

# 6

## Circular Motion

### 6-1 Centripetal Acceleration and Force

#### Period, Frequency, and Speed

*Vocabulary* **Period:** The time it takes for one full rotation or revolution of an object.

*Vocabulary* **Frequency:** The number of rotations or revolutions per unit time.

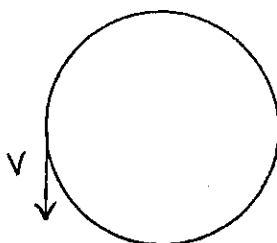
Period and frequency are reciprocals of each other. In other words,

$$T = \frac{1}{f} \quad \text{and} \quad f = \frac{1}{T}$$

Since period is a measure of time, its SI unit is the **second**, while the unit for frequency is the reciprocal of this, or 1/second. Another way of writing 1/second is with the unit **hertz (Hz)**.

When an object spins in a circle, the distance it travels in one revolution is the circumference of the circle,  $2\pi r$ . The time it takes for one revolution is the period,  $T$ . Therefore,

$$\text{speed} = \frac{2\pi(\text{radius})}{\text{period}} \quad \text{or} \quad v = \frac{2\pi r}{T}$$



where  $v$  is called the **linear** or **tangential speed** because at any given time, the velocity is tangent to the circle as shown in the diagram. Although the velocity is constant in magnitude (speed), it is always changing direction.

## Centripetal Acceleration and Centripetal Force

An object can move around in a circle with a constant speed yet still be accelerating because its direction is constantly changing. This acceleration, which is always directed in toward the center of the circle, is called **centripetal acceleration**. The magnitude of this acceleration is written as

$$\text{centripetal acceleration} = \frac{(\text{linear speed})^2}{\text{radius}} \quad \text{or} \quad a_c = \frac{v^2}{r}$$

If a mass is being accelerated toward the center of a circle, it must be acted upon by an unbalanced force that gives it this acceleration. This force, called the **centripetal force**, is always directed inward toward the center of the circle. The magnitude of this force is written as

$$\text{centripetal force} = (\text{mass})(\text{centripetal acceleration})$$

$$\text{or} \quad F_c = ma_c = \frac{mv^2}{r}$$

The units for centripetal acceleration and centripetal force are  $\text{m/s}^2$  and N, respectively.

### Solved Examples

**Example 1:** After closing a deal with a client, Kent leans back in his swivel chair and spins around with a frequency of 0.5 Hz. What is Kent's period of spin?

*Given:*  $f = 0.5 \text{ Hz}$

*Unknown:*  $T = ?$

*Original equation:*  $T = \frac{1}{f}$

$$\text{Solve: } T = \frac{1}{f} = \frac{1}{0.5 \text{ Hz}} = 2 \text{ s}$$

**Example 2:** Curtis' favorite disco record has a scratch 12 cm from the center that makes the record skip 45 times each minute. What is the linear speed of the scratch as it turns?

**Solution:** The record makes 45 revolutions every 60. seconds, so find the period of the record first.

$$T = \frac{60. \text{ s}}{45 \text{ rev}} = 1.3 \text{ s}$$



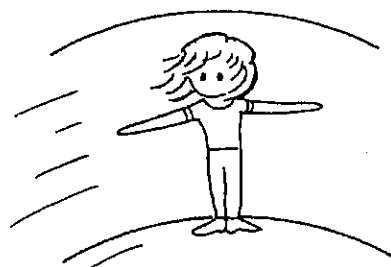
*Given:*  $r = 12 \text{ cm}$   
 $T = 1.3 \text{ s}$

*Unknown:*  $v = ?$

*Original equation:*  $v = \frac{2\pi r}{T}$

$$\text{Solve: } v = \frac{2\pi r}{T} = \frac{2\pi(12 \text{ cm})}{1.3 \text{ s}} = 58 \text{ cm/s}$$

- Example 3:** Missy's favorite ride at the Topsfield Fair is the rotor, which has a radius of 4.0 m. The ride takes 2.0 s to make one full revolution.
- What is Missy's linear speed on the rotor?
  - What is Missy's centripetal acceleration on the rotor?



