Physics 200B Lab 7
Work and energy

OBJECTIVES

- To extend the intuitive notion of work as physical effort to a formal mathematical definition of work, W, as a function of both the force on an object and its displacement.
- To develop an understanding of how the work done on an object by a force can be measured.
- To understand the concept of kinetic energy and its relationship to the net work done on an object as embodied in the *work-kinetic energy principle.*

OVERVIEW

Two new concepts are useful in studying various types of physical interactions: work and energy. In this lab, you will begin the process of understanding the scientific definitions of work and energy, which are somewhat different from the way these words are used in everyday language. You will first consider the work done on an object by a constant force. There are, however, many cases where the force is not constant. For example, the force exerted by a spring increases the more you stretch the spring. In this lab you will learn how to measure and calculate the work done by any force that acts on an object (even a force that changes with time).

Energy (and the concept of conservation of energy) is a powerful and useful concept in all the sciences. You will begin the study of energy in this lab by considering kinetic energy—a type of energy that depends on the velocity of an object and its mass. By comparing the change of an object's kinetic energy to the net work done on it, it is possible to understand the relationship between these two quantities in idealized situations. This relationship is known as the *work-kinetic energy principle.*

INVESTIGATION 1: THE CONCEPT OF PHYSICAL WORK

Note: All of the definitions of work in this unit apply only to very simple objects that can be idealized as point masses or are essentially rigid objects that don't deform appreciably when acted on by a force. The reason for limiting the definition to such objects is to avoid considering forces that cause the shape of an object to change or cause it to spin instead of changing the velocity or position of its center of mass.

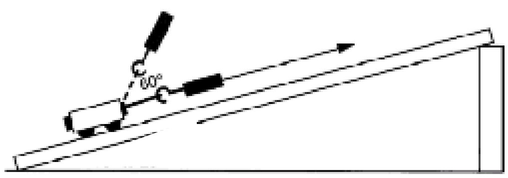
If such an object experiences a constant force, the *work* done by that force is defined as the scalar (dot) product of the force and the displacement of the center of mass of the object. Thus, when the force and displacement are not parallel, the work is calculated by $W = Fd\cos\theta$, where W represents the work done by the force, F is the force, d is the displacement of the center of mass of the object, and θ is the angle between F and d. Note that if the force and displacement are in the same direction, the *work done by the force is positive.* On the other hand, a force acting in a direction opposite to displacement does *negative work.* For example, an opposing force that is acting to slow down a moving object is doing *negative work.*

Activity 1-1: Calculating Work When the Force and Displacement Lie Along the Same Line and When They Don't

In this activity you will measure the force needed to pull a cart up an inclined ramp using a force probe. You will examine two situations. First you will exert a force parallel to the surface of the ramp, and then you will exert a force at an angle to the ramp. You will then see how to calculate the work when the force and displacement are not in the same direction.

1. Open the experiment file called **Force and Work (L11Al-2).** This will enable you to display force data for a time interval of 10 s.

2. Set up the force probe, cart, and ramp as shown in the diagram below. Attach a short string (about 15 cm) to the front of the cart and make a loop in its end for the force probe. Support one end of the ramp so that it is inclined to an angle of about 10°.



3. Hook the force probe through the loop in the string. **Zero** the force probe without pulling on the string. Begin graphing force vs. time as you pull the cart up the ramp slowly at *a constant velocity.* Pull the cart so that the string is always *parallel to the ramp.* Pull the cart a measured distance along the ramp, say 1.2 m.

4. Store your data (Experiment/Store Latest Run) so that the graph remains **persistently displayed on the screen** for comparison to the next graph.

Prediction 1-1: Suppose that the force is not exerted along the line of motion but is in some other direction. If you pull the cart up along the same ramp in the same way as before (again with a constant velocity), only this time with a force that is not parallel to the surface of the ramp, will the force probe measure the same force, a larger force, or a smaller force?

Now you'll test your prediction by measuring the force needed to pull the cart up along the ramp at a constant velocity, pulling at an angle of 60° to the surface of the ramp.

5. **Zero** the force probe without pulling on it. Attach it to the loop in the string as before. Measure the 60° angle with a protractor. Begin graphing force as you pull the cart up at a slow constant speed as shown in the diagram above. Be sure the cart does not lift off the surface of the ramp, and keep the force probe at a 60˚ angle as shown so that the string pulls straight out on the force probe hook.

6. Use the **analysis and statistics features** in the software to find the average (mean) force applied to the cart in both cases during the time intervals when the cart was moving with a constant velocity. Do not include the force to get the cart moving. Also record the distance you pulled the cart along the surface.

Average force pulling parallel to surface: _________N ; standard deviation: _________N

Average force pulling at 60° to the surface: __________N; standard deviation: ________N

Distance pulled: ___________+/-__________ m

Question 1-1: Was the average force measured by the force probe significantly different when the cart was pulled at 60° to the surface than when the cart was pulled parallel to the surface? Did the result agree with your prediction?

