Lifting

Introduction
A study of Newton’s Three Laws of Motion might lead one to the conclusion that the only way to move massive objects is to apply massive forces. As anyone who has ever played on a seesaw knows, this is not true. Our last activity, which closely mimics the actions of a seesaw, demonstrates this point. A small force applied to the rigid arm (the meter stick) a long distance away from the pivot lifted a larger object that was positioned much closer to it. The reason, as stated before, is because the torques (the perpendicular force times the distance from the pivot point) due to the two objects are equal in magnitude and opposite in direction when in this configuration.

This system of a long rod resting on a pivot is known as a lever and is an example of a force multiplier (a device that increases the amount of force applied to it). The most common examples of force multipliers are the lever, the inclined plane, the pulley, the wedge, and the screw. Ancient cultures knew of these devices and used them to great advantage, especially in building stunning pieces of architecture such as the Pyramids. The importance of them cannot be overlooked, even today. Though we are a very mechanized society, we still use them, such as when we employ a loading ramp (inclined plane) or in a crane (lever and pulley).

Simple Machines
To see how the lever works, take a different look at the results of the last configuration in the center of mass activity. In that configuration, a 1000 gram mass was placed at 10 centimeters along the meter stick, while a 200 gram mass was placed at 90 centimeters. Depending upon how massive the meter stick that was used was, this gave a center of mass that was about 15 centimeters from the position of the 1000 gram mass and about 65 centimeters from that of the 200 gram mass. Seen in the light of the previous activity, this makes perfect sense, as the larger mass at 10 centimeters moves the center of mass closer to it than the smaller mass at 90 centimeters.

However, another way to look at this is to think about the forces acting upon the individual masses. Gravity is pulling down on both of the masses, as well as that of the meter stick. The large force of gravity down on the larger mass is offset by the force of the meter stick upward at that point in order for them to be in equilibrium. From where is this upward force coming? The meter stick is a rigid object, and forces that are pointed down on the right side of the pivot point will result in an upward force on the left side of the pivot. A small fraction of the upward force is from the differences in the mass of the meter stick on opposite sides of the pivot point, i.e. the center of mass of the meter stick is to the right of the pivot point. The larger fraction of the upward force, though, is due to the force of gravity on the 200 gram mass. While this force is 1/5 of that on the 1000 gram mass, the fact that it is being applied so far from the pivot point allows it to offset the larger force on the larger mass which is closer to the pivot point.

This is the same thing as stating that the torques that the two masses are applying to the meter stick about the pivot point are about equal (remember the torque due to the weight of the meter stick). The torque on an object is due to forces that are applied perpendicular to a line that goes through the point
about which the object will pivot. If the object is freely floating, the natural pivot point would be the center of mass. For objects that are attached to other objects, the pivot point could be one of an infinite number of points. In our example in Figure 1, it is the pivot support (in blue) of the meter stick. The magnitude of the torque on an object is equal to the magnitude of the perpendicular force times the distance from the point at which the force is applied to the pivot point. Thus, in our example, the torque due to the larger mass is

\[ m_1gR_1 = (1 \text{ kg})(9.8 \text{ m/s}^2) R_1 \]

while the torque due to the smaller mass is

\[ m_2gR_2 = (.2 \text{ kg})(9.8 \text{ m/s}^2) R_2 \]

Since the torque depends upon on the length of the distance between the applied force and the pivot point, it is easy to see that one does not necessarily need a massive force in order to create a massive torque. One can generate large torques using small forces, as long as the distance is large. And with a large torque, one can move massive objects, as our last activity showed. This is a reason why the lever is called a simple machine, as it is a non-mechanized device that can greatly increase the force output by a human. As Archimedes once boasted, all that he needed was a firm place to stand and a lever long enough, and he could move the world.

**Biological Systems**

To find examples of levers in everyday life, we need look no further than the inside of our own bodies. Every diarthrotic (movable) joint in the body is operated by the lever action of a muscle pulling against a pivot. Figure 2 shows a simplified diagram of a human arm that is lifting a cube. The humerus bone is represented by the vertical line, while the radius and ulna are shown as the horizontal line. The bicep muscle is represented by strands of lines that attach to the humerus bone and the forearm across the elbow. Note that this setup forms a lever, with the elbow as the pivot point and the point at which the bicep tendon attaches to the forearm as the defining point for the lever arm. In the diagram, the distance of the lever arm is 4 cm. This lever is used to lift objects placed in the hand (as well as the entire forearm).

