

Balancing Demonstrations

Student Objectives

Students answer their driving question and investigation questions through independent research, and then deliver this research to their classmates in a concise presentation form that includes a presentation website with video content. The student will:

Mandatory

- ◆ Know the meaning of the terms “center of mass” and “center of gravity”.
- ◆ Present five demonstrations showing how to balance a complex system, object, or shape. Each is to be built from one of the five sets of equipment selected from the Investigation section of the Student Handout.
- ◆ Demonstrate that an object in static equilibrium (balanced) has its center of mass (or center of gravity) above its base of support, or directly below its pivot point (point of contact).
- ◆ Demonstrate that an object whose center of mass (center of gravity) is not above its base of support, or directly below its pivot point, or point of suspension, will experience torque that will cause the object to rotate out of balance.
- ◆ Understand that a balanced object in static equilibrium experiences zero net torque.
- ◆ Show an obvious understanding of each demonstration and explain the requirements for balancing each system, and why those requirements are necessary.

TEKS Objectives

This lab correlates to the following TEKS objectives:

- P.3 The student uses critical thinking, scientific reasoning, and problem solving to make informed decisions within and outside the classroom. The student is expected to:
- B. communicate and apply scientific information extracted from various sources such as current events, news reports, published journal articles, and marketing materials.

Project Background

The center of mass of an object (sometimes called center of gravity) is the point about which the total mass of the object is distributed equally, both in magnitude and distance: the point at which an object would be perfectly balanced if suspended from.

For example: a sphere constructed from a material with uniform density (the same mass per unit volume throughout) would have its center of mass (CM) exactly at its center (Figure 1). There are equal amounts of mass distributed in distance and magnitude about that point. If the sphere didn't have a uniform density, its center of mass would not be at its center, but rather, in a location near the area of highest density (Figure 2). Also, the location of an object's center of mass may not be within the boundaries of object at all, similar to the semi-circular rod in Figure 3.

Perfectly balanced objects are said to be in “static equilibrium:” a state in which an object is at rest and the total net force experienced by the object is zero. Balanced objects include things standing as well as things that are

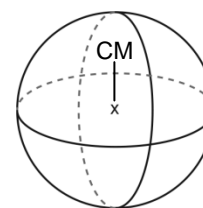


Figure 1. Uniform

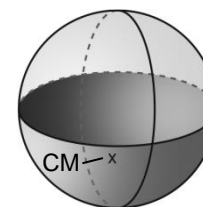


Figure 2. Non-uniform density sphere

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hanging, but in both cases there is a similar thread that helps these objects to stay balanced: static equilibrium can only occur when an object's center of mass is above its base of support for standing objects, or directly below its point of suspension (point of contact) for hanging objects.

If the center of mass of a standing object were to exist in an area not above its base of support, or not below its suspension point for a hanging object, the object would experience an unbalanced force from Earth's gravity that would cause the object to rotate, fall, or topple over (Figure 4). This force can be assumed to act on the object's center of mass, and the rotation produced is about the object's base of support for standing objects, or the point of suspension for hanging objects. This rotation, brought on by a force, is described by the *torque* experienced by the object:

$$\tau = \mathbf{r} \times \mathbf{F}$$

$$\tau = rF \sin \theta$$

Eq.1

Where torque τ is equal to the cross product of the unbalanced force vector \mathbf{F} and the displacement vector \mathbf{r} (the vector connecting the rotational axis to the applied force vector).

To summarize, perfectly balanced objects in static equilibrium experience zero net force, and consequently, zero net torque. Non-zero net torque, as a result of gravitational force, will exist if the center of mass of a standing object is not directly over its base of support, or the center of mass of a hanging object is not directly under its point of suspension.

In this project, the student will choose five sets of equipment, each set associated with a specific balancing demonstration, from a list of ten equipment sets found in the Investigation section of the student handout. It will be the responsibility of the student to determine how each chosen set can be used to demonstrate how a complex system can be balanced about a singular point. In each demonstration, the student must show a complex system created from the equipment in the set, what requirements are necessary to balance the system, and why those requirements are necessary.

For a short description of the demonstration generally associated with each set of equipment listed in the Investigation section of the student handout, please see the table in the Presentation Guidelines section below.

Materials and Special Preparation

The student handout for this activity lists ten sets of equipment that the student will choose from. Of that equipment, the items listed in the table below require special preparation. Please review these items and the preparation notes for each prior to providing the items to the student:

Equipment

Preparation Notes

◆ Soda can	The soda can must be empty.
◆ Board with 9" nail	Hammer one 9" nail vertically into the very center of a small piece (2" x 4" x 10") of wood. Only hammer the nail in approximately 0.5" to 1" deep.

