

# General Physics Lab 8

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## Static Equilibrium

### Objectives:

- To test the hypothesis that a body in static equilibrium is subject to zero net torque.

### Equipment:

- Wooden Ruler
- Scotch Tape
- Duct Tape
- Spring Balance
- Thread
- Cardstock Triangle
- Measuring Tape
- Protractor
- At least 50 Pennies

### Physical Principles:

#### Two Conditions of Static Equilibrium

The 1<sup>st</sup> Condition of Static Equilibrium is that the vector sum of forces acting on an object must be zero. In 2-D, this becomes,

$$\sum F_x = 0 \quad \text{and} \quad \sum F_y = 0 \quad (1)$$

This condition prevents linear accelerations, either vertically or horizontally.

The 2<sup>nd</sup> Condition prevents rotations and insists that the vector sum of torques acting on an object about any point must be zero, such that,

$$\sum \tau = 0 \quad (2)$$

where torque is defined by,

$$\tau = Fr \sin(\theta) \quad (3)$$

with  $r$  being the distance along the lever arm from the point of rotation to where the force is applied, and  $\theta$  being the angle between the applied force,  $F$ , and the lever arm,  $r$ . By convention, counterclockwise torques are considered positive and clockwise torques are considered negative.

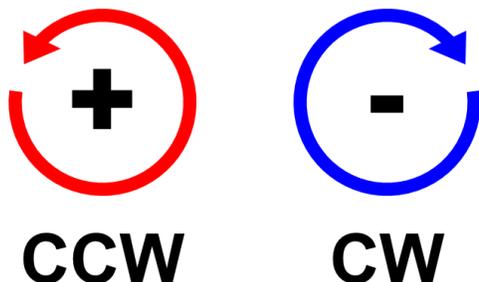


Fig. 1: Torque Sign Convention  
Torque that tries to rotate an object counterclockwise is considered positive.  
Torque that tries to rotate an object clockwise is considered negative.

## Procedure:

### Setup

1. Measure the entire length,  $L$ , of the wooden ruler in meters, including any of the ruler that extends past the end markings (see Fig. 2). Record this in your eJournal.
2. Divide the length,  $L$ , by 2 to find the center of gravity of the ruler. Record this distance,  $x_{cg}$ , in your eJournal. Note that this assumes a uniform density throughout the ruler and no holes in it. While these factors will shift the center of gravity a very small amount, the effect is negligible.

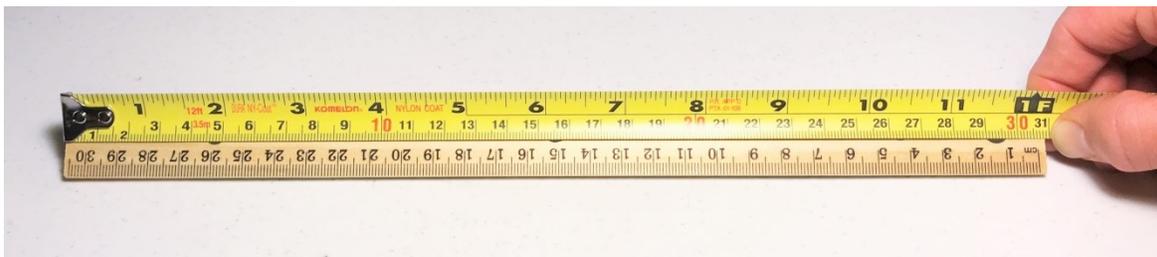


Fig. 2: Measure the full length of the ruler, including any parts that extend past the markings. You can make this measurement with a measuring tape or a longer ruler if you have one.

3. Cut a length of thread about 30-40 cm in length and tie a loop knot on one end (see Fig. 3a).
4. Tear off a 15 cm long half-width strip of duct tape, and tape the other (un-knotted) end of the thread to the 30 cm end of the ruler as shown in Fig. 3.

