3.2 Analyzing Forces in Circular Motion

How would you design a highway turn in which northbound traffic would go around a curve and become westbound, as in **Figure 1(a)**? Which design shown in **Figure 1(b)** is preferable?

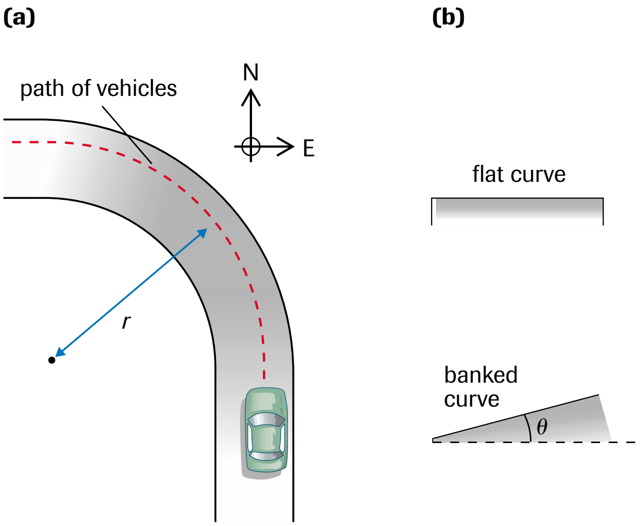

Figure 1
(a) A car travelling around a curve undergoes centripetal acceleration since the curve is an arc with radius *r*.
(b) Would the best design of a highway turn have a flat curve or a banked curve?

> ***LEARNING TIP***
> **The Direction of the Net Force in Uniform Circular Motion**
> Since centripetal acceleration is directed toward the centre of the circle, the net force must also be directed toward the centre of the circle. This force can usually be determined by drawing an FBD of the object in uniform circular motion.

Cars negotiating curves on highways provide an example of circular motion. You learned in Section 3.1 that an object travelling at a constant speed in a circle or an arc experiences centripetal acceleration toward the centre of the circle. According to Newton's second law of motion, centripetal acceleration is the result of a net force acting in the direction of the acceleration (toward the centre of the circle) and perpendicular to the instantaneous velocity vector.

It is important to note that this net force is no different from other forces that cause acceleration: it might be gravity, friction, tension, a normal force, or a combination of two or more forces. For example, if we consider Earth travelling in a circular orbit around the Sun, the net force is the force of gravity that keeps Earth in its circular path.

We can combine the second-law equation for the magnitude of the net force, $\sum F = ma$, with the equation for centripetal acceleration, $a_c = \frac{v^2}{r}$:

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

where $\sum F$ is the magnitude of the net force that causes the circular motion, m is the mass of the object in uniform circular motion, v is the speed of the object, and r is the radius of the circle or arc.

The equations for centripetal acceleration involving the period and frequency of circular motion can also be combined with the second-law equation. Thus, there are three common ways of writing the equation:

$$\sum F = \frac{mv^2}{r} = \frac{4\pi^2 mr}{T^2} = 4\pi^2 mrf^2$$

SAMPLE problem 1

A car of mass 1.1×10^3 kg negotiates a level curve at a constant speed of 22 m/s. The curve has a radius of 85 m, as shown in **Figure 2**.

(a) Draw an FBD of the car and name the force that provides the centripetal acceleration.

(b) Determine the magnitude of the force named in (a) that must be exerted to keep the car from skidding sideways.

(c) Determine the minimum coefficient of static friction needed to keep the car on the road.

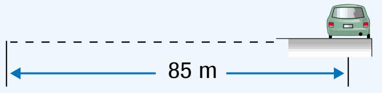

Figure 2
The radius of the curve is 85 m.

Solution

(a) **Figure 3** is the required FBD. The only horizontal force keeping the car going toward the centre of the arc is the force of static friction ($\vec{F}_S$) of the road on the wheels perpendicular to the car's instantaneous velocity. (Notice that the forces parallel to the car's instantaneous velocity are not shown in the FBD. These forces act in a plane perpendicular to the page; they are equal in magnitude, but opposite in direction because the car is moving at a constant speed.)

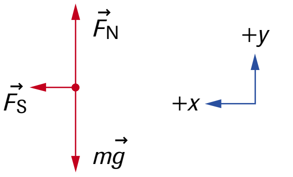

Figure 3
The FBD of the car on a level curve

(b) $m = 1.1 \times 10^3$ kg
$v = 22$ m/s
$r = 85$ m
$F_S = ?$

$$F_S = \frac{mv^2}{r} = \frac{(1.1 \times 10^3 \text{ kg})(22 \text{ m/s})^2}{85 \text{ m}}$$

$$F_S = 6.3 \times 10^3 \text{ N}$$

The magnitude of the static friction force is 6.3×10^3 N.