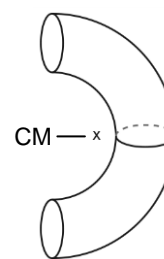


Figure 3. CM outside shape

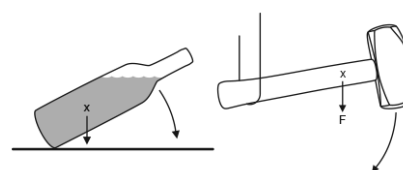


Figure 4. Objects experiencing torque due to their CM being not above the point of contact/suspension

Safety and Maintenance

Be certain that students pay attention to the following maintenance recommendations, and add these important safety precautions to their normal laboratory procedures:

- ◆ All balancing objects may fall. Have students use caution to ensure that none of the objects being balancing are in danger of breaking or causing injury if they fall.
- ◆ Students may choose to cut the bottom of, and drill a bottle-neck-sized hole into, the piece of wood that is part of Set #5. Have students use extreme caution when using power tools or other tools and always follow the safety guidelines published by the tool's manufacturer.

Presentation Guidelines

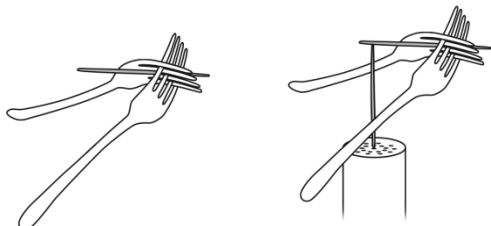
Use the following guidelines to assess the student's preparation, content knowledge, and presentation delivery.

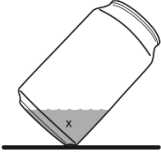
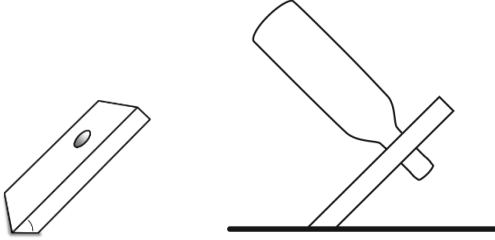
Investigation Guidelines

Although the student has the freedom to determine how each set of equipment listed in the Investigation section of the student handout can be used to create a balancing demonstration, each set of equipment listed has a specific demonstration associated with it. These demonstrations are specified in the table below as "Suggested Demonstrations" for each equipment set. A short description of each demonstration is also included, as well as an indication of difficulty level associated with each to provide information that can help assess student knowledge.

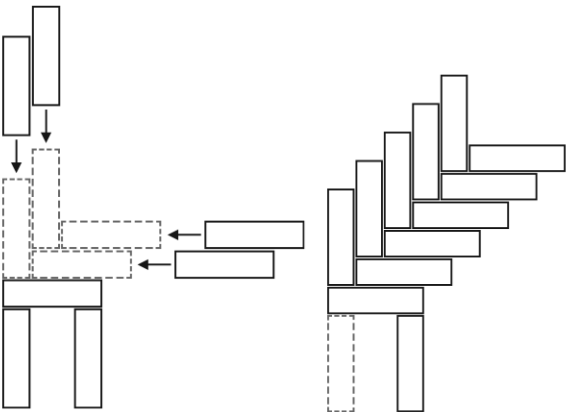
SET #	Equipment	Suggested Demonstration	Difficulty
1	<ul style="list-style-type: none"> ◆ Balancing bear, or similar toy ◆ Thread 	<p>Tie the thread between two elevated points (one point slightly higher than the other). Set the wheel on the balancing bear on the suspended thread at the elevated end. Allow the bear to balance on the string and roll down the string.</p> <p>The balancing bear does not tip over or fall off the thread because the system's center of mass (bear and all) is directly below the thread (the point at which the system is suspended), between the counterweights. Because the center of mass is directly below the point at which the bear is suspended, it experiences zero net torque.</p>	Easy

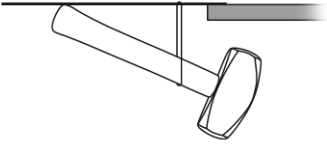
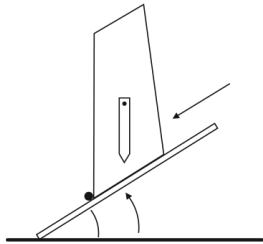
Balancing Demonstrations

SET #	Equipment	Suggested Demonstration	Difficulty
2	<ul style="list-style-type: none"> ◆ Balancing bird ◆ Toothpick ◆ Salt shaker 	<p>Place a toothpick into one of the holes on the salt shaker so the toothpick stands vertically out of the salt shaker. Set the beak of the balancing bird on the tip of the vertical toothpick. The bird will balance on the tip of the toothpick.</p> <p>The bird does not tip over or fall off the toothpick because the bird's center of mass is directly below the tip of its beak (the point at which the system is suspended). A majority of the mass of the bird is in the tips of its wings which are below its beak. This causes the center of mass to be lower than the bird's beak and directly below the tip of the toothpick. Because the center of mass is directly below the point at which the bird is suspended, it experiences zero net torque.</p>	Easy
3	<ul style="list-style-type: none"> ◆ Fork (2), or 1 fork and 1 spoon ◆ Toothpick (2) ◆ Salt shaker 	<p>Press the tines of the two forks together (or the spoon into the tines of the fork) so the two form a "V" shape. Slide a toothpick firmly between the tines so the toothpick extends inward between the forks, and just slightly above the plane formed by the two forks.</p> <p>Place a toothpick into one of the holes on the salt shaker so it stands vertically from the salt shaker. Balance the forks and toothpick system on the toothpick extending vertically out of the salt shaker by resting the toothpick extending from the forks on the tip of the other toothpick.</p> <div style="text-align: center;">  </div> <p>The forks and toothpick system does not tip over or fall off the toothpick because the system's center of mass is directly below the tip of the vertical toothpick (the point at which the system is suspended). A majority of the mass of the system is in the handles of the forks. This causes the center of mass to be lower than the tip of the toothpick. Because the center of mass is directly below the point at which the system is suspended, it experiences zero net torque.</p>	Moderate

