10 CIRCULAR MOTION

Objectives

- Describe the two types of circular motion. (10.1)
- Describe the relationship among tangential speed, rotational speed, and radial distance. (10.2)
- Describe the factors that affect the centripetal force acting on an object. (10.3)
- Explain the "centrifugal-force effect." (10.4)
- Explain why centrifugal force is not considered a true force. (10.5)

This chapter entirely omits the "right hand rule," where fingers of the right hand represent the motion of a rotating body and the thumb represents the positive vector of motion. Please spare undue emphasis on this material, which your students can get into in a later course.

PAUL

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MATERIALS marble, paper plate, scissors

EXPECTED OUTCOME Students will observe that the marble moves in a circular path along the rim of the plate.

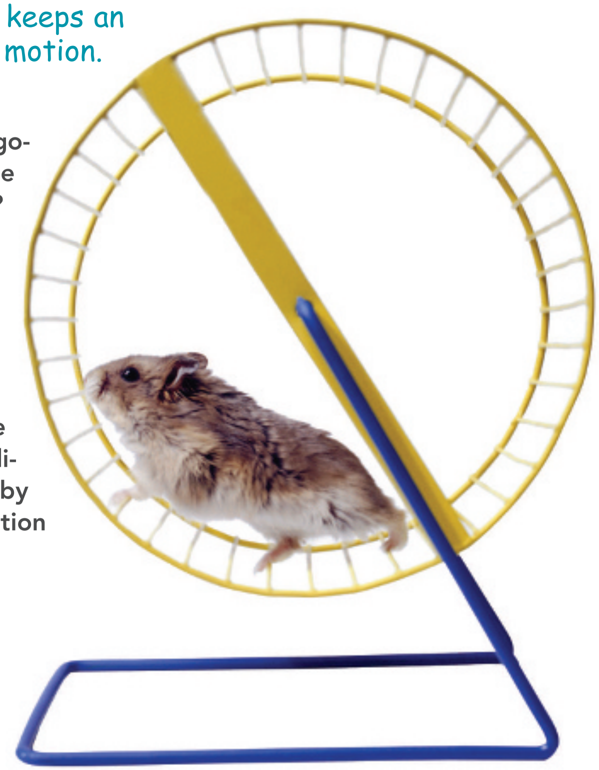
ANALYZE AND CONCLUDE

1. See Expected Outcome. The marble moves off in a straight line where the rim is not present.
2. Apply a series of inward pushes on the marble.
3. An inward directed force is necessary to keep an object moving in a circle.

10 CIRCULAR MOTION

THE BIG IDEA Centripetal force keeps an object in circular motion.

Which moves faster on a merry-go-round, a horse near the outside rail or one near the inside rail? If you swing a tin can at the end of a string in a circle over your head and the string breaks, does the can fly directly outward, or does it continue its motion without changing its direction? While a hamster rotates its cage about an axis, does the hamster rotate or does it revolve about the same axis? These questions indicate the flavor of this chapter. We begin by discussing the difference between rotation and revolution.



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Why Do Objects Move in Circles?

1. Roll a marble around the rim of a paper plate.
2. Using a pair of scissors, cut a 90° wedge-shaped piece from the plate.
3. Roll the marble around the rim of the modified plate.

Analyze and Conclude

1. **Observing** Describe the motion of the marble before and after a section of the plate was removed.
2. **Predicting** What could you do to keep the marble moving in a circle?
3. **Making Generalizations** What is required to keep any object moving in a circle?

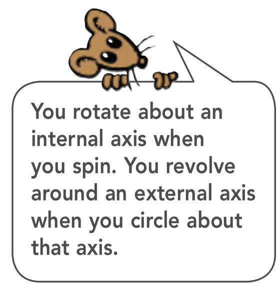
10.1 Rotation and Revolution

Both the Ferris wheel shown in Figure 10.1 and an ice skater doing a pirouette turn around an axis. An **axis** is the straight line around which rotation takes place.

FIGURE 10.1 The Ferris wheel turns about an axis.

Two types of circular motion are rotation and revolution. When an object turns about an *internal* axis—that is, an axis located within the body of the object—the motion is called **rotation,** or *spin.* Both the Ferris wheel and the skater rotate. When an object turns about an *external* axis, the motion is called **revolution.** Although the Ferris wheel rotates, the riders *revolve* about its axis.

Earth undergoes both types of rotational motion. It revolves around the sun once every $365\frac{1}{4}$ days,[10.1.1] and it rotates around an axis passing through its geographical poles once every 24 hours.[10.1.2]



CONCEPT CHECK What are two types of circular motion?

10.2 Rotational Speed

We began this chapter by asking which moves faster on a merry-go-round, a horse near the outside rail or one near the inside rail. Similarly, which part of a turntable moves faster? On the pre-CD record player shown in Figure 10.2, which part of the record moves faster under the stylus—the outer part where the ladybug sits or a part near the orange center? If you ask people these questions you'll probably get more than one answer, because some people will think about linear speed while others will think about rotational speed.

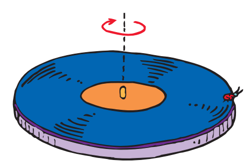


FIGURE 10.2 The turntable *rotates* around its axis while a ladybug sitting at its edge *revolves* around the same axis.

10.1 Rotation and Revolution

Key Terms
axis, rotation, revolution

Teaching Tip Distinguish between a rotation (spin about an axis located within a body) and a revolution (movement around an axis outside the body). A wheel rotates; its rim revolves. Describe the case of a satellite spinning (rotating) while it orbits Earth (revolving).

Ask Does a tossed football rotate or revolve? *It rotates.* **Does a ball whirled overhead at the end of a string rotate or revolve?** *It revolves about you.*

CONCEPT CHECK Two types of circular motion are rotation and revolution.

Teaching Resources
- Presentation*EXPRESS*
- Interactive Textbook
- Conceptual Physics Alive! DVDs *Rotation*

10.2 Rotational Speed

Key Terms
linear speed, tangential speed, rotational speed

Common Misconceptions
Linear speed and rotational speed are the same.

FACT Linear speed is the distance moved per unit of time while rotational speed is the number of rotations per unit of time.

The linear speed on a rotating surface is the same at all radial distances.

FACT Linear speed varies with the distance from the axis of rotation.

▶ **Teaching Tip** Distinguish between rotational speed and linear speed by describing the examples of riding at different radial positions on a merry-go-round. When the linear speed is tangent to a curved path, we speak of *tangential speed*.

Demonstration

Place two coins on the top of a turntable, one near the center and the other near the edge. Rotate the turntable and show that the outer coin has a greater linear speed. Explain that both coins have the same rotational speed—they undergo the same number of revolutions per second. (Or, stick two pieces of clay to the turntable, one near the center and one near the edge. Place pencils upright in the clay and let the turntable rotate. The different tangential speeds will be evident.)

▶ **Teaching Tip** Compare the speeds of the coins to the speeds of different parts of an old phonograph record beneath the stylus. Linear velocity that is perpendicular to the radial direction is the same as tangential velocity ($v = r\omega$). Give examples such as being able to see detail on the hub cap of a moving car while not seeing similar detail on the tire.