(c) $g = 9.8$ N/kg

We know from part (b) that the static friction is 6.3×10^3 N and from **Figure 3** that $F_N = mg$. To determine the minimum coefficient of static friction, we use the ratio of the maximum value of static friction to the normal force:

$$\mu_S = \frac{F_{S,max}}{F_N} = \frac{6.3 \times 10^3 \text{ N}}{(1.1 \times 10^3 \text{ kg})(9.8 \text{ N/kg})}$$

$$\mu_S = 0.58$$

The minimum coefficient of static friction needed is 0.58. This value is easily achieved on paved and concrete highways in dry or rainy weather. However, snow and ice make the coefficient of static friction less than 0.58, allowing a car travelling at 22 m/s to slide off the road.

SAMPLE problem 2

A car of mass 1.1×10^3 kg travels around a frictionless, banked curve of radius 85 m. The banking is at an angle of 19° to the horizontal, as shown in **Figure 4**.

(a) What force provides the centripetal acceleration?

(b) What constant speed must the car maintain to travel safely around the curve?

(c) How does the required speed for a more massive vehicle, such as a truck, compare with the speed required for this car?

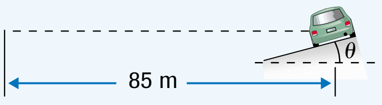

Figure 4
The radius of the curve is 85 m.

Solution

(a) From the FBD shown in **Figure 5**, you can see that the cause of the centripetal acceleration, which acts toward the centre of the circle, is the horizontal component of the normal force, $F_N \sin \theta$. Thus, the horizontal acceleration, a_x, is equivalent to the centripetal acceleration, a_c. (Notice that the FBD resembles the FBD of a skier going downhill, but the analysis is quite different.)

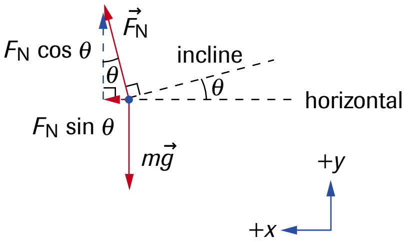

Figure 5
The FBD of the car on a banked curve

(b) $m = 1.1 \times 10^3$ kg

$r = 85$ m

$\theta = 19°$

$v = ?$

We take the vertical components of the forces:

$$\sum F_y = 0$$
$$F_N \cos \theta - mg = 0$$
$$F_N = \frac{mg}{\cos \theta}$$

Next, we take the horizontal components of the forces:

$$\sum F_x = ma_c$$
$$F_N \sin \theta = ma_c$$
$$\frac{mg}{\cos \theta} \sin \theta = ma_c$$
$$mg \tan \theta = \frac{mv^2}{r}$$
$$v^2 = gr \tan \theta$$
$$v = \pm\sqrt{gr \tan \theta}$$
$$= \pm\sqrt{(9.8 \text{ m/s}^2)(85 \text{ m})(\tan 19°)}$$
$$v = \pm 17 \text{ m/s}$$

We choose the positive square root, since v cannot be negative. The speed needed to travel safely around the frictionless curve is 17 m/s. If the car travels faster than 17 m/s, it will slide up the banking; if it travels slower than 17 m/s, it will slide downward.

(c) The speed required for a more massive vehicle is the same (17 m/s) because the mass does not affect the calculations. One way of proving this is to point to our expression $v^2 = gr \tan \theta$: v depends on g, r, and θ but is independent of m.

SAMPLE problem 3

A 3.5-kg steel ball in a structural engineering lab swings on the end of a rigid steel rod at a constant speed in a vertical circle of radius 1.2 m, at a frequency of 1.0 Hz, as in **Figure 6**. Calculate the magnitude of the tension in the rod due to the mass at the top (A) and the bottom (B) positions.

Solution

$m = 3.5$ kg

$r = 1.2$ m

$f = 1.0$ Hz

$F_T = ?$

In both FBDs in **Figure 7**, the tension in the rod is directed toward the centre of the circle. At position A, the weight, *mg,* of the ball acts together with the tension to cause the centripetal acceleration. At position B, the tension must be greater than at A because the tension and the ball's weight are in opposite directions and the net force must be toward the centre of the circle. In each case, $+y$ is the direction in which the centripetal acceleration is occurring.