**Solution:** The ride takes 2.0 s to make one full revolution, so the period is 2.0 s.

a. *Given:*  $r = 4.0 \text{ m}$   
 $T = 2.0 \text{ s}$

*Unknown:*  $v = ?$   
*Original equation:*  $v = \frac{2\pi r}{T}$

*Solve:*  $v = \frac{2\pi r}{T} = \frac{2\pi(4.0 \text{ m})}{2.0 \text{ s}} = 13 \text{ m/s}$

b. *Given:*  $v = 13 \text{ m/s}$   
 $r = 4.0 \text{ m}$

*Unknown:*  $a_c = ?$   
*Original equation:*  $a_c = \frac{v^2}{r}$

*Solve:*  $a_c = \frac{v^2}{r} = \frac{(13 \text{ m/s})^2}{4.0 \text{ m}} = 42 \text{ m/s}^2$

- Example 4:** Captain Chip, the pilot of a 60 500-kg jet plane, is told that he must remain in a holding pattern over the airport until it is his turn to land. If Captain Chip flies his plane in a circle whose radius is 50.0 km once every 30.0 min, what centripetal force must the air exert against the wings to keep the plane moving in a circle?

**Solution:** First, convert km to m and min to s.

$$50.0 \text{ km} = 5.00 \times 10^4 \text{ m} \quad 30.0 \text{ min} = 1.80 \times 10^3 \text{ s}$$

Before solving for the centripetal force, find the speed of the airplane.

*Given:*  $T = 1.80 \times 10^3 \text{ s}$   
 $r = 5.00 \times 10^4 \text{ m}$

*Unknown:*  $v = ?$   
*Original equation:*  $v = \frac{2\pi r}{T}$

*Solve:*  $v = \frac{2\pi r}{T} = \frac{2\pi(5.00 \times 10^4 \text{ m})}{1.80 \times 10^3 \text{ s}} = 175 \text{ m/s}$

Use this speed to solve for the centripetal force.

*Given:*  $m = 60\,500 \text{ kg}$   
 $v = 175 \text{ m/s}$   
 $r = 5.00 \times 10^4 \text{ m}$

*Unknown:*  $F_c = ?$   
*Original equation:*  $F_c = \frac{mv^2}{r}$

*Solve:*  $F_c = \frac{mv^2}{r} = \frac{(60\,500 \text{ kg})(175 \text{ m/s})^2}{5.00 \times 10^4 \text{ m}} = 3.71 \times 10^4 \text{ N}$

## Practice Exercises

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**Exercise 1:** Marianne puts her favorite Backstreet Boys disc in her CD player. If it spins with a frequency of 1800 revolutions per minute, what is the period of spin of the compact disc?

Answer: \_\_\_\_\_

**Exercise 2:** Hamlet, a hamster, runs on his exercise wheel, which turns around once every 0.5 s. What is the frequency of the wheel?

Answer: \_\_\_\_\_

**Exercise 3:** A sock stuck to the inside of the clothes dryer spins around the drum once every 2.0 s at a distance of 0.50 m from the center of the drum. a) What is the sock's linear speed? b) If the drum were twice as wide but continued to turn with the same frequency, would the linear speed of a sock stuck to the inside be faster than, slower than, or the same speed as your answer to part a?

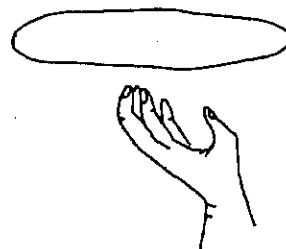
Answer: a. \_\_\_\_\_

Answer: b. \_\_\_\_\_

**Exercise 4:** What is the radius of an automobile tire that turns with a frequency of 11 Hz and has a linear speed of 20.0 m/s?

Answer: \_\_\_\_\_

**Exercise 5:** Luigi twirls a round piece of pizza dough overhead with a frequency of 60 revolutions per minute. a) Find the linear speed of a stray piece of pepperoni stuck on the dough 10. cm from the pizza's center. b) In what direction will the pepperoni move if it flies off while the pizza is spinning? Explain the reason for your answer.



Answer: a. \_\_\_\_\_

Answer: b. \_\_\_\_\_

**Exercise 6:** Earth turns on its axis approximately once every 24 hours. The radius of Earth is  $6.38 \times 10^6$  m. a) If some astronomical catastrophe suddenly brought Earth to a screeching halt (a physical impossibility as far as we know), with what speed would Earth's inhabitants who live at the equator go flying off Earth's surface? b) Because Earth is solid, it must turn with the same frequency everywhere on its surface. Compare your linear speed at the equator to your linear speed while standing near one of the poles.