Ask **If a meter stick supported at the 0-cm mark swings like a pendulum from your fingers, how fast at any given moment is the 100-cm mark moving compared to the 50-cm mark?** *The 100-cm mark is twice as far from the center of rotation as the 50-cm mark and thus has twice the linear speed.*

think!

At an amusement park, you and a friend sit on a large rotating disk. You sit at the edge and have a rotational speed of 4 RPM and a linear speed of 6 m/s. Your friend sits halfway to the center. What is her rotational speed? What is her linear speed?
Answer: 10.2.1

Types of Speed

Linear speed, which we simply called speed in Chapter 4, is the distance traveled per unit of time. A point on the outer edge of a merry-go-round or turntable travels a greater distance in one complete rotation than a point near the center. So the linear speed is greater on the outer edge of a rotating object than it is closer to the axis. The speed of something moving along a circular path can be called **tangential speed** because the direction of motion is always tangent to the circle. For circular motion, we can use the terms linear speed and tangential speed interchangeably.

Rotational speed (sometimes called angular speed) is the number of rotations per unit of time. All parts of the rigid merry-go-round and the turntable rotate about their axis *in the same amount of time.* Thus, all parts have the same rate of rotation, or the same *number of rotations per unit of time.* It is common to express rotational speed in revolutions per minute (RPM).[10.2.1] For example, phonograph turntables that were common in the past rotate at $33\frac{1}{3}$ RPM. A ladybug sitting anywhere on the surface of the turntable in Figure 10.3 revolves at $33\frac{1}{3}$ RPM.

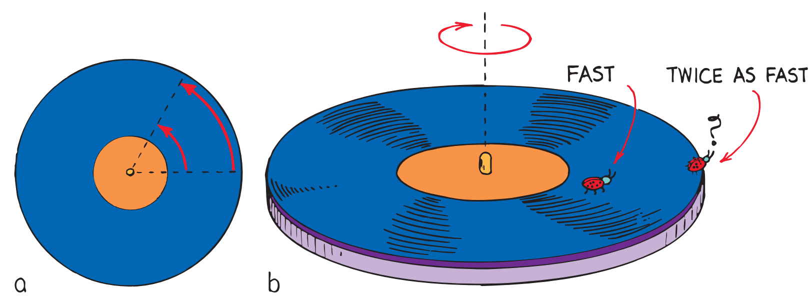


FIGURE 10.3 ▶
All parts of the turntable rotate at the same rotational speed. **a.** A point farther away from the center travels a longer path in the same time and therefore has a greater tangential speed. **b.** A ladybug sitting twice as far from the center moves twice as fast.

Tangential and Rotational Speed

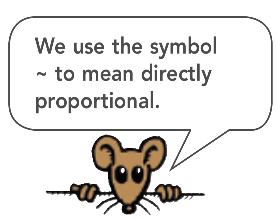
Tangential speed and rotational speed are related. Have you ever ridden on a giant rotating platform in an amusement park? The faster it turns, the faster your tangential speed is. Tangential speed is directly proportional to the rotational speed and the radial distance from the axis of rotation. So we state[10.2.2]

$$\text{Tangential speed} \sim \text{radial distance} \times \text{rotational speed}$$

In symbol form,

$$v \sim r\omega$$

where v is tangential speed and ω (pronounced oh MAY guh) is rotational speed. You move faster if the rate of rotation increases (bigger ω). You also move faster if you are farther from the axis (bigger r).



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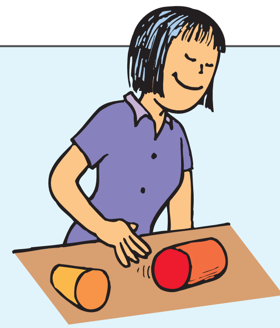
How Does Linear Speed Depend on Radius?



1. Roll a cylindrical can across a table. Note the path the rolling can takes.
2. Now roll an ordinary tapered drinking cup on the table. Does the cup roll straight or does it curve?
3. Does the wide end of the cup cover more distance as it rotates?
4. **Think** Is the linear speed of the wide end of the tapered cup greater than the linear speed of the narrow end?

At the axis of the rotating platform, you have no tangential speed, but you do have rotational speed. You rotate in one place. As you move away from the center, your tangential speed increases while your rotational speed stays the same. Move out twice as far from the center, and you have twice the tangential speed. This is true for the ladybugs in Figure 10.3. Move out three times as far, and you have three times as much tangential speed.

To summarize: In any rigidly rotating system, all parts have the same rotational speed. However, the linear or tangential speed can vary. **Tangential speed depends on rotational speed and the distance from the axis of rotation.**

Railroad Train Wheels Why does a moving freight train stay on the tracks? Most people assume that flanges at the edge of the wheel prevent the wheels from rolling off the tracks. However, these flanges are only in use in emergency situations or when they follow slots that switch the train from one set of tracks to another. So how do the wheels of a train stay on the tracks? They stay on the tracks because their rims are slightly tapered.

A curved path occurs when a tapered cup rolls, as shown in Figure 10.4. The wider part of the cup travels a greater distance per revolution. As illustrated in Figure 10.5, if you fasten a pair of cups together at their wide ends and roll the pair along a pair of parallel tracks, the cups will remain on the track and center themselves whenever they roll off center. This occurs because when the pair rolls to the left of center, for example, the wider part of the left cup rides on the left track while the narrow part of the right cup rides on the right track. This steers the pair toward the center. If it "overshoots" toward the right, the process repeats, this time toward the left, as the wheels tend to center themselves.

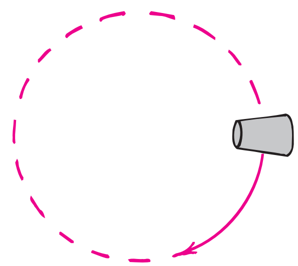


FIGURE 10.4 ▲
A tapered cup rolls in a curve because the wide part of the cup rolls faster than the narrow part.

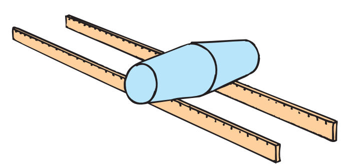


FIGURE 10.5 ▲
A pair of cups fastened together will stay on the tracks as they roll.

discover!

MATERIALS cylindrical can

EXPECTED OUTCOME The tapered cup will follow a curved path as it rolls.

THINK The wide end of the cup covers more distance as it rotates so its linear speed is greater. Linear speed depends on radius.

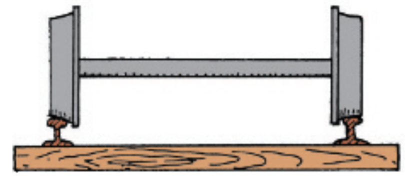
The Discover! activity on this page nicely leads into a fascinating concept—how the tapered wheels of railroad cars keep a train on the track. This is the most interesting consequence of $v = r\omega$ that I know of, and students find the concept fascinating!

PAUL

Demonstration

You can simulate the action of railroad wheels on tracks with a pair of foam cups. Tape them together at their wide ends. Roll them along a pair of parallel meter sticks, or ideally along a curved track. You can also connect a pair of tapered rubber stoppers with a dowel or glass tube. Interest is perked with such a demonstration!