At position A:

$$\begin{aligned} \sum F_y &= ma_c \\ F_T + mg &= 4\pi^2 mrf^2 \\ F_T &= 4\pi^2 mrf^2 - mg \\ &= 4\pi^2(3.5 \text{ kg})(1.2 \text{ m})(1.0 \text{ Hz})^2 - (3.5 \text{ kg})(9.8 \text{ N/kg}) \\ F_T &= 1.3 \times 10^2 \text{ N} \end{aligned}$$

When the ball is moving at the top of the circle, the magnitude of the tension is 1.3×10^2 N.

At position B:

$$\begin{aligned} \sum F_y &= ma_c \\ F_T - mg &= 4\pi^2 mrf^2 \\ F_T &= 4\pi^2 mrf^2 + mg \\ &= 4\pi^2(3.5 \text{ kg})(1.2 \text{ m})(1.0 \text{ Hz})^2 + (3.5 \text{ kg})(9.8 \text{ N/kg}) \\ F_T &= 2.0 \times 10^2 \text{ N} \end{aligned}$$

When the ball is moving at the bottom of the circle, the magnitude of the tension is 2.0×10^2 N.

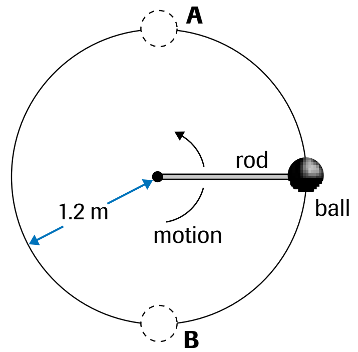

Figure 6
The system diagram for the steel ball and the rod in Sample Problem 3

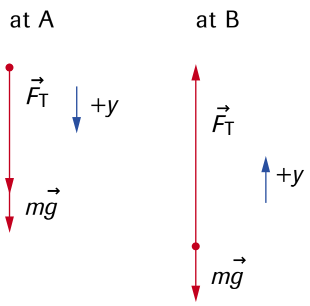

Figure 7
The FBDs at positions A and B

Case Study: The Physics of the Looping Roller Coaster

The first loop-the-loop roller coaster, built in the early part of the 20th century, consisted of a circular loop as illustrated in **Figure 8(a)**. With this design, however, the coaster had to be so fast that many people were injured on the ride and the design was soon abandoned.

Today's looping coasters have a much different design: a curve with a radius that starts off large, but becomes smaller at the top of the loop. This shape, called a *clothoid loop*, is illustrated in **Figure 8(b)**.

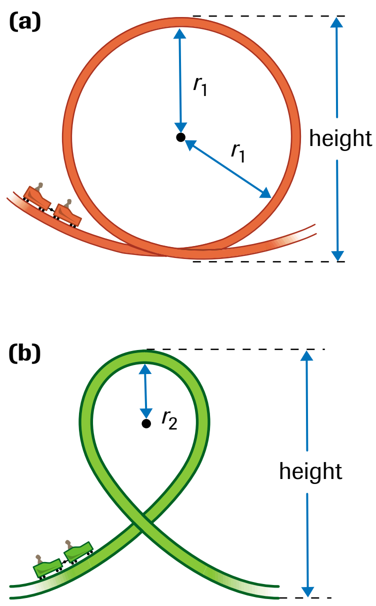

Figure 8
Two different loop designs used in roller coasters
(a) The circular loop used almost a century ago
(b) The clothoid loop used in today's looping coasters

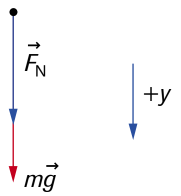

Figure 9
The FBD of the rider at the top of a roller-coaster loop

We can apply physics principles to compare the two designs. We will assume that in both designs, the magnitude of the normal force felt by a rider of mass m at the top of the loop is double his or her own weight, mg. (This means that the normal force has a magnitude of $2mg$.) This assumption allows us to calculate how fast each coaster must travel to achieve the same force on the rider.

Figure 9 shows the FBD of a rider at the top of the loop. The magnitude of the net force acting on the rider at that instant, ΣF, can be used to determine an expression for the speed of the coaster. Note that in this case study, we will use the subscript "old" to represent the older, circular loop and the subscript "new" to represent the newer, clothoid loop. We will also estimate that the ratio of the radius in the old design to the radius in the new design is 2.0 : 1.0.

$$\begin{aligned}
\sum F &= ma_c \\
F_N + mg &= \frac{mv^2}{r} \\
2mg + mg &= \frac{mv^2}{r} \\
3g &= \frac{v^2}{r} \\
v^2 &= 3gr \\
v &= \sqrt{3gr} \quad \text{(rejecting the negative square root as meaningless)}
\end{aligned}$$

Next, we find the ratio of the speeds of the two designs required to satisfy these conditions:

$$r_{old} = 2.0r_{new}$$

$$\begin{aligned}
\frac{v_{old}}{v_{new}} &= \sqrt{\frac{3gr_{old}}{3gr_{new}}} \\
&= \sqrt{\frac{r_{old}}{r_{new}}} \\
&= \sqrt{\frac{2.0r_{new}}{r_{new}}} \\
&= \sqrt{2.0} \\
v_{old} &= 1.4v_{new}
\end{aligned}$$

Thus, the speed of the roller coaster of the older design had to be 1.4 times as fast as the roller coaster of the new design to have the same force act on the riders, even though the heights of the two loops are equal.

