# 8 Rotational Motion



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The photo openers credit four influential educators: Paul Stokstad, the founder of Pasco, a supplier of high-quality physics apparatus, Jacque Fresco, my original inspiration guiding me to physics (who is featured in this chapter's personality profile), late friend Mary Beth Monroe, who was very active in the organization AAPT (American Association of Physics Teachers), and CCSF physics instructor Diana Lininger Markham.

It is often said that rotational motion is analogous to linear motion and therefore should not be difficult to learn. Really? Consider the numerous distinctions between motions that are (1) linear, (2) rotational, (3) revolutional, (4) radial, (5) tangential, and (6) angular. I remember as a student being told that rotational motion would be easy to learn since it is an extension of linear motion. But alas, at that time my grasp of linear motion was anything but a secure foundation. Many students are still grappling with speed, velocity, and acceleration. And we have centripetal and centrifugal forces, real and fictitious, not to mention torques. So there is a myriad of ideas and material to understand in this chapter. Is it any wonder why students find rotational motion a steep hill to climb? Since a study of rotational motion is considerably more complex than a study of linear motion, caution your students to be patient with themselves if they don't immediately comprehend what has taken centuries to master. To keep coverage manageable, the chapter does not treat rotational kinetic energy.

One of the most intriguing examples of $v = r\omega$ is the beveled shape of railroad wheels. A train is able to round a corner in the same way a tapered glass rolls in a circle along a tabletop. Or the way a person with one leg shorter than the other tends to walk in a circle when lost in the woods. This is the feature of the box Wheels on Railroad Trains. Fascinating, especially when demonstrated with a pair of tapered cups taped at their wide ends that roll along a pair of metersticks. At CCSF, Will Maynez built a beautiful "roller coaster" along which a set of tapered wheels faithfully follow the curved track. Most impressive!

Martha Lietz at Niles West High School does a nice activity with torques. She places the ends of a board on two bathroom scales and sets the scales to zero. Then she challenges her students to calculate where a person of a given weight should stand on the board so one scale would read 75 pounds. The scale displays are covered when students do this, until they think they are in the proper position. Whole-body physics!

Although torques is a vector quantity, I don't emphasize it in this chapter. For example I omit entirely 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. I have always felt that the reason for this and other hand rules in introductory physics courses has been to provide some instructors the opportunity to write tricky exam questions. Wisdom in general, and in physics teaching, is knowing what can be overlooked. I suggest you overlook the vector nature of torque, which continuing students can get into in a follow-up course.

A nice activity for demonstrating centripetal force was introduced to me by physics teacher Howie Brand: Have a small group of students around a small table (ideally circular) blow air through straws at a Ping-Pong ball so that it will move in a circular path. They will experience the fact that the ball must be blown radially inward.

Rotation often involves what is called the Coriolis effect. As the name implies, it is an effect and not a force. It occurs only in situations involving rotation. Our Earth rotates. A cannon fired northward from the equator has a horizontal component of velocity equal to the tangential speed of the rotating Earth at that point. But it lands at a location far enough north where Earth's tangential speed is less. Hence it misses the true-north target. Likewise firing from any latitude to another. It "seems" as if the shell were deflected by some force. Toss a ball from a rotating carousel and you'll see the ball deflect from a straight-line path. But a non-rotating observer sees the path as straight. The effect is dramatic with winds that tend to flow *around* regions of high and low pressure, running parallel to the lines of constant pressure on a weather map (isobars), instead of flowing in a direct path. In the Northern Hemisphere, air flowing radially inward across the isobars toward the low pressure deflects to the right. In the Southern Hemisphere, the deflection is to the left.

A common misconception is that water flowing down a drain turns in one direction in the Northern hemisphere and in the opposite direction in the Southern Hemisphere. This is not so in something as small as a kitchen sink. But yes for larger parcels of air. The Coriolis force that is strong enough to direct winds of hurricanes when acting over hundreds of miles, is far too weak to stir a small bowl of water as it runs down a drain. To say it does is to say that one side of the bowl is moving at a different speed relative to Earth's axis than the other side. It does. But how much? That's the amount of your Coriolis force.

The classic oldie but goodie PSSC film, "Frames of Reference" goes well with this chapter.

This chapter can be skipped or skimmed if a short treatment of mechanics is desired. Note that this chapter has more figures than any in the book—54 of them.

**Practicing Physics Book**:

• Torques
• Torques and Rotation
• Acceleration and Circular Motion
• The Flying Pig
• Banked Airplanes
• Banked Track
• Leaning On
• Simulated Gravity and Frames of Reference

**Problem Solving Book**:
Many problems with a bit of trigonometry are employed.

**Laboratory Manual**:

• Twin-Baton Paradox A Puzzle, With a *Twist* (Activity)
• It's All in the Wrist *Experiencing Torque "Firsthand"* (Activity)
• Will it Go Round in Circles? *Accelerating at Constant Speed* (Demonstration)
• Sit On It and Rotate *Take Physics for a Spin* (Activity)

**Next-Time Questions** (in the Instructor Resource DVD):

• Falling Metersticks • Woman on the Plank • Trucks on a Hill • Tether Ball • Rotating Disk
• Kagan Roll • Wrench Pull • Two Spheres • Rolling Cans • Can Spurt • Berry Shake • Normal Forces
• Broom Balance • Centrifugal Force • Skateboard Lift • Post Wrap

**Hewitt-Drew-It! Screencasts**:

•*Circular Motion* •*RR Wheels* •*Centripetal Force* •*Centrifugal Force* •*Torque* •*Balanced Torques*
•*Torques on a Plank* •*Skateboard Torques* •*Angular Momentum*

The suggested lecture should take two or three class periods.

**SUGGESTED LECTURE PRESENTATION**

Cite the difference between rotational and linear speed—examples of riding at various radial positions on a merry-go-round, or the various speeds of different parts of a rotating turntable. A couple of coins on a turntable, one close to the axis and the other near the edge, dramatically show the greater speed of the outer one. Cite the motion of "tail-end Charlie" at the skating rink.

