Chapter 8

Extended Bodies at Rest

8.1 Extended and rigid bodies

OALG 8.1.1 Observe and find a pattern

Equipment: a book and a pencil.

For this activity, you need a book with a glossy cover, a pencil or a ruler, a smooth desk or a table, and a way to mark lines on the surface of the table.

a. Use the pencil eraser or the ruler to push several different points on the bottom edge of the book that you put on the smooth surface. Identify a pattern in the direction of the forces that do not cause the object to rotate. *Hint:* Draw lines on the object in the direction of the forces that the pencil eraser or ruler exert on the object.

b. Compare the pattern you found with the pattern in Observational Experiment Table 8.1 on page 219 in the textbook (do not forget to watch the video of experiments). Are they similar?

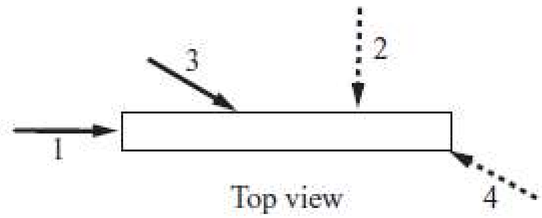
OALG 8.1.2 Observe and explain

Equipment: cardboard shape and a sowing pin.

Use a piece of hard carboard to cut out an irregular shaped object similar to the one in Observational Experiment Table 8.1. Use the same procedure to find the center of mass of your object. Then take a pin and use it to support the object at the center of mass. Did it work? If you are having trouble, read the subsection "Where is the gravitational force exerted on the rigid body" on page 220 in the textbook and repeat the experiment.

OALG 8.1.3 Represent and reason

Imagine that you place a board on your desk and push it in different directions, as illustrated below. Forces 1 and 3 cause the board to slide, and forces 2 and 4 cause it to both slide and rotate. Find the center of mass of the board. What assumptions did you make?



OALG 8.1.4 Read and interrogate

Read and interrogate Section 8.1 in the textbook and answer Review Question 8.1.

OALG 8.1.5 Practice

Answer Questions 1, 2, and 4 on page 243 in the textbook.

8.2 Torque: a new physical quantity

OALG 8.2.1 Observe and find a pattern

Equipment: meter stick, play-dough, a marker, several identical-mass washers (or nuts).

For this experiment, you need a meter stick, or a plank about 1 m long, a marker, play-dough or modeling clay, and several identical-mass washers or nuts.

Place the marker horizontally on the table and secure it in place with some play-dough so it cannot roll. Place the meter stick on top of the marker so that it balances at the 50 cm mark and doesn't touch the surface of the table (if you have a stick, find its center of mass by balancing). Note: If your meter stick doesn't balance at exactly 50 cm, add either a paper clip or some play-dough to a suitable place on the meterstick so that it does. Now, place different numbers of washers (or nuts) to the left and right of the balance point. Figure out where you need to place the washers in order for the system to balance and complete the following table:

Number of washers on the left	**Distance of left washer group from the middle**	**Number of washers on the right**	**Distance of right washer group from the middle**
1	20 cm	1	
1	20 cm	2	
2	30 cm	3	