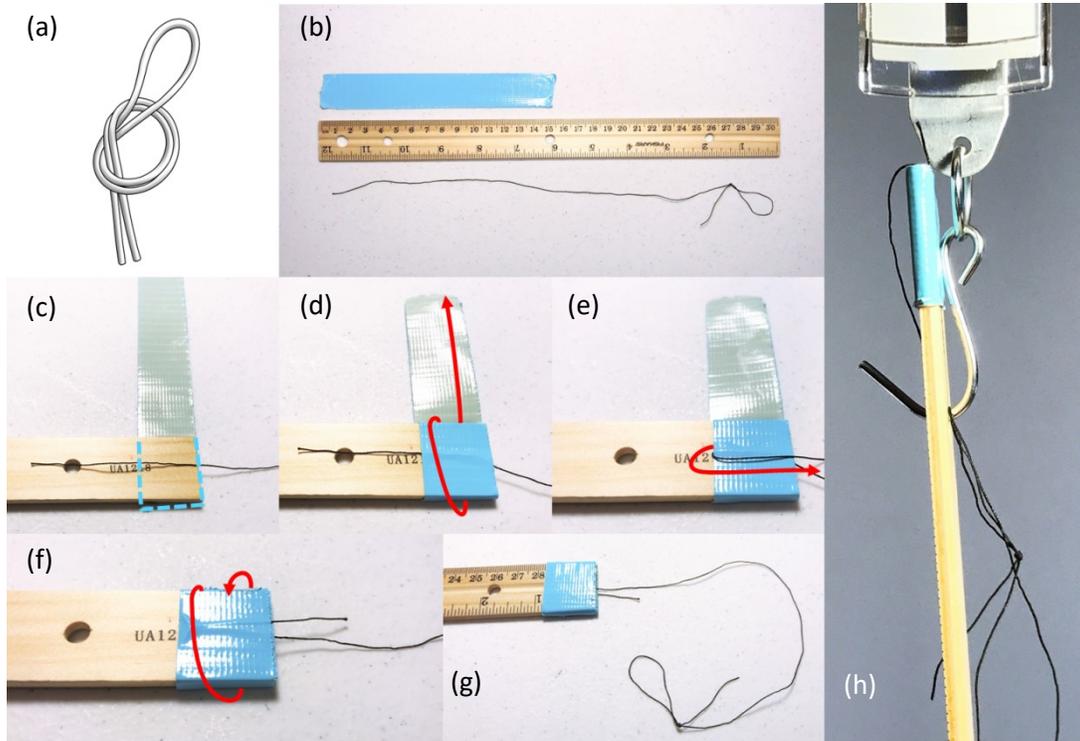


Fig. 3: (a, b) Tie an overhand loop knot at one end of the thread. (c, d) Tape the unknotted thread end to the back side of the ruler at the 30 cm end. (e, f, g) Fold the thread back on itself over the tape and wrap the tape around it again to keep the thread from slipping out. (h) Zero the spring balance and weigh the ruler.

5. Hang the spring balance by the top hook and zero it.
6. Hang the wooden ruler on the spring balance and record its mass in kg (see Fig. 3h). If your ruler does not have holes in it, you can hang it by the thread loop.
7. For the weights on the ruler, you will use some of the penny stacks from the previous labs. For this experiment, you will need 5-7 stacks of pennies (see Fig. 4a).
8. Weigh each stack on the spring balance as shown in Fig. 4b, using a piece of Scotch tape to attach the stack to the hook. It may be useful if you write the mass on each stack as you measure them. They should all be about the same but some could deviate a little.
9. Group the stacks and place the groups at any two locations along the ruler, except the middle or the ends (see Fig. 4c).

Note: While you can place the penny stacks anywhere along the ruler (other than the middle or ends), you may be able to reduce the experimental error if you place more of the weight farther from the point of rotation (closer to the 30 cm end). If the distance is larger, any small measurement error in the distance will have a smaller effect on the overall error. Likewise, small errors in the force measurement will have a smaller effect due to the larger force exerted on the spring balance. Both of these factors combine to help reduce the experimental error.

10. Tape the stacks of pennies to the ruler and record their masses,  $m_1$  and  $m_2$ , in kg and their positions,  $x_1$  and  $x_2$  in meters. The mass of each group is the sum of the individual masses for that group (see Fig. 4c). The position for each group is the distance from the 0 cm end of the ruler to the center position between the stacks in the group. In order to include any unmarked length past the 0 cm mark, use the measuring tape measure the distance from the end of the ruler to the center of the weights (see Fig. 4d).



Fig. 4: (a) Set aside 5-7 stacks of pennies (10 pennies in each stack). (b) Measure the individual masses of each stack on the spring balance, and (c) tape them on 2 locations along the ruler. The mass of each group is the total mass of all the stacks in the group. (d) The position of each group is the distance from the 0 cm end of the ruler to the center of the group.

11. Use a protractor to verify the angle of the cardstock triangle. The angle from the vertical dashed line is nominally  $60^\circ$  which means its complementary angle should be  $30^\circ$  (see Fig. 5a). If the angle is not  $30^\circ$ , use the measured angle instead of  $30^\circ$  for your calculations.
12. Use small pieces of Scotch tape to attach the cardstock triangle to the 30 cm end of the ruler. Position it so that its base extends past the end a small amount (about 0.5 cm) so that the thread coming up from the bottom edge of the ruler will line up close to the angled edge of the triangle. Tape it on both sides so it can stand upright (see Fig. 5b). This will help you align the angle of the spring balance.
13. Support the 0 cm end of the ruler on a thick book or other short ledge and tape it down so it will not slide off (see Fig. 5c). Try to position it as close to the edge as possible so it can pivot around the very end of the ruler.