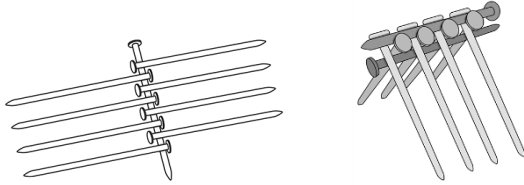
SET #	Equipment	Suggested Demonstration	Difficulty
4	<ul style="list-style-type: none"> ◆ Soda can ◆ Water 	<p>Fill the empty soda can approximately 1/3 full with water. Place the can onto a table and lean the can with water at a 45° angle so the groove around the bottom of the can rests on the table. The can will balance at a 45° angle on its own, but only with water in the can. Without water, or with additional water in the can, the can will not balance at that angle.</p>  <p>When the can is empty, or completely full of water, the center of mass of the can is approximately in the center of the can. When the can is leaned at a 45° angle, the center of mass is not directly above its support base and the can experiences a non-zero torque that causes it to tip over.</p> <p>When the can is only 1/3 full and leans at a 45° angle, its center of mass is directly over its support base, causing the net torque to be zero, and the can balances.</p>	Moderate
5	<ul style="list-style-type: none"> ◆ Long-necked bottle, empty or full ◆ Wooden board, 1" x 4" x 18" 	<p>Drill a hole slightly larger in diameter than the neck of the bottle into one end of the board, approximately 1.5 inches away from the end of the board. Cut the opposite end of the board flat at a 45° angle.</p>  <p>Place the bottle neck into the hole and rest the bottle and board on the table. If the system doesn't balance, adjust the position of the bottle by sliding it further into the hole. If the system still doesn't balance, cut an additional 1" of length off the angled end of the board, maintaining a 45° angle at the end. Check for balance, and keep removing length from the board 1" at a time. The system will eventually balance, similar to Figure 11.</p> <p>This system balances because the center of mass of the system is just under the bottle, but directly above the support base of the board, which causes the net torque on the system to be zero.</p>	Difficult

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SET #	Equipment	Suggested Demonstration	Difficulty
6	♦ Jenga® blocks	<p>Assemble the Jenga blocks similar to the pattern shown in the figure. Add more Jenga blocks to the top of the structure in a horizontal block-vertical block pattern until the structure has at least five horizontal pieces and five vertical pieces. Slowly remove the left support piece from beneath the structure and the structure will balance on its own.</p>  <p>This system balances because the center of mass of the total system is directly above the lowest vertical piece, which is directly above the support base of the entire system. Because of this the net torque on the system is zero and it maintains static equilibrium.</p>	Difficult
7	♦ Inflatable, self-righting, punching toy (bop bag)	<p>When the toy is inflated and placed upright it maintains static equilibrium because the majority of the mass in the toy is at its base, over the point of contact between it and the floor. When the toy is punched or pushed, it experiences a torque that causes it to rotate, but then it rotates right back to equilibrium because the center of mass is no longer directly over the point of contact between itself and the floor.</p> <p>Gravity causes a torque that rotates the toy when the center of mass is no longer over its support base. This torque causes the toy to right itself until the center of mass is over the point of contact again.</p>	Easy

SET #	Equipment	Suggested Demonstration	Difficulty
8	<ul style="list-style-type: none"> ◆ Hammer ◆ String ◆ Ruler 	<p>Tie a loop of string approximately 2–3" in diameter. Hold the hammer under the ruler length-wise and place the loop of string around both, similar to the figure. Slide the string and the hammer down the length of the ruler until approximately 2–3" of the hammerhead extends beyond the end of the ruler. Place the end of the ruler onto the edge of a table with the hammerhead hanging under the table. The ruler will extend horizontally in equilibrium with just a small piece of the ruler being supported by the table.</p>  <p>The system maintains static equilibrium because its center of mass is directly under the point of contact between the ruler and the table. The result is a zero net torque on the system. The reason the system's center of mass is in a strange location is because most of the mass within the system is in the hammerhead, which extends under the table.</p>	Moderate
9	<ul style="list-style-type: none"> ◆ PASCO Stability model ◆ Small flat wooden board, 20" x 10" x 	<p>Place the stability model vertically on the board with the longer base touching the board. The hanging arrow indicates the center of mass of the model and where it aligns vertically with its base. When the model is standing on its longer base, the center of mass is above its base of support, implying that the net torque on the model is zero and it will maintain static equilibrium.</p> <p>Flip the model over so the shorter base is touching the board. In this position the center of mass is not over its base of support, so when it is released it will experience a torque that causes it to rotate and topple over.</p>  <p>Place the stability model vertically on the board with the longer base touching the board. Place your finger on the board at the front edge of the model and begin to lift the other end of the board.</p> <p>Slowly continue to tip the board until the arrow indicating the center of mass is pointing at your finger, at which time the model will topple over due to the center of mass no longer being over its base of support.</p>	Moderate