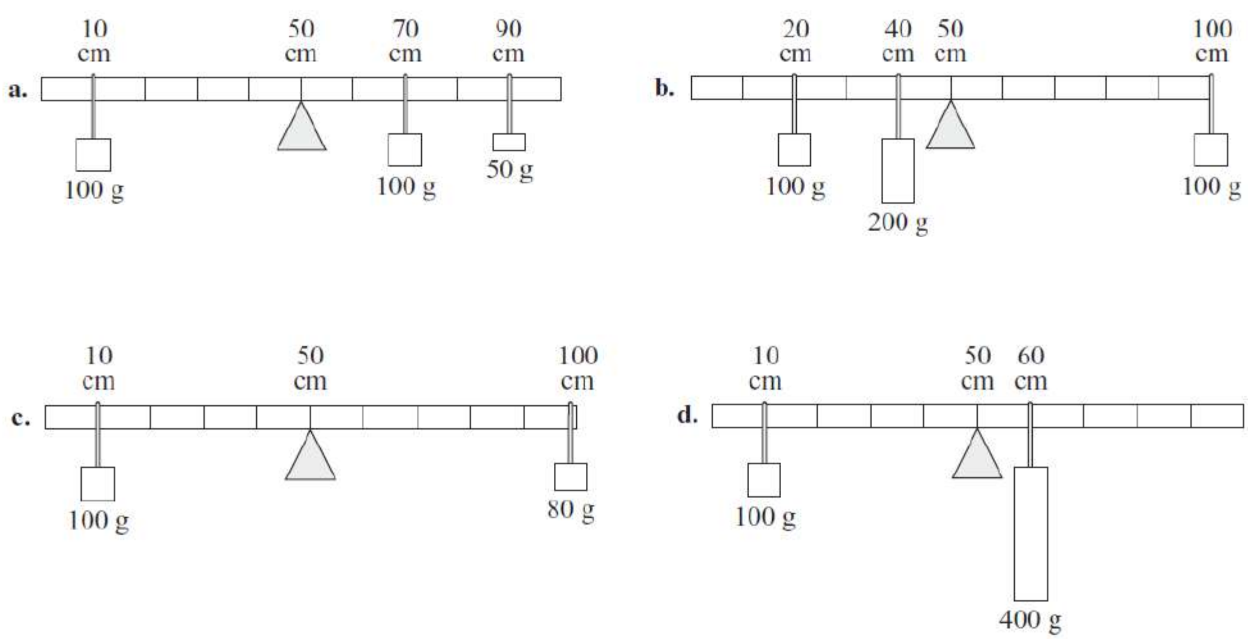
4	30 cm	3	

a. For each situation, draw a picture of the meter stick showing all of the forces exerted on it. In other words, sketch the apparatus and draw an extended-body force diagram for the meter stick, showing forces and points where those forces are exerted on the meter stick.

b. Find a pattern that relates the distances of the washers from the balance point and the magnitudes of the forces the washers exert on the meter stick. What is the relationship between the positions (as measured from the middle) of the left and right groups of washers, and the force that each group exerts on the meterstick?

8.2.3 Observe and find a pattern

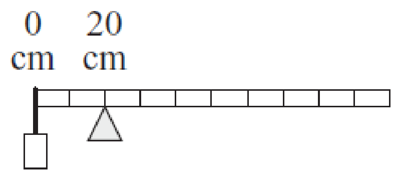
A meter stick is balanced at its center. When you hang blocks with different masses from different positions on the stick, as shown in the illustrations that follow, the stick remains balanced. Draw *all* forces exerted on the stick by these other objects. Remember to include the force exerted by Earth on the stick. Devise a rule to explain this behavior (or extend the rules you developed in the previous activity). Ensure that the rule is compatible with *all* of the experiments.



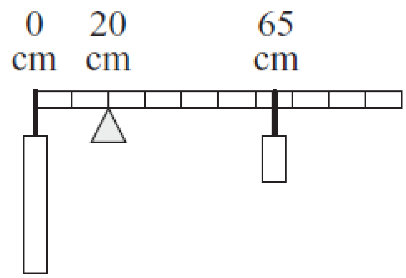
Describe the rule you devised, both in words and mathematically.

8.2.4 Test your idea

A fulcrum supports a uniform meter stick as shown below. The center of mass of the meter stick is at its middle (at the 50 cm mark). Use the rule you developed earlier to predict the mass of the meter stick in the following two experimental illustrations. In each picture, the available objects cause the meter stick to be balanced. Hint: think of how the mass of the meterstick contributes to its balance and how you can model the distribution of the meter stick's mass to explain the balance of the meter stick.



$m_{\text{object}} = 130$ g



$m_{\text{left object}} = 300$ g, $m_{\text{right object}} = 70$ g

OALG 8.2.5 Read and Interrogate

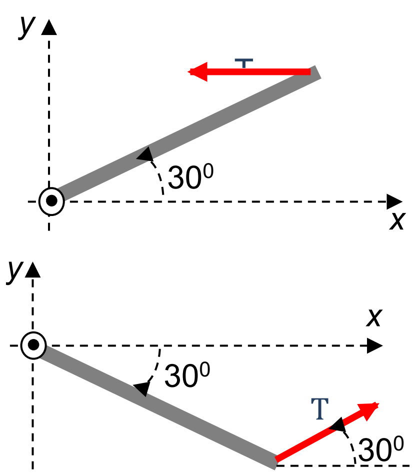
Read and interrogate Section 8.2 on pages 220 – 225.