Practice

Understanding Concepts

1. (a) Determine the speed required by a coaster that would cause a rider to experience a normal force of $2mg$ at the top of a clothoid loop where the radius is 12 m. Express your answer both in metres per second and in kilometres per hour.
   (b) How fast would a coaster on a circular loop of the same height have to travel to create the same normal force? Express your answer in kilometres per hour.

Answers

1. (a) 19 m/s; 68 km/h
   (b) 95 km/h

So far in our discussion of forces and circular motion, we have seen that centripetal acceleration can be caused by a variety of forces or combinations of forces: static friction (in Sample Problem 1); the horizontal component of a normal force (in Sample Problem 2); gravity (Earth orbiting the Sun); gravity and a tension force (in Sample Problem 3); and gravity and a normal force (in the Case Study). The net force that causes centripetal acceleration is called the **centripetal force**. Notice that centripetal force is *not* a separate force of nature; rather it is a net force that can be a single force (such as gravity) or a combination of forces (such as gravity and a normal force).

centripetal force net force that causes centripetal acceleration

Practice

Understanding Concepts

2. Draw an FBD of the object in *italics,* and name the force or forces causing the centripetal acceleration for each of the following situations:

(a) The *Moon* is in an approximately circular orbit around Earth.

(b) An *electron* travels in a circular orbit around a nucleus in a simplified model of a hydrogen atom.

(c) A *snowboarder* slides over the top of a bump that has the shape of a circular arc.

3. The orbit of Uranus around the Sun is nearly a circle of radius 2.87×10^{12} m. The speed of Uranus is approximately constant at 6.80×10^3 m/s. The mass of Uranus is 8.80×10^{25} kg.

(a) Name the force that causes the centripetal acceleration.
(b) Determine the magnitude of this force.
(c) Calculate the orbital period of Uranus, both in seconds and in Earth years.

4. A bird of mass 0.211 kg pulls out of a dive, the bottom of which can be considered to be a circular arc with a radius of 25.6 m. At the bottom of the arc, the bird's speed is a constant 21.7 m/s. Determine the magnitude of the upward lift on the bird's wings at the bottom of the arc.

5. A highway curve in the horizontal plane is banked so that vehicles can proceed safely even if the road is slippery. Determine the proper banking angle for a car travelling at 97 km/h on a curve of radius 450 m.

6. A 2.00-kg stone attached to a rope 4.00 m long is whirled in a circle horizontally on a frictionless surface, completing 5.00 revolutions in 2.00 s. Calculate the magnitude of tension in the rope.

7. A plane is flying in a vertical loop of radius 1.50 km. At what speed is the plane flying at the top of the loop if the vertical force exerted by the air on the plane is zero at this point? State your answer both in metres per second and in kilometres per hour.

8. An 82-kg pilot flying a stunt airplane pulls out of a dive at a constant speed of 540 km/h.

(a) What is the minimum radius of the plane's circular path if the pilot's acceleration at the lowest point is not to exceed $7.0g$?
(b) What force is applied on the pilot by the plane seat at the lowest point in the pullout?

Applying Inquiry Skills

9. You saw in Sample Problem 3 that when an object is kept in circular motion in the vertical plane by a tension force, the tension needed is greater at the bottom of the circle than at the top.

(a) Explain in your own words why this is so.
(b) Describe how you could safely demonstrate the variation in tension, using a one-hole rubber stopper and a piece of string.

Answers

3. (b) 1.42×10^{21} N
   (c) 2.65×10^9 s; 84.1 a
4. 5.95 N
5. 9.3°
6. 1.97×10^3 N
7. 121 m/s or 436 km/h
8. (a) 3.3×10^2 m
   (b) 6.4×10^3 N

Answer

11. (a) 23 m/s

Making Connections

10. (a) How do the banking angles for on- and off-ramps of expressways compare with the banking angles for more gradual highway turns? Why?
(b) Why is the posted speed for a ramp lower than the speed limit on most highways?

