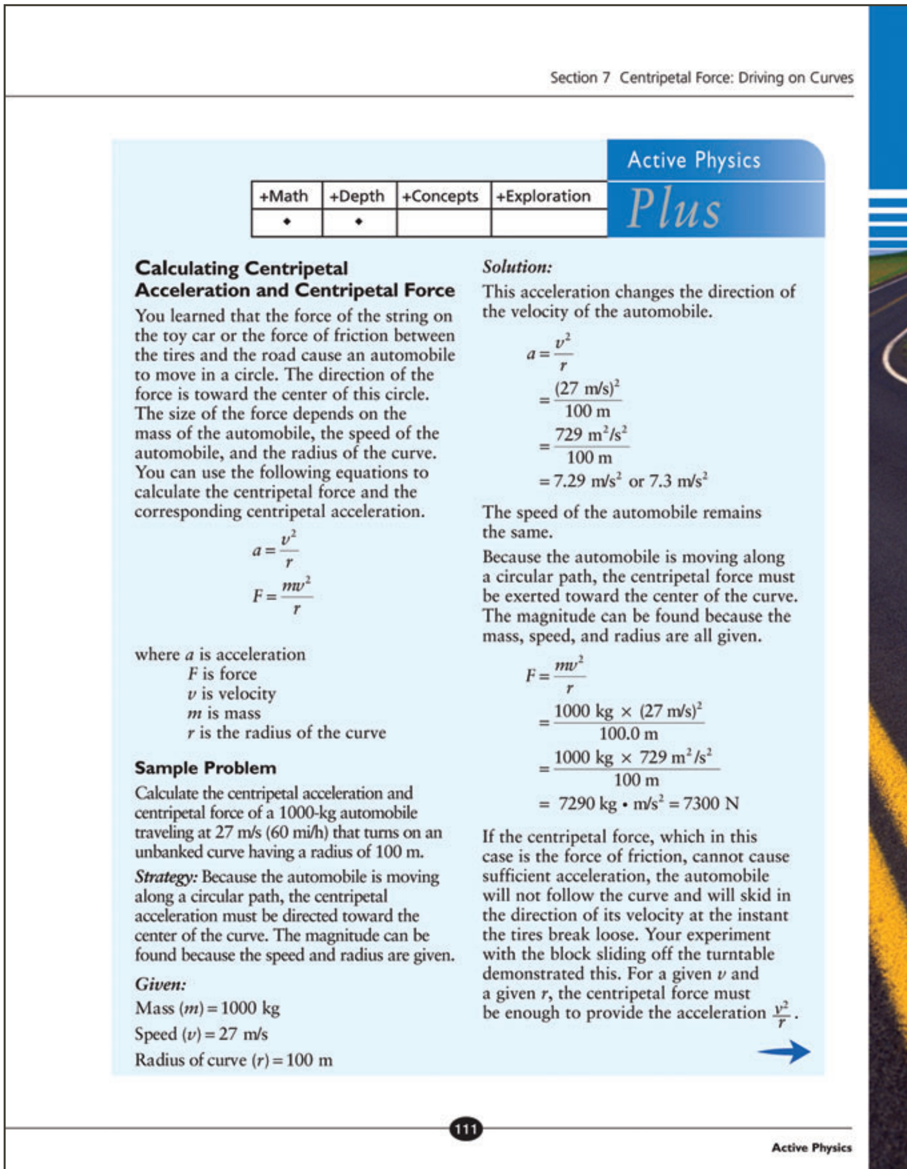
6.

The force that keeps Earth moving in a (roughly) circular path around the Sun is the force of gravitational attraction between Earth and the Sun. This force on Earth is always directed toward the center of the solar system (the Sun).



Active Physics *Plus*

+Math	+Depth	+Concepts	+Exploration
•	•		

Calculating Centripetal Acceleration and Centripetal Force

You learned that the force of the string on the toy car or the force of friction between the tires and the road cause an automobile to move in a circle. The direction of the force is toward the center of this circle. The size of the force depends on the mass of the automobile, the speed of the automobile, and the radius of the curve. You can use the following equations to calculate the centripetal force and the corresponding centripetal acceleration.

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

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

where a is acceleration
F is force
v is velocity
m is mass
r is the radius of the curve

Sample Problem

Calculate the centripetal acceleration and centripetal force of a 1000-kg automobile traveling at 27 m/s (60 mi/h) that turns on an unbanked curve having a radius of 100 m.

Strategy: Because the automobile is moving along a circular path, the centripetal acceleration must be directed toward the center of the curve. The magnitude can be found because the speed and radius are given.

Given:

Mass (m) = 1000 kg

Speed (v) = 27 m/s

Radius of curve (r) = 100 m

Solution:

This acceleration changes the direction of the velocity of the automobile.

$$a = \frac{v^2}{r} = \frac{(27\ \text{m/s})^2}{100\ \text{m}} = \frac{729\ \text{m}^2/\text{s}^2}{100\ \text{m}} = 7.29\ \text{m/s}^2 \text{ or } 7.3\ \text{m/s}^2$$

The speed of the automobile remains the same.

Because the automobile is moving along a circular path, the centripetal force must be exerted toward the center of the curve. The magnitude can be found because the mass, speed, and radius are all given.

$$F = \frac{mv^2}{r} = \frac{1000\ \text{kg} \times (27\ \text{m/s})^2}{100.0\ \text{m}} = \frac{1000\ \text{kg} \times 729\ \text{m}^2/\text{s}^2}{100\ \text{m}} = 7290\ \text{kg} \cdot \text{m/s}^2 = 7300\ \text{N}$$

If the centripetal force, which in this case is the force of friction, cannot cause sufficient acceleration, the automobile will not follow the curve and will skid in the direction of its velocity at the instant the tires break loose. Your experiment with the block sliding off the turntable demonstrated this. For a given v and a given r, the centripetal force must be enough to provide the acceleration $\frac{v^2}{r}$.