Balancing Demonstrations

SET #	Equipment	Suggested Demonstration	Difficulty
10	<ul style="list-style-type: none"> ◆ Board with one 9" nail driven, vertically, into the center of the board ◆ 9" nails (10) 	<p>Place one nail on its side on the table. Lay 8 nails atop the first nail with their heads touching the first nail in an alternating pattern.</p>  <p>Lay the last nail atop the 8 alternating nails just above the first nail with its head opposite that of the first, as in the figure above. While carefully squeezing the first and last nails together (this will capture the 8 alternating nails), lift the entire system and balance it atop the vertical nail in the board.</p> <p>The system will remain in static equilibrium because its center of mass is directly under the point of contact between the vertical nail and the horizontal nail. The center of mass of the system is lower than the point of contact due to the majority of the system's mass being in the ends of the 8 hanging nails.</p>	Difficult

Presentation Delivery Guidelines

Follow these guidelines to assess the student's preparation and presentation delivery to the class. To receive excellent marks, students have:

Preparation:	<ul style="list-style-type: none"> ◆ clearly invested at least 3–4 hours doing topical research ◆ brought and assembled all equipment necessary for their presentation ◆ prepared a supporting handout for their presentation ◆ prepared a thorough presentation discussion for their classmates
Delivery:	<ul style="list-style-type: none"> ◆ delivered their presentation content clearly and thoroughly, not speaking so quickly that the student audience cannot follow ◆ integrated their research and experimental setup into the presentation as visual support ◆ answered all question posed by their classmates to the best of their ability ◆ answered all question posed by their classmates correctly and thoughtfully
Website:	<ul style="list-style-type: none"> ◆ prepared a website explaining their project and the driving question associated with it ◆ included a thorough, well-written, explanation of the answer to their driving question and the theory behind the over-arching concept ◆ included supporting pictures, videos, and research references (including web-links)
Video:	<ul style="list-style-type: none"> ◆ recorded a supporting video for their website ◆ edited the supporting video in an attempt to produce a good–excellent quality video ◆ included a thorough, well-spoken, explanation of the answer to their driving question and the theory behind the over-arching concept ◆ included footage of their experimental setup with an explanation
Handout:	<ul style="list-style-type: none"> ◆ prepared a supporting handout for their presentation ◆ included a brief, but well-written, explanation of the answer to their driving question and the theory behind the over-arching concept ◆ included pictures of their experimental setup with explanation ◆ included references to all web-links and to the presentation website URL (or QR code)

Extension and Synthesis Questions

Below are sample responses to the questions in the Extension and Synthesis Questions section in the student handout.

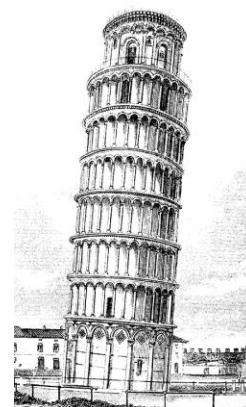
1. What do the terms “center of gravity” and “center of mass” mean, and how are they different?

"Center of mass" is a term used to describe the point about which the total mass of an object is distributed equally, both in magnitude and distance; the point at which an object would be perfectly balanced if suspended from. "Center of gravity" describes the point at which the weight of a system is distributed equally, both in magnitude and distance. Without the presence of gravity, "center of gravity" does not exist, but "center of mass" does.

2. If an object is not moving (static equilibrium) what is the net force acting on it? What is the net torque? How do you know?

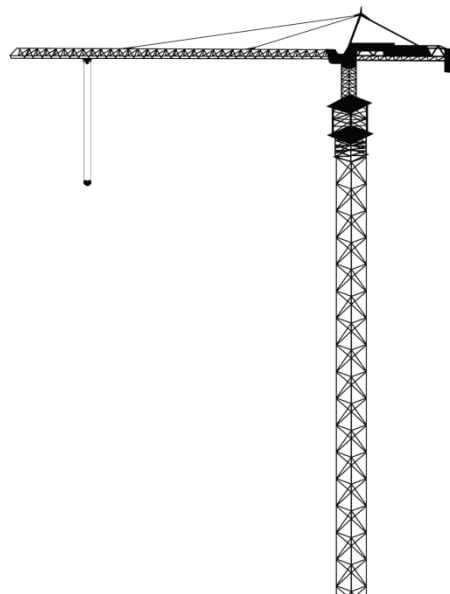
If an object is in static equilibrium, the net force acting on it is zero, and so is the net torque. We know this because the system is not rotating and because torque is the cross product of the net force vector and the distance from the rotational axis of the object. Because force is zero, so is torque.

3. The Tower of Pisa is a famous cathedral bell tower in Italy. It may be most famous for its unique tilt as a result of the ground under one side of the tower being too soft to support it. To the right is an image of the Tower of Pisa. Although the tower appears as if it is about to topple over, it does not. Explain why this is so.