11. Railroad tracks are banked at curves to reduce wear and stress on the wheel flanges and rails, and to prevent the train from tipping over.
(a) If a set of tracks is banked at an angle of 5.7° from the horizontal and follows a curve of radius 5.5×10^2 m, what is the ideal speed for a train rounding the curve?
(b) How do banked curves on railroads reduce wear and stress?

Rotating Frames of Reference

We saw in Section 2.5 that an accelerating frame of reference is a noninertial frame in which Newton's law of inertia does not hold. Since an object in circular motion is accelerating, any motion observed *from that object* must exhibit properties of a noninertial frame of reference. Consider, for example, the forces you feel when you are the passenger in a car during a left turn. You feel as if your right shoulder is being pushed against the passenger-side door. From Earth's frame of reference (the inertial frame), this force that you feel can be explained by Newton's first law of motion: you tend to maintain your initial velocity (in both magnitude and direction). When the car you are riding in goes left, you tend to go straight, but the car door pushes on you and causes you to go in a circular path along with the car. Thus, there is a centripetal force to the left on your body, as depicted in **Figure 10(a)**. The corresponding FBD (as seen from the side) is shown in **Figure 10(b)**.

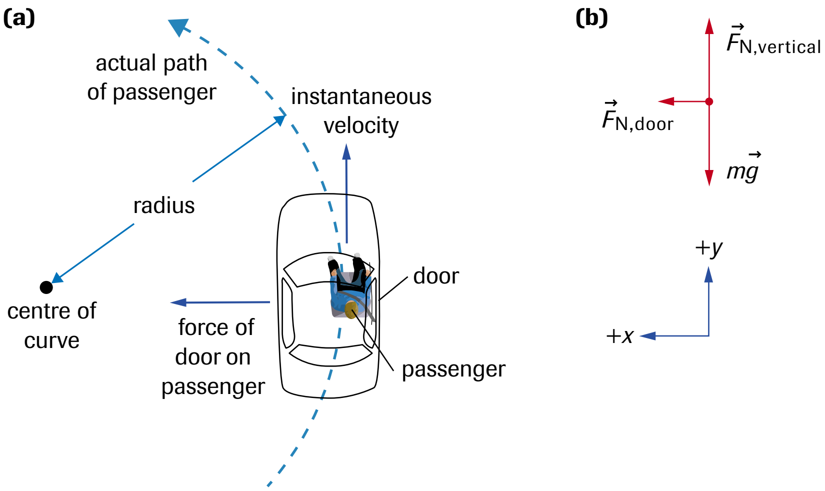

Figure 10
(a) The top view of a passenger in a car from Earth's frame of reference as the car makes a left turn
(b) The side-view FBD of the passenger

centrifugal force fictitious force in a rotating (accelerating) frame of reference

Consider the same situation from the accelerating frame of reference of the car. You feel as if something is pushing you toward the outside of the circle. This force away from the centre is a fictitious force called the **centrifugal force**. This situation, and the corresponding FBD involving the centrifugal force, are shown in **Figure 11**. Since the passenger is stationary (and remains so) in the rotating frame, the sum of the forces in that frame is zero.

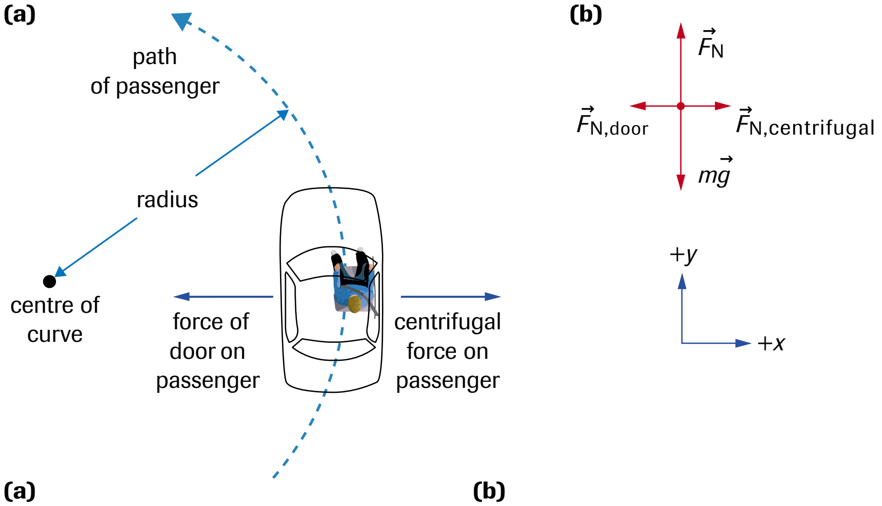

Figure 11
(a) Top view of a passenger from the car's frame of reference as the car makes a left turn
(b) The side-view FBD of the passenger, showing the fictitious force in the accelerating frame of reference