OALG 8.2.6 Practice

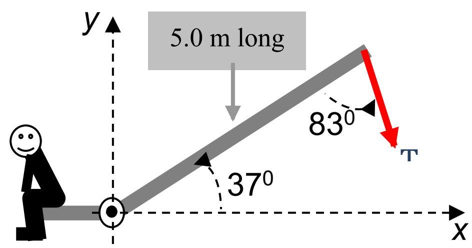
Determine the torque caused by the force described in each case:

a. A rope exerts a 100-N tension force on the end of the 2.0-m long beam shown at the right. Determine the torque caused by this force.

b. A rope exerts a 100-N tension force on the 5.0-m long beam shown at the right. Determine the torque caused by this force.



c. A rope exerts a 100-N tension force on the end of the 5.0-m long beam shown at the right. Determine the torque caused by this force.



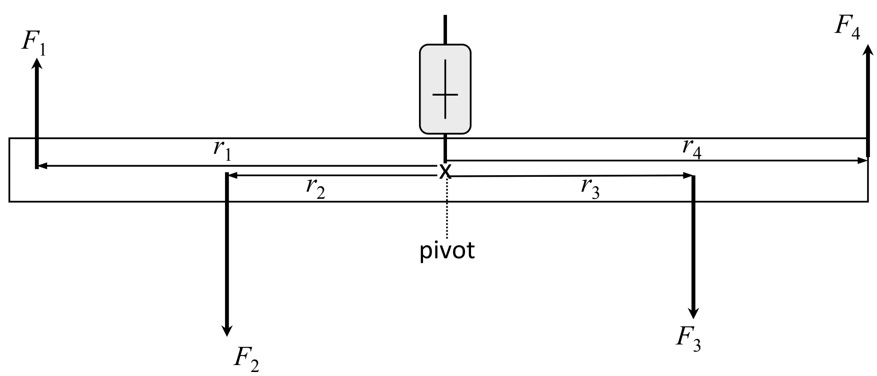
d. Solve problems 1 and 4 on pages 244 - 245 in the textbook.

8.3 Conditions of equilibrium

OALG 8.3.1 Observe and explain

a. Watch this video [https://youtu.be/MV_2BKINOx4] and describe your observations.
b. Use the ideas you developed above and summarized in Section 8.2 in the textbook to explain why the placement of the bob did not matter for the balancing of the board.

OALG 8.3.2 Represent and reason



Four forces are exerted at different points on a meter stick (as shown in the diagram above) that is held up at its center of mass by a spring scale. The meter stick is in static equilibrium (not moving and not rotating). Write a mathematical expression (in terms of F_1 to F_4 and r_1 to r_4) for the rotational condition for static equilibrium about the pivot point shown in the figure. How might you develop a rule about the "direction" of torque and incorporate that into your equation for rotational equilibrium? Once finished, compare your expression to Equation 8.3 on page 228. How are they similar? How are they different?