FIGURE 10.6 ▼
The tapered shape of railroad train wheels (shown exaggerated here) is essential on the curves of railroad tracks.

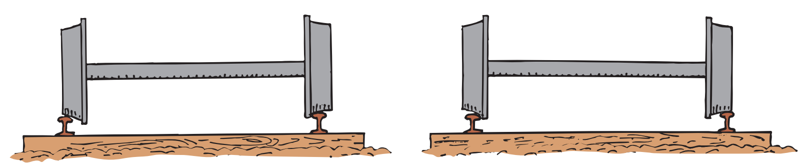


think!

Train wheels ride on a pair of tracks. For straight-line motion, both tracks are the same length. But which track is longer for a curve, the one on the outside or the one on the inside of the curve?
Answer: 10.2.2

The wheels of railroad trains are similarly tapered, as shown in Figure 10.6. This tapered shape is essential on the curves of railroad tracks. On any curve, the distance along the outer part is longer than the distance along the inner part, as illustrated in Figure 10.3a. So whenever a vehicle follows a curve, its outer wheels travel faster than its inner wheels. For an automobile, this is no problem because the wheels roll independent of each other. For a train, however, pairs of wheels are firmly connected like the pair of fastened cups, so they rotate together. Opposite wheels have the same RPM at any time. But due to the slightly tapered rim of the wheel, when a train rounds a curve, wheels on the outer track ride on the wider part of the tapered rims (and cover a greater distance in the same time) while opposite wheels ride on their narrower parts (covering a smaller distance in the same time). This is illustrated in Figure 10.7. In this way, the wheels have different linear speeds for the same rotational speed. This is $v \sim r\omega$ in action! Can you see that if the wheels were not tapered, scraping would occur and the wheels would squeal when a train rounded a curve on the tracks?

CONCEPT CHECK: What is the relationship among tangential speed, rotational speed, and radial distance?



a Narrow part of left wheel goes slower, so wheels curve to left.

b Wide part of left wheel goes faster, so wheels curve to right.

FIGURE 10.7 ▲
When a train rounds a curve, the wheels have different linear speeds for the same rotational speed.

▶ **Teaching Tip** Tell students that a moving train sometimes sways side-to-side as it rolls along the track. These are the corrective motions that keep it on the track.

CONCEPT CHECK: Tangential speed depends on rotational speed and the distance from the axis of rotation.

Teaching Resources

- **Reading and Study Workbook**
- **Laboratory Manual** *34*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** *10-1*

10.3 Centripetal Force

Velocity involves both speed and direction. When an object moves in a circle, even at constant speed, the object still undergoes an acceleration because its direction is changing. This change in direction is due to a net force (otherwise the object would continue to go in a straight line).

Any object moving in a circle undergoes an acceleration that is directed to the center of the circle—a *centripetal acceleration.*[10.3.1] Centripetal means "toward the center." Correspondingly, the force directed toward a fixed center that causes an object to follow a circular path is called a **centripetal force.** The force you feel from the wall while on a rotating carnival centrifuge is a centripetal force. It forces you into a circular path. If it ceased to act, you'd move in a straight line, in accord with the law of inertia.

Examples of Centripetal Forces If you whirl a tin can on the end of a string, as shown in Figure 10.8, you find you must keep pulling on the string—exerting a centripetal force. The string transmits the centripetal force, pulling the can from a straight-line path into a circular path. Centripetal forces can be exerted in a variety of ways. The "string" that holds the moon on its almost circular path, for example, is gravity. Electrical forces provide the centripetal force acting between an orbiting electron and the atomic nucleus in an atom. Anything that moves in a circular path is acted on by a centripetal force.

Centripetal force is not a basic force of nature, but is simply the label given to any force, whether string tension, gravitation, electrical force, or whatever, that is directed toward a fixed center. If the motion is circular and executed at constant speed, this force acts at right angles (perpendicular) to the path of the moving object.

When an automobile rounds a corner, for example, friction between the tires and the road provides the centripetal force that holds the car in a curved path. This is illustrated in Figure 10.9a. If friction is insufficient (due to an oily surface, gravel, etc.), the tires slide sideways and the car fails to make the curve. As shown in Figure 10.9b, the car tends to skid tangentially off the road.

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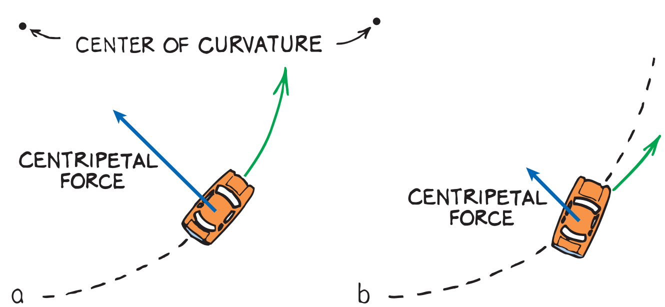
FIGURE 10.8 ▲
The force exerted on a whirling can is toward the center. No outward force acts on the can.



◀ **FIGURE 10.9**
Centripetal force holds a car in a curved path.
a. For the car to go around a curve, there must be sufficient friction to provide the required centripetal force.
b. If the force of friction is not great enough, skidding occurs.

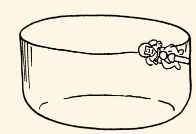
10.3 Centripetal Force

Key Term
centripetal force

▶ **Teaching Tip** Define centripetal force as any force that causes a body to move in a circular path—or in part of a circular path, such as rounding a corner while riding a bicycle.

▶ **Teaching Tip** Whirl a tin can securely fastened at the end of a string above your head. Expand on the idea that a centripetal force is exerted on the whirling can at the end of the string. The string pulls radially inward on the can, and the can pulls outward on the string—so there is an outward-acting force on the string. Stress that this outward force does not act on the can. Only an inward force acts on the can.

Ask **A motorcycle runs on the inside of a bowl-shaped track.**



Is the force that holds the motorcycle in a circular path an inward- or outward-directed force? *It is an inward-directed force—a centripetal force. An outward-directed force acts on the inner wall, which may bulge as a result, but no outward-directed force acts on the motorcycle.*

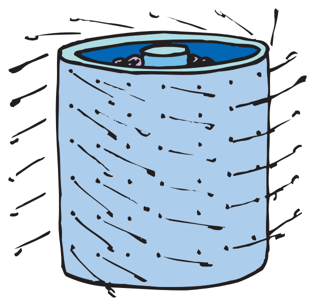


FIGURE 10.10 ▲
The clothes in a washing machine are forced into a circular path, but the water is not, and it flies off tangentially.

Centripetal force plays the main role in the operation of a centrifuge, which you may use in a biology lab to separate particles in a liquid. A household example is the spinning tub in an automatic washer like the one shown in Figure 10.10. In its spin cycle, the tub rotates at high speed and the tub's wall produces a centripetal force on the wet clothes, forcing them into a circular path. The holes in the tub's wall prevent the tub from exerting the same force on the water in the clothes. The water escapes tangentially out the holes. Strictly speaking, the clothes are forced away from the water; the water is not forced away from the clothes. Think about that.