**Circular Motion**

Only for a rigid rotating system such as a solid turntable or a stiff spoke does the equation $v = r\omega$ apply—the greater the distance from the axis of rotation, the greater the linear speed. Don't be surprised to find students applying this relationship to a nonrigid system, such as a system of planets. They are confused about Mercury, which orbits relatively fast about the Sun, and Neptune, which orbits very slow. Horses running around a circular track obey $v = r\omega$ only if they are constrained, like joined by a giant nonflexible spoke.

**Railroad Train Wheels (RR Wheels)**

A fascinating application of $v = r\omega$ is presented in the box on railroad train wheels. Fasten a pair of cups with wide ends connected, and with small ends connected, and roll them along a pair of metersticks. Very impressive! That's my niece, Professor Cathy Candler, in Figure 8.8. The screencast on RR Wheels nicely ties together the taper of cups with the taper of the rims of RR wheels.

Side point: Toilet tissue rolls are smaller in diameter than rolls of toilet tissue years ago. Since more tissue makes a complete circle on the outer part of the roll, decreasing the diameter only slightly means appreciably less tissue per roll.

While we're on the subject of circles, you might ask why manhole covers are round (asked in the Check Point on page 138 of the textbook). The answer is so that some moron type doesn't drop them accidentally into the manhole. If they were square, they could be tipped up on edge and dropped through the hole on the diagonal. Similarly with ovals. But a circular hole will defy the most determined efforts. Of course there is a lip around the inside of the manhole that cover rests on, making the diameter of the hole somewhat less than the diameter of the cover.

**Rotational Inertia**

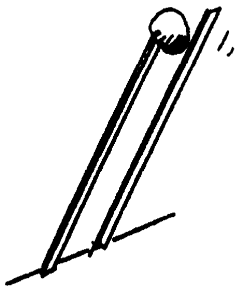
Compare the idea of inertia and its role in linear motion to rotational inertia (moment of inertia) in rotational motion. The difference between the two involves the role of *distance* from a rotational axis. The greater the distance of mass concentration, the greater the resistance to rotation. Discuss the role of the pole for the tightrope walker in Figure 8.10. A novice tightrope walker might begin with the ends of the pole in supporting slots, similar to the training wheels on a beginner's bicycle. If the pole has adequate rotational inertia, the slots mainly provide psychological comfort as well as actual safety. Just as the training wheels could be safely removed without the rider's knowledge, the slots could be safely removed without the walker's knowledge.

Show how a longer pendulum has a greater period and relate this to the different strides of long and short-legged people. Imitate these strides yourself—or at least with your fingers walking across the desk.

> DEMONSTRATION: This is a good one. Have two 1 meter pipes, one with two lead plugs in the center, the other with plugs in each end. They appear identical. Weigh both to show the same weight. Give one to a student (with plugs in ends) and ask her to rotate it about its center (like in Figure 8.9). Have another student do the same with the pipe that has the plugs in the middle. Then have them switch. Good fun. Then ask for speculations as to why one was noticeably more difficult to rotate than the other.

> DEMONSTRATION: As in Check Point 1 on page 138, have students try to balance on a finger a long stick with a massive lead weight at one end. Try it first with the weight at the fingertip, then with the weight at the top. Or you can use a broom, or long-handled hammer. Relate this to the ease with which a circus performer balances a pole full of people doing acrobatics, and cite how much more difficult it would be for the performer to balance an empty pole!

Also relate this demonstration and the continued adjustments you have to execute to keep the object balanced to the similar adjustments that must be made in keeping a rocket vertical when it is first fired. Amazing! As Tenny Lim and Mark Clark demonstrate in Figure 8.35, the Segway Transporter employs the same physics. The Segway behaves as we do—when it leans forward it increases its speed to keep its CG above a point of support.

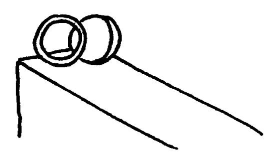


DEMONSTRATION (As in Check Point 2 on page 138): Fasten a mass to the end of a meterstick. A blob of clay works fine. Set it on end on your lecture table, along with another meterstick with no attached mass. When you let go of the sticks, they'll topple to the tabletop. Ask which stick will reach the tabletop first. [The plain stick wins due to the greater rotational inertia of the clay-top stick. There is more to this than simply greater rotational inertia, for torque is increased as well. If the clay is located at the middle of the stick, the effects of greater torque and greater rotational inertia balance each other and both sticks fall together.]

Discuss the variety of rotational inertias shown in Figure 8.15. Stress the formulas are for comparison, and point out why the same formula applies to the pendulum and the hoop (all the mass of each is at the same distance from the rotational axis). State how reasonable the smaller value is for a solid disk, given that much of its mass is close to the rotational axis.

The rotational inertia of a thin-walled hollow sphere, missing from the drawings in Figure 8.15, is given by Sanjay Rebello in Figure 8.16. Sanjay was an enormous help in developing the PowerPoint presentations of Conceptual Physics. Thanx Sanjay!

DEMONSTRATION: Place a hoop and disk at the top of an incline and ask which will have the greater acceleration down the incline. Do not release the hoop and disk until students have discussed this with their neighbors. Try other shapes after your class makes reasoned estimates.



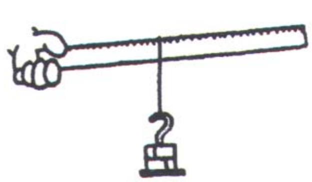
**Center of Mass and Torque**

Depart a bit from the order of the chapter and begin a discussion of center of mass before treating torque. Do this by tossing a small metal ball across the room, stating it follows a smooth curved path—a parabola. Then pick up an irregularly shaped piece of wood, perhaps an L-shape, and state that if this were thrown across the room it would not follow a smooth path, but would wobble all over the place—a special place, the place presently being discussed—the center of mass, or center of gravity. Illustrate your definition with figures of different shapes, first those where the center of mass lies within the object and then to shapes where the center of mass lies outside the objects.

CHECK QUESTION: Where is the center of mass of a donut?