The tower is leaning but doesn't fall because the center of mass of the tower is still over its base of support, despite its leaning angle.

4. Observe the crane to the right. Assume the vertical tower is fixed and the horizontal arm can rotate freely (vertically and horizontally) atop the vertical tower. If the horizontal arm is in static equilibrium, where is its center of mass located? How do you know?



If the arm is in static equilibrium its center of mass is either directly above or directly below the point at which attaches to the vertical tower. For an object to be in static equilibrium it must be at rest and experience zero net force and zero torque. This will only happen if an object's center of mass is directly over or directly below its point of support.

5. Without moving its position, imagine the crane lifted a piece of metal whose mass was greater than that of the entire horizontal arm. How would the center of mass of the horizontal arm change once the metal was lifted? How would that change its equilibrium?

By lifting a heavy piece of metal, the center of mass of the system (arm plus metal) would shift toward the area of the highest mass density. This would be near the metal being lifted, considering that it is nearly the same weight as the entire arm. If the center of mass of the arm system was shifted away from the point of contact between it and the vertical tower, the crane would then experience a non-zero net torque that would cause the arm to rotate.

6. Assuming the horizontal arm on the crane rotates freely, what is one thing you could do to the crane to keep the horizontal arm in equilibrium when the metal from the previous question is lifted?

A counter-weight could be added to the other side of the crane, farther from the rotational axis. This would help to keep the center of mass over the point of contact between the arm and the vertical tower.

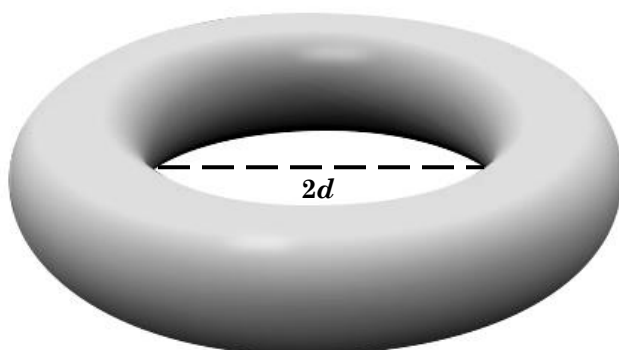
7. When a person opens a door is the person producing torque? If yes, how do you know?

Yes. When the person opens the door it begins to rotate (a change in rotational motion). An object that experiences a change in rotational motion must be experiencing a non-zero net torque.

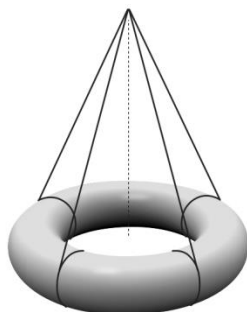
8. Why does a person carrying a heavy package while walking lean back slightly? What would happen if the person didn't lean backward while carrying the package? Why?

When a person carries a package, the added mass of the package changes the location of that person's center of mass. To keep from experiencing a torque that would cause one to fall over, a person leans to keep their center of mass over their base of support.

9. Below is an image of a solid metal ring with an inside diameter equal to $2d$. If the ring has uniform density throughout, where is its center of mass? How could you balance the ring on a single point? Explain your answer. Would you need to any additional materials to balance the ring? If yes, what would those materials be and how would you use them?



Because the metal ring is uniform in size and density, its center of mass would be directly in the center of the ring's opening. To balance the ring you would need to have some way to make the point of contact directly above the center of the ring's opening. One could use string or rope tied across the opening of the ring so the ring hangs just below the point of contact.

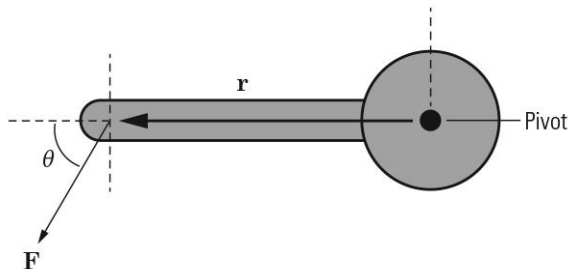


Balancing Demonstrations

Multiple Choice Questions

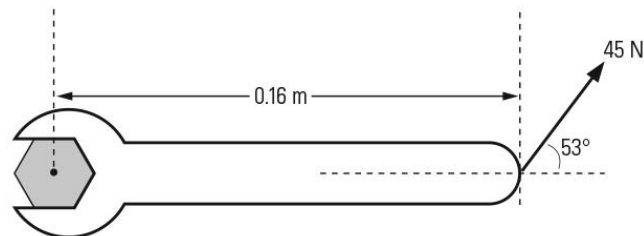
Select the best answer to each of the questions below. Record your answer on the answer sheet using upper case letters.

