Name________________________________ Date_________________

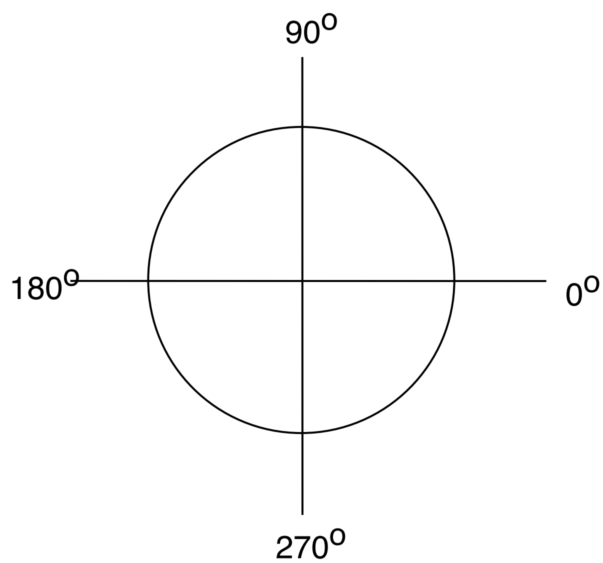
Pre-Lab Preparation Sheet for Lab 11:

EQUILIBRIUM

(*Due at the beginning of Lab 11*)

Directions:
Unless told by your lab instructor, complete this lab in groups of **two students.** Review these lab procedures and answer these basic questions before coming to lab.

1. Using a protractor, a ruler and the instructions described in Activity 1-1, draw the force vectors that would correspond to a 100g mass hung at 115° and a 150g hung at 210°.



2. What value for the acceleration due to gravity near the surface of the earth will you use in this lab?

3. What is the scale that will be used in this lab for drawing force vectors?

4. If an object is in translational equilibrium, what can we say about it?

5. If an object is in rotational equilibrium, what can we say about it?

Name_________________________________Date_____________________Partners________________________________

LAB 11: EQUILIBRIUM

OBJECTIVES

- To compare the algebraic and graphical methods of representing translational equilibrium
- To determine what constitutes static translational equilibrium
- To determine what constitutes static rotational equilibrium
- See how rotational and translational equilibrium can be related.

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INVESTIGATION 1: TRANSLATIONAL EQUILIBRIUM

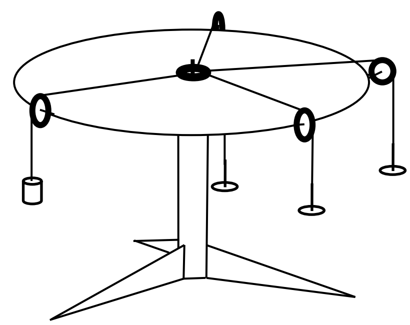


Figure 1: The force table

An object is said to be in *translational equilibrium* when the forces on it add up to zero ($\Sigma\vec{F} = 0$). In this investigation, we will look at the special case of *static translational equilibrium*, where both the acceleration and the velocity are zero, that is the object remains in one position. You will use the horizontal "force tables" shown in Fig. 1 to apply various forces in various directions on a ring centered on top of the table. The trick will be to apply the forces in such a way that the ring will remain in place when the pin is removed for each of the given scenarios. In short, after pulling out the pin, you should be able to reinsert the pin through the center hole of the ring without having to adjust the ring.

You will need the following:

- Horizontal force table
- 4 low friction pulleys
- 1 hanging mass (100 g) and 3 mass hangers (5 g each)
- Slotted masses (1 g, 2 g, 5 g, 10 g, 20 g, and 50 g), several of each
- 1 protractor

Activity 1-1: Translational Equilibrium

In this investigation, you will investigate how to maintain static equilibrium with more than two forces. On the next page, you will be given five different situations in which you will need to add some appropriate mass at some appropriate location to restore static equilibrium.

As an example of how to complete the sketches, suppose you have 1.00 N directed along the 0˚ line, 0.50 N directed along the 135° line and 2.00 N directed along the 240° line. (Incidentally, the numbers used in this example will NOT keep the ring in static equilibrium. They are only being used to illustrate how to sketch the force vectors that you will be finding in each of the scenarios below.) Using the scale of 1.0 cm = 0.50 N, you would then draw a 2.0 cm arrow along the 0° line, a 1.0 cm arrow along the 135° line and a 4.0 cm arrow along the 240° line as shown in Fig.2 below.

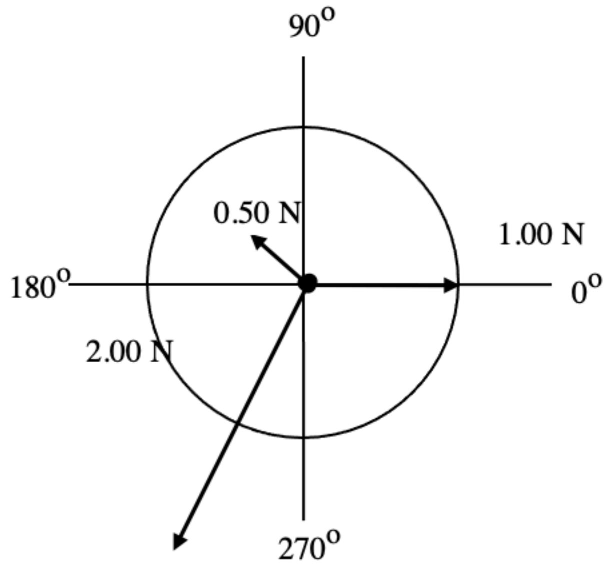


Fig 2: Example of how to sketch the force vectors in the grid.