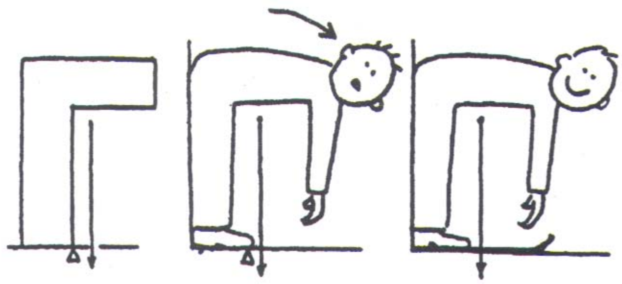
Consider the motion of a basketball tossed across the room when a heavy weight is attached to one side. The wobble is evident. Likewise for suns with planet, a welcome feature to astronomy types.

Ask your students if they "have" a CG. Acknowledge that the CG in men is generally higher than in women (1%-2%), mainly because women tend to be proportionally smaller in the upper body, and heavier in the pelvis. On the average it lies about 6 inches above the crotch, a bit below the bellybutton. Interestingly enough, the reason for the bellybutton being where it is relates to CG. A fetus turning in its mother's womb would rotate about its CG, the likely place for its umbilical cord. Standing erect with heavy side down simulates an average woman. Standing with heavy side up, simulates an average man. A baseball bat likewise makes this point. Interestingly, When we bend over, of course, the CG extends beyond the physical body.

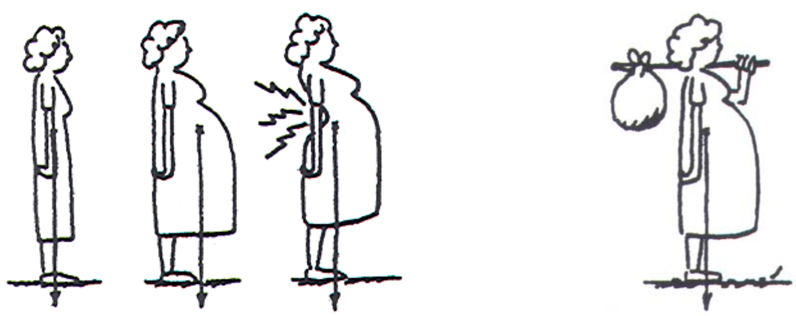


Pass around a meterstick with a weight that can be suspended at different places. This is "Torque Feeler," an important activity that can be done in your classroom as Mary Beth Monroe shows in the chapter photo opener. Students hold the meterstick horizontally and note that different torques when the weight's distance is varied. The difference between force and torque is felt! How nice when students can feel physics!

Place an L-shaped body on the table and show how it topples—because its center of mass lies outside a point of support. Sketch this on the board. Then stand against a wall and ask if it is possible for one to bend over and touch their toes without toppling forward. Attempt to do so. Sketch this next to the L-shape as shown. By now your board looks like the following:



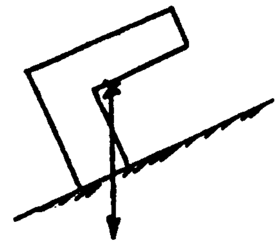
Discuss a remedy for such toppling, like longer shoes or the wearing of snowshoes or skis. Sketch a pair of skis on the feet of the person in your drawing. Seem to change the subject and ask why a pregnant woman often gets back pains. Sketch a woman before and after getting pregnant, showing how the CG shifts forward—beyond a point of support for the same posture. (This whole idea goes over much better in lecture than as reading material, so is not found in this edition. So now you can introduce it as a fresh idea in class.) Make a third sketch showing how a woman can adjust her posture so that her CG is above the support base bounded by her feet, sketching lastly, the "marks of pain." Ask the class how she could prevent these pains, and if someone in class doesn't volunteer the idea of wearing skis, do so yourself and sketch skis on her feet in the second drawing.



Lead your class into an alternate solution, that of carrying a pole on her shoulder, near the end of which is a load. Erase the skis and sketch in the pole and load as shown. Acknowledge the objection that she would have to increase the mass of the load as the months go by, and ask what else can be done. Someone should volunteer that she need only move the load closer to the end, which in effect shifts the overall CG in a favorable direction. This routine is effective and sparks much class interest. However, you must be very careful that you don't offend your students, particularly your female students. Whenever you single out any "minority"(?) you run the risk of offending members of that minority group or those sensitive to the feelings of members of that group. We instructors, whether male or female ourselves, are for the most part conscious of this and therefore make our examples as general as possible—mixing "shes" and "hes" whenever these pronouns come up. But in the case of a person becoming pregnant, it's a definite "she." Any classroom laughter that your presentation elicits should be, after all, directed to the situation and not particularly toward the woman. In any event, we are in sad shape when we cannot laugh at ourselves occasionally.

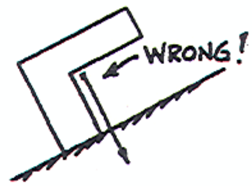
CHECK QUESTION: Why does a hiker with a heavy backpack lean forward when standing or walking?

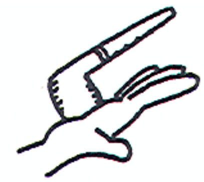
Return to your chalkboard sketches of L-shaped objects and relate their tipping to the torques that exist. Point out the lever arms in the sketches.



CHECK QUESTION: An L-shaped object with CG marked by the X rests on an incline as shown. Draw this on your paper and mark it appropriately to determine whether the object will topple or not.

Comment: Be prepared for some students to sketch in the "vertical" line through the CG perpendicular to the slope as shown.

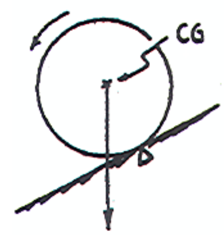


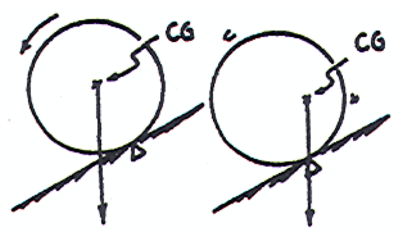
A simple example of this is to balance a pipe (smoking kind) on your hand when held at an angle.

Cite examples involving the CG in animals and people—how the long tails of monkeys enable them to lean forward without losing balance—and how people lean backwards when carrying a heavy load at their chests, and how the coolie method with the load distributed in two parts suspended at the ends of a pole supported in the middle is a better way.