The diagram below shows a handle to open a propane gas valve. The pivot on the right side of the handle is a distance r from the point where force F is applied to turn the handle. The angle θ is the angle between vectors F and r . Use the diagram below to answer questions 1 through 3:



- What is the equation that expresses the magnitude of the force that produces rotation about the pivot?
 - $F \cos \theta$
 - $F \sin \theta$
 - $F \cos \theta + F \sin \theta$
 - None of these
- As a result of the force F , the torque on the handle is _____.
 - at a maximum because it is being applied perpendicularly
 - at a minimum because it is being applied perpendicularly
 - at some value between the minimum and maximum because it is being applied at an angle with respect to the position vector r
 - zero because the handle is not in motion
- In which direction does the torque vector point?
 - Out of the page
 - To the right
 - To the left
 - In the direction of rotation
- Someone has over-tightened the cap on a bottle of barbecue sauce. A bottle lid opener is to be used to open the lid. How much force is necessary to apply 50.0 N m of torque to the cap if the lid has a diameter of 4.00 cm and the bottle opener has a handle 20.0 cm? Assume the force is applied perpendicularly to the handle.
 - 227 N
 - 250 N
 - 208 N
 - 288 N

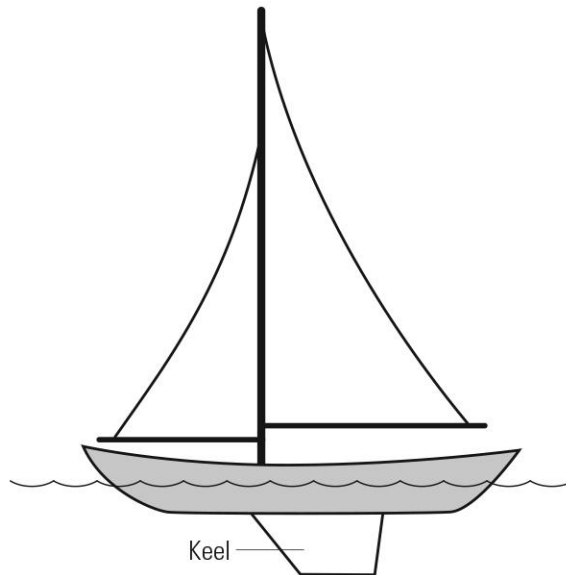
5. A hexagonal bolt is tightened by applying a force to a wrench, as shown at right. What is the magnitude of the torque about the center of the bolt? What is the direction of the torque vector?



- A. 7.2 N m, into the page
 B. 7.2 N m, out of the page
 C. 5.4 N m, into the page
 D. 5.4 N m, out of the page
6. Which of the following statements are true regarding center of mass and center of gravity:
- I. Center of mass and center of gravity are the same thing; the terms can be used interchangeably.
 - II. Center of gravity is the location of an object's weight and coincides with its center of mass.
 - III. On earth, center of mass and center of gravity are located at the same point for an object.
 - IV. The center of mass of an object may not be located within the object.
- A. I and II
 B. II and IV
 C. Only III
 D. II, III, and IV
7. How does stable static equilibrium differ from unstable static equilibrium?
- A. Objects in stable static equilibrium may be able to slide but must not be able to roll.
 - B. Objects in stable static equilibrium return to equilibrium after being displaced by a force.
 - C. Objects in stable static equilibrium have more kinetic energy than those in unstable static equilibrium.
 - D. The vector sum of all the external forces acting on objects in stable static equilibrium must be zero.
8. Two children ride a seesaw at the playground. One of the children is seated at one end of the toy, while the other child is seated much closer to the fulcrum, or pivot point of the seesaw. The seesaw remains motionless and horizontal because _____.
- A. the seesaw experiences no component of force from the children's weight perpendicular to the lever arm
 - B. the torques produced by each child's weight act in the same direction but are counteracted by the fulcrum
 - C. the seesaw is a special example of a first class lever
 - D. the torques produced by each child's weight must sum to zero

9. Consider a tablet sitting motionless on a table, the blades of an airplane's rotating propeller, a truck's tire as it travels in a straight line at constant speed, and a hockey puck sliding across a frictionless surface with constant velocity. Which of these objects is in equilibrium? Which of these objects is in static equilibrium?
- A. Equilibrium: truck's tire, hockey puck; Static equilibrium: propeller blades
 - B. Equilibrium: truck's tire, hockey puck; Static equilibrium: tablet
 - C. Equilibrium: all the objects; Static equilibrium: hockey puck
 - D. Equilibrium: all the objects; Static equilibrium: tablet

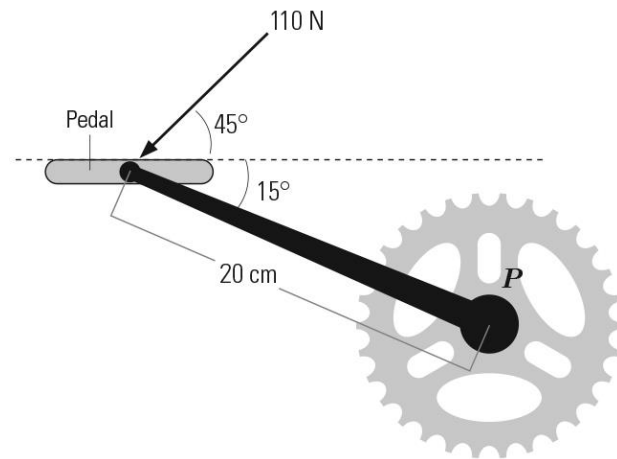
Many sailboats have keels, as shown in the diagram. Although this increases a boat's mass and therefore density, it helps to stabilize the boat in the water by prevent it from tipping over.