OALG 8.3.4 Explain

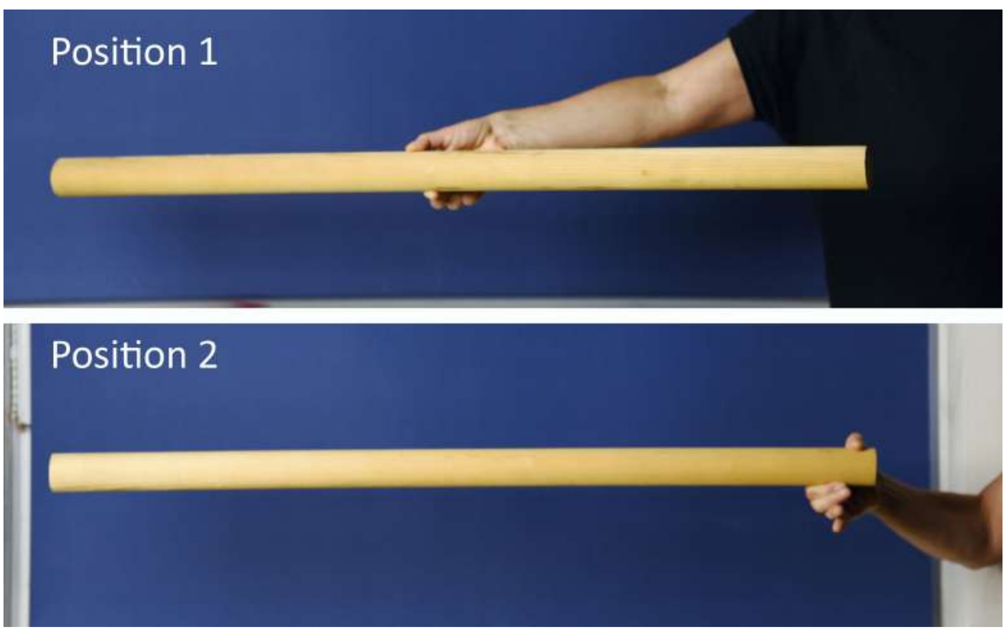
a. Use the patterns and rules that you devised in the previous activities to summarize what you know about the sum of the forces exerted on an object that is in static equilibrium and the sum of the torques caused by these forces. *Note:* Physicists give signs to torques. The torque caused by a force that tends to rotate an object counterclockwise about some pivot point is taken to be a positive torque, and the torque caused by a force that tends to rotate the object clockwise is taken to be negative.

b. Summarize your ideas in the form of two mathematical representations (one for the sum of the forces and one for the sum of the torques) and put them on your whiteboard. Compare your representations with those in Section 8.3 in the textbook.

OALG 8.3.5 Observe and explain

Equipment: a thick stick or plank that is about 1 m to 1.5 m long.

Find a thick stick or a plank that is about 1.0-m to 1.5-m long. Hold the plank in two positions as shown in the photos below.



a. In which position is it more difficult to hold the plank?

b. Draw extended body force diagrams for both situations (the plank is the system). What forces are exerted on the plank? How does the force diagram help explain why it is much more difficult to hold the plank in position 2 than in position 1? Assume that your hand is in contact with the plank at two points where the fingers are touching the plank.

OALG 8.3.5 Read and interrogate

Read and interrogate Section 8.3 and answer Review Question 8.3.

OALG 8.3.6 Practice

Answer Questions 7, 12, and 14 on pages 243-244. Solve Problems 8-10, 16, 17, 21, and 23 on pages 245-246 in the textbook.

8.4 Center of mass

OALG 8.4.1 Design an application experiment

Equipment: meter stick, a small object of known mass, tape.

You have a meter stick (or a plank) of unknown mass and a small object of known mass (about 100 g) that you can fix onto the meterstick and a scale (a kitchen scale). If you have a plank, you need to also have a length measuring device. Design an experiment to determine the mass of the meter stick using your knowledge of static equilibrium.

a. Draw a picture of the experimental set-up.

b. Describe the procedure in words.

c. Apply the concepts of equilibrium to develop mathematical representations that can be used to predict the mass of the meter stick. Then predict its mass using your mathematical representations.

d. Use a scale to measure its mass and compare the result to the predicted value.

e. How can you explain the difference between the predicted and measured value?

OALG 8.4.2 Test an idea

Your friend says that the mass of any object is distributed evenly around its center of mass. Design an experiment to test your friend's idea. You have a meter stick, a set of small objects of different masses, masking tape, and a mass measuring scale. Describe your experiment and predict the outcome based on your friend's idea. Then, conduct the experiment and collect and analyze your data. What can you say about your friend's idea? If you are having trouble, analyze Figure 8.17 on page 233. Also, read and interrogate sub-section "Mass distribution and the center of mass" in Section 8.4 in the textbook.

OALG 8.4.3 Represent and reason

Equipment: bread knife.

You balance a bread knife by laying the flat side across one finger. Where is the center of mass of the knife? How does the mass of the knife on the left side of the balance point compare to the mass of the knife on the right side of the balance point? Exhibit extreme caution when balancing the bread knife. Do not use an extremely sharp one.

OALG 8.4.4 Read and interrogate

Read and interrogate Section 8.4 in the textbook and answer Review Question 8.4.

OALG 8.4.5 Practice

Answer Question 11 on page 244 and solve Problems 27, 29, and 32 on page 246 in the textbook.