Active Physics Plus

Have students write in their logs what they know by now about centripetal force. Asking them to consider the direction of centripetal force and how the size of this force is determined will help them solve the problems in this section. You might want one student to come up to the board and show the solution to a problem. You could then use this opportunity to direct questions to the other students in your class so that each student has the opportunity to understand how mathematical calculations explain concepts.

1.a)

The force of friction must be sufficient to provide the necessary centripetal force for the automobile to negotiate the curve. Using the formula for centripetal force,

$$F_c = \frac{mv^2}{r} = \frac{(1000\text{ kg})(14\text{ m/s})^2}{40\text{ m}} = 4900\text{ N.}$$

1.b)

$$F_c = \frac{mv^2}{r} = \frac{(1000\text{ kg})(20\text{ m/s})^2}{40\text{ m}} = 10{,}000\text{ N}$$

$$F_c = 10{,}000\text{ N or } 5100\text{ N}$$

additional frictional force.

1.c)

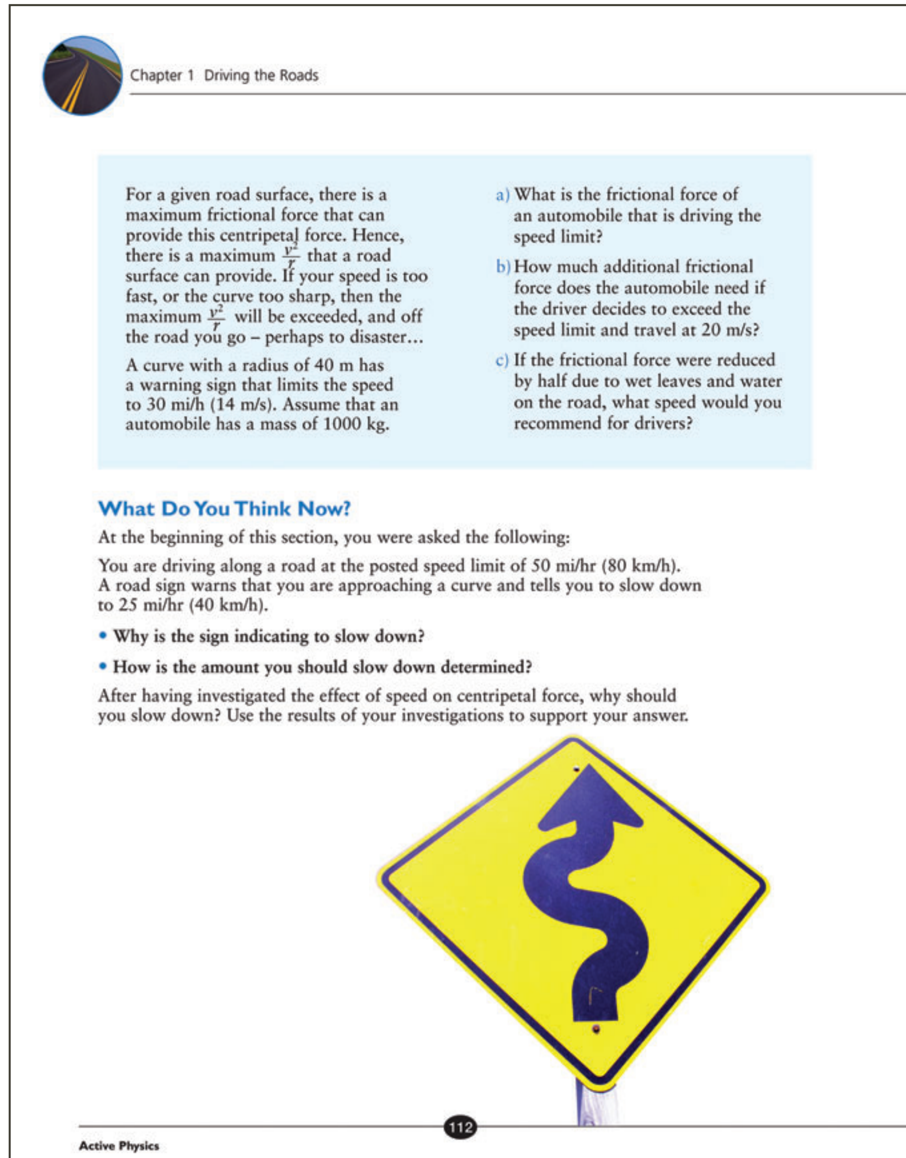
Reducing the frictional force in *a)* by half would make it 2450 N. Using

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

$$v = \sqrt{\frac{rF_c}{m}} = \sqrt{\frac{(40\text{ m})(2450\text{ N})}{1000\text{ kg}}} = 9.9\text{ m/s.}$$

What Do You Think Now?

Ask students to go back to the *What Do You Think?* questions and revise their responses in light of what they have learned about centripetal force. Be sure to insist that speed limits are posted to ensure the safety of drivers and passengers. You should be able to gauge their level of confidence by how comfortable and quick they are in responding to the questions. Toward the end of your discussion, you may provide them with answers in *A Physicist's Response*.


Chapter 1 Driving the Roads

For a given road surface, there is a maximum frictional force that can provide this centripetal force. Hence, there is a maximum $\frac{v^2}{r}$ that a road surface can provide. If your speed is too fast, or the curve too sharp, then the maximum $\frac{v^2}{r}$ will be exceeded, and off the road you go – perhaps to disaster…

A curve with a radius of 40 m has a warning sign that limits the speed to 30 mi/h (14 m/s). Assume that an automobile has a mass of 1000 kg.

a) What is the frictional force of an automobile that is driving the speed limit?

b) How much additional frictional force does the automobile need if the driver decides to exceed the speed limit and travel at 20 m/s?

c) If the frictional force were reduced by half due to wet leaves and water on the road, what speed would you recommend for drivers?