Ask why a ball rolls down a hill. State that "because of gravity" is an incomplete answer. Gravity would have it slide down the hill. The fact it rolls, or rotates, is evidence of an unbalanced torque. Sketch this on your chalkboard.




DEMONSTRATION: Show how a "loaded disk" rolls *up* an inclined plane. After class speculation, show how the disk remains at rest on the incline. Modify your chalkboard sketch to show how both the CG with respect to the support point is altered, and the absence of a lever arm and therefore the absence of a torque.




On rolling: Cliff birds lay eggs that are somewhat pear-shaped. This shape assures that the eggs roll in circles, and don't easily roll off precarious nesting places.

Discuss wrenches and clarify lever arm distances (Figure 8.20). Cite how a steering wheel is simply a modified wrench, and why trucks and heavy vehicles before the advent of power steering used large-diameter steering wheels.

DEMONSTRATION: Attempt to stand from a seated position without putting your feet under the chair. Explain with center of gravity and torques.

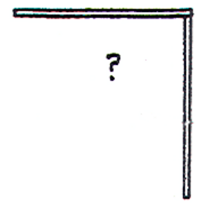

DEMONSTRATION: Do as Michael Bimmerle does and stick a piece of masking tape on an easy-to-move door. Place the tape near the middle and when you pull the door, the tape becomes unstuck. Progressively move the tape closer toward the edge away from the hinges and the tape sticks better. Near the edge the tape will stick and open the door without pulling off. More torque for less force.

**Seesaws**

Extend rotation to seesaws, as in Figures 8.18 and 8.19. Explain how participants on a seesaw can vary the net torque by not only sliding back and forth, but by leaning. In this way the location of their CGs and hence the lever arm distance is changed. Discuss the boy playing by himself in the park (Think and Discuss 111), and how he is able to rotate up and down by leaning toward and away from the fulcrum.

DEMONSTRATION: Make a candle seesaw by trimming the wick so both ends are exposed, and balance the candle by a needle through the center. Rest the ends of the needle on a pair of drinking glasses. Light both ends of the candle. As the wax drips, the CG shifts, causing the candle to oscillate.

CHECK QUESTION: To balance a horizontal meterstick on one finger, you'd place your finger at the 50-cm mark. Suppose you suspend an identical meterstick vertically from one end, say the 0-cm end. Where would you place your finger to balance the horizontal stick? [At the 25-cm mark, where equal weights would each be 25 cm distant.]




DEMONSTRATION: Place a heavy plank on your lecture table so that it overhangs. Walk out on the overhanging part and ask why you don't topple. Relate this to a solitary seesaw example. (Note the version of this in the NTQs.) This is also treated in the screencast 'More on Torques.'

Here's a neat application of CG that is not in the text, but is another NTQ. If you gently shake a basket of berries, the larger berries will make their way to the top. In so doing the CG is lowered by the more compact smaller berries settling to the bottom. You can demonstrate this with a Ping-Pong ball at the bottom of a container of dried beans, peas, or smaller objects. When the container is shaken, the Ping-Pong ball surfaces, lowering the CG of the system. This idea can be extended to the Ping-Pong ball in a glass of water. The CG of the system is lowest when the Ping-Pong ball floats. Push it under the surface and the CG is raised. If you do the same with something more dense than water, the CG is lowest when it is at the bottom.

**Centripetal Force**

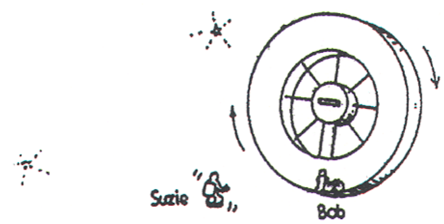
Whirl an object tied to the end of a string overhead and ask if there is an outward or an inward force exerted on the whirling object. Explain how no outward or centrifugal force acts on the whirling object (the only outward directed force is the reaction force *on the string*, but not on the object). Emphasize also that centripetal force is not a force in its own right, like gravity, but is the name for any force that pulls an object into a curved path.

DEMONSTRATION: Swing a bucket of water in a vertical circle and show that the water doesn't spill (when centripetal force is at least equal to the weight of the water). All your students have heard of this demonstration, but only a few have actually seen it done. Why doesn't the water fall at the top of the path? [The answer is intriguing—it does! You have to pull the bucket down as fast as the water falls. Similarly, a space shuttle above falls—just as much as the round Earth curves! Nothing holds the water up; nothing holds the satellite up.] Both are falling—nice physics!

The "trick" of this demonstration is to pull the bucket down as fast as the water falls so both fall the same vertical distance in the same time. Too slow a swing produces a wet teacher. As said, the water in the swinging bucket is analogous to the orbiting of a satellite. Both the swinging water and a satellite such as the orbiting space shuttle 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!

CHECK QUESTION: A motorcycle runs on the inside of a bowl-shaped track (sketched in Think and Explain 89). 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.]

**Centrifugal Force in a Rotating Frame**
The concept of centrifugal force is useful when viewed from a rotating frame of reference. Then it seems as real as gravity to an occupant—like inside a rotating space habitat. State how it differs from a real force in that there is no agent such as mass. The magnetic force on a magnet, for example, is caused by the presence of another magnet; the force on a charge is caused by the presence of another charge. Whereas a real force is an interaction between one body and another, there is no reaction counterpart to centrifugal force. Distinguish centrifugal force from the action-reaction pairs of forces at the feet of an astronaut in a rotating habitat.




Discuss rotating space habitats. Show how *g* varies with both the radial distance from the hub and the rotational rate of the structure. The Earth has been the cradle of humankind; but humans do not live in the cradle forever. We will likely leave our cradle and inhabit structures of our own building; structures that will serve as lifeboats for the planet Earth. Their prospect is exciting.

DEMONSTRATION: Do as Diana Lininger Markham does in the chapter opening photos and swing a drink in an overhead circle without spilling a drop. The surface of the liquid remains parallel to the dish when freely swinging. (I witnessed this method of carrying cups of tea or other beverages though crowded areas without spilling while visiting Turkey—very impressive.) A smaller gadget that does the same, *SpillNot*, (P4-2500) is available from Arbor Scientific.