(a)

(b)

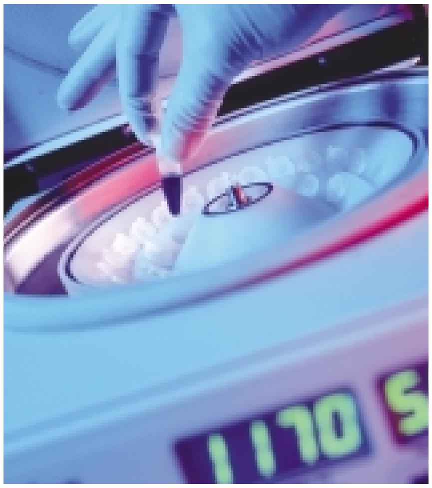

Figure 12
(a) This centrifuge located at the Manned Spacecraft Center in Huston, Texas, swings a three-person gondola to create *g*-forces experienced by astronauts during liftoff and re-entry conditions.
(b) A medical centrifuge used to separate blood for testing purposes

centrifuge rapidly-rotating device used for separating substances and training astronauts

A practical application of centrifugal force is the **centrifuge**, a rapidly-rotating device used for such applications as separating substances in solution according to their densities and training astronauts. **Figure 12** shows some applications of a centrifuge.

Figure 13 shows the operation of a typical centrifuge. Test tubes containing samples are rotated at high frequencies; some centrifuges have frequencies higher than 1100 Hz. A dense cell or molecule near the top of a tube at position A tends to continue moving at a constant speed in a straight line (if we neglect fluid friction due to the surrounding liquid). This motion carries the cell toward the bottom of the tube at position B. Relative to the rotating tube, the cell is moving away from the centre of the circle and is settling out. Relative to Earth's frame of reference, the cell is following Newton's first law of motion as the tube experiences an acceleration toward the centre of the centrifuge.

Another rotating noninertial frame of reference is Earth's surface. As Earth rotates daily on its axis, the effects of the centrifugal acceleration on objects at the surface are very small; nonetheless, they do exist. For example, if you were to drop a ball at the equator, the ball would fall straight toward Earth's centre because of the force of gravity. However, relative to Earth's rotating frame of reference, there is also a centrifugal force

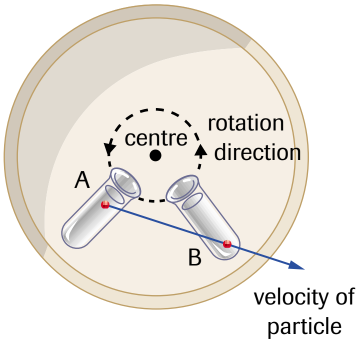

Figure 13
As the centrifuge rotates, a particle at position A tends to continue moving at a constant velocity, thus settling to the bottom of the tube.

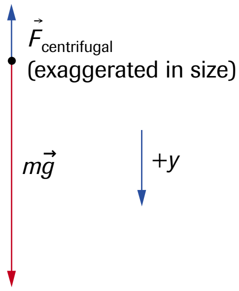

Figure 14
A ball dropped at the equator experiences not only the force of gravity, but also a small centrifugal force. This FBD of the ball is in Earth's rotating frame of reference.

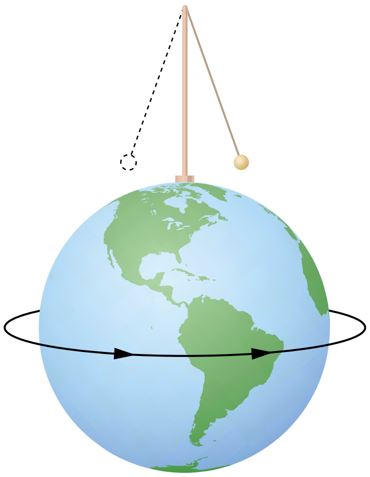

Figure 15
A Foucault pendulum at the North Pole for the Try This Activity

directed away from Earth's centre. (This is Newton's first law of motion in action; you feel a similar, though much greater effect when travelling at a high speed over the hill of a roller coaster track.) Thus, the net force on the ball in Earth's rotating frame is less than the force of gravity in a nonrotating frame of reference. This is illustrated in the FBD of the ball in **Figure 14**. The acceleration of the ball at the equator is about 0.34% less than the acceleration due to gravity alone. The magnitude of the centrifugal force is a maximum at the equator, and decreases to zero at the Poles.