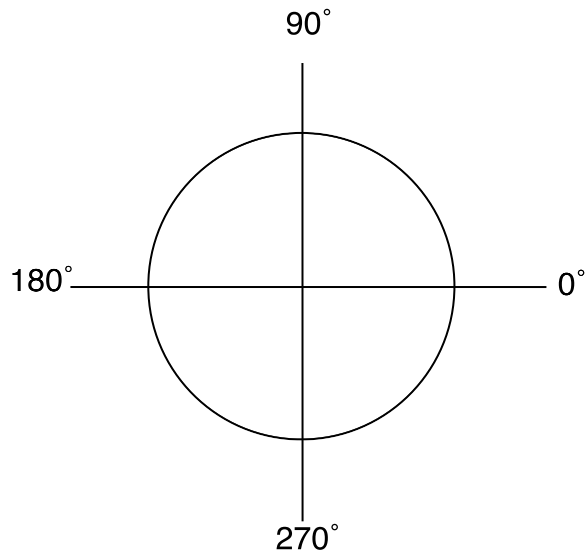
1. In each of the following situations, start with 100 g hanging from the 0° mark. *For ease of calculation, you may use $g=10m/sec^2$ in all parts of this lab*.
2. Experimentally determine the mass(es) and/or location(s) required to restore static equilibrium.
3. After you establish static equilibrium, record the mass(es) and the corresponding force(s) for that mass as well as the location(s).
4. Below each situation is an overhead view of the force table. Carefully sketch all the forces acting on the ring for that situation by drawing the force vectors for each hanging mass by using the following scale: A 1.0 cm long arrow corresponds to a 0.5 N force. (If you had 1.0 N pulling along the 0° line, you would draw an arrow 2.0 cm long pointing to the right as shown here: →)
5. Use the ruler to accurately measure the proper length for each vector and the protractor to accurately sketch the direction of each force.

Note: In the **Homework Questions**, you will be asked to graphically "add" the force vectors for each scenario in a "head-to-tail" fashion. To make interpretation of your results easier, the vectors you sketch need to accurately reflect the relative magnitudes **and** direction of the forces acting on the ring. Be sure to use a protractor and straightedge when making your sketches.

A. With a pulley at 90° and another at 210°, what masses are required to hold the ring in static equilibrium (fixed position) when 100 g hangs from the 0° mark?

Place ________ g at 90° and _________ g at 210° to restore equilibrium.

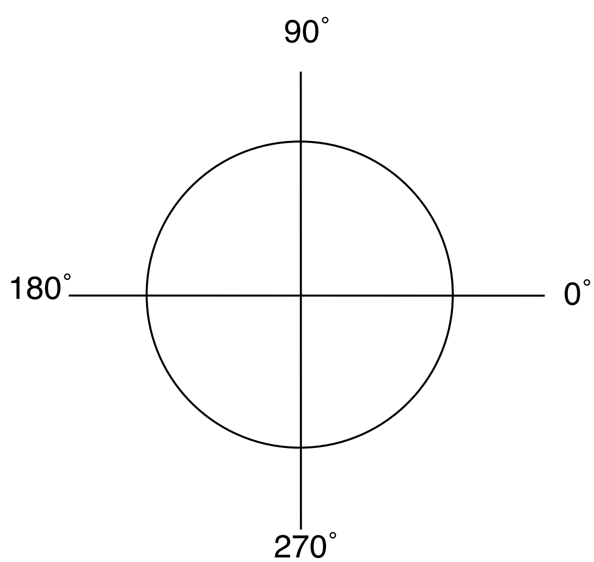
These correspond to _________ N acting at 90° and _________ N acting at 210°.



B. With a pulley at 120° and another at 240°, what masses are required to hold the ring in static equilibrium when 100 g hangs from the 0° mark?

Place ________ g at 120° and ________ g at 240° to restore equilibrium.

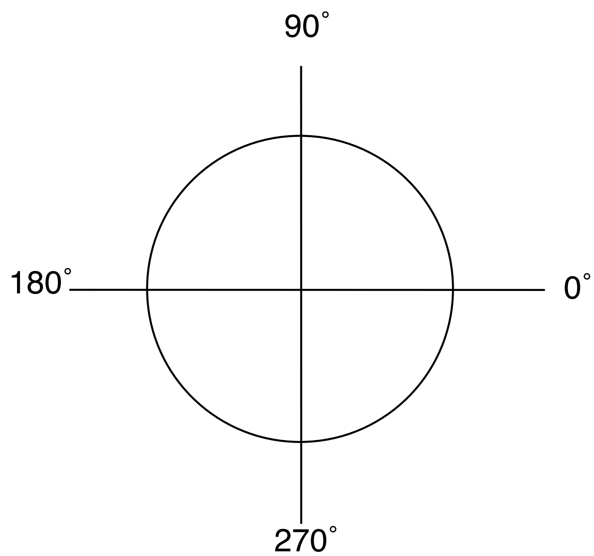
These correspond to _________ N acting at 120° and ________ N acting at 240°.



