Lab 3: Work and Energy

I. Before you come to lab...

II. Background

III. Introduction

A. This lab is about work, and how work connects force and energy. As a playground for these ideas, we will continue to explore the system we saw last week in the Gauss gun. The interaction of the magnet and balls is in some ways a "mystery" interaction, because we don't know what the force law is or what the potential energy is. However, we can tell that there is energy associated with that interaction, because it appears that the magnetic interaction can be a source of kinetic energy. So there is a potential energy function for the magnetic interaction. Even though we don't have a way of measuring energy directly, we can use our understanding of work to get at the potential energy by measuring the magnetic *force* at different distances. Once we know the energies, we can explain why the kinetic energy changes so much in the operation of the Gauss gun, as we saw last week.

B. Objectives for this lab:

- **1.** Understand the relationship between work and force
- **2.** Understand the relationship between work and energy
- **3.** Explore the role of work in the context of conservation of energy
- **4.** Determine the difference in potential energy between two different configurations

IV. Materials

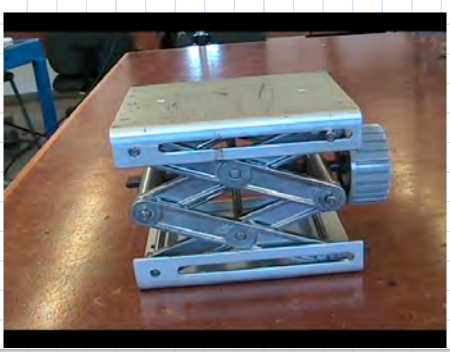
A. Force sensor

- **1.** The force sensor is a small box with a hook that can measure the forces applied to the hook. It is mounted on a horizontal bar.

- **2.** The force sensor connects to the computer via the LabPro interface and the data can be read into a computer using the Logger Pro software. The sign of the force reading is considered to be positive if you pull on the hook, and negative if you push on it.
- **3.** There is a switch on the force sensor which toggles between force ranges of ±10 N and ±50 N. The ±10 N setting has higher sensitivity and is more desirable to use most of the time, but if you are measuring forces larger than 10 N, obviously you will have to use the ±50 N setting. When you flip the switch, Logger Pro will ask you to either change it back or use the sensor setting; click the option to use the sensor setting.

B. Lab jack

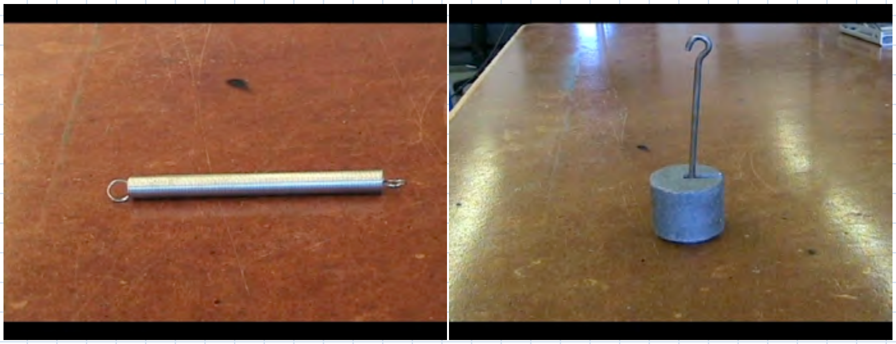
- **1.** This is a simple piece of equipment that enables you to adjust the height of a small platform.



2. The height of the jack can be controlled by turning the knob on the side.

C. Spring and mass stand with hook

1. The spring is just a coiled spring. It can be stretched, but not compressed.



2. The mass stand and masses can be used to stretch the spring.

D. Magnet and steel ball bearings

1. These are the same magnets and ball bearings that you used last week in the Gauss gun.
2. Today we'll be using them to explore force, work, and energy.