8.5 Skills for analyzing situations using equilibrium conditions

OALG 8.5.1 Practice problem solving strategy

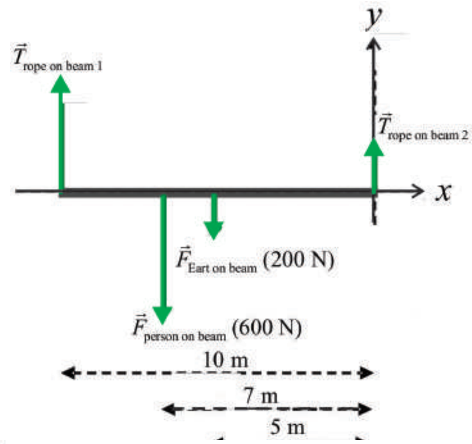
Use the problem solving strategy to solve the following problem, and then compare your solution to the one in Example 8.5 in the textbook. After you have corrected your solution if needed, work on the *Try it yourself* exercise.

Imagine that you are holding a 6.0-kg lead ball in your hand with your arm bent. The ball is 0.35 m from the elbow joint. The biceps muscle attaches to the forearm 0.050 m from the elbow joint and exerts a force on the forearm that allows it to support the ball. The center of mass of the 12-N forearm is 0.16 m from the elbow joint. Estimate the magnitude of (a) the force that the biceps muscle exerts on the forearm and (b) the force that the upper arm exerts on the forearm at the elbow.

Sketch and translate • Construct a labeled sketch of the situation; mark knowns and unknowns. Choose an axis of rotation. • Choose a system for analysis.	
Simplify and diagram • Decide whether you will model the system as a rigid body or as a point-like object. • Construct a force diagram for the system. Include the chosen coordinate system and the axis of rotation (the origin of the coordinate system).	
Represent mathematically • Use the force diagram to apply the conditions of equilibrium.	
Solve and evaluate • Solve the equations for the quantities of interest. • Evaluate the results. Check to see if their magnitudes are reasonable and if they have the correct signs and units. Also see if they have the expected values in limiting cases.	

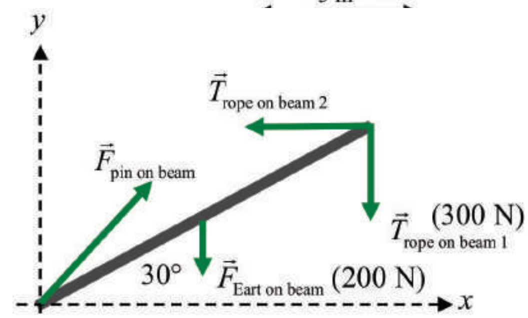
OALG 8.5.2 Represent and reason

A force diagram for a beam is shown at the right. Apply the first and second conditions of equilibrium for this situation and solve for the unknown forces. Draw a picture of a situation that the diagram might describe.



OALG 8.5.3 Represent and reason

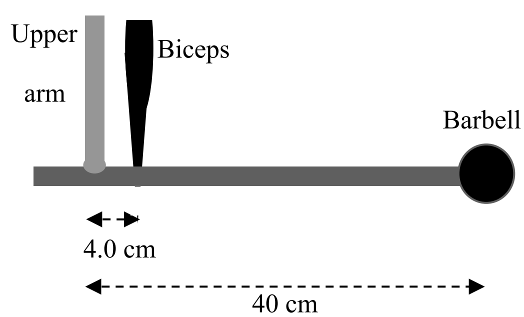
A force diagram for a 2.0-m long uniform beam is shown at the right. Apply the first and second conditions of equilibrium for this situation and solve for the unknown forces. Draw a picture of a situation that the diagram might describe. What assumptions did you make?



OALG 8.5.4 Real-world application

Equipment: a barbell (above 10 lbs) or a heavy book, a meter stick or another length measuring instrument.

a. Lift the barbell by doing a bicep curl. Watch the change of the shape of your bicep. What is the role of the bicep in lifting the barbell? Where is it attached to the arm?