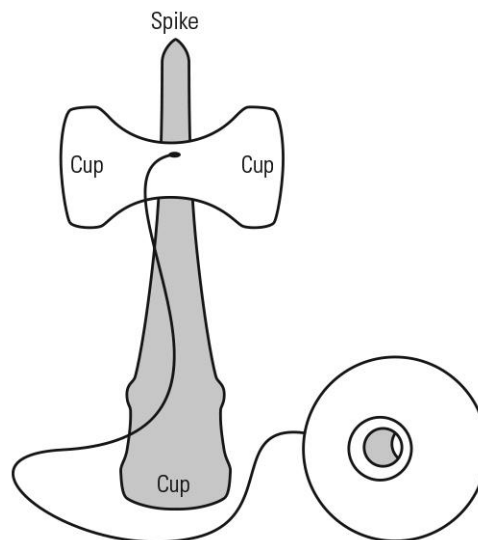
10. This type of sailboat design provides stability because _____.
- A. the keel helps counteract the torque created by the wind's horizontal force on the sails
 - B. the keel helps the boat to move forward through the water, instead of sideways
 - C. the change in mass affects the buoyant force on the sailboat, which is associated with stability
 - D. the change in mass and density alter the sailboat's position in the water, such that the hull displaces more water

- 11.** A mountain bike rider pushes against the pedal of his bike with a 110-N force, as shown in the image at right. The pedal shaft is 20.0 cm in length. Find the magnitude of the torque about point P.

- A. 18 N m
 B. 19 N m
 C. 3.8 N m
 D. 6.2 N m



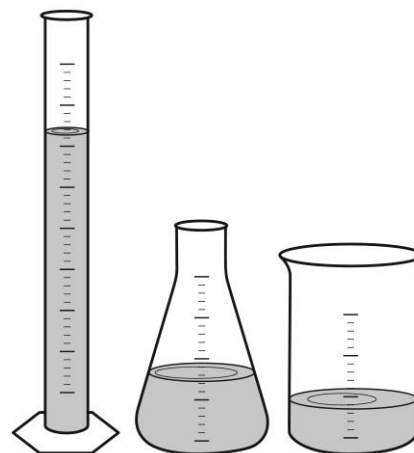
Kendama is a game of skill in which the player tries to catch a ball, connected by a string to the handle, in one of three small cups or the spike on the handle of the toy, as shown.



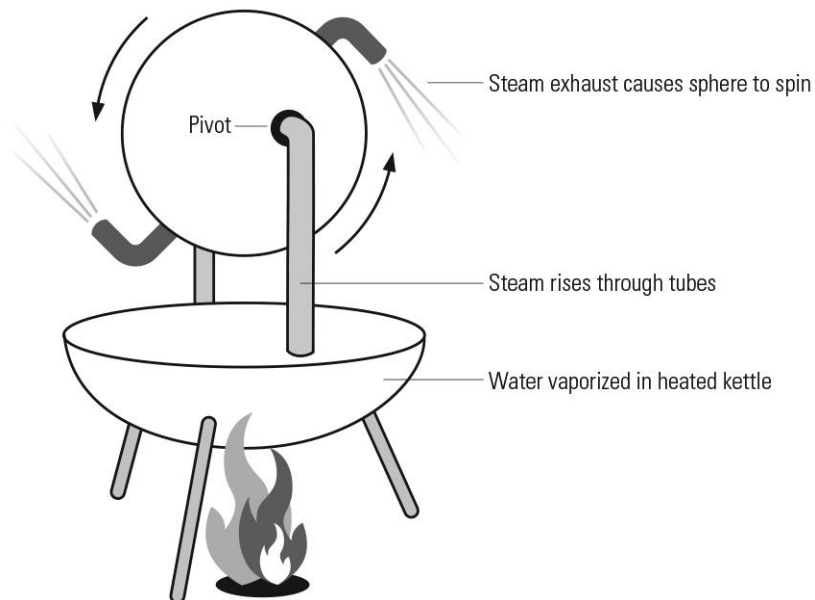
- 12.** In terms of equilibrium, why is the central point, or spike, of the handle considered the most difficult place to catch the ball?
- A. The spike acts as a pivot about which all the torques and forces on the ball must balance.
- B. The ball has its maximum potential energy, relative to the handle, just as it begins to rest on the spike.
- C. The spike represents an unstable equilibrium point until the ball's hole becomes aligned with the spike.
- D. All of these statements are true.

13. Consider three items of laboratory glassware: a graduated cylinder, an Erlenmeyer flask, and a beaker, as shown, but not to scale. Each vessel has the same mass, and each contains the same volume of water (density 1.0 g/mL). Rank the containers in order from greatest to least stability.