Calculating Centripetal Forces ✓ **The centripetal force on an object depends on the object's tangential speed, its mass, and the radius of its circular path.** Greater speed and greater mass require greater centripetal force. Traveling in a circular path with a smaller radius of curvature requires a greater centripetal force. In equation form,[10.3.2]

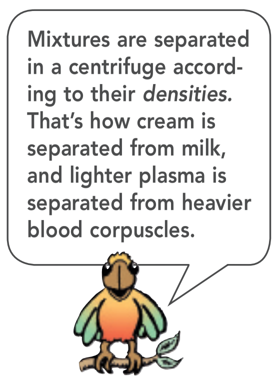
$$\text{Centripetal force} = \frac{\text{mass} \times \text{speed}^2}{\text{radius of curvature}}$$

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

Centripetal force, F_c, is measured in newtons when m is expressed in kilograms, v in meters/second, and r in meters.

Adding Force Vectors Figure 10.11 is a sketch of a conical pendulum—a bob held in a circular path by a string attached above. This arrangement is called a conical pendulum because the string sweeps out a cone. Only two forces act on the bob: **mg,** the force due to gravity, and tension **T** in the string. Both are vectors. Figure 10.12 shows vector **T** resolved into two perpendicular components, $\mathbf{T}_x$ (horizontal), and $\mathbf{T}_y$ (vertical). (We show these vectors as dashed to distinguish them from the tension vector **T**). Interestingly, if vector **T** were replaced with forces represented by these component vectors, the bob would behave just as it does when it is supported only by **T**. (Recall from Chapter 5 that resolving a vector into components is the reverse of finding the resultant of a pair of vectors. More on resolving vectors is in Appendix D and in the *Concept-Development Practice Book.*)

Since the bob doesn't accelerate vertically, the net force in the vertical direction is zero. Therefore the component $\mathbf{T}_y$ must be equal and opposite to **mg**. What do we know about component $\mathbf{T}_x$? That's the net force on the bob, the centripetal force! Its magnitude is mv/r^2, where r is the radius of the circular path. Note that centripetal force lies along the radius of the circle swept out.



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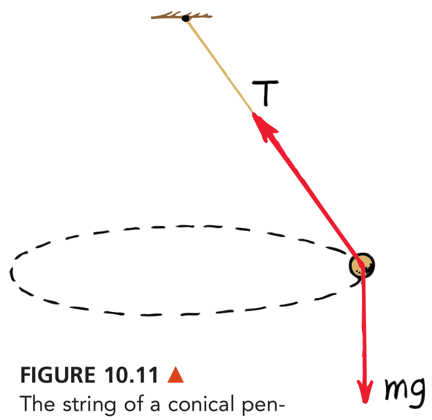


FIGURE 10.11 ▲
The string of a conical pendulum sweeps out a cone.

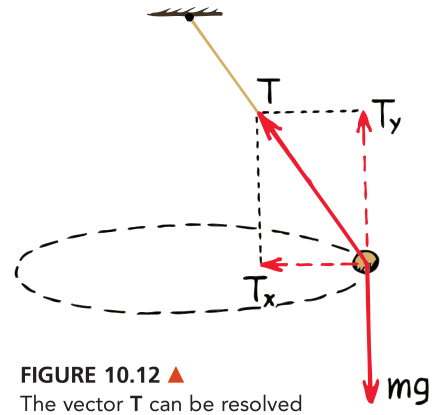
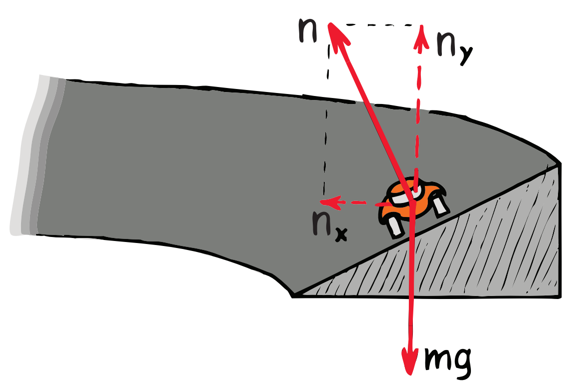


FIGURE 10.12 ▲
The vector **T** can be resolved into a horizontal (T_x) component and a vertical (T_y) component.

As another example, consider a vehicle rounding a banked curve, as illustrated in Figure 10.13. Suppose its speed is such that the vehicle has no tendency to slide down the curve or up the curve. At that speed, friction plays no role in keeping the vehicle on the track (interestingly, the angle of banked curves are chosen for zero friction at the designated speed). Only two forces act on the vehicle, one **mg,** and the other the normal force **n** (the support force of the surface). Note that **n** is resolved into $\mathbf{n}_x$ and $\mathbf{n}_y$ components. Again, $\mathbf{n}_y$ is equal and opposite to **mg**, and $\mathbf{n}_x$ is the centripetal force that keeps the vehicle in a circular path.

Whenever you want to identify the centripetal force that acts on a circularly moving object, it will be the net force that acts exactly along the radial direction—toward the center of the circular path.

CONCEPT CHECK **What factors affect the centripetal force acting on an object?**



◀ **FIGURE 10.13**
Centripetal force keeps the vehicle in a circular path as it rounds a banked curve.

▶ **Teaching Tip** The car in Figure 10.13 will successfully go around a banked track even if the track is 100% slippery ice (providing the car has the proper speed). Calculating this speed is an interesting problem posed in Appendix F as the first of the problems involving trigonometry.

CONCEPT CHECK The centripetal force on an object depends on the object's tangential speed, its mass, and the radius of its circular path.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book** *10–1*
- **Laboratory Manual** *35*
- **Transparency** *15*
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Questions** *10-2, 10-3*

10.4 Centripetal and Centrifugal Forces

Key Term
centrifugal force

Common Misconceptions

Things moving in a circular path are pulled outward by some force.

FACT The only force that is exerted on an object that moves in a circular path is one directed toward the center of circular motion.

If the string that holds an object in a circular path breaks, the object will move radially outward.

FACT When the string breaks, the object will move in a direction tangent to its circular path.

Ask **Why can't the rope in Figure 10.15 be horizontal when whirling the can?** *Vectors are central to this answer. There has to be a vertical component of the string tension equal to the weight of the whirling can. A horizontal string has no vertical component!*

▶ **Teaching Tip** Review Newton's first law. Distinguish centripetal force as a real, inward force, and centrifugal force as a fictitious, outward force.

▶ **Teaching Tip** Centrifugal force is the name given to a radially outward-acting force, and it is useful only in a rotating frame of reference. The inward push feels like an outward pull to the occupants in a rotating system. State how it differs from a real force in that there is no interaction—that is, there is no mass out there pulling on it. Whereas a real force is an interaction between one body and another, there is no reaction counterpart to the centrifugal force that is felt.

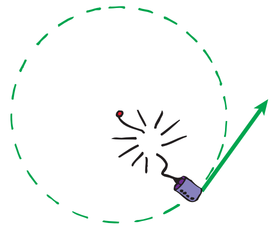


FIGURE 10.14 ▲
When the string breaks, the whirling can moves in a straight line, tangent to—not outward from the center of—its circular path.