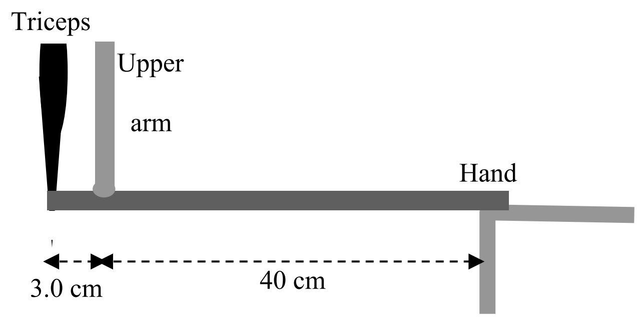


b. Consider the axis of rotation to be in the elbow joint. How far away is the barbell from the axis of rotation? How far is the bicep from the axis of rotation? Estimate the force that the biceps muscle exerts on the forearm holding the barbell. What assumptions did you make in working the problem? If you are having trouble, go back to Example 8.5 in the textbook for help.

OALG 8.5.5 Real-world application

Push down on a table top with your hand as shown in the figure on the right. What do you feel? Which muscles tense: biceps or triceps? Do these muscles pull down or up?

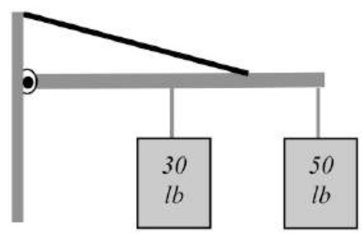
Now, imagine that your hand exerts an 80-N force while pressing down on a table 40 cm from the elbow joint between the upper arm and the lower arm (forearm). Determine the tension in the triceps muscle pulling 3.0 cm from the joint. What assumptions did you make in working the problem? If you need help, consult Figure 8.18 on page 233 in the textbook.



OALG 8.5.6 Real-world application

Read and interrogate the subsection "Lifting from a bent position" on page 236 in the textbook. Then solve the following problem:

The woman at the right is lifting a 30-lb barbell. A mechanical model of her upper body is shown below the photo. The beam is her backbone and the cable is her back muscles (a complex set of muscles in the real back). Earth exerts a 30-lb gravitational force on her upper body at its center of mass. Earth exerts a 50-lb gravitational force on her head, arms, and the barbell at the end of the beam. The back muscle (the cable) connects 0.20 m from the right end of the 0.60 m long beam (the backbone) and makes a 15° angle with the beam. Apply the conditions of equilibrium to the beam and use them to estimate the force that one primary back muscle (it is a complex system) exerts on the backbone and the force that the hinge (joint) exerts on the backbone on the left side. If you are having trouble, consult Example 8.7 on page 236 in the textbook. (Each year more than half a million Americans get serious back problems by lifting this way.)



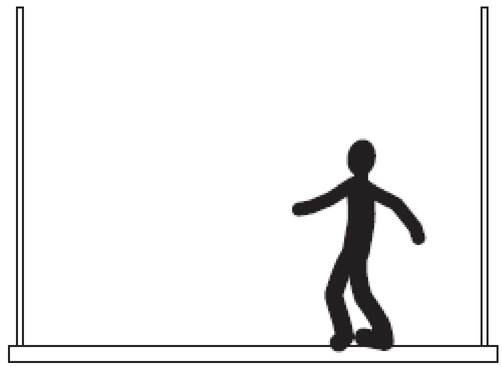
OALG 8.5.7 Equation Jeopardy

The conditions of equilibrium applied to two processes are shown below. Fill in the table that follows using the information in the mathematical representations. Remember that *N* stands for normal force and
N for Newton, the unit of force.

a. Mathematical representations	$+(2.0\text{ N})(0.25\text{ m})+N(0)+(1.0\text{ N})(0)-T_2(0.40\text{ m})=0$ $-(2.0\text{ N})+N-(1.0\text{ N})-T_2=0$		
Determine the unknown quantities in the equations.		**Draw an extended-body force diagram consistent with the equations.**	
Describe a possible situation in words.		**Sketch the situation.**	
b. Mathematical representations	$+F_{\text{pin}}(0)-(2\text{ N})(0.5\text{ m})-(6\text{ N})(1.0\text{ m})+T_1(1.0\text{ m})\sin 37°=0$ x equation: $F_{\text{pin}}\cos\theta-T_1\cos 37°=0$ y equation: $F_{\text{pin}}\sin\theta-(2\text{ N})-(6\text{ N})+T_1\sin 37°=0$		
Determine the unknown quantities in the equations.		**Draw a force diagram consistent with the equations.**	
Describe a possible situation in words.		**Sketch the situation.**	

OALG 8.5.8 Evaluate the solution

The problem: An 800-N painter stands 3.0 m from the right side of a 10.0-m-long beam of a scaffold, which is connected to cables at each end (see the diagram below). The force exerted by Earth on the uniform beam is 200 N. Determine the forces that the cables exert on each end of the beam. Assume that $g = 10\text{N/kg}$.