C. With a pulley at 105° and another at 210°, what masses are required to hold the ring in static equilibrium when 100 g hangs from the 0° mark?

Place ________ g at 105° and ________ g at 210° to restore equilibrium.

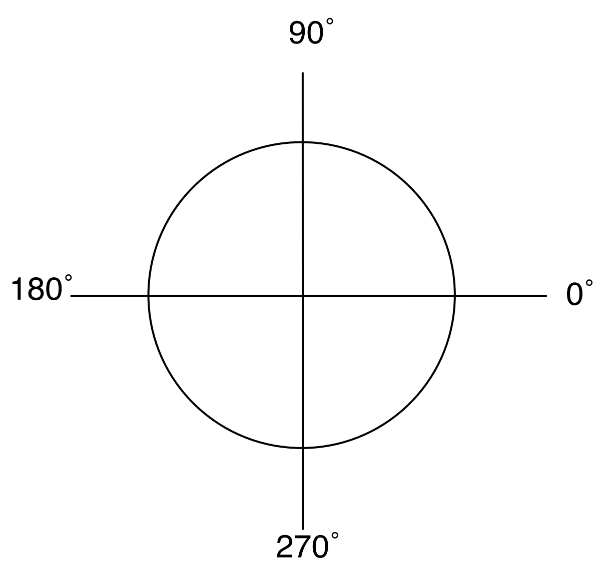
These correspond to ______ N acting at 105° and _________ N acting at 210°.



D. With 100 g still fixed at the 0° mark and 50 g hanging at the 75° mark, find the mass and location needed to hold the ring in static equilibrium? (Hint: This task can be done most easily if you find the location first by holding the third string in your hand and adjusting your pull appropriately until the correct location has been found. Once the location is known, put a pulley at that location and then adjust the mass to find the force needed to restore static equilibrium.)

Place ________ g at the ________° mark to restore equilibrium.

This corresponds to a force of ______N acting at the _____° mark.



E. With 100 g still fixed at the 0° mark and 130 g hanging at the 60° mark, choose <u>any</u> value for a third mass. Record your choice:

A third mass of ______ g is chosen.

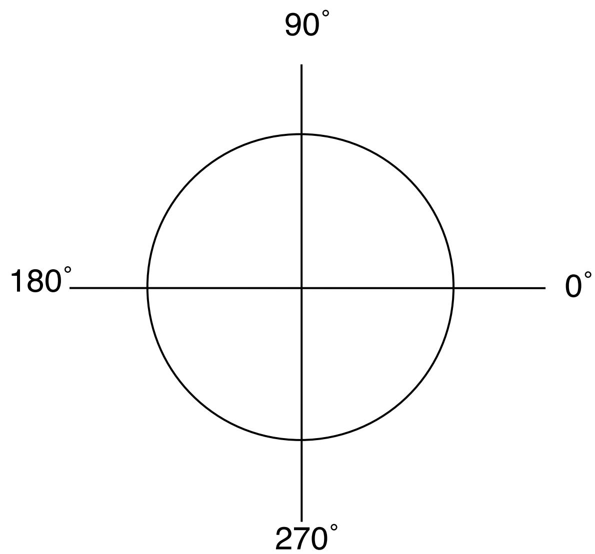
This corresponds to a force of _____N.

Place your third mass at the 270° mark and then find the size of a <u>fourth</u> <u>mass</u> and the location where it is needed to restore static equilibrium. (You can employ the same hint as provided in Situation D above.)

Place a fourth mass of ____ g at the ____° mark to restore equilibrium.

This corresponds to a force of _____N acting at the ______° mark.

Sketch your force vectors in the diagram below.



Question 1-1: If you had the freedom to choose the value and the location of the third mass in Situation E above, what would have been the easiest choice to make? Why?

INVESTIGATION 2: ROTATIONAL EQUILIBRIUM

In this investigation you will explore principles of balance by hanging various masses in different locations along a meter stick. There are three main parts to this investigation. The first part involves placing the pivot at the center-of-mass of the meter stick. The third part involves an "off-center" placement of the pivot. In each part, by hanging various masses at various locations you will produce torques about the pivot. The object is to balance the meter stick and computer the torques involved on each side of the fulcrum for each case.

You will need the following:

- 1 meter stick
- 1 set of standard gram masses
- 1 pivot stand with pivot
- 4 mass hangers
- 1 pan balance or electronic balance

Activity 2-1: Pivot at Center of Mass

Prediction 2-1: Where would you expect to position the pivot for the lone meter stick to balance on its own when placed on the pivot stand?

1. Using the meter stick, pivot stand and pivot, assemble a "see-saw" and adjust the pivot so that the meter stick alone balances horizontally. Position the pivot on the meter stick so the tabs of the pivot are toward the upper edge of the meter stick when the centimeter numbers are upright as shown in Fig. 1. This will allow the stick to balance easily and allow you to read the positions on the meter stick.