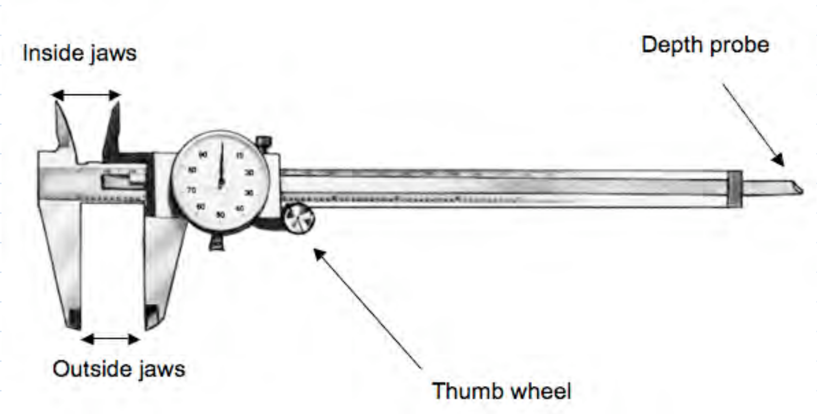
E. Tubing clamp

1. The tubing clamp consists of a clear plastic tube open at both ends, and a clamp to tighten around the tube.

2. We'll use the tubing clamp in this lab to hold one ball and one magnet. There are two possible configurations: either the magnet is on the end and the ball is on the inside (as shown in the diagram), or the ball is on the end and the magnet is on the inside. Both configurations will be used in the lab (for different measurements); but in either case, you should make sure to clamp both the ball and the magnet inside the tube, so that neither one can be removed without undoing the clamp.

F. Dial caliper

1. A caliper is a device for measuring small distances very precisely:



2. The caliper has three measuring modes: outside jaws that you can use to measure the thickness of something; inside jaws that you can use to measure the size of an opening (the inner diameter of a pipe, for instance); and a depth probe that you

can use to measure the depth of a hole. The jaws can be moved with the thumb wheel until they fit the distance being measured. Then the linear scale along the caliper indicates the length roughly, and the dial indicates the length much more precisely.

3. For the calipers we will be using in the lab, the dial spins once every 2 mm, and the smallest tick mark on the dial corresponds to a change of 0.02 mm.

G. Shim stock

1. These are simply pieces of aluminum or plastic cut to a certain thickness. You can use them to separate the magnet from a ball by a certain amount. (Unlike steel, aluminum does not affect the magnetic interaction.)
2. You can use the caliper to measure the thickness of each piece of shim.

V. Procedure

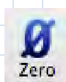
A. Before you begin:

1. Take a picture of yourselves using Photo Booth and drag it into the space below:

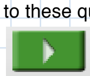
2. Tell us your names:

B. Playing around with the force sensor

1. Open the file Lab3.cmbl in Logger Pro.
2. Set the force sensor to the ±50 N range.
3. You should see a digital meter in the lower left which is the reading on the force sensor. Watch what happens when you push or pull on the hook of the sensor. What if you hang something from the hook? Which direction gives positive force readings, pushing or pulling?

4. Try clicking the 

button. What happens? Pull on the hook and click it again. What now? (You don't have to write answers to these questions; they're just things for you to notice and learn.)

5. Click the  Collect button and watch what happens to the Force vs Time graph on the right. Push or pull on the hook while it is collecting. The collection runs automatically for 10 seconds. You can, of course, just click the button again to collect more data.

6. When you are satisfied with your understanding of the force sensor, you can move on.

C. Work done by a spring

1. Turn to page 2 in the Logger Pro file.
2. Set up the force sensor so that the hook hangs downward about 40-50 cm higher than the table, and flip the range switch to the ±10 N setting. If Logger Pro complains about this change, click "Use the sensor setting" instead of "OK."
3. Hang the spring from the hook and then zero the force sensor by clicking the 

button.
4. Place 500 g on the mass stand and put it on top of the lab jack. Adjust the height of the jack so that you can hang the hook of the mass stand from the spring while the stand is still resting on the jack. The spring should be slightly stretched, as shown:

5. Measure the height of the lab jack above the table, and measure the spring force using the force sensor. The meter on the Logger Pro screen will probably jump around a little bit, but you can easily estimate it to the nearest 0.1 N.
6. Lower the lab jack (and everything on it) by 1 cm, and measure the force again, but make sure that the mass stand is still resting easily on the lab jack. (If the mass is hanging, raise the lab jack by 5 or 10 cm and start over.) Repeat until you have a total of five force measurements at 1 cm intervals.
7. Enter the data into the table on page 1 of your Logger Pro file. Distance = 0 corresponds to whichever height you started at, which is *not* the same thing as the relaxed position of the spring.
8. Make a graph of the force exerted by the spring versus distance and paste it below. (Scale the graph so that the relevant part of it is showing.)