Proposed solution:

$$+T_{\text{left}}\left(10.0\text{ m}\right)+\left(200\text{ N}\right)\left(5.0\text{ m}\right)+\left(800\text{ N}\right)\left(3.0\text{ m}\right)+T_{\text{right}}\left(0\right)=0$$

$$+T_{\text{left}}=-340\text{ N}$$

$$+T_{\text{left}}+(200\text{ N})+(800\text{ N})+T_{\text{right}}=0$$

$$T_{\text{right}}=-660\text{ N}$$

a. Identify any missing elements or errors in the solution.

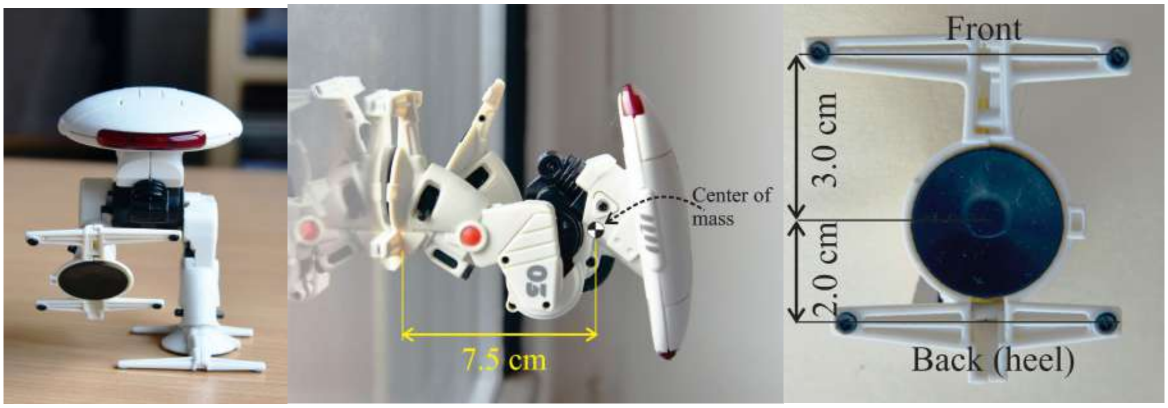
b. Provide a corrected solution if there are errors.

OALG 8.5.9 Regular problem

Any time you have to climb a ladder, you want the ladder to remain in static equilibrium. At what angle should a 60-kg painter place his ladder against the wall in order to climb two-thirds of the way up the ladder and have the ladder remain in static equilibrium? The ladder's mass is 10 kg and its length is 6.0 m. The exterior wall of the house is very smooth, meaning that it exerts a negligible friction force on the ladder. The coefficient of static friction between the floor and the ladder is 0.50.

OALG 8.5.9 Real-world application

Widow climbing robot A 0.150-kg toy robot can climb up a window (see the figures below) using suction cups on its feet. The center of mass of the robot is shown on the photo in the middle, and the details of its foot on the photo on the right.



a. Propose a simplified model of the robot that will allow you to determine the forces that other objects exert on the robot when it is in the position shown on the photo in the middle (the robot is at rest). Draw a sketch of the model. (*Hint*: Note that the robot's right foot is not touching the window; also note that the front part of the left foot is not touching the window; replace the forces exerted on the suction cup with a single force in the center of the cup).

b. Determine the forces that other objects exert on the robot when it is in the position shown on the photo in the middle. Indicate any assumptions that you made.

c. The robot in the middle photo is facing upward. Discuss how the forces exerted on the robot will change if the robot is facing downward and then determine these forces.

d. In which case is it more likely that the suction cups will detach from the window: when the robot is facing up or when it is facing down? Explain.

OALG 8.5.10 Practice

Solve Problems 50-54 and 56-58 on pages 248-249 in the textbook.