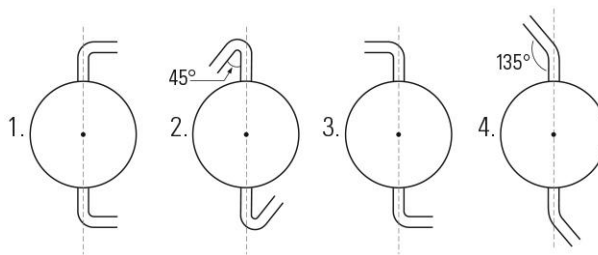
- A. beaker, flask, cylinder
- B. cylinder, beaker, flask
- C. flask, cylinder, beaker
- D. flask, beaker, cylinder



Hero of Alexandria is credited with building an aeolipile, a type of action-reaction steam engine, as seen here. Historians and engineers disagree as to whether his engine could have done useful work. Replicas of this engine are often built by science and engineering students.



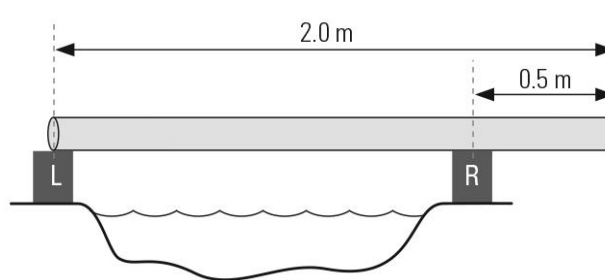
14. Rank the following aeolipile designs in order from largest to smallest torques:



- A. 1, 2 and 4 tie, 3
- B. 2, 3 and 1 tie, 4
- C. 3, 2 and 4 tie, 1
- D. 4, 2, 3, 1

15. A log weighing 500.0 N is laid across cinder block supports on each bank of a stream to form a bridge, as shown in the diagram. What is the magnitude of the normal force from the block on the right? Assume the log has uniform density.

- A. 333 N
- B. 167 N
- C. 228 N
- D. 375 N



Assessment Rubric Level II		Name: Math Class:				
Component	To receive highest marks the student:	4 Expert	3 Prac- titioner	2 Appren- tice	1 Novice	0 No Attempt
1. Preparation and Research	<input type="checkbox"/> Clearly invested several hours doing relevant research <input type="checkbox"/> Brought and prepared all items necessary for their presentation <input type="checkbox"/> Prepared supporting handout for their presentation <input type="checkbox"/> Prepared a thorough presentation discussion for their classmates					
2. Demonstrations, Models, or Experiments	<input type="checkbox"/> Obtained all necessary materials and used them to thoroughly explore the guiding questions for Part 1 of the investigation <input type="checkbox"/> Completed and documented results, data, and observations of any guiding questions investigated in Parts 1 – 3 of the investigation <input type="checkbox"/> Performed experiments or demonstrations proficiently for others, or explained clearly a model and the concepts the student investigated with the model					
3. Content	<input type="checkbox"/> Presented written and spoken explanations that were mathematically accurate and paraphrased in the student's own words <input type="checkbox"/> Answered all questions posed by their teacher or classmates correctly and thoughtfully <input type="checkbox"/> Answered project synthesis and real-world application questions correctly and thoroughly <input type="checkbox"/> Communicated clearly an understanding of the connection between their model or experiments and the driving question and theory behind the over-arching concept					
4. Technology	<input type="checkbox"/> Prepared a website explaining their project and the driving question associated with it, including: <ul style="list-style-type: none"> • A thorough, well-written explanation of the answer to the driving question and the theory behind the over-arching concept • Supporting pictures, videos, and research references (including web-links) <input type="checkbox"/> Recorded a supporting video for the website <ul style="list-style-type: none"> • Edited the supporting video in an attempt to produce a good–excellent quality video • Included footage of their experimental setup with an explanation • Included a thorough, well-spoken explanation of the answer to the driving question and the theory behind the over-arching concept <input type="checkbox"/> Produced a project brochure with 2 QR codes linking to video and to website					
5. Interdisciplinary Connections	<input type="checkbox"/> Chose and completed ELA option to best illustrate the project's objectives and monitor student progress <input type="checkbox"/> Included the ELA component on project website as separate page with appropriate design <input type="checkbox"/> Chose a related SS connection based on consultation with SS teacher <input type="checkbox"/> Included the SS connection on project website as separate page with appropriate design <input type="checkbox"/> Included ELA component and SS connection in video presentation					
6. Real-World Application and Extension	<input type="checkbox"/> Identified in written and spoken explanations the application of the topic to the real world, including specific examples <input type="checkbox"/> Thoroughly discussed relevance of the topic to real life					
7. Presentation	<input type="checkbox"/> Delivered their content clearly and thoroughly, in an organized, logical manner <input type="checkbox"/> Integrated their research and experimental setup into the presentation as visual support					
Total Points for Investigation (Maximum of 24 Points)						

Guidelines for Marks:

4 = **Expert:** Distinguished command of the topic; students show insightful and sophisticated communication of their understanding

3 = **Practitioner:** Strong command of the topic; students show reasonable and purposeful communication of their understanding

2 = **Apprentice:** Moderate command of the topic; students show adequate but basic communication of their understanding

1 = **Novice:** Partial command of the topic; students show limited and insufficient communication of their understanding

0 = **No Attempt**