Answer: a. \_\_\_\_\_

Answer: b. \_\_\_\_\_

**Exercise 7:** Jessica is riding on a merry-go-round on an outer horse that sits at a distance of 8.0 m from the center of the ride. Jessica's sister, Julie, is on an inner horse located 6.0 m from the ride's center. The merry-go-round turns around once every 40.0 s. a) Explain which girl is moving with the greater linear speed. b) What is the centripetal acceleration of Julie and her horse?

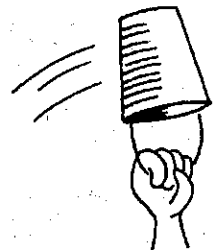
Answer: a. \_\_\_\_\_

Answer: b. \_\_\_\_\_

**Exercise 8:** A cement mixer of radius 2.5 m turns with a frequency of 0.020 Hz. What is the centripetal acceleration of a small piece of dried cement stuck to the inside wall of the mixer?

Answer: \_\_\_\_\_

**Exercise 9:** A popular trick of many physics teachers is to swing a pail of water around in a vertical circle fast enough so that the water doesn't spill out when the pail is upside down. If Mr. Lowell's arm is 0.60 m long, what is the minimum speed with which he can swing the pail so that the water doesn't spill out at the top of the path?



Answer: \_\_\_\_\_

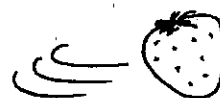
**Exercise 10:** To test their stamina, astronauts are subjected to many rigorous physical tests before they fly in space. One such test involves spinning the astronauts in a device called a *centrifuge* that subjects them to accelerations far greater than gravity. With what linear speed would an astronaut have to spin in order to experience an acceleration of 3 g's at a radius of 10.0 m? ( $1\text{ g} = 10.0\text{ m/s}^2$ )

Answer: \_\_\_\_\_

**Exercise 11:** At the Fermilab particle accelerator in Batavia, Illinois, protons are accelerated by electromagnets around a circular chamber of 1.00-km radius to speeds near the speed of light before colliding with a target to produce enormous amounts of energy. If a proton is traveling at 10% the speed of light, how much centripetal force is exerted by the electromagnets? (Hint: The speed of light is  $3.00 \times 10^8$  m/s,  $m_p = 1.67 \times 10^{-27}$  kg)

Answer: \_\_\_\_\_

**Exercise 12:** Roxanne is making a strawberry milkshake in her blender. A tiny, 0.0050-kg strawberry is rapidly spun around the inside of the container with a speed of 14.0 m/s, held by a centripetal force of 10.0 N. What is the radius of the blender at this location?



Answer: \_\_\_\_\_

## 6-2 Torque

### Vocabulary

**Torque:** A measurement of the tendency of a force to produce a rotation about an axis.

$$\text{torque} = \text{perpendicular force} \times \text{lever arm} \quad \text{or} \quad \tau = F \times d$$

The lever arm,  $d$ , is the distance from the pivot point, or fulcrum, to the point where the component of the force perpendicular to the lever arm is being exerted. The longer the lever arm, the larger the torque. This is why it is easier to loosen a tight screw with a long wrench than with your hand or a short pair of tweezers.

If a torque causes a counterclockwise rotation of an object around the fulcrum, it is positive. If the torque causes a clockwise rotation of an object around the

fulcrum, it is negative. This convention works even if the object remains balanced and the torques just *attempt* to cause a rotation.

The SI unit for torque is the **newton-meter (N·m)**. However, unlike work, which is measured in the same unit, torque is not a form of energy and is not equivalent to a joule.

In most of the exercises in this book, all the torques are balanced. For example, if two people are sitting on either side of a seesaw and they want to remain level, they can position themselves so that all the torques on one side of the seesaw equal all the torques on the other side. The total torque on a system equals the sum of all the individual torques, or

$$\tau = (F_1 \times d_1) + (F_2 \times d_2) + \dots$$

The ... means that there may be more than only two torques acting on a system at any one time. Keep in mind that when an object is balanced, all the torques must also balance. Therefore, the total torque,  $\tau$ , is zero.

#### Vocabulary

**Center of Gravity:** The point on any object that acts like the place at which all the weight is concentrated.

The weight of an object, which acts as if it is concentrated at the center of gravity, is one of the forces that can cause it to rotate. The weight produces a torque if the object is not supported at its center of gravity.

### Solved Examples

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**Example 5:** Ned tightens a bolt in his car engine by exerting 12 N of force on his wrench at a distance of 0.40 m from the fulcrum. How much torque must Ned produce to turn the bolt?