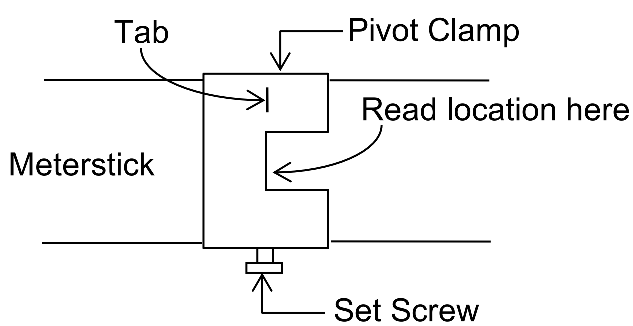


Fig. 1: How the pivot fits on the meterstick.

Question 2-1: Is the pivot located exactly where you predicted (to the nearest millimeter?) If not, where did you have to place the pivot? Why do you think this is so?

The position of the pivot (or *fulcrum*) where the lone meter stick balances is called the *center-of-mass* (abbreviated CM) of the meter stick.

2. Start by placing the 200 g mass 20 cm to the right of the fulcrum by hanging the mass from a hanger and positioning the hanger on the meter stick.

Prediction 2-2: With the 200 g already hanging on the stick, at what location on the meter stick would you expect to place a 100 g mass for the meter stick to balance? How far away from the fulcrum is this position?

3. Test your prediction by hanging the 100 g mass on the meter stick in such a way that the meter stick is in balance, as shown in Fig. 2 below.

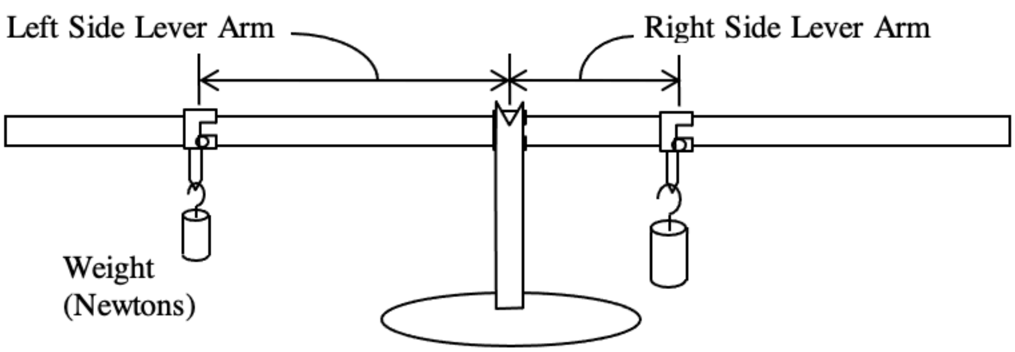


Fig. 2: Balanced meter stick

Question 2-2: Is the 100 g mass located exactly where you predicted (to the nearest mm)? If not, now far from the fulcrum did you have to place the 100 g mass? Why do you think this is so?

Question 2-3: Did you consider the masses of the hangers that clamp the standard masses to the meter stick? Do you think it matters?

4. If you did not take the mass hangers into account, measure the masses of the mass hangers and include them in your total mass measurement. In the data tables that follow, you should record the <u>total mass</u> (including the hangers). Use the data from above for Trial 1 in Table 1. Enter the masses in kilograms.

5. Calculate the weight of the mass in Newtons and record in Table 1. Recall that Weight = mg. (To get the force in Newtons, convert your mass to kilograms. Take $g = 10\ m/s^2$.)

6. For the remaining trials, choose different masses to place at various locations on each side and record those masses in Table 1. Do not forget to include the masses of the hangers! Arrange the positions of the masses so that the meter stick will be in balance.

7. Record the distance that each mass hangs from the fulcrum. These are the *lever arms* on each side.

Trial	Left Side Total Mass (kg)	Left Side Force (N)	Left Side Lever Arm (m)	Right Side Total Mass (kg)	Right Side Force (N)	Right Side Lever Arm (m)
1						
2						
3						

Table 2-1: Fulcrum at CM of stick and one mass located on each side

8. Calculate the "turning effect" or *torque* on each side (*Torque = lever arm x F* or $\tau = r \times F$) and record your results in Table 2-2 below.

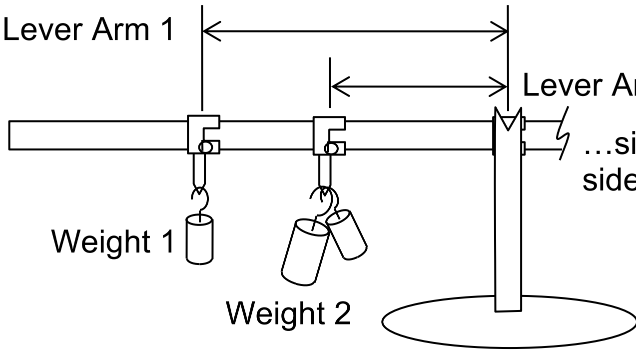
Trial	Left Side Torque (Nm)	Right Side Torque (Nm)
1		
2		
3		

Table 2-2: Calculate torque on each side from Table 2-1

Question 2-4: For each of these trials, what do you notice about the torque on each side of the fulcrum when the stick is in balance? Is this what you expected? Why or why not?