**Angular momentum**
Just as inertia and rotational inertia differ by a radial distance, and just as force and torque also differ by a radial distance, so momentum and angular momentum also differ by a radial distance. Relate linear momentum to angular momentum for the case of a small mass at a relatively large radial distance—an object you swing overhead.

For the more general case, angular momentum is simply the product of rotational inertia $I$ and angular velocity $\omega$. This is indicated in Figure 8.52.

DEMONSTRATION: With weights in your hand, rotate on a platform as shown in Figure 8.52. Simulate the slowing down of the Earth when ice caps melt and spread out.

DEMONSTRATION: Show the operation of a gyroscope—either a model or a rotating bicycle wheel as my late son James demonstrates in Figure 8.50.

Regarding the falling cat of Figure 8.54, J. Ronald Galli of Weber State University in Utah cautions that a falling cat bends its spine to swing about and twist in an opposite direction to land feet first—all the while maintaining a total angular momentum of zero.

Regarding Think and Explains 93 through 97: When answering these, demonstrate again on the rotating platform, holding the weights over your head to simulate Earth washing toward the equator, melting ice caps spreading toward the equator by lowering your hands in an outstretched position to simulate Earth and water flowing toward the equator. To simulate the effects of skyscraper construction, hold the weights short of fully stretched, then extend your arms full-length.

**Going Further with Rolling**

Rolling things have two kinds of kinetic energy: That due to linear motion, and that due to rotational motion. So an object rolling down an incline will lag behind a freely sliding object because part of a rolling object's kinetic energy is in rotation. If this is clear, then the following question is in order for your better students.

> NEXT-TIME QUESTION: Which will roll with the greater acceleration down an incline, a can of water or a frozen can of ice? Double credit for a good explanation of what is seen. [The can of liquid will undergo appreciably more acceleration because the liquid is not made to rotate with the rotating can. It in effect "slides" rather than rolls down the incline, so practically all the KE at the bottom is in linear speed with next-to none in rotation. Fine, one might say, then if the liquid doesn't rotate, the can ought to behave as an empty can, with the larger rotational inertia of a "hoop" and lag behind. This brings up an interesting point: The issue is not which can has the greater rotational inertia, but which has the greater rotational inertia compared to its mass (note the qualifier in the legend of Figure 8.14). The liquid content has appreciably more mass than the can that contains it; hence the non-rolling liquid serves to increase the mass of the can without contributing to its rotational inertia. It gives the can of liquid a relatively small rotational inertia compared to its mass.]

You can follow through by asking which can will be first in rolling to a stop once they meet a horizontal surface. The can hardest to "get going" is also the can hardest to stop—so given enough horizontal distance, the slowest can down the incline rolls farther and wins the race!

> CHALLENGE: At the bottom of an incline are two balls of equal mass—a solid one and a thin-walled hollow one. Each is given the same initial speed. Which rolls higher up the incline before coming to a stop? [The answer is the hollow ball.] In terms of rotational inertia, whether a ball is hollow or solid makes a big difference. A thin-walled hollow ball, having much of its mass along its radius, has a relatively large rotational inertia ($^2/_3MR^2$). A solid ball, having much of its mass near its center, has less rotational inertia ($^2/_5MR^2$). The ball with the greater rotational inertia out-rolls a lower-inertia ball. Hence the hollow ball rolls farther up the incline before it comes to a stop.

Another way to look at it is in terms of energy. The balls begin their upward travel with kinetic energy of two kinds—translational and rotational. Although their initial translational KEs are the same, the hollow ball begins with more rotational KE due to its greater rotational inertia. So the hollow ball has more total KE at the base of the incline, which means it must have more PE at the top. The hollow ball indeed goes higher.

Does mass make a difference? No. As with the mass of a pendulum bob, or the mass of a freely-falling object, mass makes no difference. Sent rolling up an incline with equal speeds, any hollow ball will out-roll any solid ball. That's right—a tennis ball will roll higher than a bowling ball or a marble.

If you instead release both balls from a rest position at the top of an incline, the hollow ball "out-rests" the solid ball, is slower to gain speed, and lags behind the solid ball. The solid ball reaches the bottom first. Inertia is a resistance to *change*.

## Answers and Solutions for Chapter 8

### Reading Check Questions

1. Tangential speed is measured in meters per second; rotational speed in RPM (revolutions per minute) or rotations per second.
2. Only tangential speed varies with distance from the center.
3. The wide part has a greater tangential speed than the narrow part.
4. The wide part of the wheel has a greater radius than the narrow part, and hence a greater tangential speed when the wheel rolls.
5. Rotational inertia is the resistance to a change in rotational motion, which is similar to plane inertia which is a resistance to a change in velocity.
6. Rotational inertia also depends on the distribution of mass about an objects axis of rotation.
7. Rotational inertia increases with increasing distance.
8. Smallest when rotation is about the lead; next when at a right angle about the middle, and most when about a right angle at the end.
9. Easier to get swinging when held closer to the massive end.
10. Bent legs have mass closer to the axis of rotation and therefore have less rotational inertia.
11.A solid disk has less rotational inertial and will accelerate more.
12. A torque tends to change the rotational motion of an object.
13. The lever arm is the shortest distance between the applied force and rotational axis.
14. For a balanced system, both clockwise and counterclockwise torques have equal magnitudes.
15. The stick 'wobbles,' spins really, about its CM (or CG).
16. A baseball's CM and CG are at its center. Both are closer to the massive end of a baseball bat.
17. Your CG is beneath the rope.
18. The CM of a soccer ball is at its center.
19. For stable equilibrium the CG must be above a support base, and not extend beyond it.
20. The CG of the tower lies above and within the support base of the tower.
21. In attempting so, your CG extends beyond your support base, so you topple.
22. The direction of the force is inward, toward the center of rotation.
23. The force on the clothes is inward.
24. When the string breaks, no inward force acts and via with the law of inertia, the can moves in a straight line.
25. No force is responsible, for you tend to move forward in a straight line and the car curves into you.
26. It's called fictitious because there is no reaction counterpart to centrifugal force.
27. Rotational motion results in a centrifugal force that behaves like the force of gravity.
28. Linear momentum involves straight-line motion; angular momentum involves rotational motion.
29. The angular momentum of a system remains constant when no net torque acts.
30. Angular momentum remains the same, while her rate of spin doubles.