10.4 Centripetal and Centrifugal Forces

In the preceding examples, circular motion is described as being caused by a center-directed force. Sometimes an outward force is also attributed to circular motion. This apparent outward force on a rotating or revolving body is called **centrifugal force.** *Centrifugal* means "center-fleeing," or "away from the center." In the case of the whirling can, it is a common misconception to state that a centrifugal force pulls outward on the can. If the string holding the whirling can breaks, as shown in Figure 10.14, it is often wrongly stated that centrifugal force pulls the can from its circular path. But in fact, when the string breaks the can goes off in a tangential straight-line path because *no* force acts on it. We illustrate this further with another example.

Suppose you are the passenger in a car that suddenly stops short. If you're not wearing a seat belt you pitch forward toward the dashboard. When this happens, you don't say that something forced you forward. You know that you pitched forward because of the *absence* of a force, which a seat belt provides. Similarly, if you are in a car that rounds a sharp corner to the left, you tend to pitch outward against the right door. Why? Not because of some outward or centrifugal force, but rather because there is no centripetal force holding you in circular motion. The idea that a centrifugal force bangs you against the car door is a misconception.

So when you swing a tin can in a circular path, as shown in Figure 10.15, there is *no* force pulling the can outward. Only the force from the string acts on the can to pull the can inward. The outward force is *on the string,* not on the can.

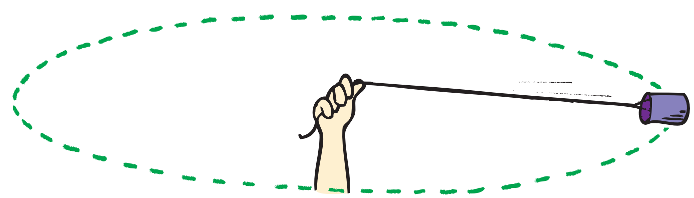
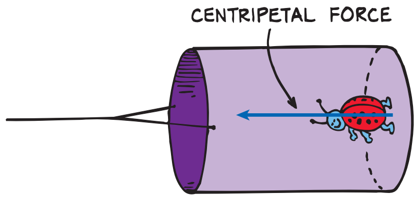


FIGURE 10.15 ▲
The only force that is exerted on the whirling can (neglecting gravity) is directed *toward* the center of circular motion. This is a *centripetal* force. No outward force acts on the can.



◀ **FIGURE 10.16**
The can provides the centripetal force necessary to hold the ladybug in a circular path.

Now suppose there is a ladybug inside the whirling can, as shown in Figure 10.16. The can presses against the bug's feet and provides the centripetal force that holds it in a circular path. The ladybug in turn presses against the floor of the can. Neglecting gravity, the *only* force exerted *on the ladybug* is the force of the can on its feet. From our outside stationary frame of reference, we see there is no centrifugal force exerted on the ladybug. ✓ **The "centrifugal-force effect" is attributed not to any real force but to inertia—the tendency of the moving body to follow a straight-line path.**

CONCEPT CHECK What causes the "centrifugal-force effect"?

discover!

Why Doesn't the Water Fall Out of the Bucket?

1. Fill a bucket halfway with water.
2. Swing the bucket of water in a vertical circle fast enough that the water won't fall out at the top.
3. **Think** Why does the water stay in the bucket?

10.5 Centrifugal Force in a Rotating Reference Frame

Our view of nature depends on the frame of reference from which we view it. For instance, when sitting in a fast-moving vehicle, we have no speed at all relative to the vehicle, but we have an appreciable speed relative to the reference frame of the stationary ground outside. From one frame of reference we have speed; from another we have none—likewise with force. Recall the ladybug inside the whirling can. From a stationary frame of reference outside the whirling can, we see there is *no* centrifugal force acting on the ladybug inside the whirling can. However, we do see centripetal force acting on the can and the ladybug, producing circular motion.

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CONCEPT CHECK The "centrifugal-force effect" is attributed not to any real force but to inertia—the tendency of the moving body to follow a straight-line path.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book** *10–2*
- **Problem-Solving Exercises in Physics** *7-1*
- **Transparency** *15*
- **Presentation*EXPRESS***
- **Interactive Textbook**

discover!

MATERIALS bucket, water

EXPECTED OUTCOME The water will not spill at the top when the centripetal force is at least equal to the weight of the water.

THINK Although the water doesn't fall *out* of the bucket, it still falls. The trick is to swing the bucket fast enough that the bucket falls as fast as the water inside falls. Because the bucket is revolving, the water moves tangentially as it falls—and stays in the bucket.

Many of your students will have heard of this demonstration, but only a few have actually seen it done. They will particularly enjoy seeing YOU do it, and the prospect of seeing you "all wet!" Don't simply discuss this: DO IT!

PAUL

10.5 Centrifugal Force in a Rotating Reference Frame

The water in the swinging bucket is analogous to the orbiting of a satellite. Both the swinging water and a satellite are falling. Because of their tangential velocities, they fall in a curve; just the right speed for the water in the bucket, and just the right greater speed for the space shuttle. Tying these related ideas together is good teaching!

PAUL

CONCEPT CHECK Centrifugal force is an effect of rotation. It is not part of an interaction and therefore it cannot be a true force.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

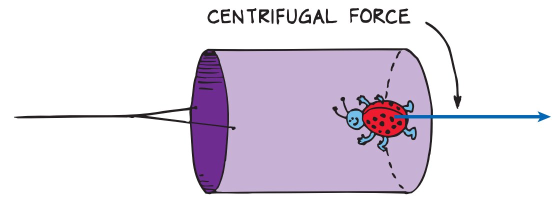
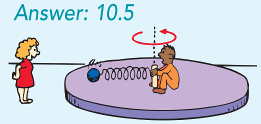


FIGURE 10.17 From the reference frame of the ladybug inside the whirling can, the ladybug feels as if she is being held to the bottom of the can by a force that is directed away from the center of circular motion.

think!

A heavy iron ball is attached by a spring to a rotating platform, as shown in the sketch. Two observers, one in the rotating frame and one on the ground at rest, observe its motion. Which observer sees the ball being pulled outward, stretching the spring? Which observer sees the spring pulling the ball into circular motion?
Answer: 10.5



But nature seen from the reference frame of the rotating system is different. In the rotating frame of reference of the whirling can, shown in Figure 10.17, both centripetal force (supplied by the can) *and* centrifugal force act *on the ladybug.* To the ladybug, the centrifugal force appears as a force in its own right, as real as the pull of gravity. However, if she were to stop rotating, she would feel no such force. Thus, there is a fundamental difference between the gravity-like centrifugal force and actual gravitational force. Gravitational force is always an interaction between one mass and another. The gravity we feel is due to the interaction between our mass and the mass of Earth. However, in a rotating reference frame the centrifugal force has no agent such as mass—there is no interaction counterpart.

Centrifugal force is an effect of rotation. It is not part of an interaction and therefore it cannot be a true force. For this reason, physicists refer to centrifugal force as a *fictitious force,* unlike gravitational, electromagnetic, and nuclear forces. Nevertheless, to observers who are in a rotating system, centrifugal force is very real. Just as gravity is ever present at Earth's surface, centrifugal force is ever present within a rotating system.