**Given:**  $F = 12 \text{ N}$   
 $d = 0.40 \text{ m}$

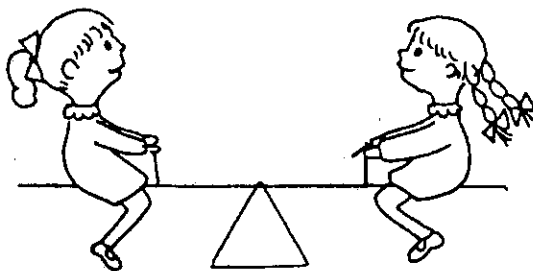
**Unknown:**  $\tau = ?$   
**Original equation:**  $\tau = F \times d$

**Solve:**  $\tau = F \times d = (12 \text{ N})(0.40 \text{ m}) = 4.8 \text{ N}\cdot\text{m}$

**Example 6:** Mabel and Maude are seesawing on the school playground and decide to see if they can move to the correct location to make the seesaw balance. Mabel weighs 400. N and she sits 2.00 m from the fulcrum of the seesaw. Where should 450.-N Maude sit to balance the seesaw?

**Solution:** It helps to draw a diagram of the situation to allow yourself to visualize what is happening.





Given:  $F_1 = 400. \text{ N}$   
 $F_2 = 450. \text{ N}$   
 $d_1 = 2.00 \text{ m}$

Unknown:  $d_2 = ?$   
 Original equation:  
 $\tau = (F_1 \times d_1) + (F_2 \times d_2)$

*Solve:* If 400.-N Mabel makes the seesaw turn in a counterclockwise direction, then 450.-N Maude makes the seesaw turn in a clockwise direction. Therefore,  $\tau = (F_1 \times d_1) + -(F_2 \times d_2)$ . If the seesaw is balanced, then  $\tau = 0$  and the equation becomes  $\tau = (F_1 \times d_1) + -(F_2 \times d_2) = 0$ , or  $(F_1 \times d_1) = (F_2 \times d_2)$ . Therefore,

$$d_2 = \frac{(F_1 \times d_1)}{F_2} = \frac{(400. \text{ N})(2.00 \text{ m})}{450. \text{ N}} = 1.78 \text{ m from the fulcrum.}$$

## Practice Exercises

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**Exercise 13:** A water faucet is turned on when a force of 2.0 N is exerted on the handle, at a distance of 0.060 m from the pivot point. How much torque must be produced to turn the handle?

Answer: \_\_\_\_\_

**Exercise 14:** Nancy, whose mass is 60.0 kg, is working at a construction site and she sits down for a bite to eat at noon. If Nancy sits on the very end of a 3.00-m-long plank pivoted in the middle on a saw horse, how much torque must her co-worker provide on the other end of the plank in order to keep Nancy from falling on the ground?

Answer: \_\_\_\_\_

**Exercise 15:** Barry carries his tray of food to his favorite cafeteria table for lunch. The 0.50-m-long tray has a mass of 0.20 kg and holds a 0.40-kg plate of food 0.20 m from the right edge. Barry holds the tray by the left edge with one hand, using his thumb as the fulcrum, and pushes up 0.10 m from the fulcrum with his finger tips. How much upward force must his finger tips exert to keep the tray level? b) How might Barry make the tray easier to carry if he still chooses to use only one hand?

Answer: a. 14.0 N

Answer: b. Barry could move the plate closer to the fulcrum.

**Exercise 16:** Soon-Yi is building a mobile to hang over her baby's crib. She hangs a 0.020-kg toy sailboat 0.010 m from the left end and a 0.015-kg toy truck 0.20 m from the right end of a bar 0.50 m long. If the lever arm itself has negligible mass, where must the support string be placed so that the arm balances?

Answer: 0.15 m from the left end

**Exercise 17:** Orin and Anita, two paramedics, rush a 60.0-kg man from the scene of an accident to a waiting ambulance, carrying him on a uniform 3.00-kg stretcher held by the ends. The stretcher is 2.60 m long and the man's center of mass is 1.00 m from Anita. How much force must Orin and Anita each exert to keep the man horizontal?