### Think and Do

31. Open ended.

32. You'll note the cups roll off the track!

33. Yes, this happens because the CG hangs below the point of support.

34. Women have lower CGs than men. Their feet are also smaller. So women have the advantage in the toppling contest because their CG is more likely to be above a support base.

35. Facing the wall is more difficult! For both sexes the CG extends beyond the support base defined by the balls of the feet to the wall.
36. Your fingers will meet in the center. When a finger is farther from the center than the other, it presses with less force on the stick and slides. The process alternates until both fingers are at the center.

37. If the coin is on the line to the center of rotation, the 'normal' force on the coin provides a centripetal force to keep it steadily rotating.

### Plug and Chug

38. $\tau$ = 0.2 m $\times$ 50 N = 10 m·N.
39. $\tau$ = 0.5 m $\times$ 50 N = 25 m·N.
40. $F$ = (2 kg)(3 m/s)$^2$/2.5 m = 7.2 N.

41. $F$ = (80 kg)(3 m/s)$^2$/2 m = 360 N.

42. Ang momentum = $mvr$ = (80 kg)(3 m/s)(2 m) = 480 kg·m$^2$/s.

43. Twice: Ang momentum = $mvr$ = (80 kg)(6 m/s)(2 m) = 960 kg·m$^2$/s.

## Think and Solve

44. In accord with $v = r\omega$, the greater the radius (or diameter), the greater the tangential speed. So the wide part rolls faster. It rolls 9/6 = 3/2 = 1.5 times faster.

45.(a) Torque = force × lever arm = (0.25 m) (80 N) = 20 N·m.
(b) Force = 200 N. Then (200 N)(0.10 m) = 20 N·m.
(c) Yes. These answers assume that you are pushing perpendicular to the wrench handle. Otherwise, you would need to exert more force to get the same torque.

46.The mass of the rock is 1 kg. (A reverse of the Check Point on page 142.)

47. The 1-kg mass weighs 10 N. At the 50-cm mark, torque = 10 N × 0.5 m = 5 N·m.
At the 75-cm mark, torque = 10 N × 0.75 m = 7.5 N·m, and at the 100-cm mark,
torque = 10 N × 1.0 m = 10 N·m. So at the 75-cm mark the torque is 7.5/5 = 1.5 times as much, and at the 100-cm mark the torque is twice what it is at the 50-cm mark.

48. From $F = mv^2/r$, substituting, $T = mv^2/L$. (a) Rearranging, $m = TL/v^2$.
(b) Substituting numerical values, $m$ = (10N)(2m)/(2m/s)$^2$ = 5 kg.

49.The artist will rotate 3 times per second. By the conservation of angular momentum, the artist will increase rotation rate by 3. That is
$I\omega_{before} = I\omega_{after}$
$I\omega_{before} = [(^I/3)I(3\omega)]_{after}$

50. (a) In the absence of an unbalanced external torque the angular momentum of the system is conserved. So (angular momentum)$_{initial}$ = (angular momentum)$_{final}$., where angular momentum is $mvL$.
From $mv_0L = mv_{new}(0.33L)$ we get $v_{new} = v_0(L/0.33L) = v_0/0.33 = 3.0v_0$.
(b) $v_{new} = v_0/(0.33)$ = (1.0 m/s)/(0.33) = 3.0 m/s.

## Think and Rank

51. B, C, A
52. C, A, B
53. B, A, C
54. B, C, A
55. C, A, B

## Think and Explain

56. Sam's rotational speed $\omega$, RPMs, remains the same, assuming the Ferris wheel is powered and not "free wheeling." Sam's tangential speed, $v = r\omega$ is half because the radial distance $r$ is half. Answers are different because tangential speed $v$ depends on distance from the spin axis, while rotational speed $\omega$ does not.

57.Sue's tires have a greater rotational speed for they have to turn more times to cover the same distance.

58.For the same twisting speed $\omega$, the greater distance $r$ means a much greater speed $v$.

59.The amount of taper is related to the amount of curve the railroad tracks take. On a curve where the outermost track is say 10% longer than the inner track, the wide part of the wheel will also have to be at least 10% wider than the narrow part. If it's less than this, the outer wheel will rely on the rim to stay on the track, and scraping will occur as the train makes the curve. The "sharper" the curve, the more the taper needs to be on the wheels.

60.Yes, rotational inertia is enhanced with long legs. The bird's foot is directly below the bird's CM.

61.Rotational inertia and torque are most predominantly illustrated with this vehicle, and the conservation of angular momentum also plays a role. The long distance to the front wheels means greater rotational inertia of the vehicle relative to the back wheels, and also increases the lever arm of the front wheels without appreciably adding to the vehicle's weight. As the back wheels are driven clockwise, the chassis tends to rotate counterclockwise (conservation of angular momentum) and thereby lift the front wheels off the ground. The greater rotational inertia and the increased clockwise torque of the more distant front wheels counter this effect.

62. The bowling ball wins. A solid sphere of any mass and size beats both a solid cylinder and a hollow ball of any mass and size. That's because a solid sphere has less rotational inertia per mass than the other shapes. A solid sphere has the bulk of its mass nearer the rotational axis that extends through its center of mass, whereas a cylinder or hollow ball has more of its mass farther from the axis. The object with the least rotational inertia per mass is the "least lazy" and will win races.

63. The ball to reach the bottom first is the one with the least rotational inertia compared with its mass—that's the softball (as in the answer to the previous question).

64. The lever arm is the same whether a person stands, sits, or hangs from the end of the seesaw, and certainly the person's weight is the same. So the net torque is the same also.

65. No, for by definition, a torque requires both force and a lever arm.

66. In the horizontal position the lever arm equals the length of the sprocket arm, but in the vertical position, the lever arm is zero because the line of action of forces passes right through the axis of rotation. (With cycling cleats, a cyclist pedals in a circle, which means they push their feet over the top of the spoke and pull around the bottom and even pull up on the recovery. This allows torque to be applied over a greater portion of the revolution.)

67. No, because there is zero lever arm about the CM. Zero lever arm means zero torque.

68. Friction between the ball and the lane provides a torque, which spins the ball.

69. A rocking bus partially rotates about its CM, which is near its middle. The farther one sits from the CM, the greater is the up and down motion—as on a seesaw. Likewise for motion of a ship in choppy water or an airplane in turbulent air.