Question 1-2: In a physics sense, was more work done when pulling the cart over this distance with a force parallel to the incline, a force at 60º to the incline, or was it roughly the same? Support your answer with a calculation (include uncertainty).

Question 1-3: Explain, using one of Newton's Laws, why you had to pull with a constant force in order to keep the cart moving at a constant velocity in this case.

! Checkpoint 1

INVESTIGATION 2: WORK DONE BY CONSTANT AND NONCONSTANT FORCES

Many forces in nature are not constant. A good example is the force exerted by a spring as you stretch it. In this investigation you will see how to calculate work and power when a nonconstant force acts on an object.

You will start by looking at a somewhat different way of calculating the work done by a constant force by using the area under a graph of force vs. position. It turns out that, unlike the equations we have written down so far, which are only valid for constant forces, the method of finding the area under the graph will work for both constant and changing forces.

Activity 2-1: Work Done by a Constant Lifting Force

In this activity you will measure the work done when you lift an object from the floor through a measured distance. You will use the force probe to measure the force, and the motion detector to measure distance.

1. The motion detector should be on the floor, under its protective cage, pointing upward.

2. Open the experiment file called **Work in Lifting (L11A2-1).** This will allow you to display velocity and force for 10 s.

3. **Zero** the force probe with the hook pointing vertically downward. Then hang a 200-g mass from its end, and tape an index card to the bottom of the mass to serve as a reflector for the ultrasound. Begin graphing and lift the mass at a slow, constant speed through a distance of about 1.0 m, starting at least 0.5 m above the motion detector.

Question 2-1: Did the force needed to move the mass depend on how high it was off the floor, or was it reasonably constant? Does this make sense?

4. Change to a force vs. position graph by clicking on the “time” label on the horizontal axis of the force graph and selecting “position.”

5. Use the **analysis and statistics features** of the software to find the average force over the distance the mass was lifted. Record this force and distance below.

Average force: ____________N Standard deviation: ______________ N

Distance lifted: ____________+/-____________m

6. Calculate the work done by you in lifting the mass. Show your calculation and include units and uncertainty.

Work done:

7. Notice that force times distance is also the area of the rectangle under the force vs. position graph. Find the area under the curve directly by using the Analyze|Integral function in the software.

Area under force vs. position graph:

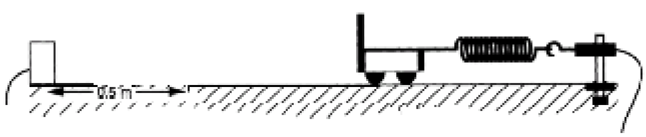
Question 2-2: How do the two calculations of the work compare? Would you agree that they're calculating the same thing?

Comment: The area under the force vs. position curve always gives the correct value for work done by the force, even when the force is not constant. (If you've studied calculus you may have noticed that calculating the work by finding the area under the force vs. position graph is the same as integrating the force with respect to position.)

Activity 2-2: Work Done by a Nonconstant Spring Force

In this activity you will measure the work done when you stretch a spring through a measured distance. First you will collect data for force applied by a stretched spring vs. distance the spring is stretched, and you will plot a graph of force vs. distance. Then, as in Activity 2-1, you will be able to calculate the work done by finding the area under this graph.

1. If you haven't already, lower the end of the ramp so it's horizontal. Set up the cart, motion detector, force probe, and spring as shown in the diagram. If your position data looks poor, you may want to tape an index card to the cart to get better reflections for the motion sensor.



Comment: We assume that the force measured by the force probe is the same as the force applied by the cart to the end of the spring. This is a consequence of *Newton's third law.*

2. Open the experiment file called **Distance Graphs** (L01A1-1a) and move the cart around while collecting data to be sure that the motion detector sees the cart over the whole distance of interest, from the position where the spring is just unstretched to the position where it is stretched about 0.5 m.

3. Open the experiment file **Stretching Spring** (L11E2-2) to display force vs. position axes.

4. **Zero** the force probe with the spring hanging loosely. Then pull the cart along the track until the spring is stretched about 0.5 m. Then begin graphing force vs. position and use your hand to make the cart move with a fairly slow, constant velocity away from the motion detector until the spring is unstretched. (Keep your hand out of the way of the motion detector.) Be sure the graph goes all the way to the point where the spring is unstretched.

Question 2-3: Compare this force vs. position graph to the one you got lifting the mass in Activity 2-1. Is the spring force a constant force? Describe any changes in the force as the spring becomes less stretched.

Question 2-4: Can you use the equation $W = Fd\cos\theta$ for calculating the work done by a nonconstant force like that produced by a spring?