8.6 Stability of equilibrium

OALG 8.6.1 Observe and explain

You have probably observed that it is easier to balance and avoid falling while standing in a moving bus or subway train if you spread your feet apart in the direction of motion. By doing this, you are increasing the area of support - the area of contact between an object and the surface it is supported by.

a. Draw force diagrams and consider the torques exerted on two people by the gravitational force and normal forces at their feet when they are on a slowing-down train. Person A is standing with their feet close together and person B is standing with their feet wide apart. If you are having trouble, consult Figure 8.21 on page 238 in the textbook.

b. Who is more likely to fall? Explain.

c. Devise a rule for the stability of equilibrium. Compare your rule to the rule on page 238 in the textbook. Are they the same or different?

OALG 8.6.2 Test your idea

Equipment: box full of crackers.

a. Place a full box of crackers on a flat but rough surface, such as a wooden desk. Its center of mass is at its geometric center. Place the box so that the tall side is upward. Tilt the box a little and release it. Tilt the box at larger and larger angles. Use the rule you developed in Activity 8.6.1 to predict the angle at which the box will tip over.

b. Conduct the experiment and record the outcome. Did it match the prediction?

c. Then remove some crackers from the box and make a new prediction. Conduct the experiment and record the outcome. Did it match the prediction?

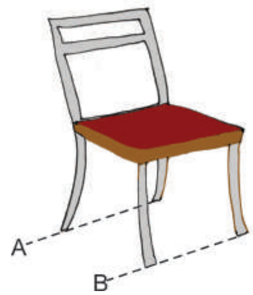
d. What is your conclusion about the conditions for the stability of equilibrium?

e. Compare your finding to those in Testing Experiment Table 8.4 in the textbook on page 238 (do not forget to watch the video). Are they the same or different? Explain.

OALG 8.6.3 Apply your knowledge I

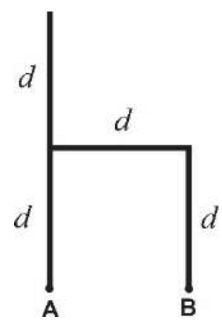
Equipment: chair.

a. Obtain a simple chair (see the figure below) and try to tip it over by slowly tilting it either around axis A or axis B. In which case do you need to tilt the chair at a larger angle to tip it over? Estimate both angles.



b. Explain the outcome of your experiment qualitatively using physics arguments. Put your explanation on a whiteboard.

c. Assume the following simplified model of a chair (the figure below shows a side view). All parts of the chair are made of the same board. Determine the tipping angle for tilting the chair around A and the tipping angle for tilting the chair around B. Put all your diagrams and calculations on a whiteboard.

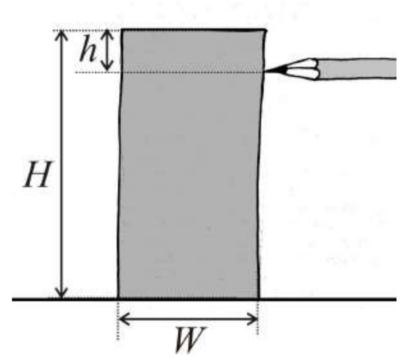


d. Compare the result that you got in **c.** with the outcome of your experiments with the real chair and explain any discrepancies between the two.

OALG 8.6.4 Apply your knowledge II

Equipment: A solid block (such as a wooden block), a pencil.

While searching through the literature for simple experiments that will allow you to determine the coefficient of static friction, you came across the following method:



Using a pencil, exert a force in a horizontal direction on a wooden block (height H, width W) and try to tip the block over. Start at the top of the block and move down in small increments (see the figure on the right and watch the video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-8-6-4]). At some point you will reach a distance h where the block will not tip but rather slide forward. Repeat the procedure several times to determine the distance h where this transition happens, as precisely as possible. The coefficient of static friction between the block and the supporting surface is determined by the following mathematical representation:

$$\mu_s = \frac{W}{2(H-h)}$$

a. Obtain a block and run the experiment described above.

b. Evaluate the mathematical representation given above. Then derive the representation.

c. Why does the result not depend on the mass of the block? Explain.

8.6.4 Read and interrogate

Read and interrogate Section 8.6 in the textbook and answer Review Question 8.6.