What Do You Think Now?

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

You are driving along a road at the posted speed limit of 50 mi/hr (80 km/h). A road sign warns that you are approaching a curve and tells you to slow down to 25 mi/hr (40 km/h).

- **Why is the sign indicating to slow down?**
- **How is the amount you should slow down determined?**

After having investigated the effect of speed on centripetal force, why should you slow down? Use the results of your investigations to support your answer.

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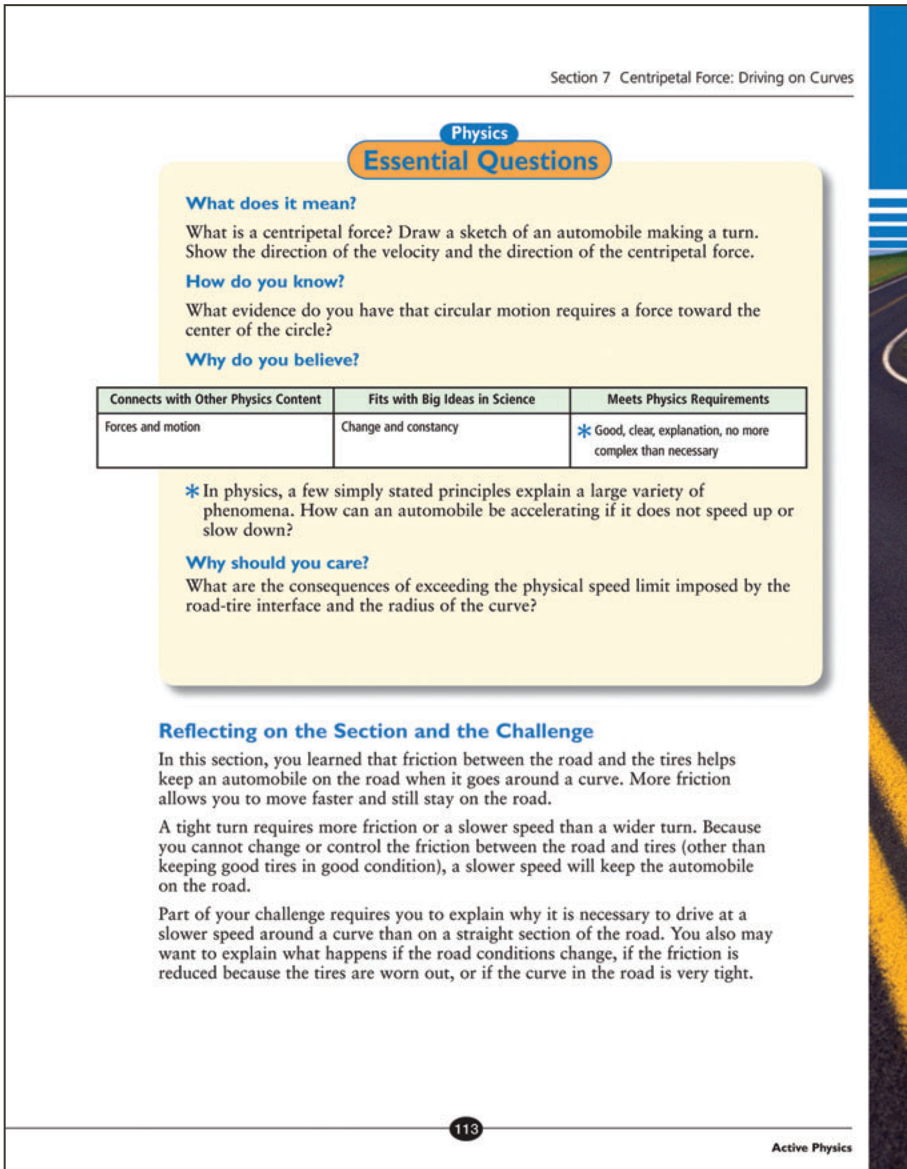
Active Physics



Physics
Essential Questions

What does it mean?

What is a centripetal force? Draw a sketch of an automobile making a turn. Show the direction of the velocity and the direction of the centripetal force.

How do you know?

What evidence do you have that circular motion requires a force toward the center of the circle?

Why do you believe?

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

* In physics, a few simply stated principles explain a large variety of phenomena. How can an automobile be accelerating if it does not speed up or slow down?

Why should you care?

What are the consequences of exceeding the physical speed limit imposed by the road-tire interface and the radius of the curve?

Reflecting on the Section and the Challenge

In this section, you learned that friction between the road and the tires helps keep an automobile on the road when it goes around a curve. More friction allows you to move faster and still stay on the road.

A tight turn requires more friction or a slower speed than a wider turn. Because you cannot change or control the friction between the road and tires (other than keeping good tires in good condition), a slower speed will keep the automobile on the road.

Part of your challenge requires you to explain why it is necessary to drive at a slower speed around a curve than on a straight section of the road. You also may want to explain what happens if the road conditions change, if the friction is reduced because the tires are worn out, or if the curve in the road is very tight.

Reflecting on the Section and the Challenge

Ask students to reflect on how they can use their knowledge of friction and centripetal force in their *Chapter Challenge*. They should be able to extend their learning by explaining why it is safer to drive at slower speeds around a curve. In their challenge, students should mention the factors that can be controlled to avoid the possibility of an accident while driving around a curve. They should also mention factors that cannot be controlled while driving around a curve.

Physics Essential Questions

What does it mean?

A centripetal force is a force that keeps an object moving in a circle at constant speed. The centripetal force is the additional name given to the friction between the road and the tires that keeps the automobile moving in a circular path. It is not an additional force. (The sketch should have an arrow from the circumference of the circle pointing to the center along a radial line. The velocity is along a tangent to the circle.)

How do you know?