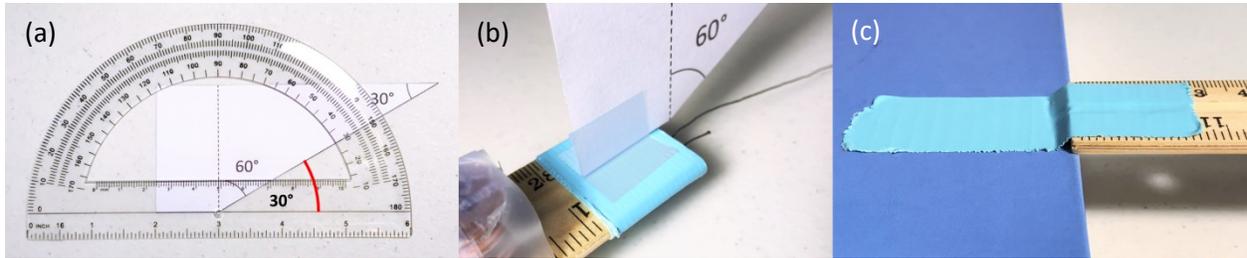


Fig. 5: (a) On the cardstock triangle, measure the complementary angle to the labeled  $60^\circ$  angle. (b) Tape the cardstock triangle to the 30 cm end of the ruler so that the base of it extends past the end of the ruler. (c) Support the 0 cm end of the ruler on a thick book or ledge with only the very end of the ruler supported. Add some tape too keep it from sliding off.

### Force Measurement at $90^\circ$

1. Connect the vertically zeroed spring balance hook to the thread loop at the 30 cm end and lift it up so that the ruler is level (horizontal) and the thread and spring balance are perpendicular to the ruler (see Fig. 6a).
2. Adjust the spring balance angle until the thread is parallel to the vertical dashed line on the triangle card.
3. Read the force in Newtons from the spring balance and record it in your eJournal.

### Force Measurement at $30^\circ$

1. Keep the ruler level and pull the spring balance out at an angle until the thread is at the same angle as the edge of the triangle card (see Fig. 6b).
2. Read the force in Newtons from the spring balance and record it in your eJournal.

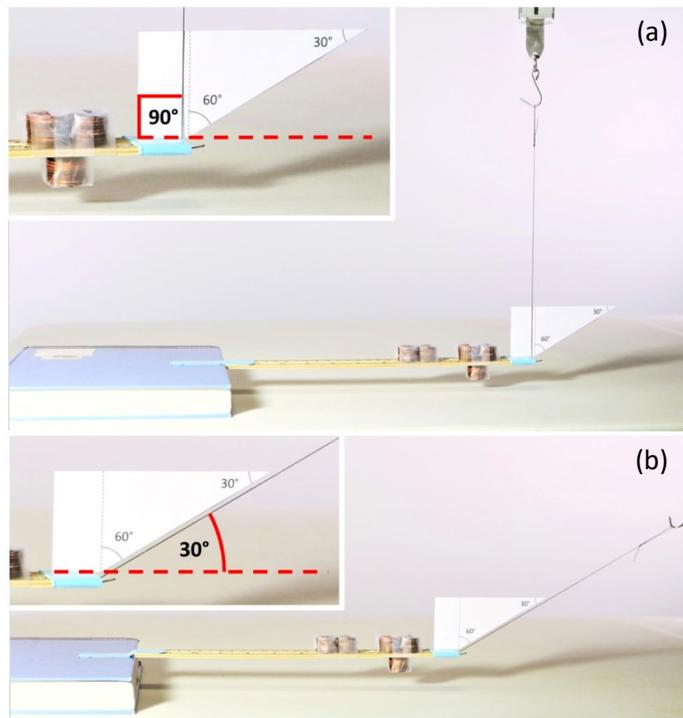


Fig. 6: Horizontal ruler loaded with stacks of pennies. The ruler is supported on the right by the edge of a book and suspended on the left by a spring balance. (a) All forces act at  $90^\circ$  to the beam. (b) Spring balance force acts at  $30^\circ$  to the beam.

## Analysis:

### Torque from Perpendicular Forces Acting on a Horizontal Beam

A free-body diagram of the beam displays the presence of five vertical forces.