CONCEPT CHECK **Why is centrifugal force not considered a true force?**

Physics on the Job

Roller Coaster Designer
Since 1884, when the first American roller coaster was constructed, roller coasters have evolved into thrilling machines that rise over 100 meters high and reach speeds of over 150 km/h. Roller coaster designers, or mechanical design engineers, use the laws of physics to create rides that are both exciting and safe. In particular, designers must understand how roller coasters can safely navigate tall loops without exerting too much force on the riders. Designers of modern roller coasters first test their designs on computers to identify any problems before construction begins. Many private companies design roller coasters for amusement parks throughout the world.

10 REVIEW

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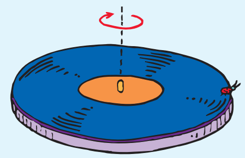
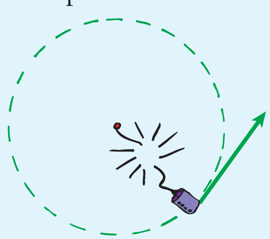
Concept Summary

- Two types of circular motion are rotation and revolution.



- Tangential speed depends on rotational speed and the distance from the axis of rotation.
- The centripetal force on an object depends on the object's tangential speed, its mass, and the radius of its circular path.
- The "centrifugal-force effect" is attributed not to any real force but to inertia—the tendency of the moving body to follow a straight-line path.



- Centrifugal force is an effect of rotation. It is not part of an interaction and therefore it cannot be a true force.

Key Terms

axis *(p. 171)*
rotation *(p. 171)*
revolution *(p. 171)*
linear speed *(p. 172)*
tangential speed *(p. 172)*
rotational speed *(p. 172)*
centripetal force *(p. 175)*
centrifugal force *(p. 178)*

think! Answers

10.2.1 Her rotational speed is also 4 RPM, and her linear speed is 3 m/s.

10.2.2 Similar to Figure 10.3a, the outer track is longer—just as a circle with a greater radius has a greater circumference.

10.5 The observer in the reference frame of the rotating platform states that centrifugal force pulls radially outward on the ball, which stretches the spring. The observer in the rest frame states that centripetal force supplied by the stretched spring pulls the ball into circular motion. (Only the observer in the rest frame can identify an action–reaction pair of forces; where action is spring-on-ball, reaction is ball-on-spring. The rotating observer can't identify a reaction counterpart to the centrifugal force because there isn't any.)

10 REVIEW

Teaching Resources

- **Teacher*EXPRESS***
- **Virtual Physics Lab** *13*
- **Conceptual Physics Alive! DVDs** *Rotation*

10 ASSESS

Check Concepts

1. Rotation—about an axis within the body; revolution—around an axis external to the body
2. Revolve
3. Linear—distance/time; rotational—angle/time or number of rotations/time
4. Tangential speed
5. Directly, $v = r\omega$
6. Directly, $v = r\omega$
7. Outer diameter has a greater linear speed.
8. Inward, toward the center of the circle
9. Inward
10. Centripetal
11. Lack of a force; Newton's first law—inertia
12. Bug on can, can on bug
13. No; no; none
14. It is not part of an interaction.

10 ASSESS

Check Concepts

Section 10.1

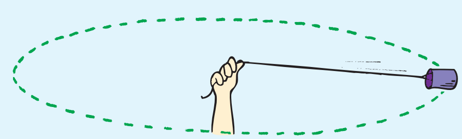
1. Distinguish between a rotation and a revolution.
2. Does a child on a merry-go-round revolve or rotate around the merry-go-round's axis?

Section 10.2

3. Distinguish between linear speed and rotational speed.
4. What is linear speed called when something moves in a circle?
5. At a given distance from the axis, how does linear (or tangential) speed change as rotational speed changes?
6. At a given rotational speed, how does linear (or tangential) speed change as the distance from the axis changes?
7. When you roll a cylinder across a surface it follows a straight-line path. A tapered cup rolled on the same surface follows a circular path. Why?

Section 10.3

8. When you whirl a can at the end of a string in a circular path, what is the direction of the force that acts on the can?



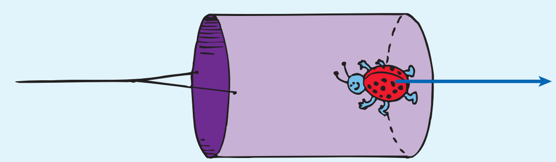
9. Does an inward force or an outward force act on the clothes during the spin cycle of an automatic washer?

Section 10.4

10. When a car makes a turn, do seat belts provide you with a centripetal force or centrifugal force?
11. If the string that holds a whirling can in its circular path breaks, what causes the can to move in a straight-line path—centripetal force, centrifugal force, or a lack of force? What law of physics supports your answer?

Section 10.5

12. Identify the action and reaction forces in the interaction between the ladybug and the whirling can in Figure 10.17.

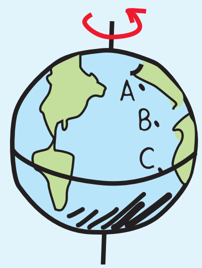


13. A ladybug in the bottom of a whirling tin can feels a centrifugal force pushing it against the bottom of the can. Is there an outside source of this force? Can you identify this as the action force of an action–reaction pair? If so, what is the reaction force?
14. Why is the centrifugal force the ladybug feels in the rotating frame called a fictitious force?

Think and Rank

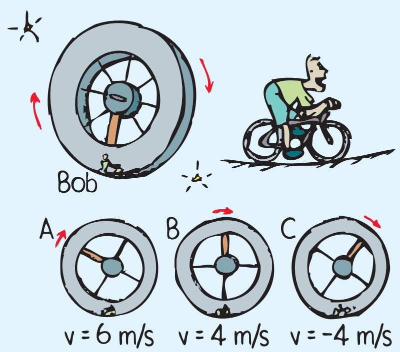
Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, then separate them with an equal sign. (e.g., A = B)

15. Three locations on our rotating world are shown. Rank these locations from greatest to least for the following quantities.



a. rotational speed about Earth's polar axis
b. tangential speed

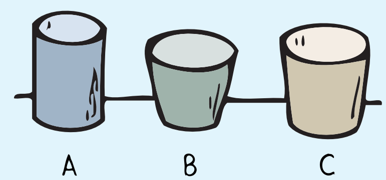
16. Biker Bob rides his bicycle inside the rotating space station at the speeds and directions given. The tangential speed of the floor of the station is 10 m/s clockwise.



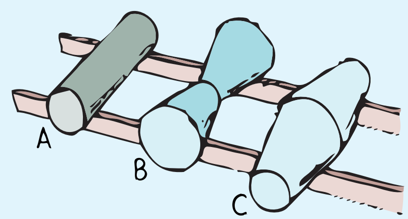
a. Rank his speeds from highest to lowest relative to the stars.
b. Rank the normal forces on Bob from largest to smallest.

17. Inside Biker Bob's space station is a ladder that extends from the inner surface of the rim to the central axis. Bob climbs the ladder (toward the center). Point A is at the floor, point B is halfway to the center, and point C is at the central axis.
a. Rank the linear speeds of Bob relative to the center of the station, from highest to lowest. Or are the speeds the same at all parts of the ladder?
b. Rank the support forces Bob experiences on the ladder rungs, from greatest to least. Or are the support forces the same in all locations?