When the toy car is attached to a fixed string, the car moves in a circle. If the string breaks or is let go, the car travels along a straight line.

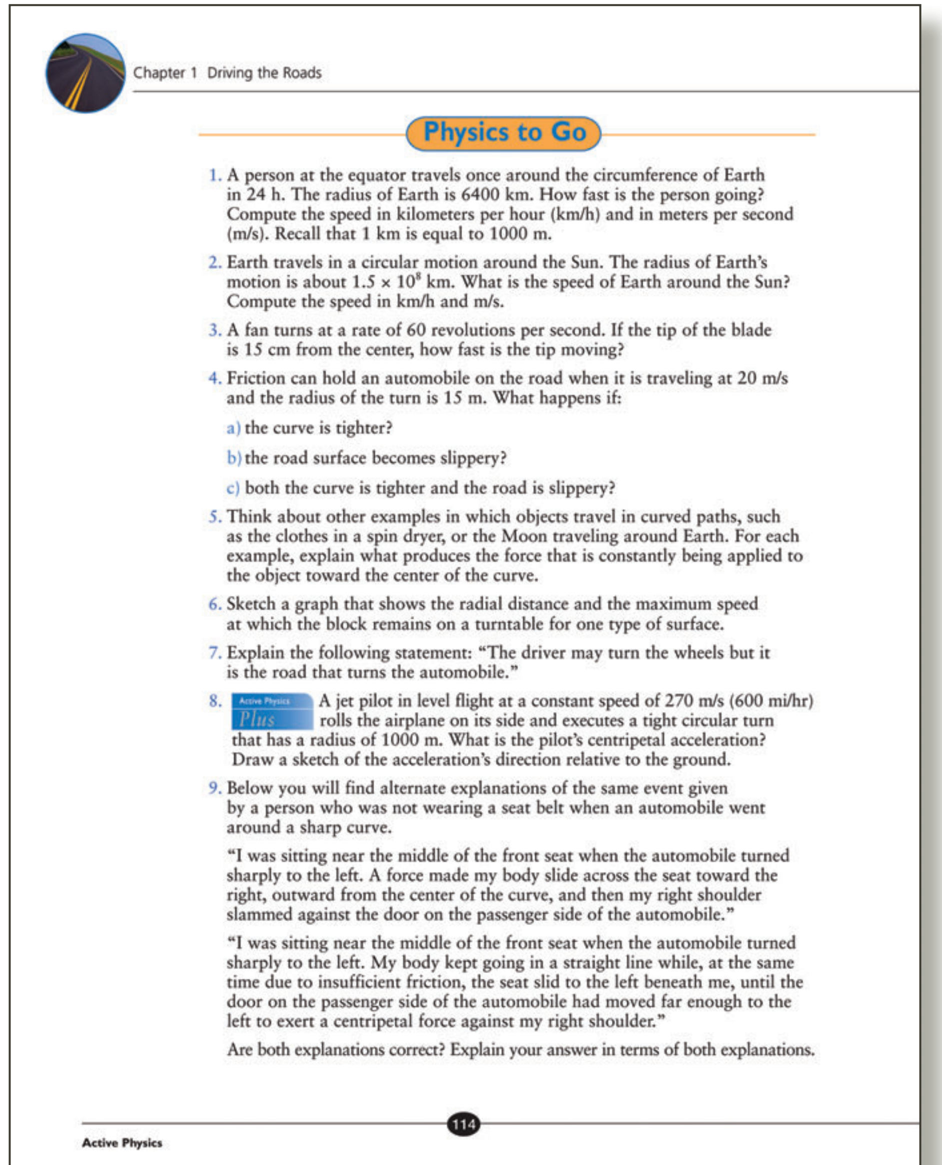
Why do you believe?

Acceleration can produce a change in direction of the velocity. Since acceleration is defined as a change in velocity with respect to time, the magnitude or direction of the velocity or both can change during acceleration.

Why should you care?

If you exceed the speed limit, the force of friction may not be large enough to provide the required centripetal force to keep your automobile moving in a circle. The automobile would then slip off the road, hitting a tree or a guard rail, or whatever comes in its way.

Physics to Go



Physics to Go

1. A person at the equator travels once around the circumference of Earth in 24 h. The radius of Earth is 6400 km. How fast is the person going? Compute the speed in kilometers per hour (km/h) and in meters per second (m/s). Recall that 1 km is equal to 1000 m.
2. Earth travels in a circular motion around the Sun. The radius of Earth's motion is about 1.5×10^8 km. What is the speed of Earth around the Sun? Compute the speed in km/h and m/s.
3. A fan turns at a rate of 60 revolutions per second. If the tip of the blade is 15 cm from the center, how fast is the tip moving?
4. Friction can hold an automobile on the road when it is traveling at 20 m/s and the radius of the turn is 15 m. What happens if:
   a) the curve is tighter?
   b) the road surface becomes slippery?
   c) both the curve is tighter and the road is slippery?
5. Think about other examples in which objects travel in curved paths, such as the clothes in a spin dryer, or the Moon traveling around Earth. For each example, explain what produces the force that is constantly being applied to the object toward the center of the curve.
6. Sketch a graph that shows the radial distance and the maximum speed at which the block remains on a turntable for one type of surface.
7. Explain the following statement: "The driver may turn the wheels but it is the road that turns the automobile."
8. Active Physics Plus A jet pilot in level flight at a constant speed of 270 m/s (600 mi/hr) rolls the airplane on its side and executes a tight circular turn that has a radius of 1000 m. What is the pilot's centripetal acceleration? Draw a sketch of the acceleration's direction relative to the ground.
9. Below you will find alternate explanations of the same event given by a person who was not wearing a seat belt when an automobile went around a sharp curve.

   "I was sitting near the middle of the front seat when the automobile turned sharply to the left. A force made my body slide across the seat toward the right, outward from the center of the curve, and then my right shoulder slammed against the door on the passenger side of the automobile."