Activity 2-2: Adding Multiple Torques

Suppose that in addition to a given weight hanging on one side of the fulcrum, you have another weight hanging at a second location on the same side of the fulcrum. When there is more than one force acting through a different lever arm, then the total torque on that side of the fulcrum is just the sum of the individual torques generated by each weight alone. The situation is illustrated in Fig. 3.



$Torque_{left\text{-}side}$ = $(Force\ 1)_{Left}$ x $(Lever\ Arm\ 1)_{Left}$ + $(Force\ 2)_{Left}$ x $(Lever\ Arm\ 2)_{Left}$

$Torque_{right\text{-}side}$ = $(Force\ 1)_{Right}$ x $(Lever\ Arm\ 2)_{Right}$ + $(Force\ 1)_{Right}$ x $(Lever\ Arm\ 2)_{Right}$

Figure 3: Calculation of Net Torque from Multiple Weights at Multiple Locations

In this part, you will make the meter stick balance when you have three or four masses hanging at different positions. You will use two masses at two different locations on the left side and one mass somewhere on the right side in Trial 1 and in Trial 2 you will use two masses at two different locations on the left side and two masses at two different locations on the right side as shown in Fig. 4 below.

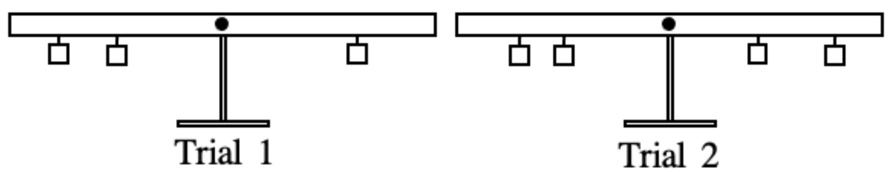


Figure 4: Set-ups for Activity 2-2

1. Using three mass values of your choice, set up the meter stick so that it balances as shown for Trial 1.

2. Record your data in Table 2-3 and complete the calculations for the total torque on each side of the fulcrum.

3. Repeat steps 1 and 3, using four mass values of your choice so that the meter stick balances as shown for Trial 2.

4. For each trial, calculate the total torque on each side of the fulcrum and record your result in Table 2-4 below. (See Fig. 3 for guidance in calculation of the total torque.)

Trial	Side	Mass 1 (kg)	Force 1 (N)	Lever Arm 1 (m)	Mass 2 (kg)	Force 2 (N)	Lever Arm 2 (m)
1	Left						
	Right				0	0	0
2	Left						
	Right						

Table 2-3: Fulcrum at CM of stick and multiple masses at multiple locations.

Trial	Side	Torque 1 τ_1 (Nm)	Torque 2 τ_2 (Nm)	Total Torque $\tau_1 + \tau_2$ (Nm)
1	Left			
	Right			
2	Left			
	Right			

Table 2-4: Calculating total torque.

Question 2-5: How do the total torques on each side of the fulcrum compare when the stick is in balance? Is this what you expected? Why or why not?

Activity 2-3: Off-Center Fulcrum

In this part, you will move the fulcrum off the center-of-mass (say to the 20 cm or 30 cm mark on the meter stick) and perform three trials.

Question 2-6: With the fulcrum off-center and no additional weights attached, what should happen to the meter stick when placed on the pivot? What does this suggest about the torque on each side of the fulcrum?

The three situations that are to be tested are shown in Fig. 5 below.

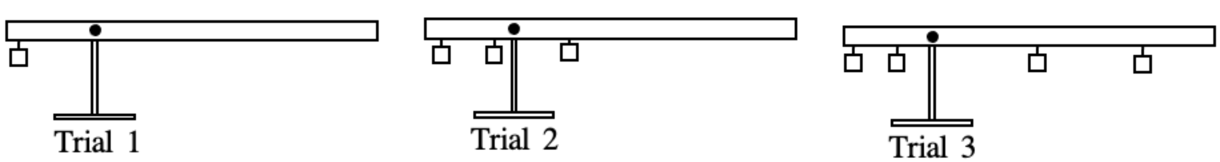


Figure 5: Set-ups to use in Activity 2-3.

1. Remove all the mass hangers and the pivot and measure the mass of your meter stick. Record this mass in Table 2-5.

2. Choose an off-center location (at least 20 cm from the center-of-mass of the meter stick) to position the fulcrum. Record the distance between the location of the fulcrum and the center-of-mass of the meter stick.

3. Add a single mass in such a way that the meter stick will balance as shown in Trial 1 of Figure 5. Record the data for Trial 1 in Table 2-5.

4. Set up the situations as shown in Trial 2 and Trial 3 of Figure 5 and record your data. For Trial 2, use two masses (different locations) on the left side and one mass on the right side. For Trial 2, use two masses (different locations) on each side.

NOTE: In Tables 5 and 6, each Trial assumes that the right side of the stick is the longer side when the fulcrum is off-center.

Question 2-7: Why do you suppose you need to measure the mass of the meter stick and the distance that the fulcrum is from the center-of-mass?

Question 2-8: Why do you suppose that it was unnecessary to measure the mass of the meter stick in Activity 2-1 and Activity 2-2?