18. The three cups shown below are rolled on a level surface. Rank the cups by the amount they depart from a straight-line path (most curved to least curved).



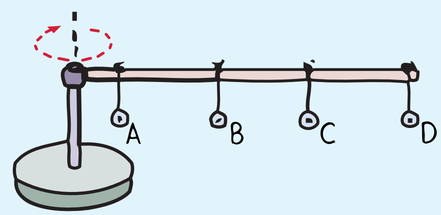
19. Three types of rollers are placed on slightly inclined parallel meter stick tracks, as shown below. Rank the rollers, in terms of their ability to remain stable as they roll, from greatest to least.



Think and Rank

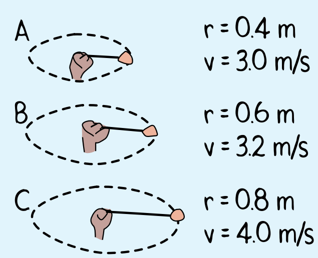
15. a. A = B = C
b. C, B, A
16. a. C, B, A
b. C, B, A
17. a. A, B, C
b. A, B, C
18. B, C, A
19. C, A, B

20. A meterstick is mounted horizontally above a turntable as shown. Identical metal washers are hung at the positions shown. The turntable and meterstick are then spun. Rank from greatest to least, the following quantities for the washers.

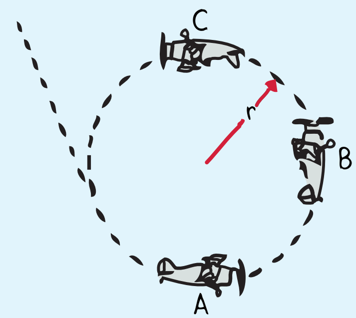


a. rotational speed
b. linear speed
c. angle the string makes with the vertical
d. inward force on each
e. outward force on each

21. A ball is swung in a horizontal circle as shown below. The ball swings from various lengths of rope at the speeds indicated. Rank the tension in the ropes from greatest to least.



22. Paula flies a loop-the-loop maneuver at constant speed. Two forces act on Paula, the force due to gravity and the normal force of the seat pressing on her (which provides the sensation of weight). Rank from largest to smallest the normal forces on Paula at points A, B, and C.



Plug and Chug

The equation for centripetal force is shown below.

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

23. A string is used to whirl a 2-kg toy in a horizontal circle of radius 2.5 m. Show that when the toy moves at 3 m/s the tension in the string (the centripetal force) is 7.2 N.

24. A 60-kg ice skater moving at 5 m/s grabs a 6-m rope and is swept into a circular path. Find the tension in the rope.

25. A 2-kg iron ball is swung in a horizontal circular path at the end of a 1.6-m length of rope. Assume the rope is very nearly horizontal and the ball's speed is 10 m/s. Calculate the tension in the rope.

20. a. A = B = C = D
b. D, C, B, A
c. D, C, B, A
d. D, C, B, A
e. None on any! (force is only inward)

21. A, C, B

22. A, B, C

Plug and Chug

23. $F = [(2\text{ kg})(3\text{ m/s})^2]/(2.5\text{ m}) = 7.2\text{ N}$

24. $F = [(60\text{ kg})(5\text{ m/s})^2]/(6\text{ m}) = 250\text{ N}$

25. $F = [(2\text{ kg})(10\text{ m/s})^2]/(1.6\text{ m}) = 125\text{ N}$

26. $F = [(70\text{ kg})(3\text{ m/s})^2]/(2\text{ m}) = 315\text{ N}$

Think and Explain

27. Sue's tires have more rotational speed because it takes more rotations to cover the same distance.

28. a. The rotational speed ω for the small wheel is twice that for the big wheel.
b. The tangential speeds of both wheels are equal to the speed of the belt.

29. For the same twisting speed ω, the greater distance r means greater speed v.

30. More taper means more turning ability so more taper is needed on sharp curves.

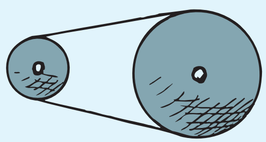
31. In a direction tangent to the merry-go-round—same direction you are moving when you let go

26. A 70-kg person sits on the edge of a horizontal rotating platform 2 m from the center of the platform and has a tangential speed of 3 m/s. Calculate the force of friction that keeps the person in place.

Think and Explain

27. Dan and Sue cycle at the same speed. The tires on Dan's bike are larger in diameter than those on Sue's bike. Which wheels, if either, have the greater rotational speed?

28. A large wheel is coupled to a wheel with half the diameter as shown.



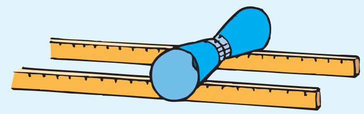
a. How does the rotational speed of the smaller wheel compare with that of the larger wheel?
b. How do the tangential speeds at the rims compare (assuming the belt doesn't slip)?

29. Use the equation $v = r\omega$ to explain why the end of a fly swatter moves much faster than your wrist when swatting a fly.

30. The wheels of railroad trains are tapered, a feature especially important on curves. For sharp curves, should the wheels be less tapered or more tapered?

31. If you lose your grip on a rapidly spinning merry-go-round and fall off, in which direction will you fly?

32. Consider the pair of cups taped together as shown. Will this design correct its motion and keep the pair of cups on the track? Predict before you try it and see!

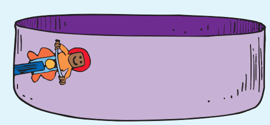


33. Which state in the United States has the greatest tangential speed as Earth rotates around its axis?

34. The speedometer in a car is driven by a cable connected to the shaft that turns the car's wheels. Will speedometer readings be more or less than actual speed when the car's wheels are replaced with smaller ones?

35. Keeping in mind the concept from the previous question, a taxi driver wishes to increase his fares by adjusting the size of his tires. Should he change to larger tires or smaller tires?

36. A motorcyclist is able to ride on the vertical wall of a bowl-shaped track, as shown. Does centripetal force or centrifugal force act on the motorcycle? Defend your answer.



37. When a soaring eagle turns during its flight, what is the source of the centripetal force acting on it?

32. No; when the outer part of the wheel rides on the track, tangential speed is increased. This tends to turn the wheels off the track.

33. Hawaii because it is closest to the equator. Look at a globe from the top. Without parallax, it looks like a disk. Hawaii, farther from the center, has the greatest tangential speed as Earth rotates. For this reason, Hawaii is a favored place from which to launch satellites; Earth's speed assists the launch.

34. More; the rims of smaller wheels don't move as far per rotation, so a car with smaller wheels goes slower than the speedometer shows.

35. Smaller; speedometer and odometer readings will be higher.

36. From the vantage point of the track, a center-directed force (centripetal) acts on the motorcycle.

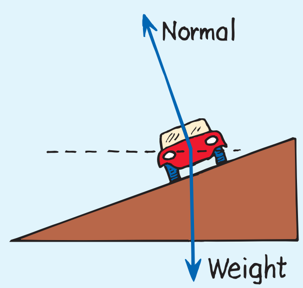
37. The motion through the air, together with the bank angle of the wings, produces a force of which a component is centripetal.