9. Graphically calculate the following quantities. (Don't worry about uncertainties.)
   - **a.** The work required to stretch the spring from 0 to 2 cm

   - **b.** The work required to stretch the spring from 2 cm to 4 cm

   - **c.** Are these equal to each other? Why or why not?

10. Calculate the work done *by the spring* in stretching from 0 to 4 cm.

11. Consider the potential energy U_{spring}. What is the difference in U_{spring} between the initial (less stretched) position of the spring and its final (more stretched) position? (Hint: is there a relationship between ΔU and the work done by the spring?)

    In which position is the potential energy greater?

12. Save your work in both Logger Pro and NoteBook before moving on to the next part.

D. Force exerted by a magnet

1. Turn to page 3 of the Logger Pro file.
2. Remove the spring from the force sensor, and also put aside the mass stand and lab jack. With the force sensor on the ±10 N setting, hang the yellow string with the ball bearing from the hook of the force sensor and 

it.
3. Set up the magnet and ball in the tubing clamp such that the ball is on the outside and the magnet is below it, and clamp it

tightly. The tube should still hold the outer diameter of the ball snugly; only a small part of the ball needs to protrude from the end of the tube.

4.

Click the Collect button and watch what happens to the Force vs Time graph as you touch the tubing clamp to the hanging ball and then pull straight down. The force increases to match the force with which you pull, but only up to a certain maximum value, after which the ball is released and the force goes back to zero. *The maximum force reached before release* is equal to the magnetic force on the ball.

- **a.** Draw a FBD for the hanging ball and explain why this is true. (Hint: from your FBD, can you write an expression for the number read by the force sensor? Remember, the only force that the sensor knows about is the string force, but you zeroed the sensor when the ball was hanging. What does zeroing the sensor do?)

- **b.** Take a photo of your FBD and place it here:

5.

Every time you click Collect, you can take 10 seconds' worth of data. Touch the tubing clamp ball to the hanging ball and pull straight down until release at least three or four times during the 10 seconds, and compare the values of the peak force each time. They should be pretty similar, at least to within a few tenths of a newton. If they are not, do it over. (You can just click Collect again to take fresh data.)

6. Estimate, to the nearest 0.1 N, the average value of the maximum force from your 3-4 releases. Record this number in the table named "Magnet Ball Ball" on page 2 of the Logger Pro file, with a corresponding distance of 0.

7. Now repeat the measurement except this time, put a very thin shim between the two balls so that they don't quite touch. (You can start with the thinnest shim you have, which is a piece of clear plastic wrap.) You should see that the magnetic force at this small separation is slightly less than it was the first time. Measure both the force, using the method in step 5, and the separation distance (using the caliper to measure the thickness of your shim), and record it in the next row of the "Magnet Ball Ball" data table.

8. Continue repeating the measurements with thicker and thicker shims until the force finally drops to nearly zero. (If you want to get distances that are in between thicknesses available to you, you can fold the plastic pieces, or you can stack multiple shims together.)
Be careful—if you are using a rigid shim, as opposed to a floppy piece of cellophane, make sure you are not using the shim to push upwards on the hanging ball during the measurement. The shim should never be out of contact with the tubing clamp ball; otherwise the thickness of the shim will not be equal to the separation distance during your force measurement. Record all of your measurements in the same data table. You should end up with about 5-8 data points total.

9. Now unclamp the tube and switch the order of the magnet and ball inside, so that the magnet is on the outside and the ball is below it. The top of the magnet should stick out slightly from the edge of the tube.