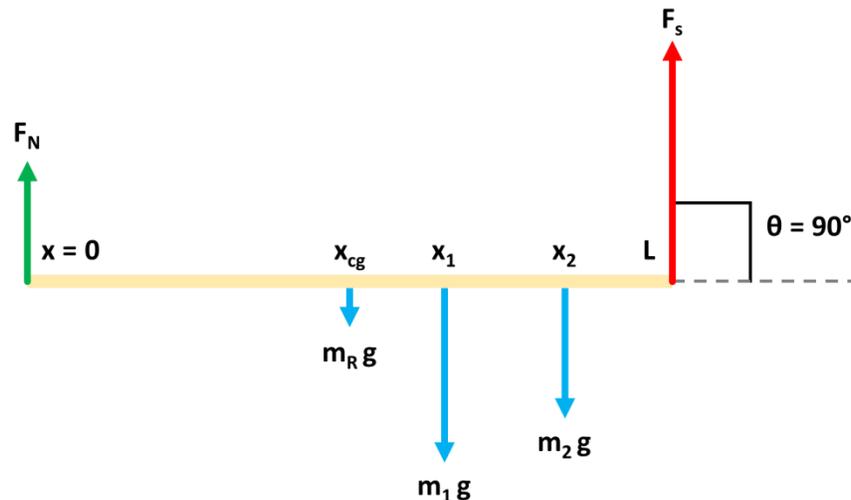


Fig. 7: Free body diagram with perpendicular forces acting on a beam.

1. Compute each torque about the point  $x = 0$  using Eq. (3) – where the angle between the force and lever arm is consistently  $90^\circ$ . Pay special attention to whether the torque is clockwise (-) or counterclockwise (+). Note that  $F_N$  does not exert any torque around the point  $x = 0$  because its distance from that point is zero.
2. Sum all of the counterclockwise torques and all of the clockwise torques separately.
3. Add the CCW and CW torques together to determine if the net torque about the point  $x = 0$  is zero (see Eq. 2). Remember that the CW torque is negative.
4. Check how close the sum of the torques is to zero by finding a percent difference between the magnitudes of the CW torques and the CCW torques, since they should be equivalent in magnitude but opposite in direction.

$$\%Diff = \frac{||CCW \tau| - |CW \tau||}{|CCW \tau|} \times 100\% \quad (4)$$

## Torque from Non-Perpendicular Forces Acting on a Horizontal Beam

For the case of the non-perpendicular force acting on the beam, the free-body diagram displays the presence of four vertical forces and one force angled at some angle,  $\theta$ . As before, you will compute the torques and check to see whether they sum to zero.

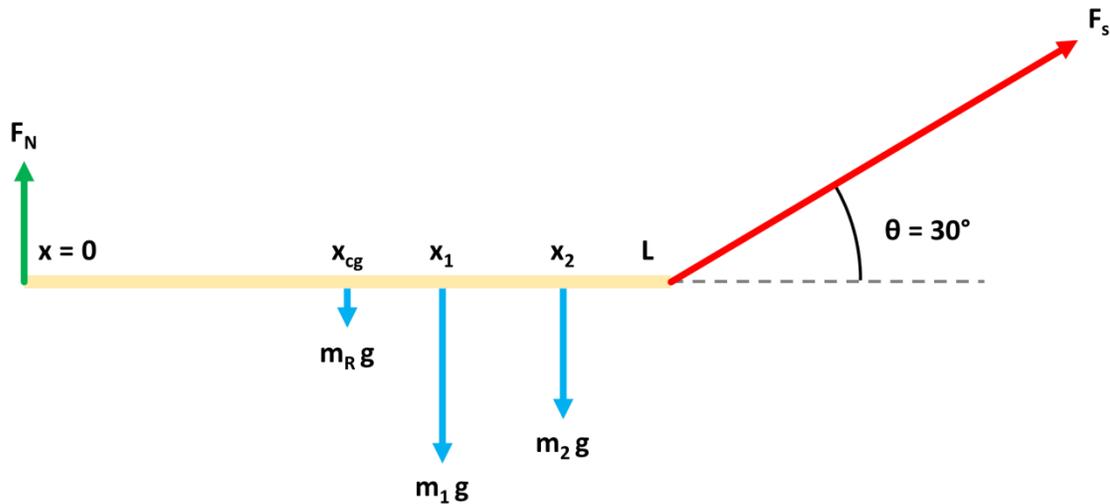


Fig. 8: Free body diagram with a non-perpendicular force acting on a beam.

1. Compute each torque about the point  $x = 0$  using Eq. (3) – where the angle between  $F_s$  and the lever arm is  $30^\circ$  (or if your angle was different, use that instead). Pay special attention to whether the torque is clockwise (-) or counterclockwise (+). Note that  $F_N$  does not exert any torque around the point  $x = 0$  because its distance from that point is zero.
2. Sum all of the counterclockwise torques and all of the clockwise torques separately.
3. Add the CCW and CW torques together to determine if the net torque about the point  $x = 0$  is zero (see Eq. 2). Remember that the CW torque is negative.
4. Check how close the sum of the torques is to zero by finding a percent difference between the magnitudes of the CW torques and the CCW torques, since they should be equivalent in magnitude but opposite in direction. Refer to Eq. (4).