70. With your legs straight out, your CG is farther away and you exert more torque sitting up. So sit-ups are more difficult with legs straight out, a longer lever arm.

71. The long drooping pole lowers the CG of the balanced system—the tightrope walker and the pole. The rotational inertia of the pole contributes to the stability of the system also.

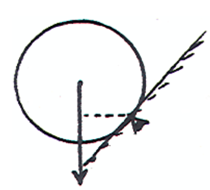
72. You bend forward when carrying a heavy load on your back to shift the CG of you and your load above the area bounded by your feet—otherwise you topple backward.

73. The wobbly motion of a star is an indication that it is revolving about a center of mass that is not at its geometric center, implying that there is some other mass nearby to pull the center of mass away from the star's center. This is one of the ways in which astronomers have discovered planets existing around stars other than our own.

74. Two buckets are easier because you may stand upright while carrying a bucket in each hand. With two buckets, the CG will be in the center of the support base provided by your feet, so there is no need to lean. (The same can be accomplished by carrying a single bucket on your head.)

75. The Earth's atmosphere is a nearly spherical shell, which like a basketball, has its center of mass at its center, i.e., at the center of the Earth.

76. The CG of a ball is not above a point of support when the ball is on an incline. The weight of the ball therefore acts at some distance from the point of support which behaves like a fulcrum. A torque is produced and the ball rotates. This is why a ball rolls down a hill.



77. It is dangerous to pull open the upper drawers of a fully-loaded file cabinet that is not secured to the floor because the CG of the cabinet can easily be shifted beyond the support base of the cabinet. When this happens, the torque that is produced causes the cabinet to topple over.

78. An object is stable when its PE must be raised in order to tip it over, or equivalently, when its PE must be increased before it can topple. By inspection, because of its narrow base the first cylinder undergoes the least change in PE compared to its weight in tipping. So it is the least stable. The third truncated pyramid requires the most work, so it is the most stable.

79. The CG of truck at the left on the lower part of the incline, is not above its support base, and will tip. The CGs of the two other trucks are above their support bases and won't tip. So only the first of the three trucks will tip.

80. In accord with the equation for centripetal force, twice the speed corresponds to four times the force.

81. No—in accord with Newton's first law, in the absence of force a moving object follows a straight-line path.

82. Yes. Letting the equation for centripetal force guide our thinking, increased speed at the same radial distance means greater centripetal force. If this greater centripetal force isn't provided, the car will skid.

83. Newton's first and third laws provide a straight-forward explanation. You tend to move in a straight line (Newton's first law) but are intercepted by the door. You press against the door because the door is pressing against you (Newton's third law). The push by the door provides the centripetal force that keeps you moving in a curved path. Without the door's push, you wouldn't turn with the car—you'd move along a straight line and be "thrown out." Explanation doesn't require invoking centrifugal force.

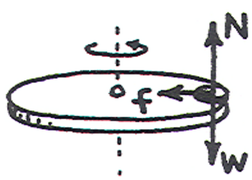
84. On a banked road the normal force, at right angles to the road surface, has a horizontal component that provides the centripetal force. Even on a perfectly slippery surface, this component of the normal force can provide sufficient centripetal force to keep the car on the track.

85. A car can remain on a perfectly slippery banked track if the horizontal component of its normal force is sufficient to provide the required centripetal force.

86. There is no component of force parallel to the direction of motion, which work requires.

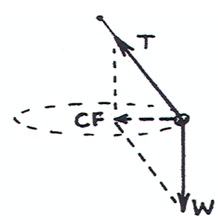
87. In accord with Newton's first law, at every moment her tendency is to move in a straight-line path. But the floor intercepts this path and a pair of forces occur; the floor pressing against her feet and her feet pressing against the floor—Newton's third law. The push by the floor on her feet provides the centripetal force that keeps her moving in a circle with the habitat. She senses this as an artificial gravity.

88.



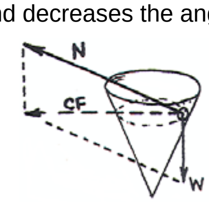

89. (a) Except for the vertical force of friction, no other vertical force except the weight of the motorcycle + rider exists. Since there is no change of motion in the vertical direction, the force of friction must be equal and opposite to the weight of motorcycle + rider. (b) The horizontal vector indeed represents the normal force. Since it is the only force acting in the radial direction, horizontally, it is also the centripetal force. So it's both.

90. The resultant is a centripetal force.




91. As you crawl outward, the rotational inertia of the system increases (like the masses held outward in Figure 8.52). In accord with the conservation of angular momentum, crawling toward the outer rim increases the rotational inertia of the spinning system and decreases the angular speed.

92.



93. Soil that washed down the river is being deposited at a greater distance from the Earth's rotational axis. Just as the man on the turntable slows down when one of the masses is extended, the Earth slows in its rotational motion, extending the length of the day. The amount of slowing, of course, is exceedingly small.

94. Rotational inertia would increase. By angular momentum conservation, the rotation of the Earth would slow (just as a skater spins slower with arms outstretched), tending to make a longer day.

95. In accord with the conservation of angular momentum, as the radial distance of mass increases, the angular speed decreases. The mass of material used to construct skyscrapers is lifted, slightly increasing the radial distance from the Earth's spin axis, which tends to slightly decrease the Earth's rate of rotation, making the days a bit longer. The opposite effect occurs for falling leaves as their radial distance from the Earth's axis decreases. As a practical matter, these effects are entirely negligible!

96. In accord with the conservation of angular momentum, if mass moves closer to the axis of rotation, rotational speed increases. So the day would be ever so slightly shorter.

97. In accord with the conservation of angular momentum, if mass moves farther from the axis of rotation, as occurs with ice caps melting, rotational speed decreases. So the Earth would slow in its daily rotation.

98. Without the small rotor on its tail, the helicopter and the main rotor would rotate in opposite directions. The small rotor on the tail provides a torque to offset the rotational motion that the helicopter would otherwise have.