38. Yes, if the horizontal component of normal force is equal to the centripetal force required. A banked track provides a normal force on a vehicle. This force has a component along the radial (horizontal) direction that supplies a centripetal force on the vehicle. If it is just right, no friction force is needed for the vehicle to turn on the track.

39. The horizontal component of the normal force supplies the centripetal force.

10 ASSESS *(continued)*

38. A car resting on a level road has two forces acting on it: its weight (down) and the normal force (up). Recall from Chapter 4 that the normal force is the support force, which is always perpendicular to the supporting surface. If the car makes a turn on a level road, the normal force is still straight up. Friction between the wheels and road is the only centripetal force providing curved motion. Suppose the road is banked so the normal force has a component that provides centripetal force as shown in the sketch. Do you think the road could be banked so that for a given speed and a given radius of curvature, a vehicle could make the turn without friction? Explain.



39. Friction is needed for a car rounding a curve. But if the road is banked, friction may not be required at all. What, then, supplies the needed centripetal force?

40. Under what conditions could a car remain on a banked track covered with slippery ice?

41. A racing car on a flat circular track needs friction between the tires and the track to maintain circular motion. How much more friction is required for twice the speed?

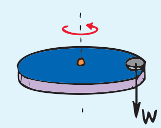
42. Can an object move along a curved path if no force acts on it?

43. When you are in the front passenger seat of a car turning left, you may find that you feel pressed against the right door. Why do you press against the door? Why does the door press on you? Does your explanation involve a centrifugal force or Newton's laws?

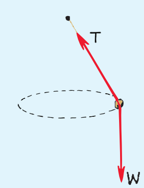
44. As a car speeds up when rounding a curve, does centripetal acceleration also increase? Use an equation to defend your answer.

45. Explain why a centripetal force does not do work on a circularly moving object.

46. The sketch shows a coin at the edge of a turntable. The weight of the coin is shown by the vector **W**. Two other forces act on the coin, the normal force and a force of friction. The friction force prevents the coin from sliding off the edge. Draw in force vectors for both of these.



47. The sketch shows a conical pendulum. The bob swings in a circular path. The tension **T** and weight **W** are shown by vectors. Draw a parallelogram with these vectors and show that their resultant lies in the plane of the circle (recall the parallelogram rule in Chapter 5). What name do we use for this resultant force?



40. If the horizontal component of the normal force equals the centripetal force, then the car stays on the banked track with no need for friction.

41. Four times as much, as centripetal force varies as speed squared.

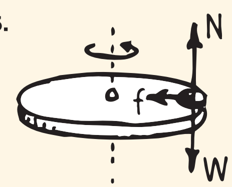
42. No, because it is accelerated, which requires a net force.

43. By Newton's first law, you press against the door due to inertia. The door stops you with an inward force, and you push back in accordance with Newton's third law.

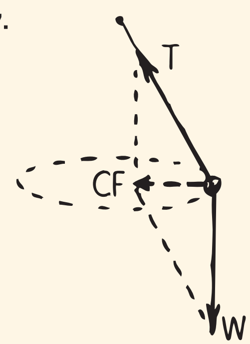
44. Yes, centripetal acceleration increases. From $F = ma = mv^2/r$, $a = v^2/r$.

45. Work requires a force or component of force in the direction of motion. Since centripetal force is perpendicular to motion, there is no component of force in the direction of motion and therefore no work.

46.



47.



The resultant force is called the centripetal force.

Think and Solve

48. Consider a bicycle that has wheels with a circumference of 2 m. Solve for the linear speed of the bicycle when its wheels rotate at 1 revolution per second.

49. Solve for the tangential speed of a passenger on a Ferris wheel that has a radius of 10 m and rotates once in 30 s.

50. A wheel of radius r meters rolls across a floor at 2 rotations per second. Begin with speed = distance/time and show that the speed of the wheel rolling across the floor is $4\pi r$ m/s.

51. Megan rides a horse at the outer edge of a merry-go-round. She is located 6 m from the central axis and is a bit frightened of the speed. So her parents place her on a horse 3 m from the axis. While on the inner horse, how will her linear speed compare with her speed on the outer horse?

52. Emily rides on a horizontal rotating platform of radius r at an amusement park and moves at speed v one-third the way from the center to the outer edge.
a. If the rotation rate of the platform remains constant, what will be her linear speed when she moves to the outer edge?
b. If Emily's linear speed was 1.0 m/s at one-third the radius from the center, show that she would move at 3.0 m/s at the outer edge.

53. From the equation $F = \frac{mv^2}{r}$, calculate the tension in a 2-m length of string that whirls a 1-kg mass at 2 m/s in a horizontal circle.

54. Answer the previous question for each of the following cases.
a. twice the mass
b. twice the speed
c. twice the length of string (radial distance)
d. twice the mass, twice the speed, and twice the distance all at the same time

55. A turntable that turns 10 revolutions each second is located on top of a mountain. Mounted on the turntable is a laser that emits a bright beam of light. As the turntable and laser rotate, the beam also rotates and sweeps across the sky. On a dark night the beam reaches some clouds 10 km away.
a. How fast does the spot of laser light sweep across the clouds?
b. How fast does the spot of laser light sweep across clouds that are 20 km away?
c. At what distance will the laser beam sweep across the sky at the speed of light (300,000 km/s)?

56. Harry Hotrod rounds a corner in his sports car at 50 km/h. Fortunately, a force of friction holds him on the road. If he rounds the corner at twice the speed, how much greater must the force of friction be to prevent him from skidding off the road? (You can solve this by using a simple proportion.)

More Problem-Solving Practice
Appendix F

Think and Solve

48. The bicycle moves 2 m with each rotation, $v = d/t = 2\text{ m}/1\text{ s} = 2$ m/s.

49. Speed $= d/t = 2\pi r/t = 2\pi(10\text{ m})/30\text{ s} = 2.1$ m/s

50. Speed $= d/t$ = twice the circumference/second $= 2(2\pi r)/\text{s} = 4\pi r$ m/s

51. Rotational speed is constant. From $v = r\omega$, half the r means half the speed. So, when she is 3 m from the axis her speed is half of what it was when she was 6 m from the axis.

52. **a.** From $v \sim r$ three times r means three times v. So she travels at speed $3v$.
b. Speed at the edge $= 3v = 3(1.0\text{ m/s}) = 3.0$ m/s

53. $F = mv^2/r = [(1\text{ kg})(2\text{ m/s})^2]/(2\text{ m}) = 2$ N

54. **a.** Twice, 4 N
b. Four times, 8 N
c. Half, 1 N
d. Four times, 8 N

55. **a.** $v = 2\pi r/t = (6.28)(10\text{ km})/(0.1\text{ s}) = 628$ km/s
b. At twice the distance, speed is twice, or 1256 km/s.
c. $v = 2\pi r/t$, $r = vt/2\pi = (300{,}000\text{ km/s} \times 0.1\text{ s})/2\pi = 4777$ km

56. $F_c \sim v^2$, so twice the speed requires 4 times the centripetal force, and therefore 4 times the friction force.

Teaching Resources
- Computer Test Bank
- Chapter and Unit Tests