As a force multiplier, this lever is very poor, as the ratio of forces is less than one. Since the lever arm is so short, the amount of weight that can be lifted by the hand is much smaller than the force that must be supplied by the muscle. For example, if the object that is being lifted is 32 cm from the elbow joint, then the bicep muscle will have to apply 8 times more force to move the object than it would if no lever was involved.

At first glance, this would seem to be rather inefficient. However, consider what is taking place. In the first place, the distance that the muscle must contract in order to move the weight is much smaller than it would normally be. With this 1:8 ratio of distances, the bicep would only have to contract 1 centimeter in order to lift the cube 8 centimeters. If we were to reverse the situation so that there was more mechanical advantage (ex. 1 N of force from the bicep would lift 8 N of cube), then the bicep would have to contract 8
centimeters in order to lift the cube 1 centimeter. This would require a very different type of muscle tissue in order to operate over such a wide range of distances.

Another point to consider is the speed with which the object can be moved. In the same amount of time that the muscle is contracting a short distance, the cube is being moved a large distance. Thus, the speed of the cube will be 8 times what that of the muscle is. This ability to magnify the speed of the arm is very important, especially for performing tasks like throwing or deflecting objects.

**Activity**

In this capstone activity, we will investigate how the bicep muscle works to lift objects held in the hand. We will do this using a simplified model of the arm as shown in Figure 3. This model consists of a rod attached to a pivot that will mimic the elbow joint. A string attached to the rod near the pivot goes up over the pulley, where weights can be hung from the other end. This string models the bicep muscle that is attached to the lower arm near the elbow. At the far end of the rod are slots for attaching masses that will mimic an object being held in the hand. If we ignore other forces in the system (assume they are small), then we should find that

\[ F_d t = F_p d_p \]

Since the forces at the “tendon” and the “hand” are being provided by gravity, this means that

\[ m_g d_t = m_p g d_p \quad \text{or} \quad m_t d_t = m_p d_p \]

With this equipment, we will study the amount of force that is required by the bicep to hold the arm at a 90° angle when a weight is held in the hand. The procedure for doing this is as follows:

1. Set up the equipment as in Figure 3 and secure the necessary masses to hang on the “arm”
2. With a ruler or meter stick and a volunteer from your group, measure the distance from the middle of the elbow joint to the bicep tendon of insertion while the volunteer’s arm is at a 90° angle. Then measure from the middle of the elbow joint to the middle of the palm. Record these measurements on the activity sheet.
3. Attach the string at a distance from the pivot point that is equal to the distance from the elbow to the tendon. Attach mass hanger at a distance from the pivot equal to the distance from the elbow to the palm.
4. Place a total mass (hanger plus mass) equal to 50 grams at the “palm” location.
5. With the string run over the pulley and attached to a mass hanger, begin adding mass to the holder until the rod becomes horizontal. Record this mass on the activity sheet.
6. Increase the total mass at the "palm" location to 100 grams. Repeat step 5.
7. Continue adding 50 grams at a time until you have reached 250 grams at the palm location.
8. Calculate the theoretical masses that should be required with each 50 gram increment and record these on the activity sheet. Calculate the percent difference.
9. Answer the questions on the activity sheet.
Distance from elbow to tendon = \( d_t = \) _________________ cm

Distance from elbow to palm = \( d_p = \) _________________ cm

<table>
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<th>No.</th>
<th>( m_p )</th>
<th>Meas. ( m_t )</th>
<th>Theor. ( m_t )</th>
<th>% Difference</th>
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<tr>
<td>5</td>
<td>250 gm</td>
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1. How close is your measured “tendon” mass to the theoretical value? What are the possible sources of systematic errors that could explain the differences that you see?

2. What would be the advantage of having the insertion point of the tendon closer to the elbow joint? What would be the advantage of having it further away? (Try doing this on the model to see if your answers are correct)