Mass of meter stick: m_{stick} = ______ kg				Weight of meter stick: W_{stick} = _______ N			
Center-of-mass of meters tick: CM = ______ m							
Distance between center-of-mass of meter stick and the "off-center" fulcrum: $D_{cm,f}$ = ________ m							
Trial	Side	Mass 1 (kg)	Force 1 (N)	Lever Arm 1 (m)	Mass 2 (kg)	Force 2 (N)	Lever Arm 2 (m)
1	Left				0	0	0
	Right	0	0	0	0	0	0
2	Left						
	Right				0	0	0
3	Left						
	Right						

Table 2-5: Fulcrum moved away from CM of meter stick

5. Calculate the torque caused by the meter stick itself and record the value in Table 2-6 below.

6. For each trial, calculate the total torque on each side of the fulcrum and record your result in Table 2-6.

	Torque due to meter stick: (W_{stick}) x ($D_{CM,f}$) = _______Nm (Be sure to add this torque to whichever side is longer)				
Trial	Side	Torque 1 (Nm)	Torque 2 (Nm)	Torque due to meter stick (Nm)	Total Torque (Nm)
1	Left		0	0	
	Right	0	0		
2	Left			0	
	Right		0		
3	Left			0	
	Right				

Table 2-6

Question 2-9: How do the torques on each side of the fulcrum compare when the stick is in balance? Is this what you expected? Why or why not?

Activity 2-4: Newton's Second Law

Up to now in this Investigation, we have only talked about the torques (moments) on the meter stick since it is allowed to freely rotate.

Question 2-10: Does Newton's Second Law apply in this case to the meter stick in Activity 2-3? If not, what stops it from applying? If it does, what can we say about the net force on the meter stick?

Draw a free-body diagram of the meter stick in Trial 3 of Activity 2-3 in the space below.

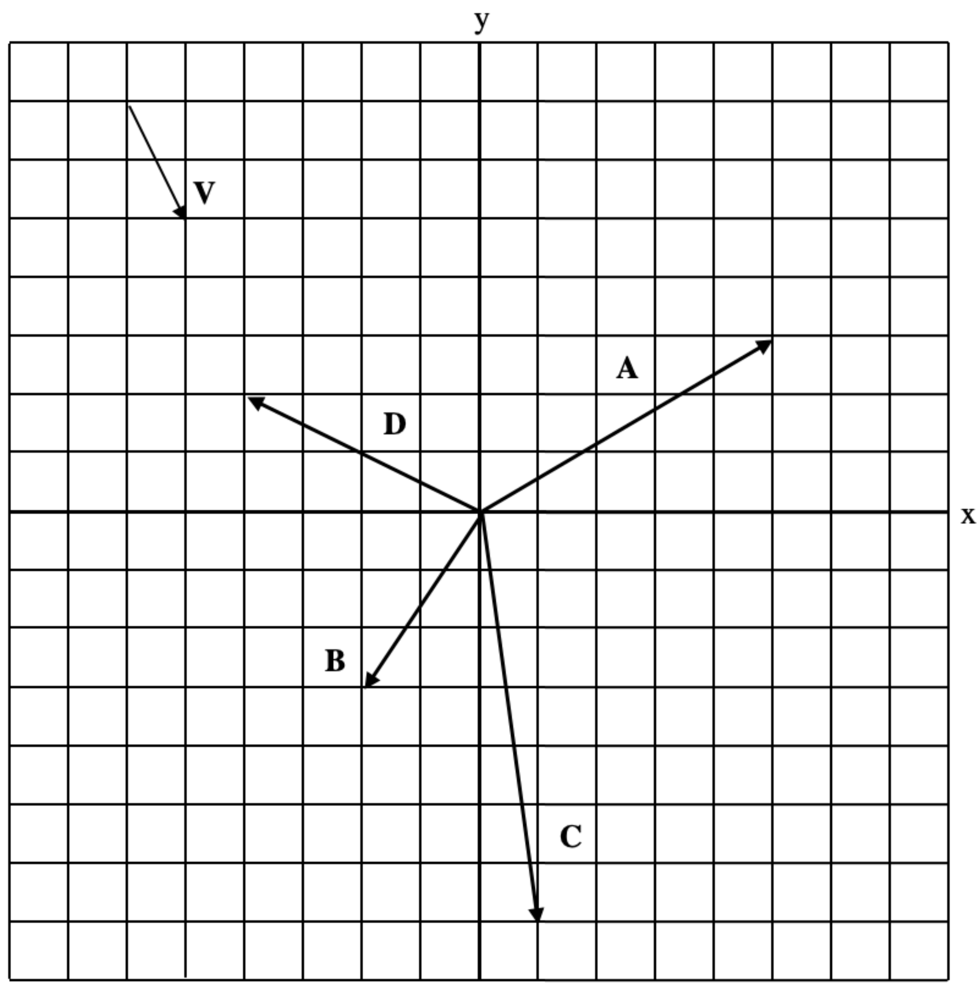
Name________________________________Date____________________Partners______________________________

HOMEWORK FOR LAB 11: EQUILIBRIUM

Part I: Vectors

Questions 1-3 refer to the vectors shown on the grid below.