5. Use the Analyze|Integral function in the software to find the work done in stretching the spring and record it below.

Work by force (area under force vs. position graph):

6. The work done by the spring should also be equal to $\frac{1}{2}kx_i^2 - \frac{1}{2}kx_f^2$, where k is the spring constant. Let's calculate the work using this equation and see if it agrees with the value found by taking the area under the force vs. position graph. First, read the beginning and ending (unstretched) position values from your graph:

beginning position:

ending (unstretched) position:

Now determine x_i and x_f (remember, both are measured from the spring's unstretched position):

x_i:

x_f:

Now we need the spring constant k. The spring constant is the ratio of the force F needed to stretch the spring a distance x to the amount of stretch ($k=F/x$). Use the force probe to stretch the spring a measured distance (say, 20 cm), and measure the force needed to do so. Record the amount of stretch and the force, and calculate the spring constant.

Amount of stretch:

Force needed to stretch spring:

Spring constant:

Now we can calculate the work done by the spring according to $W = \frac{1}{2}kx_i^2 - \frac{1}{2}kx_f^2$.

Work done by spring:

Question 2-5: Compare the work calculated in part 6 to the work found in part 5. Do the results of these two methods of finding the work done by the spring agree fairly well?

Question 2-6: Is the work done by the spring positive or negative? What does the sign mean in this case?

! Checkpoint 2

INVESTIGATION 3: KINETIC ENERGY AND THE WORK-KINETIC ENERGY PRINCIPLE

When an object moves, it possesses a form of energy because of the work that was done to start it moving. This energy is called *kinetic energy*. The mathematical formula is $KE = \frac{1}{2}mv^2$. The unit of kinetic energy is the joule (J), the same as the unit of work.

Activity 3-1: Your Kinetic Energy

In this activity you will examine how you can graph the kinetic energy of your body in real time.

Open the experiment file **Kinetic Energy (L11A3-2)** to display velocity and KE vs. time axes.

To display kinetic energy you will need to know your mass in kilograms. Use the fact that 1.0 kg weighs 2.2 lb on Earth to find your mass in kilograms.

Mass: _______________+/-_____________kg

Enter your mass in the kinetic energy formula by going under Data|Column Options|Kinetic Energy, and replacing the mass in the formula with your mass (**only change the number for the mass, all the other symbols and numbers should be left alone**). You are ready to record your velocity and kinetic energy as you walk. Begin graphing while walking away from the motion detector slowly, then more quickly, and then back toward the motion detector slowly and then more quickly.

Question 3-1: In what ways does the kinetic energy graph differ from the velocity graph? Is it possible to have negative kinetic energy? Explain.

Question 3-2: Consider a car moving along a road with a given speed. What would happen to its kinetic energy if your speed doubled? What would happen if its mass doubled?

! Checkpoint 3

When you apply a force to an object that has no other forces acting on it, the object accelerates. The force does work and the kinetic energy of the object increases. Clearly, there is some relationship between the work done on the object and the change in its kinetic energy. In the next activity, you will examine this relationship, called the *work-kinetic energy principle,* by doing work on a cart with a spring.

Activity 3-2: Work-kinetic energy Principle

1. Open the experiment file called **Work-kinetic energy (L11A3-3)** to display force and kinetic energy vs. position axes.

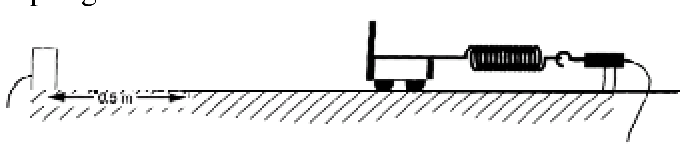
2. Measure and record the mass of the cart and flag (if being used), and enter this value in the formula for kinetic energy as before, by going under Data|Column Options|Kinetic Energy, and replacing the mass in the formula with the mass of the cart + flag.

Mass of cart and flag: ________________+/-_________kg

3. Set up the ramp, cart, flag (if needed), motion detector, force probe, and spring as shown in the diagram that follows.

4. Be sure that the motion detector sees the cart over the whole distance of interest- from the position where the spring is stretched about 0.5 m to the position where it is just about unstretched.

5. **Zero** the force probe with the spring hanging loosely. Then pull the cart along the track so that the spring is stretched about 0.5 m from the unstretched position.



6. Begin graphing, and release the cart, allowing the spring to pull it back to the unstretched position. Grab the cart before it hits the force probe!

Note that the top graph displays the force applied by the spring on the cart vs. position. It is possible to find the work done by the spring force for the displacement of the cart between any two positions. This can be done by finding the area under the curve using the Analyze|Integral function in the software, as you did earlier. The kinetic energy of the cart can be found directly from the bottom graph for any position of the cart using the Analyze|Examine feature.

7. Find the change in kinetic energy of the cart after it is released from the initial position (where the kinetic energy is zero) to a later position (don't go beyond the position where your hand began to stop the cart). Also find the work done by the spring up to that position. Record the values of work and change in kinetic energy in the table below. Repeat for a different pair of initial and final positions.

work (J)	initial KE (J)	final KE (J)	change in KE (J)

Question 3-3: How does the work done on the cart by the spring compare to its change in kinetic energy? Does this agree with the work-kinetic energy theorem?

! Checkpoint 4