   "I was sitting near the middle of the front seat when the automobile turned sharply to the left. My body kept going in a straight line while, at the same time due to insufficient friction, the seat slid to the left beneath me, until the door on the passenger side of the automobile had moved far enough to the left to exert a centripetal force against my right shoulder."

   Are both explanations correct? Explain your answer in terms of both explanations.

1.

$v = d/t$, where $d = 2\pi r$. Therefore, $d = 2\pi(6,400,000 \text{ m}) \approx 40,000,000$ m.

Speed in meters per second

Using $\pi = 3.14$, $d = 40,000,000$ m and $v = (40,000,000 \text{ m})/(86,400 \text{ s}) = 460$ m/s ≈ 1000 mi/h.

Speed in kilometers per hour

Using $v = d/t$, where $d = 2\pi r = 2\pi(6,400 \text{ km}) = 40,192$ km and $t = 24$ h, yields, $v = 40,000 \text{ km}/24 \text{ h} \approx 1700$ km/h.

2.

Speed in meters per second

Using $v = d/t$ and $\pi = 3.14$,

$d = 2\pi r = 2\pi\left(1.5 \times 10^{11} \text{ m}\right) = 9.42 \times 10^{11}$ m and $t = \left(365 \text{ days}\right)\left(24 \text{ h/day}\right)\left(60 \text{ min/h}\right)\left(60 \text{ s/min}\right) = 31,536,000$ s.

Therefore,

$$v = \frac{9.42 \times 10^{11} \text{ m}}{31,536,000 \text{ s}} = 30,000 \text{ m/s} \approx 67,000 \text{ mi/h}.$$

Speed in kilometers per hour

Using $v = d/t$, $d = 2\pi r = 2\pi \times \left(1.5 \times 10^8 \text{ km}\right) = 9.42 \times 10^8$ km and $t = \left(365 \text{ days}\right)\left(24 \text{ h/day}\right) = 8760$ h, $v = \dfrac{9.42 \times 10^8 \text{ km}}{8760 \text{ h}} = 107,500 \text{ km/h} \approx 110,000$ km/h.

3.

The time for one revolution of the blade is

$$t = \frac{1 \text{ rev}}{60 \text{ s}} = 0.017 \text{ s},$$

and the distance traveled is

$d = 2\pi r = 2\pi\left(15 \text{ cm}\right) = 94.2$ cm.

Using $v = d/t$, $v = \dfrac{94.2 \text{ cm}}{0.017 \text{ s}} \approx \dfrac{1}{n}$

5500 cm/s = 55 m/s or 120 mi/h.

4.a)

As the curve gets sharper, the force of friction required to hold the automobile on the road needs to increase; otherwise, the automobile may go off the road.

4.b)

If the road becomes slippery, the friction will be reduced. Therefore, the automobile must travel at a slower speed.

CHAPTER 1

4.c)

If the turn is both tighter and more slippery, the automobile has to go much slower than otherwise.

5.

Many examples will come from the students. Check the physics involved with their explanations, and the centripetal force is in fact acting toward the center of the curve. The clothes in a spin dryer will be getting the centripetal force from the drum of the dryer acting toward the center of the dryer. The Moon gets its centripetal force from the gravitational force exerted by Earth on the Moon.

6.

The graph should show that the radius is directly proportional to the velocity squared. This relationship should be a straight line. If the radius is plotted against only the velocity, then there will still be an increasing relationship — as the radius increases, the velocity increases, but the increase is not linear.

7.

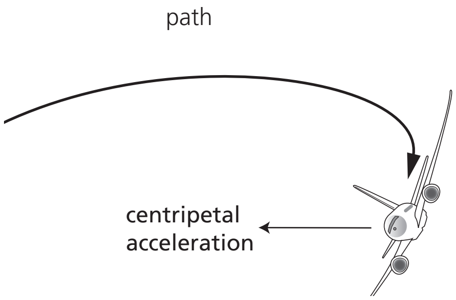
If there were no friction, the automobile would continue in a straight line even if the driver turned the steering wheel. It is the friction of the road on the tire that causes the automobile to turn.

8. Active Physics *Plus*

$$a = \frac{v^2}{r} = \frac{(270 \text{ m/s})^2}{1000 \text{ m}} = 73 \text{ m/s}^2$$

or 7.4 g

With the plane of the circle parallel to the ground, the acceleration points horizontally from the plane to the center of the circle. Students' sketches should appear like the one below.



9.

The person will go straight unless there is a centripetal force to make him or her go around the curve with the automobile. This force would be supplied by the door. The person who claimed a force pushed him or her outward is incorrect. There was no real force acting on the person, since he or she was merely going straight as the automobile turned inward and the seat slid underneath. In terms of "force" as it's meant in Newton's laws of motion, the second explanation is correct. The "force" described in the first explanation only appears to the person traveling in a circle and not to anyone who is observing from a stationary point of view.

NOTES

10.

Answers will vary. Frictional forces on the wheels are needed to supply the centripetal force to keep the race car moving in a curved path. Without friction (the outside unbalanced force), the inertia of the object will keep it moving in a straight line.

11.

Vehicles can negotiate a curve with a large radius more quickly than one with a smaller radius. If the curve radius decreases (the curve gets "tighter"), the driver may not lower the vehicle's speed enough to allow friction to apply the necessary centripetal force, and go off the road. A tight curve requires a greater frictional centripetal force than a more open one at the same speed.