A detailed analysis of the motion of particles in a rotating frame of reference would show that another fictitious force is involved. This force, perpendicular to the velocity of the particle or object *in the rotating frame*, is called the **Coriolis force**. It is named after the French mathematician Gaspard Gustave de Coriolis (1792–1843). Notice that this fictitious force acts on objects that are in motion relative to the rotating frame.

For most objects moving at Earth's surface, the effect of the Coriolis force is not noticeable. However, for objects that move very quickly or for a very long time, the effect is important. For example, the Coriolis force is responsible for the rotation of many weather patterns, such as the low-pressure systems that rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.

TRY THIS activity — The Foucault Pendulum

In 1851, Jean Foucault, a French physicist, set up a pendulum to illustrate that Earth is a rotating frame of reference. The Foucault pendulum consists of a heavy bob suspended on a long wire; Foucault used a 28-kg bob attached to a 67-m wire. However, you can use a much smaller pendulum with a globe to model a Foucault pendulum.

(a) How would you use a globe and a simple pendulum to illustrate the behaviour of a Foucault pendulum swinging at the North Pole, as in **Figure 15**? Describe what you would observe at that location.
(b) How does the observed behaviour of a Foucault pendulum at the equator differ from the observed behaviour at your latitude?
(c) If possible, set up a demonstration of your answer to (a).

Practice

Understanding Concepts

12. You are standing on a slowly rotating merry-go-round, turning counterclockwise as viewed from above. Draw an FBD for your body and explain your motion
(a) in Earth's frame of reference (assumed to have negligible rotation)
(b) in the frame of reference of the merry-go-round

13. When you stand on the merry-go-round in question 12, you hold a string from which is suspended a rubber stopper of mass 45 g. You are 2.9 m from the centre of the merry-go-round. You take 4.1 s to complete one revolution.
(a) Draw a system diagram, showing the situation at the instant you are moving due east.
(b) Draw an FBD of the stopper in Earth's frame of reference for a person looking eastward from behind you.
(c) Draw an FBD of the stopper in your frame of reference.
(d) What angle does the string make with the vertical?
(e) What is the magnitude of the tension in the string?

14. (a) Show that the acceleration of an object dropped at the equator is about 0.34% less than the acceleration due to gravity alone.
(b) What is the difference between your weight at the equator (in newtons) and your weight (from acceleration due to gravity alone)?

Answers

13. (d) 35°
(e) 5.4×10^{-2} N

Coriolis force fictitious force that acts perpendicular to the velocity of an object in a rotating frame of reference

Applying Inquiry Skills

15. You take a horizontal accelerometer (the type with three small beads in transparent tubing, as in **Figure 3** in the introduction to this chapter) onto an amusement-park ride rotating in the horizontal plane to determine your centripetal acceleration (**Figure 16**). The mass of the central bead in the accelerometer is 1.1 g. The ride rotates clockwise as viewed from above, at a frequency of 0.45 Hz. You are 4.5 m from the centre.

Figure 16
As this ride begins, it rotates in the horizontal plane, allowing a rider to use a horizontal accelerometer to measure the acceleration.

(a) How would you hold the accelerometer to obtain the reading?
(b) What is the magnitude of your centripetal acceleration?
(c) At what angle from the vertical is the central bead in the accelerometer?
(d) Determine the magnitude of the normal force exerted by the accelerometer on the bead.

Making Connections

16. Research the origin and design of Foucault pendulums. Where is the Foucault pendulum closest to your home? (*Hint:* Science centres and university astronomy or physics departments may have a demonstration pendulum in operation.)

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SUMMARY Analyzing Forces in Circular Motion

- The net force acting on an object in uniform circular motion acts toward the centre of the circle. (This force is sometimes called the centripetal force, although it is always just gravity, the normal force, or another force that you know already.)
- The magnitude of the net force can be calculated by combining Newton's second-law equation with the equations for centripetal acceleration.
- The frame of reference of an object moving in a circle is a noninertial frame of reference.
- Centrifugal force is a fictitious force used to explain the forces observed in a rotating frame of reference.
- Centrifuges apply the principles of Newton's first law of motion and centrifugal force.
- The Coriolis force is a fictitious force used to explain particles moving in a rotating frame of reference.

Answers

15. (b) $36\ m/s^2$
    (c) 75°
    (d) 4.1×10^{-2} N

DID YOU KNOW?

Physics and Military Action
In World War I, during a naval battle near the Falkland Islands, British gunners were surprised to observe their shells landing about 100 m to the left of their targets. The gun sights had been adjusted for the Coriolis force at 50° N latitude. However, the battle was in the Southern Hemisphere, where this force produces a deflection in the opposite direction.

DID YOU KNOW?