10. Repeat the measurement process (steps 5-8) for this configuration, except this time you'll populate the lower data table, called "Ball Magnet Ball." NB: you will find that the attractive force in this configuration is much larger, in fact, larger than the 10 N range of the force sensor. So you will need to set the force sensor to the ±50 N setting. After you flip that switch, Logger Pro will complain again (tell it "Use sensor setting"), and you'll need to Zero the force sensor again with the ball hanging freely.

11. Because the attractive force is much larger in this configuration, you'll need to use thicker and thicker shims before the force drops off to zero. However, you don't need to take quite as many data points at very short separation distances. Again, 5-8 data points is sufficient, although they will be at larger separation distances than in the first data table.

12. Save your work before moving on to the next part.

E. Work done by a magnet

1. Now turn to page 4 of the Logger Pro file.

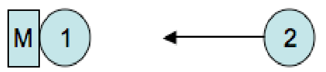
2. You'll see both of your data tables that you populated with your measurements in the previous part. Create graphs of magnetic force vs separation distance for both configurations, magnet-ball-ball and ball-magnet-ball. Paste those graphs here:

- **a.** Magnet-ball-ball

- **b.** Ball-magnet-ball

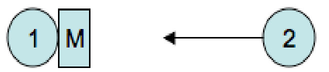
3. Using your graphs, calculate the following quantities:

- **a.** the *work done by the magnetic force on ball 2* as the separation decreases from very far away to zero, like so:



$W_{mag \rightarrow 2}$ =

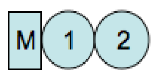
- **b.** the *work done by the magnetic force on ball 2* as the separation decreases from very far away to zero, like so:



$W_{mag \rightarrow 2}$ =

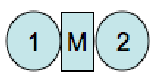
4. Consider the magnetic potential energy U_{mag}, which depends on the separation distance and the ordering of the objects. Suppose we define U_{mag} to be equal to zero when the magnet+ball 1 are together, very far away from ball 2.

- **a.** What is U_{mag} for this configuration? (Be careful about signs!)



U_{mag}(magnet ball ball) =

- **b.** What is U_{mag} for this configuration?



U_{mag}(ball magnet ball) =

F. Putting it together

- **1.** Now calculate the *difference* in potential energies between the two configurations:
  $\Delta U_{mag} = U_{mag}$(magnet ball ball) - U_{mag}(ball magnet ball) =

  Is this quantity positive or negative? Is that what you expected?

- **2.** Compare the magnitude of this number to the amount of extra kinetic energy that "appeared" when you fired the Gauss gun in last week's lab. (Don't worry about uncertainties; rough comparisons are fine.) Can you explain, using concepts of energy, what happens during the operation of the Gauss gun and why the second ball comes out so fast?

- **3.** Suppose you had made very careful measurements of ΔK in the Gauss gun last week, and ΔU_{mag} this week, with very small uncertainties. Which of the following findings would surprise you when comparing the magnitudes of ΔK and ΔU_{mag}? Why?

  - **a.** $|\Delta K| < |\Delta U_{mag}|$
  - **b.** $|\Delta K| = |\Delta U_{mag}|$
  - **c.** $|\Delta K| > |\Delta U_{mag}|$

- **4.** Hopefully your answer to the question 2 involved the conservation of mechanical energy (including magnetic potential energy). Suppose we wanted to use the same tools (magnets, balls, video camera, force sensor, etc.) to make an *independent* verification of the conservation of mechanical energy. Propose and briefly describe a different experiment that you could perform with the same equipment.

VI. Conclusion

- **A.** Submit your lab report online according to the instructions on the plastic sheet at your computer.
- **B. Super-duper important—don't even think about skipping this step!** Before you leave the lab, every member of your lab group should open a browser and go to
  http://physci.fas.harvard.edu/~yourFASusername
  and make sure that your lab report is there under the link called "Lab 3." If not, then you haven't submitted it correctly; ask a TF for help. If your lab report isn't submitted, you won't get credit for doing the lab.