1. Consider some arbitrary vector quantity, **V**, that is represented the arrow shown. Sketch an arrow showing what the vector 2**V** looks like in comparison to **V**. Then sketch an arrow showing what the vector (–½)**V** looks like in comparison to **V**.



2. In the grid above, sketch the resultant vector **R** when vectors **A** and **D** are added and then determine the horizontal and vertical components of **R**.

R_x = ____________ R_y =

3. In the grid above, sketch the resultant vector **Q** when vector **C** is subtracted from vector **B** and then determine the horizontal and vertical components of **Q**.

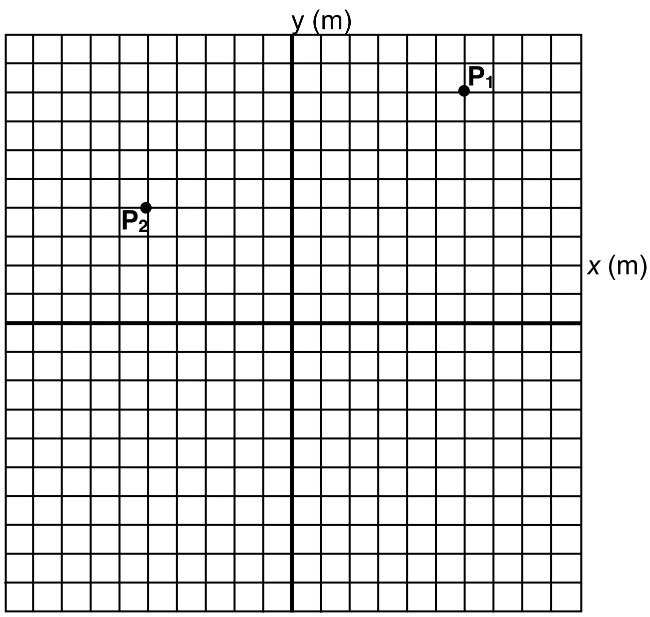
Q_x = ____________ Q_y = _________

Questions 4-6 refer to the grid shown below.

4. At a certain time, an object is at the position ***P_1*** as shown on the grid below. Carefully sketch the position vector of the object on the grid.

5. The object now moves from ***P_1*** to the new location at ***P_2*** as shown. Carefully sketch the new position vector and the displacement vector, ***ΔP***.

6. What are the horizontal and vertical components of each of the three vectors described above? (Don't forget the units!) Fill in the table below the grid.



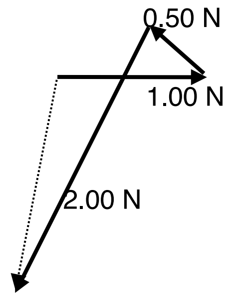
Vector	Horizontal Component	Vertical Component
P_1		
P_2		
ΔP		

7. Is it possible to add vectors that correspond to different physical quantities and get a resultant? (For example, can you combine a force vector with a position vector?)

Part II: Translational Equilibrium

We would like to introduce a concept called the polygon of forces, first used by Squire Whipple, an American engineer who developed the technique of analyzing a truss and put his ideas into a foundational 1847 book on bridge building.

1. Using graph paper, a ruler, and a protractor, for each of the five situations you examined using the force tables, carefully add the force vectors (pictorially and to scale) acting on the ring by starting with one on the forces and then adding the others one by one in a "head-to tail" fashion. Do this on your own separate sheet of graph paper and use the same scale (1N=2cm) provided in Activity 1-1. Using the numbers from the example described in beginning of Activity 1-1, the answer would look like the diagram shown at right. The dashed line is the resultant of the three forces.

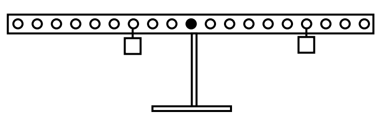


2. For each of the five situations, what do you notice about the resultant force after all the individual force vectors are added? Is this consistent with the observation that the ring remained in static equilibrium? Why or why not?

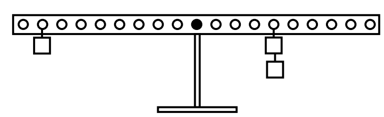
Part III: Rotational Equilibrium

1. Based on your results, determine whether the arrangements shown below will balance. (Assume each individual weight is identical.) If the system does not balance, carefully sketch where you would have to place a weight to restore balance.

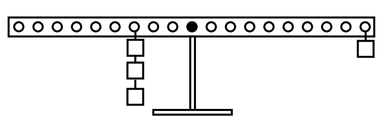
A. Balances? ____ Yes ____ No



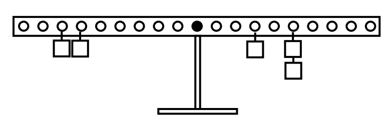
B. Balances? ____ Yes ____ No



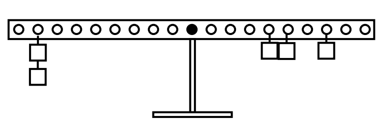
C. Balances? ____ Yes ____ No



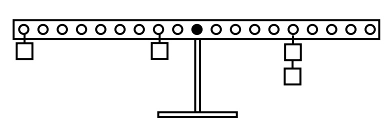
D. Balances? ____ Yes ____ No



E. Balances? ____ Yes ____ No

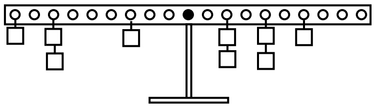


F. Balances? ____ Yes ____ No

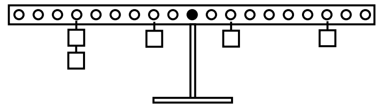


2. In each example below, is it possible to add just one weight somewhere to keep the system in balance? If so, show where would you place it. If not, why not?