99. Gravitational force acting on every particle by every other particle causes the cloud to condense. The decreased radius of the cloud is then accompanied by an increased angular speed because of angular momentum conservation. The increased speed results in many stars being thrown out into a dish-like shape.

100. In accord with Newton's first law, moving things tend to travel in straight lines. Surface regions of a rotating planet tend to fly off tangentially, especially at the equator where tangential speed is greatest. More predominantly, the surface is also pulled by gravity toward the center of the planet. Gravity wins, but bulging occurs at the equator because the tendency to fly off is greater there. Hence a rotating planet has a greater diameter at the equator than along the polar axis.

**Think and Discuss**

101. Large diameter tires mean you travel farther with each revolution of the tire. So you'll be moving faster than your speedometer indicates. (A speedometer actually measures the RPM of the wheels and displays this as mi/h or km/h. The conversion from RPM to the mi/h or km/h reading assumes the wheels are a certain size.) Oversize wheels give too low a reading because they really travel farther per revolution than the speedometer indicates, and undersize wheels give too high a reading because the wheels do not go as far per revolution.

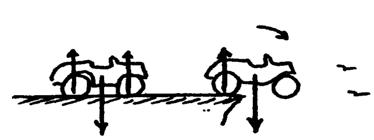
102. The tangential speeds are equal, for they have the same speed as the belt. The smaller wheel rotates twice as fast because for the same tangential speed, and $r$ half, $\omega$ must be twice. $v_{(\text{big wheel})} = r\omega$; $v_{(\text{small wheel})} = (r/2 \times 2\omega)$.

103. Two conditions are necessary for mechanical equilibrium, $\Sigma F = 0$ and $\Sigma Torque = 0$.

104. Before leaving the cliff, front and back wheels provide the support base to support the car's weight. The car's CM is well within this support base. But when the car drives off the cliff, the front wheels are the first to leave the surface. This shifts the support base to the region between the rear wheels, so the car tips forward. In terms of torques, before driving off the cliff, the torques are balanced about the CM between the front and back wheels. But when the support force of the front wheels is absent, torque due to the support force of the rear wheels rotates the car forward about its CM making it nose forward as shown. At high speed, the time that this torque acts is less, so less rotation occurs as it falls.

105. Friction by the road on the tires produces a torque about the car's CM. When the car accelerates forward, the friction force points forward and rotates the front of the car upward. When braking, the direction of friction is rearward, and the torque rotates the car in the opposite direction so the rear end rotates upward (and the nose downward).





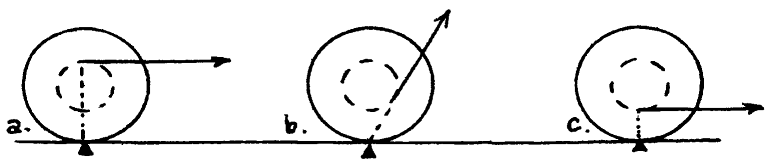
106. If you roll them down an incline, the solid ball will roll faster. (The hollow ball has more rotational inertia compared with its weight.)

107. Don't say the same, for the water slides inside the can while the ice is made to roll along with the can. When the water inside slides, it contributes weight rather than rotational inertia to the can. So the can of water will roll faster. (It will even beat a hollow can.)

108. Lightweight tires have less rotational inertia, and are easier to get up to speed.

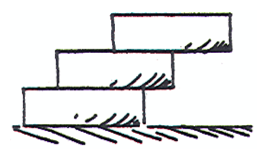
109. Advise the youngster to use wheels with the least rotational inertia—lightweight solid ones without spokes (more like a disk than hooplike).

110. In all three cases the spool moves to the right. In (a) there is a torque about the point of contact with the table that rotates the spool clockwise, so the spool rolls to the right. In (b) the pull's line of action extends through (not about) the point of table contact, yielding no lever arm and therefore no torque; but with a force component to the right; hence the spool slides to the right without rolling. In (c) the torque produces clockwise rotation so the spool rolls to the right.




111. The weight of the boy is counterbalanced by the weight of the board, which can be considered to be concentrated at its CG on the opposite side of the fulcrum. He is in balance when his weight multiplied by his distance from the fulcrum is equal to the weight of the entire board multiplied by the distance between the fulcrum and the midpoint (CG) of the board. (How do the relative weight of boy and board relate to the relative lever arms?)

112. The top brick would overhang $^3/4$ of a brick length as shown. This is best explained by considering the top brick and moving downward; i.e., the CG of the top brick is at its midpoint; the CG of the top two bricks is midway between their combined length. Inspection will show that this is $^1/4$ of a brick length, the overhang of the middle brick. (Interestingly, with a few more bricks, the overhang can be greater than a brick length, and with a limitless number of bricks, the overhang can be made as large as you like.)



113. The track will remain in equilibrium as the balls roll outward and until the ball rolls off the track. This is because the CG of the system remains over the fulcrum. For example, suppose the billiard ball has twice the mass of the golf ball. By conservation of momentum, the twice-as-massive ball will roll outward at half the speed of the lighter ball, and at any time be half as far from the starting point as the lighter ball. So there is no CG change in the system of the two balls. So the torques produced by the weights of the balls multiplied by their relative distances from the fulcrum are equal at all points—because at any time the less massive ball has a correspondingly larger lever arm.

114. The center of mass of the bird is slightly below its beak, the point at which it rests on Diana's finger. So the bird is "hanging" on Diana's finger. This is accomplished by lead or some very dense metal embedded in the wing tips of the bird.

115. The equator has a greater tangential speed than latitudes north or south. When a projectile is launched from any latitude, the tangential speed of the Earth is imparted to the projectile, and unless corrections are made, the projectile will miss a target that travels with the Earth at a different tangential speed. For example, if the rocket is fired south from the Canadian border toward the Mexican border, its Canadian component of speed due to the Earth's turning is smaller than Earth's tangential speed further south. The Mexican border is moving faster and the rocket falls behind. Since the Earth turns toward the east, the

rocket lands west of its intended longitude. (On a merry-go-round, try tossing a ball back and forth with your friends. The name for this alteration due to rotation is the Coriolis effect.)

116. Acceleration caused this force. His body was accelerated by support at his head, but his brain was not so supported. In effect, the back of his head exerted a force on his head, with the cause being too-great an acceleration.