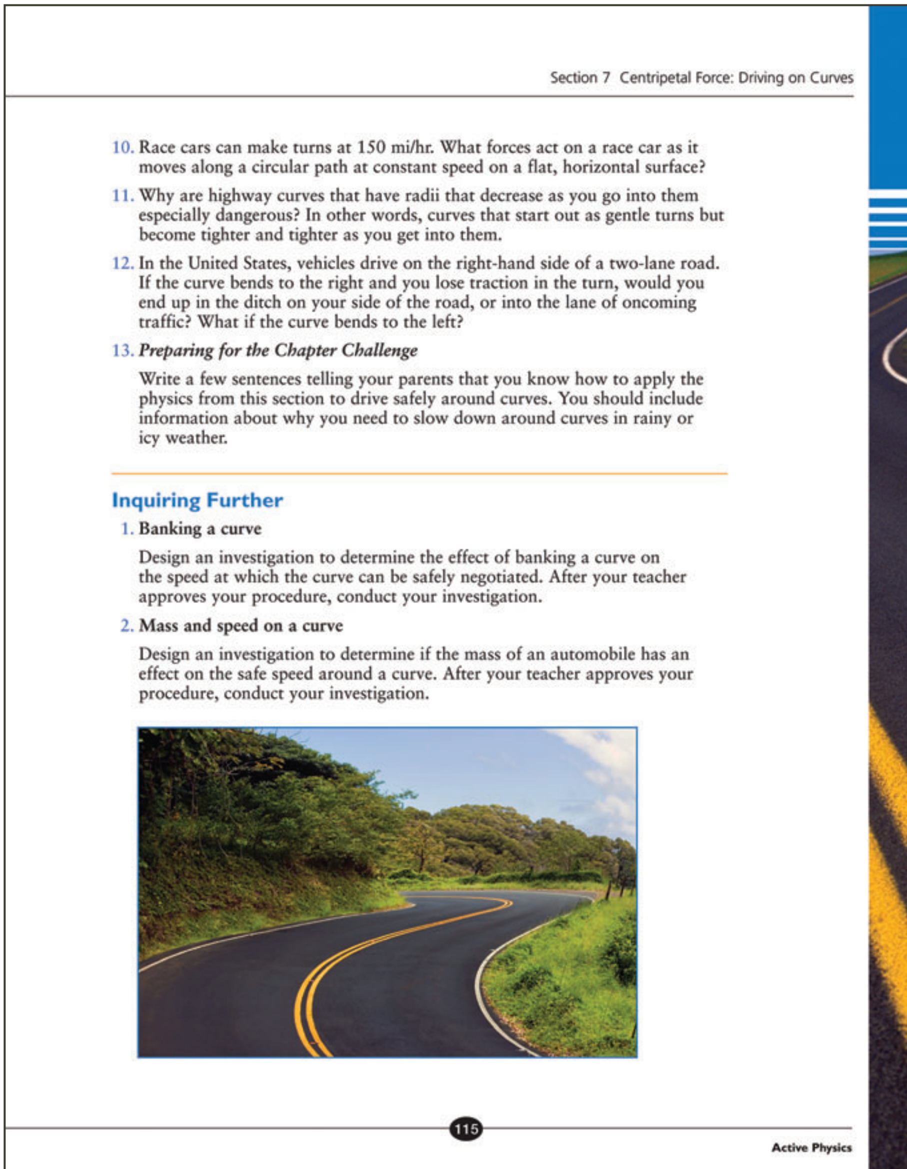
12.

When driving on the right-hand side of the road, if the road curves to the right, and the automobile loses friction, the automobile will go into the oncoming lane of traffic. If the road curves to the left under the same circumstances, the automobile would skid off the road.

13.

Preparing for the Chapter Challenge

Students' answers should include a discussion of how the safe speed to travel around a curve depends upon the friction available (dry roads will have greater friction than wet roads, or roads with snow) and the radius of the curve (the larger the radius, the greater the safe speed).



10. Race cars can make turns at 150 mi/hr. What forces act on a race car as it moves along a circular path at constant speed on a flat, horizontal surface?
11. Why are highway curves that have radii that decrease as you go into them especially dangerous? In other words, curves that start out as gentle turns but become tighter and tighter as you get into them.
12. In the United States, vehicles drive on the right-hand side of a two-lane road. If the curve bends to the right and you lose traction in the turn, would you end up in the ditch on your side of the road, or into the lane of oncoming traffic? What if the curve bends to the left?
13. ***Preparing for the Chapter Challenge***

    Write a few sentences telling your parents that you know how to apply the physics from this section to drive safely around curves. You should include information about why you need to slow down around curves in rainy or icy weather.

Inquiring Further

1. **Banking a curve**

   Design an investigation to determine the effect of banking a curve on the speed at which the curve can be safely negotiated. After your teacher approves your procedure, conduct your investigation.
2. **Mass and speed on a curve**

   Design an investigation to determine if the mass of an automobile has an effect on the safe speed around a curve. After your teacher approves your procedure, conduct your investigation.

Inquiring Further

1.

Students may choose to duplicate the exercise they completed with the turntable. The students should suggest using the procedure in the *Investigate*, substituting blocks of different masses to simulate vehicles of varying mass as they negotiate the curves.

2.

As the mass of an automobile increases, the force of friction between the automobile and the road also increases in direct proportion, providing the required centripetal force for the automobile. If the students do not understand fully, point out that this is the reason posted speed limits for curves are the same for all vehicles. It should be pointed out that these posted limits might not apply to large trucks for a different reason. Although the frictional force also increases for trucks, the location of the force (on the tires) may cause a different effect on an automobile than on a truck.