Shuttle Launches
Tangential centrifugal force assists in the launching of NASA's space shuttles. All shuttles are launched eastward, in the same direction as Earth's rotation. This is really an application of Newton's first law because even before a shuttle is launched, its speed is the speed of the ground at that location. Can you state why Toronto is a less satisfactory location for a space centre than Cape Canaveral, and Yellowknife still less satisfactory than Toronto?

Section 3.2 Questions

Understanding Concepts

1. Which of the two designs in **Figure 1(b)** at the beginning of this section is better? Why?
2. A 1.00-kg stone is attached to one end of a 1.00-m string, of breaking strength 5.00×10^2 N, and is whirled in a horizontal circle on a frictionless tabletop. The other end of the string is kept fixed. Find the maximum speed the stone can attain without breaking the string.
3. A 0.20-kg ball on the end of a string is rotated in a horizontal circle of radius 10.0 m. The ball completes 10 rotations in 5.0 s. What is the magnitude of the tension in the string?
4. In the Bohr-Rutherford model of the hydrogen atom, the electron, of mass 9.1×10^{-31} kg, revolves around the nucleus. The radius of the orbit is 5.3×10^{-11} m and the period of revolution of the electron around the nucleus is 1.5×10^{-16} s.
   (a) Find the magnitude of the acceleration of the electron.
   (b) Find the magnitude of the electric force acting on the electron.
5. A 1.12-m string pendulum has a bob of mass 0.200 kg.
   (a) What is the magnitude of the tension in the string when the pendulum is at rest?
   (b) What is the magnitude of the tension at the bottom of the swing if the pendulum is moving at 1.20 m/s?
6. When you whirl a small rubber stopper on a cord in a vertical circle, you find a critical speed at the top for which the tension in the cord is zero. At this speed, the force of gravity on the object is itself sufficient to supply the necessary centripetal force.
   (a) How slowly can you swing a 15-g stopper like this so that it will just follow a circle with a radius of 1.5 m?
   (b) How will your answer change if the mass of the stopper doubles?
7. An object of mass 0.030 kg is whirled in a vertical circle of radius 1.3 m at a constant speed of 6.0 m/s. Calculate the maximum and minimum tensions in the string.
8. A child is standing on a slowly rotating ride in a park. The ride operator makes the statement that in Earth's frame of reference, the child remains at the same distance from the centre of the ride because there is no net force acting on him. Do you agree with this statement? Explain your answer.

Applying Inquiry Skills

9. You are on a loop-the-loop roller coaster at the inside top of a loop that has a radius of curvature of 15 m. The force you feel on your seat is 2.0 times as great as your normal weight. You are holding a vertical accelerometer, consisting of a small metal bob attached to a sensitive spring (**Figure 17**).
   (a) Name the forces that act toward the centre of the circle.
   (b) Determine the speed of the coaster at the top of the loop.
   (c) Name the forces contributing to the centripetal force on the bob of the accelerometer.
   (d) If the accelerometer is calibrated as in **Figure 17**, what reading will you observe at the top of the loop? (*Hint:* Draw an FBD of the accelerometer bob when it is inverted in Earth's frame of reference at the top of the ride. Assume two significant digits.)
   (e) What are the most likely sources of random and systematic error in trying to use a vertical accelerometer on a roller coaster?

Making Connections

10. Very rapid circular motion, particularly of machinery, presents a serious safety hazard. Give three examples of such hazards—one from your home, one from an ordinary car, and one from the workplace of a friend or family member. For each hazard, describe the underlying physics and propose appropriate safety measures.
11. Centrifuges are used for separating out components in many mixtures. Describe two applications of centrifuges from one of the following areas: the clinical analysis of blood, laboratory investigations of DNA and proteins, the preparation of dairy products, and sample analyses in geology.

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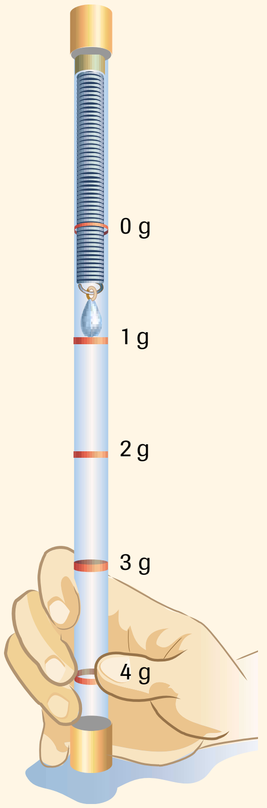

Figure 17
This vertical accelerometer is calibrated in such a way that when it is at rest, the scale reads "1*g*" at the bottom of the bob.