Answer: 315 N each

## 6-3 Moment of Inertia and Angular Momentum

### Vocabulary

**Moment of Inertia:** The resistance of an object to changes in its rotational motion.

The equation for the moment of inertia varies depending upon the shape of the rotating object. For an object rotating around an axis at a distance  $r$ ,

$$\text{moment of inertia} = (\text{mass})(\text{radius})^2 \quad \text{or} \quad I = mr^2$$

The SI unit for moment of inertia is the **kilogram · meter squared ( $\text{kg} \cdot \text{m}^2$ )**.

Other moments of inertia can be found in your textbook, and are summarized as follows.

$$\text{hoop rotating about its center: } I = mr^2$$

$$\text{hoop rotating about its diameter: } I = \left(\frac{1}{2}\right)mr^2$$

$$\text{solid cylinder: } I = \left(\frac{1}{2}\right)mr^2$$

$$\text{stick rotating about its center of gravity: } I = \left(\frac{1}{12}\right)m\ell^2$$

$$\text{stick rotating about its end: } I = \left(\frac{1}{3}\right)m\ell^2$$

$$\text{solid sphere rotating about its center of gravity: } I = \left(\frac{2}{5}\right)mr^2$$

Newton's first law says that inertia is the tendency of an object to stay at rest or remain in motion in a straight line with a constant speed unless acted upon by an unbalanced force. Similarly, an object that is rotating tends to continue spinning at a constant rate unless an unbalanced force acts to alter that rotation. This is called the rotational inertia.

Think of moment of inertia as being the rotational equivalent of the term "mass." Just as inertia is greater for a greater mass, rotational inertia is greater for a greater moment of inertia.

### Vocabulary

**Angular Momentum:** The measure of how difficult it is to stop a rotating object.

$$\text{angular momentum} = (\text{mass})(\text{velocity})(\text{radius}) \quad \text{or} \quad L = mvr$$

The SI unit for angular momentum is the **kilogram · meter squared per second ( $\text{kg} \cdot \text{m}^2/\text{s}$ )**.

Think of angular momentum as being the rotational equivalent of *linear momentum*. Just as linear momentum is the product of the mass and the velocity, angular momentum is the product of the mass and the velocity for an object rotating at a distance  $r$  from the axis.

Momentum is conserved when no outside forces are acting. Similarly, angular momentum is conserved when no outside torques are acting. A spinning ice skater has angular momentum. When the skater pulls her arms in (decreasing her radius of spin), she spins faster (increasing her velocity). Doing so conserves her angular momentum.

## Solved Examples

**Example 7:** On the Wheel of Fortune game show, a contestant spins the 15.0-kg wheel that has a radius of 1.40 m. What is the moment of inertia of this disk-shaped wheel?

**Solution:** A disk is a thin cylinder, so the moment of inertia of a disk is the same as that of a cylinder.

*Given:*  $m = 15.0 \text{ kg}$   
 $r = 1.40 \text{ m}$

*Unknown:*  $I = ?$

*Original equation:*  $I = \left(\frac{1}{2}\right)mr^2$

*Solve:*  $I = \left(\frac{1}{2}\right)(15.0 \text{ kg})(1.40 \text{ m})^2 = 14.7 \text{ kg} \cdot \text{m}^2$

**Example 8:** Trish is twirling her 0.60-m majorette's baton that has a mass of 0.40 kg. What is the moment of inertia of the baton as it spins about its center of gravity?

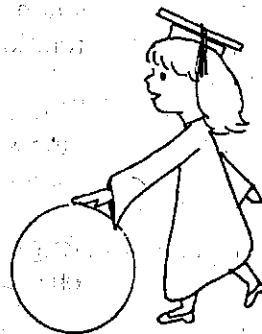
*Given:*  $m = 0.40 \text{ kg}$   
 $\ell = 0.60 \text{ m}$

*Unknown:*  $I = ?$

*Original equation:*  $I = \left(\frac{1}{2}\right)m\ell^2$

*Solve:*  $I = \left(\frac{1}{2}\right)m\ell^2 = \left(\frac{1}{2}\right)(0.40 \text{ kg})(0.60 \text{ m})^2 = 0.072 \text{ kg} \cdot \text{m}^2$

**Example 9:** At Wellesley College in Massachusetts there is a favorite tradition called hoop rolling. In their caps and gowns, seniors roll wooden hoops in a race in which the winner is said to be the first in the class to marry. Hilary rolls her 0.2-kg hoop across the finish line. The moment of inertia of the hoop is  $0.032 \text{ kg} \cdot \text{m}^2$ . What is the radius of the hoop?