1-7b Blackline Master

TOURING SEDAN

0-60 mph	**7.2 s**
0-¼ mi	**15.4 s**
Top speed	**est 143 mph**
Skidpad	**0.83 g**
Slalom	**61.9 mph**
Brake rating	**excellent**

TEST CONDITIONS

Temperature	70°F
Wind	calm
Elevation	1010 ft

ENGINE

Type	aluminum bloc and heads, **V-6**
Valvetrain	doch 4 valve/cyl
Displacement	155 cu in./2544 cc
Bore × stroke	3.24 × 3.11 in./ 82.4 × 79.0 mm
Compression ratio	10.0:1
Horsepower (SAE)	**195 bhp @ 6625 rpm**
Bhp/liter	76.7
Torque	**165 lb-ft @ 5625 rpm**
Maximum engine speed	6750
Fuel injection	elect. sequential port
Fuel	prem unleaded, 91 pump oct

CHASSIS & BODY

Layout	**front engine/front drive**
Body/frame	unit steel
Brakes	
Front	**10.9-in. vented discs**
Rear	**9.9-in. vented discs**
Assist type	vacuum; ABS
Total swept area	366 sq in.
Wheels	cast alloy, **16 × 6½**
Tires	steel-belted touring, **P205/55ZR-16**
Steering	**rack & pinion** power assist
Overall ratio	14.5:1
Turns, lock to lock	2.7
Turning circle	38.4 ft
Suspension	
Front	**struts,** lower A-arms, coil springs, tube shocks, anti-roll bar
Rear	**struts**, trailing links, dual lower lateral links, coil springs, tube shocks, anti-roll bar

DRIVE TRAIN

Transmission .... **5-sp manual**

Gear	Ratio	Overall ratio	(Rpm) Mph
1st	3.42:1	13.89:1	(6750) 34
2nd	2.14:1	8.69:1	(6750) 55
3rd	1.45:1	5.89:1	(6750) 81
4th	1.03:1	4.18:1	(6750) 114
5th	0.77:1	3.13:1	(6750) 143

Final drive ratio 4.06:1

Engine rpm @ 60 mph in 5th 2650

GENERAL DATA

Curb weight	**3055 lb**
Test weight	3180 lb
Weight dist (with driver), f/r, %	63/37
Wheelbase	106.5 in.
Track, f/r	59.2 in./58.5 in.
Length	**183.9 in.**
Width	**69.1 in.**
Height	**54.5 in.**
Ground clearance	8/2 in.
Trunk space	18.0 + 7.0 cu ft

MAINTENANCE

Oil/filter	5000 mi/5000 mi
Tuneup	100,000 mi
Basic warranty	36 mo/36,000 mi

ACCOMMODATIONS

Seating capacity	**5**
Head room, f/r	39.0 in./35.0 in.
Seat width, f/r	2 × 20.5 in./50.0 in.
Front-seat leg room	43.0 in.
Rear-seat leg room	25.0 in.
Seatback adjustment	85 deg
Seat travel	8.5 in.

INTERIOR NOISE

Idle in neutral	54 dBA
Maximum in 1st gear	78 dBA
Constant 50 mph	66 dBA
70 mph	71 dBA

INSTRUMENTATION

160-mph speedometer, 8000-rpm tach, coolant temp, fuel level

ACCELERATION

Time to speed	Seconds
0-35 mph	2.5
0-40 mph	3.8
0-50 mph	5.2
0-60 mph	7.2
0-70 mph	9.3
0-80 mph	11.6
0-90 mph	14.8
0-100 mph	18.8
Time to distance	
0-100 ft	3.3
0-500 ft	8.4
0-1320 ft (¼ mi)	15.4 @ 91.5 mph

FUEL ECONOMY

Normal driving	20.0 mpg
EPA city/highway	20/29 mpg
Cruise range	270 miles
Fuel capacity	14.5 gal

BRAKING

Minimum stopping distance	
From 60 mph	135 ft
From 80 mph	228 ft
Control	excellent
Pedal effort for 0.5 g stop	na
Fade, effort after six 0.5 g stops from 60 mph	na
Brake feel	excellent
Overall brake rating	excellent

HANDLING

Lateral accel (200-ft skidpad)	0.83 g
Balance	moderate understeer
Speed thru 700-ft slalom	61.9 mph
Balance	mild understeer
Lateral seat support	very good

Subjective ratings consists of excellent, very good, good, average, poor; na means information is not available

SPORTS CAR

0-60 mph	**5.2 s**
0-¼ mi	**13.8 s**
Top speed	**est 165 mph**
Skidpad	**na**
Slalom	**62.5 mph**
Brake rating	**excellent**

TEST CONDITIONS

Temperature	86°F
Wind	calm
Elevation	est 700 ft

ENGINE

Type	aluminum bloc and heads, **V-8**
Valvetrain	ohv 2 valve/cyl
Displacement	346 cu in./5666 cc
Bore × stroke	3.90 × 3.62 in./99.0 × 92.0 mm
Compression ratio	10.0:1
Horsepower (SAE)	**345 bhp @ 5600 rpm**
Bhp/liter	60.9
Torque	**350 lb-ft @ 4400 rpm**
Maximum engine speed	6000
Fuel injection	elect. sequential port
Fuel	prem unleaded, 91 pump oct

CHASSIS & BODY

Layout	**front engine/rear drive**
Body/frame	fiberglass/steel unit frame
Brakes	
Front	**12.8-in. vented discs**
Rear	**12.0-in. vented discs**
Assist type	vacuum; ABS
Total swept area	433 sq in.
Swept area/ton	257 sq in.
Wheels	cast magnesium; **17 × 8½ f 18 × 9½ r**
Tires	steel-belted sports; **P245/45ZR-17 f, P275/40ZR-18 R**
Steering	**rack & pinion** variable power assist
Overall ratio	16.1:1
Turns, lock to lock	2.7
Turning circle	38.5 ft
Suspension	
Front	**upper & lower A-arms,** Transverse composite monoleaf spring, tube shocks, anti-roll bar
Rear	**upper & lower A-arms,** toe links, transverse composite monoleaf spring, tube shocks, anti-roll bar

DRIVE TRAIN

Transmission: **6-sp manual**

Gear	Ratio	Overall ratio	(Rpm) Mph
1st	2.66:1	9.10:1	(6000) 52
2nd	1.78:1	6.09:1	(6000) 77
3rd	1.30:1	4.45:1	(6000) 105
4th	1.00:1	3.42:1	(6000) 137
5th	0.74:1	2.53:1	est (5365) 165
6th	0.50:1	1.71:1	est (3625) 165