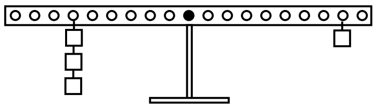
A.



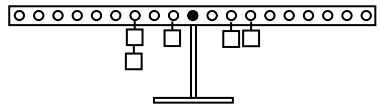
B.



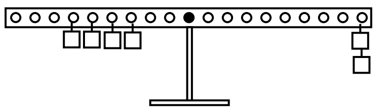
C.



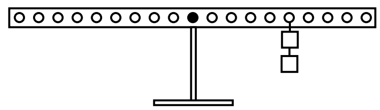
D.



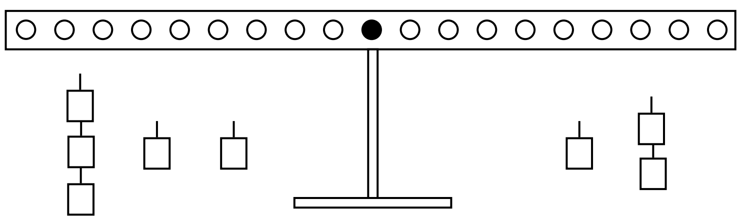
E.



F.

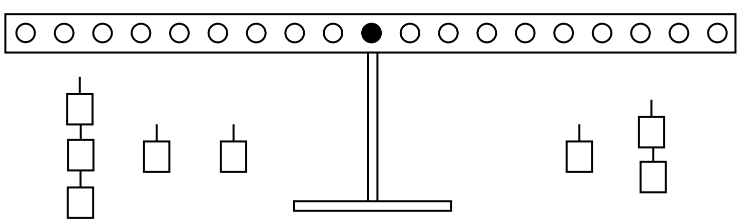


3. Find three different ways to hang the weight arrangements shown below to make the system balance. Sketch your arrangements below.



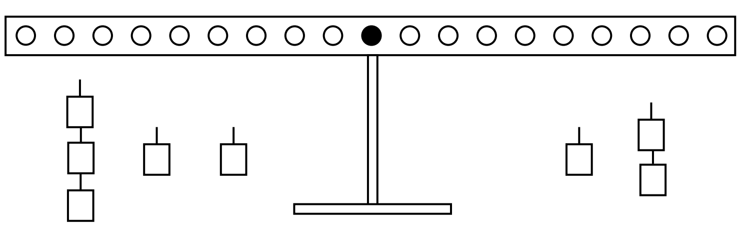
Keep these arrangements as shown on this side.

Keep these arrangements as shown on this side.



Keep these arrangements as shown on this side.

Keep these arrangements as shown on this side.

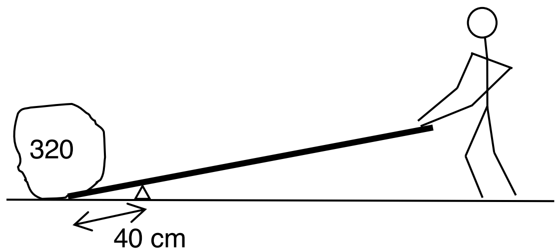


Keep these arrangements as shown on this side.

Keep these arrangements as shown on this side.

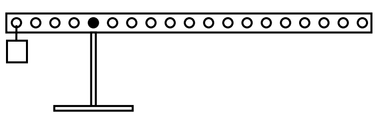
4. If a 1.0 kg mass (including the hanger) is hung 5 cm from a pivot (which is centered on a meterstick), is it possible to balance the meterstick with a total mass of 50 g on the other side? If so, where do you have to place the 50 g. If not, why not?

5. Suppose you needed to move a boulder that weighs 320 N. You have a rigid bar that is 2.0 m long to use as a lever. You place one end of the bar under the stone with a fulcrum 40 cm from the stone. If you push on the other end of the lever, how much force will you need to exert. Ignore the weight of the lever for this exercise.

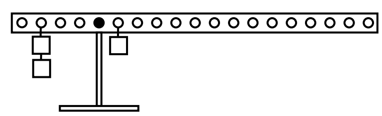


6. For the systems shown below, the pivot is shifted to the locations shown. If the stick has weight equal to that of 1 weight, determine whether the system is in balance. For each system which is not in balance, can you add just one weight to restore balance? If so, where would you place it? If not, why not?

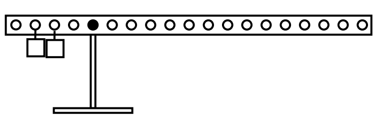
A. Balances? ____ Yes ____ No



B. Balances? ____ Yes ____ No



C. Balances? ____ Yes ____ No



D. Balances? ____ Yes ____ No