*Given:*  $m = 0.2 \text{ kg}$

$I = 0.032 \text{ kg} \cdot \text{m}^2$

*Unknown:*  $r = ?$

*Original equation:*  $I = mr^2$

*Solve:*  $r = \sqrt{\frac{I}{m}} = \sqrt{\frac{0.032 \text{ kg} \cdot \text{m}^2}{0.2 \text{ kg}}} = \sqrt{0.16 \text{ m}^2} = 0.4 \text{ m}$

**Example 10:** Jupiter orbits the sun with a speed of 2079 m/s at an average distance of 71 398 000 m. a) If Jupiter has a mass of  $1.90 \times 10^{27} \text{ kg}$ , what is its angular momentum as it orbits?

Given:  $m = 1.90 \times 10^{27} \text{ kg}$   
 $v = 2079 \text{ m/s}$   
 $r = 71\,398\,000 \text{ m}$

Unknown:  $L = ?$   
Original equation:  $L = mvr$

Solve:  $L = mvr = (1.90 \times 10^{27} \text{ kg})(2079 \text{ m/s})(71\,398\,000 \text{ m}) = 2.82 \times 10^{38} \text{ kg} \cdot \text{m}^2/\text{s}$

## Practice Exercises

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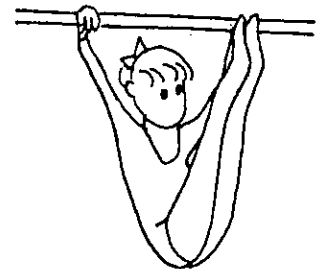
**Exercise 18:** Veanna is in Las Vegas waiting for her number to be called at the roulette wheel, a large 3.0-kg disk of radius 0.60 m. What is the moment of inertia of the wheel?

Answer: \_\_\_\_\_

**Exercise 19:** Earth has a mass of  $5.98 \times 10^{24} \text{ kg}$  and a radius of  $6.38 \times 10^6 \text{ m}$ . What is the moment of inertia of Earth as it turns on its axis?

Answer: \_\_\_\_\_

**Exercise 20:** Olga, the 50.0-kg gymnast, swings her 1.6-m-long body around a bar by her outstretched arms. a) What is Olga's moment of inertia? b) If Olga were to pull in her legs, thereby cutting her body length in half, how would this change her moment of inertia? (Assume her mass is evenly distributed all along her body.)



Answer: a. \_\_\_\_\_

Answer: b. \_\_\_\_\_

**Exercise 21:** Priya removes her 0.012-kg, 0.60-cm-diameter wedding band and spins it on the coffee table on its edge. What is the moment of inertia of the ring?

Answer: \_\_\_\_\_

**Exercise 22:** Hickory dickory dock, the 20.0-g mouse ran up the clock, and took turns riding on the 0.20-m-long second hand, the 0.20-m-long minute hand, and the 0.10-m-long hour hand. What was the angular momentum of the mouse on each of the three hands?

Answer: \_\_\_\_\_

Answer: \_\_\_\_\_

Answer: \_\_\_\_\_

**Exercise 23:** In a physics experiment, Ingrid, the ice skater, spins around in the rink at 1.2 m/s with each of her arms stretched out 0.70 m from the center of her body. In each hand she holds a 1.0-kg mass. If angular momentum is conserved, how fast will Ingrid begin to spin if she pulls her arms to a position 0.15 m from the center of her body?

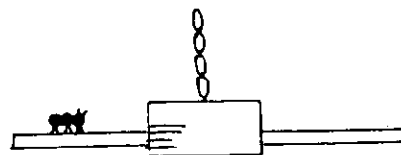
Answer: \_\_\_\_\_

### **Additional Exercises**

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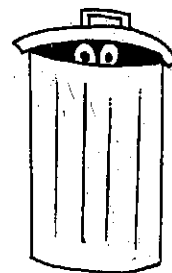
**A-1:** In the Biblical tale of David and Goliath, the giant is slain when David hits him with a rock that he has spun around overhead in a sling. If the rock is spun with a frequency of 100 revolutions per minute, what is the rock's period?

- A-2:** Ashton the ant is crawling on the still blade of a ceiling fan when the fan is turned on, causing Ashton to go for a ride. If Ashton sits on the fan blade at a distance of 0.80 m from the center of the fan and turns with a frequency of 1.2 Hz, a) how fast does Ashton spin? b) If Ashton slips off the spinning fan, describe the path he will take.