Final drive ratio	3.42:1
Engine rpm @ 60 mph in 6th	1320

GENERAL DATA

Curb weight	**est 3240 lb**
Test weight	**est 3380 lb**
Weight dist (with driver), f/r, %	51/49
Wheelbase	104.5 in.
Track, f/r	62.0 in./62.0 in.
Length	**179.7 in.**
Width	**73.6 in.**
Height	**47.7 in.**
Ground clearance	3/7 in.
Trunk space	13. 5 cu ft (top up)/ 10.8 cu ft (top down)

MAINTENANCE

Oil/filter change	7500 mi/7500 mi
Tuneup	100,000 mi
Basic warranty	36 mo/36,000 mi

ACCOMMODATIONS

Seating capacity	**2**
Head room, f/r	36.5 in.
Seat width	2 × 18.0 in.
Leg room	43.5 in.
Seatback adjustment	45 deg
Seat travel	8.0 in.

INTERIOR NOISE

Idle in neutral	61 dBA
Maximum in 1st gear	78 dBA
Constant 50 mph	73 dBA
70 mph	76 dBA

INSTRUMENTATION

200-mph speedometer, 7500-rpm tach, coolant temp, fuel level, volts, oil press.

ACCELERATION

Time to speed	Seconds
0-30 mph	2.0
0-40 mph	2.9
0-50 mph	4.2
0-60 mph	5.2
0-70 mph	6.6
0-80 mph	8.7
0-90 mph	10.9
0-100 mph	13.3
Time to distance	
0-100 ft	3.0
0-500 ft	7.5
0-1320 ft (¼ mi):	13.8 @ 102.1 mph

FUEL ECONOMY

Normal driving	est 18.5 mpg
EPA city/highway	18/28 mpg
Cruise range	270 miles
Fuel capacity	19.1 gal

BRAKING

Minimum stopping distance	
From 60 mph	118 ft
From 80 mph	209 ft
Control	excellent
Pedal effort for 0.5 g stop	na
Fade, effort after six 0.5 g stops from 60 mph	na
Brake feel	excellent
Overall brake rating	excellent

HANDLING

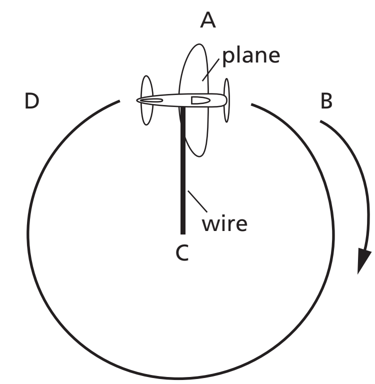
Lateral accel (200-ft skidpad)	na
Balance	na
Speed thru 700-ft slalom	62.5 mph
Balance	moderate understeer
Lateral seat support	excellent

Subjective ratings consists of excellent, very good, good, average, poor; na means information is not available

SECTION 7 QUIZ

1-7c Blackline Master

1. The diagram to the right shows a model airplane attached to a wire flying in a horizontal circle in the clockwise direction. If the wire breaks when the plane is in the position shown, the airplane will move toward point



   a) A   b) B

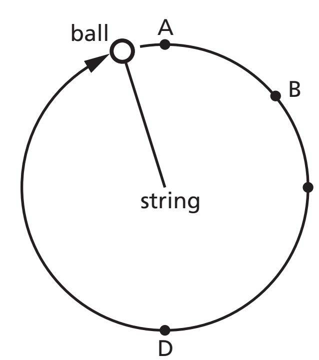
   c) C   d) D

2. The centripetal force acting on the plane at the position shown is directed toward point

   a) A   b) B

   c) C   d) D

3. A ball attached to a string is moving at a constant speed in a horizontal circular path. A target is near the path as shown in the diagram to the right. At which point along the path should the string be released if the ball is to hit the target?



   a) A   b) B

   c) C   d) D

4. A student is spinning a turntable with a wooden block resting on it. The block is located 10 cm from the center of the table, and the turntable is rotating 15 times every minute. What is the speed of the wooden block on the turntable?

   a) 1.5 cm/s   b) 31.4 cm/s

   c) 20.7 cm/s   d) 15.7 cm/s

5. In *Question 4*, the force that holds the wooden block on the turntable while it is spinning is provided by the force of

   a) gravity.   b) the student's hand.

   c) Earth's magnetic field.   d) friction.

SECTION 7 QUIZ ANSWERS

1. b) The velocity of an object traveling in a circular path is always tangent to the circle at that point. If the centripetal force stops (the wire breaks), the plane will continue in a straight-line path, according to Newton's first law.

2. c) The centripetal force is provided by the wire, which is being pulled toward the center of the circle, at point C.

3. b) Because an object's velocity is always tangent to the circle when it is traveling around a circular path, the object must be released at point B to strike the target. This can be verified by drawing a tangent to the circle pointing in the direction of rotation at all four positions. It will be seen that only the tangent from point B intersects the target, giving a hit.

4. d) The speed of the spinning block is given by $v = d/t$, where d is the circumference. The circumference $= 2\pi r = 2(3.14) \times (10\text{ cm}) = 62.8\text{ cm}$. The time it takes the block to rotate around the table, covering a distance equal to the circumference is derived from the rotations/minute – 60 s for 15 rotations means 4 s for 1 rotation. To find the speed, $v = d/t = (62.8\text{ cm})/(4\text{ s}) = 15.7\text{ cm/s}$.

5. d) The force of friction is what keeps the block on the spinning turntable. Although the force of gravity helps to determine the size of the frictional force, it is in the wrong direction (downward) to provide the needed horizontal force to keep the block spinning in a circle. The student's hand is not holding the block on the table, but rather spinning the turntable.