- A-3:** In "Rumpelstiltskin," the miller's daughter is spinning straw into gold on a spinning wheel that turns at a speed of 7.5 m/s, making one revolution every 0.50 s. How long is a strand of gold that makes one complete turn around the wheel?
- A-4:** A 3.20-kg hawk circles overhead in search of prey. a) If the hawk circles once every 10.0 s in a circle 12.0 m in radius, what is the linear speed of the hawk? b) What centripetal force allows him to remain in a circle? c) What is providing the centripetal force?
- A-5:** Sasha's favorite ride at the fair is the Ferris wheel that has a radius of 7.0 m. a) If the ride takes 20.0 s to make one full revolution, what is the linear speed of the wheel? b) What centripetal force will the ride exert on Sasha's 50.0-kg body? c) Does Sasha feel as if she is being pulled in or out by the ride? d) Explain the difference between what she feels and what is really happening at the top and bottom of the wheel.
- A-6:** In order for Sasha (in A-5) to feel weightless at the top of the ride, a) at what linear speed must the Ferris wheel turn? b) At this speed, how much will she appear to weigh at the bottom of the Ferris wheel?
- A-7:** Earth orbits the sun approximately once every 365.25 days at an average distance of about  $1.5 \times 10^{11}$  m. The mass of Earth is  $5.98 \times 10^{24}$  kg. a) What is the centripetal acceleration of Earth? b) What is the centripetal force of the sun on Earth? c) What is the centripetal force of Earth on the sun? d) If this force exists between the sun and Earth, does this mean that Earth is "falling into" the sun? Explain.
- A-8:** Most doorknobs are placed on the side of the door opposite the hinges instead of in the center of the door. a) Why is this so? b) If a torque of  $1.2 \text{ N} \cdot \text{m}$  is required to open a door, how much force must be exerted on a doorknob 0.76 m from the hinges compared to a doorknob in the middle of the door, 0.38 m from the hinges?
- A-9:** Priscilla is working out in the gym with a 2.00-kg mass that she holds in one hand and gradually lifts up and down. a) Will Priscilla find it easier to lift the mass if she pivots her arm at the shoulder or at the elbow? b) If Priscilla's arm is 0.60 m long from her shoulder to her palm and 0.28 m long from her elbow to her palm, how much torque must she produce in each case to lift the weight?

- A-10:** Leif and Paige are rearranging the heights of their movable bookshelves; they remove one of the 2.00-kg, 0.60-m-long shelves by the two of them holding opposite ends. A 5.00-kg stack of books is piled up on the shelf 0.20 m from Leif. How much force must Leif and Paige each exert to hold the shelf level?
- A-11:** Brewster hits a 0.30-kg pool ball across the pool table and sinks it in the side pocket. If the pool ball has a radius of 3.5 cm, what is its moment of inertia as it rolls?
- A-12:** Rocky, a raccoon, squeezes into a 0.60-m-diameter cylindrical trash can to find a late-night snack. However, the can tips over and begins to roll. If Rocky and the can have a combined mass of 40.0 kg, what is the moment of inertia of the system?
- A-13:** Mieko sharpens a knife on a grinding wheel whose angular momentum is  $27 \text{ kg} \cdot \text{m}^2/\text{s}$ . The 5.0-kg wheel has a radius of 0.30 m. What is the linear speed of the wheel?



### Challenge Problems for Further Study

- B-1:** The "Bake-a-Lite" Cake Company truck is on its way to deliver a birthday cake for the MacKenzie party when it rounds a curve of radius 20.0 m at a speed of 12 m/s. What coefficient of friction is needed between the cake pan and the truck in order to keep the pan from slipping?
- B-2:** On his way home from the office, Steven's car rounds an unbanked curve that has a radius of 100 m. If the coefficient of friction between the tires and the road is 0.40, what is the fastest speed at which the car can round this curve without risking an accident?
- B-3:** Pretending to be Tarzan, 50.0-kg Zach swings from the end of a 5.0-m-long rope attached to a tree branch. The tree branch will break if subjected to a force greater than 750 N. What is the maximum speed with which Zach can swing in order to avoid breaking the branch?
- B-4:** Hanging in front of the office of Lewis Skeirik, D.D.M., is a sign that weighs 120 N and is suspended at the end of a 0.80-m-long support beam that weighs 10.0 N, as shown. What is the tension in a supporting wire that holds the sign at an angle of  $20.0^\circ$ ?

